

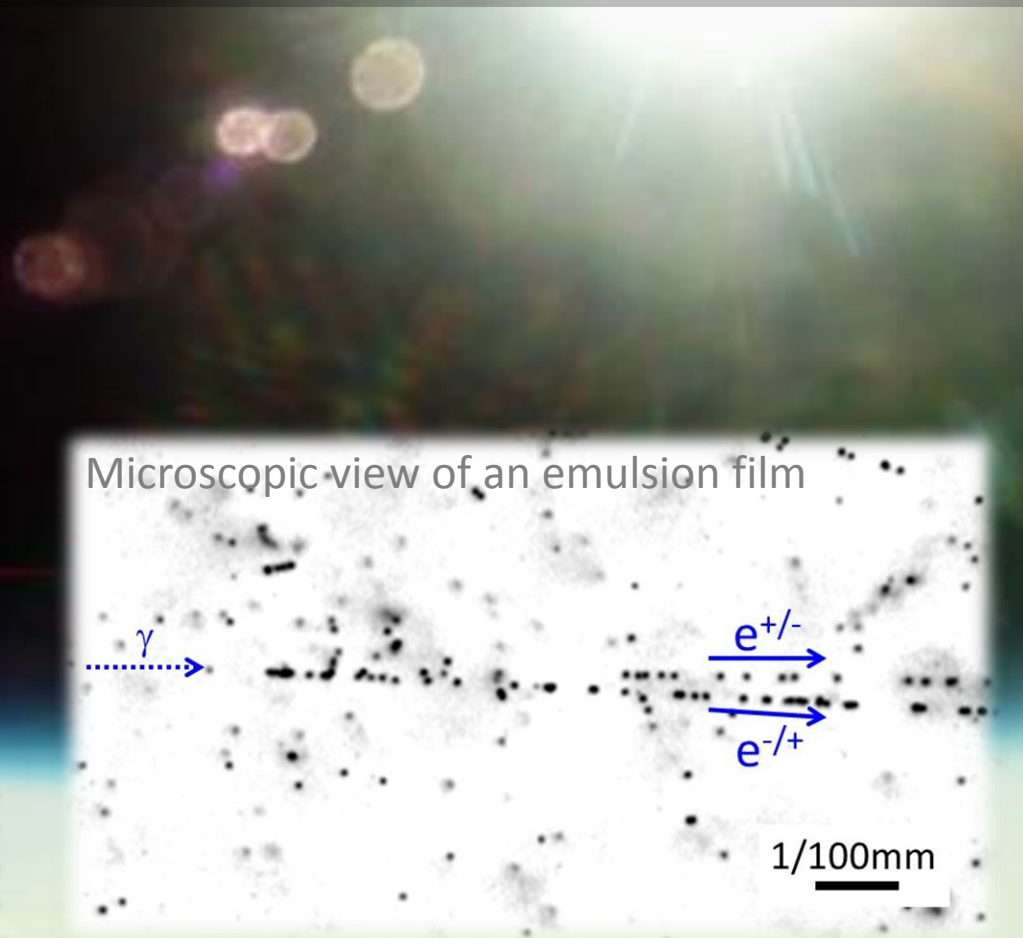
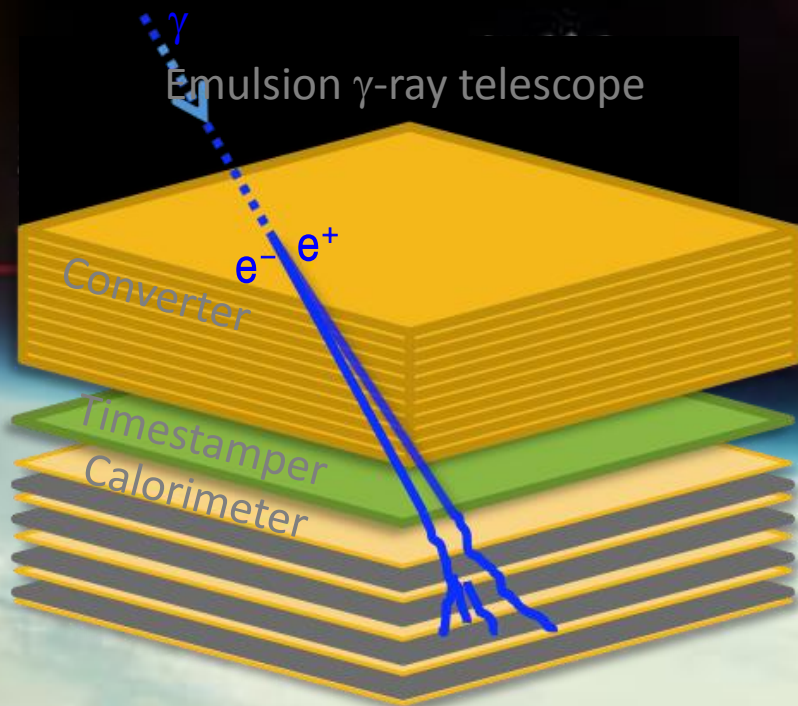
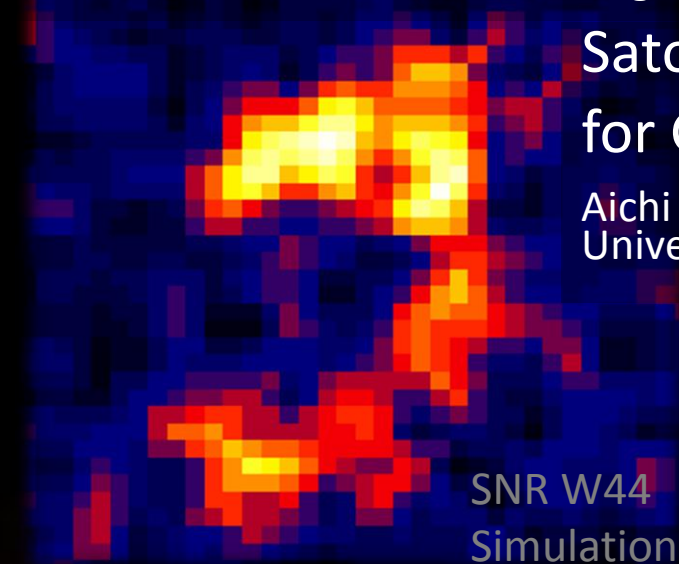
# GRAINE project

$\gamma$ -ray observations by balloon-borne emulsion telescope with a high angular resolution, polarization sensitivity and large-aperture-area

Satoru Takahashi (Kobe Univ.)

for GRAINE collaboration, PI: S. Aoki (Kobe Univ.)

Aichi University of education, ISAS/JAXA, Kobe University, Nagoya University, Okayama University of science, Utsunomiya University



BG photo : GRAINE2011, JAXA scientific ballooning (taken by NHK)

# Fermi's Five-year View of the Gamma-ray Sky ( $>1\text{GeV}$ )

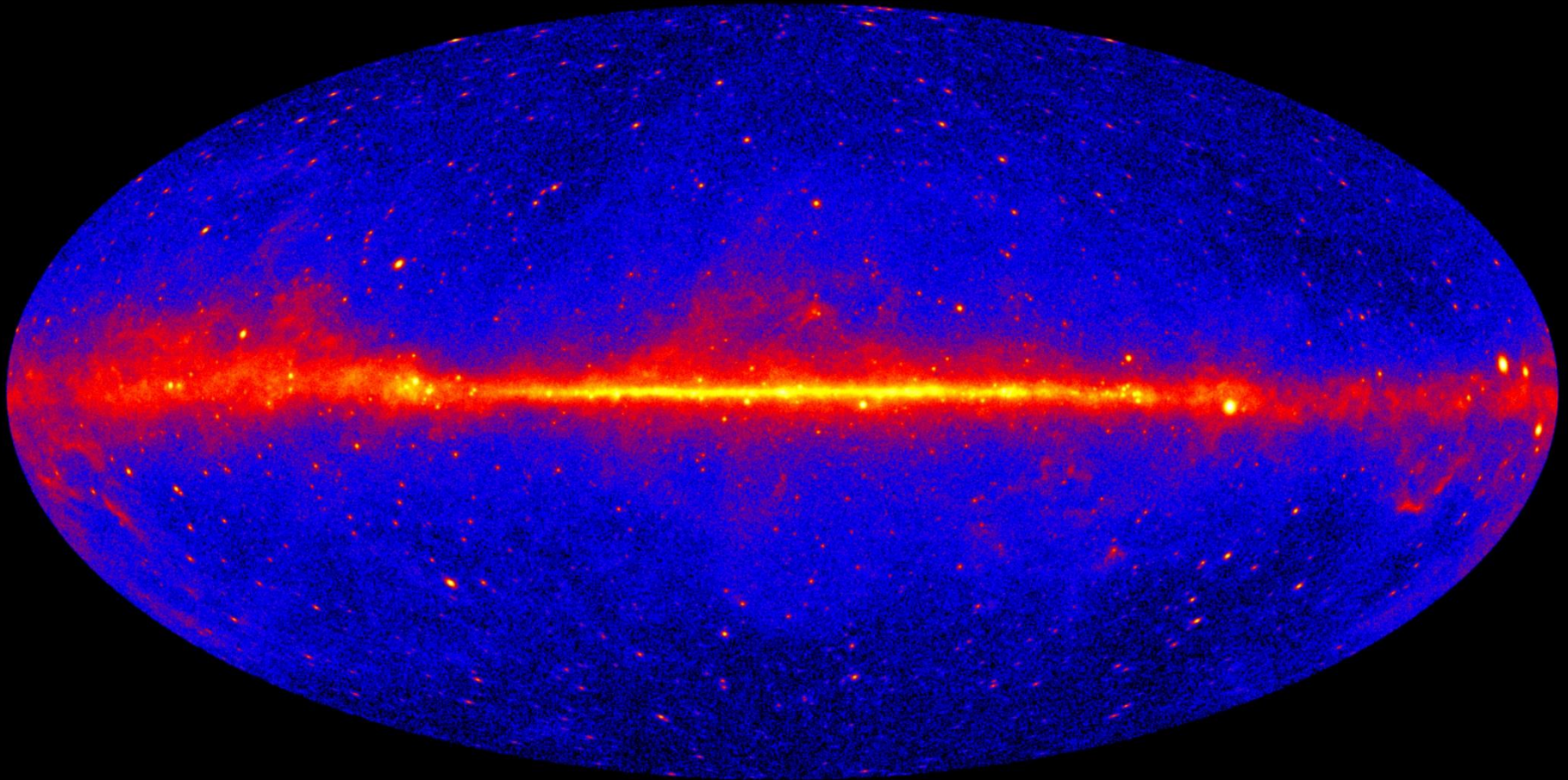


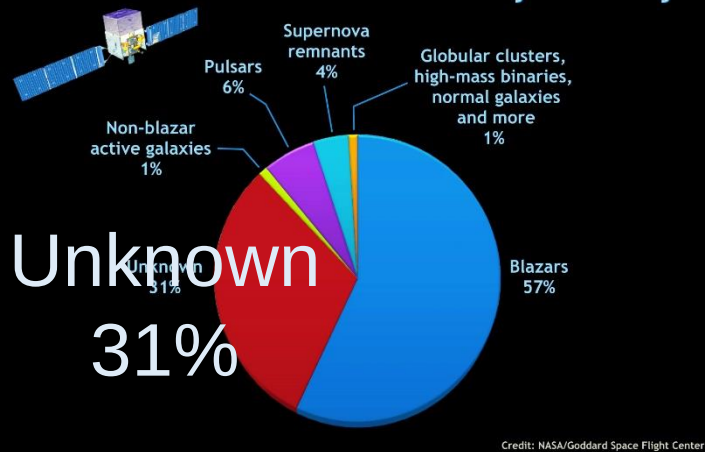
Image credit: NASA/DOE/Fermi LAT Collaboration

$>3000$  sources (3FGL)



# Un-ID

What has Fermi found: The LAT two-year catalog



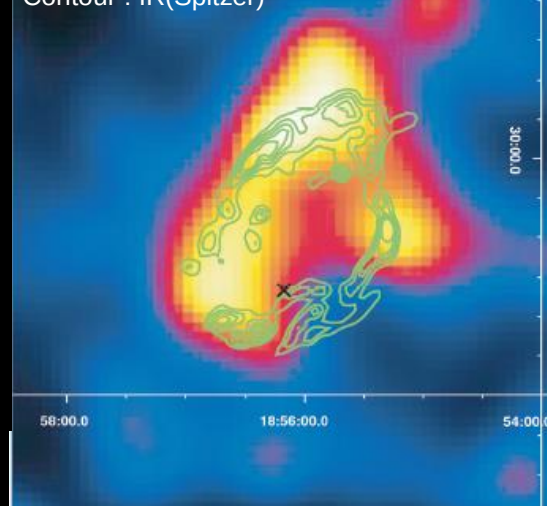
# Morphology

## SNR W44

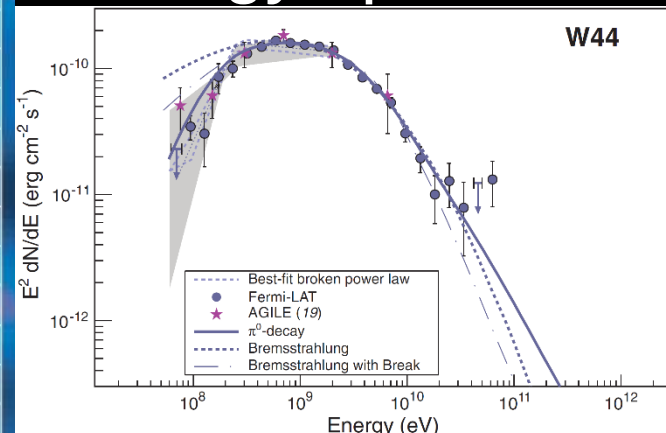
Abdo et al., Science, 2010

Color : 2-10GeV gamma-ray (Fermi LAT)

Contour : IR(Spitzer)



# Energy spectrum



M. Ackermann et al. Science, 2013

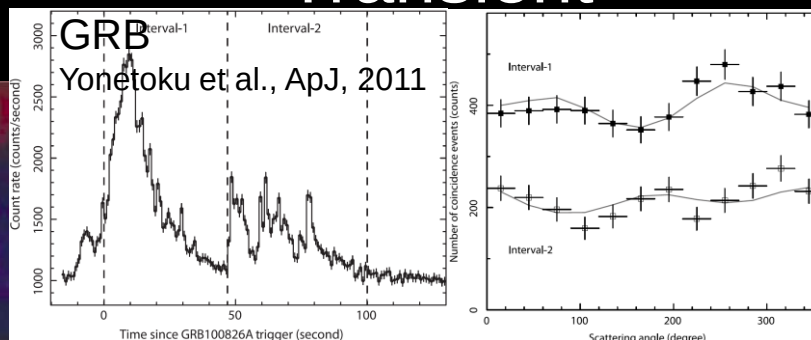
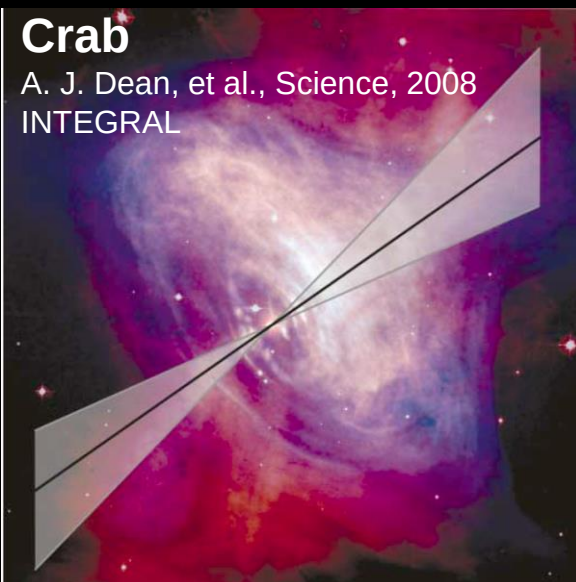
# Transient

## Polarization

### Crab

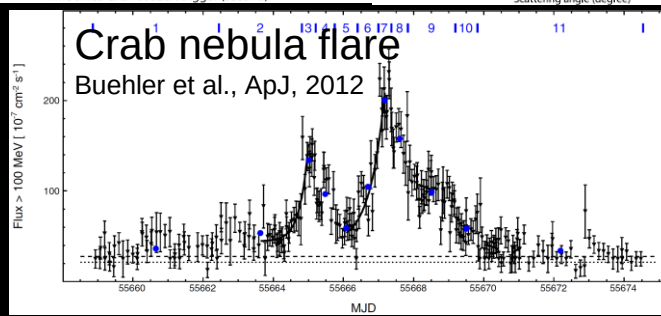
A. J. Dean, et al., Science, 2008

INTEGRAL

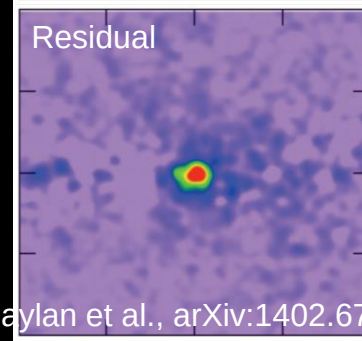
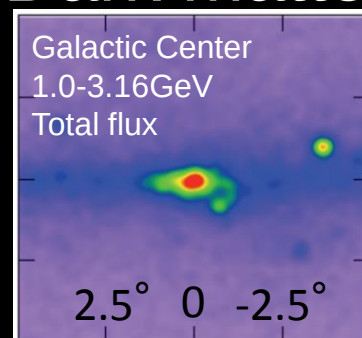


