GRAINE project

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

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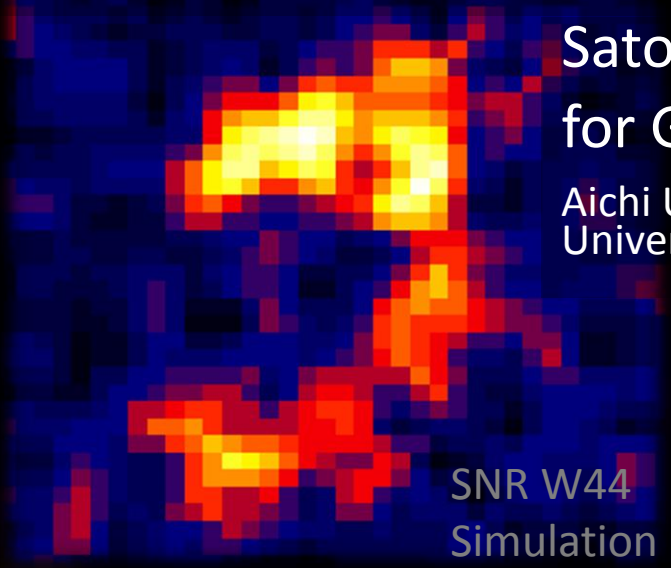
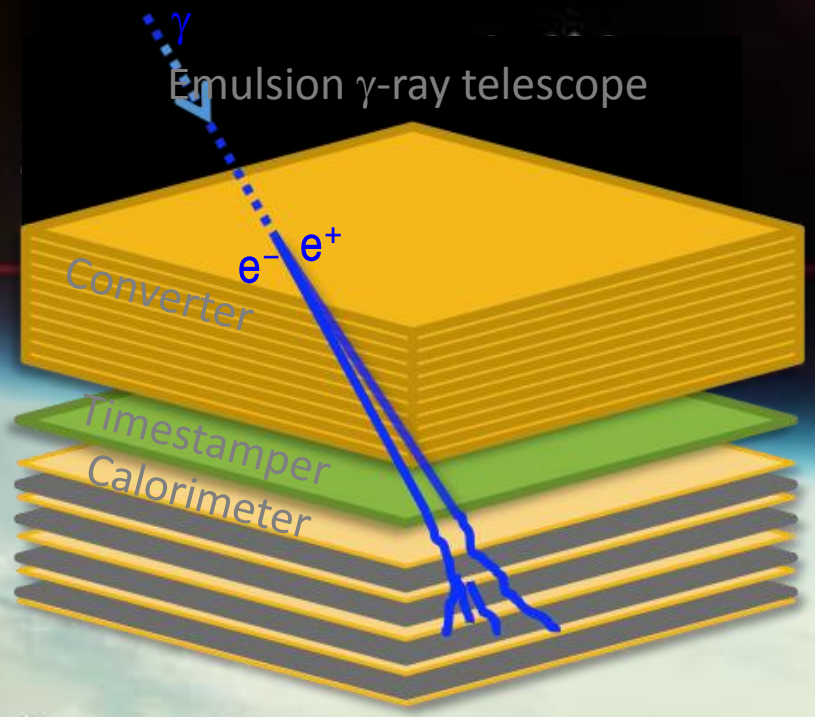
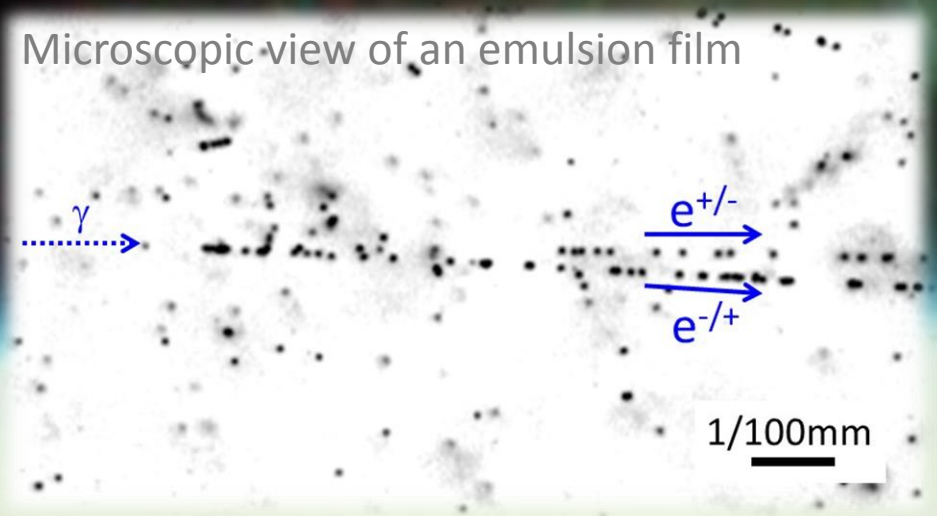
for GRAINE collaboration, PI: S. Aoki (Kobe Univ.)

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



SNR W44
Simulation





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

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

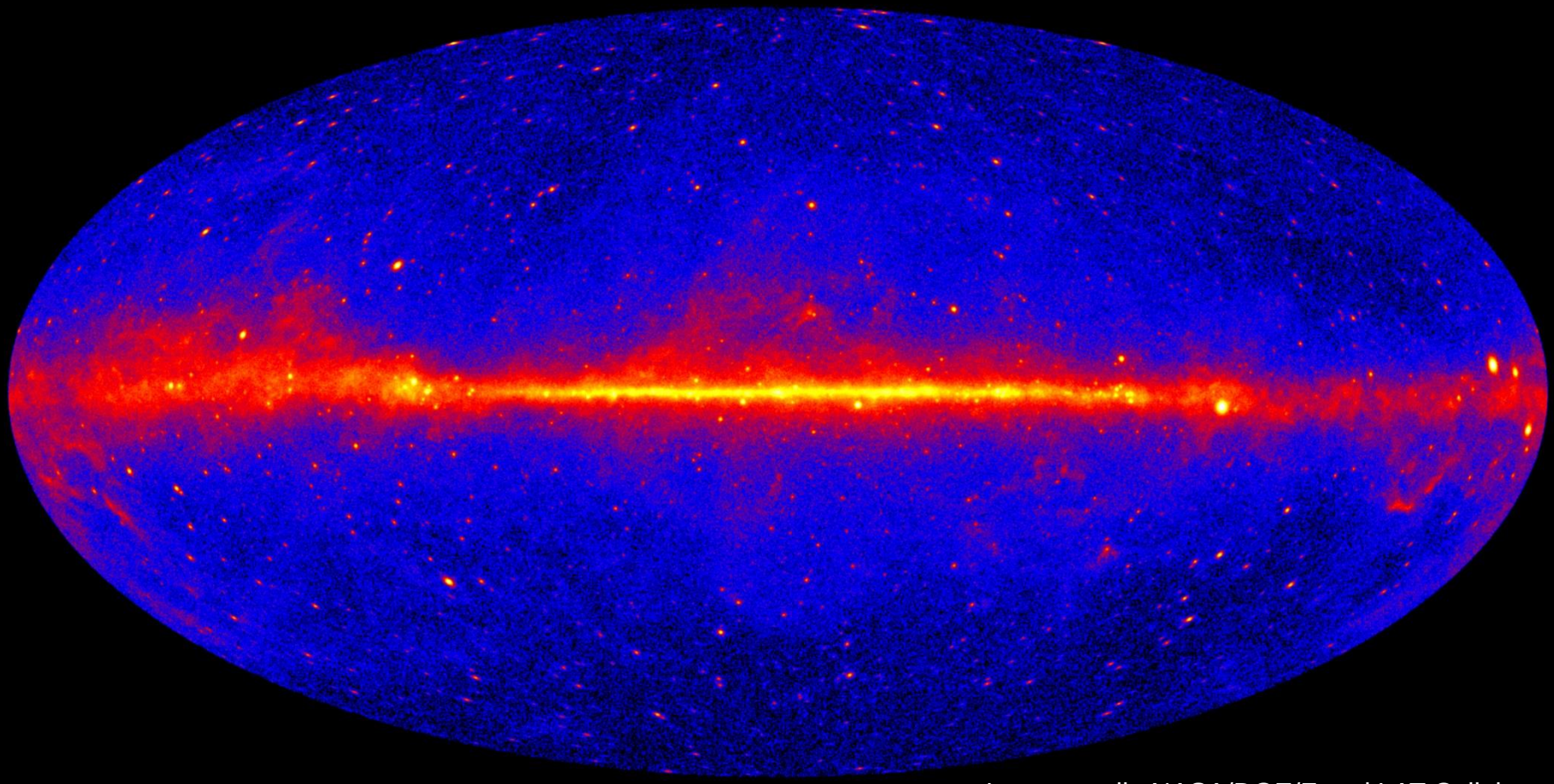
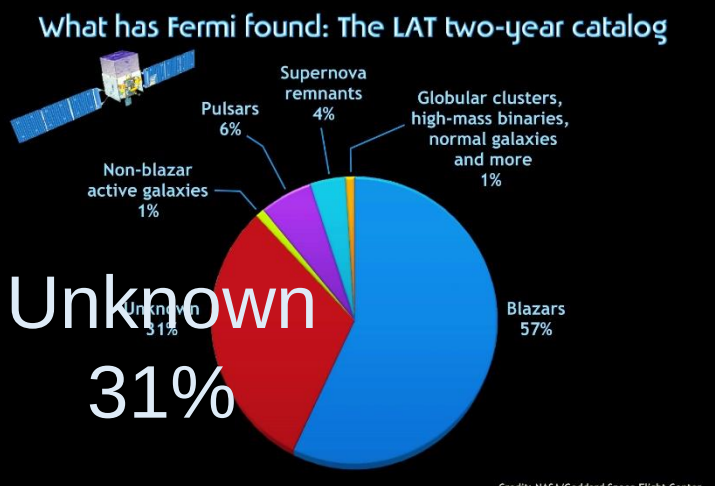


Image credit: NASA/DOE/Fermi LAT Collaboration

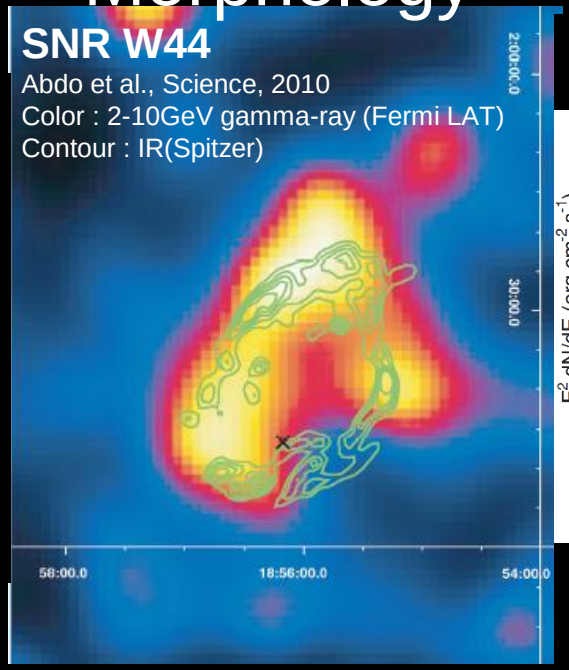
>3000 sources (3FGL)

Un-ID

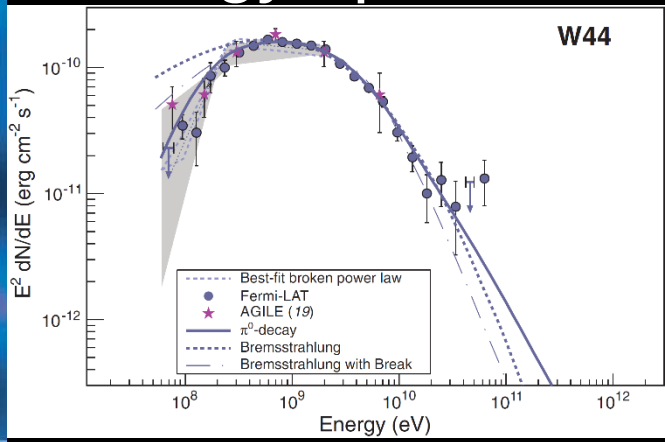


Unknown 31%

Morphology



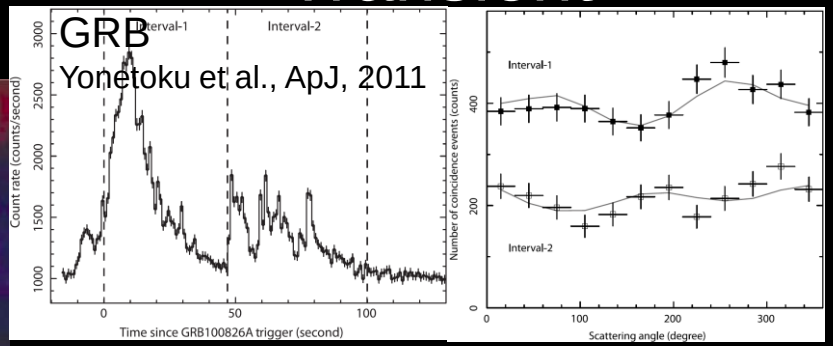
Energy spectrum

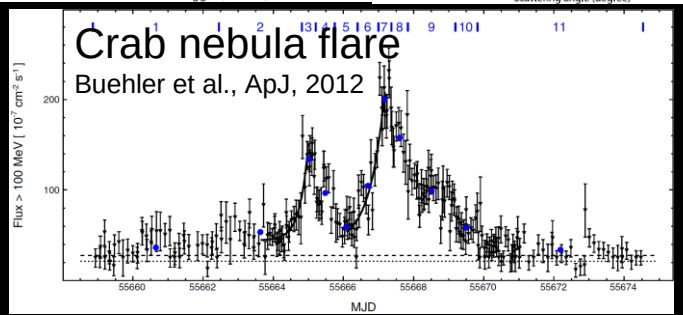


M. Ackermann et al. Science, 2013

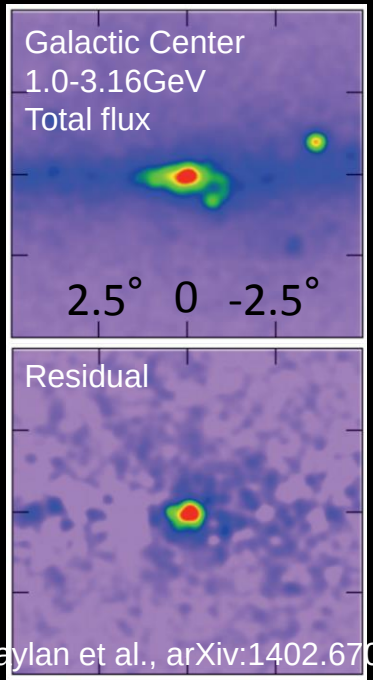
Polarization

Transient





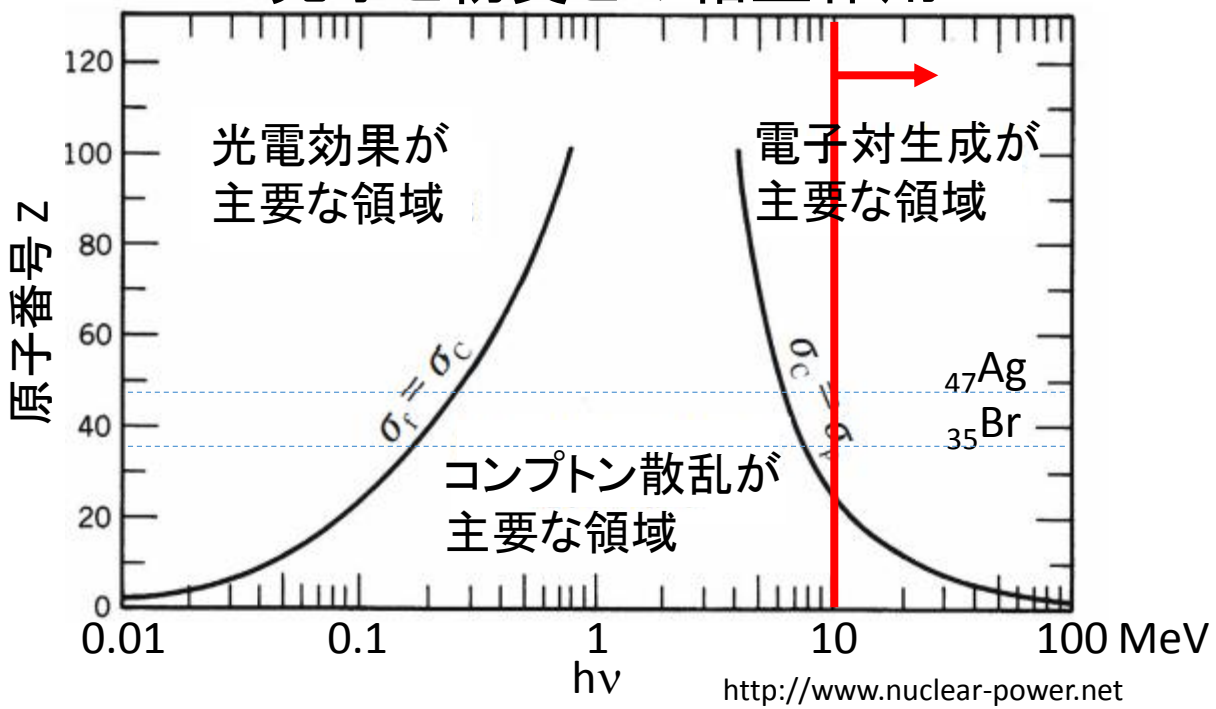
Dark matter



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



http://www.nuclear-power.net

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

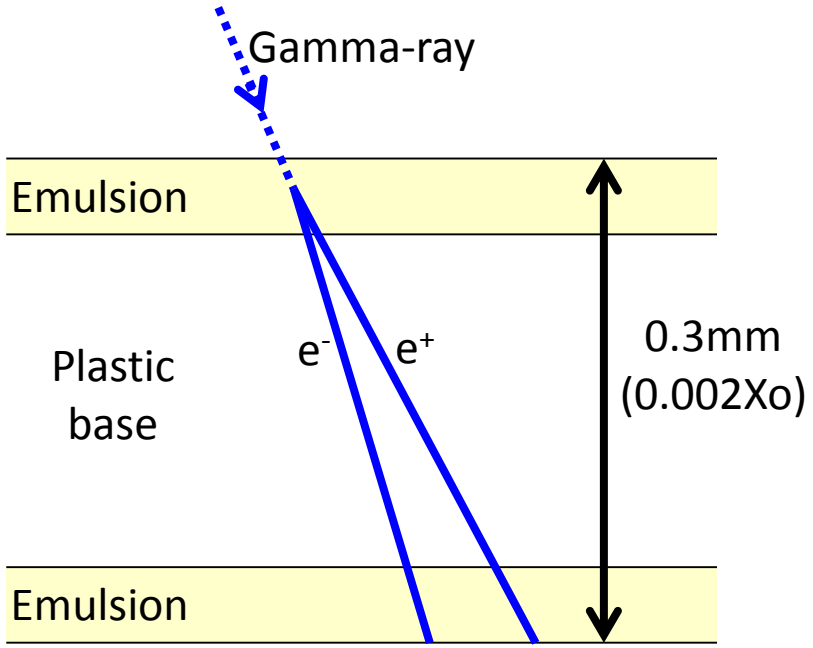
Intrinsic position accuracy ~60nm

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

GRAINE

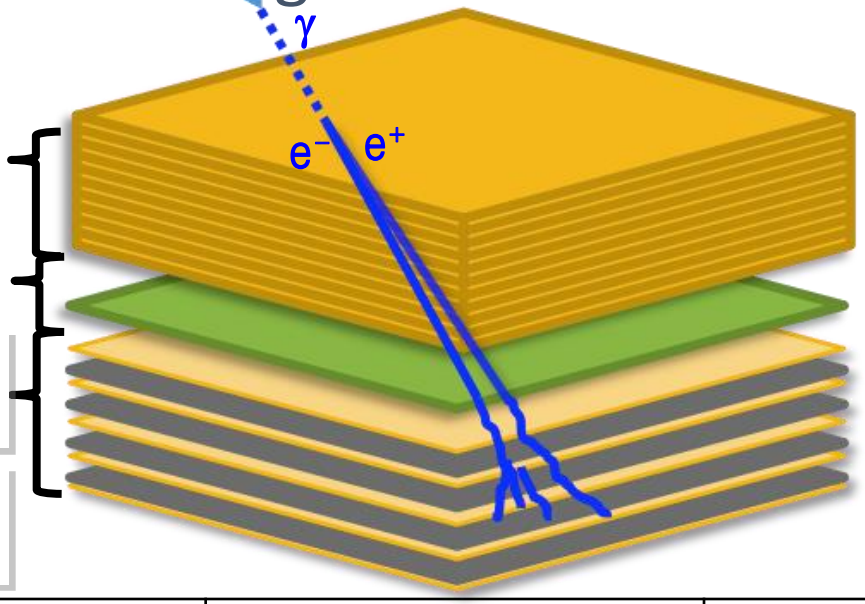
Gamma-Ray Astro-Imager with Nuclear Emulsion

