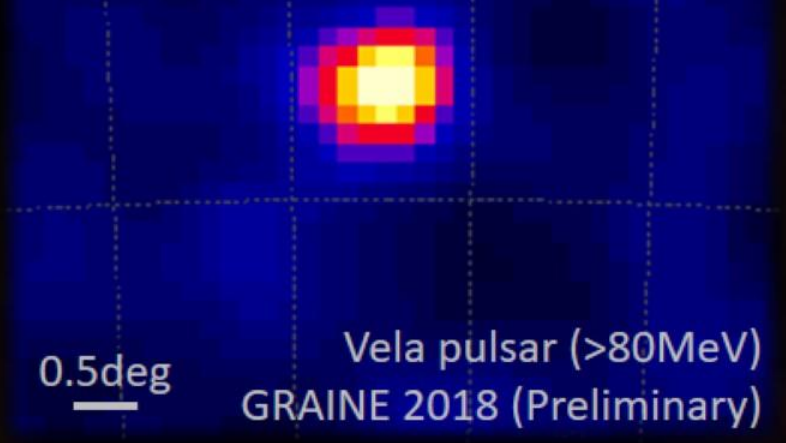
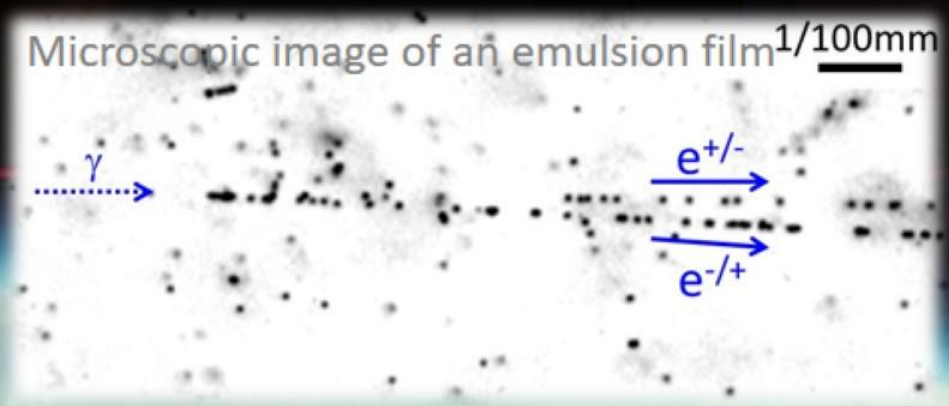
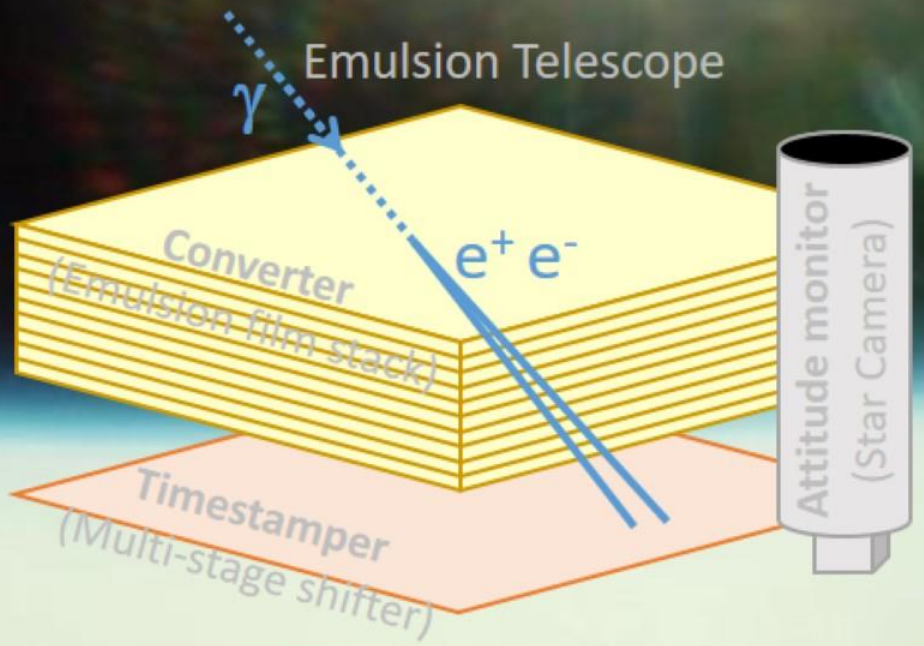
GRAINE precise γ-ray observations: latest results on 2018 balloon-borne experiment and prospects on next/future scientific experiments

Satoru Takahashi (Kobe Univ) for GRAINE collaboration
Aichi U of Education, Gifu U, Kobe U, Nagoya U, Okayama U of Science
PI: Shigeki Aoki (Kobe Univ)







BG image: GRAINE 2011, JAXA Ballooning (Photo by NHK)

All-sky map by Fermi Gamma-ray Space Telescope using nine years of data collected from 2008 to 2017

