

# GRAINE計画：( $\gtrsim 10\text{MeV}$ )

## エマルジョン望遠鏡による宇宙ガンマ線の観測計画

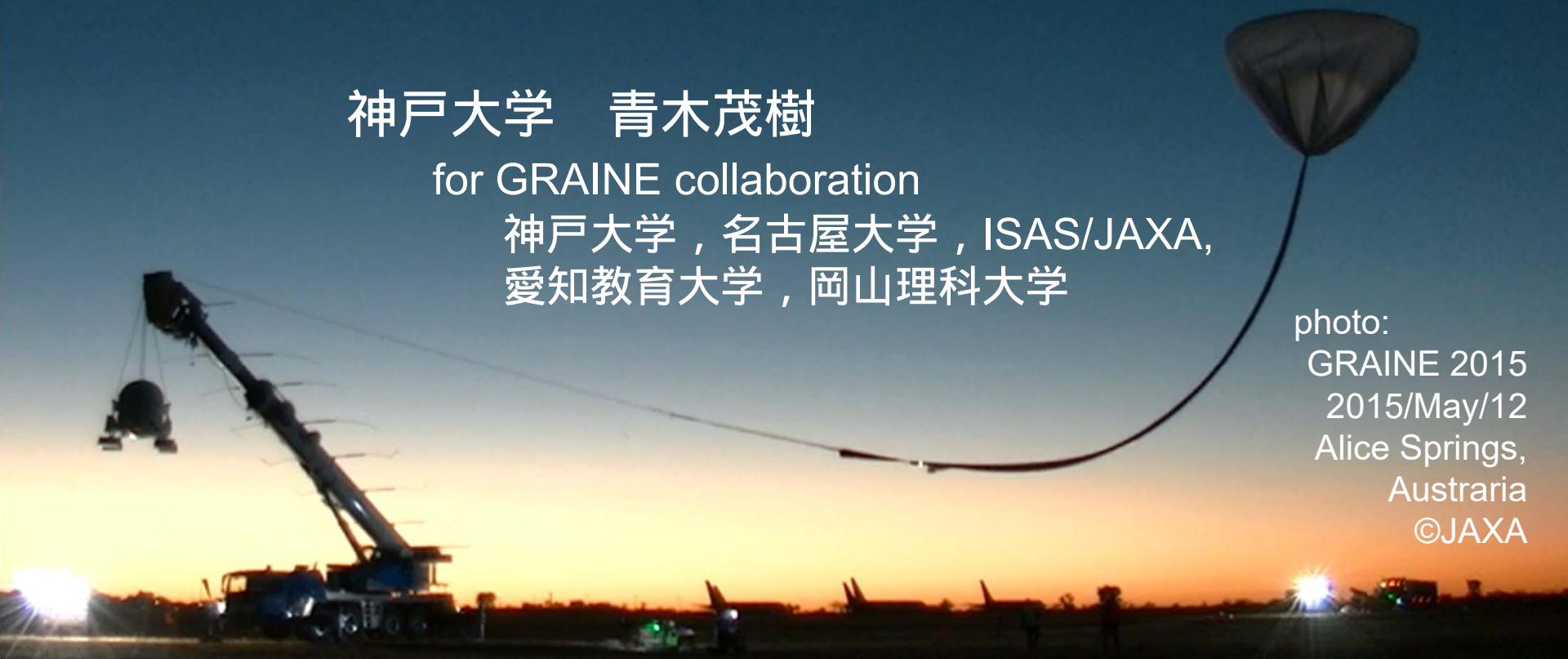
GRAINE = Gamma-Ray Astro-Imager with Nuclear Emulsion

神戸大学 青木茂樹

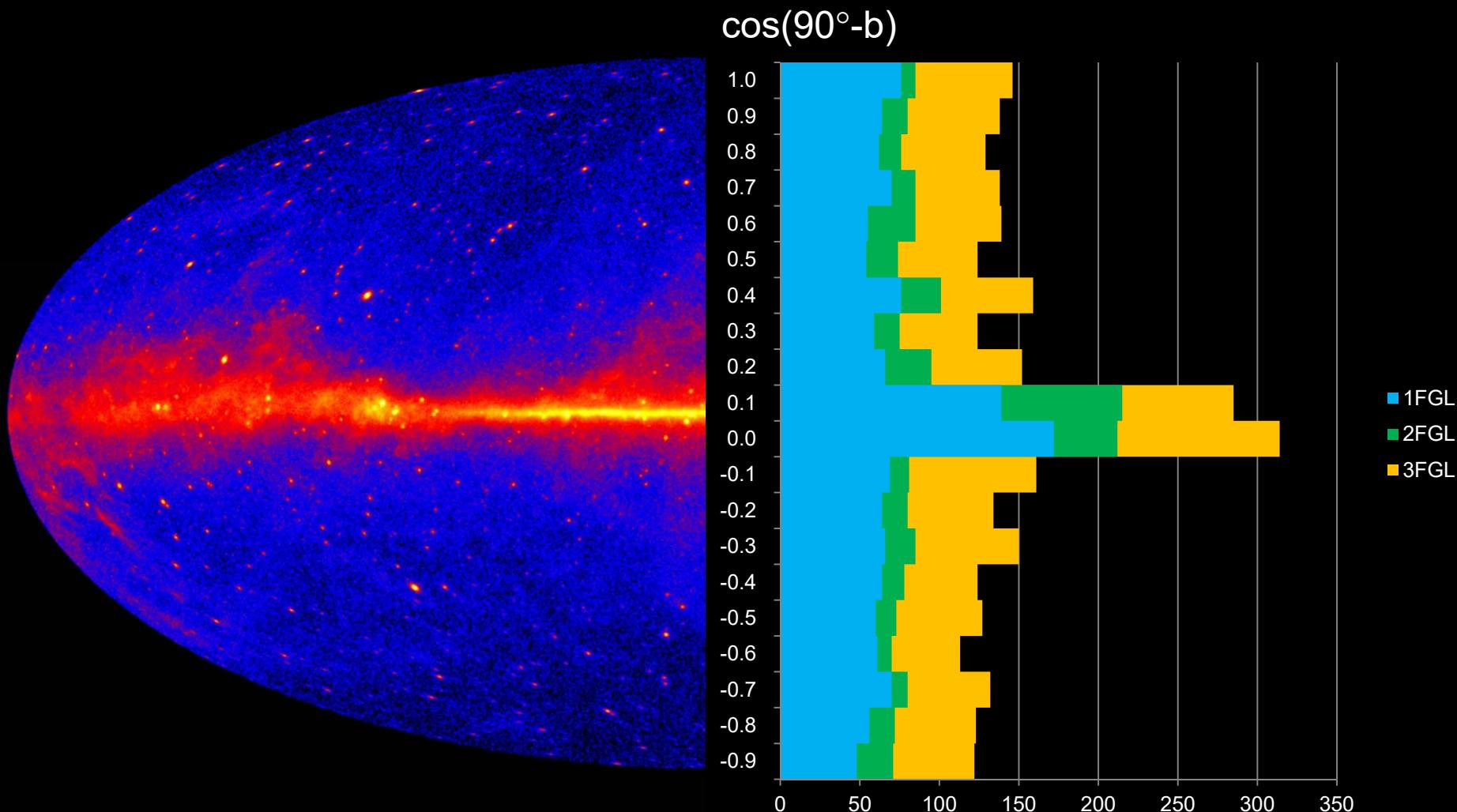
for GRAINE collaboration

神戸大学，名古屋大学，ISAS/JAXA，  
愛知教育大学，岡山理科大学

photo:  
GRAINE 2015  
2015/May/12  
Alice Springs,  
Australia  
©JAXA

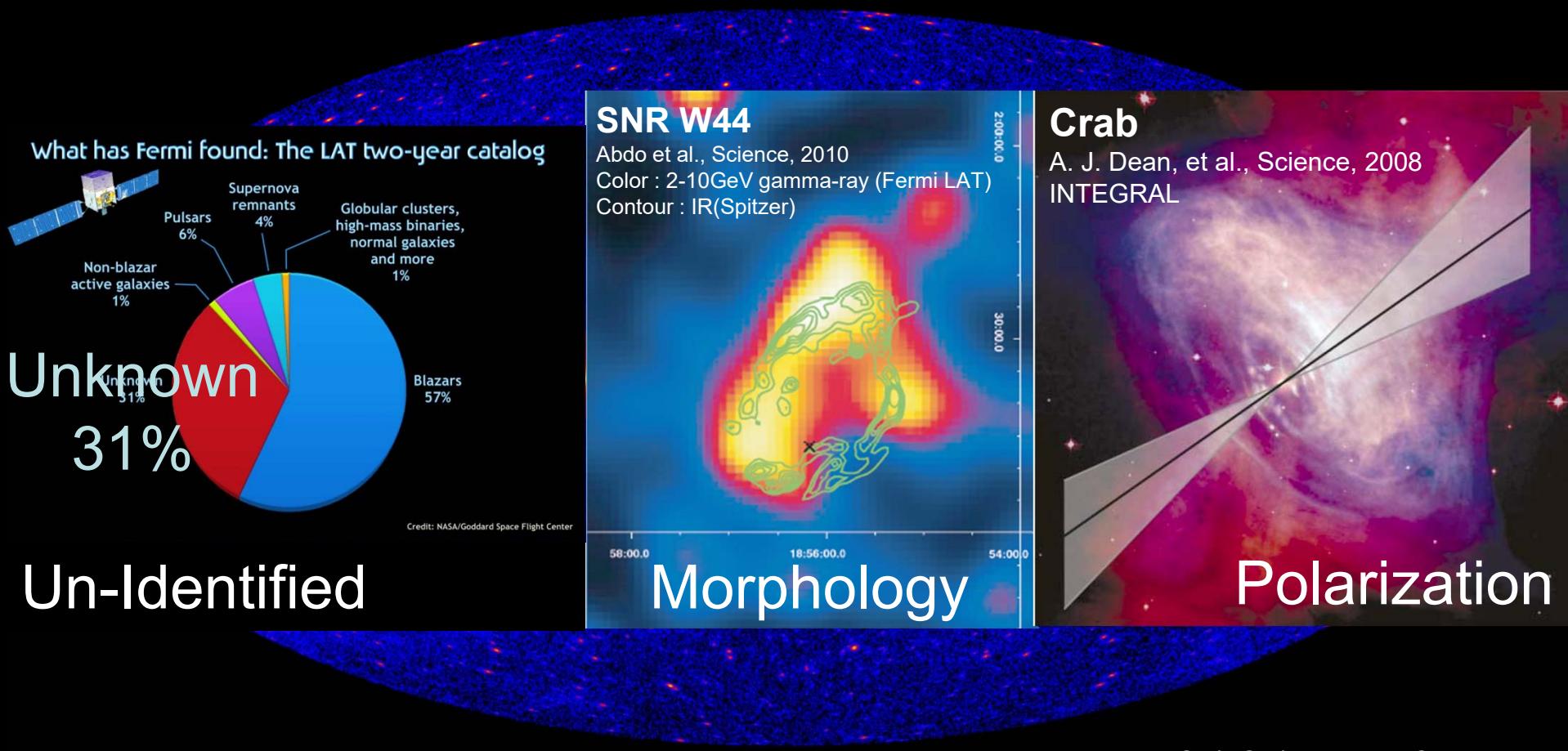


# Fermi's Five-year View of the Gamma-ray Sky



>3000 sources (3FGL)

# Fermi's Five-year View of the Gamma-ray Sky



>3000 sources (3FGL)

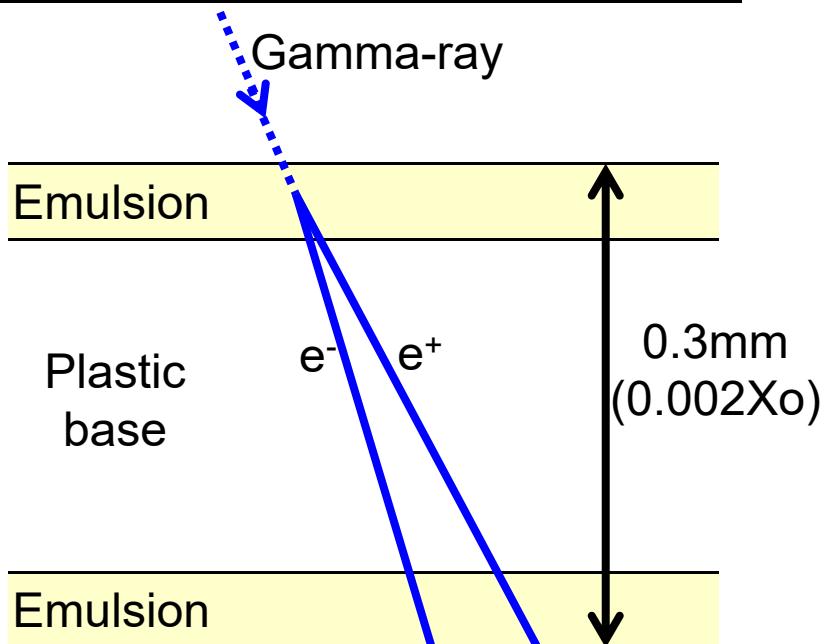
# Nuclear emulsion

Microscopic view  
10micron

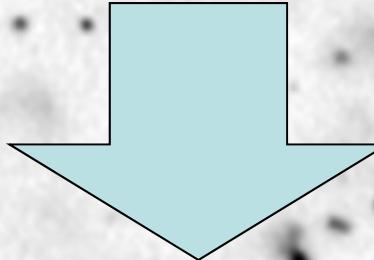
Gamma-ray  
.....>

$e^{+/}$   
 $e^{-/+}$

Cross sectional view of an emulsion film



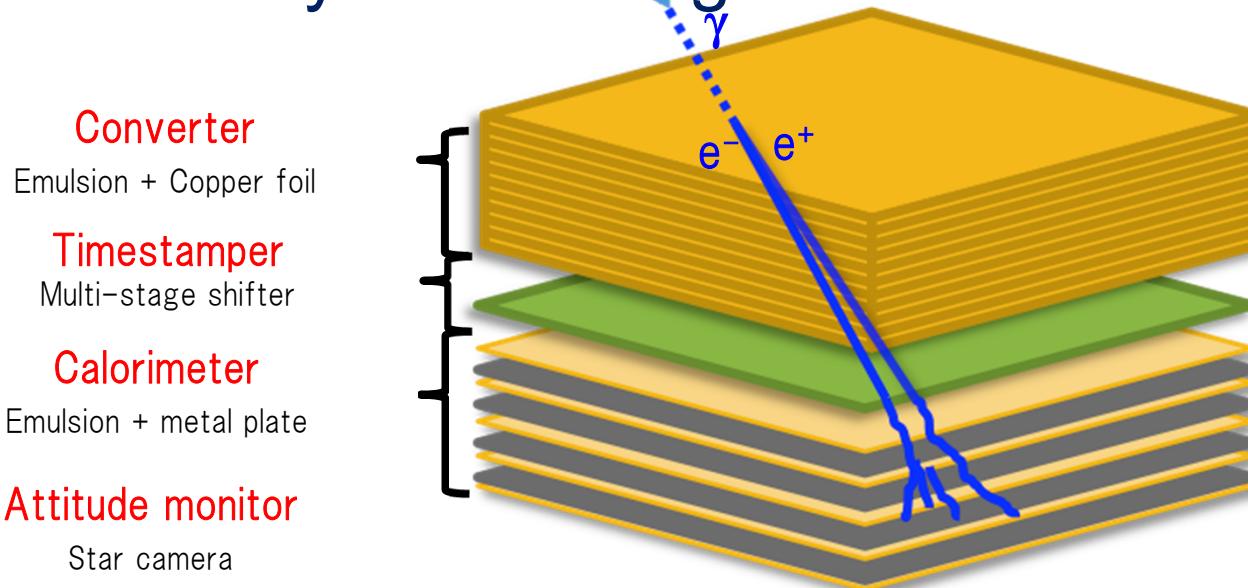
Powerful tracking device  
>High spatial resolution : ~1micron  
>Small radiation length : 0.002X<sub>0</sub>



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

# GRAINE

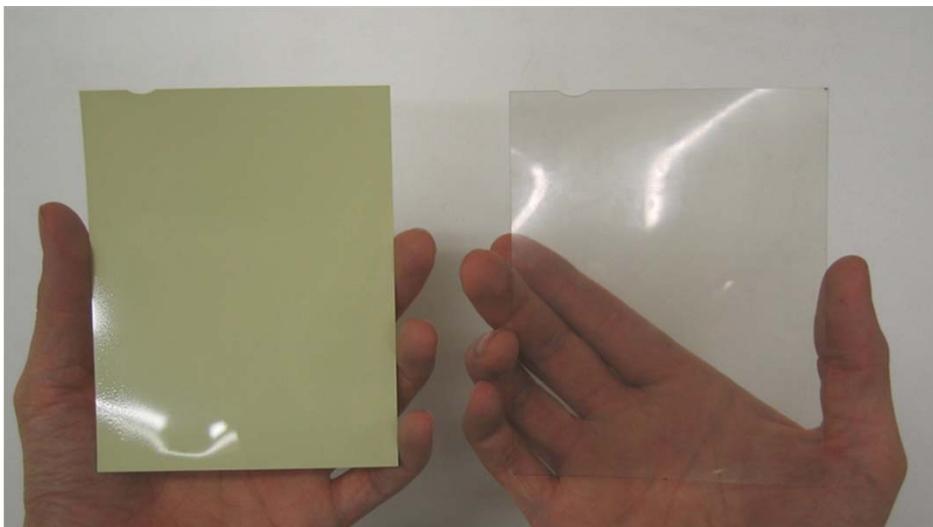
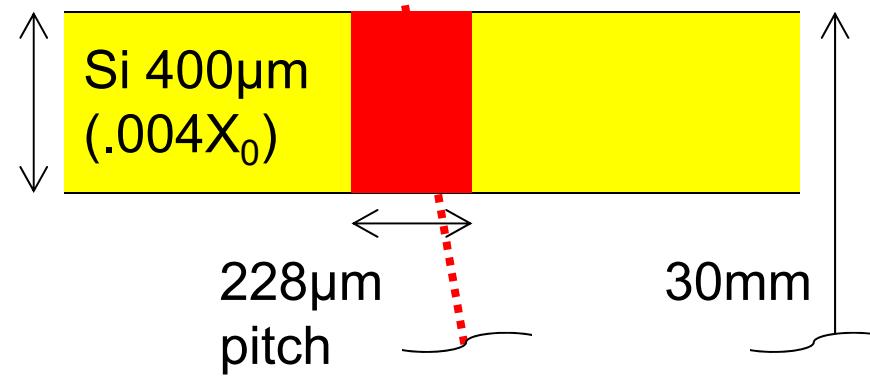
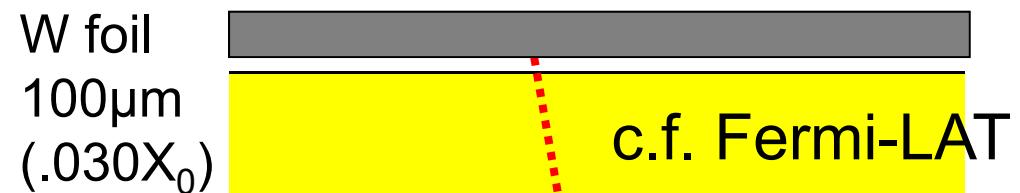
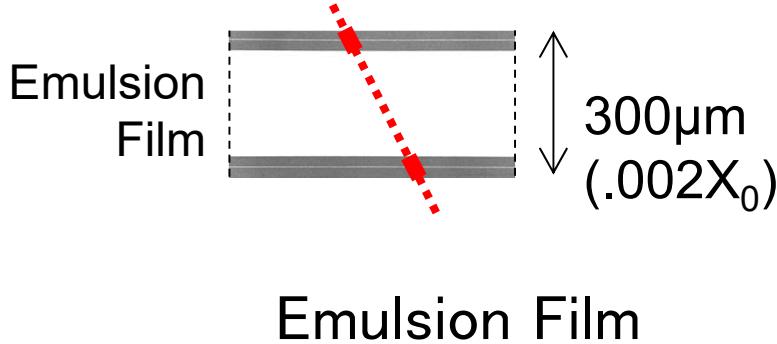
## Gamma-Ray Astro-Imager with Nuclear Emulsion



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

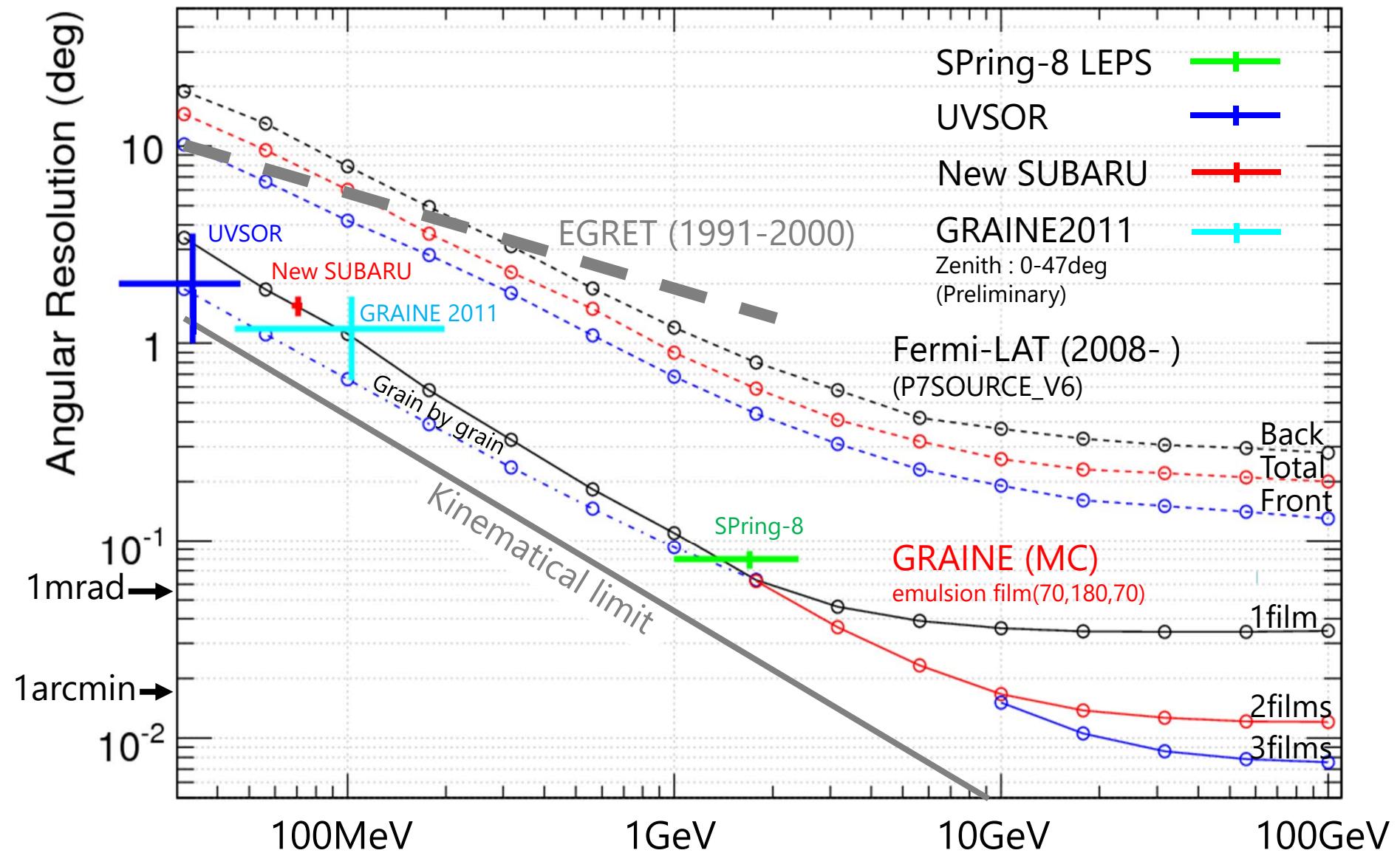
	Fermi LAT	GRAINE
Angular resolution @100MeV	6.0deg (105mrad)	$\xrightarrow{x1/6}$ 1.0deg (17mrad)
@1GeV	0.90deg (16mrad)	$\xrightarrow{x1/9}$ 0.1deg (1.7mrad)
Energy range	20MeV – 300GeV	10MeV – 100GeV
Polarization sensitivity	No	Yes
Effective area @ 100MeV	$0.25m^2$	$\xrightarrow{x8}$ $2.1m^2 *$
@ 1GeV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