## Crab nebula flare

Buehler et al., ApJ, 2012



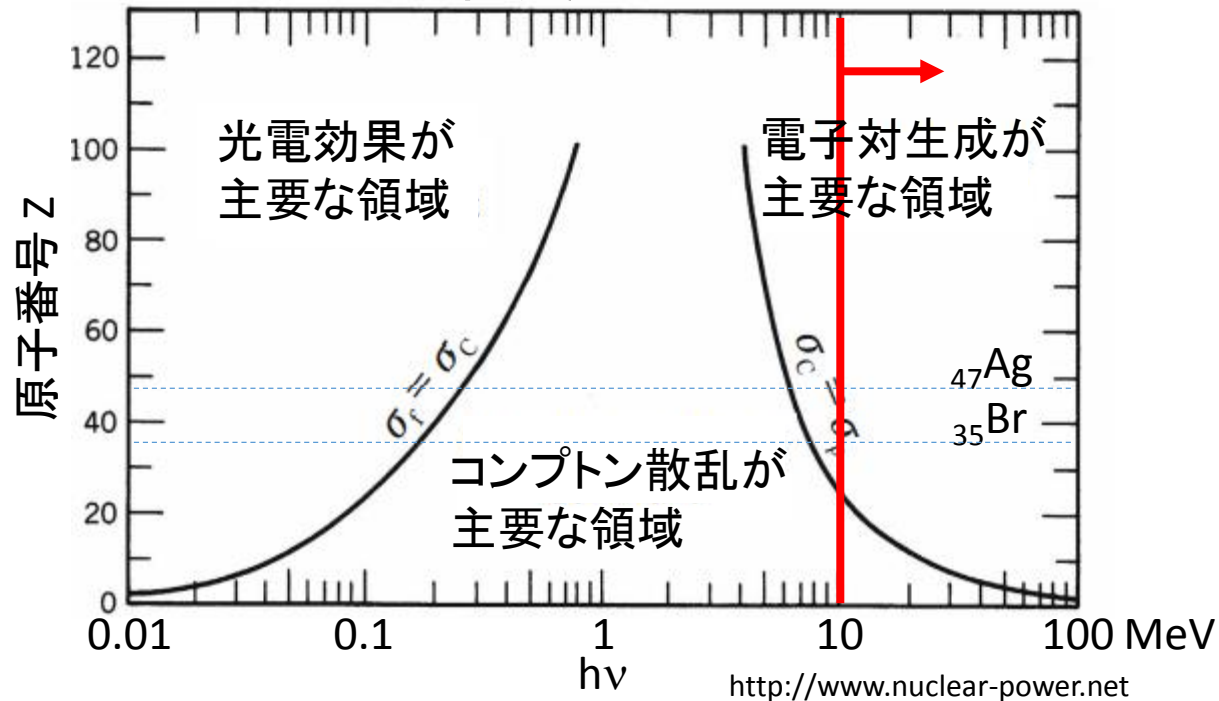
# Dark matter



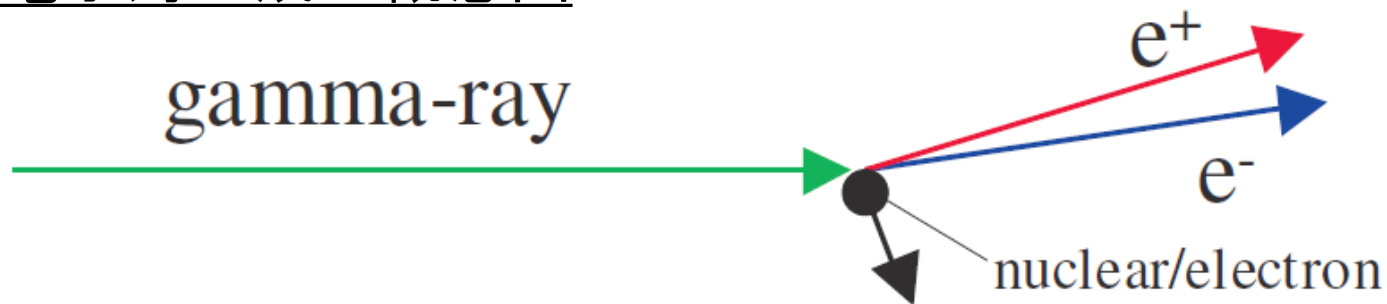
T.Daylan et al., arXiv:1402.6703v1

# 高エネルギーガンマ線の検出原理

## 光子と物質との相互作用



## 電子対生成の概念図



到来方向、到来時刻、エネルギー、偏光

# Nuclear emulsion

Microscopic view

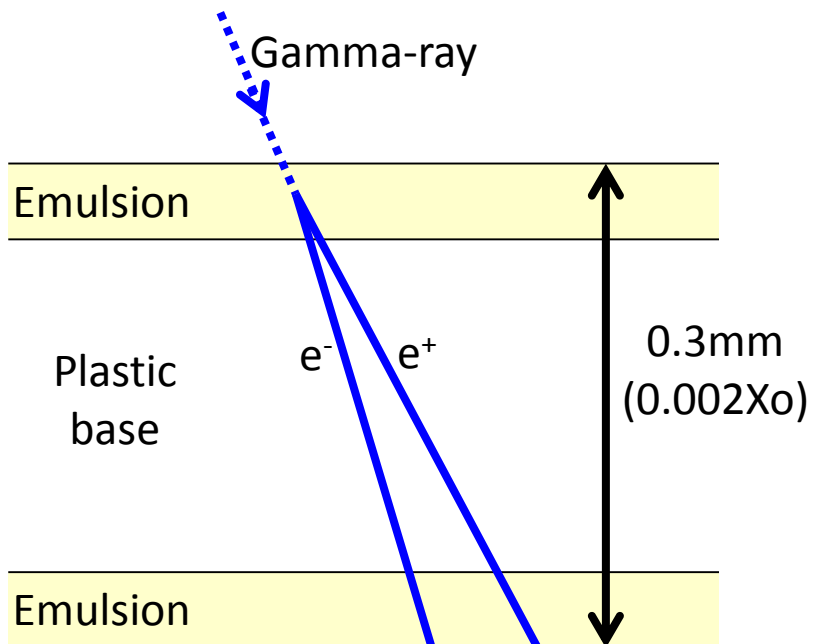
10micron

Intrinsic position accuracy  $\sim 60\text{nm}$

Gamma-ray  
→

$e^{+/-}$   
→  
 $e^{-/+}$

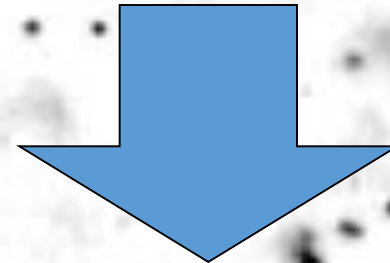
Cross sectional view of an emulsion film



Powerful tracking device

>High spatial resolution :  $<1\text{micron}$

>Small radiation length :  $0.002X_0$



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

# GRAINE

## Gamma-Ray Astro-Imager with Nuclear Emulsion

### Converter

Emulsion + Copper foil

### Timestamper

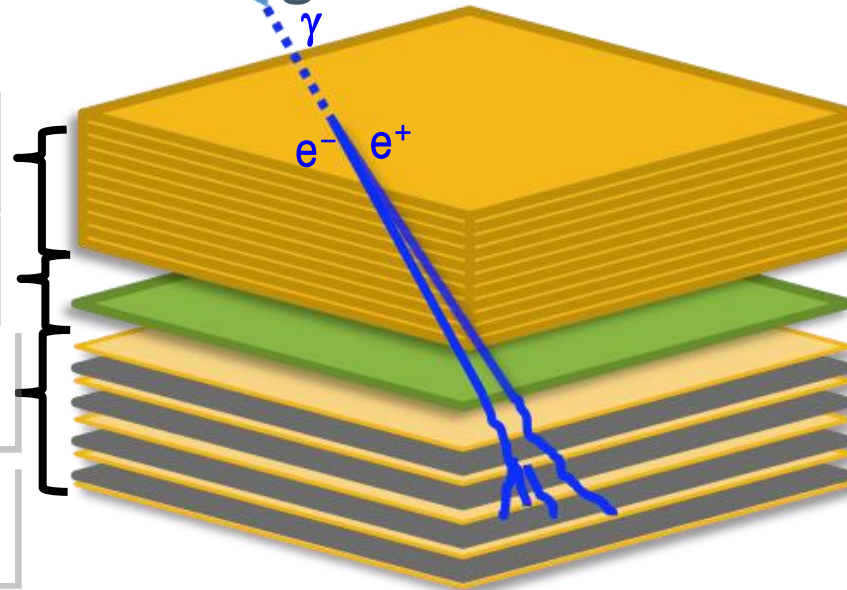
Multi-stage shifter

### Calorimeter

Emulsion + metal plate

### Attitude monitor

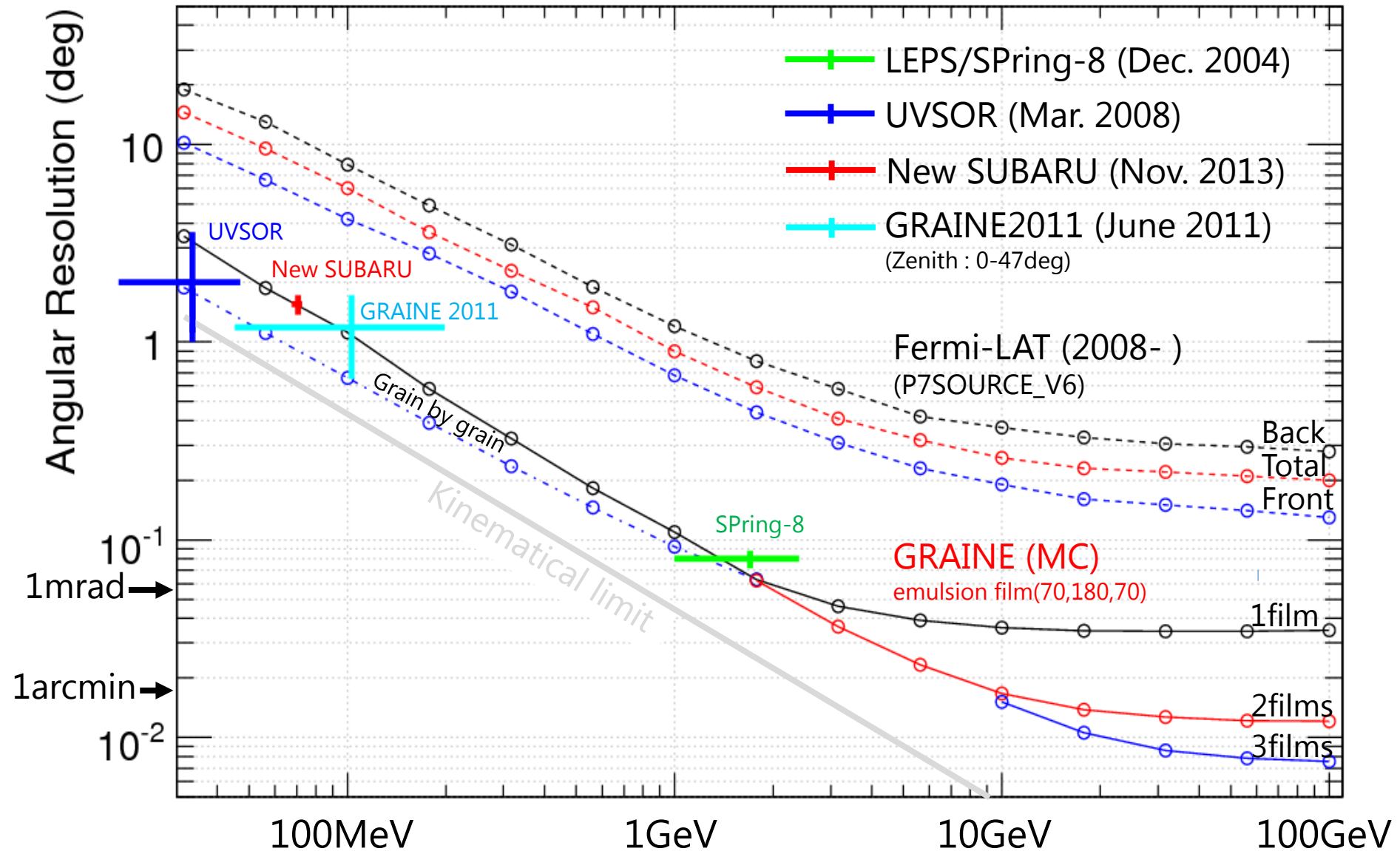
Star camera



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

|                            | Fermi LAT                 |                      | GRAINE              |
|----------------------------|---------------------------|----------------------|---------------------|
| Angular resolution @100MeV | 6.0deg (105mrad)          | $\xrightarrow{x1/6}$ | 1.0deg (17mrad)     |
| @1GeV                      | 0.90deg (16mrad)          | $\xrightarrow{x1/9}$ | 0.1deg (1.7mrad)    |
| Energy range               | 20MeV – 300GeV            |                      | 10MeV – 100GeV      |
| Polarization sensitivity   | ---                       |                      | Yes                 |
| Effective area @ 100MeV    | 0.25m <sup>2</sup>        | $\xrightarrow{x8}$   | 2.1m <sup>2</sup> * |
| @ 1GeV                     | 0.88m <sup>2</sup>        | $\xrightarrow{x3}$   | 2.8m <sup>2</sup> * |
| Dead time                  | 26.5 μ sec (readout time) |                      | Dead time free      |

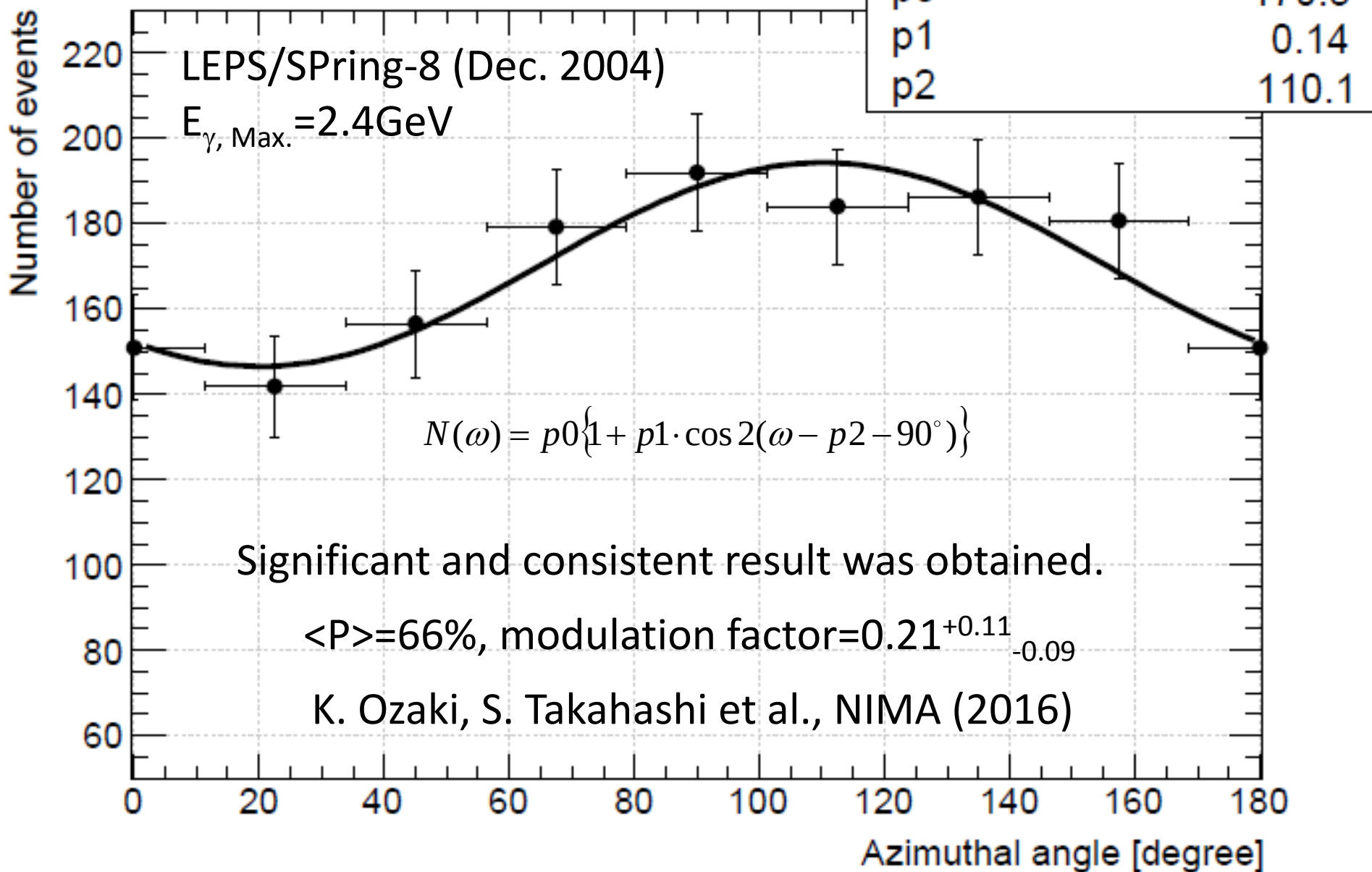
# Angular resolution





# Polarization sensitivity

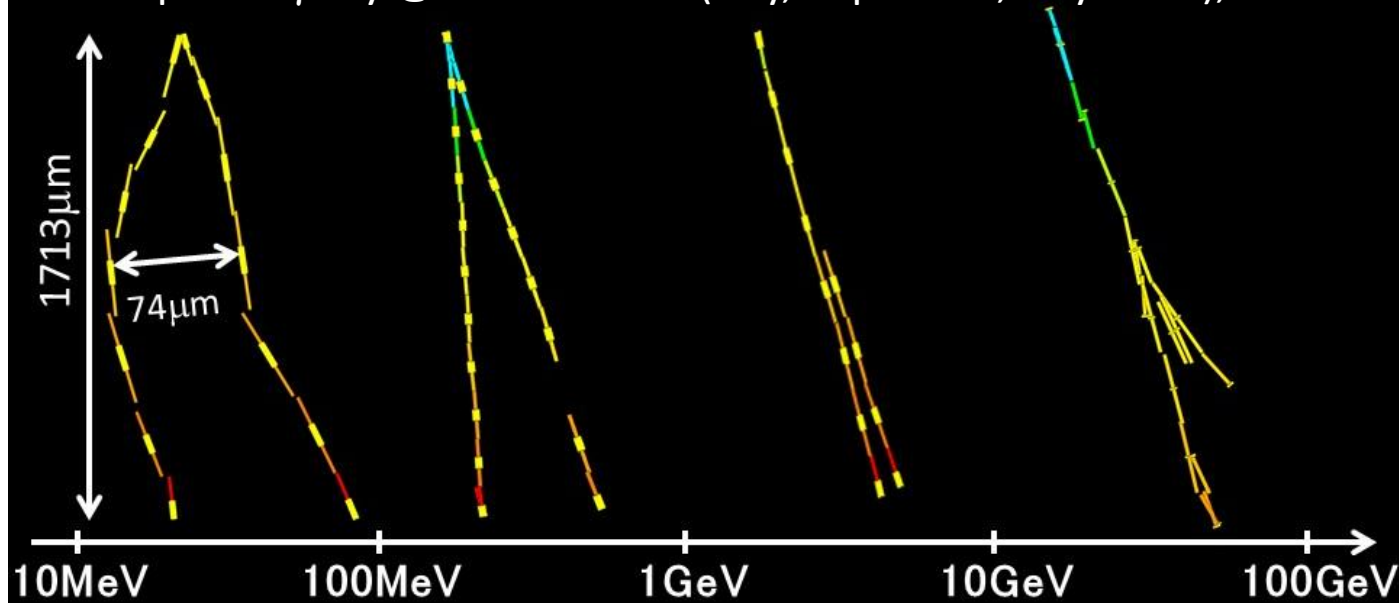
Azimuthal Distribution





# Energy range

Atmospheric  $\gamma$ -ray @Mt. Norikura (July, Sep. 2007, July 2013), et al.



