Visualization and Analysis of Trajectories of Particles using Nuclear Emulsion and Microscopy

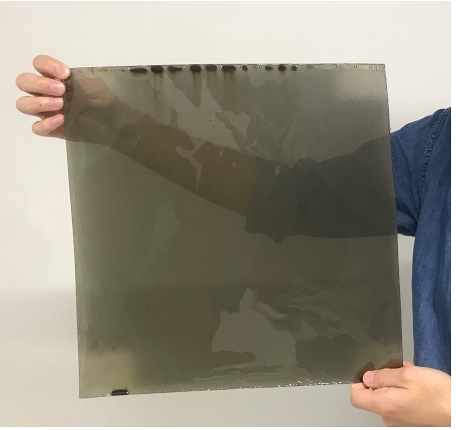
Ayumi Kasagi

Rikkyo University, Graduate School of Artificial Intelligence and Science

QBI 2023 09/29

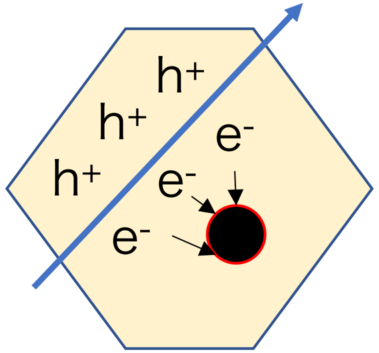
Photographic film: Nuclear emulsion

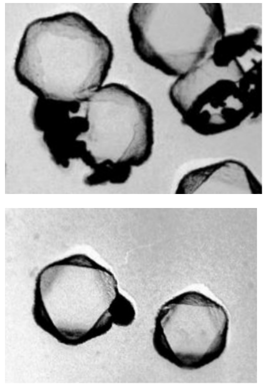
E07 type emulsion



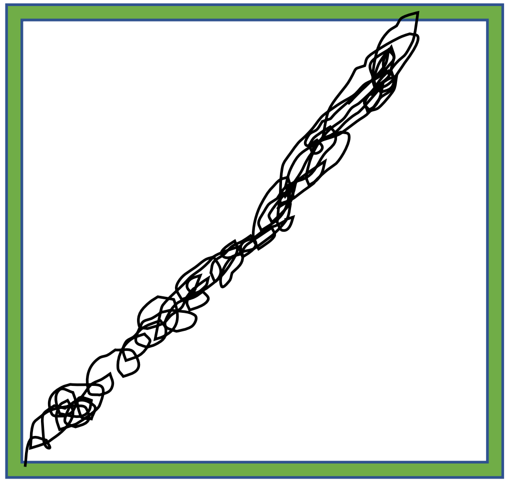
(35 cm × 35 cm × 0.6 mm)

AgBr Crystal
diameter =200 nm

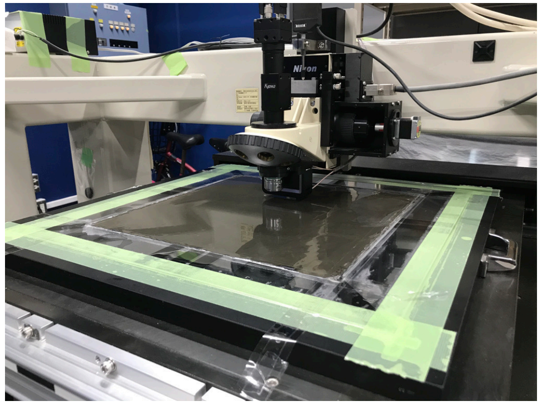




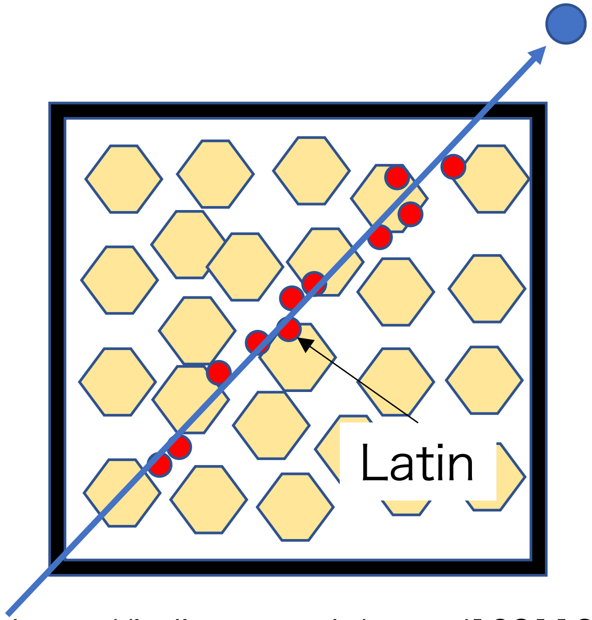
Semi-conductor
with 2.5 eV bandgap

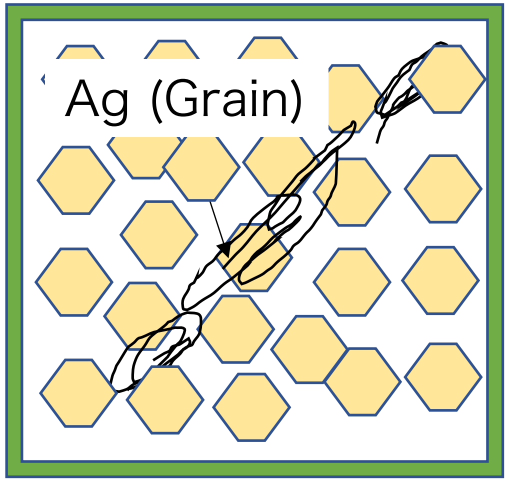


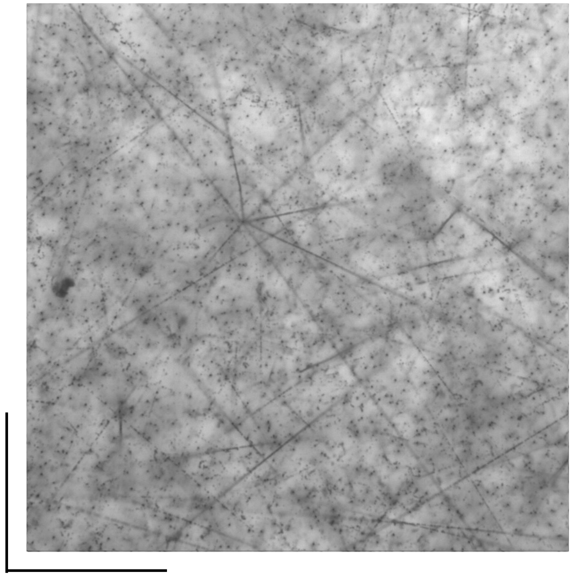
Scanning system



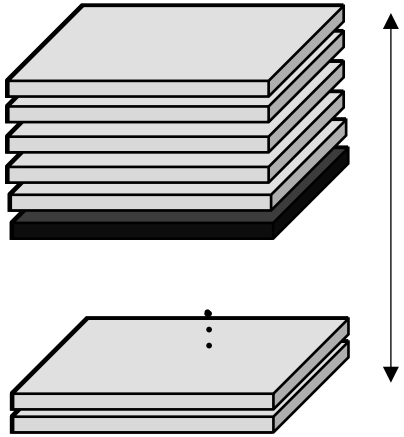
CMOS camera + LED light







100 μm

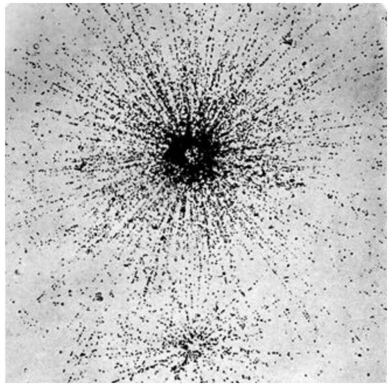


Spatial resolution: sub-μm

https://indico.cern.ch/event/1031127/contributions/4329924/attachments/2031548/3781284/EmulsionTechnology_EPNU.pdf

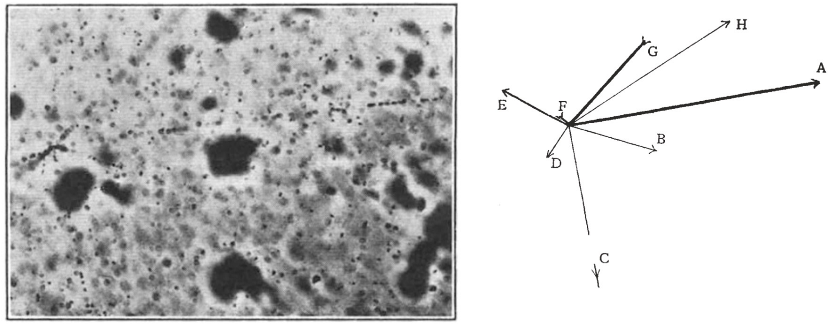
Pioneering observations with Nuclear emulsion

α-particles
(1915 S. Kinoshita et.al)



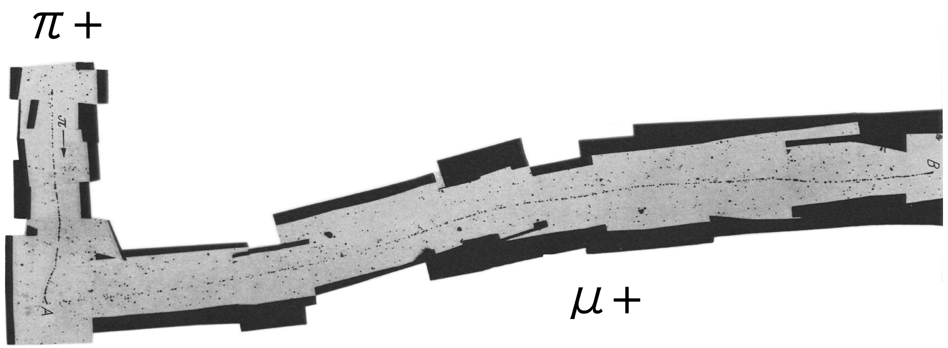
Philosophical Magazine and Jounal of Science Ser. 6, 29, 171, 420-425 (1915)

Cosmic-ray Interactions
(1937 M. Blau et al.)



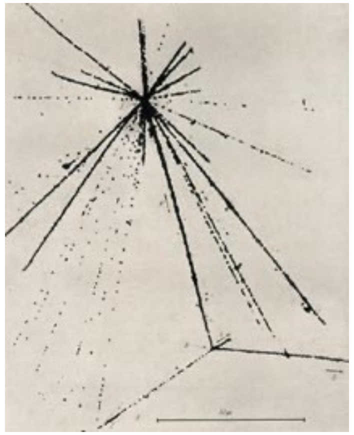
Nature 140, 585 (1937)

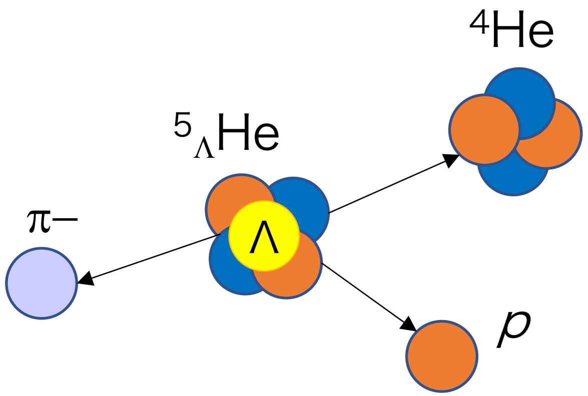
Meson particle ($\pi^+ \rightarrow \mu^+ + \nu_\mu$)
(1947 C. F. Powel et.al)



Nature 160, 453 (1947)

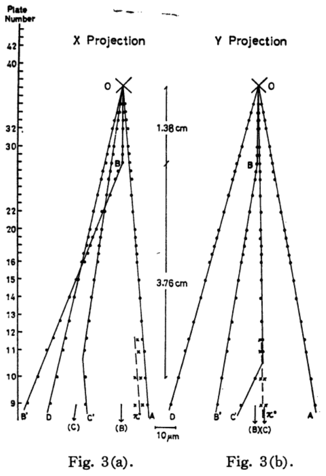
Hypernuclear weak decay
(1954 M. Danysz, J. Pniewski)

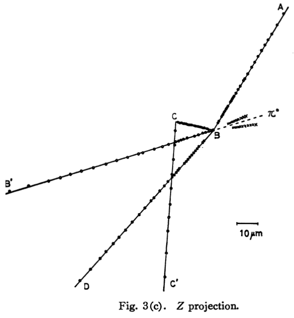




Phil. Mag. 44, 348 (1953)

Chramed particle (1971 Niu et.al)
$X(\Lambda_c^+) \rightarrow \pi^0 + p$ or $X(D^\pm) \rightarrow \pi^0 + \pi^\pm$





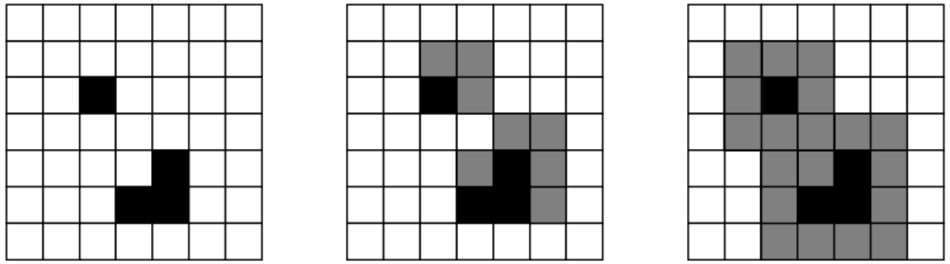
Prog. Theor .Phys., 46, 5 (1971)

Manual search with microscopes
～100 people ?