# Gamma-Ray Astro-Imager with Nuclear Emulsion



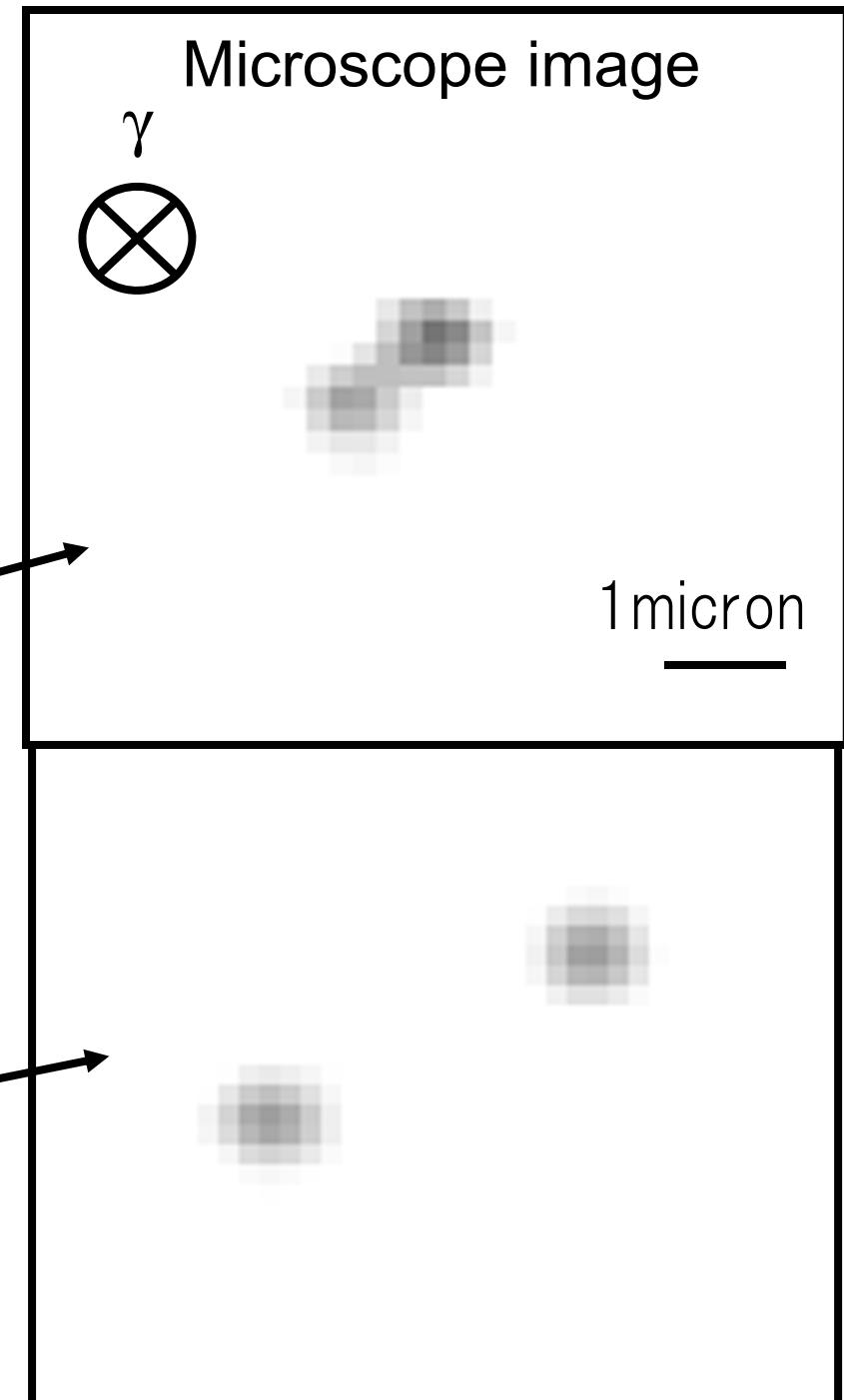
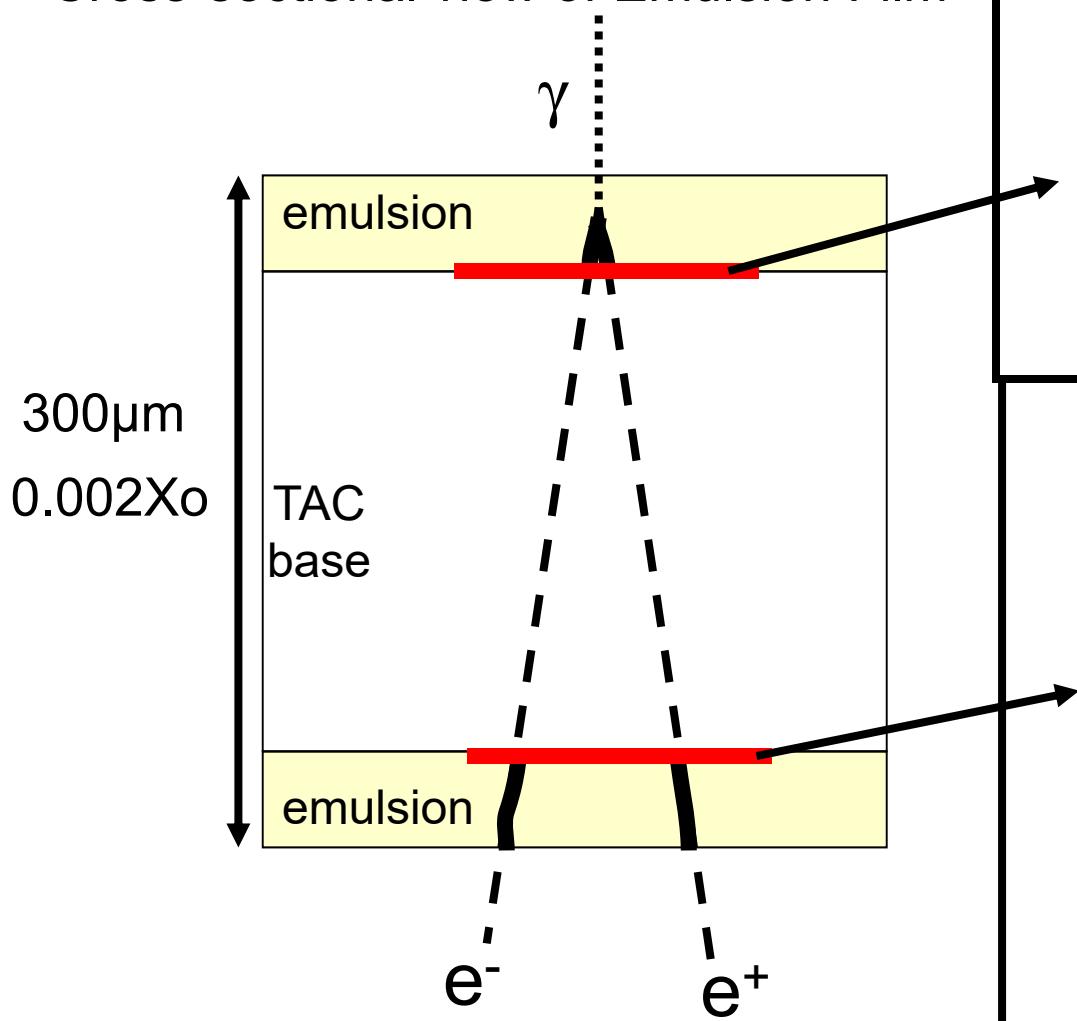
before and after  
of development

# Angular resolution



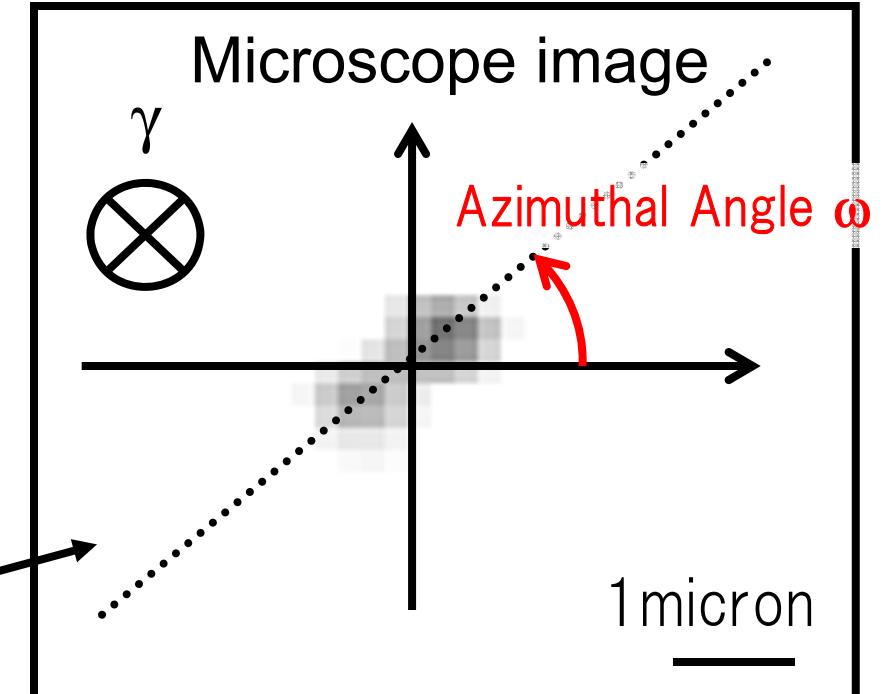
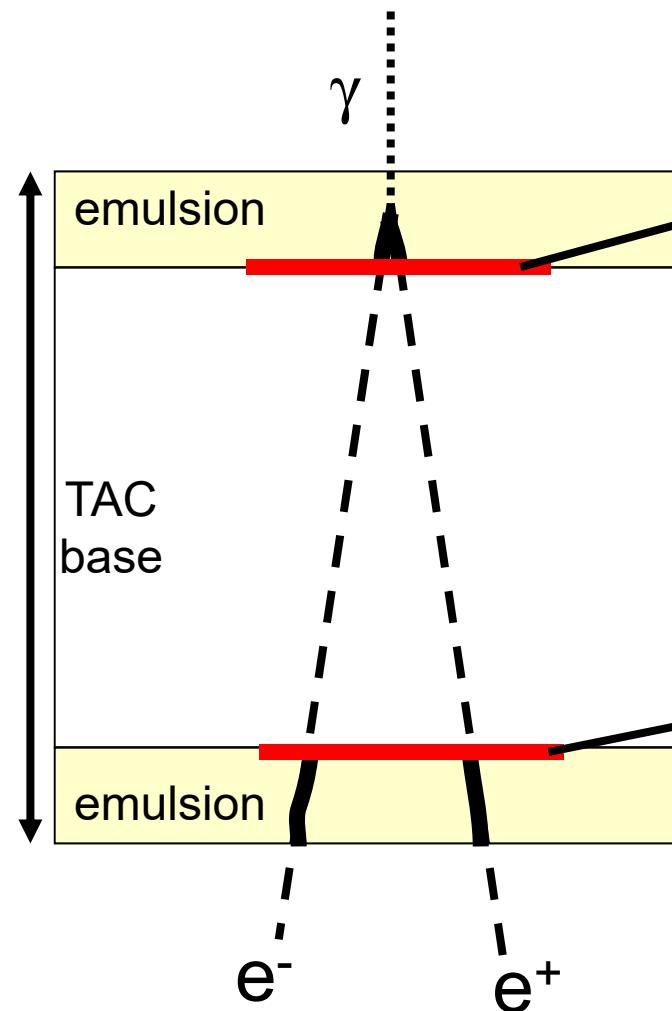
# Polarization measurement

Cross-sectional view of Emulsion Film

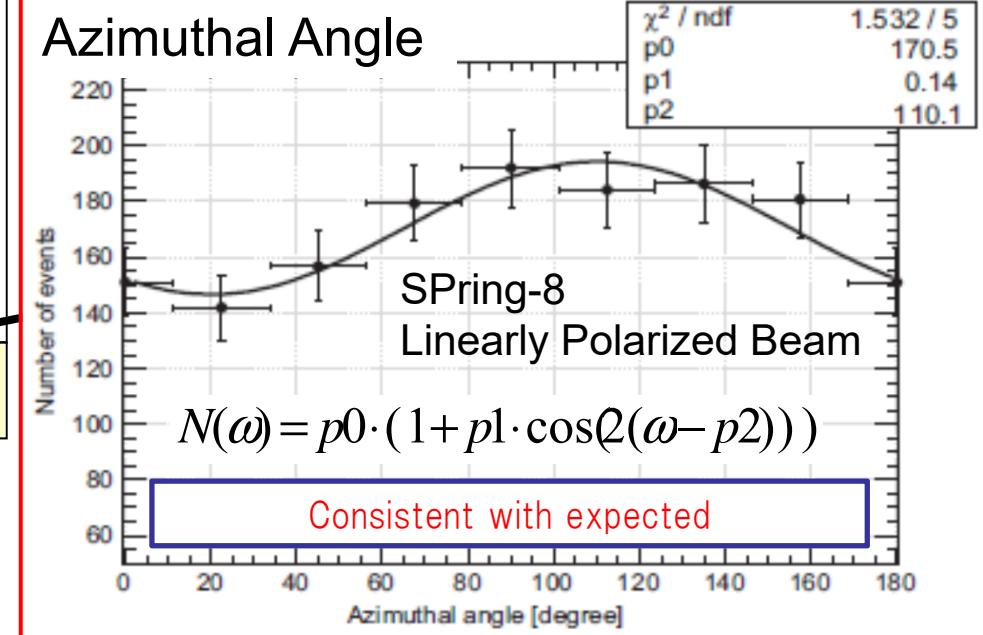


# Polarization measurement

Cross-sectional view of Emulsion Film

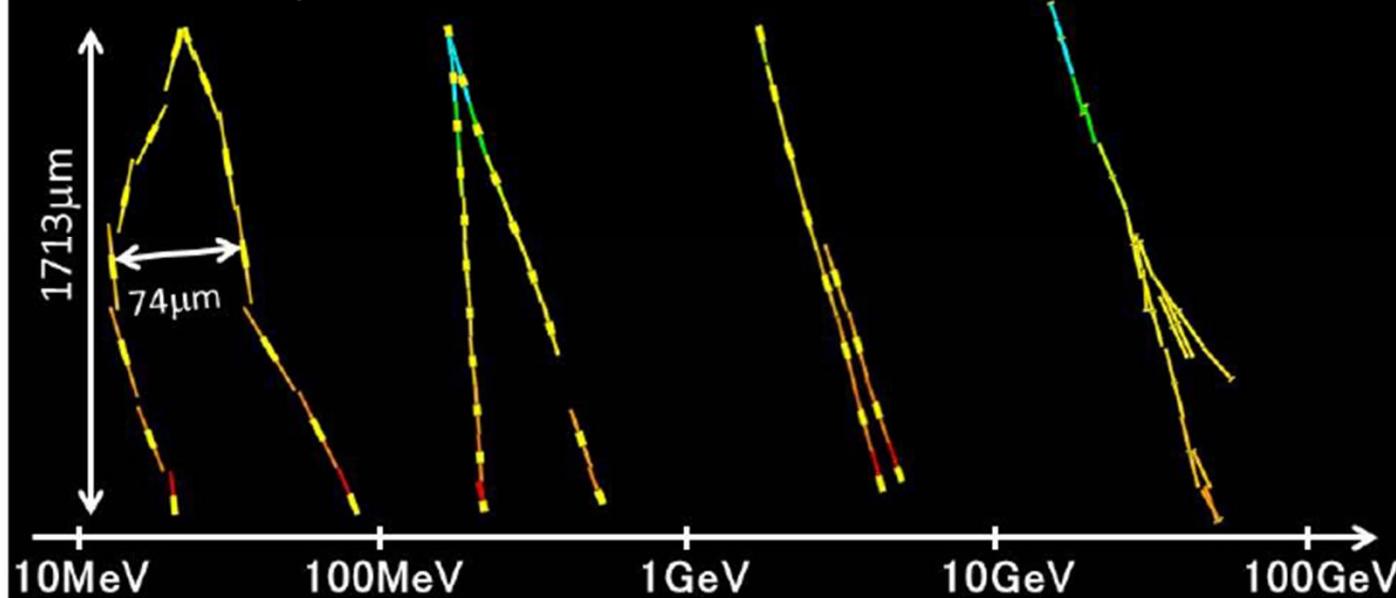


K. Ozaki et al. NIM A833 (2016) 165-168

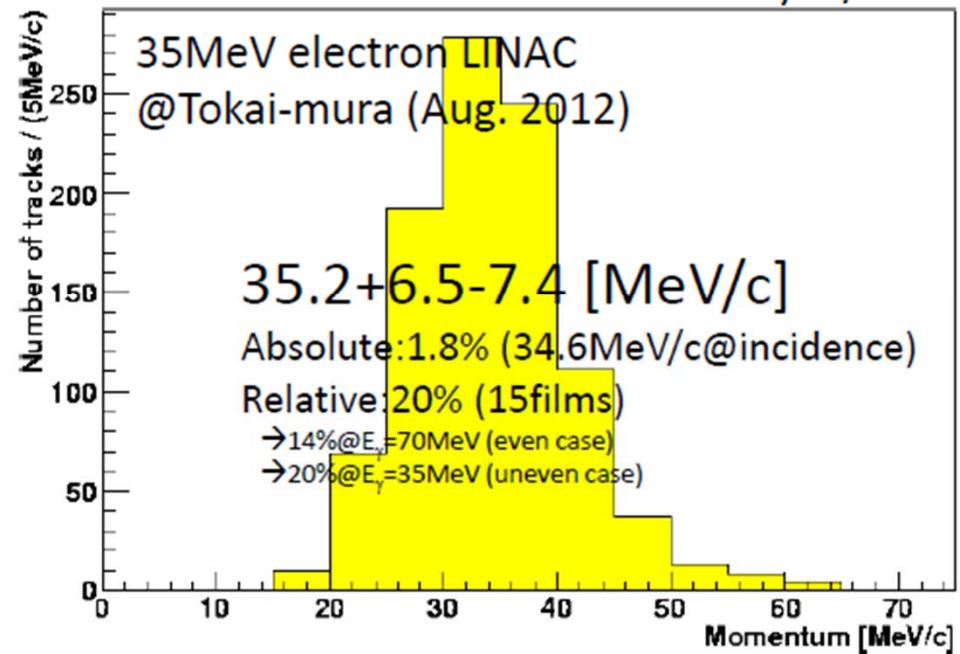


# Energy range

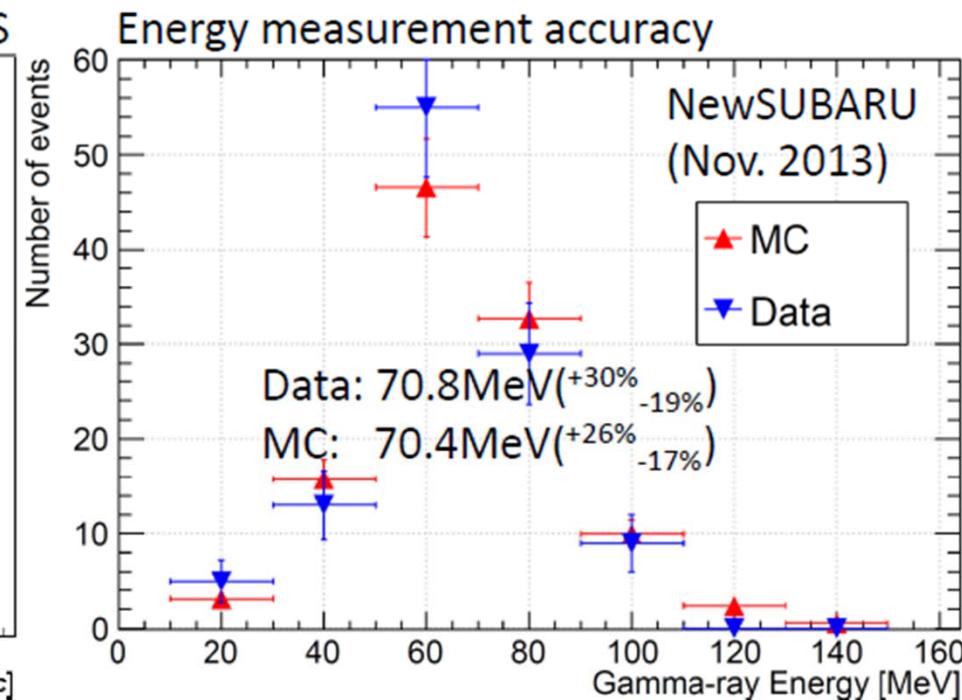
Atmospheric  $\gamma$ -ray @Mt. Norikura (July, Sep. 2007, July 2013), et al.



## Momentum measurement accuracy w/MCS

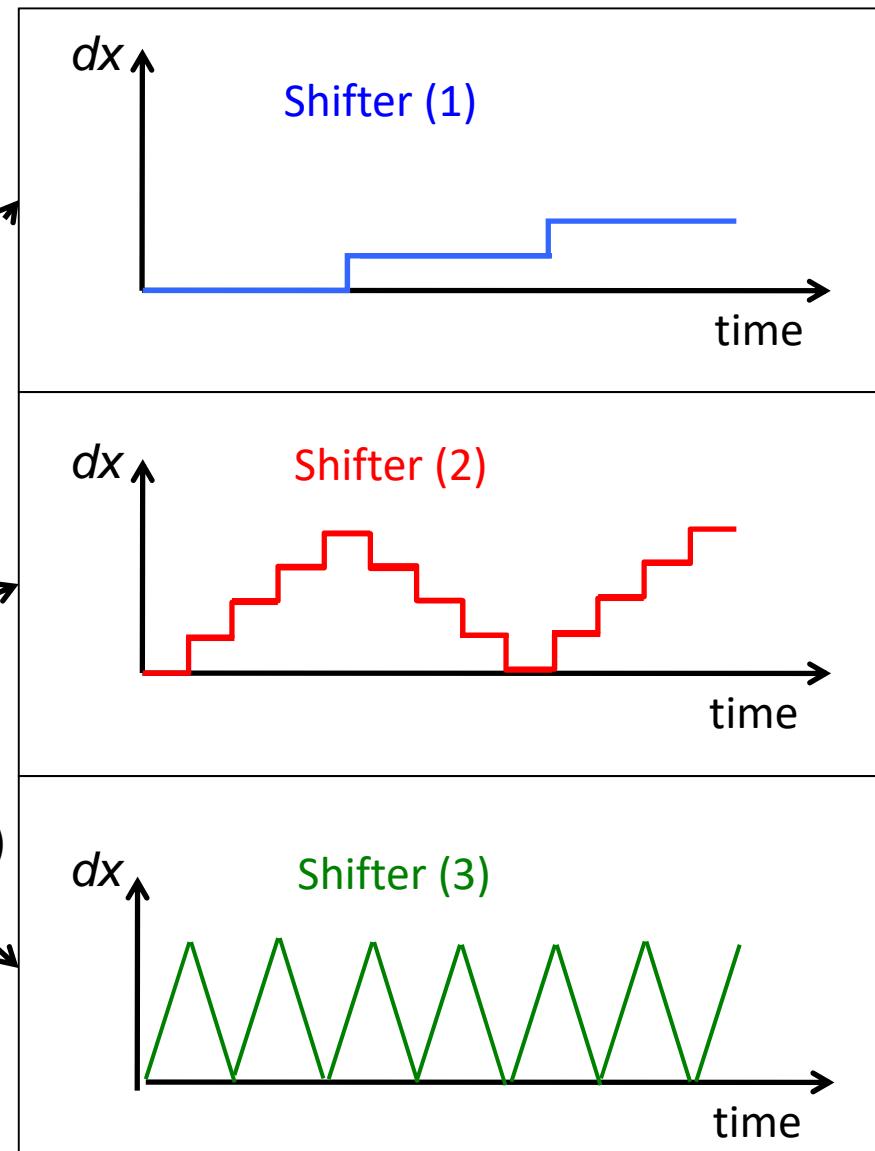
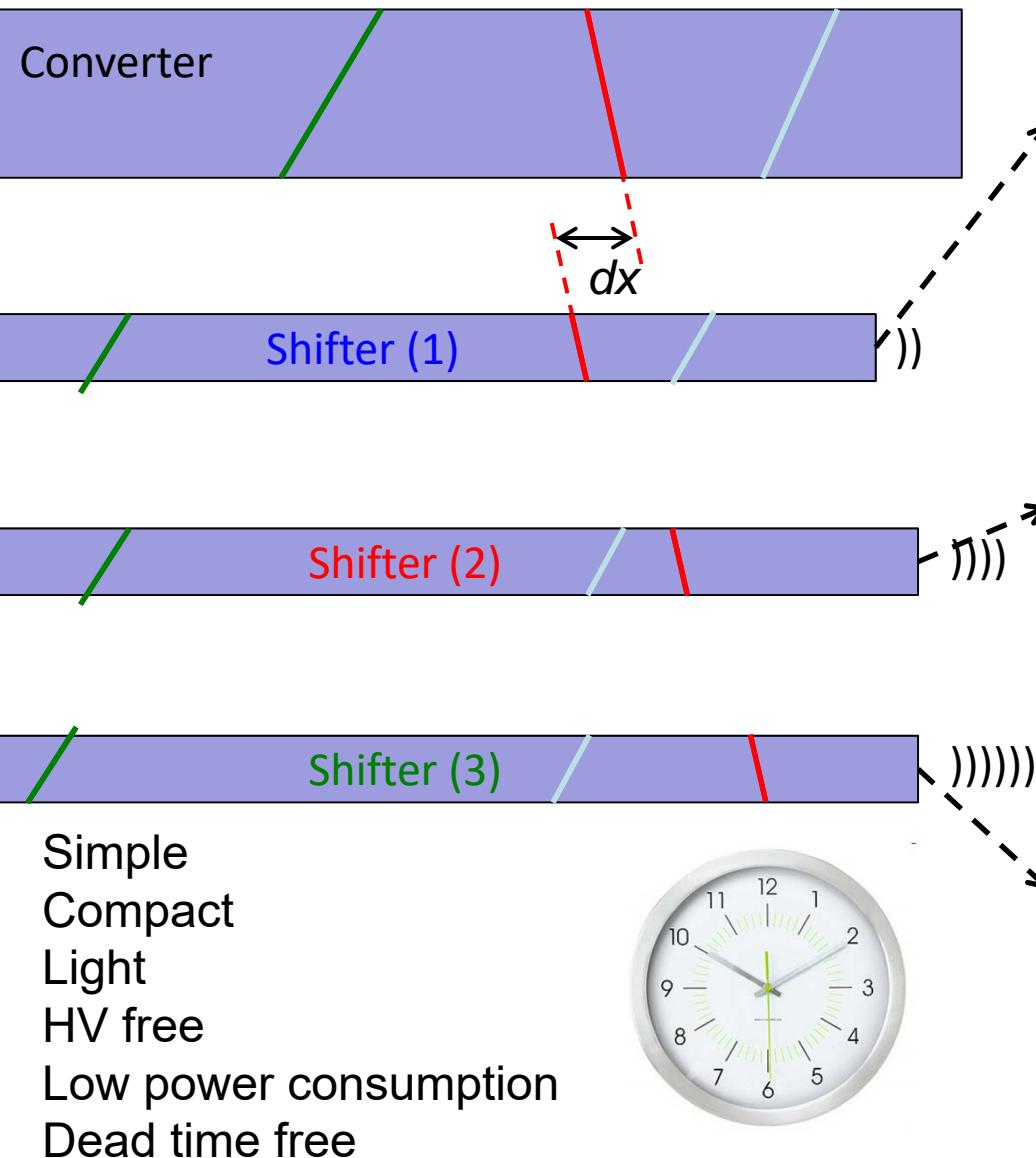


## Energy measurement accuracy

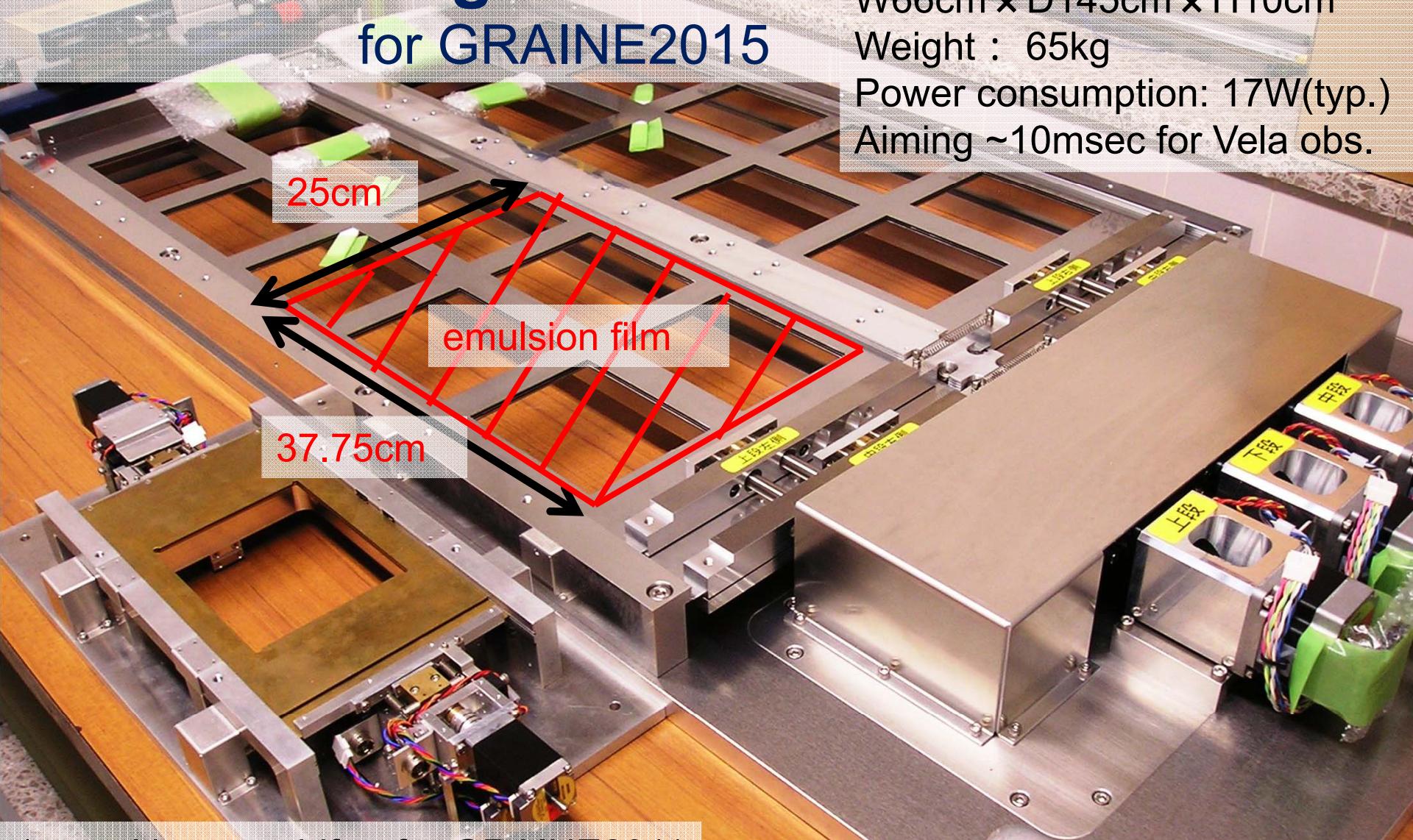


# Multi-stage shifter ( time stamper )

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



# 2nd multi stage shifter for GRAINE2015



Aperture area: 3800cm<sup>2</sup>  
W66cm × D145cm × H10cm  
Weight : 65kg  
Power consumption: 17W(typ.)  
Aiming ~10msec for Vela obs.

