

GRAINE project :

First massive production and use of
“high sensitive emulsion gel film”

Shigeki Aoki for GRAINE collaboration

Kobe University,
Nagoya University,
ISAS/JAXA,
Aichi University of Education,
Okayama University of Science,
Utsunomiya University

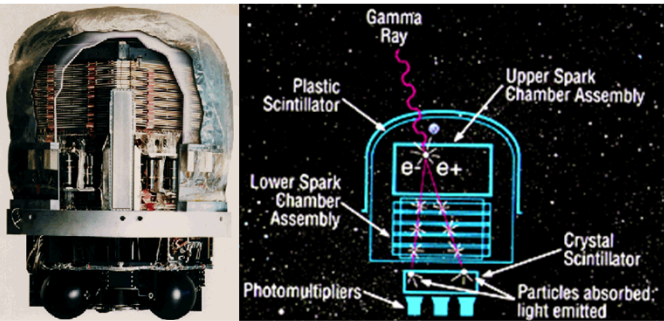
新学術領域研究「ニュートリノフロンティア」研究会2014
2014/Dec/21-23 @ Fuji Calm

photo: GRAINE 1st flight
2011 @Taiki, Hokkaido

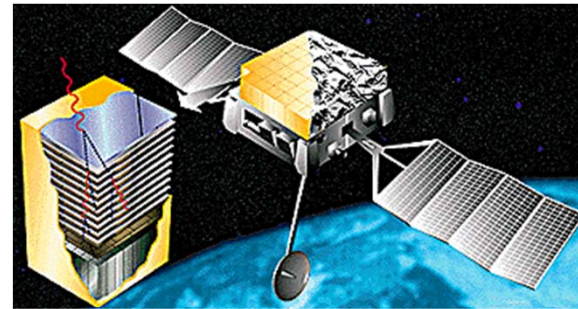


Gamma-ray Telescopes (GeV/sub-GeV region)

EGRET launched 1991
spark chamber



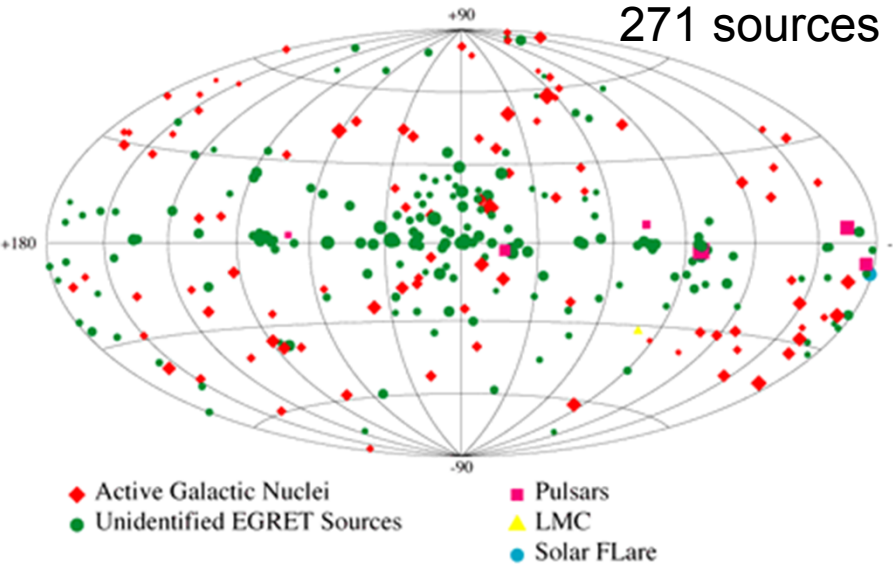
Fermi-LAT launched 2008
silicon microstrip detector



Third EGRET Catalog

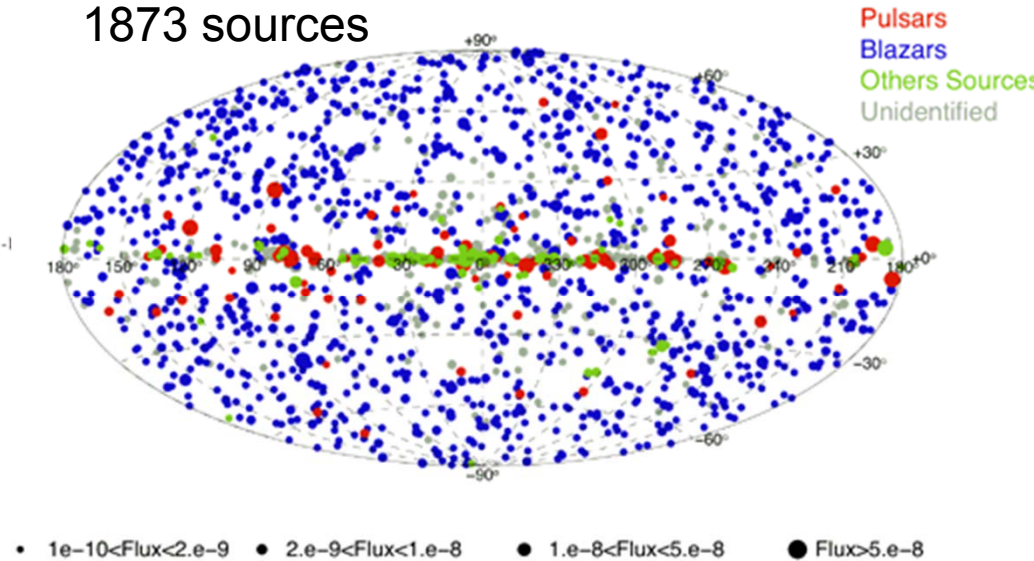
$E > 100 \text{ MeV}$

271 sources



Fermi Gamma-ray Space Telescope
The LAT γ -ray sky (second year catalog)

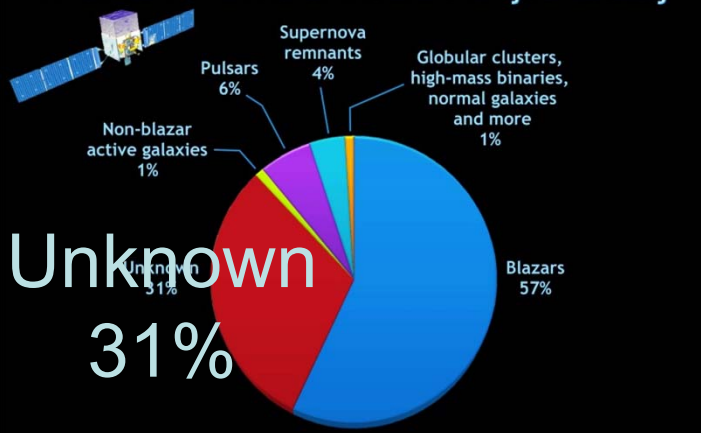
1873 sources





Fermi two-year all-sky map ($E_\gamma > 1\text{GeV}$)

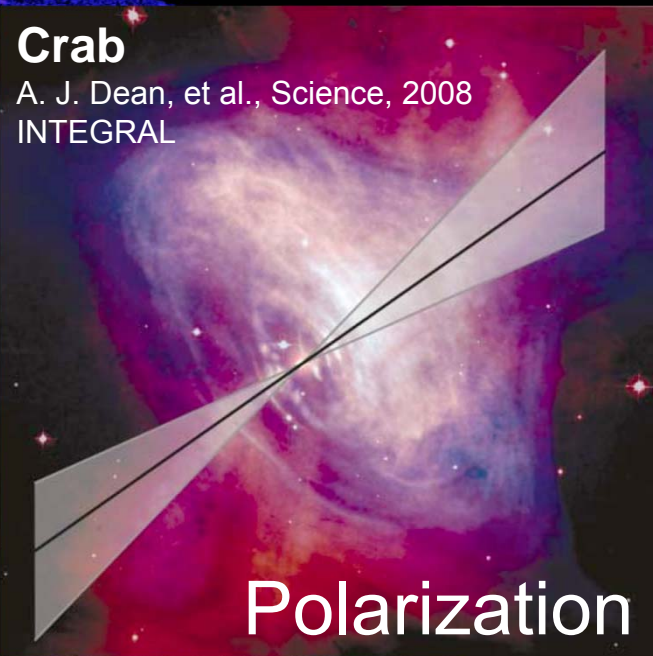
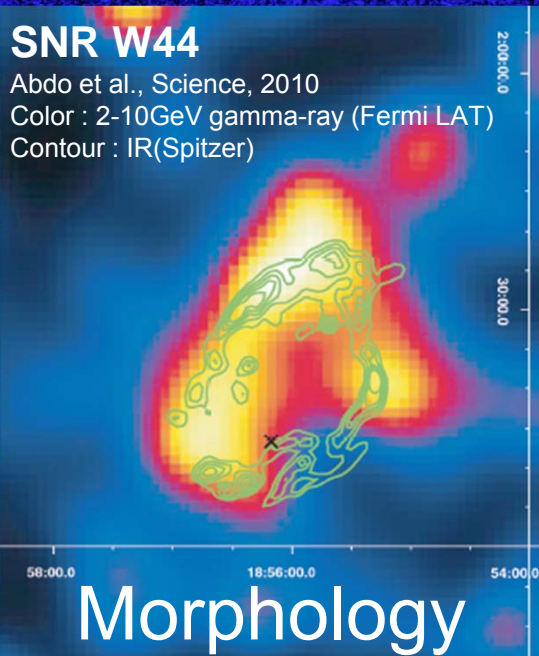
What has Fermi found: The LAT two-year catalog



Unknown
31%

Un-Identified

Credit: NASA/Goddard Space Flight Center



Credit: NASA/DOE/Fermi/LAT Collaboration

1873 sources

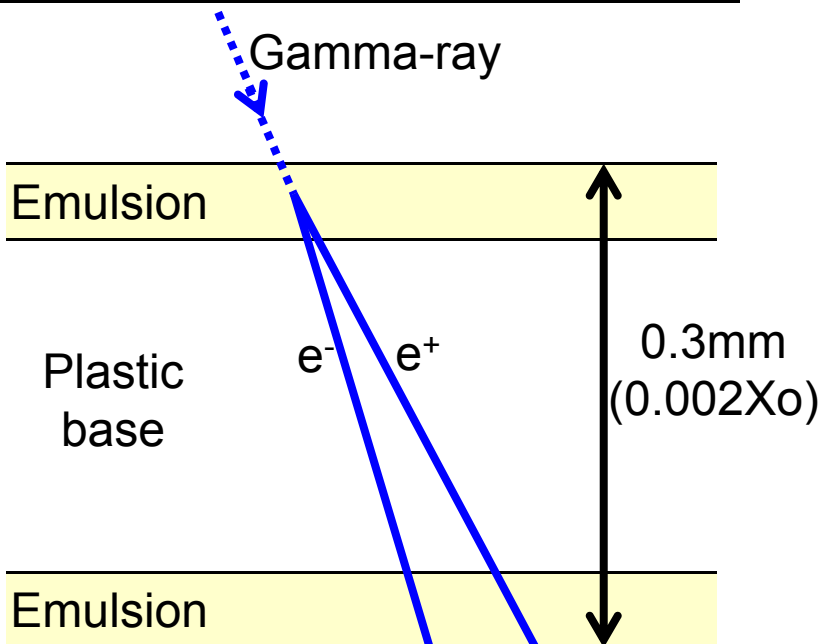
Nuclear emulsion

Microscopic view
10micron

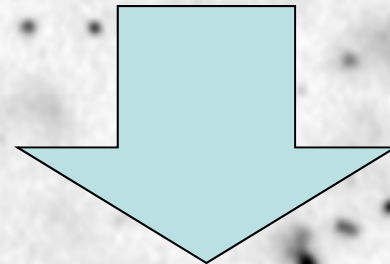
Gamma-ray
→

$e^{+/-}$
→
 $e^{-/+}$
→

Cross sectional view of an emulsion film

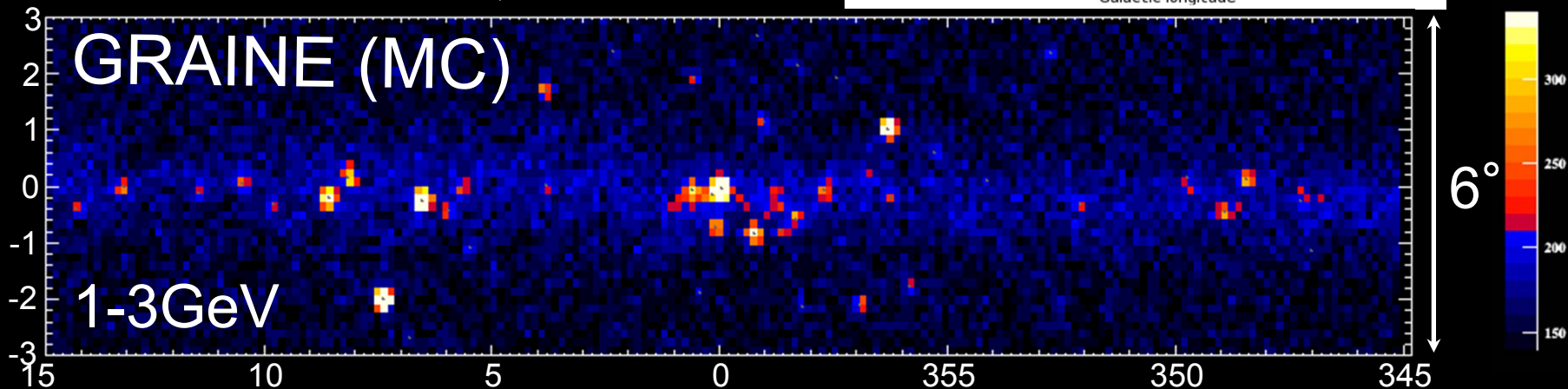
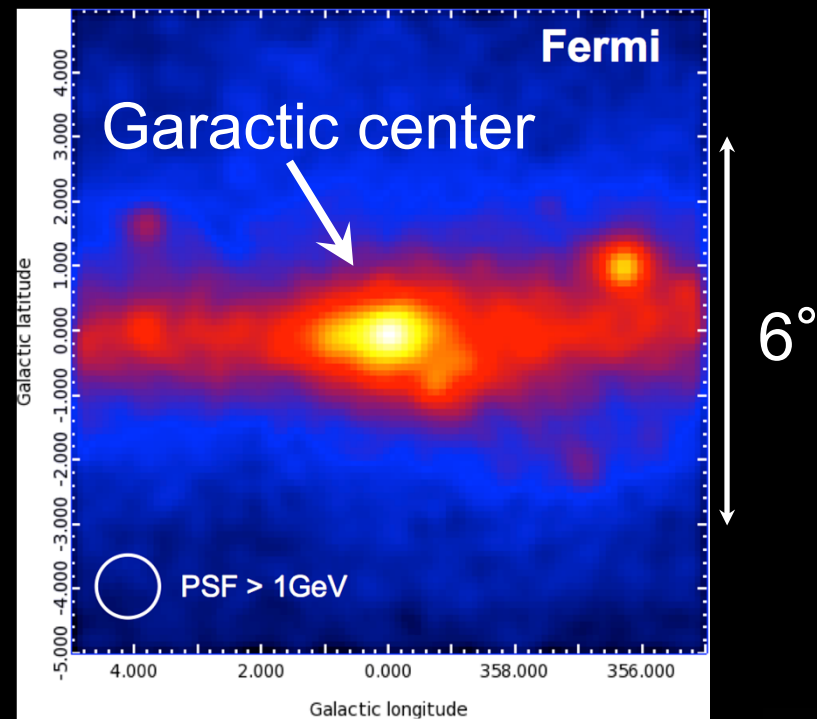
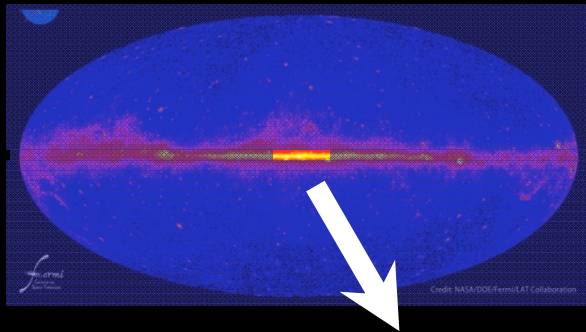


Powerful tracking device
>High spatial resolution : ~1micron
>Small radiation length : 0.002 X_o



High angular resolution for gamma-ray
Sensitive to gamma-ray polarization

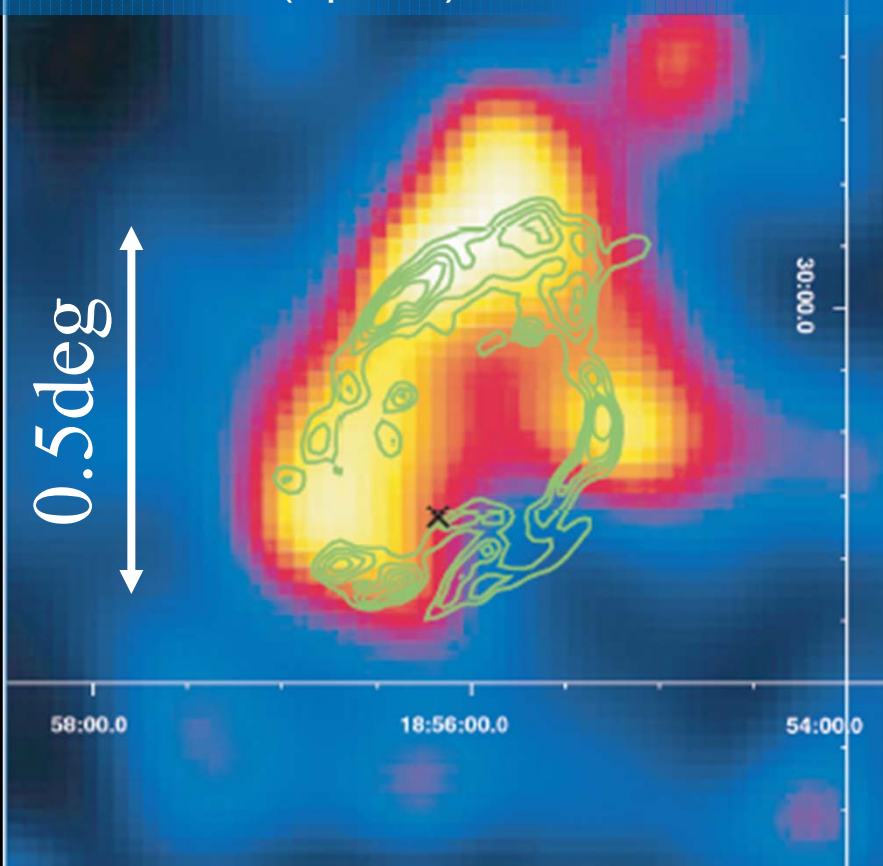
High reso. observation @ Galactic center/plane



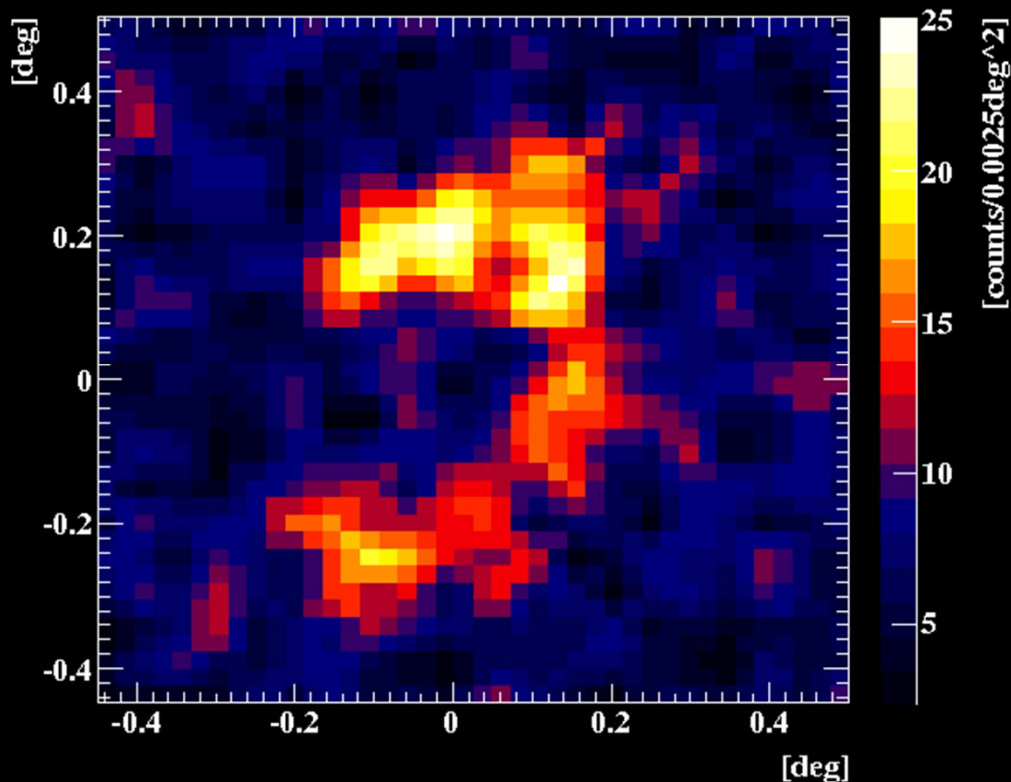
Angular Res 0.1° , Full scale, 10 flights
Signal: Point source (2FGL)
BG: Galactic diffuse (Medel: gll_iem_v05_ref1)
Atmospheric $5\text{g}/\text{cm}^2$ (Valdez et al 1970, Dahlbacka et al 1973)

High resolution imaging

SNR W44 (Abdo et al., Science, 2010)
Color : 2-10GeV gamma-ray (Fermi LAT)
Contour : IR(Spitzer)



