Nuclear Emulsion
and
Its Readout System

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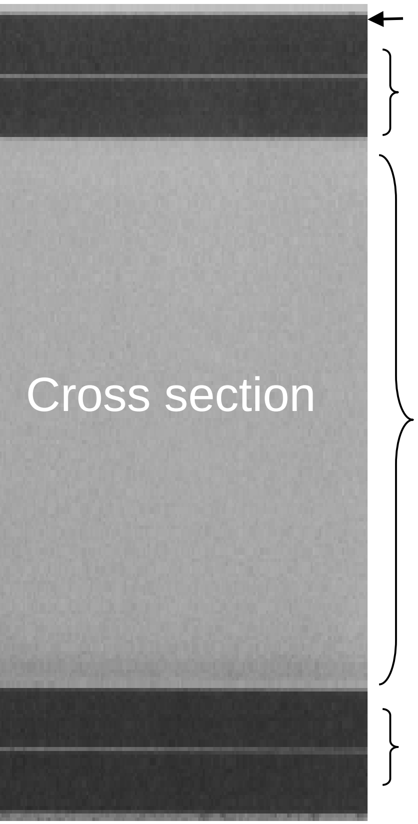
Nagoya university

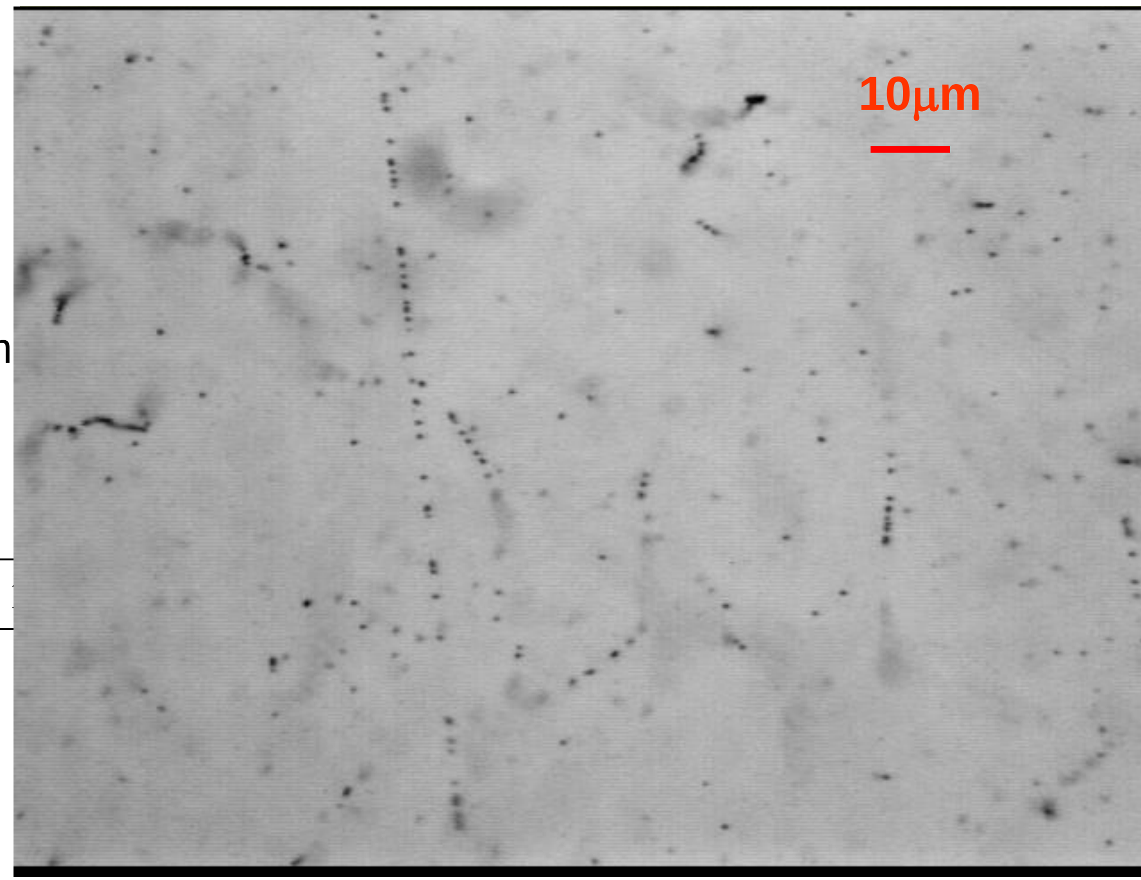
Nuclear Emulsion Film

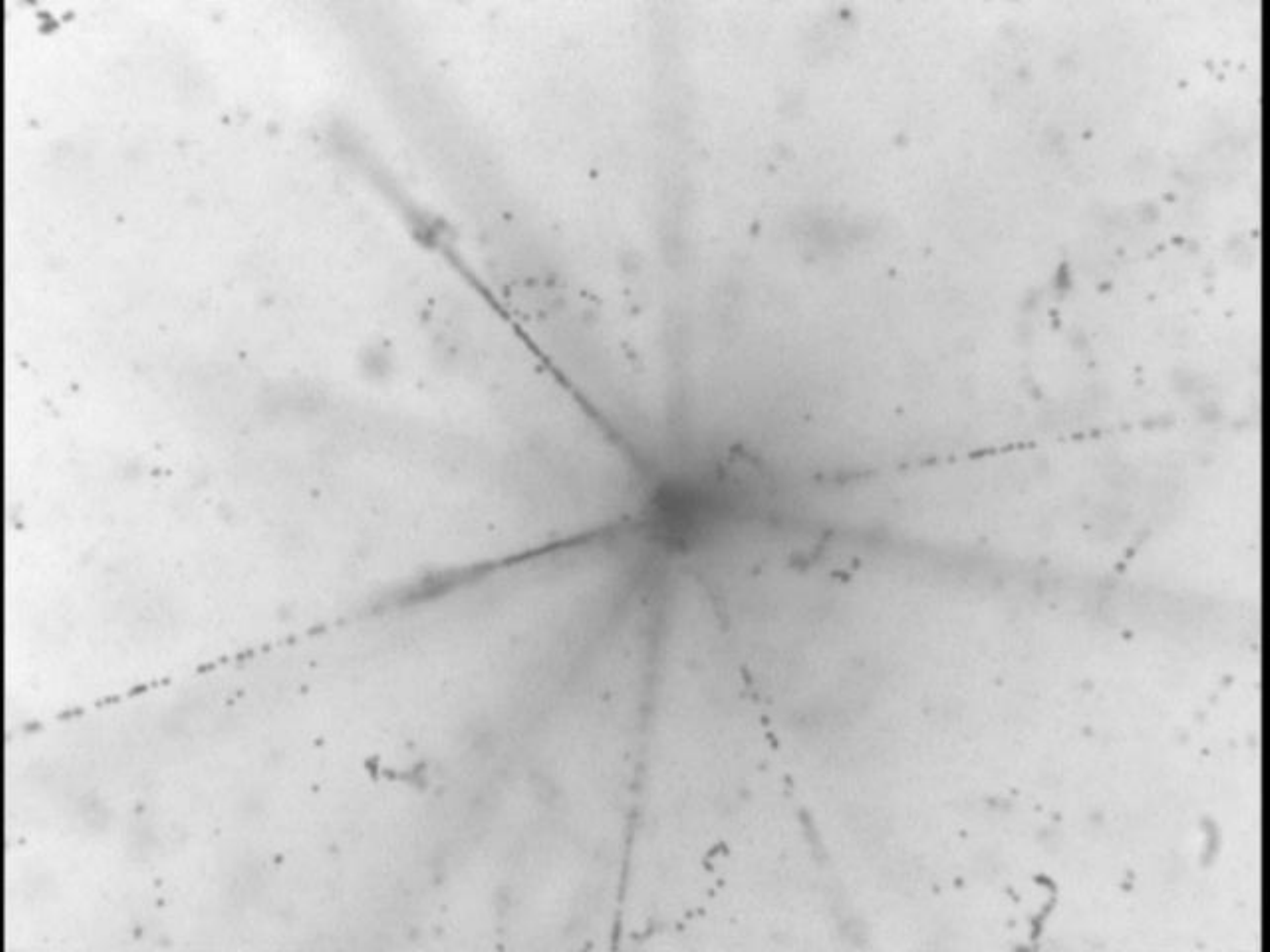
▪ Very high spatial resolution. ▪ Possible to record MIP's tracks

"OPERA film" is uniform, refreshable and mass producible.

~100,000m^2 are used in OPERA

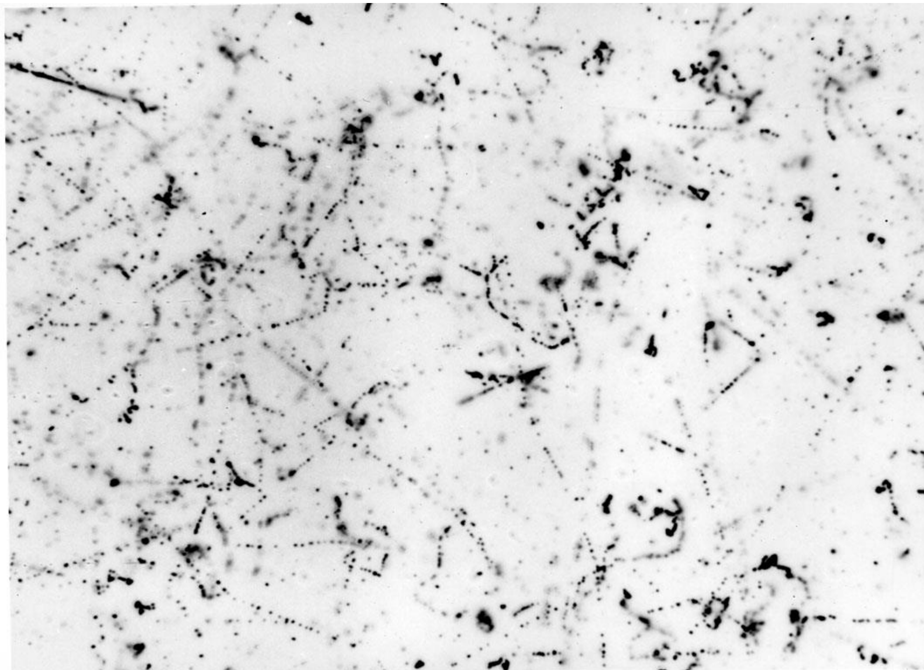


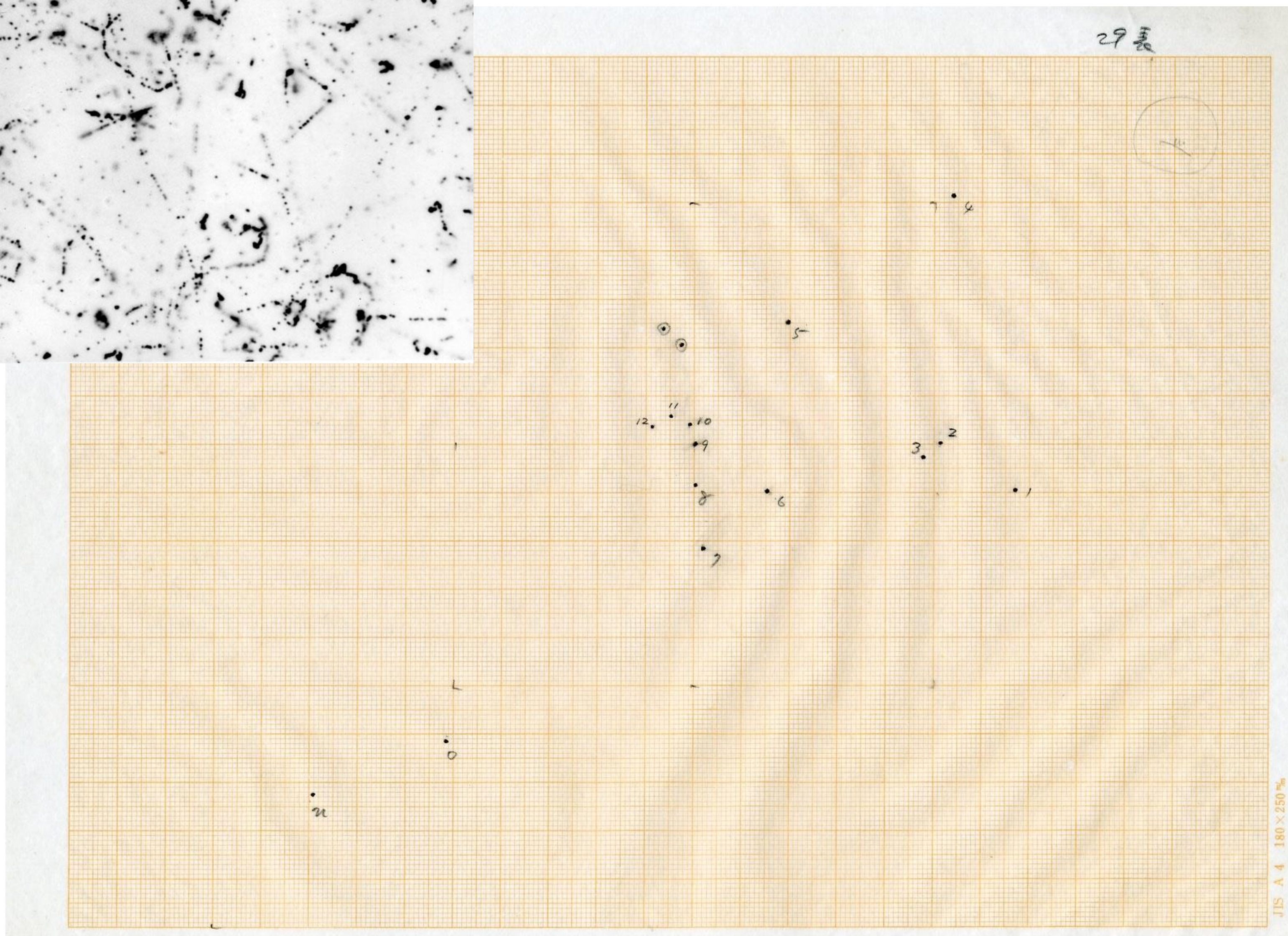




Prof. Niu’s effort

- 2-3 events / Half year
- Emulsion analysis by Eye and Hand





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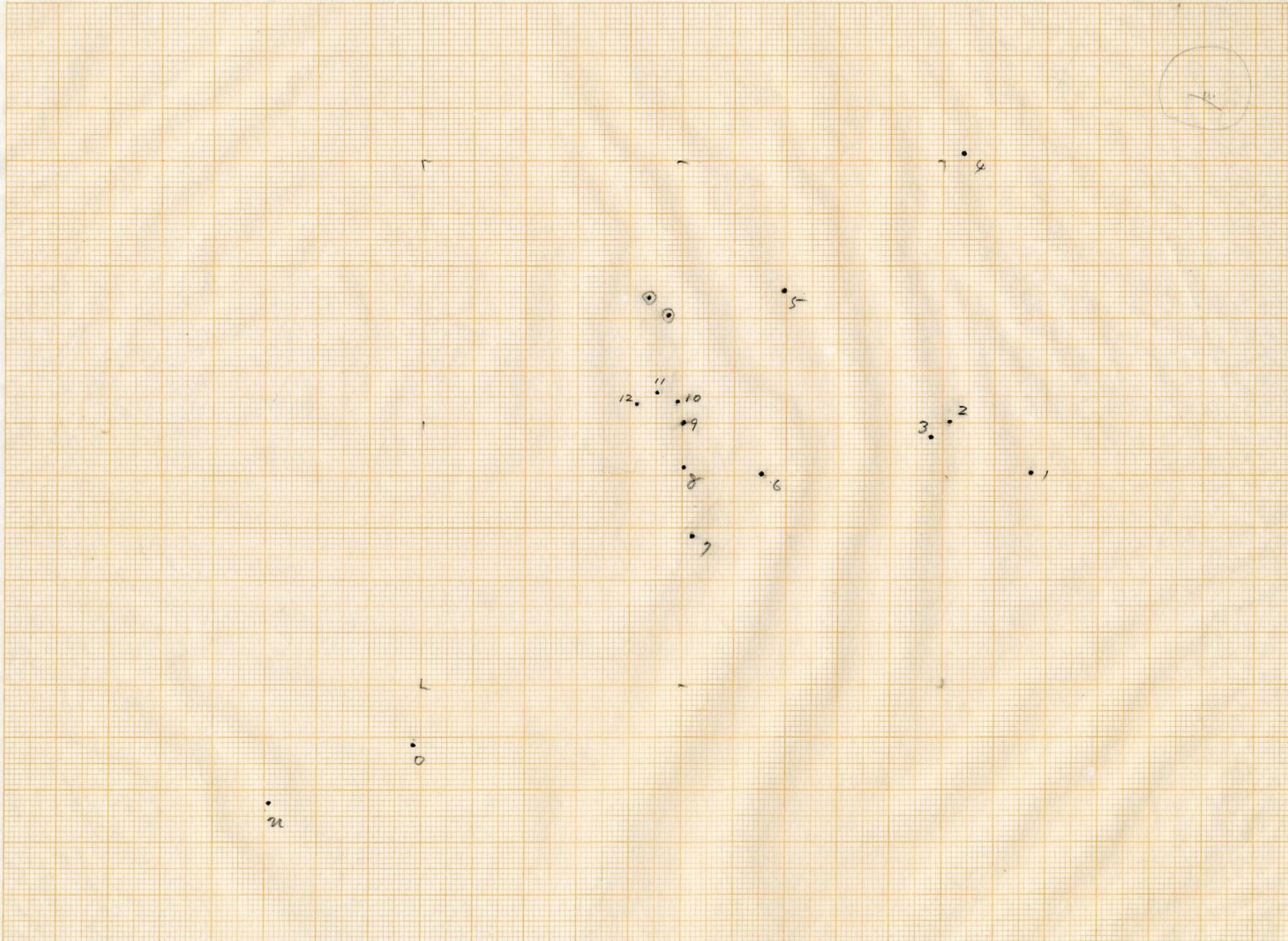
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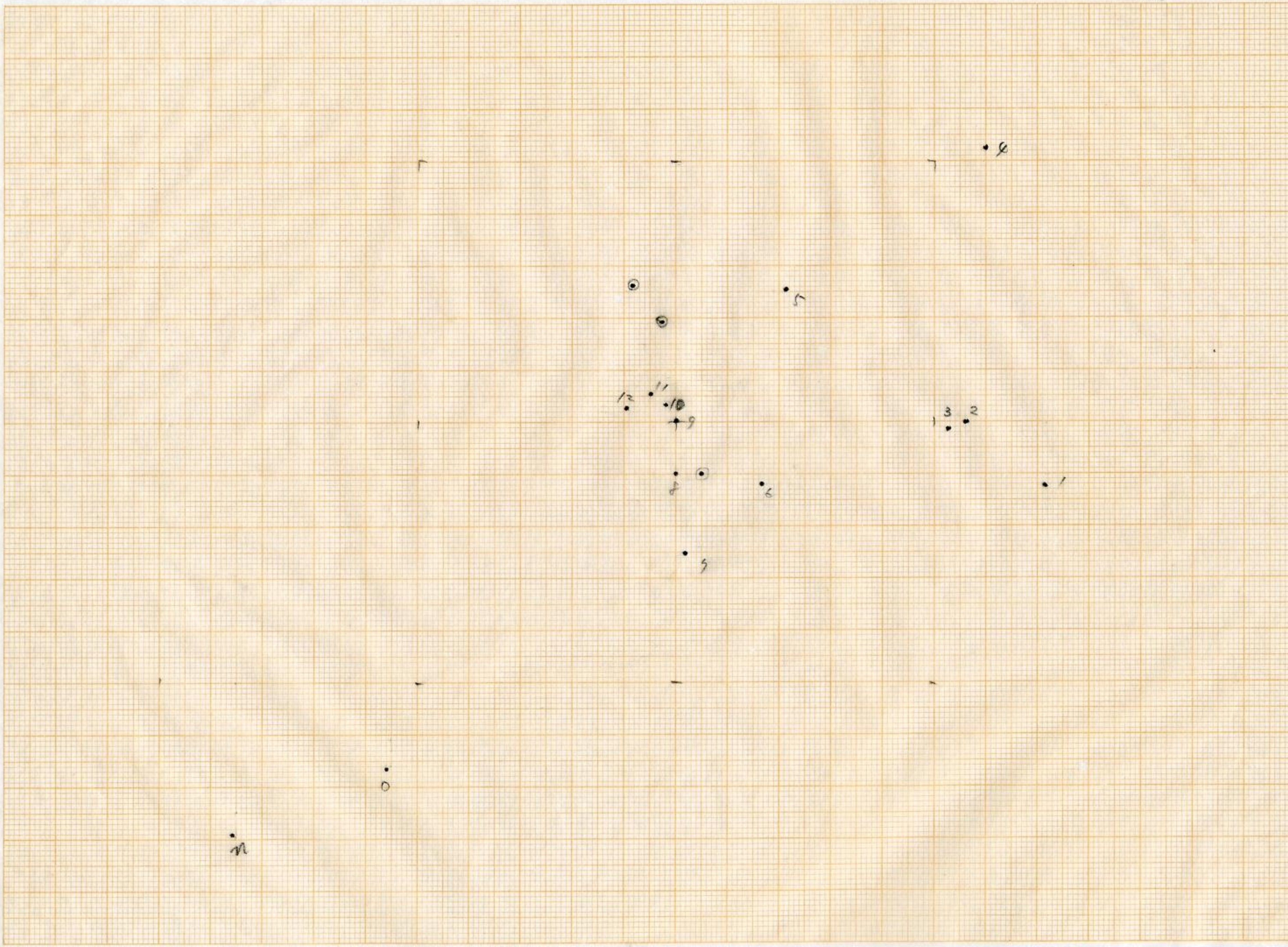
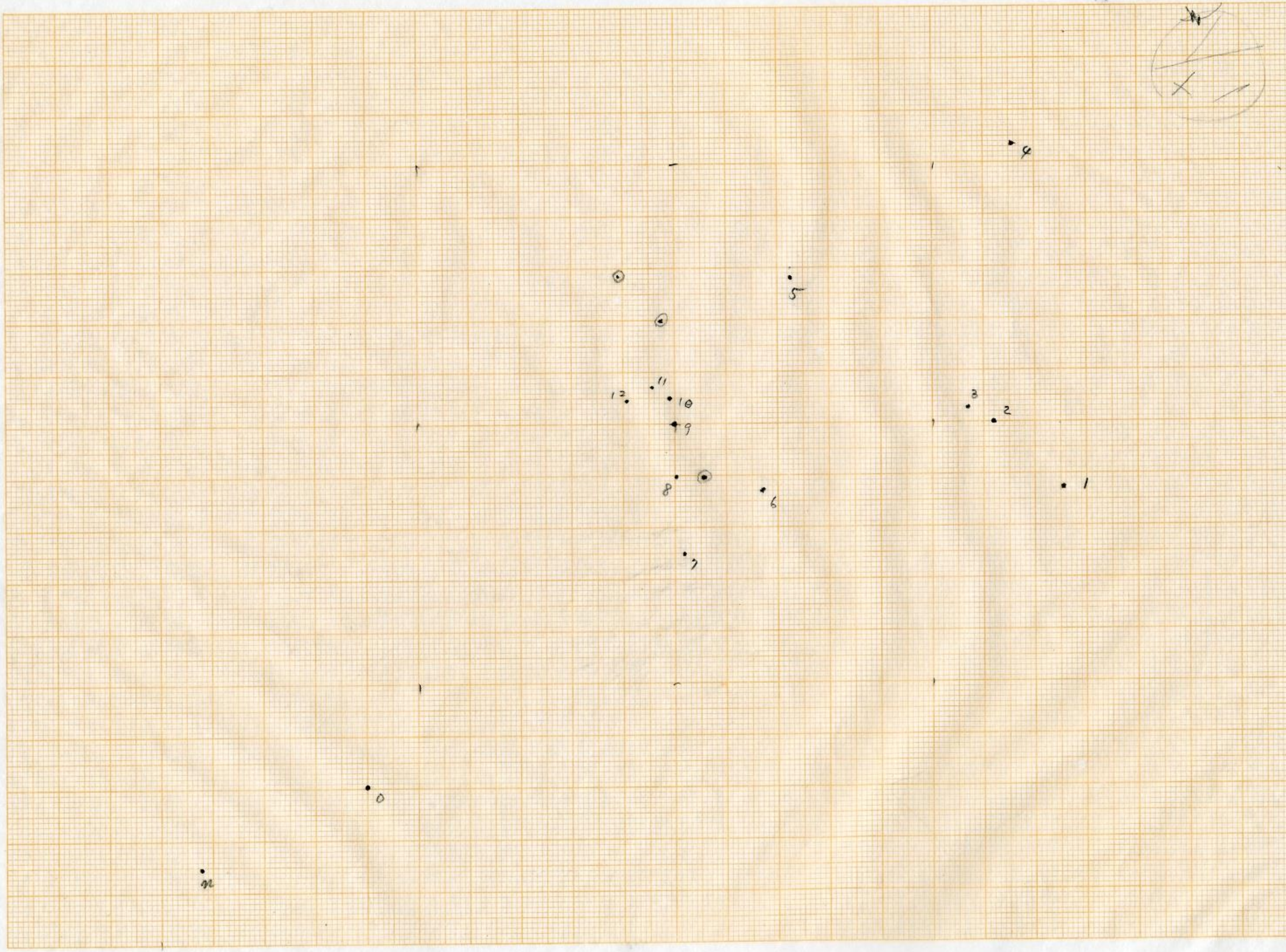


27 表

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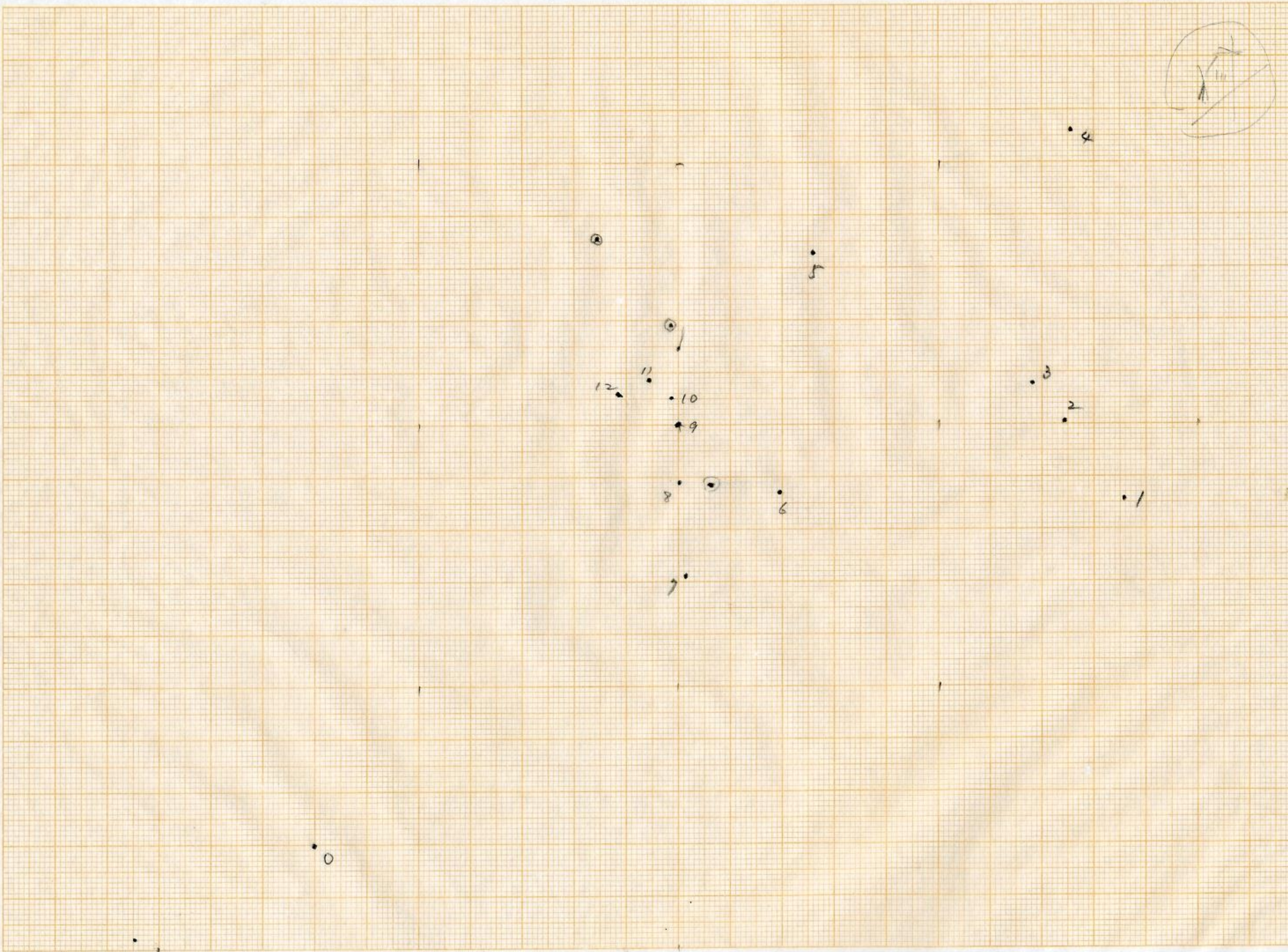