1st multi stage shifter for GRAINE2011  
Aperture area : 125cm<sup>2</sup>  
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<sup>2</sup> 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<sup>2</sup> aperture area, 14h22min (11h32min@36.0-37.4km) flight

- Overall test by detecting known gamma-ray source (Vela pulser)

- **Working Phase**

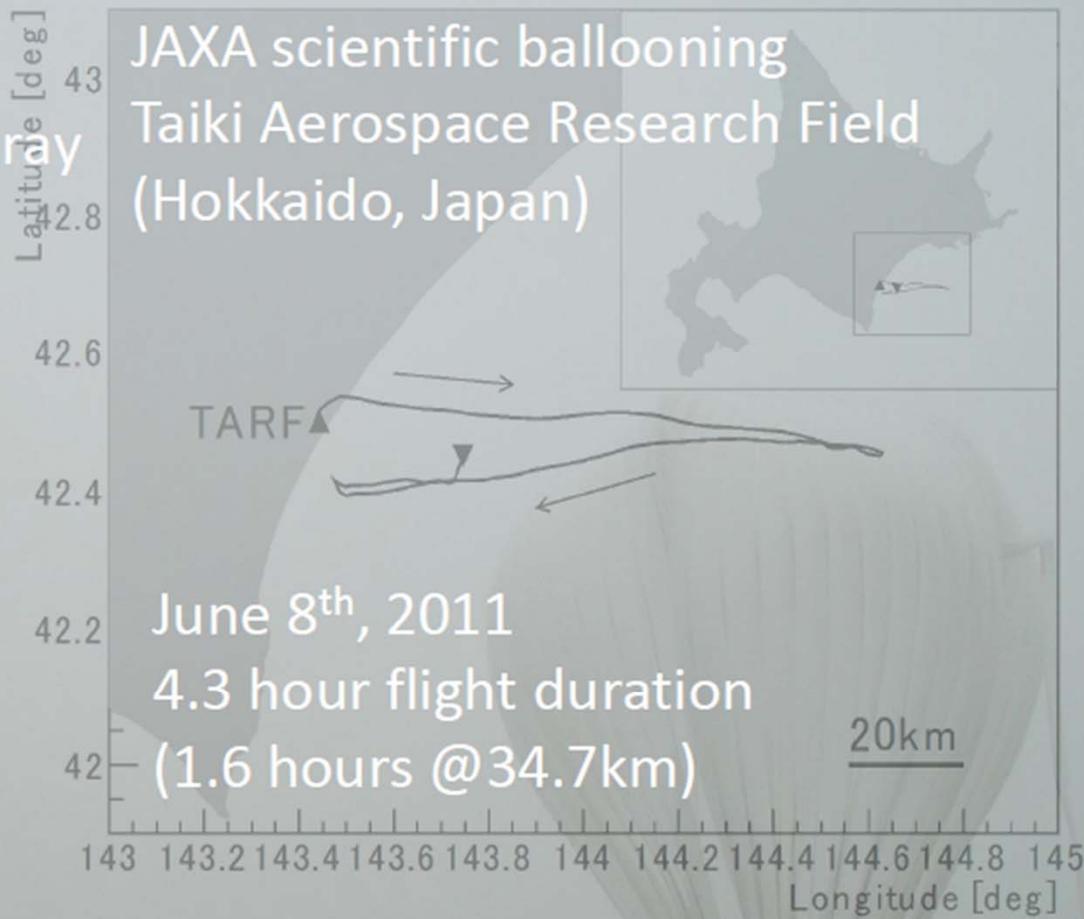
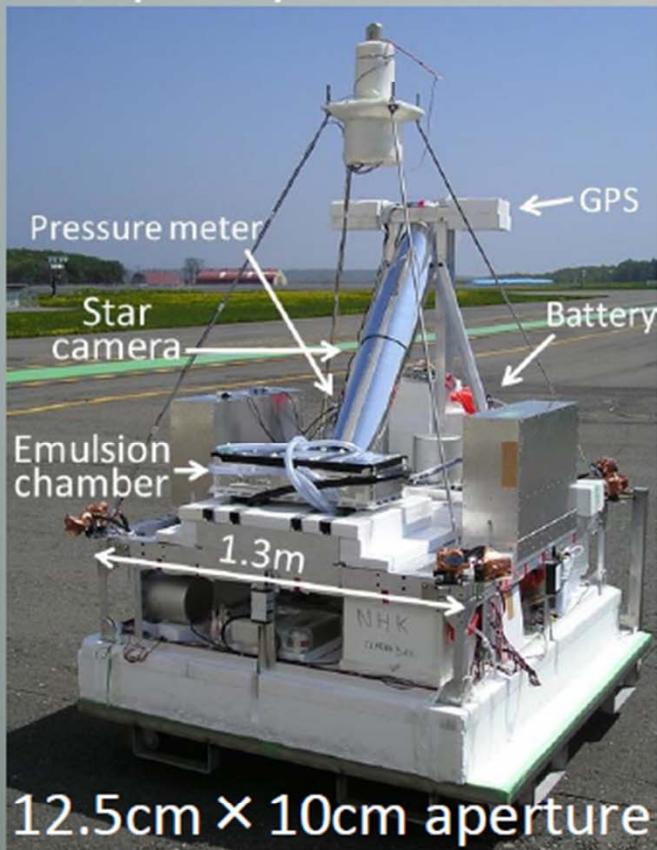
2021~ (planning)

2 to 10m<sup>2</sup> aperture area, ~36 hours flight duration

- Starting scientific observation

# GRAINE 2011

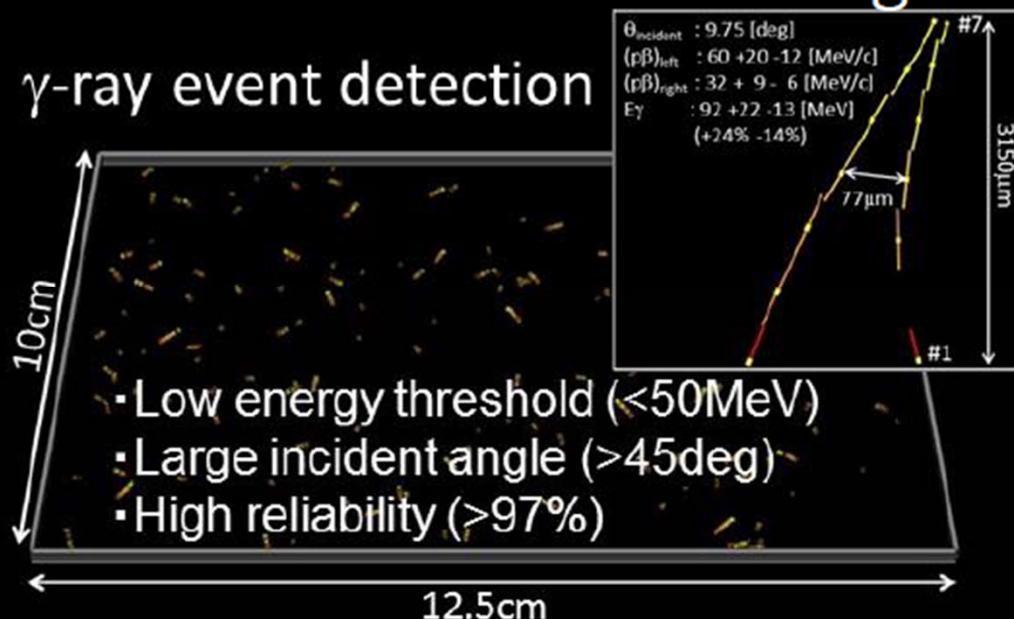
First balloon-borne emulsion  $\gamma$ -ray telescope experiment



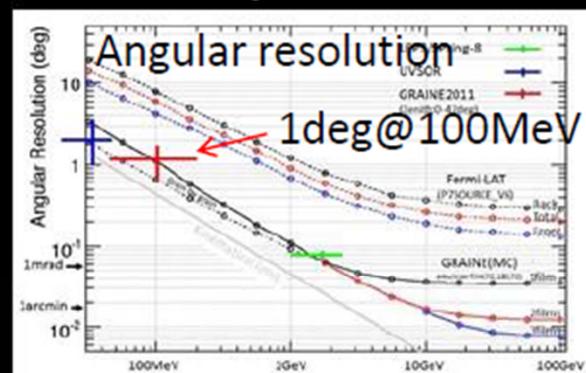
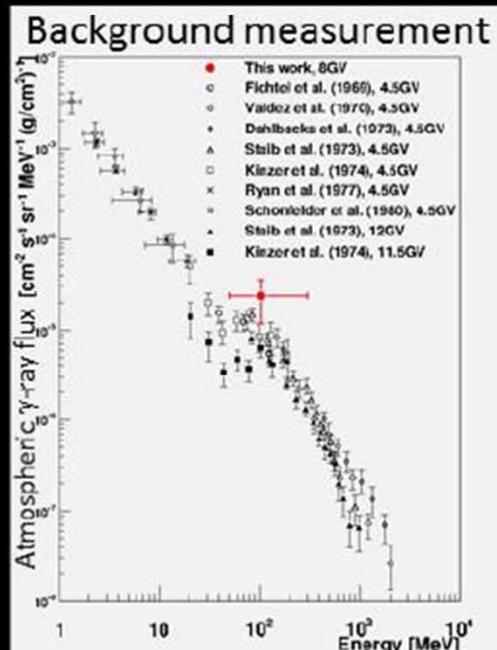
First balloon-borne experiment  
Feasibility test

# GRAINE 2011 Flight data analysis

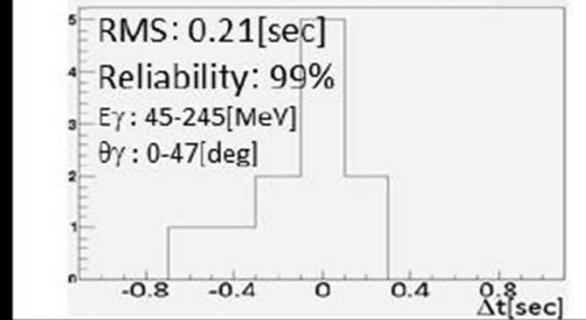
## $\gamma$ -ray event detection



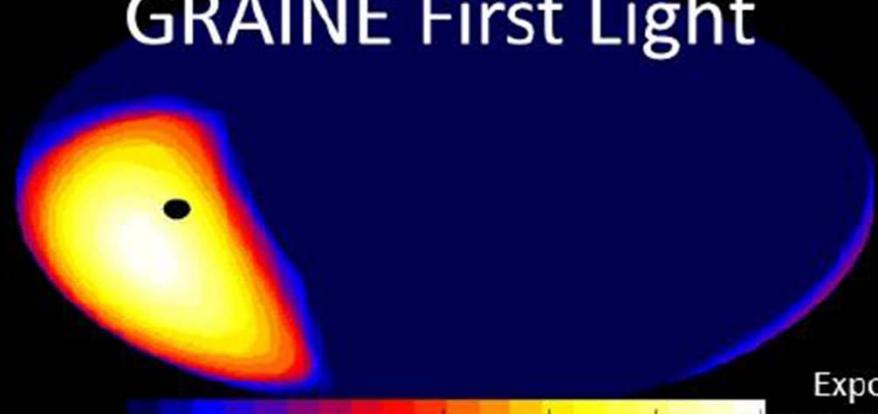
- Low energy threshold (<50 MeV)
- Large incident angle (>45 deg)
- High reliability (>97%)



## Time resolution



## GRAINE First Light



## Feasibility demonstration

# **GRAINE roadmap** (R&D has started in 2004)

- **Prototype Phase**

2011(done), TARF, JAXA Scientific Ballooning

125cm<sup>2</sup> aperture area, 4.3hours (1.6hours@34.7km) flight

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- **Demonstration Phase**

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

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- Overall test by detecting known gamma-ray source (Vela pulser)

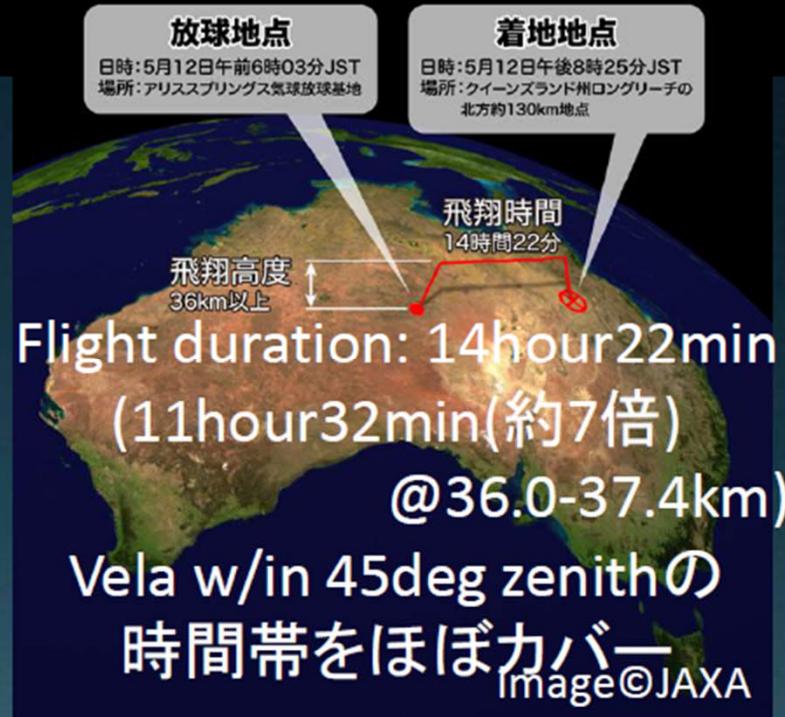
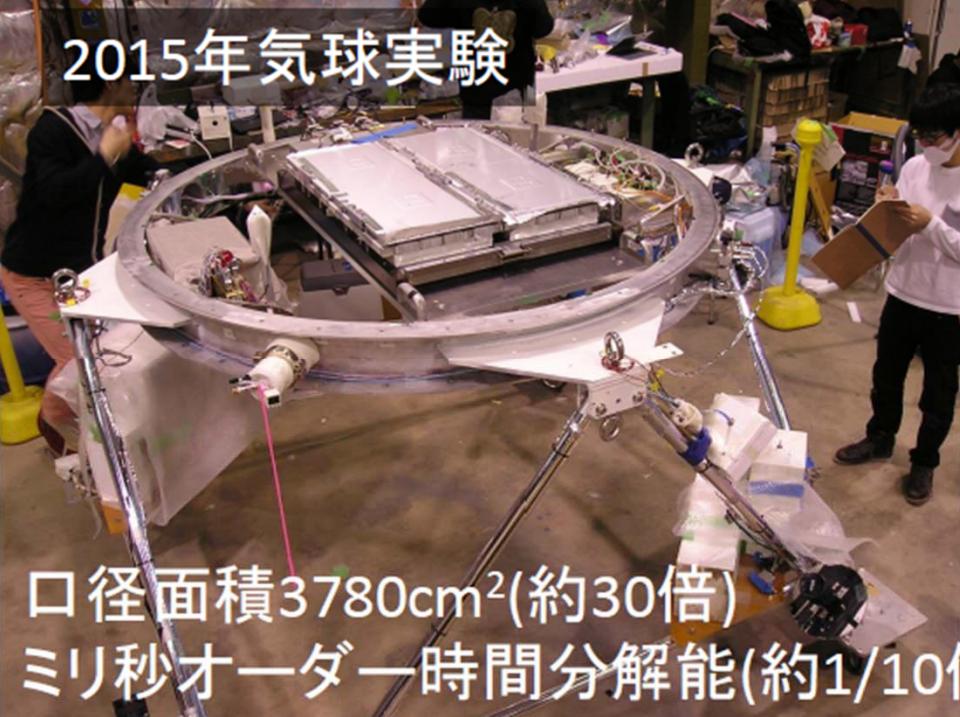
- **Working Phase**

2021~ (planning)

2 to 10m<sup>2</sup> aperture area, ~36 hours flight duration

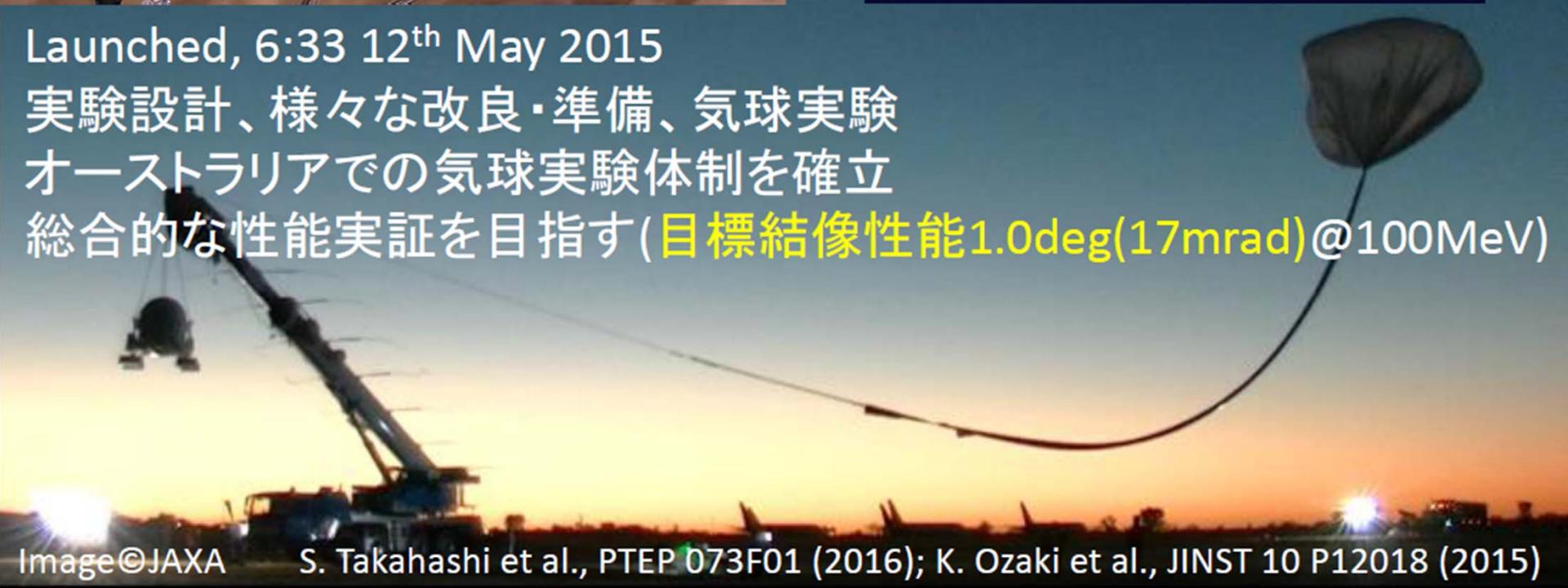
- Starting scientific observation

# 2015年気球実験

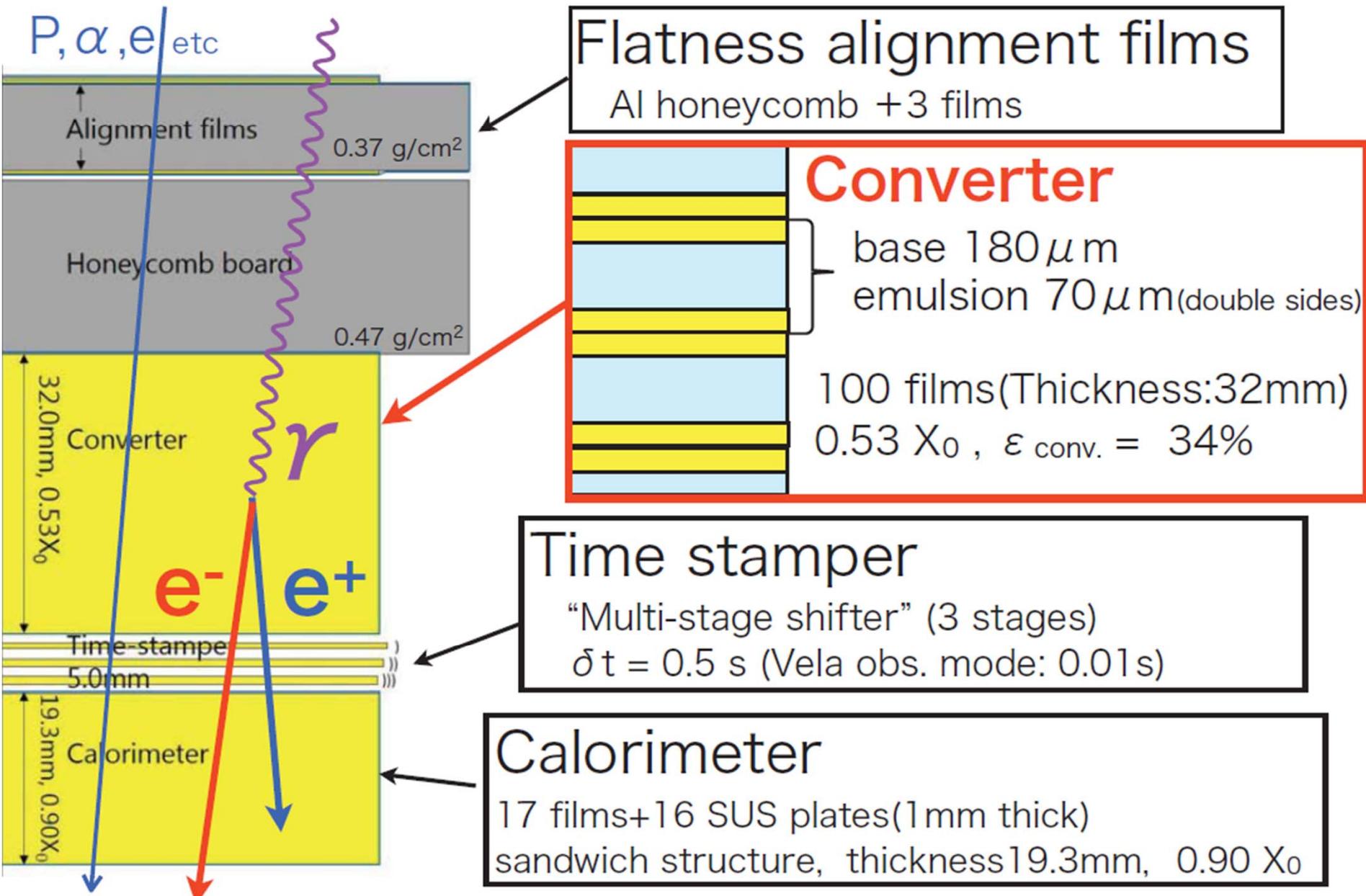


Launched, 6:33 12<sup>th</sup> May 2015

実験設計、様々な改良・準備、気球実験  
オーストラリアでの気球実験体制を確立  
総合的な性能実証を目指す(目標結像性能1.0deg(17mrad)@100MeV)