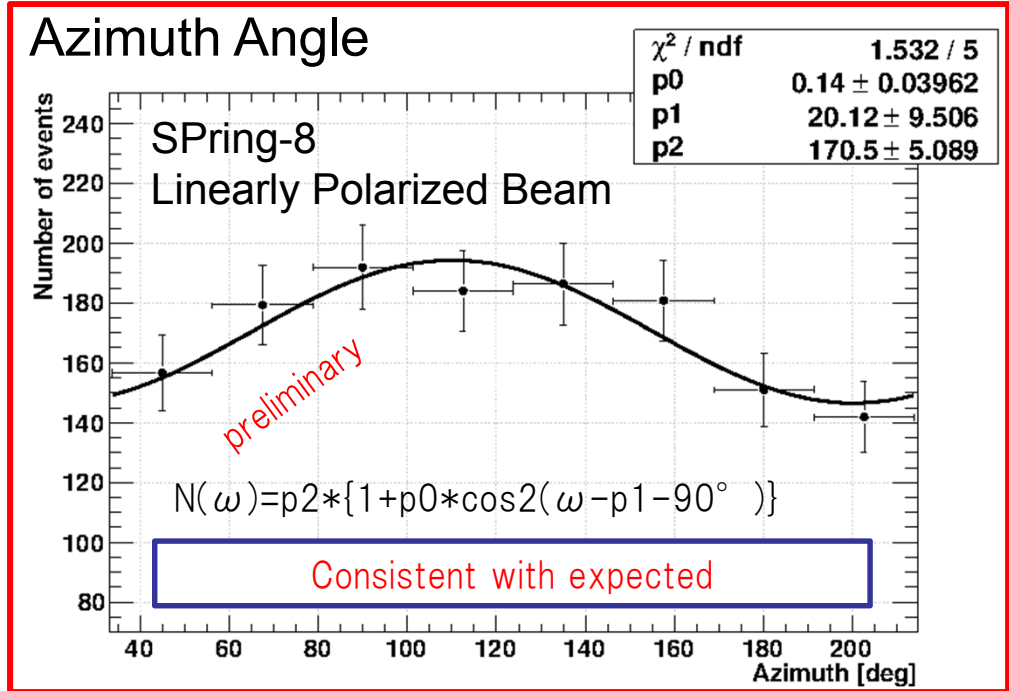
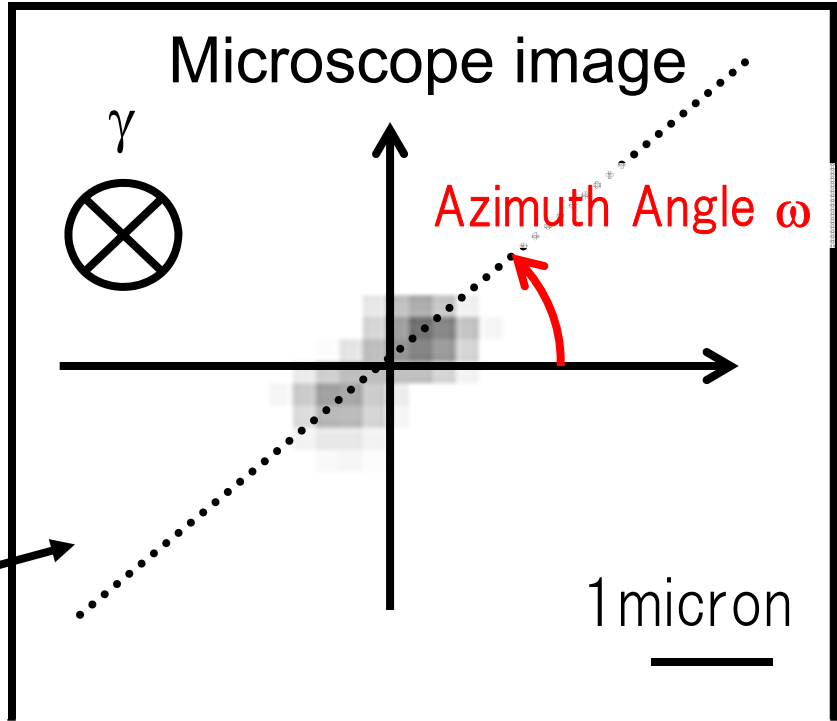
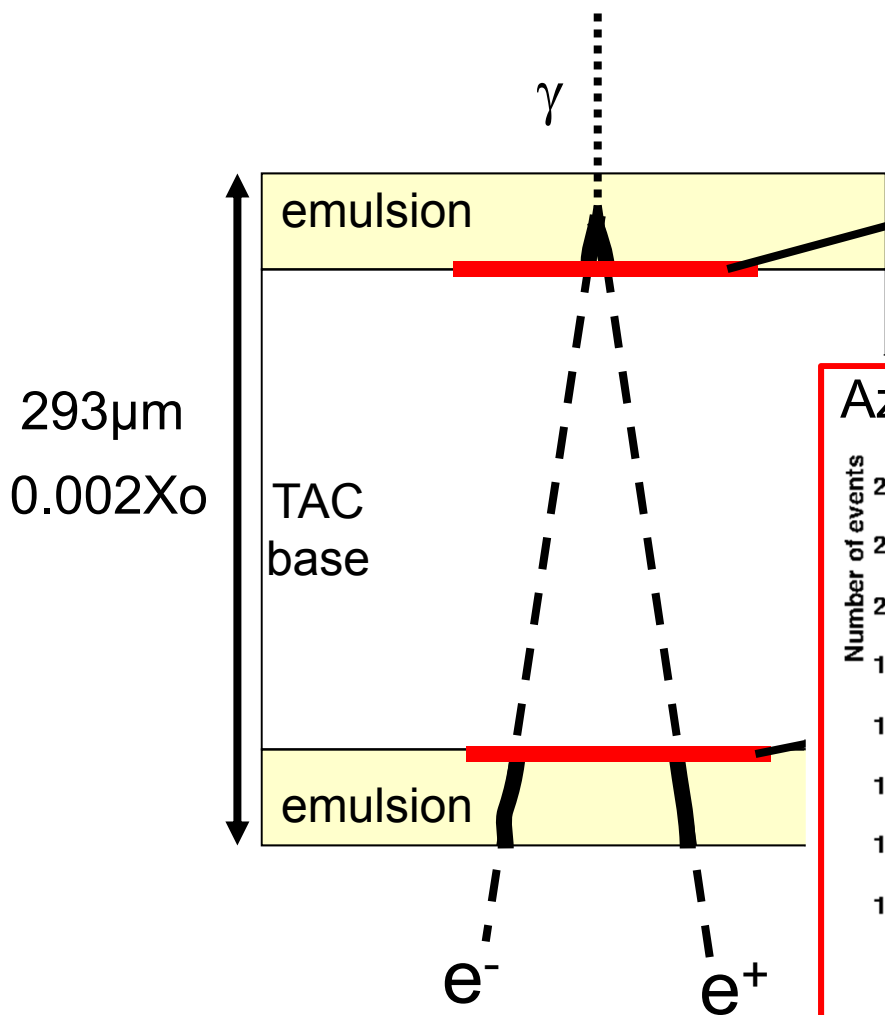
GRAINE (Simulation)



- **3flights** (41.7m²days)
- >1GeV
- Smearing IR(Spitzer) distribution
with 0.08deg(1.4mrad)
- Considering atmospheric gamma-ray(>1GeV) as BG

Polarization measurement

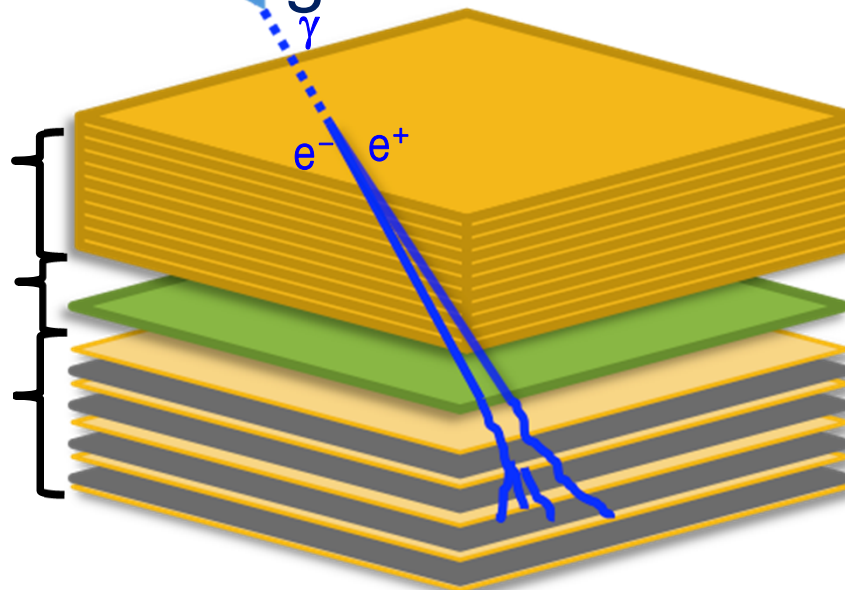
Cross-sectional view of Emulsion Film



GRAINE

Gamma-Ray Astro-Imager with Nuclear Emulsion

- Converter**
Emulsion + Copper foil
- Timestamper**
Multi-stage shifter
- Calorimeter**
Emulsion + metal plate
- Attitude monitor**
Star camera

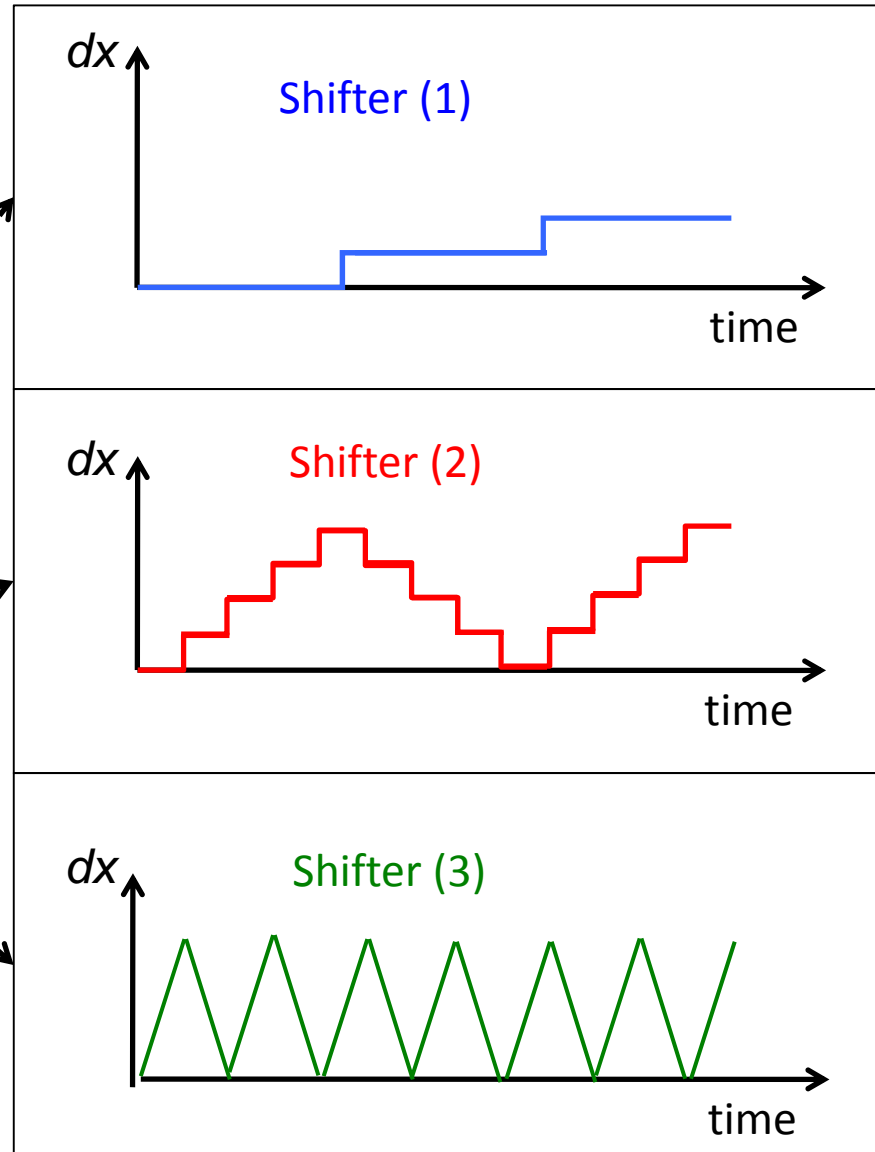
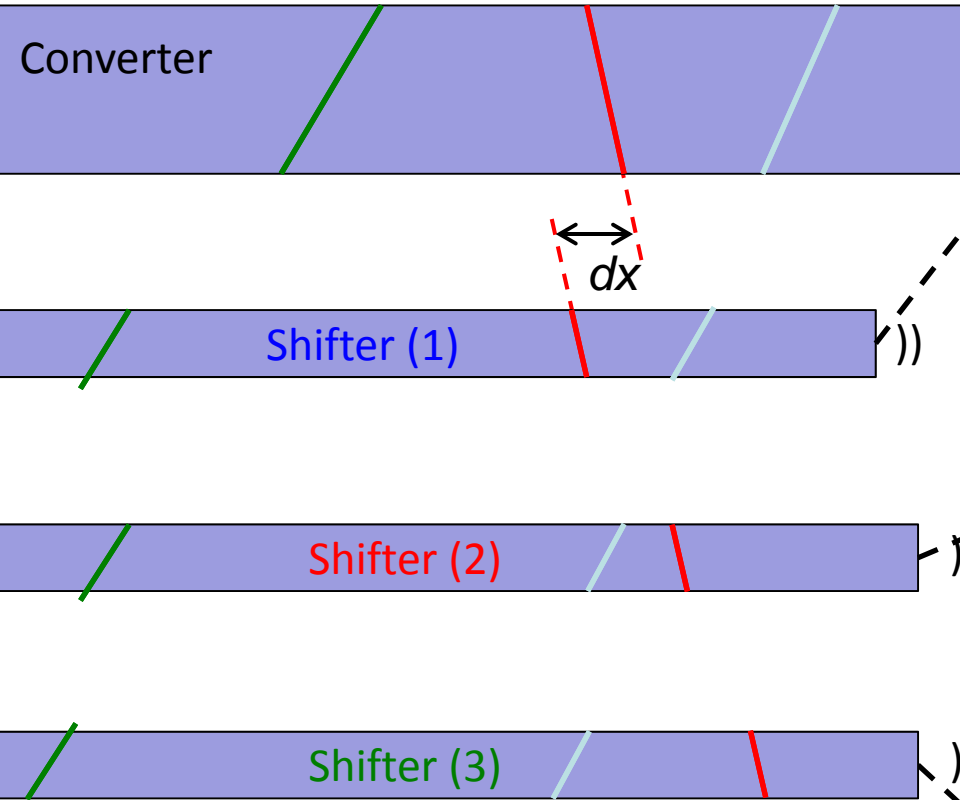


$$* 10\text{m}^2 * \epsilon_{\text{trans}} * \epsilon_{\text{conv}} * \epsilon_{\text{det}}$$

	Fermi LAT		GRAINE
Angular resolution @100MeV	6.0deg (105mrad)	x1/6 →	1.0deg (17mrad)
@1GeV	0.90deg (16mrad)	x1/9 →	0.1deg (1.7mrad)
Energy range	20MeV – 300GeV		10MeV – 100GeV
Polarization sensitivity	No		Yes
Effective area @ 100MeV	0.25m ²	x8 →	2.1m ² *
@ 1GeV	0.88m ²	x3 →	2.8m ² *
Dead time	26.5 μ sec (readout time)		Dead time free

Multi-stage shifter (time stamper)

S. Takahashi et al.
NIM A620(2010) pp.192-195

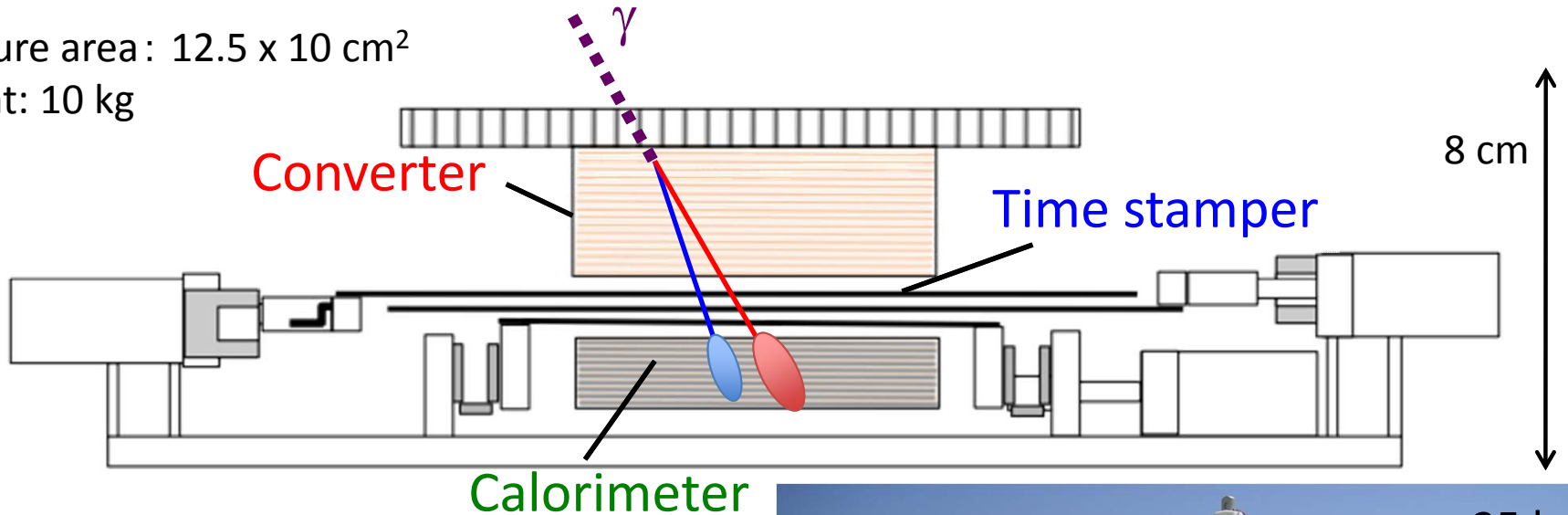


- Simple
- Compact
- Light
- HV free
- Low power consumption
- Dead time free



Emulsion Telescope @GRAINE2011

Aperture area: $12.5 \times 10 \text{ cm}^2$
Weight: 10 kg



Converter $0.54 X_0$

104 films , 91 copper foils (50 μm thick)

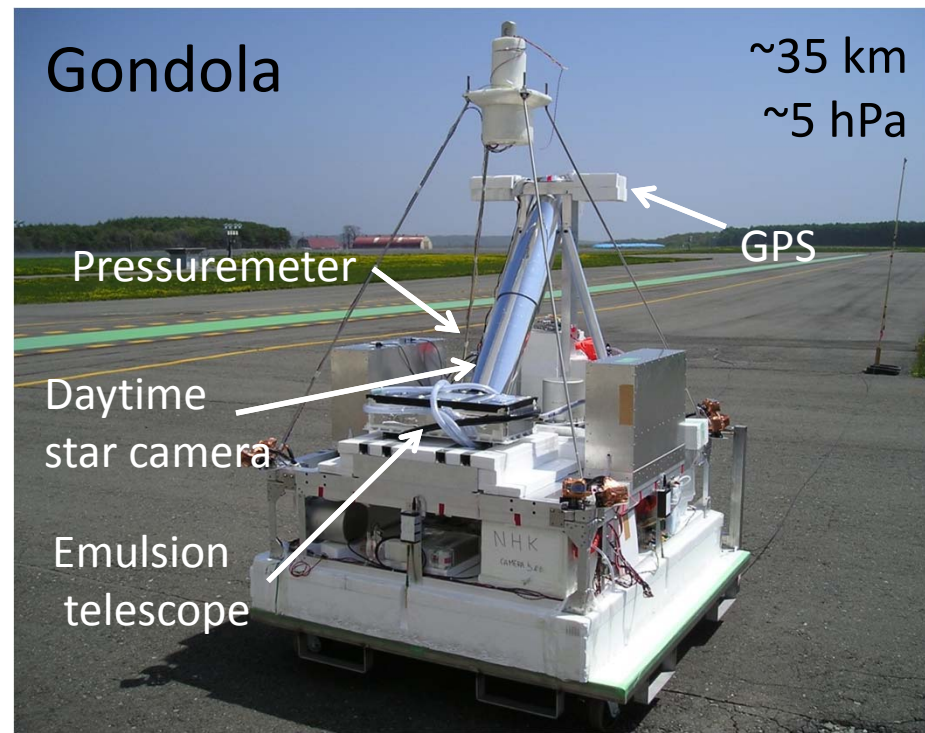
Time stamper (multi-stage shifter)

1st & 2nd stages: 2 films

3rd stage : 4 films

Calorimeter $4.0X_0$

32 Emulsion films,
27 lead plates (0.5 & 1 mm thick)



GRAINE 2011

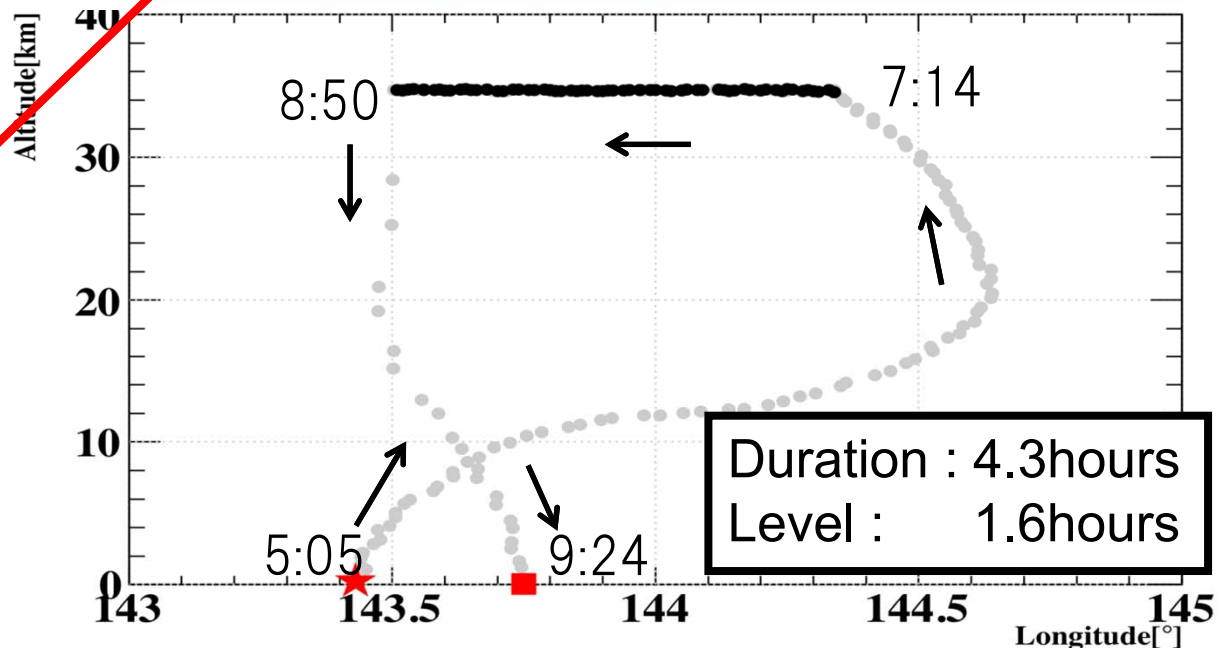
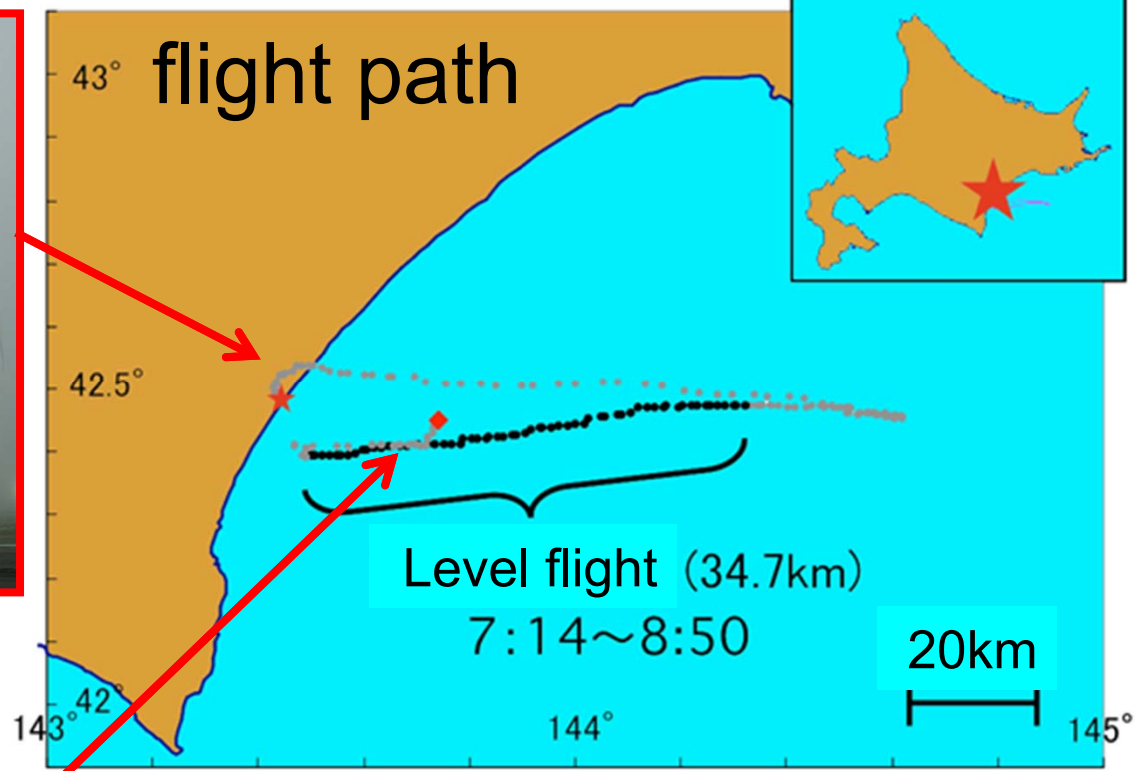
Taiki-cho, Hokkaido