Converter
Emulsion + Copper foil

Timestamper
Multi-stage shifter

Calorimeter
Emulsion + metal plate

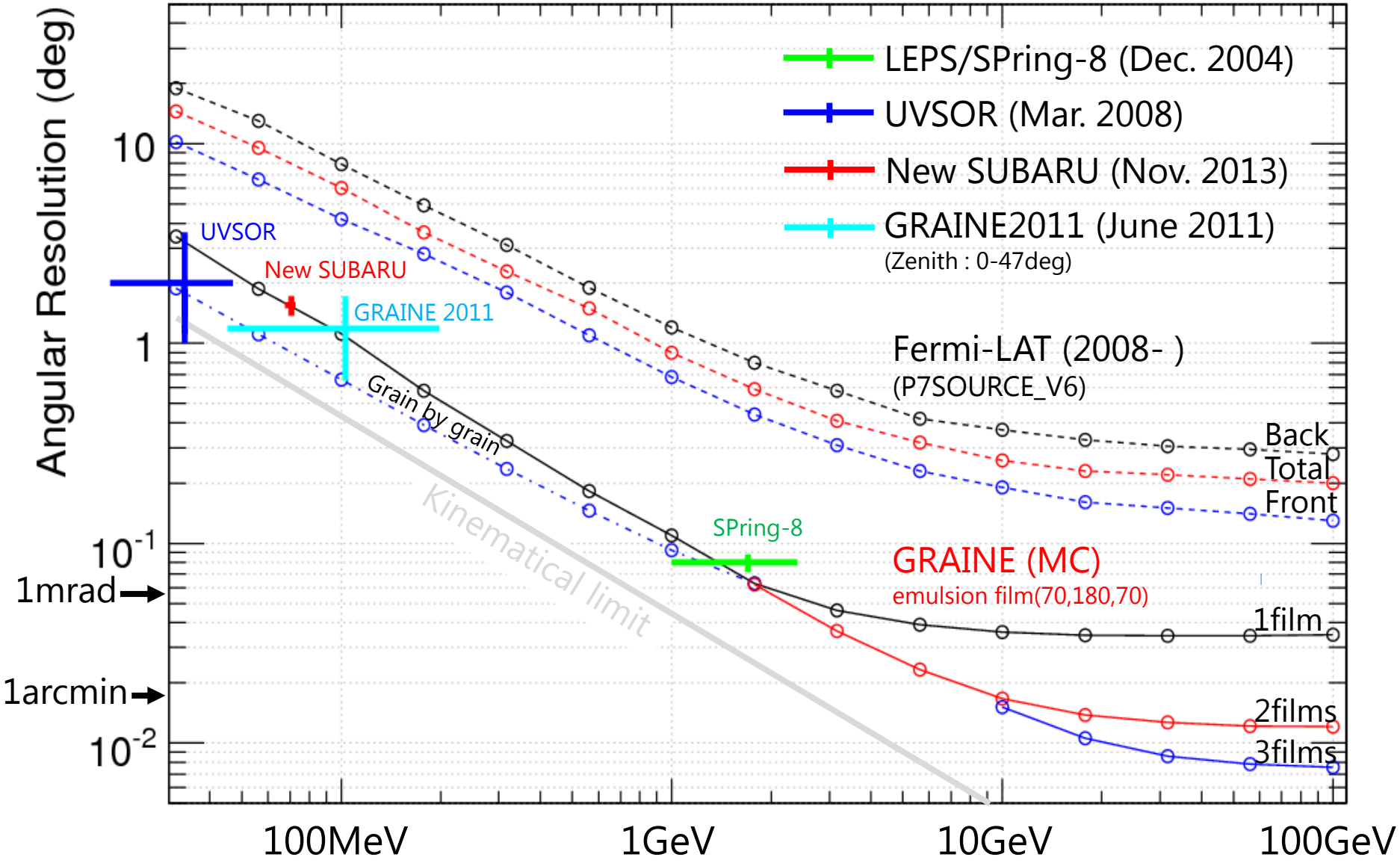
Attitude monitor
Star camera



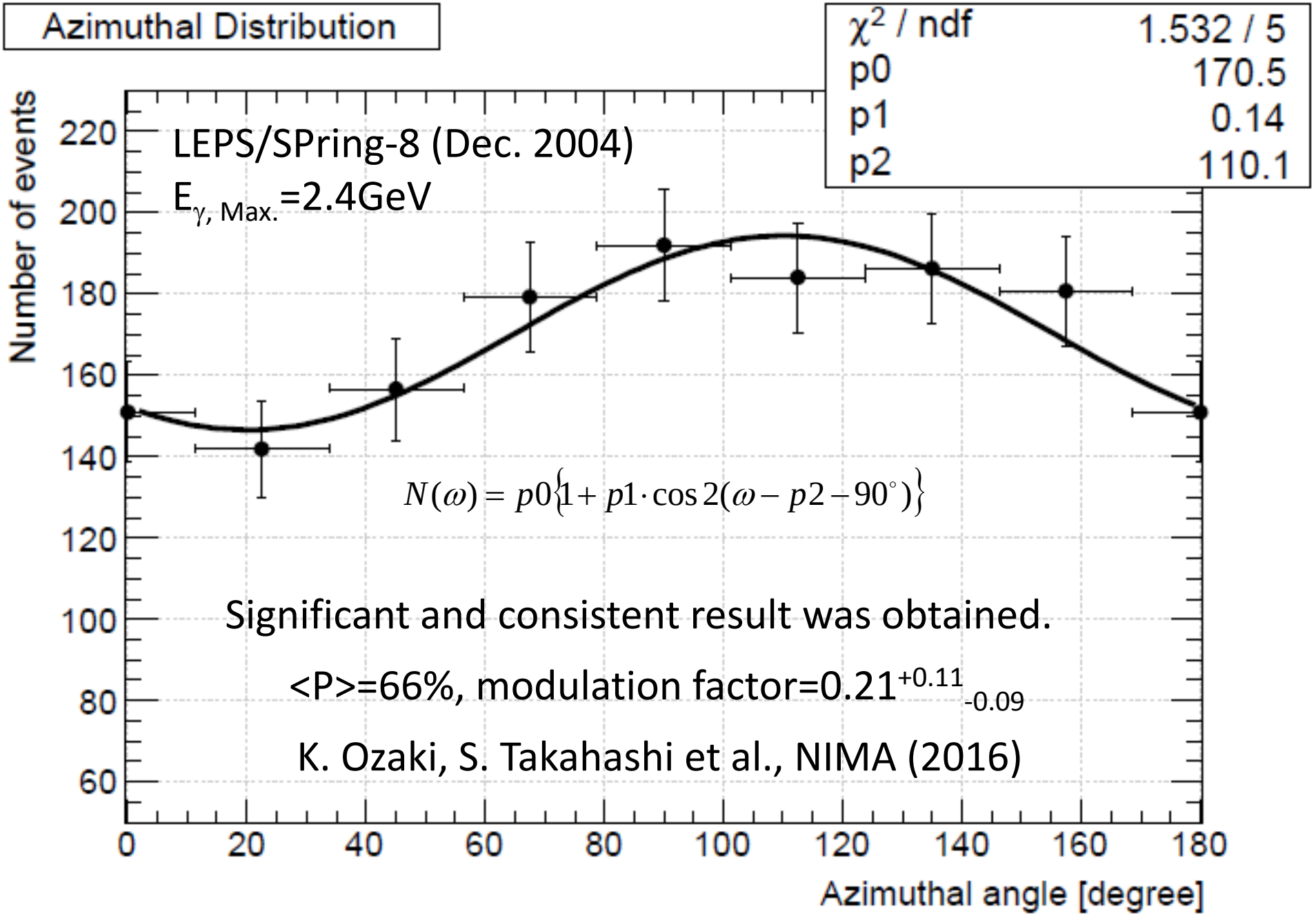
＊ $10m^2 * \varepsilon_{trans} * \varepsilon_{conv} * \varepsilon_{det}$

	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	---		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

Angular resolution



Polarization sensitivity



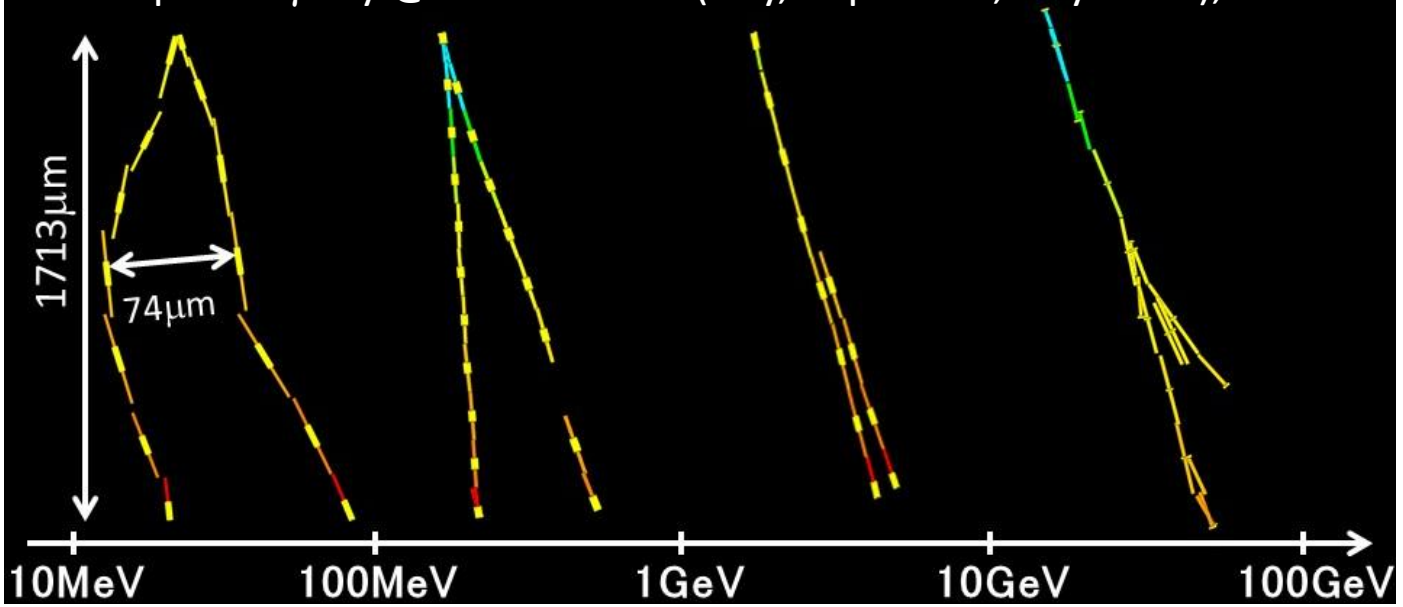
Significant and consistent result was obtained.

<P>=66%, modulation factor=$0.21^{+0.11}_{-0.09}$

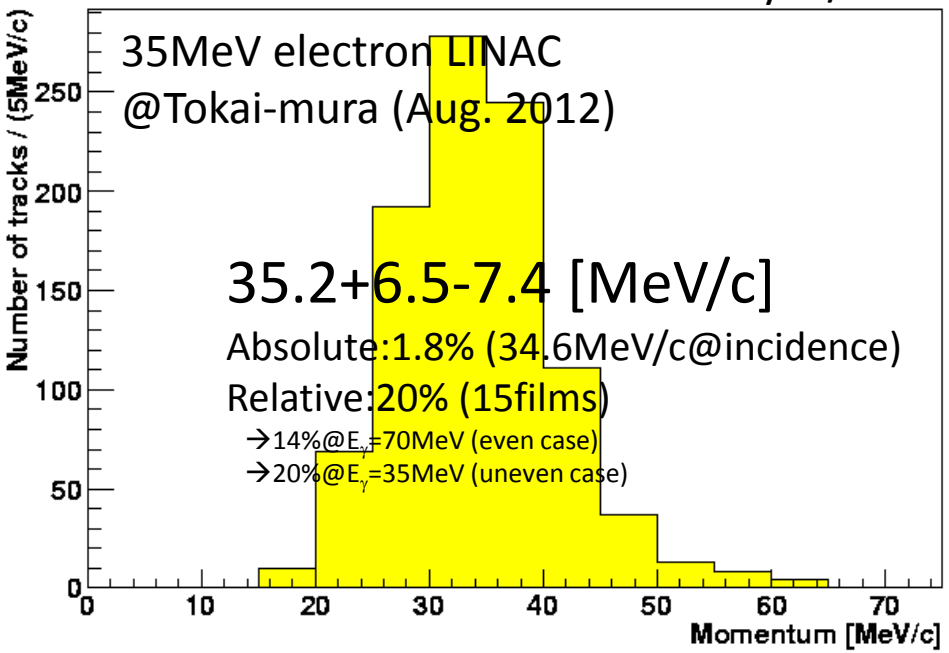
K. Ozaki, S. Takahashi et al., NIMA (2016)

Energy range

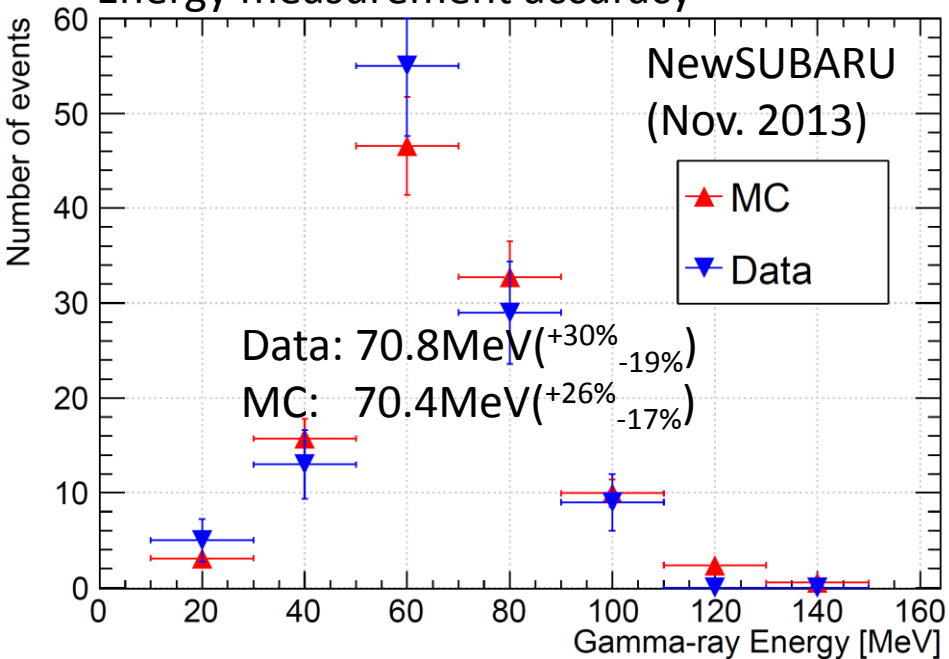
Atmospheric γ-ray @Mt. Norikura (July, Sep. 2007, July 2013), et al.