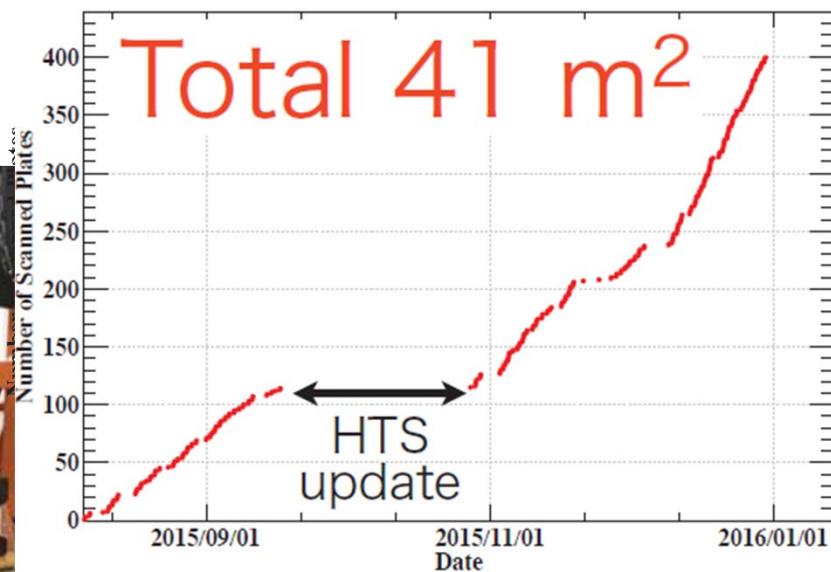
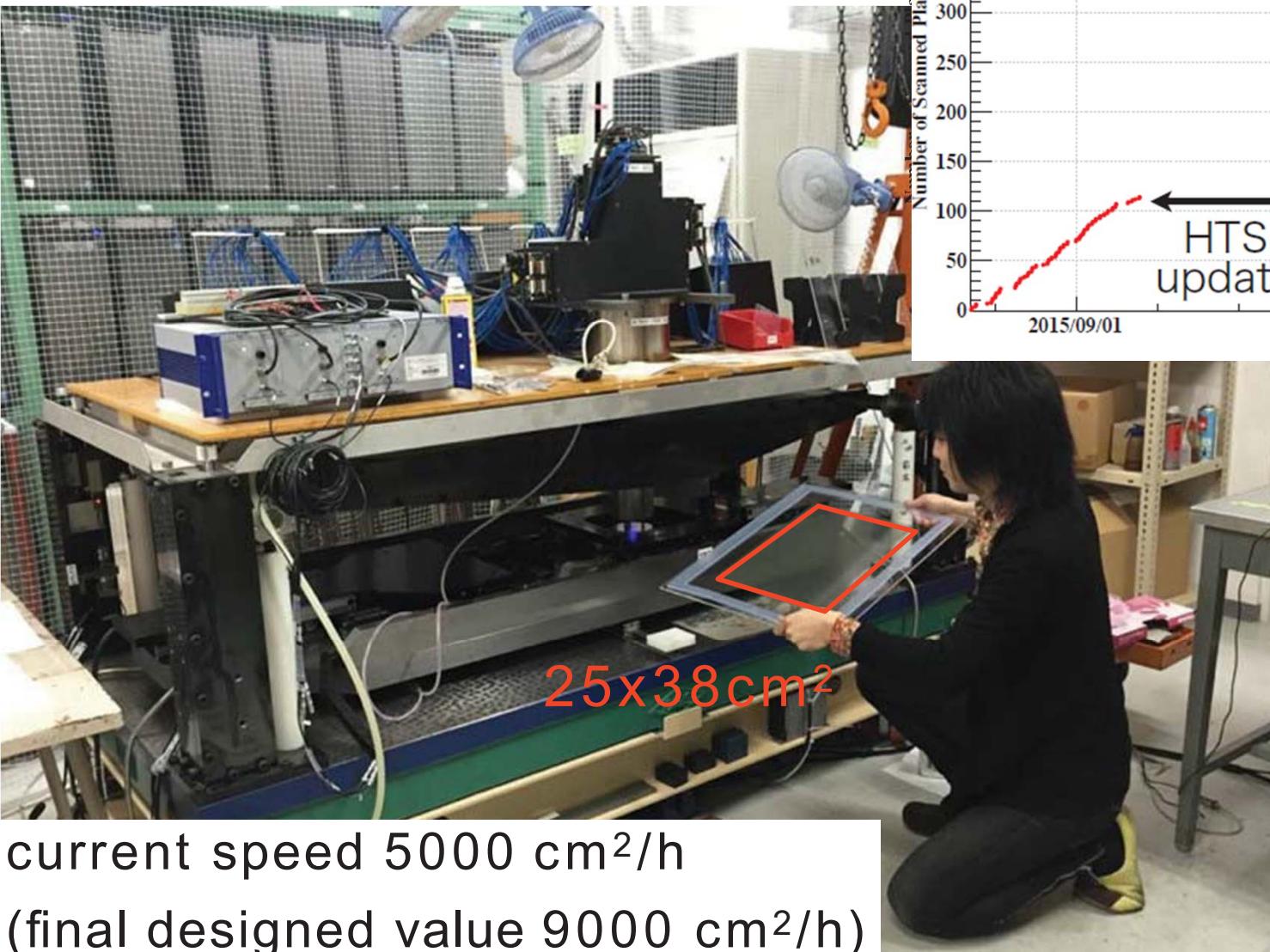