## Momentum measurement accuracy w/MCS

35MeV electron LINAC  
@Tokai-mura (Aug. 2012)

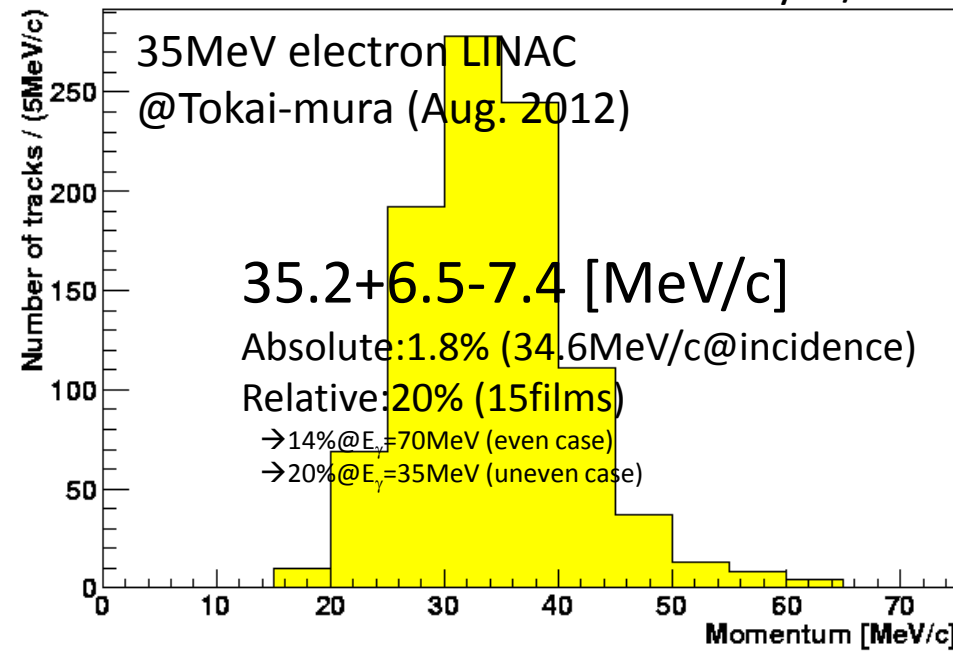
$35.2^{+6.5}_{-7.4}$  [MeV/c]

Absolute: 1.8% (34.6 MeV/c @ incidence)

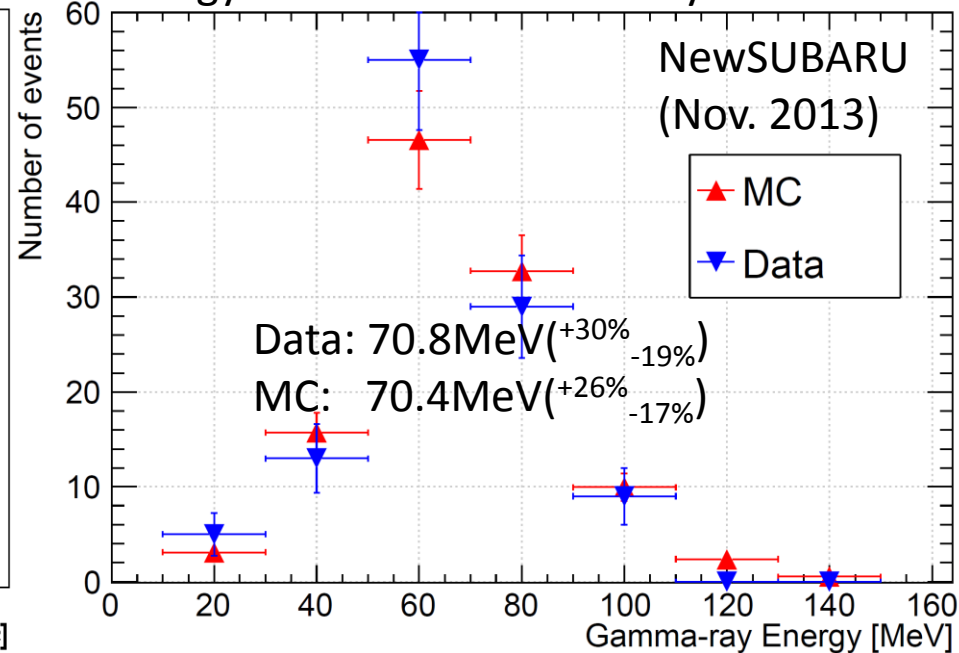
Relative: 20% (15 films)

→ 14% @  $E_\gamma = 70$  MeV (even case)

→ 20% @  $E_\gamma = 35$  MeV (uneven case)



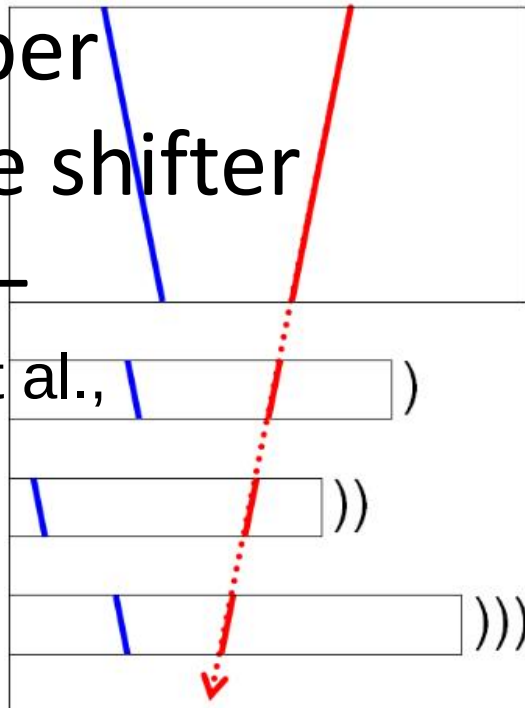
## Energy measurement accuracy



# Timestamper Multi-stage shifter

June 2007–

S.Takahashi et al.,  
NIMA(2010)



hour

min.

sec.

Number of time stamps

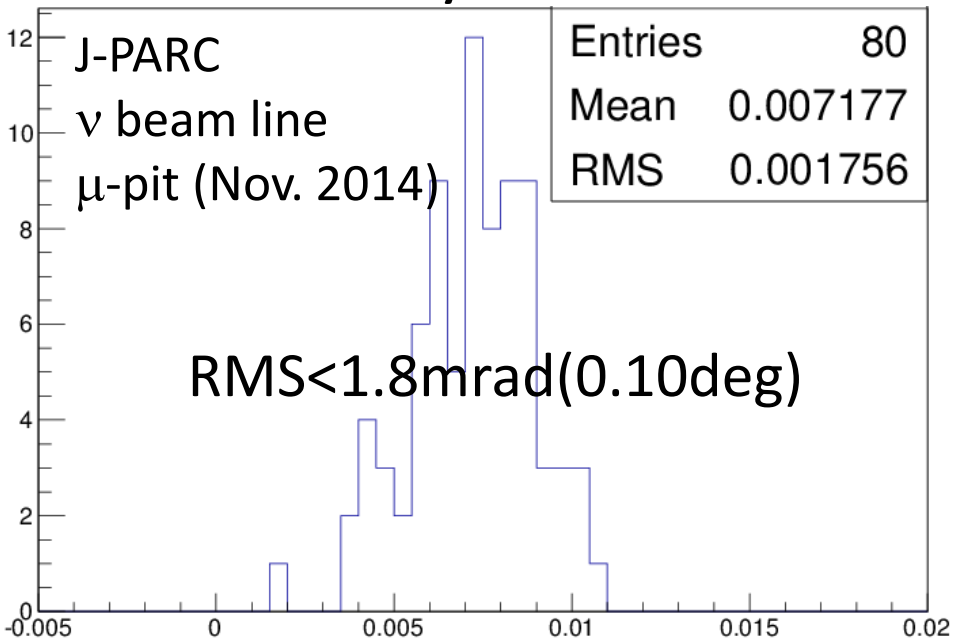
~sea level  
12hours  
2stages

60  
50  
40  
30  
20  
10  
0

| RMS         | 1.5s |
|-------------|------|
| Efficiency  | 98%  |
| Reliability | 97%  |

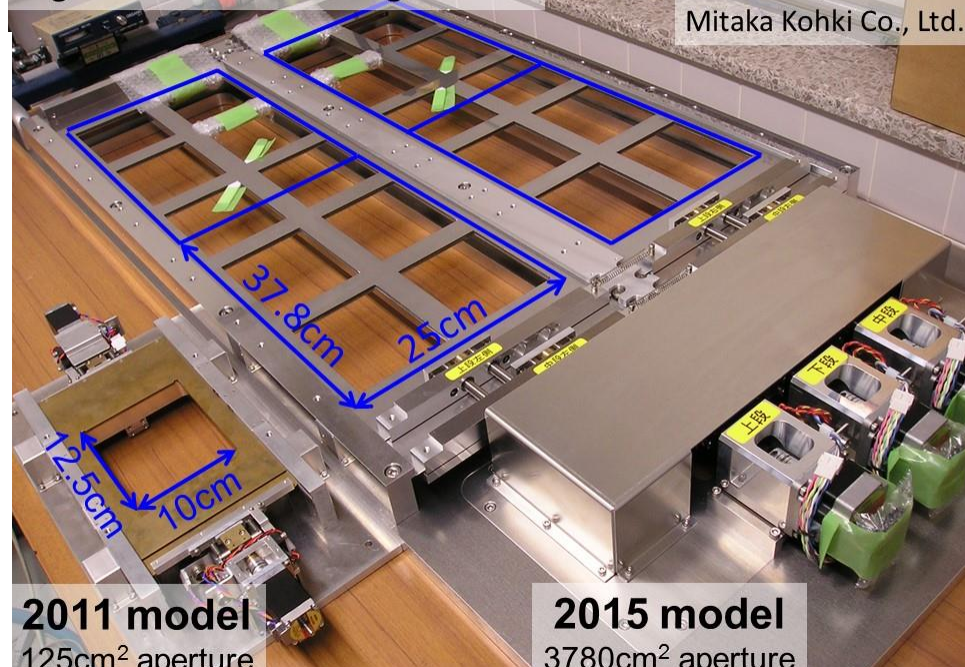
-10 -5 0 5 10  
Time difference [second]

## Flatness study



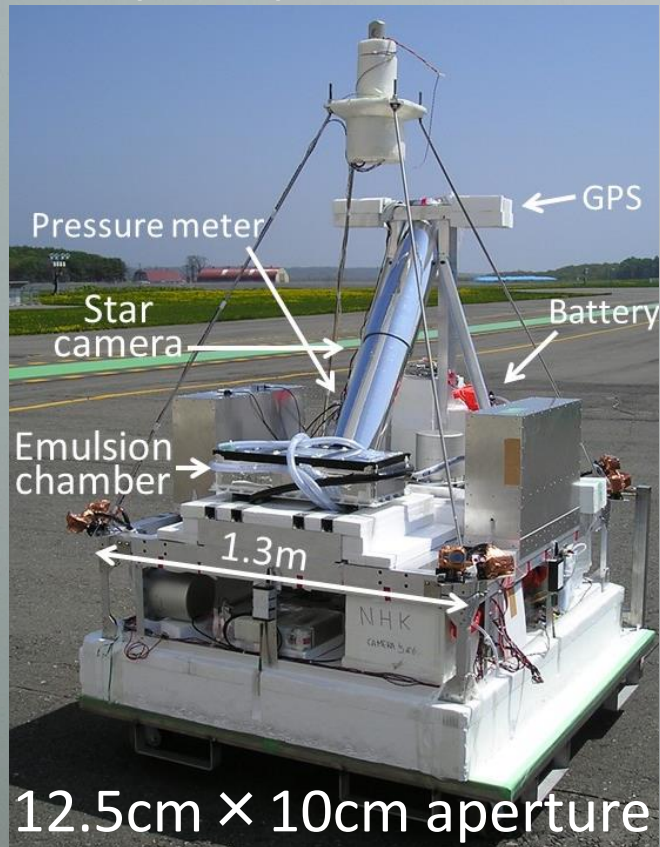
Flight model of multi-stage shifter

Co-developed with  
Mitaka Kohki Co., Ltd.

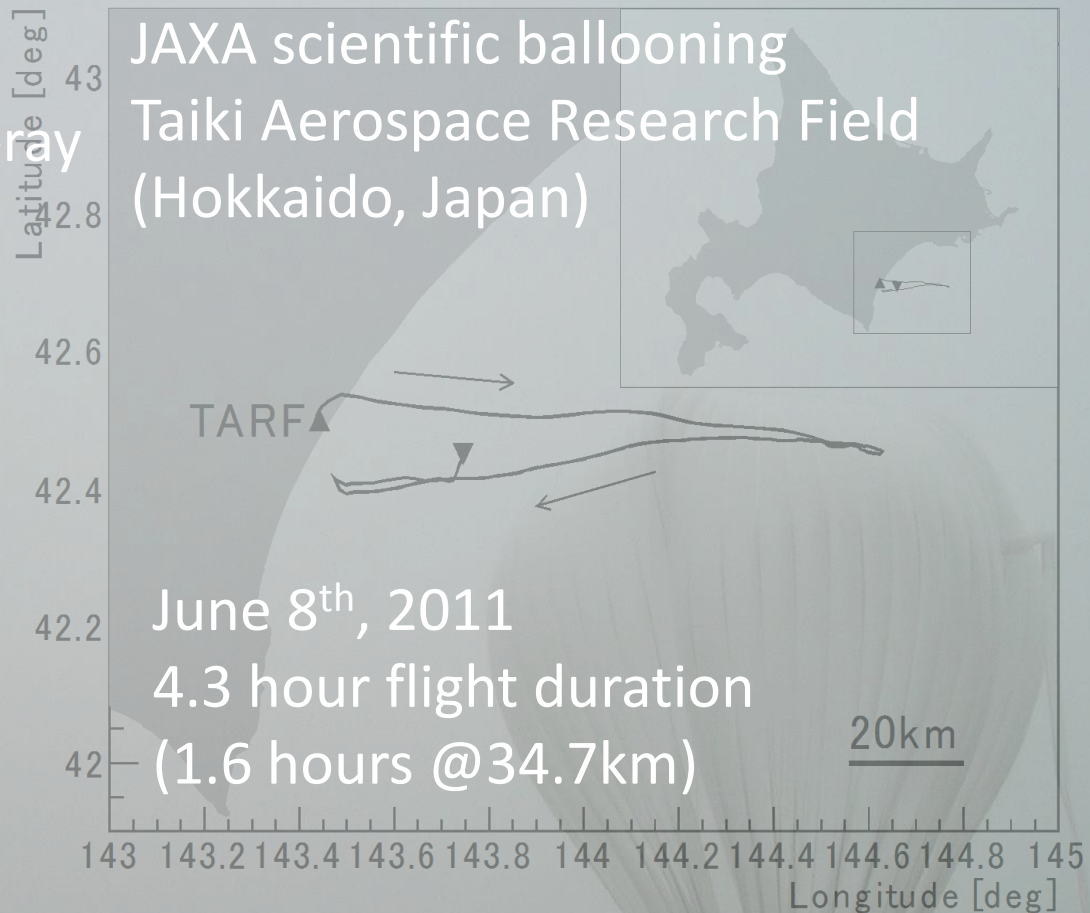


# GRAINE 2011

First balloon-borne emulsion  $\gamma$ -ray telescope experiment



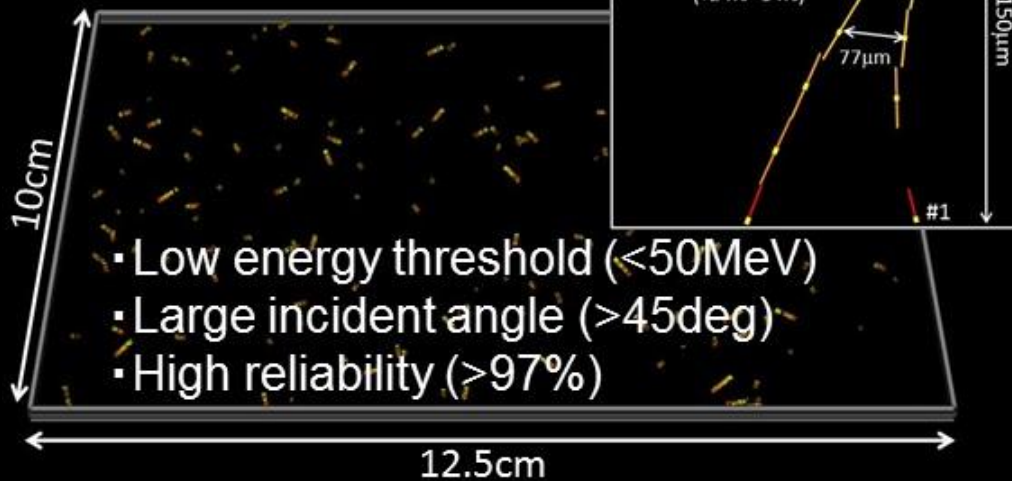
JAXA scientific ballooning  
Taiki Aerospace Research Field  
(Hokkaido, Japan)



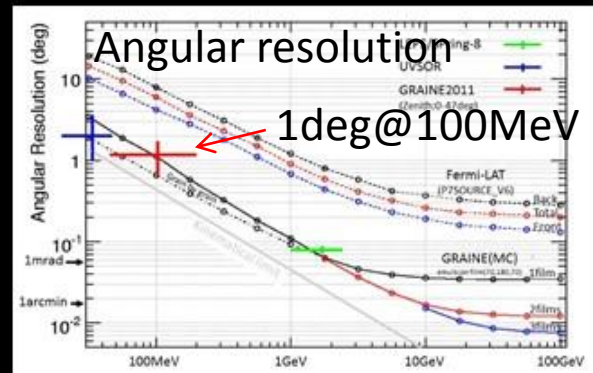


# GRAINE 2011 Flight data analysis

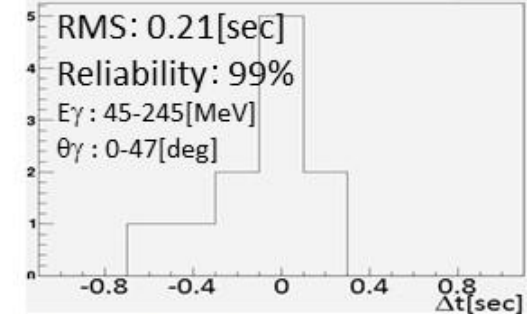
## $\gamma$ -ray event detection



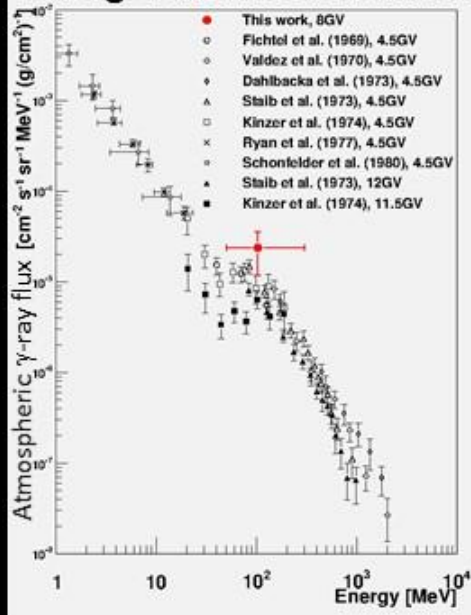
- Low energy threshold (<50MeV)
- Large incident angle (>45deg)
- High reliability (>97%)



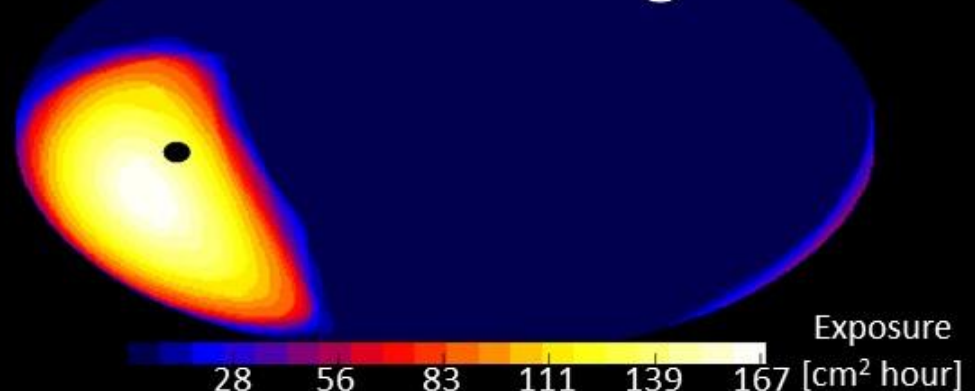
## Time resolution



## Background measurement



## GRAINE First Light

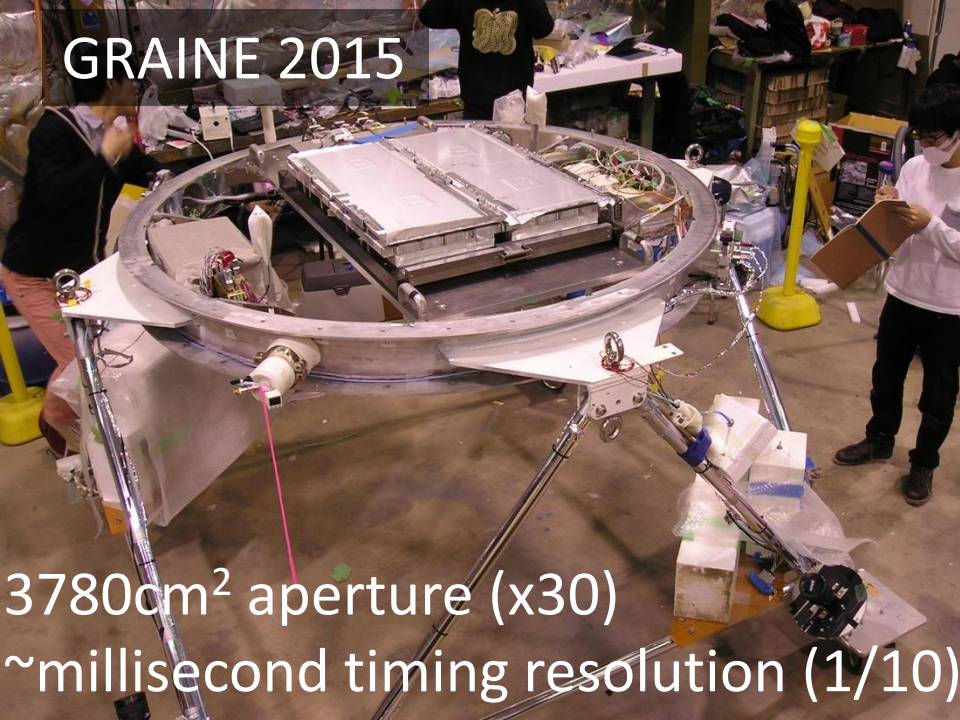


## Feasibility demonstration

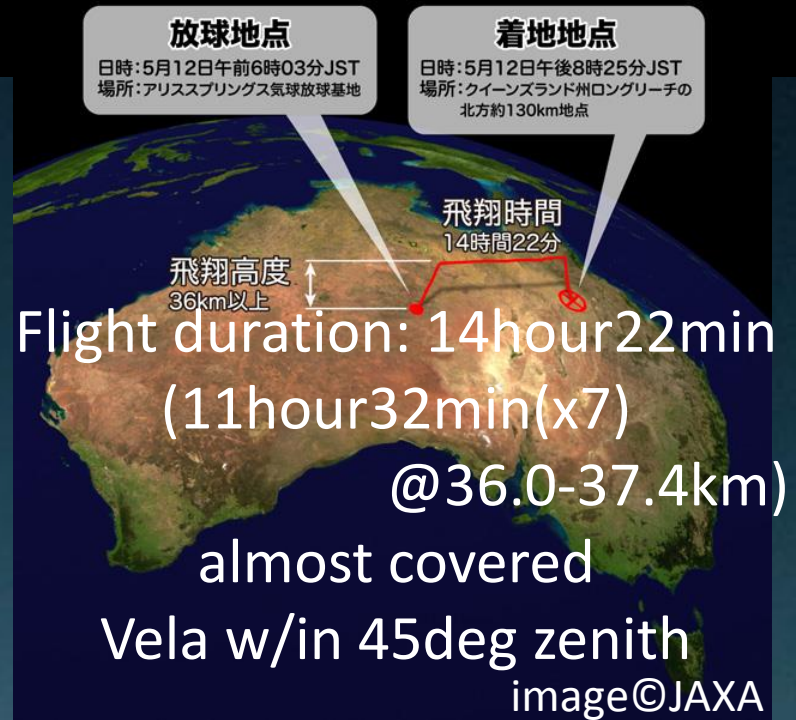
S. Takahashi et al., PTEP 043H01 (2015); H. Rokujo et al., NIM A 701, 127 (2013)