→ Automation was mandatry

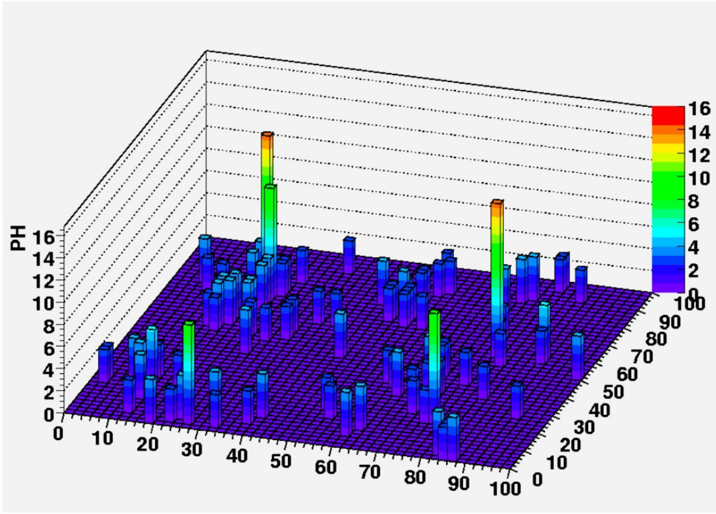
Track Selector Nagoya Univ. (F-Lab)

1.Clusterizing

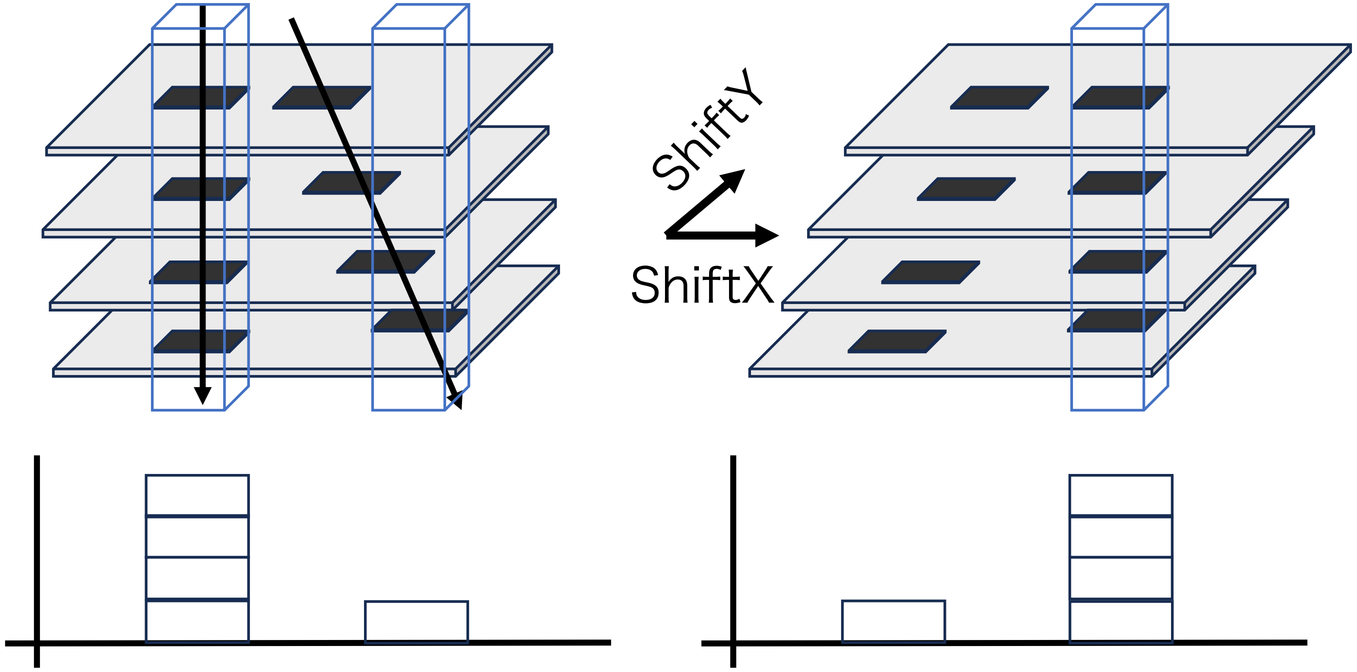


(a) 1x1　(b) 2x2　(c) 3x3

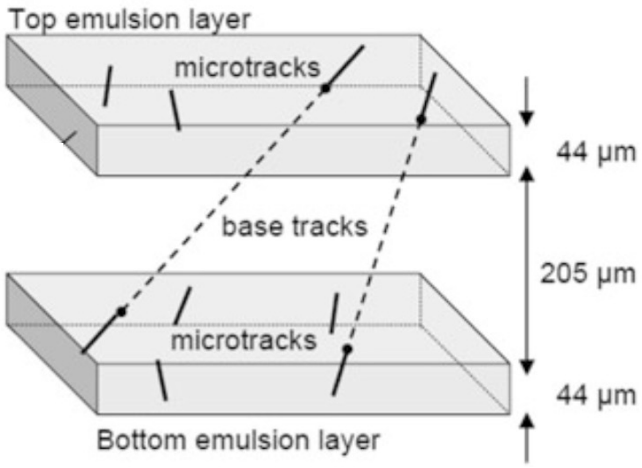
～1200 such procedures |tan θ| < 0.6



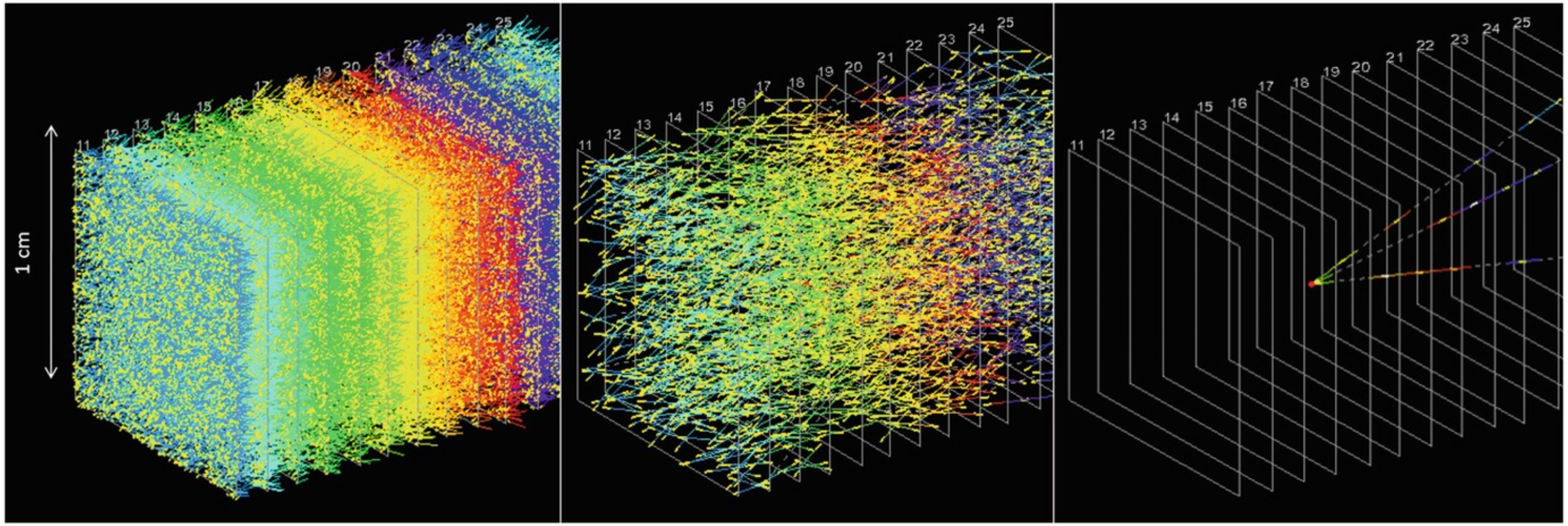
2. Reconstracting tracks in emulsion layers (Microtracks)



3. Reconstracting tracks in base (Base tracks)



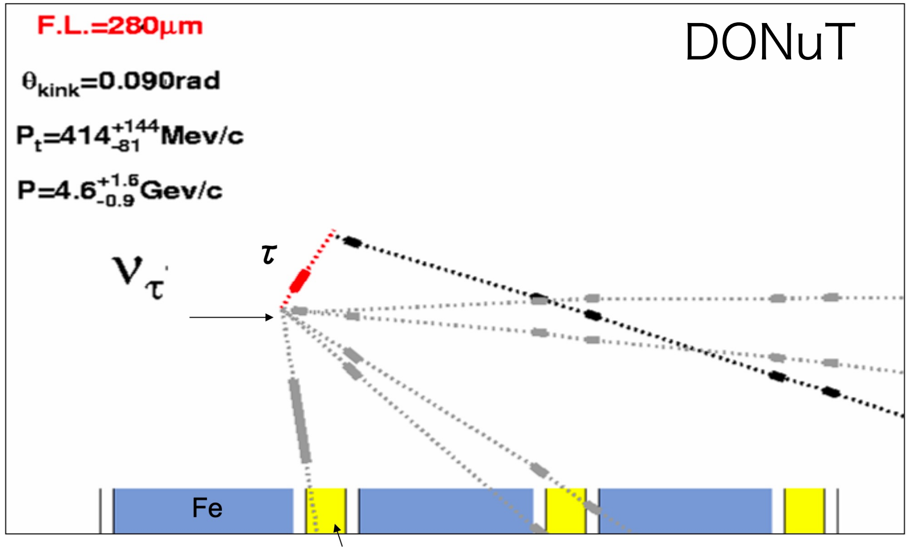
NET SCAN



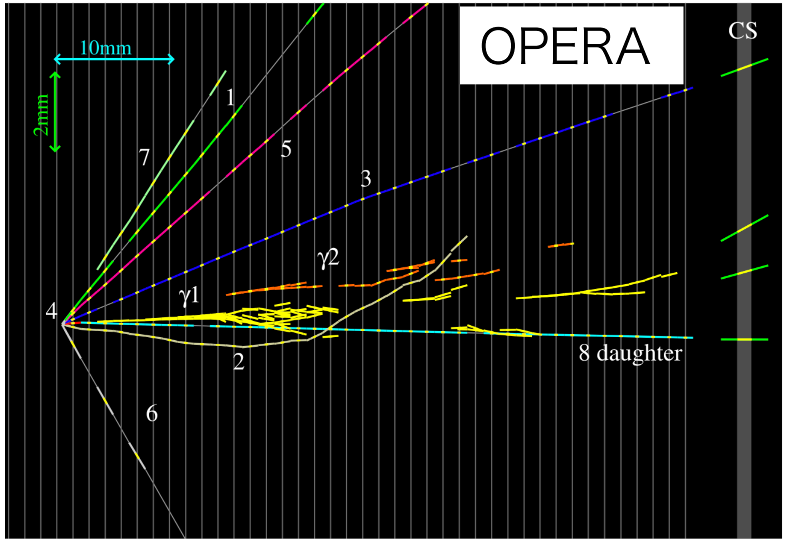
Particle Physics Reference Library pp 383–438

Connecting tracks in several tenth sheets

- Remove short tracks
- Remove penetrating tracks
- Search vertexies



PHYSICAL REVIEW D 78, 052002 (2008)



