The 3rd KMI International Symposium
2017/Jan/5-7

GRAINE project:
Cosmic Gamma-ray Observation by Balloon-Borne Telescope with Nuclear Emulsion

GRAINE = Gamma-Ray Astro-Imager with Nuclear Emulsion

Shigeki Aoki (Kobe University)
for GRAINE collaboration
Kobe University,
Nagoya University,
ISAS/JAXA,
Aichi University of Education,
Okayama University of Science

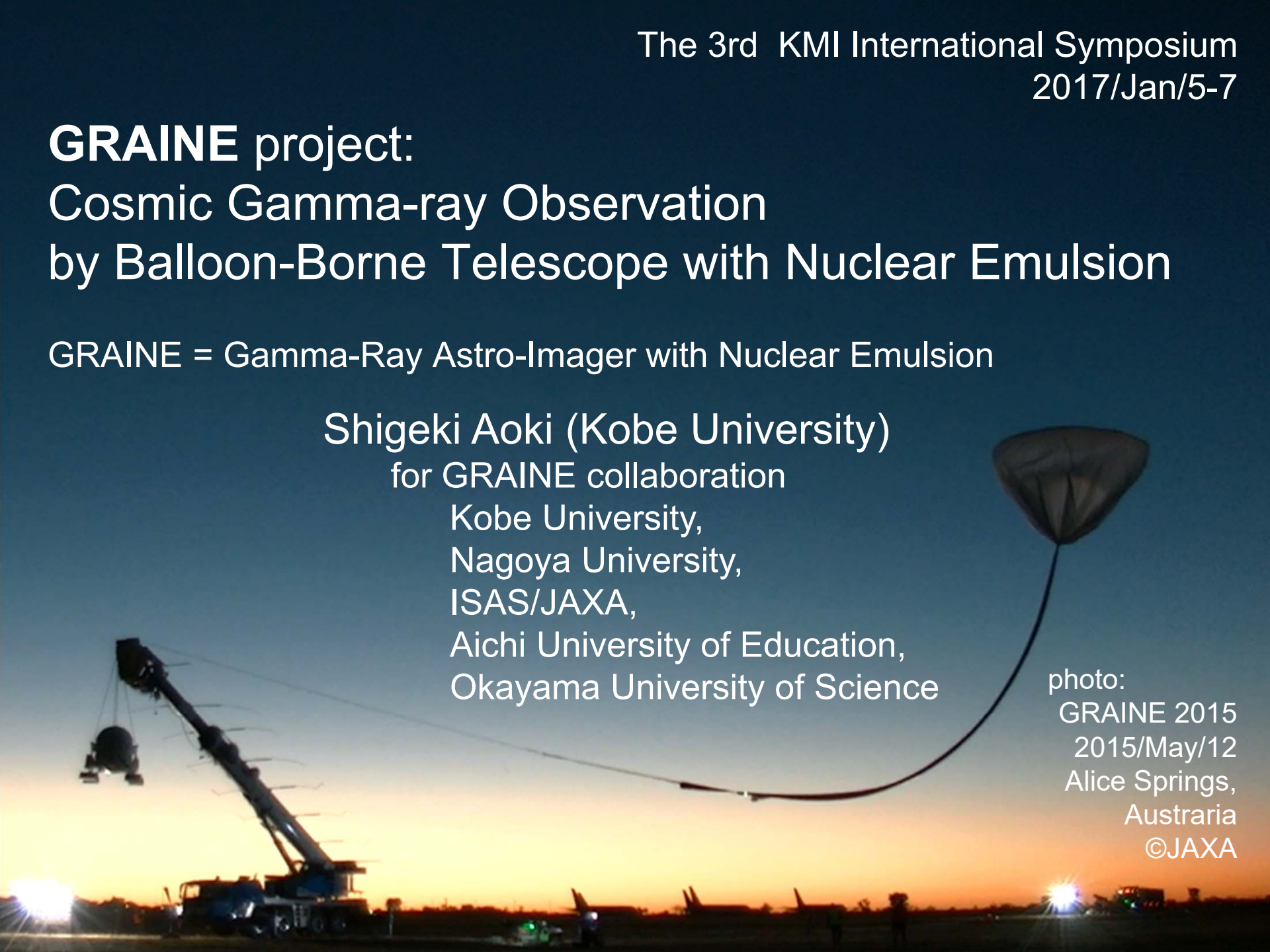
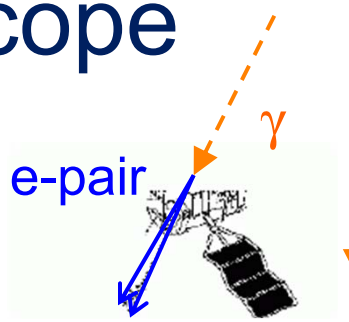


photo:
GRAINE 2015
2015/May/12
Alice Springs,
Austraria

Gamma-ray Telescope



FERMI

0.02-100 GeV

γ

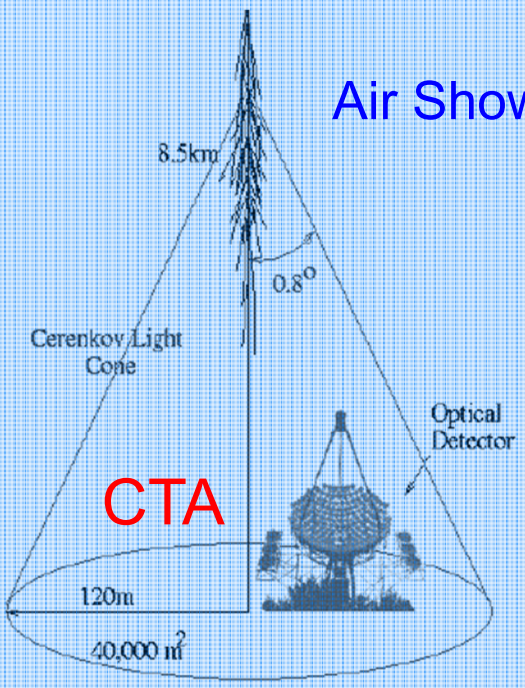
> 0.1 TeV

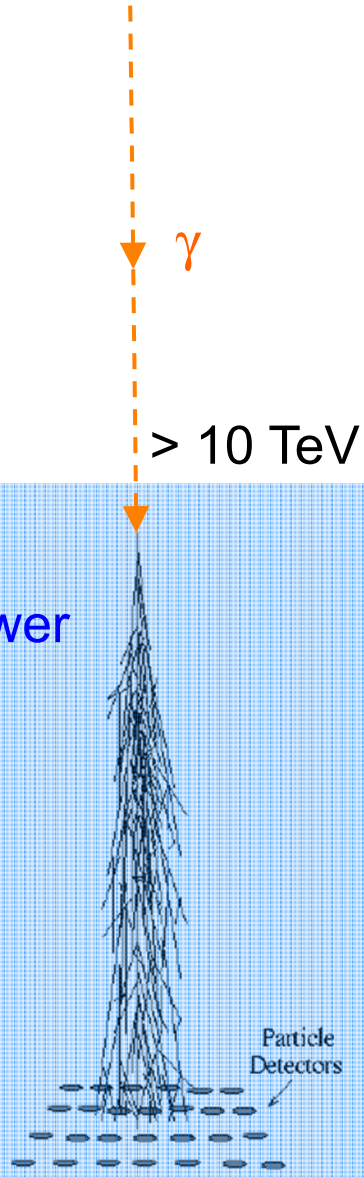
γ

> 10 TeV

Atmosphere

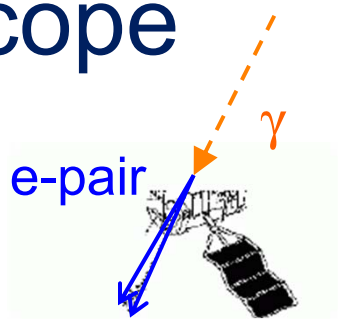
Air Shower





© http://astronomy.nmsu.edu/tharriso/ast536/ast536lecture3.html

Gamma-ray Telescope

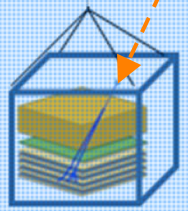


FERMI

0.02-100 GeV

γ

γ



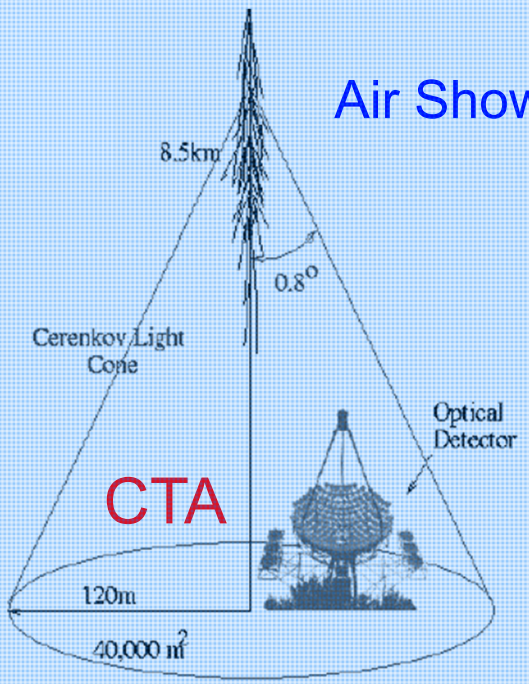
GRAINE

Atmosphere

> 0.1 TeV

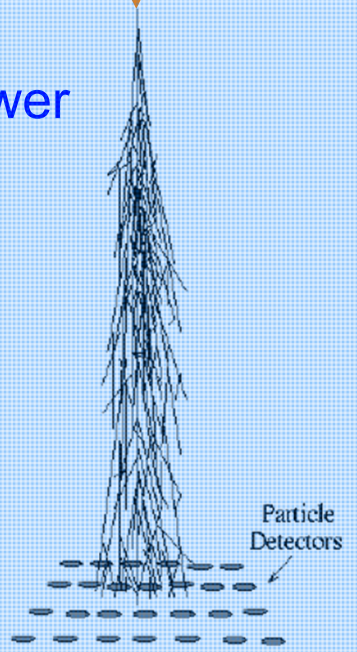
γ

Air Shower



> 10 TeV

γ



© http://astronomy.nmsu.edu/tharriso/ast536/ast536lecture3.html

Fermi's Five-year View of the Gamma-ray Sky (E > 1GeV)

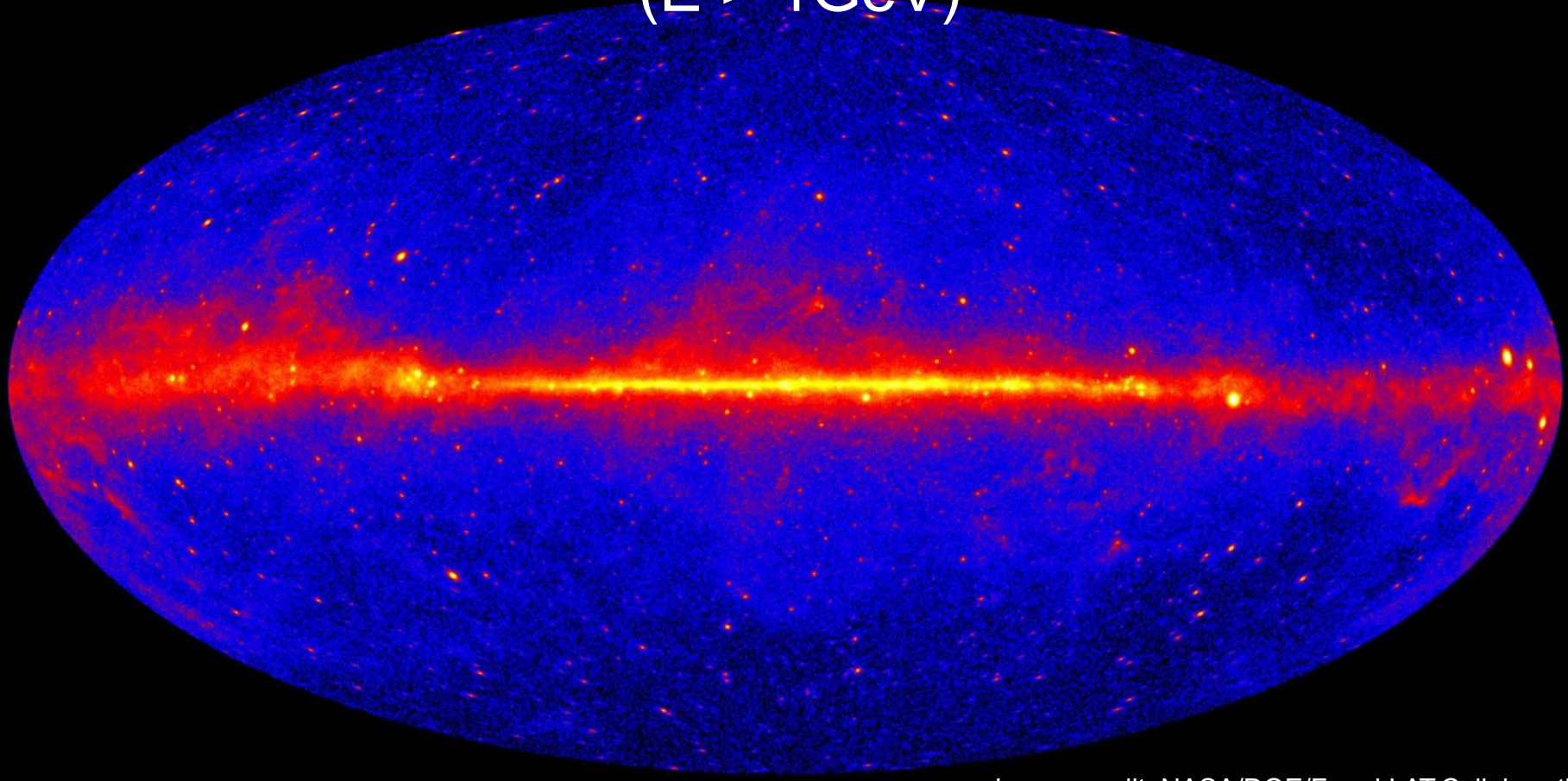
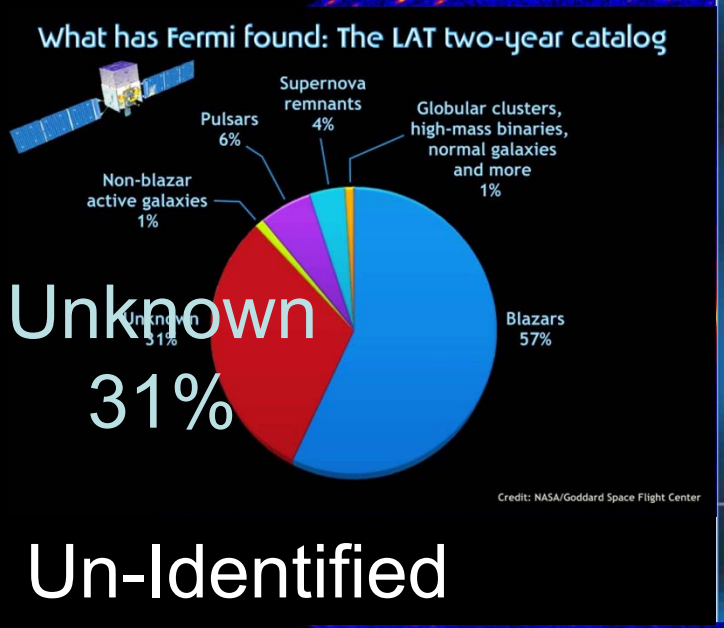


Image credit: NASA/DOE/Fermi LAT Collaboration

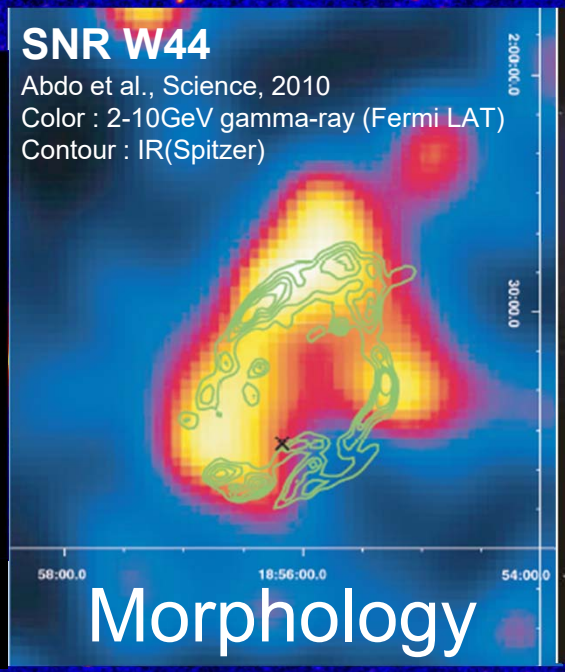
>3000 sources (3FGL)

Fermi's Five-year View of the Gamma-ray Sky (E > 1GeV)

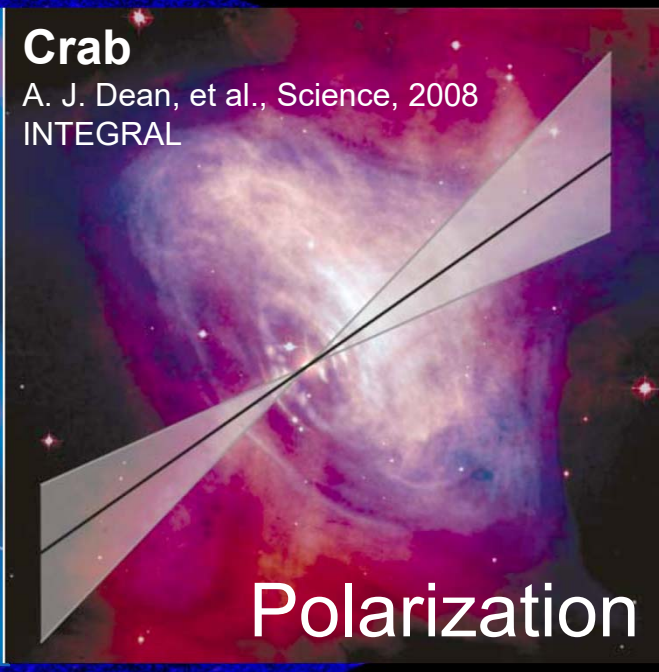


Unknown 31%

Un-Identified



Morphology



Polarization

Image credit: NASA/DOE/Fermi LAT Collaboration

>3000 sources (3FGL)

Nuclear emulsion

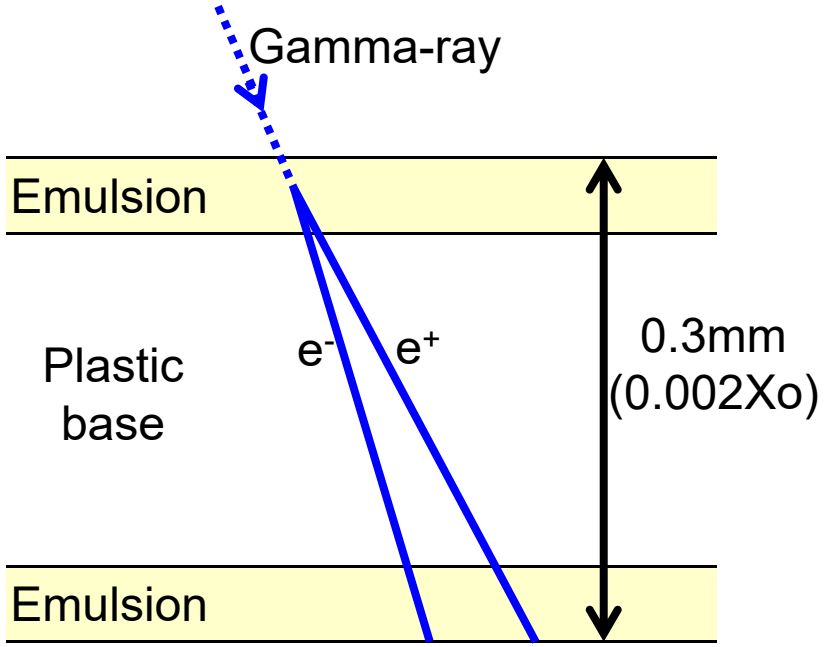
Microscopic view
10micron

Gamma-ray

$e^{+/-}$

$e^{-/+}$

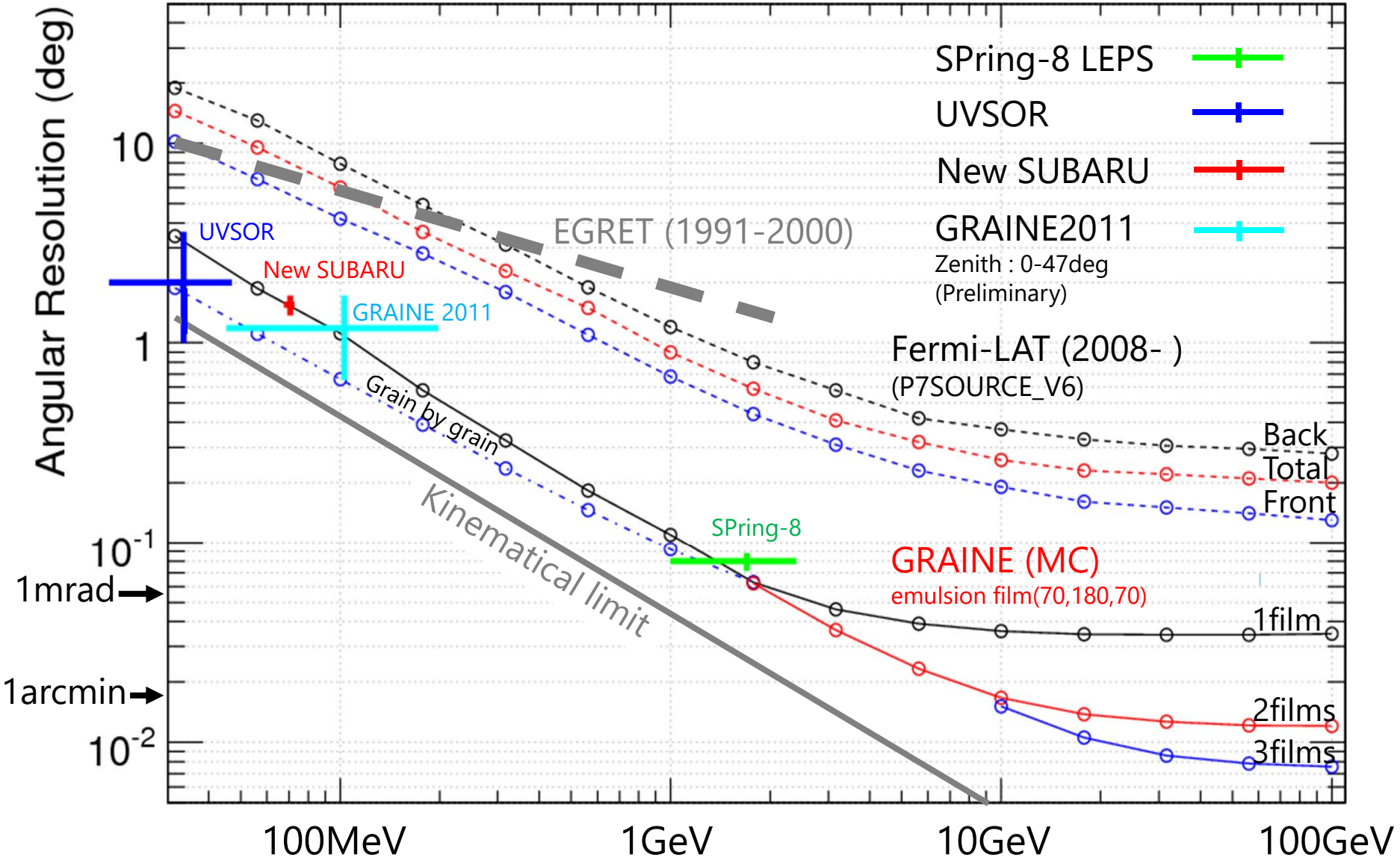
Cross sectional view of an emulsion film



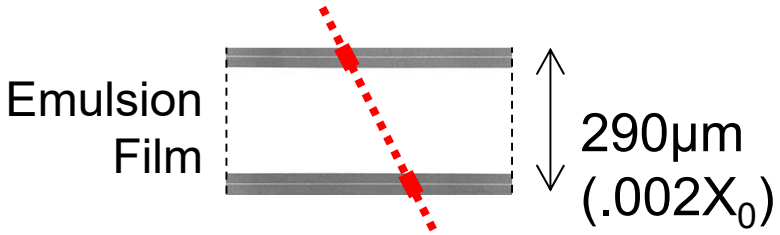
Powerful tracking device
>High spatial resolution : ~1micron
>Small radiation length : 0.002Xo

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

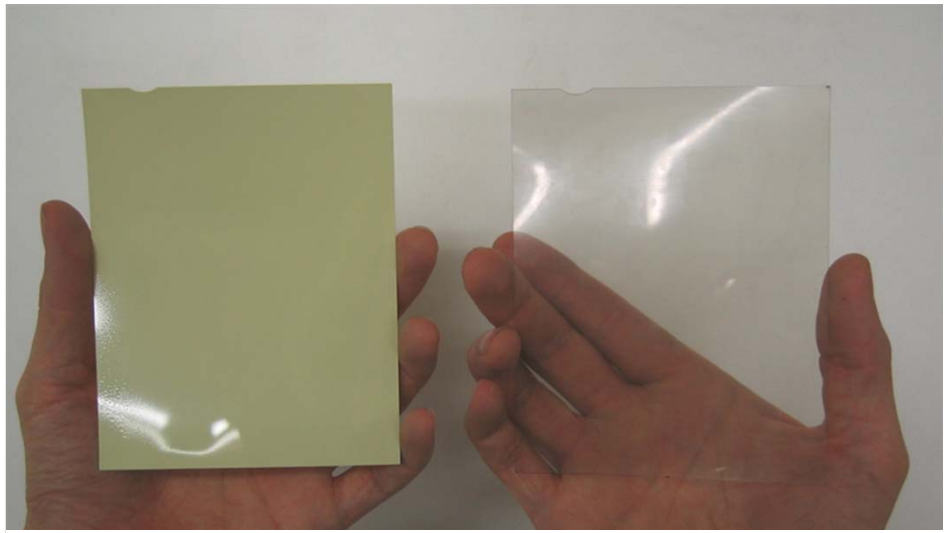
Angular resolution



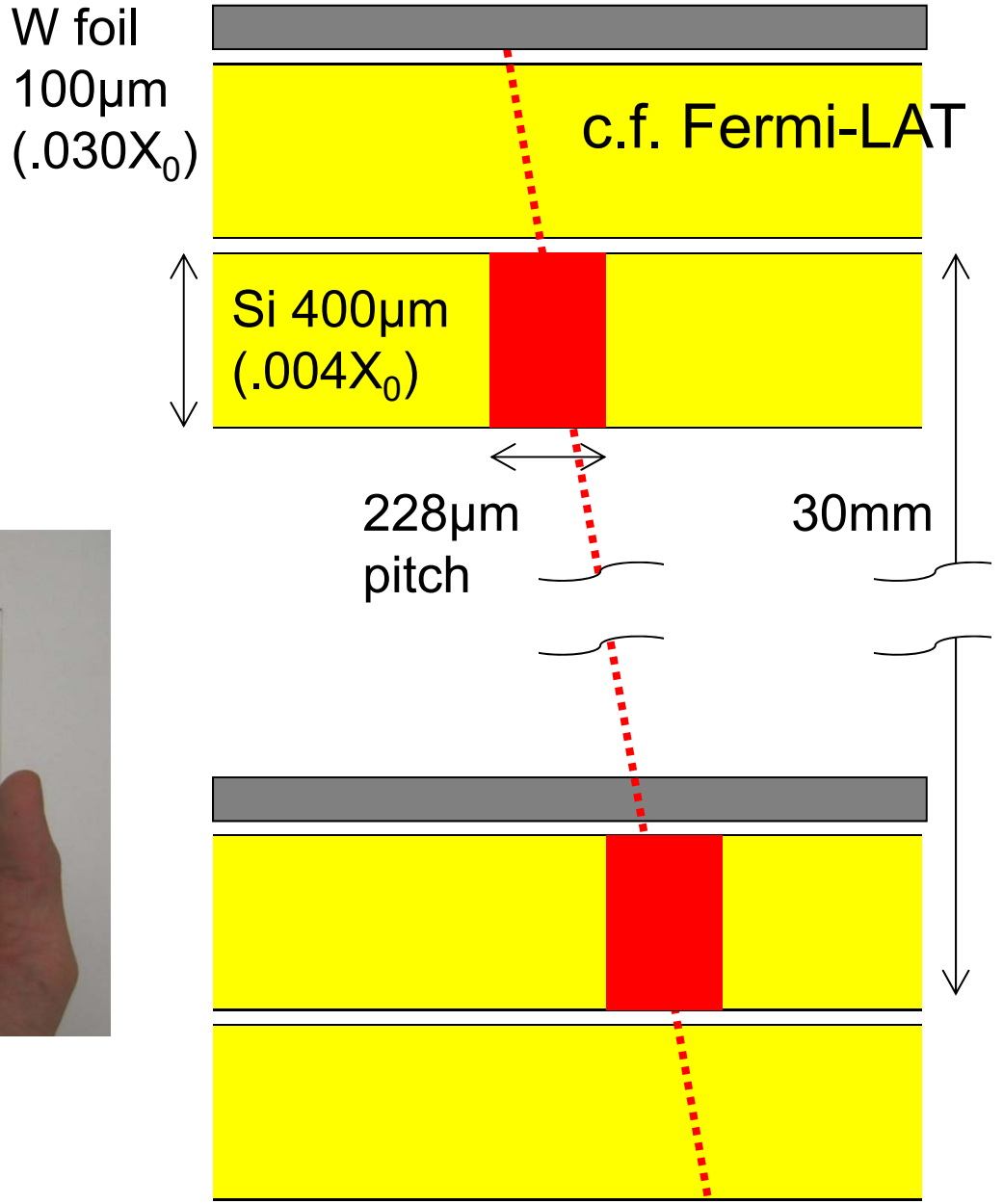
Gamma-Ray Astro-Imager with Nuclear Emulsion