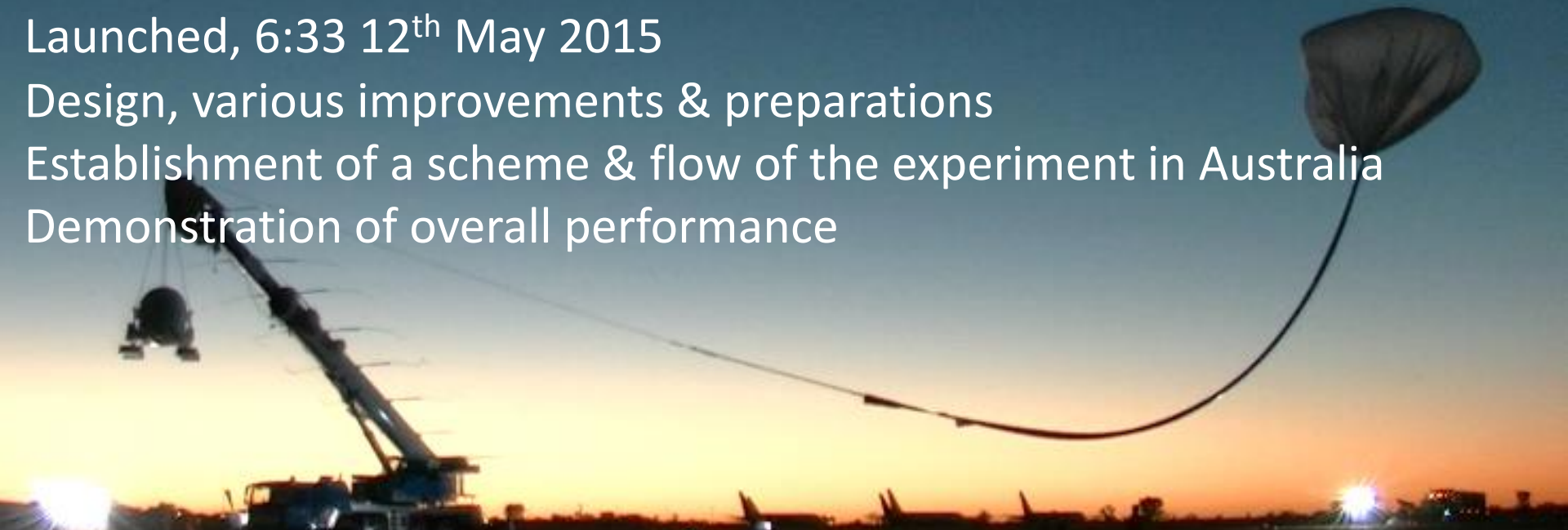
# GRAINE 2015



3780cm<sup>2</sup> aperture (x30)  
~millisecond timing resolution (1/10)



Launched, 6:33 12<sup>th</sup> May 2015  
Design, various improvements & preparations  
Establishment of a scheme & flow of the experiment in Australia  
Demonstration of overall performance

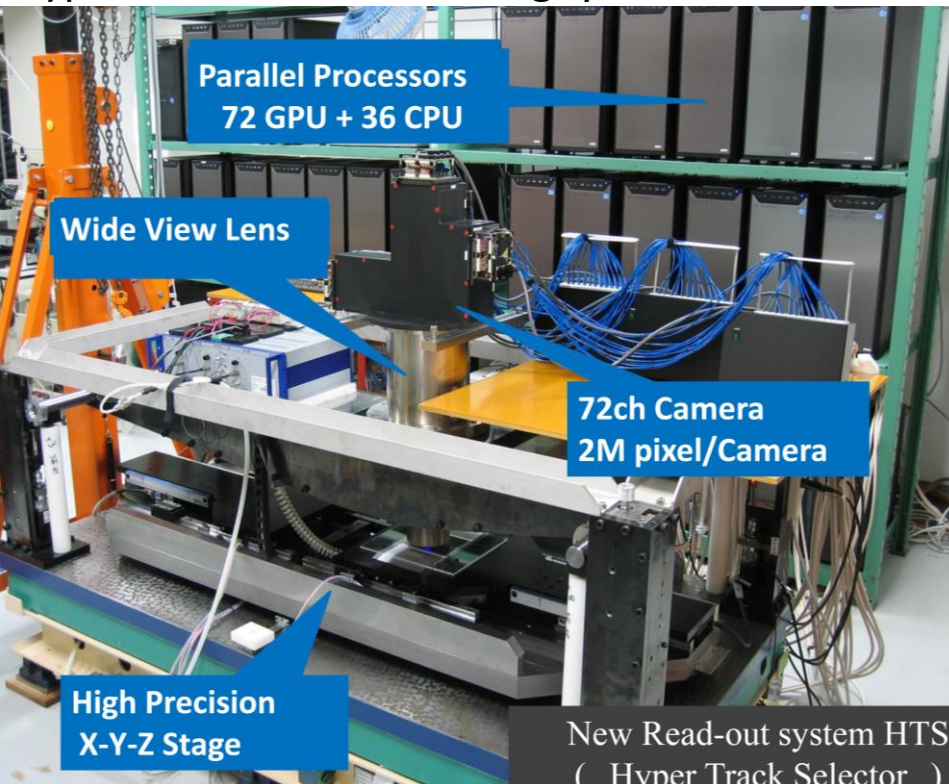


# Emulsion track read-out

After film development, surface treatment, thickness tuning, scanning parameter tuning

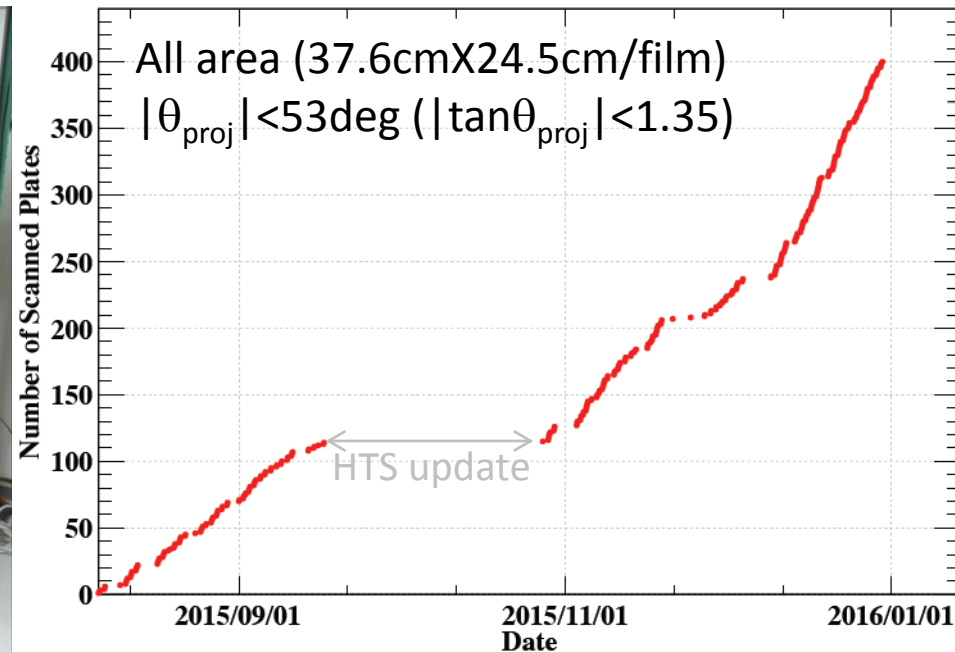
Emulsion read-out system

Hyper Track Selector @ Nagoya U



First practical scanning

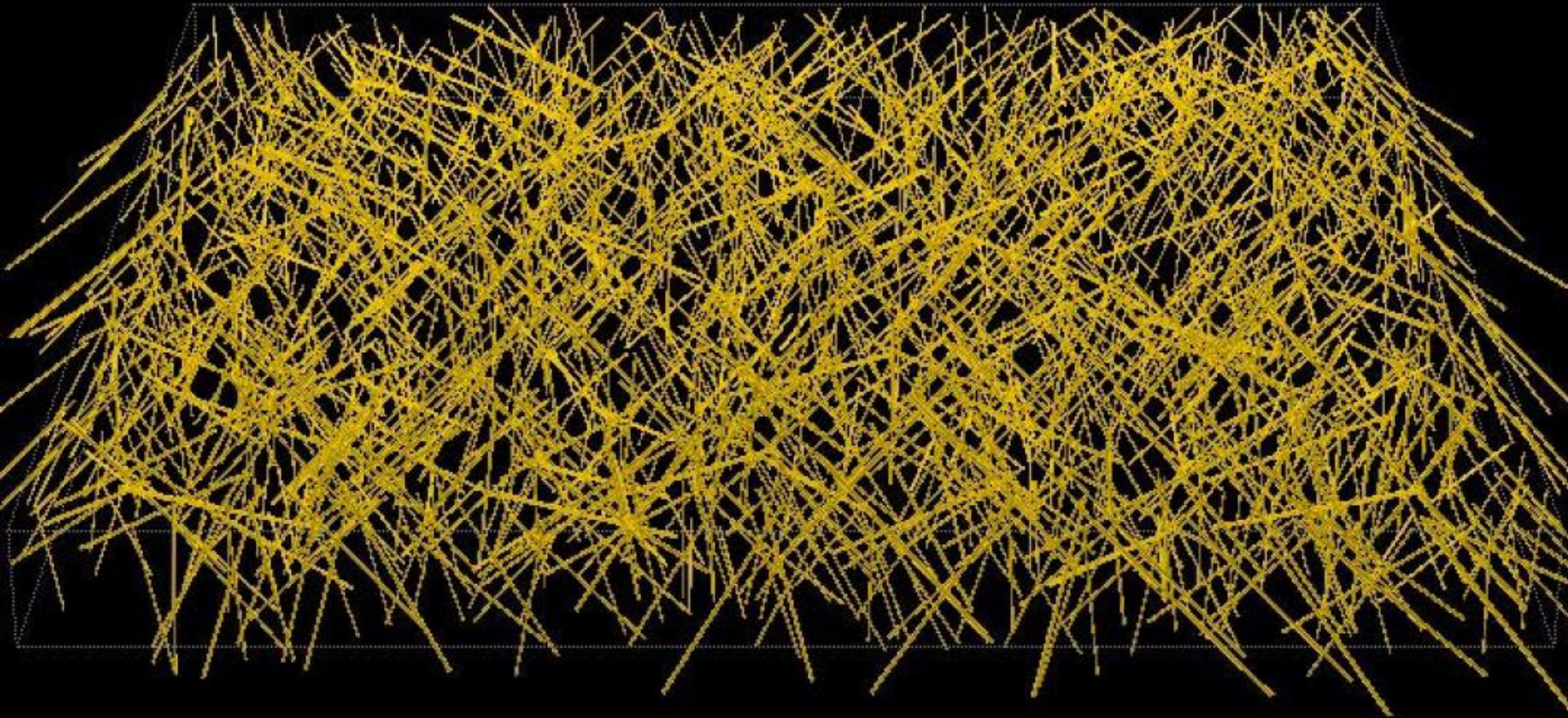
## Scanning progress



Completed for all films  
(432films, 41m<sup>2</sup>(film area basis))

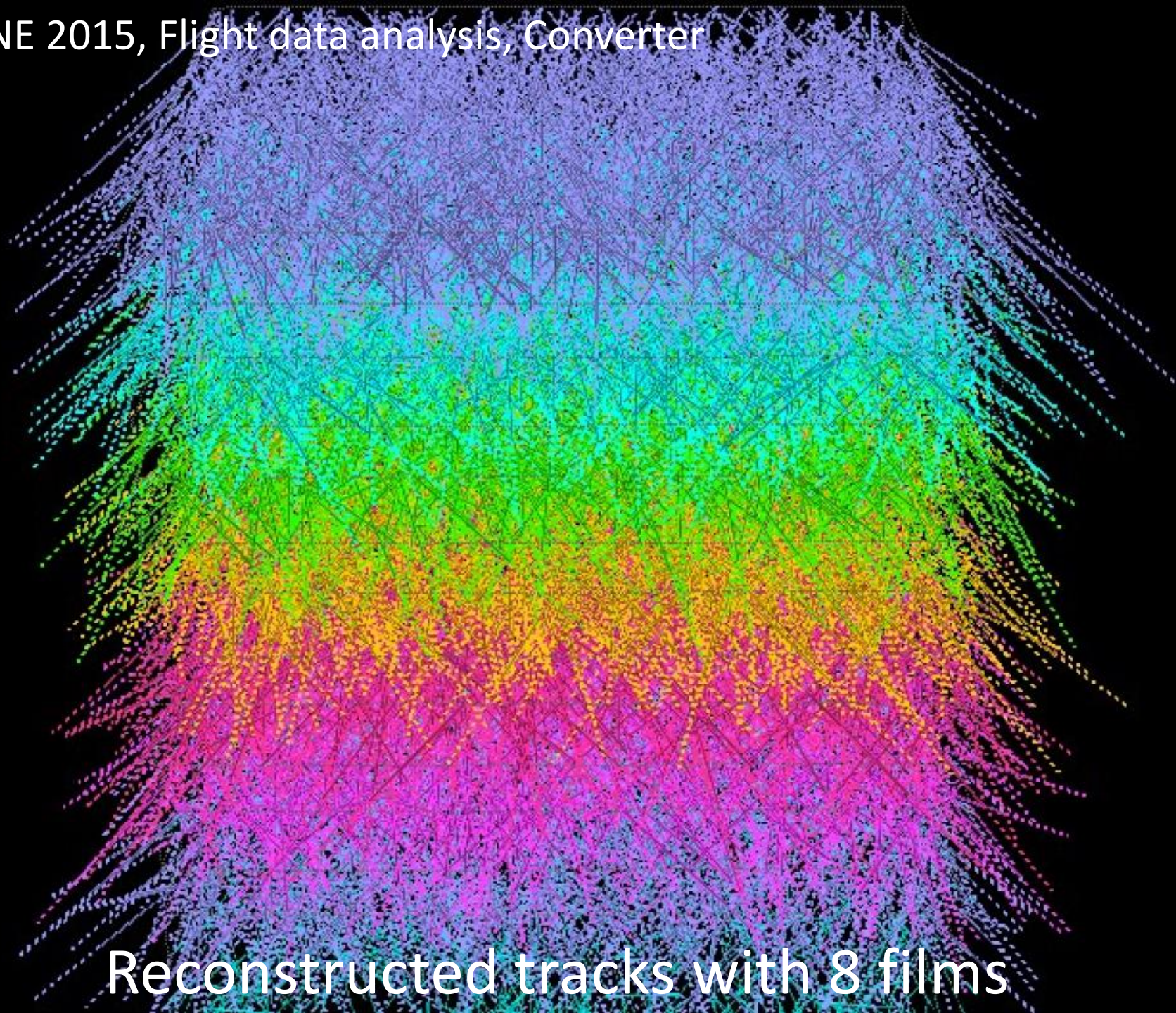
- Converter 100 films x 4units
- Timestamp 8 films x 4units