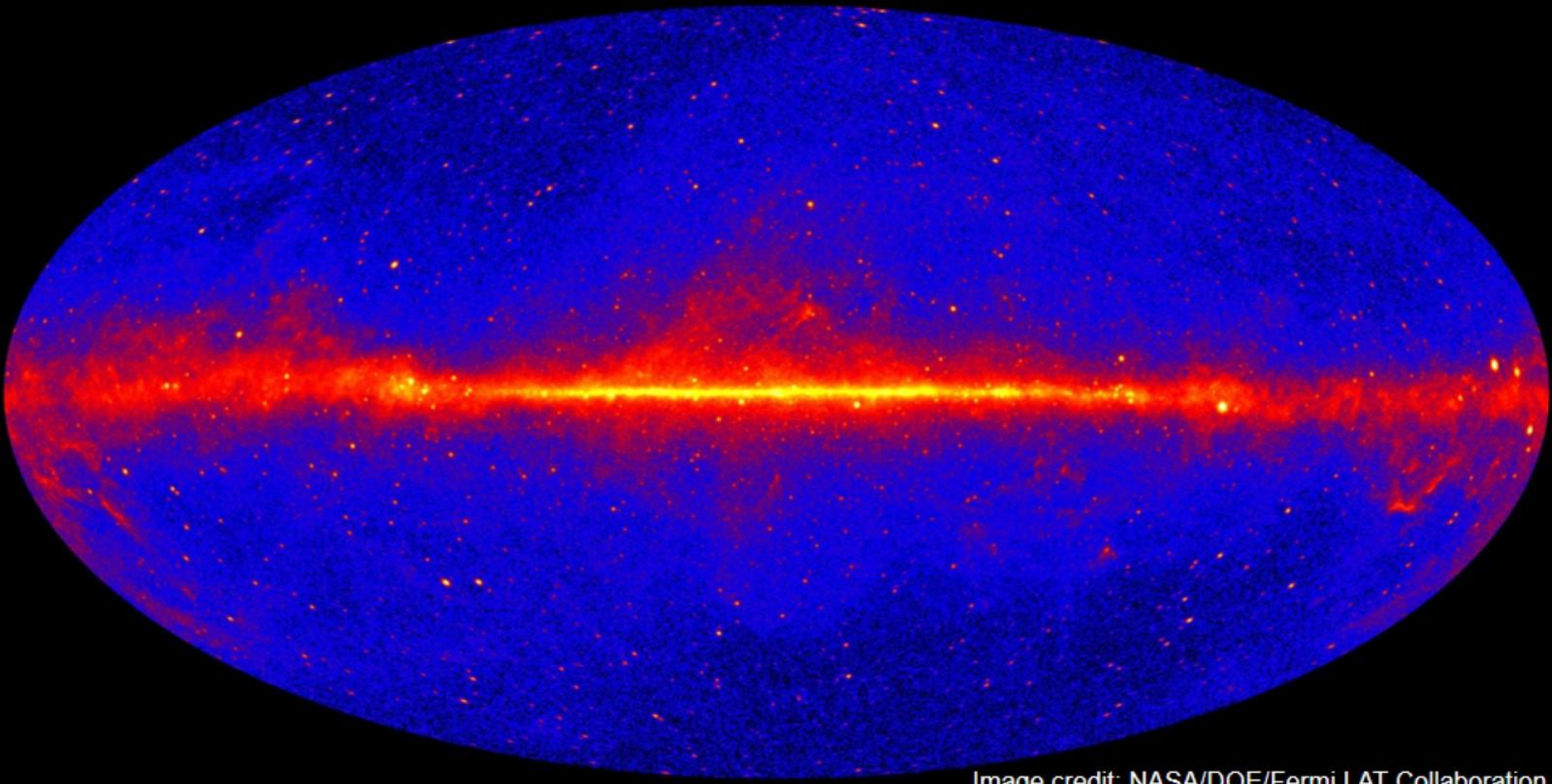


Image credit: NASA/DOE/Fermi LAT Collaboration

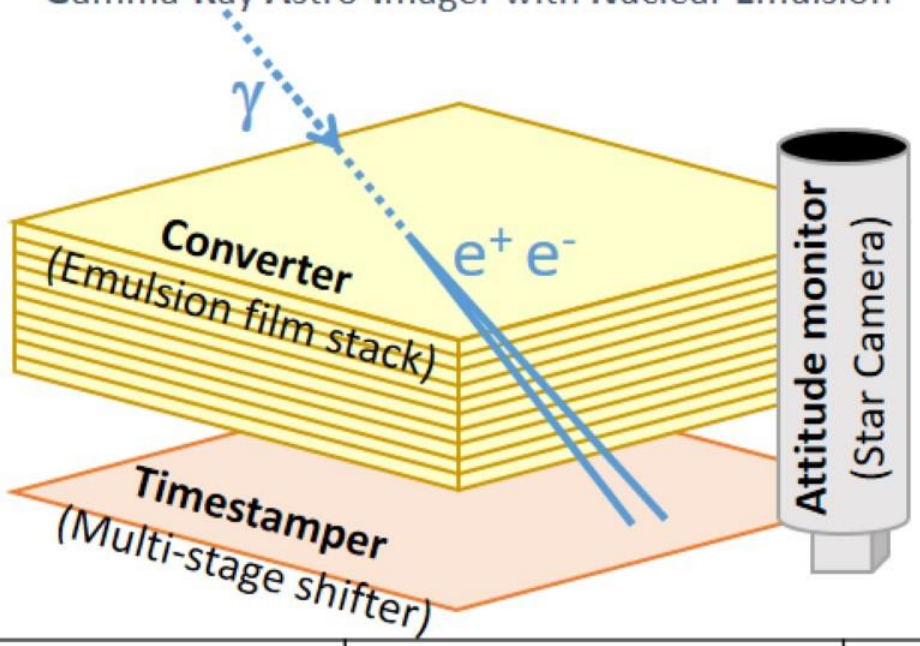
5064 sources (4FGL)