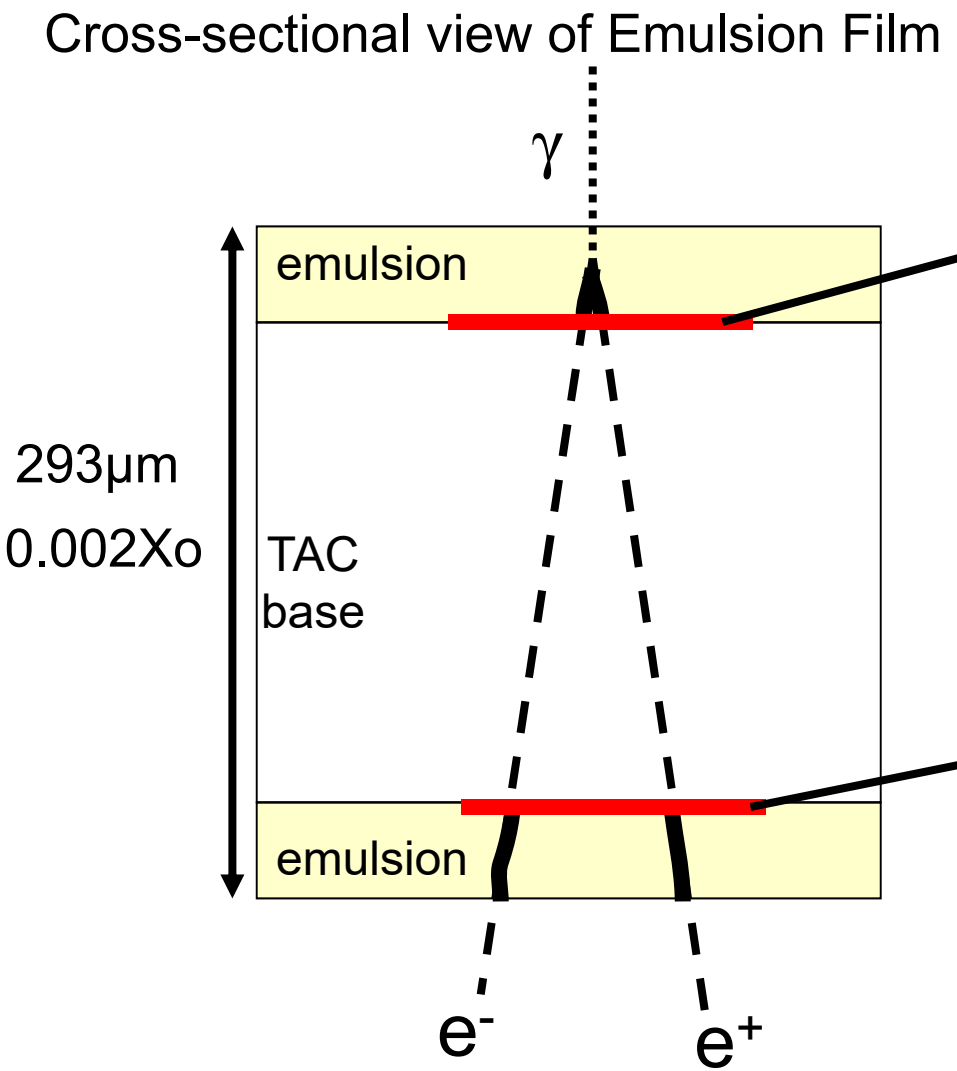
Emulsion Film

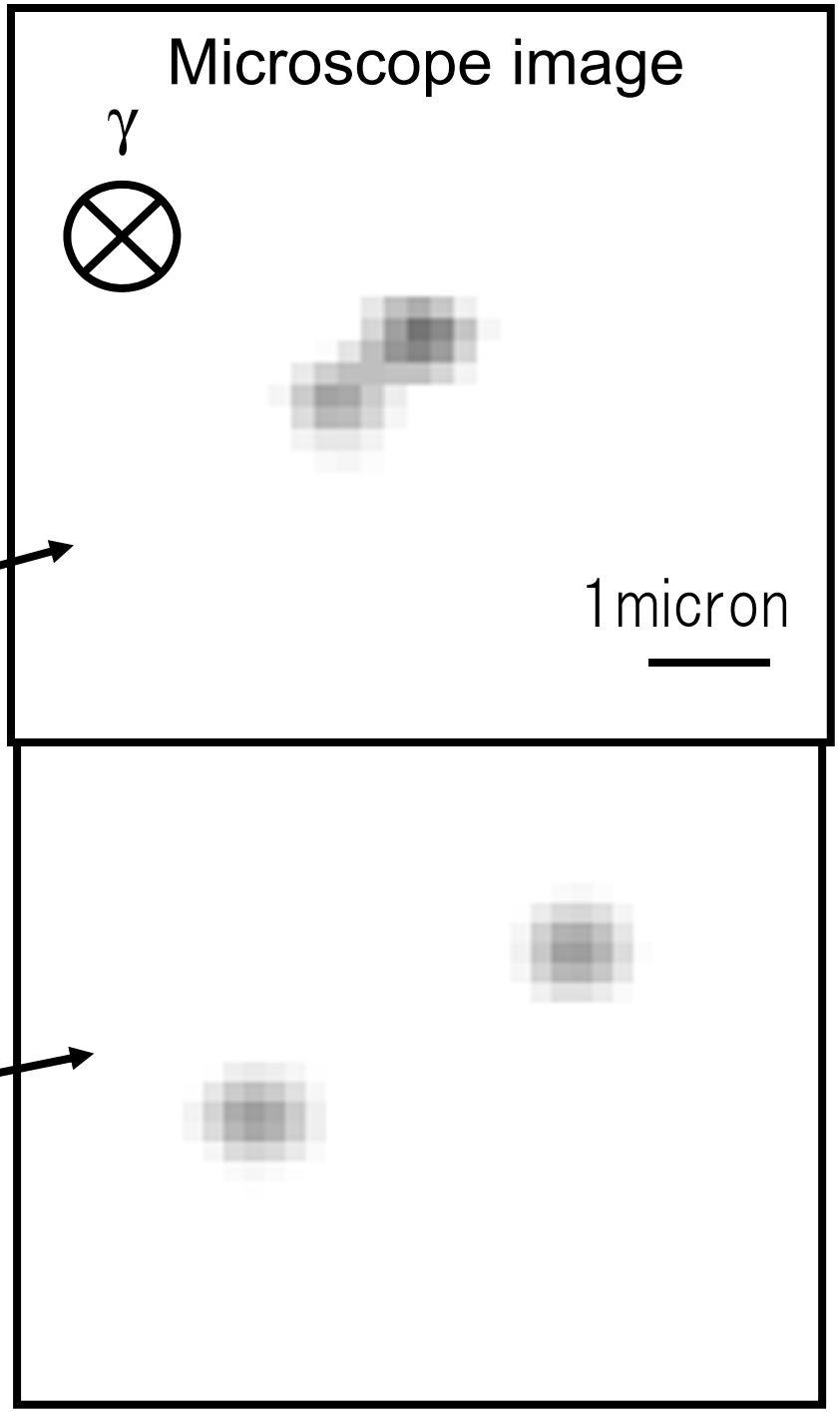


before and after
of development

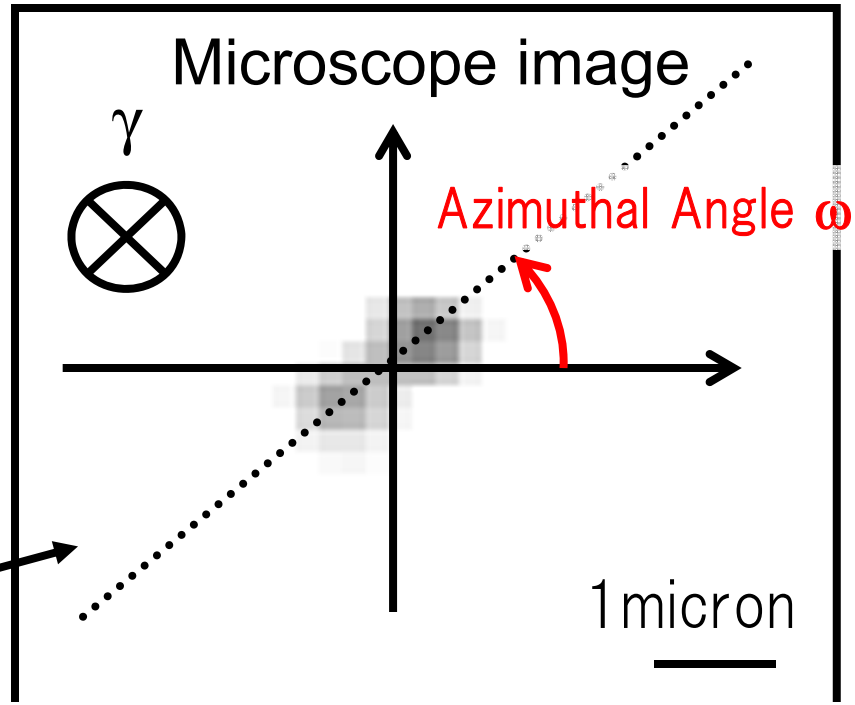


Polarization measurement



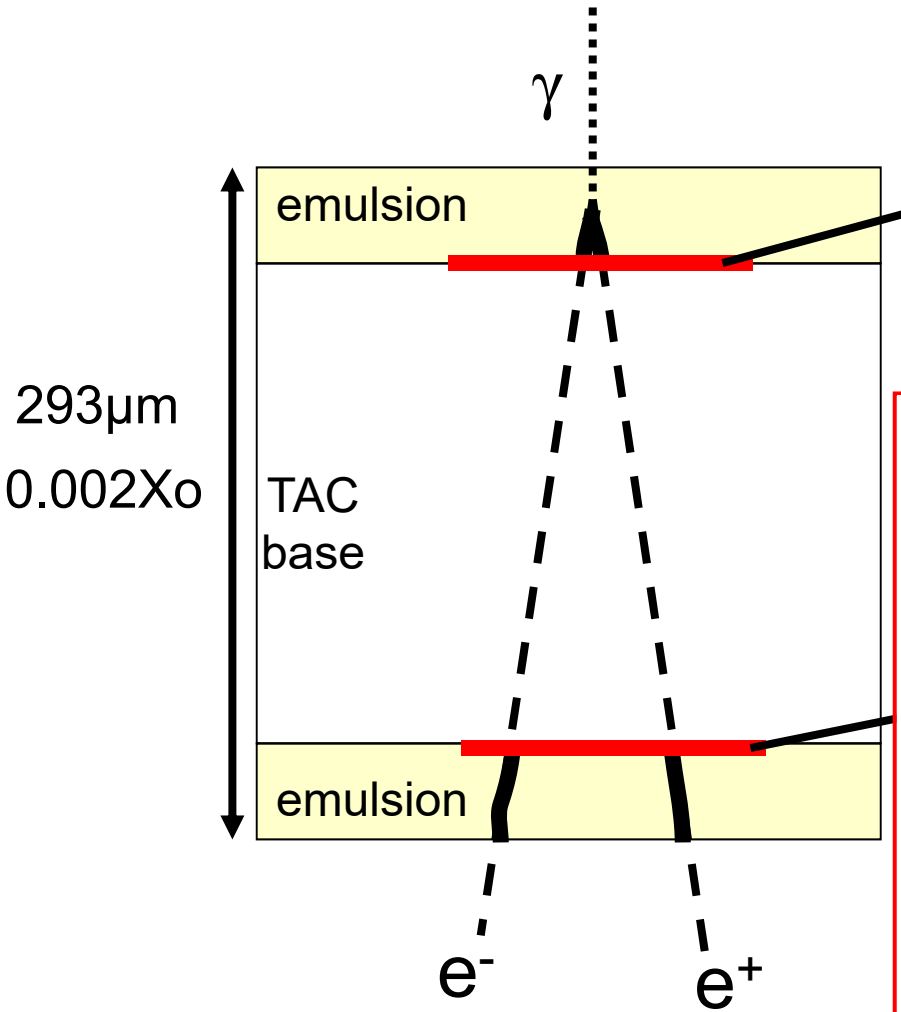


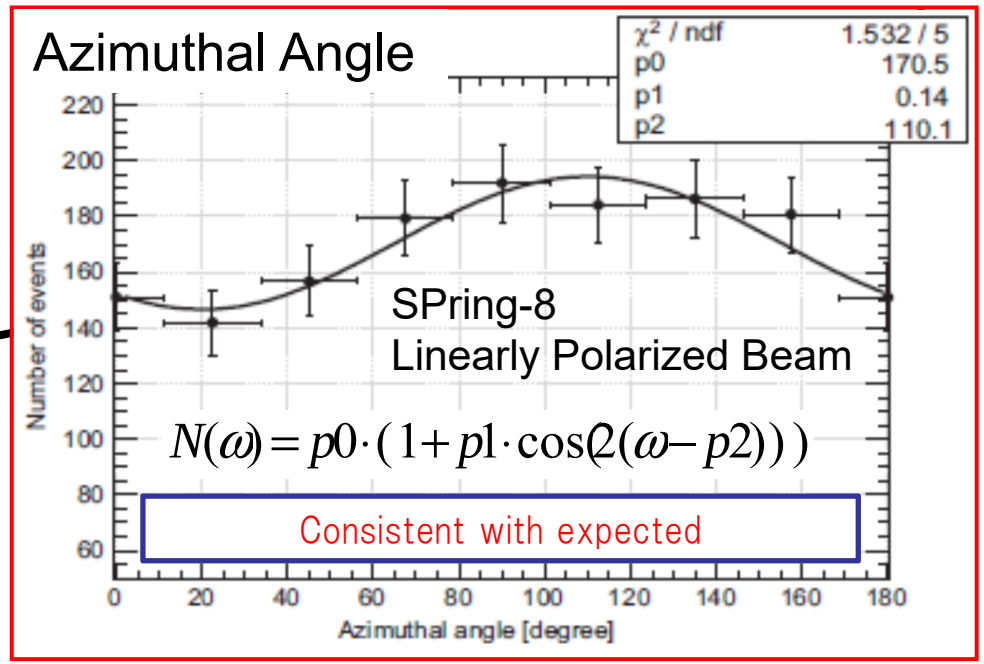
Polarization measurement



K. Ozaki et al. NIM A833 (2016) 165-168

Cross-sectional view of Emulsion Film





GRAINE

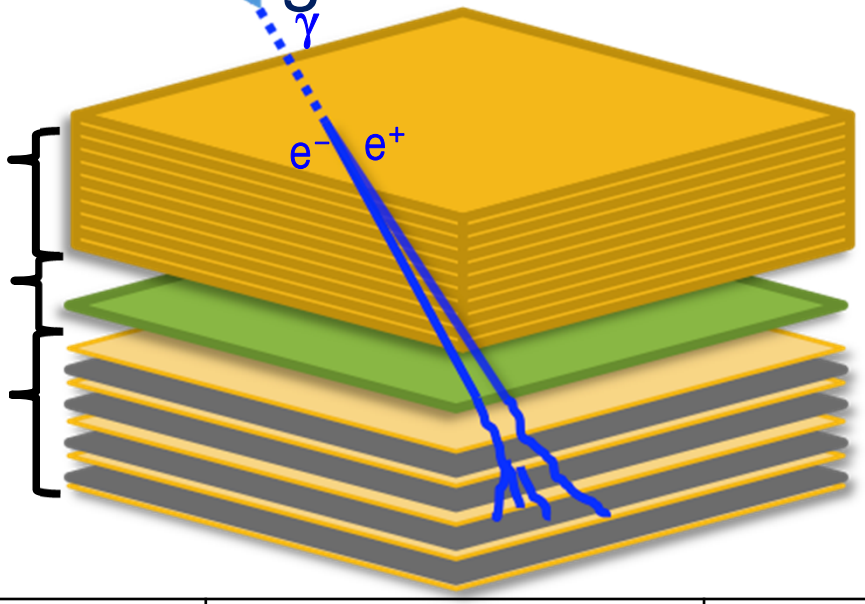
Gamma-Ray Astro-Imager with Nuclear Emulsion

Converter
Emulsion + Copper foil

Timestamper
Multi-stage shifter

Calorimeter
Emulsion + metal plate

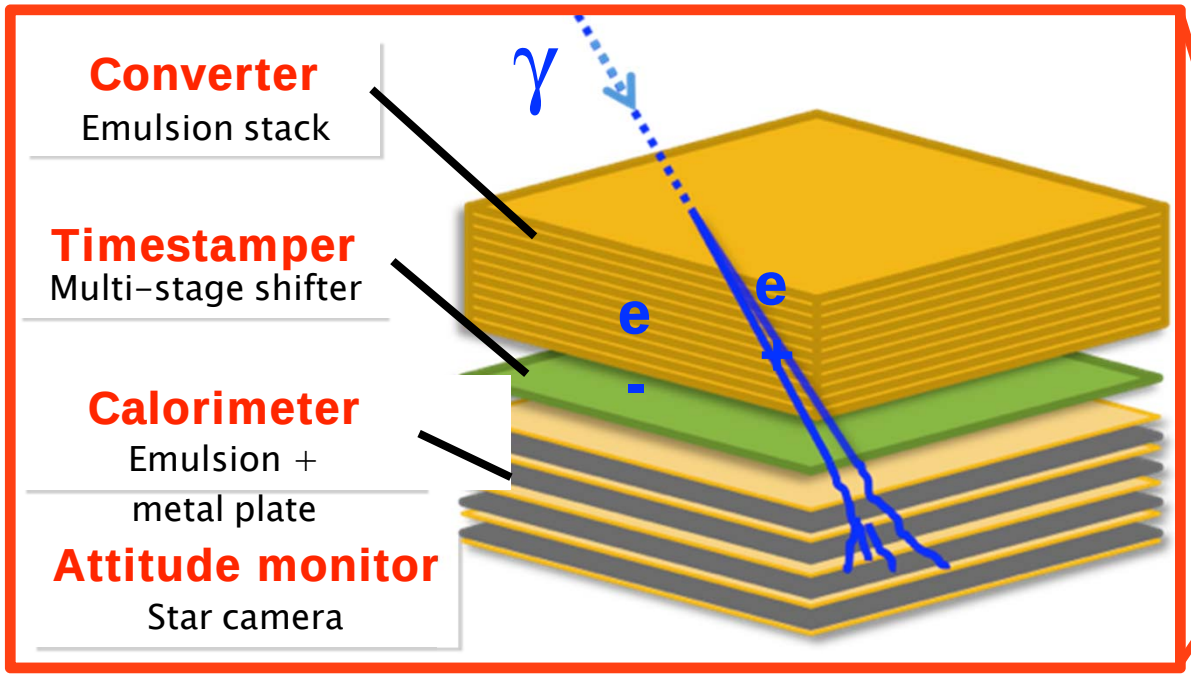
Attitude monitor
Star camera



∗ $10m^2 * \varepsilon_{trans} * \varepsilon_{conv} * \varepsilon_{det}$

	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

Emulsion gamma-ray Telescope



Balloon-borne, Large Area Telescope

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

Flow of experiment

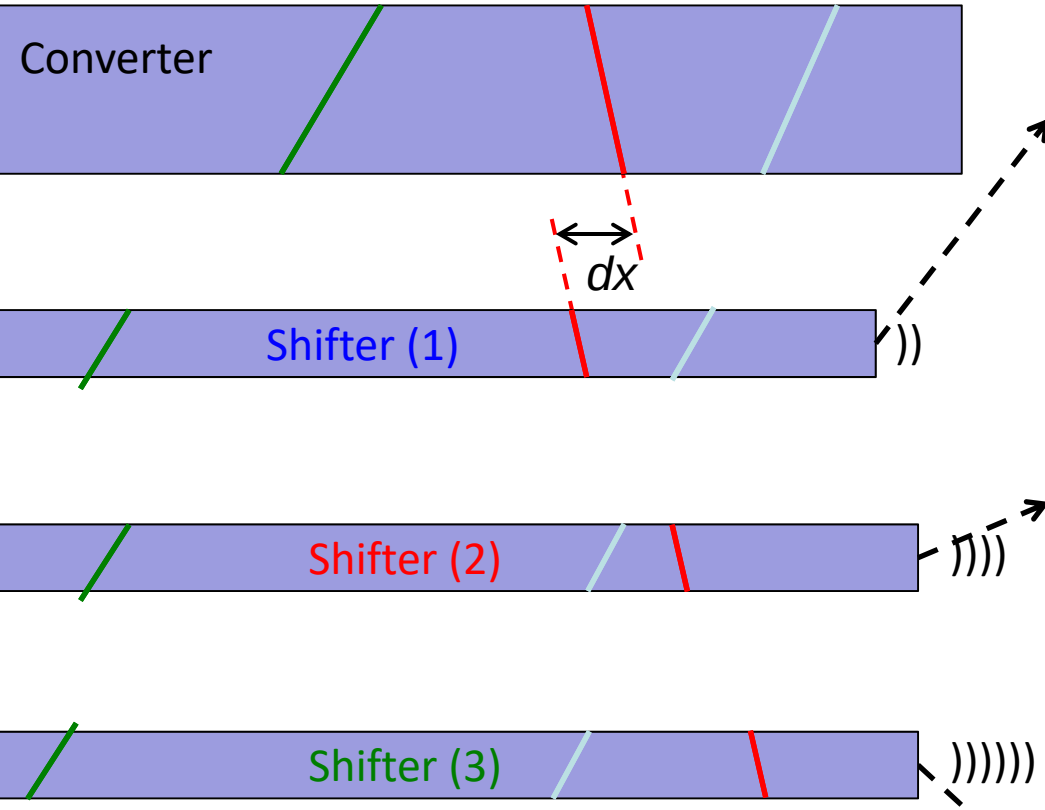
Detector preparation ← **Analysis** ← **Scanning (2nd data taking)**

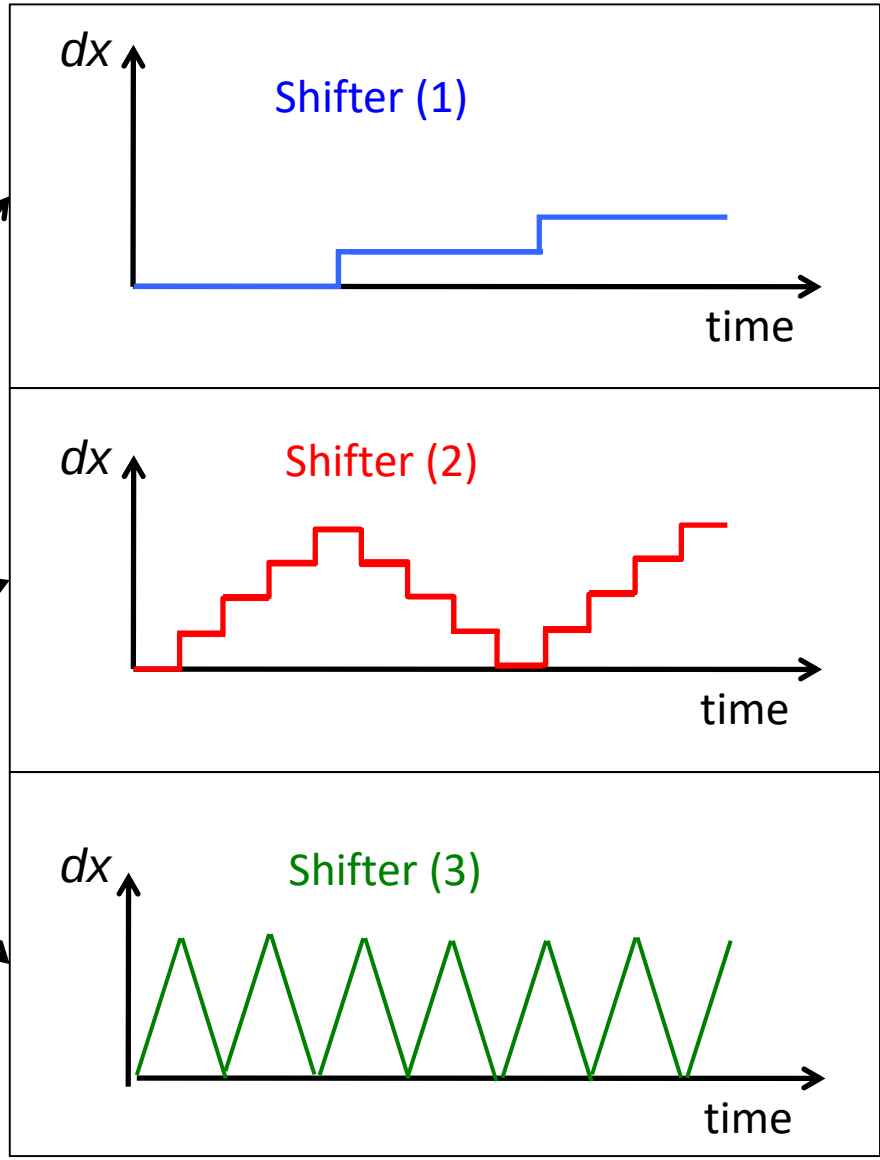
↓

Observation(balloon flight)
several days - 1 week → **Recovery of detector** ↑

Multi-stage shifter
(time stamper)

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

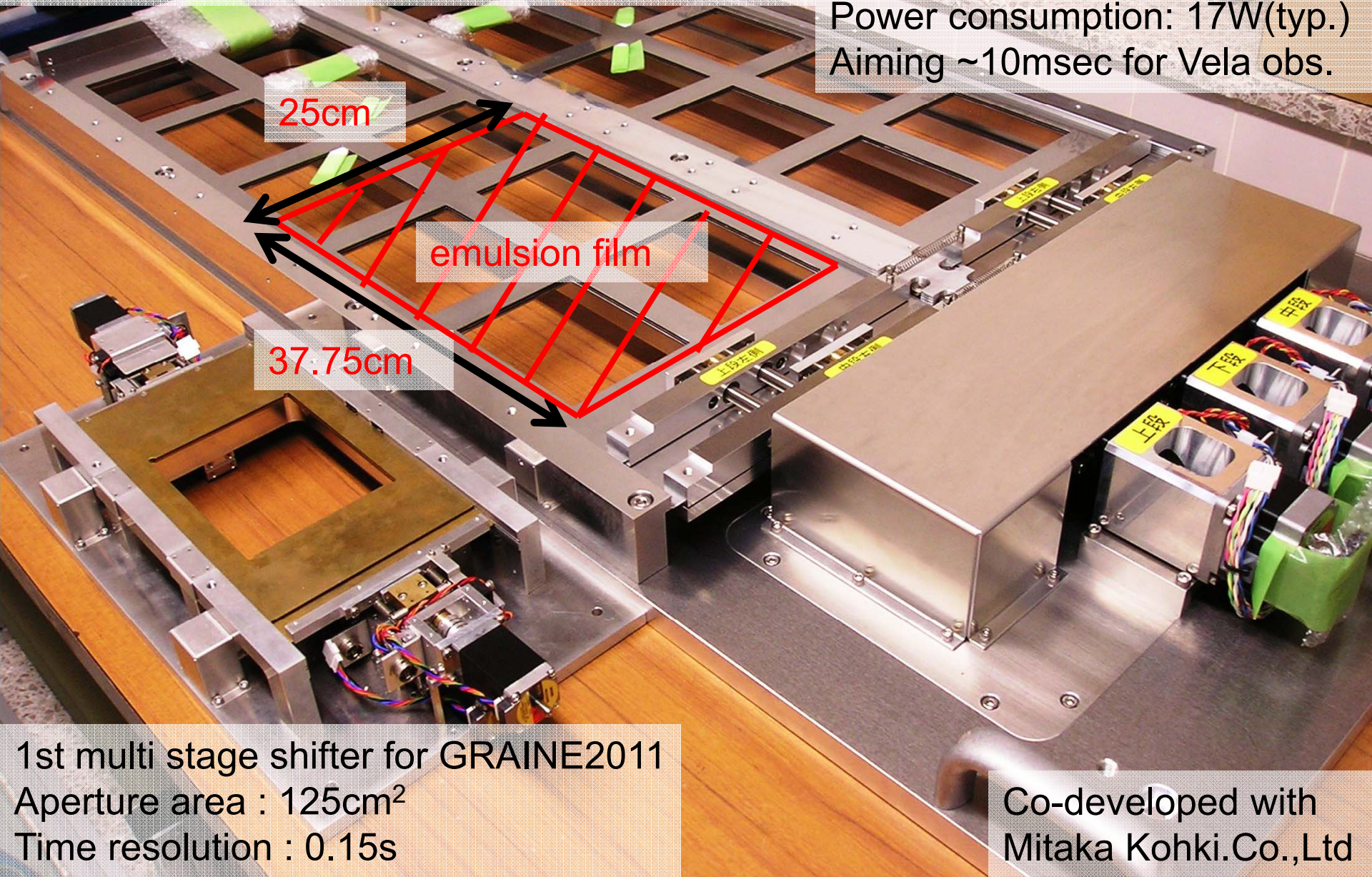




Simple
Compact
Light
HV free
Low power consumption
Dead time free

2nd multi stage shifter
for GRAINE2015

Aperture area: 3600cm^2
W66cm×D145cm×H10cm
Weight： 65kg
Power consumption: 17W(typ.)
Aiming ~10msec for Vela obs.