2 mm x 2 mm of single film  
density  $\sim 400$  tracks/mm<sup>2</sup>





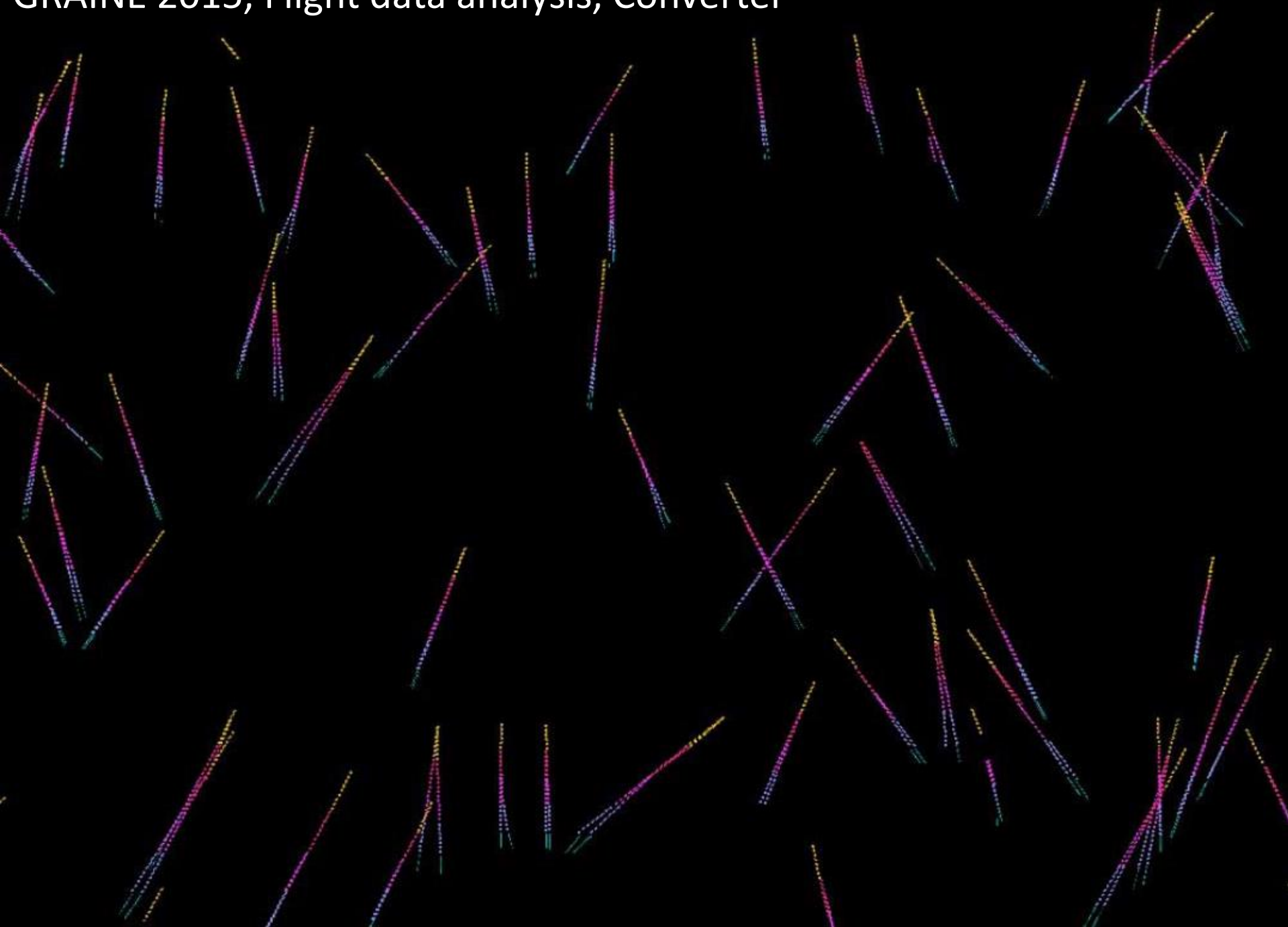
Reconstructed tracks with 8 films

# GRAINE 2015, Flight data analysis, Converter





# GRAINE 2015, Flight data analysis, Converter



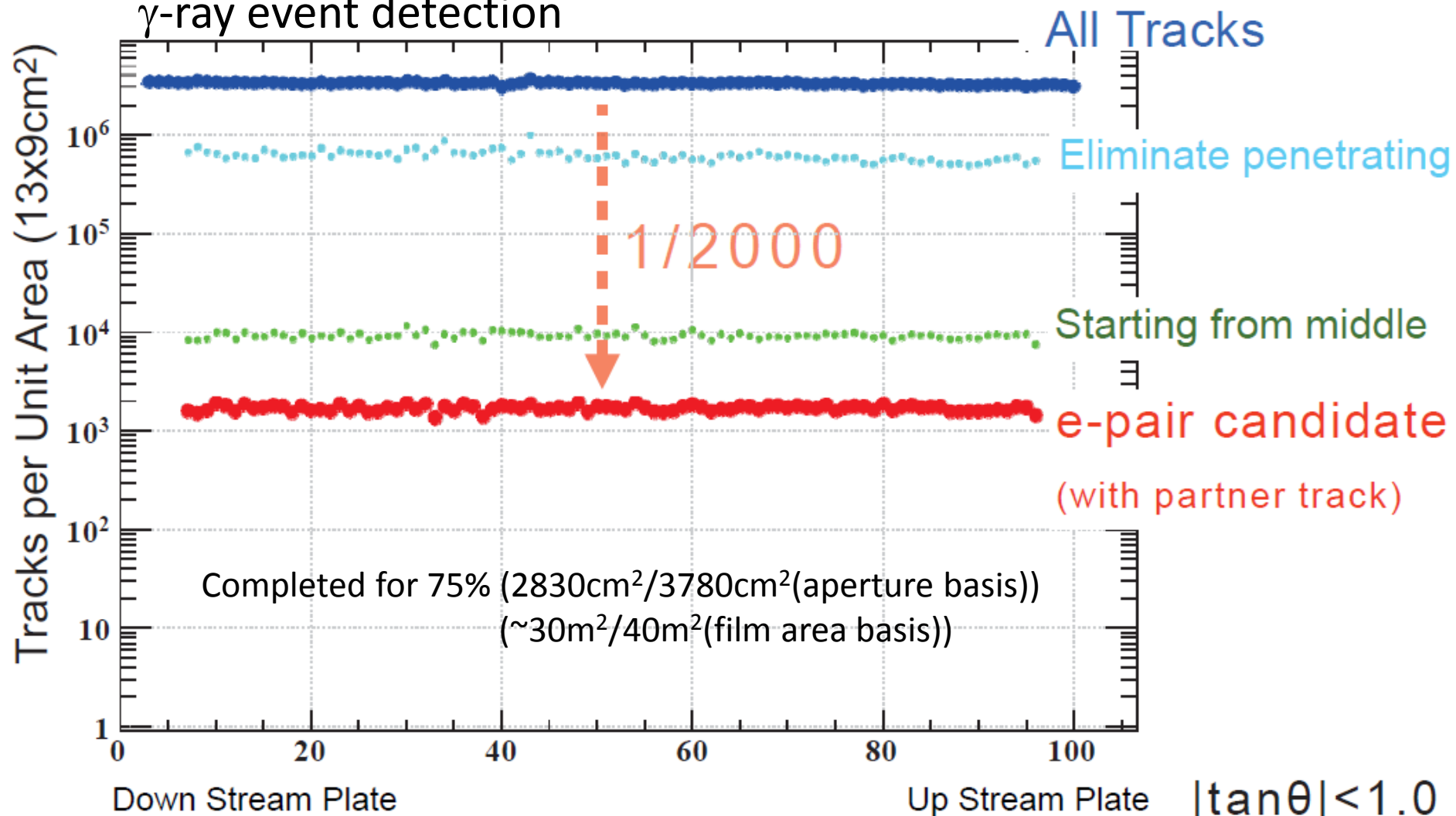


# GRAINE 2015, Flight data analysis, Converter

## Achieved improvements

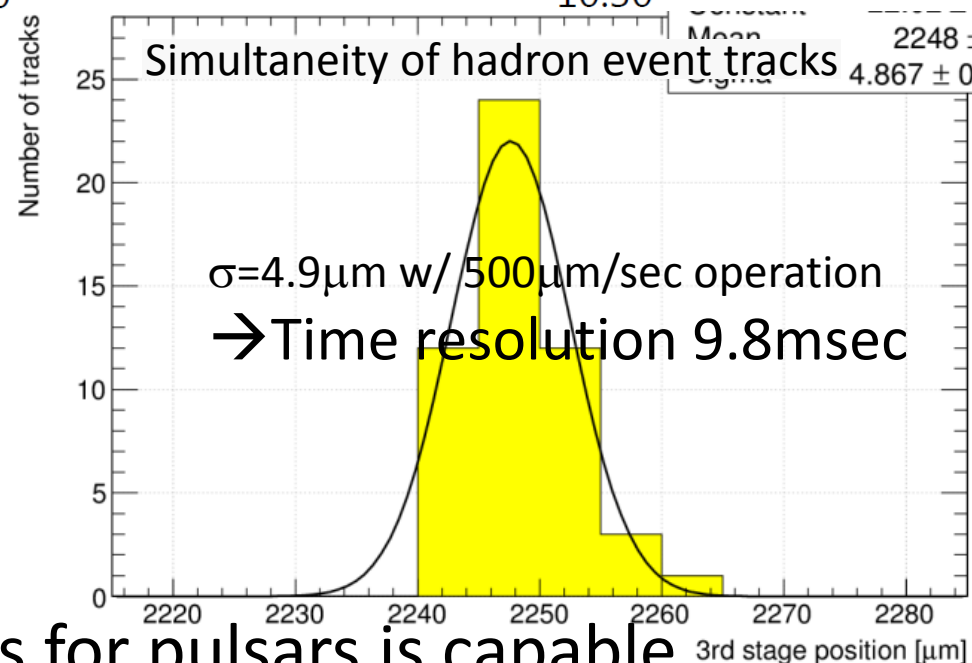
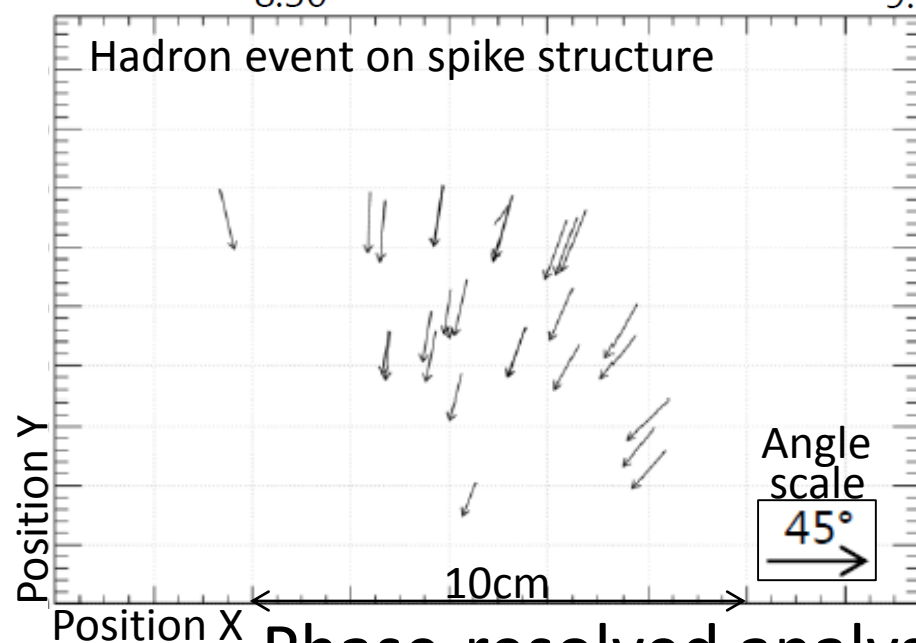
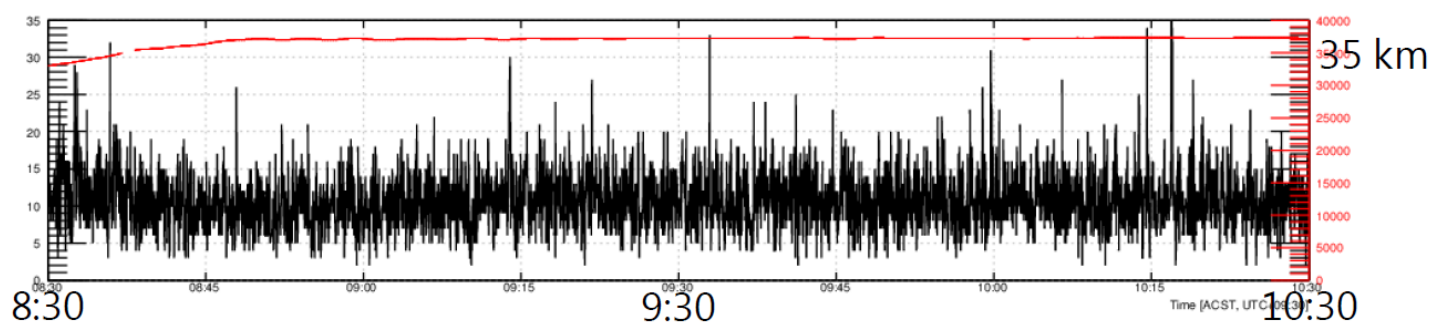
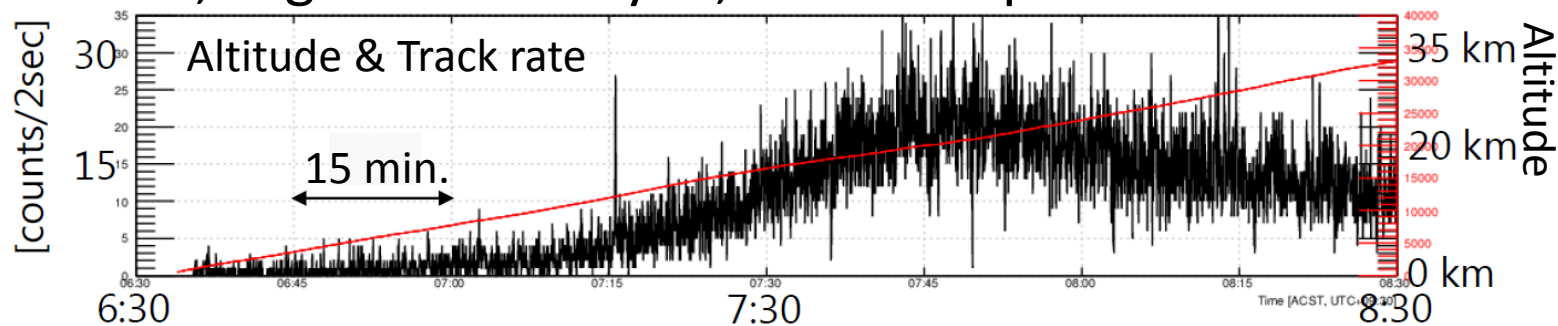
- Emulsion film S/N ratio  $\times \sim 20$ , data size  $\sim 1/20$
- Track finding inefficiency in a single film  $\sim 1/10$
- Data reduction load for  $\gamma$ -ray event detection  $\sim 1/200$

## $\gamma$ -ray event detection



$\gamma$ -ray event detection can be performed for a large area.

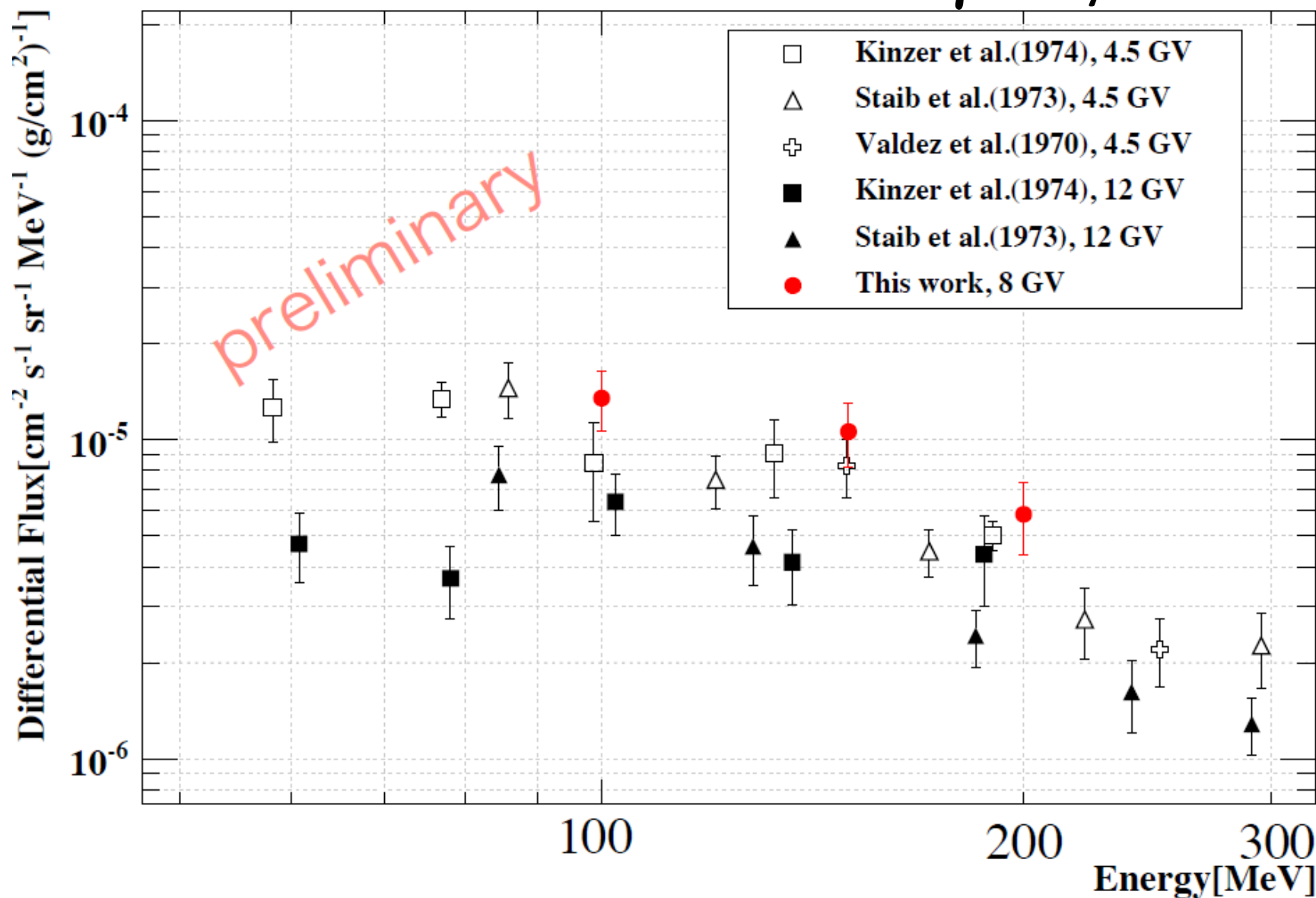
# GRAINE 2015, Flight data analysis, Timestamper



Phase-resolved analysis for pulsars is capable.

e.g. 89 msec period of Vela pulsar

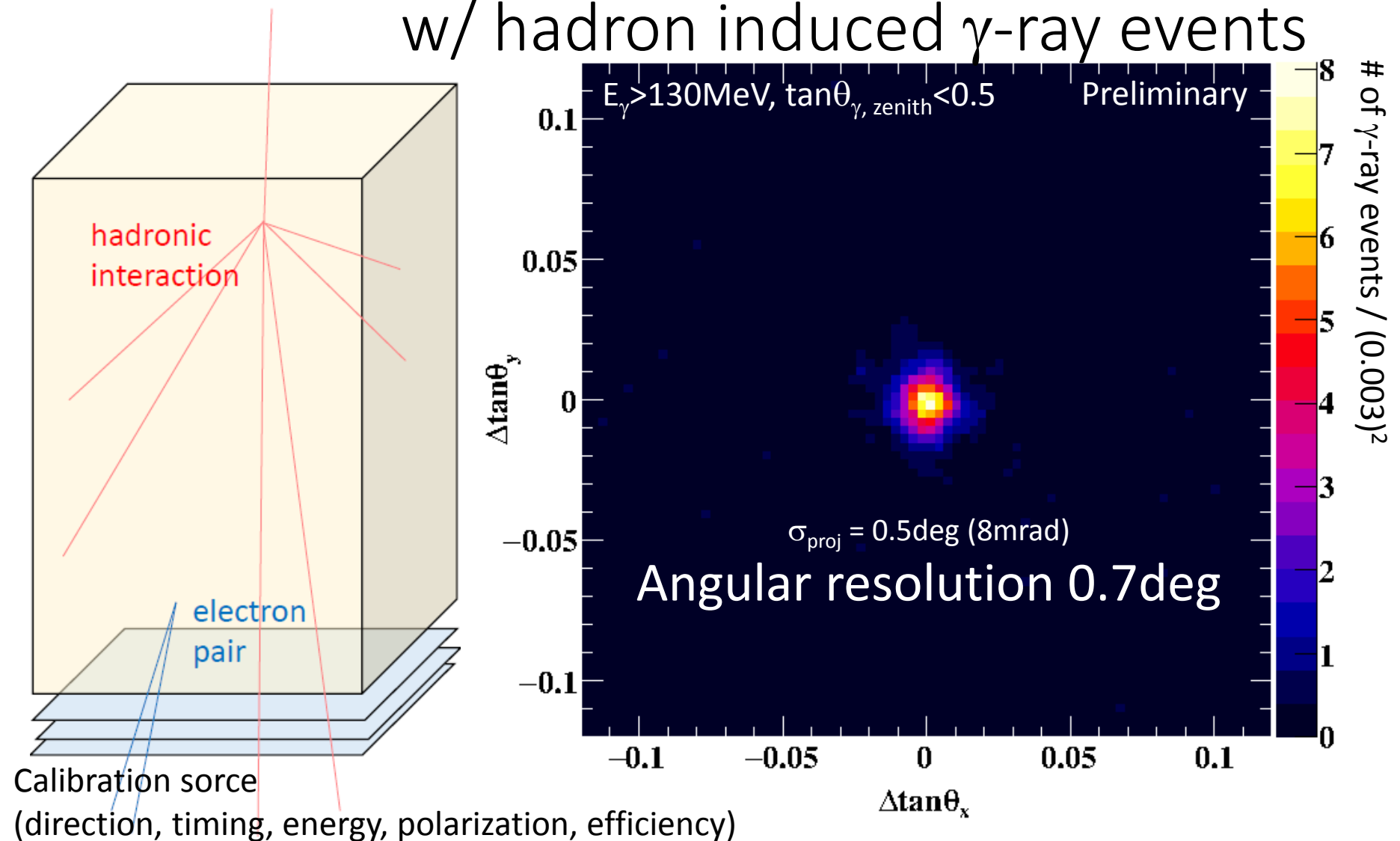
# Measurement of atm. $\gamma$ -ray flux