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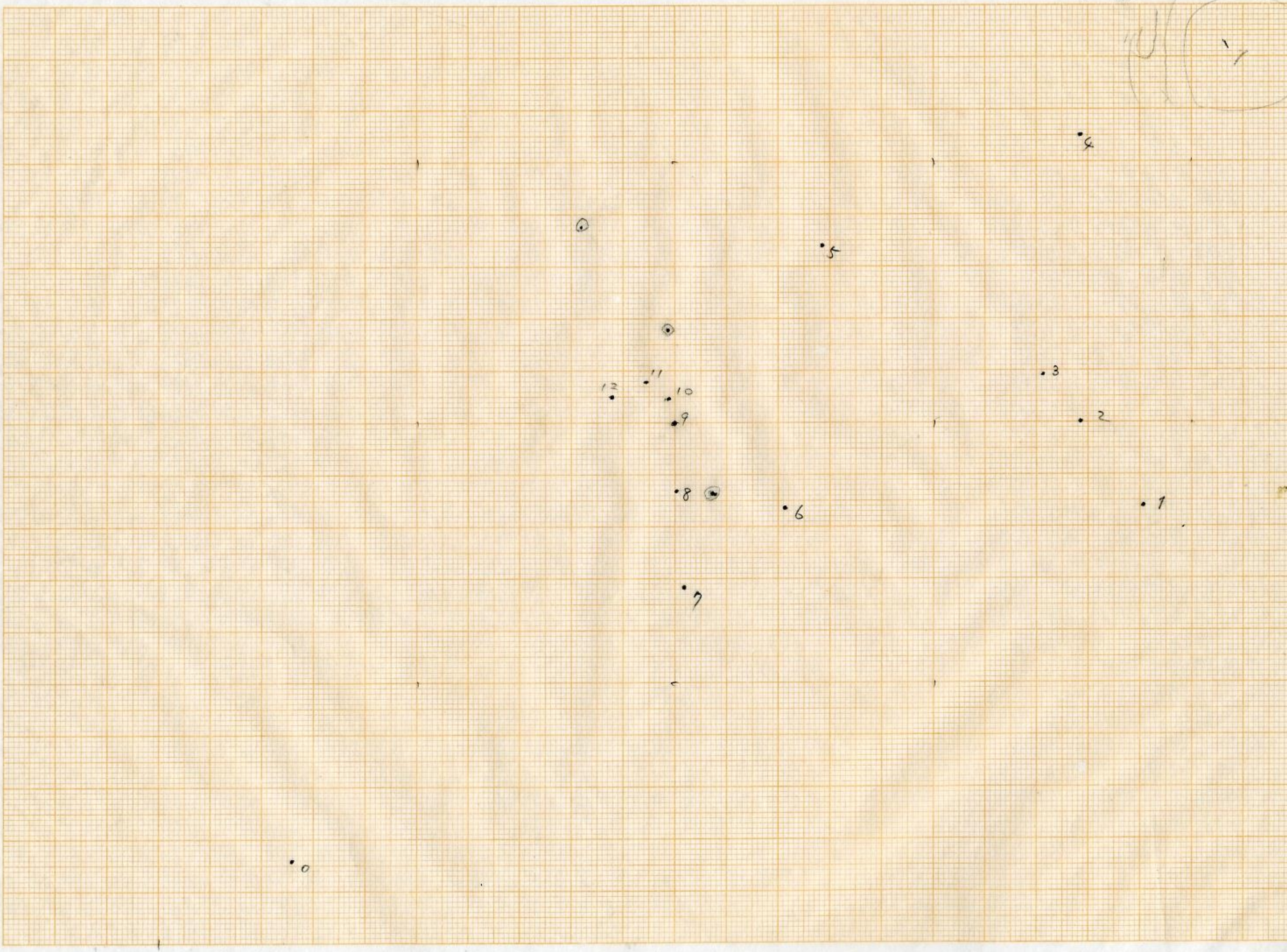
24 表



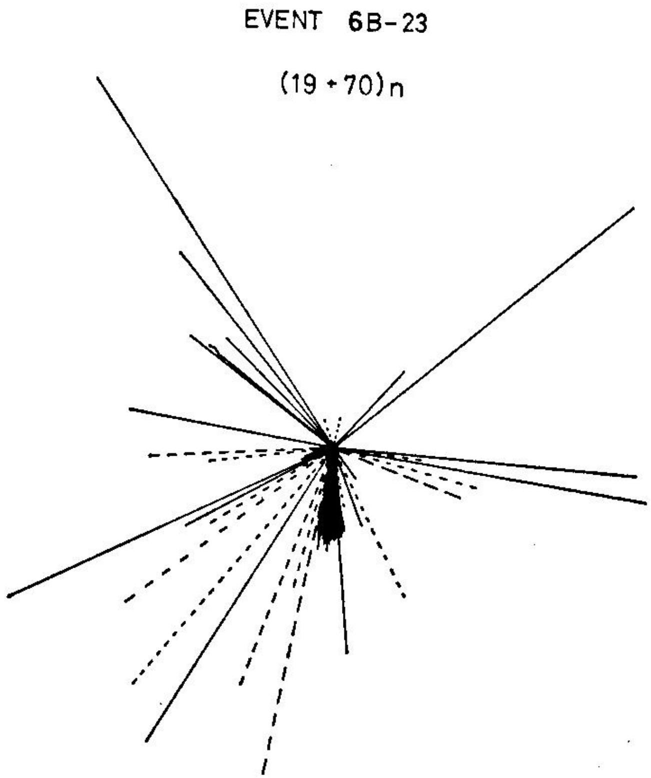


Fig. 1.

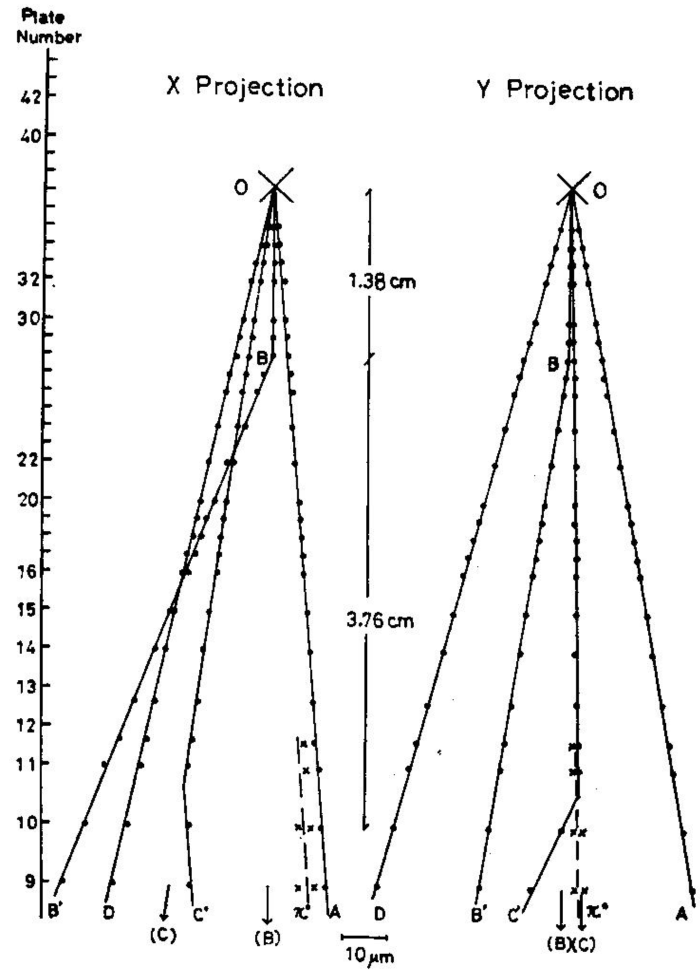


Fig. 3(a).

Fig. 3(b).

人類がはじめてチャーム粒子を認識した瞬間　　　1971

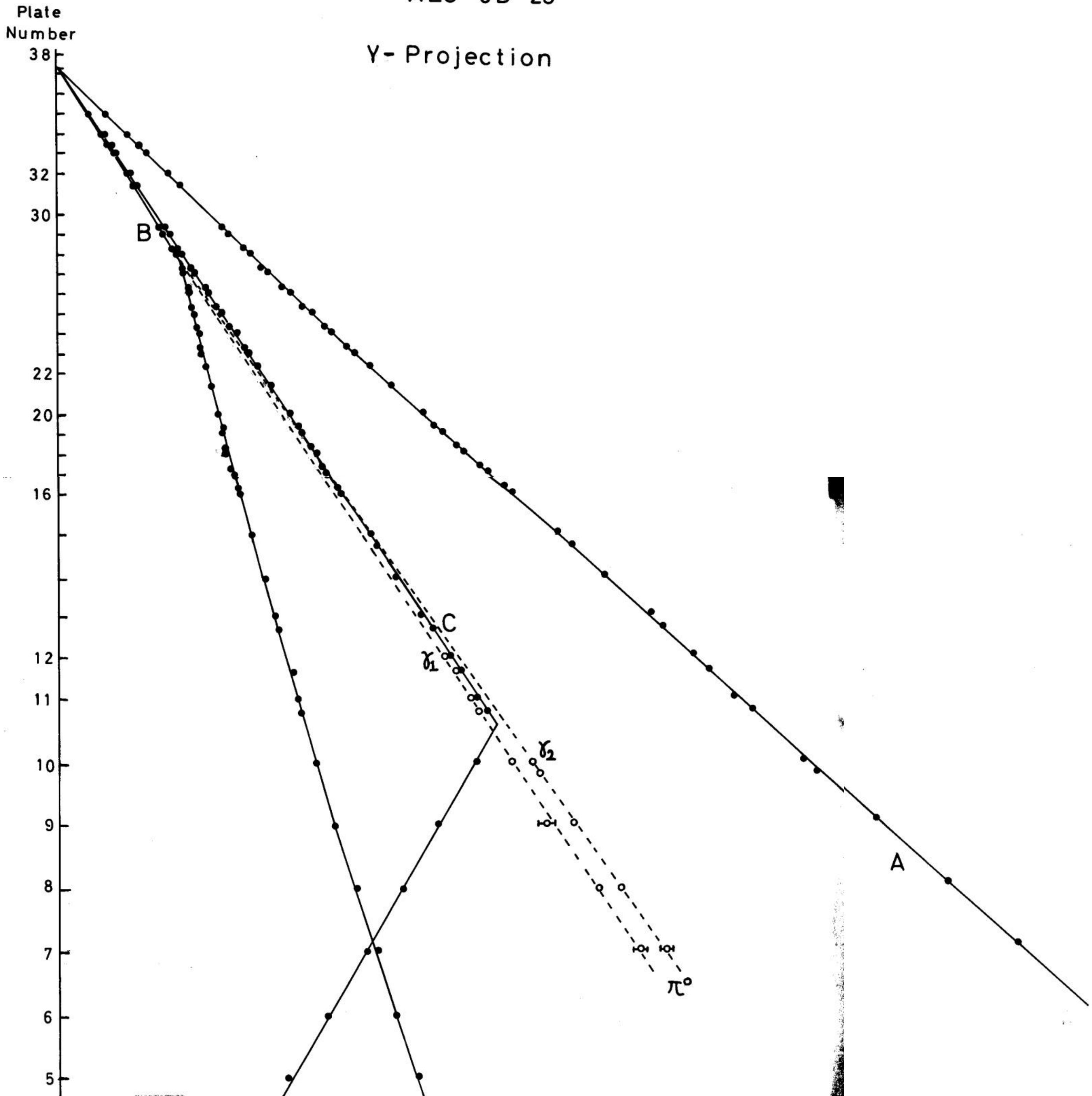


Plate Number
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γ_1
γ_2
π^0
A

Automated Emulsion Read-out system

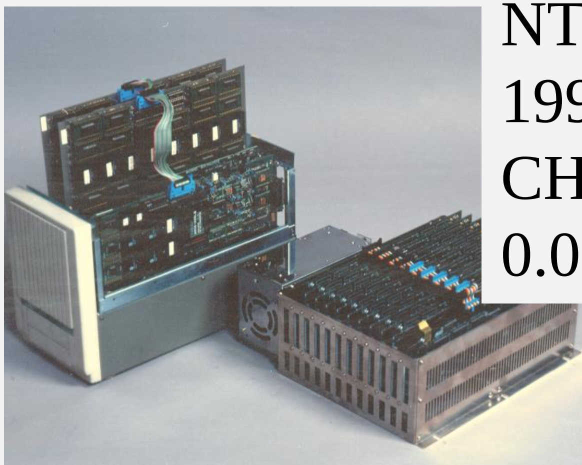
- Principle was proposed by K. Niwa in mid. 70s.

- The first system construction in 1983.
- The first application to real experiment in 1994.

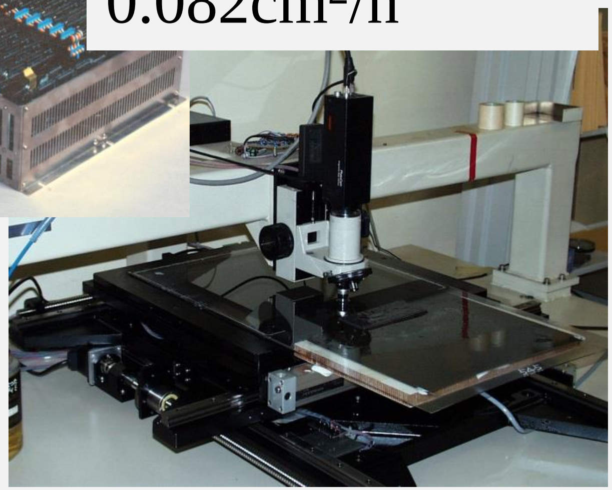
  CHORUS (CERN WA95)

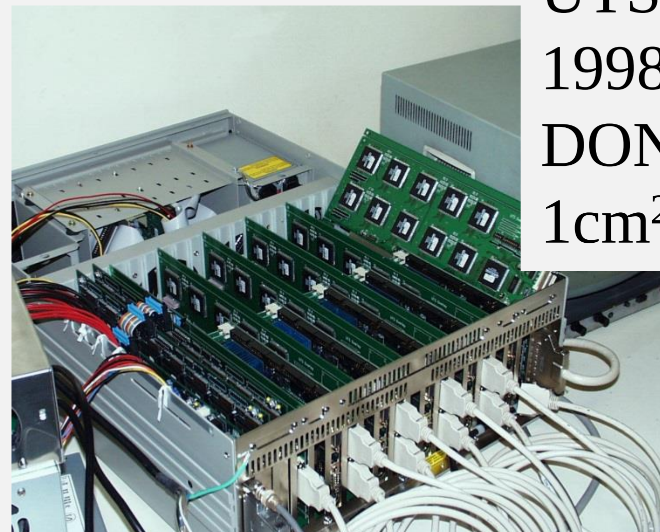
- The latest version "SUTS" was developed and applied to OPERA experiment.
  - The current speed of SUTS is 72cm^2/hrs/side

History of emulsion readout system in Nagoya

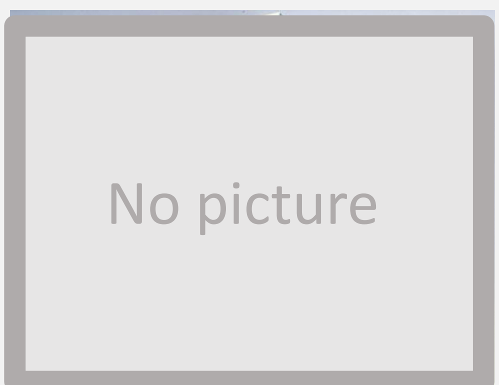


NTS (CPLD)
1994~
CHORUS
$0.082 cm^2/h$



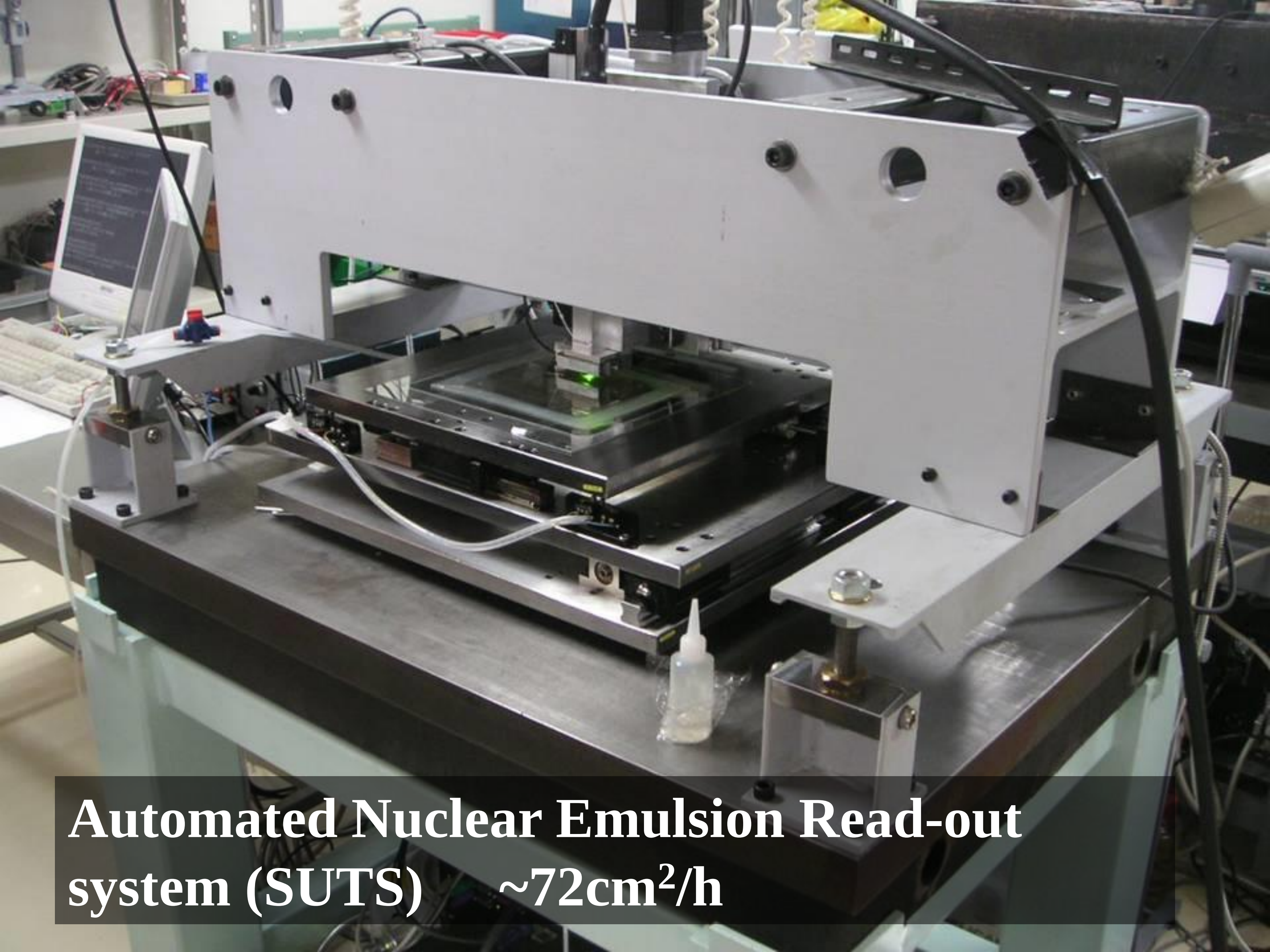


UTS (FPGA)
1998~
DONUT
$1 cm^2/h$



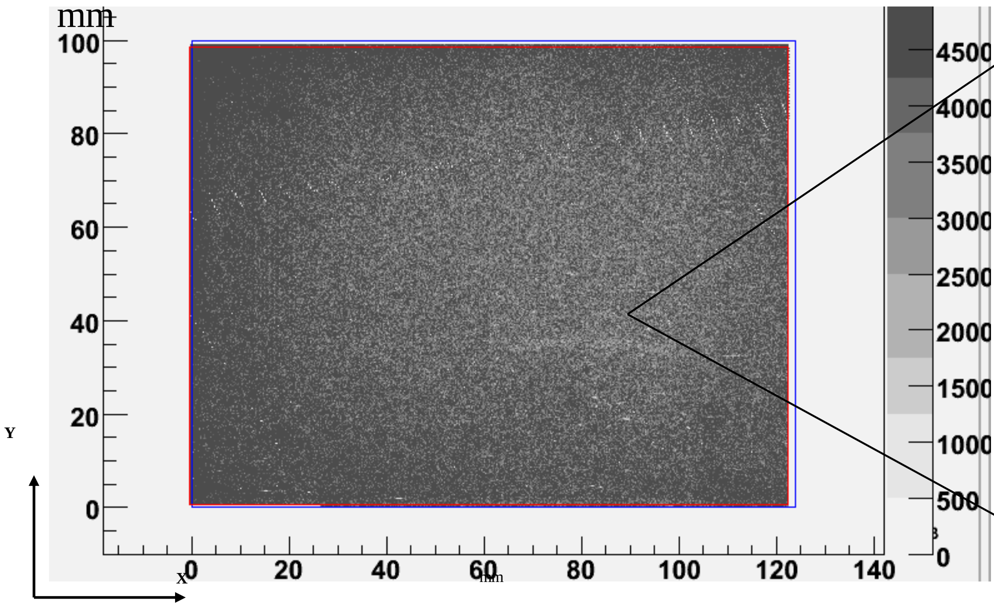
TS (TTL)
1983~
E653
$0.003 cm^2/h$

Each new system has enabled new experiment

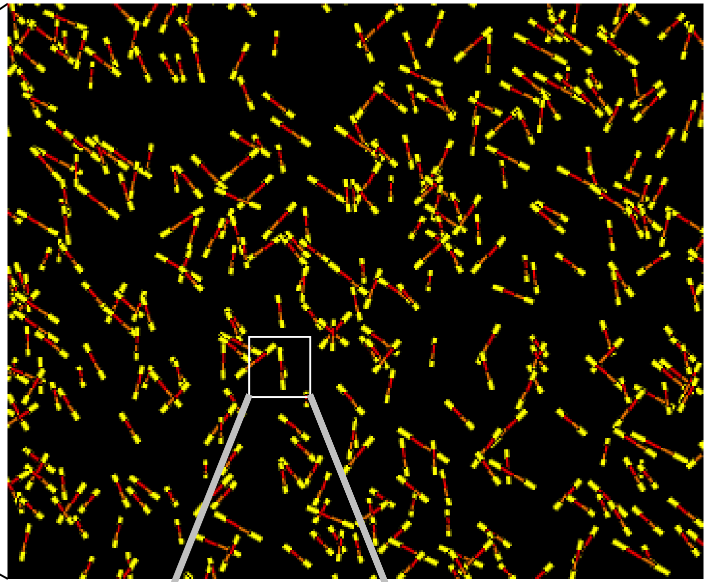


Automated Nuclear Emulsion Read-out system (SUTS) ~72cm^2/h

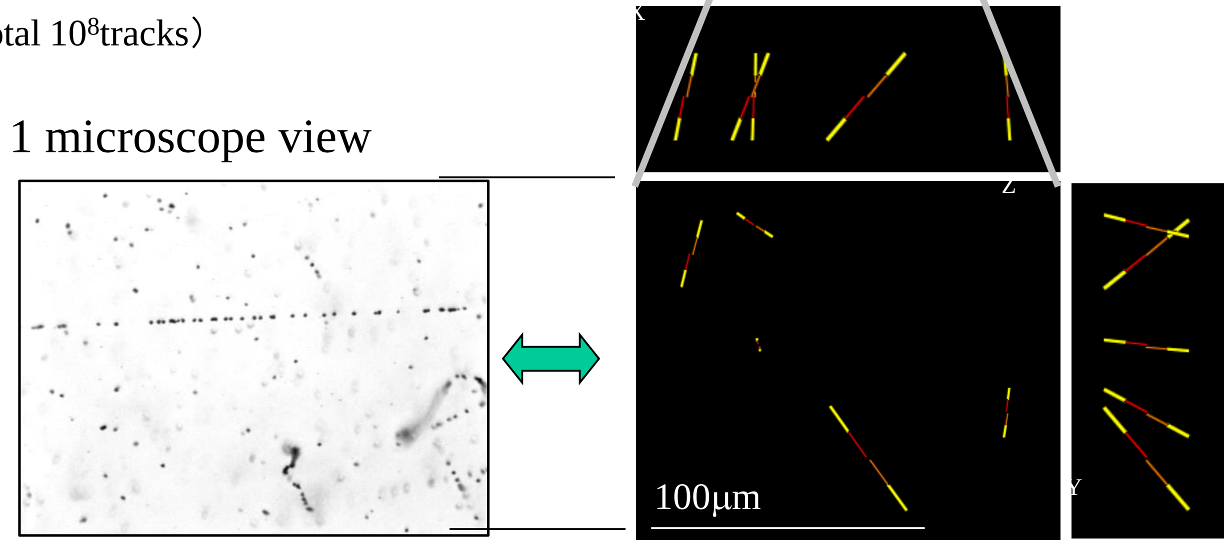
Output of Automated Emulsion Readout



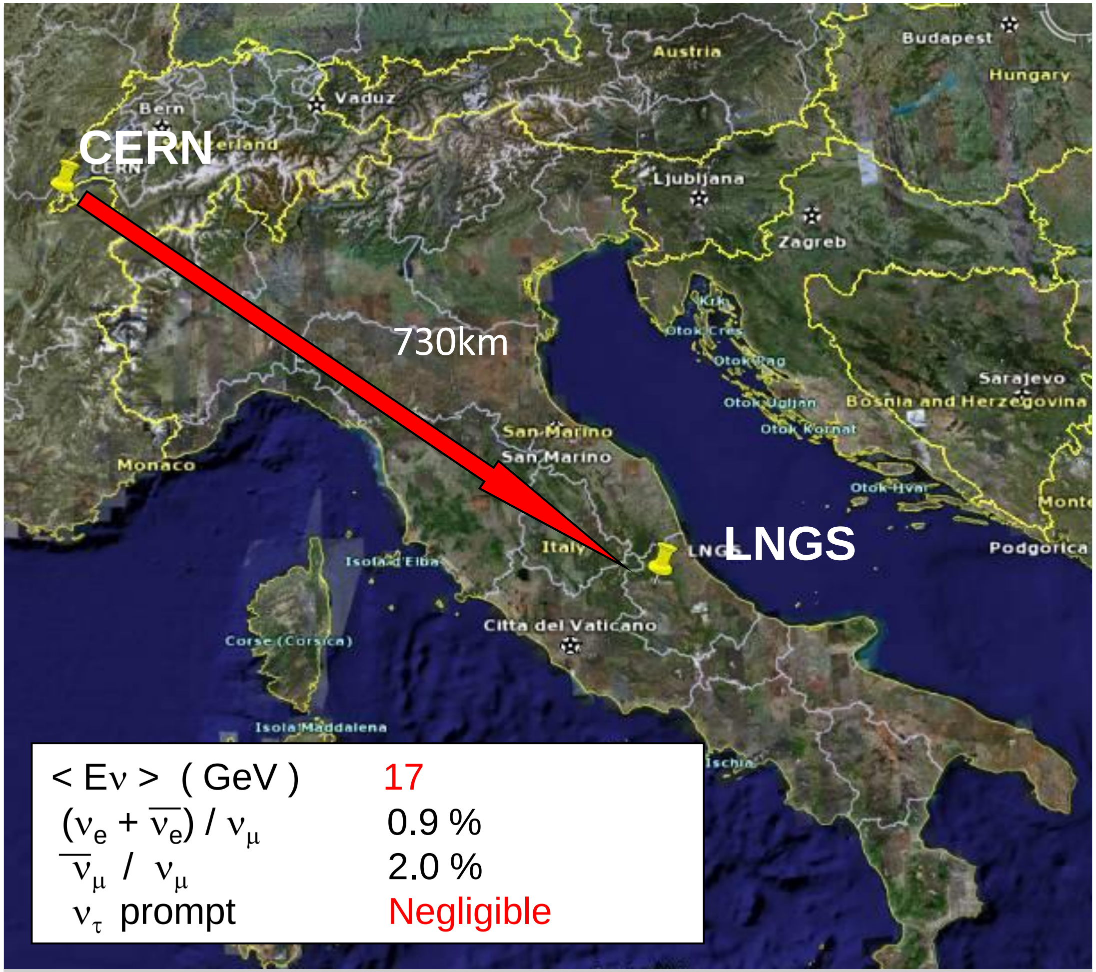
Position distribution of tracks
（OPERAフィルム１枚全面、Total 10^8tracks）