Highest angular resolution
First polarization sensitivity
Largest aperture area

GRAINE

Emulsion γ-ray telescope
Repeated long-duration balloon flights

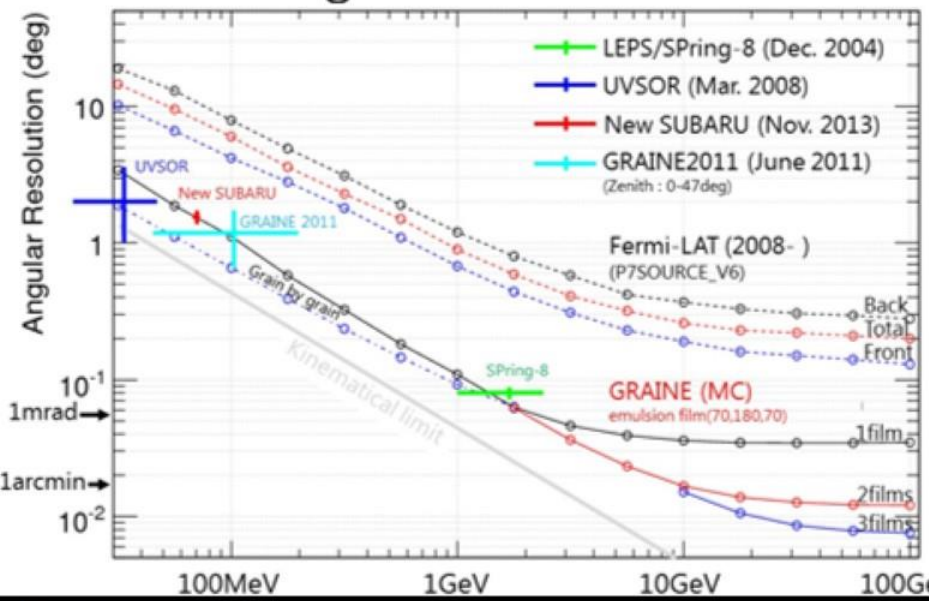
Gamma-Ray Astro-Imager with Nuclear Emulsion



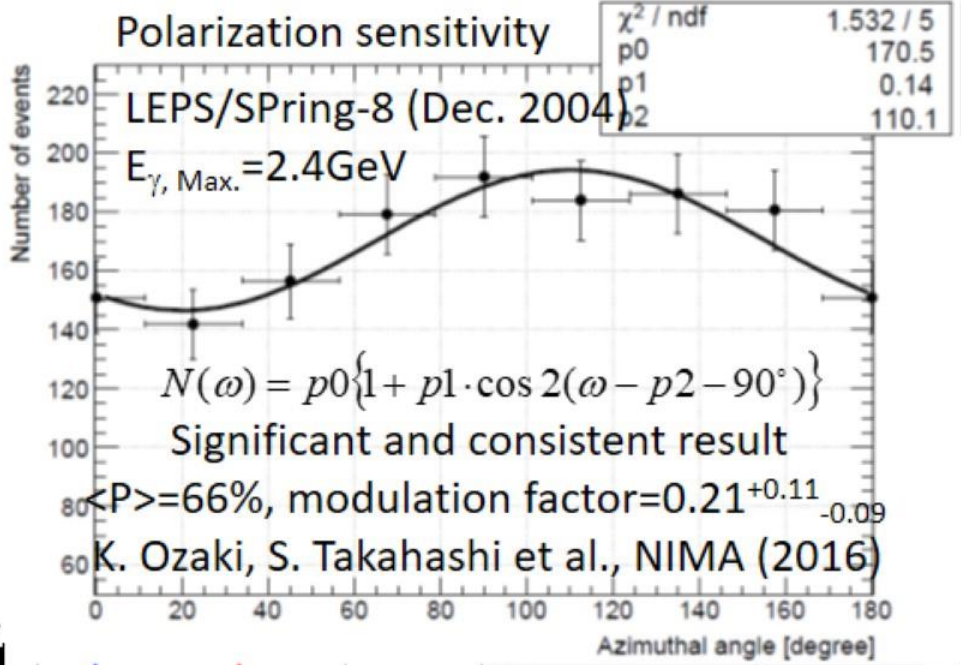
∗ $10m^2 * \varepsilon_{trans} * \varepsilon_{conv} * \varepsilon_{det}$

	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

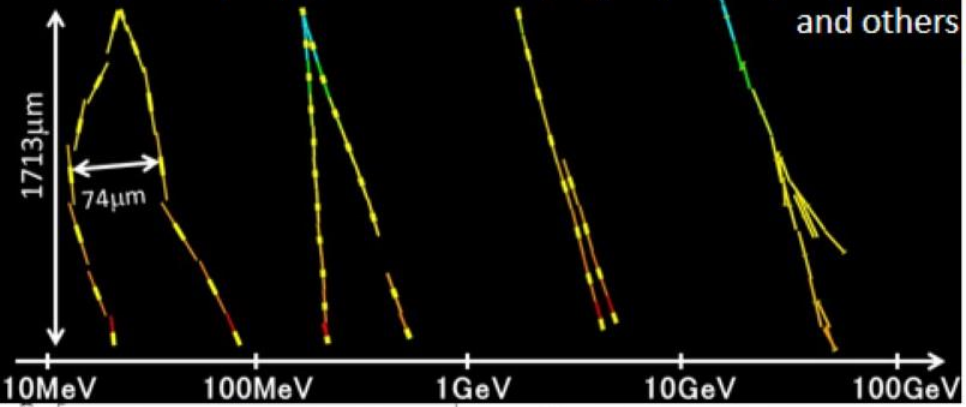


Polarization sensitivity



Energy range

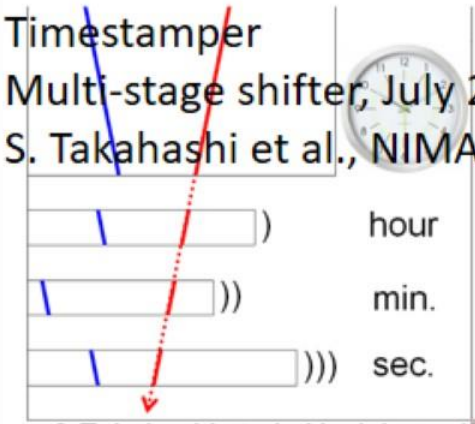
Atmospheric γ-ray @Mt. Norikura (July, Sep. 2007, July 2013), and others

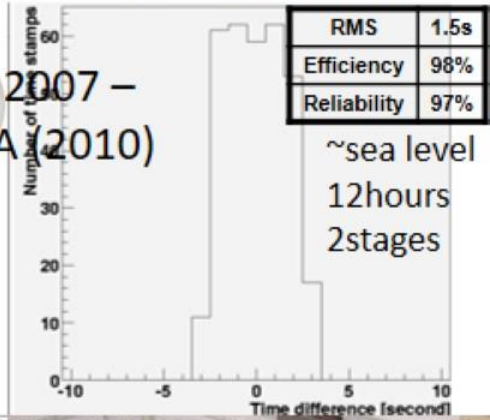


Timestamper

Multi-stage shifter, July 2007 –

S. Takahashi et al., NIMA (2010)





~sea level

12hours

2stages

Momentum w/MCS

35MeV electron LINAC

@Tokai-mura (Aug. 2012)