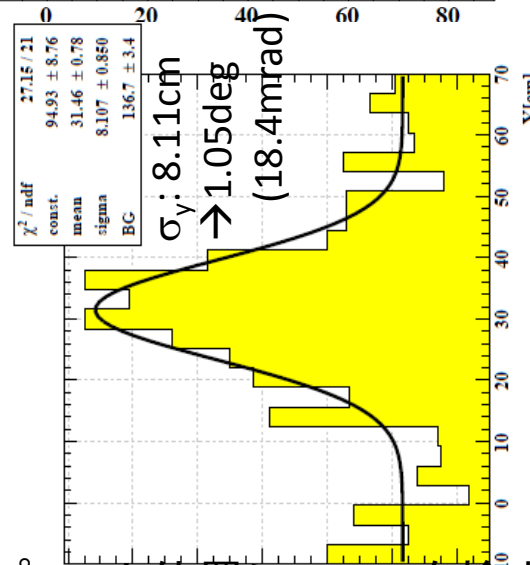
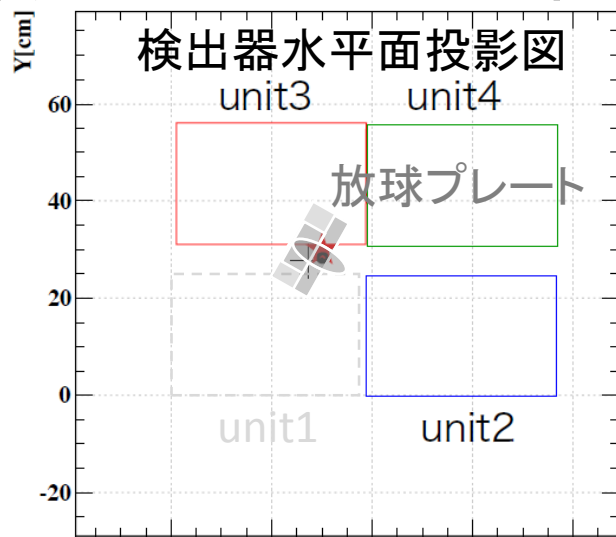
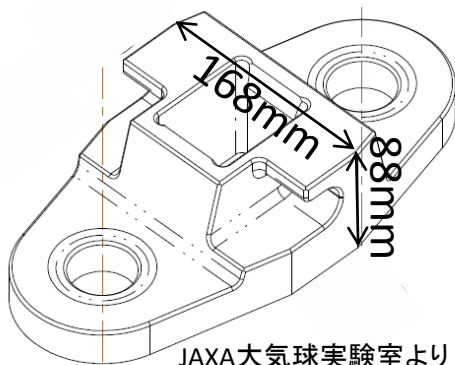
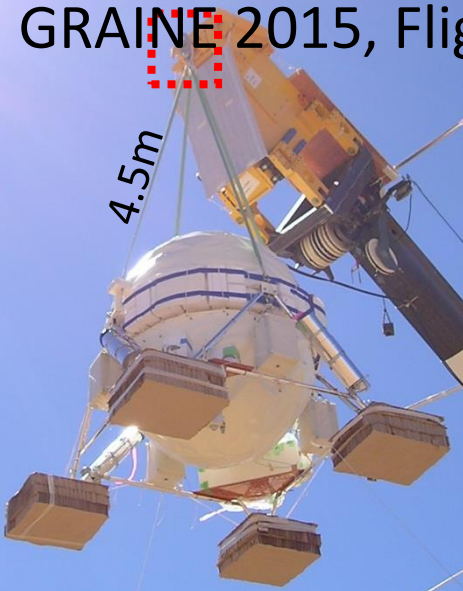
# $\gamma$ -ray imaging performance

w/ hadron induced  $\gamma$ -ray events

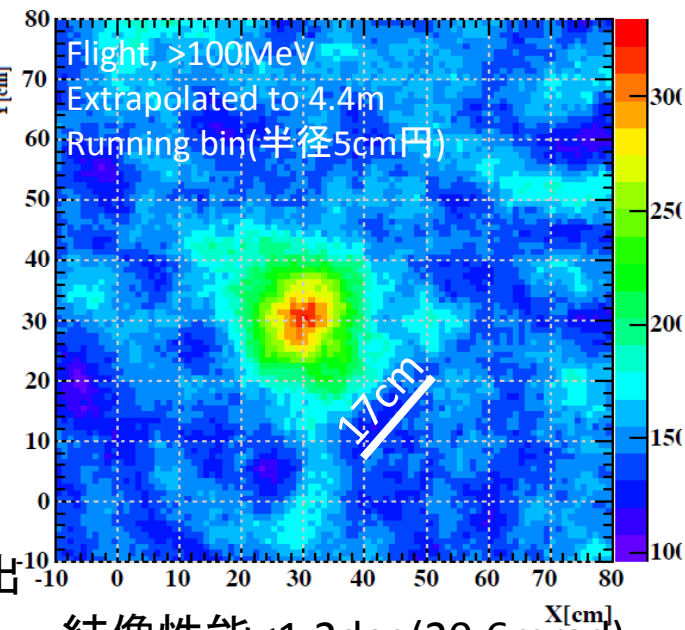
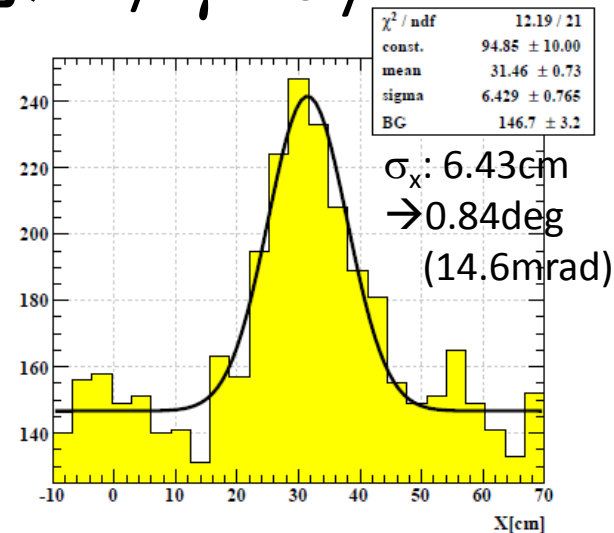


High  $\gamma$ -ray imaging performance is being obtained.

# GRAINE 2015, Flight data analysis, Converter+Timestamper 検出器外部光源 放球プレート撮像 w/ $\gamma$ -ray



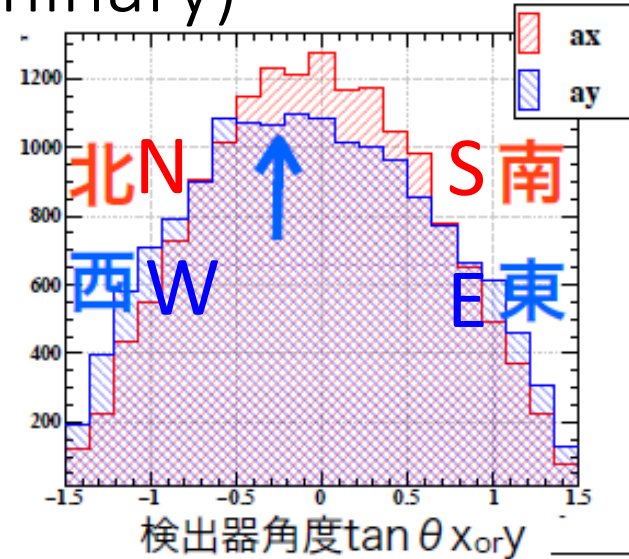
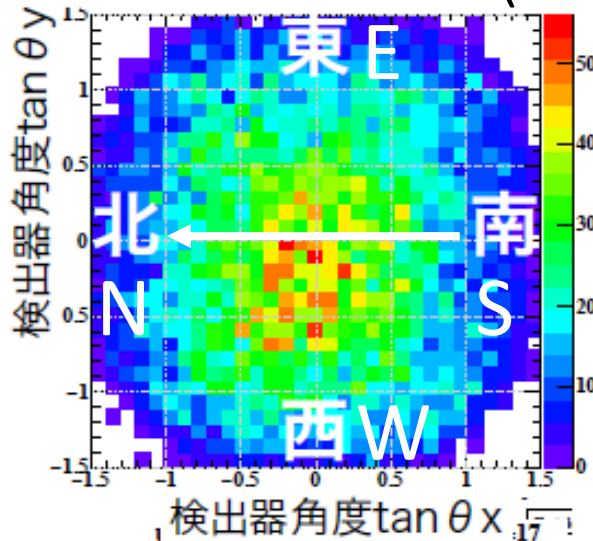
- ・放球プレート位置にexcessを検出  
(ずれ1.7cm $\rightarrow$ 0.22deg(3.9mrad))
- ・放球プレートの大きさ程度の  
広がりが見えている



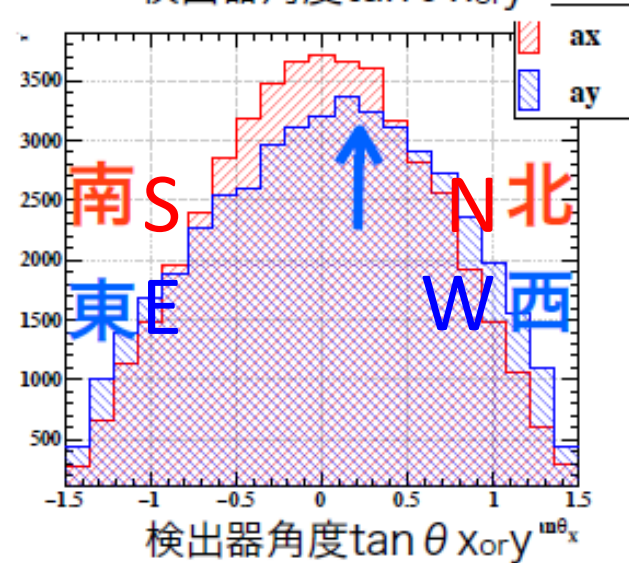
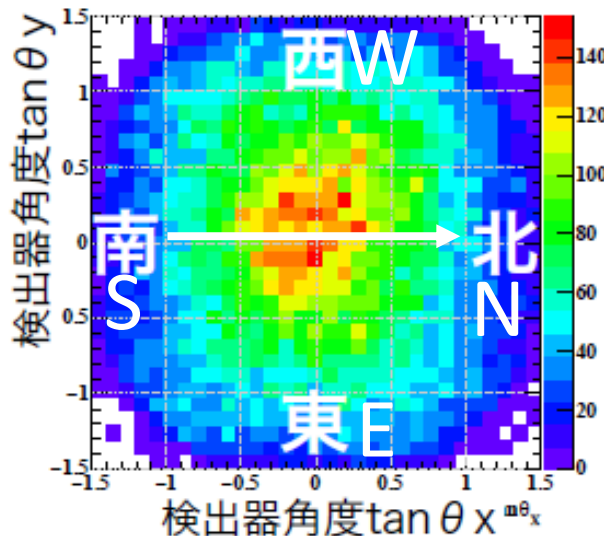
- ・結像性能<1.2deg(20.6mrad)  
(cf. 角度分解能1.0deg@100MeV)
- ・ユニットごとの結像重心のばらつき<0.06deg(1mrad)

# GRAINE 2015, Flight data analysis, Converter+Timestamp+Attitude East-west effect (Preliminary)

検出器軸が  
北向きの時



検出器軸が  
南向きの時



全系を総合した精度が確認できつつある。

処理面積や時間を増やす、時間幅を狭くするなど、精度の改善を図る。

緯度、経度、高度を考慮した東西効果について本田守弘氏(東大宇宙線研)に相談中。



# Current summary of GRAINE 2015

- 3780cm<sup>2</sup> aperture (x30, new-type emulsion films, total 48m<sup>2</sup>)
- 14.4hour flight duration (11.5hour(x7)@36.0–37.4km)
- Establishment of a scheme & flow of the experiment in Australia
- Emulsion track read-out, total 41m<sup>2</sup> w/ HTS
- Emulsion film S/N ratio  $\times \sim 20$ , data size  $\sim 1/20$
- Track finding inefficiency in a single film  $\sim 1/10$
- Data reduction load for  $\gamma$ -ray event detection  $\sim 1/200$
- Data processing of all effective area, 2830cm<sup>2</sup> aperture (total 30m<sup>2</sup>)
- $\gamma$ -ray angular resolution, 0.7deg >130MeV
- Time resolution, 9.8 msec (1/10)
- Star camera sensitivity, magnitude of 6.1  $\rightarrow$  7.5
- Limited  $\gamma$ -ray yield from Vela pulsar

# GRAINE Scientific observation roadmap

## 2018, Demonstration

Alice Springs

$\sim 0.4\text{m}^2$  aperture

$\sim 18$  hours flight duration

$< \sim 5\text{g/cm}^2$  altitude

## 2021–, Scientific flight

Alice Springs

$10\text{m}^2$  aperture

$> \sim 36$  hours flight duration

$< \sim 10\text{g/cm}^2$  altitude

Vela pulsar detection, Imaging,  
phase resolved analysis  
Galactic diffuse & Geminga  
detection/indication

Vela pulsar  
Polarization observation ( $< 50\%$ )

Pioneering polarization  
observation for high  
energy  $\gamma$ -rays

SNR W44 ( $< 200\text{MeV}$ ,  $> 200\text{MeV}$ )  
Precise spectrum measurement  
High resolution imaging

Studying cosmic ray  
sources

Galactic Center  
Obs. with  $\sim \text{arcmin}$  resolution

Resolving GeV  $\gamma$ -ray  
excess at galactic center

Transient sources  
Obs. w/ high sensitivity  
& high photon stats

Studying transient  
sources & w/ ones

# Observation of transient sources

- ❑ Large collection area,  $10\text{m}^2$

[Effective area@100MeV,  $2.1\text{m}^2$  (3.6 x Fermi LAT, cf.  $0.58\text{m}^2$  (P8R2\_TRANSIENT020\_V6) ) ]

- ❑ Wide field of view,  $>2.2\text{sr}$  (17.5% of all sky)
- ❑ High angular resolution,  $1.0\text{deg}(17\text{mrad})@100\text{MeV}$
- ❑ Polarization sensitive
- ❑ Dead time free

→ High sensitivity incl. **“Unexplored region”**

→ High photon statistics

- Energy spectrum

- Light curve

- Polarization observation

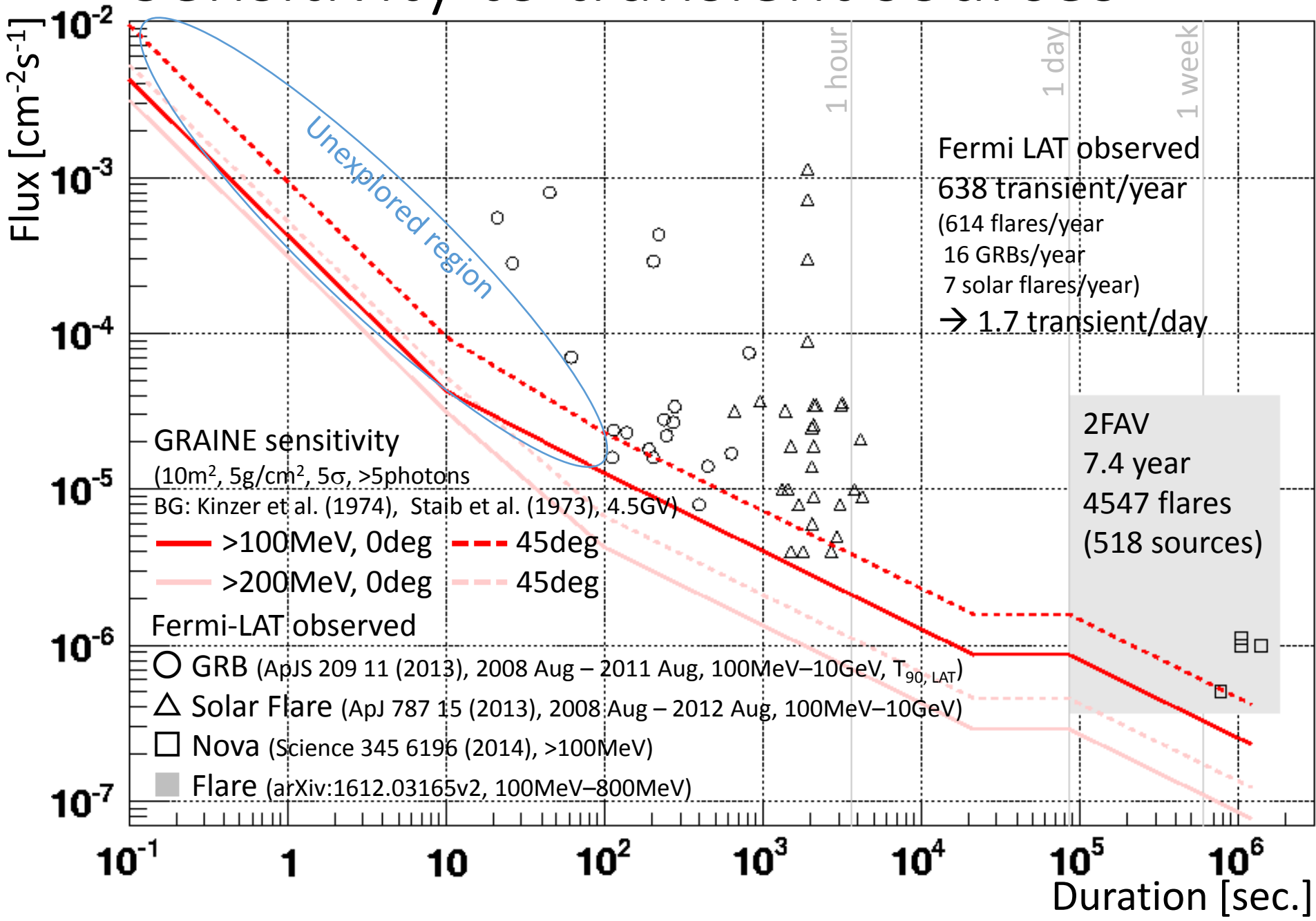
→ Good localization  $\sim 0.1\text{deg}$  @100photons