1 microscope view



OPERA $\nu_\mu \rightarrow \nu_\tau$ oscillation in appearance mode

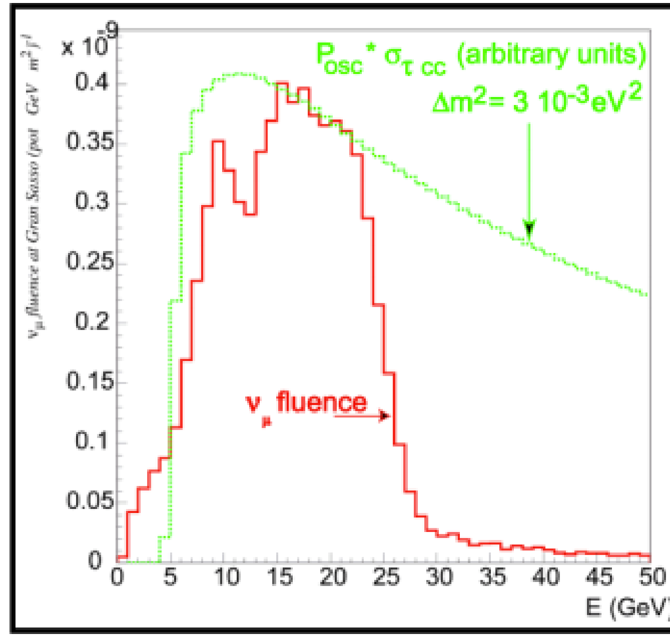


< Eν > (GeV)	17
$(\nu_e + \overline{\nu}_e) / \nu_\mu$	0.9 %
$\overline{\nu}_\mu / \nu_\mu$	2.0 %
ν_τ prompt	Negligible

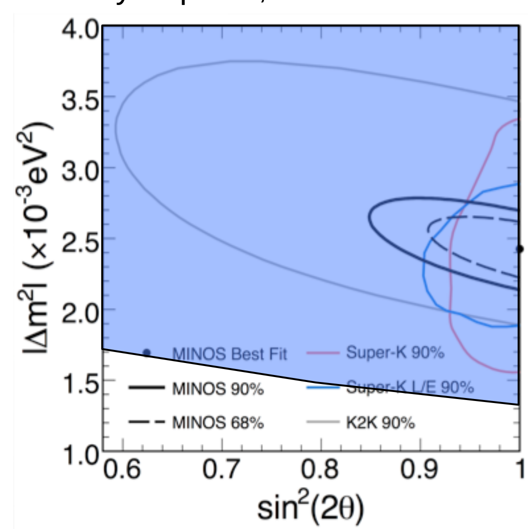
$$P(\nu_\mu \rightarrow \nu_\tau) \sim \sin^2(2\theta_{23}) \cdot \sin^2\left(1.27 \cdot \Delta m^2_{23} \cdot \frac{L}{E}\right) \sim 1.6\%$$

$\sin^2 2\theta_{23} = 1.0$, $\Delta m_{23}^2 = (2.32) \times 10^{-3}\ eV^2$

CNGS Neutrino Beam

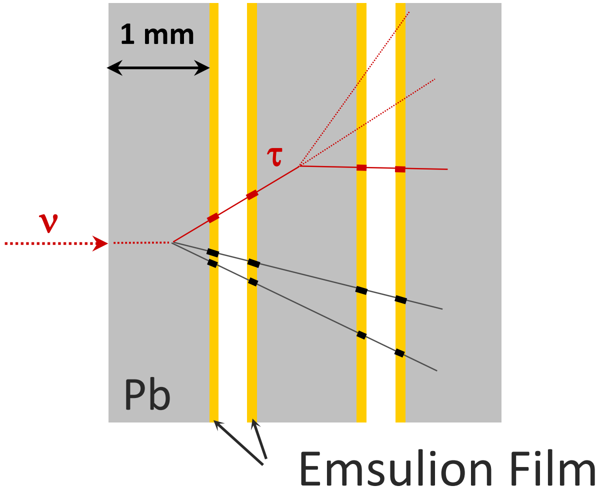


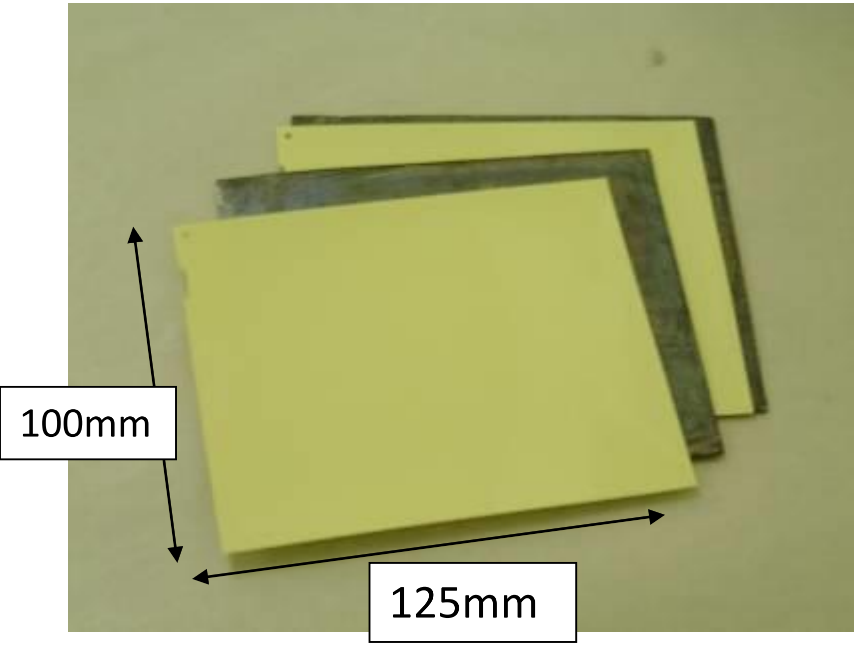
Covers the region indicated by Super-K, K2K & MINOS



OPERA ECC

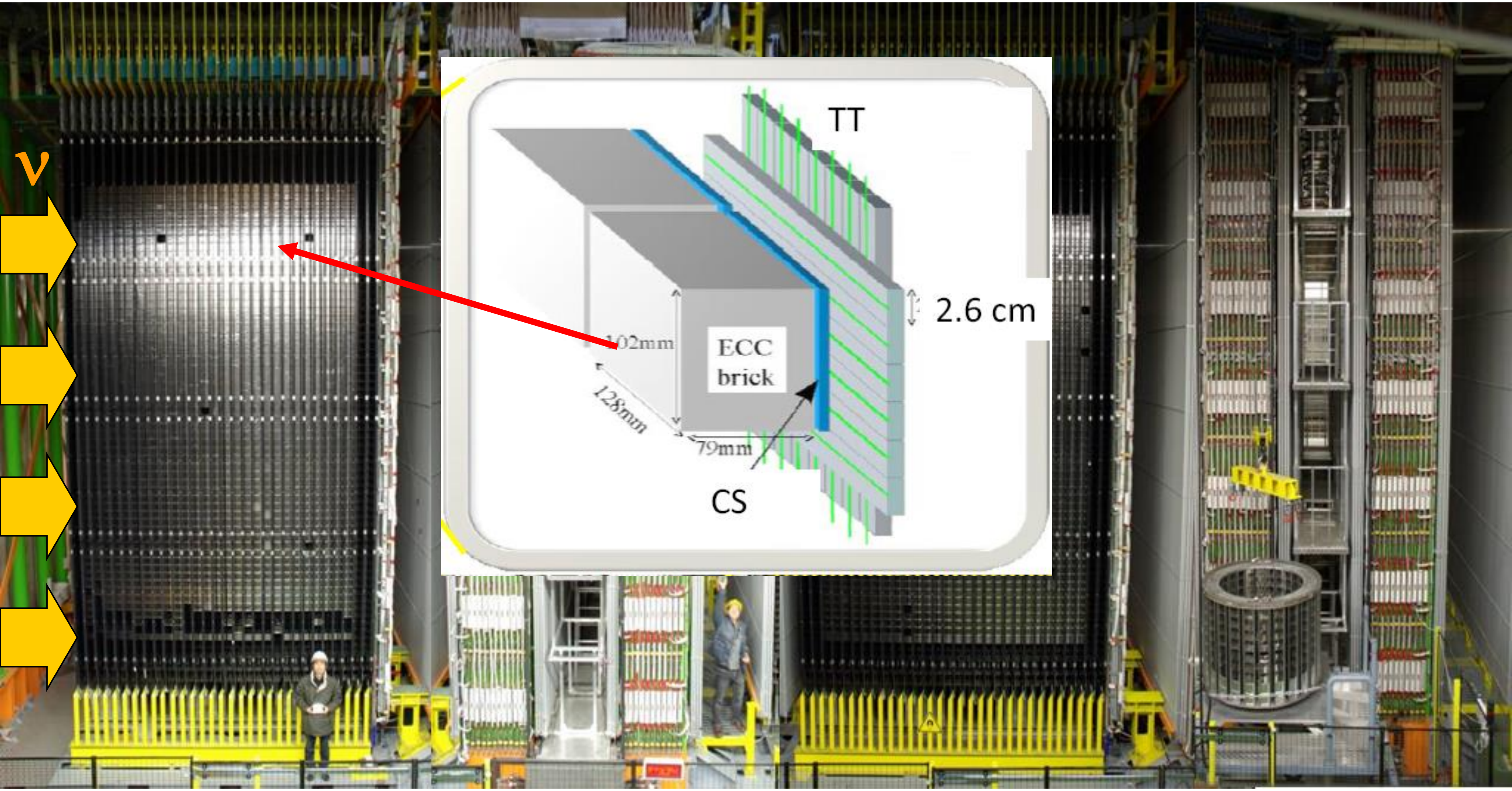
Pb Plate (1mm) / Emulsion Film Sandwich



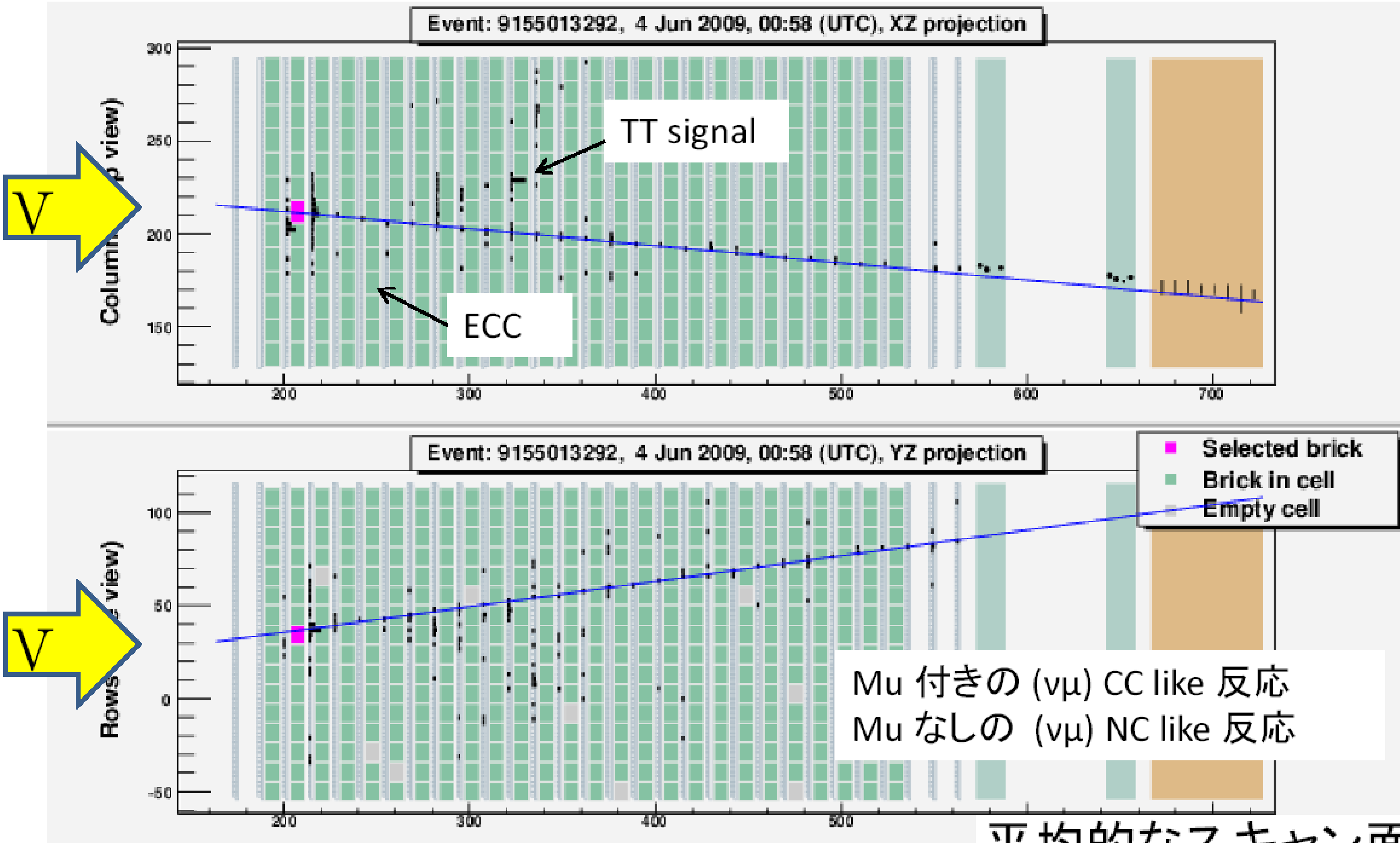


56 Lead Plates + 57 Films

~ structure same as DONUT ECC


ν
TT
2.6 cm
102mm
ECC
brick
128mm
79mm
CS

Target Tracker による Brick ID



max.30ev/day

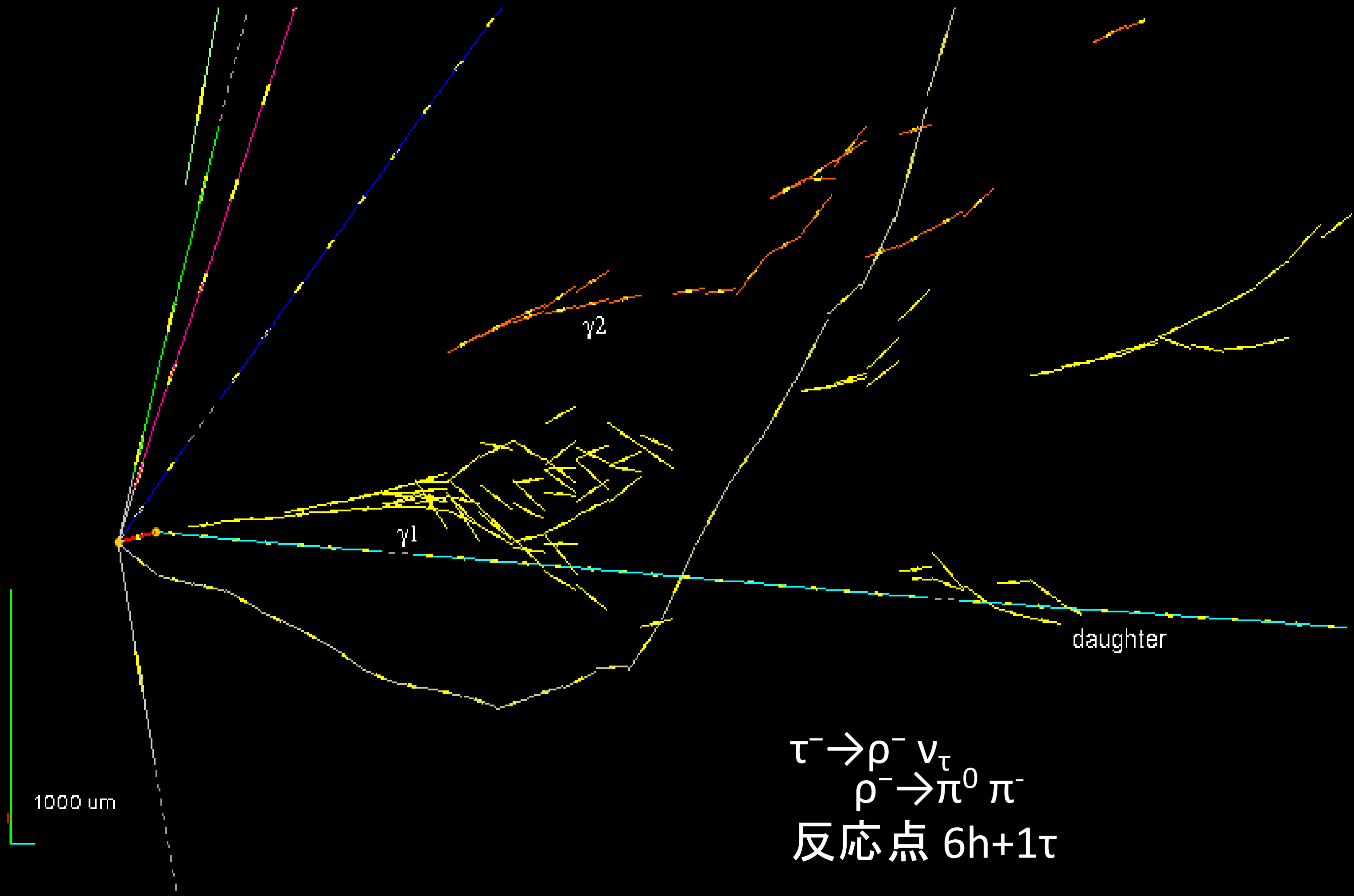
平均的なスキャン面積

CC like： 26 cm2

NC like： 61 cm2

1^{st} $\nu_\mu \rightarrow \nu_\tau$ event in OPERA

2010



$\tau^- \rightarrow \rho^- \nu_\tau$
$\rho^- \rightarrow \pi^0 \pi^-$
反応点 6h+1τ

Significance

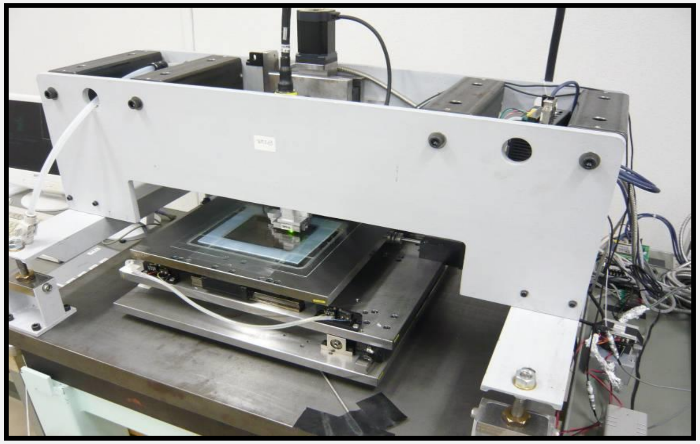
Decay channel	Expected signal	Observed	Expected background: Total	Charm decays	Hadronic re-interactions	Large-angle muon scattering
$\tau \to 1h$	0.41 ± 0.08	2	0.033 ± 0.006	0.015 ± 0.003	0.018 ± 0.005	–
$\tau \to 3h$	0.57 ± 0.11	1	0.155 ± 0.030	0.152 ± 0.030	0.002 ± 0.001	–
$\tau \to \mu$	0.52 ± 0.10	1	0.018 ± 0.007	0.003 ± 0.001	–	0.014 ± 0.007
$\tau \to e$	0.62 ± 0.12	0	0.027 ± 0.005	0.027 ± 0.005	–	–
Total	2.11 ± 0.42	4	0.233 ± 0.041	0.198 ± 0.040	0.021 ± 0.006	0.014 ± 0.007

p-value $= 1.24 \times 10^{-5}$

4.2σ Significance for the existence of $\nu_\mu \to \nu_\tau$

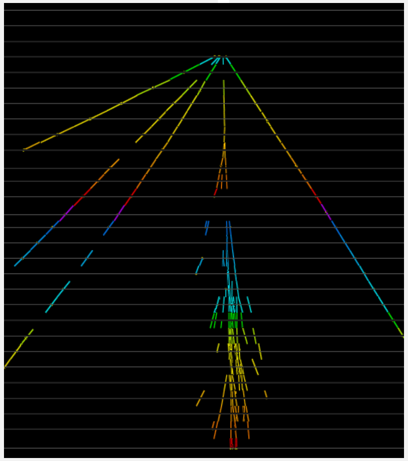
Δm^2_{23} 3.1 [1.8, 5.0] x 10^{-3} eV^2 Assuming $\sin 2\theta_{23}=1$

Launching Nuclear Emulsion into various field



High Energy Physics

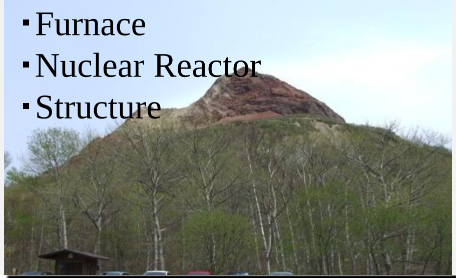
Neutrino oscillation (OPERA)

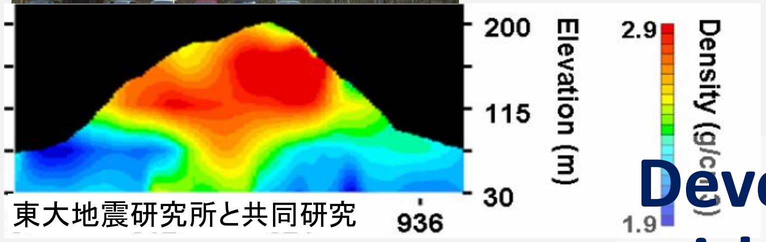


Applied physics

Muon-radiography

- Volcano
- Furnace
- Nuclear Reactor
- Structure





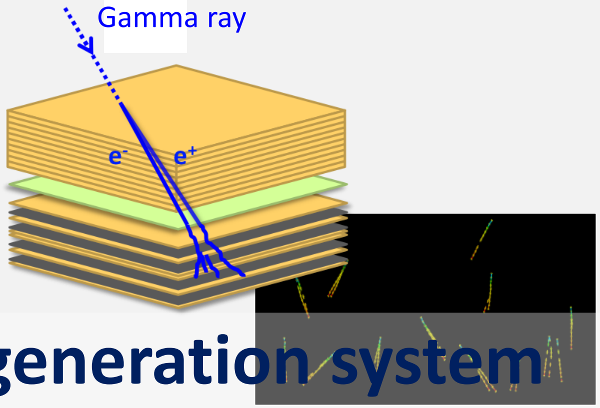
Neutron

(Direction, Energy)

- Nuclear Fusion
- Imaging
- Dosimeters
- Dark-matter

Astrophysics

Gamma ray telescope (GRAINE)



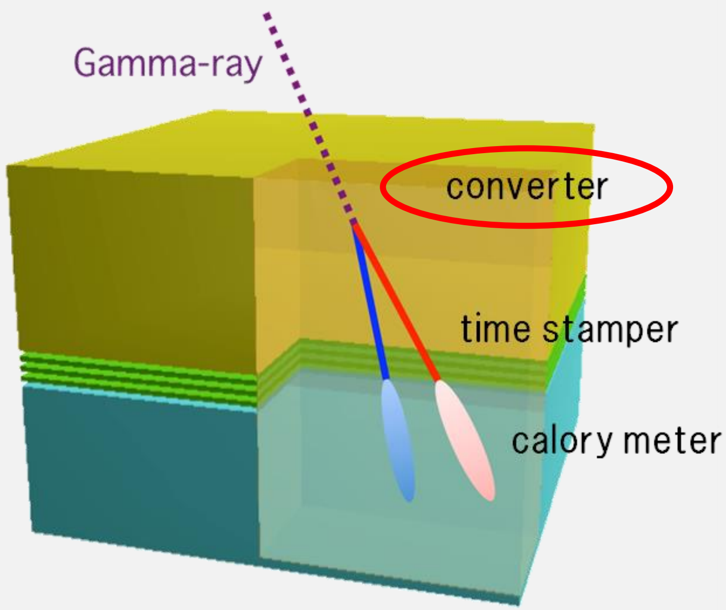
Developing next generation system with the speed of ~$1m^2/h$: HyperTS

GRAINE Gamma-Ray Astro-Imager with Nuclear Emulsion

Nagoya, Kobe, JAXA/ISAS, Aichi Edu. , Okayama Science, Utsunomiya

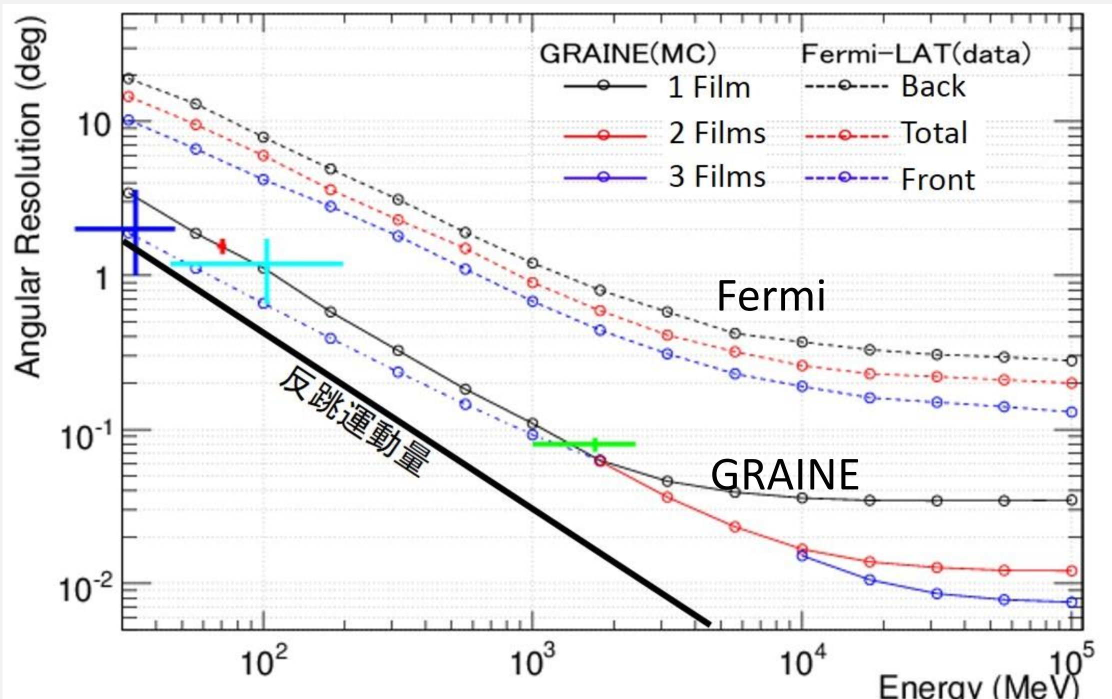
Target : 10MeV—100GeV γ-ray Balloon exp.