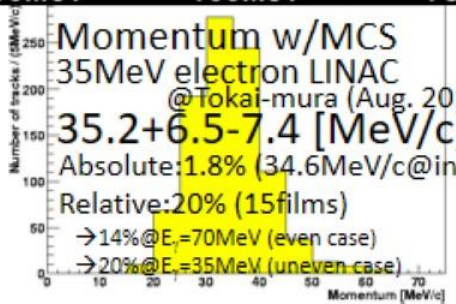
35.2+6.5-7.4 [MeV/c]

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

Relative:20% (15films)

→14%@Eγ=70MeV (even case)

→20%@Eγ=35MeV (uneven case)



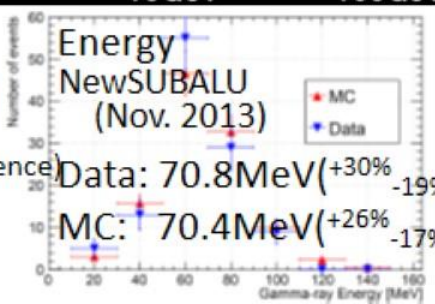
Energy

NewSUBALU

(Nov. 2013)

Data: 70.8MeV(+30% -19%)

MC: 70.4MeV(+26% -17%)



Flatness study

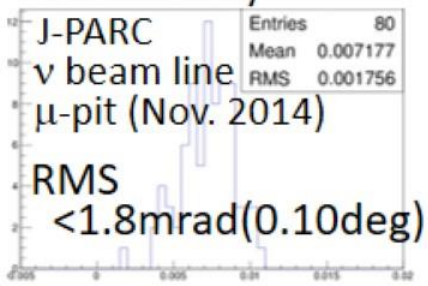
J-PARC

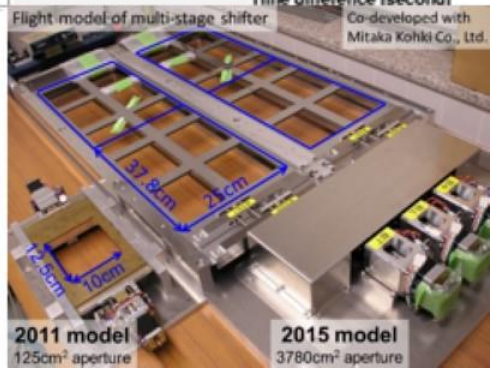
ν beam line

μ-pit (Nov. 2014)

RMS

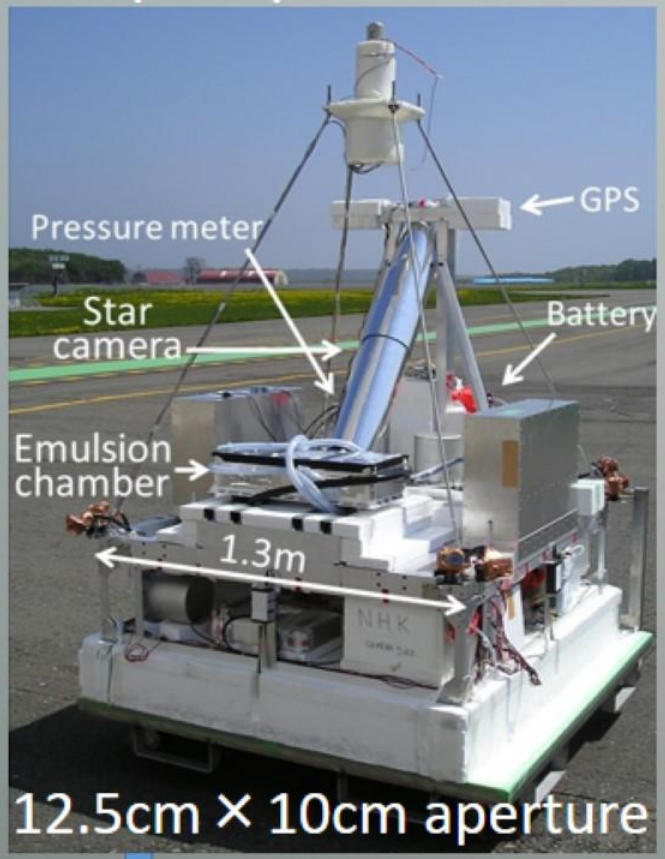
<1.8mrad(0.10deg)