- Not continuous survey

- Not real time



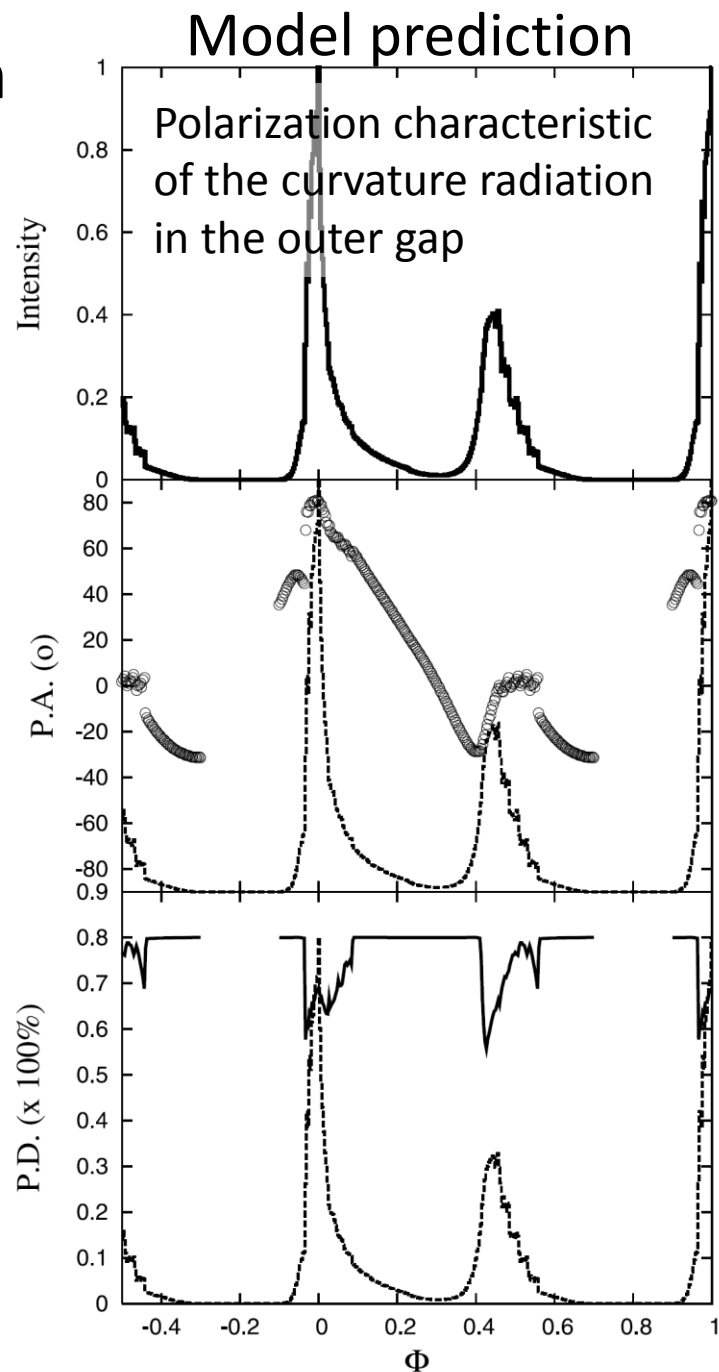
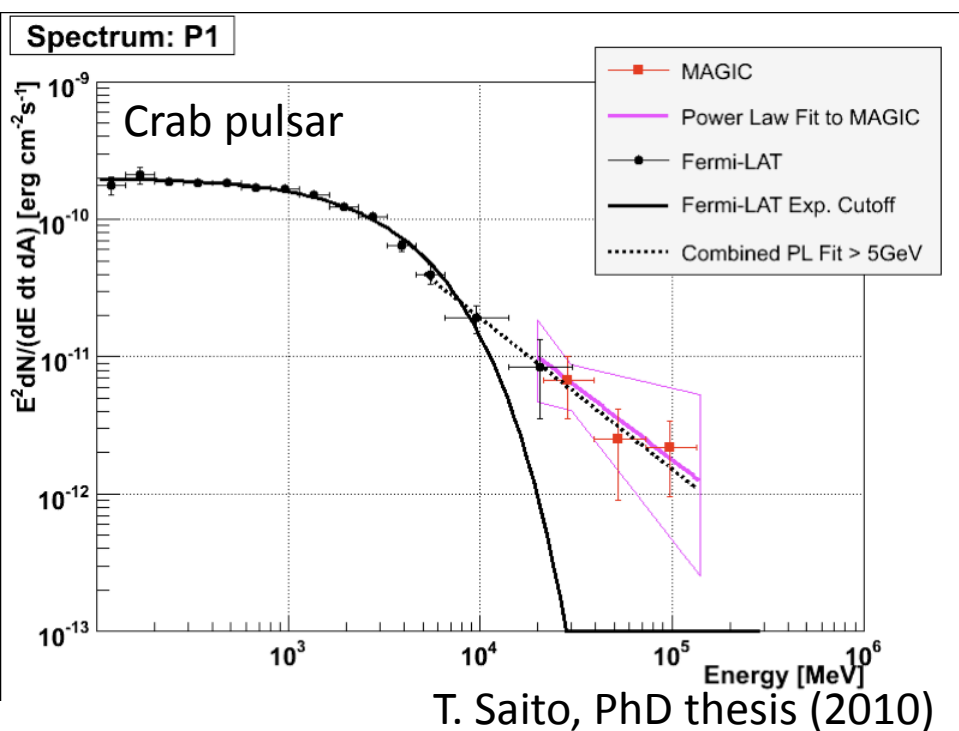
# Sensitivity to transient sources



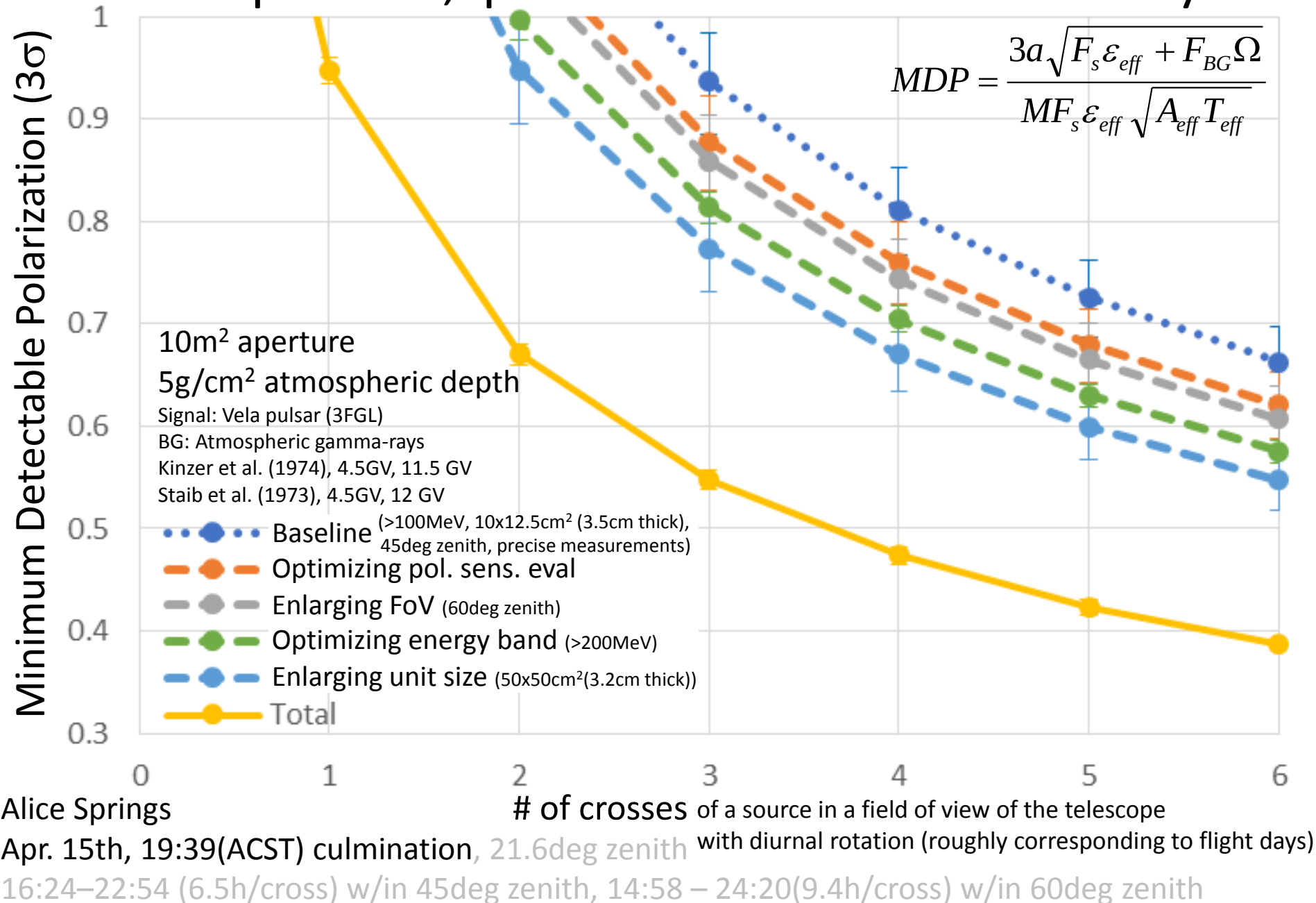
# Pioneering polarization observation for high energy $\gamma$ -rays

## Approaching emission mechanism

Pulsars, AGNs, Flares, GRBs



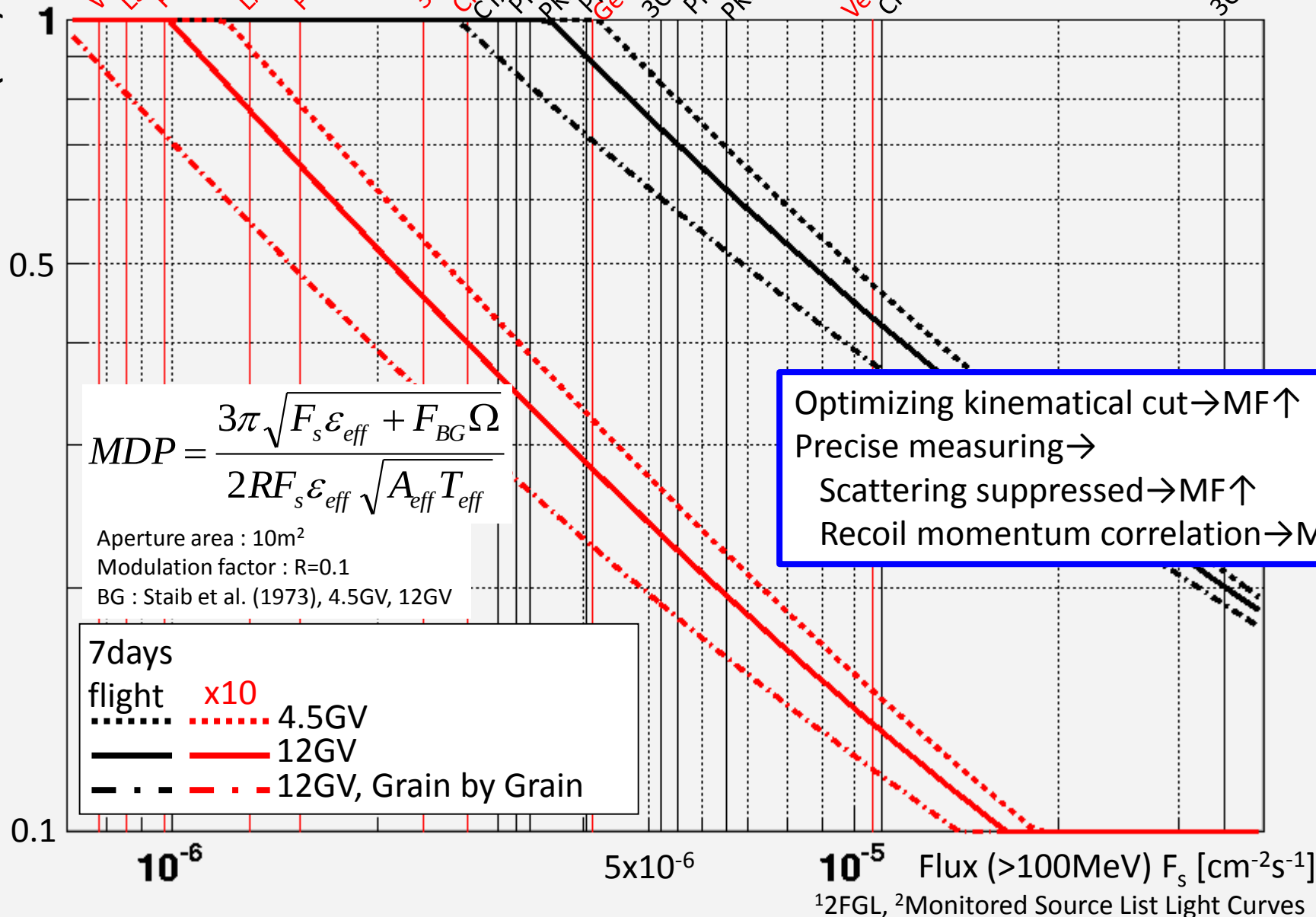
# Vela pulsar, polarization sensitivity





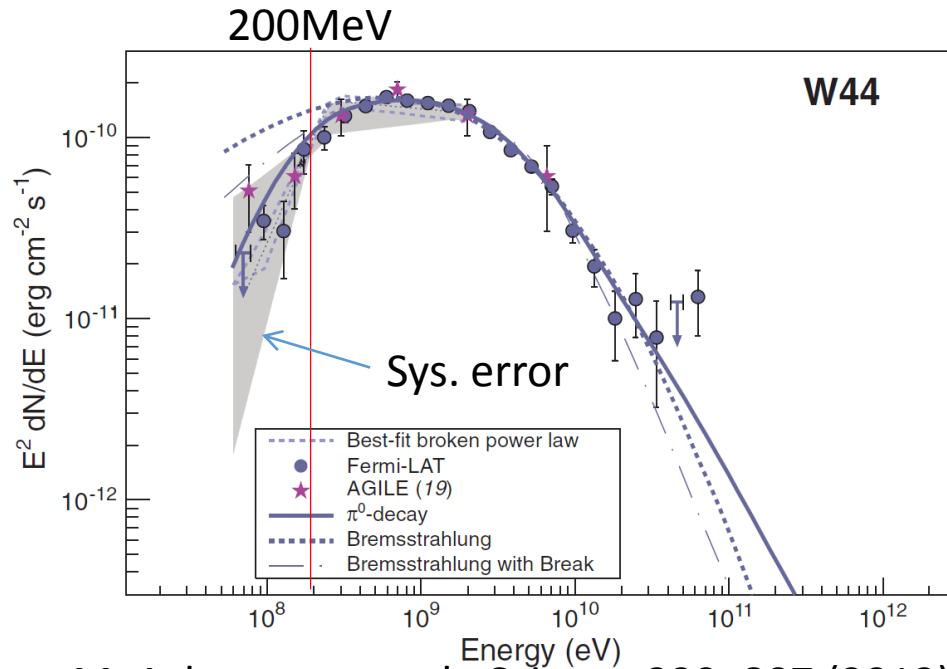
# Polarization sensitivity

Minimum Detectable Polarization ( $3\sigma$ )

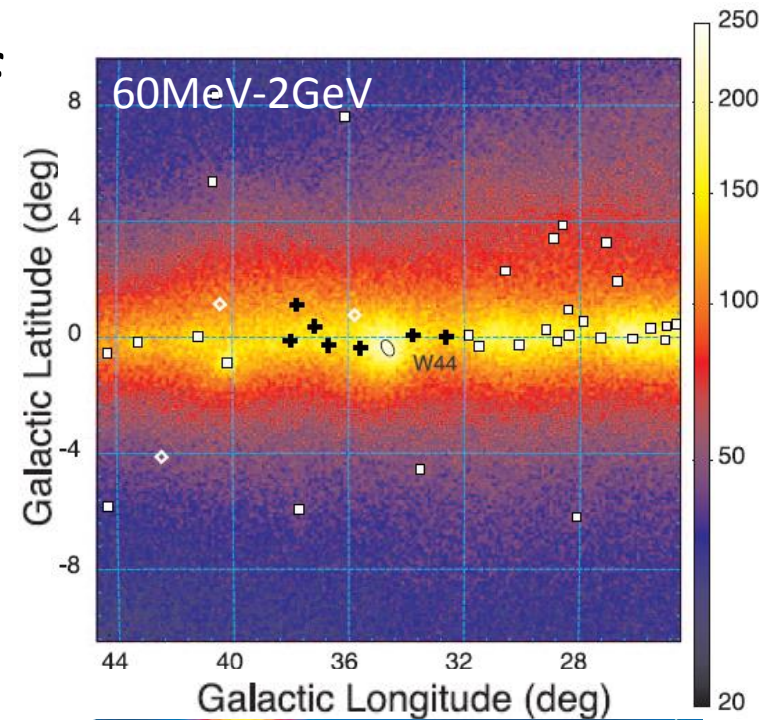


# $\pi^0$ emission: Direct evidence of proton acceleration

SNRs



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



Spatial structure:  
Emission mechanism

0.5deg  
W44

Abdo et al., Science, 2010

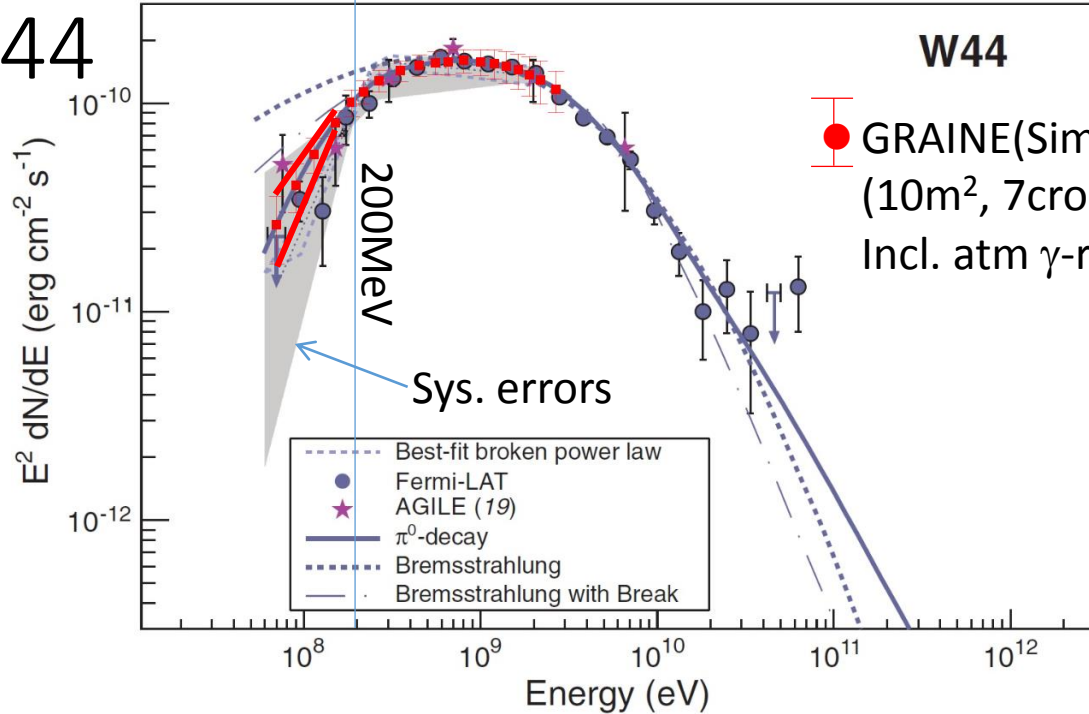
Color : 2-10GeV gamma-ray(Fermi LAT)

Contour : IR(Spitzer)

(deconvolved)

<200MeV, precise spectrum measurements  
with suppressed systematic errors  
>200MeV, investigating spatial structure

# W44

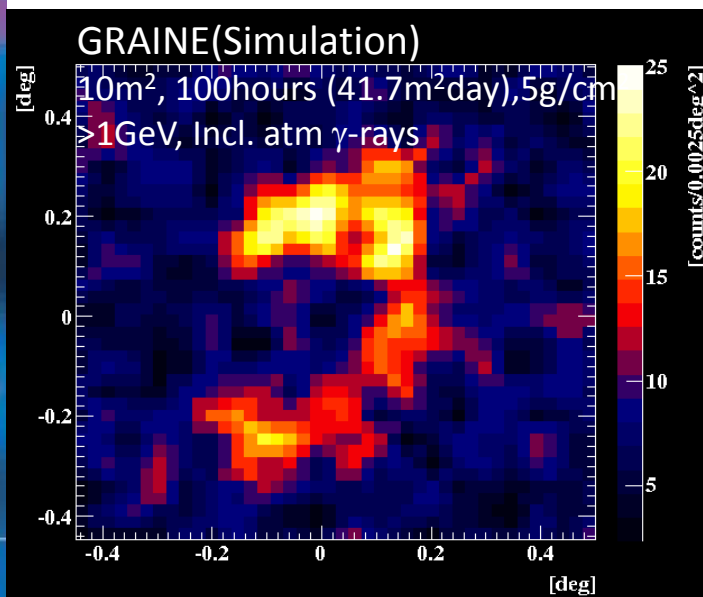
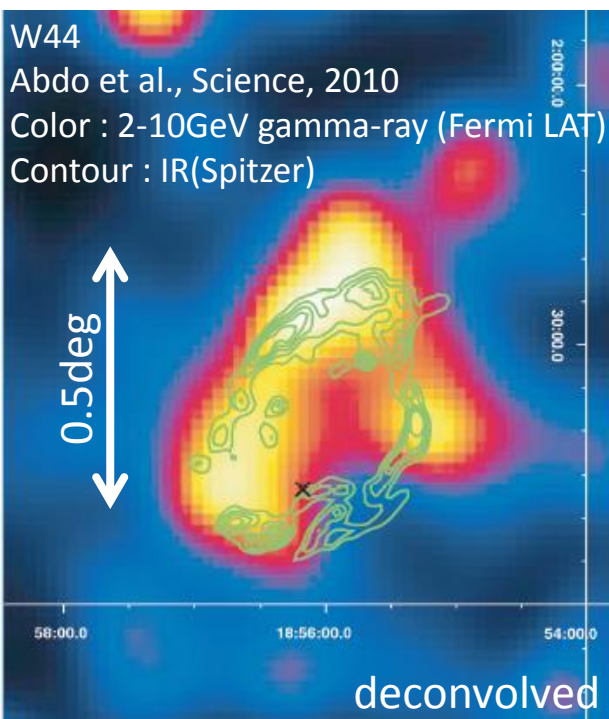


# W44

● GRAINE(Simulation)  
(10m<sup>2</sup>, 7crossX10, 5g/cm<sup>2</sup>,  
Incl. atm  $\gamma$ -rays)