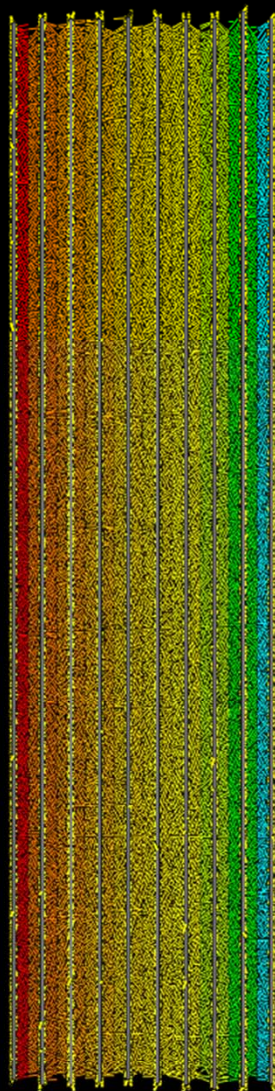
8th June 2011

5:05

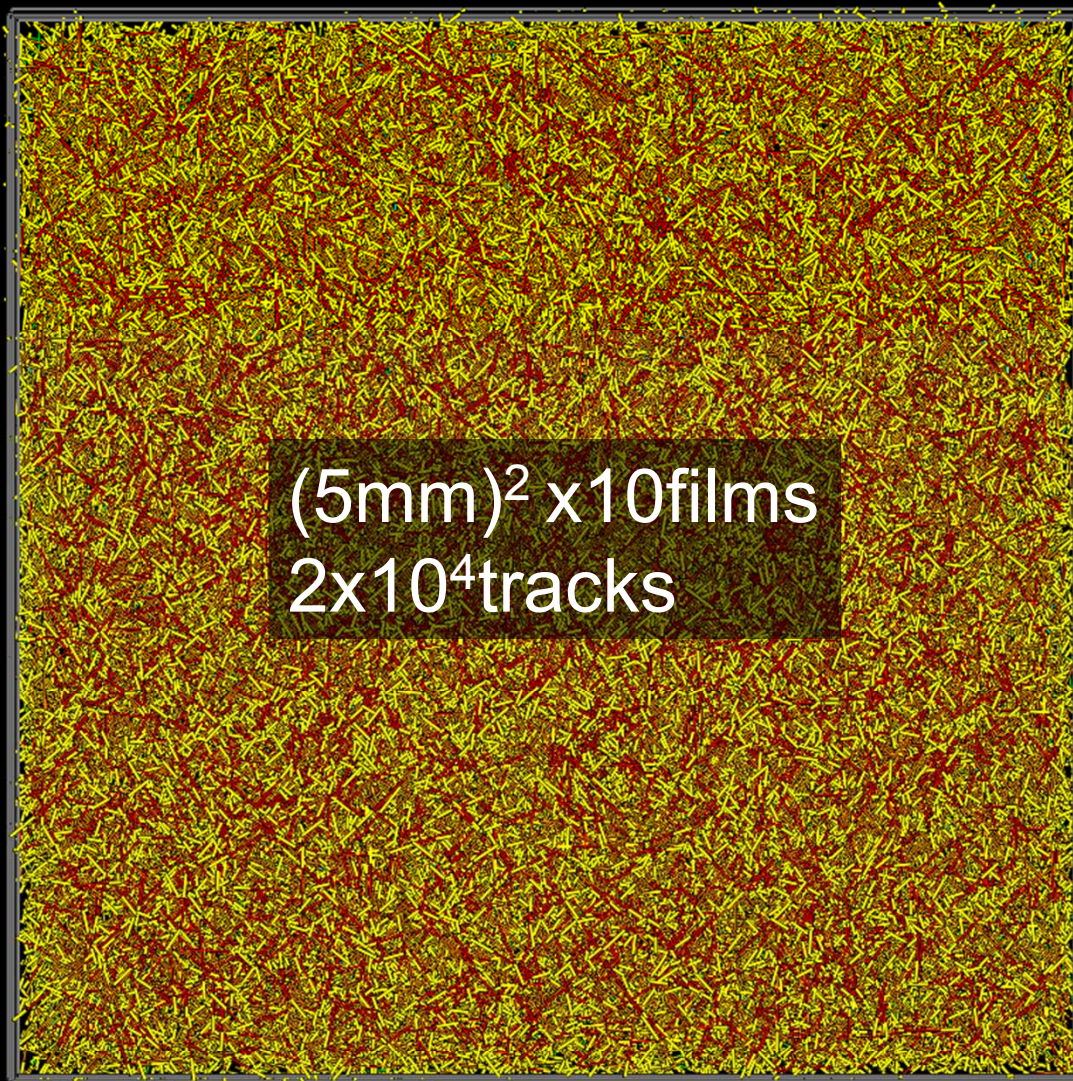


9:36



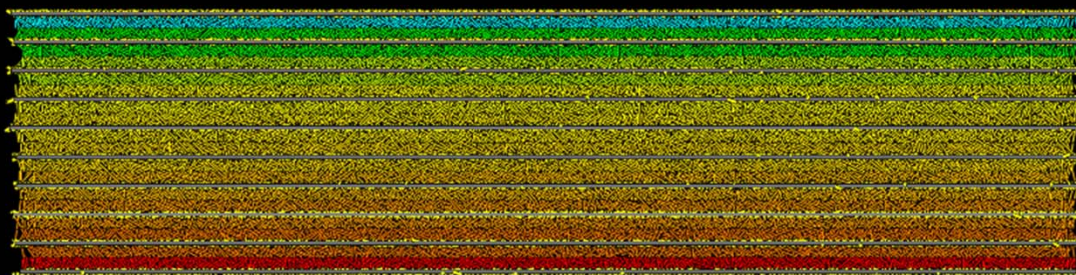


Y



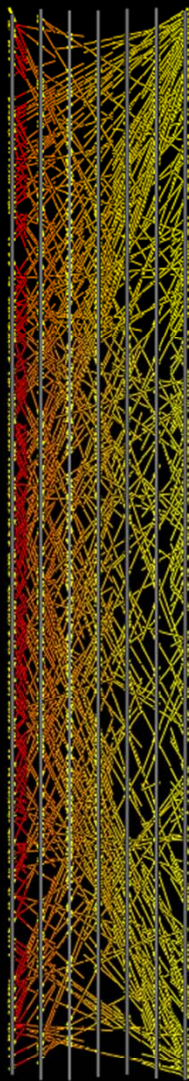
Z

$(5\text{mm})^2 \times 10\text{films}$
 $2 \times 10^4\text{tracks}$

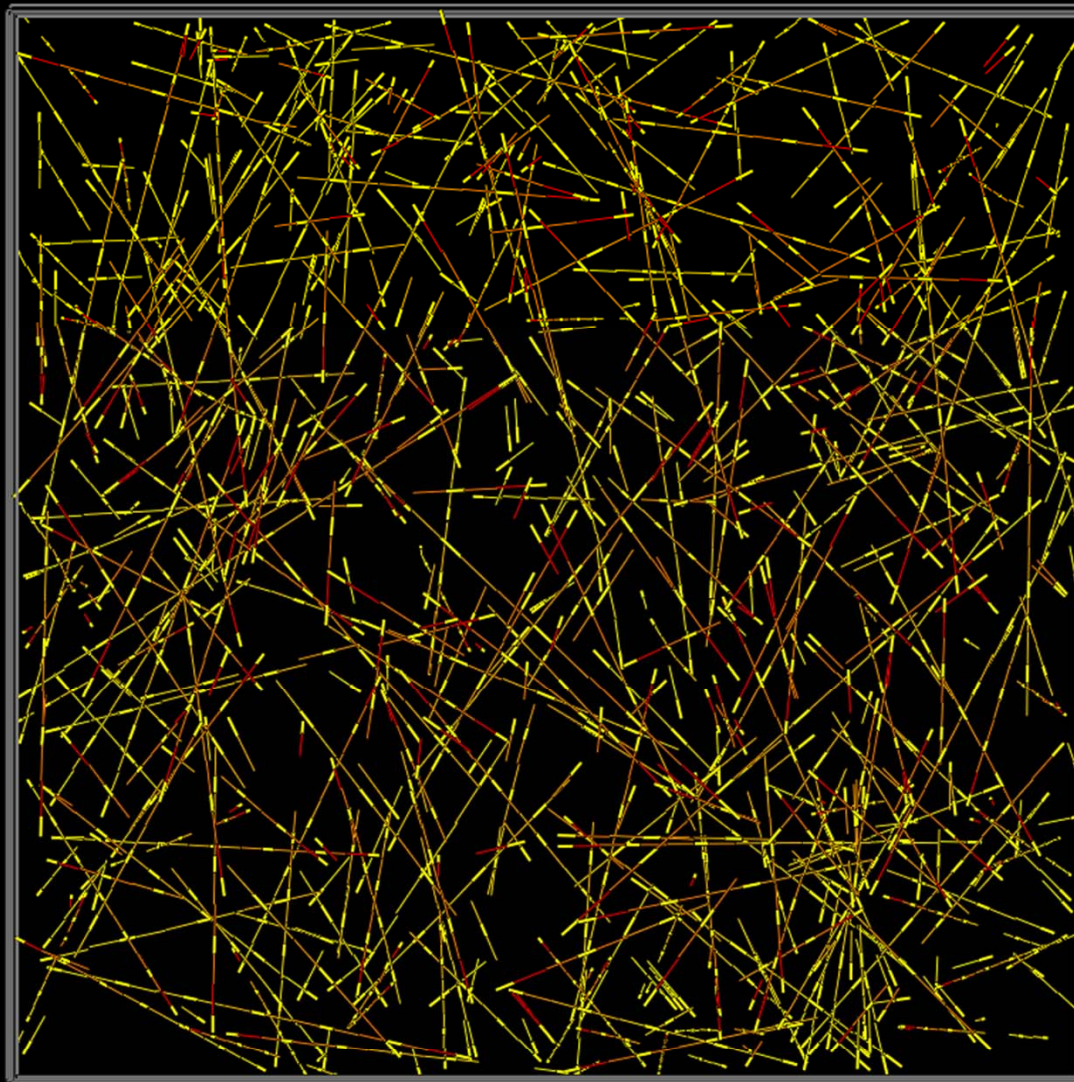


X

Converter
@GRAINE2011



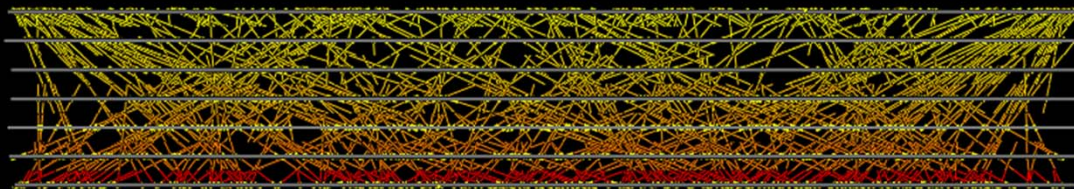
Y

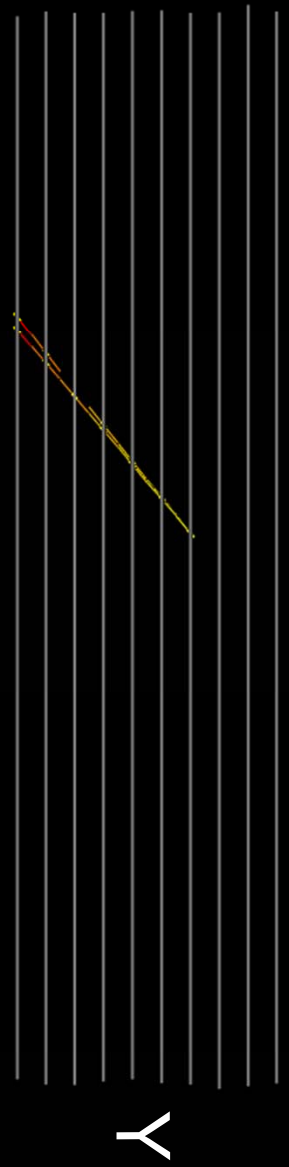


Z

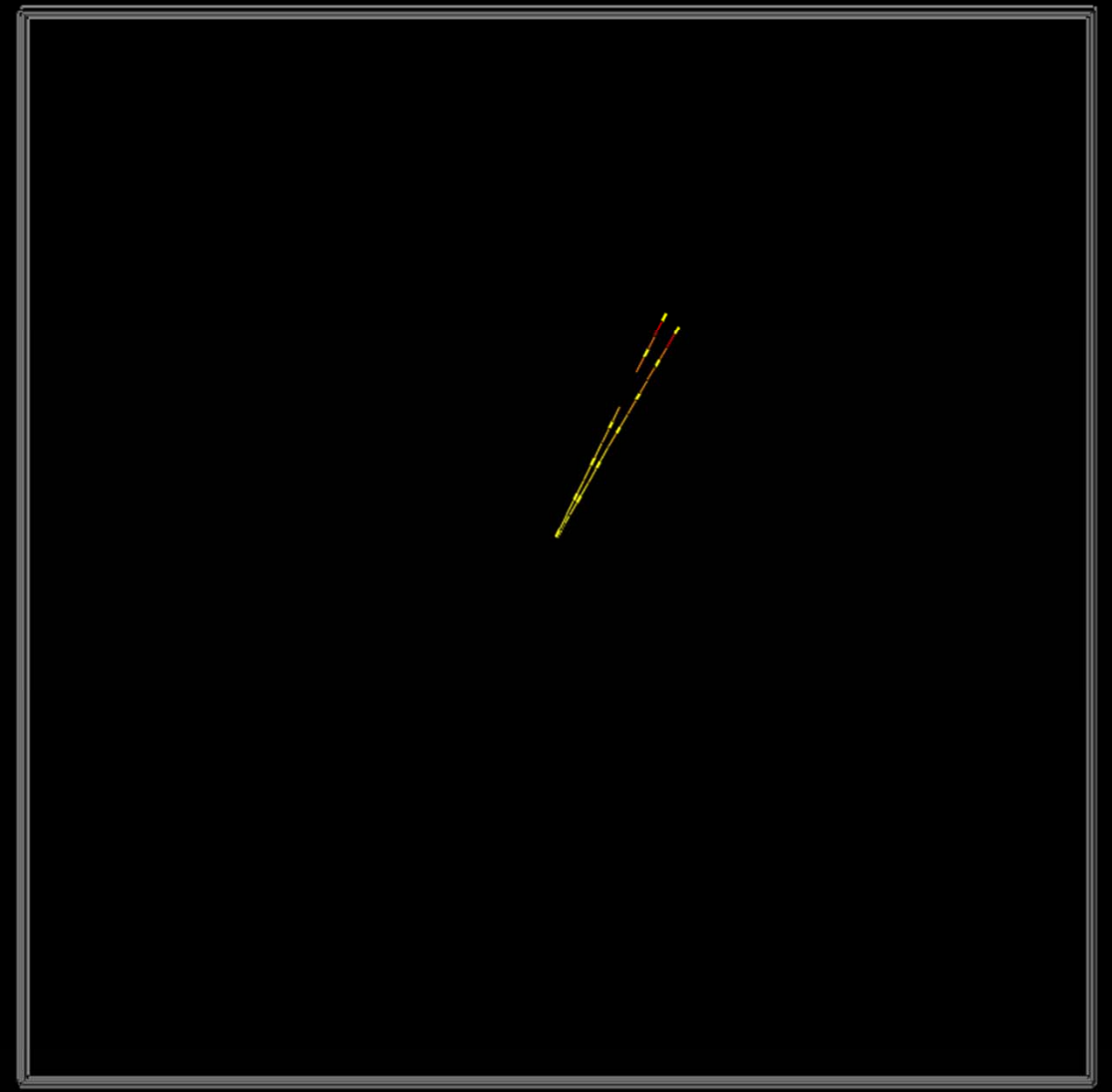
Converter
@GRAINE2011

X

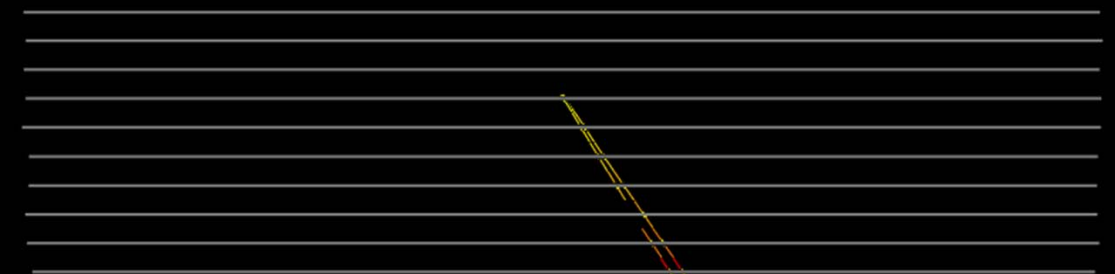




Y

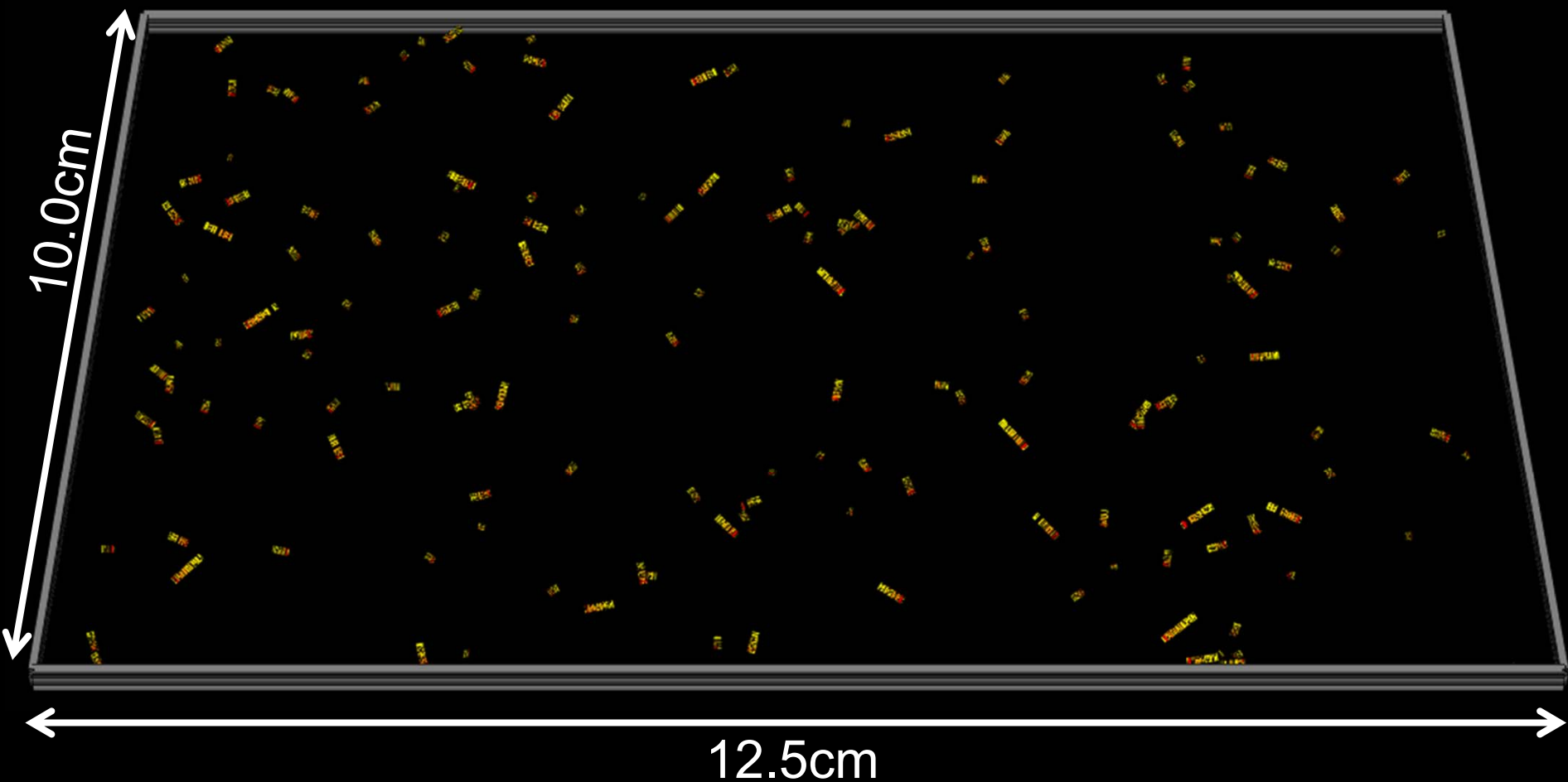


Z



X

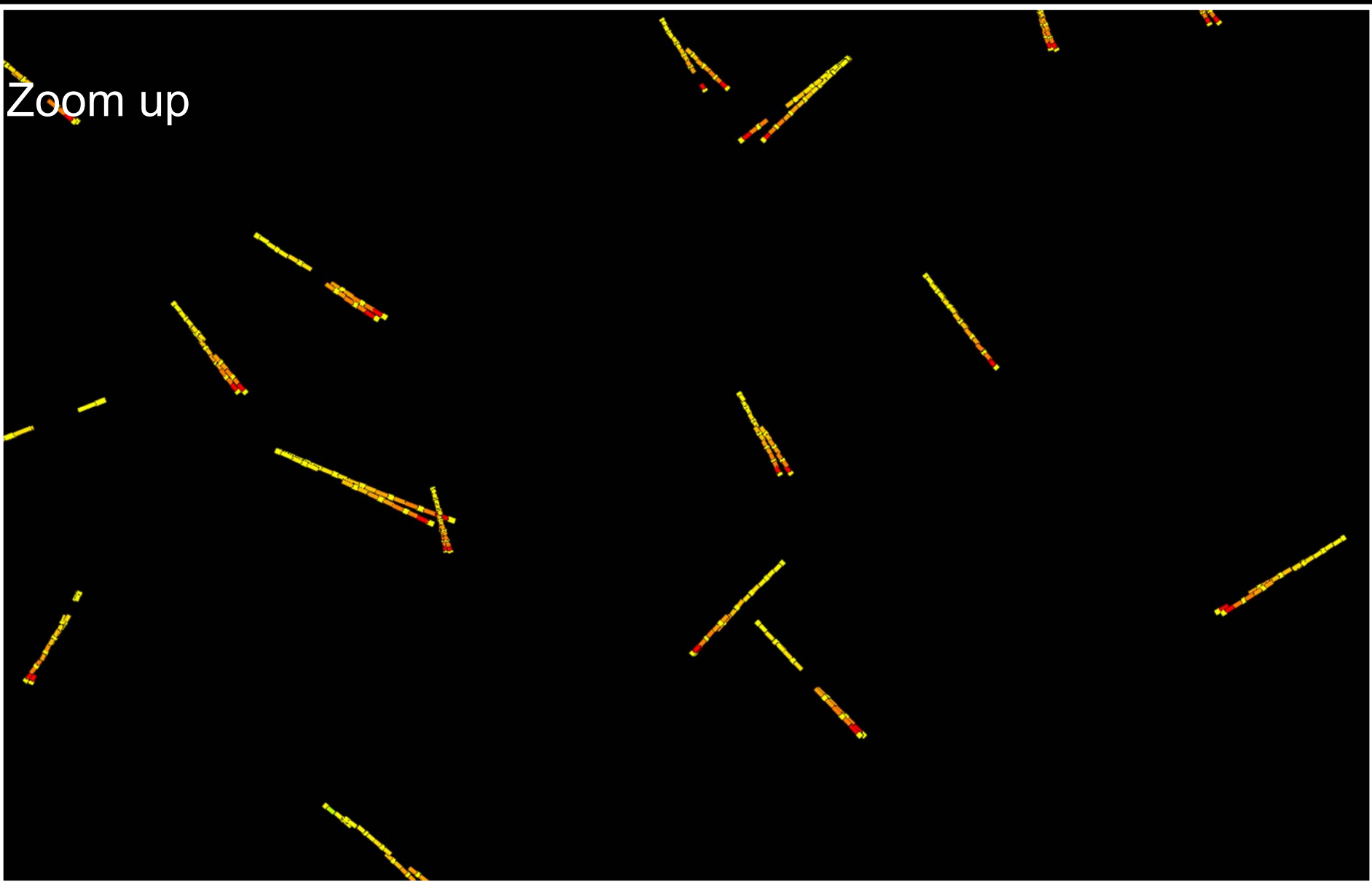
Converter
@GRAINE2011



Converter
@GRAINE2011

153events
Reliability 97%

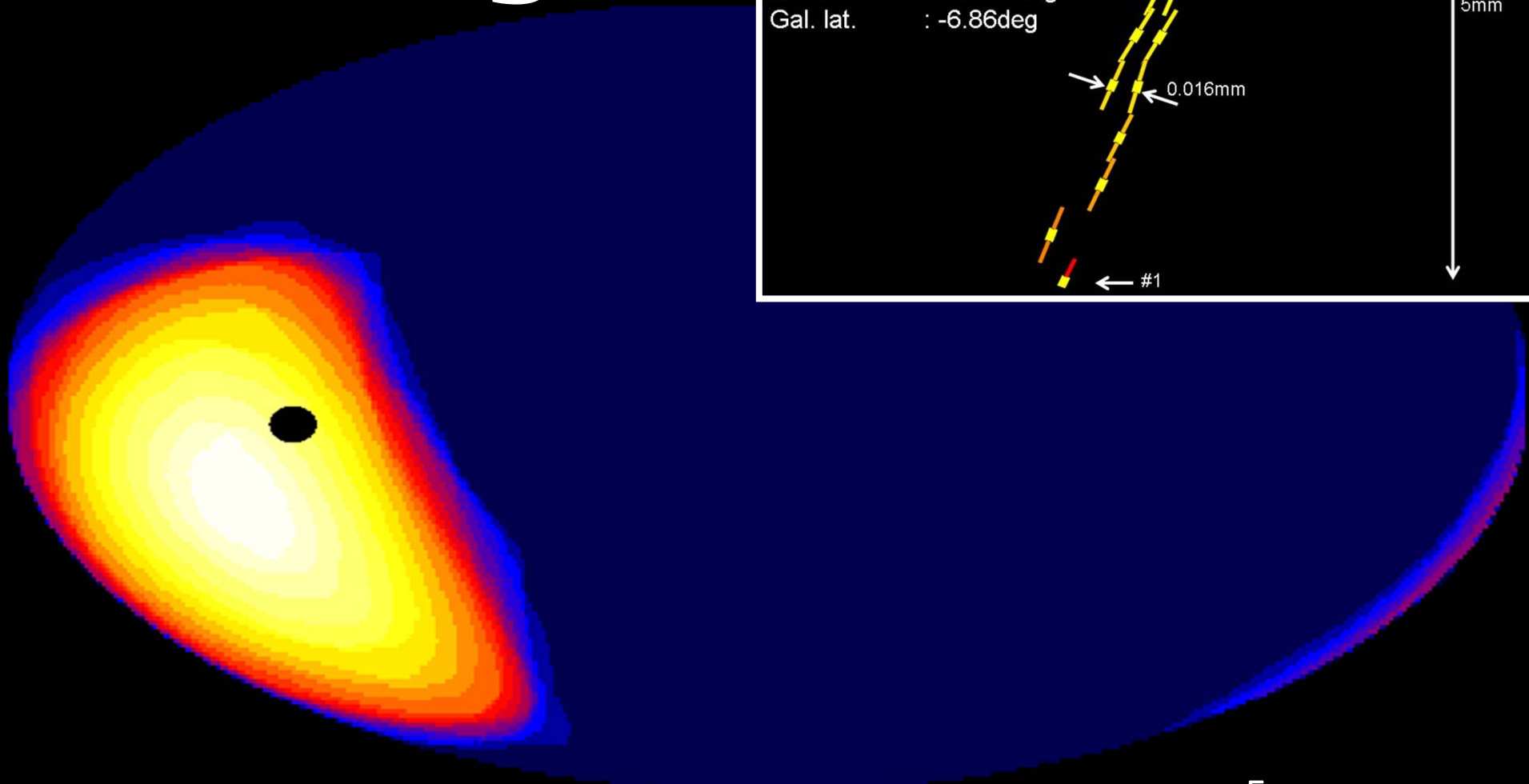
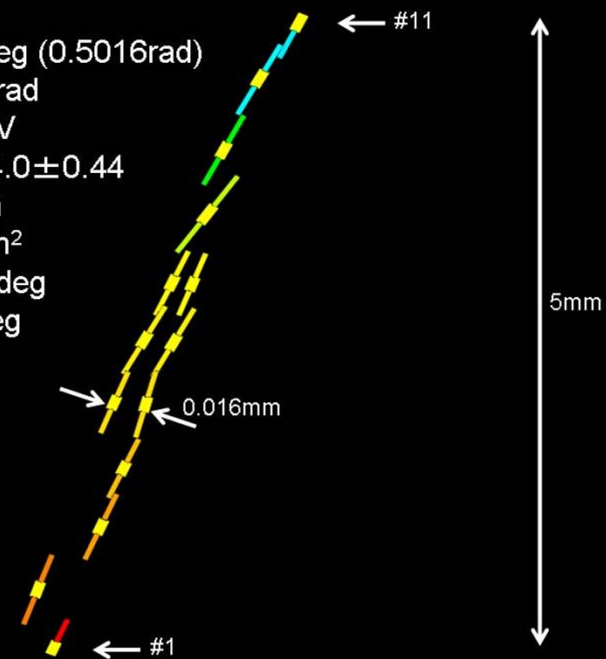
Zoom up



Converter
@GRAINE2011

GRAINE First Light

Event : 111 2986322
Start : #11 up
 θ_{incident} : 26.64deg (0.5016rad)
 θ_{open} : 0.0059rad
 $E_{\gamma}(\theta_{\text{open}})$: 340MeV
JST : 8:24:44.0 \pm 0.44