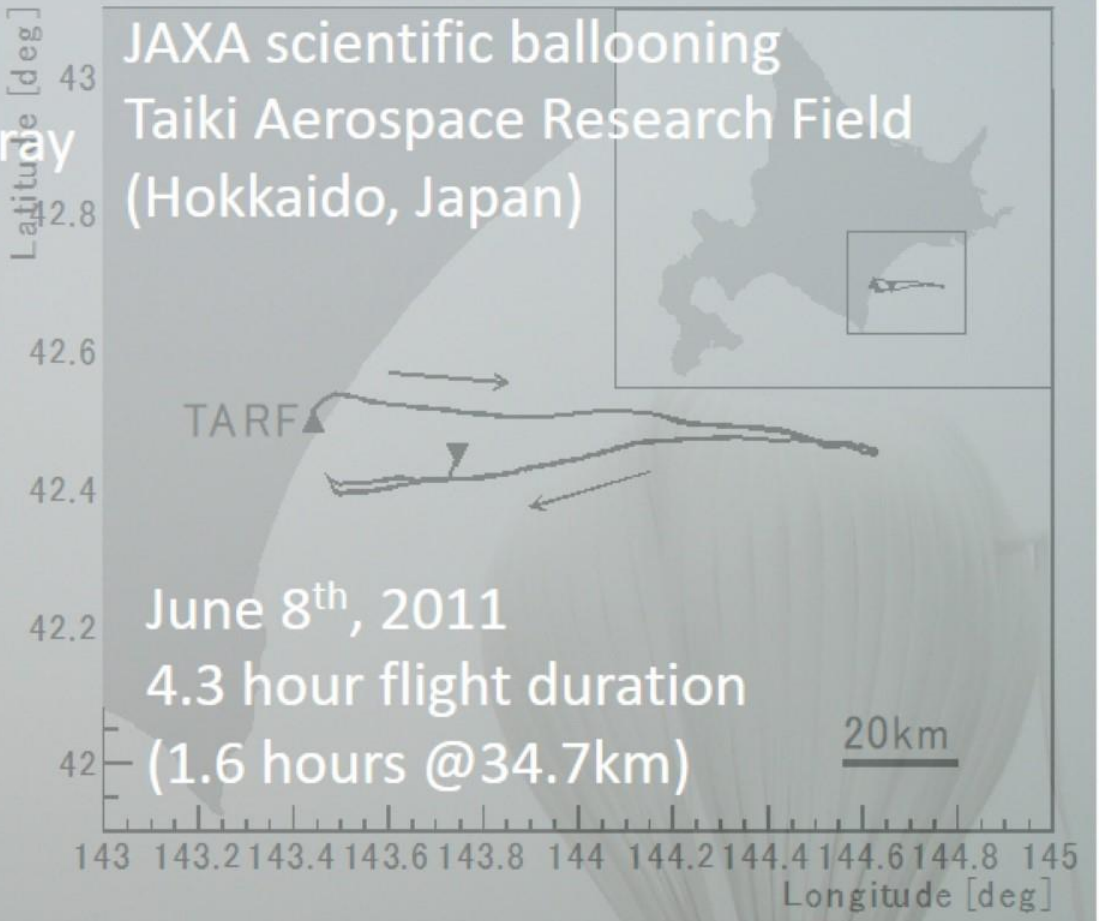


GRAINE 2011

First balloon-borne emulsion γ-ray telescope experiment



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

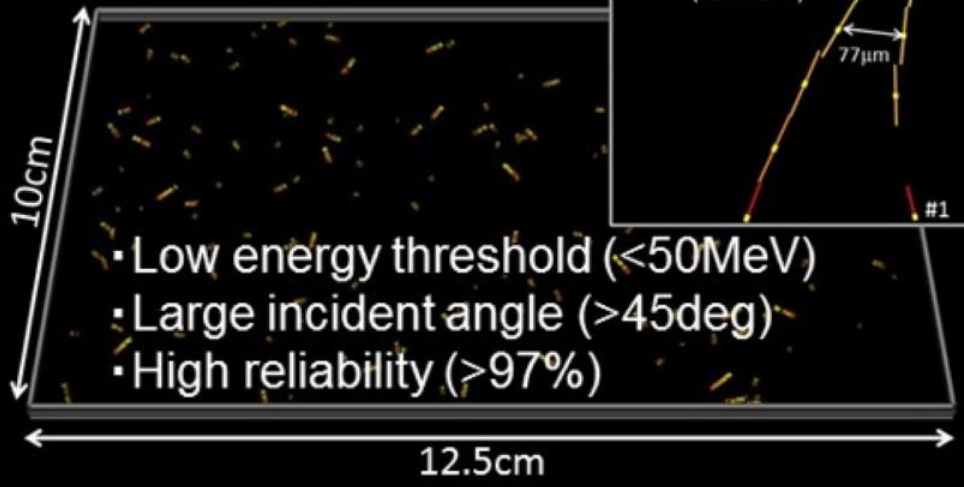


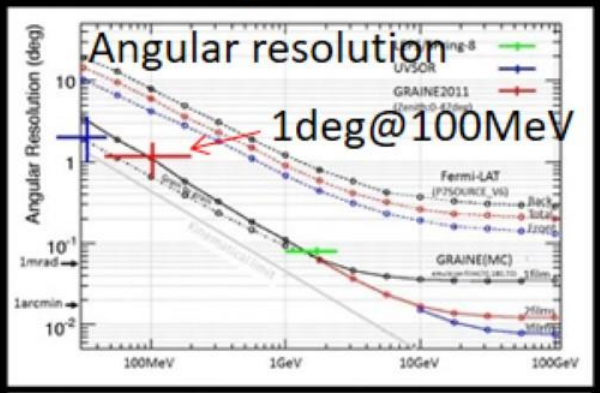
June 8th, 2011
4.3 hour flight duration
(1.6 hours @34.7km)

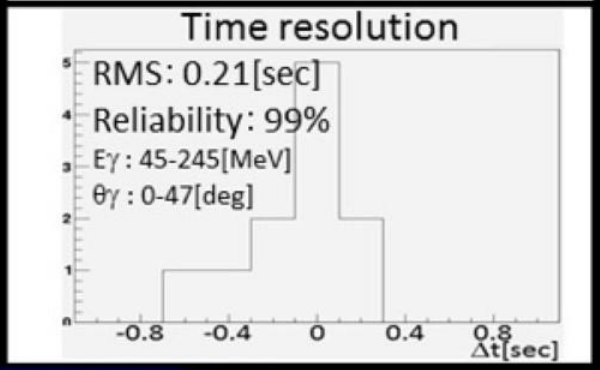
First balloon-borne experiment
Feasibility demonstration