# GRAINE-2015 Detector

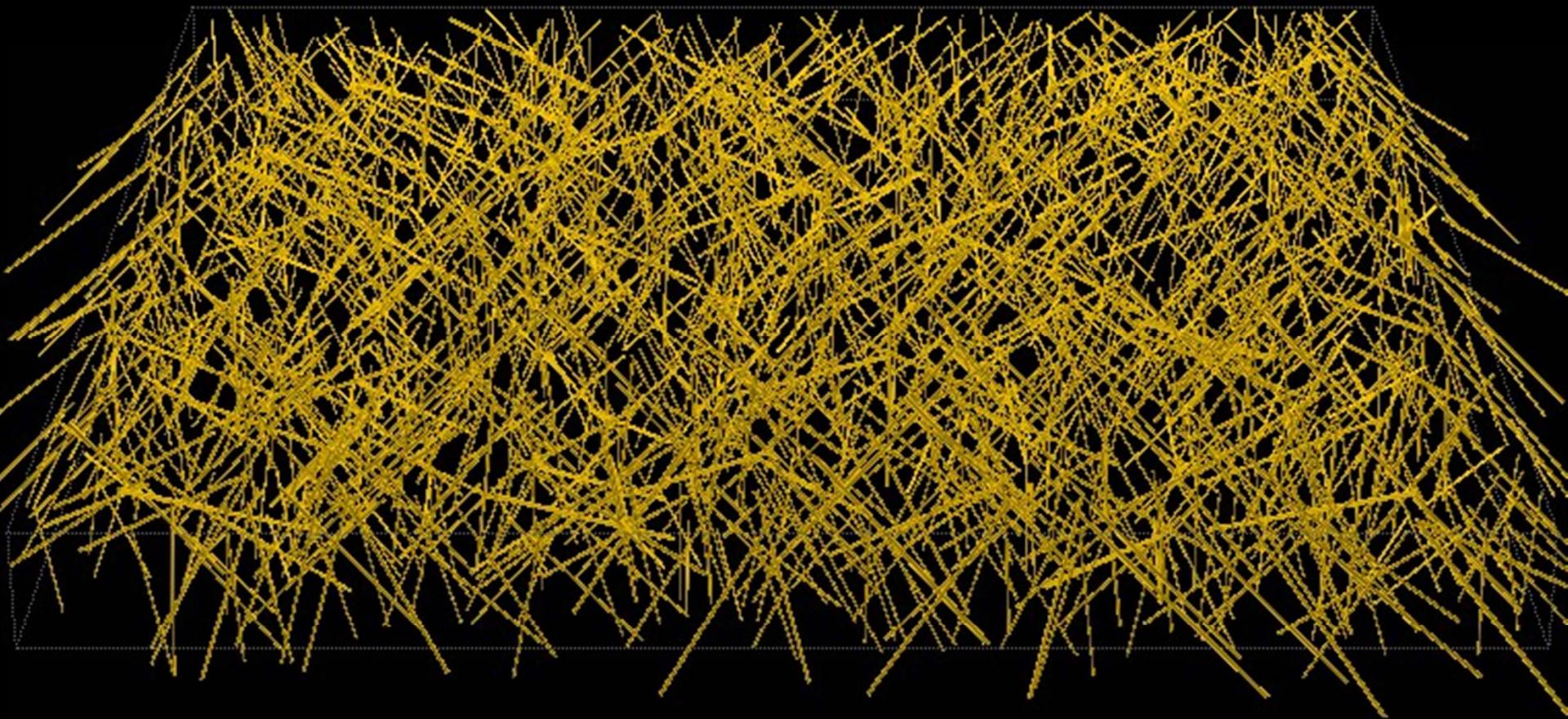


# Film Read-out by HTS@Nagoya U.

The First operation for real experimental data taking



# Flight data

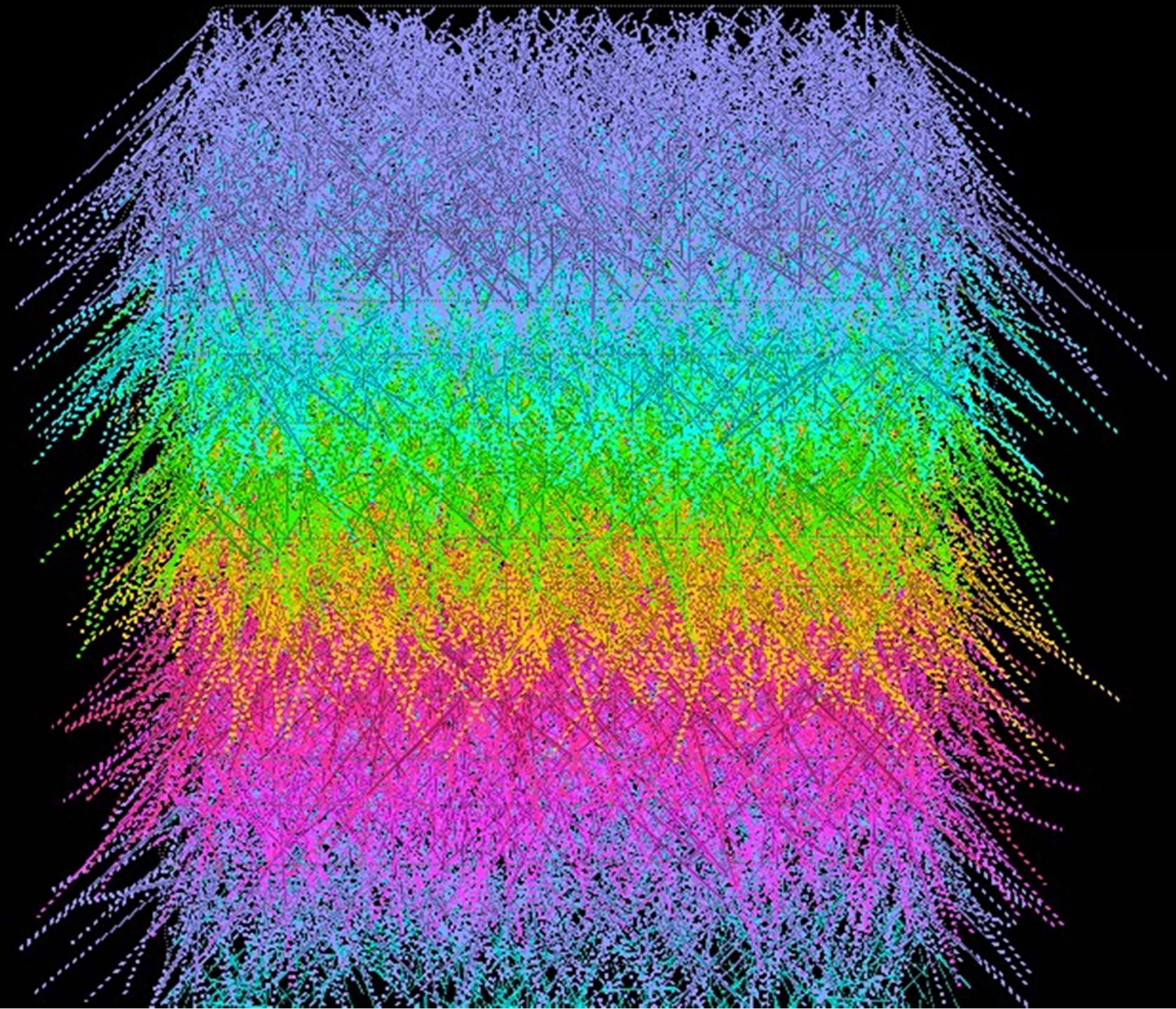


2 mm x 2 mm of single film

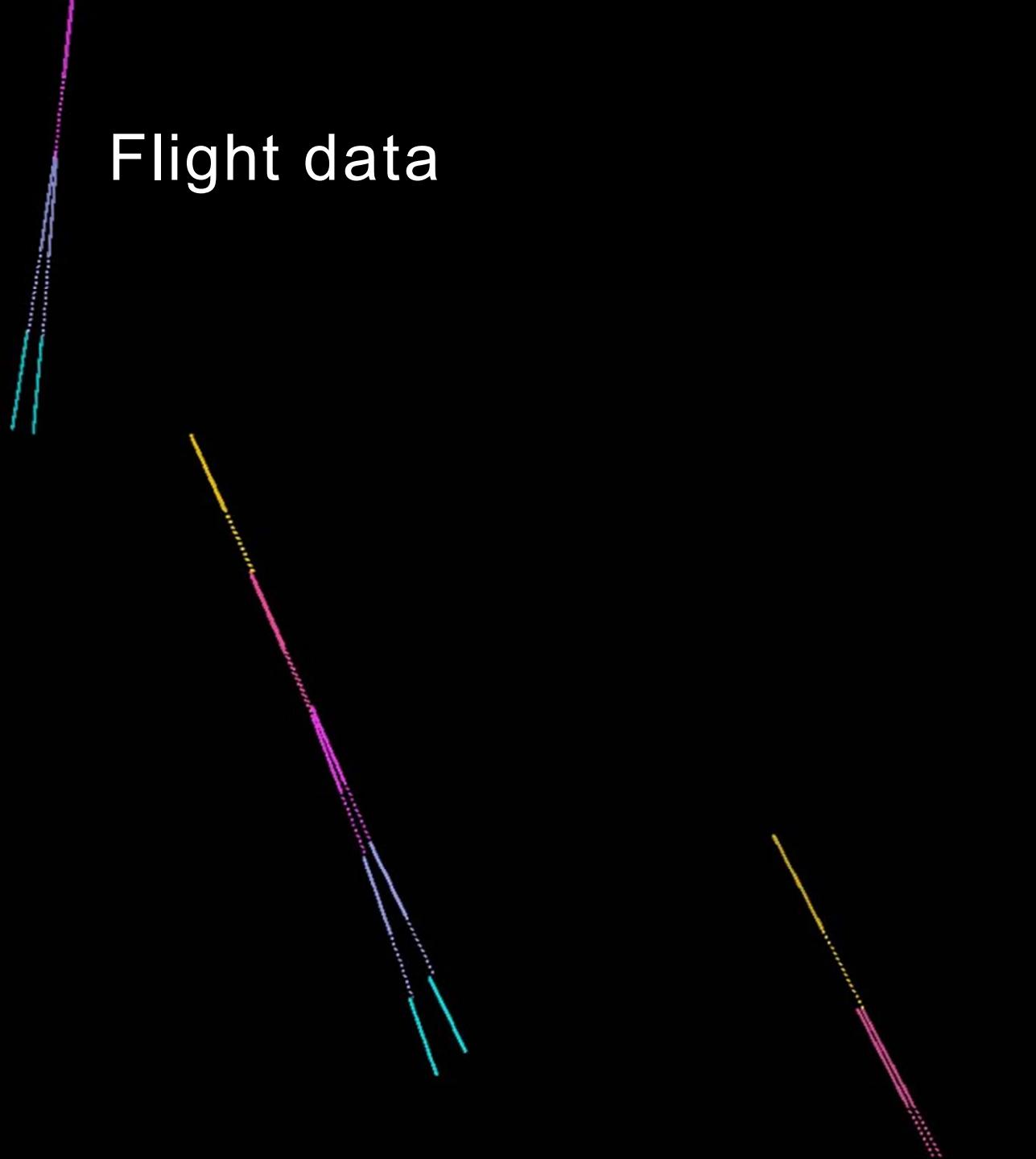
# Flight data

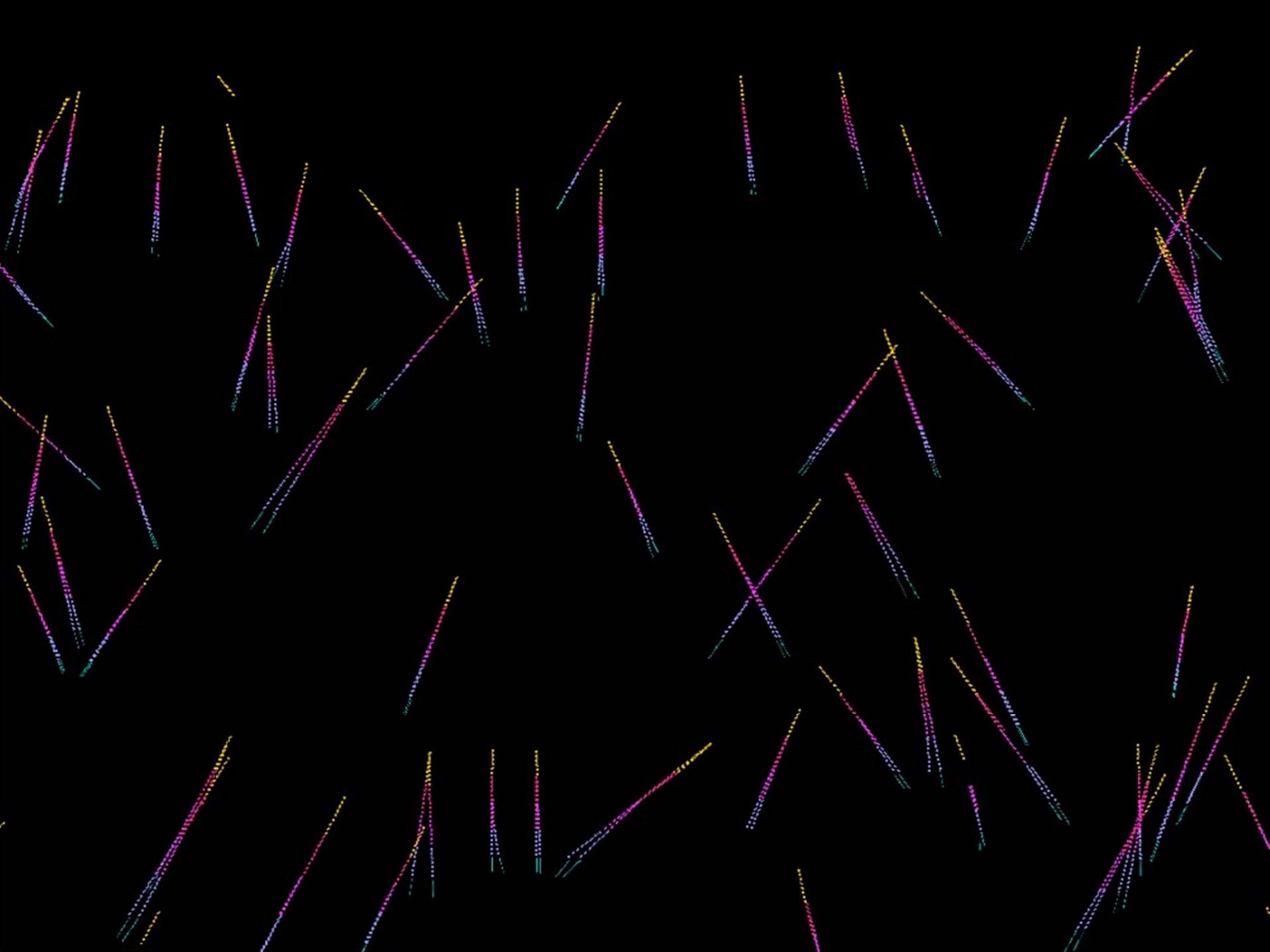


density ~400 tracks/mm<sup>2</sup>

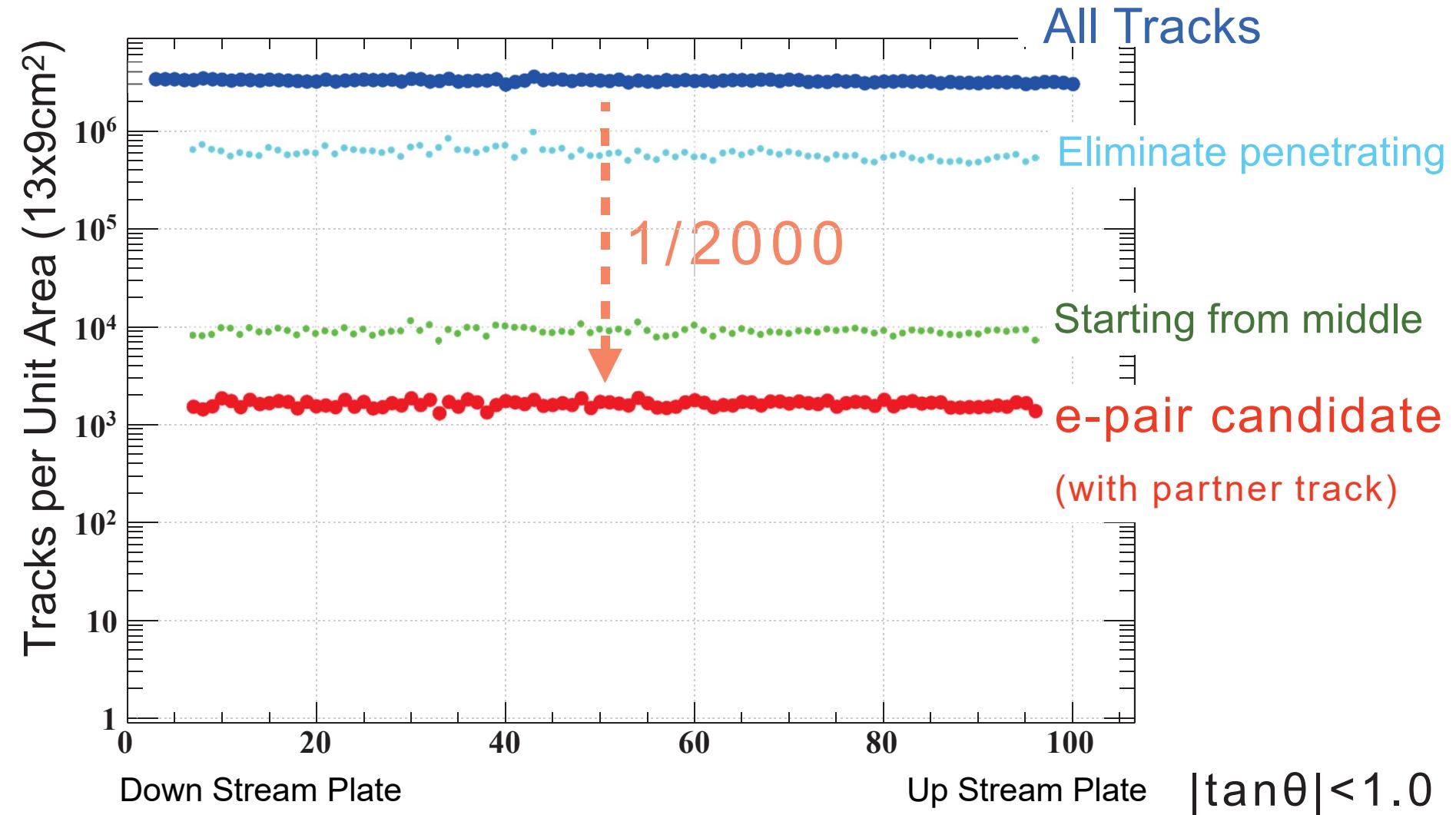


# Flight data



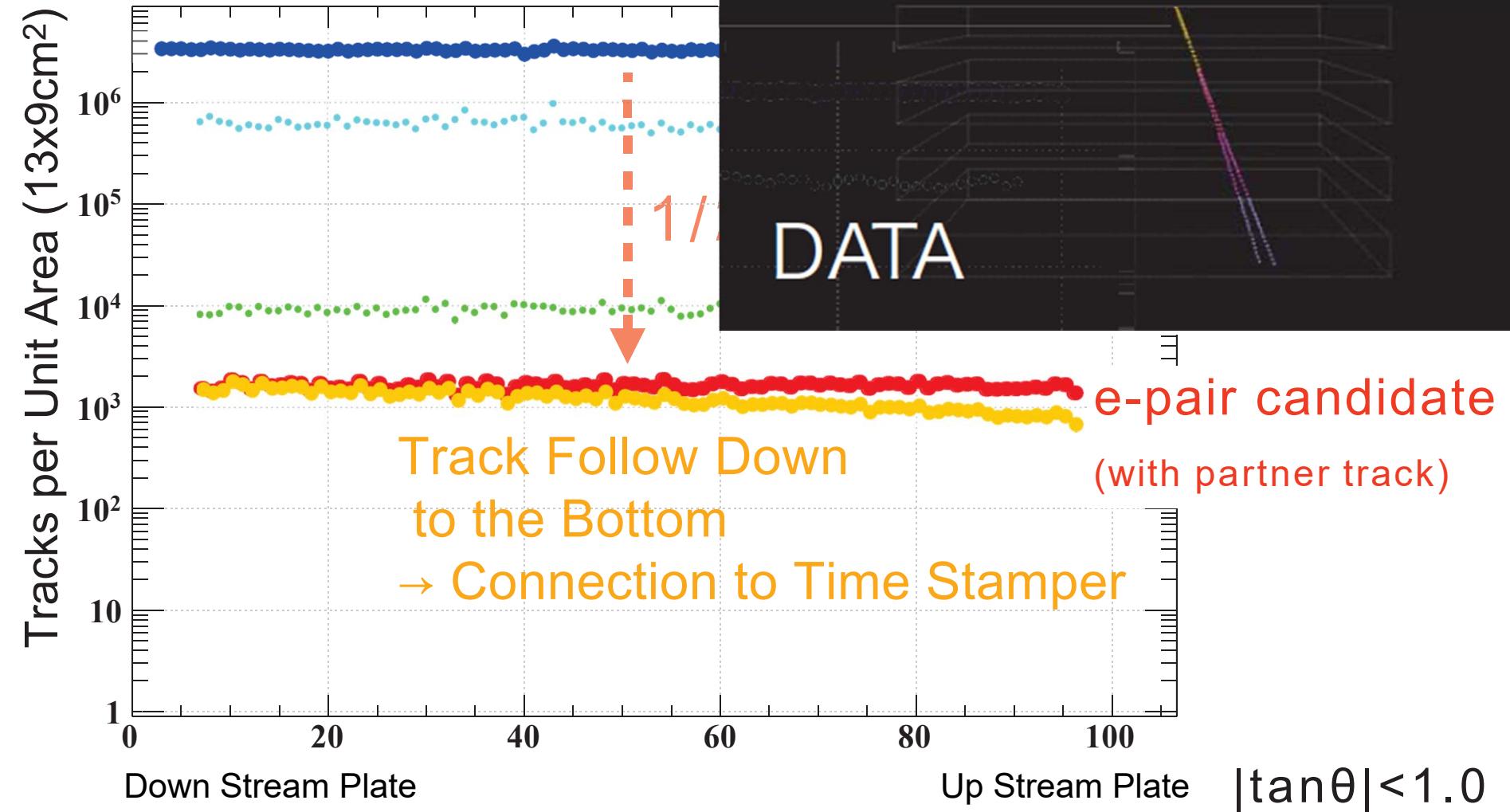


# $\gamma \rightarrow e^+e^-$ Selection

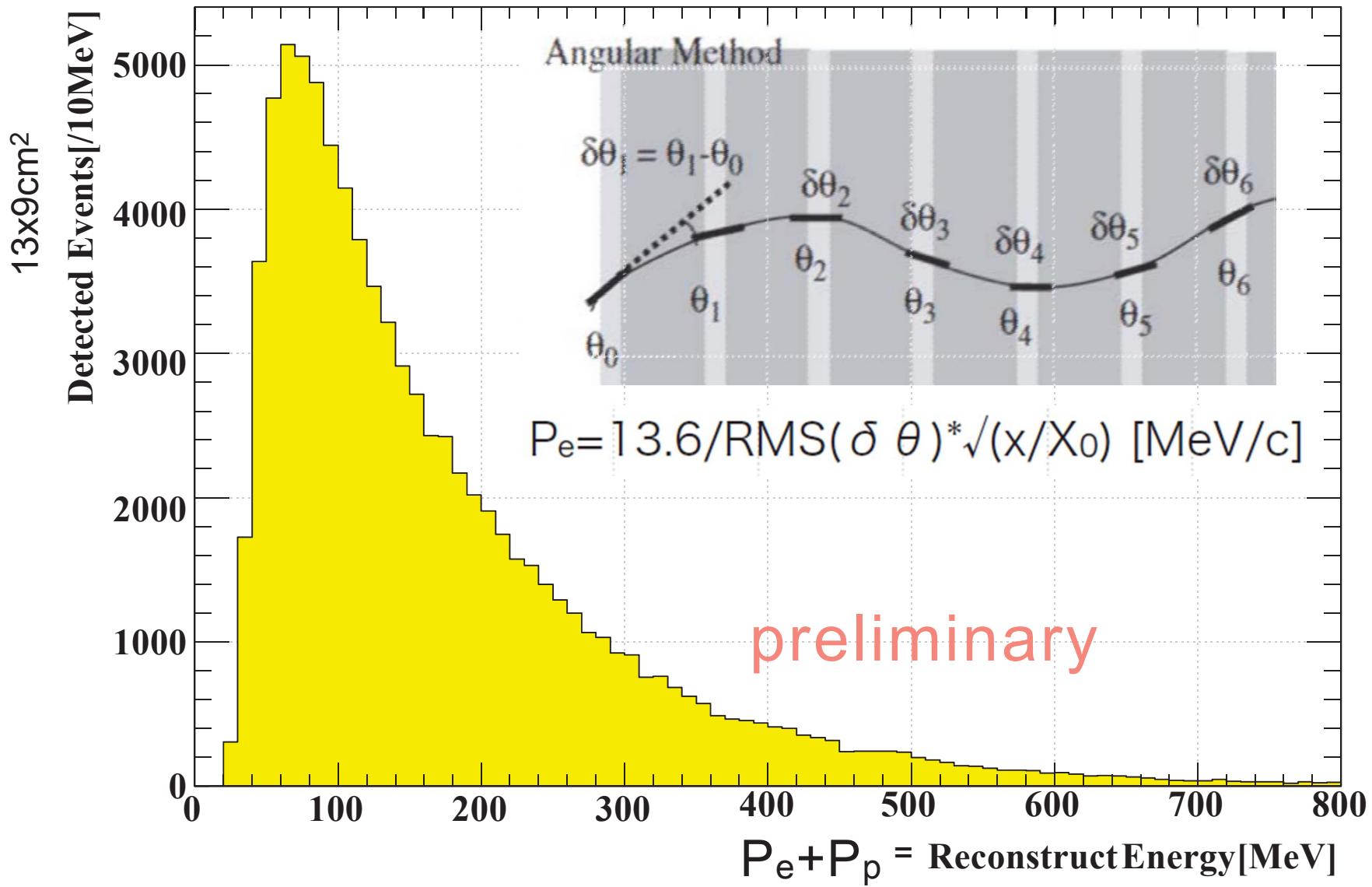


# Track Follow Down

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

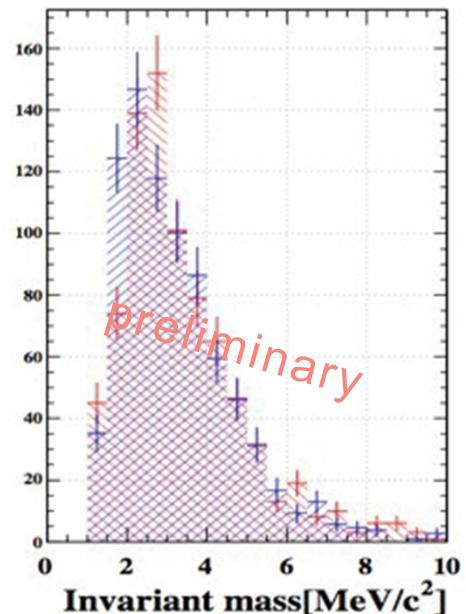
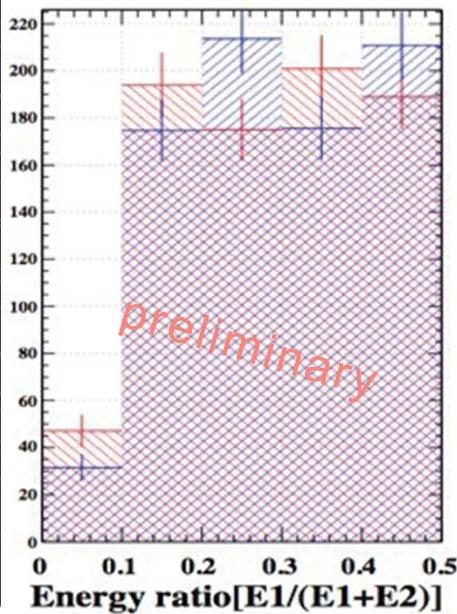
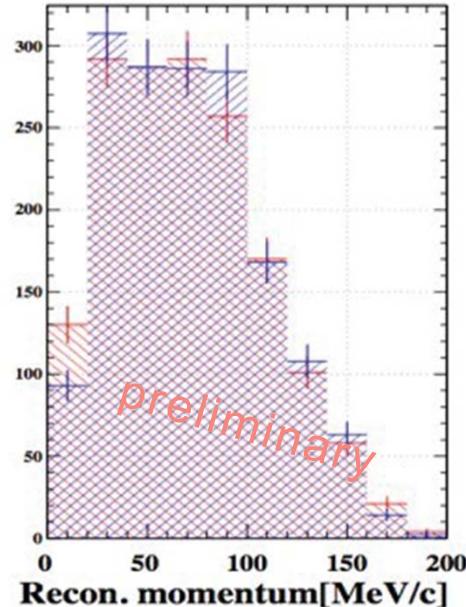
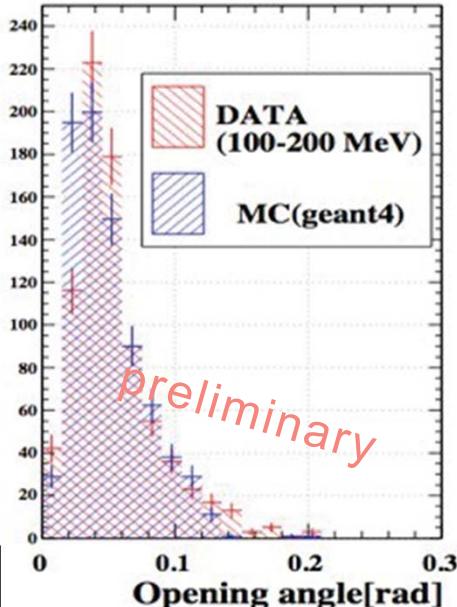
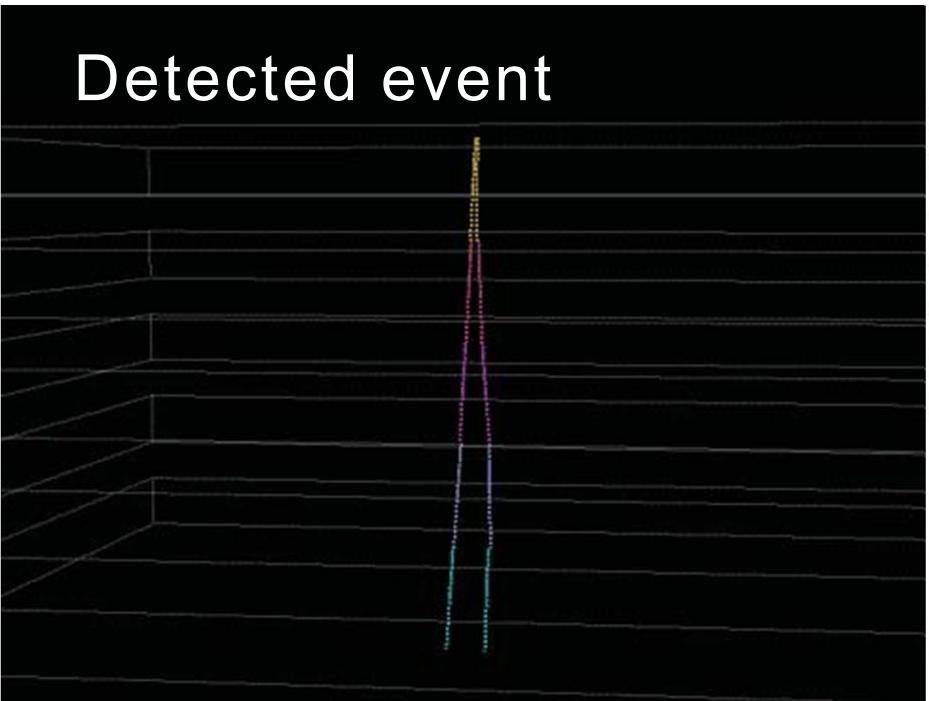


# Energy Reconstruction

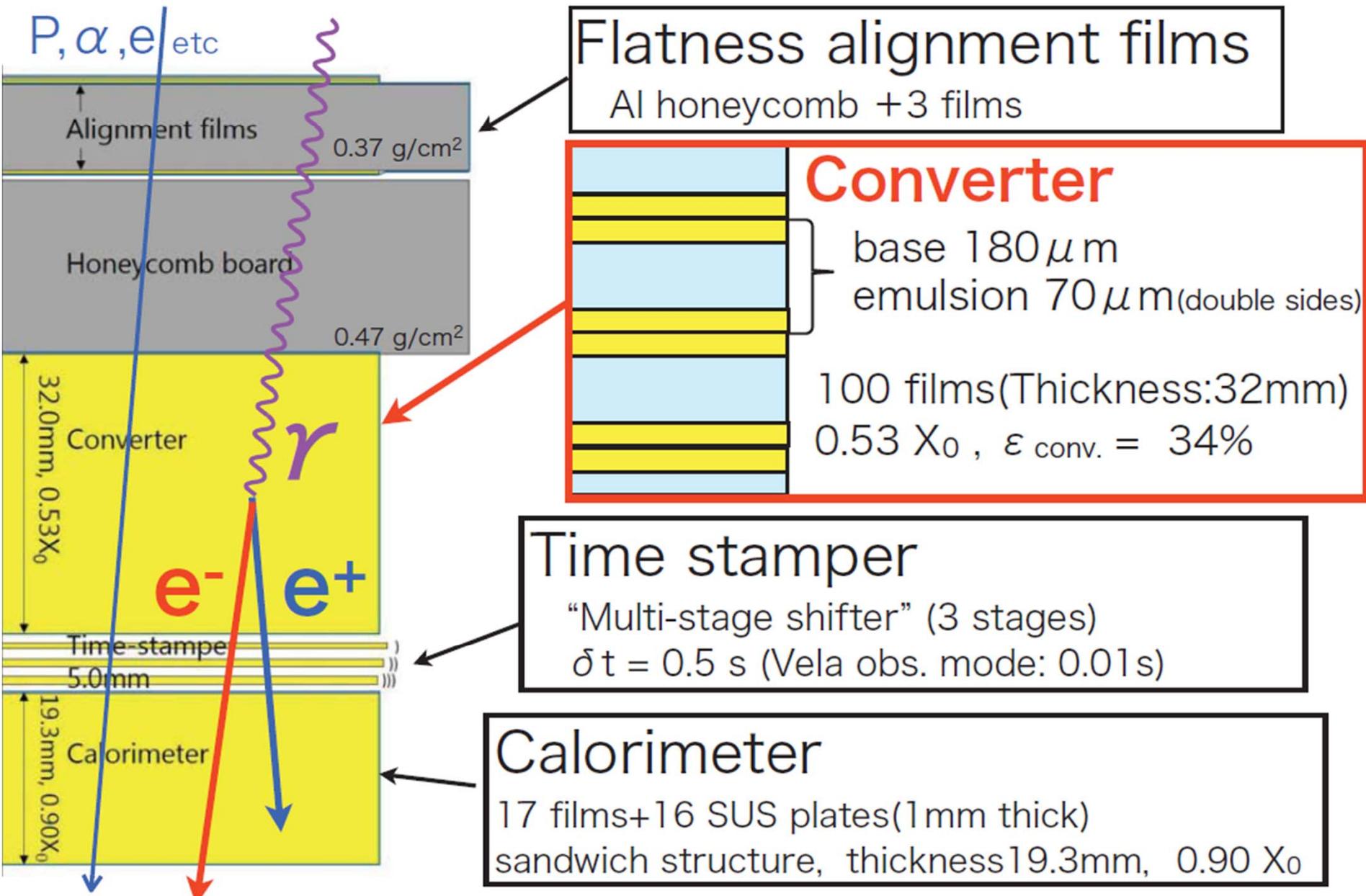


74% of total events are analyzed

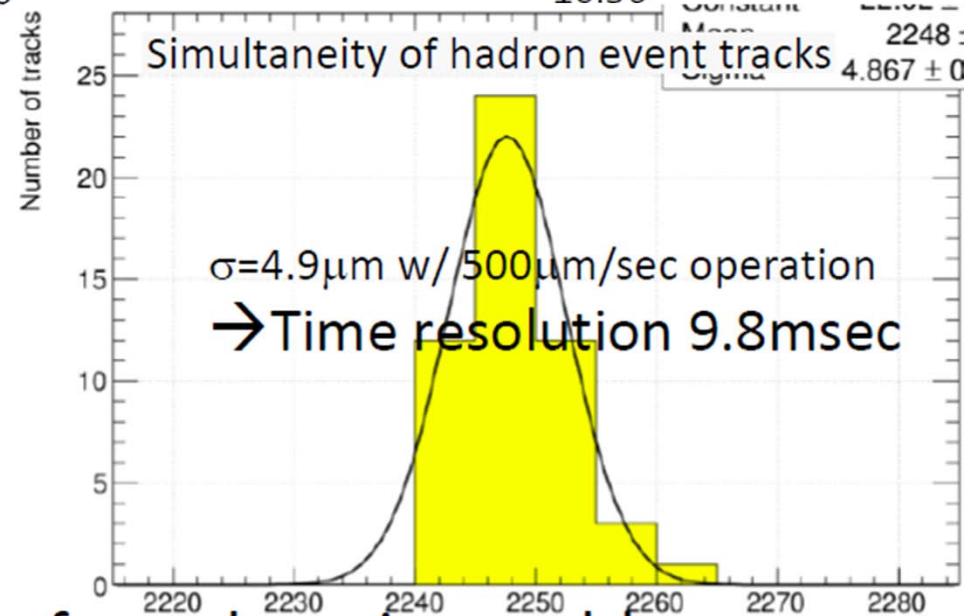
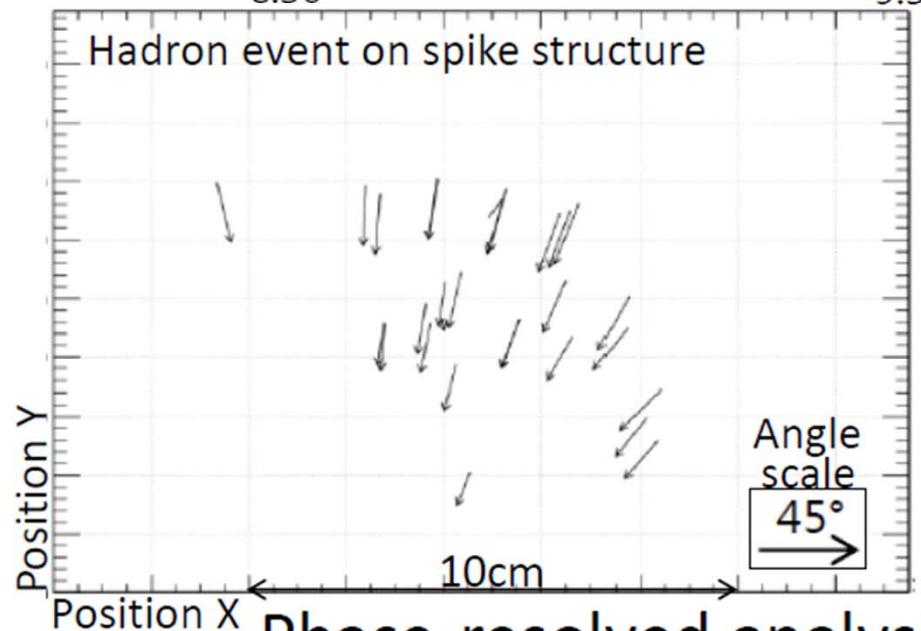
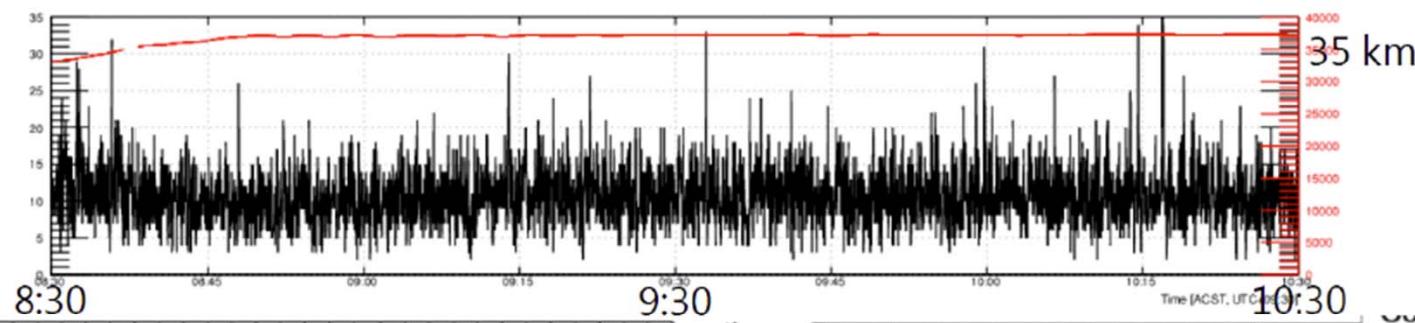
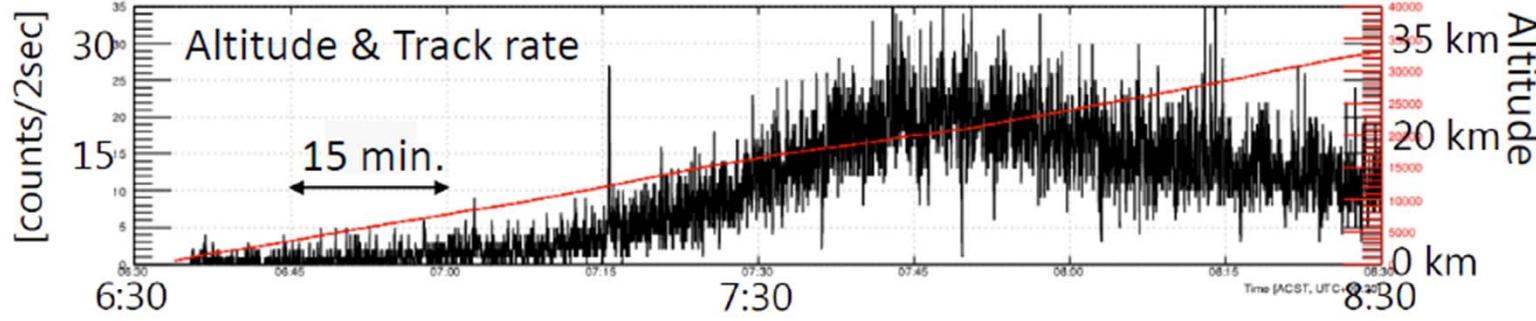
# Checking DATA MC (w/ detector response)



# GRAINE-2015 Detector



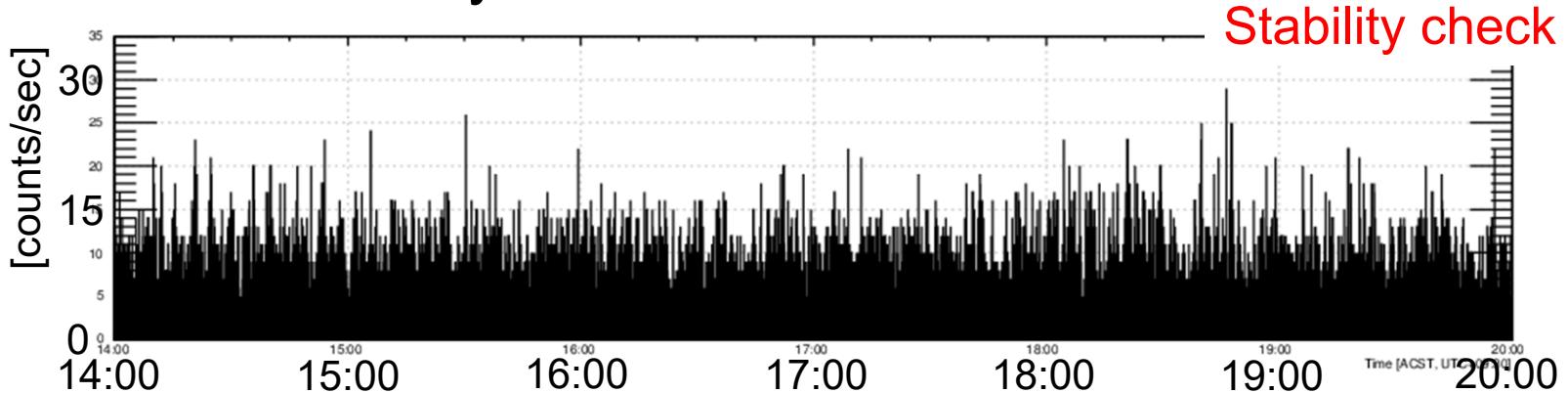
# GRAINE 2015, Flight data analysis, Timestamper



Phase-resolved analysis for pulsars is capable.  
e.g. 89msec period of Vela pulsar