Altitude : 34.6km
Atm. depth : 6.6g/cm²
Gal. lon. : 112.06deg
Gal. lat. : -6.86deg

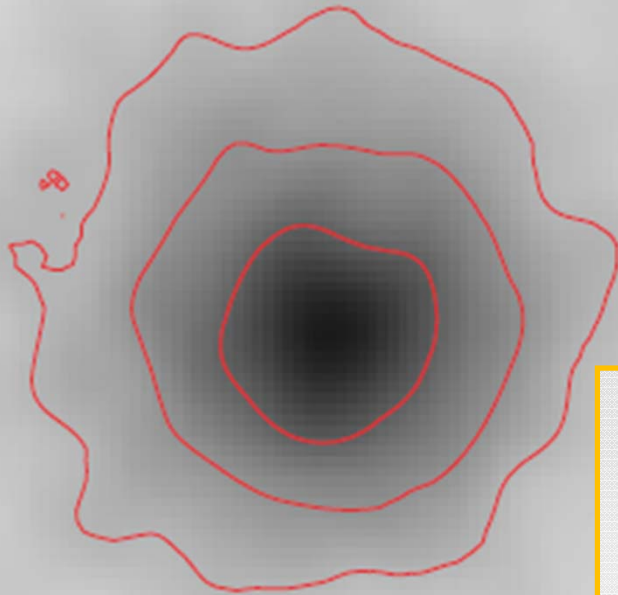


GRAINE2015

scheduled May 2015 @ Alice Springs, Australia

Gamma-ray image of Vela pulsar
by Fermi-LAT (< 300 MeV)

10°



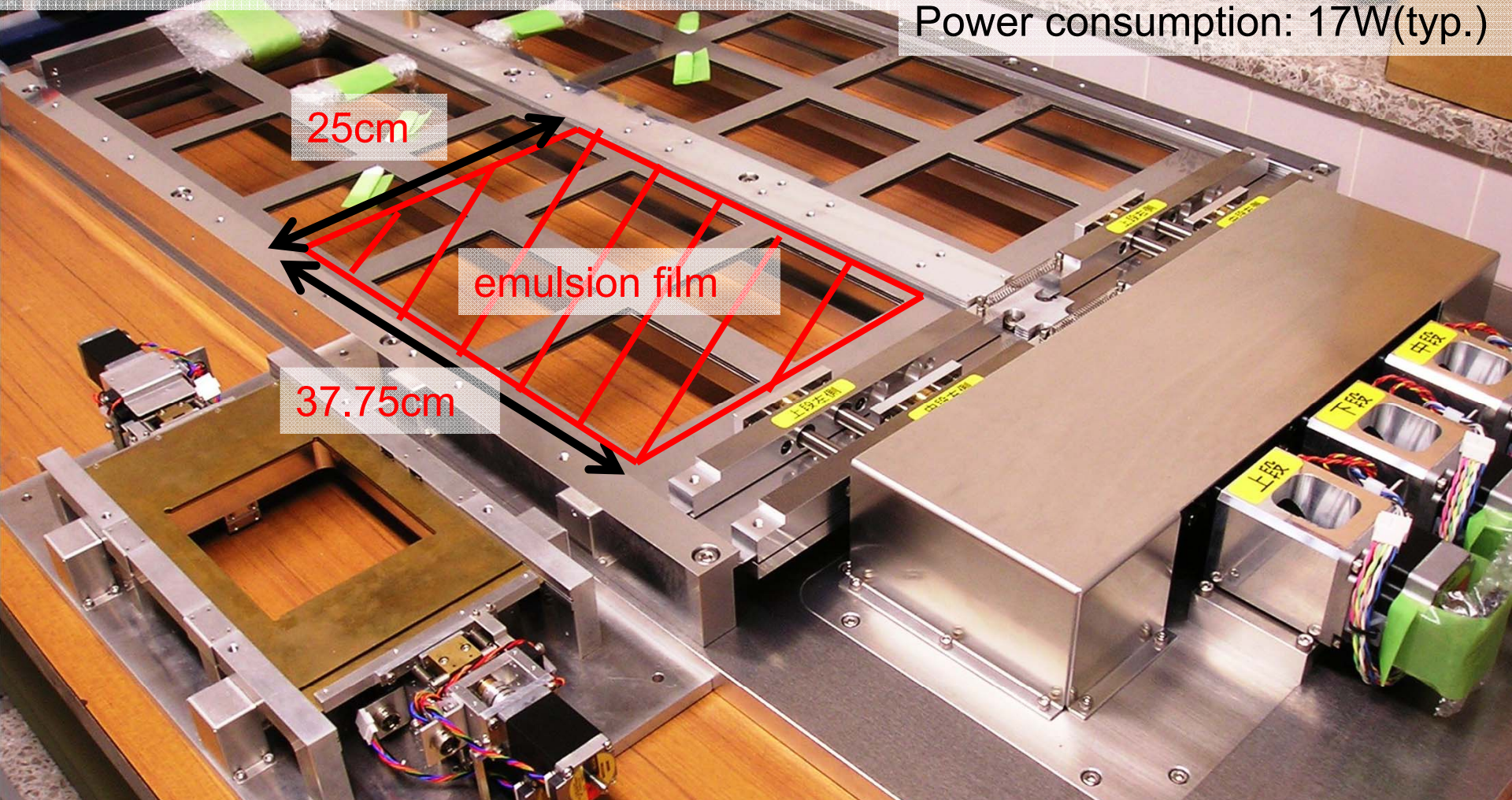
★ Vela pulsar :

- the brightest object in GeV gamma-ray
- point like source
- pulse period = 89ms
- possibility of polarization

- Finer imaging of the Vela pulsar
- Angular resolution of the Emulsion Telescope
- Phase analysis of pulsing (89ms period)
 - collaboration with the radio telescope
- Start of data accumulation for polarization study

2nd multi stage shifter for GRAINE2015

Aperture area: 3600cm^2
W66cm × D145cm × H10cm
Weight : 65kg
Power consumption: 17W(typ.)

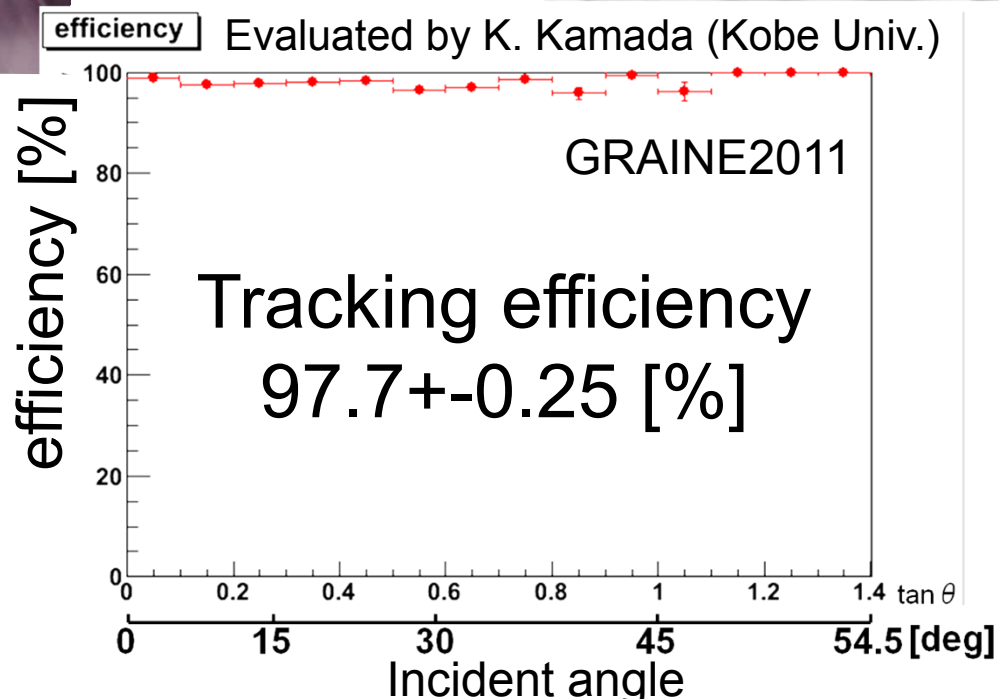
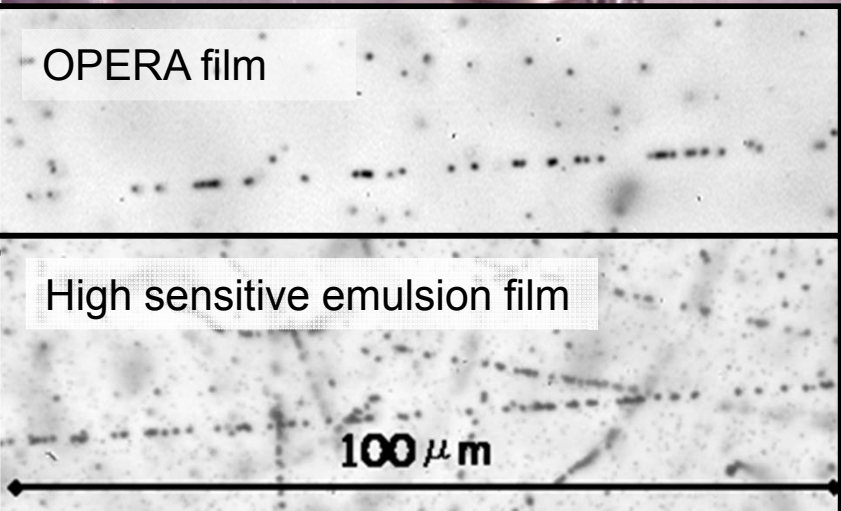
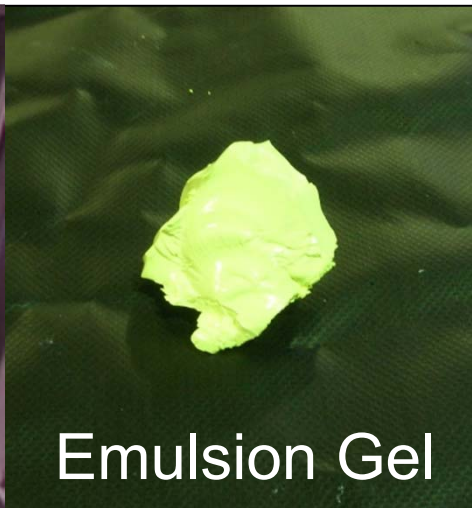
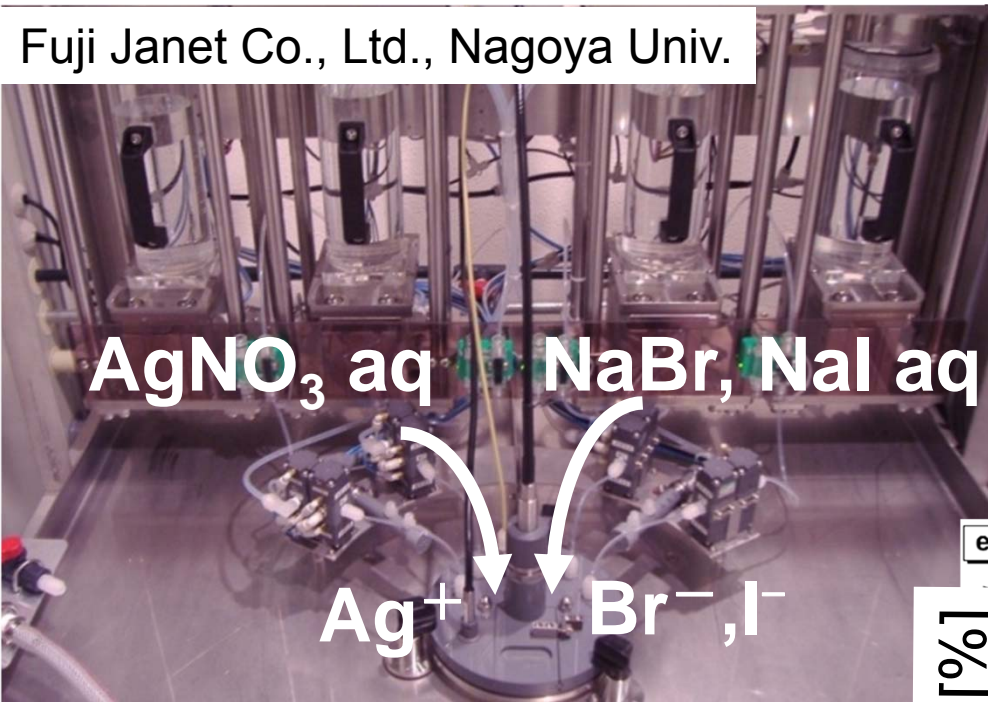


1st multi stage shifter for GRAINE2011
Aperture area : 125cm^2
Time resolution : 0.15s