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

Co-developed with
Mitaka Kohki.Co.,Ltd

GRAINE roadmap (R&D has started in 2004)

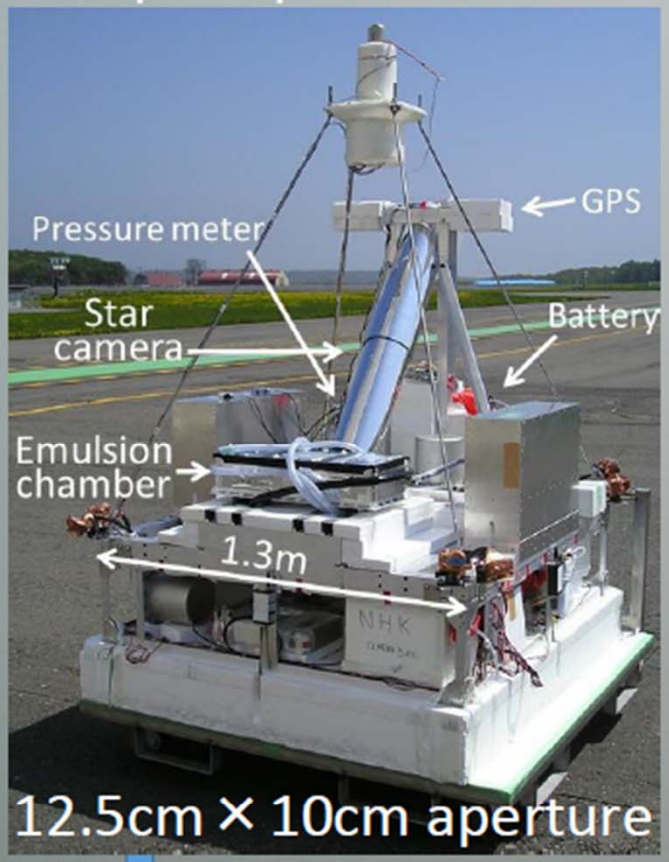
- **Prototype Phase**
  2011(done), TARF, JAXA Scientific Ballooning
  125cm^2 aperture area, 4.3hours (1.6hours@34.7km) flight
  - Working test for each element
  - Connection test between elements
  - Measurement of atmospheric gamma-rays

- **Demonstration Phase**
  2015(analyzing), Alice Springs, JAXA International Scientific Ballooning
  3850cm^2 aperture area, 14h22min (11h32min@36.0-37.4km) flight
  - Overall test by detecting known gamma-ray source (Vela pulser)

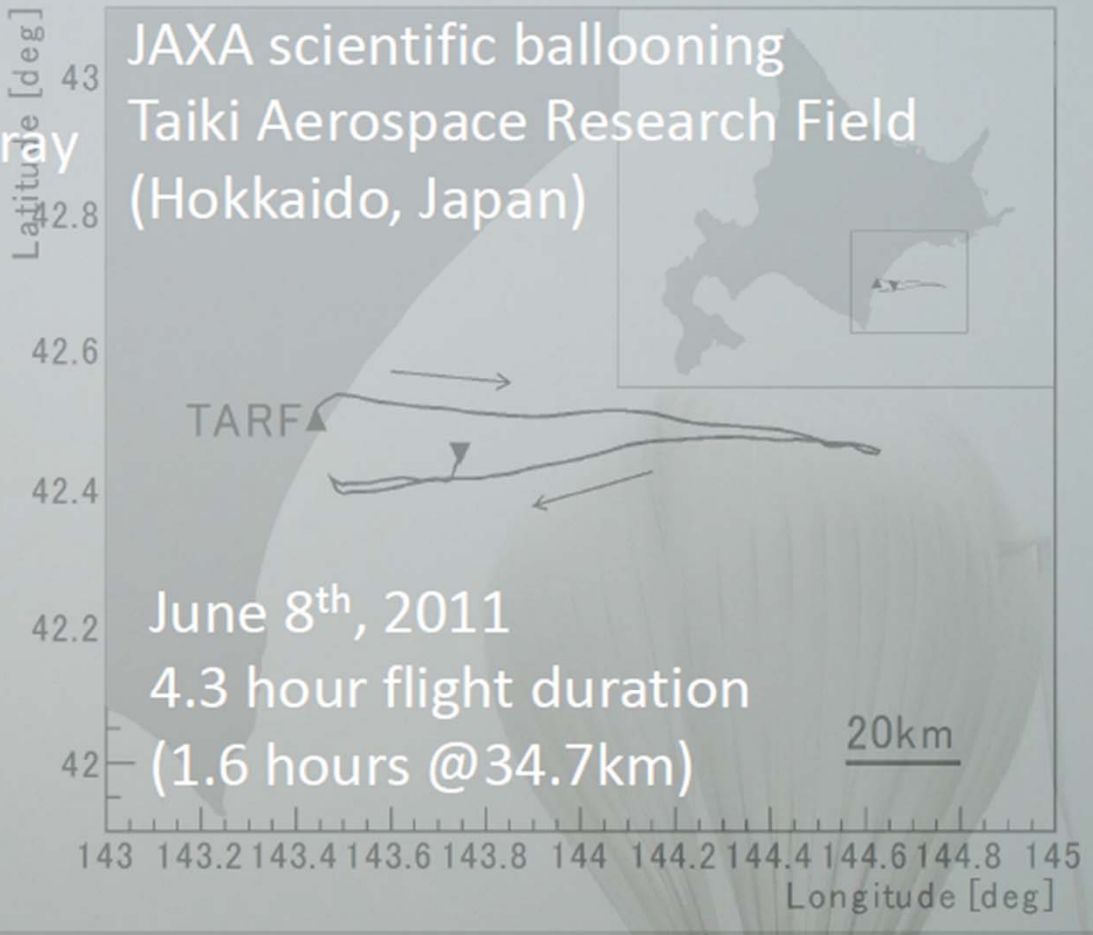
- **Working Phase**
  2018(planning)
  2 to 10m^2 aperture area, ~36 hours flight duration
  - Starting scientific observation

GRAINE 2011

First balloon-borne emulsion γ-ray telescope experiment



JAXA scientific ballooning
Taiki Aerospace Research Field
(Hokkaido, Japan)

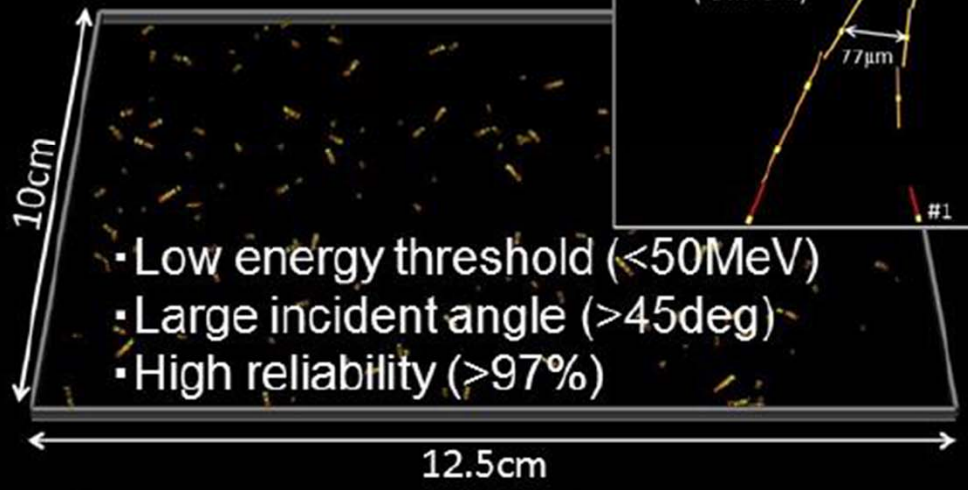


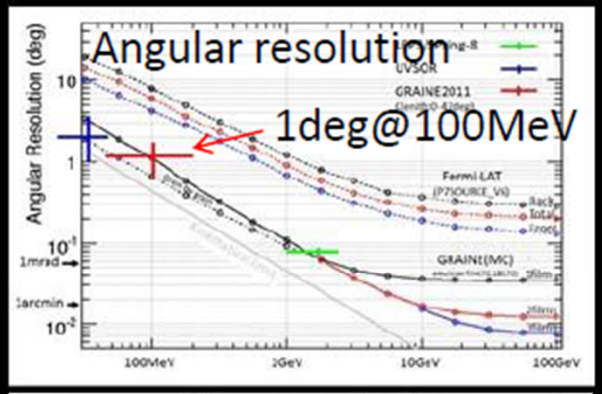
June 8th, 2011
4.3 hour flight duration
(1.6 hours @34.7km)

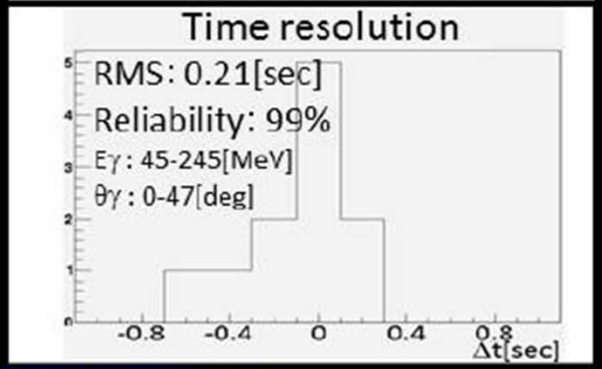
First balloon-borne experiment
Feasibility test

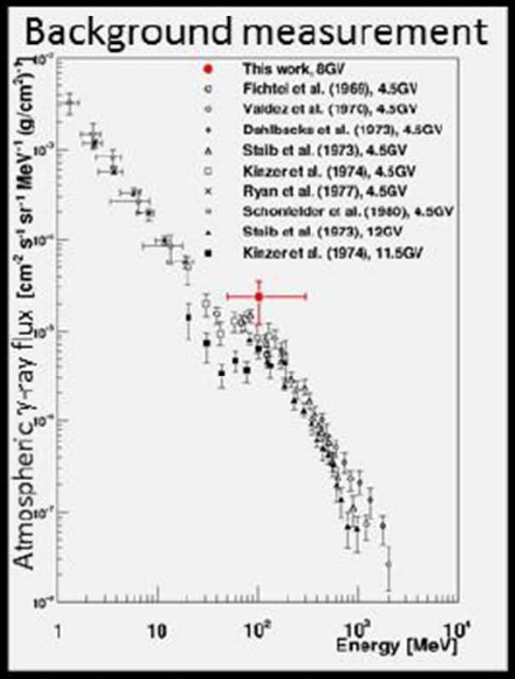
GRAINE 2011 Flight data analysis

γ-ray event detection

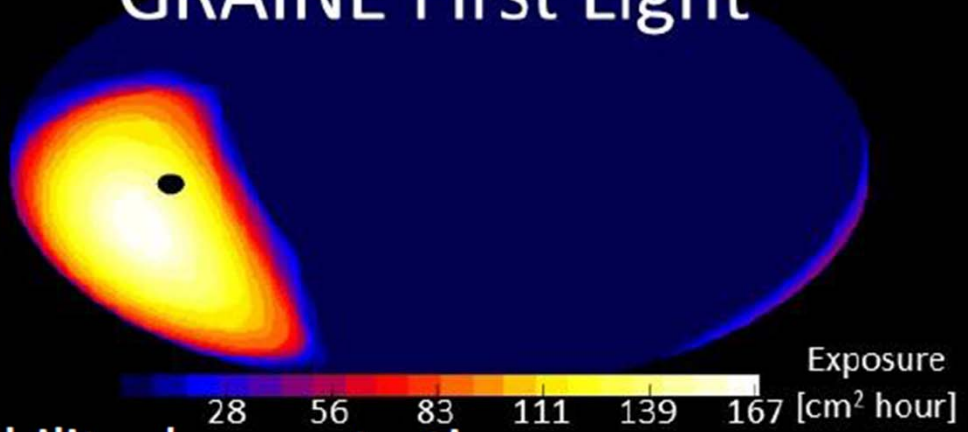








GRAINE First Light



Feasibility demonstration

S. Takahashi et al., PTEP 043H01 (2015); H. Rokujo et al., NIM A 701, 127 (2013)

GRAINE roadmap (R&D has started in 2004)

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  2011(done), TARF, JAXA Scientific Ballooning
  125cm^2 aperture area, 4.3hours (1.6hours@34.7km) flight
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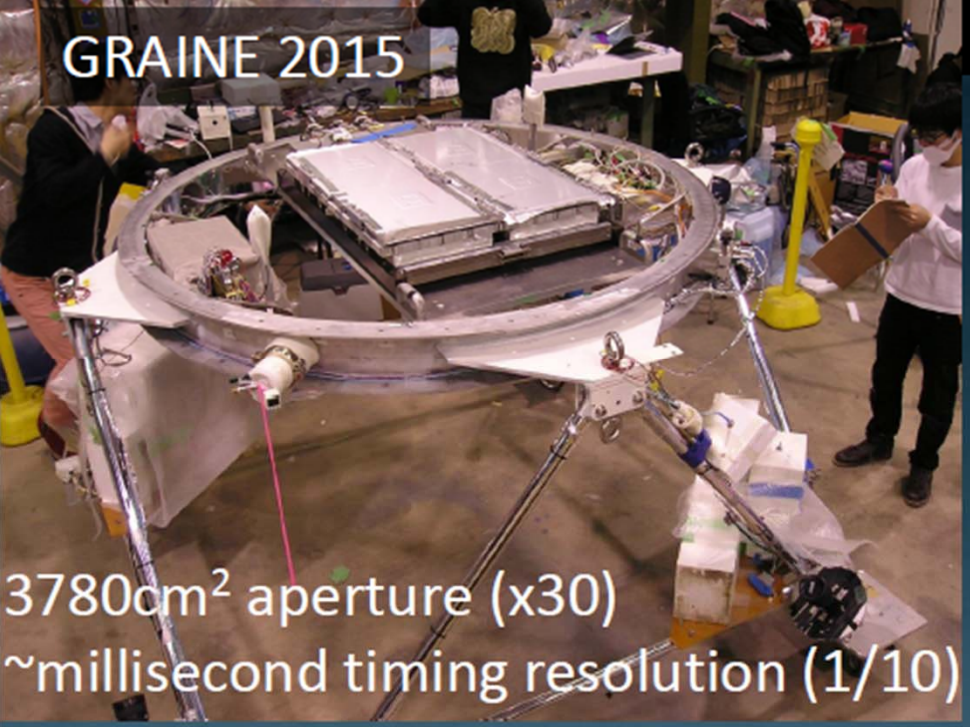
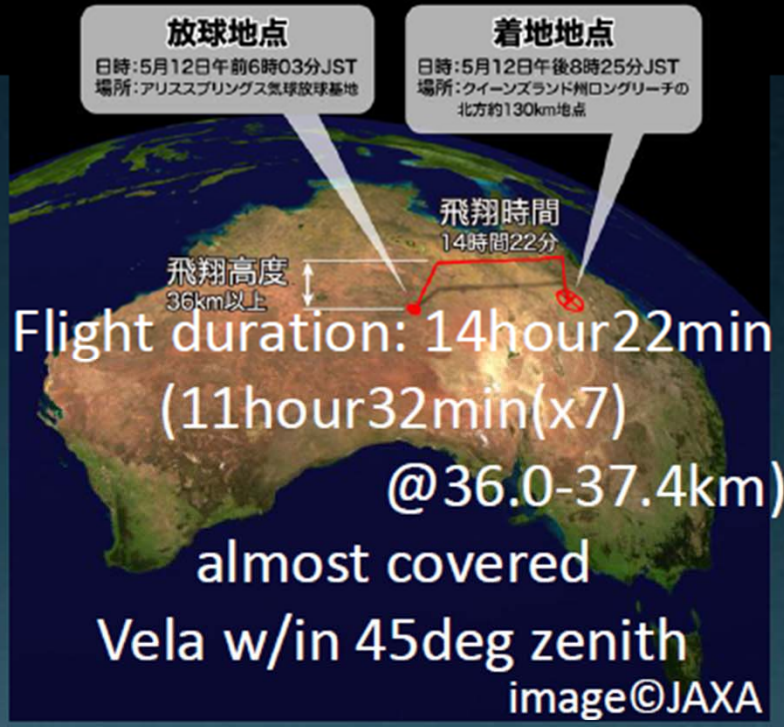




Launched, 6:33 12th May 2015

Design, various improvements & preparations

Establishment of a scheme & flow of the experiment in Australia

Demonstration of overall performance

Image©JAXA

S. Takahashi et al., PTEP 073F01 (2016); K. Ozaki et al., JINST 10 P12018 (2015)

GRAINE

Balloon-borne Emulsion Gamma-ray Telescope Project

Hiroki Rokujo (Nagoya Univ.)
for GRAINE collaboration
rokujo@flab.phys.nagoya-u.ac.jp

Gamma-Ray Astro-Imager with Nuclear Emulsion (GRAINE) is a gamma-ray observation project with a new balloon-borne emulsion gamma-ray telescope. In May 2015, we performed a balloon-borne experiment in Alice Springs, Australia, in order to demonstrate the imaging performance of our telescope. The emulsion telescope that has the aperture area of 0.4 m² was employed in this experiment. In this presentation, we will report the latest results and the status of GRAINE project.

I. GRAINE Project

■ γ-ray Observation (sub-GeV/GeV)

■ Emulsion γ-ray Telescope

High-statistic Observation
→ NEXT: Precise Observation

- High Angular Resolution
- Polarization Sensitive
- Large Aperture Area

II. Balloon Experiment in 2015

A purpose of this experiment is to **demonstrate the detector performance of emulsion telescope by detecting the Vela pulsar**, which is the brightest γ-ray source in the GeV γ-ray sky.

■ Balloon Flight

■ Detector

III. Flight Data Analysis -Gamma-ray Event Selection-

■ Gamma-ray (γ→e⁺e⁻) Event Selection

■ Detector Response

■ Kinematical Distribution of e⁺e⁻

■ Energy Reconstruction

■ Selection Efficiency(MC)

IV. Flight Data Analysis -Detector Performance Check-

■ γ-ray Imaging Test Using Launching Plate

■ Observation of Cosmic-ray East-West Effect

■ Measurement of BG Flux at 36-37km

Atmospheric γ-ray flux

Measurement is consistent with previous experiments.

V. Summary & Prospect

■ Data analysis of GRAINE-2015 Balloon Experiment

- In order to demonstrate detector performance by detection of Vela pulsar
- Established γ-ray event (γ→e⁺e⁻) selection process.
- Performance-checking data is presented. (imaging test, observation of CR E-W effect and BG measurement)

■ Next Balloon Experiment is planning.

- April 2018 in Alice Springs, Australia
- Aperture area: 0.4m² → 2.5 m² (x6.6), Flight Duration: 14 h → ~30 h (x2.1)
- Larger yield and detection of 3-5 sources

放球地点
日時:5月12日午前6時03分JST
場所:アリススプリングス気球放球基地

着地地点
日時:5月12日午後8時25分JST
場所:クイーンズランド州ロングリーチの北方約130km地点

飛翔時間
14時間22分

飛翔高度
36km以上

Flight duration: 14hour22min
(11hour32min(x7)
@36.0-37.4km)
almost covered
Vela w/in 45deg zenith
image©JAXA

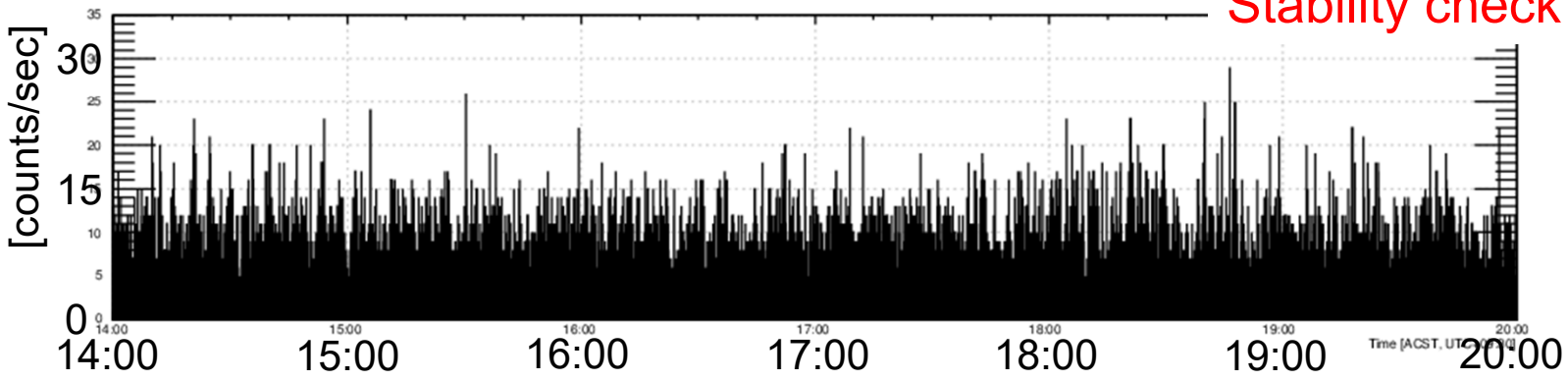
eparations
f the experiment in Australia
ce

Image©JAXA S. Takahashi et al., PTEP 073F01 (2016); K. Ozaki et al., JINST 10 P12018 (2015)

Time stamp to Gamma-ray event

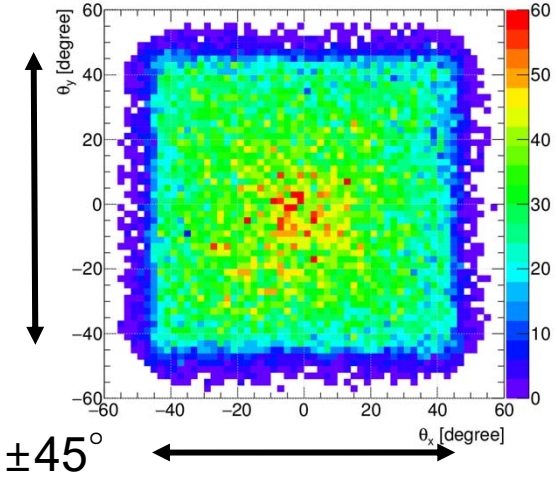
◆ Gamma-ray event rate

Stability check

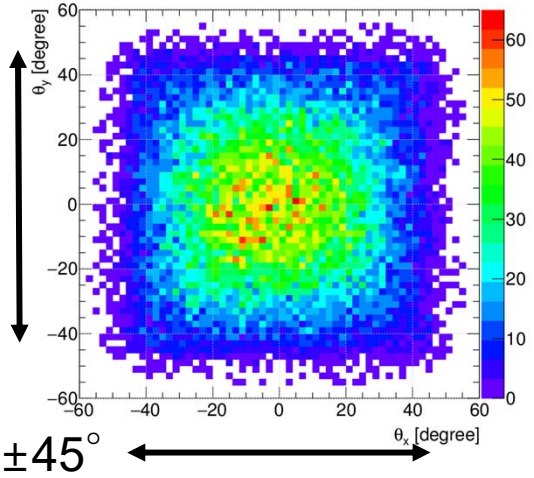


◆ Angular distribution of Gamma-ray

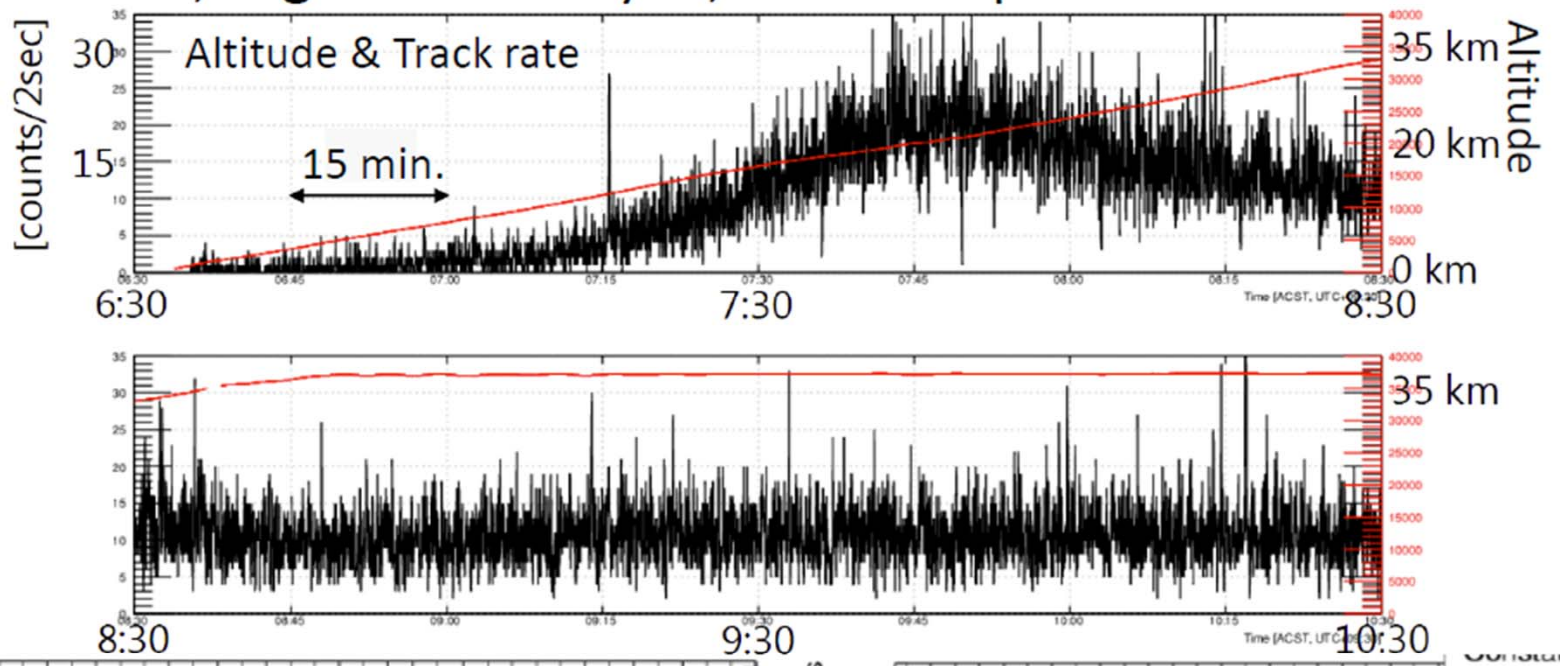
<in flight>

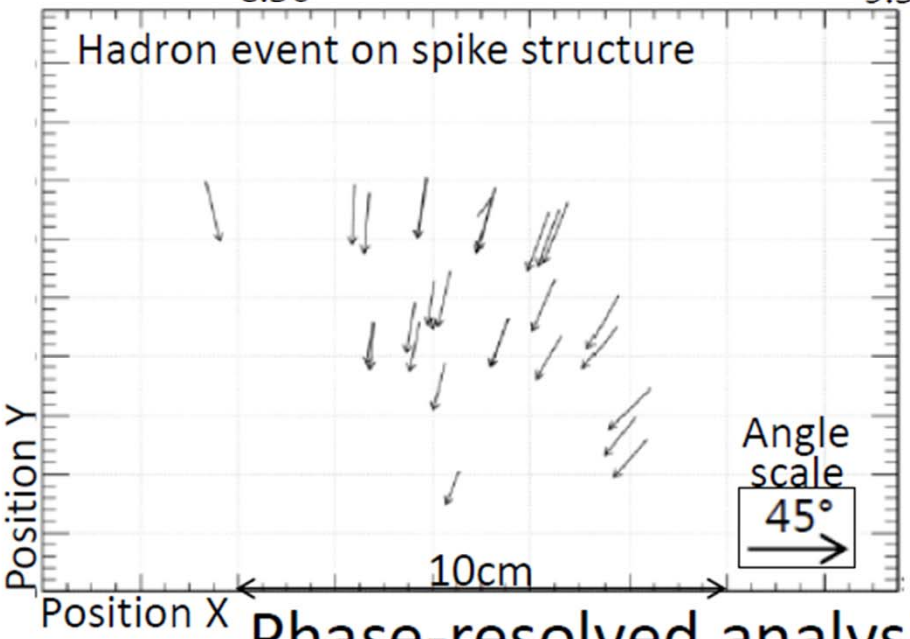


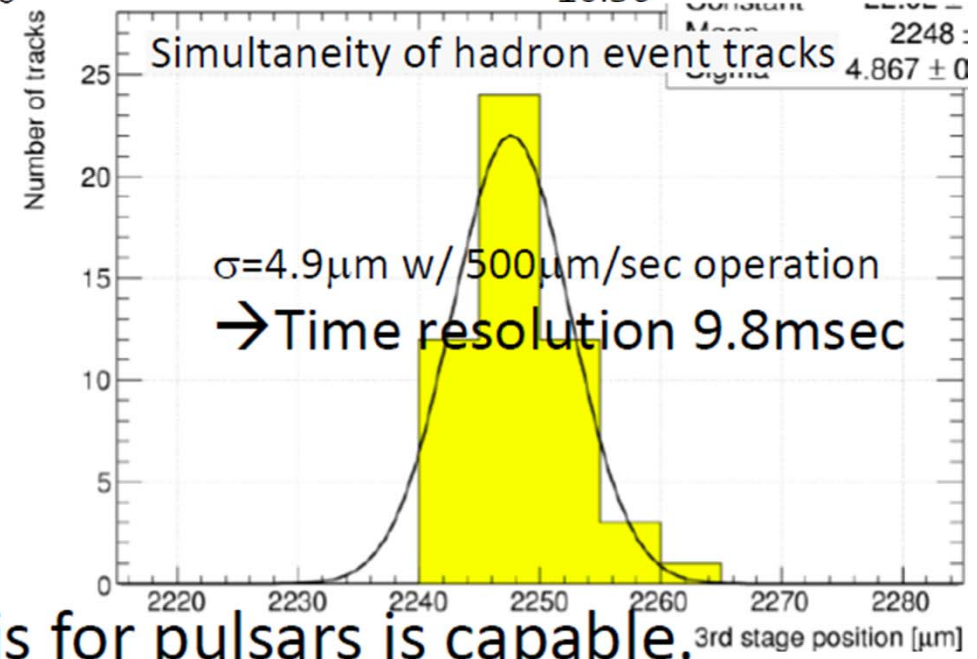
<on ground>



GRAINE 2015, Flight data analysis, Timestamper







Phase-resolved analysis for pulsars is capable.

e.g. 89msec period of Vela pulsar

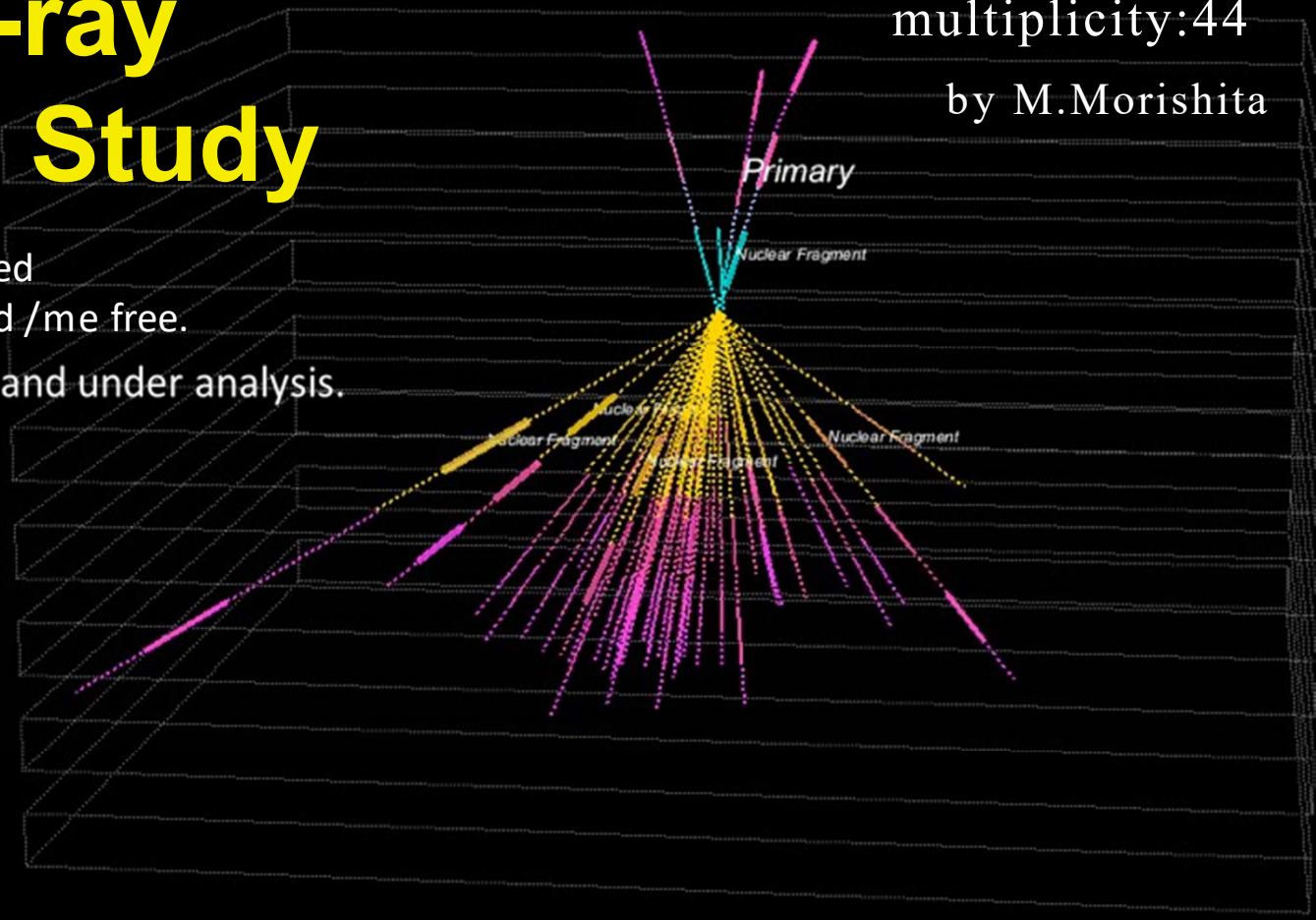
Cosmic-ray Interaction Study

multiplicity:44

by M.Morishita

All charged par/cles are recorded
in emulsion chamber with dead /me free.