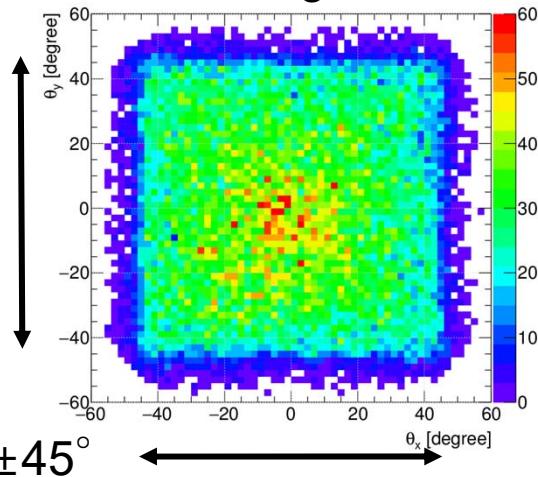
# Time stamp to Gamma-ray event

## ◆ Gamma-ray event rate

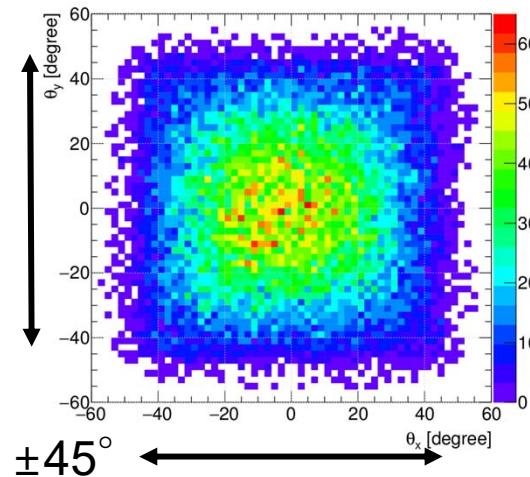


## ◆ Angular distribution of Gamma-ray

<in flight>

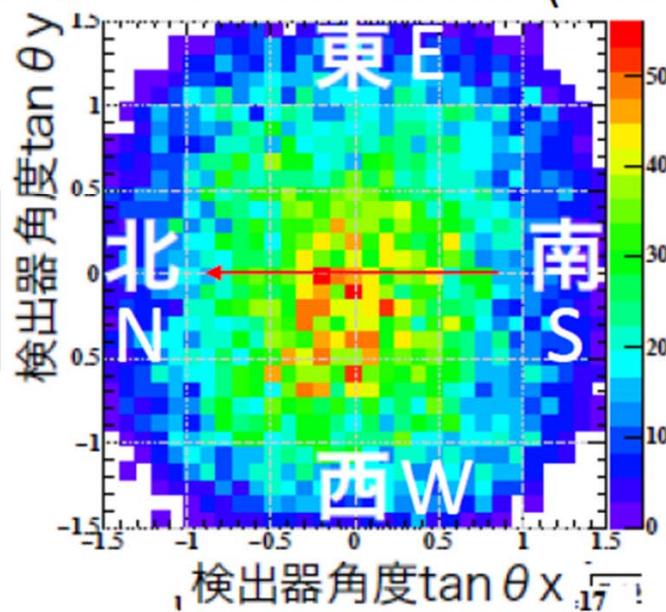


<on ground>

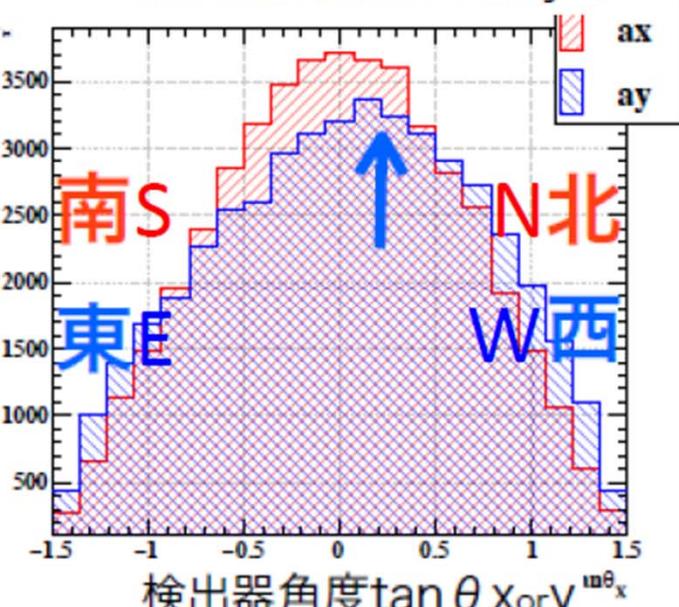
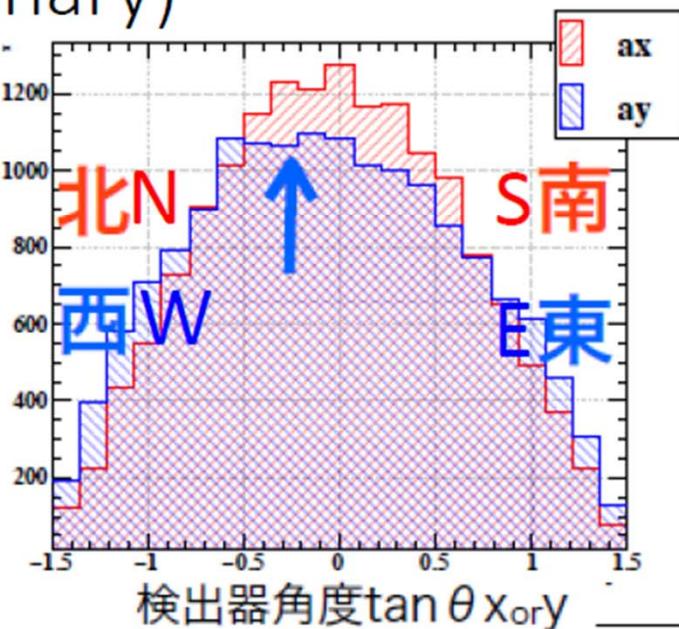
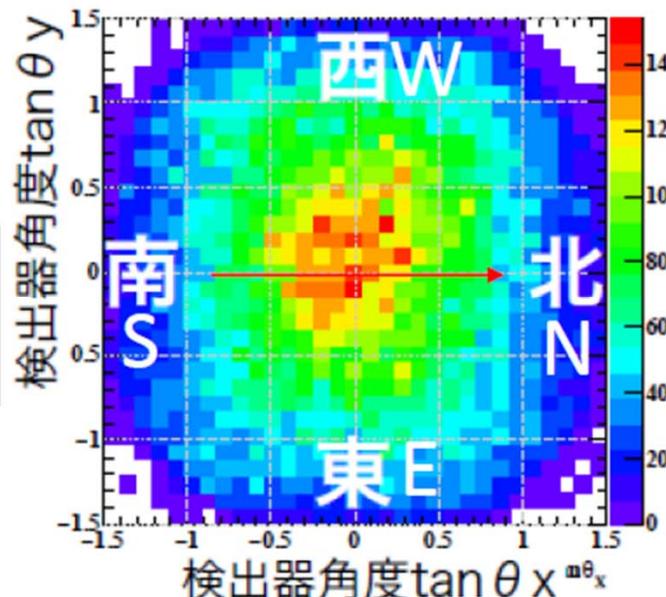


# GRAINE 2015, Flight data analysis, Converter+Timestamper+Attitude East-west effect (Preliminary)

検出器軸が  
北向きの時



検出器軸が  
南向きの時

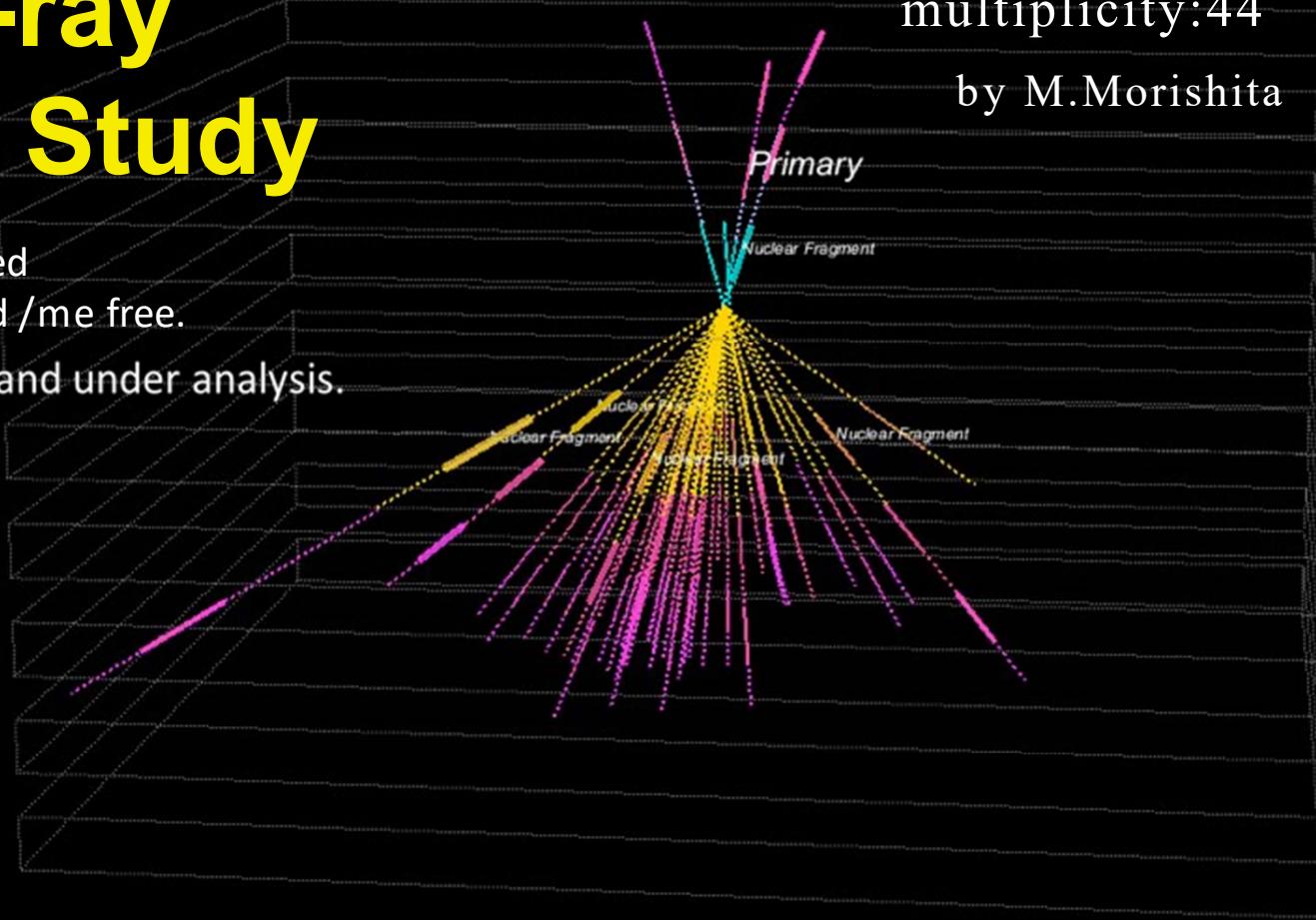


東西効果による宇宙線の異方性を検出、異方性から地磁気方位角が決定できる

# Cosmic-ray Interaction Study

All charged particles are recorded  
in emulsion chamber with dead / me free.  
 $O(10^5)$  events are detected, and under analysis.

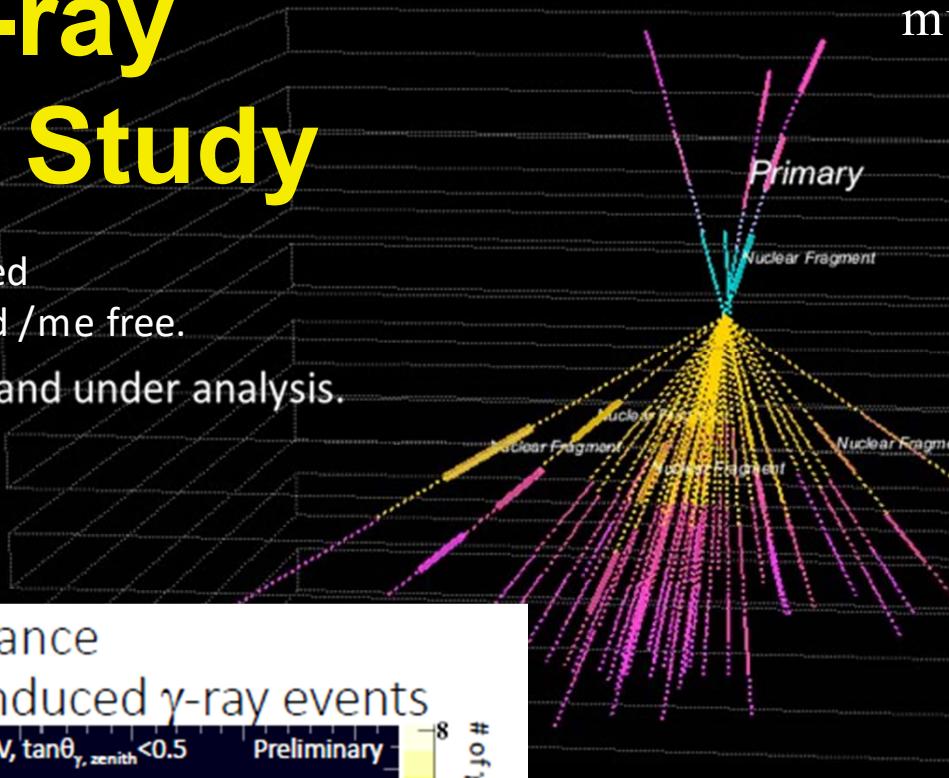
multiplicity: 44  
by M.Morishita



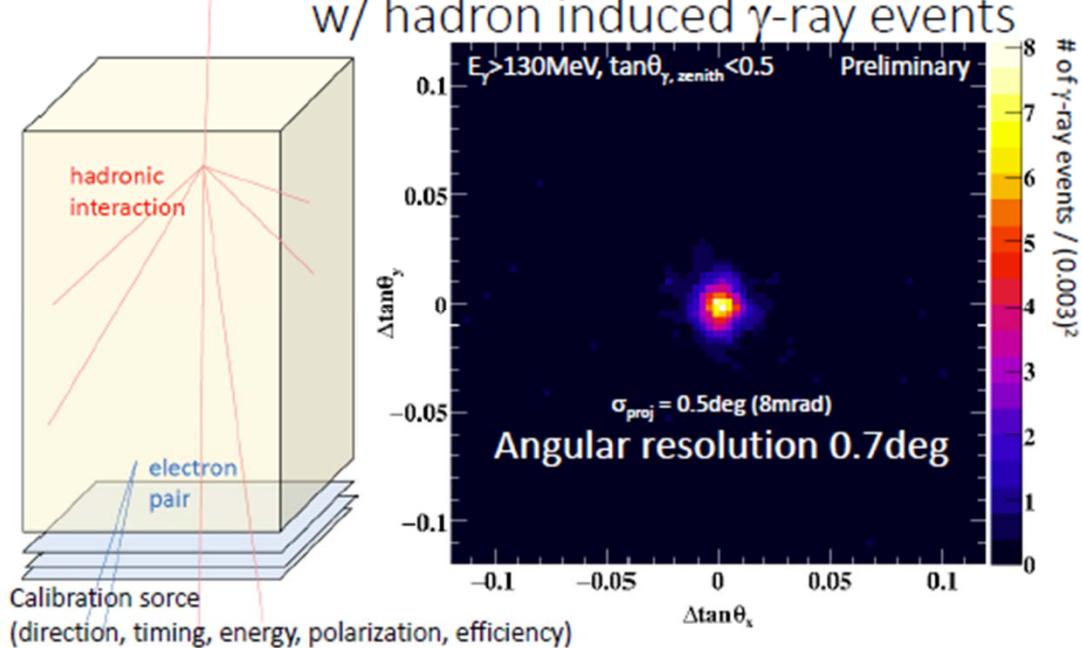
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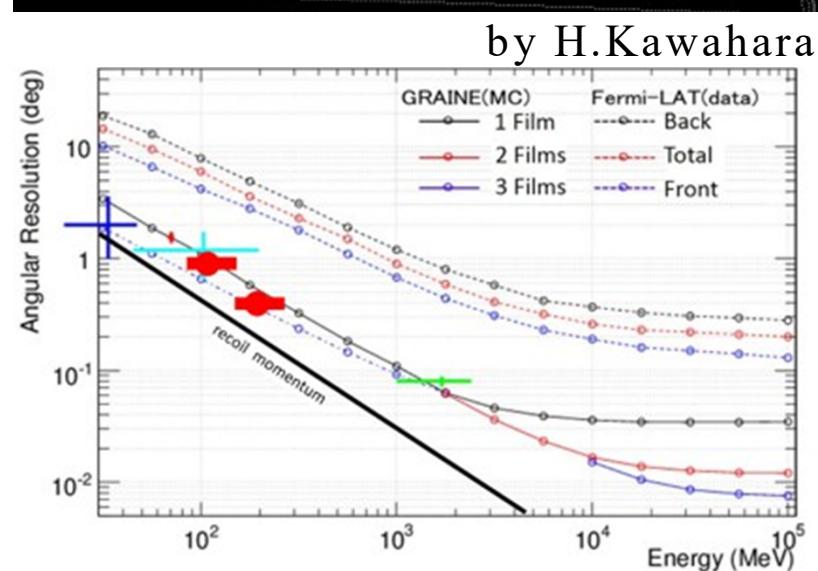
multiplicity: 44  
by M.Morishita



$\gamma$ -ray imaging performance  
w/ hadron induced  $\gamma$ -ray events

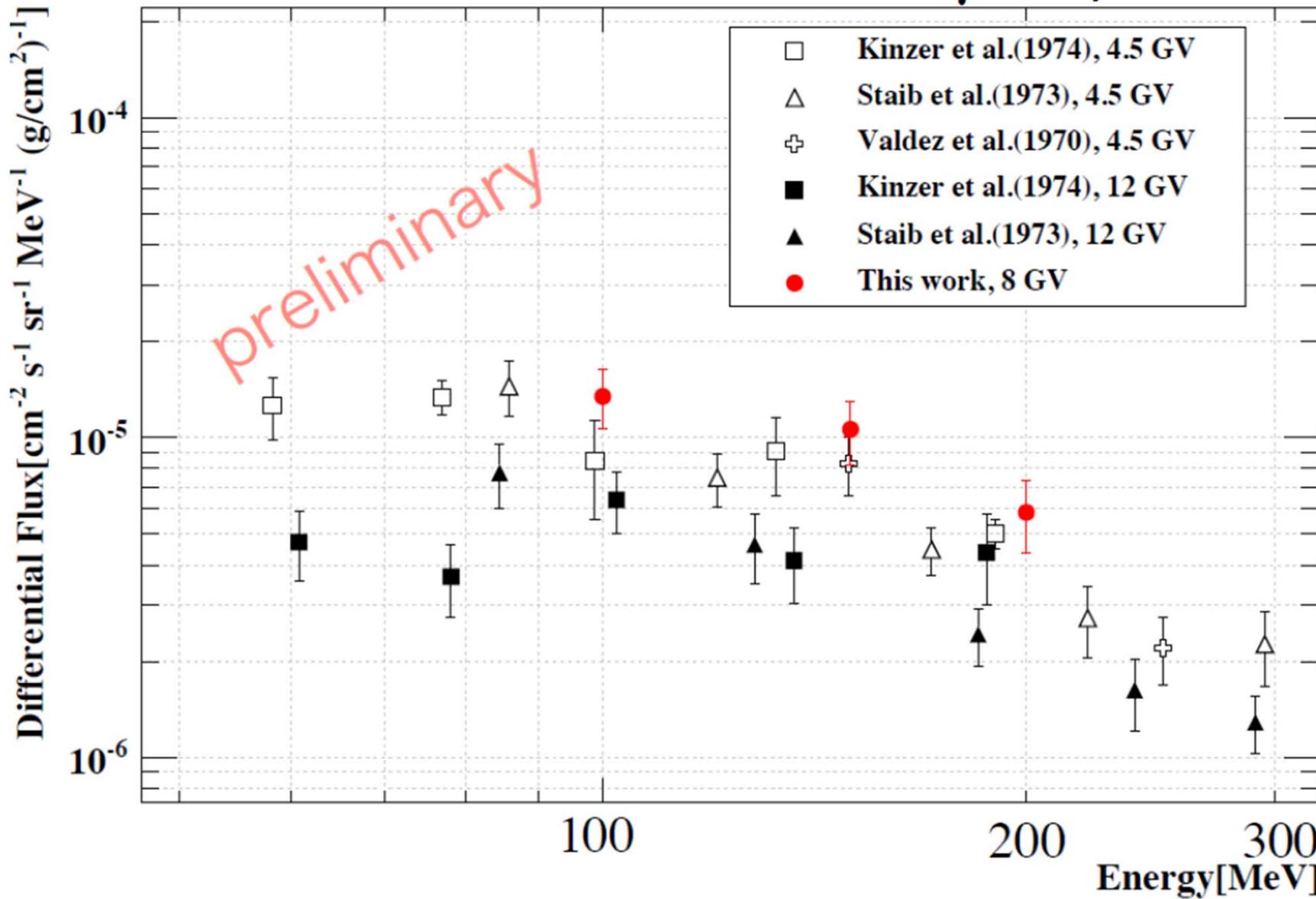


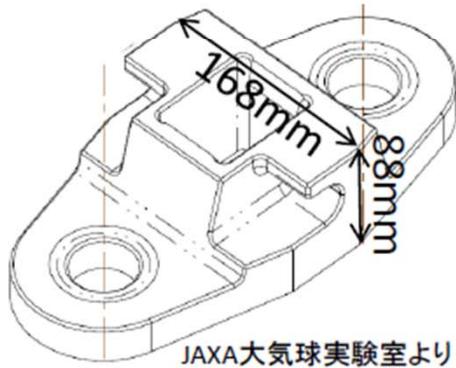
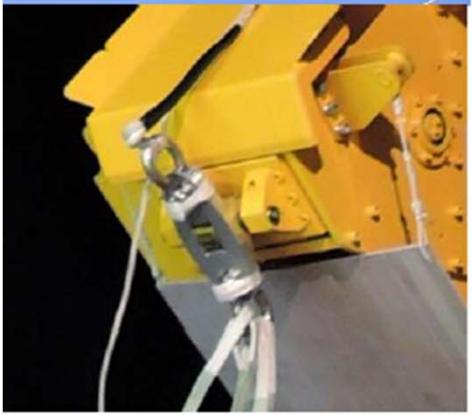
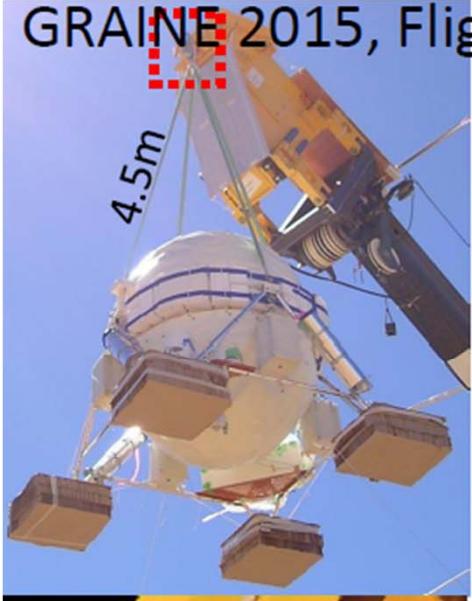
High  $\gamma$ -ray imaging performance was being obtained.



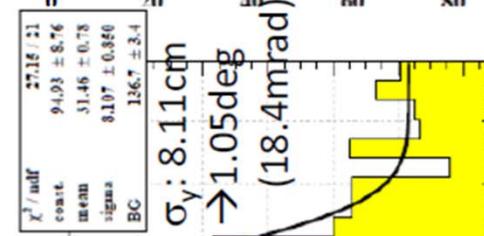
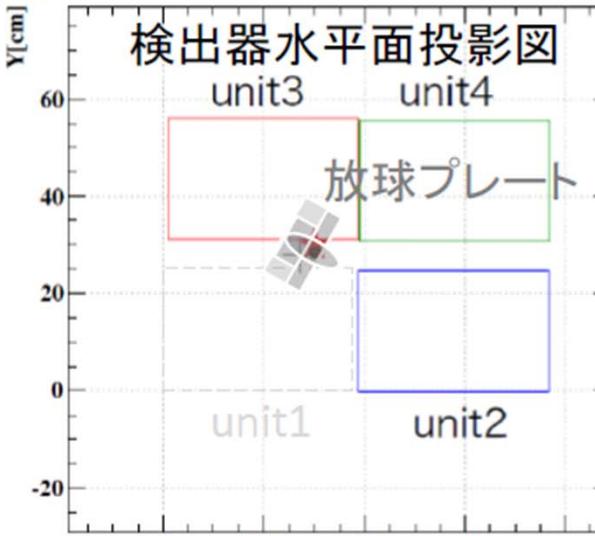
by H.Kawahara

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

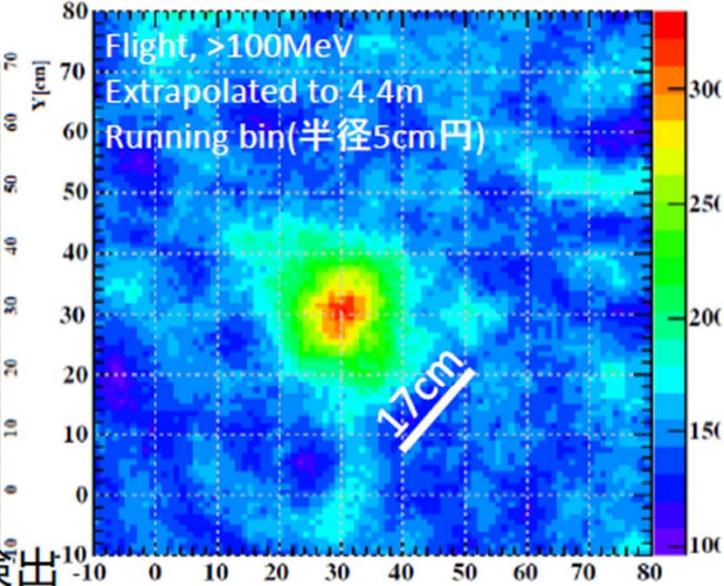
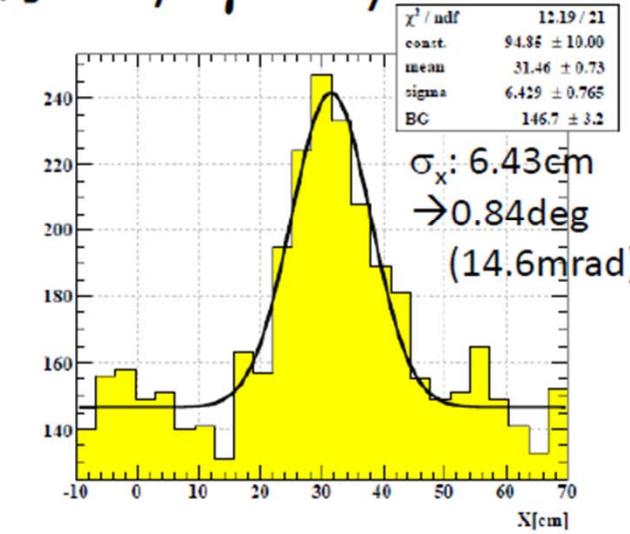




# 放球プレート撮像 w/ $\gamma$ -ray



- 放球プレート位置に excess を検出  
(ずれ  $1.7 \text{ cm} \rightarrow 0.22 \text{ deg} (3.9 \text{ mrad})$ )
- 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  $<1.2 \text{ deg} (20.6 \text{ mrad})$   
(cf. 角度分解能  $1.0 \text{ deg} @ 100\text{MeV}$ )
- ユニットごとの結像重心のばらつき  $<0.06 \text{ deg} (1 \text{ mrad})$

# 2015年気球実験

- ・口径面積3780cm<sup>2</sup>(約30倍, 新型エマルションフィルム, 総面積48m<sup>2</sup>)
- ・フライト時間14.4hour (11.5hour@36.0–37.4km (約7倍))
- ・オーストラリア気球実験scheme & flow を確立
- ・飛跡読み出し総面積41m<sup>2</sup>w/ HTS
- ・エマルションフィルムのS/N比~20倍、データサイズ~20分の1
- ・フィルムあたりの飛跡inefficiency~10分の1
- ・ガンマ線事象検出のためのデータリダクションロード~200分の1
- ・全有効面積データ処理口径面積2830cm<sup>2</sup>(総面積30m<sup>2</sup>)
- ・**ガンマ線源の結像性能<~1.0deg** cf. 角度分解能1.0deg@100MeV
- ・時間分解能0.01秒(約10倍)
- ・スターカメラ感度改善

2011年気球実験から大きく前進

# **GRAINE roadmap** (R&D has started in 2004)

- **Prototype Phase**

2011(done), TARF, JAXA Scientific Ballooning

125cm<sup>2</sup> 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<sup>2</sup> aperture area, 14h22min (11h32min@36.0-37.4km) flight

- Overall test by detecting known gamma-ray source (Vela pulser)

- **Working Phase**

2021~ (planning)

2 to 10m<sup>2</sup> aperture area, ~36 hours flight duration

- Starting scientific observation

# GRAINE Scientific observation roadmap

## 2018, Demonstration

Alice Springs

~0.4m<sup>2</sup> aperture

~24hours flight duration

<~5g/cm<sup>2</sup> altitude

## 2021–, Scientific flight

Alice Springs

10m<sup>2</sup> aperture

>~36hours flight duration

<~10g/cm<sup>2</sup> altitude

Vela pulsar  
Polarization observation (<50%)