Emulsion γ ray telescope



The incident direction of the Converted electron pairs by Emulsion

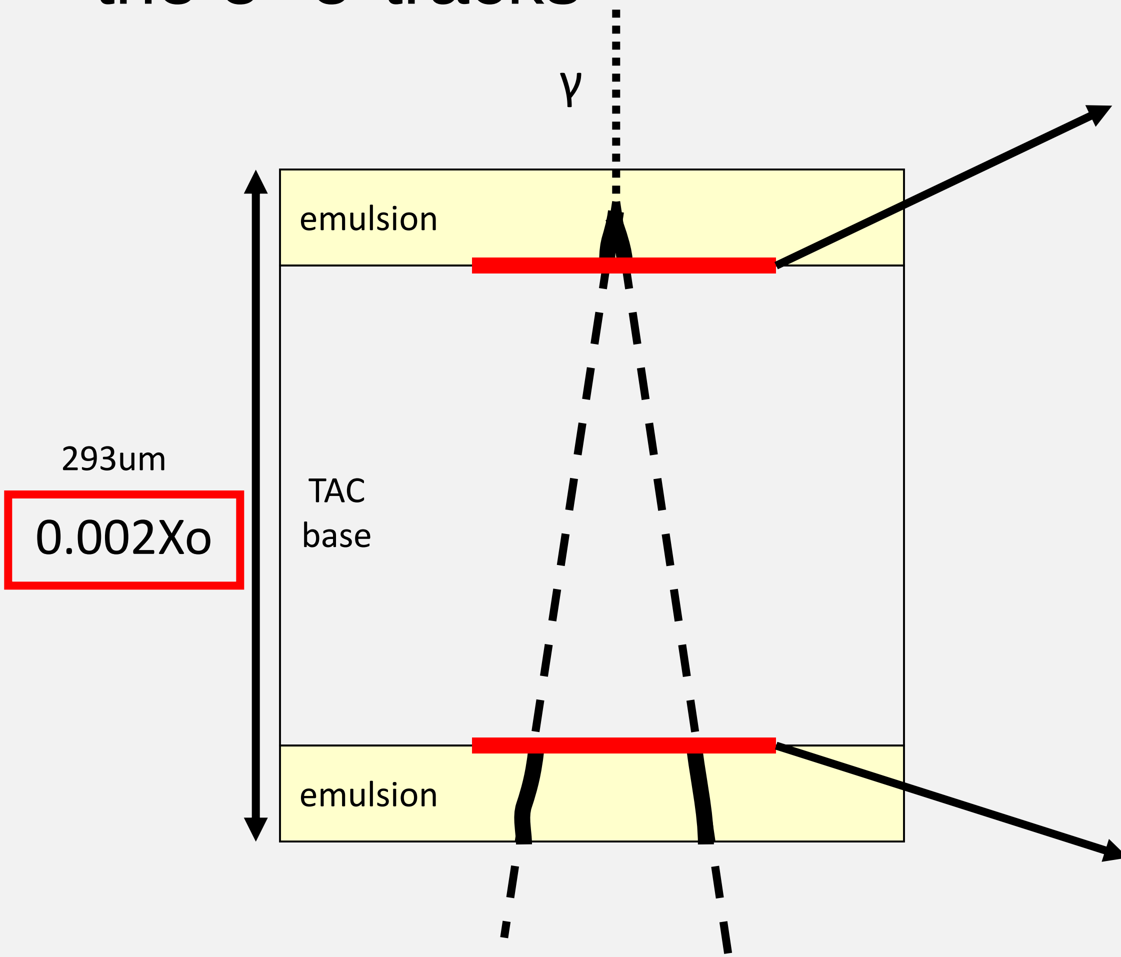
Angular Resolution of Emulsion telescope

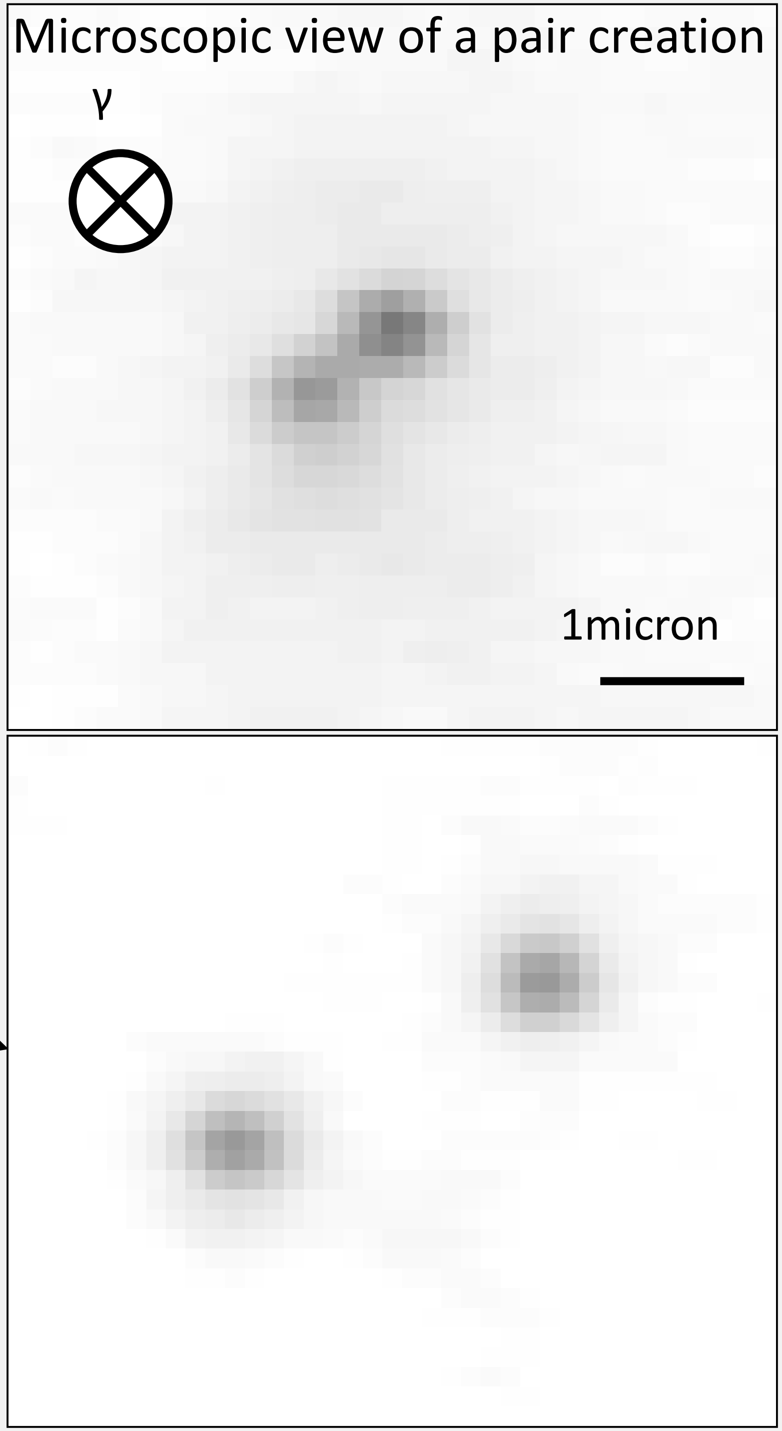


10 mrad @ 100 MeV

1.5 mrad @ 1 GeV

Precise measurement of the e^{+} e^{-} tracks



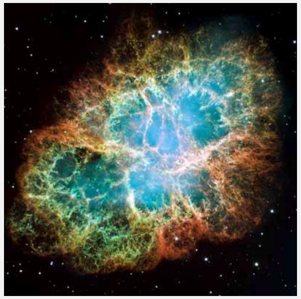


γ Ray Astronomy

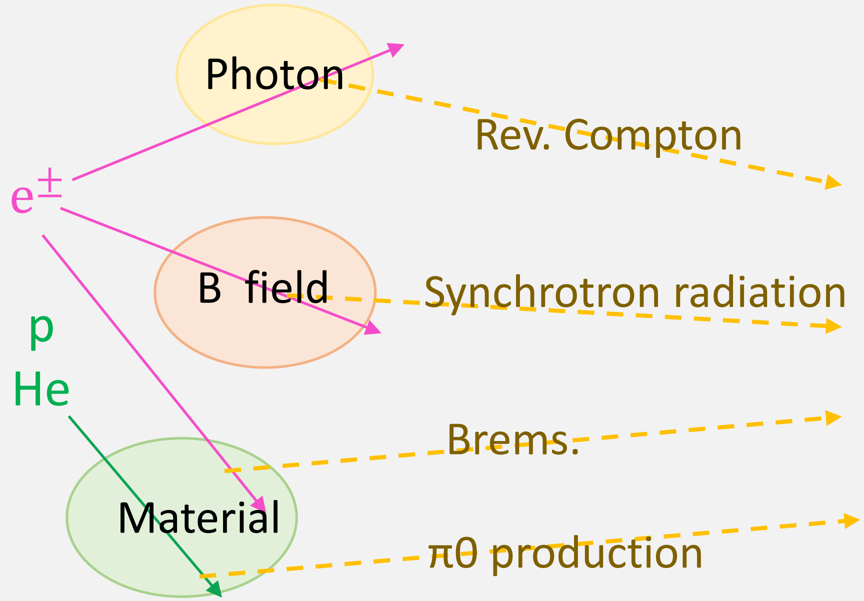
- SuperNova
- Pulsar
  (Neutron Star)
- Active Galactic Nuclei (Black Hole）

- Transit events
  GRB, flare ...

かに星雲、かにパルサー



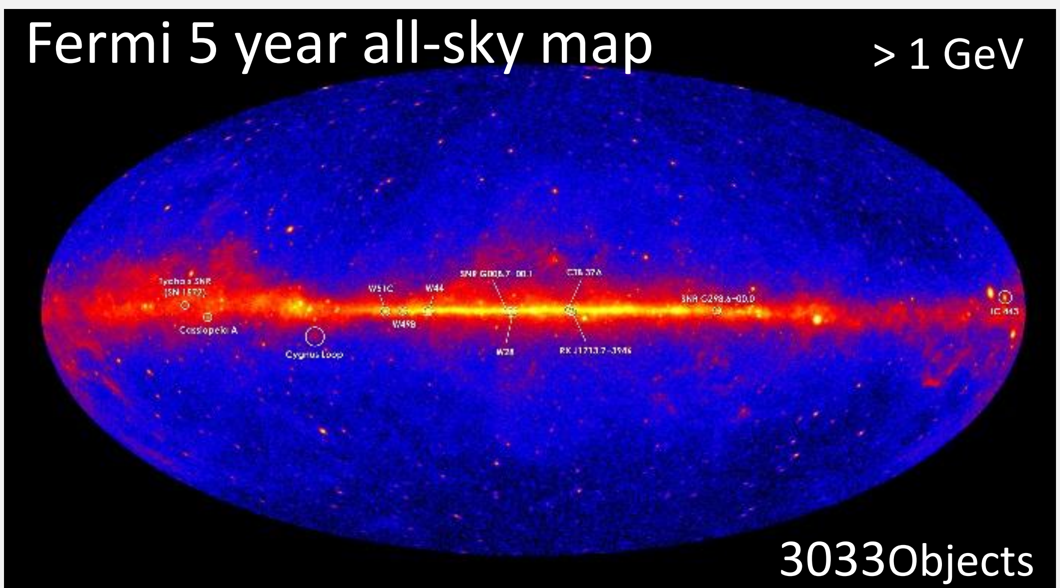
NASA　HUBBLE



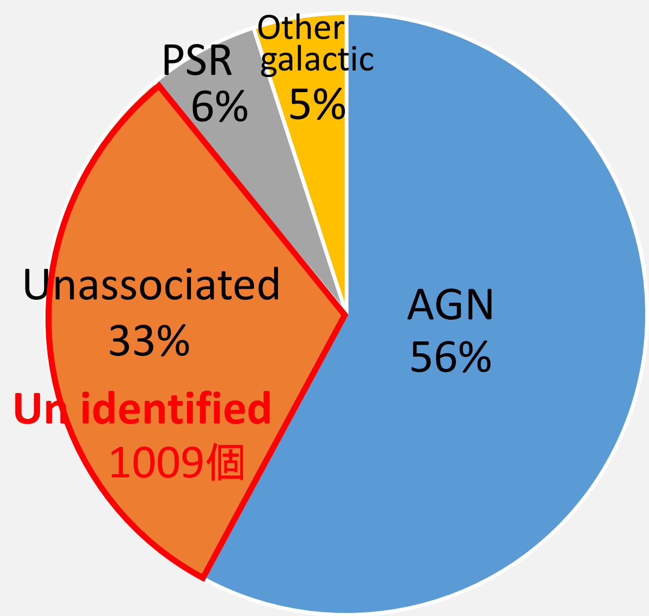
Satelite

Balloon　JAXA

Fermi-LAT の観測

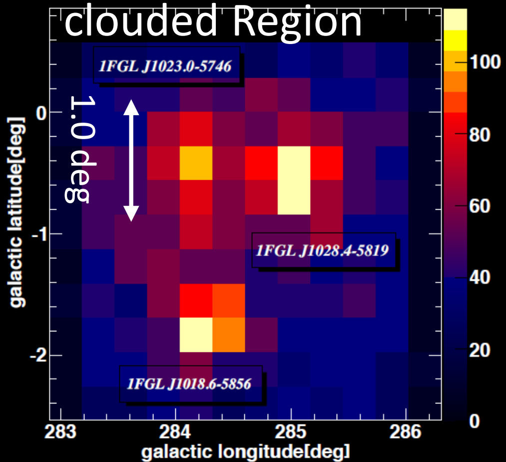


Contents of 3033



Fermi-LAT (data)

Observation of clouded Region

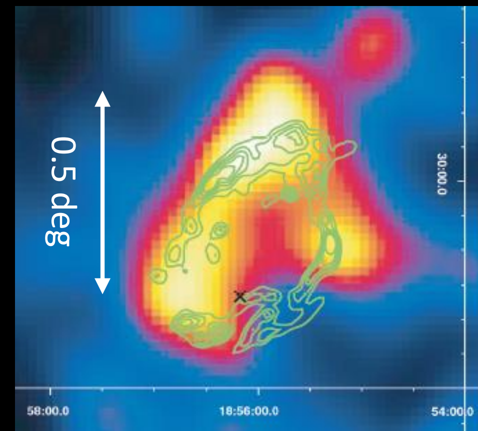


Energy
1−3 GeV

Observation
~ 6 month

1FGL J1018.6-5856
1FGL J1023.0-5746
1FGL J1028.4-5819
From Fermi Science Support Center
Fermi 1st catalog

Super Nova Remnunt



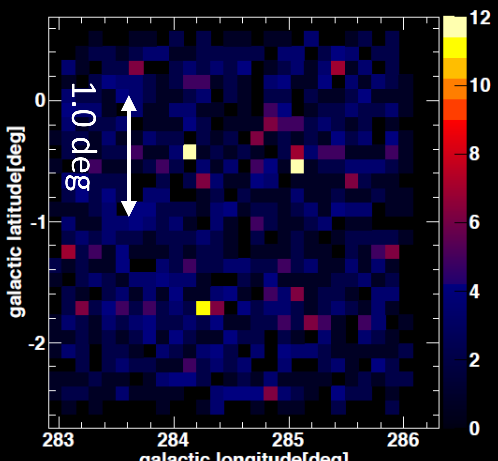
Energy
2−10 GeV

Observation
~ 6 month

SNR W44

A. A. Abdo. et al. (2010) Science

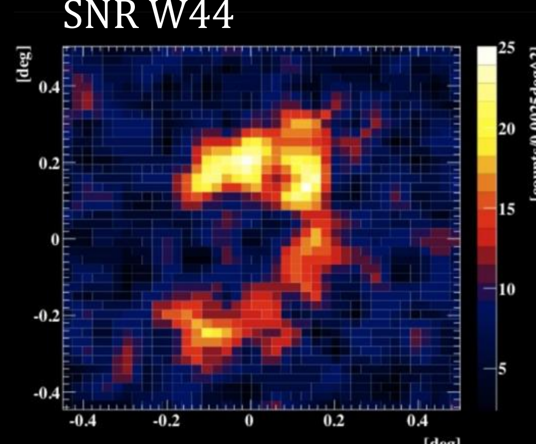
GRAINE (MC)



Energy
1−3 GeV

Observation
$\sim 150\ m^2 \cdot hour$
for 5σ detection

SNR W44

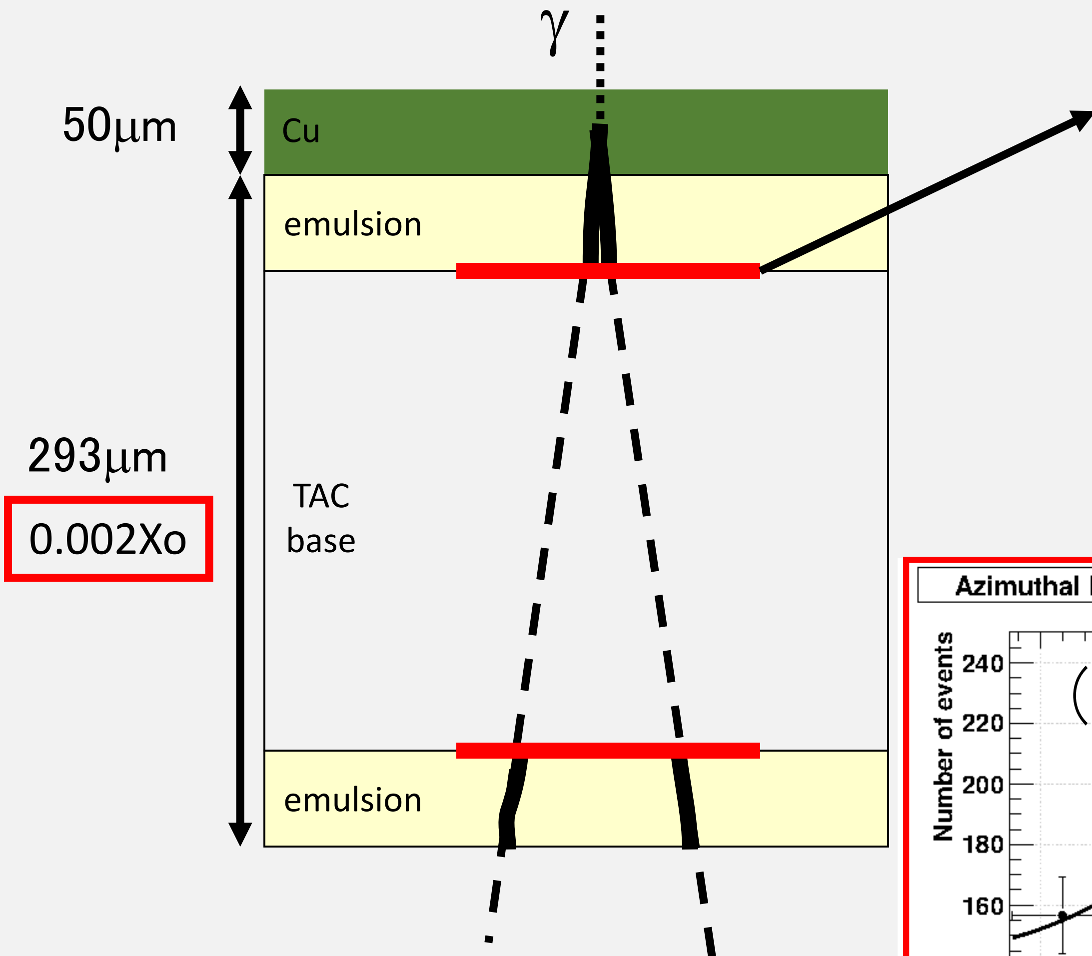


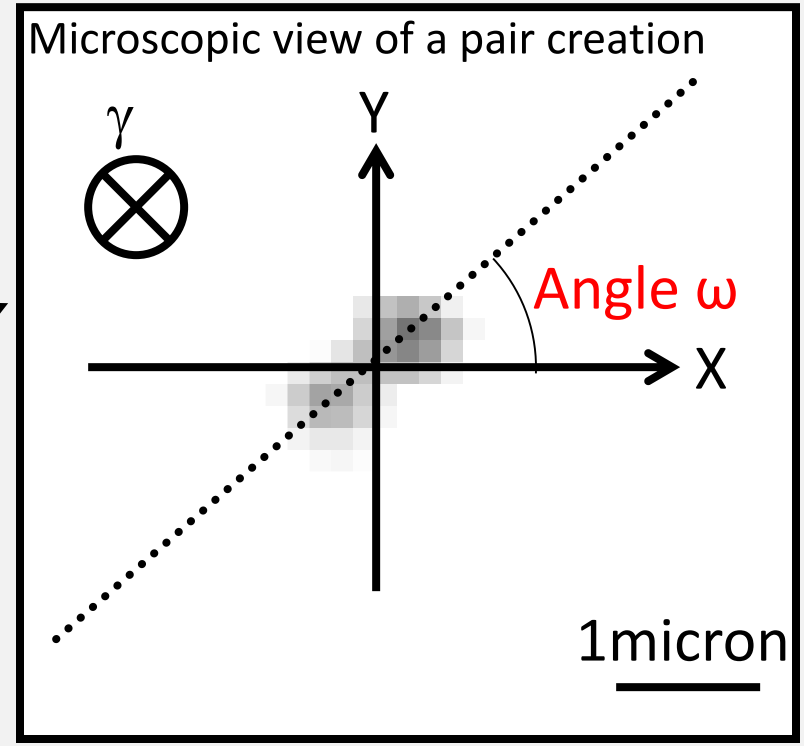
Energy
> 1 GeV

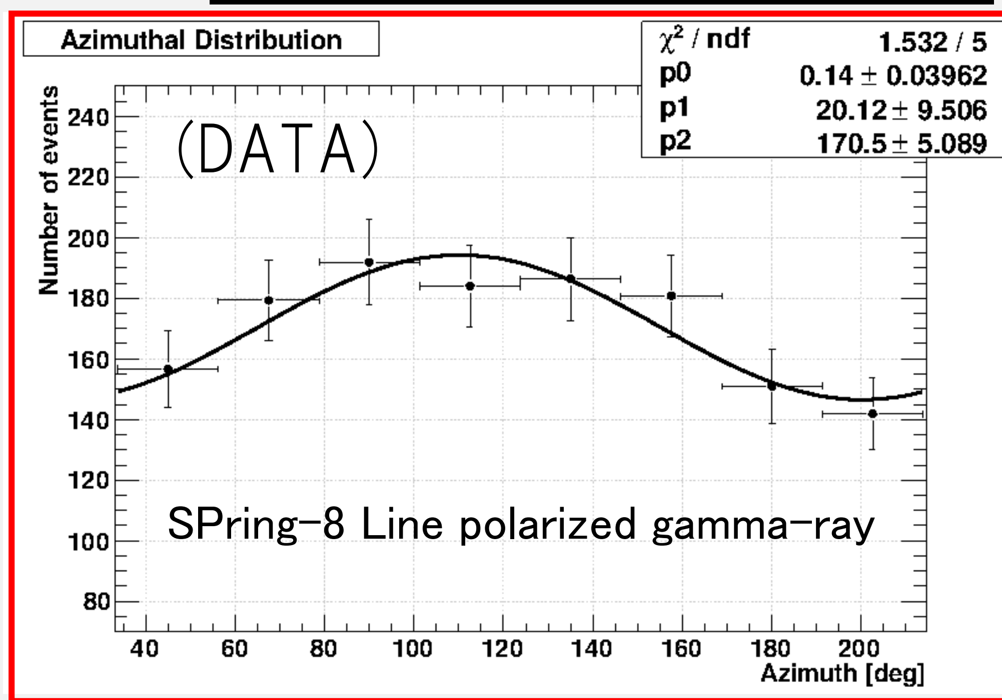
Observation
$1000\ m^2 \cdot hour$

Need to realize large aperture + long flight
Aiming $10 m^2$/Flight + 1 Weeks/Flight

Polarity Measurement

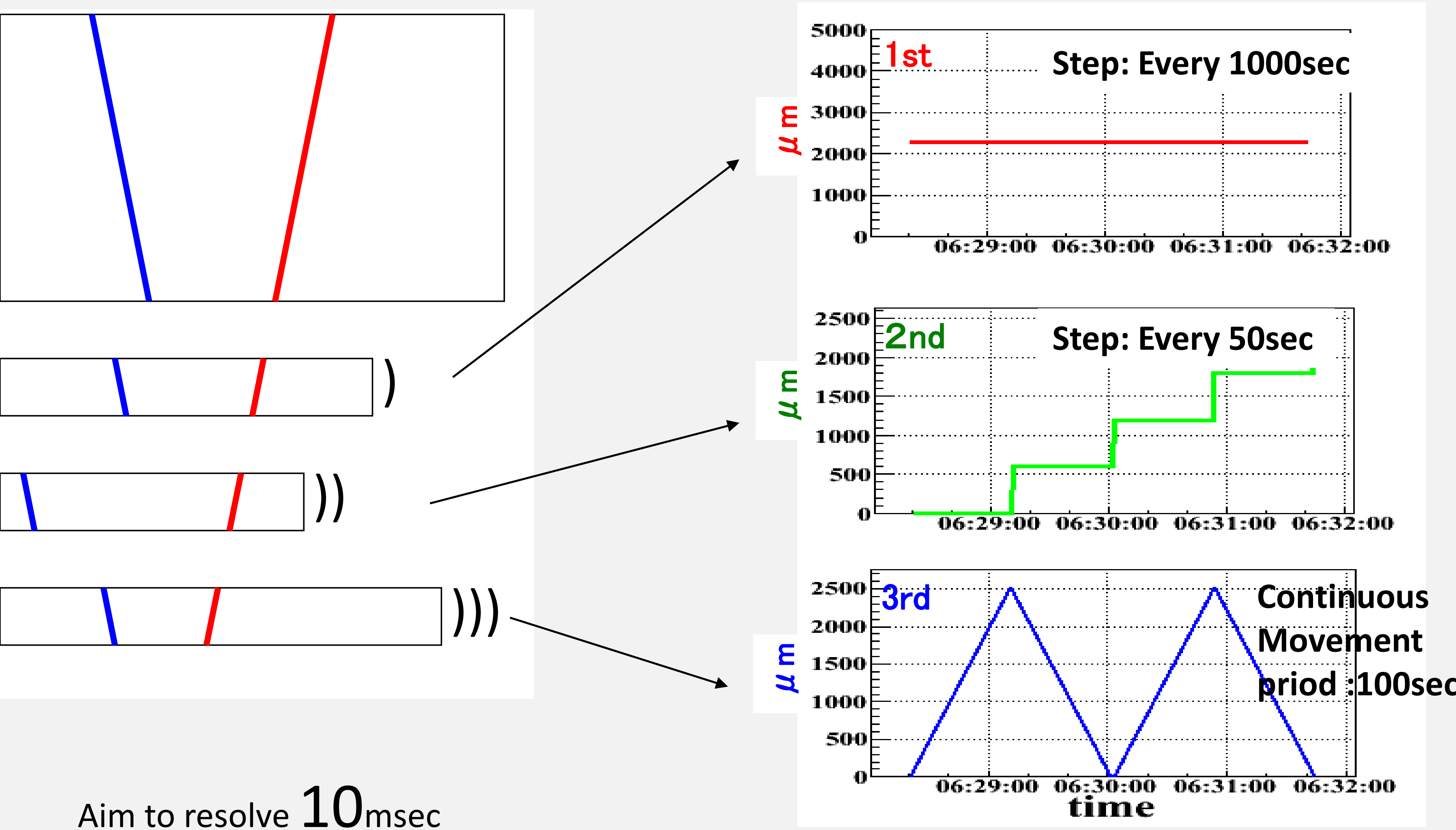






GRAINE can measure the Polarity
(Proven by 3.5 σ)
Fermi : impossible

Time Stamp System = Shifter



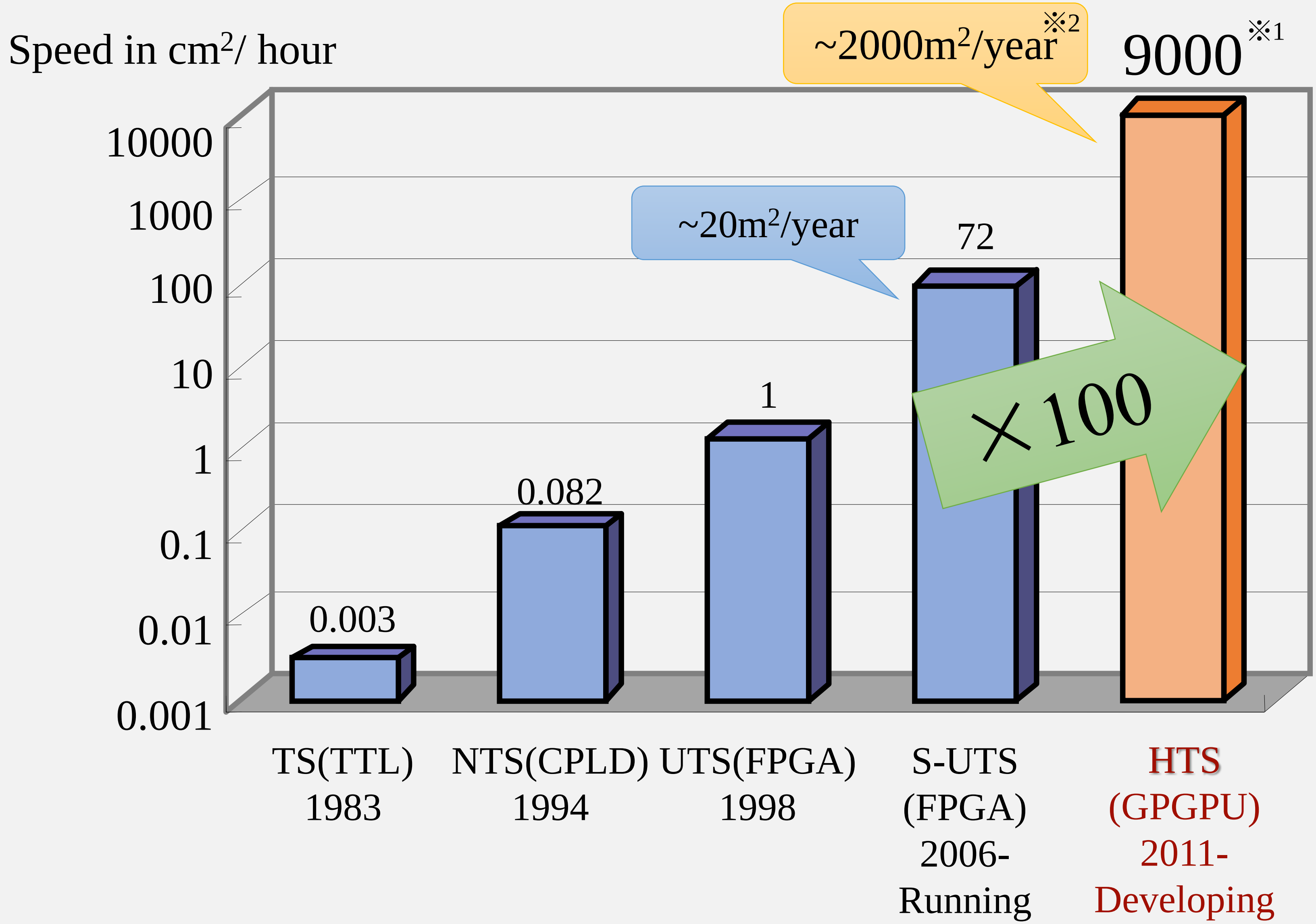
Aim to resolve 10msec

A scanning speed of 1000m^2 /year or more is required.