$O(10^5)$ events are detected, and under analysis.



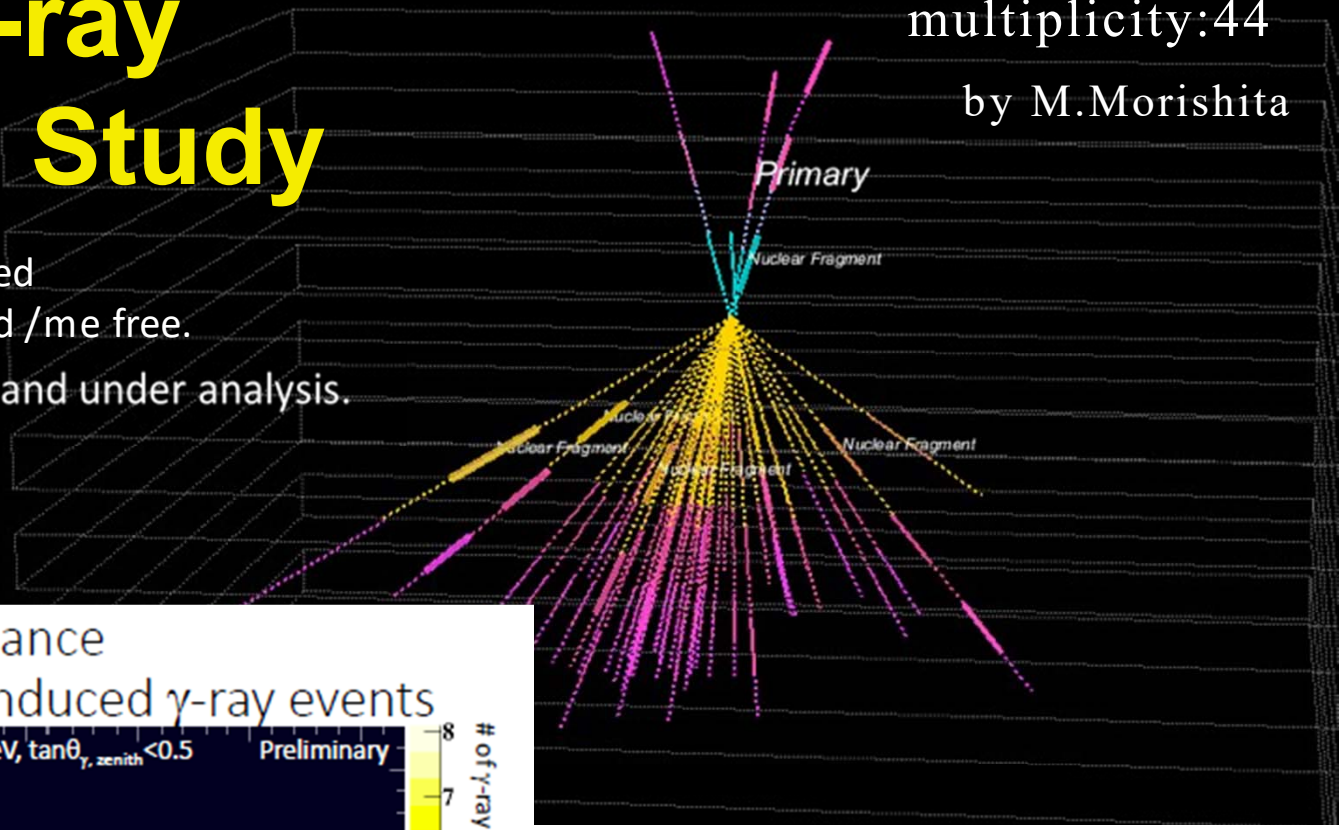
Cosmic-ray Interaction Study

multiplicity:44

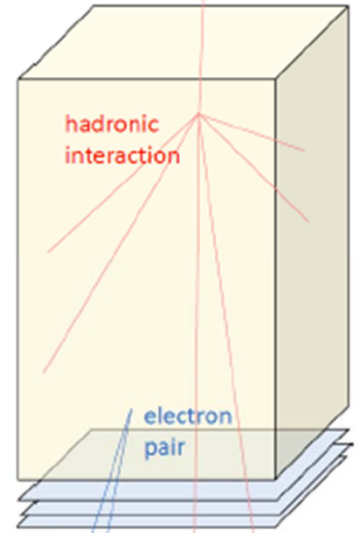
by M.Morishita

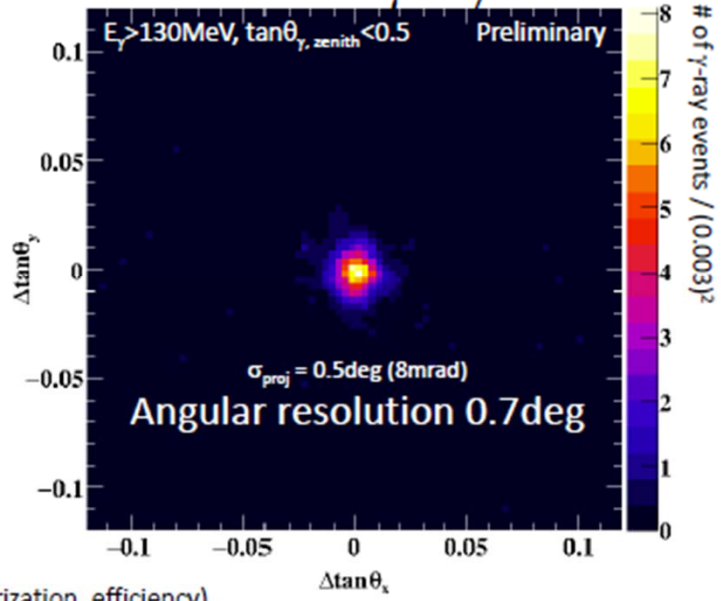
All charged par/cles are recorded
in emulsion chamber with dead /me free.

$O(10^5)$ events are detected, and under analysis.



γ-ray imaging performance w/ hadron induced γ-ray events

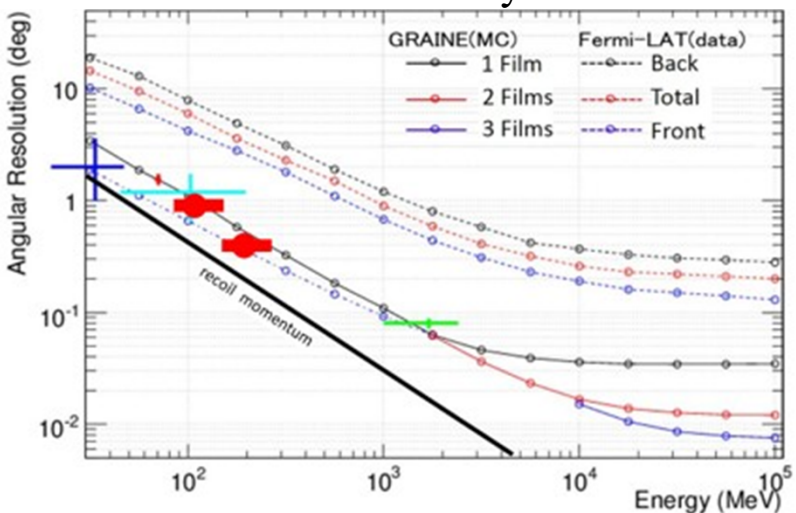




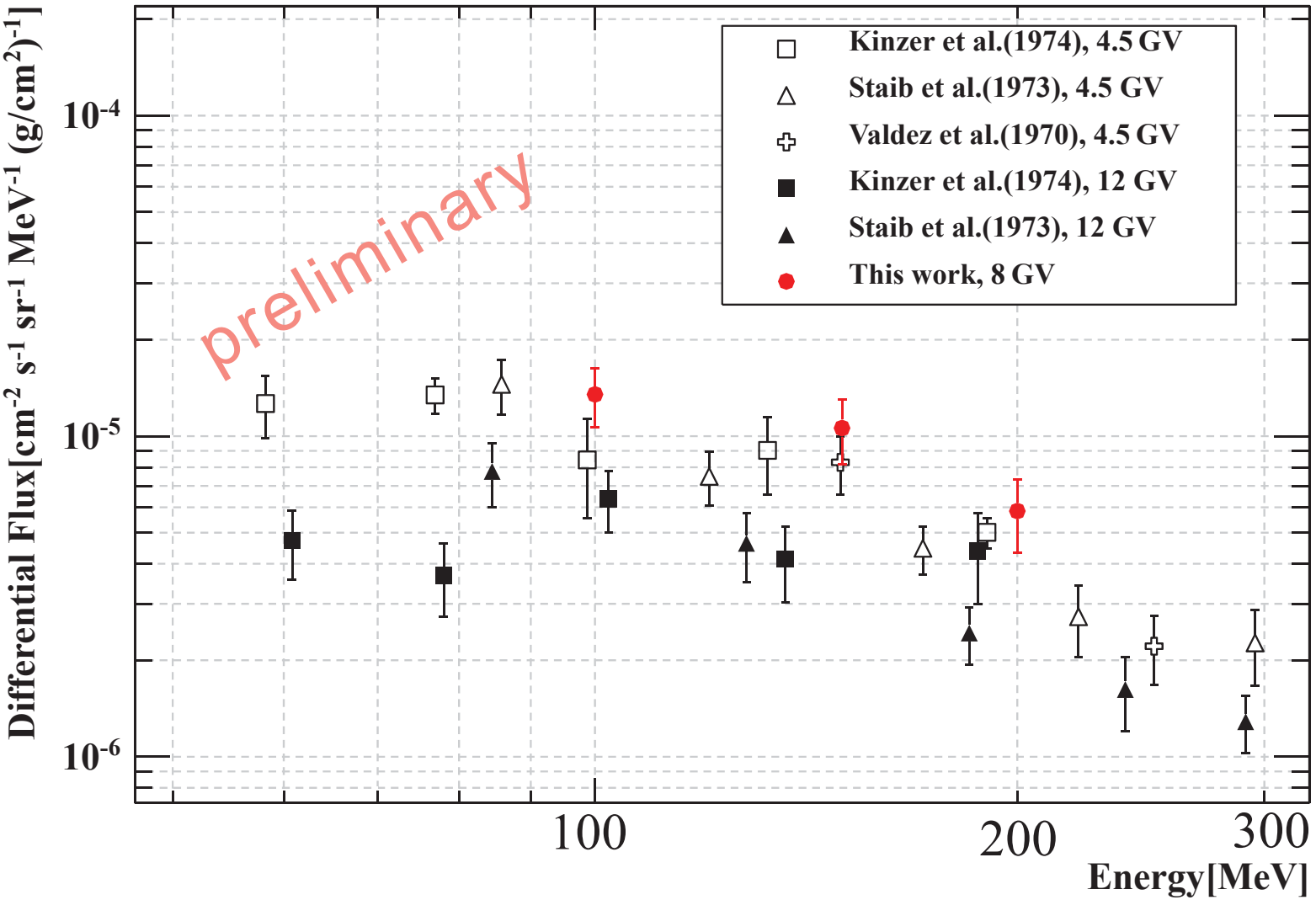
Calibration sorce
(direction, timing, energy, polarization, efficiency)

High γ-ray imaging performance was being obtained.

by H.Kawahara



Off-source region data
(atm. gamma-ray)



GRAINE roadmap (R&D has started in 2004)

- **Prototype Phase**
  2011(done), TARF, JAXA Scientific Ballooning
  125cm^2 aperture area, 4.3hours (1.6hours@34.7km) flight
  - Working test for each element
  - Connection test between elements
  - Measurement of atmospheric gamma-rays

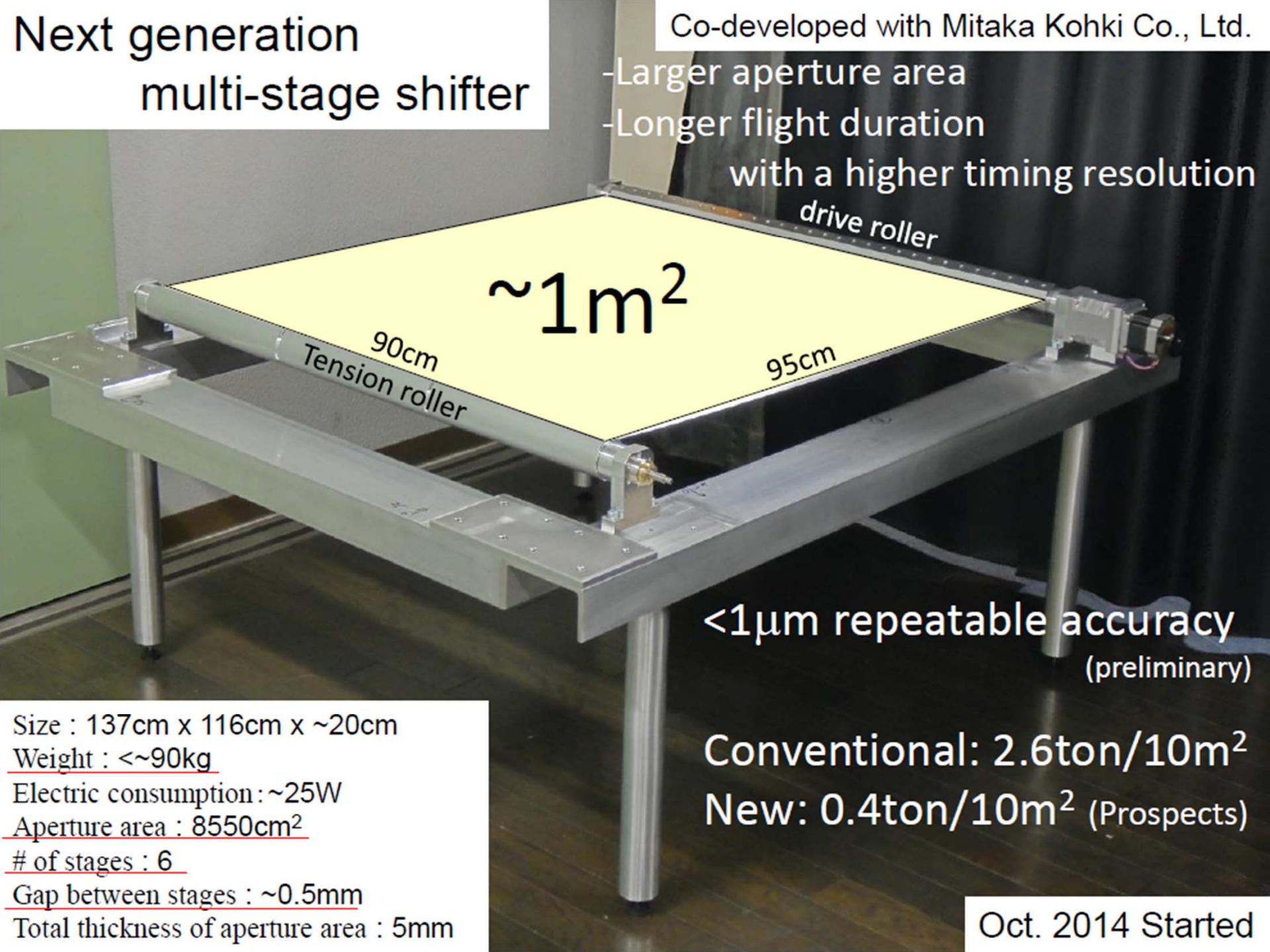
- **Demonstration Phase**
  2015(analyzing), Alice Springs, JAXA International Scientific Ballooning
  3850cm^2 aperture area, 14h22min (11h32min@36.0-37.4km) flight
  - Overall test by detecting known gamma-ray source (Vela pulser)

- **Working Phase**
  2018(planning)
  2 to 10m^2 aperture area, ~36 hours flight duration
  - Starting scientific observation

Next generation multi-stage shifter

Co-developed with Mitaka Kohki Co., Ltd.

-Larger aperture area
-Longer flight duration
with a higher timing resolution



<1μm repeatable accuracy
(preliminary)

Conventional: 2.6ton/10m²
New: 0.4ton/10m² (Prospects)

Size : 137cm x 116cm x ~20cm
Weight : <~90kg
Electric consumption : ~25W
Aperture area : 8550cm²
# of stages : 6
Gap between stages : ~0.5mm
Total thickness of aperture area : 5mm

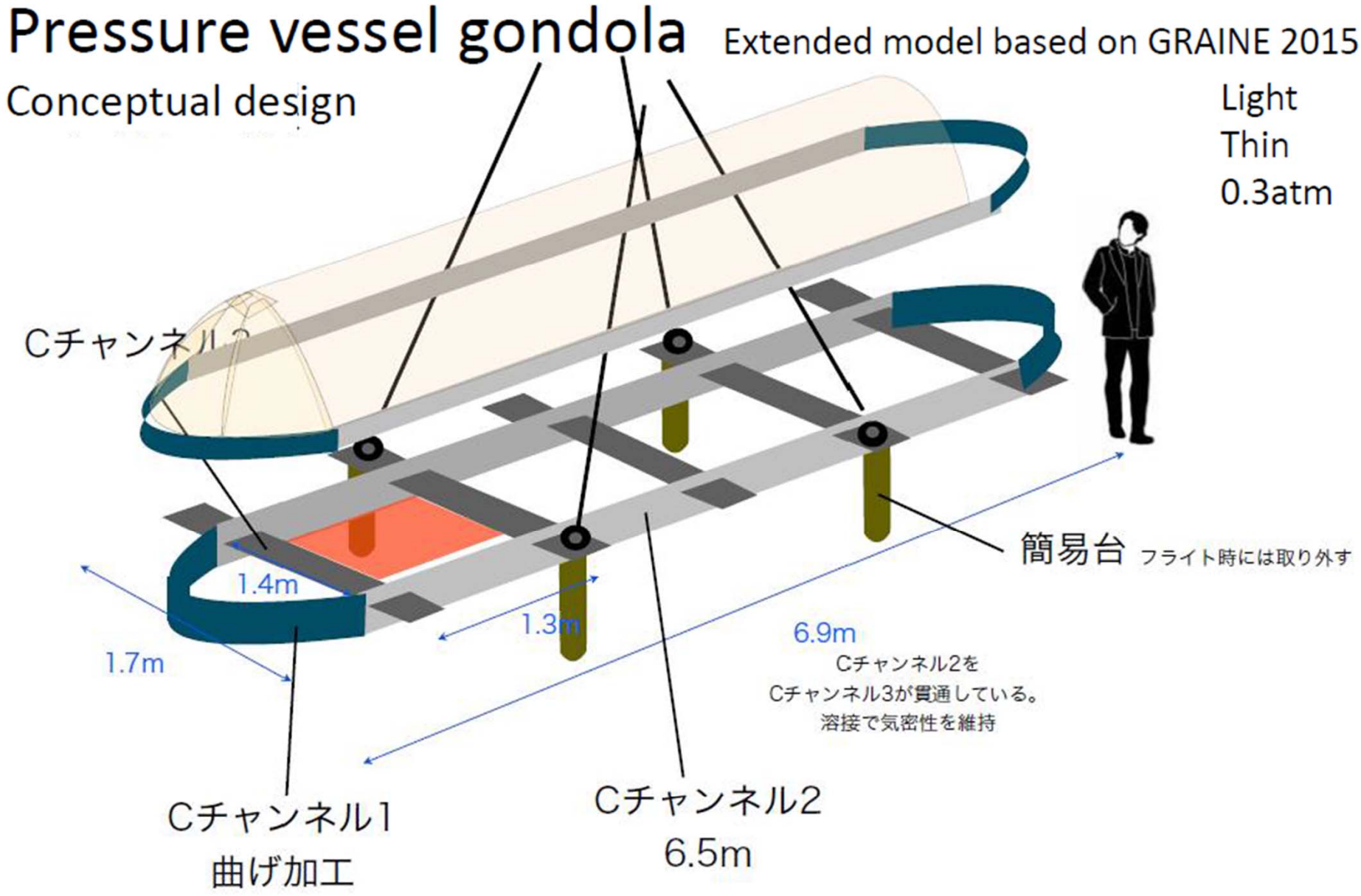
Oct. 2014 Started

Pressure vessel gondola

Extended model based on GRAINE 2015

Conceptual design

Light
Thin
0.3atm

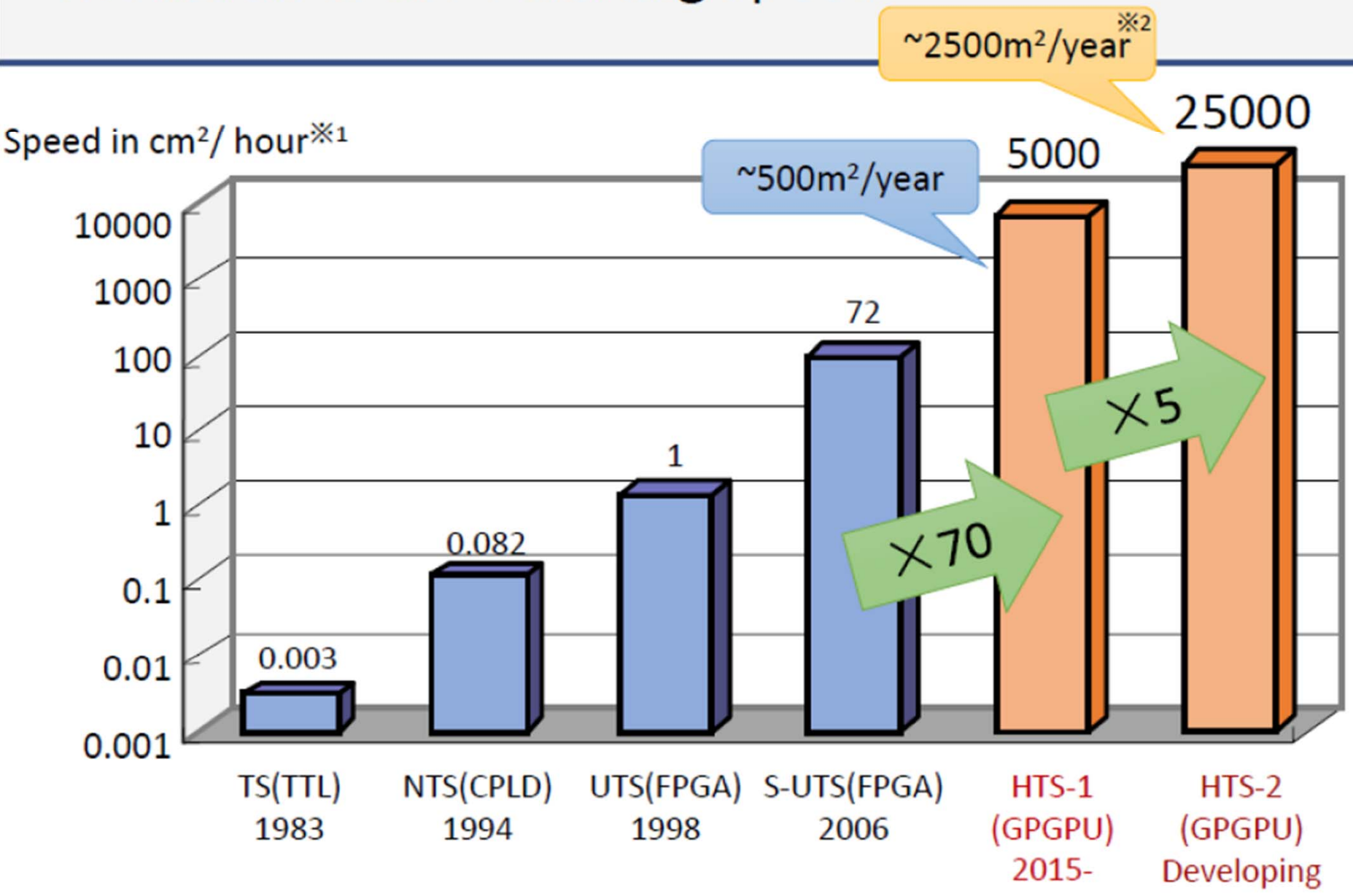


5m^2 (4units) aperture area

w/ a single pressure vessel gondola (~250kg weight)

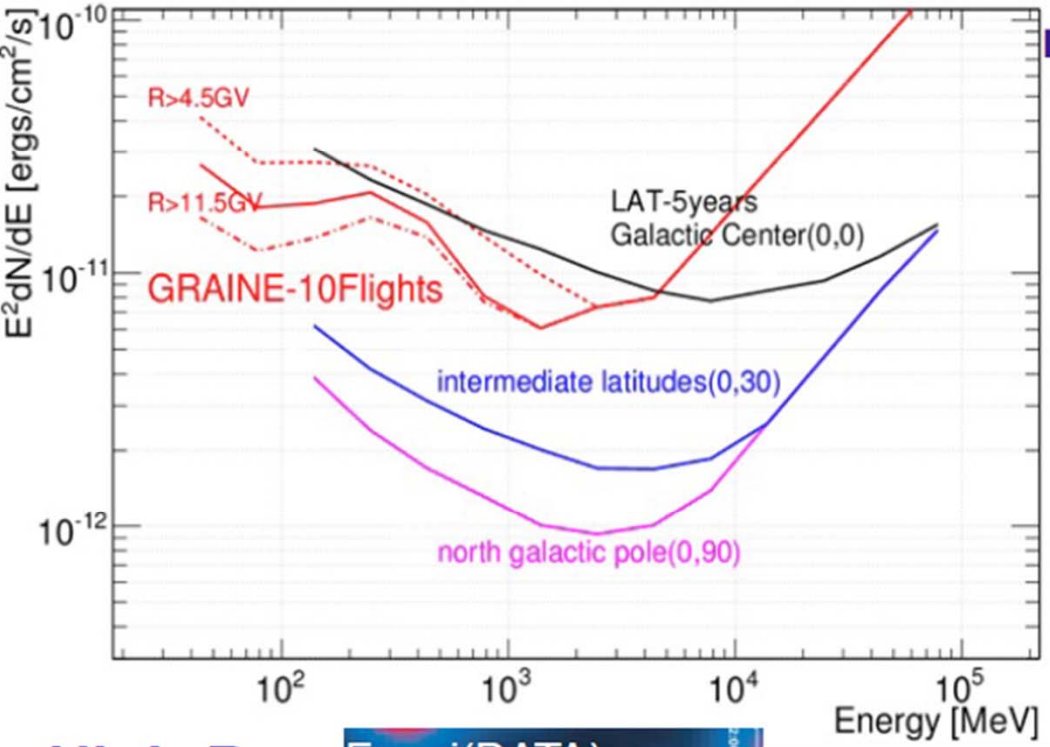
※1 Area of emulsion layer
※2 Area of the films with 24 hour shift