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

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

Studying cosmic ray  
sources

Galactic Center  
Obs. with ~arcmin resolution

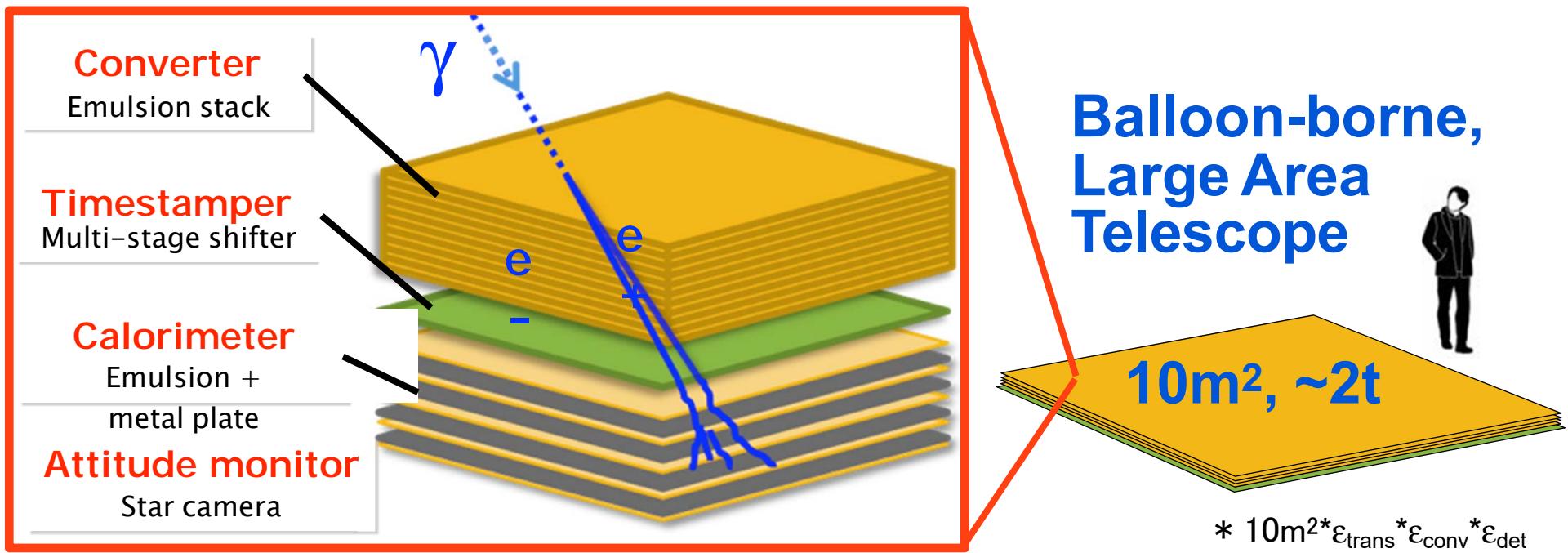
Resolving GeV  $\gamma$ -ray  
excess at galactic center

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

Studying transient  
sources & w/ ones

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

# Emulsion gamma-ray Telescope



## Flow of experiment

Detector preparation

← Analysis

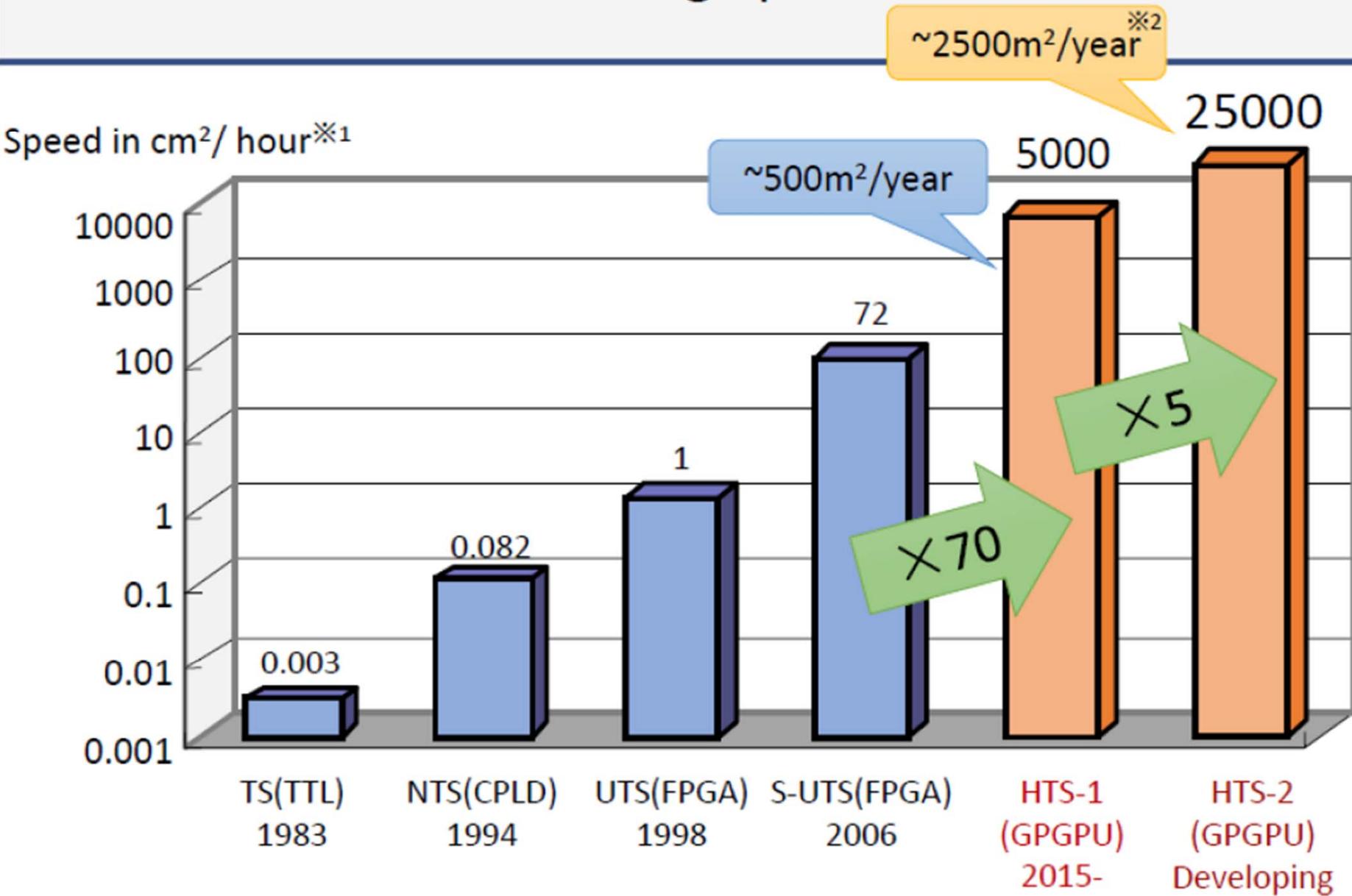
Observation(balloon flight)  
several days - 1 week

Scanning  
(2nd data taking)

→ Recovery of detector

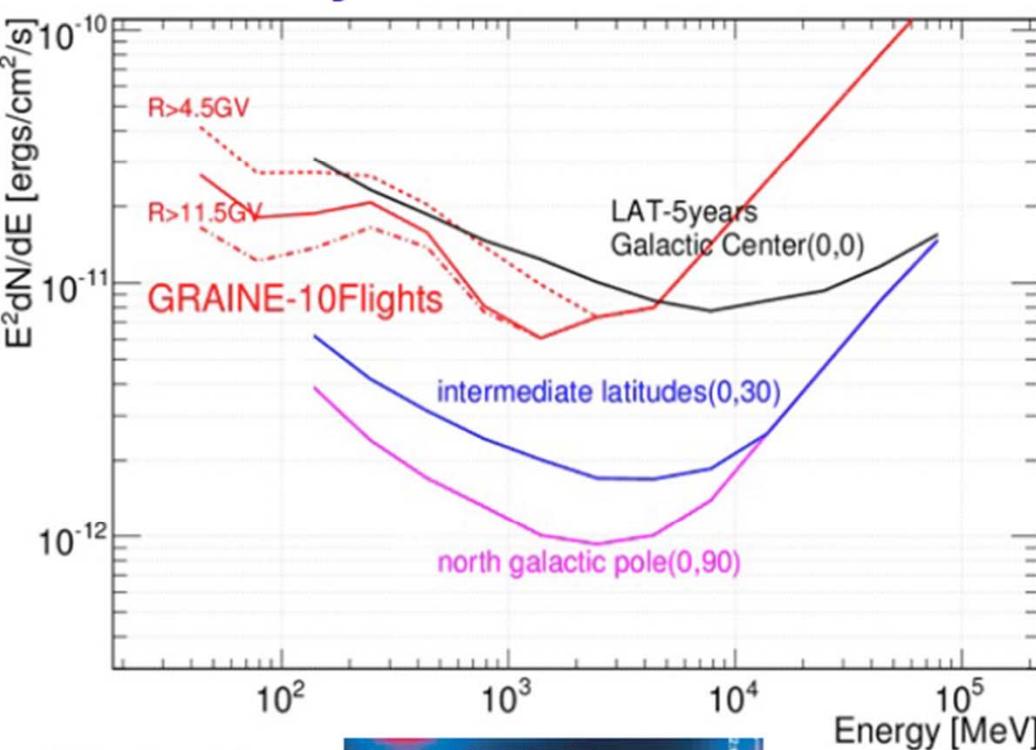
※1 Area of emulsion layer  
※2 Area of the films with 24 hour shift

# Evolution of the Scanning Speed

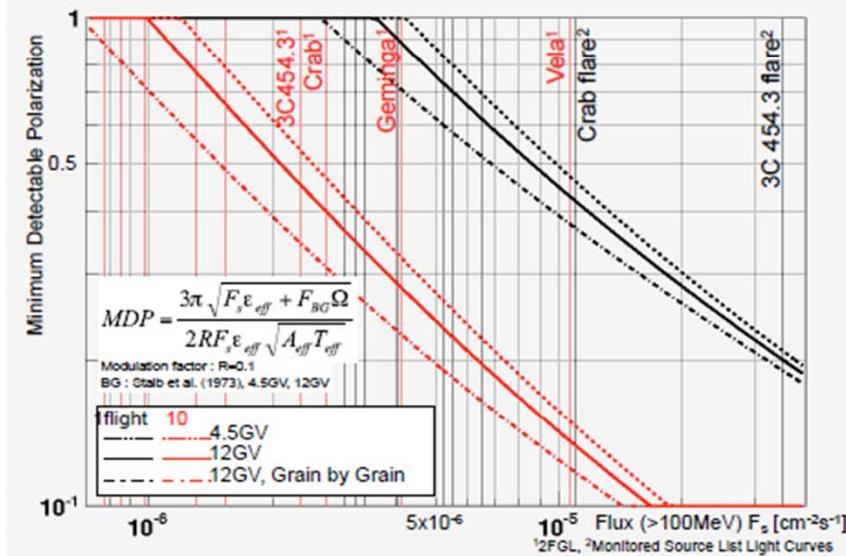


# GRAINE project

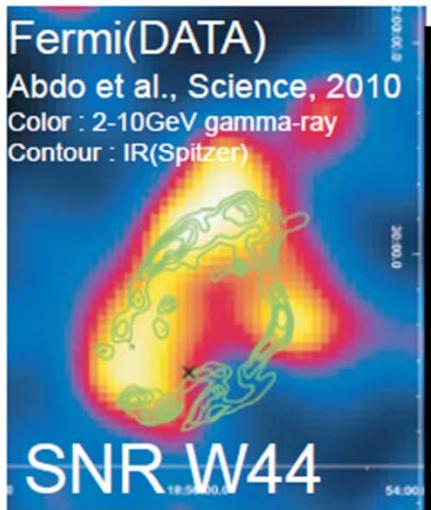
## Sensitivity



## 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, Demonstration

Alice Springs

~0.4m<sup>2</sup> aperture

~24hours flight duration

<~5g/cm<sup>2</sup> altitude

## 2021–, Scientific flight

Alice Springs

10m<sup>2</sup> aperture

>~36hours flight duration

<~10g/cm<sup>2</sup> altitude

Vela pulsar  
Polarization observation (<50%)

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

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

Studying cosmic ray  
sources

Galactic Center  
Obs. with ~arcmin resolution

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

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

Studying transient  
sources & w/ ones

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

backup

# Next generation multi-stage shifter

Co-developed with Mitaka Kohki Co., Ltd.

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

*drive roller*

$\sim 1\text{m}^2$

90cm  
*Tension roller*

95cm

<1 $\mu\text{m}$  repeatable accuracy  
(preliminary)

Size : 137cm x 116cm x ~20cm

Weight : <~90kg

Electric consumption : ~25W

Aperture area : 8550cm<sup>2</sup>

# of stages : 6

Gap between stages : ~0.5mm

Total thickness of aperture area : 5mm

Conventional: 2.6ton/10m<sup>2</sup>

New: 0.4ton/10m<sup>2</sup> (Prospects)

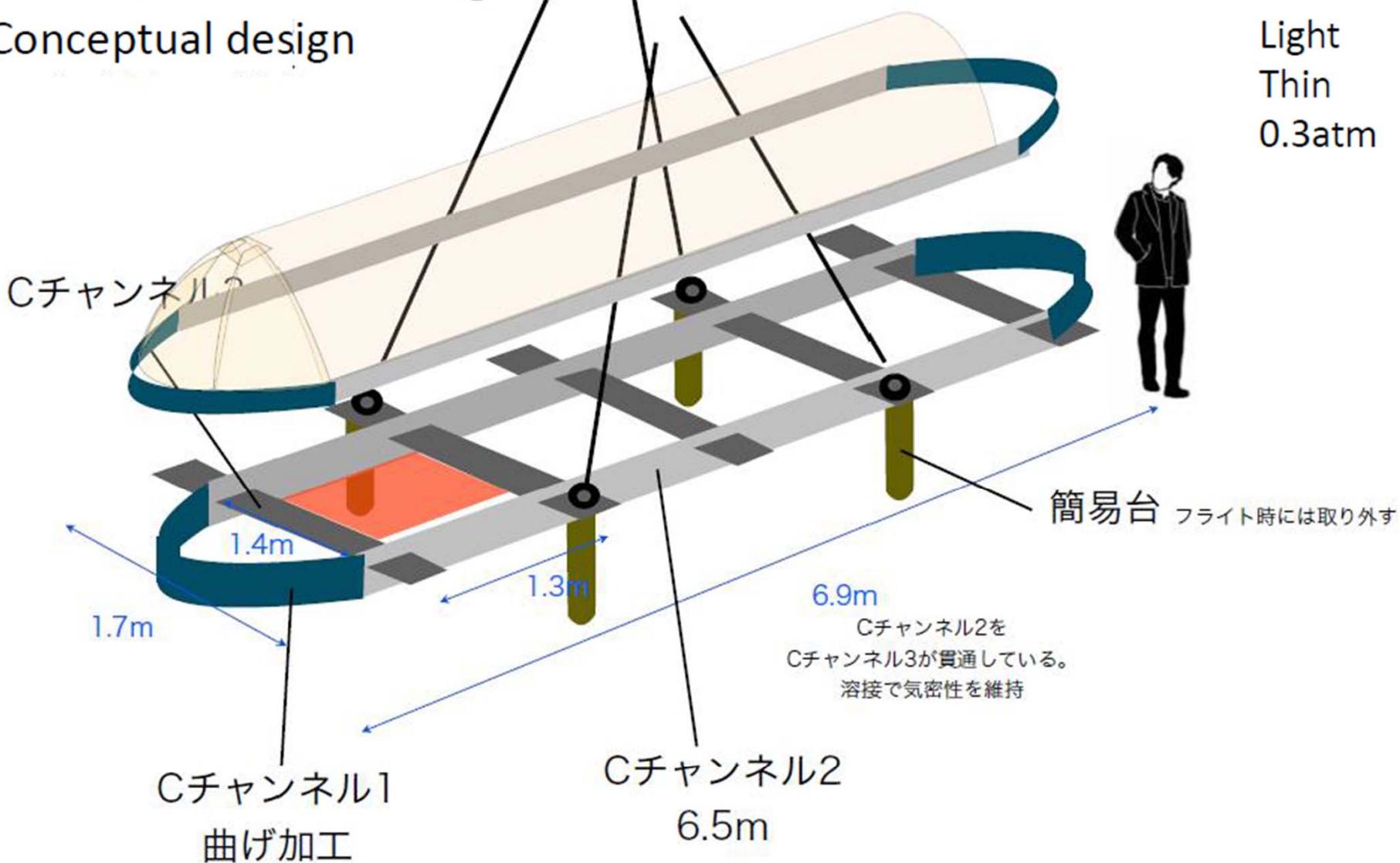
Oct. 2014 Started

# Pressure vessel gondola

Extended model based on GRAINE 2015

Conceptual design

Light  
Thin  
0.3atm

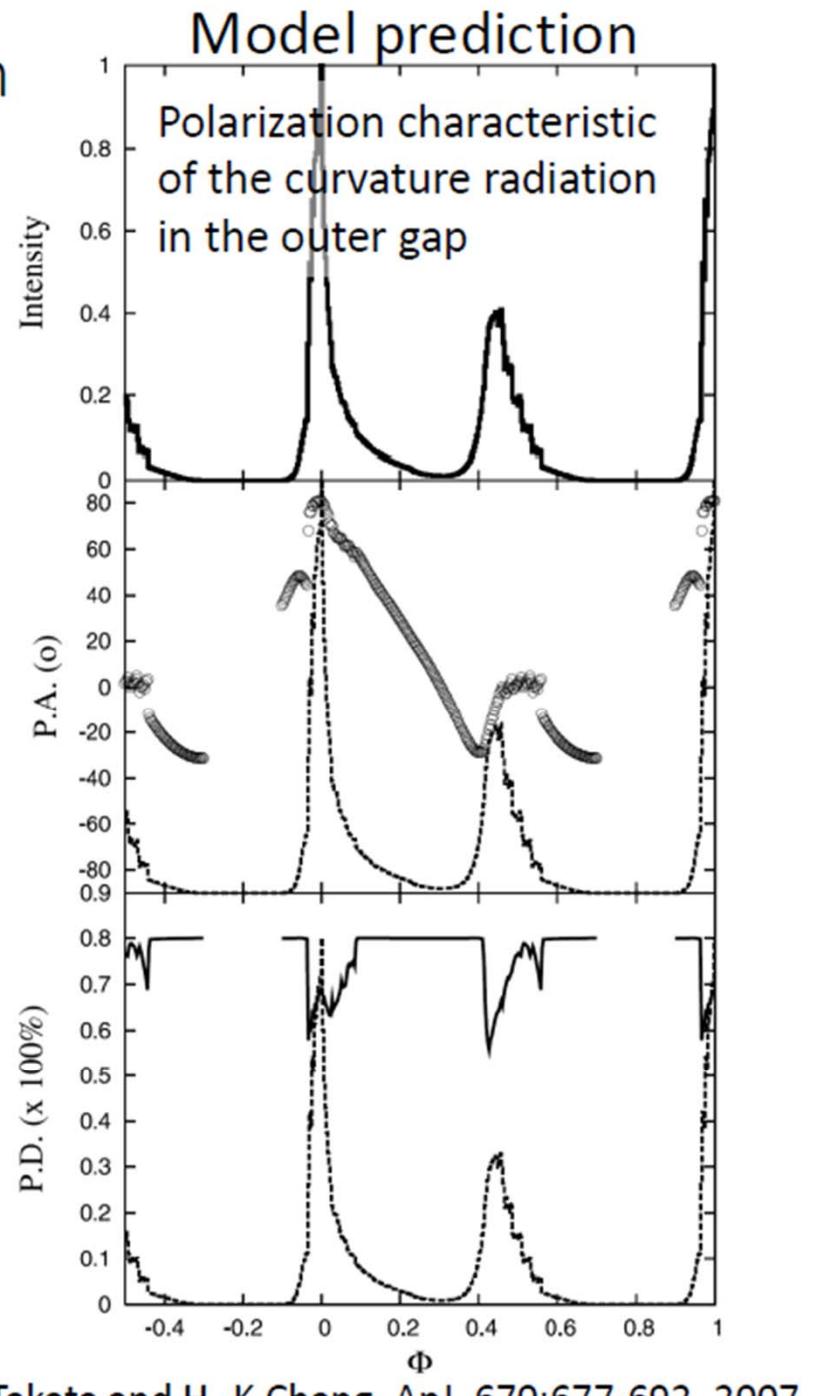
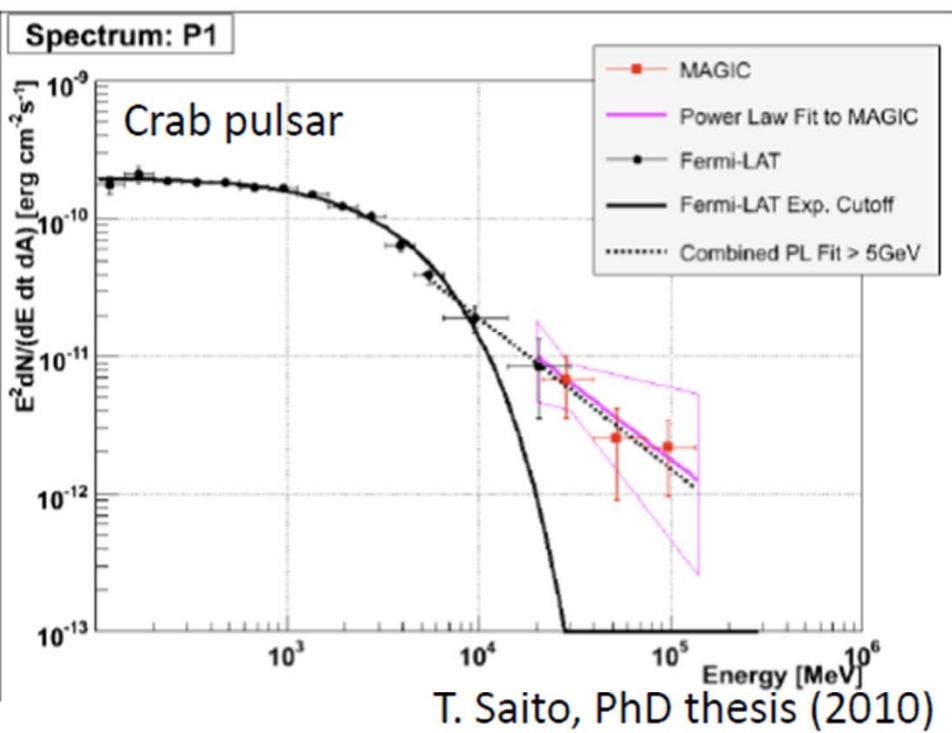


5m<sup>2</sup> (4units) aperture area

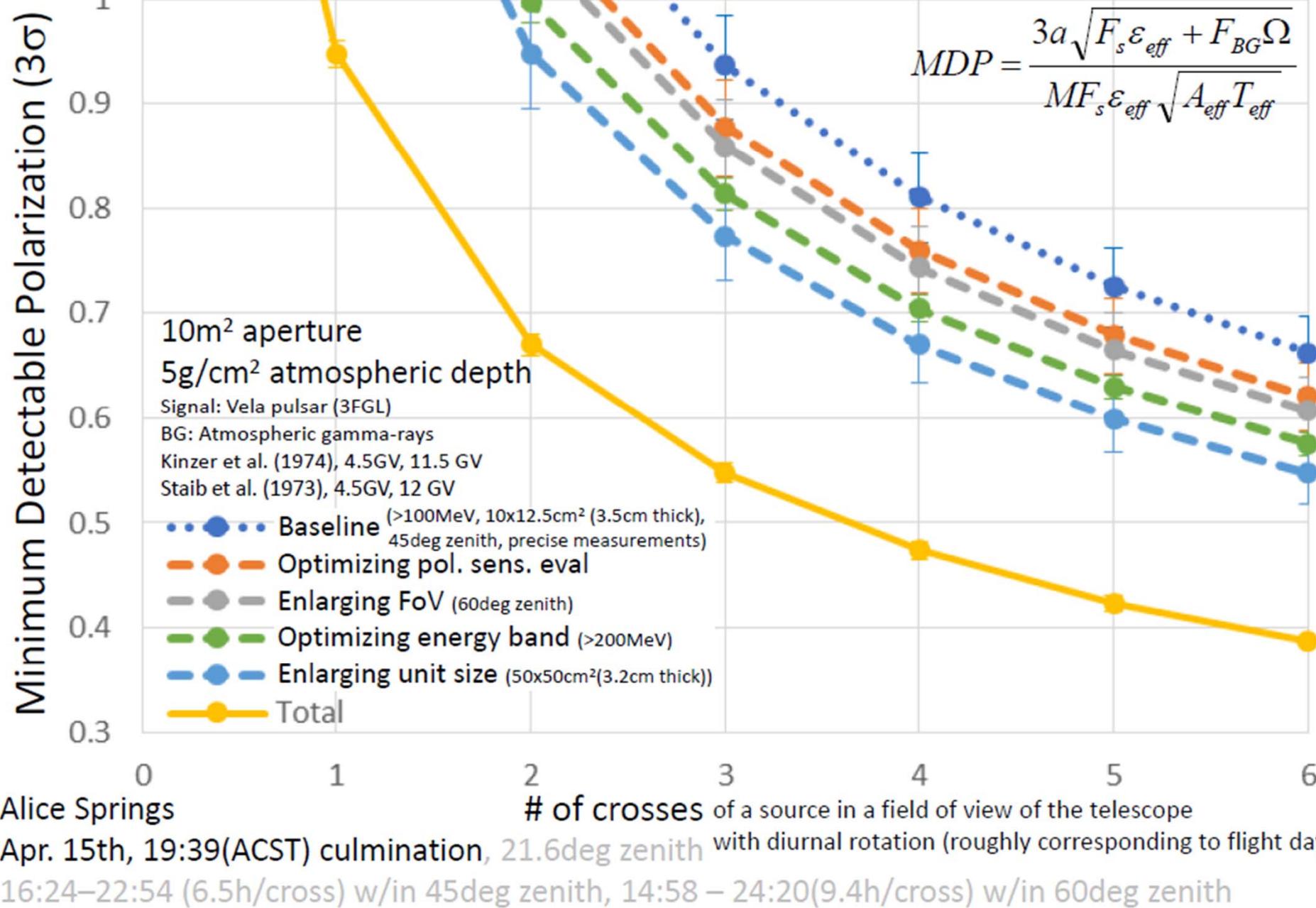
w/ a single pressure vessel gondola (~250kg weight)