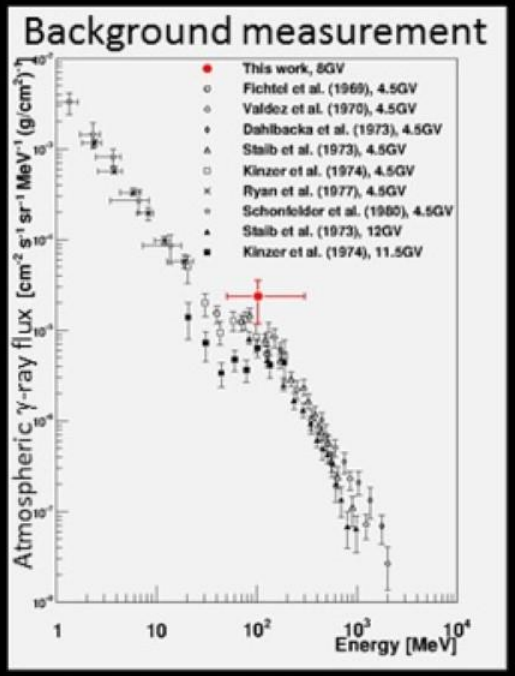
GRAINE 2011 Flight data analysis

γ-ray event detection

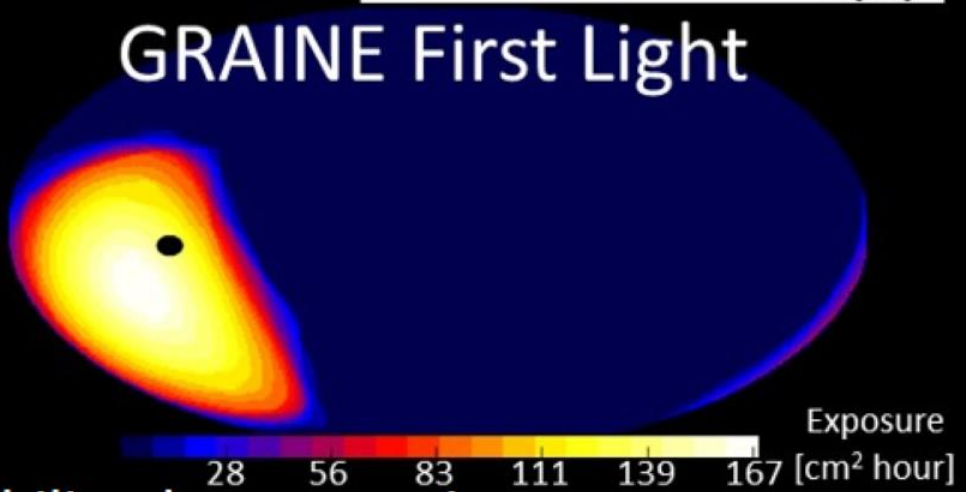






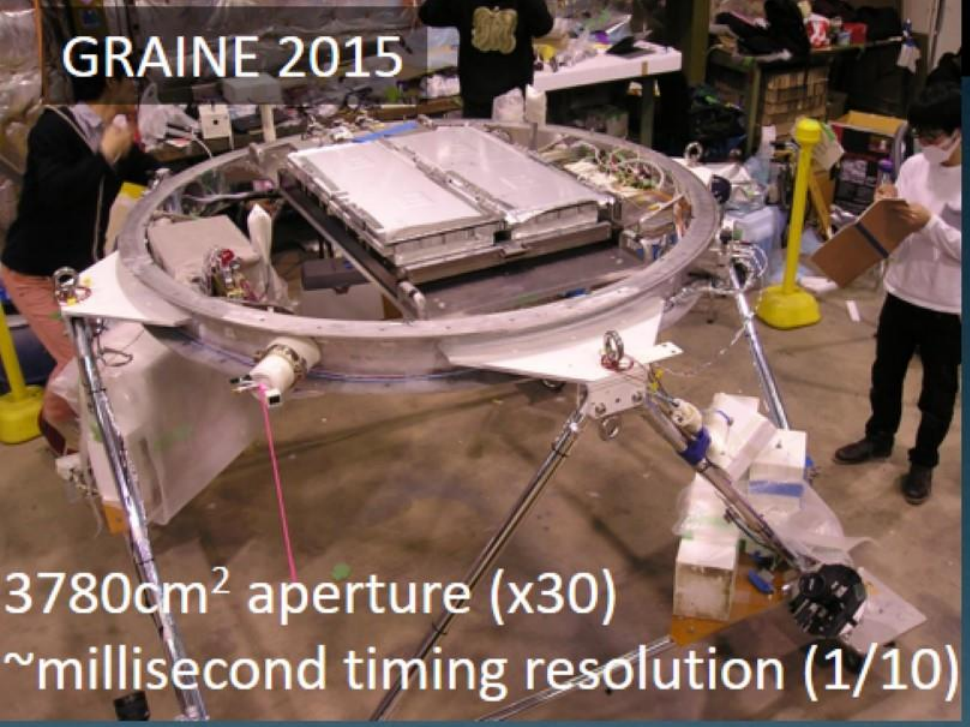


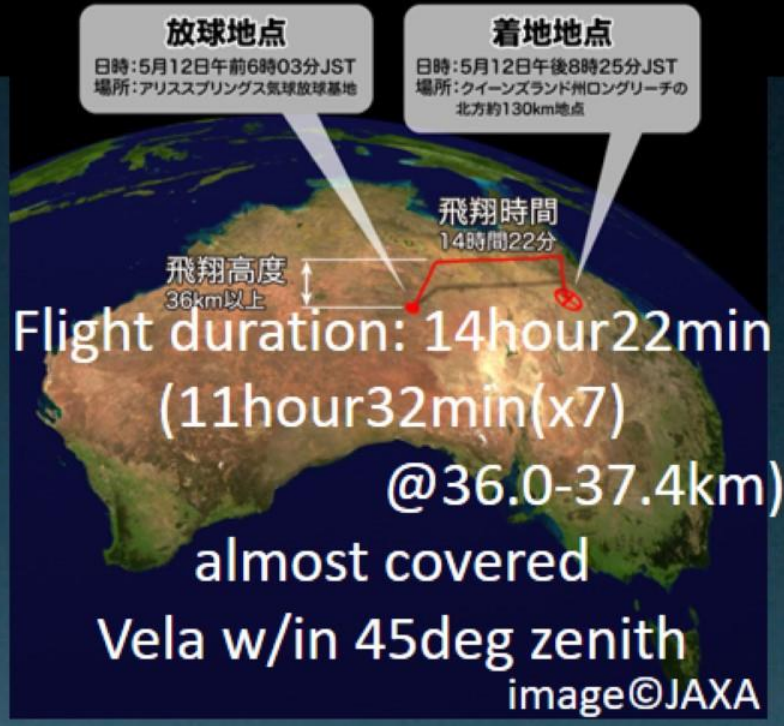
GRAINE First Light



Feasibility demonstration

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





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

Image©JAXA

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

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
- Playing a role of a precursor of a JAXA ballooning 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 active area, 2830cm^2 aperture (total 30m^2)
- γ-ray PSF ~1.0deg@100MeV
- Timestamping over the flight duration (6:30 – 20:00)
- Time resolution, 9.8 msec (~1/10)
- Star camera sensitivity, magnitude of 6.1 → 7.5

Significant progress from GRAINE 2011

H. Kawahara, et al., KMI 2017, https://pos.sissa.it/294/059; H. Rokujo, et al., PTEP 063H01 (2018); F. Mizutani et al., NIMA (Submitted).