Evolution of the Scanning Speed

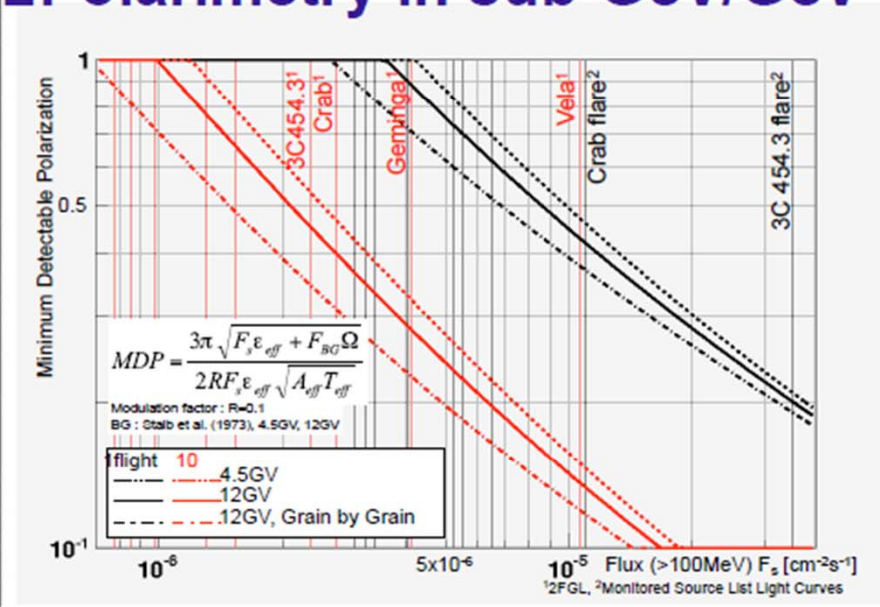


GRAINE project

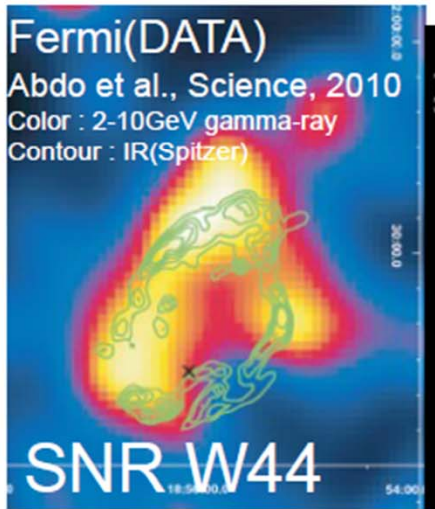
■Sensitivity

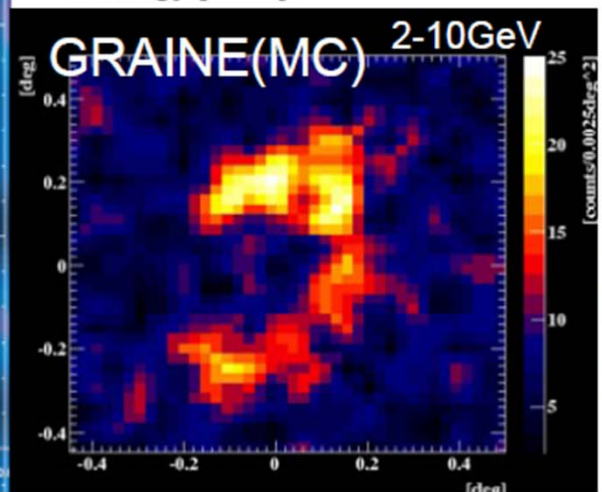


■Polarimetry in sub-GeV/GeV



■High-Res. Imaging extended sources





■ Survey of Galactic Center w/ High Res.

■ Measurement of GRB with high statistic per event

etc

GRAINE Scientific observation roadmap

2018

Alice Springs
>~1m^2 aperture, >~36hours flight duration
<~10g/cm^2 altitude
Commissioning flight

2021-

Alice Springs
10m^2 aperture, >~36hours flight duration
<~10g/cm^2 altitude
Scientific flight

-Scientific model establishment
(size, weight)
-Flight duration
-Performance demonstration
-Scientific obs. starting

Vela pulsar
Polarization observation (<50%)

Pioneering polarization observation for high energy γ-rays

SNR W44 (<200MeV, >200MeV)
Precise spectrum measurement
High resolution imaging

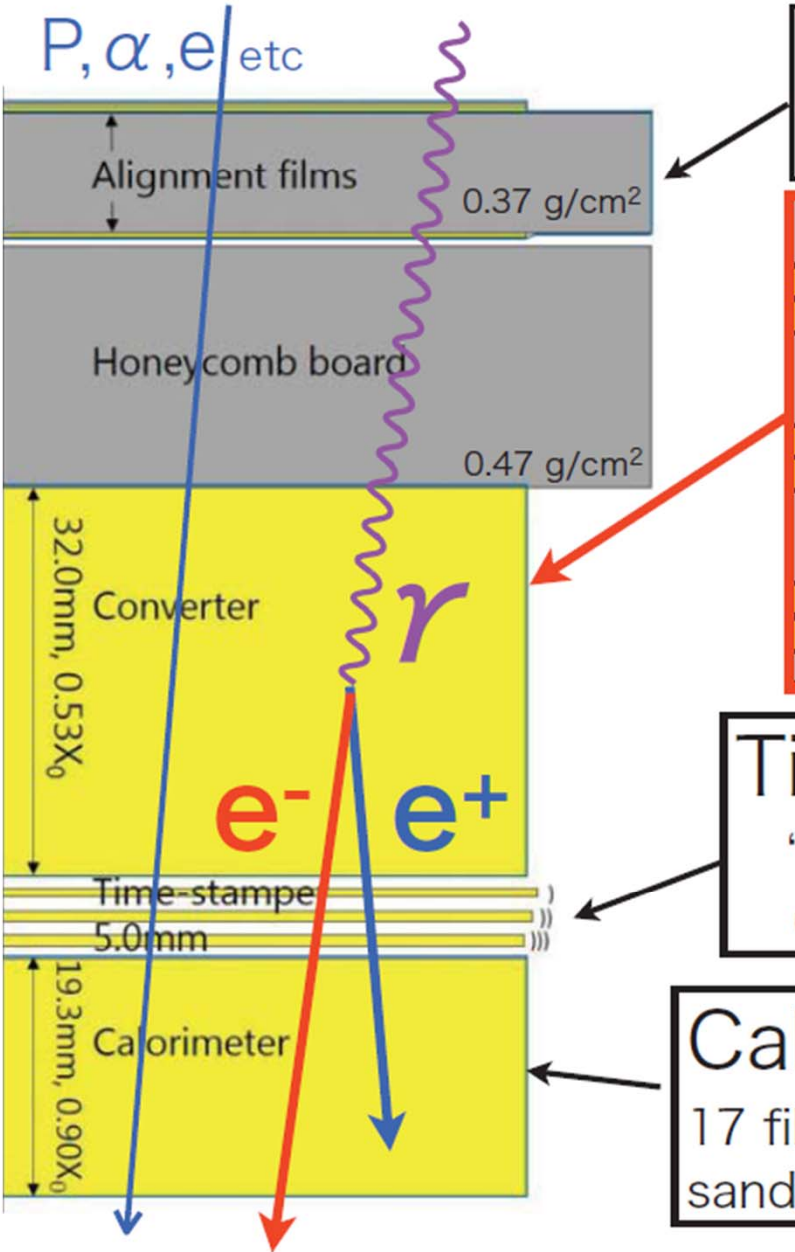
Studying cosmic ray sources

Galactic Center
Obs. with ~arcmin resolution

Resolving GeV γ-ray excess at galactic center

backup

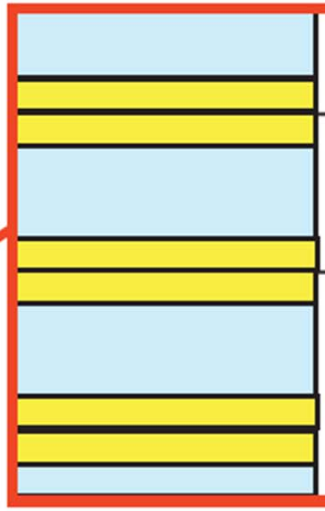
GRAINE-2015 Detector



Flatness alignment films

Al honeycomb +3 films

Converter



base 180 μm
emulsion 70 μm (double sides)

100 films(Thickness:32mm)
0.53 X_0 , $\varepsilon_{conv.}$ = 34%

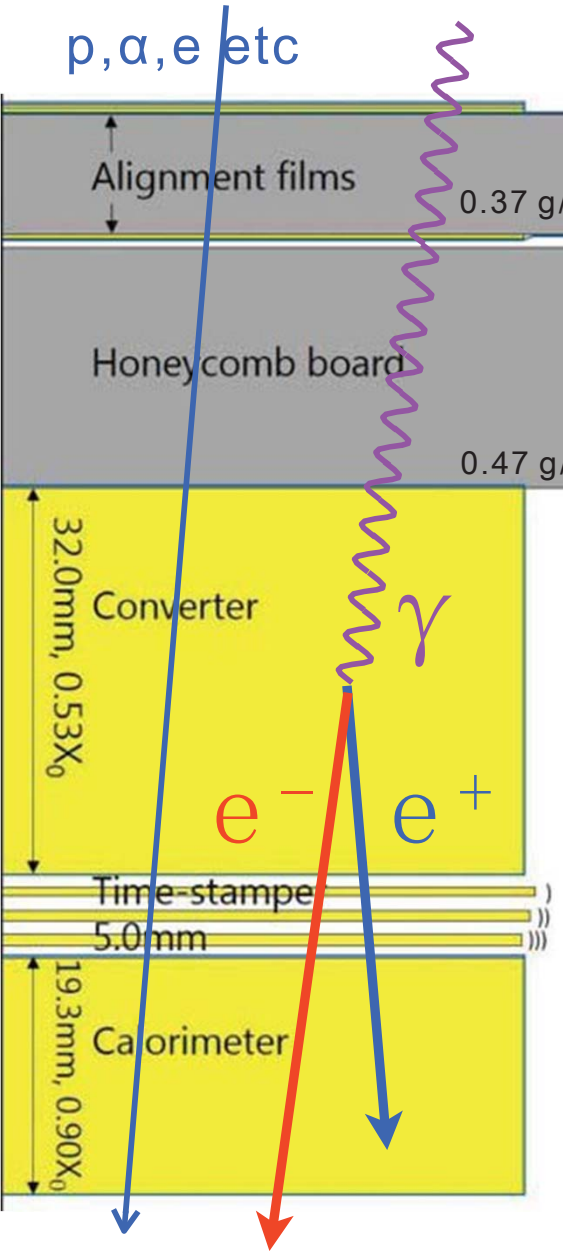
Time stamper

"Multi-stage shifter" (3 stages)
δt = 0.5 s (Vela obs. mode: 0.01s)

Calorimeter

17 films+16 SUS plates(1mm thick)
sandwich structure, thickness19.3mm, 0.90 X_0

Flow of the Analysis



Film Read-out

Converter Analysis

- Connection & Alignment
- $\gamma \rightarrow e^{+}e^{-}$ Selection
- Connection to Time Stamper

Time Stamper Analysis

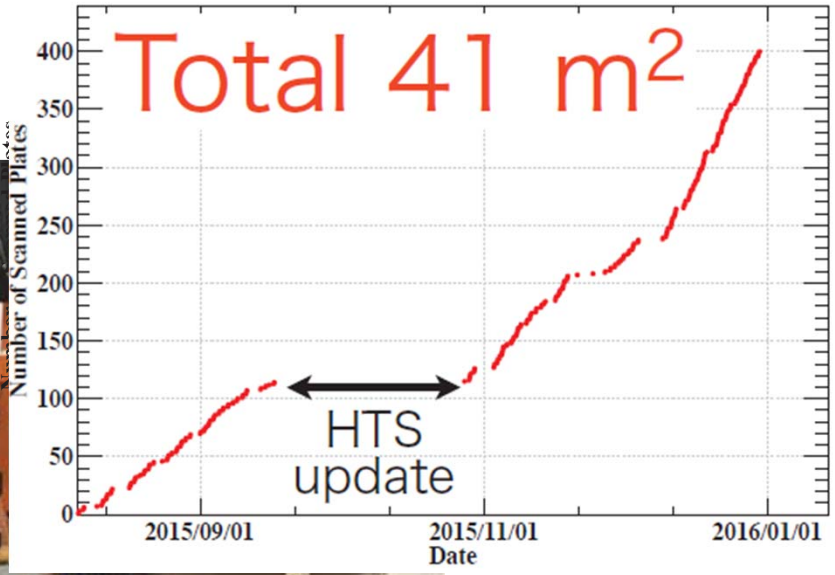
Star Camera Analysis (Attitude monitor)

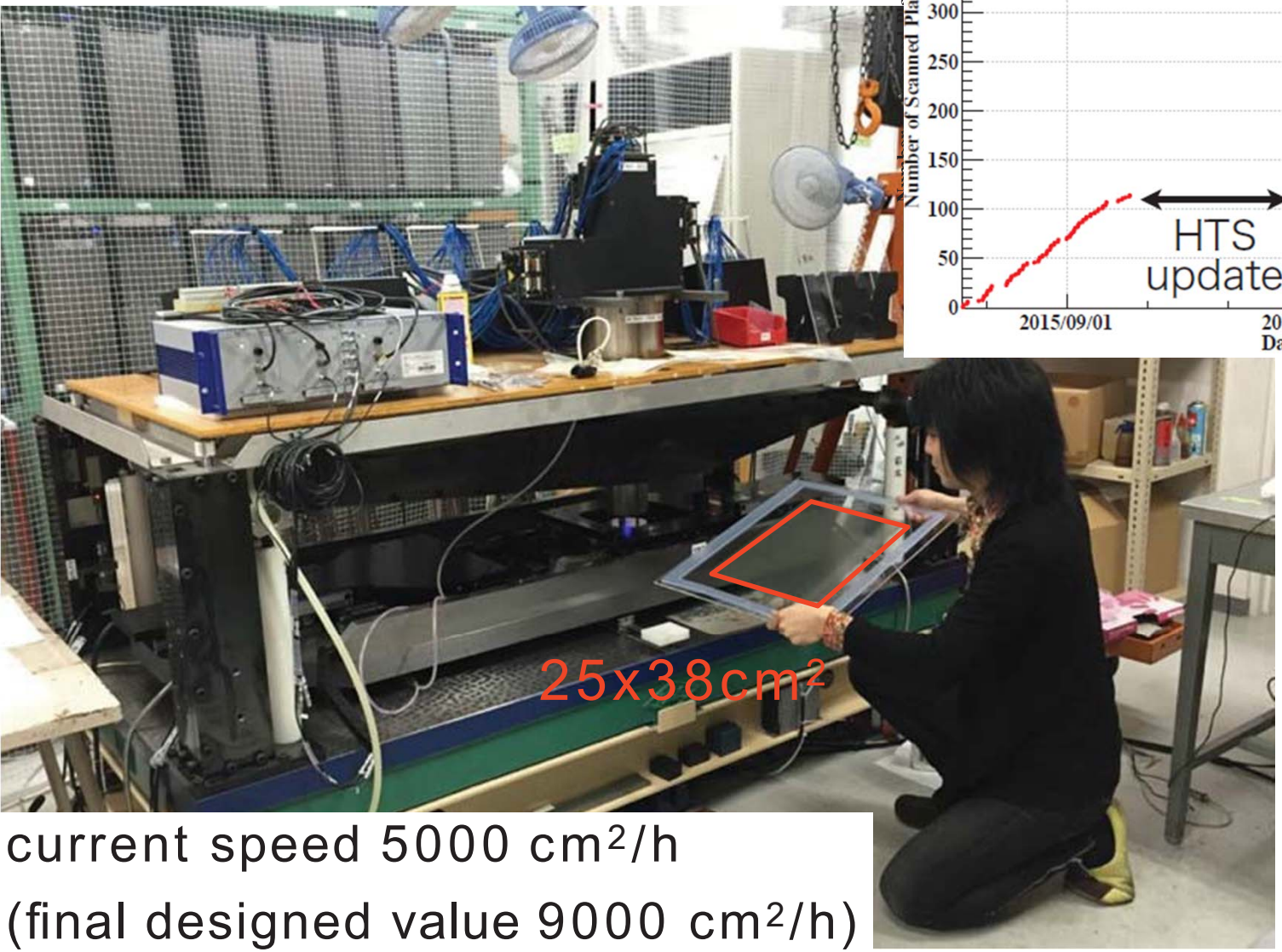
Pointing to celestial sphere

- Off Source region (BG)
- Vela region (Signal)

Film Read-out by HTS@Nagoya U.

The First operation for real experimental data taking





current speed 5000 cm²/h

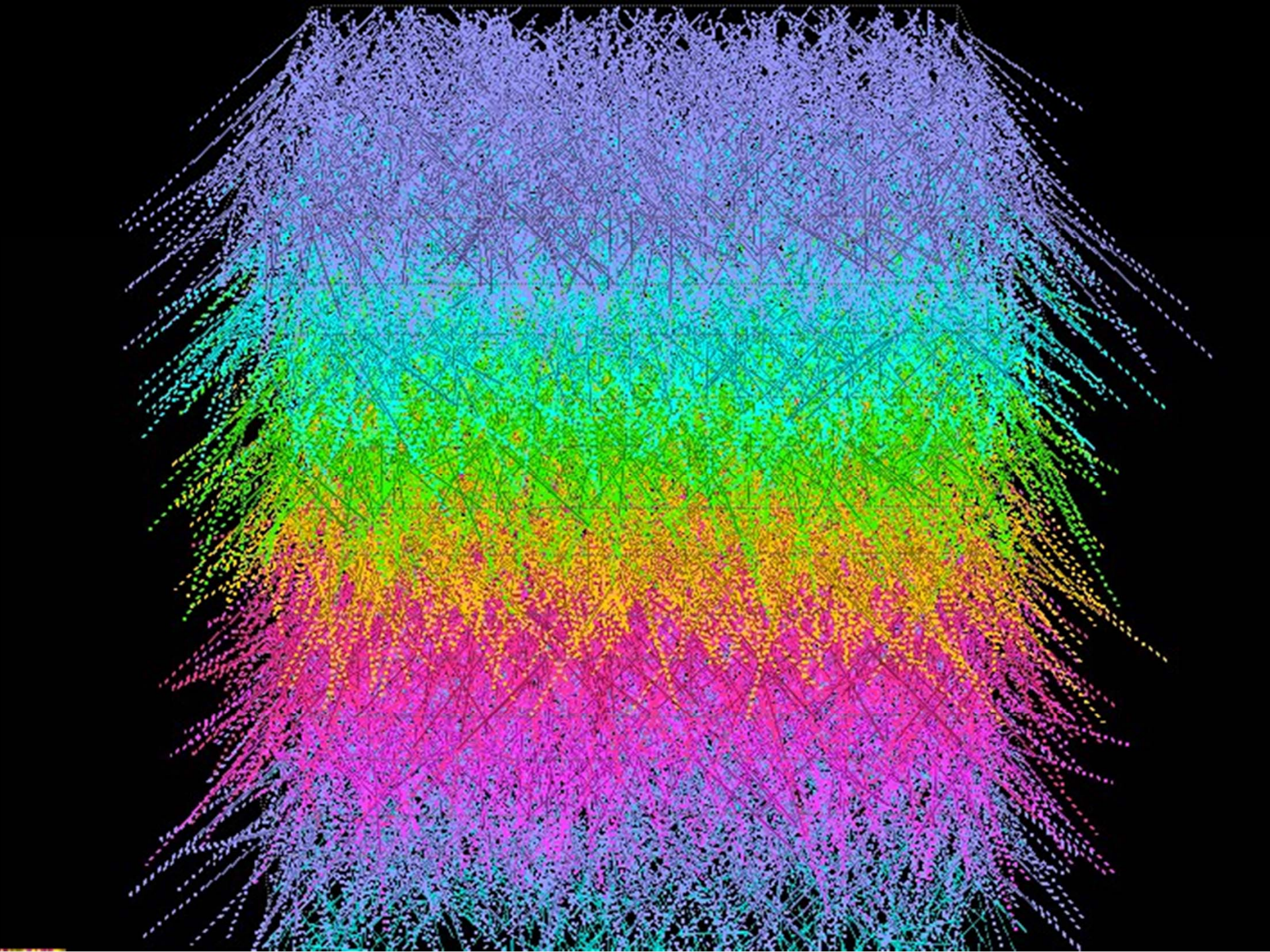
(final designed value 9000 cm²/h)