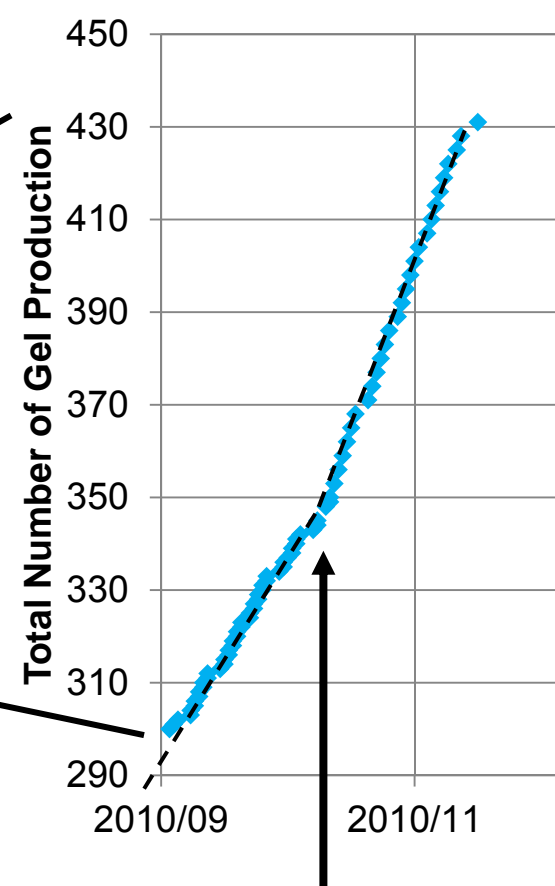
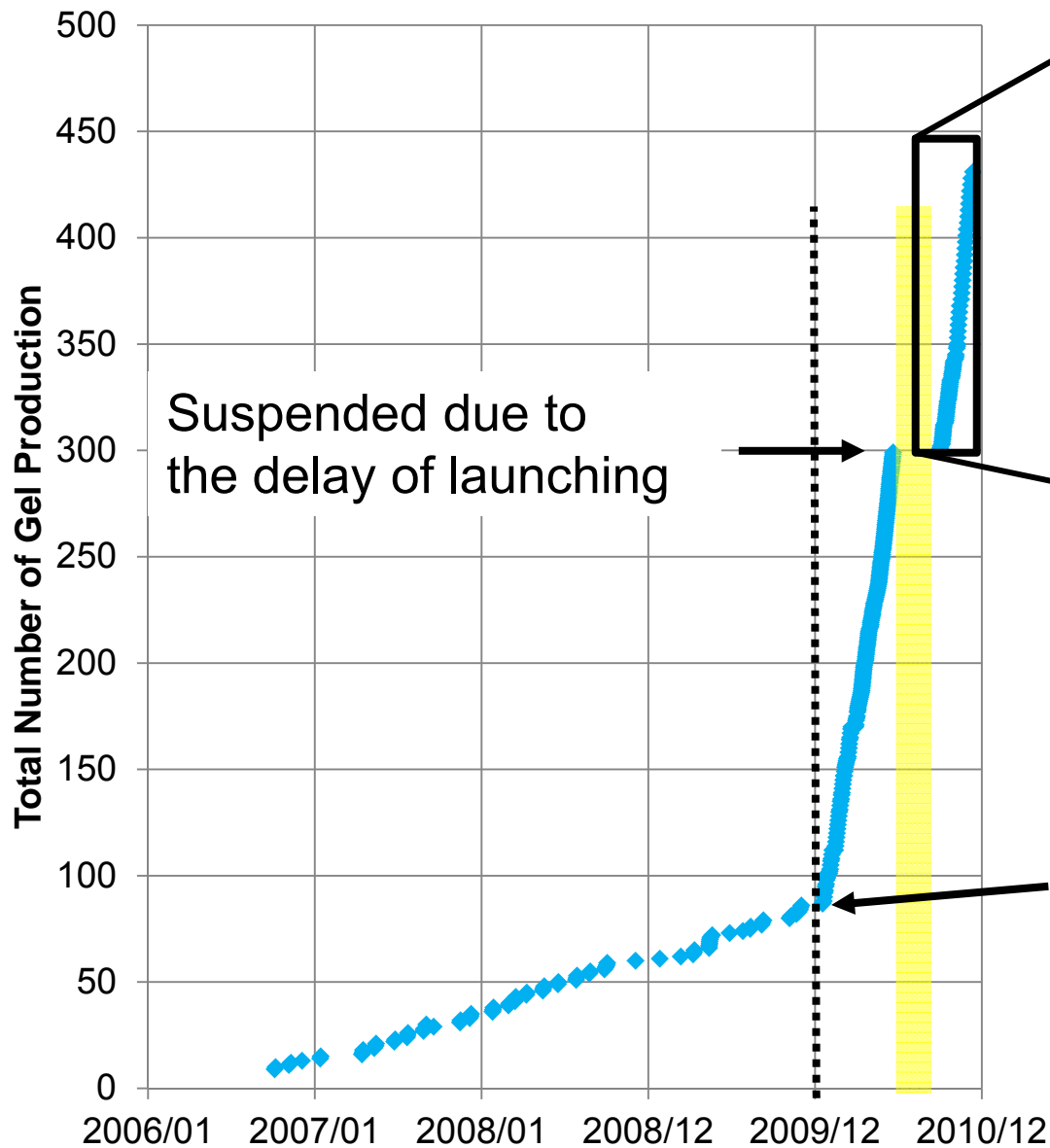
Co-developed with
Mitaka Kohki.Co.,Ltd

High sensitive Emulsion Gel

Fuji Janet Co., Ltd., Nagoya Univ.



Emulsion Gel Production

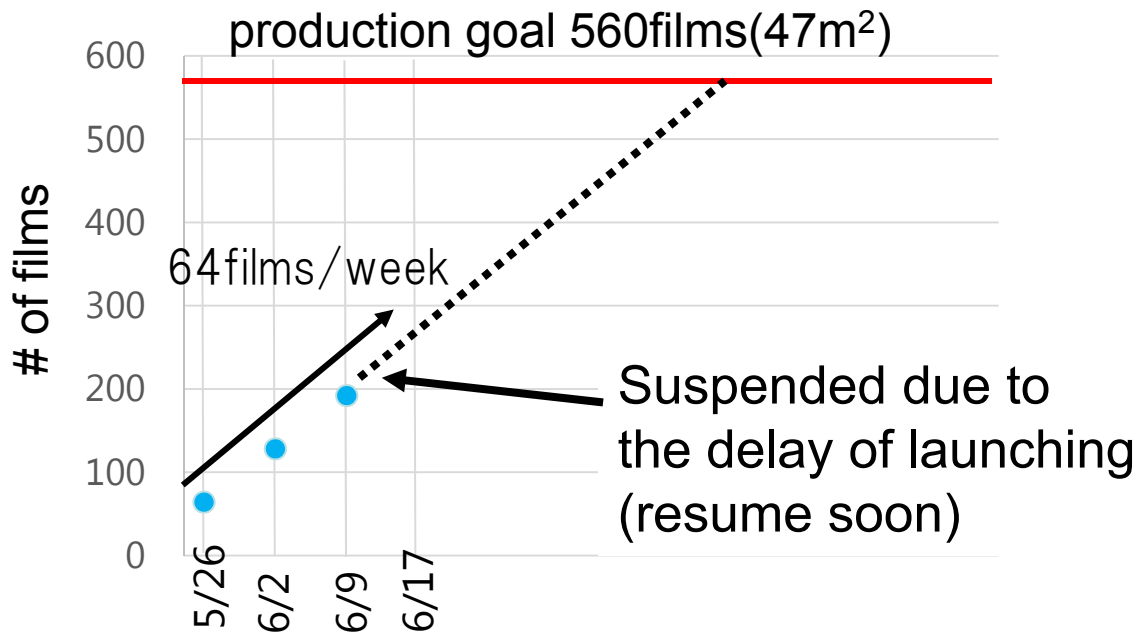
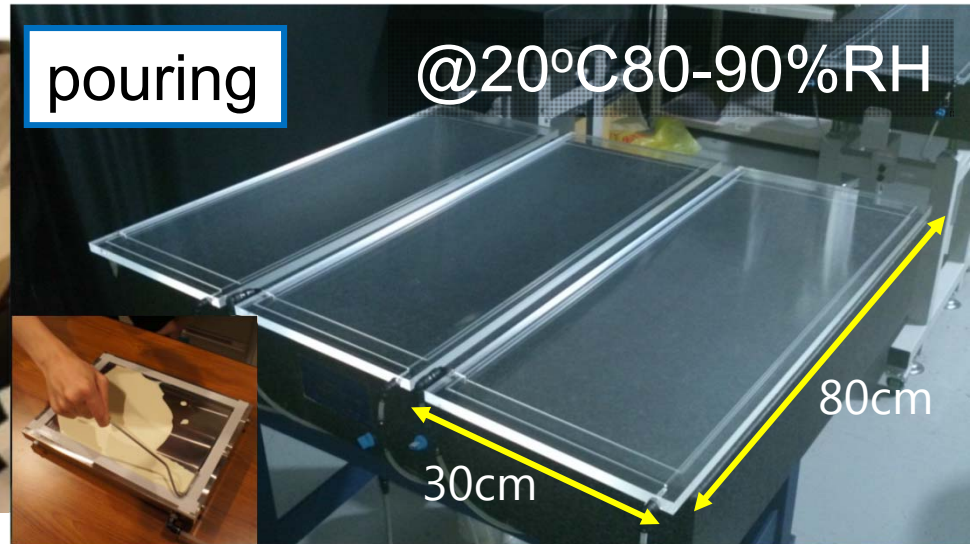


start larger scale system

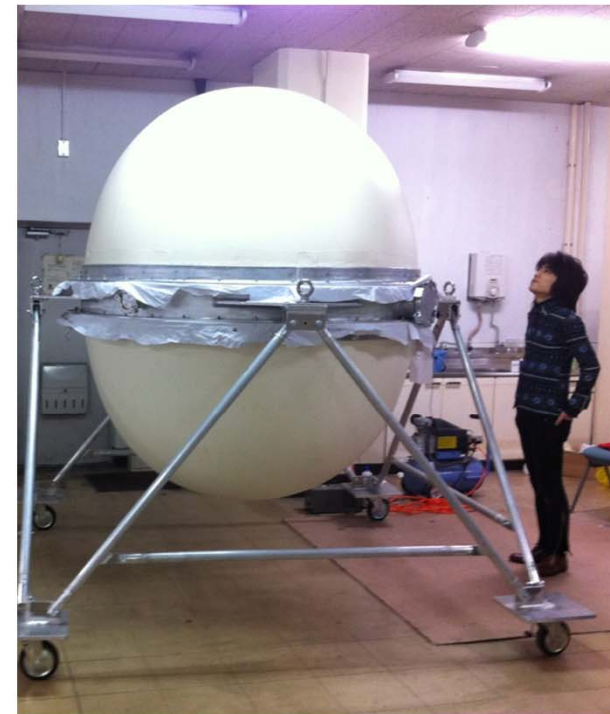
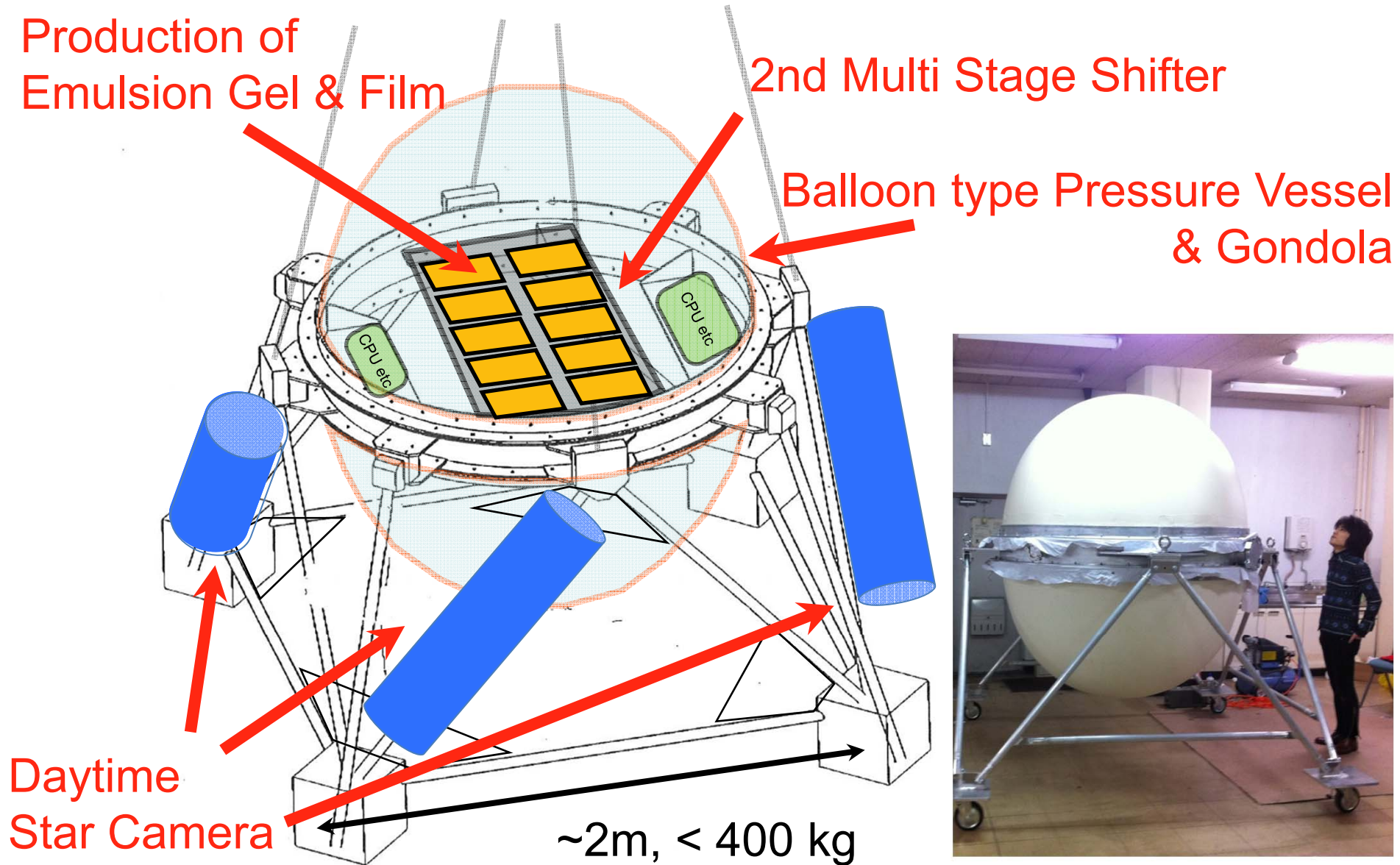
2014/01 Mass Production Start

- GRAINE
- Cosmic muon radiography
- J-PARC T60

Pouring (Film Production)



preparation for GRAINE2015



GRAINE roadmap (Summary & Outlook)

- **Prototype Phase**

2011(done), TARF, JAXA Scientific Ballooning

125cm² aperture area, 4.3hours (1.6hours@35km) flight duration

- Working test for each element
- Connection test between elements
- Measurement of atmospheric gamma-rays

- **Demonstration Phase**

2015(preparation), Alice Springs, JAXA International Scientific Ballooning

3600cm² aperture area, 1 day flight duration

- Overall test by detecting known gamma-ray source (Vela pulsar)
- Observation with highest imaging resolution

- **Working Phase**

2016 or later

~10m² aperture area, ~7days flight duration

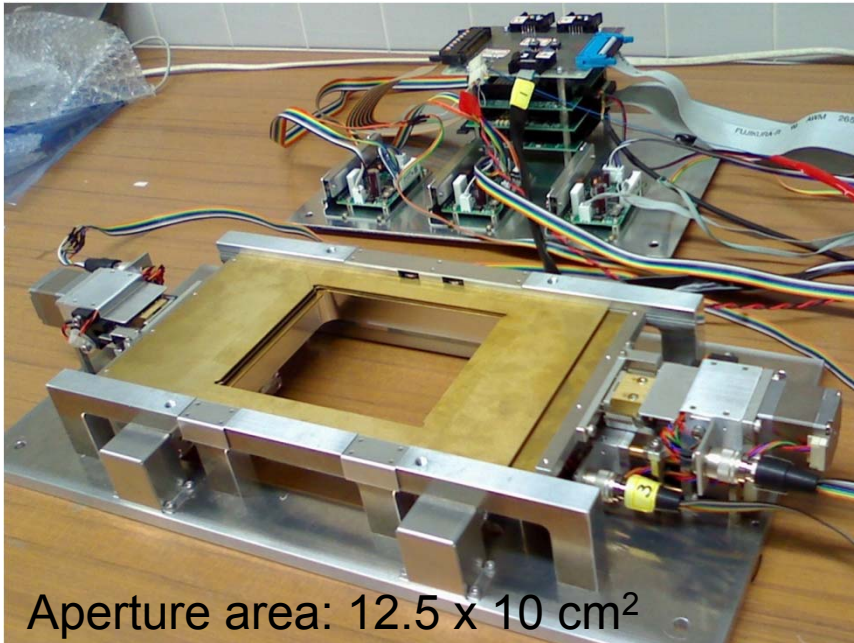
- Starting scientific observation

backup

Timestamper @GRAINE2011

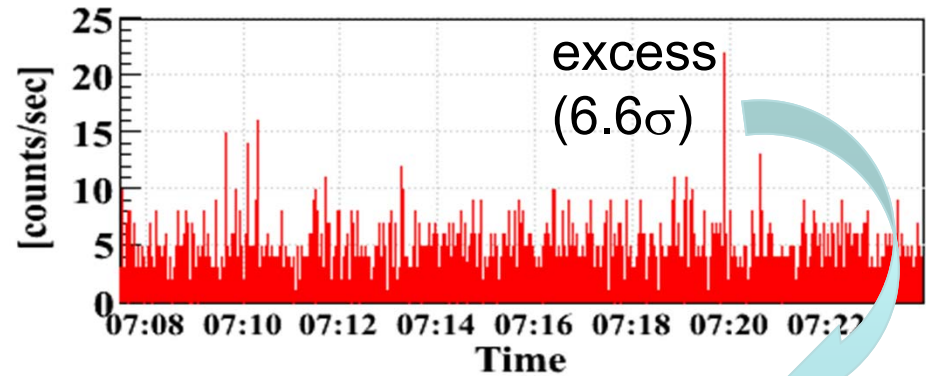
H.Rokujo, et al., NIM A, 701 (2013)

“Multi-stage shifter” 1st model

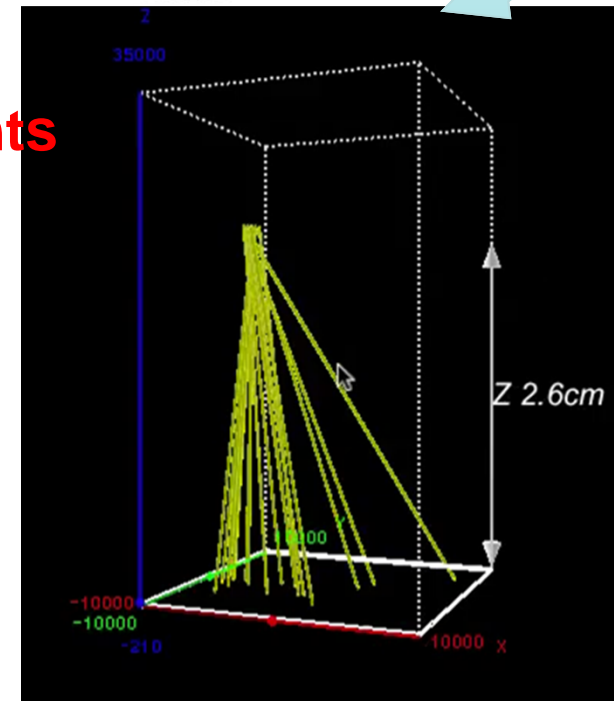


- Correct operation during whole observation time
- Giving time info. to all penetrating tracks
- Detection of hadron shower tracks by timing and 3-D spatial analysis
- Time resolution: 0.15 sec

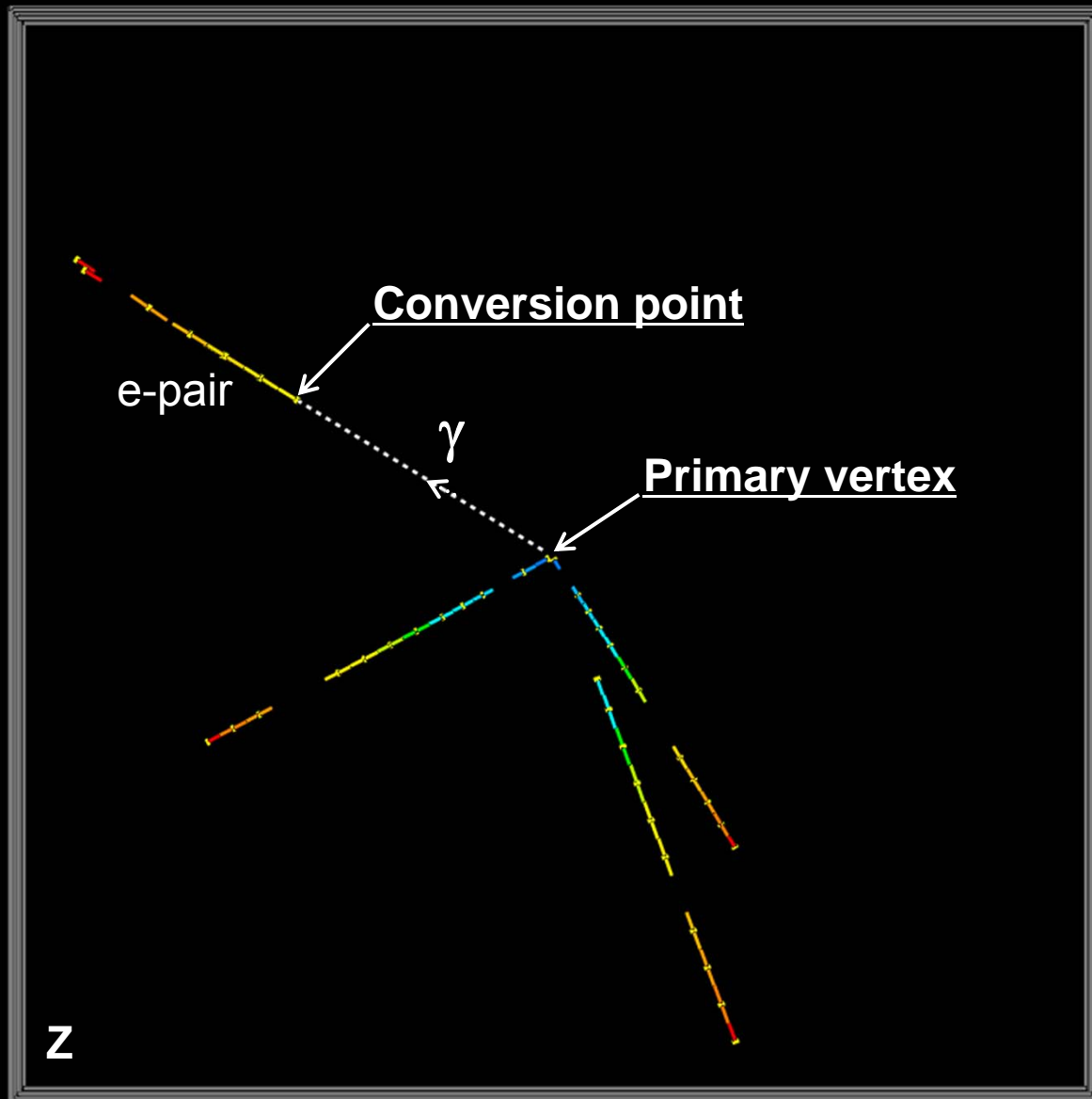
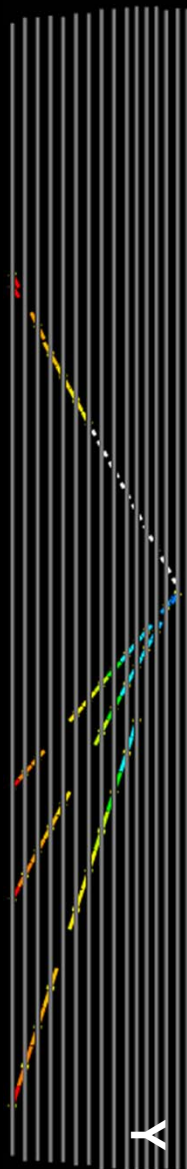
Track rate measurement @35km