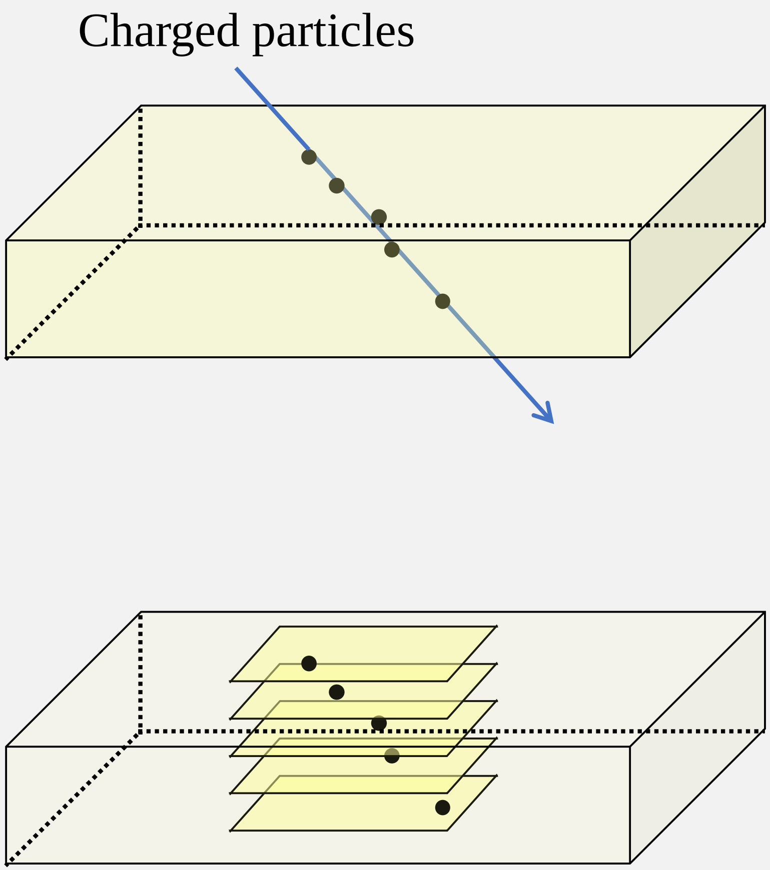
Two orders of magnitude faster.

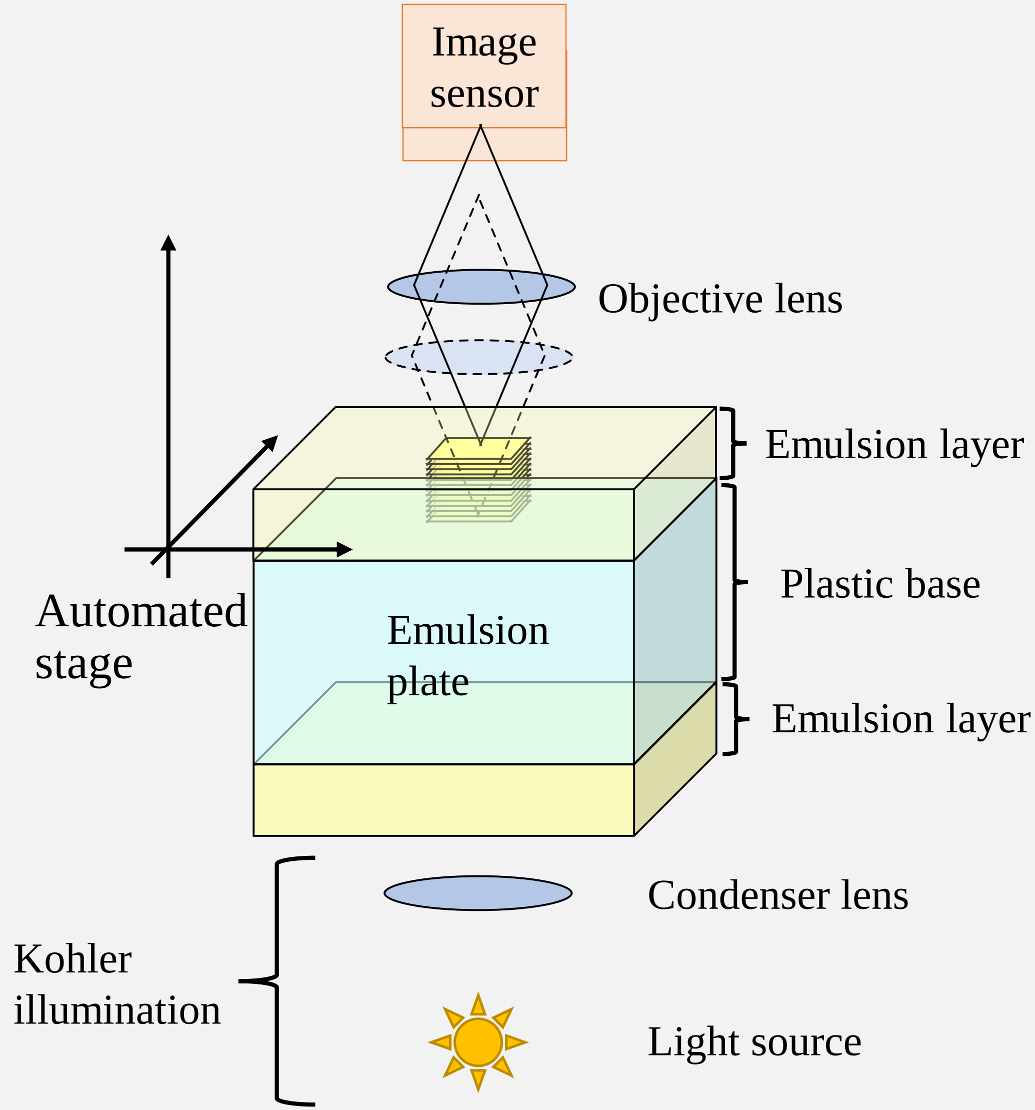
Evolution of the Scanning Speed

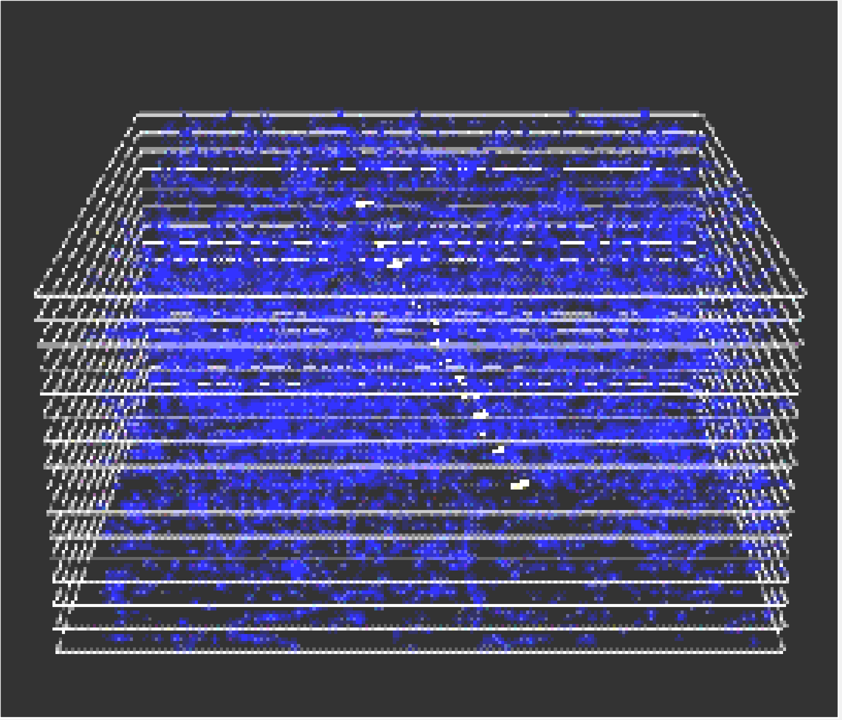
※1 Area of each layer
※2 Area of the films

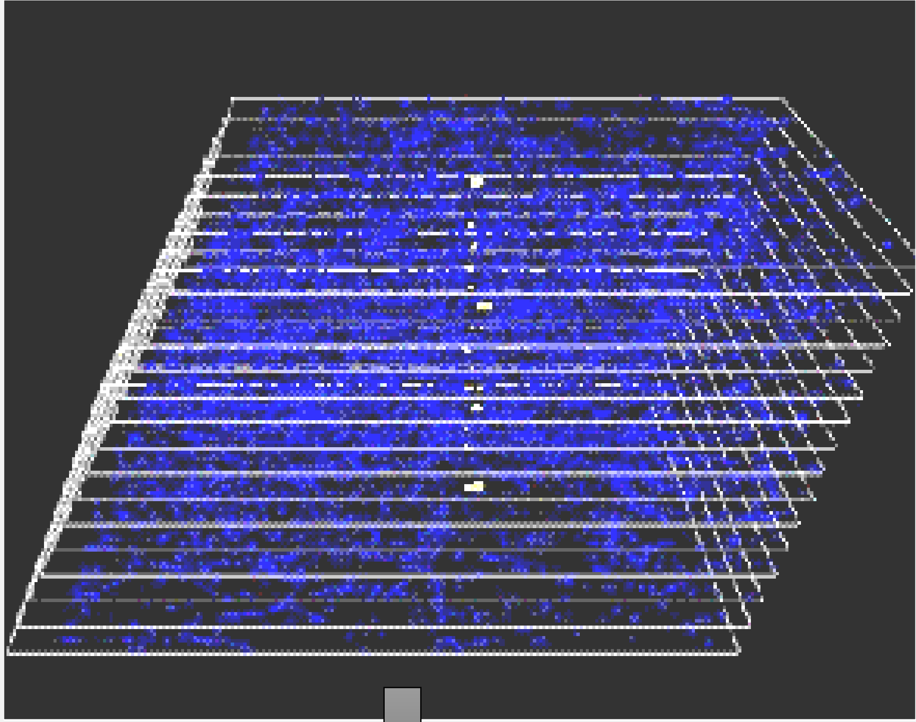


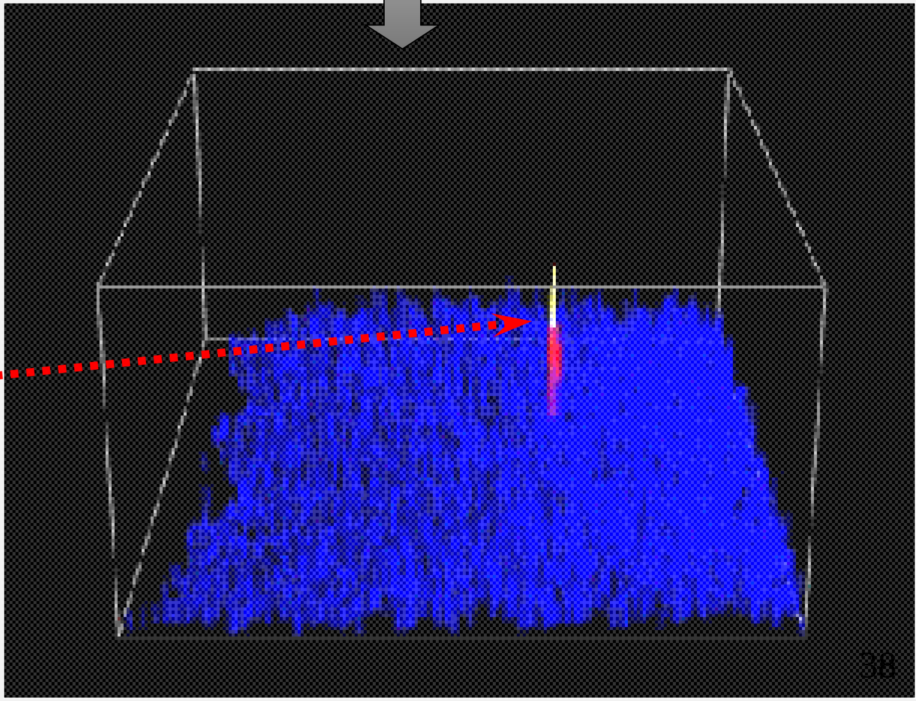
Digitizing Nuclear Emulsion











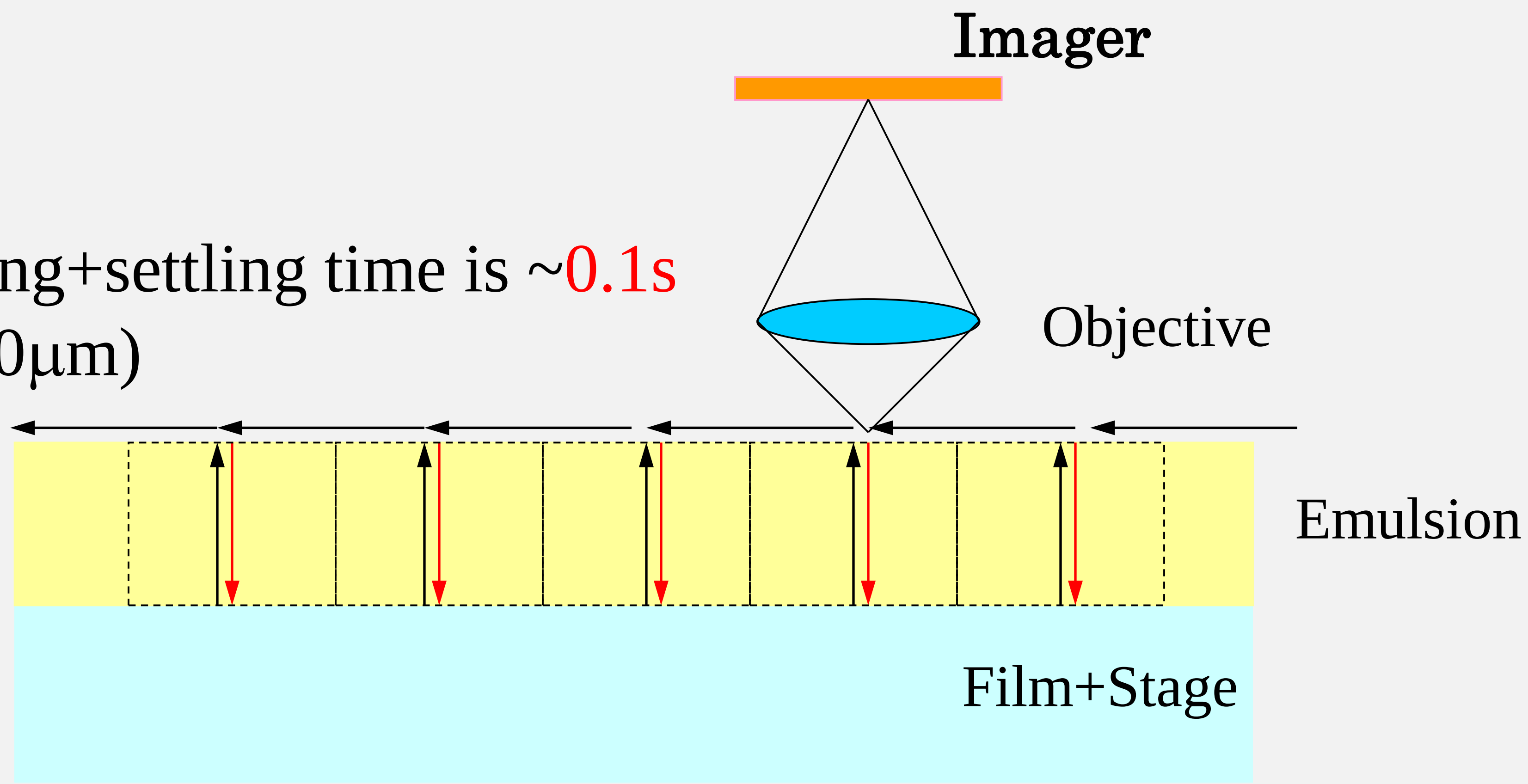
Track recognition method

- 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.
- Repeat for all angles in space, >2000 times

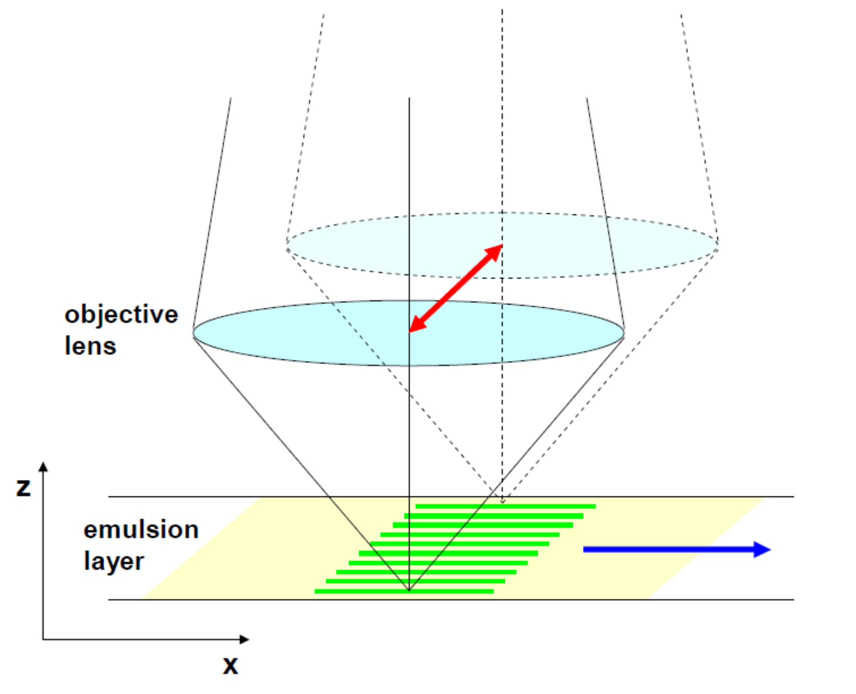
Invented by K. Niwa in 1974

Mechanics is also the bottleneck

Driving+settling time is ~0.1s
(~200μm)



The features of the previous system “SUTS”



- Ultra High Speed Camera

  Up to 3k frames per second.

  60 view/sec (20times)

- Image taking by follow shot

  No step and repeat operation can avoid a mechanical bottleneck.

  High speed motion of the objective lens can be done by piezo actuators

- Optimizing Field of View

  120mm×90mm -> 200mm×200mm (4 times area)

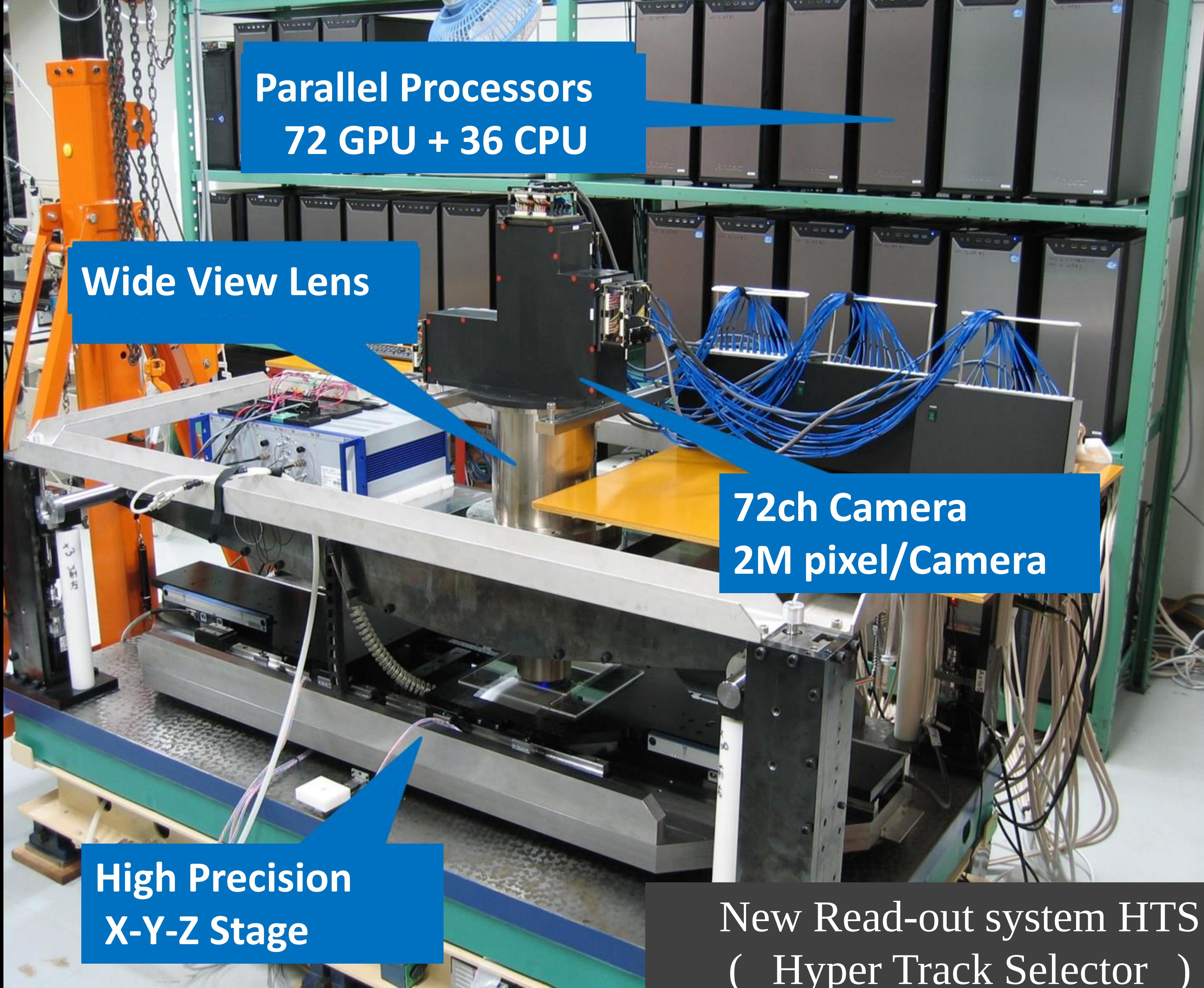
- FPGA for image processing

Maximum scanning speed is 72cm^2/h

Concept of HTS (Hyper Track Selector)

- It is difficult to drive objective much more quickly.

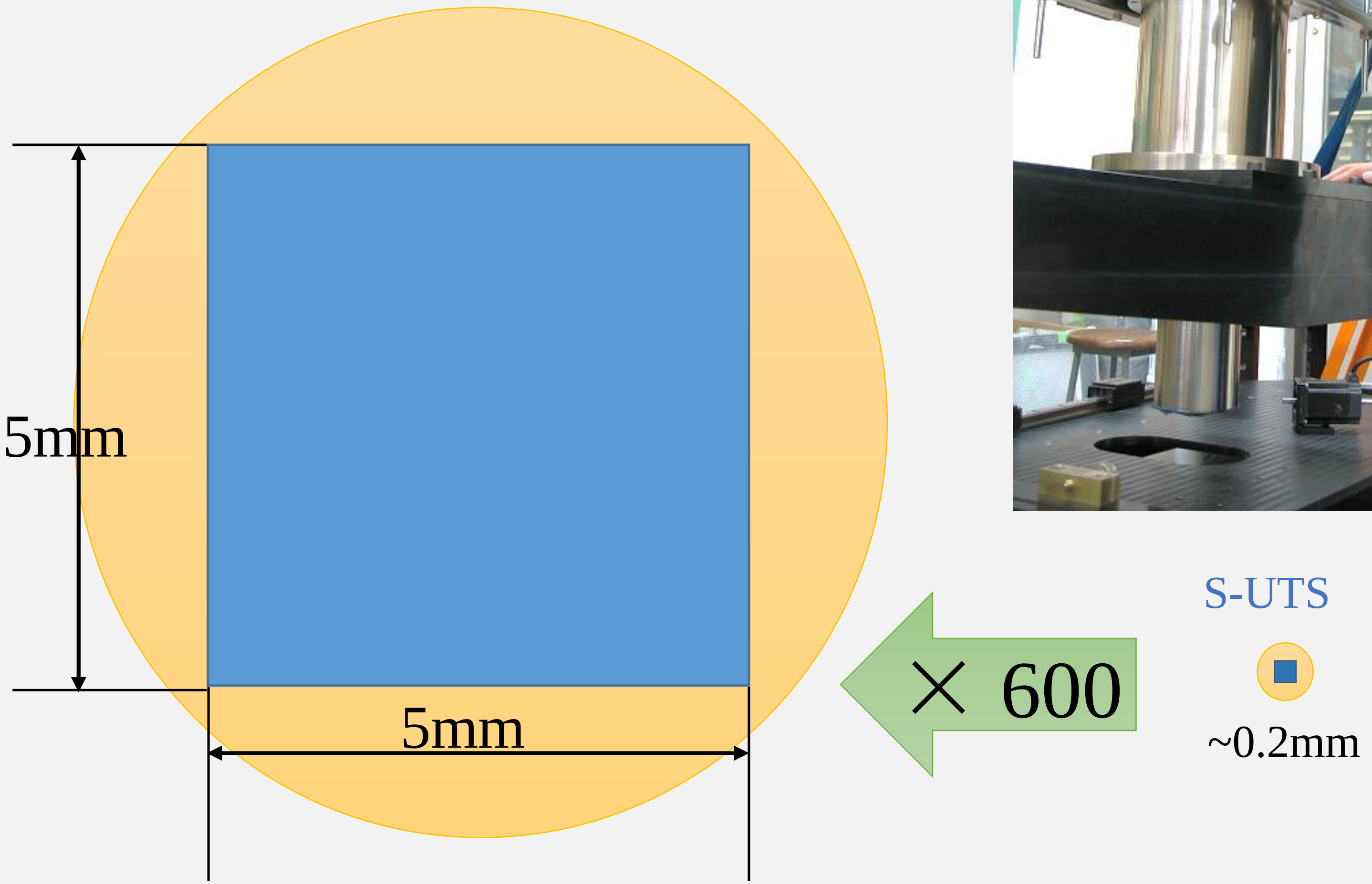
- Field of view can be a few orders of magnitude larger.