Flight
data

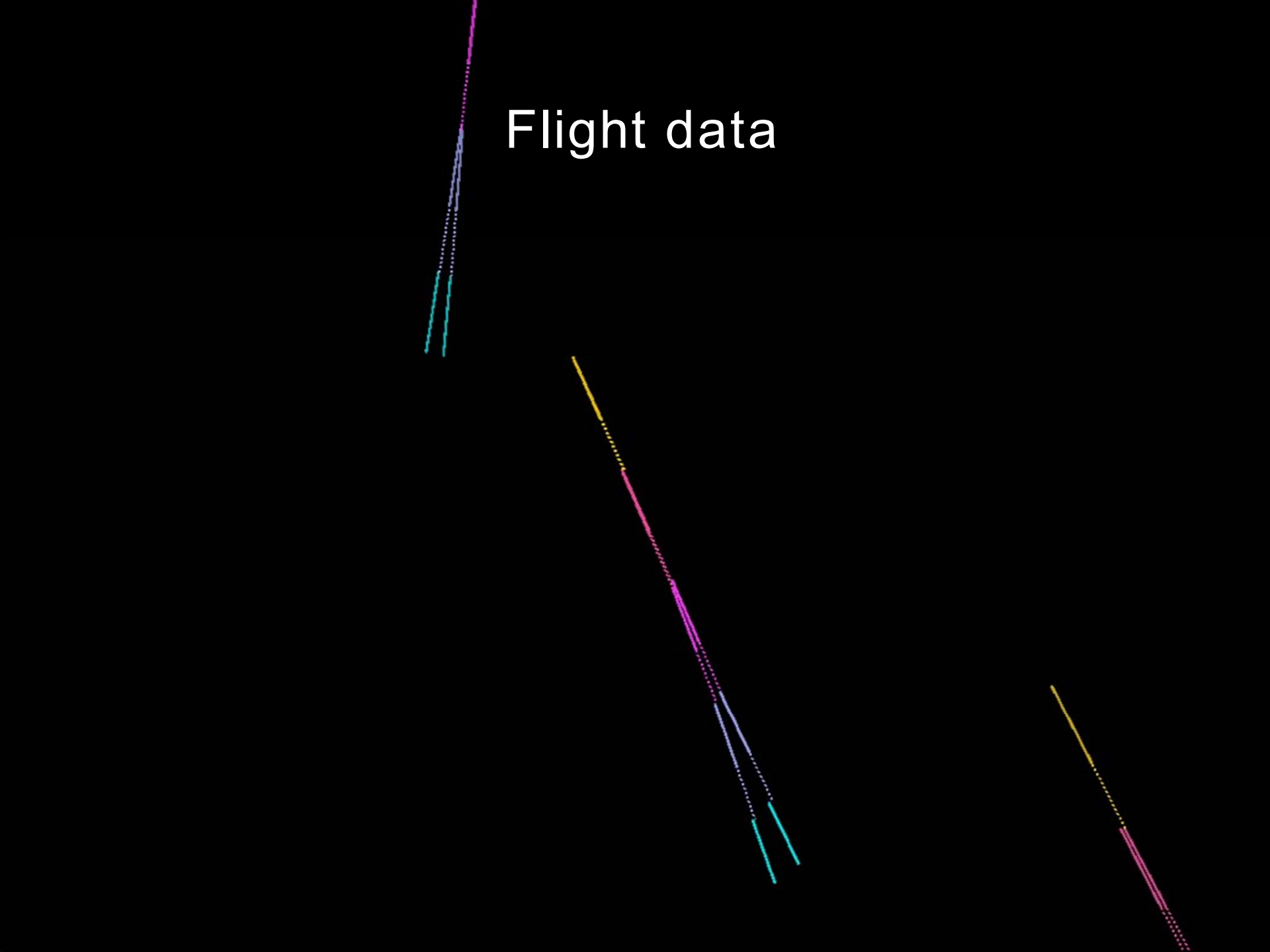
2 mm x 2 mm of single film

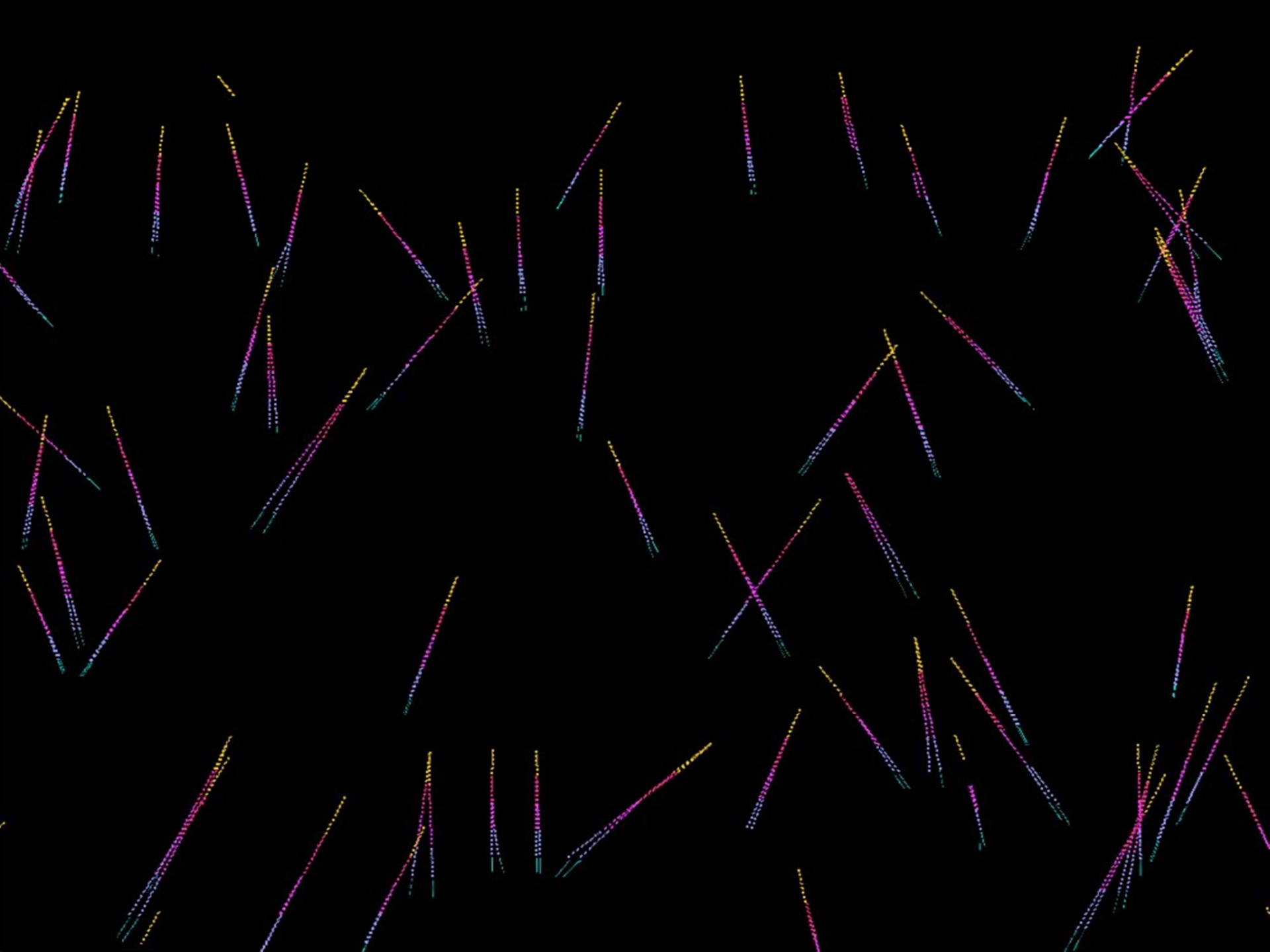
Flight data

density ~400 tracks/mm^2

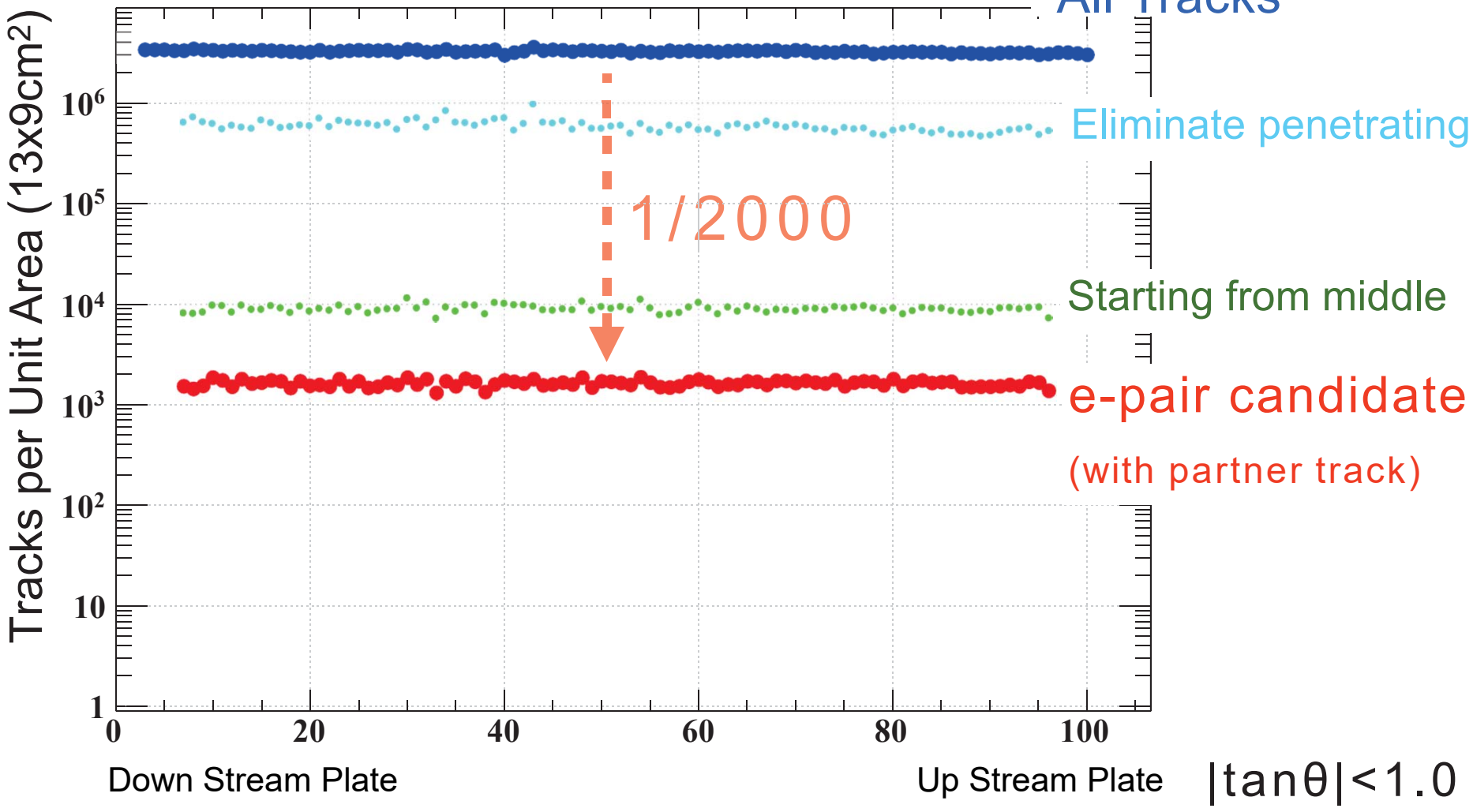


Flight data

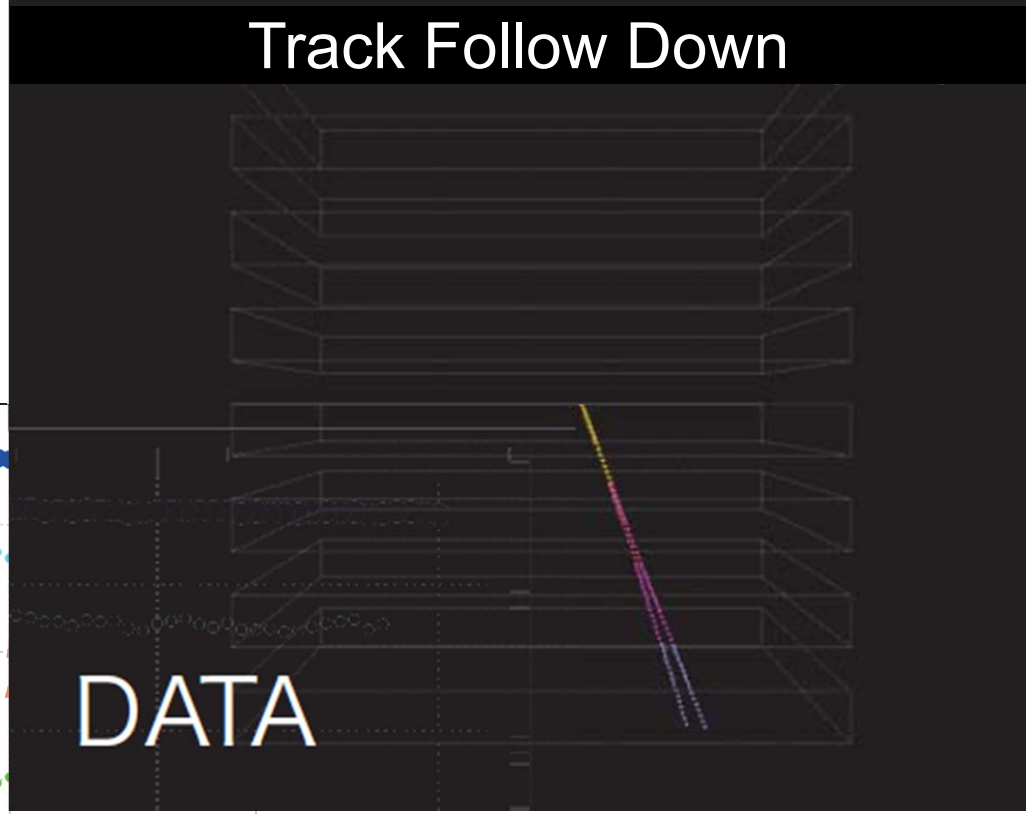




$\gamma \rightarrow e^+e^-$ Selection



$\gamma \rightarrow e^+e^-$ Selecti



Tracks per Unit Area (13x9cm²)

10^6
10^5
10^4
10^3
10^2
10
1

0 20 40 60 80 100

Down Stream Plate

Up Stream Plate

1/

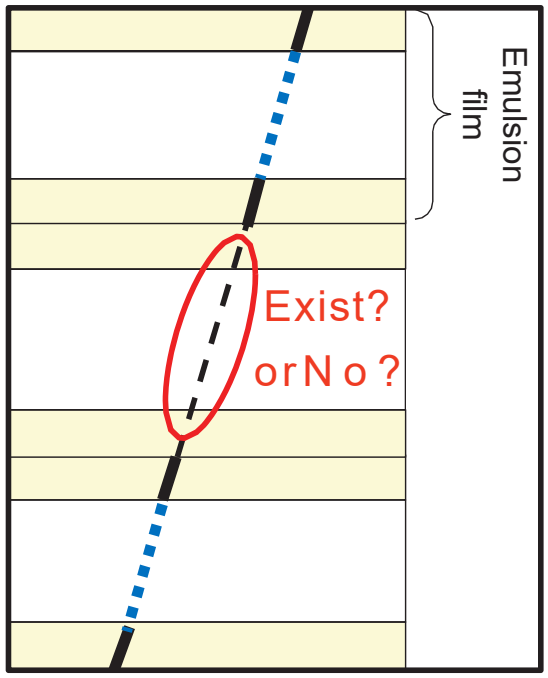
e-pair candidate

(with partner track)

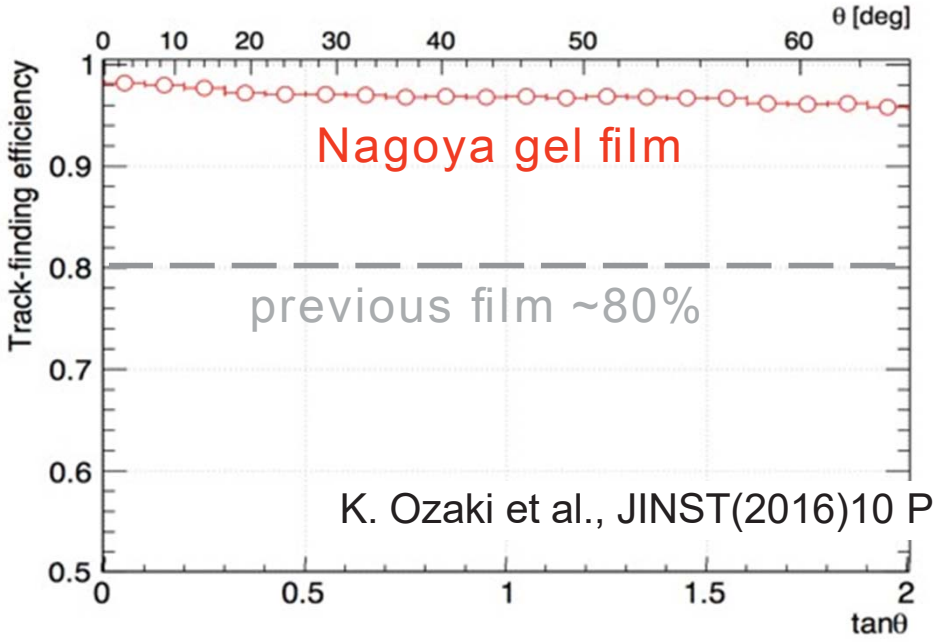
Track Follow Down
to the Bottom
→ Connection to Time Stamper

$|\tan\theta|<1.0$

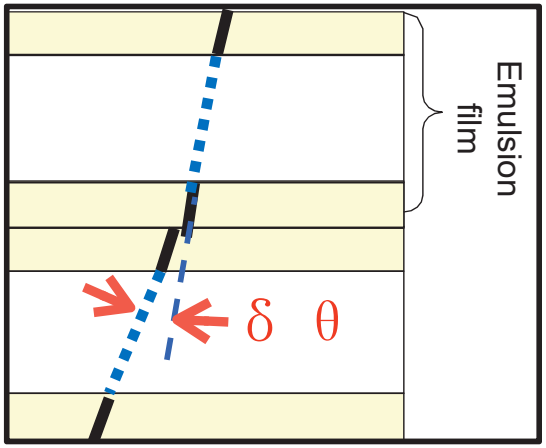
Detector Response



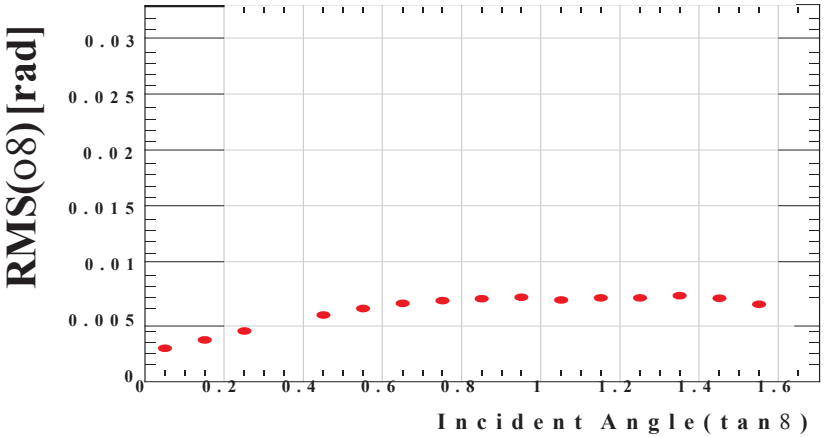
Track Detection Efficiency with Single Plate



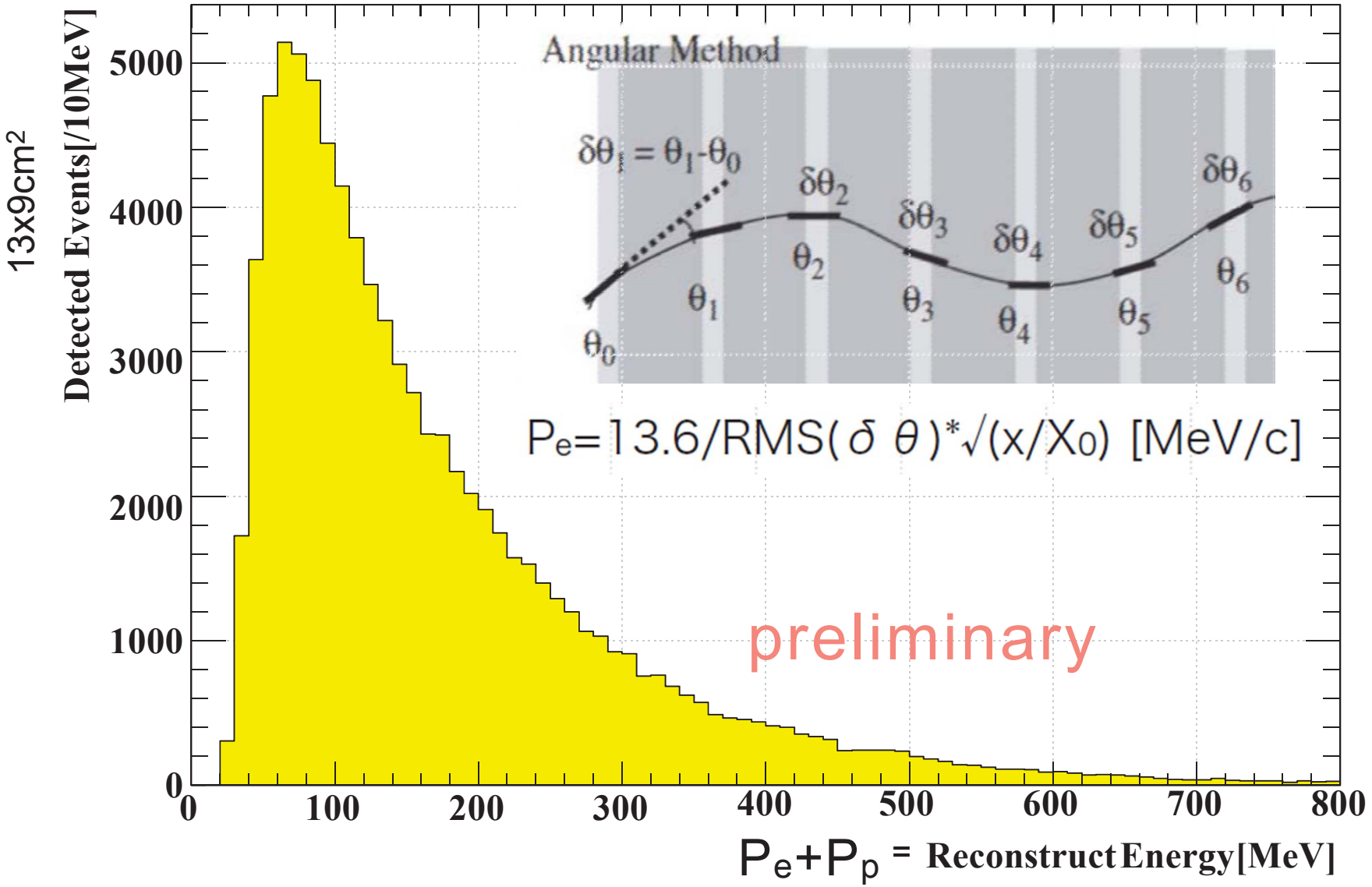
K. Ozaki et al., JINST(2016)10 P12018



Track Reconstruction Accuracy



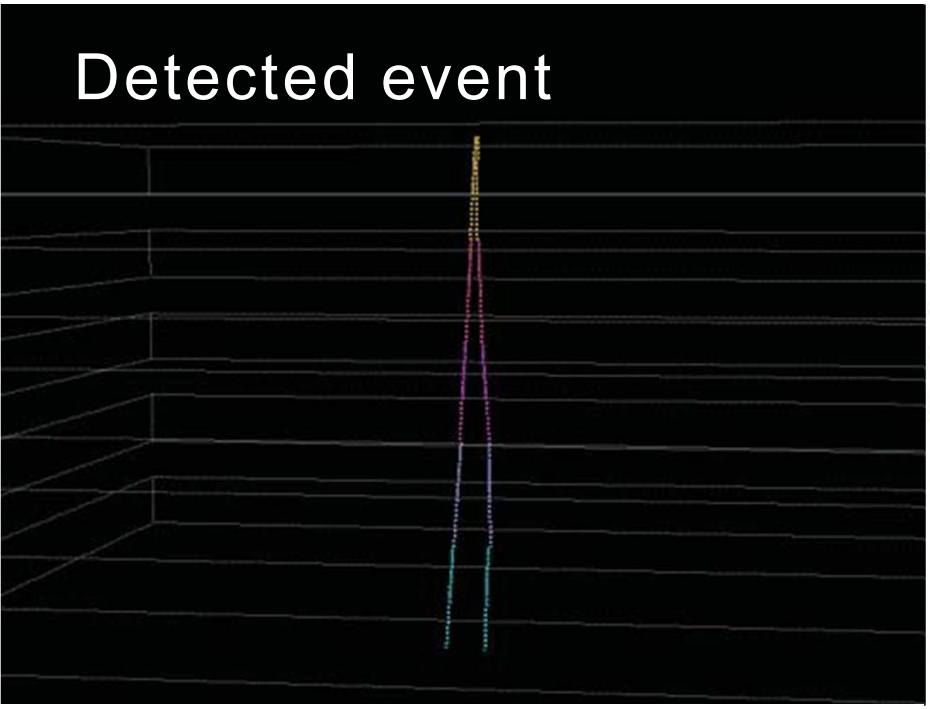
Energy Reconstruction

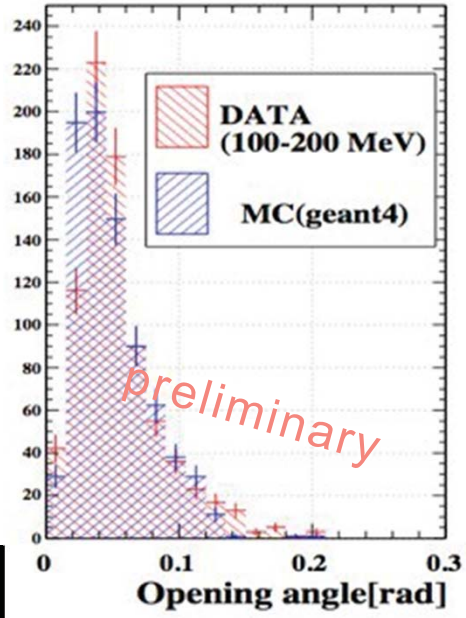


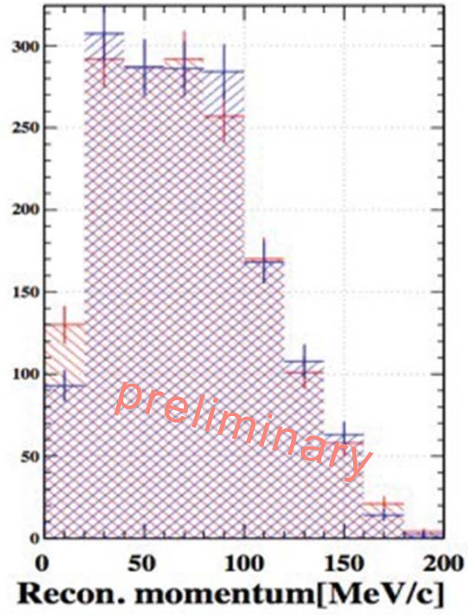
74% of total events are analyzed

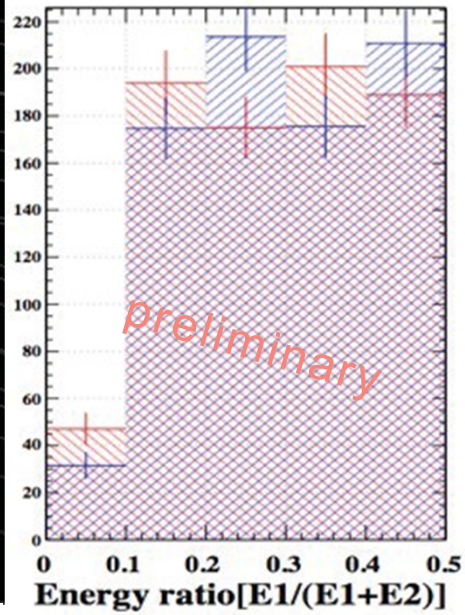
Checking DATA⇔MC

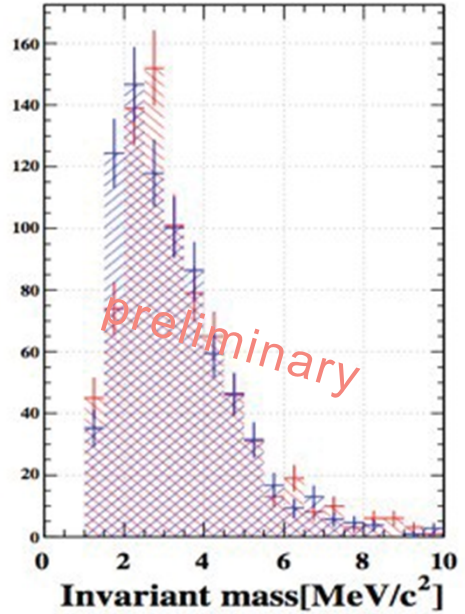
(w/ detector response)



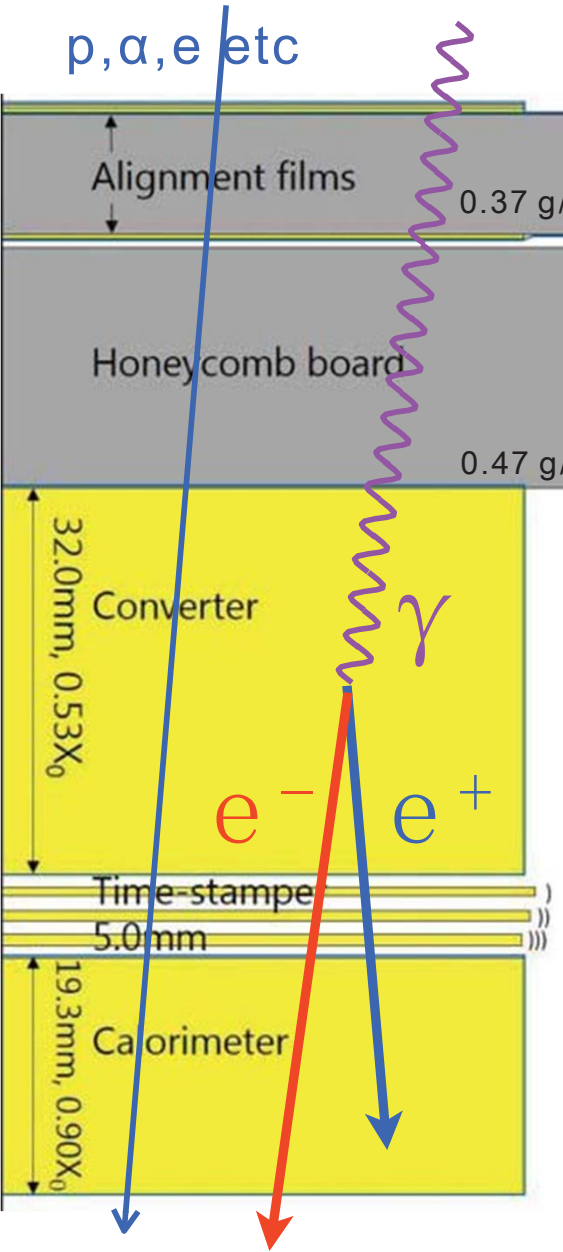








Flow of the Analysis



Film Read-out

Converter Analysis

- Connection & Alignment
- $\gamma \rightarrow e^{+}e^{-}$ Selection
- Connection to Time Stamper

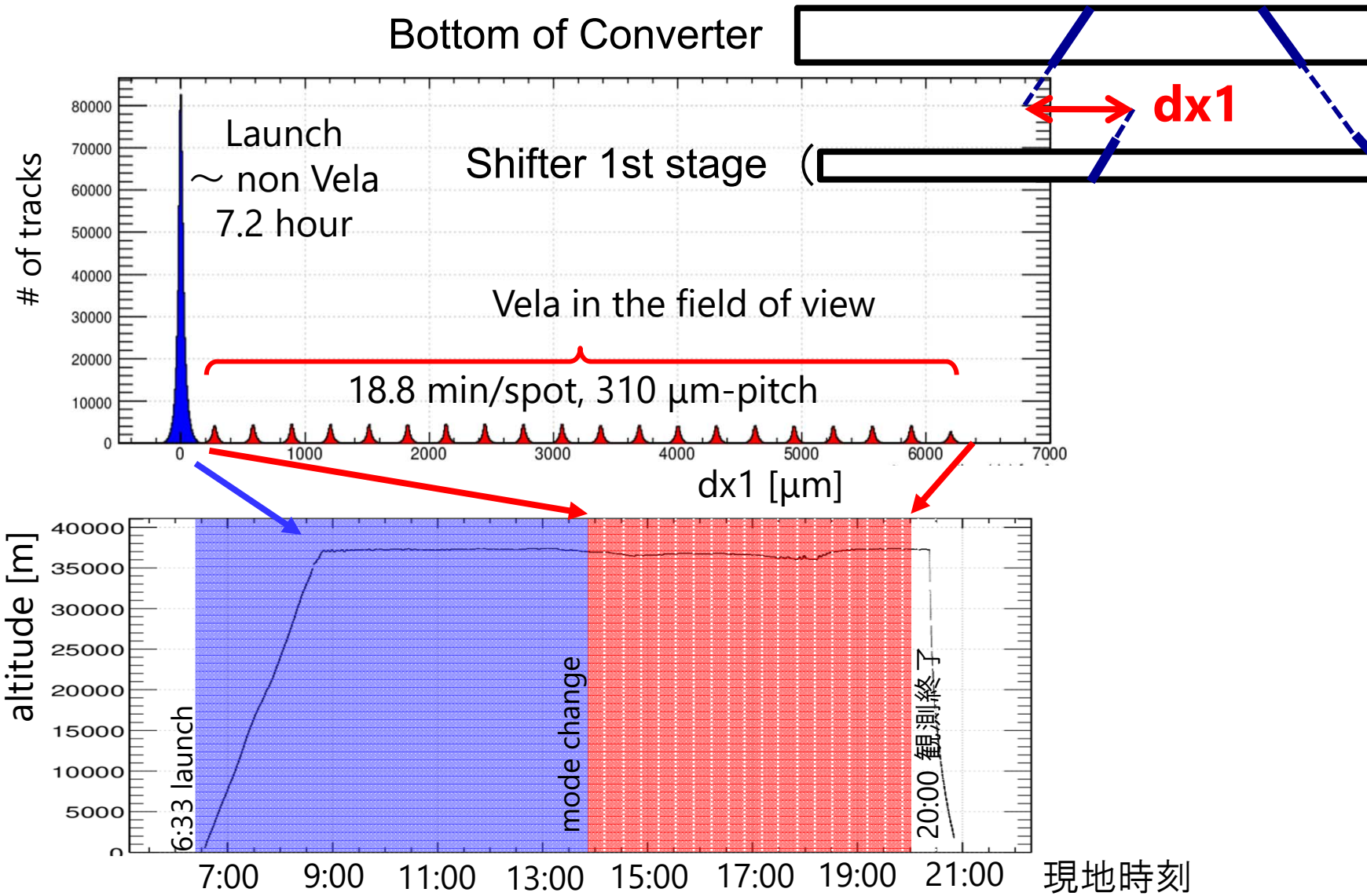
Time Stamper Analysis

Star Camera Analysis (Attitude monitor)

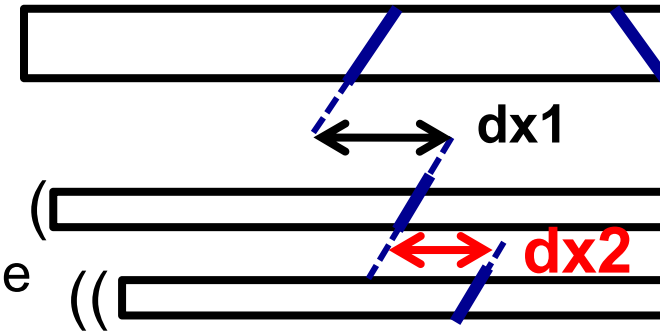
Pointing to celestial sphere

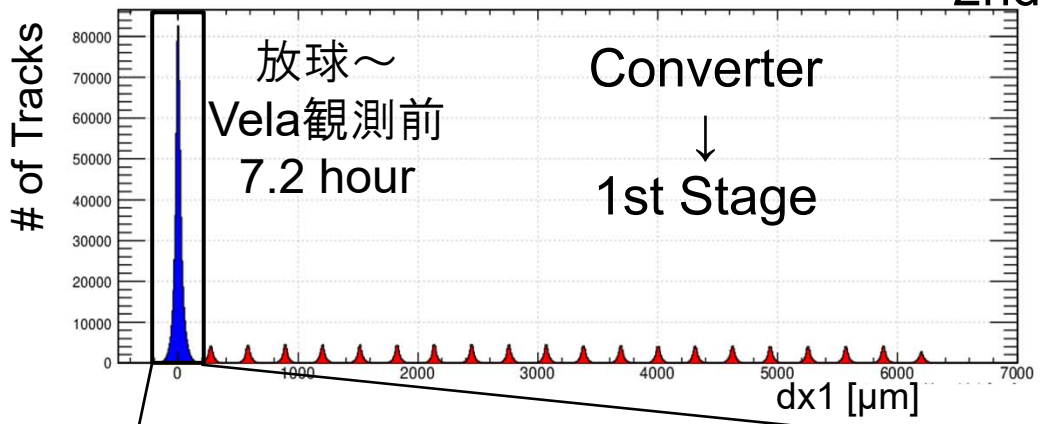
- Off Source region (BG)
- Vela region (Signal)