Detection of hadron events

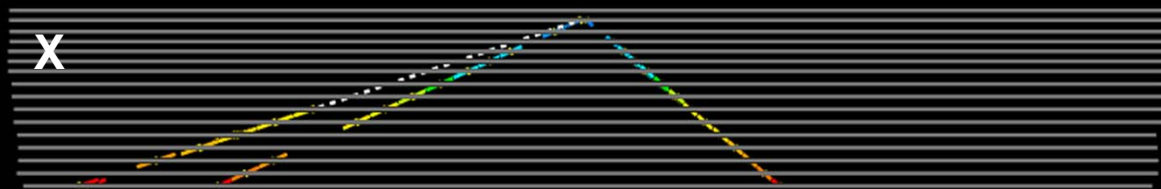


Ev : 2438038
7:18:34.5 (JST)
 $\Delta t = \pm 0.5\text{s}$
1.2cm x 1.2cm
x 16films



Pointing accuracy

$\Delta\theta_{\text{space}} : 0.65\text{deg} (0.0114\text{rad})$
 $E_{\gamma} : 45+33-10 [\text{MeV}]$
 $\theta_{\gamma} : 46.61 [\text{deg}]$



Nuclear Emulsion in Neutrino Experiment

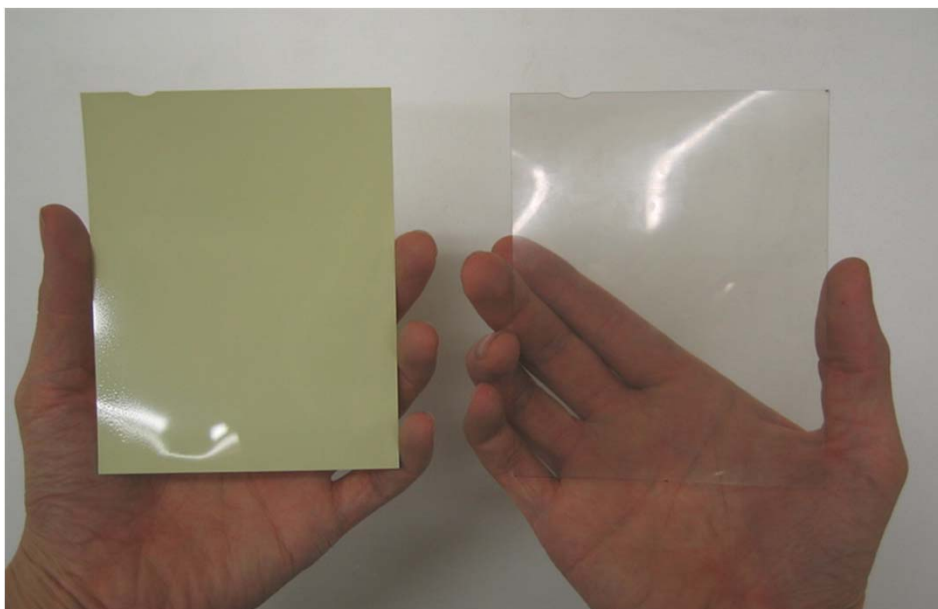
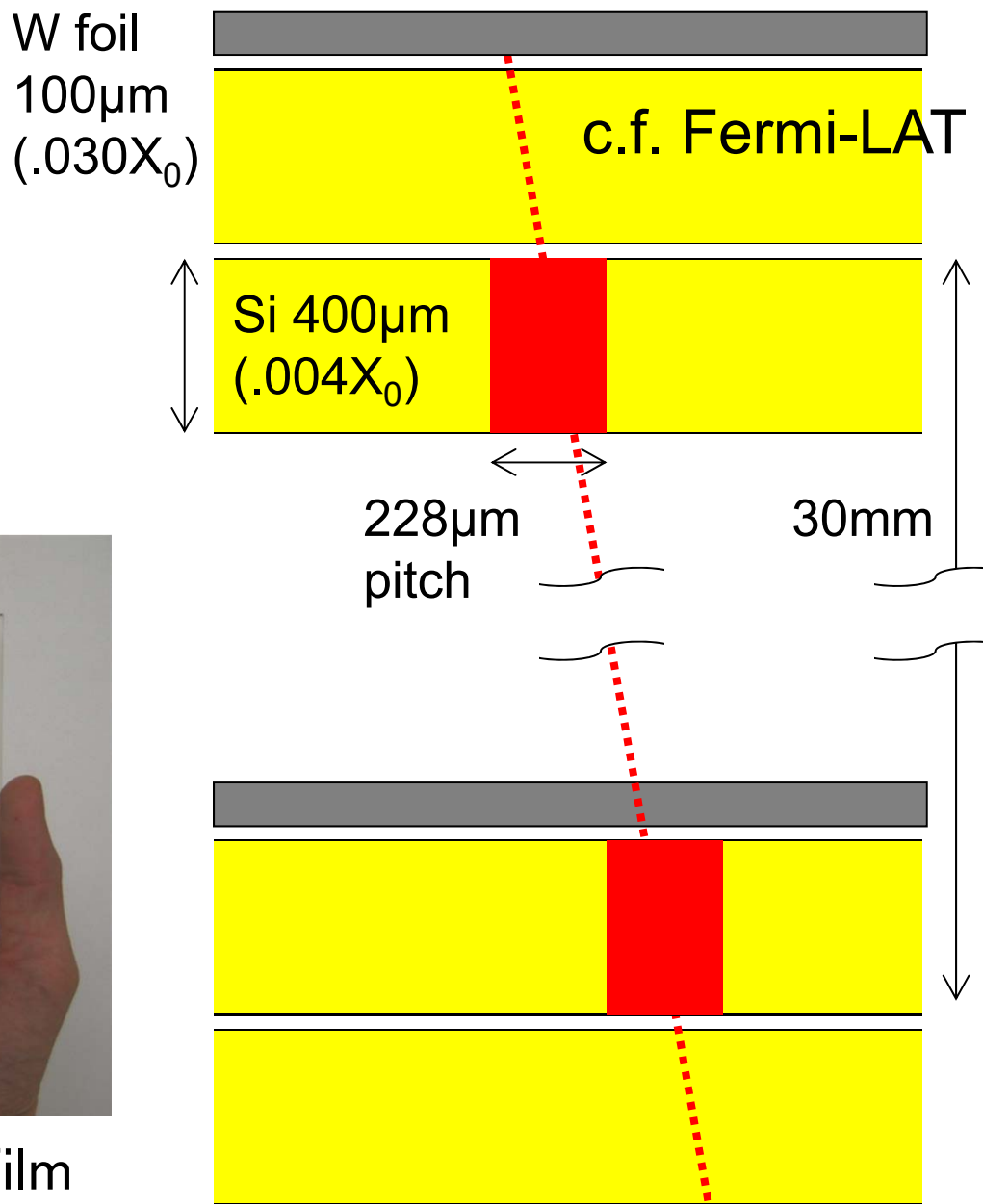
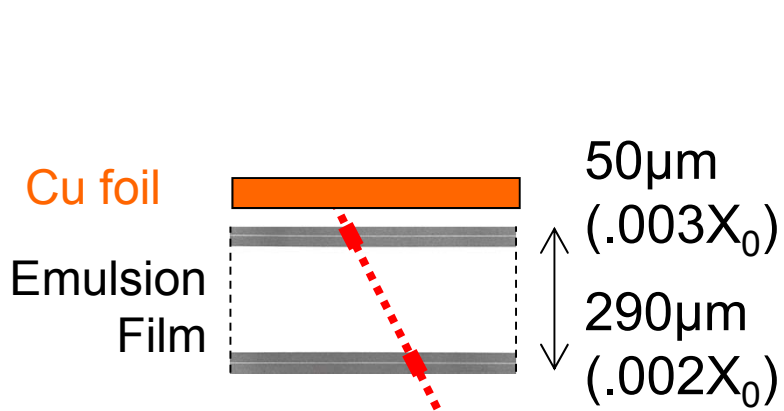
1978-1983	Fermilab E531 charm, $\nu_{\mu} \rightarrow \nu_{\tau}$	~ 0.1 ton
1990-2000	CHORUS (CERN WA95) $\nu_{\mu} \rightarrow \nu_{\tau}$, charm	~ 1 ton
1994-2001	DONUT (Fermilab E872) ν_{τ}	~ 1 ton ECC
2000-	OPERA (CERN CNGS01) $\nu_{\mu} \rightarrow \nu_{\tau}$	~ 1250 ton ECC

Handmade Emulsion Film
using Fujifilm Co. Gel

“OPERA Film”
made by Fujifilm Co.