Momentum measurement accuracy w/MCS



Energy measurement accuracy

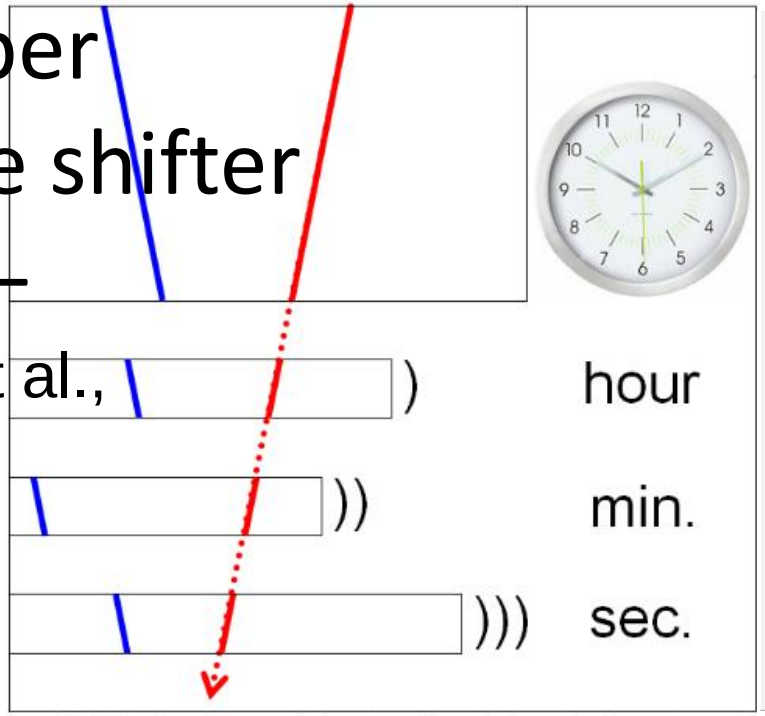


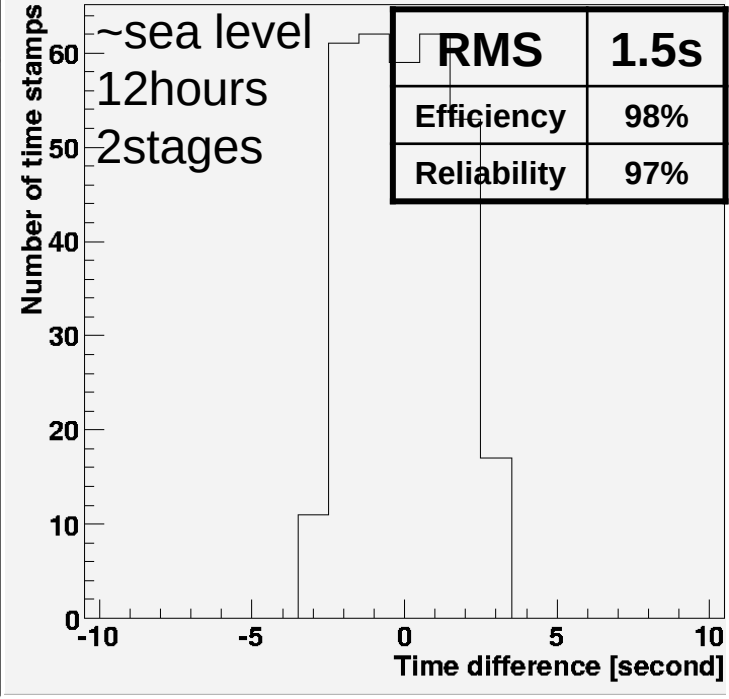
Timestamper

Multi-stage shifter

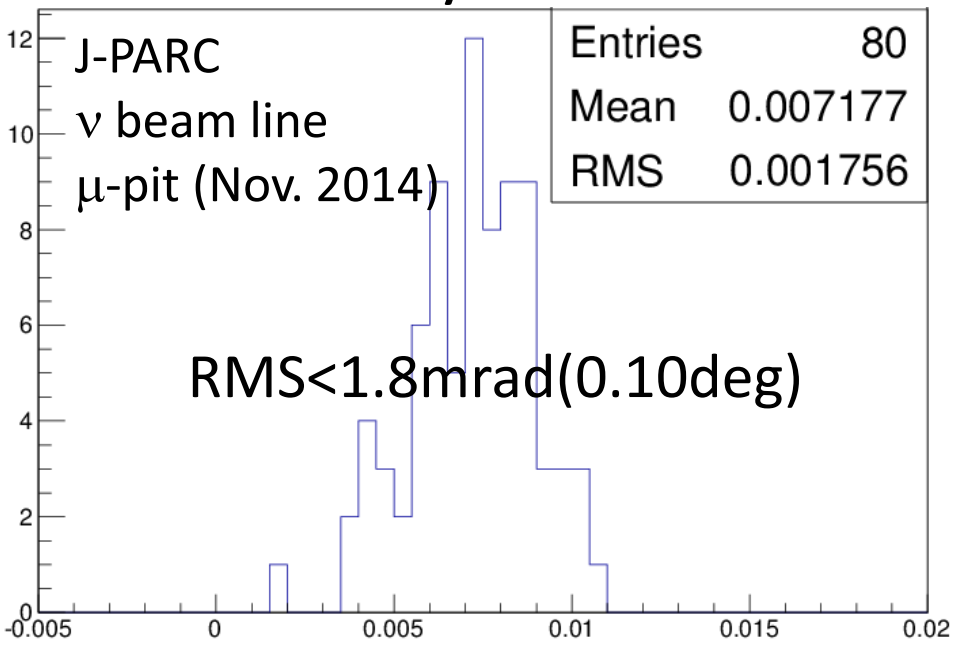
June 2007–

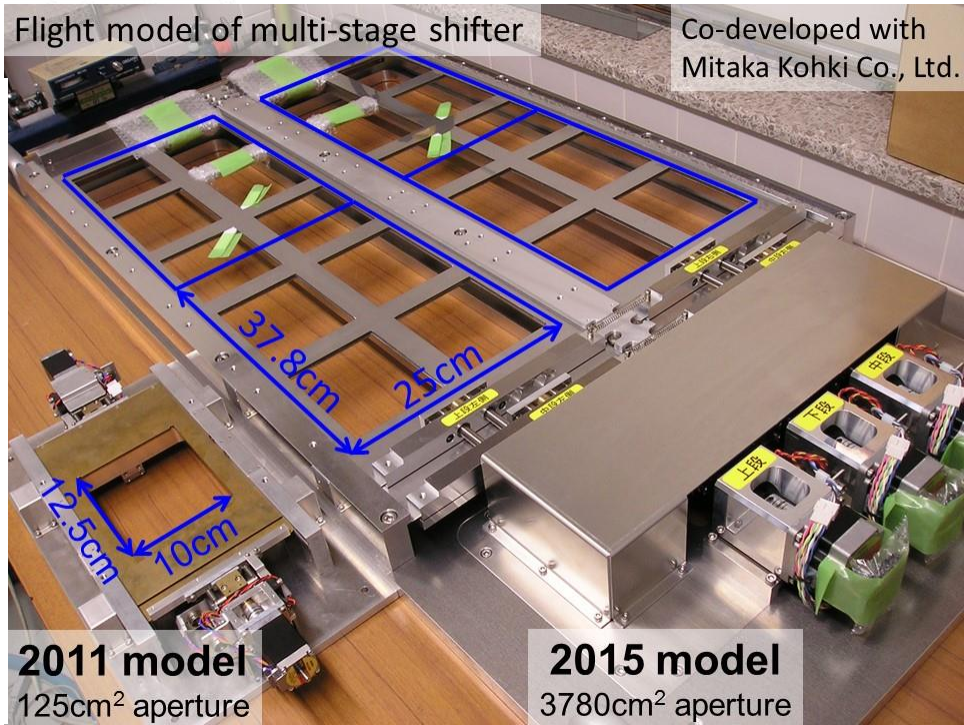
S.Takahashi et al.,
NIMA(2010)





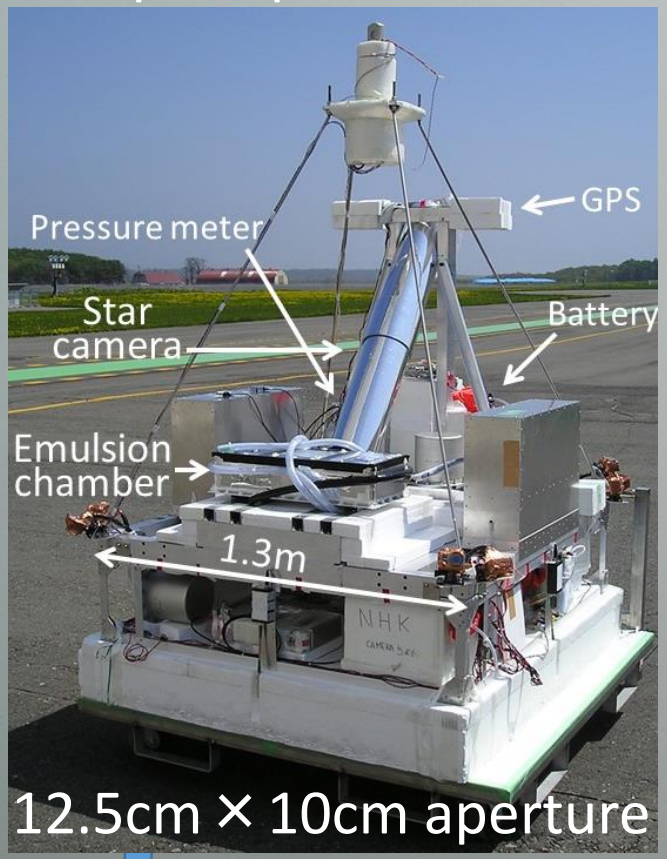
Flatness study





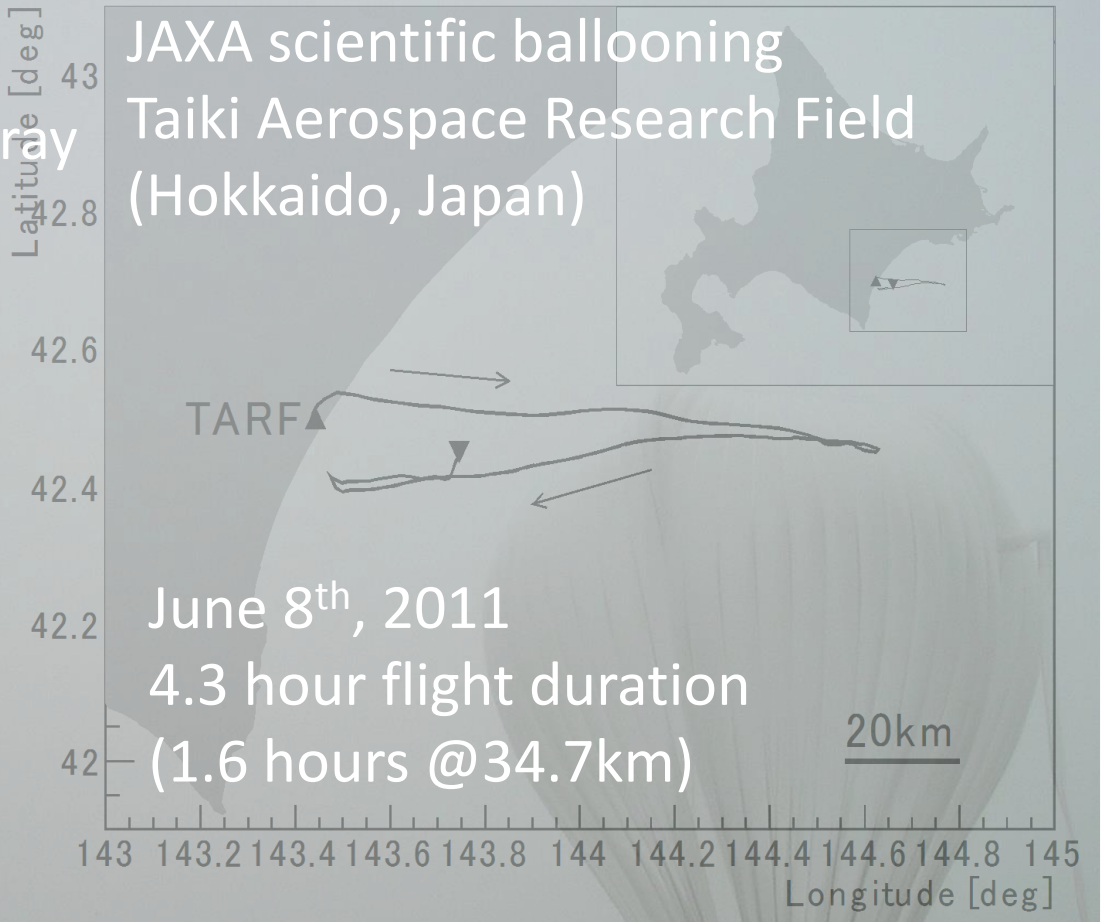
GRAINE 2011

First balloon-borne emulsion γ-ray telescope experiment



12.5cm × 10cm aperture

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

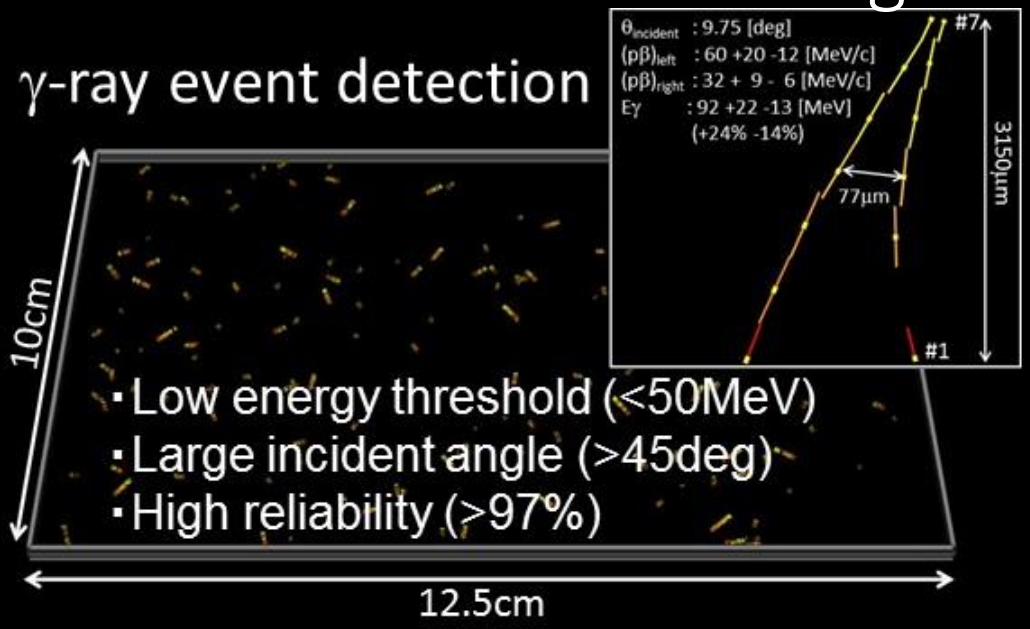


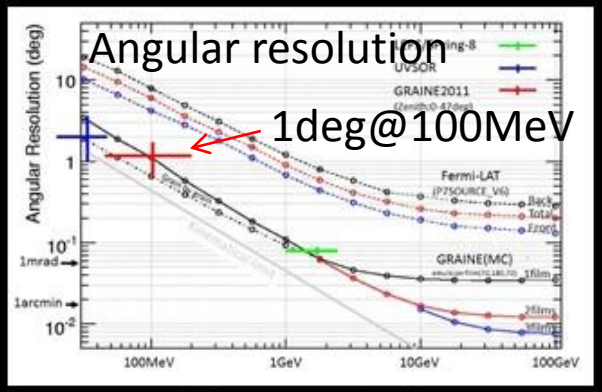
June 8th, 2011
4.3 hour flight duration
(1.6 hours @34.7km)

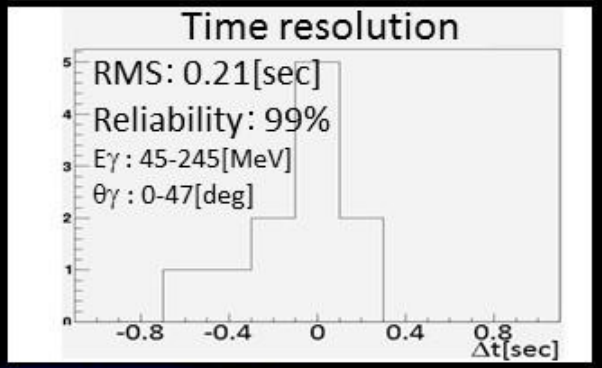
First balloon-borne experiment
Feasibility test

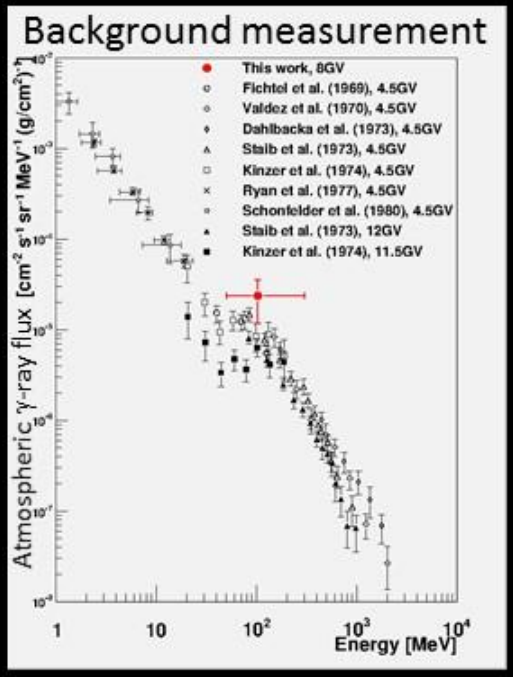
GRAINE 2011 Flight data analysis

γ-ray event detection

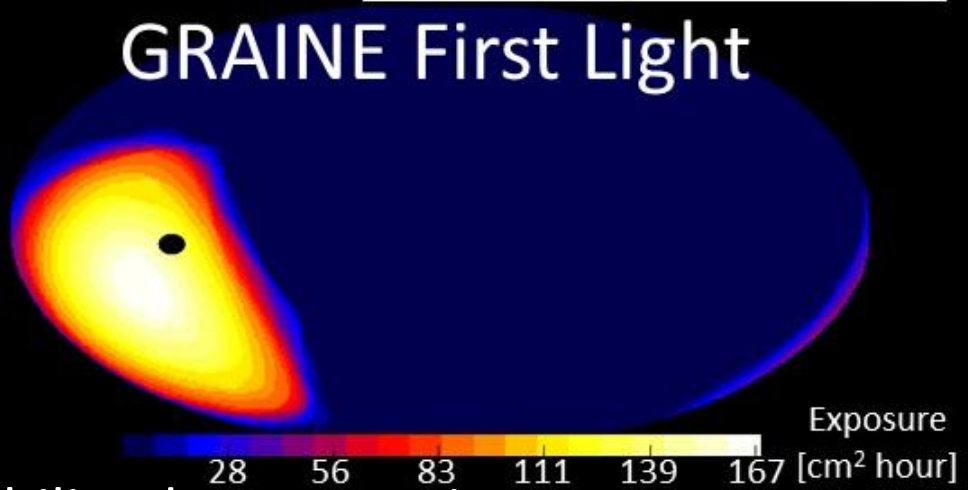








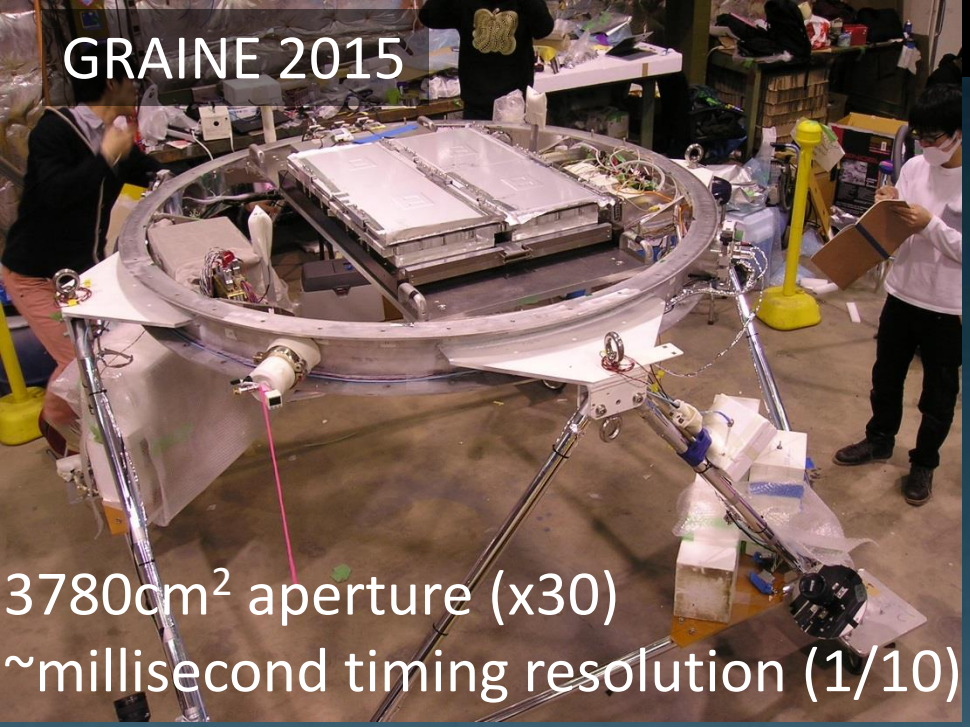
GRAINE First Light



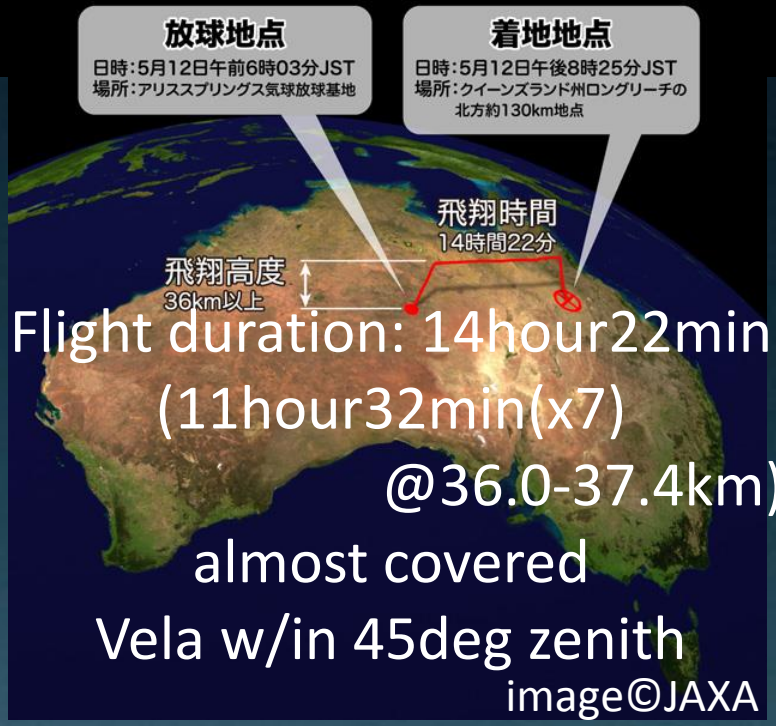
Feasibility demonstration

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

GRAINE 2015



3780cm^2 aperture (x30)
~millisecond timing resolution (1/10)