Time Stamp by Shifter 1st Stage

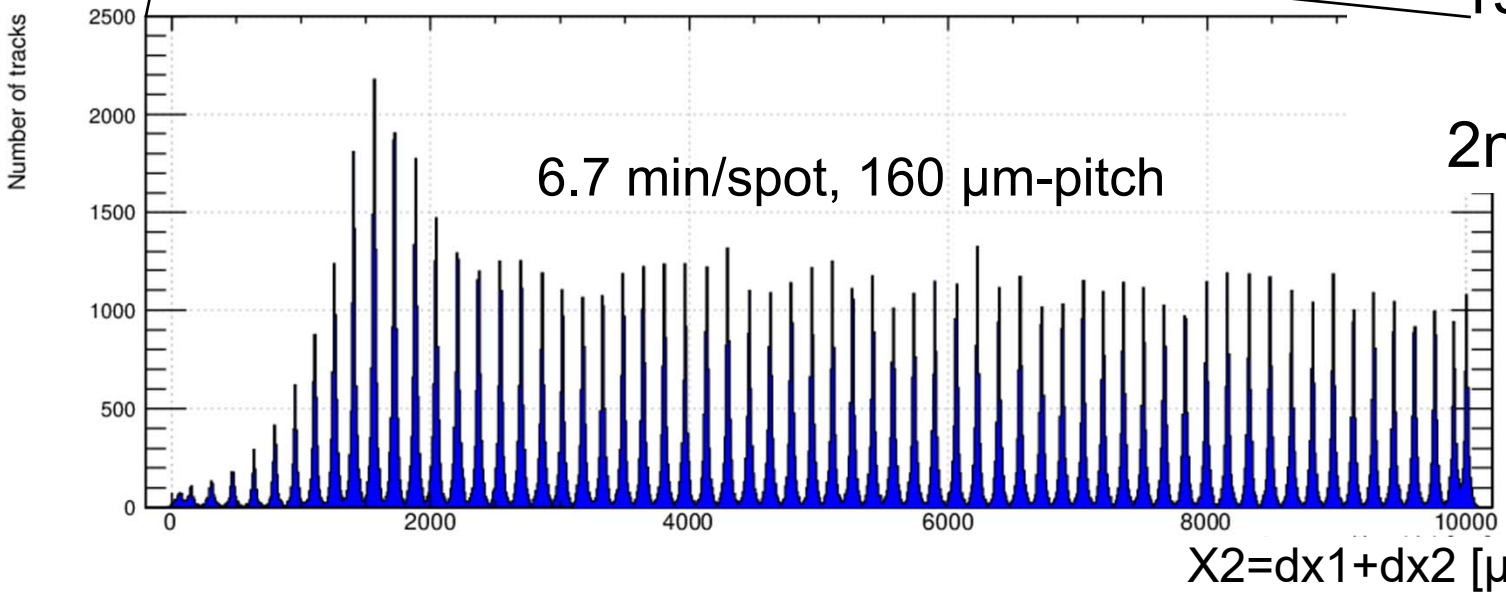


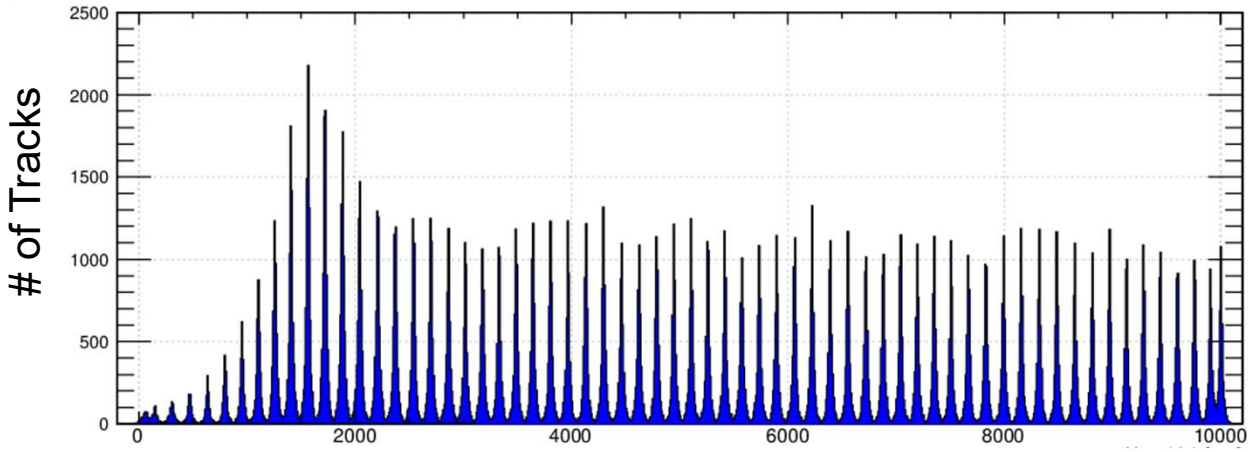
Shifter 2nd Stge



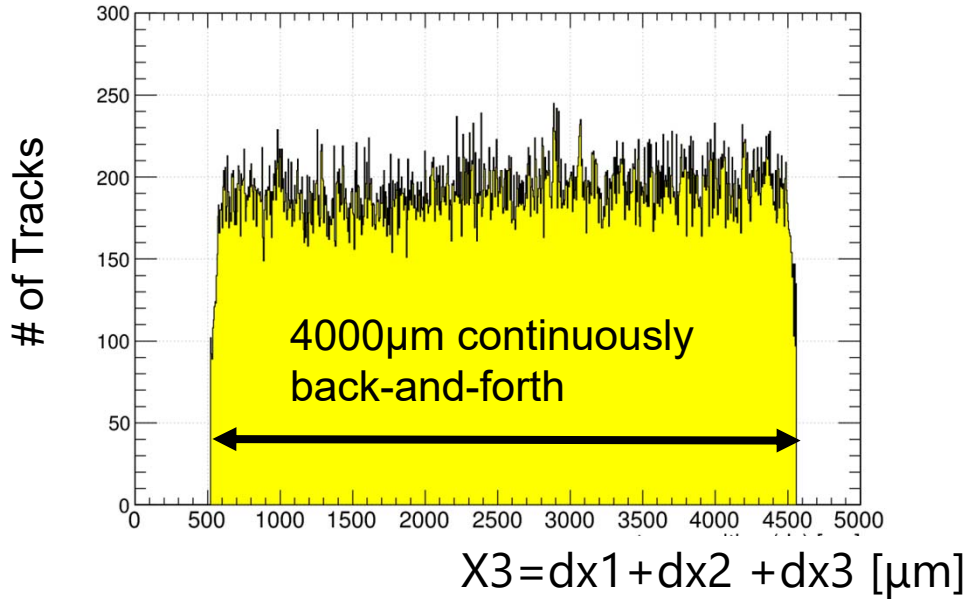


1st Stage
↓
2nd Stage





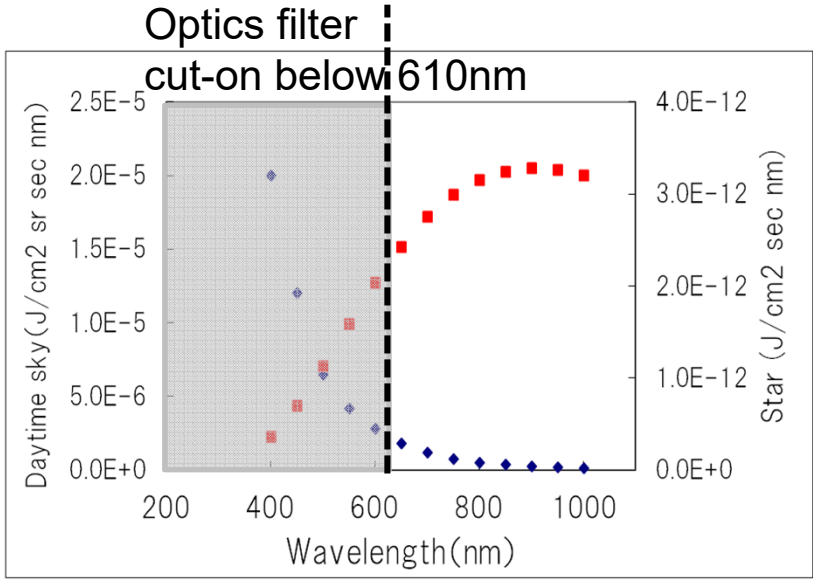
1st Stage
↓
2nd Stage



2nd Stage
↓
3rd Stage

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)

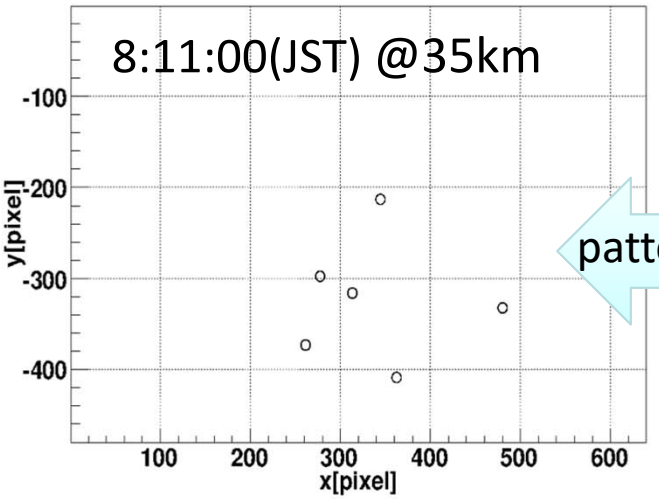
Field of View：
5.9deg(H)×4.5deg(V)
Limiting magnitude：6
Monitoring accuracy：0.16mrad

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

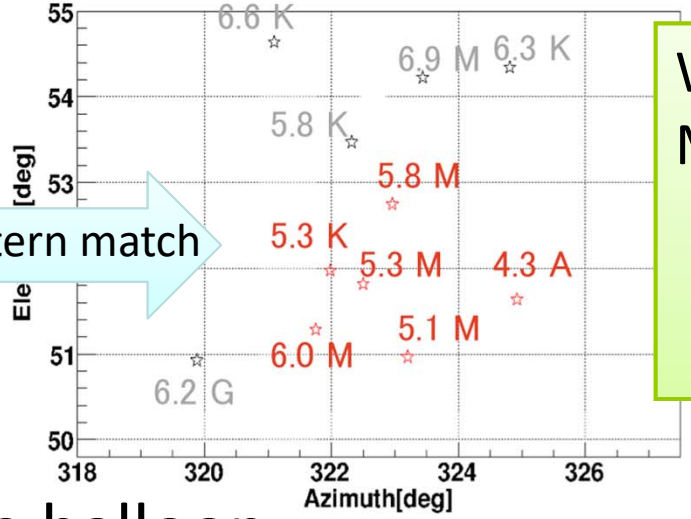
Attitude analysis

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

Daytime star camera view



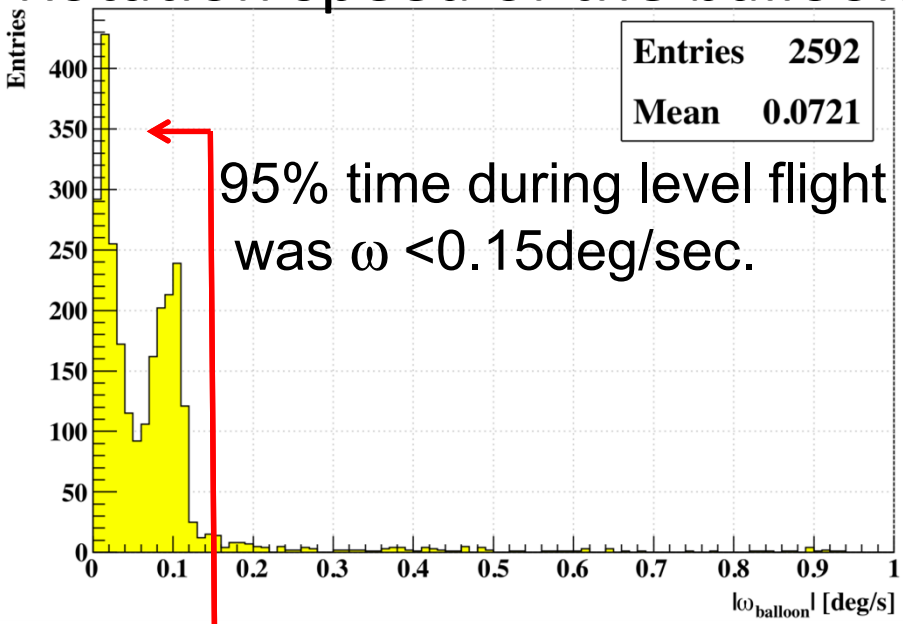
Star catalog data



pattern match

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

Rotation speed of the balloon

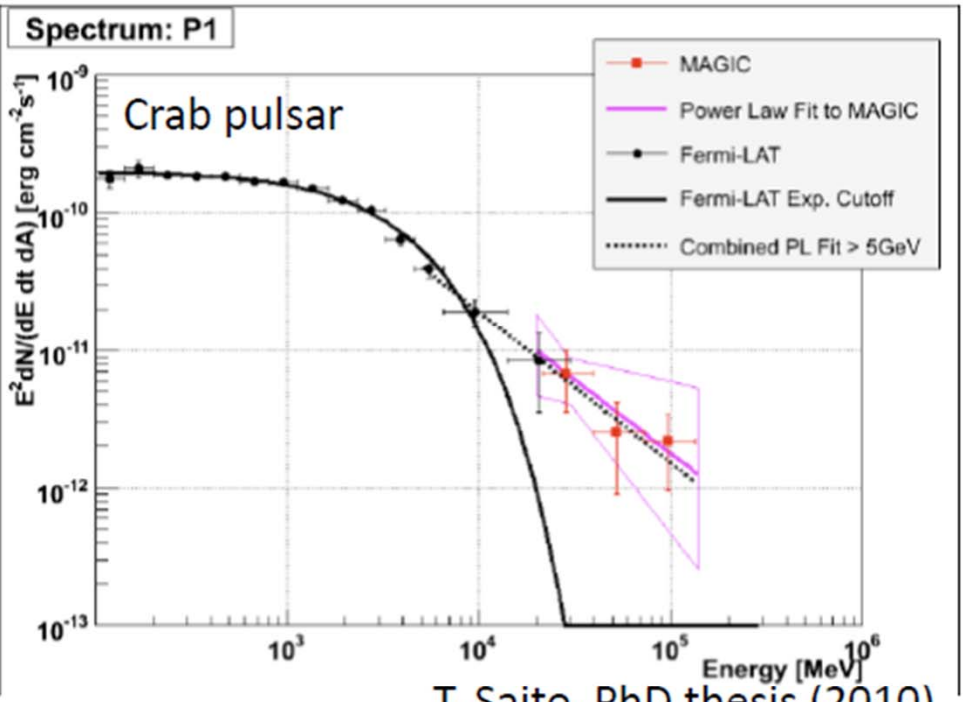


It is important to decide telescope attitude to celestial coordinate better than emulsion angular resolution(0.08deg).

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

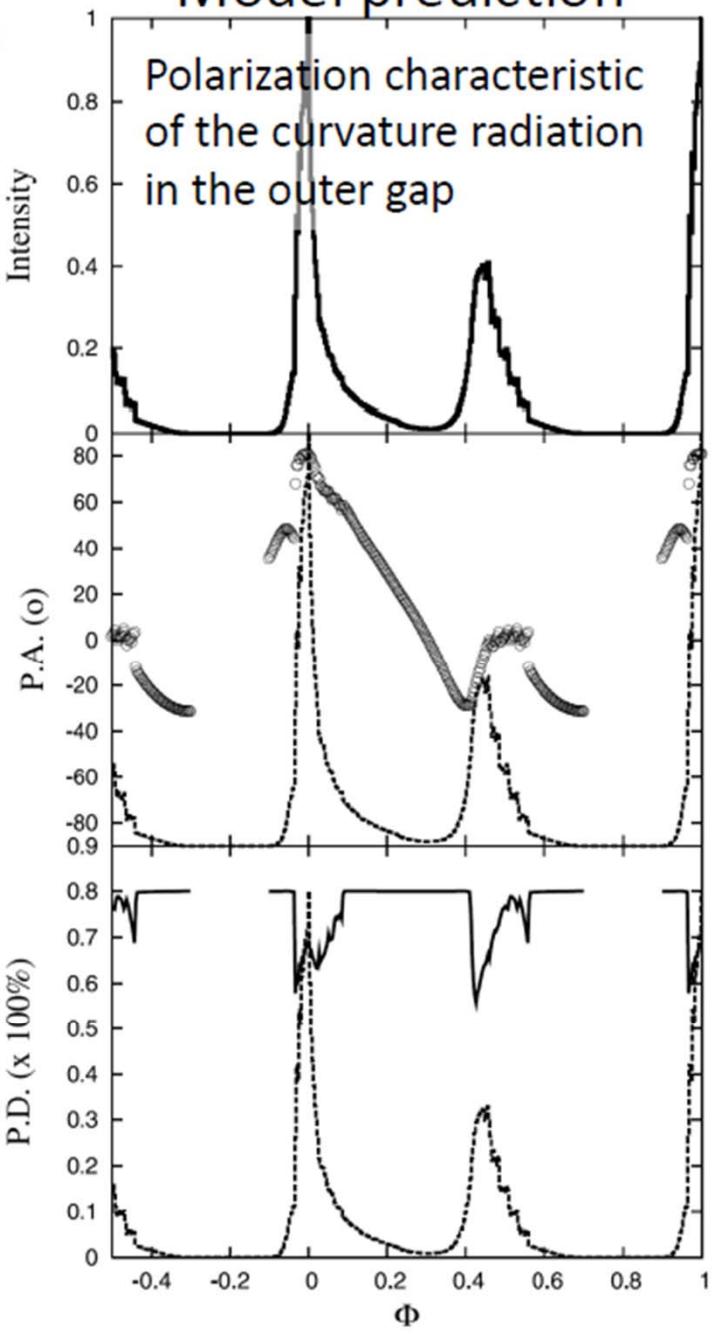
Pioneering polarization observation for high energy γ-rays
Approaching emission mechanism

Pulsars, AGNs, Flares, GRBs



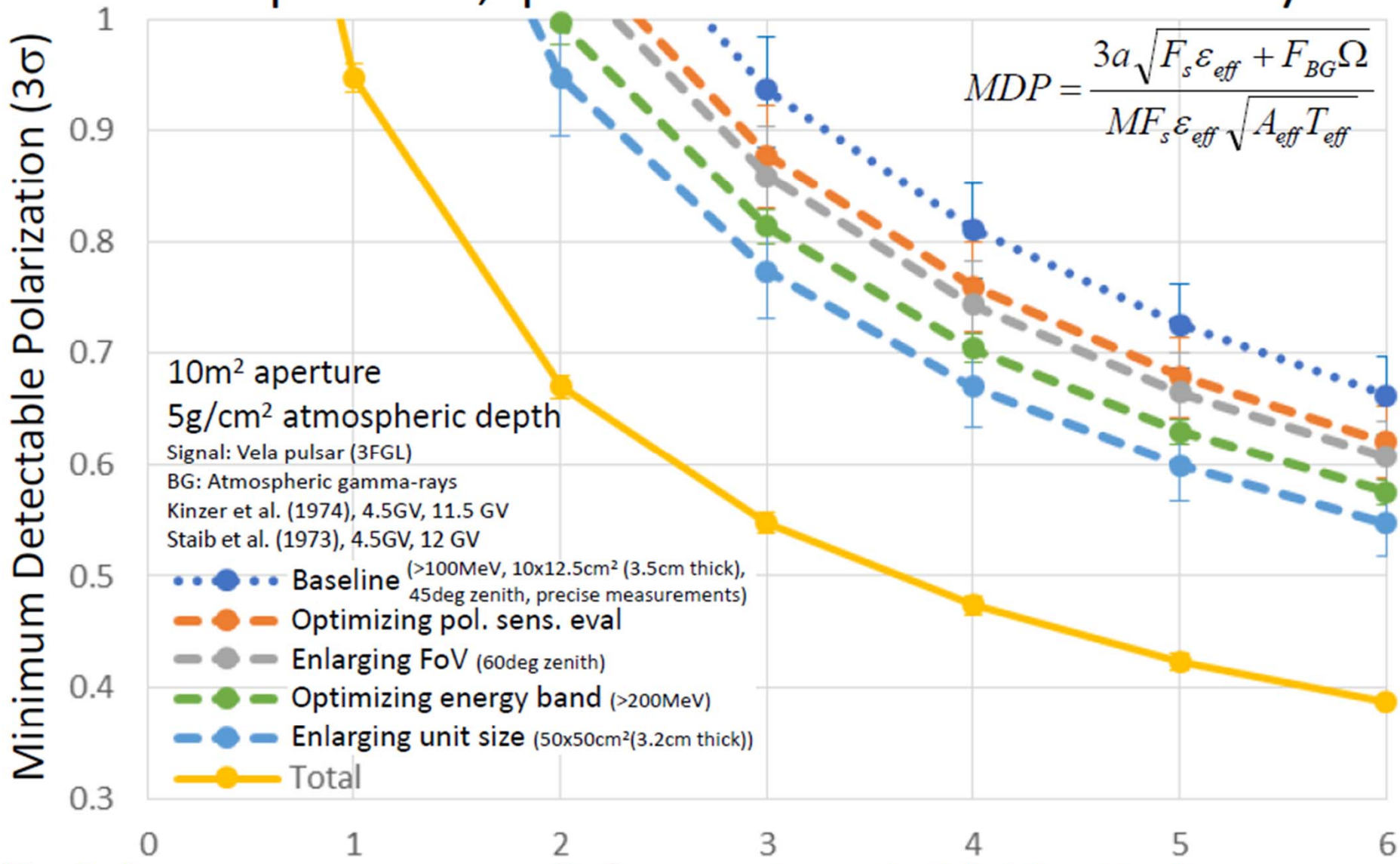
T. Saito, PhD thesis (2010)

Model prediction



J.Takata and H.-K.Chang, ApJ, 670:677-692, 2007

Vela pulsar, polarization sensitivity



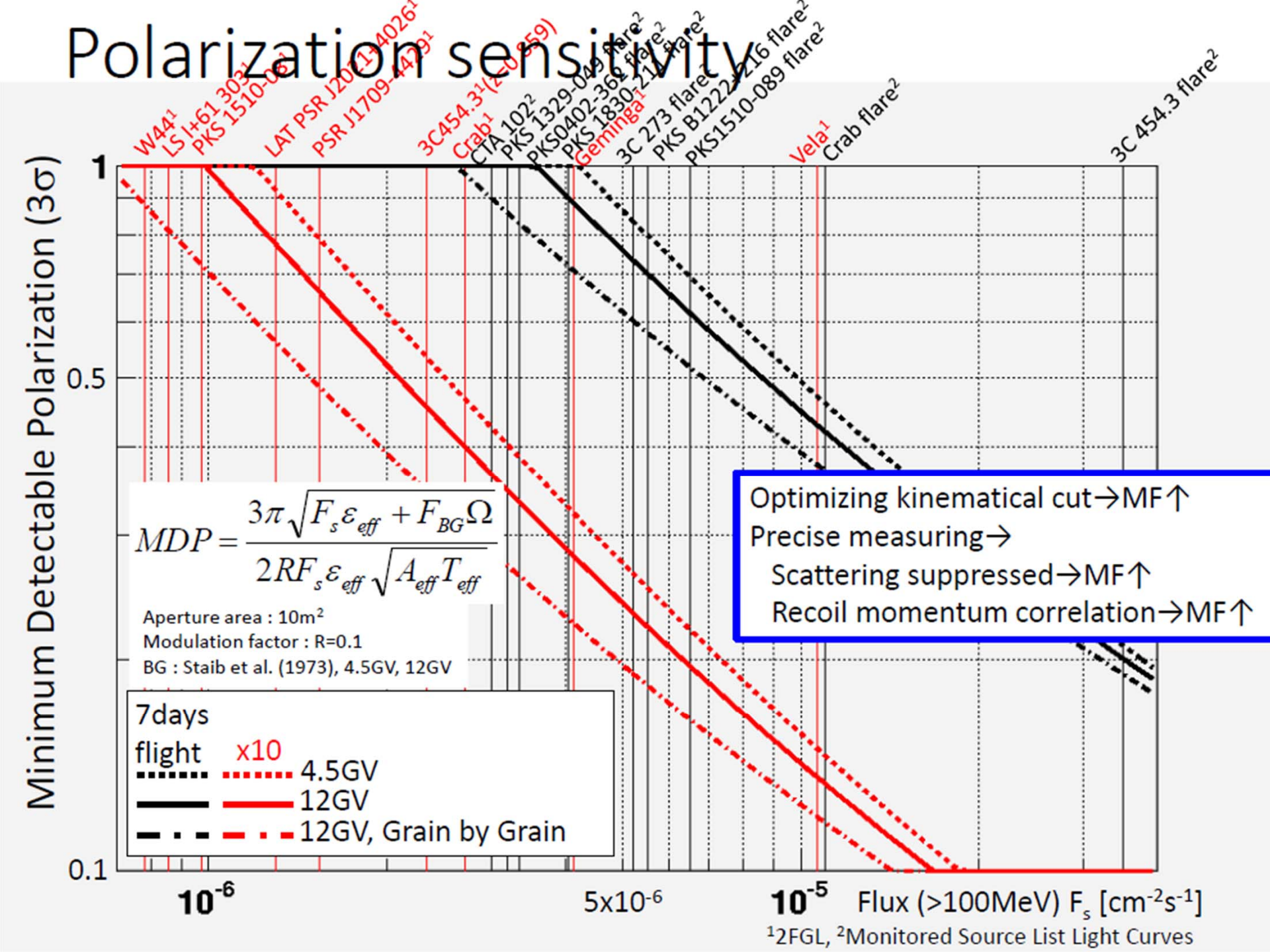
Alice Springs

Apr. 15th, 19:39(ACST) culmination, 21.6deg zenith

16:24–22:54 (6.5h/cross) w/in 45deg zenith, 14:58 – 24:20(9.4h/cross) w/in 60deg zenith

# of crosses of a source in a field of view of the telescope with diurnal rotation (roughly corresponding to flight days)

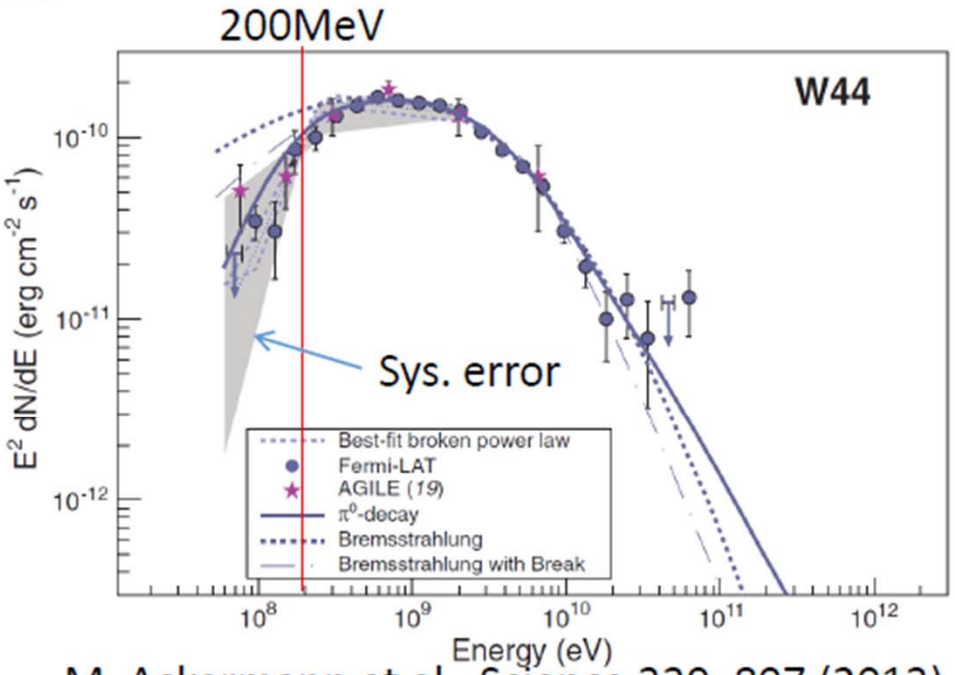
Polarization sensitivity



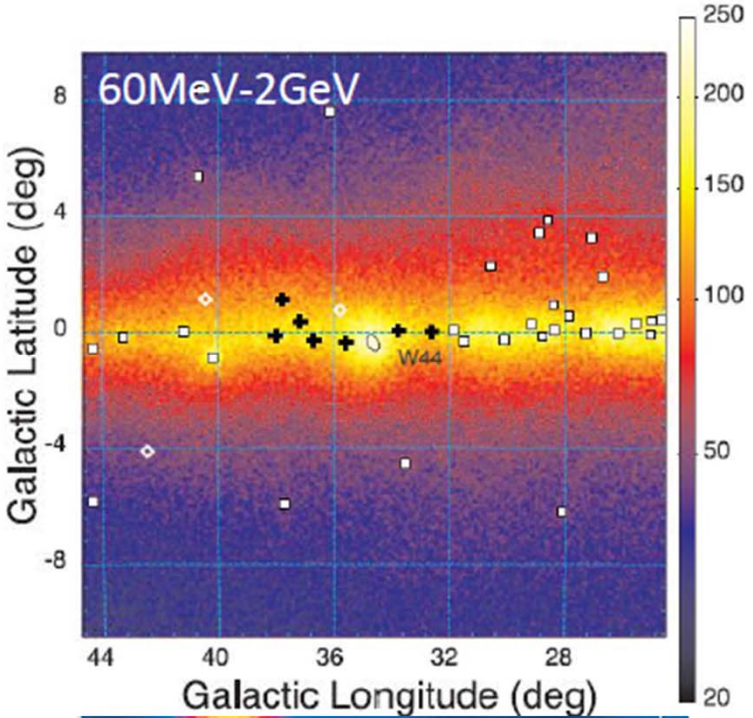
[1]2FGL, [2]Monitored Source List Light Curves