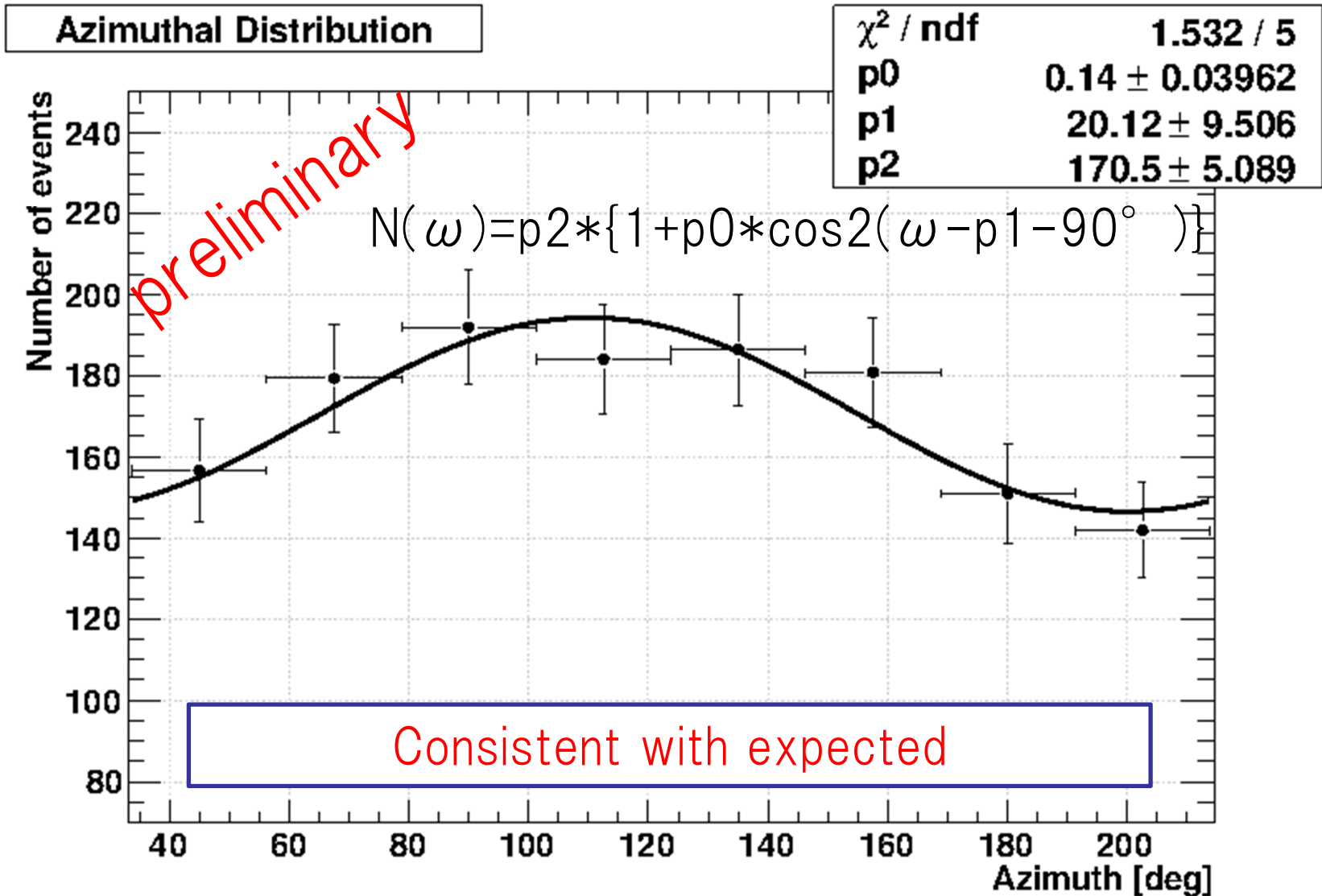


Gamma-Ray Astro-Imager with Nuclear Emulsion

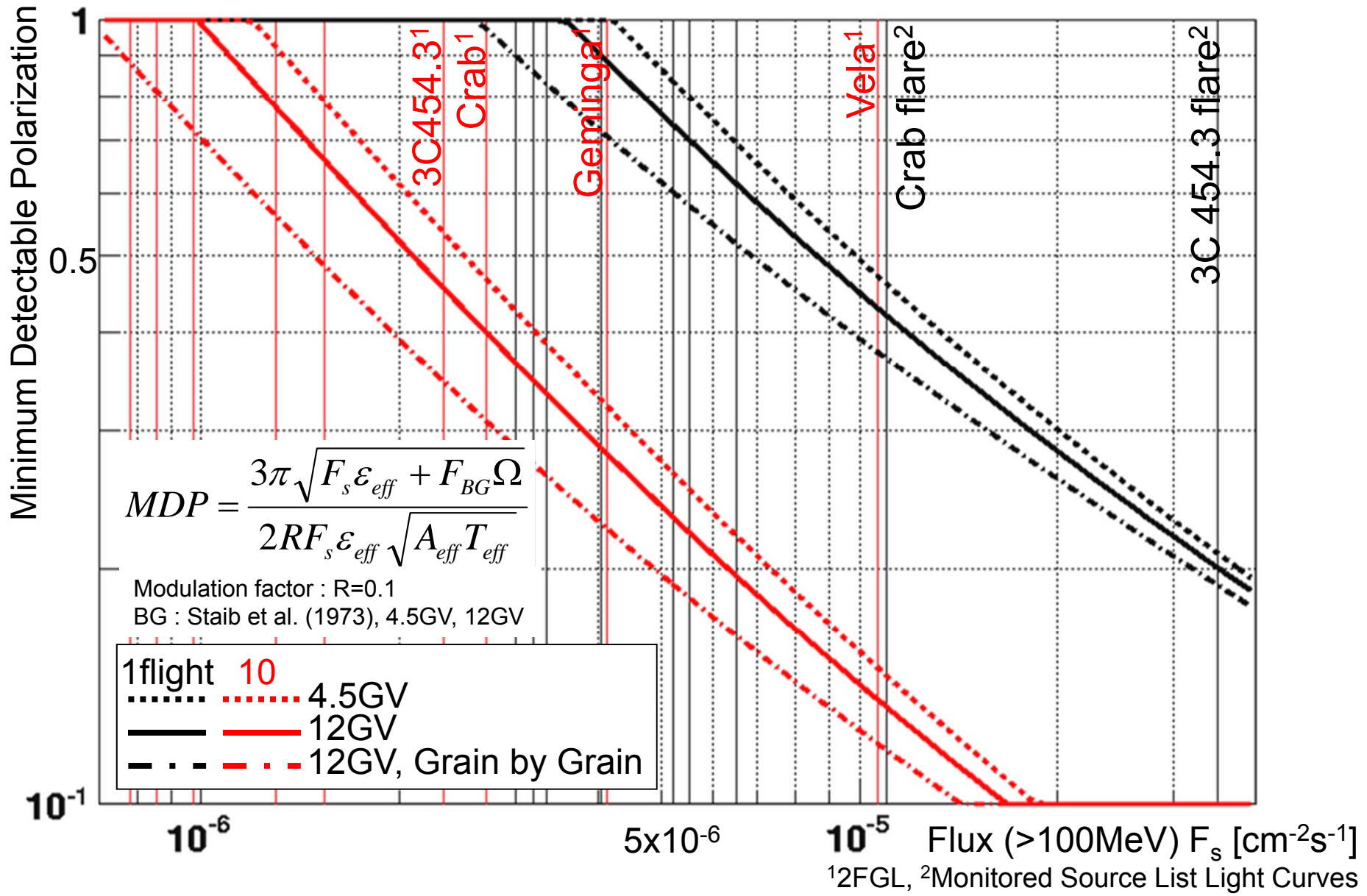


現像前、現像後のEmulsion Film

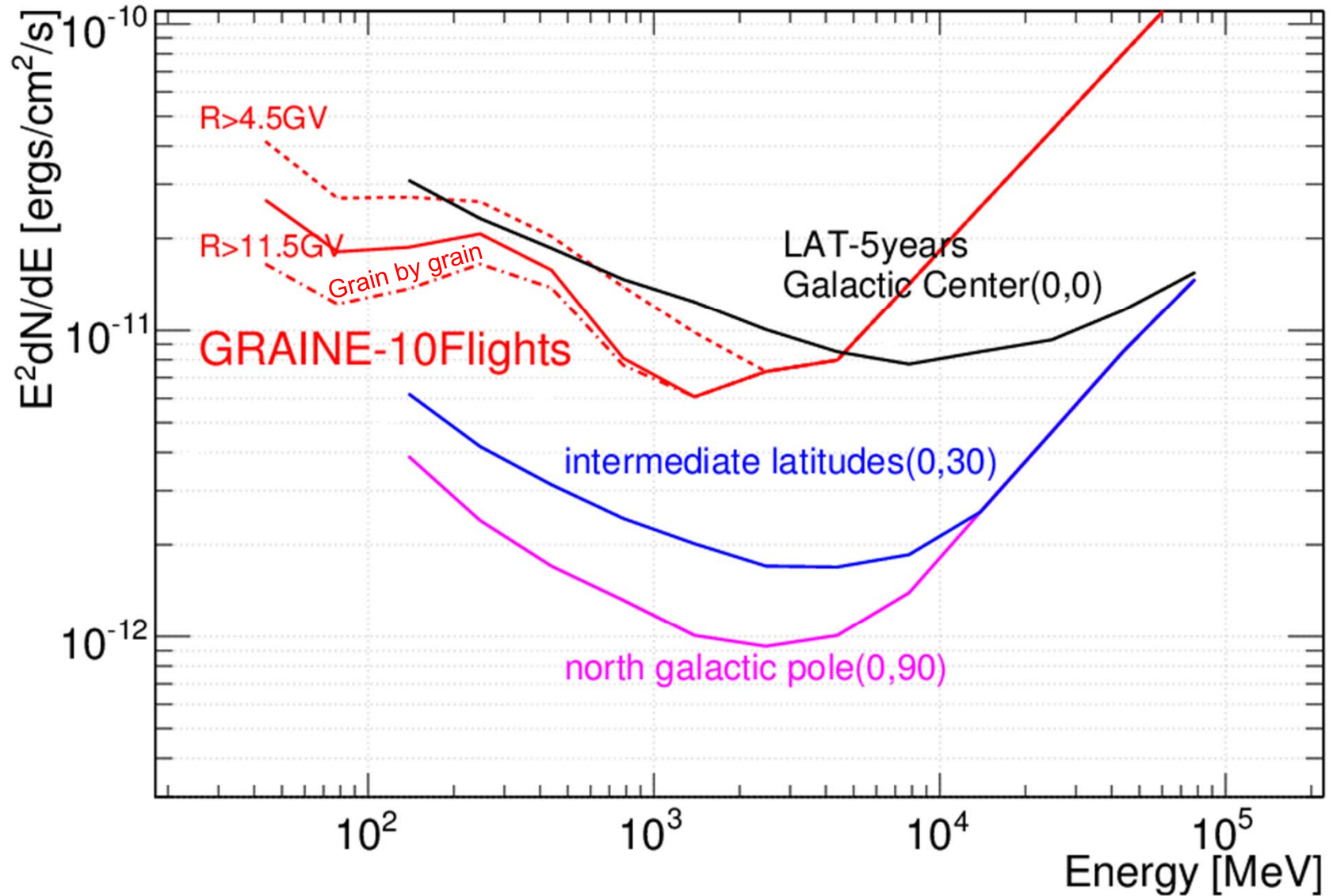
Polarization sensitivity



Polarization sensitivity



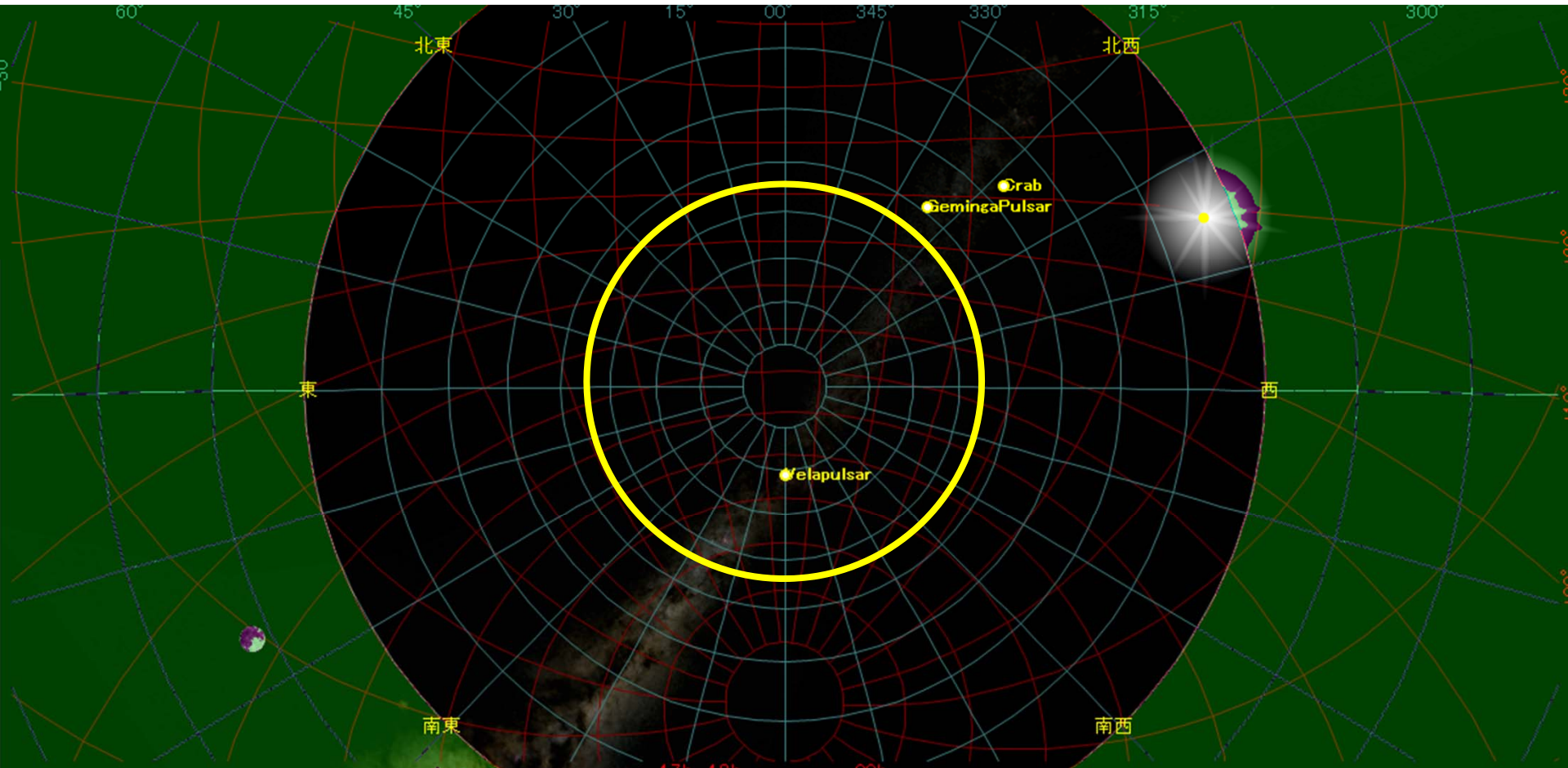
Source sensitivity





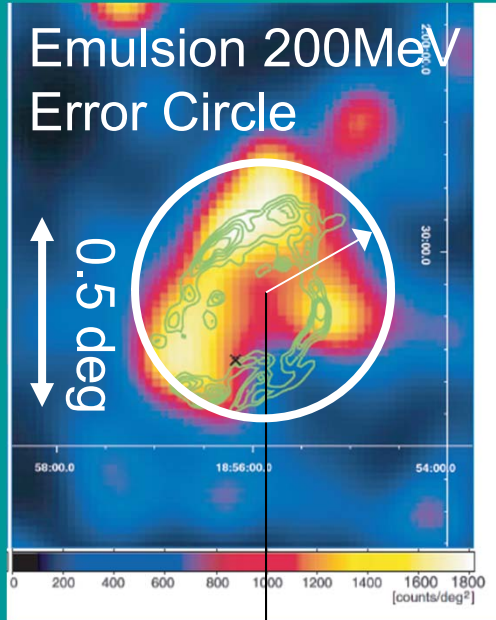
Flight duration ~1 day

Vela



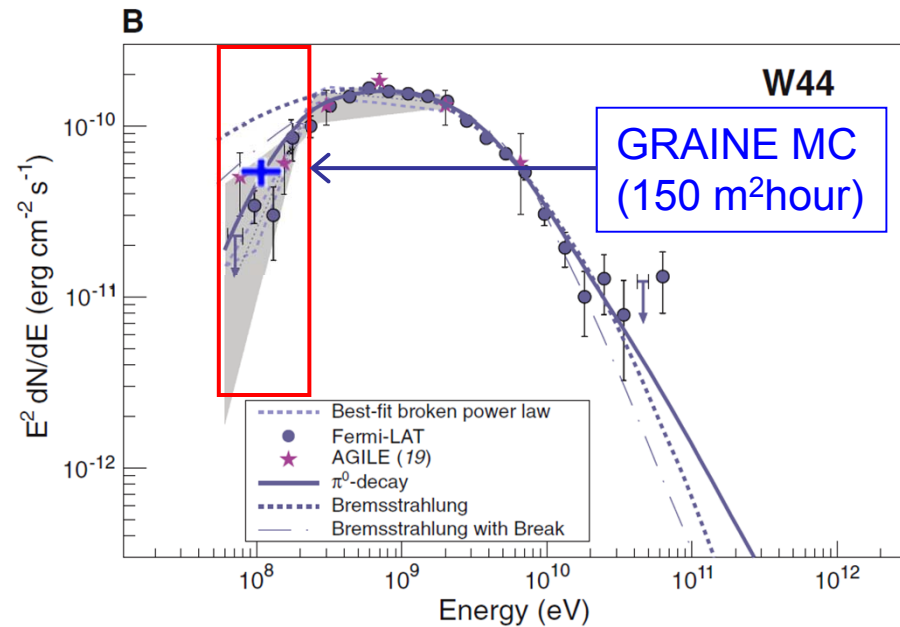
Alice Springs 2014/May/15, Culmination 17:09(NT), In FOV 6.5hours (13:53-20:24)
Lat.: -23° 40' (-0:30(JST))
Lon.: 133° 50' E

SNR W44



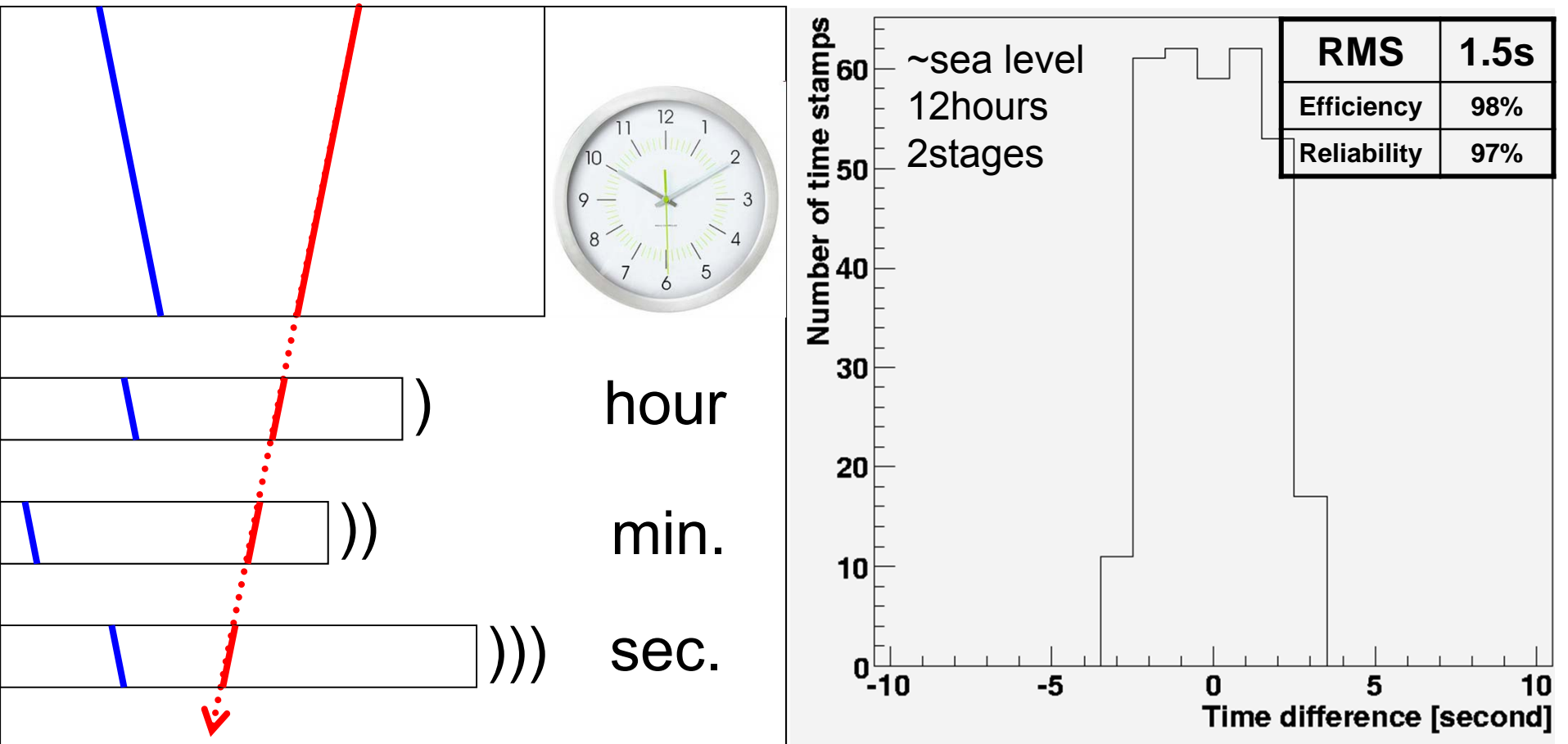
Fermi 200MeV
Error Circle

Spectrum <200MeV important for model selection



M. Ackermann *et al.*
Science **339**, 807 (2013);
DOI: 10.1126/science.1231160

Multi-stage shifter



S.Takahashi et al., Nucl. Instr. And Meth. A, 620 (2010) 192-19

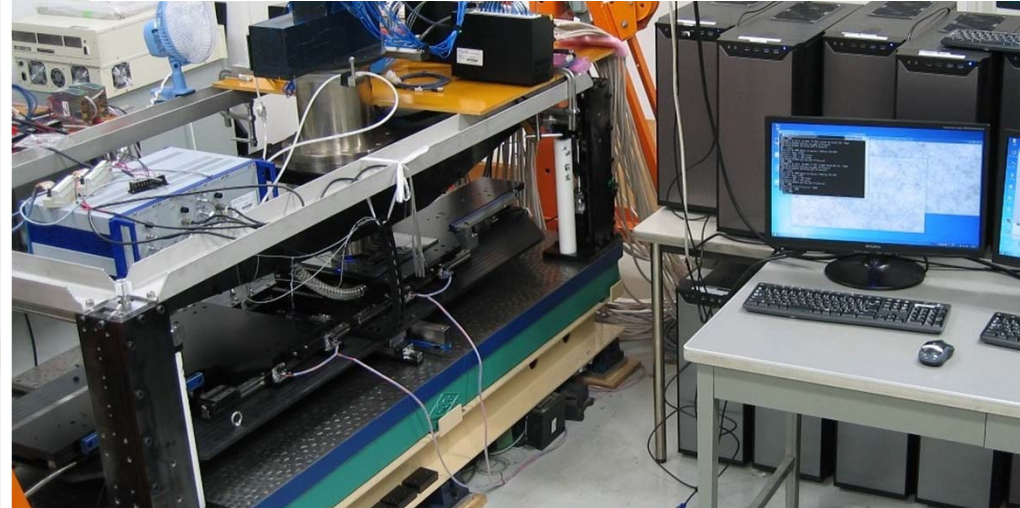
Consists of emulsion films with Small R.L., High spatial resolution

→ Low P threshold, High reliability, High efficiency, Large area

Simple component, Compact, Light, HV free, Low power consumption, Dead time fr

次世代高速飛跡読取装置HTSの開発

現行機 S-UTS 72 cm²/hour $\xrightarrow{\times 100}$ 次世代機 HTS 9000 cm²/hour

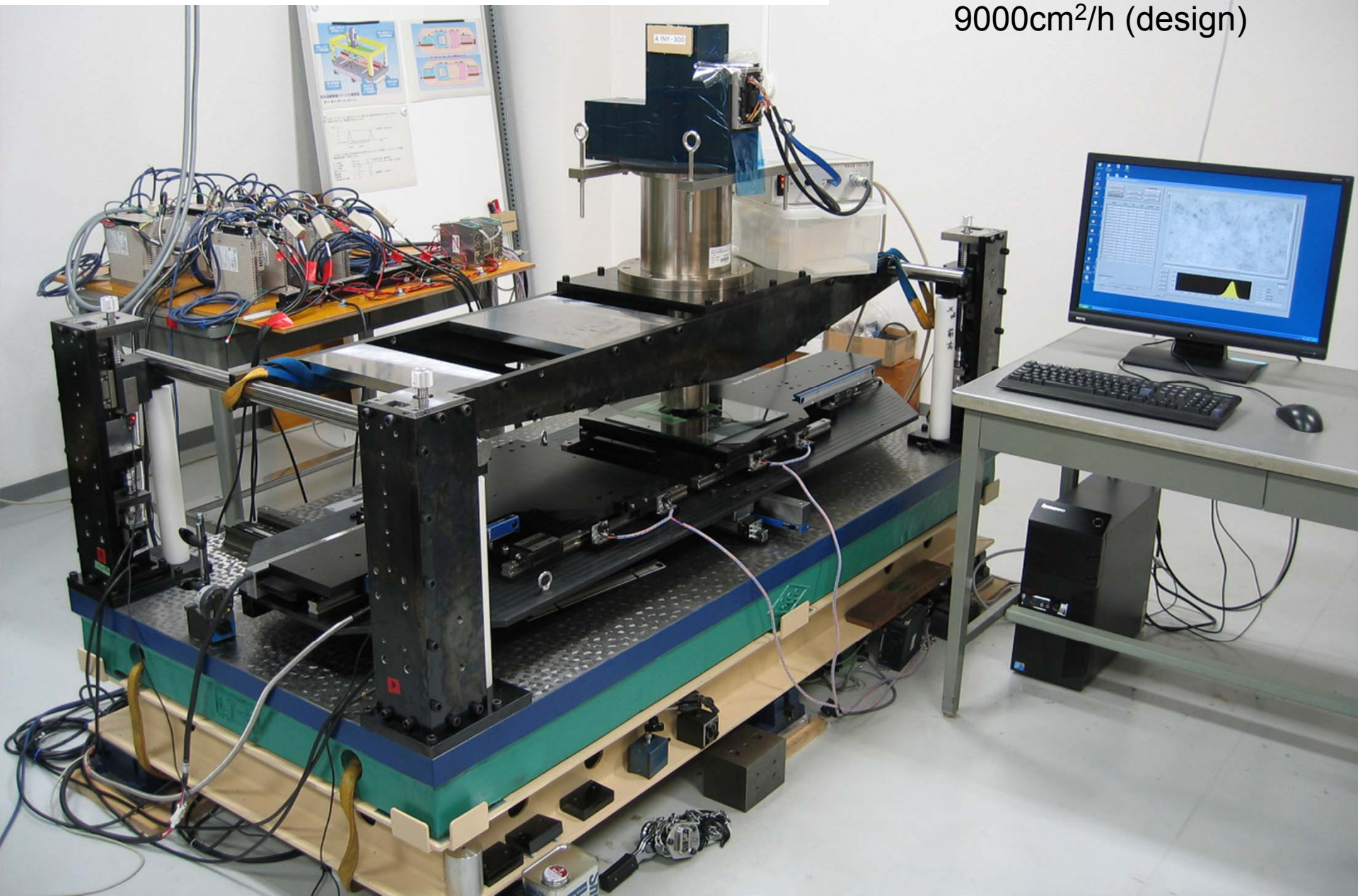


	S-UTS	HTS(現状)	HTS
読取速度	0.0072 平米/時	0.07平米/時	0.9平米/時
GRAINE 2014 フィルム総面積 50平米	600日	60日	6日
GRIANE 本観測 1000平米	12000日	1200日	100日

Automated emulsion read-out system (Nagoya Univ.)

Hyper-TS: Next Generation Read-out system

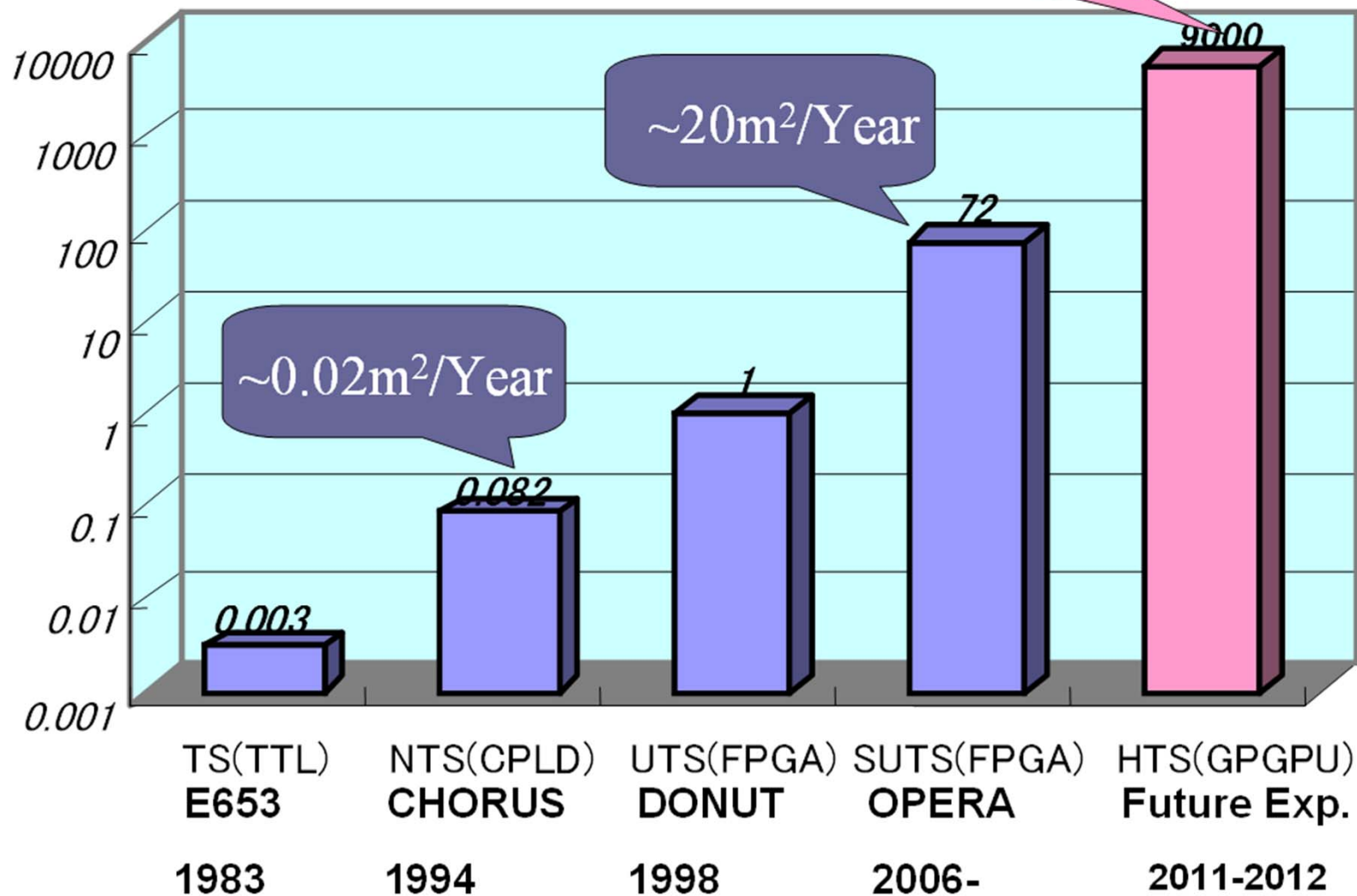
Scanning speed
9000cm²/h (design)



Automated emulsion read-out system (Nagoya Univ.)

Evolution of the Scanning Speed

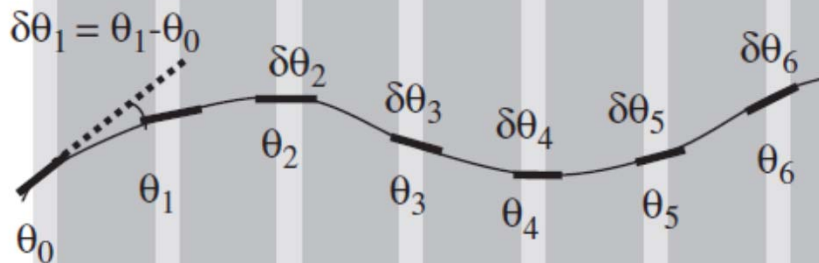
Speed in cm^2/h



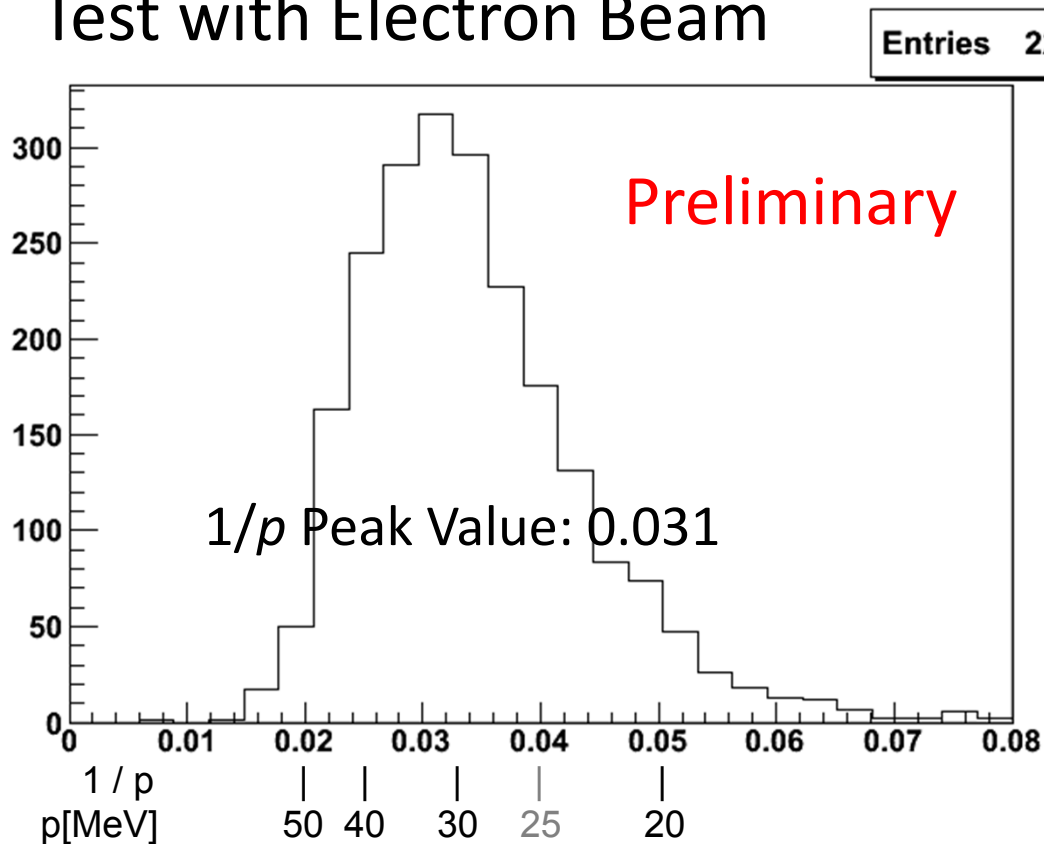
Momentum Measurement by MCS

$$(\delta\theta)_{RMS} = \frac{13.6\text{MeV}}{\beta cp} \sqrt{x/X_0 [1 + 0.038 \ln(x/X_0)]}$$

Angular Method



Test with Electron Beam



Reconstructed momentum
 $32.1^{+7.6}_{-8.8}$ [MeV/c]
(preliminary)



Day Time Star Camera

- **Optics Filter**

Schneider Optics B+W091

- **Camera Lens**

Nikon AF Nikkor 85mm F1.4D

- diameter: 60.7mm
- focal length: 85mm

- **CCD Camera**

HAMAMATSU C3077-79

(near-IR camera)