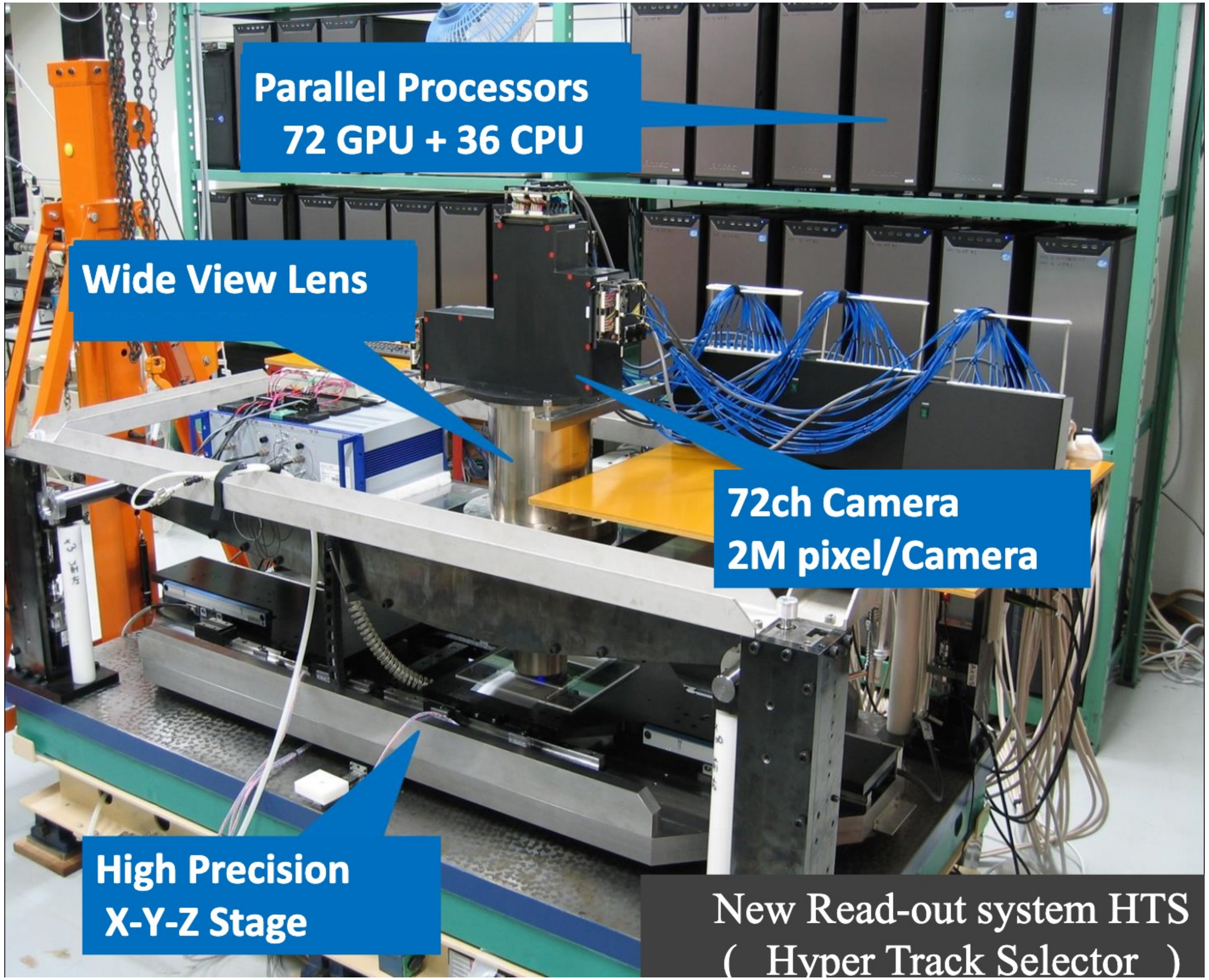
Physics Letters B 691 (2010) 138–1

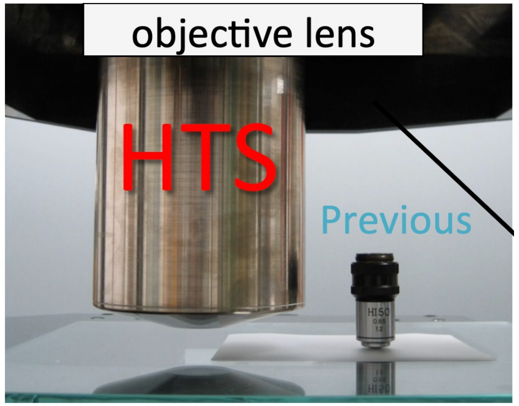
DONuT
9 ν_τ events/

OPERA
5 events of ν_τ
in 2 x 10^{20} ν_μ

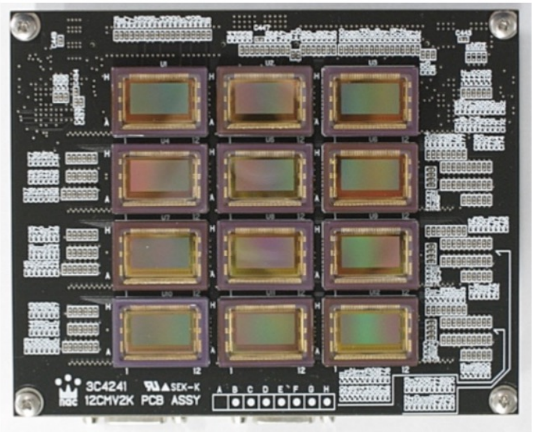
ν oscillation

Hyper Track Selector

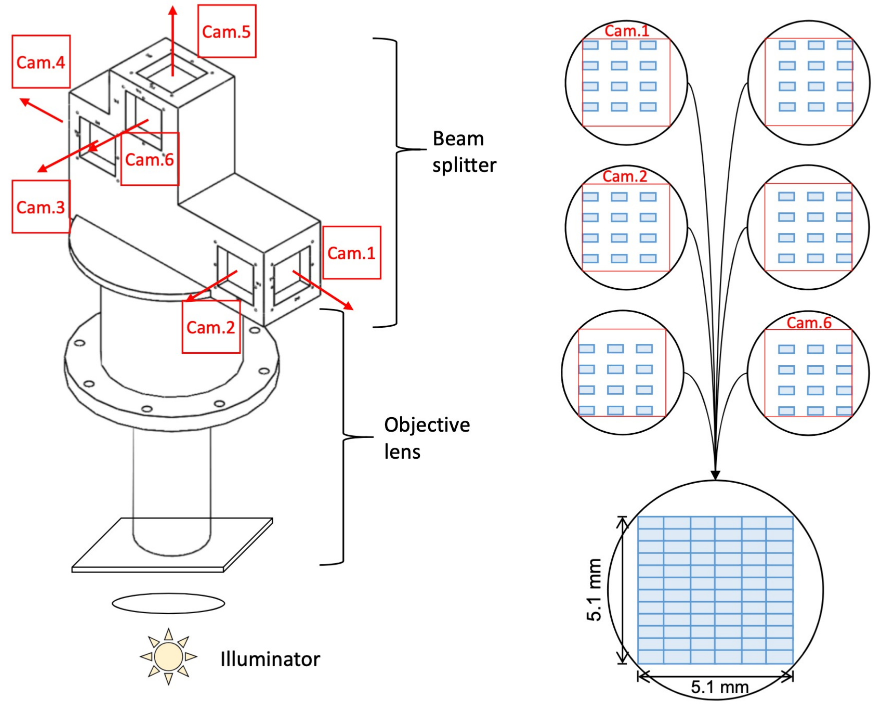




x 600 FOV (80 kg)



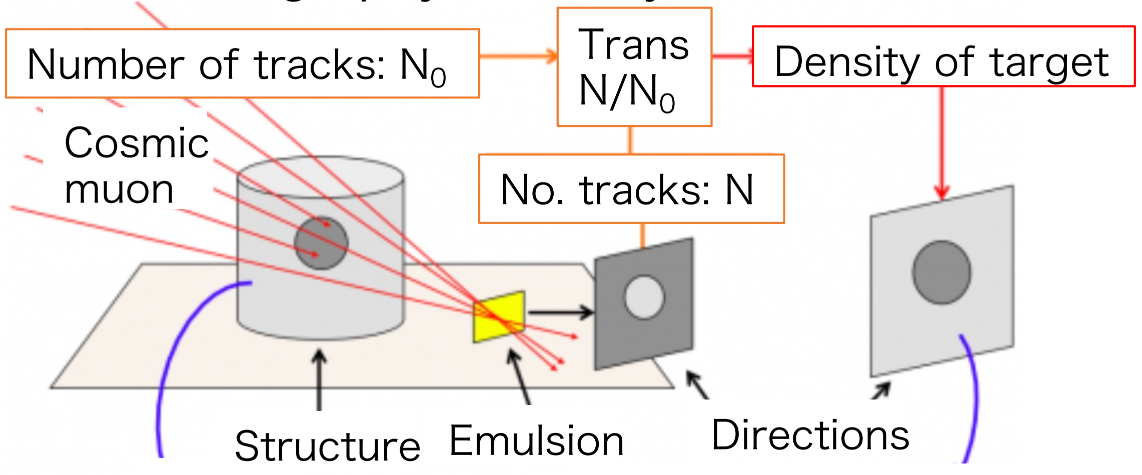
6 units: 72 sensors



M. Yoshiomto, Prog. Theor. Exp. Phys. **2017**, 103H01

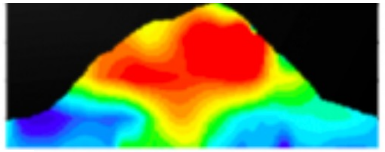
New application with Hyper Track Selector

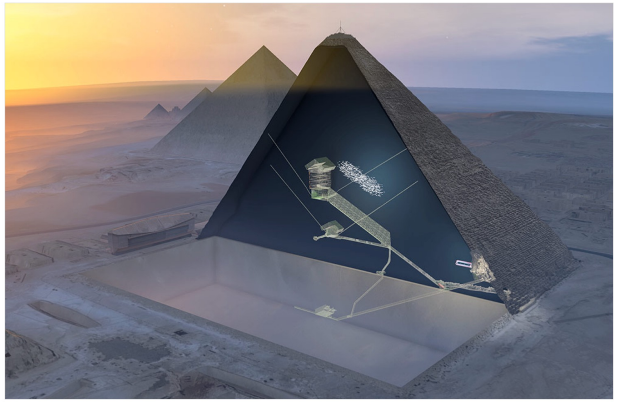
Muon radiography (Scan Pyramid)

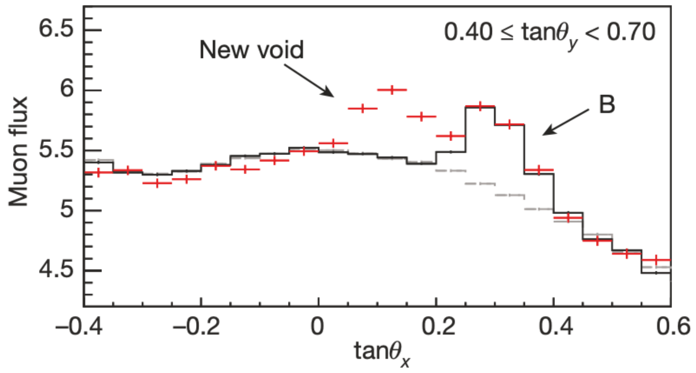


Photo

Muon imaging (densty)





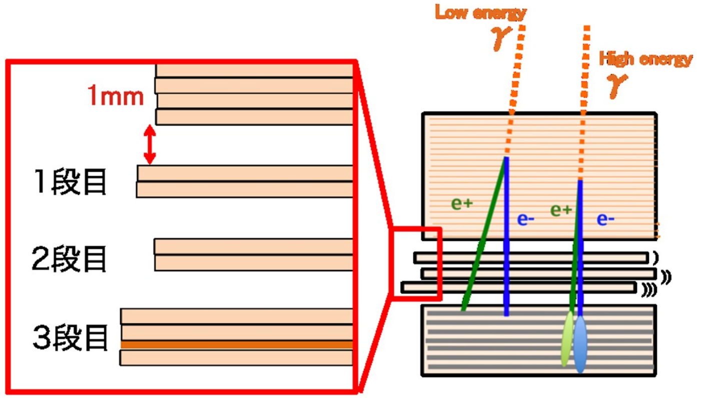


https://web-japan.org/kidsweb/hitech/17/pyramids_en.html

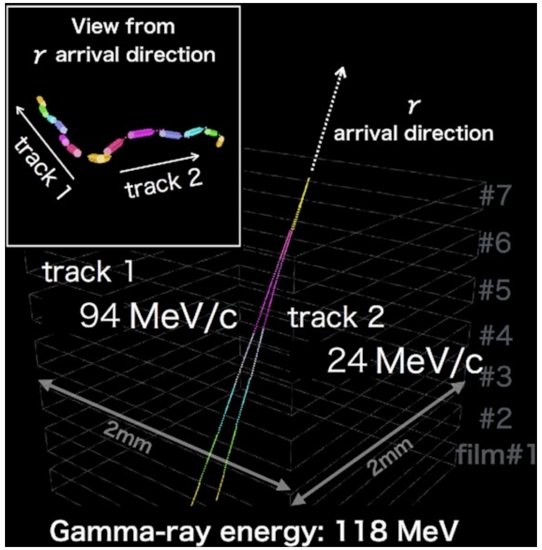
https://flab.phys.nagoya-u.ac.jp/2011/appli/muon/

GRAINE (Gamma- Ray Astro- Imager with Nuclear Emulsion)

balloon



Emulsion + time shifter



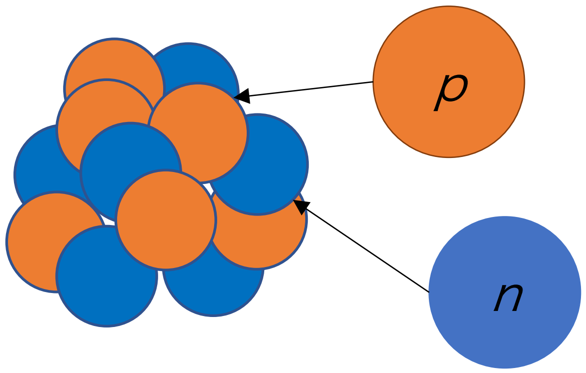
～10x better resolution than Fermi LAT to be achieved

https://flab.phys.nagoya-u.ac.jp/2011/appli/graine/

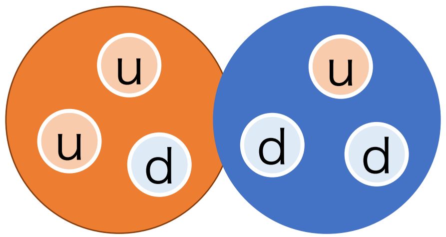
PTEP 2021,12, December 2021, 123H02

Automatic track following for Hypernuclear detection

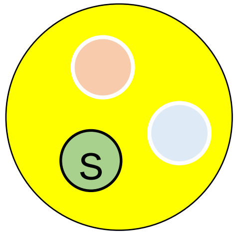
Bayon-Bayon interactions



Short-range
quark contribution?