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

image©JAXA

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

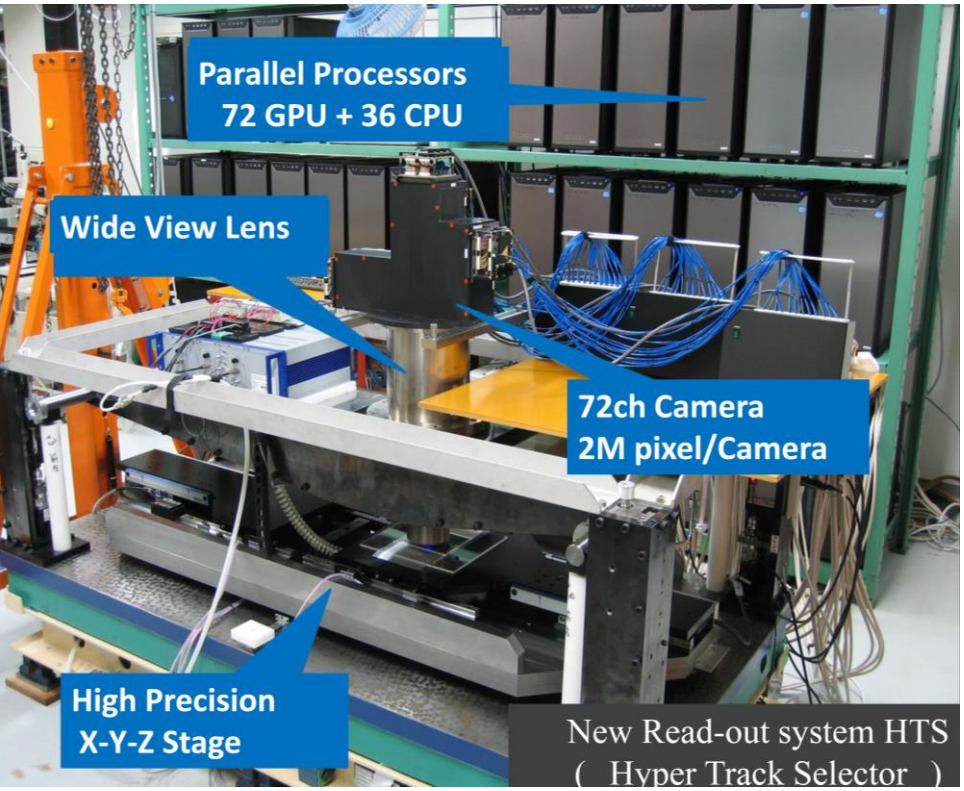
Image©JAXA

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

Emulsion track read-out

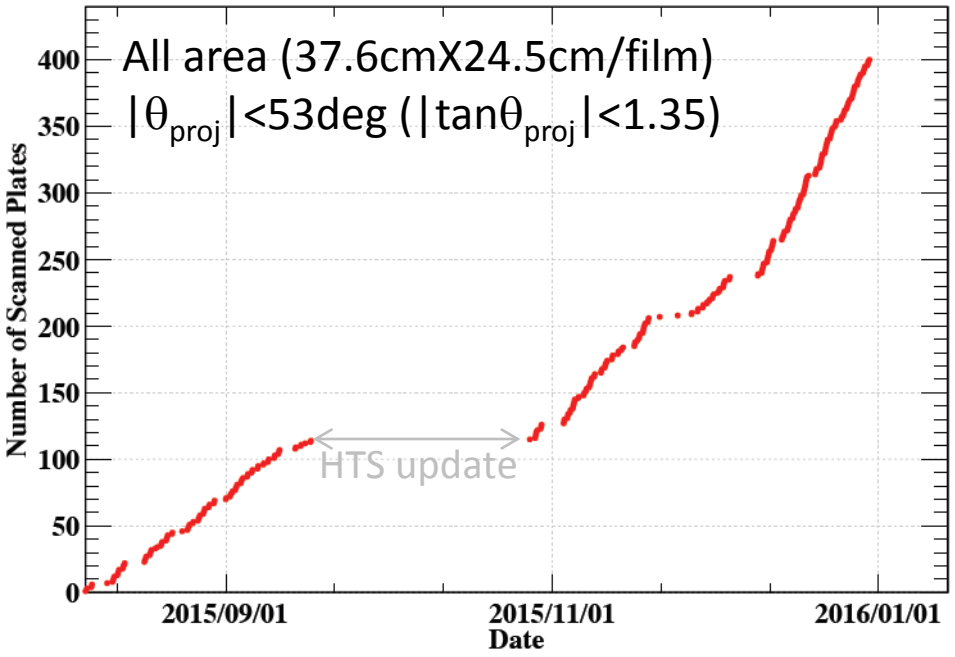
After film development, surface treatment, thickness tuning, scanning parameter tuning

Emulsion read-out system
Hyper Track Selector @ Nagoya U



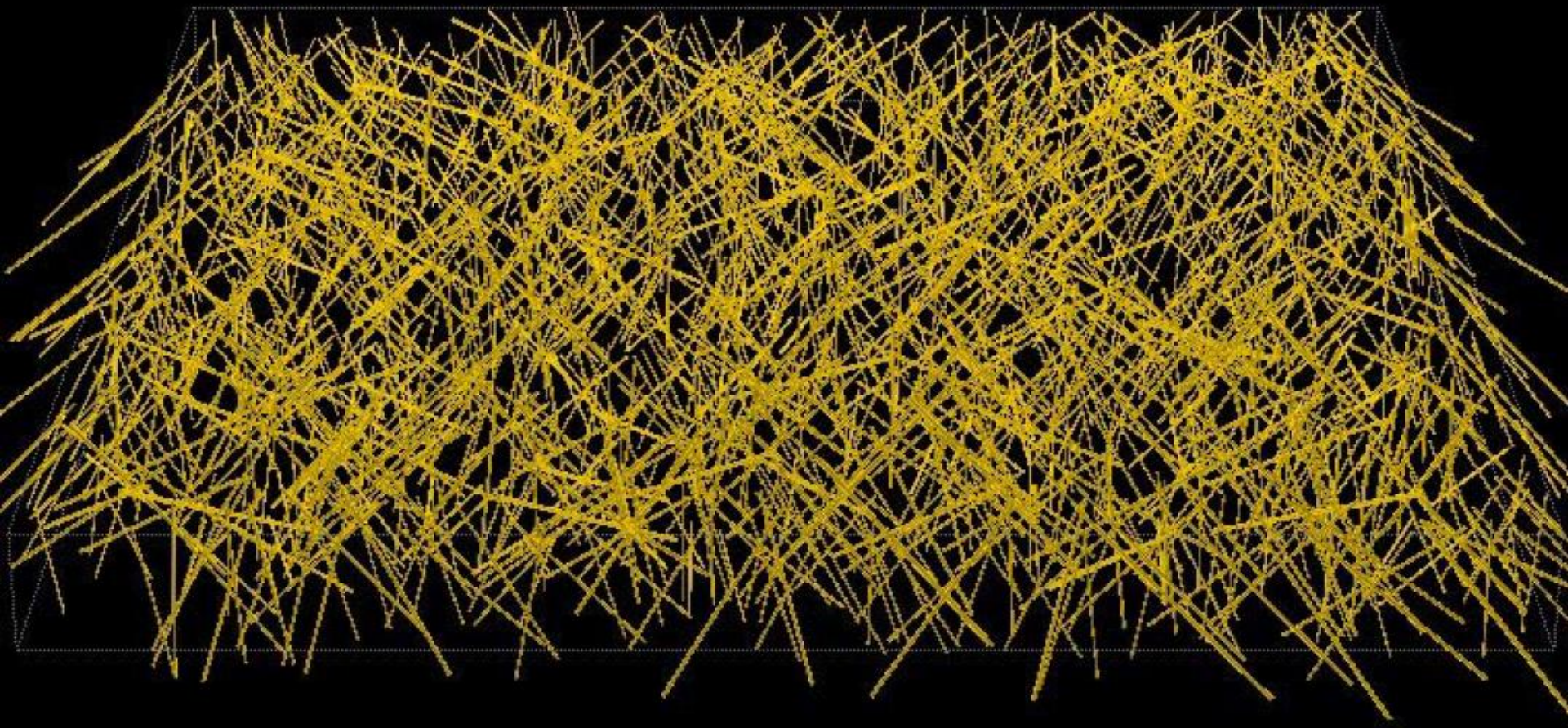
First practical scanning

Scanning progress



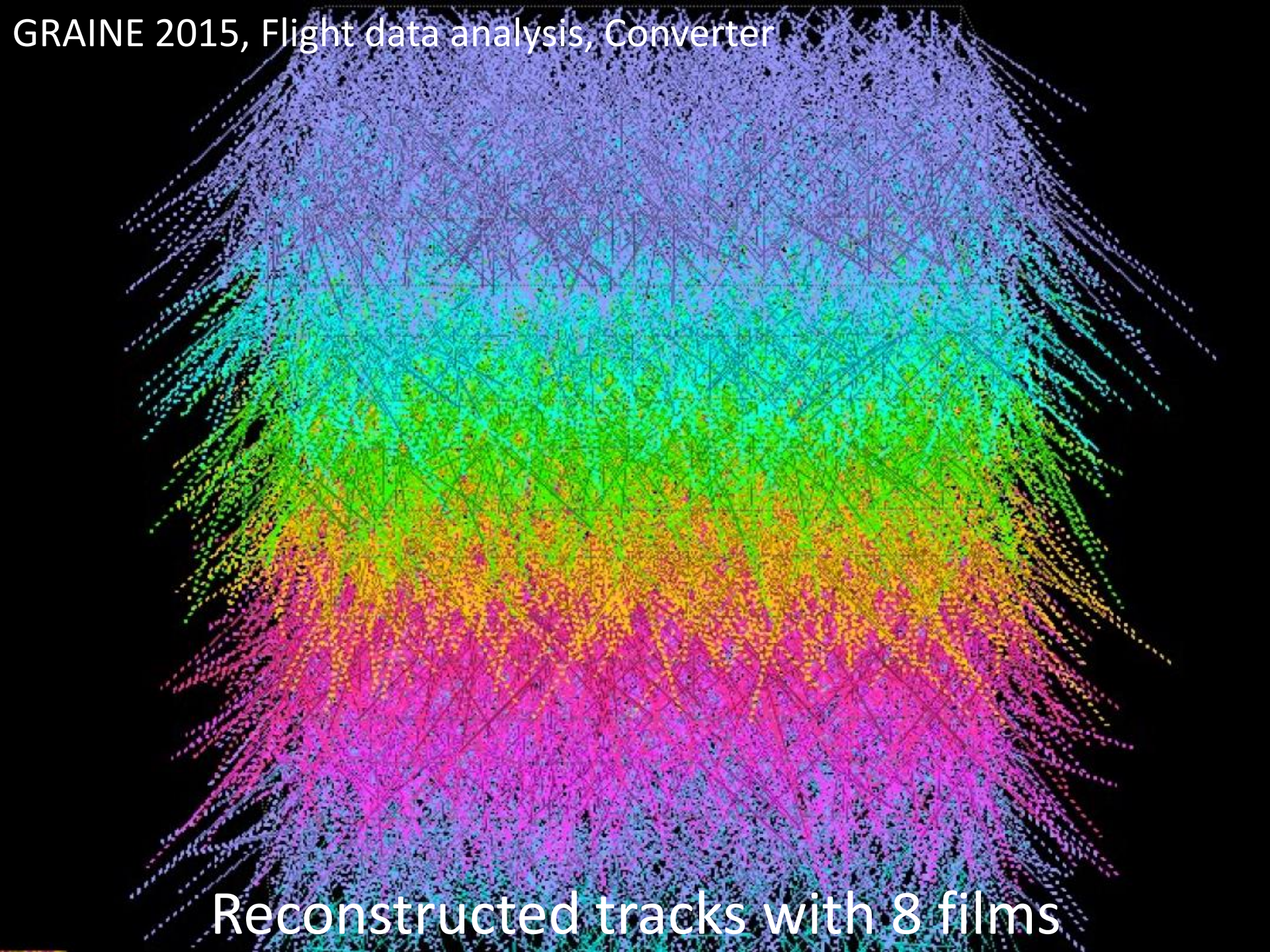
Completed for all films
(432films, 41m^2(film area basis))
-Converter 100 films x 4units
-Timestamper 8 films x 4units

GRAINE 2015, Flight data analysis, Converter



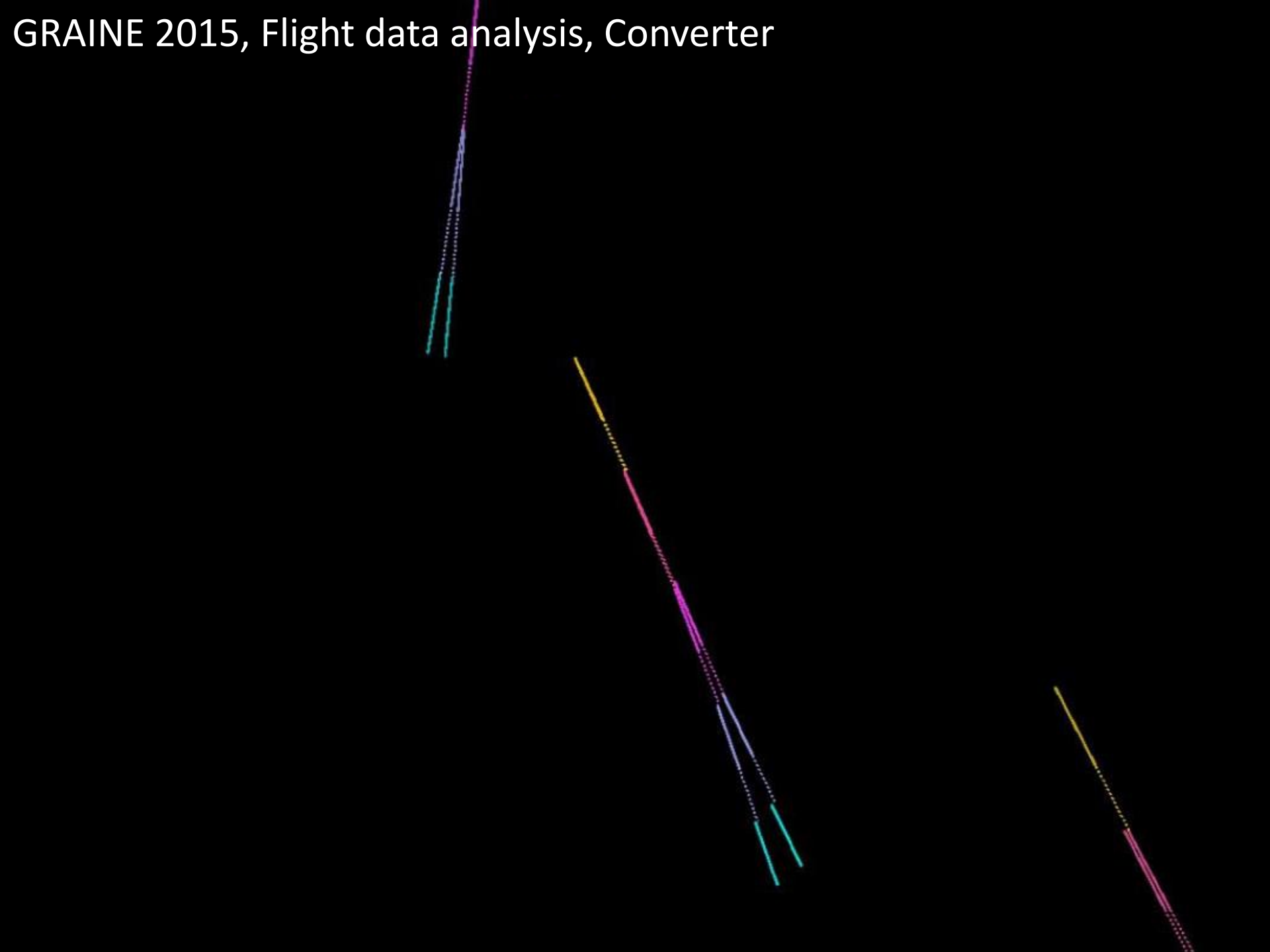
2 mm x 2 mm of single film
density ~400 tracks/mm^2

GRAINE 2015, Flight data analysis, Converter



Reconstructed tracks with 8 films

GRAINE 2015, Flight data analysis, Converter



GRAINE 2015, Flight data analysis, Converter

GRAINE 2015, Flight data analysis, Converter

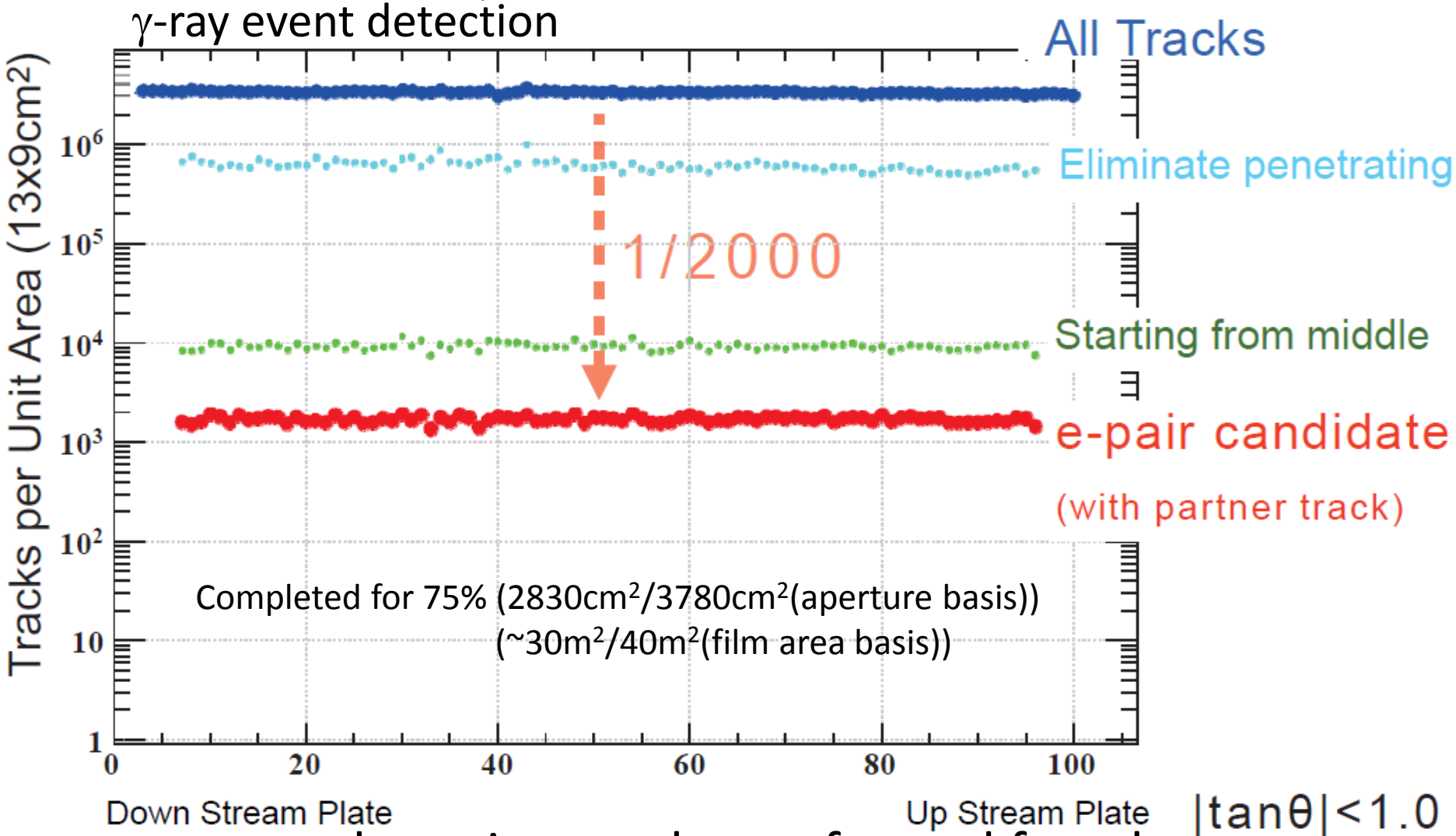
Achieved improvements

-Emulsion film S/N ratio X~20, data size ~1/20

-Track finding inefficiency in a single film ~1/10

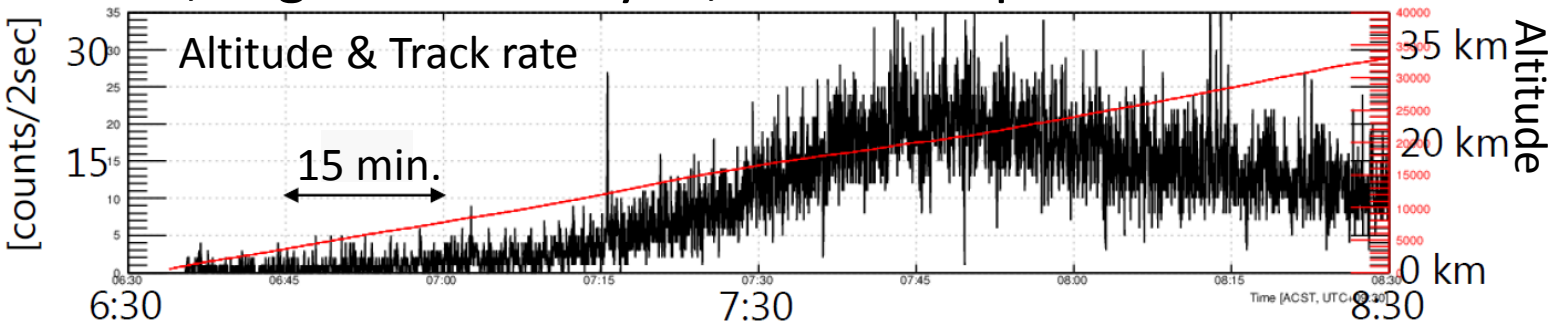
-Data reduction load for γ-ray event detection ~1/200