- pixels: 640 × 480

- **CPU board**

ADVANTECH PCM-3362

- CPU: Intel Atom N450 1.66GHz

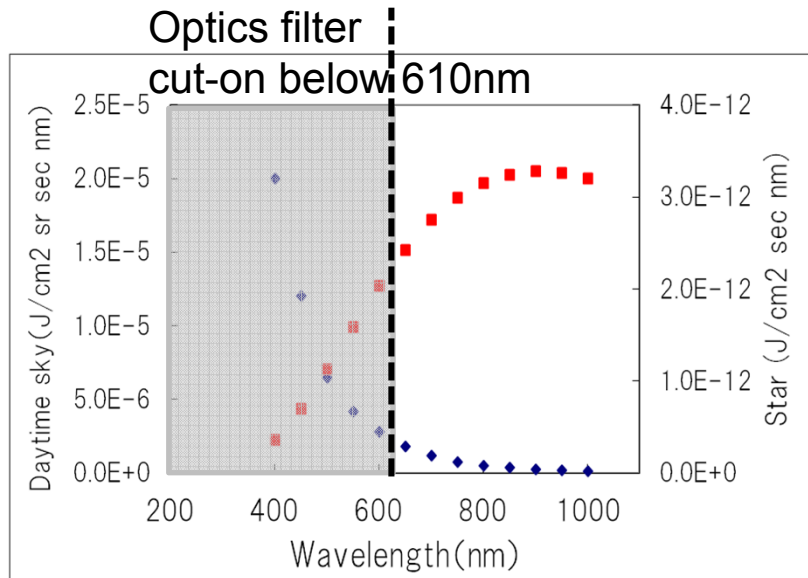
- **Video Capture board**

Sensory Frame Grabber Model 311

- ADC : 8bit
- Frame rate: 30FPS

- **SSD(128GB)**

TOSHIBA SSDN-ST128H



- ◆: Daytime sky BG (Dietz et al., 2002)
- : Star spectrum (M-type: 3200K)

Field of View:

5.9deg(H) × 4.5deg(V)

Limiting magnitude: 6

Monitoring accuracy: 0.16mrad

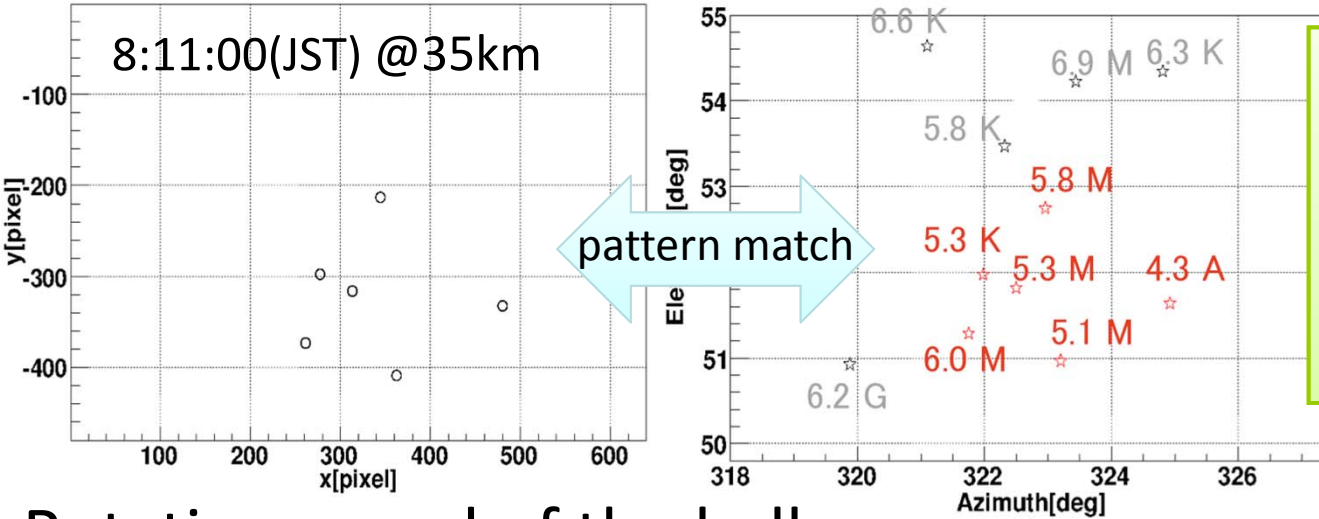
K.Ozaki, et al., Proc. of Balloon Sympo., isas12-sbs-022 (in Japanese)

Attitude analysis

K. Ozaki et al.,
Proc. of Balloon Sympto.,
isas12-sbs-022

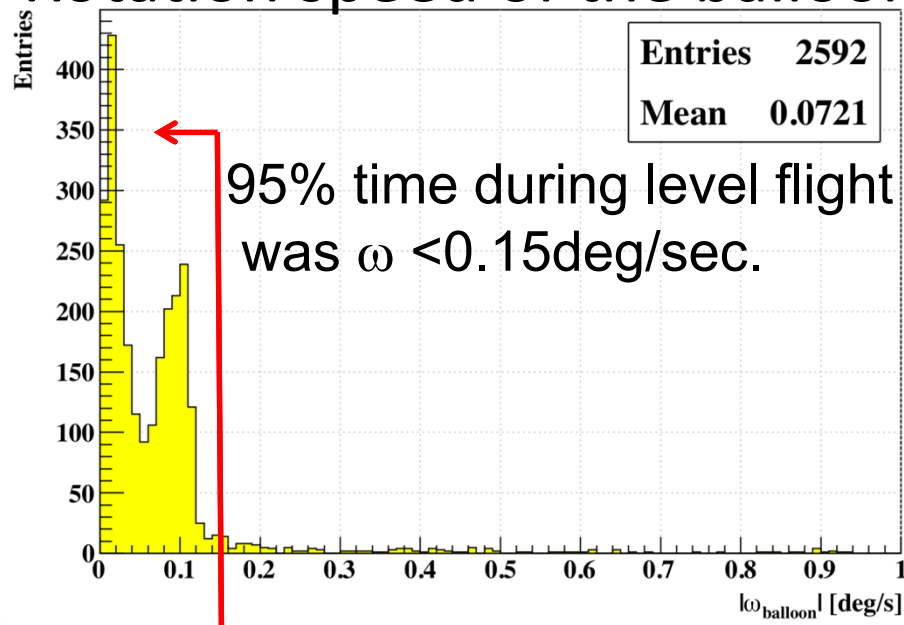
Daytime star camera view

Star catalog data



Working rate: 74 %
Monitoring
accuracy: < mrad
Elevation < 0.25mrad
Azimuth < 0.44mrad

Rotation speed of the balloon



It is important to decide telescope attitude to celestial coordinate better than emulsion angular resolution(0.08deg).

We confirmed attitude decision accuracy was $< \omega \sigma_t < 0.02 \text{deg.}$

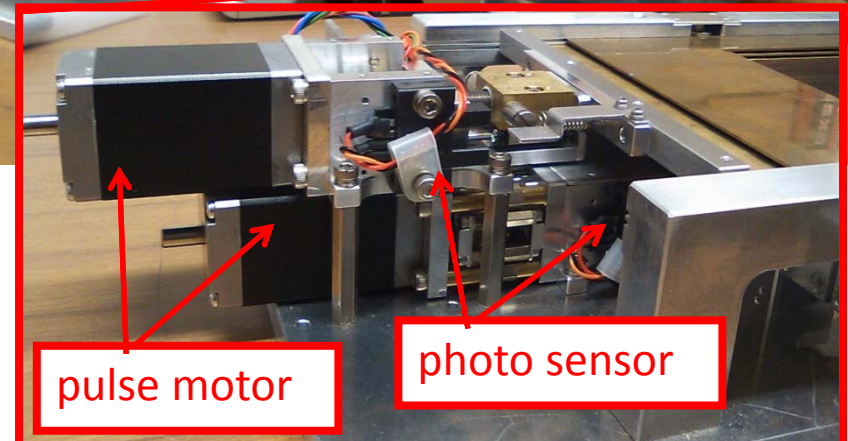
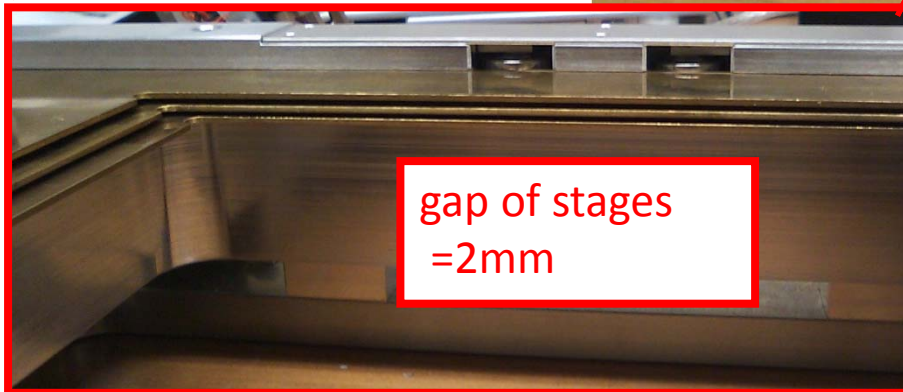
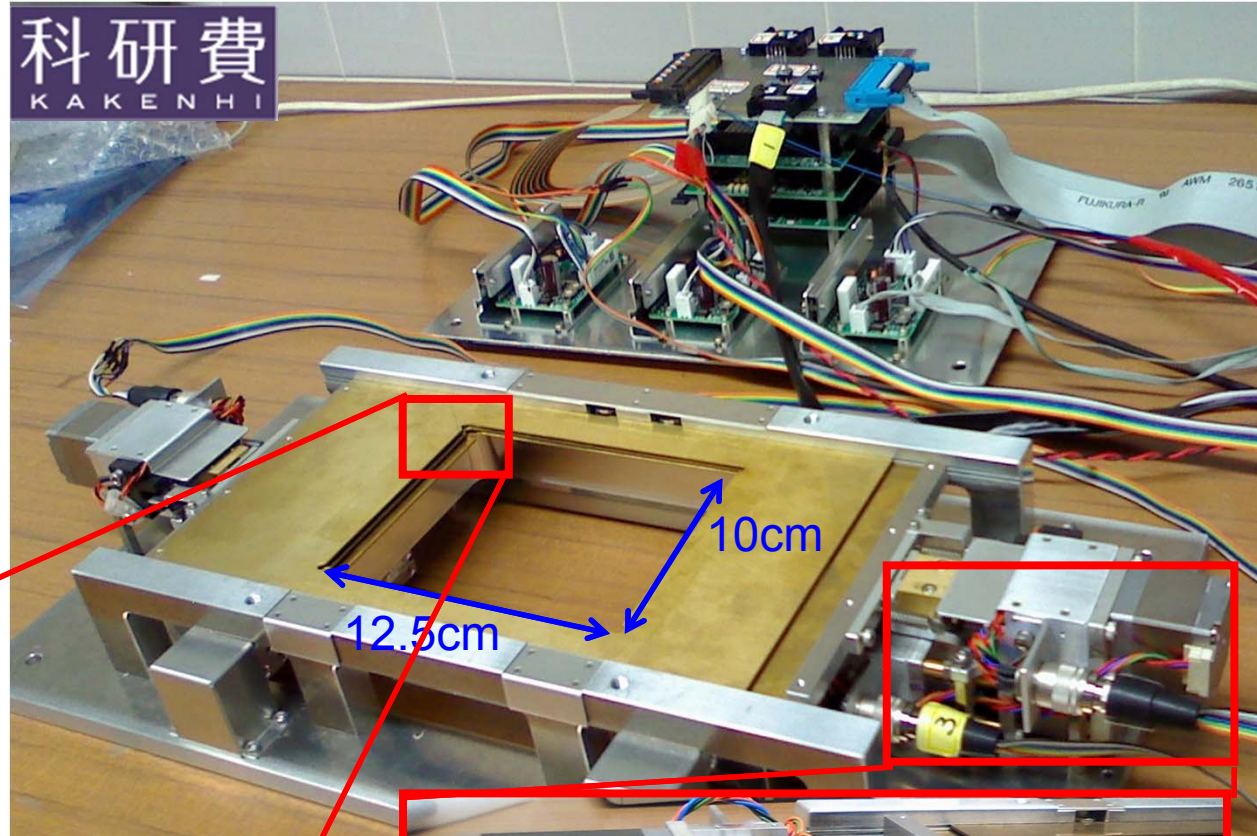
Multi-stage Shifter (Time Stamper)

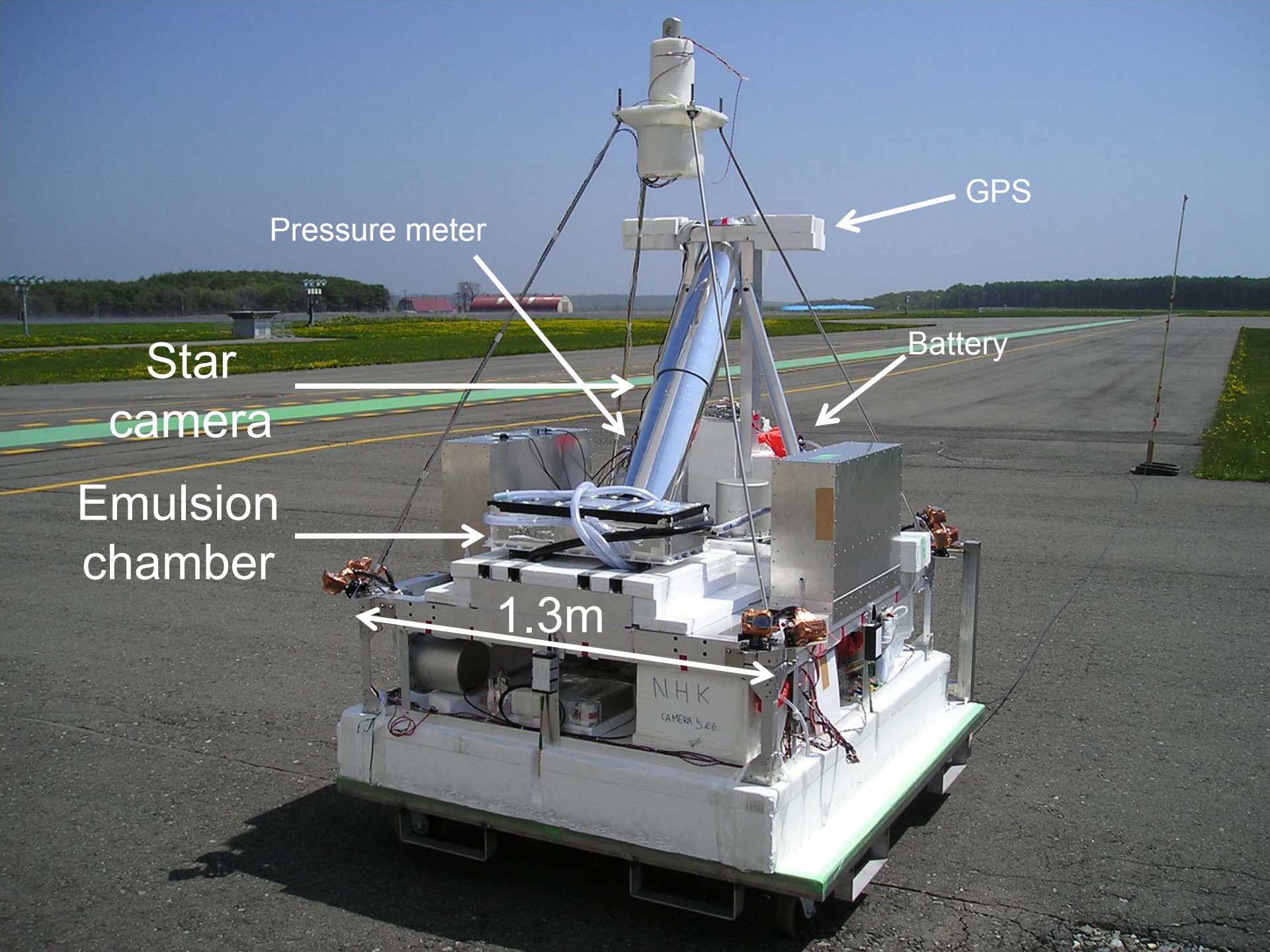
Co-developed with
Mitaka Kohki Co., Ltd.

Weight : 5 kg

Power Cons.: 20 W

Reproducibility: $1\mu\text{m}$





GPS

Pressure meter

Battery

Star
camera

Emulsion
chamber

1.3m

NHK
CAMERA 5.0

Emulsion chamber

Aperture area : 12.5cm x 10cm

◆ Flatness compensation films

OPERA film x 2

◆ Converter

102 emulsion films, 91 copper foils (50 μ m)
1.1kg, 35.0mm, 0.54Xo($\epsilon_{\text{conv}} = 34\%$)

OPERA film x 10 (go-ban part)

OPERA film x 88 + Copper foil x 88

New type gel film x 4 + Copper foil x 3

-Target & Detector

-Precise measurement of incident direction

-0.08deg@1-2GeV, 0.93deg@100MeV

-Measurement of gamma-rays polarization

-Interface of timestamper

-Energy measurement of gamma-rays (<~GeV)

-Momentum measurement of electron pair with MCS

◆ Timestamper

1st : OPERA film x 2

2nd : OPERA film x 2

3rd : OPERA film x 2

New type gel film x 1

◆ Calorimeter

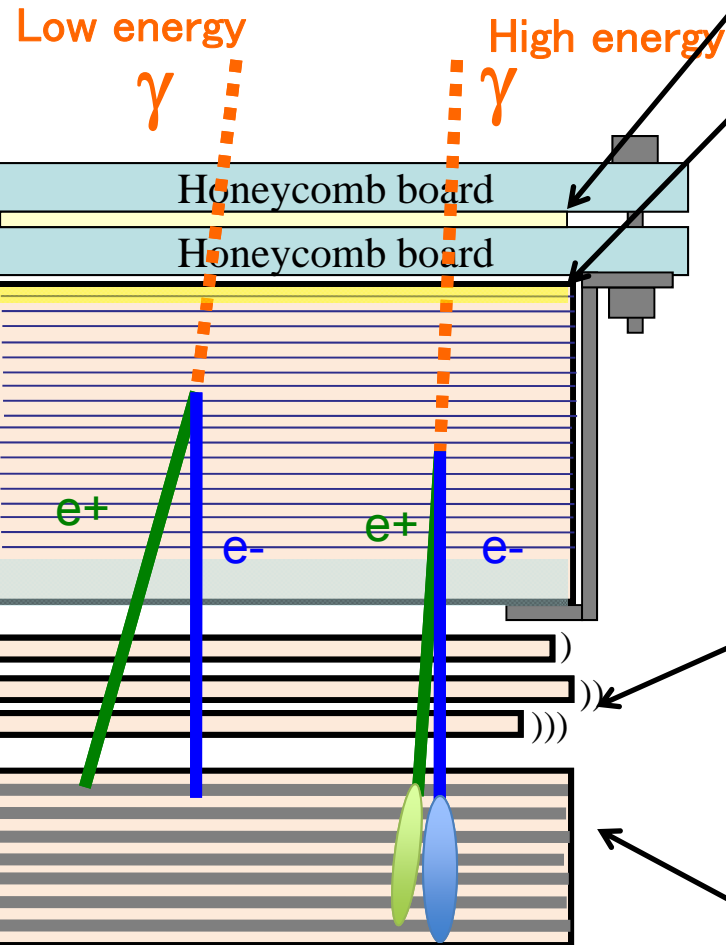
32 emulsion films, 10 (0.5mm) & 17 (1mm) lead plates

3.2kg, 31.9mm, 4.0Xo (Shower Max. @ a few GeV)

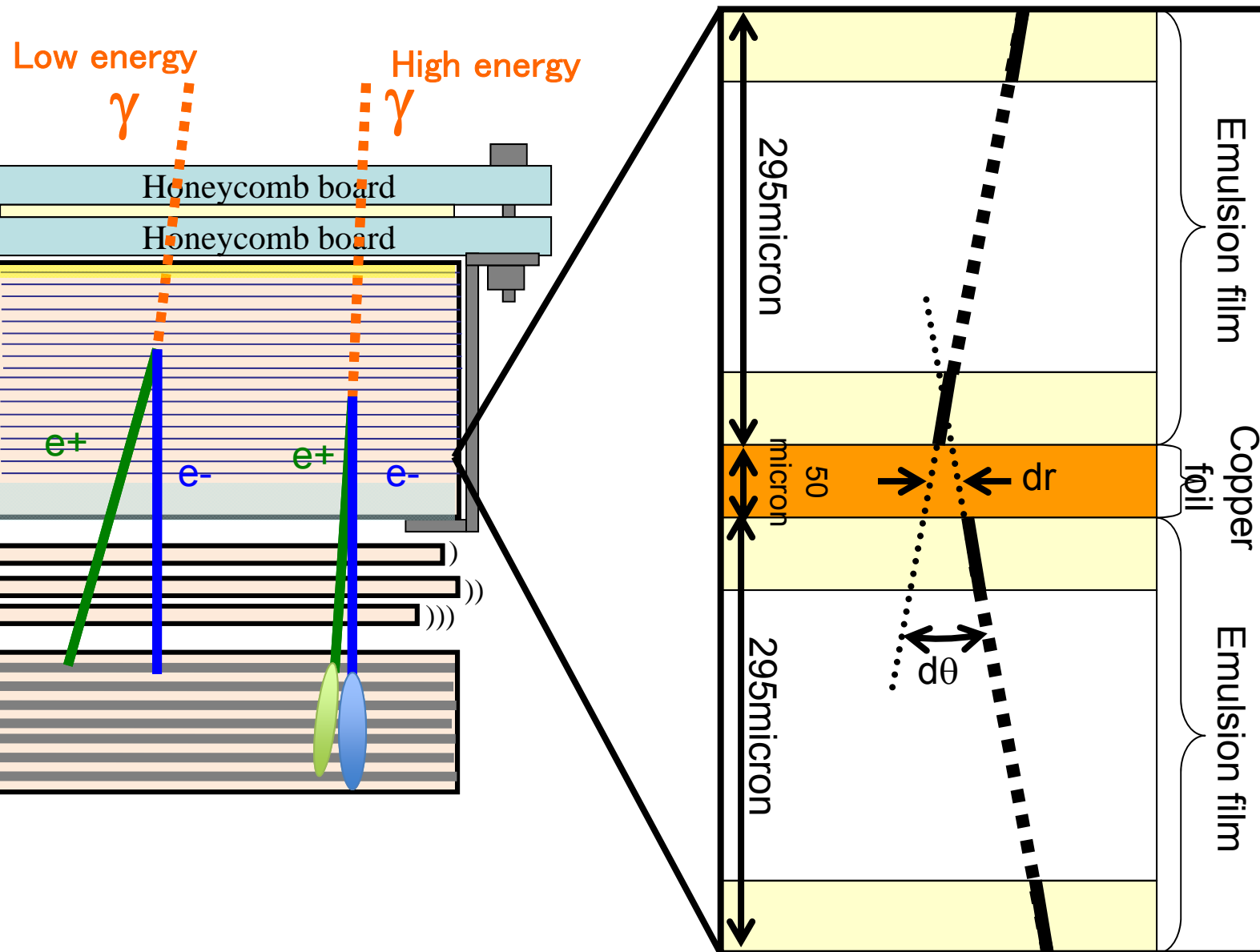
OPERA film x 5 (go-ban part)

(OPERA film + lead plate(0.5mm))x10

(OPERA film + lead plate(1mm))x17



Connection accuracy



Connection accuracy

Film#12-13

$\tan\theta < 0.1$