GRAINE 2015

γ-ray detection from Vela Pulsar (Not achieved)

Apr 2018, JAXA ballooning in Australia

Prospects for enlarging effective area x time and BG reduction

- Robustnized star camera systems → x1.77 eff. time
  - Redundant data storages, Recoverable system from errors
- Stabilized emulsion films → x1.33 eff. area
  - Established optimal parameters for production & processing
- Established multi-stage shifter setup → x1.33 eff. area x time
  - Optimized emulsion film mounting
- Corrected multi-stage shifter operation → x1/2 BG

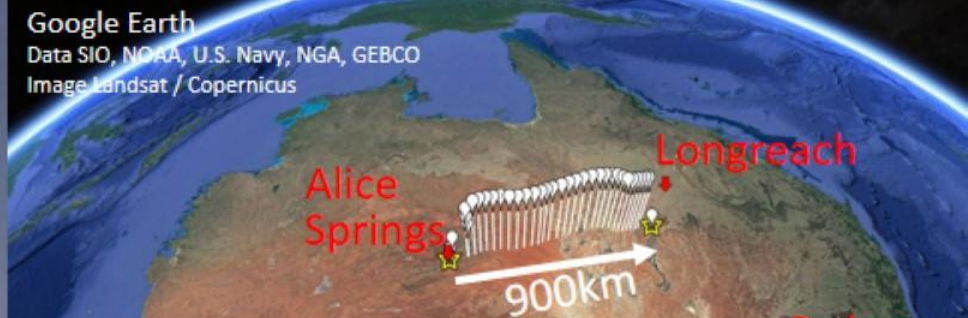
Total x6.3 improvements.

(x5, effectively)

Overall performance demonstration

Imaging resolution aimed w/i 1deg above 100MeV

GRAINE 2018



Flight duration: 17.4h (21%↑)

Level flight @38.1 – 35.4 km: 14.7h (28%↑)

Fully covered Vela pulsar in 45 deg zenith (10%↑)

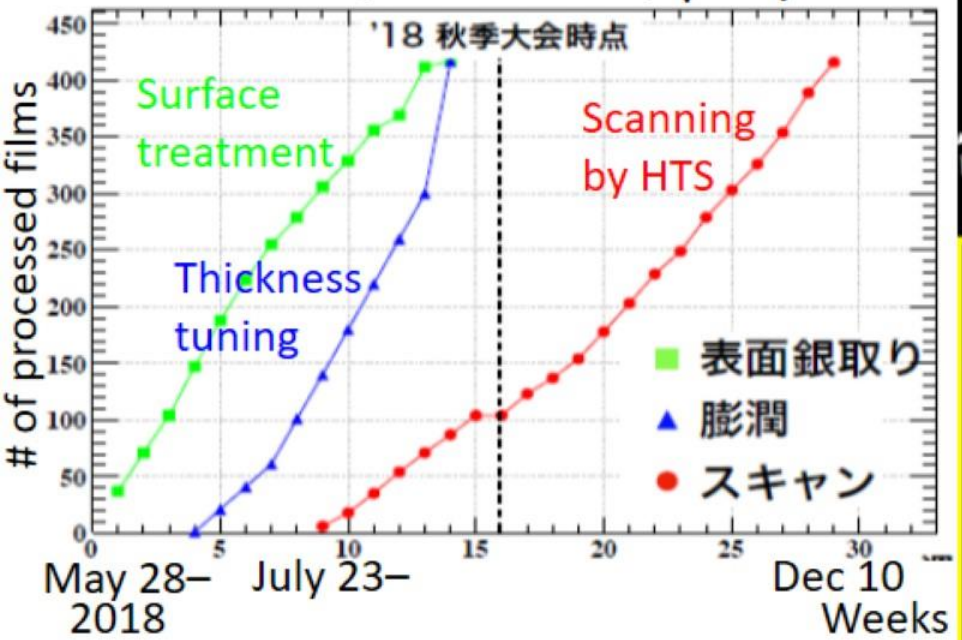
- ✓ Stably operated (Multi-stage shifter, 3 star cameras, Pressure vessel)
- ✓ Recovered (Apr 27 to Longreach)
- ✓ Developed (Apr 29 – May 13 @U Sydney)