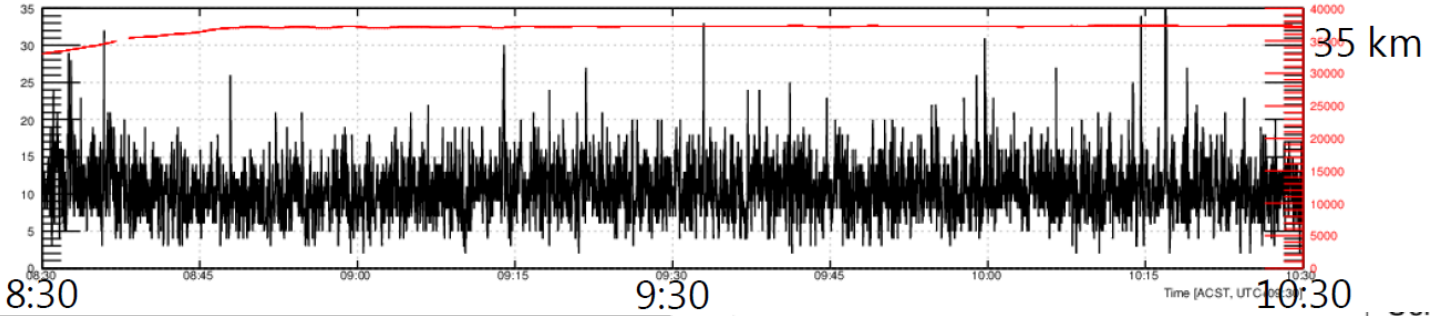
γ-ray event detection

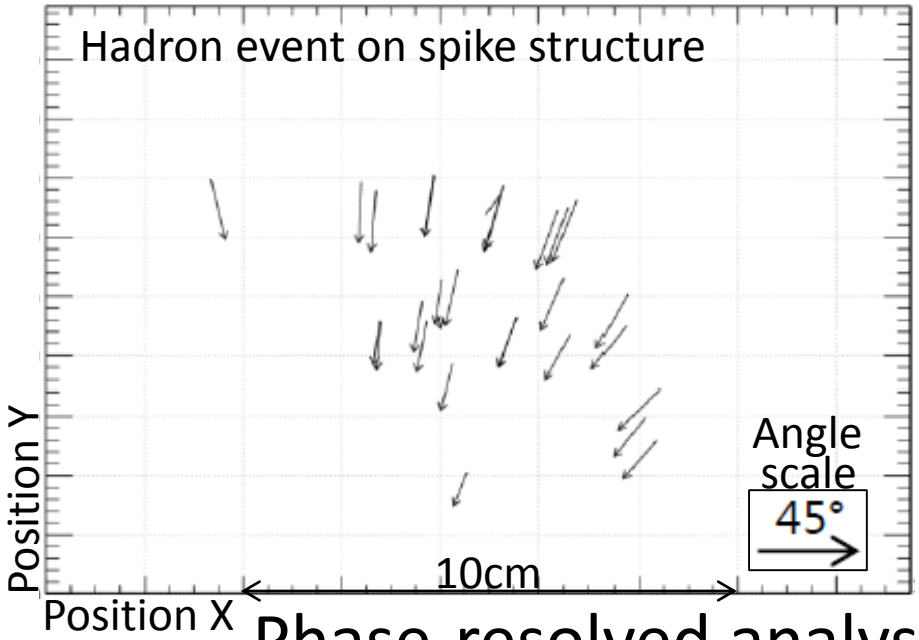


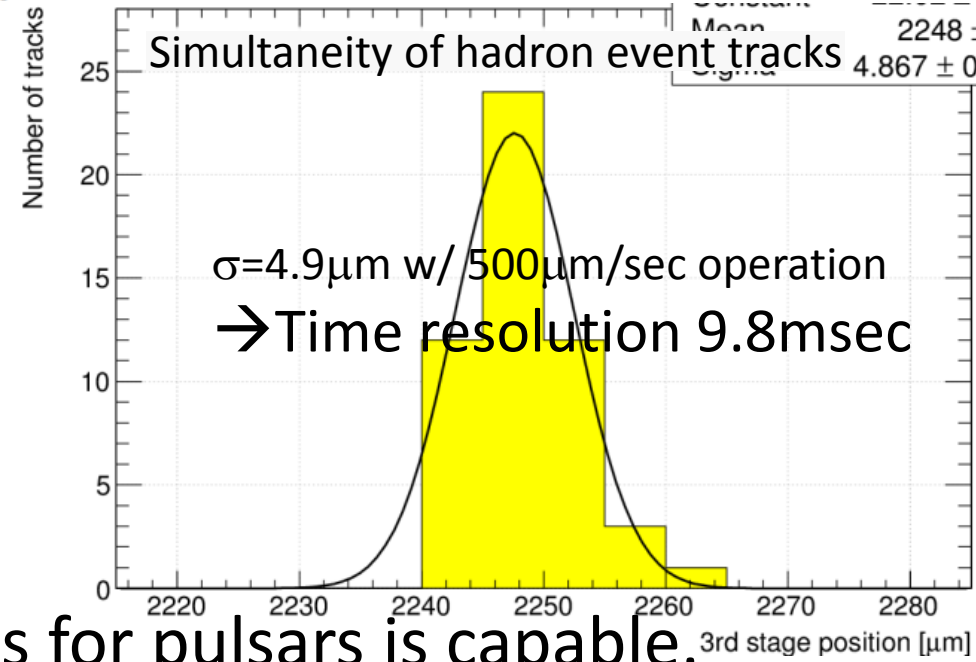
γ-ray event detection can be performed for a large area.

GRAINE 2015, Flight data analysis, Timestamper







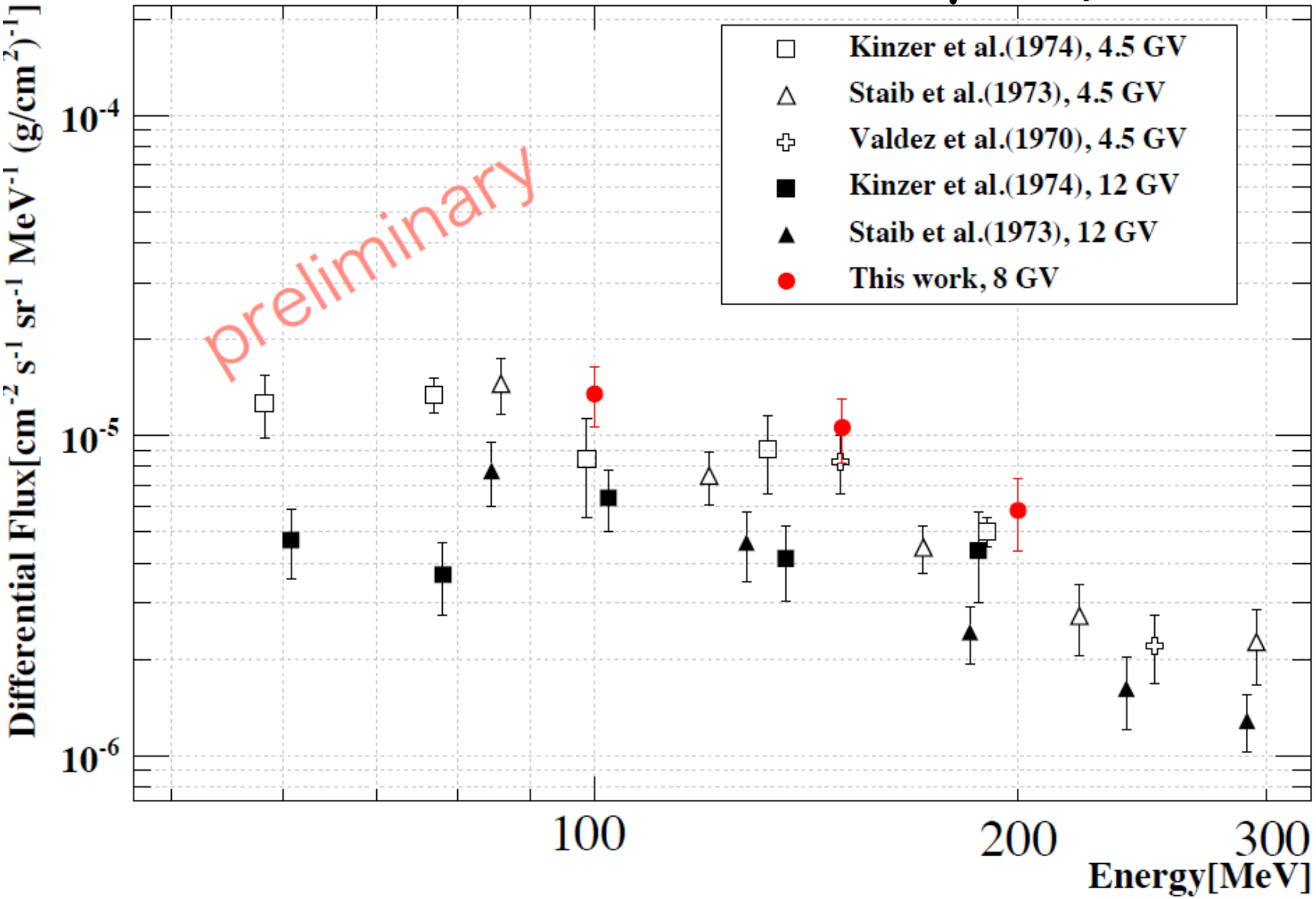


Phase-resolved analysis for pulsars is capable.

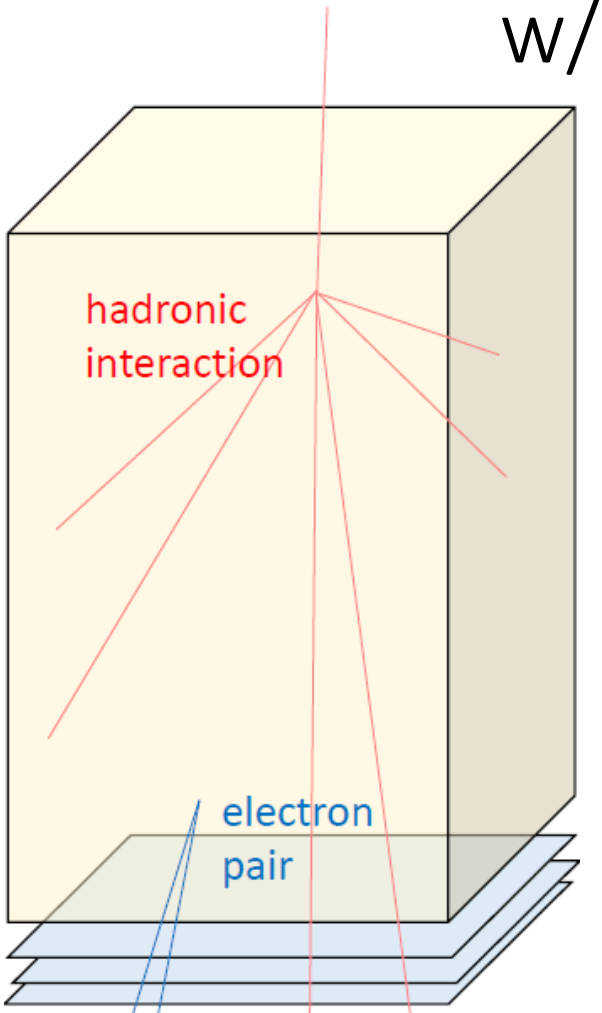
e.g. 89msec period of Vela pulsar

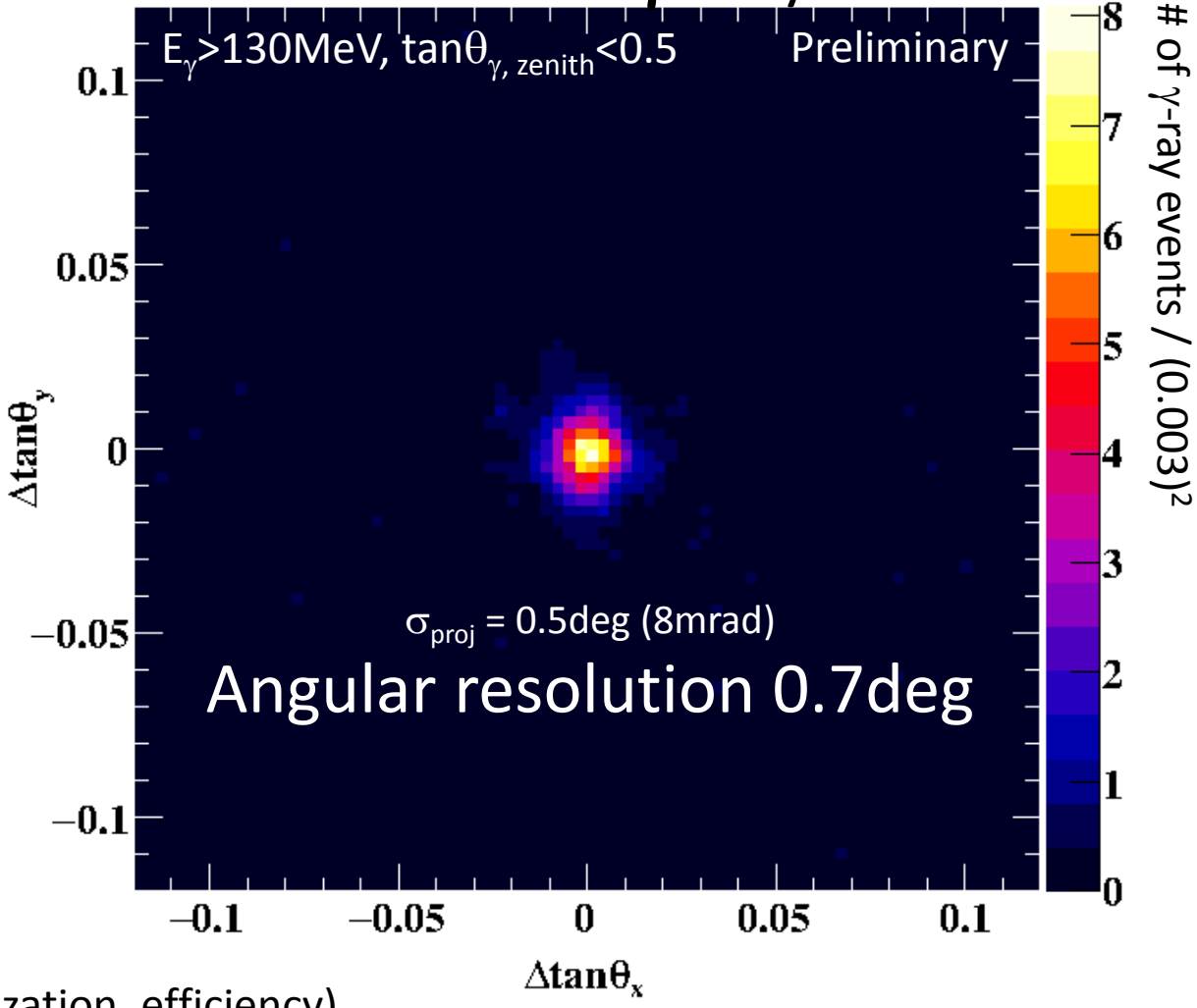
GRAINE 2015, Flight data analysis, Converter+Timestamper

Measurement of atm. γ-ray flux



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



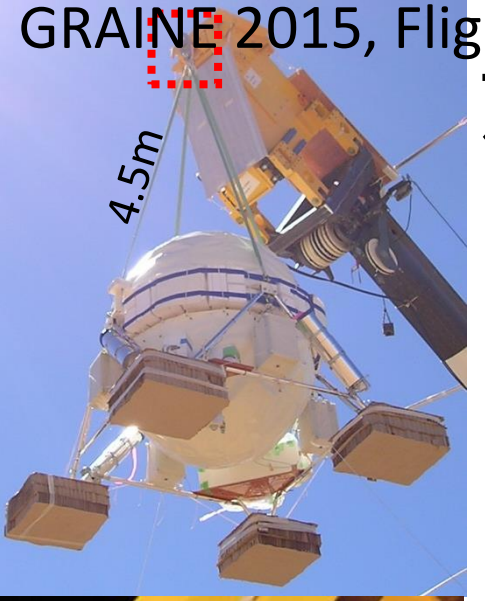


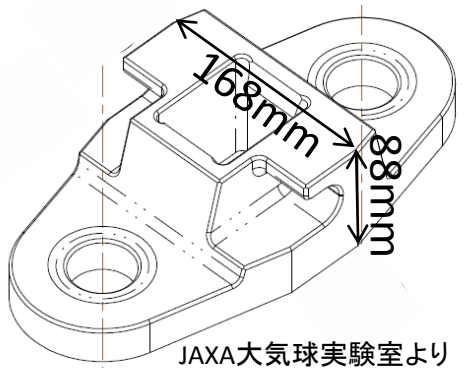
Calibration sorce
(direction, timing, energy, polarization, efficiency)

High γ-ray imaging performance is being obtained.