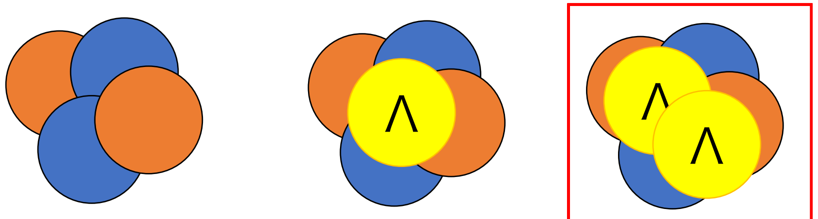


Hyperon
Λ (uds)



τ ≒ 262 ps
▲ Beam, target

Hypernuclei:
Bound state of nuclei and hyperons

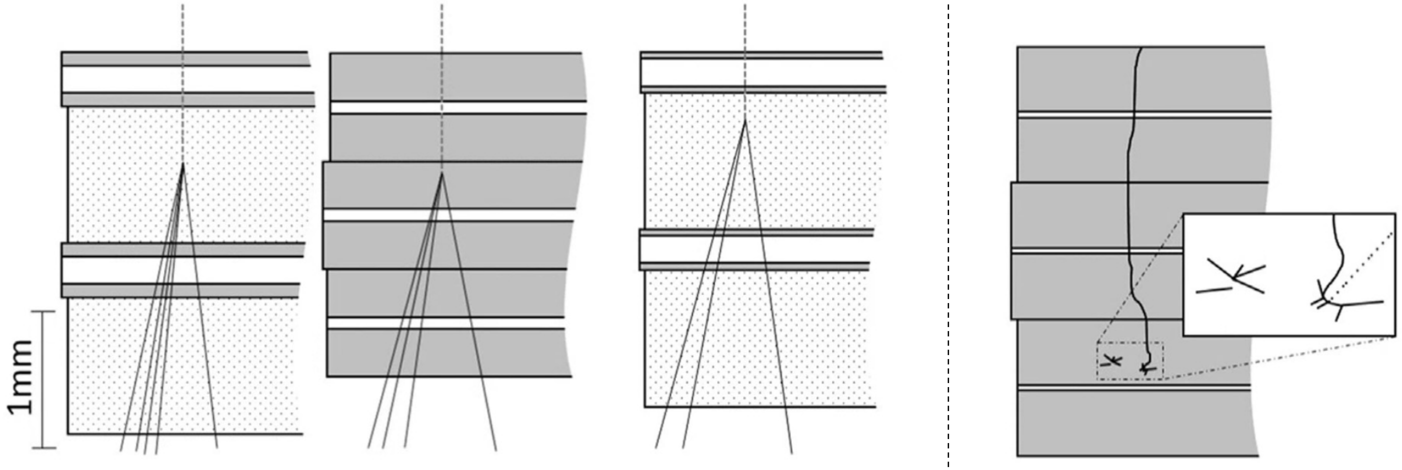


^{4}He $^{5}{}_{\Lambda}$He $^{6}{}_{\Lambda\Lambda}$He

Y-N, *Y-Y* interactions via
binding energy measurements

Detector configurations

<E_{ν}> 17 ~100 GeV <E_{Ξ^-}> ~0.15 GeV

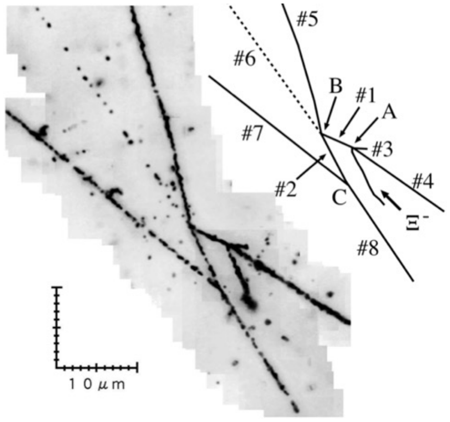


☐ Metal plate ▨ Emulsion layer ☐ Base film

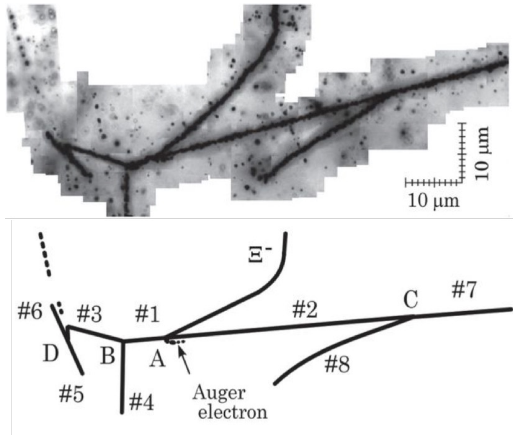
J. Yoshida et al., N.I.M. A 847 (2017) 86

Double strangeness production

$\Xi^- + p \rightarrow \Lambda + \Lambda$



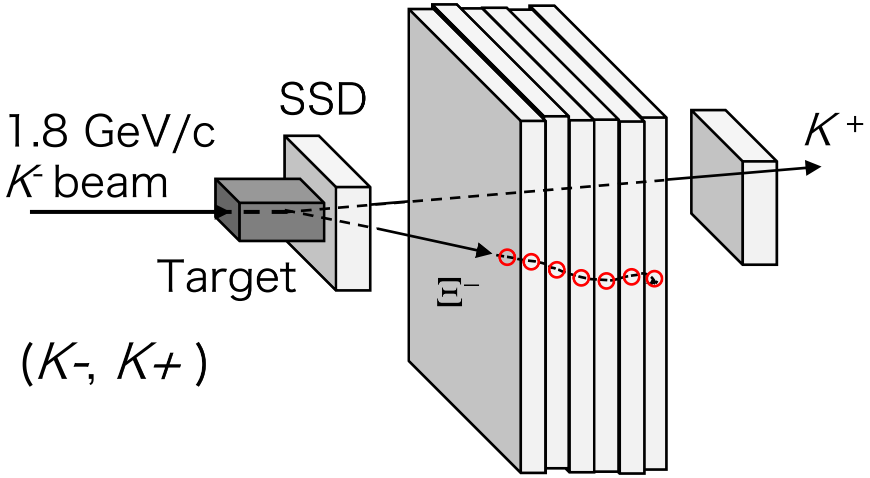
NAGARA



KISO

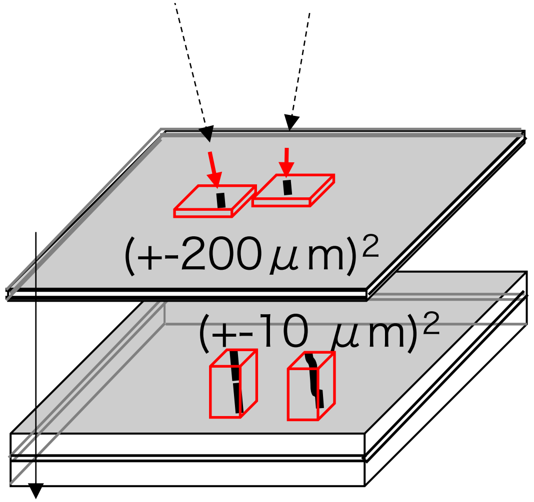
Hypernuclear detection

J-PARC E07: Search for double-strangeness hypernuclei



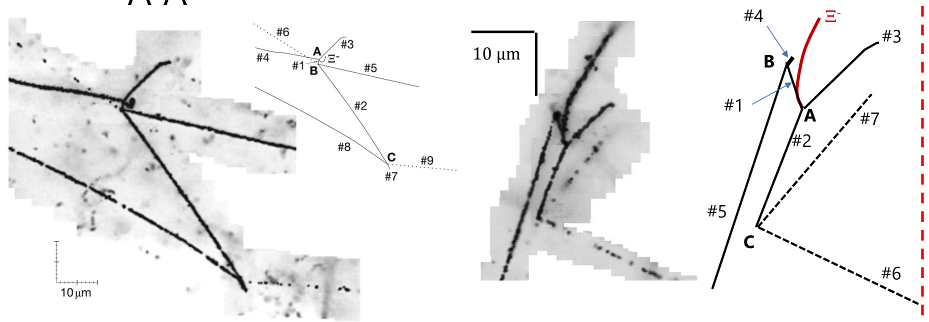
(K-, K+)

Reducing scan-area

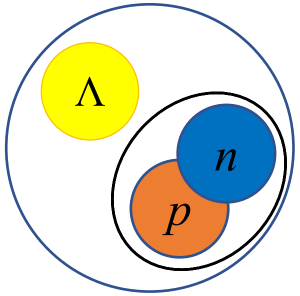


Cand. of double-strangeness: 33

$_{\Lambda\Lambda}{}^{11}$Be　　Ξ^-–^{14}N



H. Ekawa et al., PTEP, (2019)
A.N.L. Nyaw et al., BSPIJ, (2020)
S. H. Hayakawa et al., PRL, (2021)
M. Yoshimoto et al., PTEP, (2021)



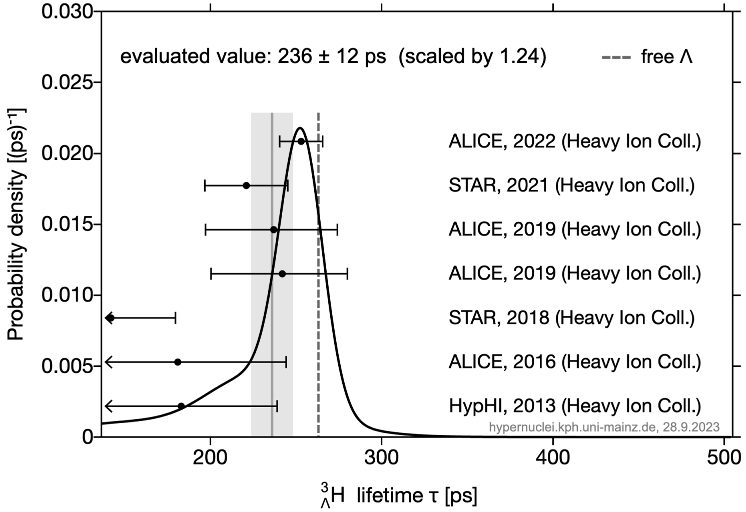
$^3{}_\Lambda$H: Hypertriton
Lightest &
Simplest

Binding energy (Λ-d)
B_Λ = 130 ± 50 keV (1973)

cf.) $^4{}_\Lambda$H ~2000 keV

τ ($^3{}_\Lambda$H) ≒ 262 ps ??

Heavy ion experiments



Short lifetime? How much bounding?

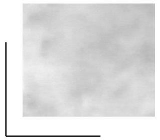
New experiments
For lifetime
GSI, RHIC, LHC, J-PARC, ELPH…

Binding energy
RHIC, LHC, MAMI-C, J-LAB, Emulsion

https://hypernuclei.kph.uni-mainz.de/

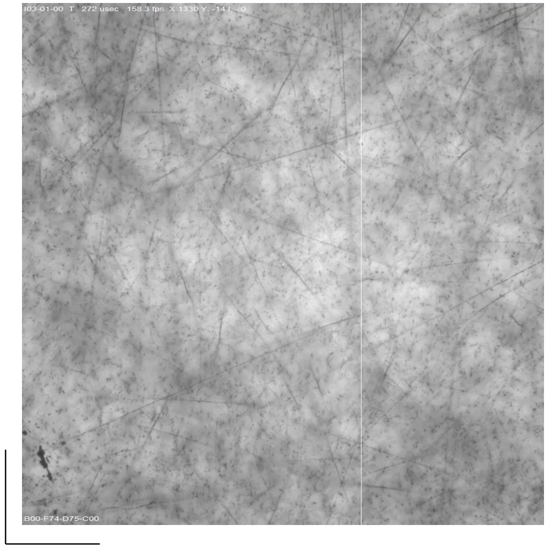
Overall scanning

Direct detection of hypernuclei

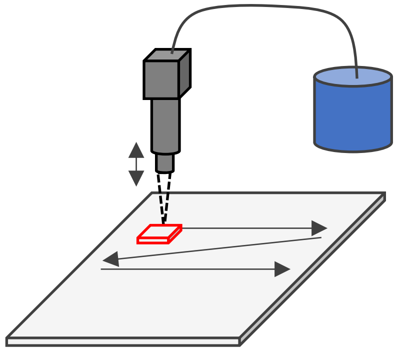


100 μm

Area: x18
Speed of Z: x2

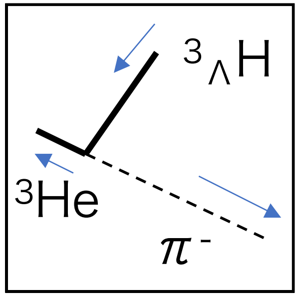


100 μm



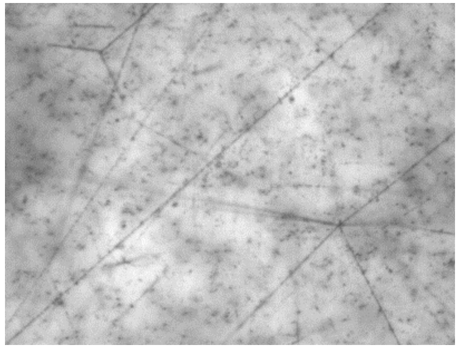
- 1300 emulsion sheets (E07)
- Independent from trigger condition

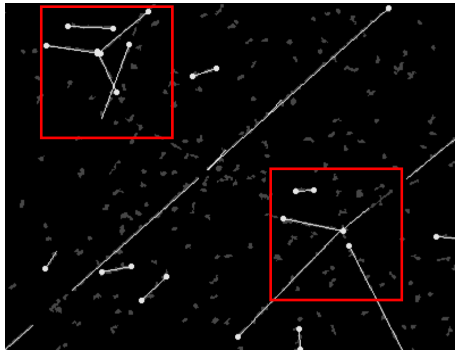
Double-straingeness: 10^3
Single-Λ: Several million



$^{3}_{\Lambda}\mathrm{H}(\text{at-rest}) \rightarrow {}^{3}\mathrm{He} + \pi^-$

Vertex picker: Line-detection

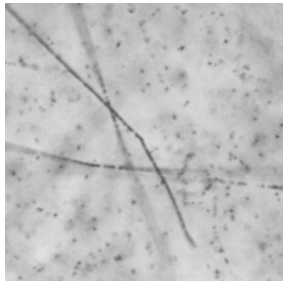




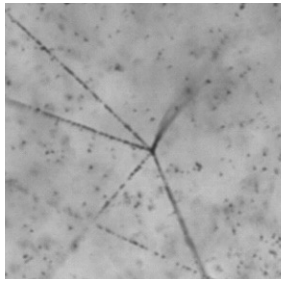
J. Yoshida, et al., N.I.M A, 847 (2017) 86-92