New Read-out system HTS
(Hyper Track Selector)

Wide field of view

Field of view (FOV) of HTS



Big Objective Lens

Resolution : ~420nm
N.A. : 0.65
Light source : g-line (436nm)
Magnitude : ×12.2
F.O.V : 5.1 (H)×5.1 (V)mm

#of image plane 6
(by Beam splitter)

Weight : 80kg

Resolution : "Numerical Aperture"

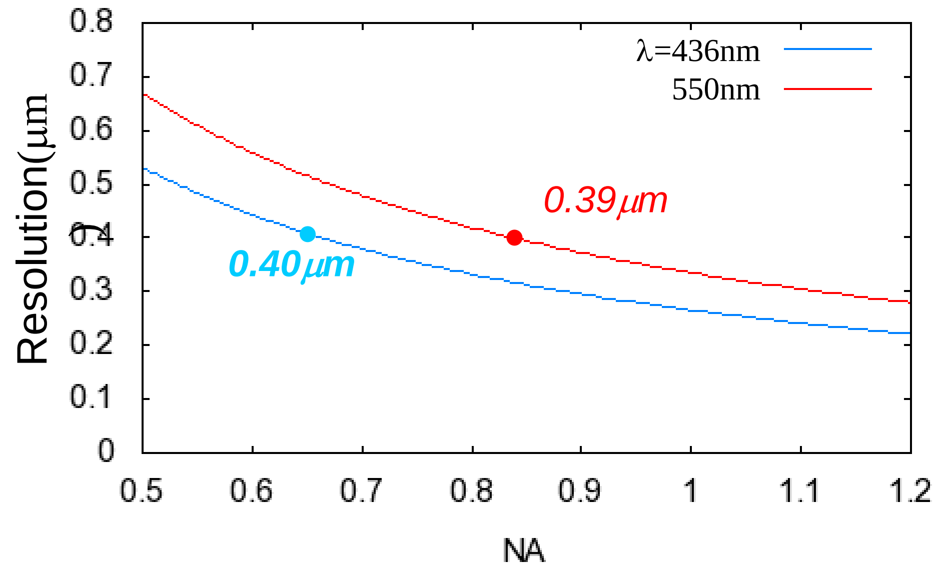
- Spatial resolution :

$$R_{res} = 0.61 \cdot \lambda / NA$$

NA=0.65, λ=436nm : 0.40μm **HTS**

NA=0.85, λ=550nm : 0.39μm **SUTS**

No significant difference



- Depth of field :

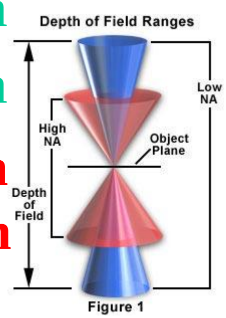
$$DOF = \boxed{1.0} \cdot n / NA + n \cdot \lambda / NA^2$$

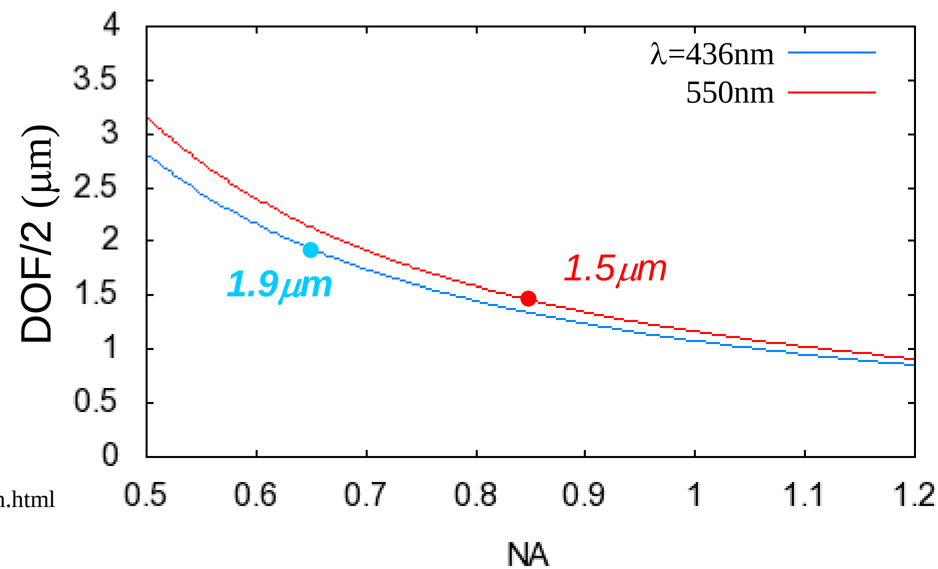
Circle of confusion (Modified BEREK formula)

NA=0.65, λ=436nm : ±1.9μm

NA=0.85, λ=550nm : ±1.5μm

27% worse, however emulsion thickness can be adjusted even after developing.

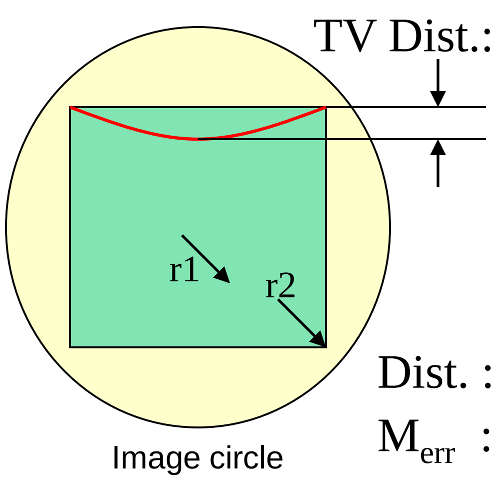




http://www.microscopyu.com/articles/formulas/formulasfielddepth.html

Distortion (Optical aberration)

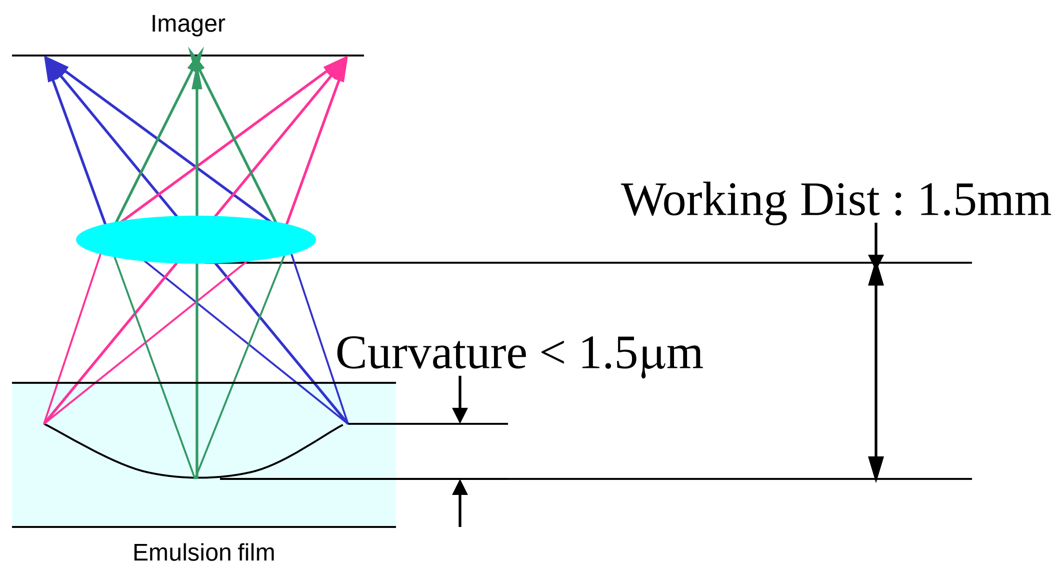
TV distortion :	0.075%	-> linearity < 4μm/5mm
Distortion :	0.25% max.	-> ~0.74% Magnification Error
Field curvature :	<1.5μm	-> No loss frame
Working distance:	1.5mm	-> Accept thick emulsion film



Dist. : $0.02 \cdot h^2$ (%)

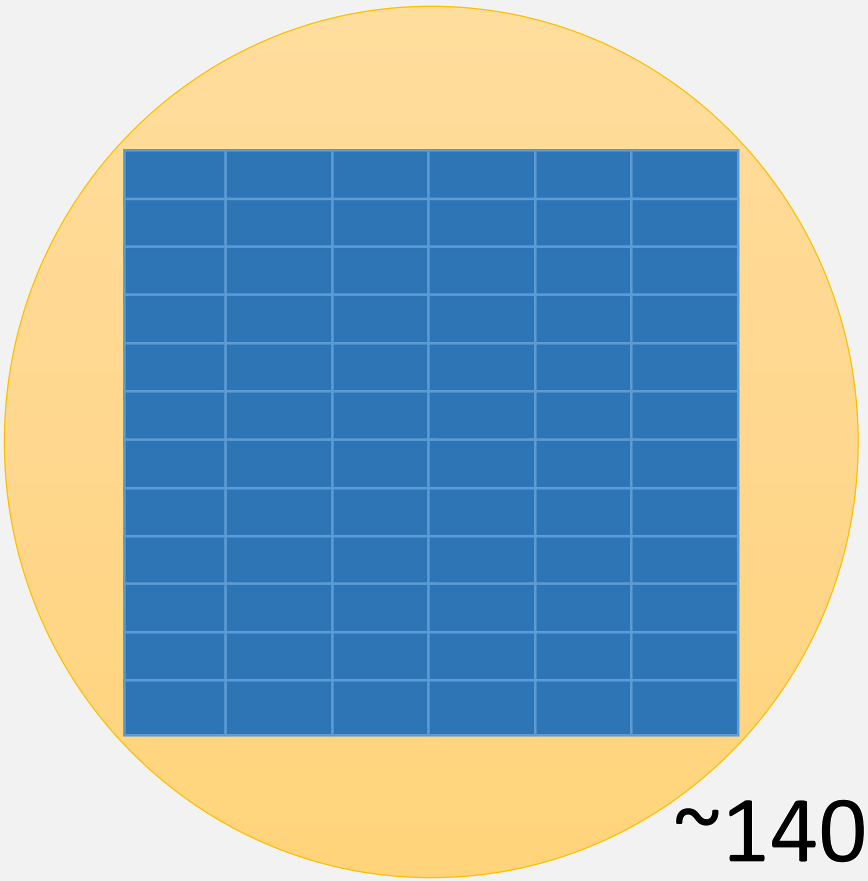
M_{err} : $0.06 \cdot h^2$ (%)

$r_2/r_1 < 1.0074$



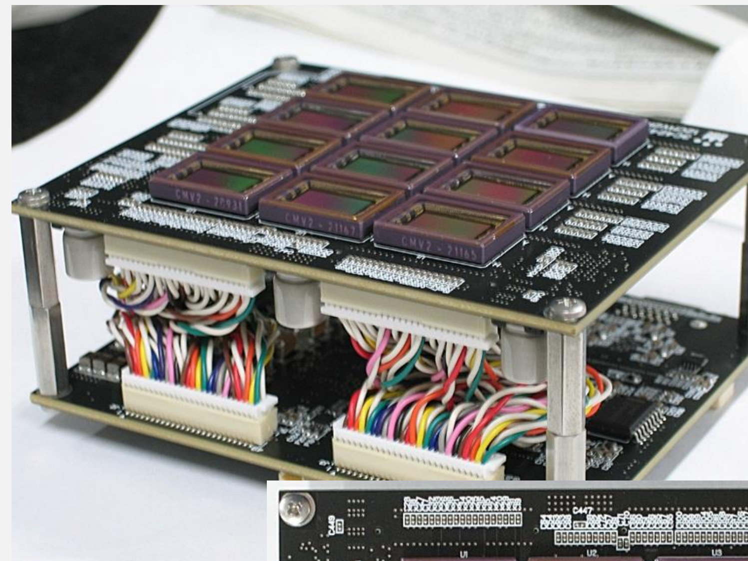
Speed and Coverage of Mosaic Imager

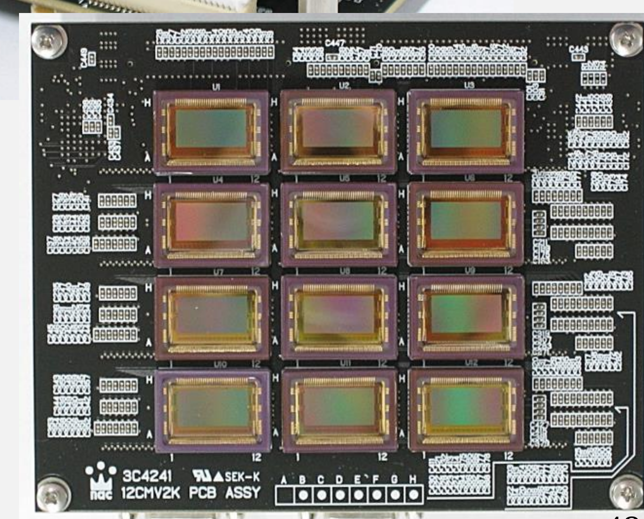
Divide FOV into 72 parts.
Need the sensor of 2M pixel and 340fps.



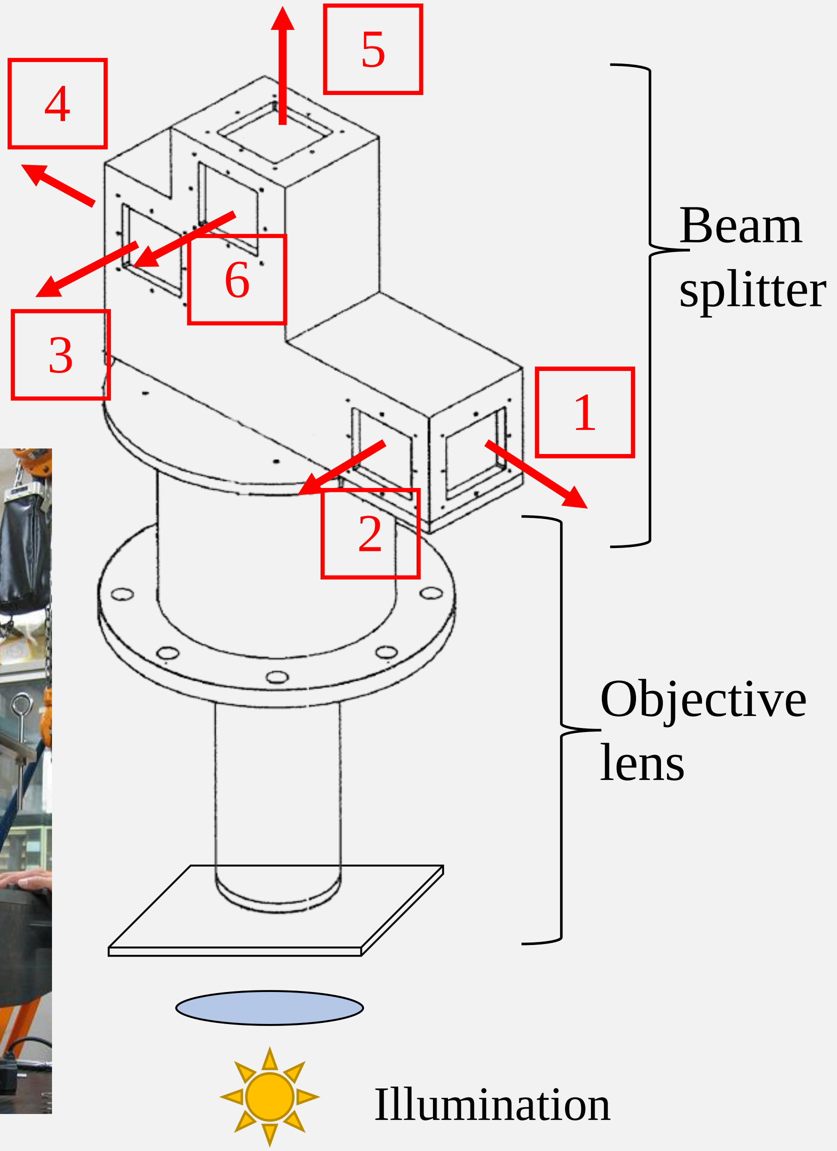
~140M Pixels

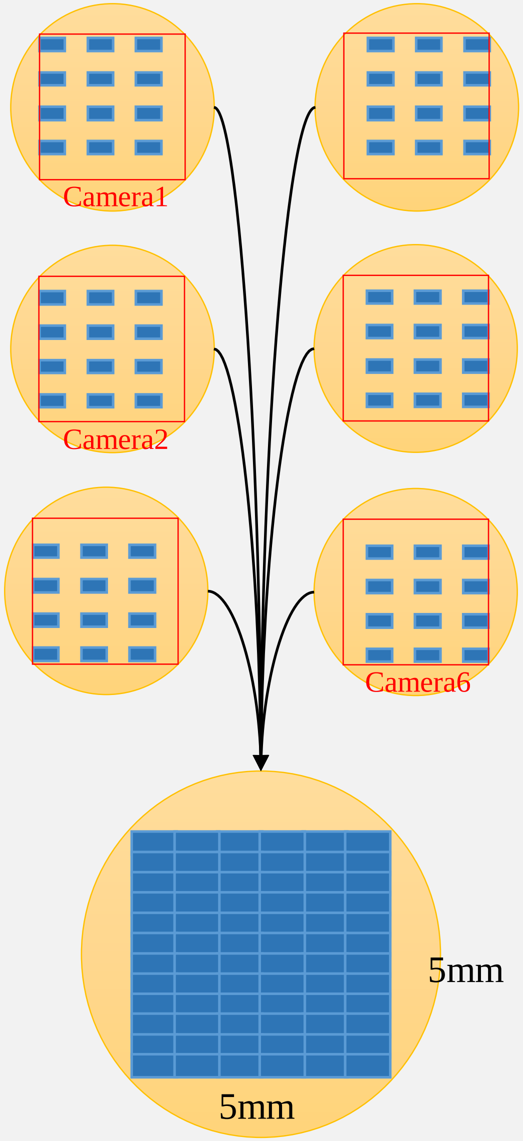
Specially developed Mosaic Imager





Mosaic Imager system





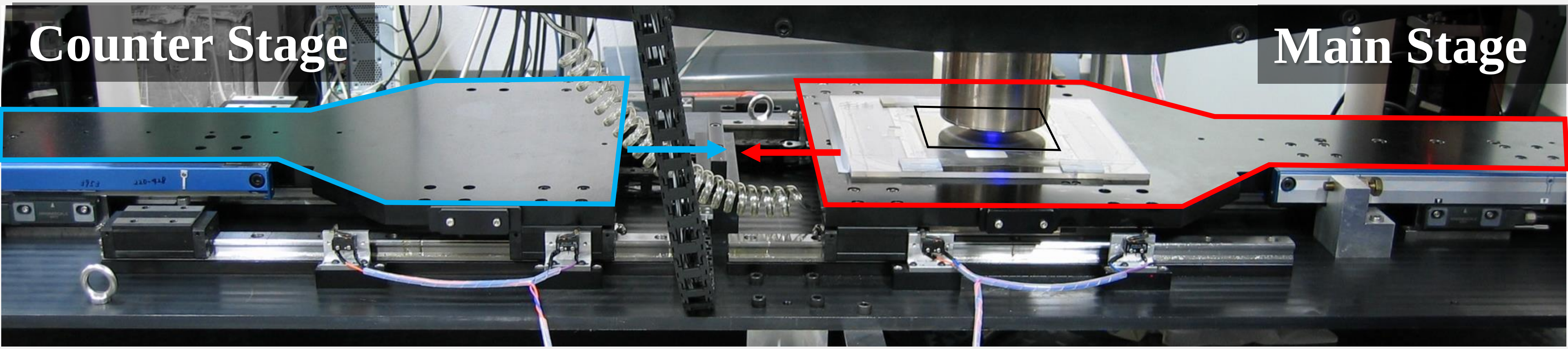
How high throughput can be achieved

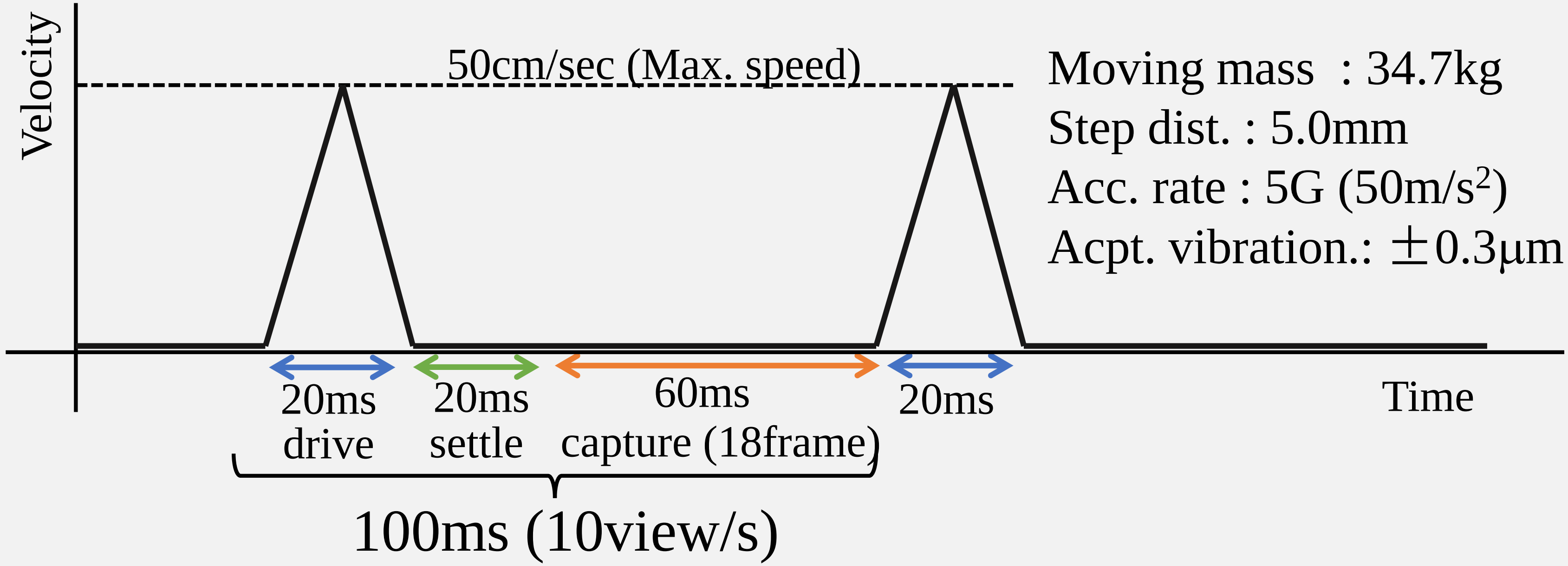
Throughput = area of FOV $\times$ Repetition rate.
FOV : 600 times larger
To achieve 100 times faster than S-UTS,
Repetition rate should be >10view/s (1/5 of SUTS)
It takes 60ms to take images at least.

- HTS takes advantage of Stop & Go in image capturing.
- Stopping accuracy should be 0.3μm.
- The key is how to stop quickly and precisely.

High precision and speed stage

Design value





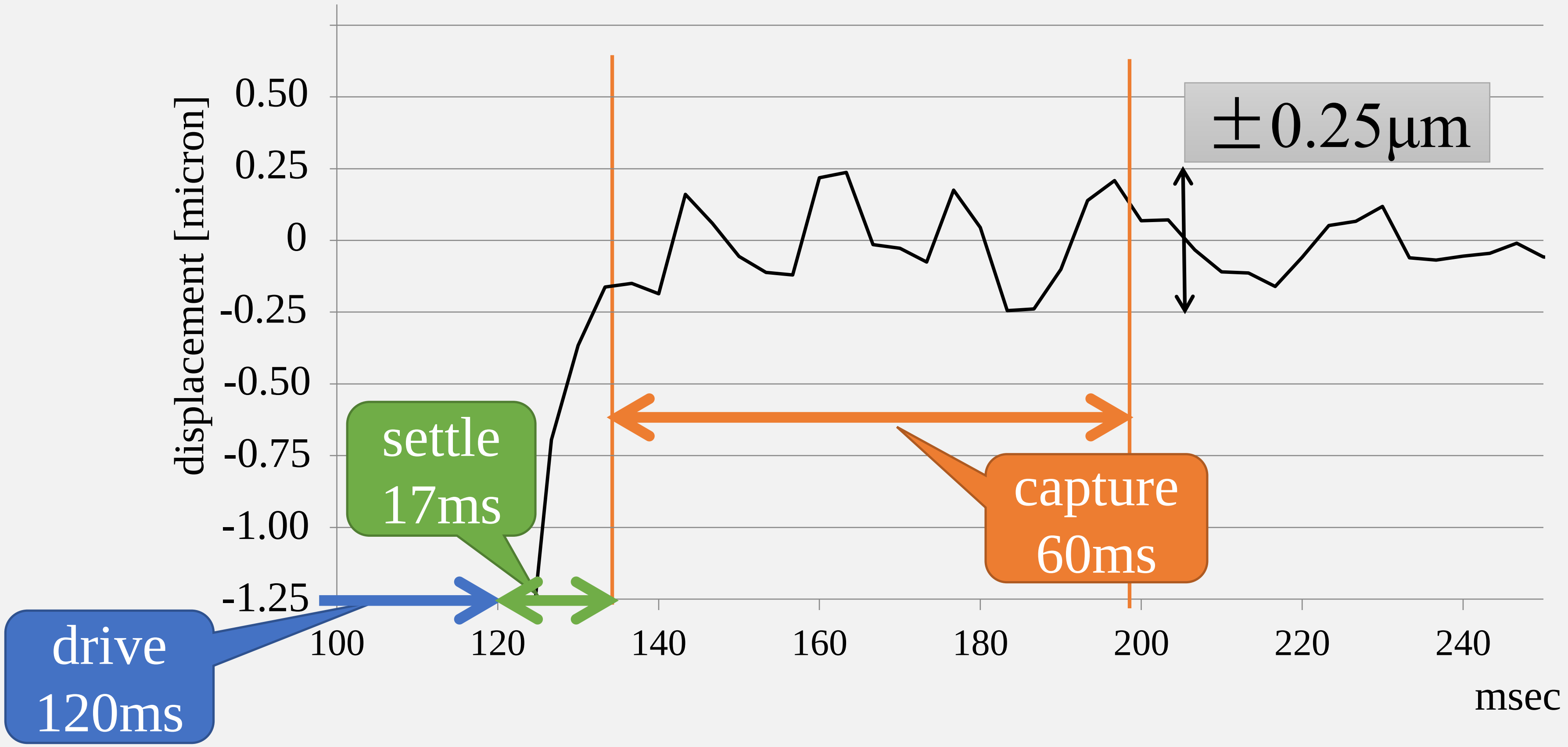
Moving mass : 34.7kg
Step dist. : 5.0mm
Acc. rate : 5G ($50m/s^2$)
Acpt. vibration.: ±0.3μm

Reaction force is canceled by counter stage

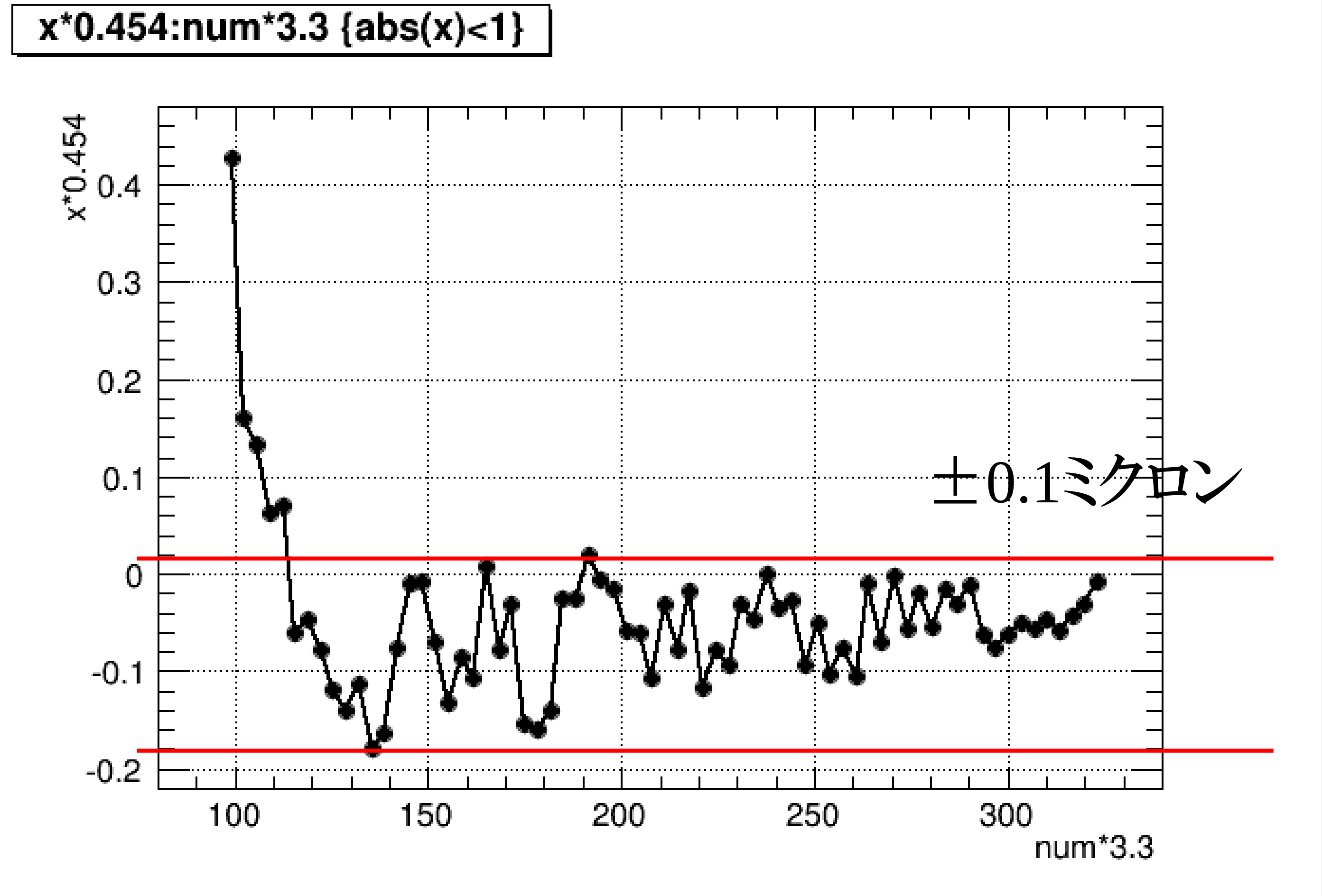
Evaluation of stage settling time

By optimizing the acceleration, 5view/sec was achieved.