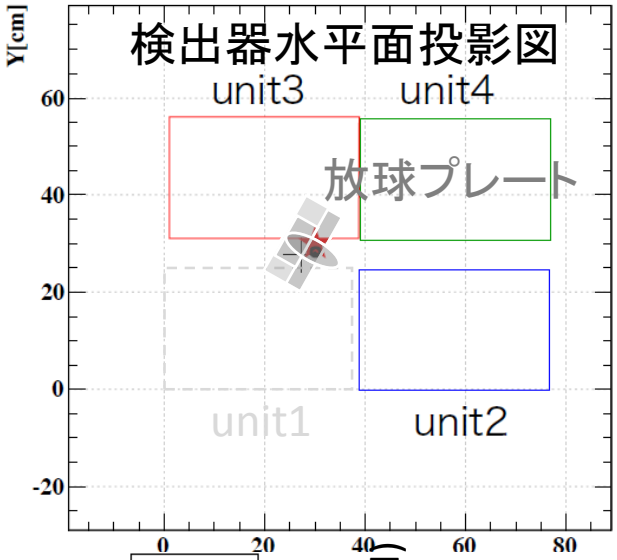
放球プレート撮像 w/ γ-ray

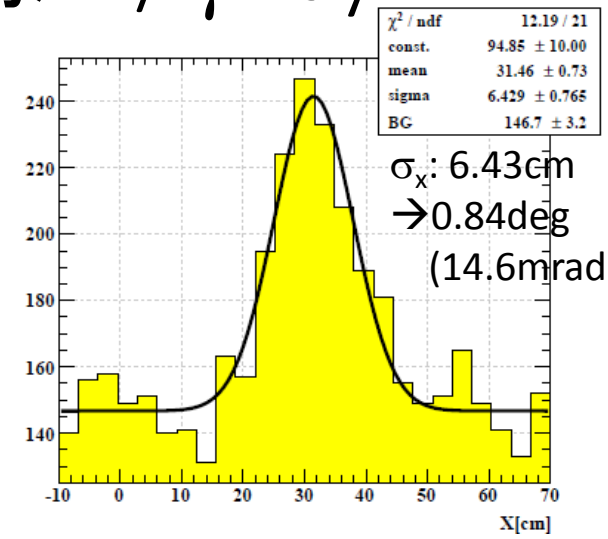
検出器外部光源

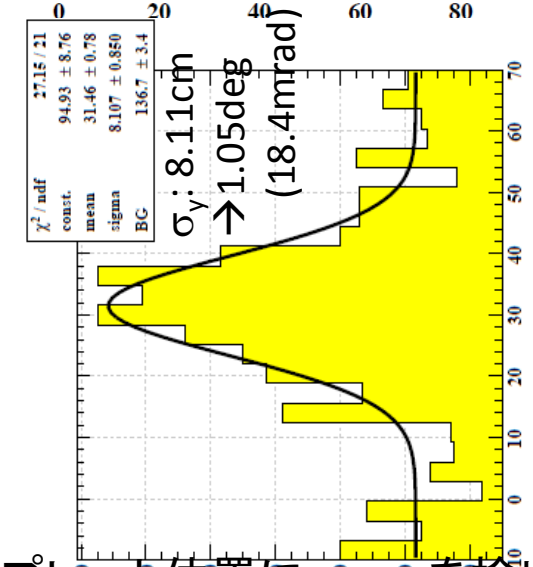


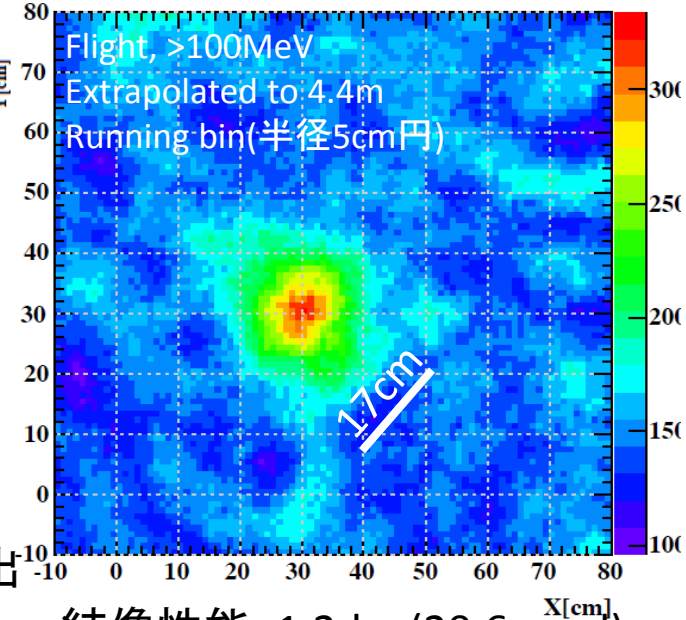


JAXA大気球実験室より









・放球プレート位置にexcessを検出
(ずれ1.7cm→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

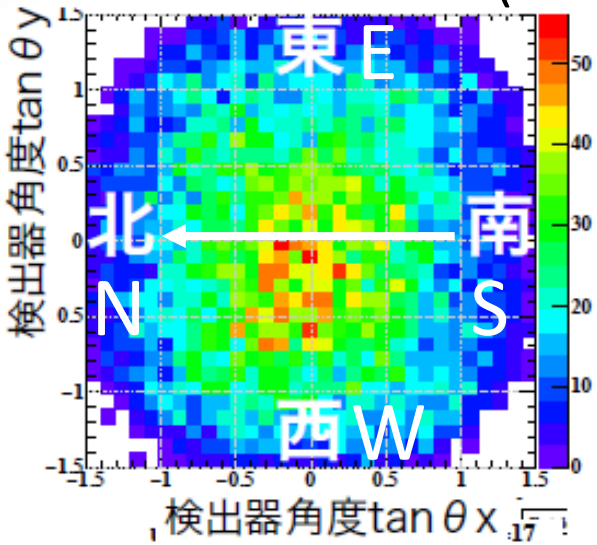
・結像性能<1.2deg(20.6mrad)
(cf. 角度分解能1.0deg@100MeV)

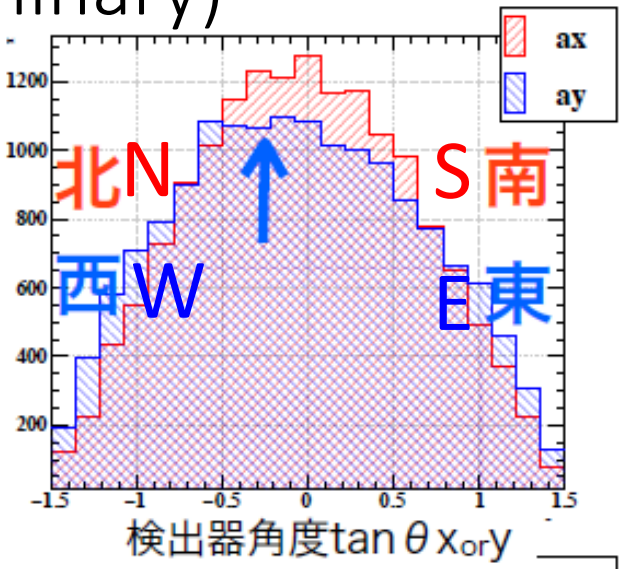
・ユニットごとの結像重心のばらつき<0.06deg(1mrad)

GRAINE 2015, Flight data analysis, Converter+Timestamper+Attitude

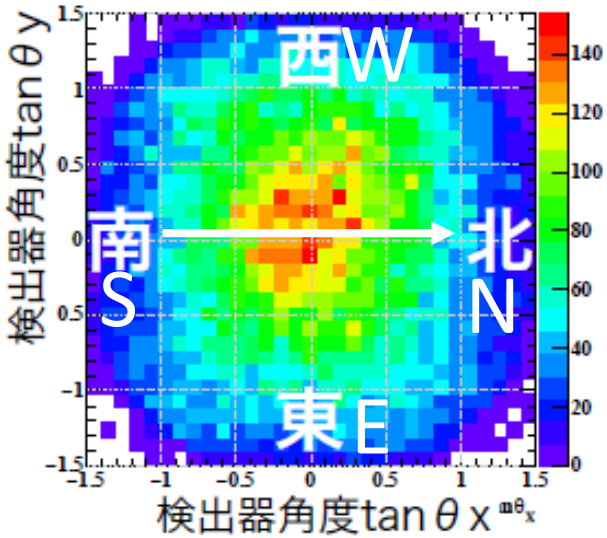
East-west effect (Preliminary)

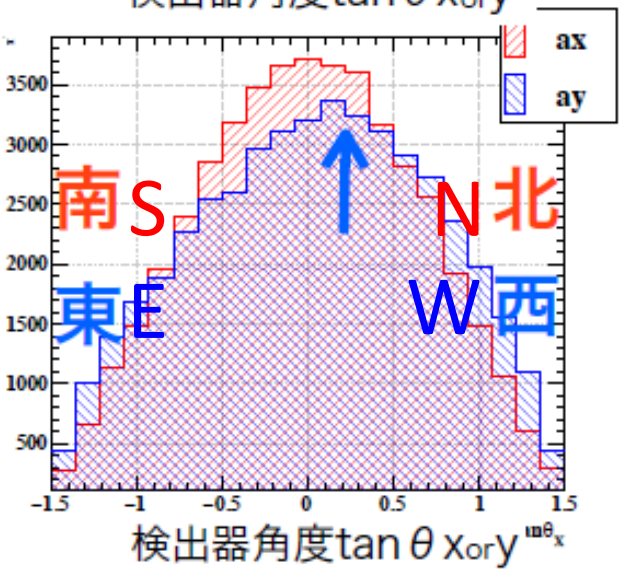
検出器軸が
北向きの時





検出器軸が
南向きの時





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^2 aperture (x30, new-type emulsion films, total 48m^2)
- 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^2 w/ HTS
- Emulsion film S/N ratio x~20, data size ~1/20
- Track finding inefficiency in a single film ~1/10
- Data reduction load for γ-ray event detection ~1/200
- Data processing of all effective area, 2830cm^2 aperture (total 30m^2)
- γ-ray angular resolution, 0.7deg >130MeV
- Time resolution, 9.8 msec (1/10)
- Star camera sensitivity, magnitude of 6.1 → 7.5

- Limited γ-ray yield from Vela pulsar

GRAINE Scientific observation roadmap

2018, Demonstration

Alice Springs
~0.4m^2 aperture
~18hours flight duration
<~5g/cm^2 altitude

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

2021–, Scientific flight

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

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

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

→ Studying transient sources & w/ ones

Observation of transient sources

- Large collection area, $10m^2$
  [Effective area@100MeV, $2.1m^2$ (3.6 x Fermi LAT, cf. $0.58m^2$ (P8R2_TRANSIENT020_V6))]
- Wide field of view, >2.2sr (17.5% of all sky)
- High angular resolution, 1.0deg(17mrad)@100MeV
- Polarization sensitive
- Dead time free

→High sensitivity incl. "**Unexplored region**"

→High photon statistics

-Energy spectrum

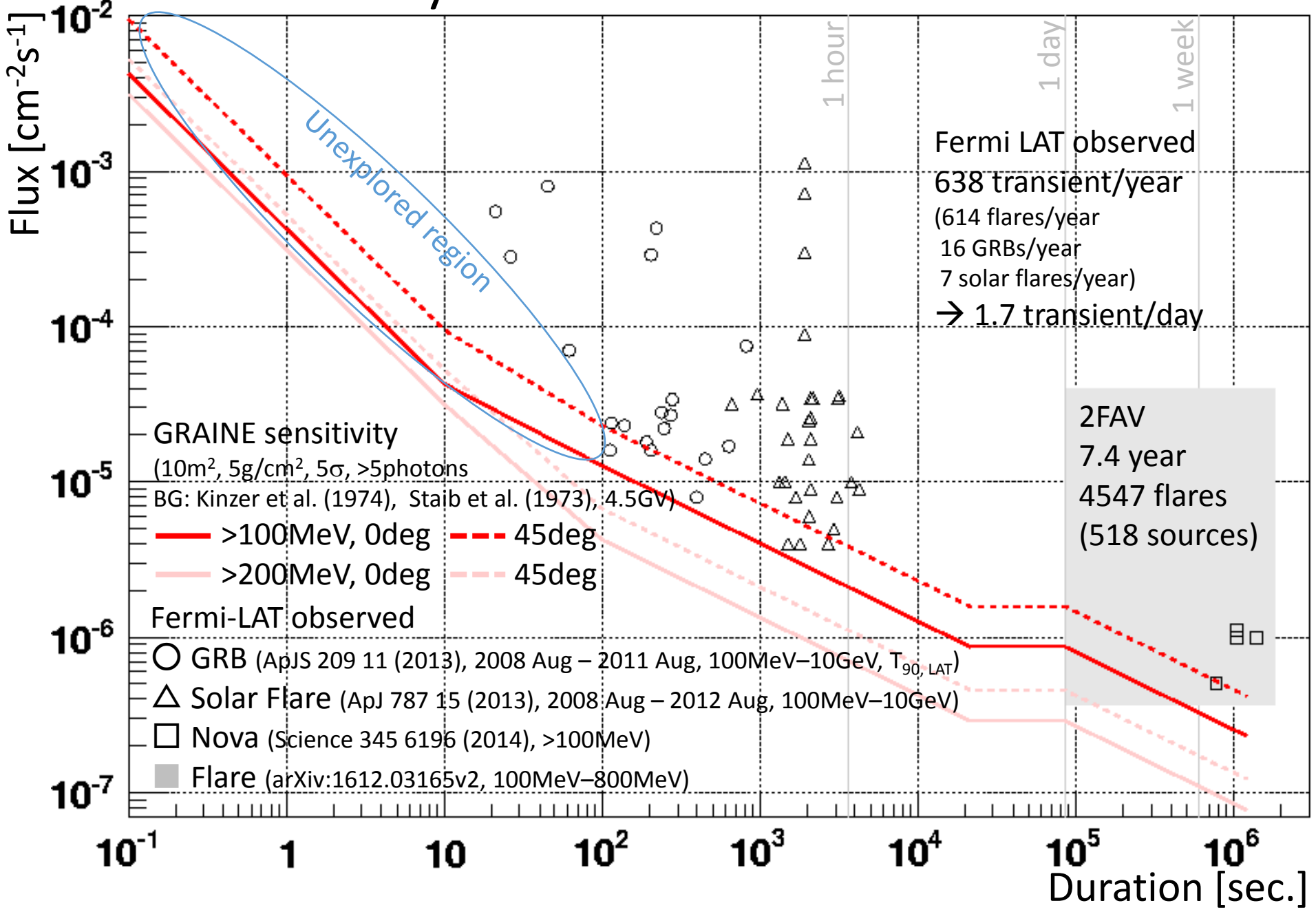
-Light curve

-Polarization observation

→Good localization ~0.1deg @100photons

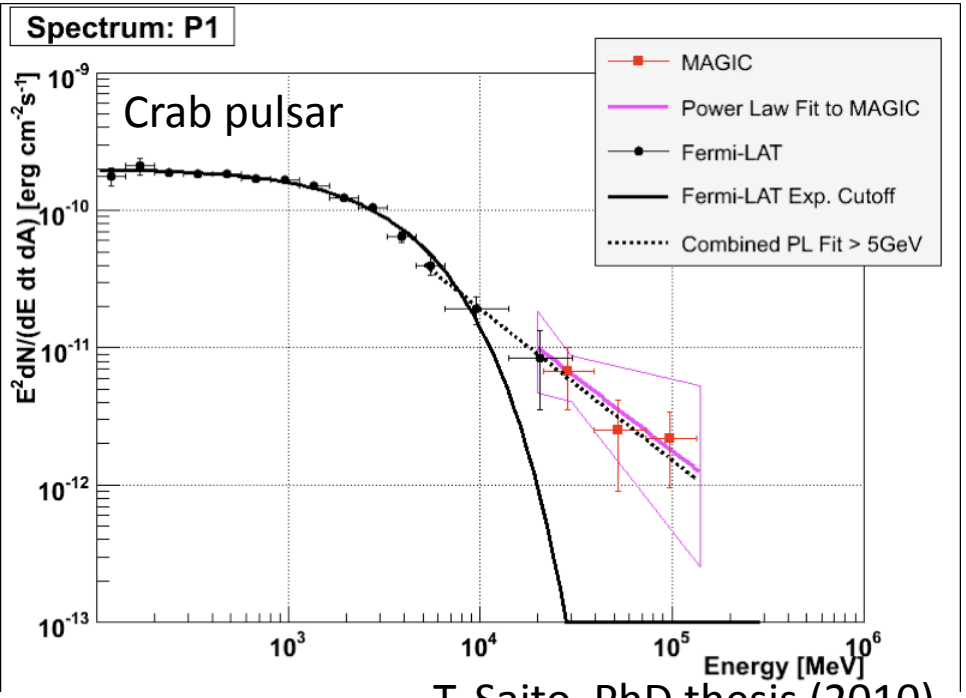
- Not continuous survey
- Not real time

Sensitivity to transient sources



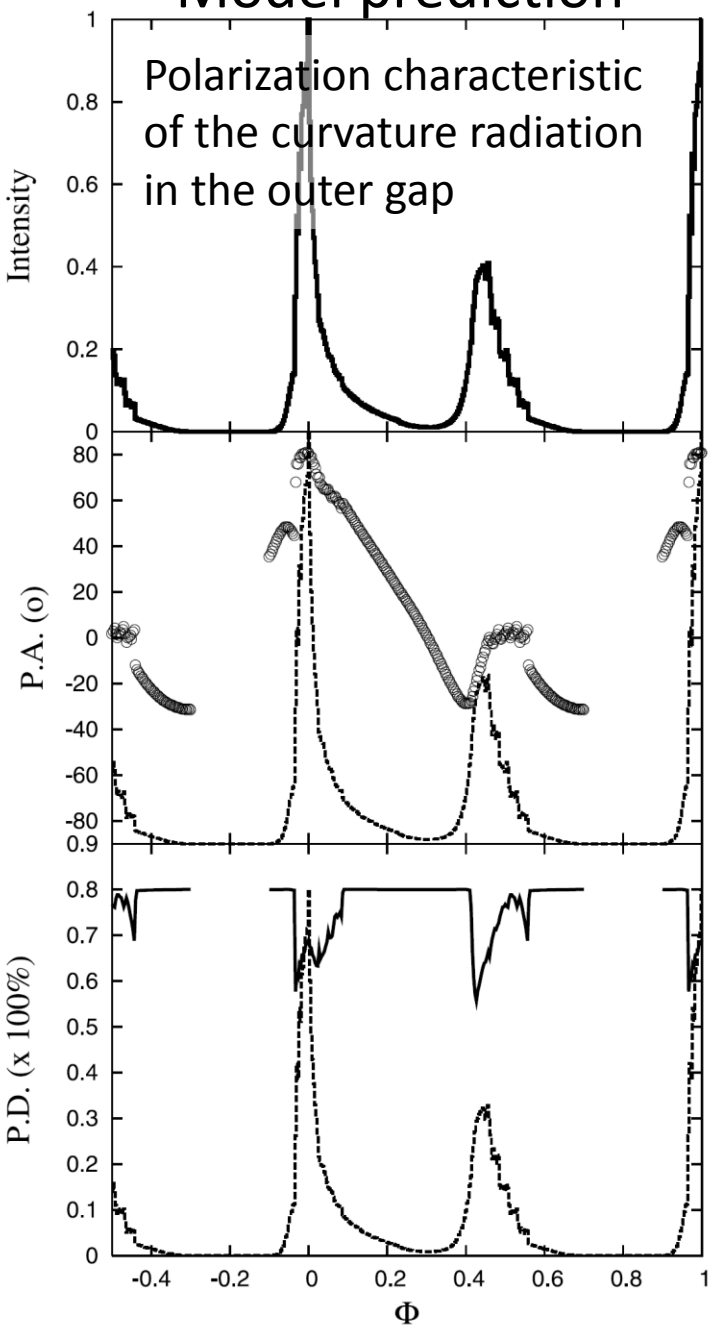
Pioneering polarization observation for high energy γ-rays
Approaching emission mechanism