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

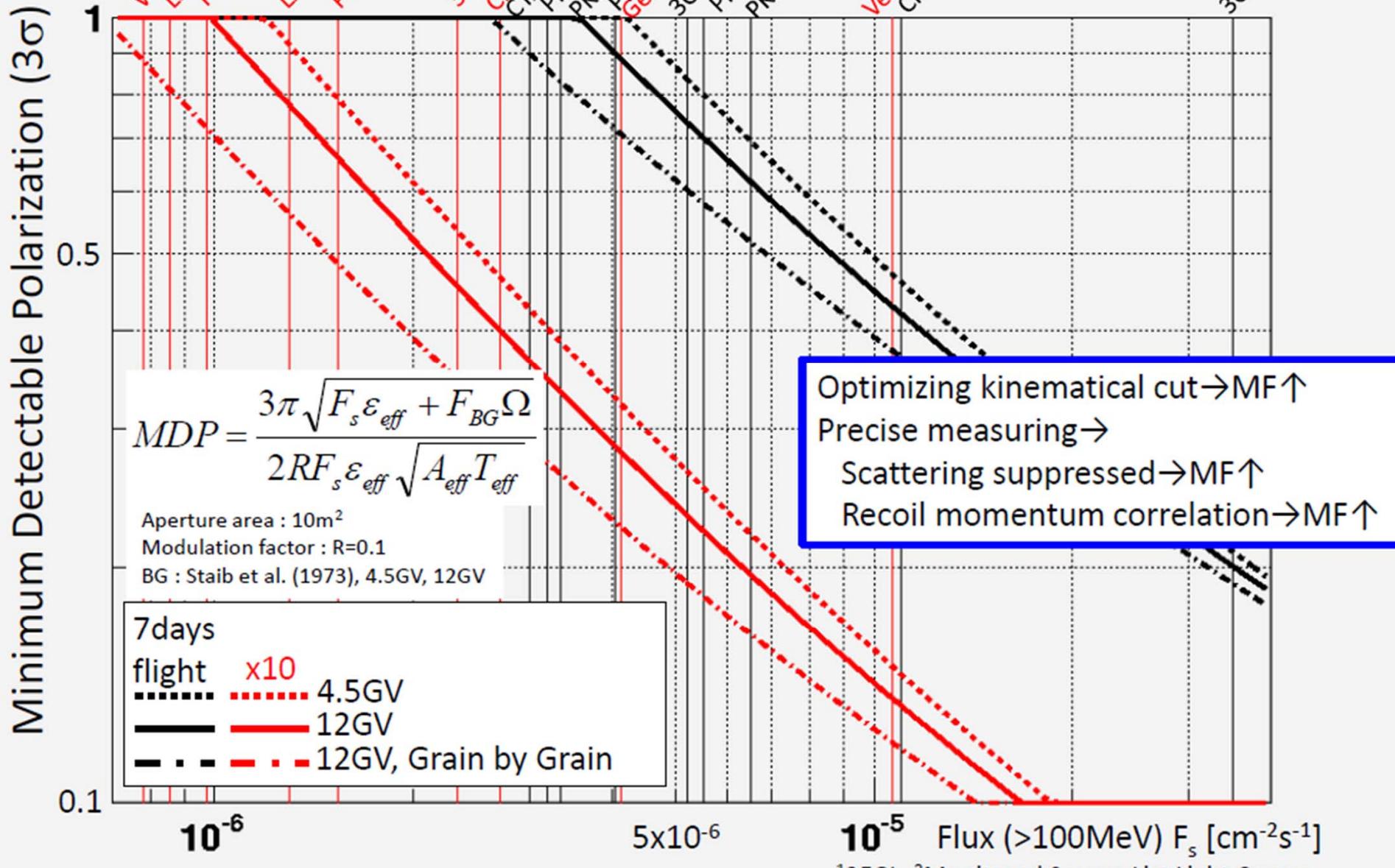
Pulsars, AGNs, Flares, GRBs



# Vela pulsar, polarization sensitivity

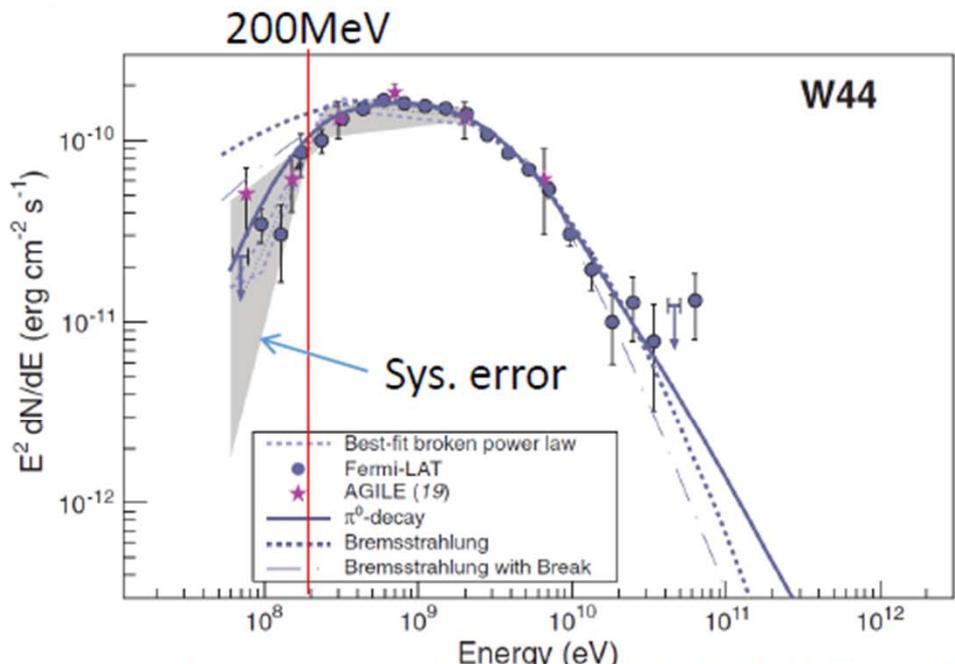


# Polarization sensitivity

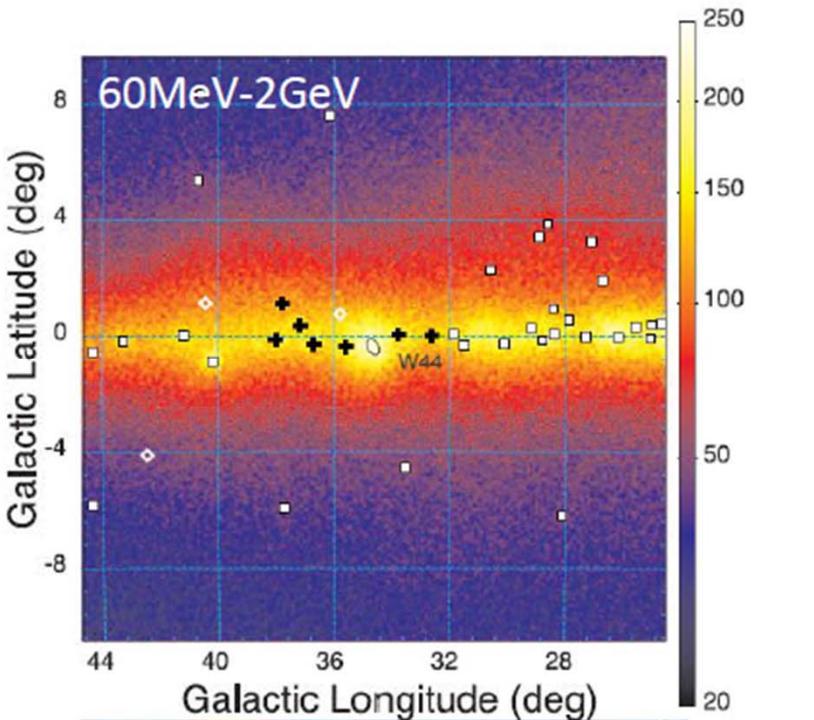


# $\pi^0$ emission: Direct evidence of proton acceleration

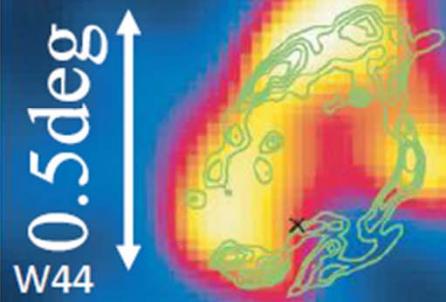
SNRs



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



Spatial structure:  
Emission mechanism



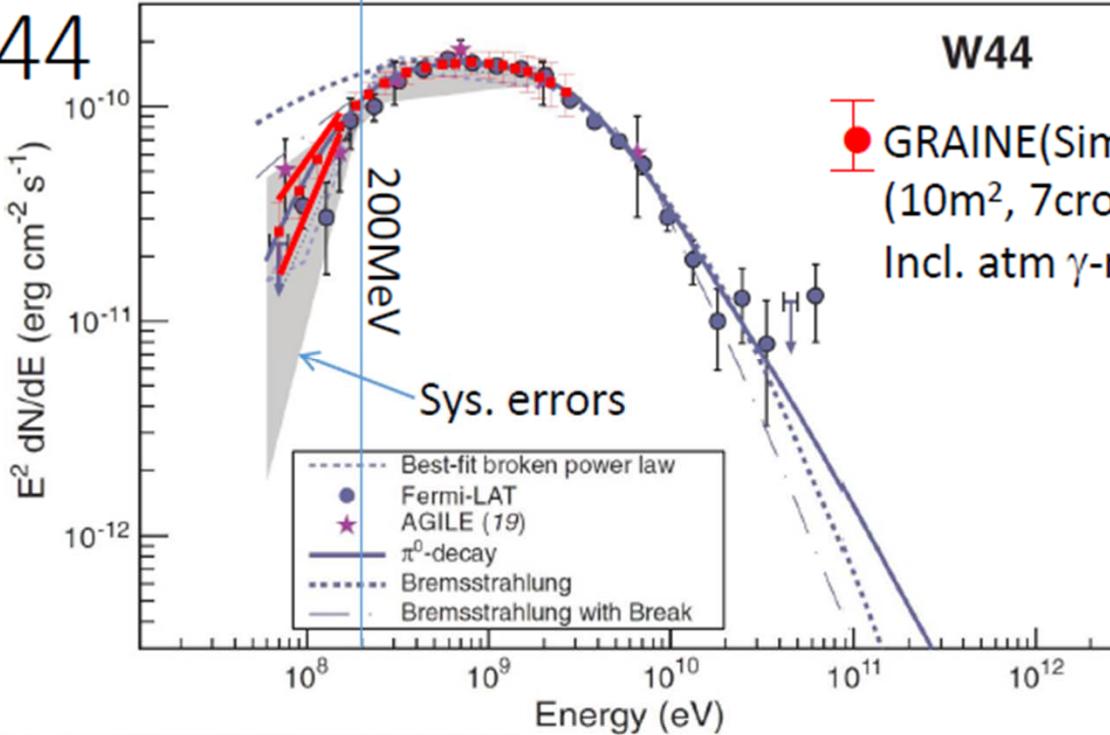
Abdo et al., Science, 2010

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



<200MeV

Precise spectral measuring  
with suppressed systematic error

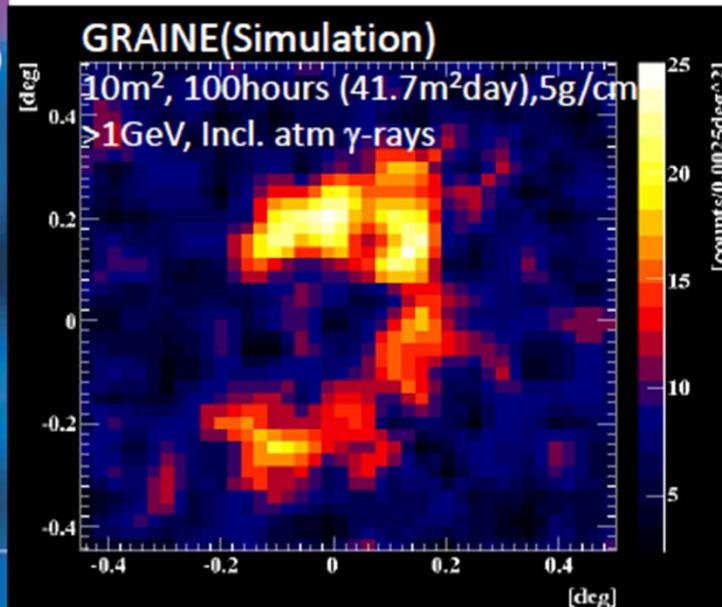
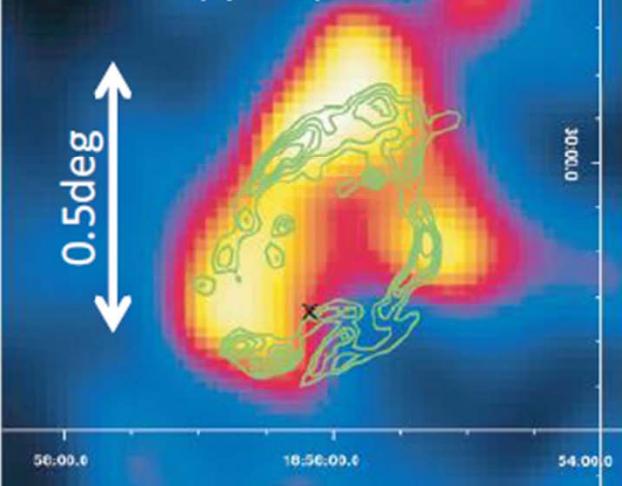
## W44

Abdo et al., Science, 2010

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

Contour : IR(Spitzer)

0.5deg

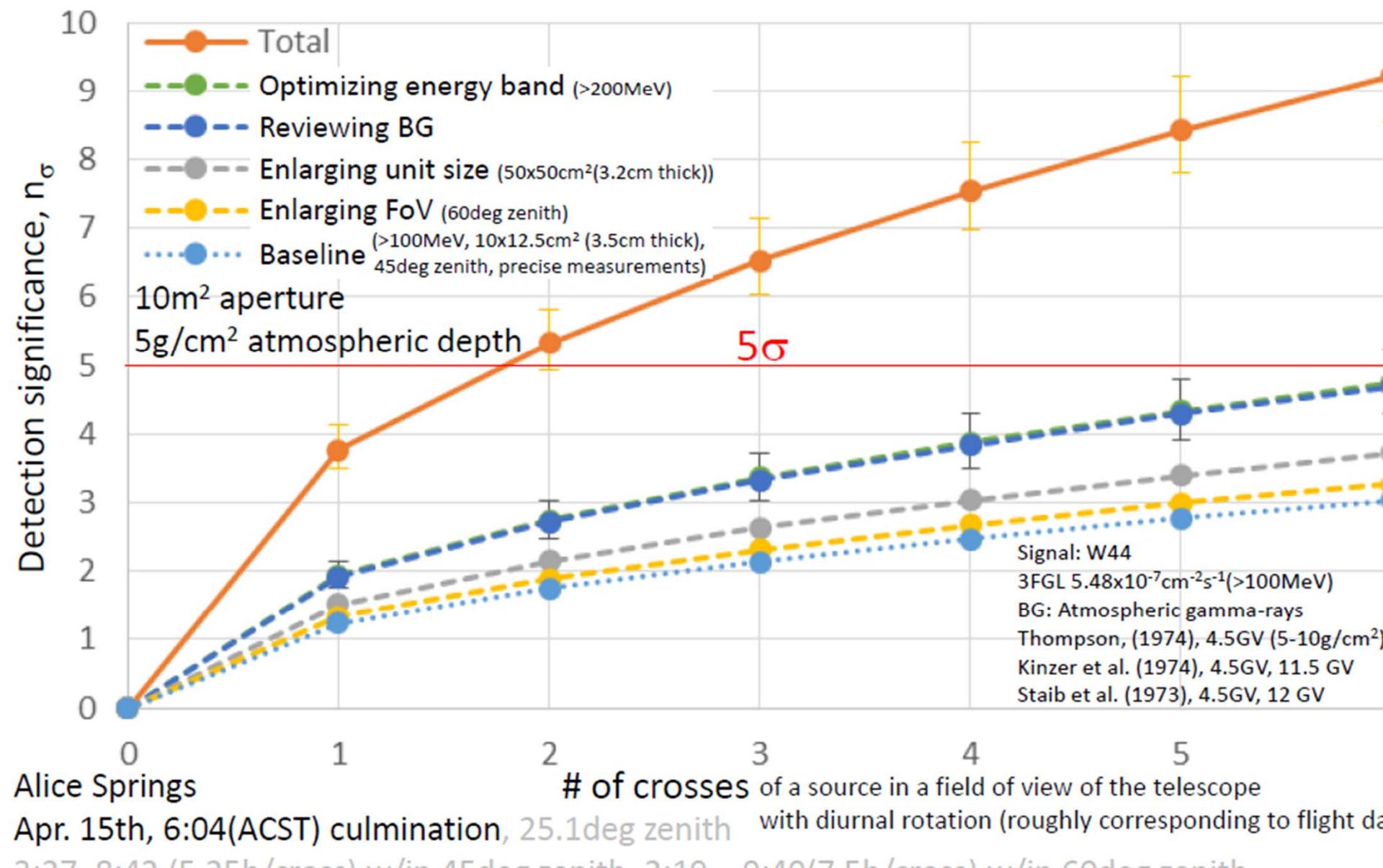


>200MeV

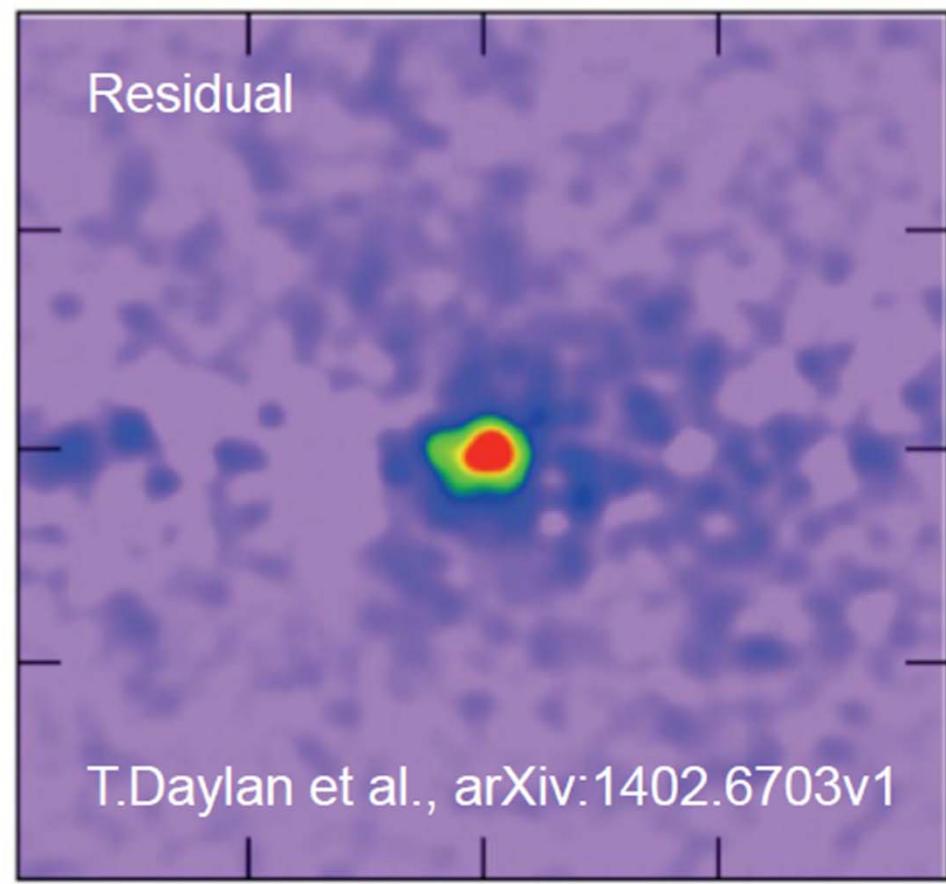
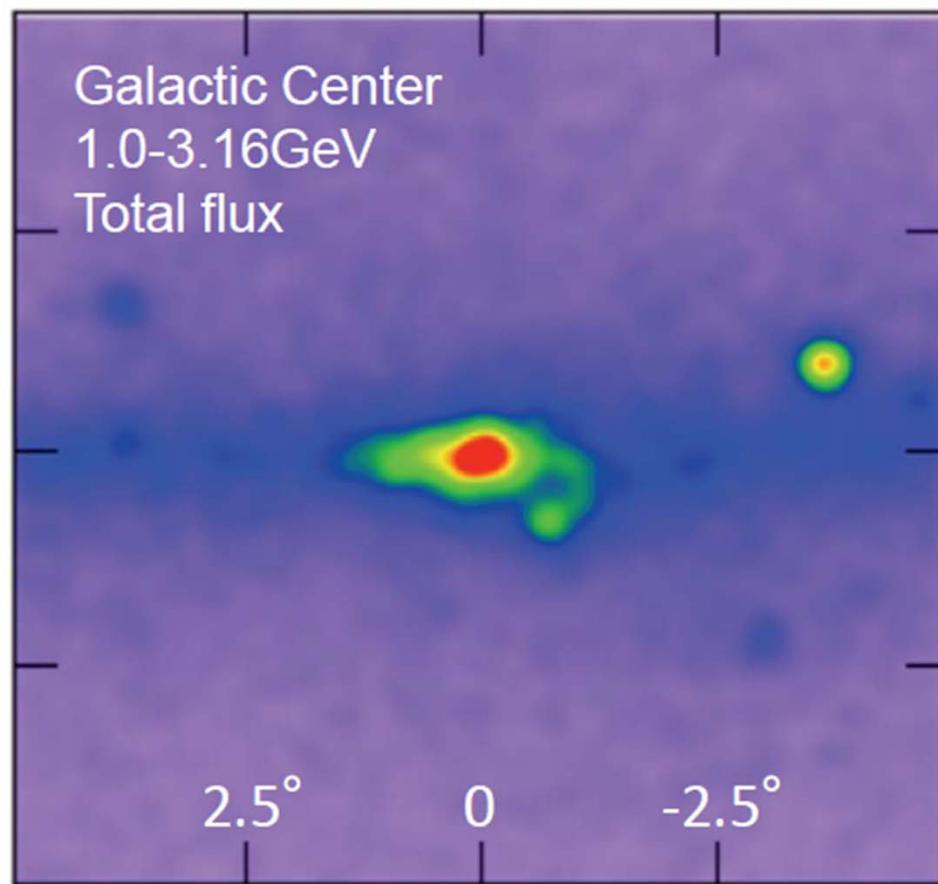
Investigating spatial structure

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

# W44 detection sensitivity

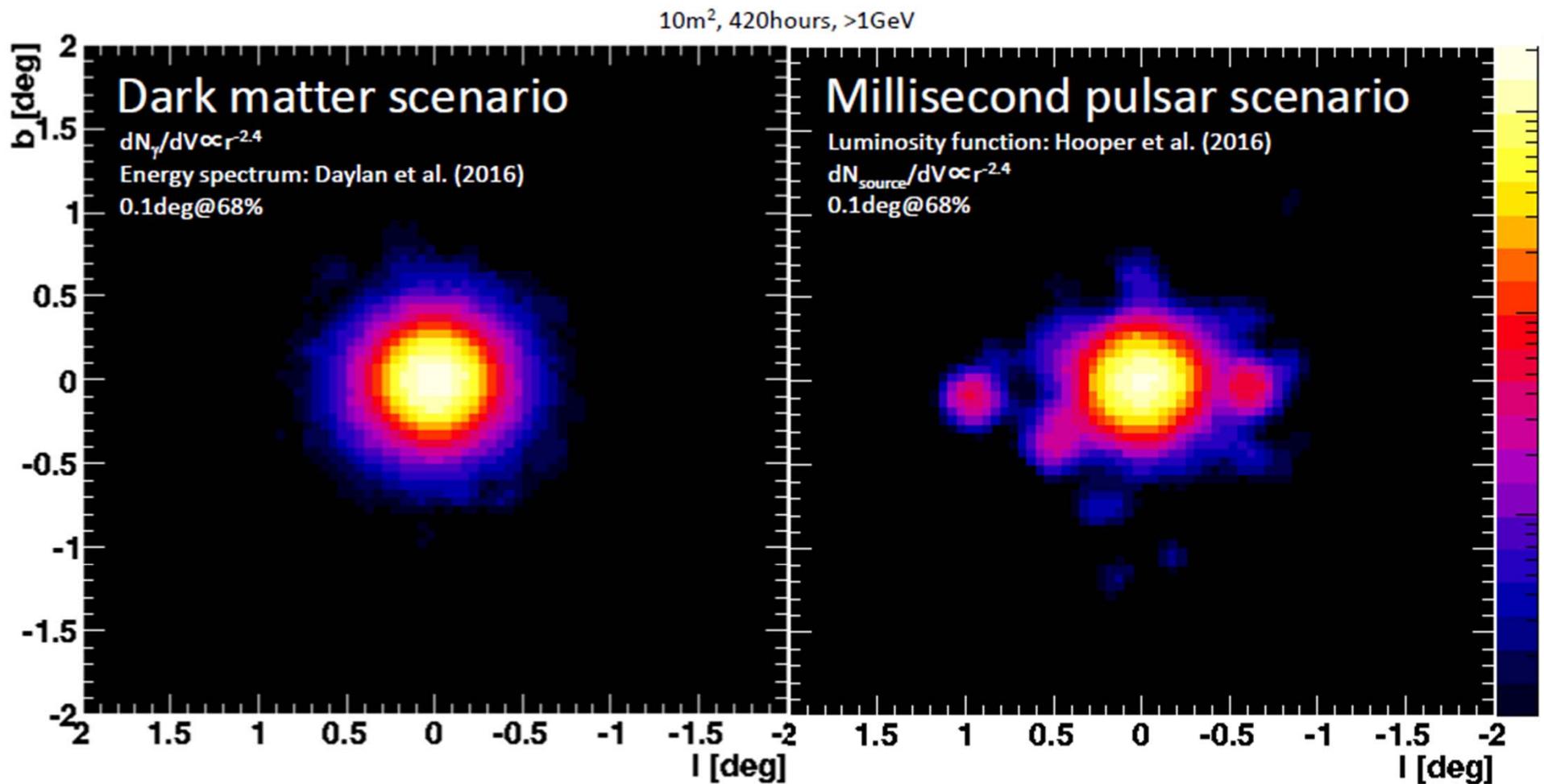


# GeV $\gamma$ -ray excess at galactic center region



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