Background

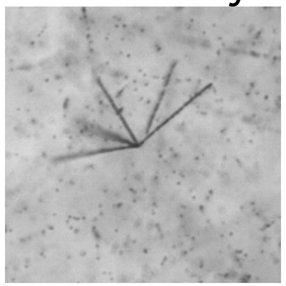
Cross



Interaction



α-decay



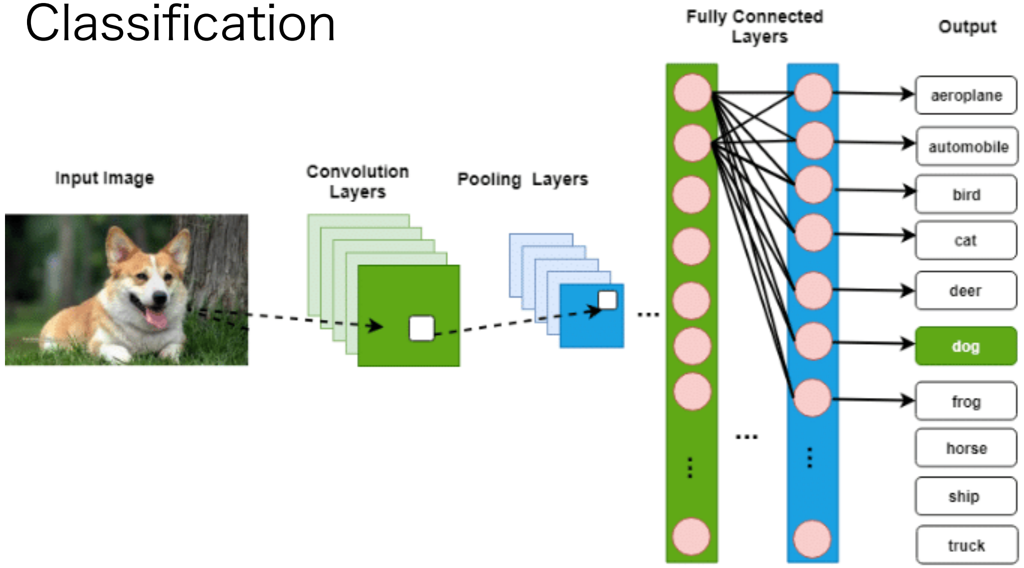
Natural RI
Th Serias

Data size:	140 PB
No. event:	10^9
Inspection:	560 years

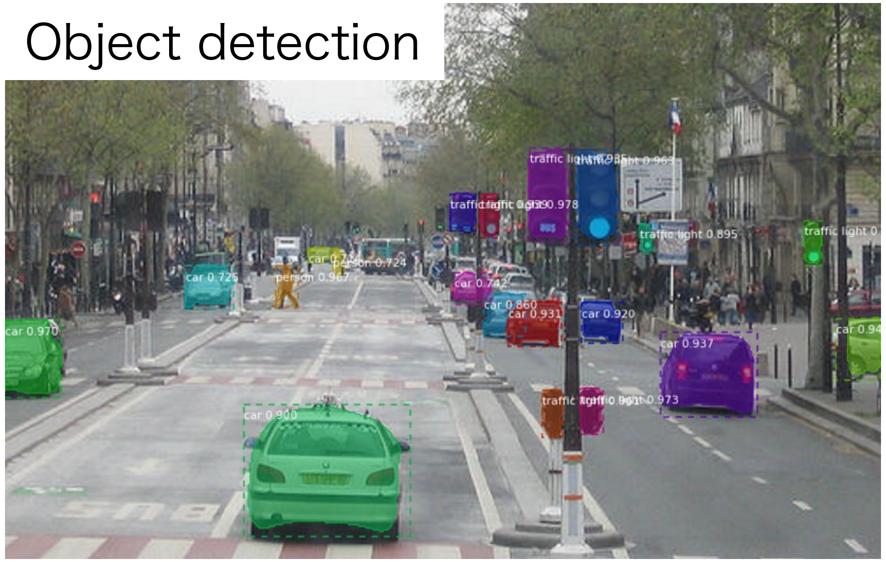
We needed Breakthrough

Machine-learning

Classification



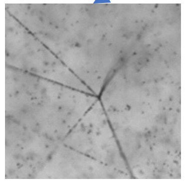
Object detection



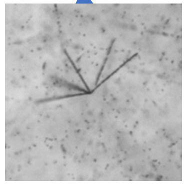
Auto pilot
Auto Payment
Security camera
…

Applications

Classification

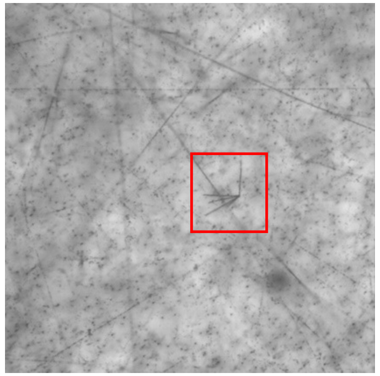


A



B

Detection



Training data: 10k～ images
→ For rare events

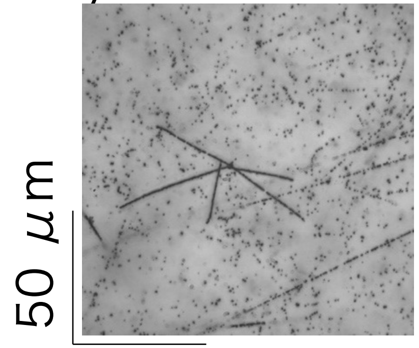
ML + Monte Carlo simulation

https://transcranial.github.io/keras-js/#/mnist-cnn
http://bdm.change-jp.com/?p=3983
A. Radvic et.al, Nature 560, 41–48 (2018)

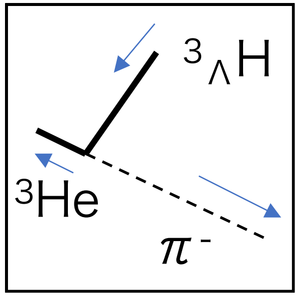
Strategy of developments

		Training data	Target
1st step ✓	Classifier with CNN Published as "J. Yoshida, et al., NIM A 989 (2021)164930"	Real images (Vertex picker)	α-decay
2nd step ✓	MC simulation + Object detection(ML)	Simulation	Calibration source
		Evaluation	
3rd step	Hypernuclear search	Simulation	$^{3}_{\Lambda}H$ (2-body decay)

α-decay



Calibration source

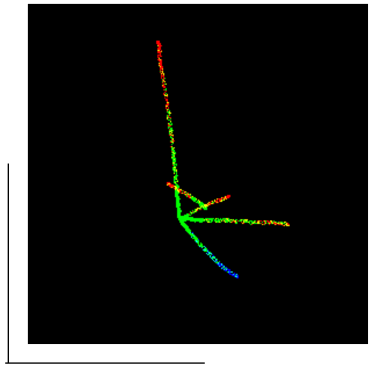


$^{3}_{\Lambda}H$ (2-body decay)

Mass detection
Precise measurement of binding energy

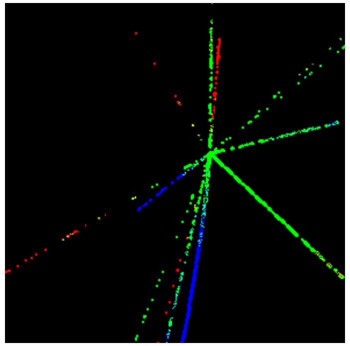
Training data

α-decay event
(Color = depth)

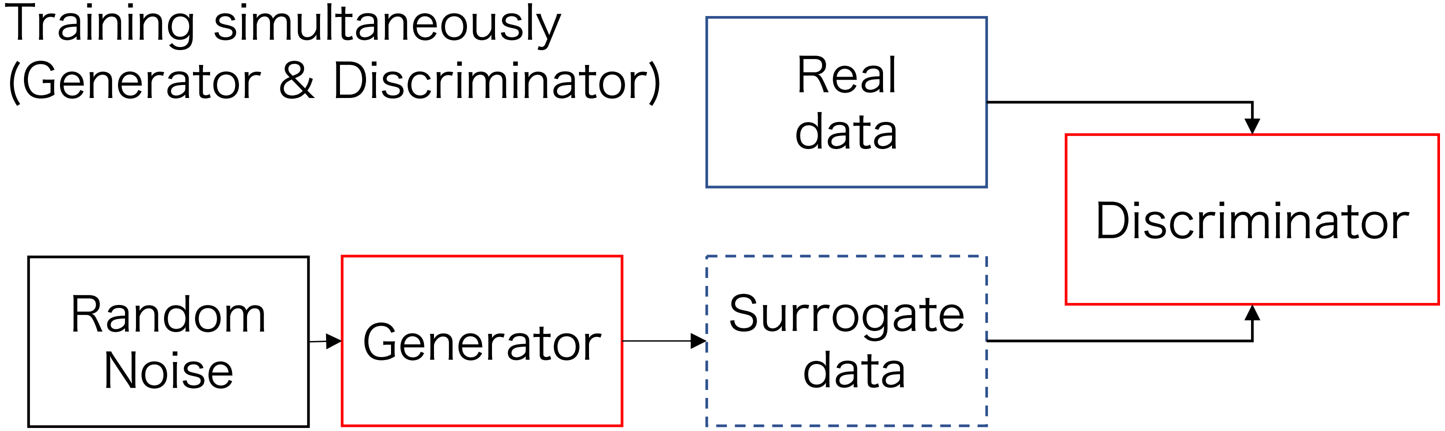


50 μm

Beam interaction
(Negative sample)



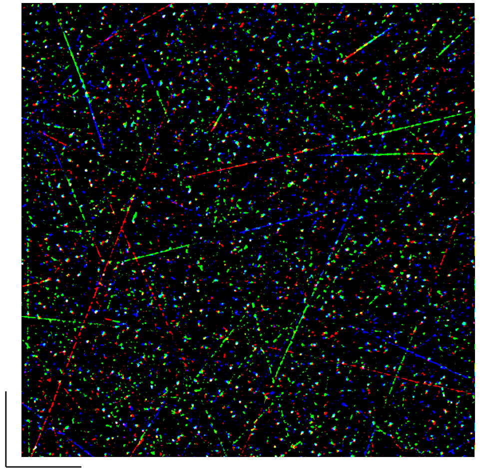
Generative Adversarial Networks (GAN)
Training simultaneously
(Generator & Discriminator)



Pix2pix: Image-style transform

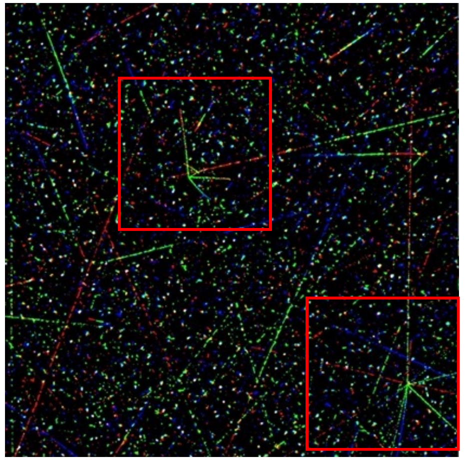
https://arxiv.org/abs/1611.07004

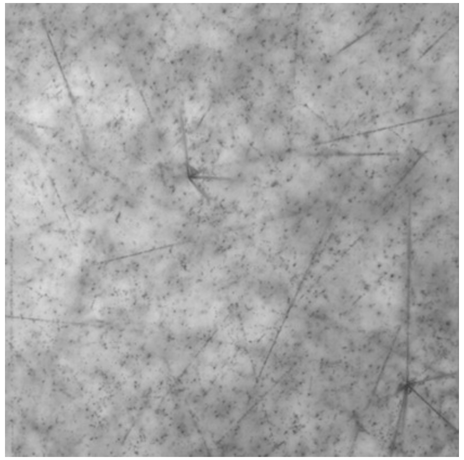
Background
(From Real images)