Pulsars, AGNs, Flares, GRBs



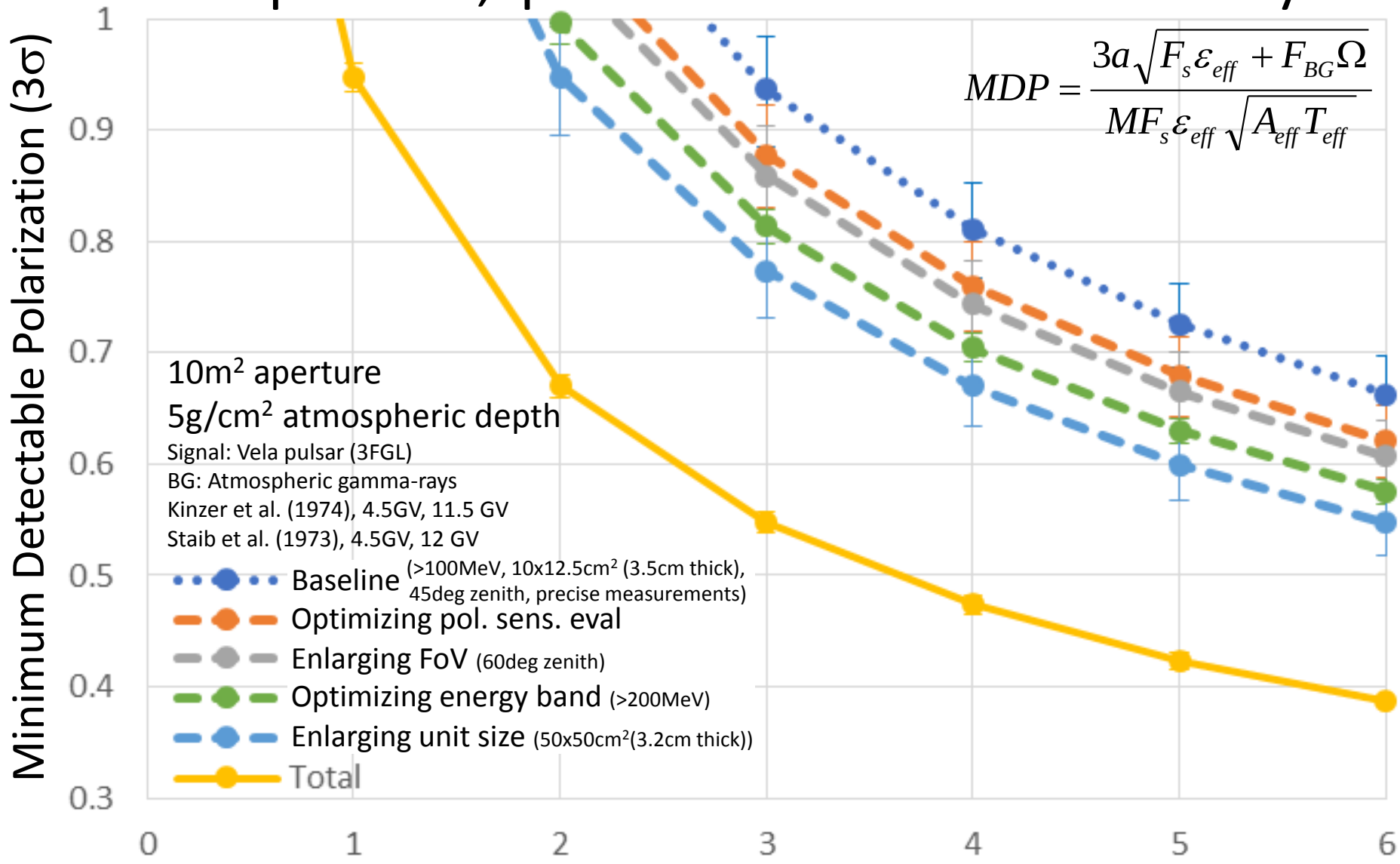
T. Saito, PhD thesis (2010)

Model prediction



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

Vela pulsar, polarization sensitivity



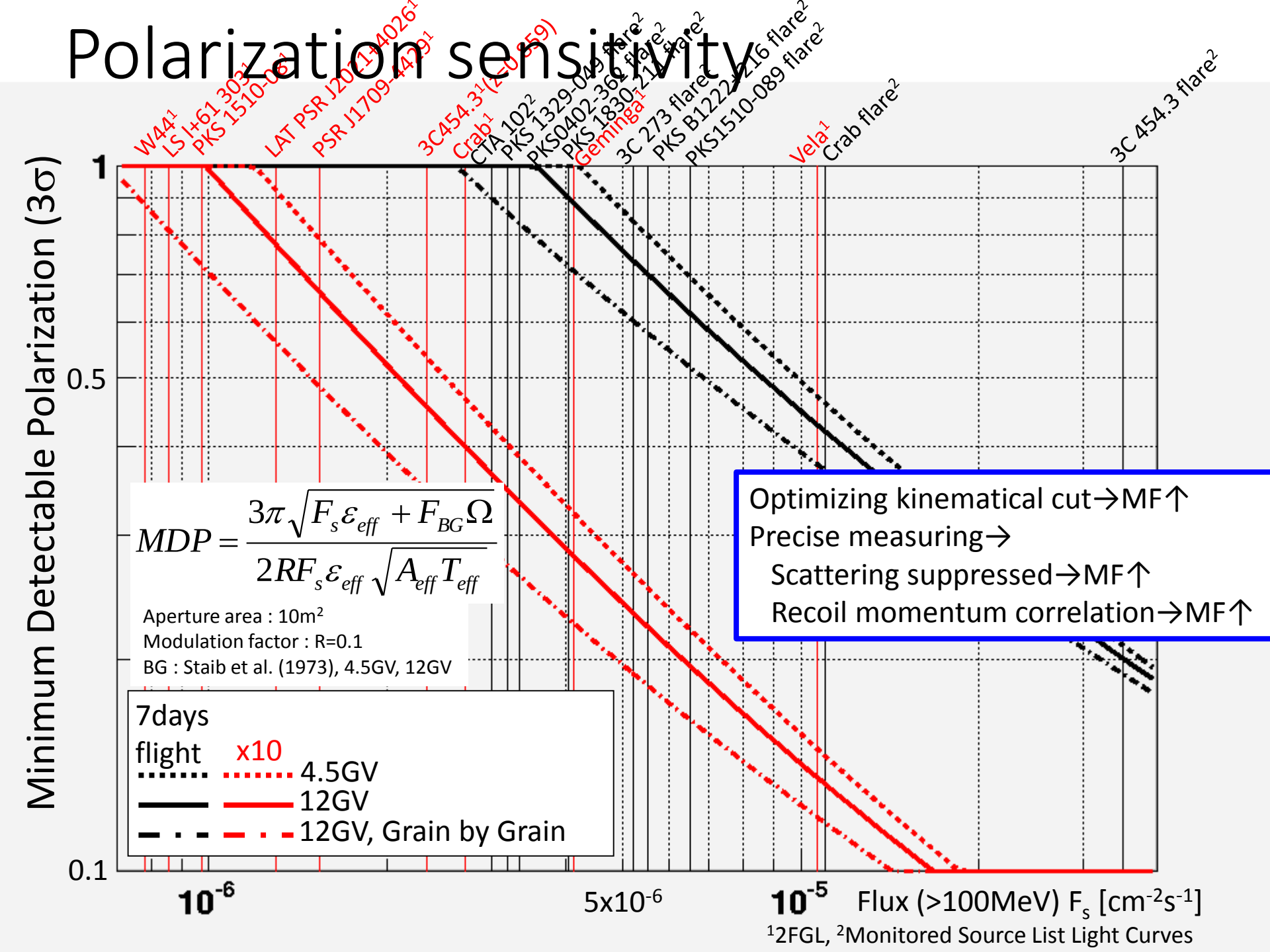
Alice Springs

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)

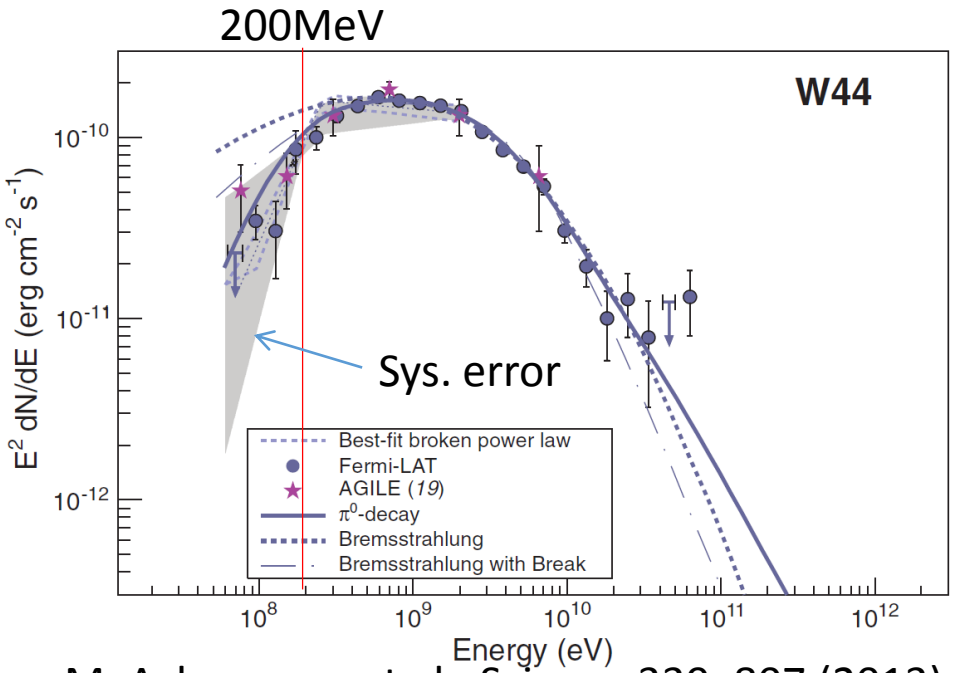
Polarization sensitivity



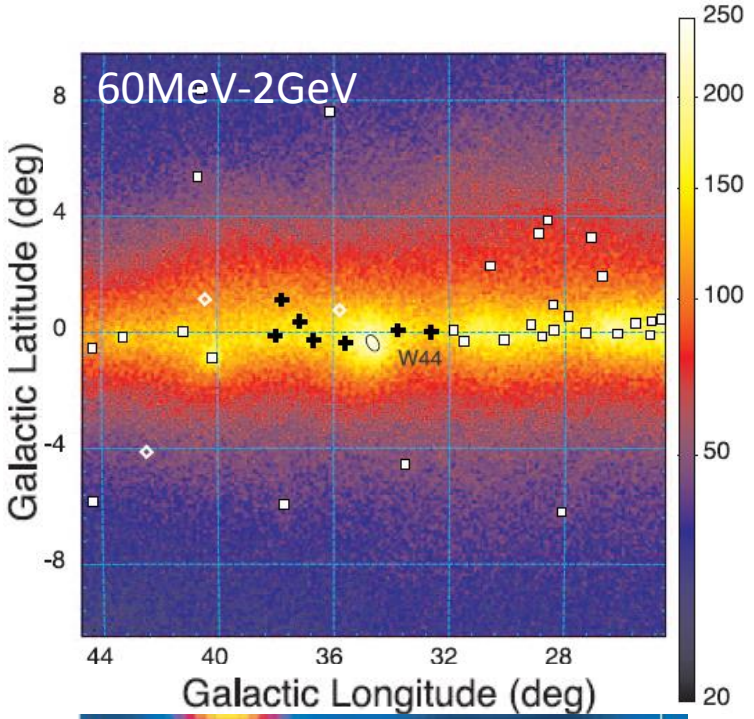
[1]2FGL, [2]Monitored Source List Light Curves

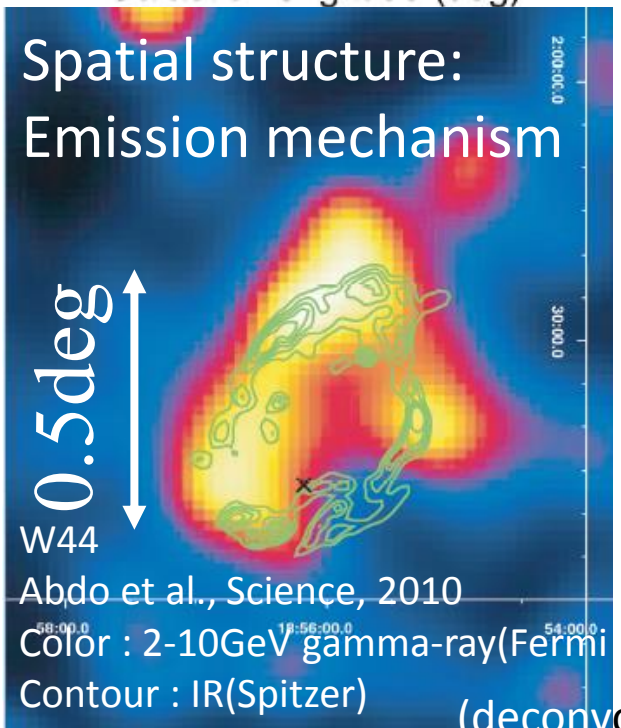
π^0 emission: Direct evidence of proton acceleration

SNRs



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

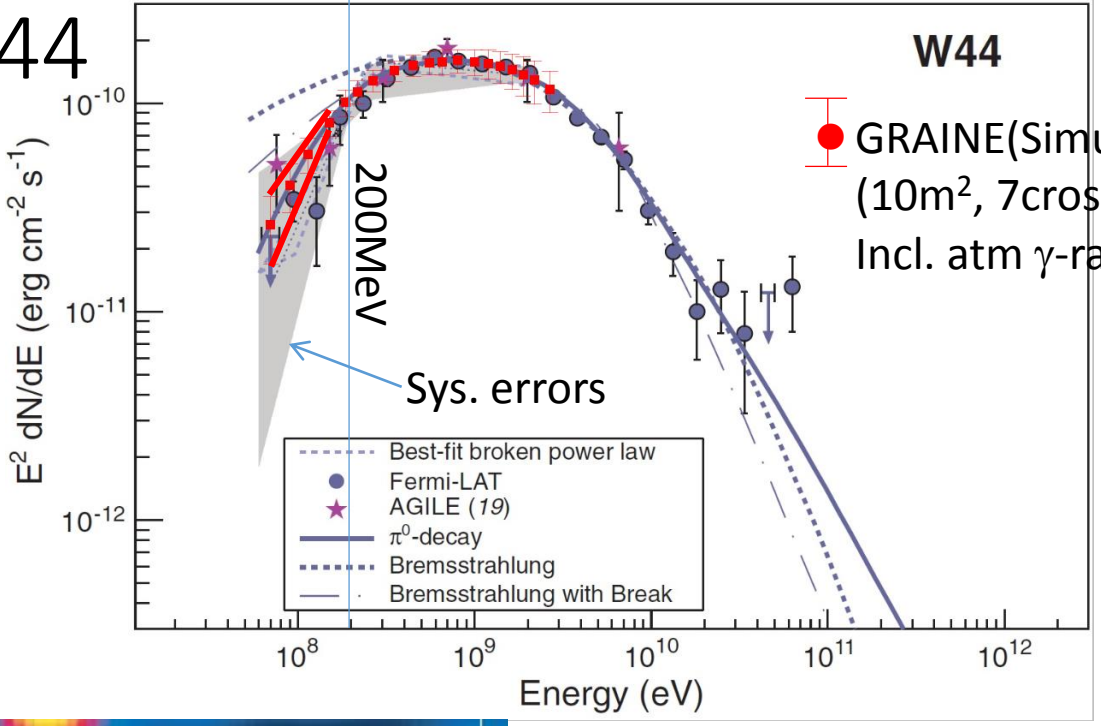




<200MeV, precise spectrum measurements with suppressed systematic errors

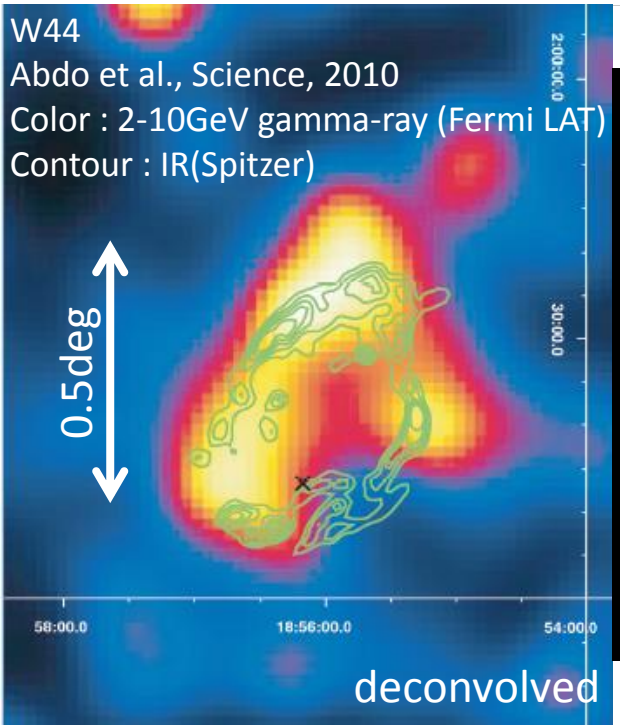
>200MeV, investigating spatial structure

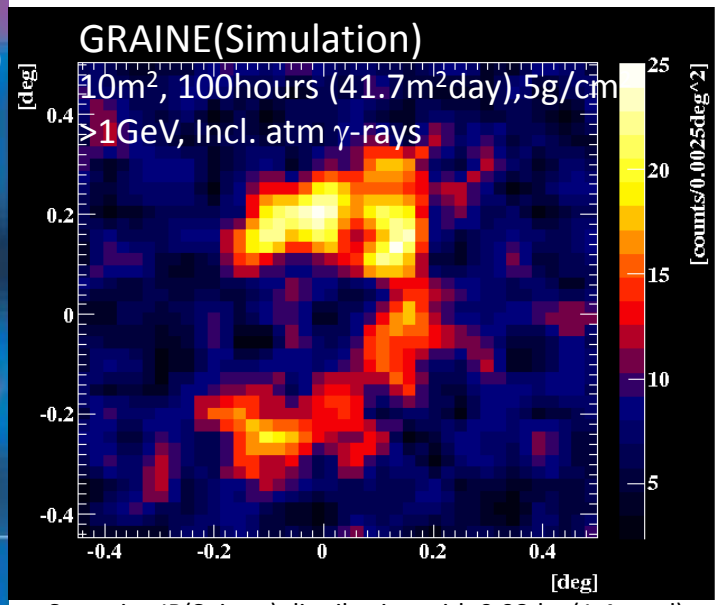
W44



GRAINE(Simulation)
(10m², 7crossX10, 5g/cm²,
Incl. atm γ-rays)