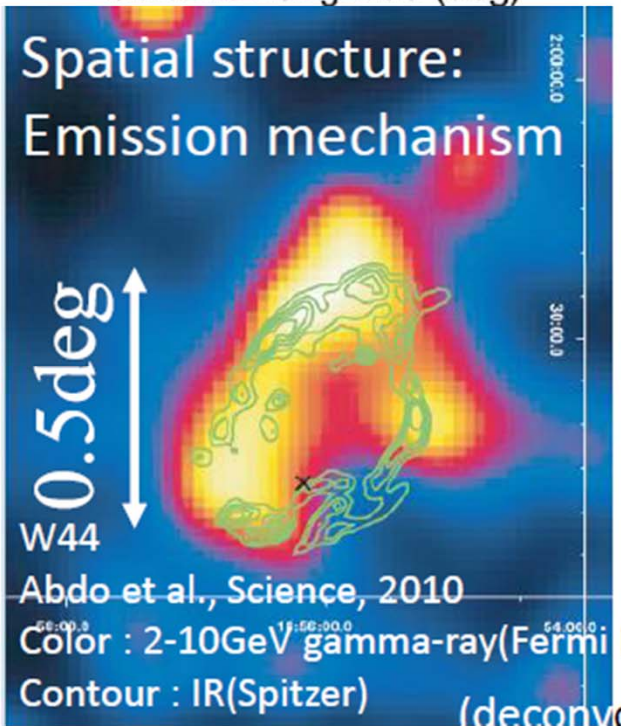
π^0 emission: Direct evidence of proton acceleration

SNRs



M. Ackermann et al., Science 339, 807 (2013)

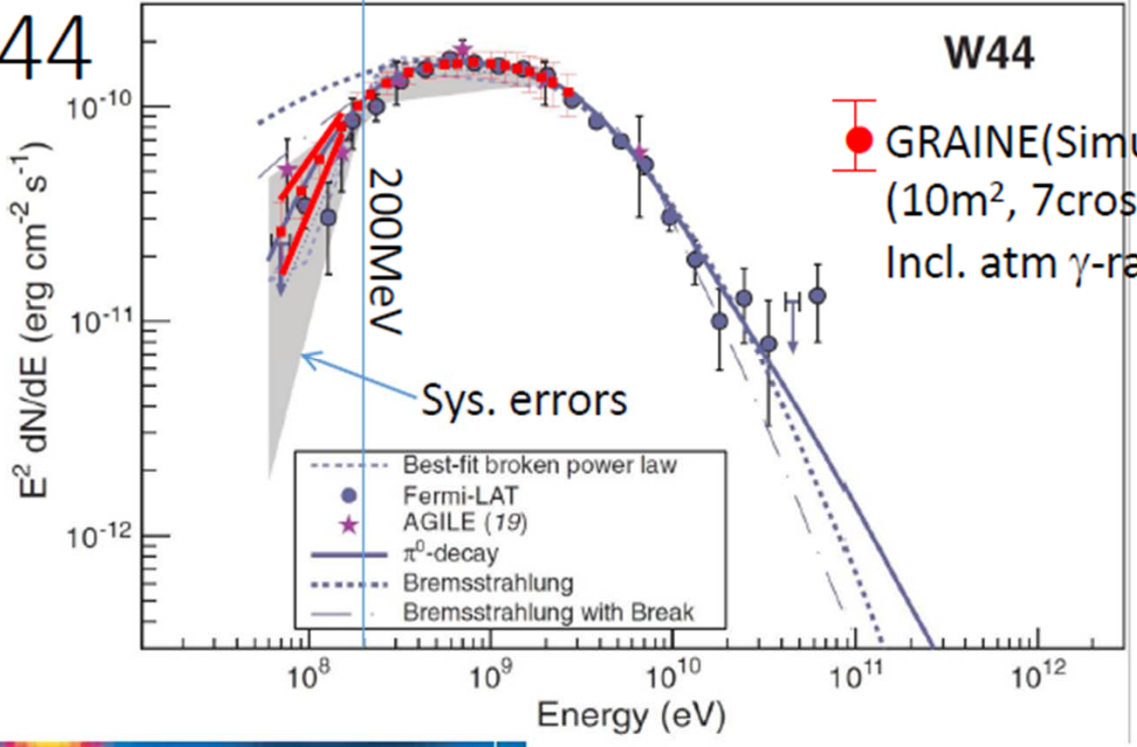




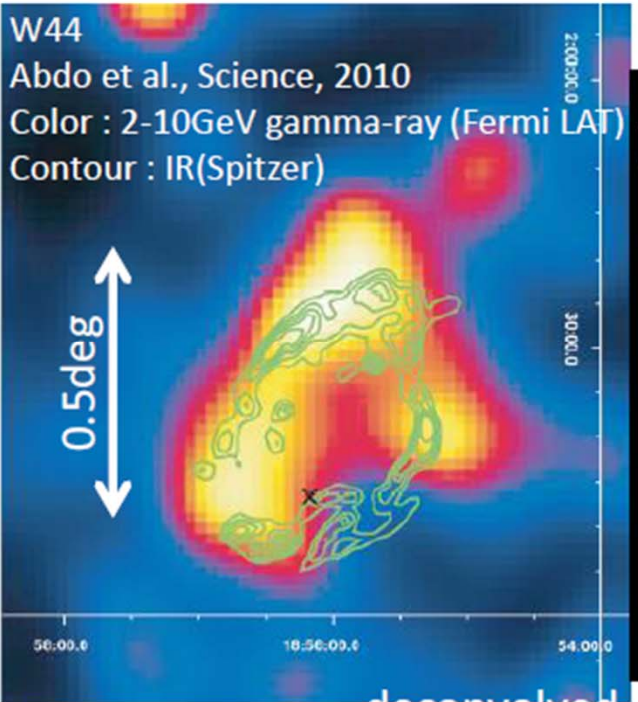
<200MeV, precise spectrum measurements with suppressed systematic errors

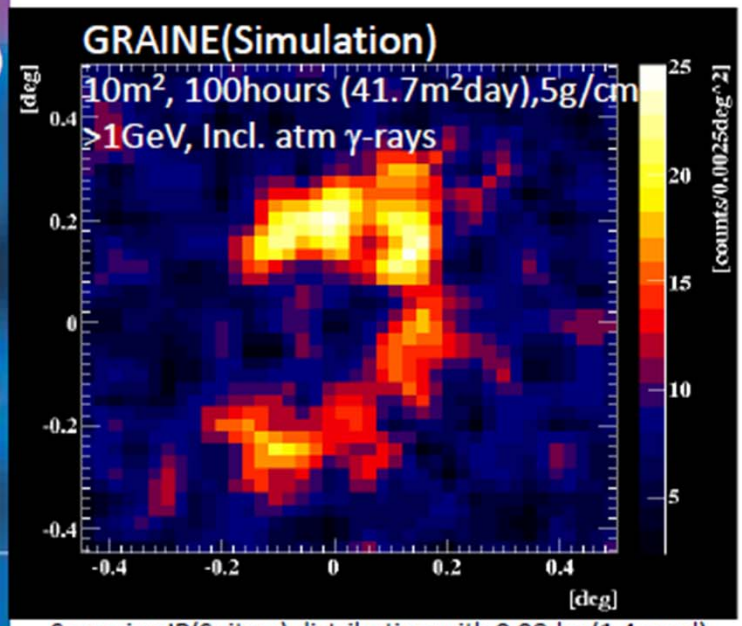
>200MeV, investigating spatial structure

W44



<200MeV
Precise spectral measuring
with suppressed systematic error



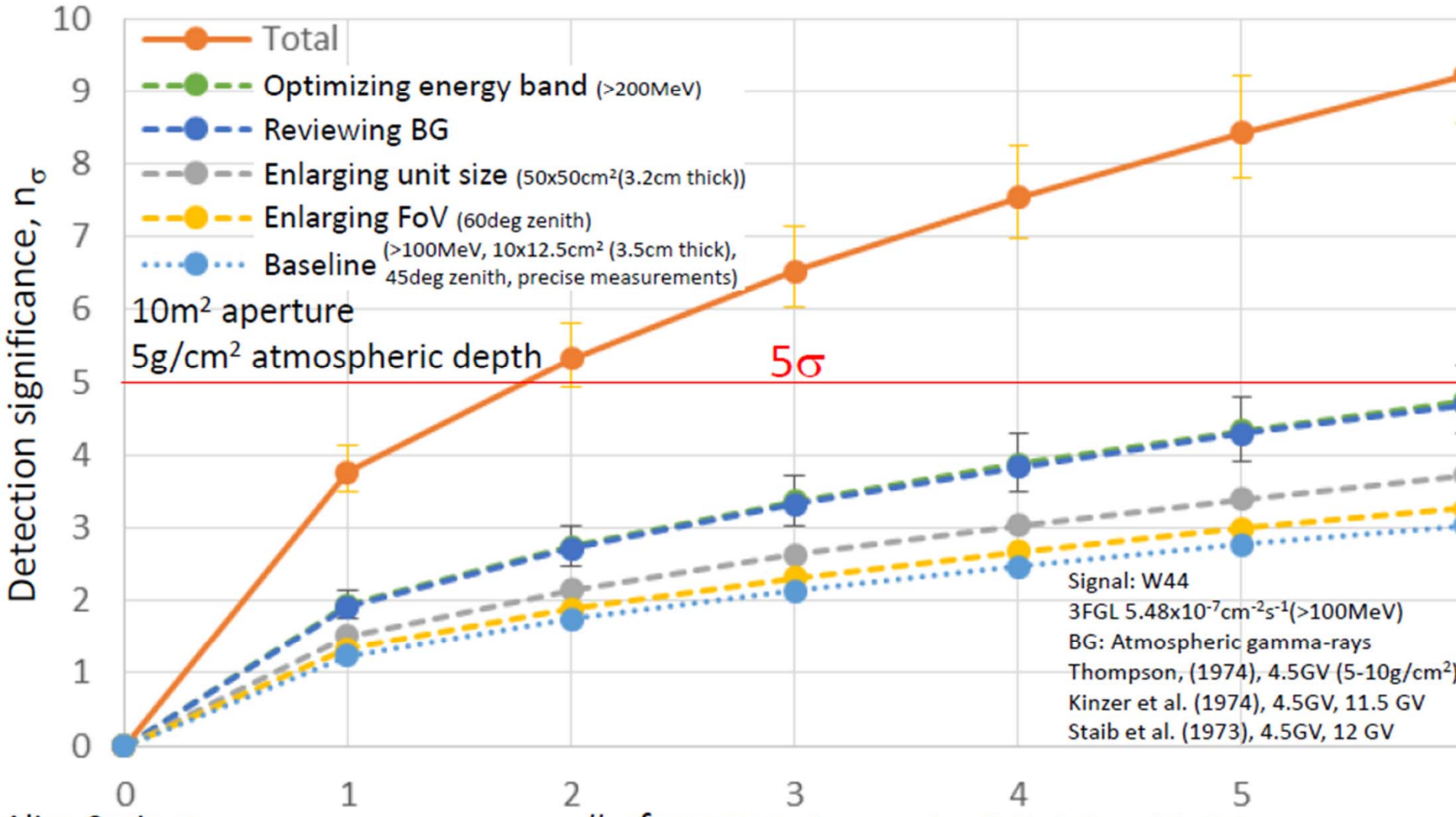


>200MeV
Investigating spatial structu

Smearing IR(Spitzer) distribution with 0.08deg(1.4mrad)

W44 detection sensitivity

$$n_\sigma = \frac{N_s}{\sqrt{N_{BG}}}$$



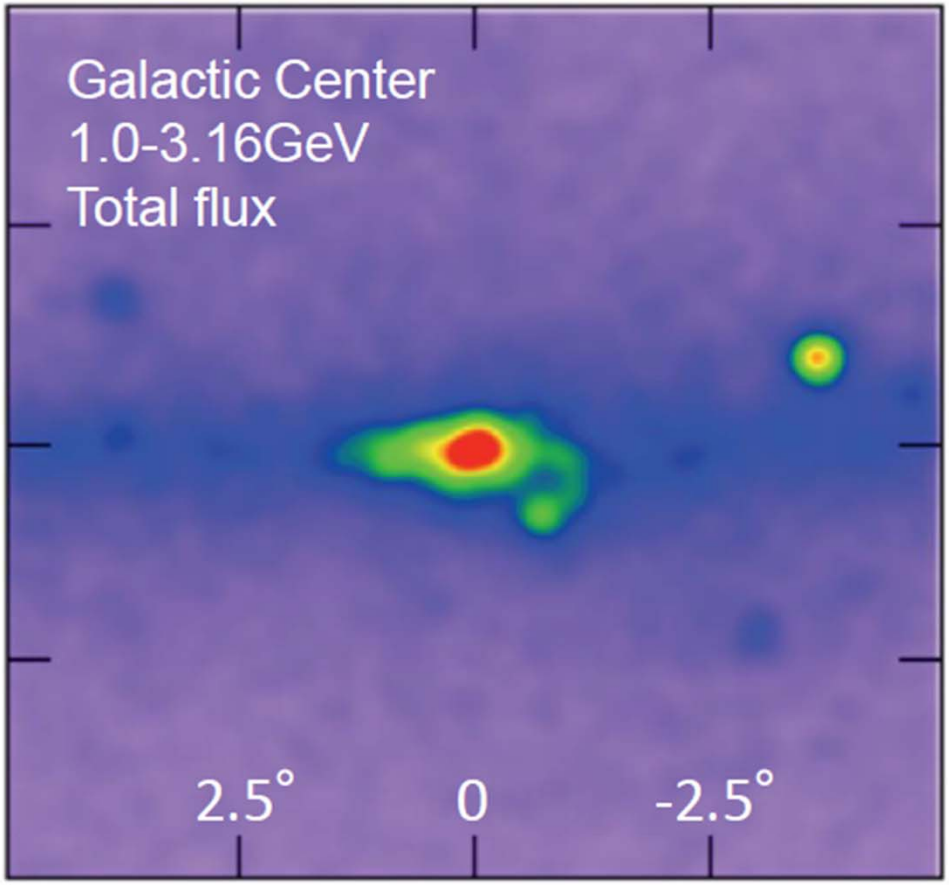
Alice Springs

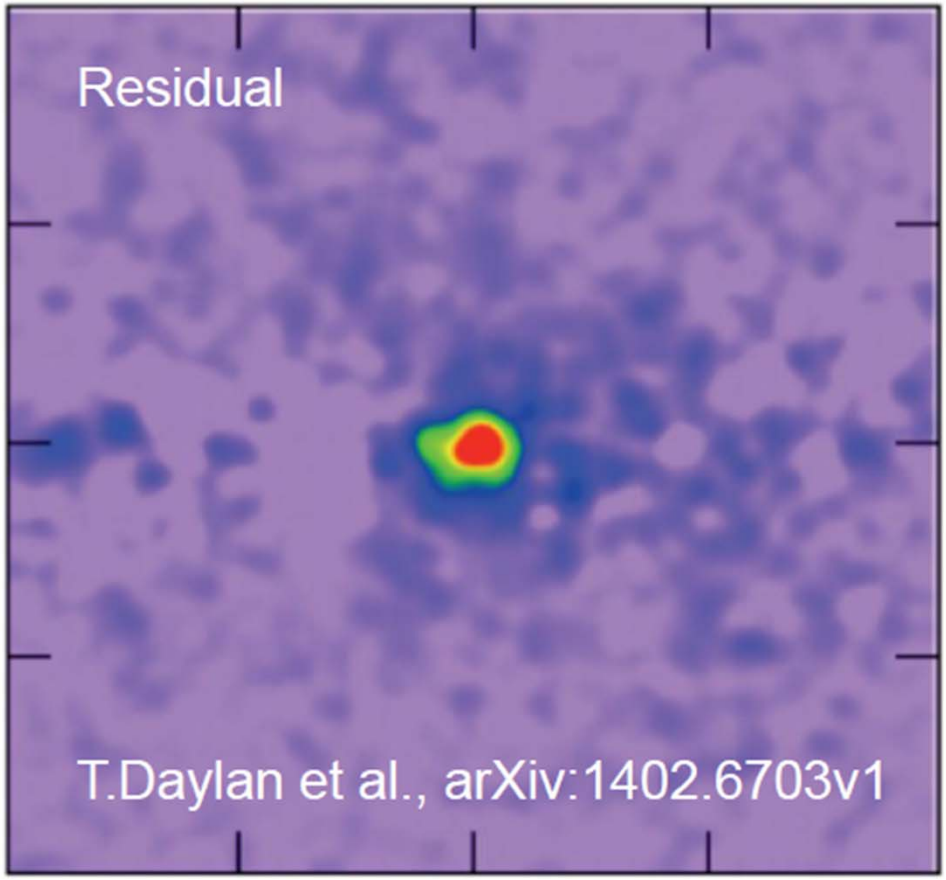
Apr. 15th, 6:04(ACST) culmination, 25.1deg zenith

of a source in a field of view of the telescope

with diurnal rotation (roughly corresponding to flight da

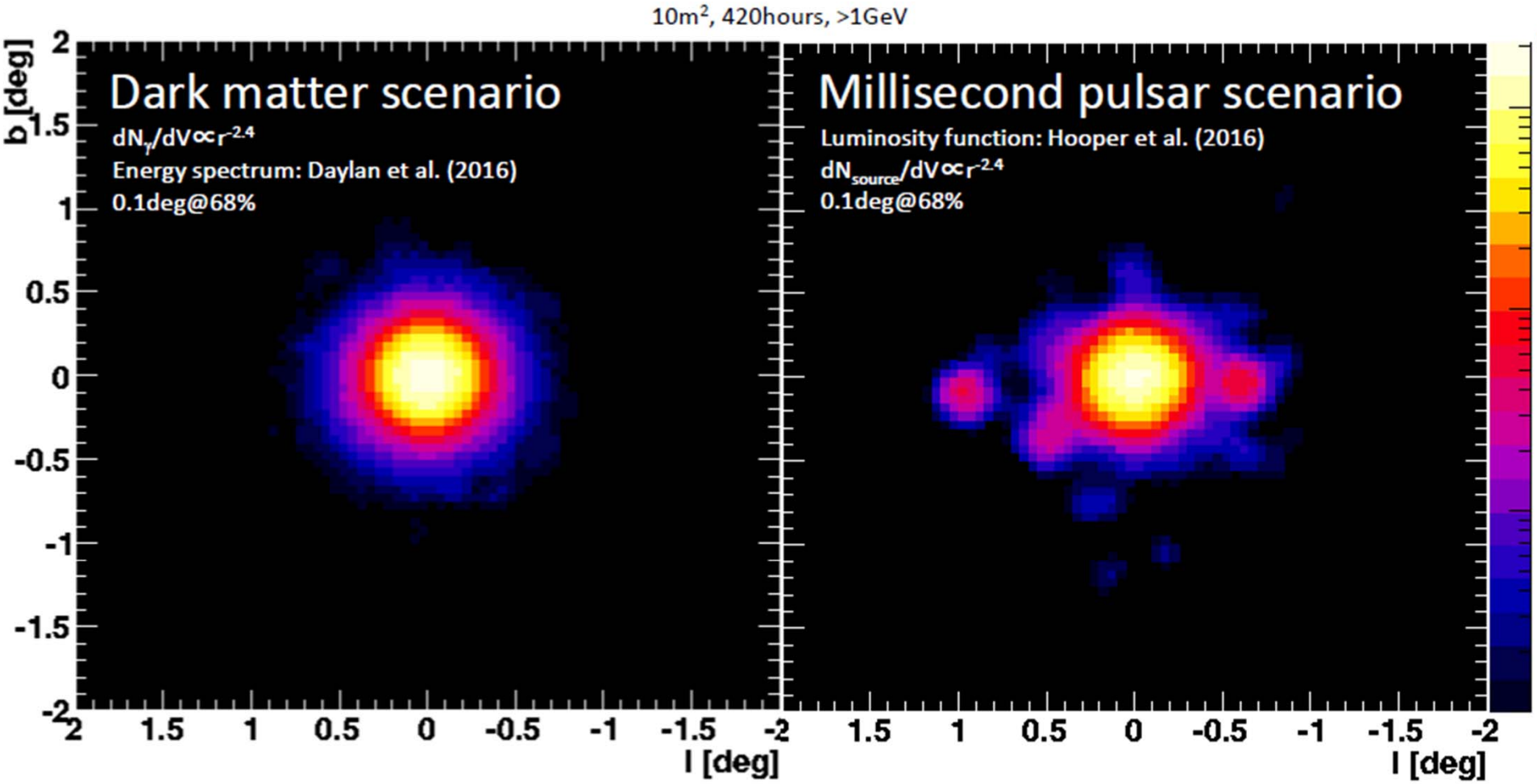
GeV γ-ray excess at galactic center region



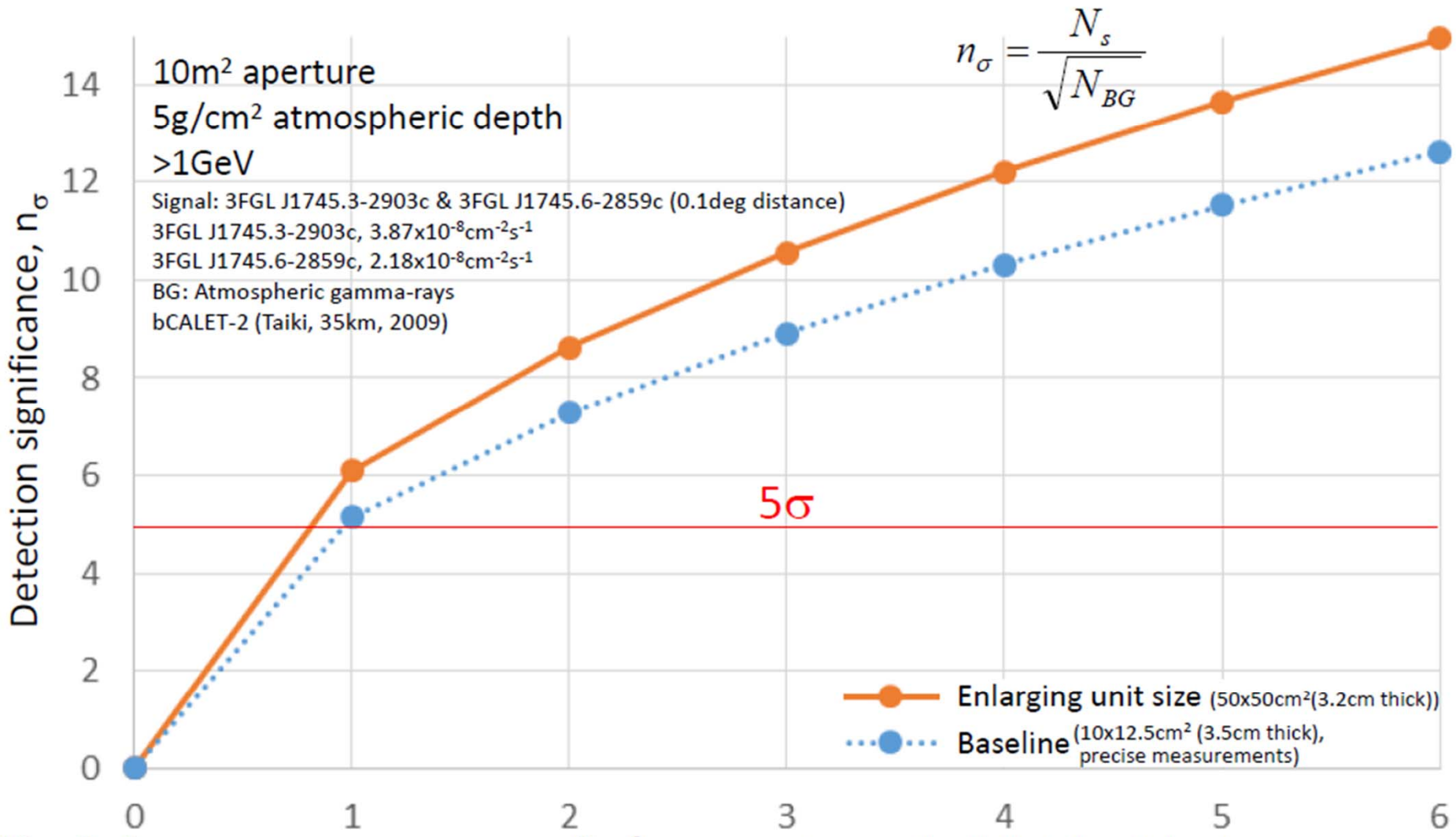


GeV γ-ray observations at galactic center region with ~arcmin resolution

Simulation of GeV γ-ray excess at galactic center regio w/ high angular resolution



Galactic center region, detection sensitivity



Alice Springs

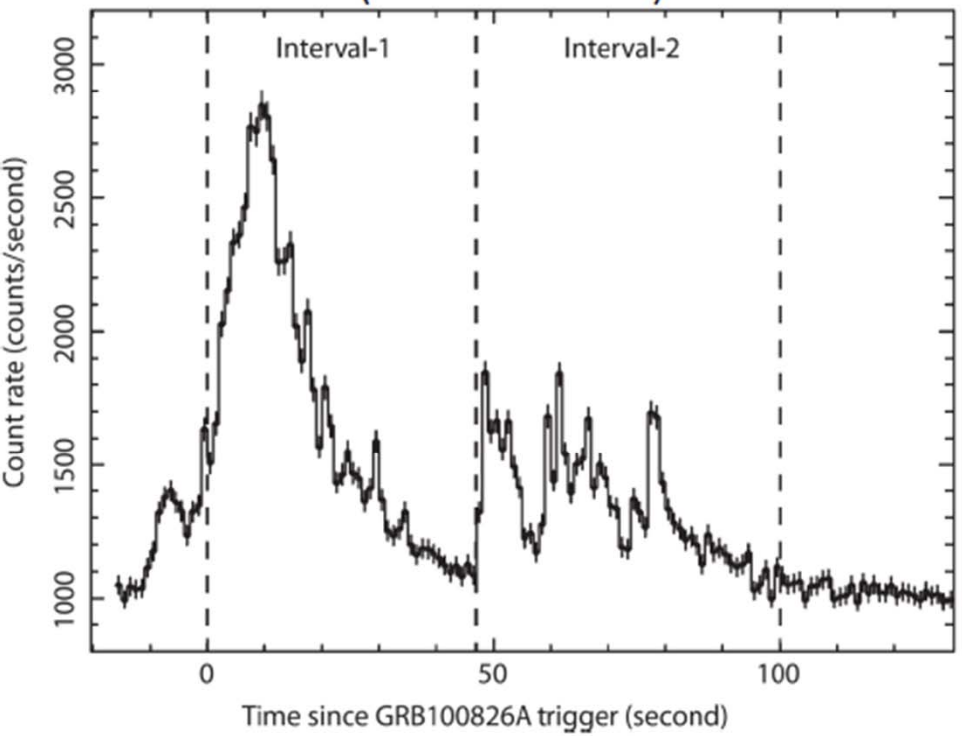
Apr. 15th, 4:53(ACST) culmination, 5.3deg zenith

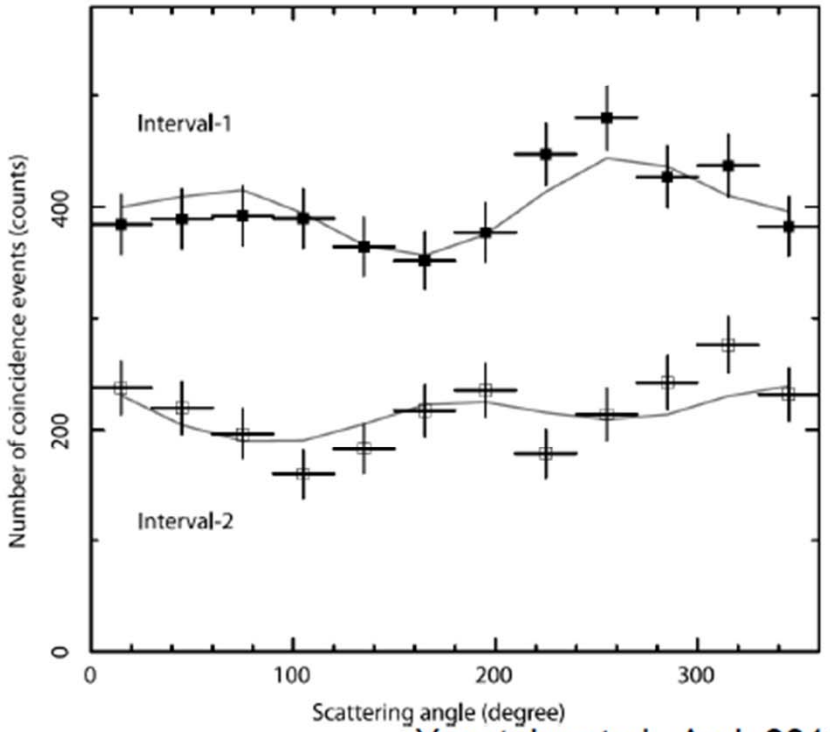
1:31–8:16 (6.75h/cross) w/in 45deg zenith

N_{signal}=132, N_{BG}=78 @ 6 crosses

Test of fundamental symmetries beyond the Planck scale

IKAROS-GAP (70keV-300keV)





Yonetoku et al., ApJ, 2011

Scale of CPT violation (rotation angle of pol. vector)

$$d\theta \simeq \xi p^2 dt / M_{Pl}$$

Constraint from GRB pol. obs. by GAP

$$|\xi| < O(10^{-15})$$

K.Toma et al., PRL 109, 241104 (2012)

By polarization observation for **high energy γ-rays** (e.g. > 100 MeV) from **distant AGNs and GRBs** by emulsion γ-ray telescope, **much strict** (five order of magnitude better) **validation** of CPT symmetry can be performed.