50 μm

Mix



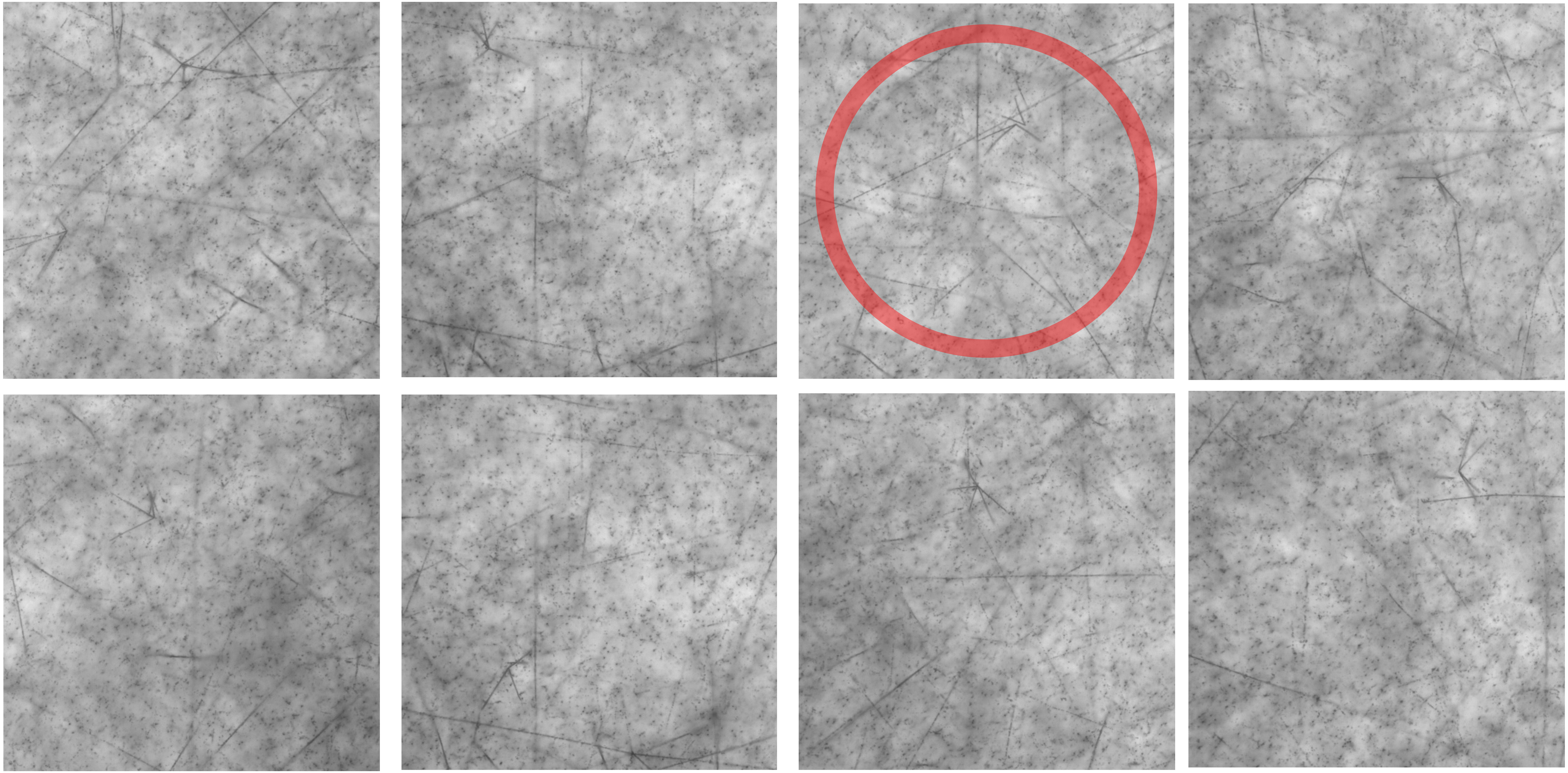


Simulated image

Zebra -> Horse

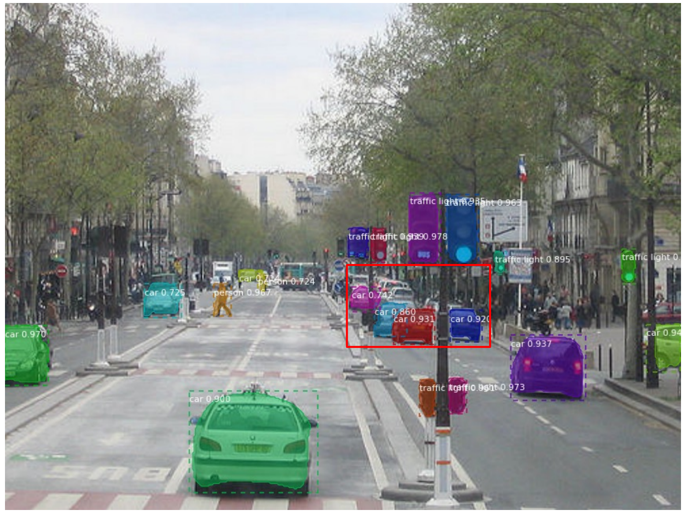
Horse -> Zebra

Which one is real?



Development of the model

Mask R-CNN



- Direct detection
- Classification: Score(0〜1)
- Segmentation

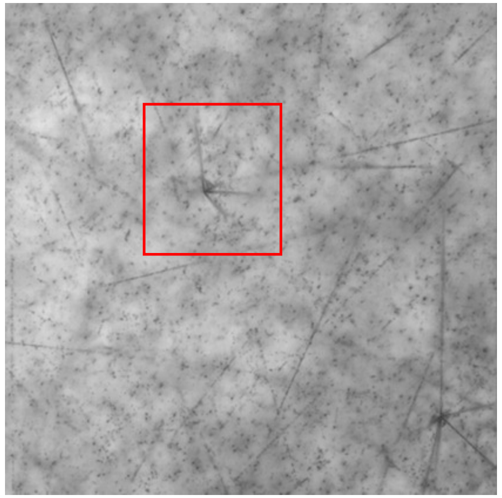
Ex. training data

Image

Mask

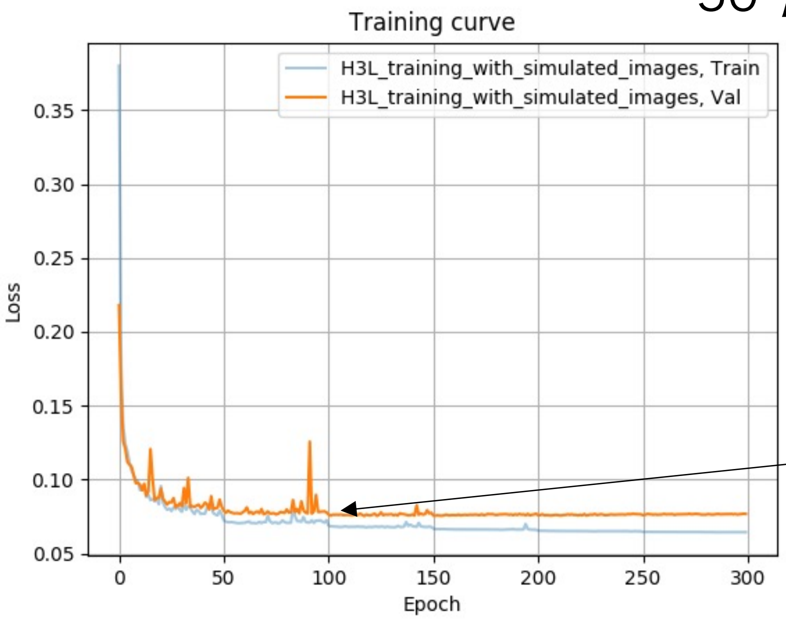
https://www.cis.upenn.edu/~jshi/ped_html/

Training data (Simulation)



50 μm

Without annotation



Pytorch tutorial (Resnet50)

Training with 30k image pairs

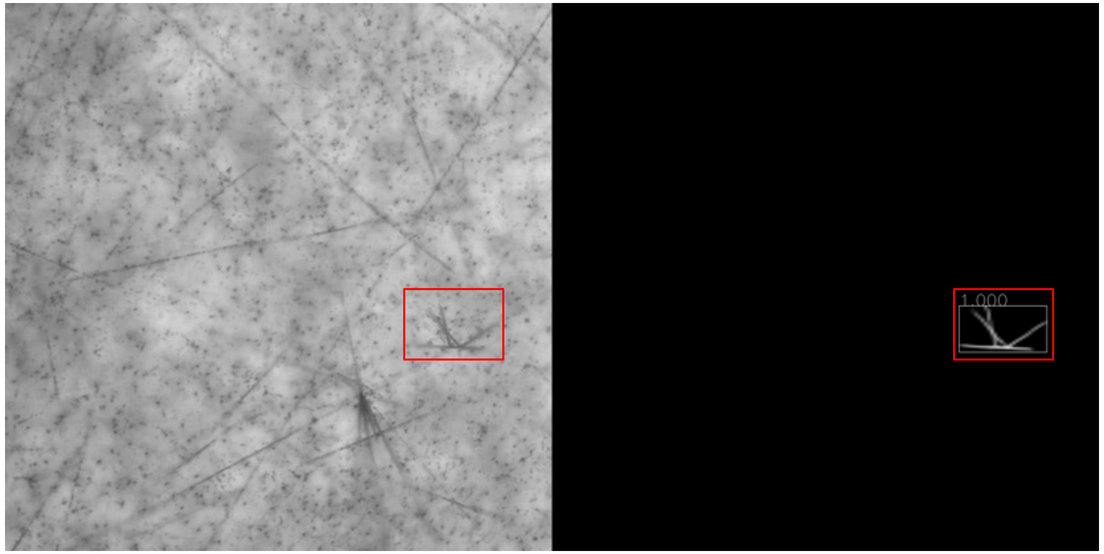
- Training:Validation = 8:2
- Iteration(Epoch) : 300,
  (Updating params to reduce Loss)