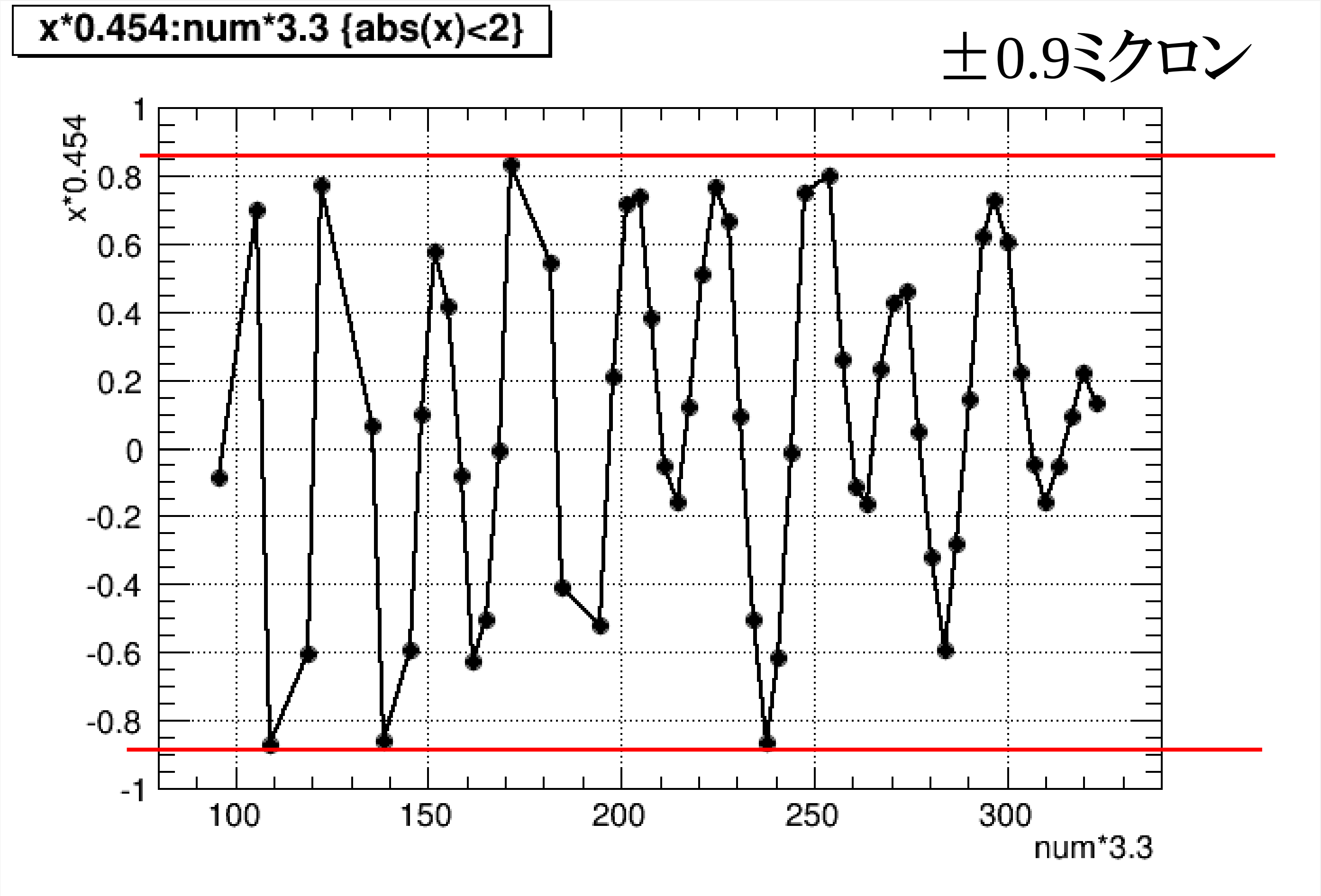
The displacement has been measured by using main optics.



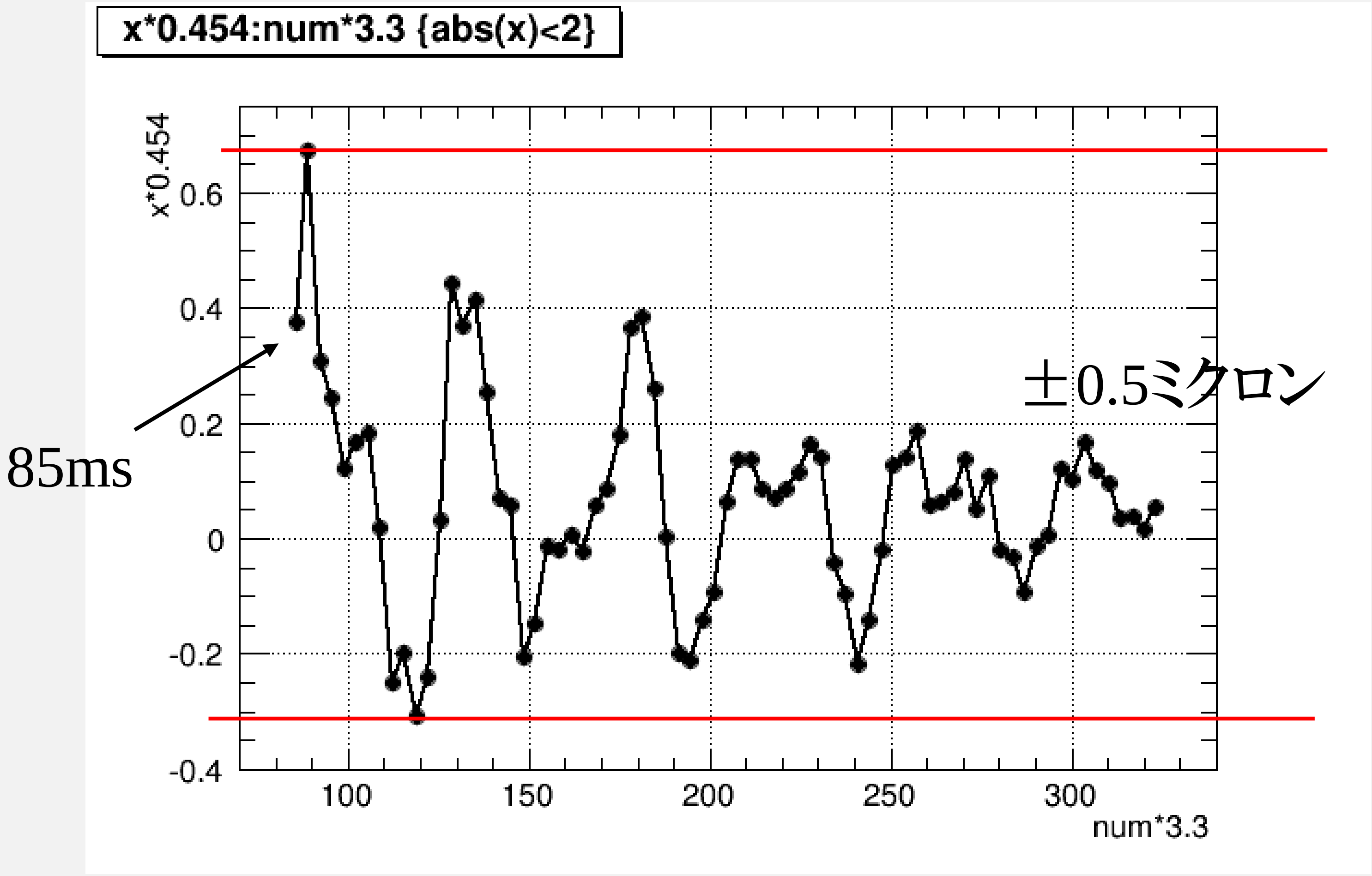
0.4G Acceleration and Stop : 115ms



0.4G Acceleration and Stop without Counter Stage

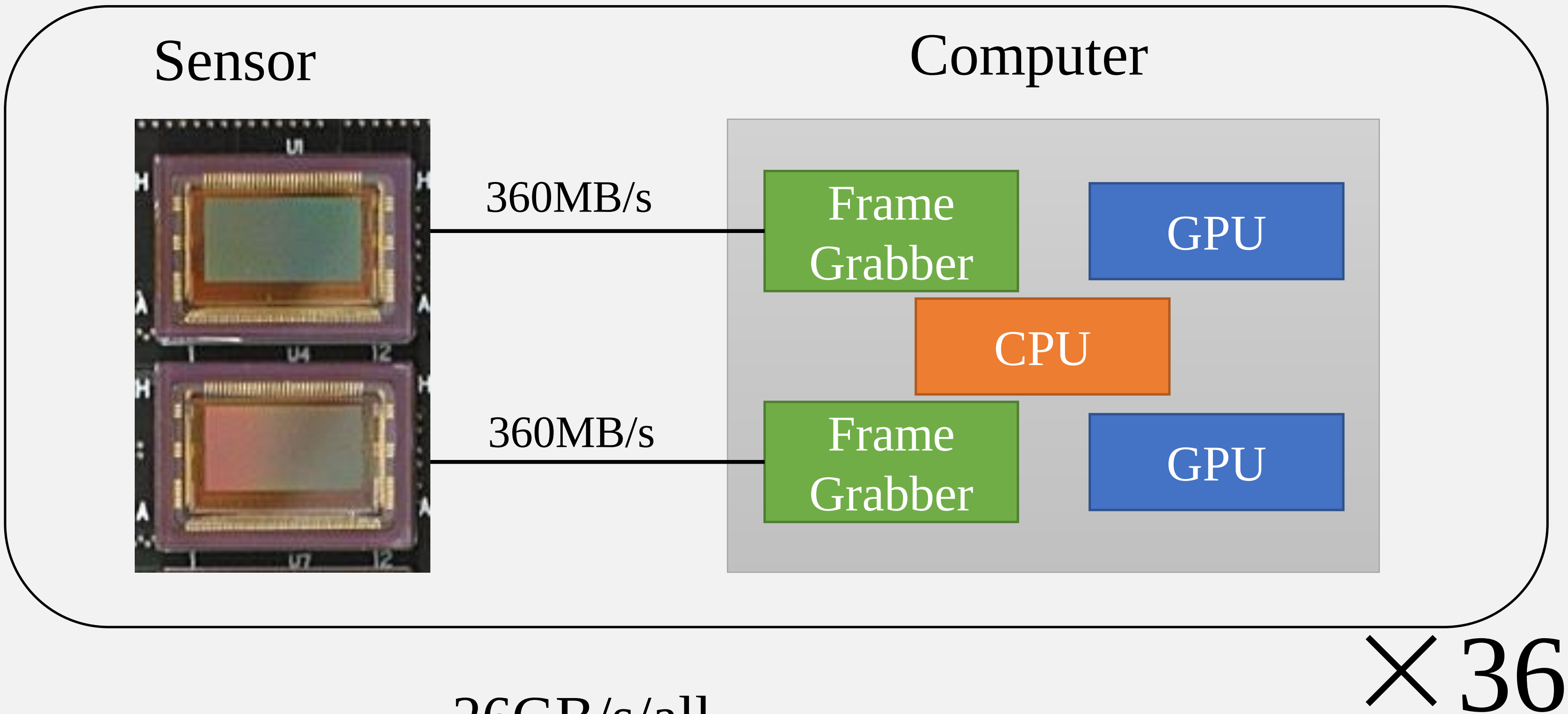


1.0G Acceleration and Stop (X-axis) : 85ms



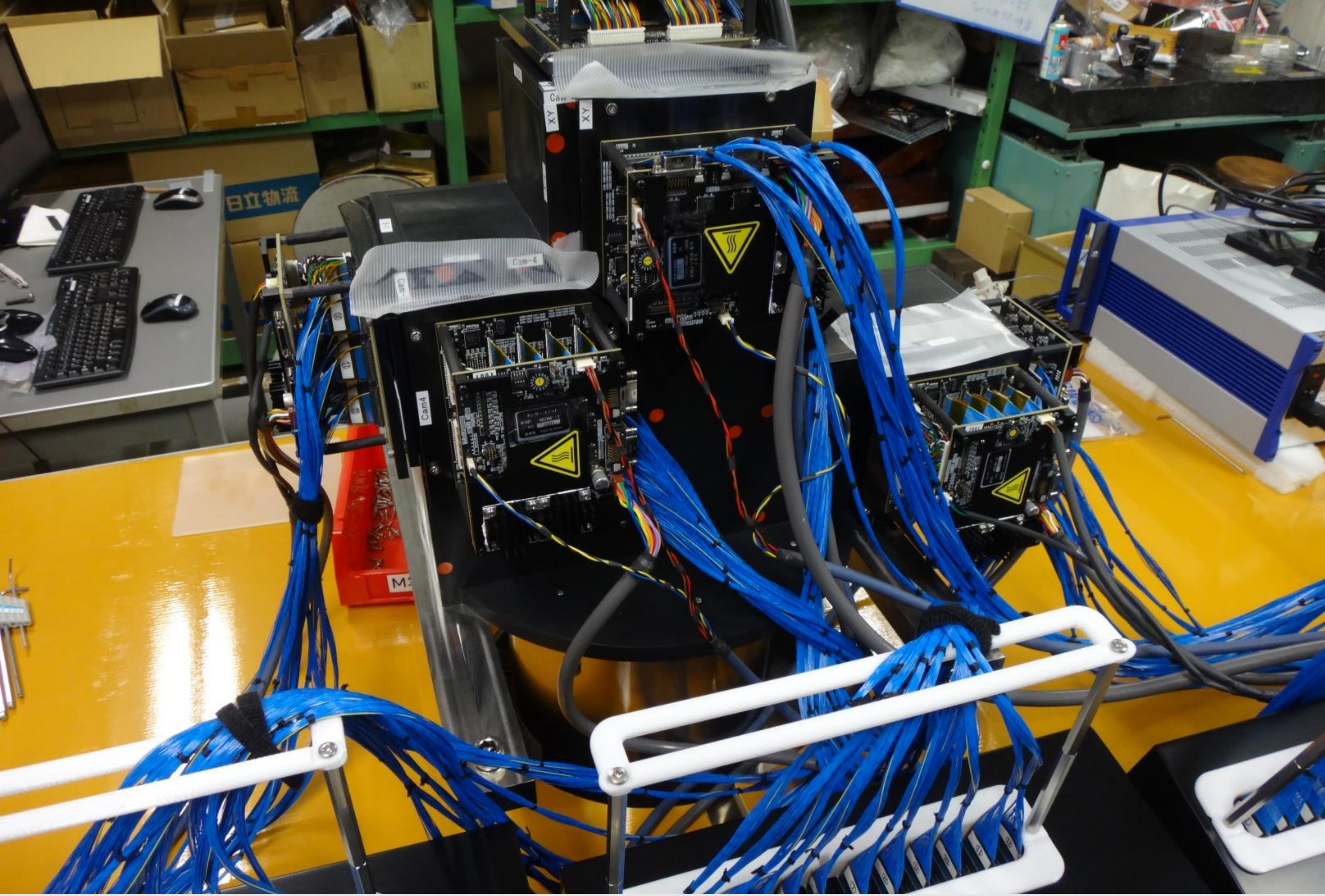
Imaging and Tracking

- Sensor 72 × 36Mbyte/view × 10view/s = 26GB/s
- Computer 36, Frame grabber board 72, GPU board72



26GB/s/all

2.6TB/plate (OPERA film)

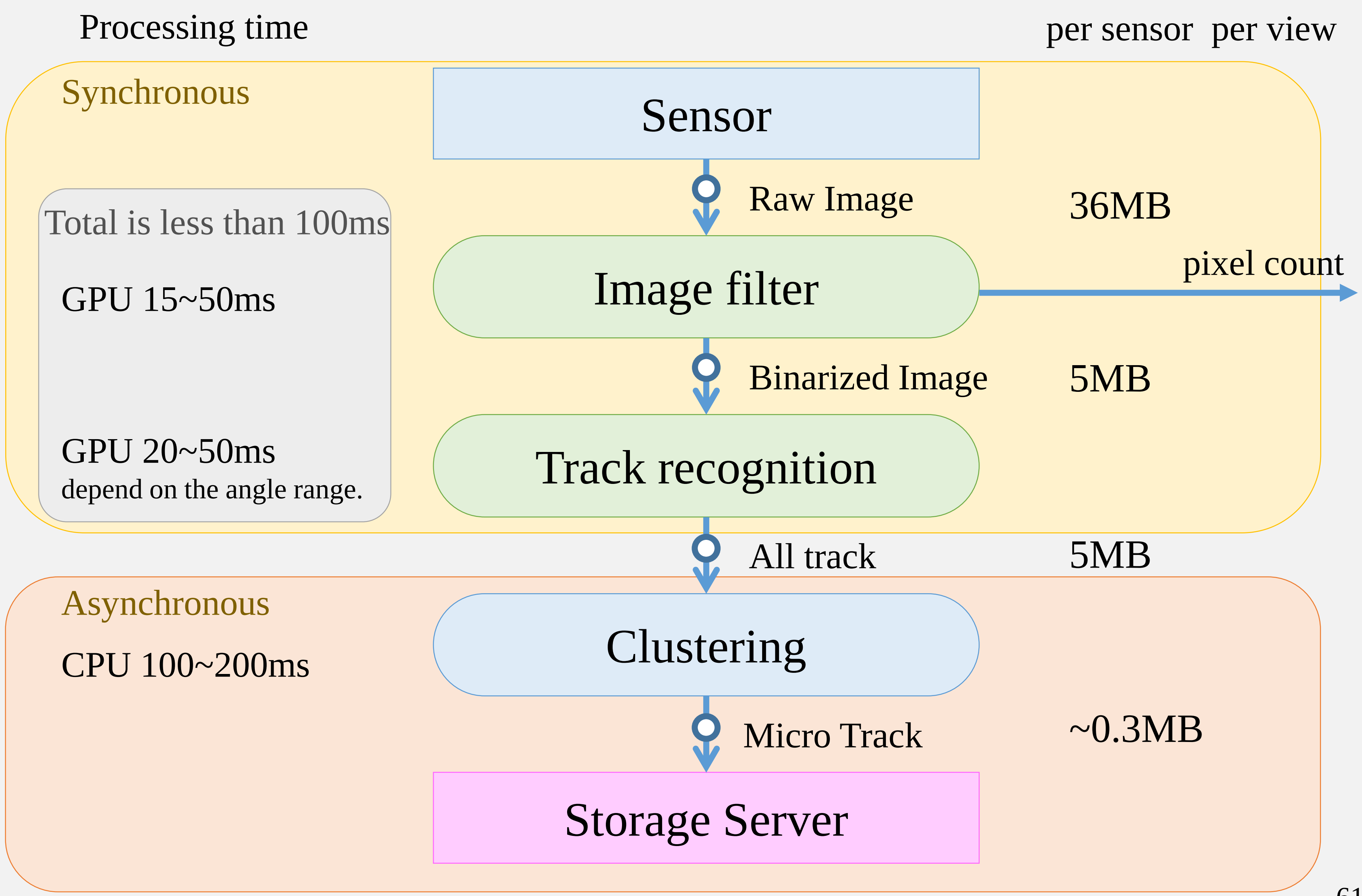


カメラモジュール 6ユニット （72センサー）

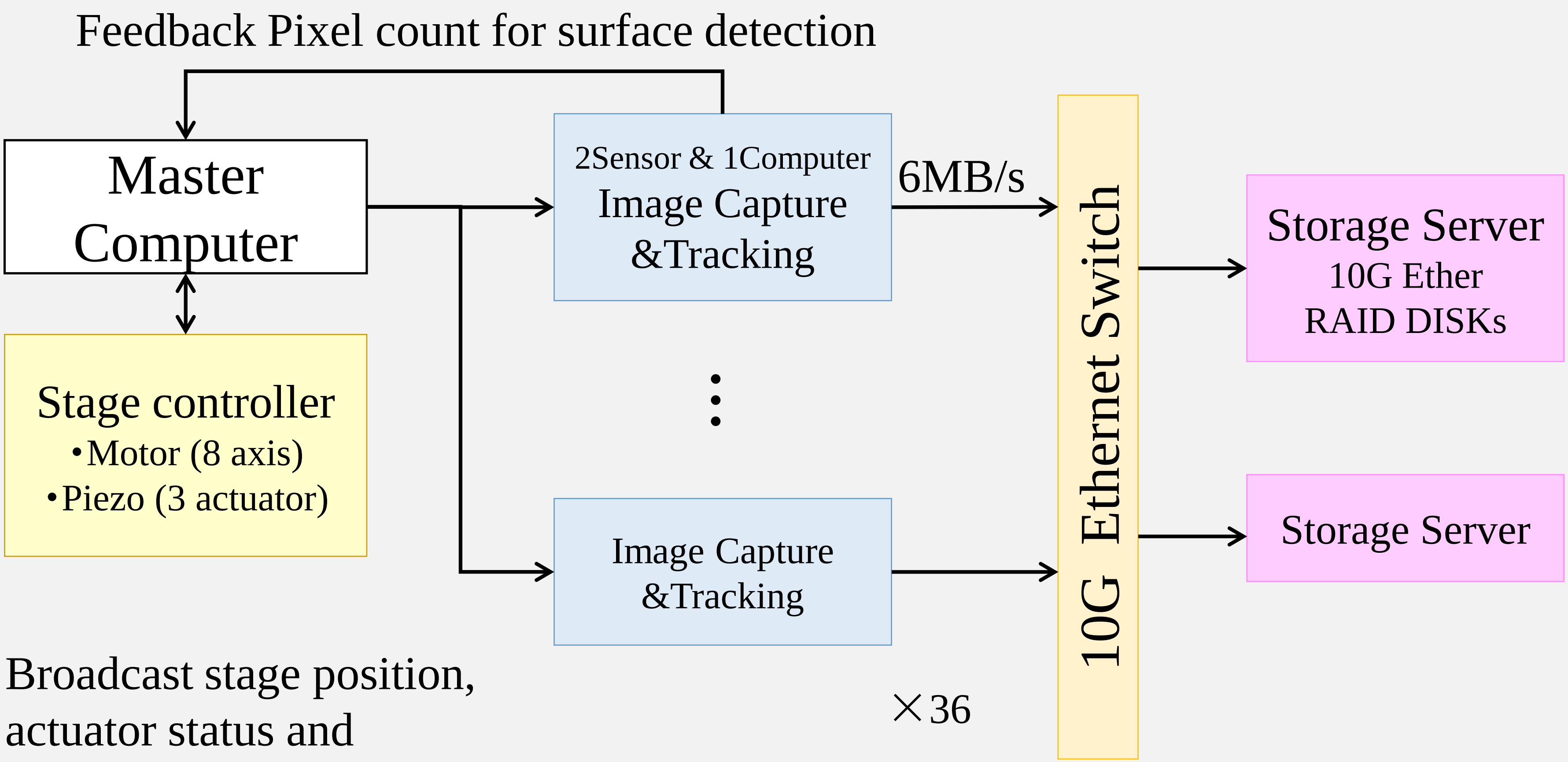
画像処理PC 36台 （GPU 72基）

画像処理PC 36台 （GPU 72基）

Image processing and Dataflow



Stage control

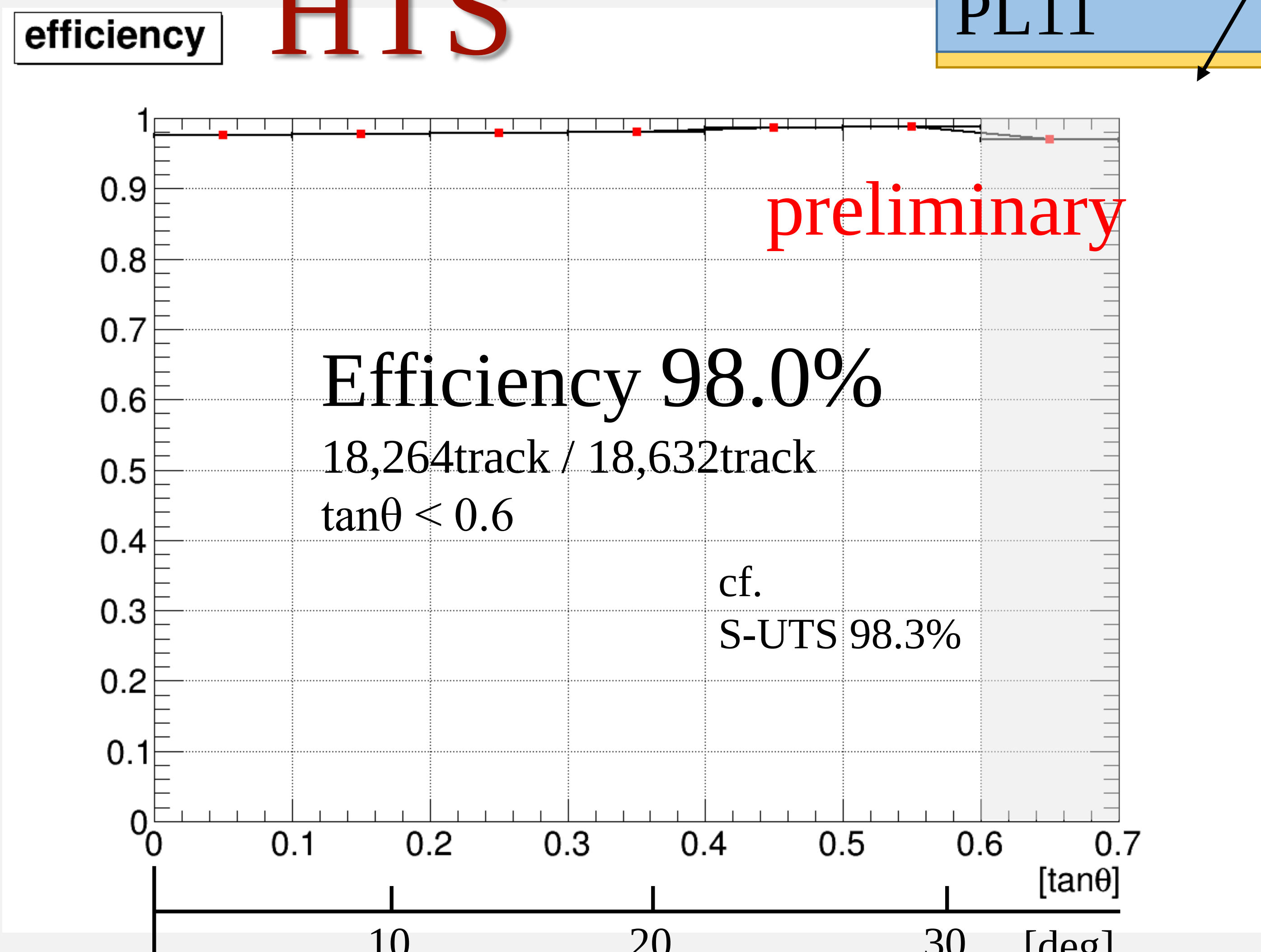


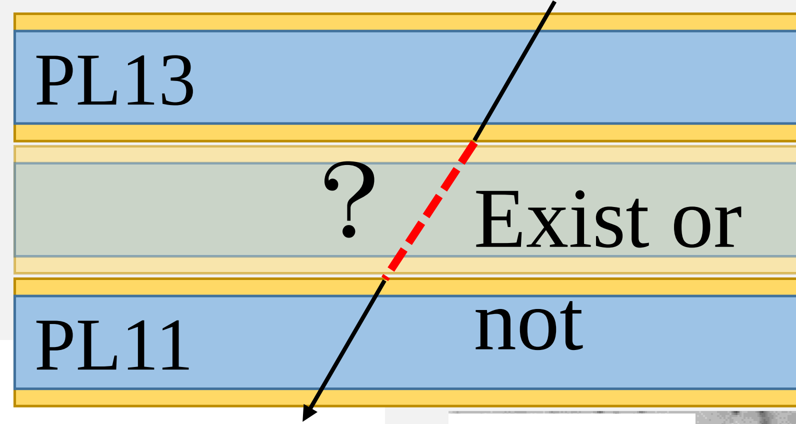
Broadcast stage position, actuator status and Trigger timing for image capture