<200MeV

Precise spectral measuring  
with suppressed systematic errors



>200MeV

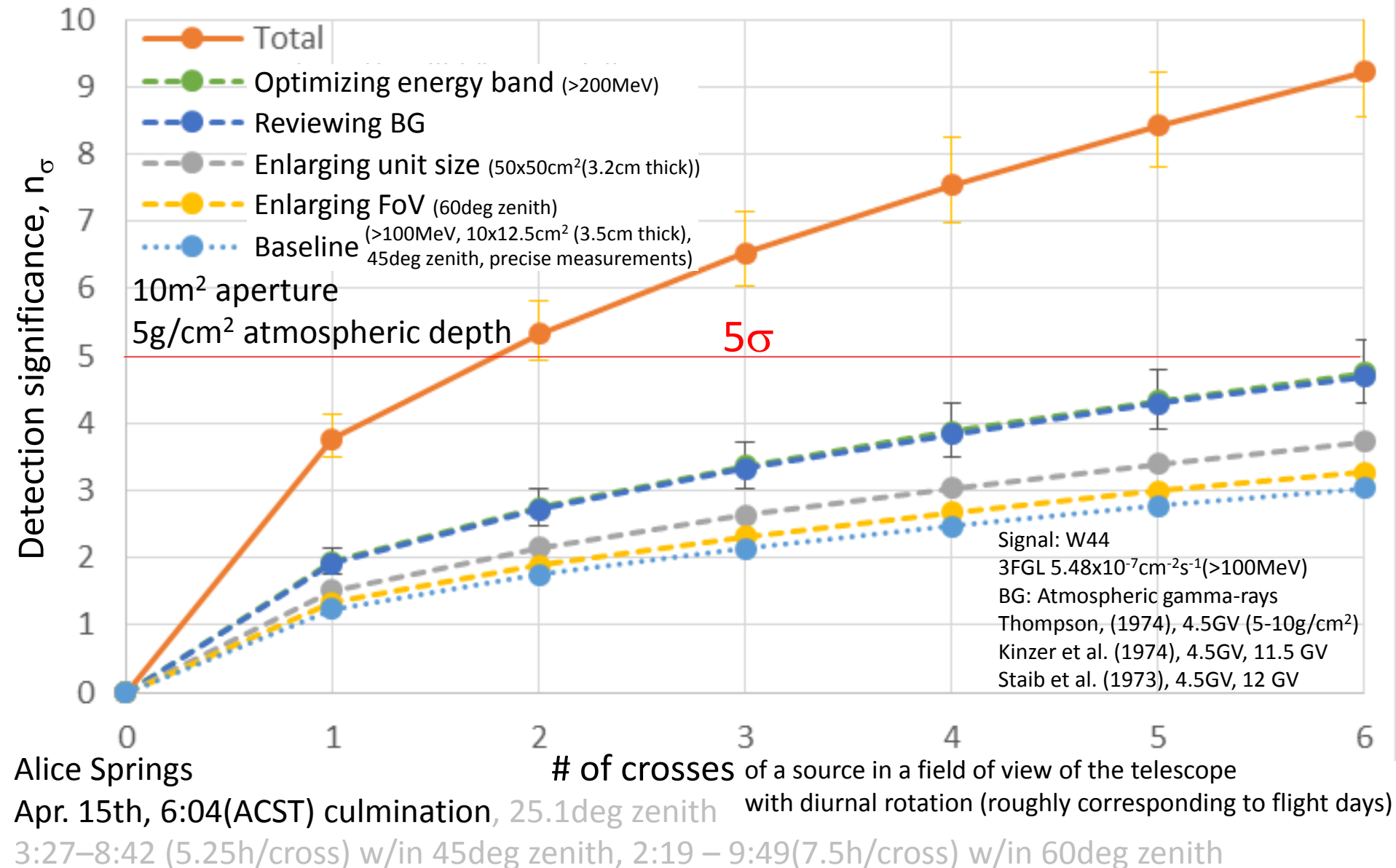
Investigating spatial structure

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

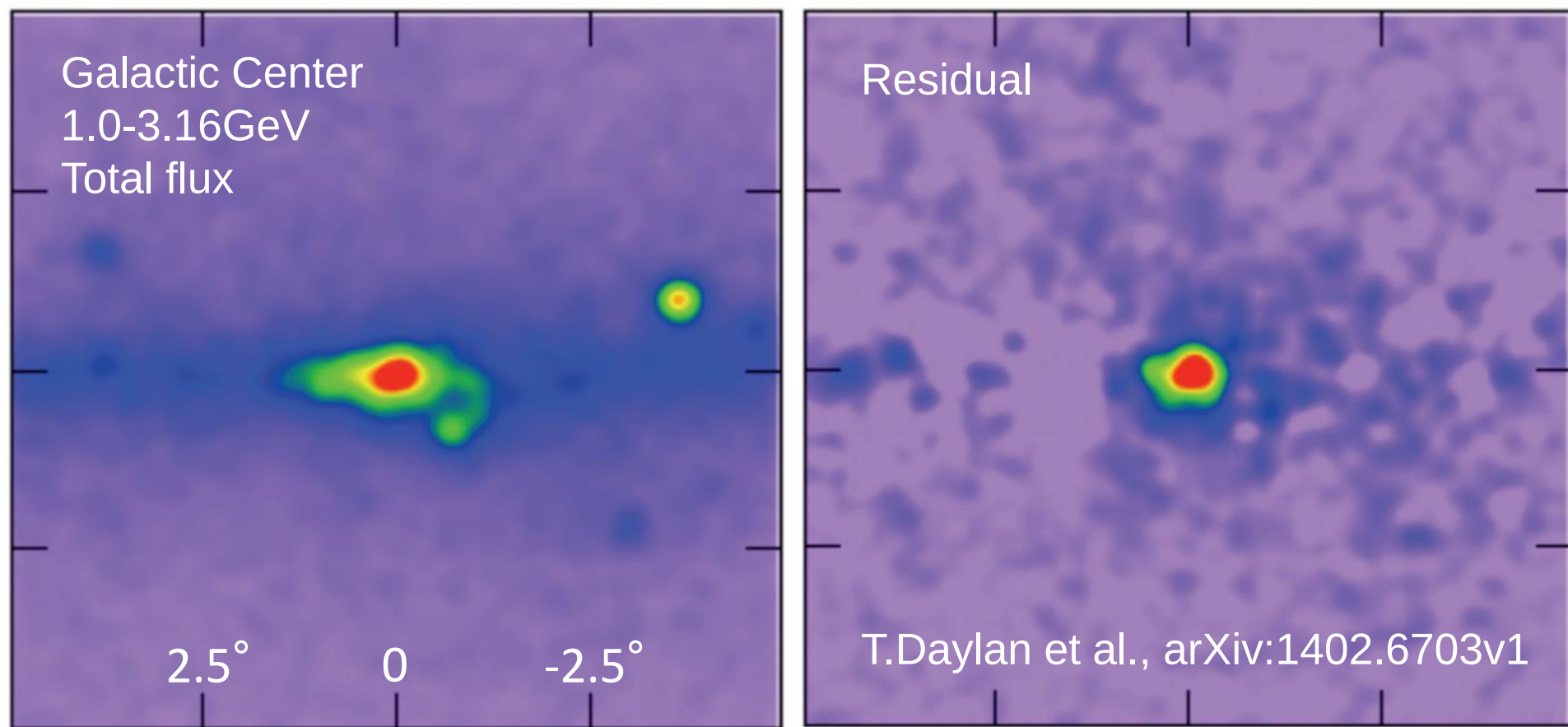


# W44 detection sensitivity

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

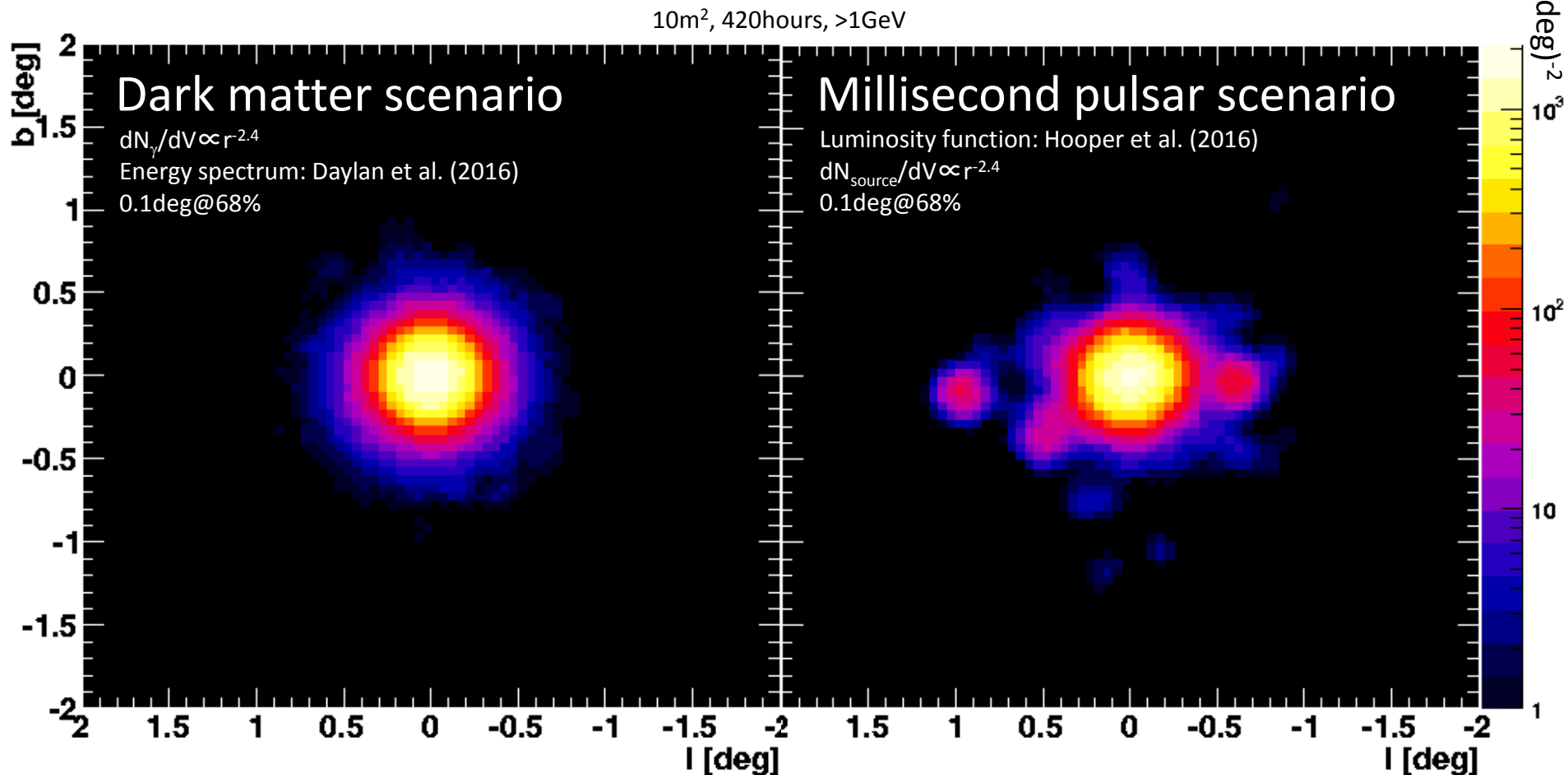


# GeV $\gamma$ -ray excess at galactic center region



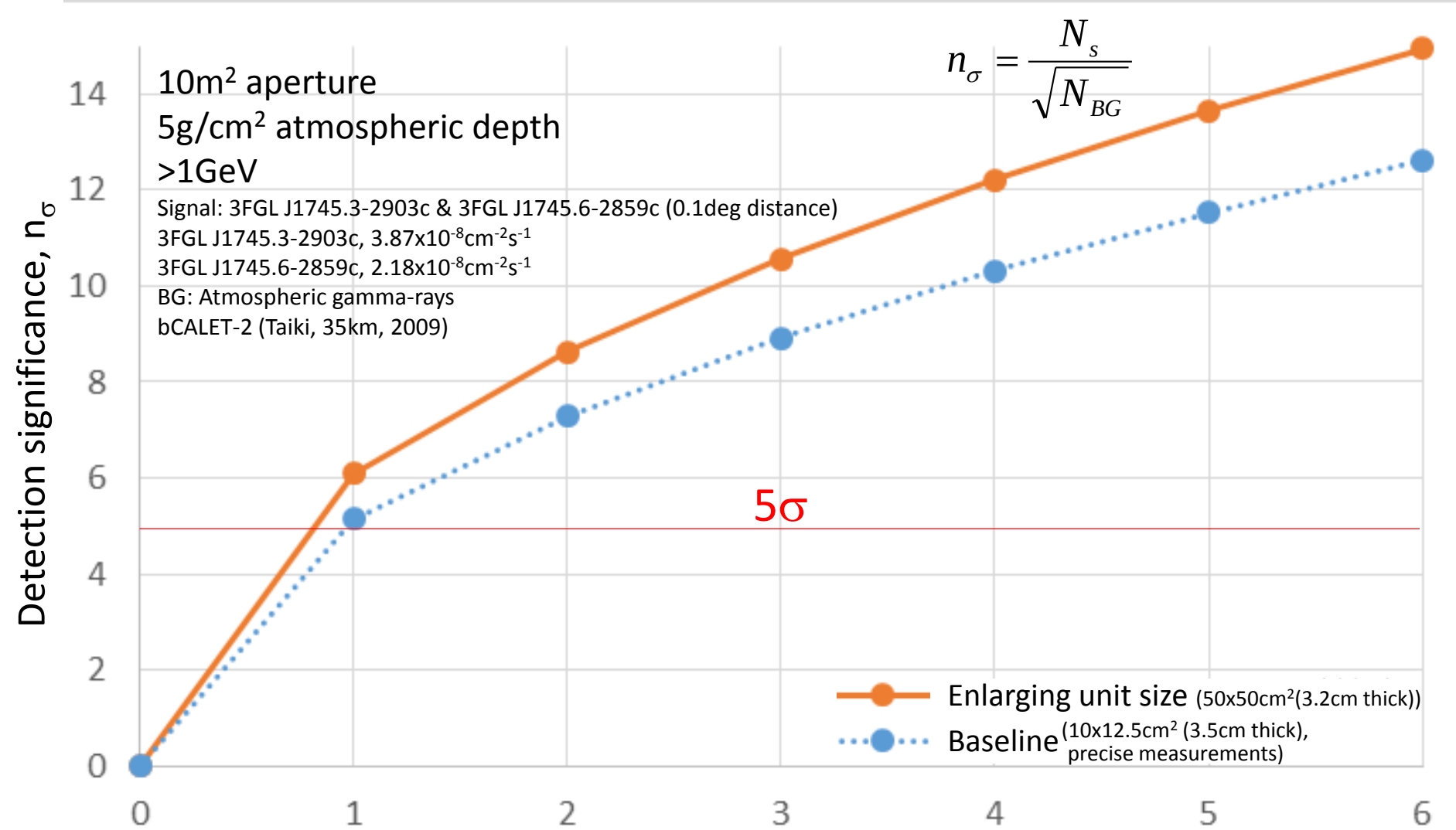
GeV  $\gamma$ -ray observations at galactic center region  
with  $\sim$ arcmin resolution

# Simulation of GeV $\gamma$ -ray excess at galactic center region w/ high angular resolution





# Galactic center region, detection sensitivity



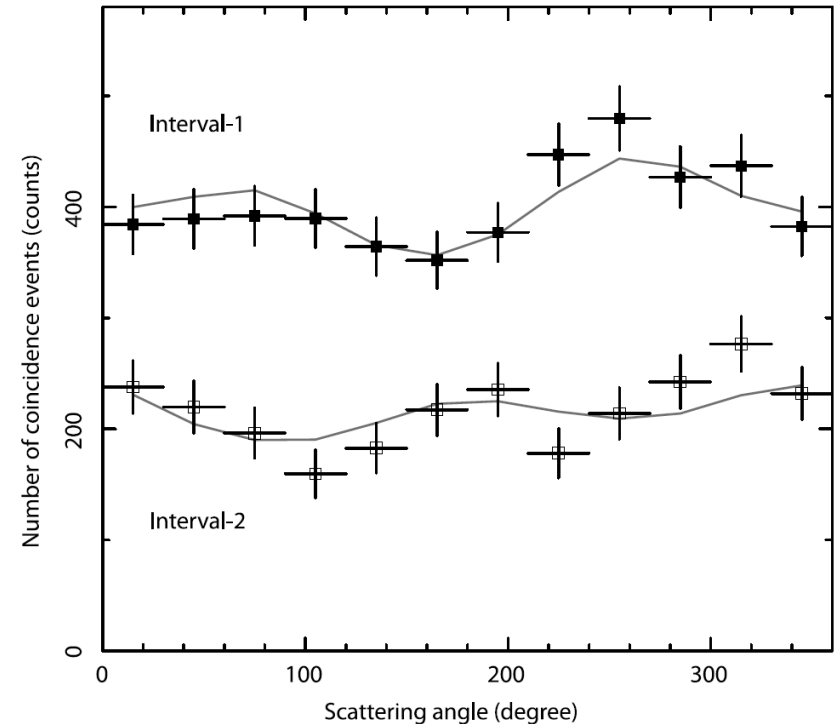
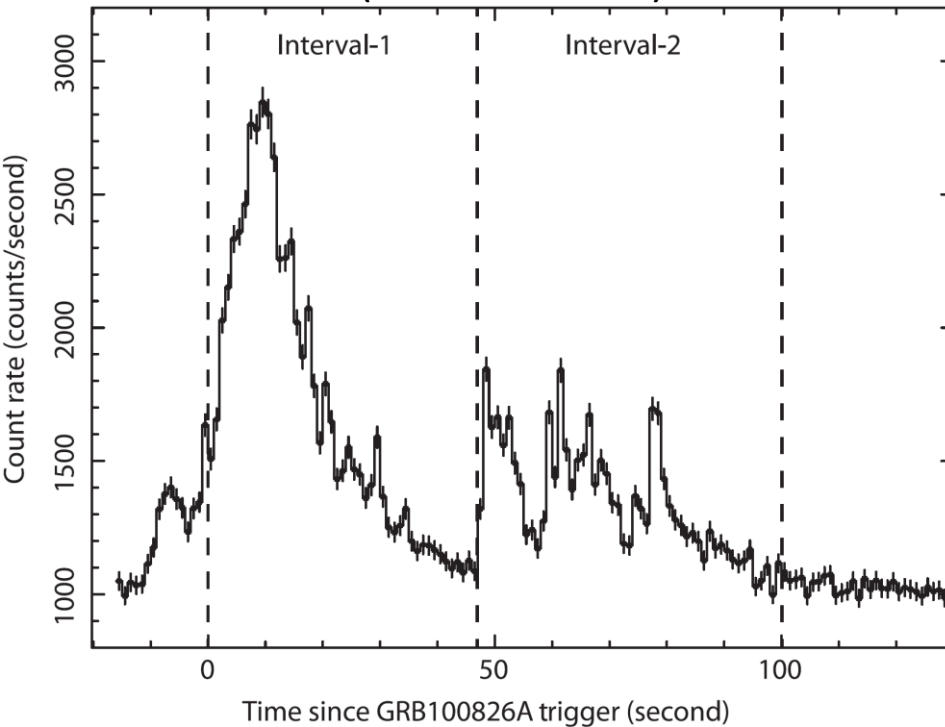
Alice Springs  
Apr. 15th, 4:53(ACST) culmination, 5.3deg zenith  
1:31–8:16 (6.75h/cross) w/in 45deg zenith

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

$N_{\text{signal}}=132, N_{\text{BG}}=78$  @ 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  $\gamma$ -rays** (e.g. > 100 MeV) from **distant AGNs and GRBs** by emulsion  $\gamma$ -ray telescope, **much strict** (five order of magnitude better) **validation** of CPT symmetry can be performed.

# GRAINE Scientific observation roadmap

## 2018, Demonstration

Alice Springs

$\sim 0.4\text{m}^2$  aperture

$\sim 18$  hours flight duration

$< \sim 5\text{g/cm}^2$  altitude

## 2021–, Scientific flight

Alice Springs

$10\text{m}^2$  aperture

$> \sim 36$  hours flight duration

$< \sim 10\text{g/cm}^2$  altitude