- Best epoch: 102

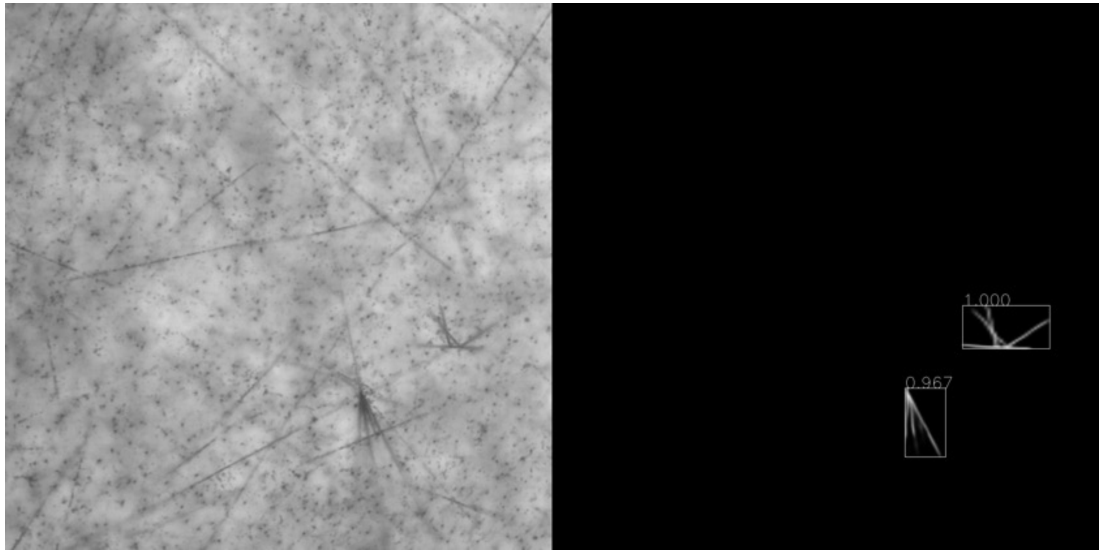
→ Test & Analysis

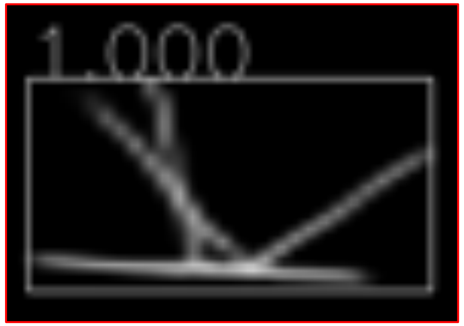
Evaluation with simulation data

Results for simulated images

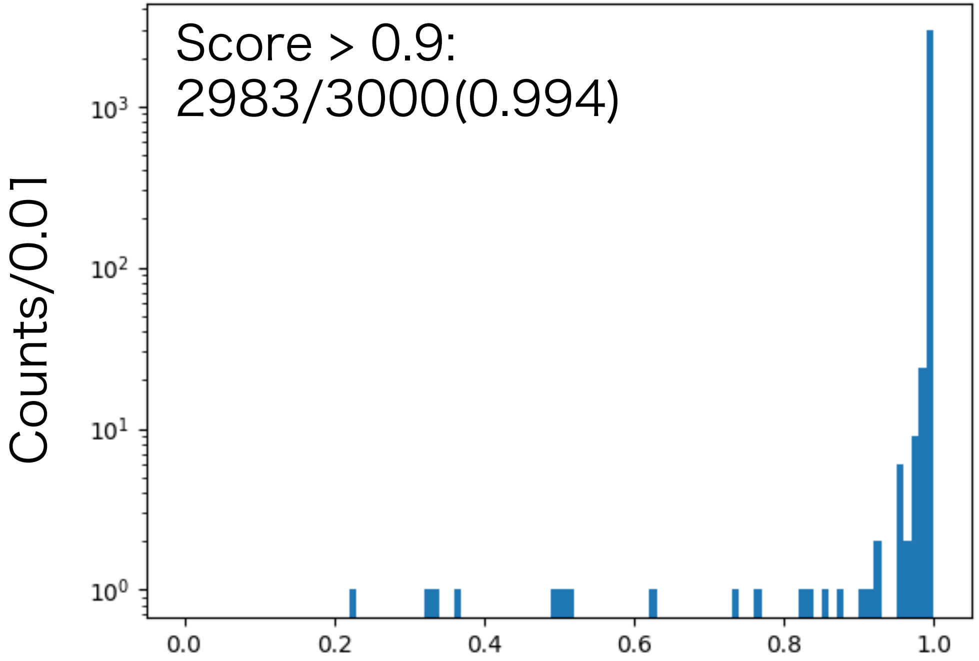


Trained without Negative sample





- Detect only α-decay event
- Segmentation



Score > 0.9: Efficency 99%
Effectivness Negative sample

Evaluation with real data

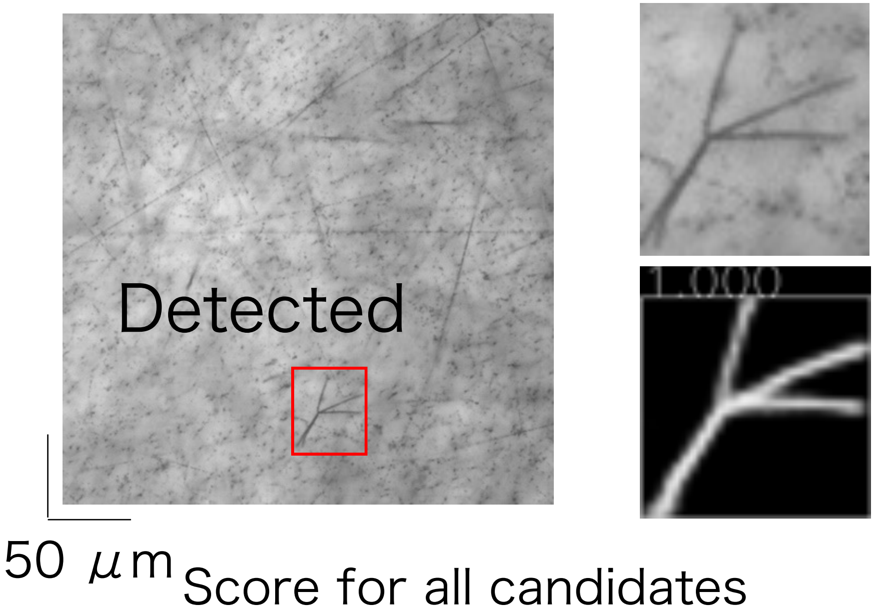
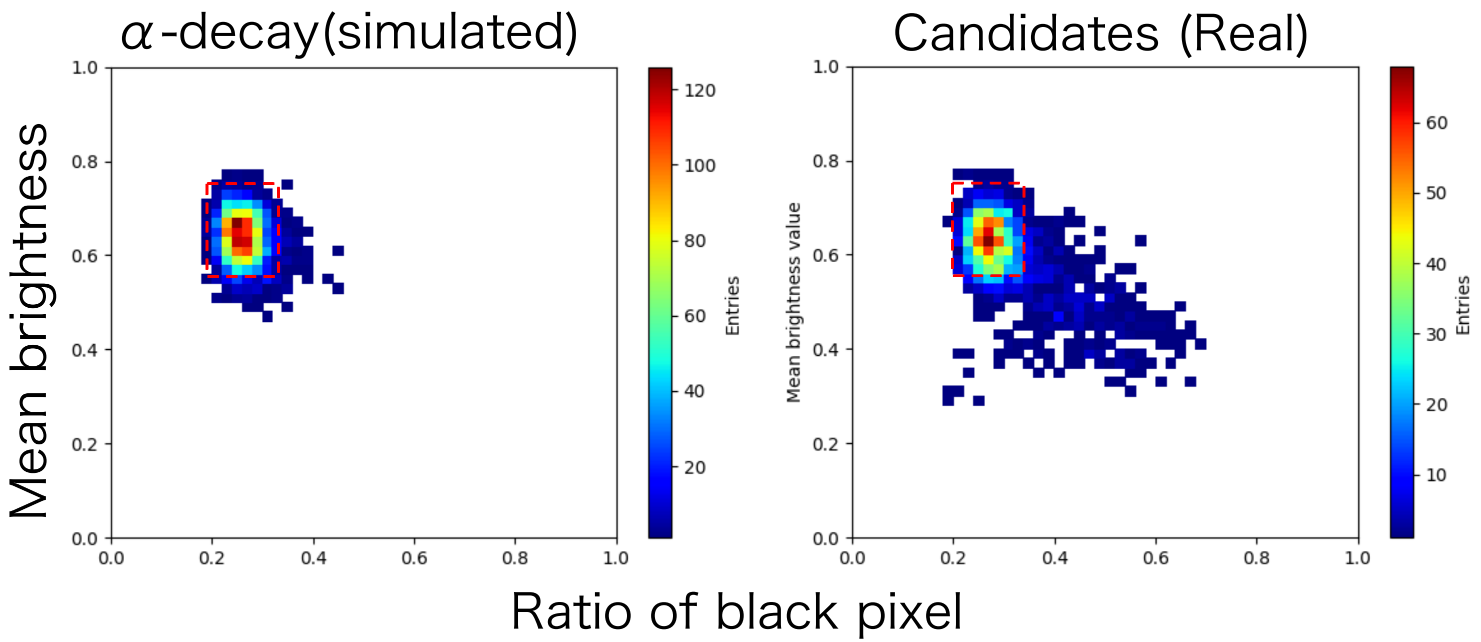
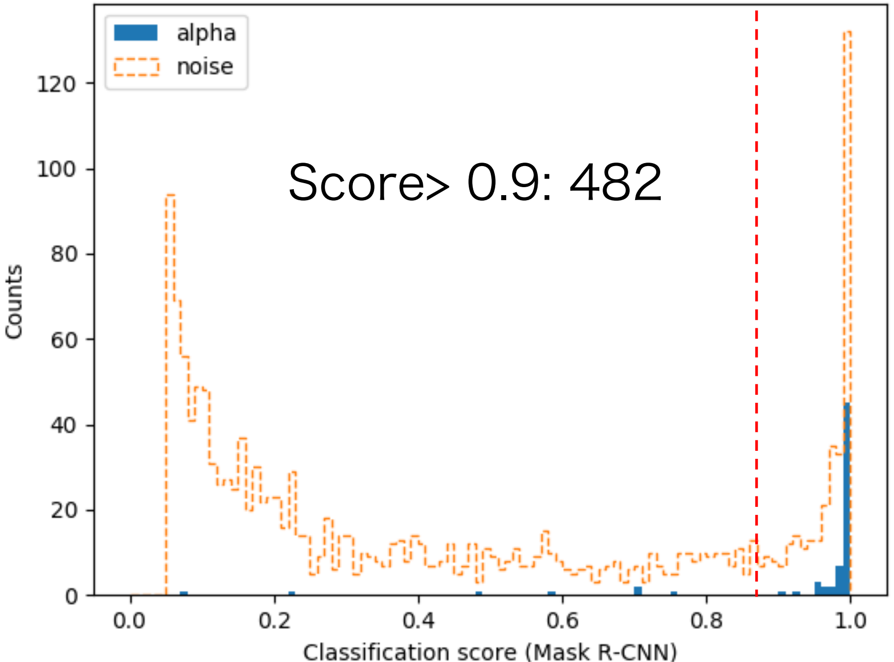


Image processing (with Mask Info.)



Score for all candidates

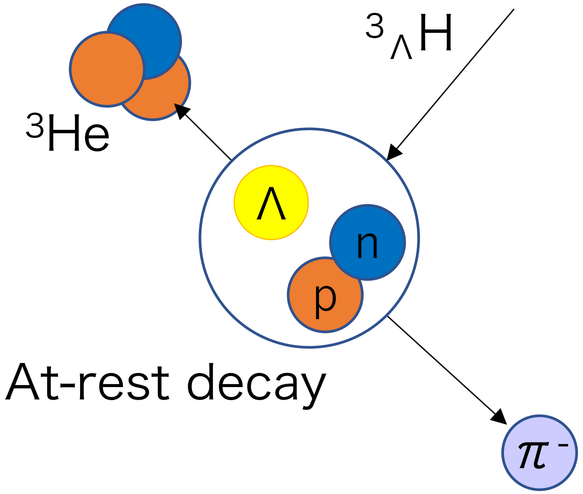


	Cand	Detected	Efficency [%]	Purity [%]
VP	3105	31/76	$40.8^{+5.6}_{-5.5}$	～1.0
VP + CNN	1347	31/76	$40.8^{+5.6}_{-5.6}$	～2.3
Mask R-CNN	482	61/76	$80.3^{+4.2}_{-4.8}$	～12.6
+ Image pro	352	61/76	$80.3^{+4.2}_{-4.8}$	～17.3

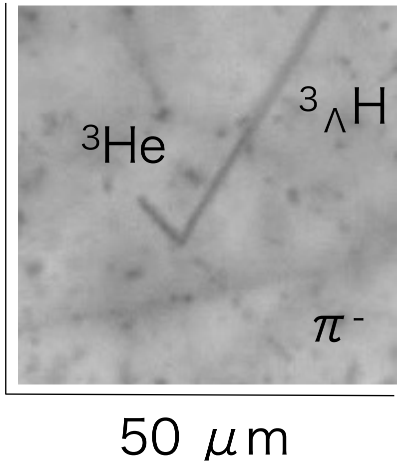
A. Kasagi, et al., N.I.M A, 1056 (2023) 168663

Hypertriton search

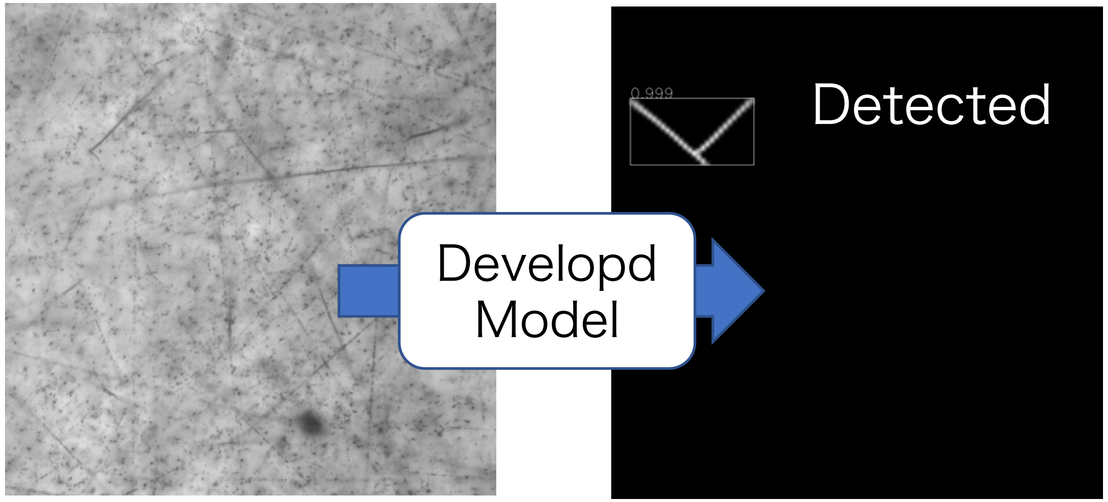
$^3{}_\Lambda H$ 2-body decay



Simulated events



Real image

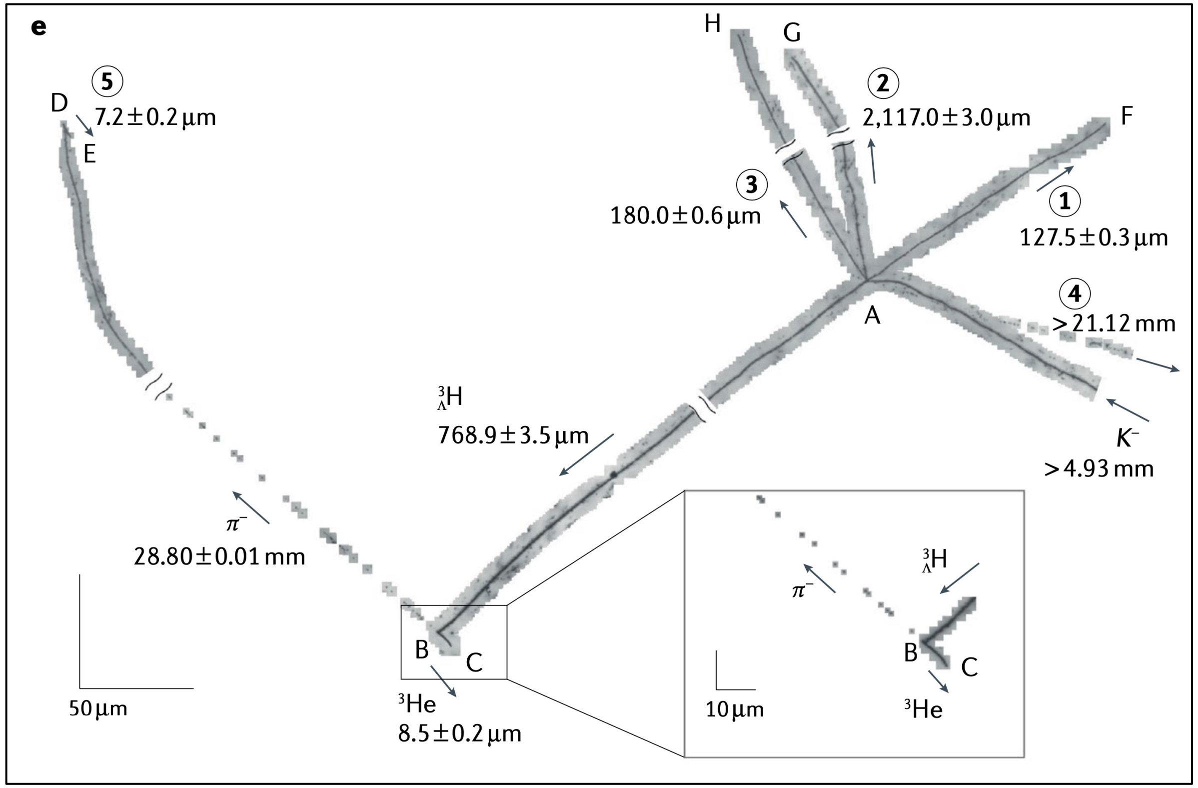


- Rare event was detected
- S/N ratio: ～1/10^4 improved

nature reviews physics

Perspective | Published: 14 September 2021

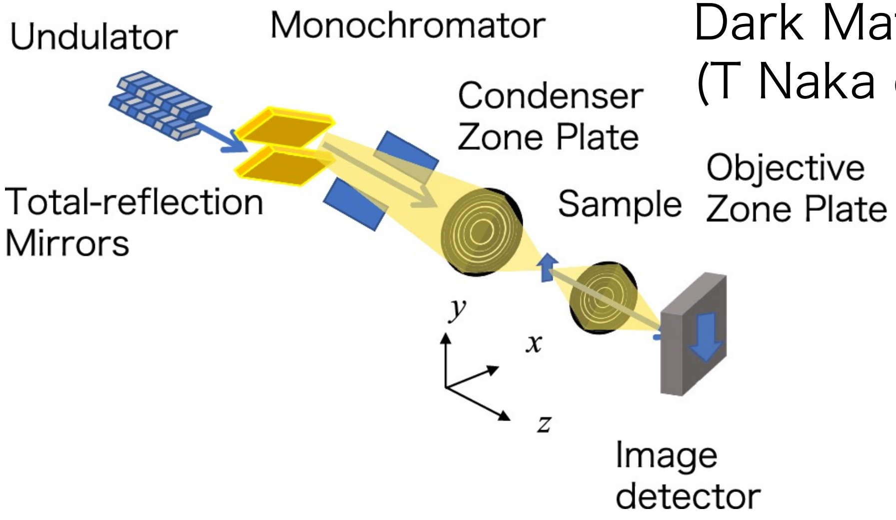
New directions in hypernuclear physics



T.R Saito et.al, Nat Rev Phys 3, 803–813 (2021)