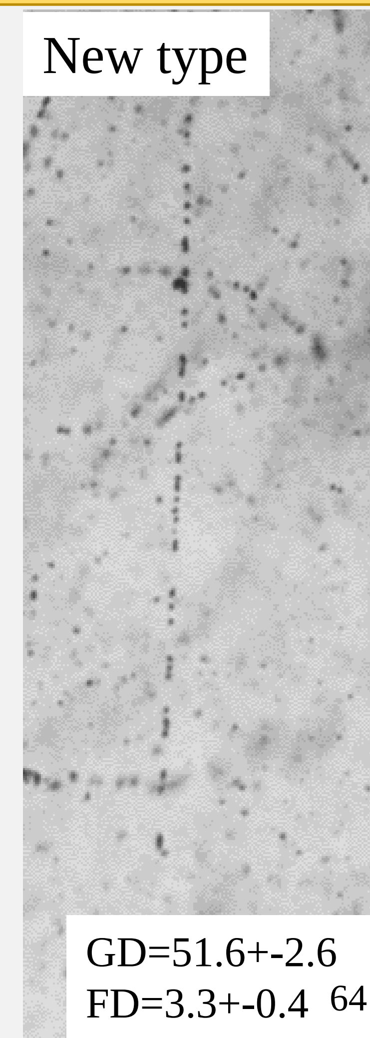
ave. 200MB/s/all
~10GB/plate

New Emulsion Film

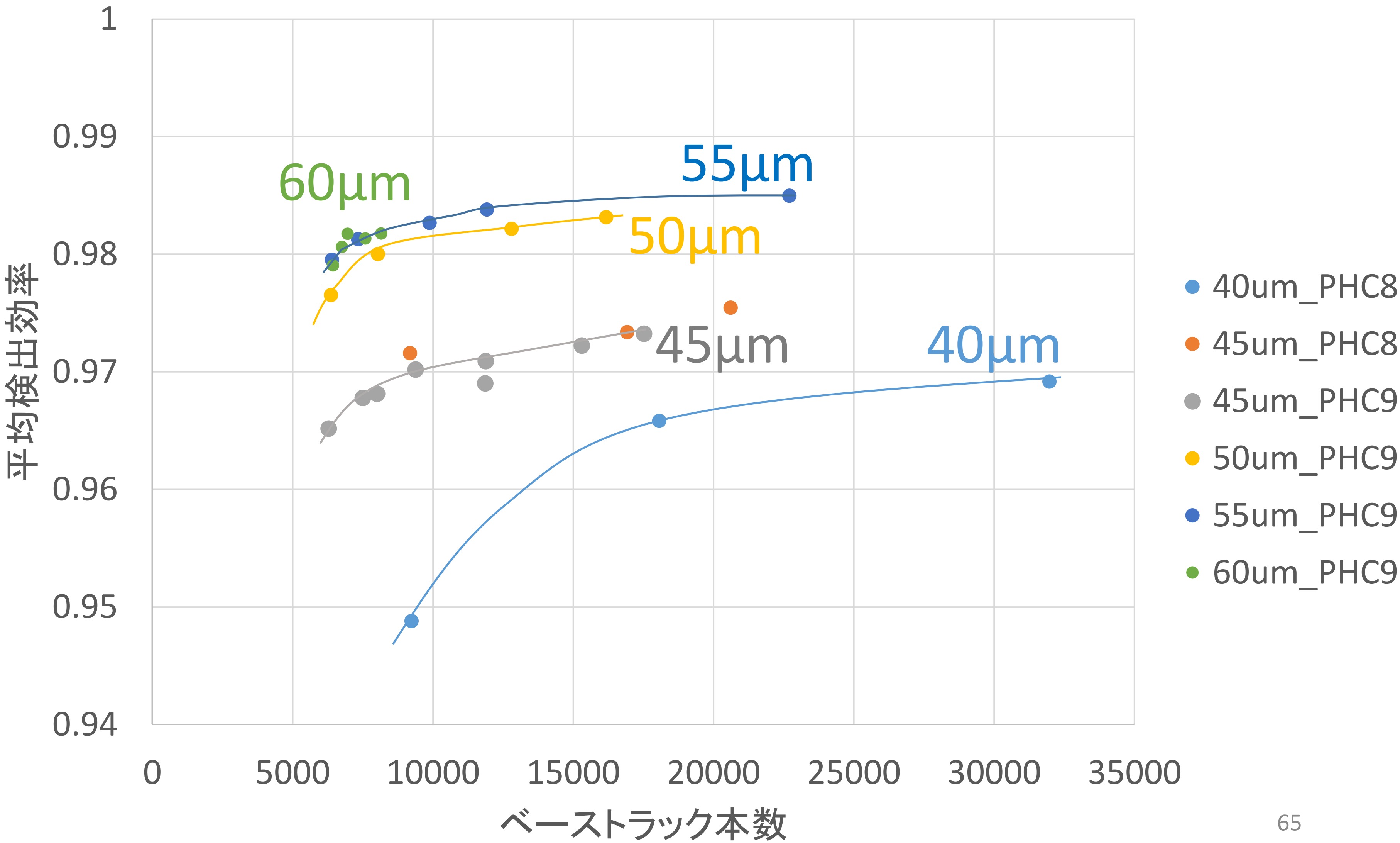
HTS







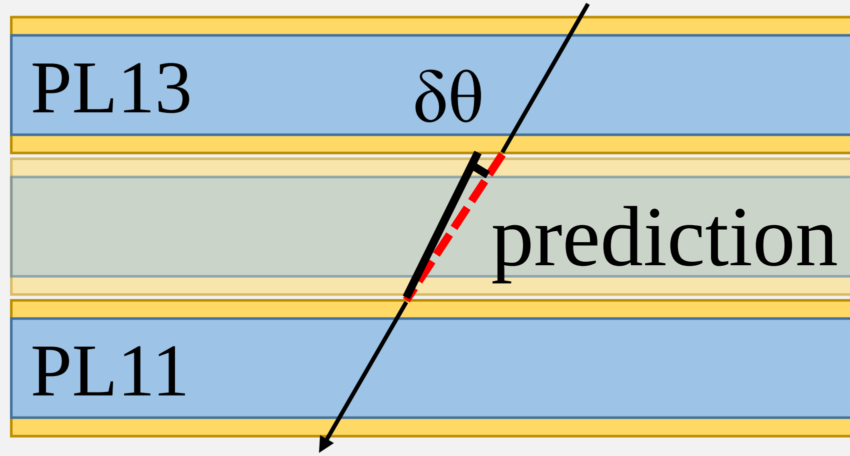
検出効率とSNの評価

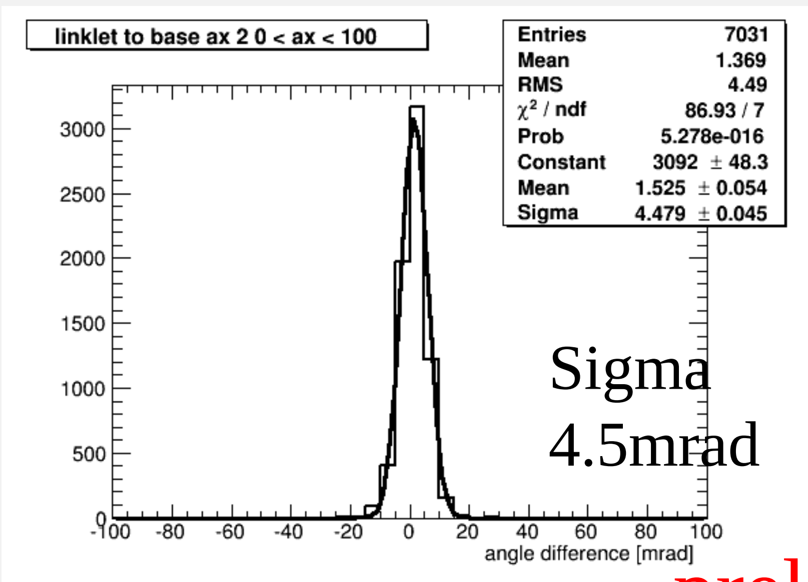


60μm
55μm
50μm
45μm
40μm
1
0.99
0.98
0.97
0.96
0.95
0.94
平均検出効率
0
5000
10000
15000
20000
25000
30000
35000
ベーストラック本数
40um_PHC8
45um_PHC8
45um_PHC9
50um_PHC9
55um_PHC9
60um_PHC9

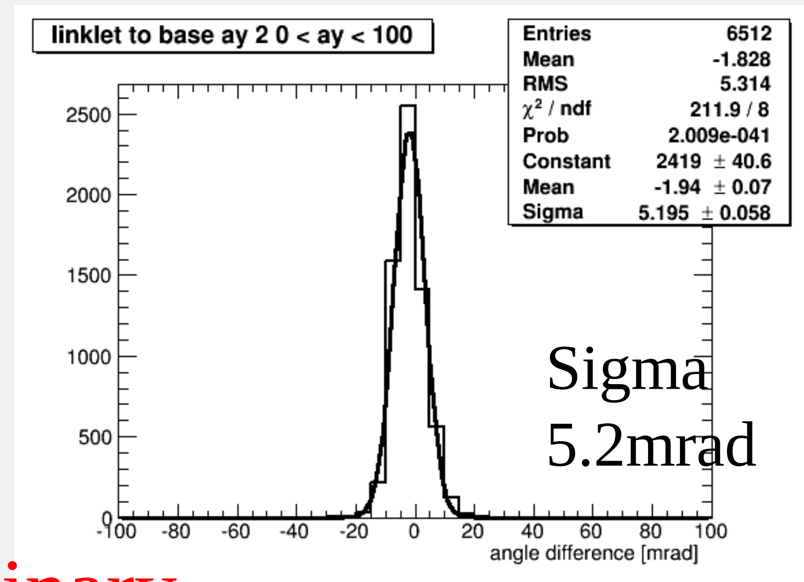
New Emulsion Film

- Angle deviation





Sigma
4.5mrad



Sigma
5.2mrad

preliminary

X-projection

Y-projection

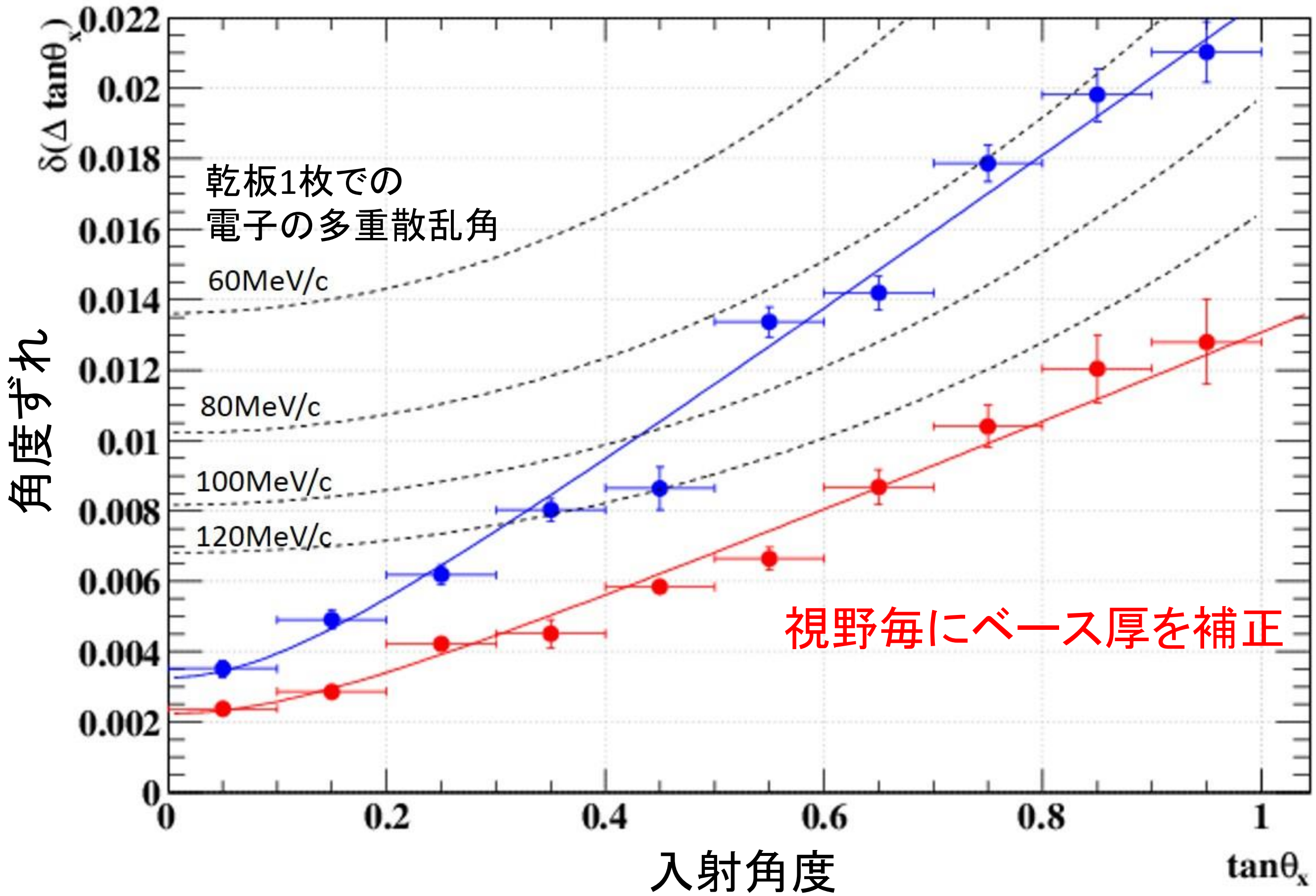
cf. S-UTS
4.8mrad

cf. S-UTS
4.3mrad

※ 2014年日本物理学会年次大会で発表.

入射角度の大きい飛跡に対する角度分解能の改善

$$\delta(\Delta \tan\theta_x) = \frac{\sqrt{2}}{b}\sqrt{2\delta x^2 + \delta b^2 \cdot \tan^2\theta_x}$$



Fitting parameter

$$\delta x = 0.28 \pm 0.04$$
$$\delta b = 2.68 \pm 0.09$$

↓

$$\delta x = 0.19 \pm 0.02$$
$$\delta b = 1.55 \pm 0.07$$

※ δx の改善はカメラセンサー数の違い.

大角度飛跡の
角度分解能が
改善した.

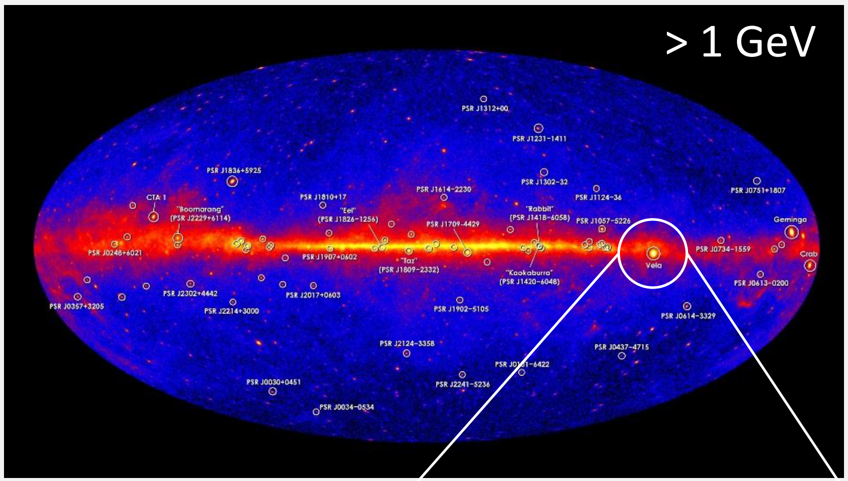
※複数回の測定で
さらに高精度化が可能.

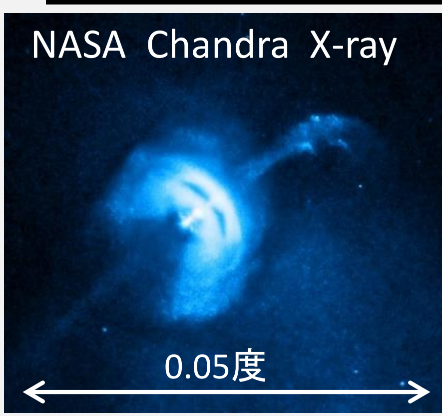
Commissioning

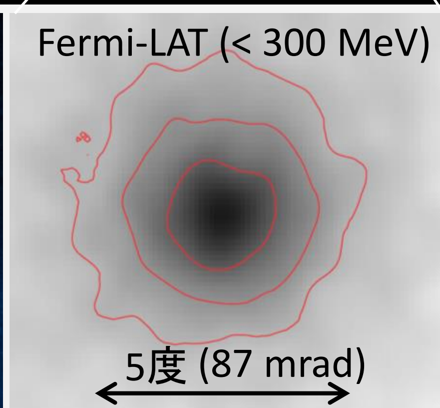
2015 Australia Flight

Aim

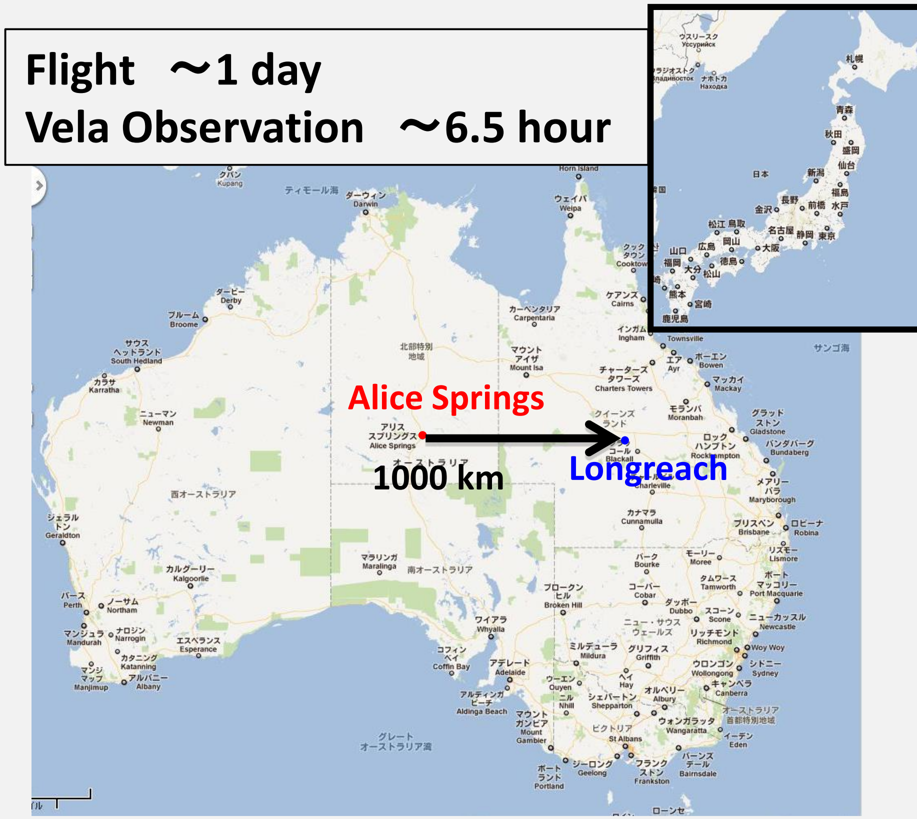
Prove the angular resolution by observing Vera Pulsar 0.5° (≈10 mrad) @100−300 MeV



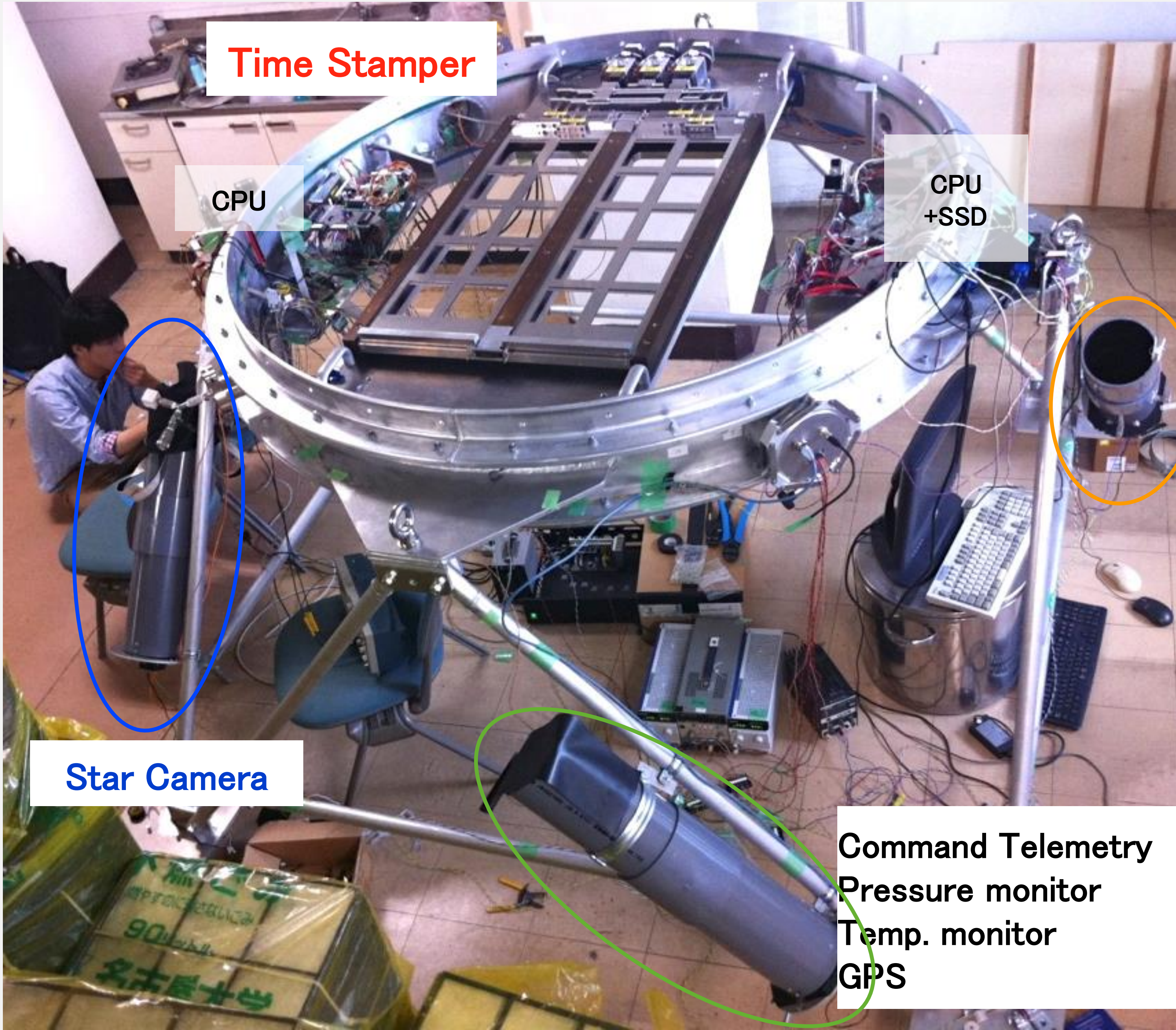




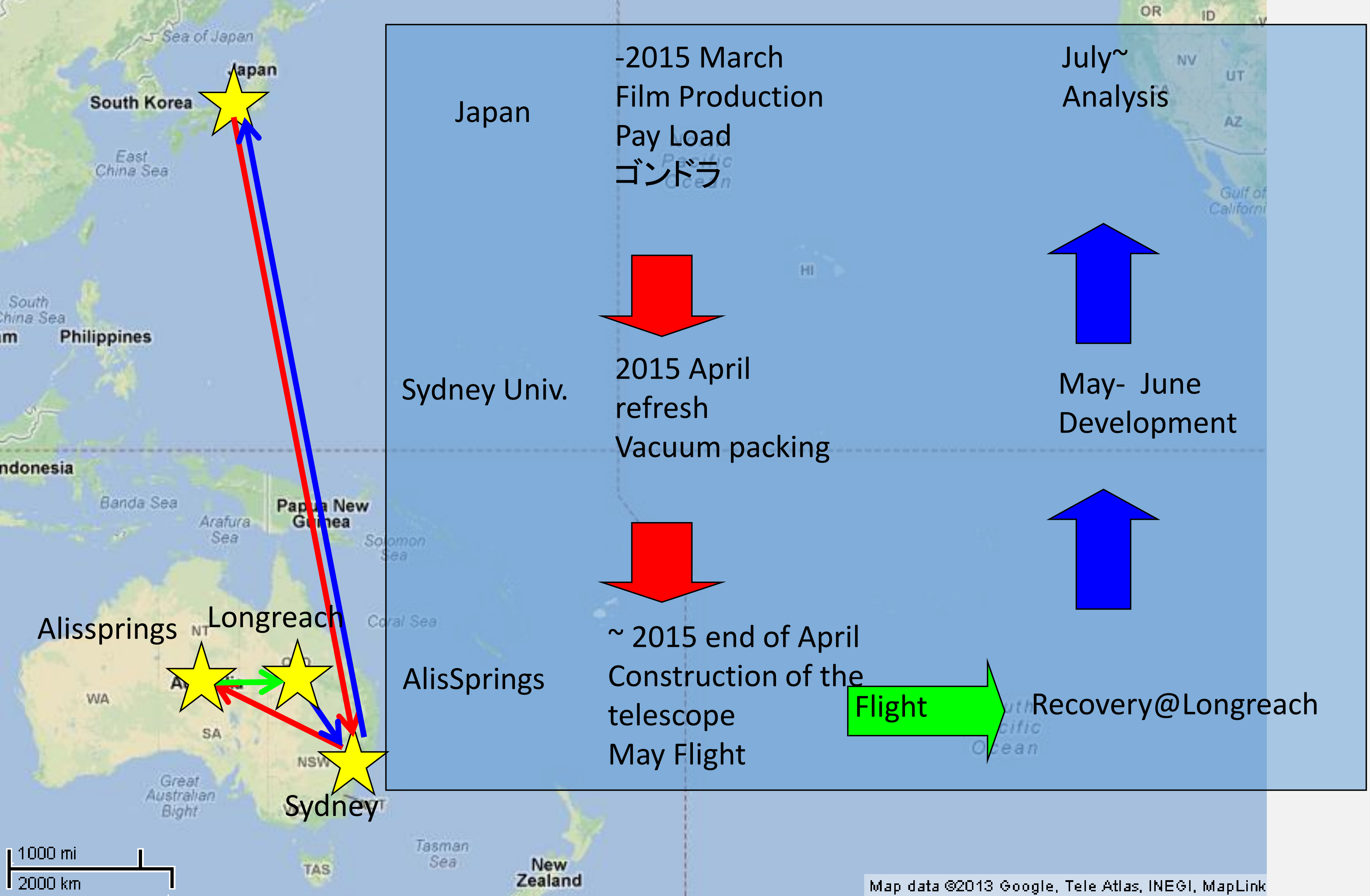
Flight 〜1 day
Vela Observation 〜6.5 hour



Vela Pulsar ($Flux \sim 1 \times 10^{-5}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$ @100MeV−10GeV)


Time Stamper
CPU
CPU
+SSD
Star Camera
Command Telemetry
Pressure monitor
Temp. monitor
GPS

Flow of the Balloon Exp. 2015



Summary and Prospect

- More Scanning Power is required.
- We are developing HTS which is 100 times faster.
- The efficiency and angle resolution are reasonably good (at the same level as the previous system).
- Commissioning of HTS will be started with GRAINE project.