<200MeV
Precise spectral measuring
with suppressed systematic errors



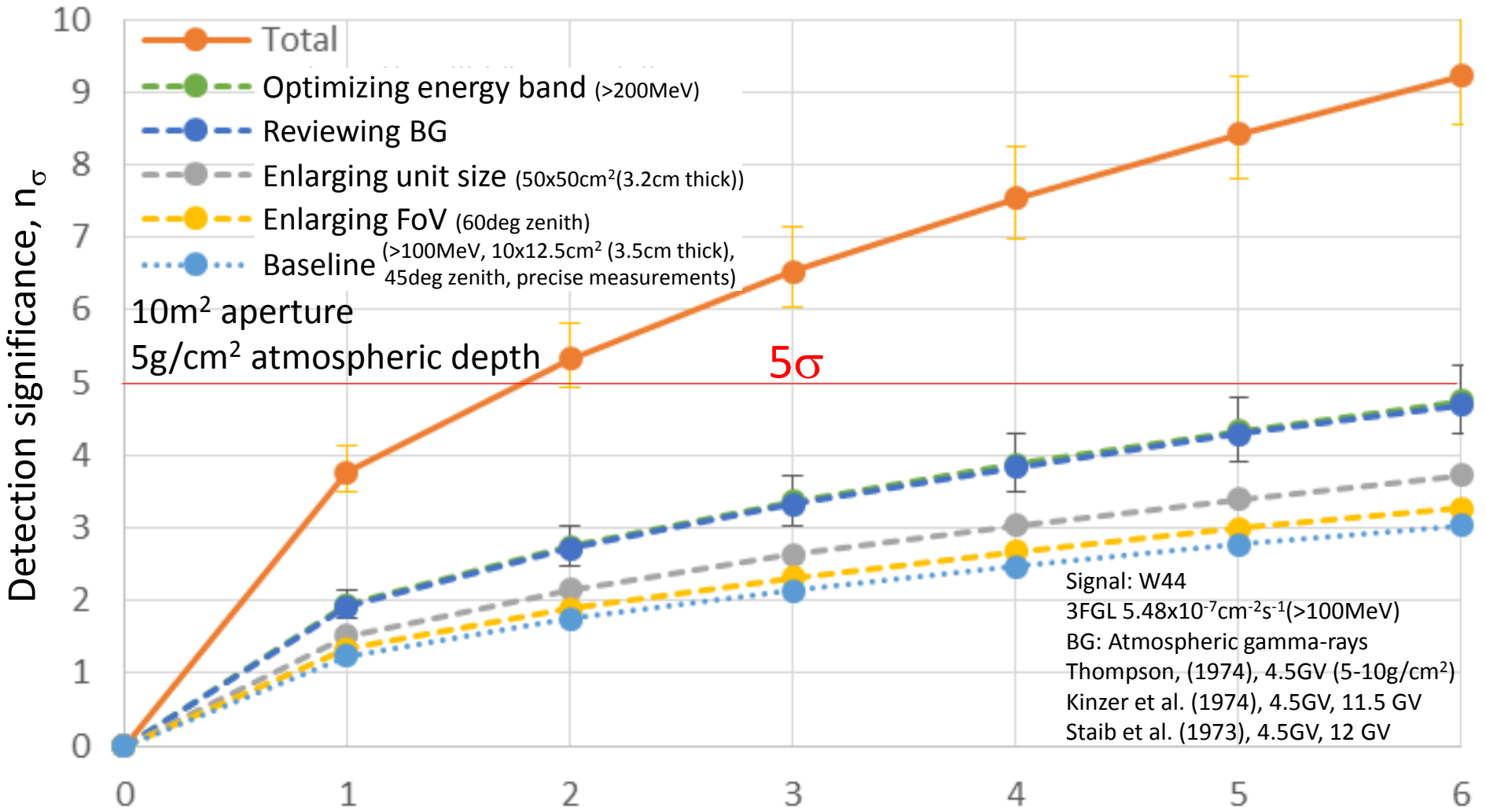


Smearing IR(Spitzer) distribution with 0.08deg(1.4mrad)
Considering atmospheric gamma-ray(>1GeV) as BG

>200MeV
Investigating spatial structure

W44 detection sensitivity

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



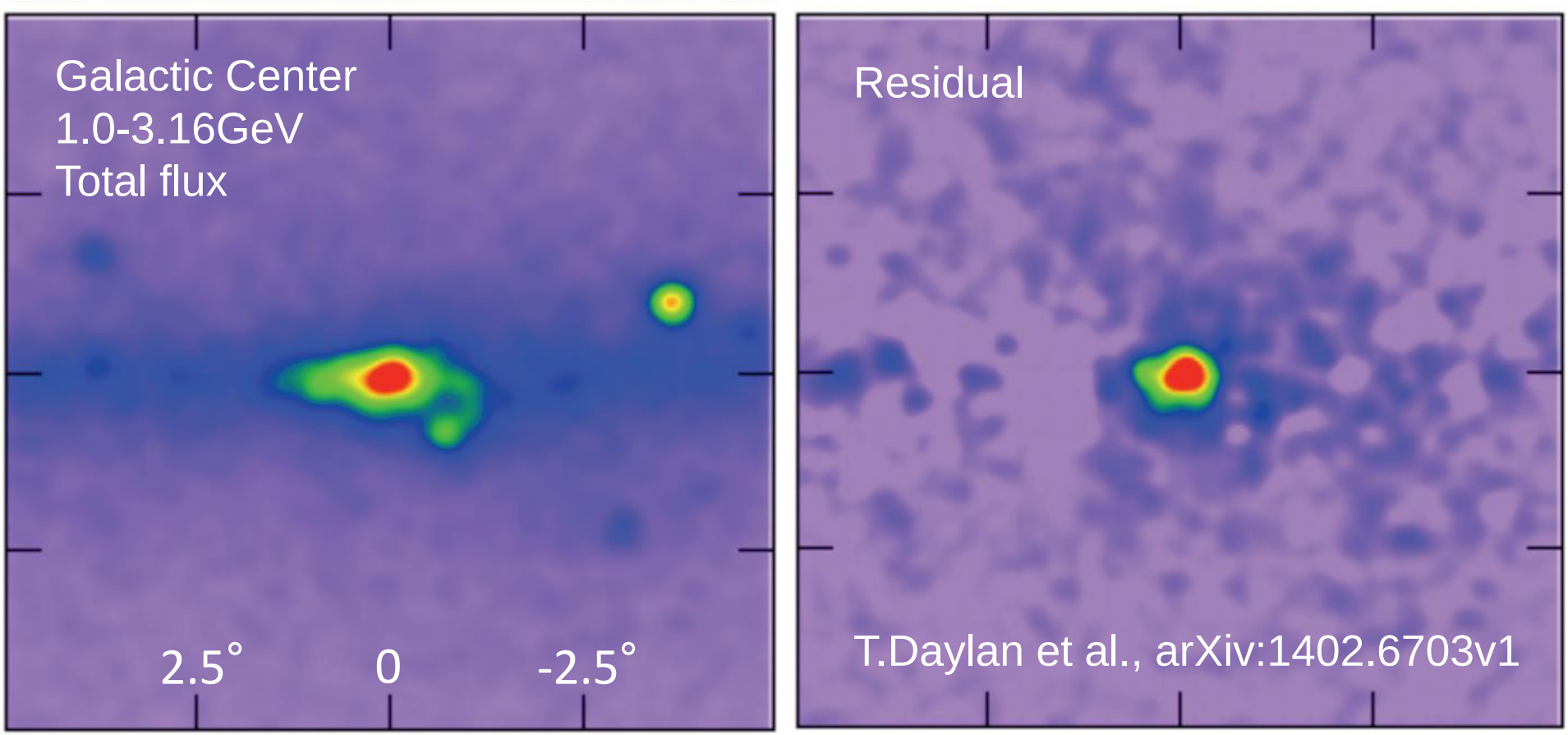
# of crosses of a source in a field of view of the telescope with diurnal rotation (roughly corresponding to flight days)

Alice Springs

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

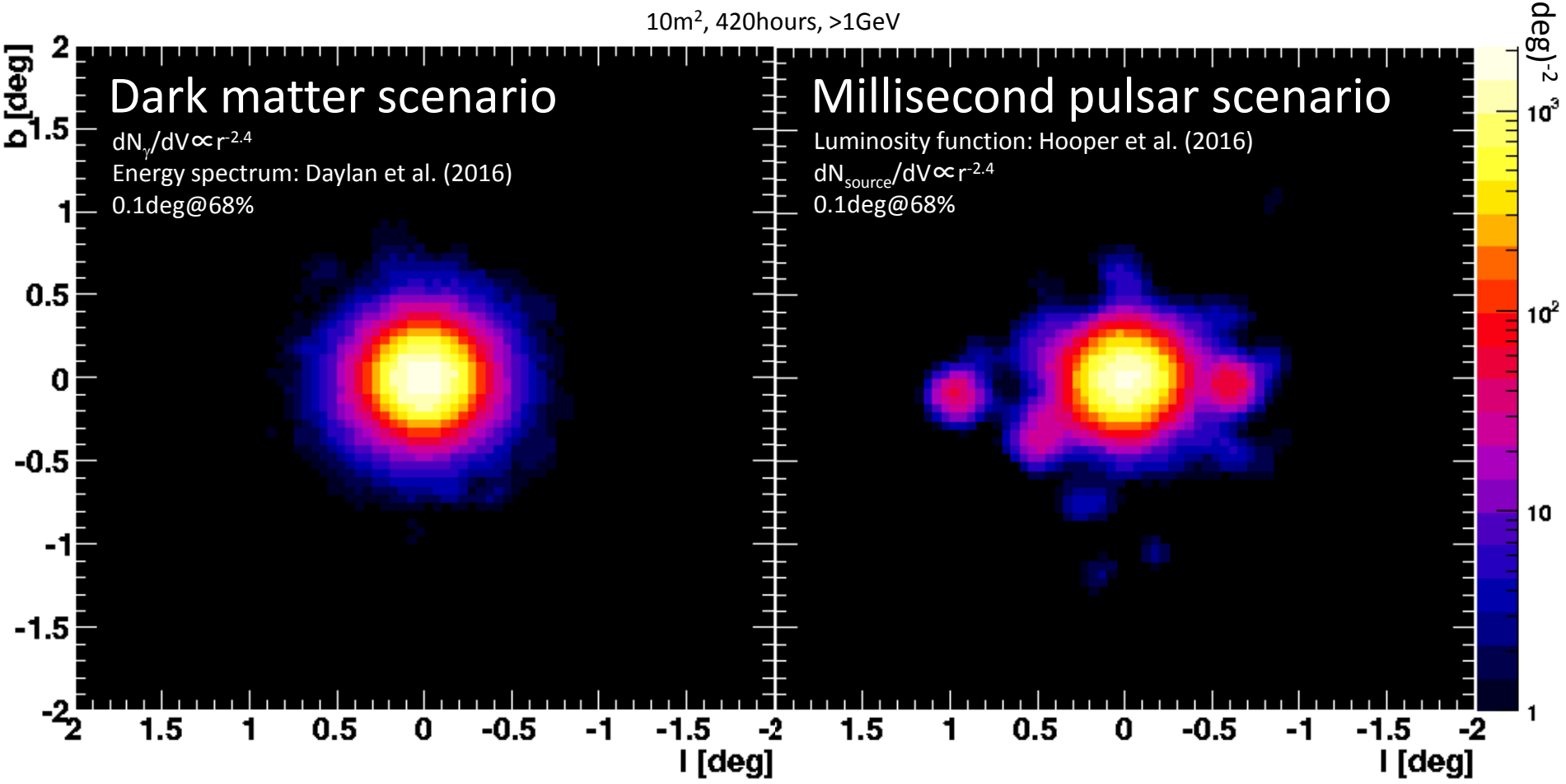
3:27–8:42 (5.25h/cross) w/in 45deg zenith, 2:19 – 9:49(7.5h/cross) w/in 60deg zenith

GeV γ-ray excess at galactic center region

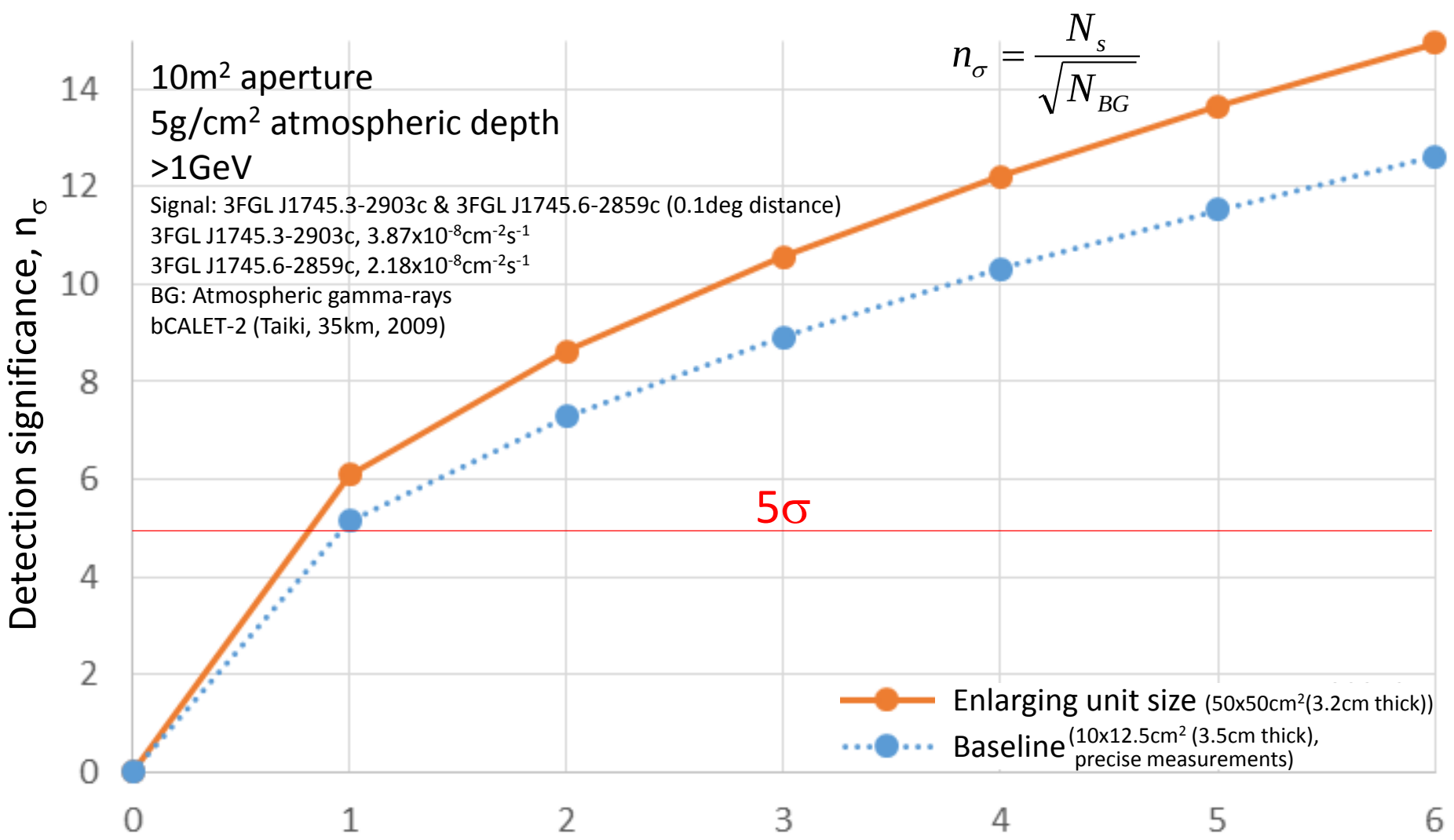


GeV γ-ray observations at galactic center region with ~arcmin resolution

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



Galactic center region, detection sensitivity



Alice Springs

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

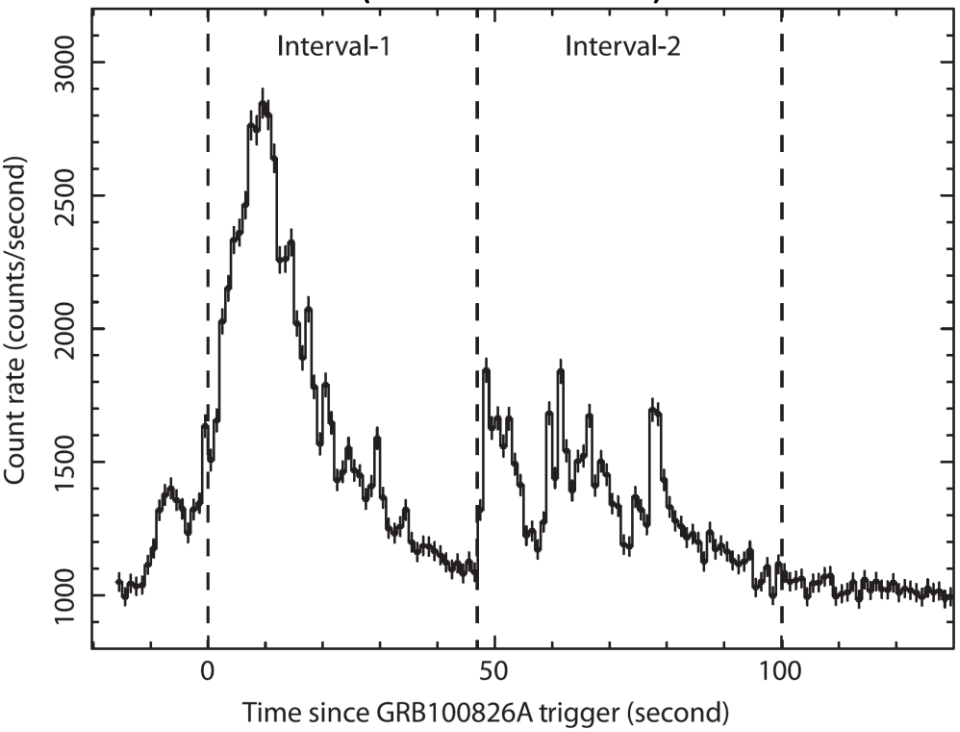
1:31–8:16 (6.75h/cross) w/in 45deg zenith

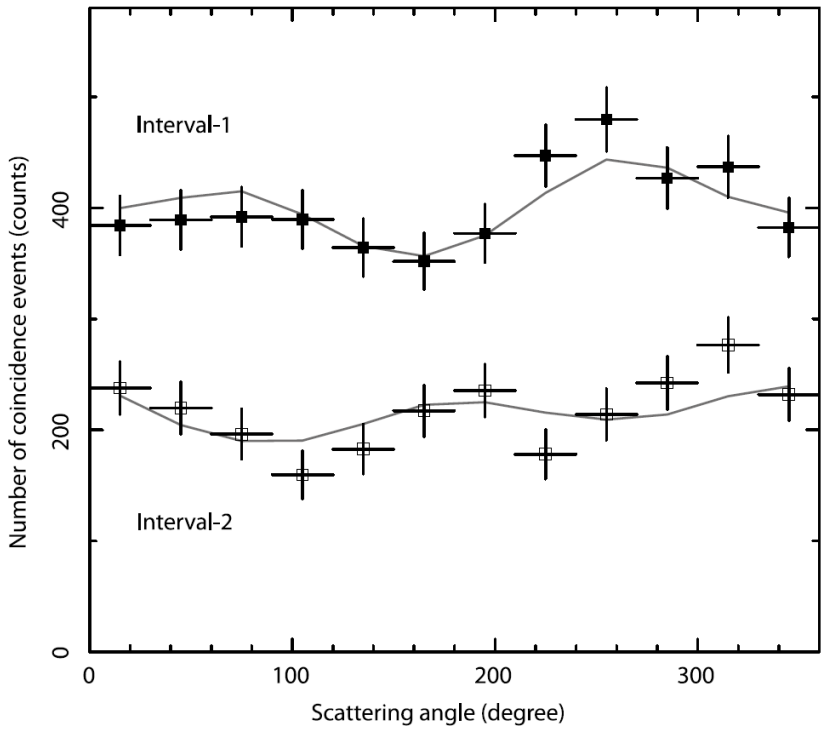
of a source in a field of view of the telescope with diurnal rotation (roughly corresponding to flight days)

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.

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