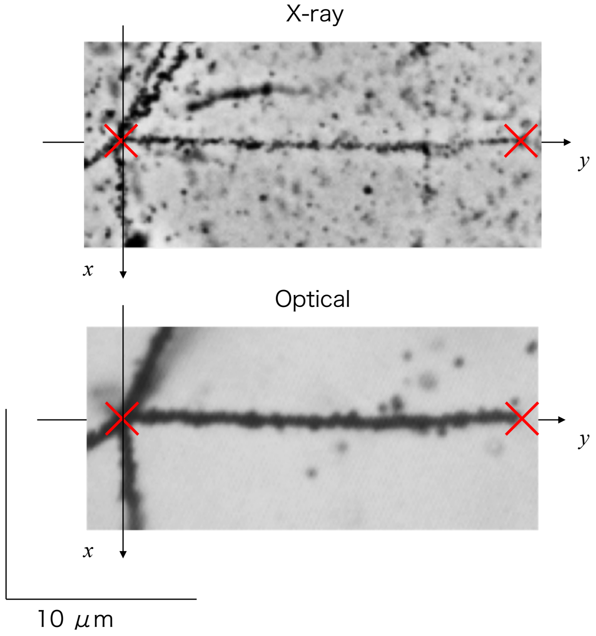
X-ray microscopy for Nuclear Emulsion

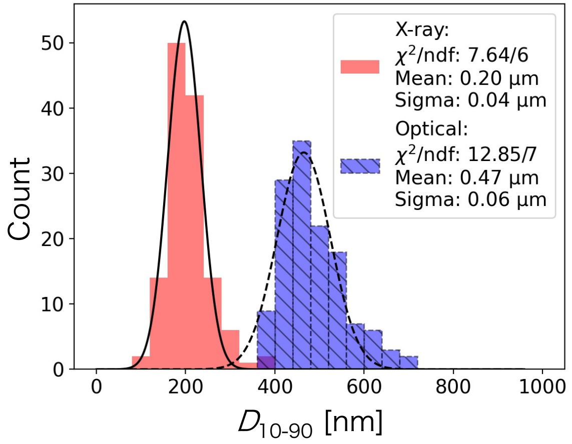
Spring-8



Initiated by
Dark Mater search
(T Naka et.al)

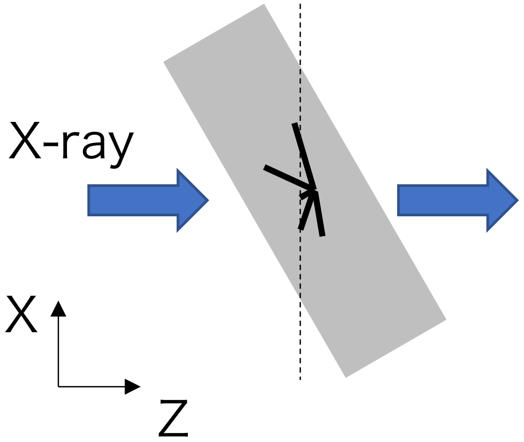
To achive higher resolution for tracks

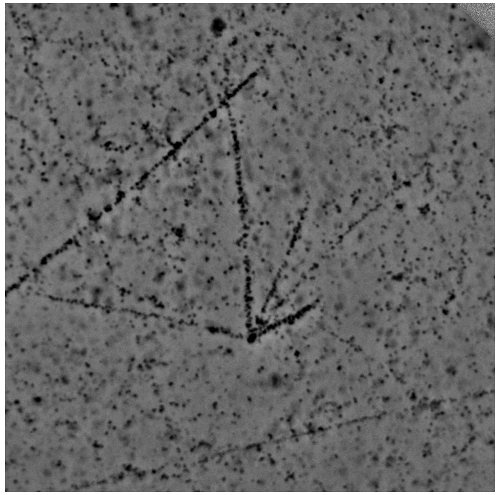


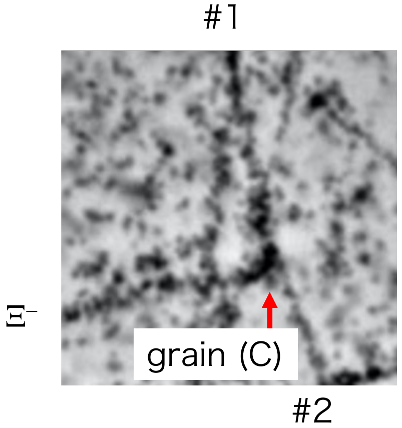


X-ray: 0.20 ± 0.04 μm
Optical: 0.47 ± 0.06 μm

3D analysis with stereo imaging







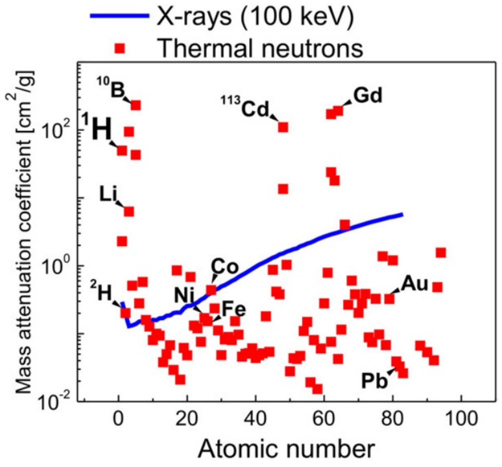
The unrelated grain was resolved
Postion acc: ± 3μm → ± 0.04 μm

Interpretation of double-strange event became possible

A. Kasagi et.al., EPJ-A. **58**, 190 (2022)

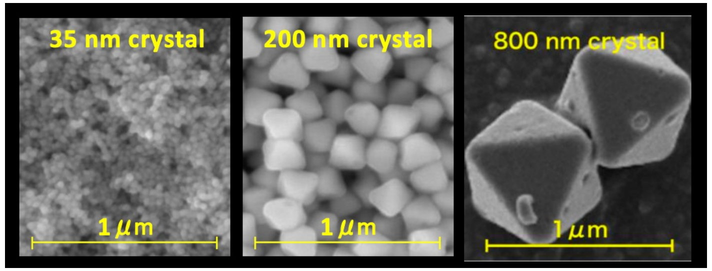
Precise Neutron imaging with tracking detector

Neutron imaging: Hydrogen, Lithium, Boron



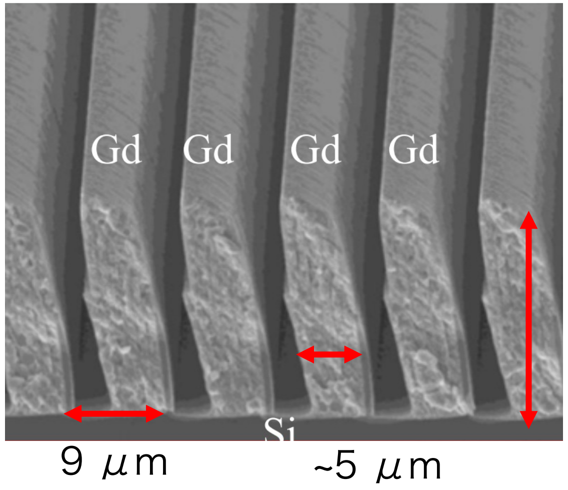
J. Phys. D: Appl. Phys. 42 (2009) 243001

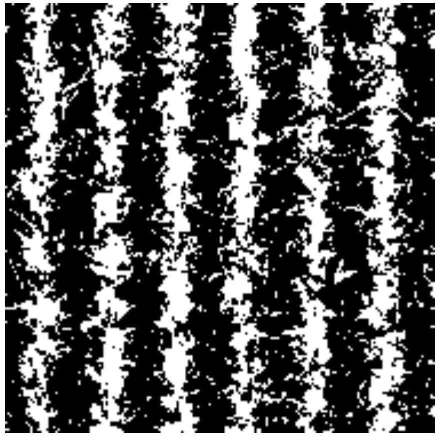
Fine-grain emulsion

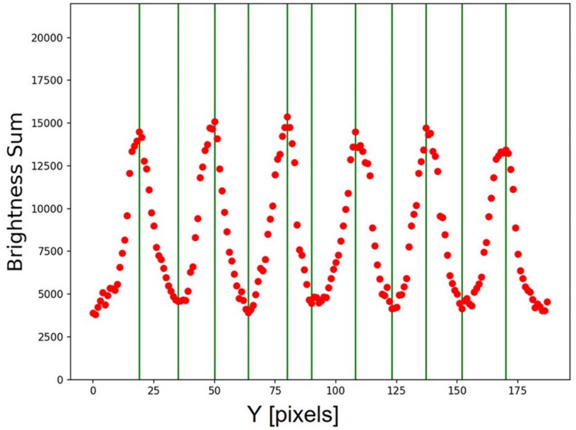


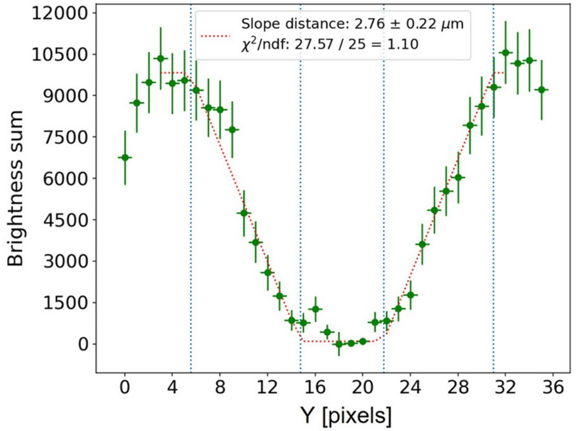
J. Imaging 2021, 7(1), 4

Tetsuo Samoto et al., 2019 Jpn. J. Appl. Phys. 58 SDDF12

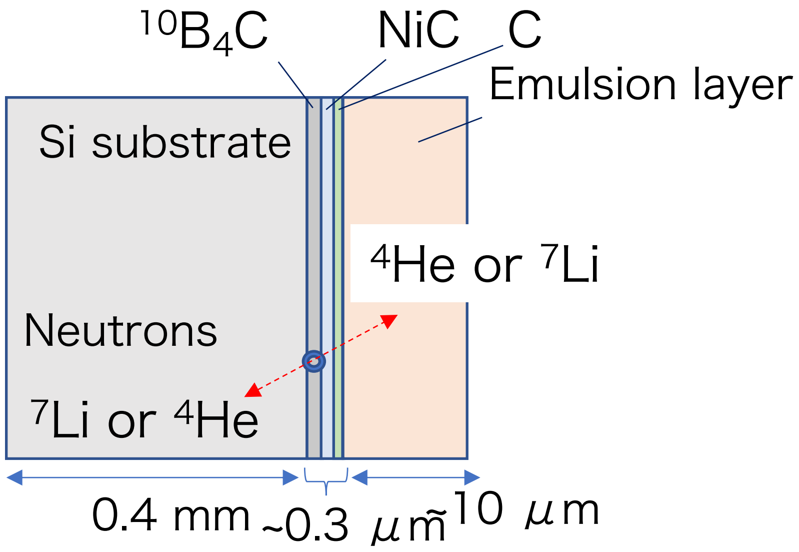


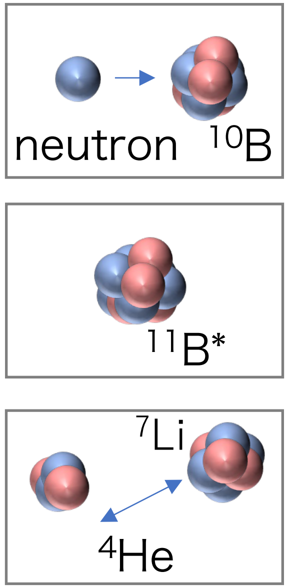






Neutron detector with emulsion





$\sigma = 0.945 \pm 0.004\ \mu m$

cf. FNTD(fluorescent nuclear track detectors)

A. Muneem et.al, J. Appl. Phys. 133, 054902 (2023)
A. Muneem et.al, Radiation Measurements 158, 106863 (2022)

Summary

Photographic film: Nuclear emulsion
- History of Pioneering Particle Detection
- Automated analysis of tracks in emulsion sheets

→ New physics experiments & new applications

Nuclear emulsion + Machine learning
- Hypernuclear event search without any triger conditions
- Machine learning for High efficency + High speed

→ Efficency: ～x2, S/N ratio: ～x17
→ Rare events can be studied with Nuclear emulsion

Further developments with nuclear emulsion
- X-ray microscopy, Neutron imaging

Unprecedented large statistical analysis + Precise measurement
Nuclear emulsion is not only historical but also matured imaging detector!