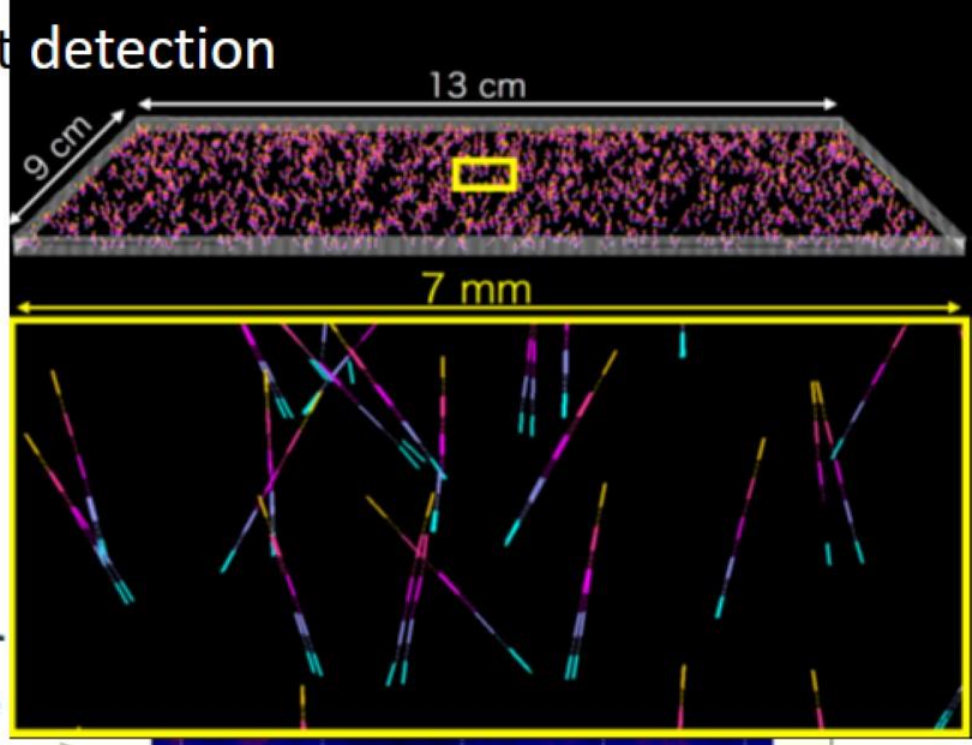
Various developments, improvements, preparations

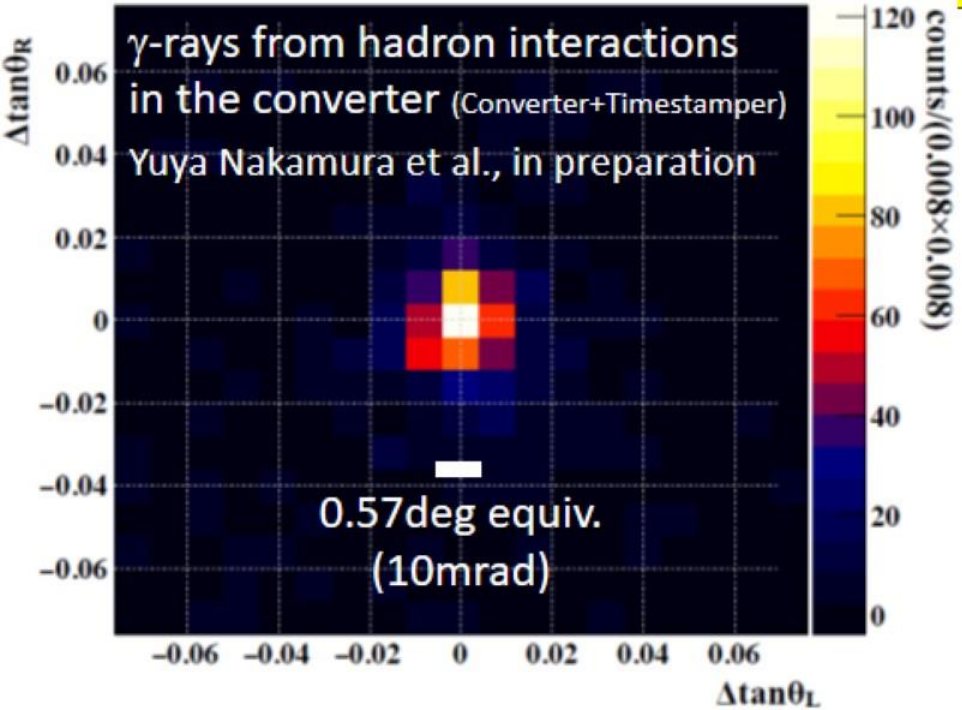
Aperture of 3780cm^2

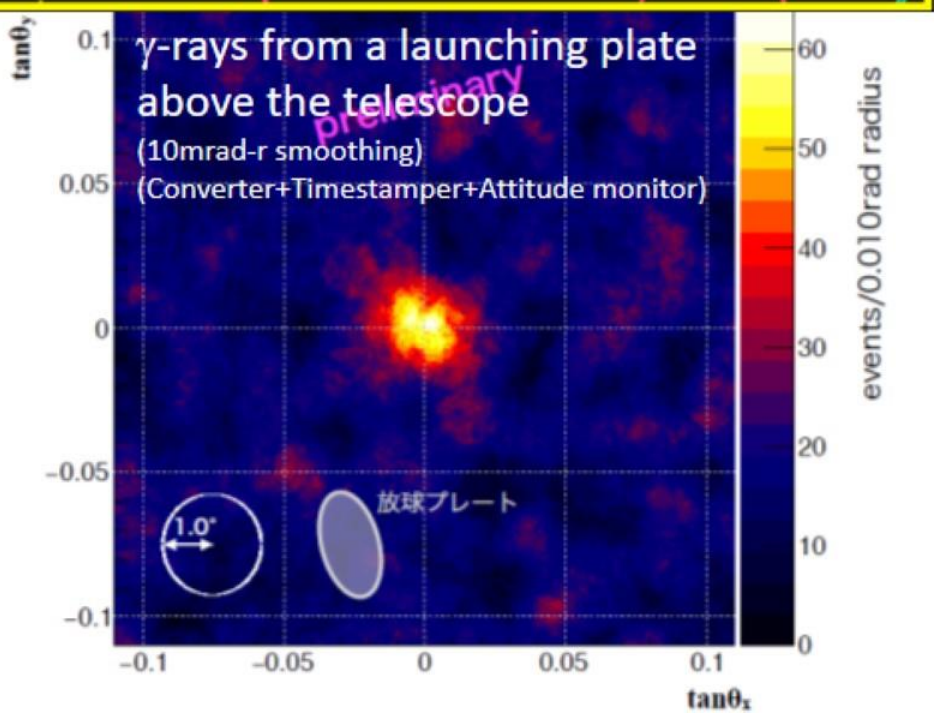
GRAINE 2018, JAXA Scientific balloon @BLS Alice Springs Australia, 6:30AM 26th April (ACST)

GRAINE 2018, Converter, γ-ray event detection

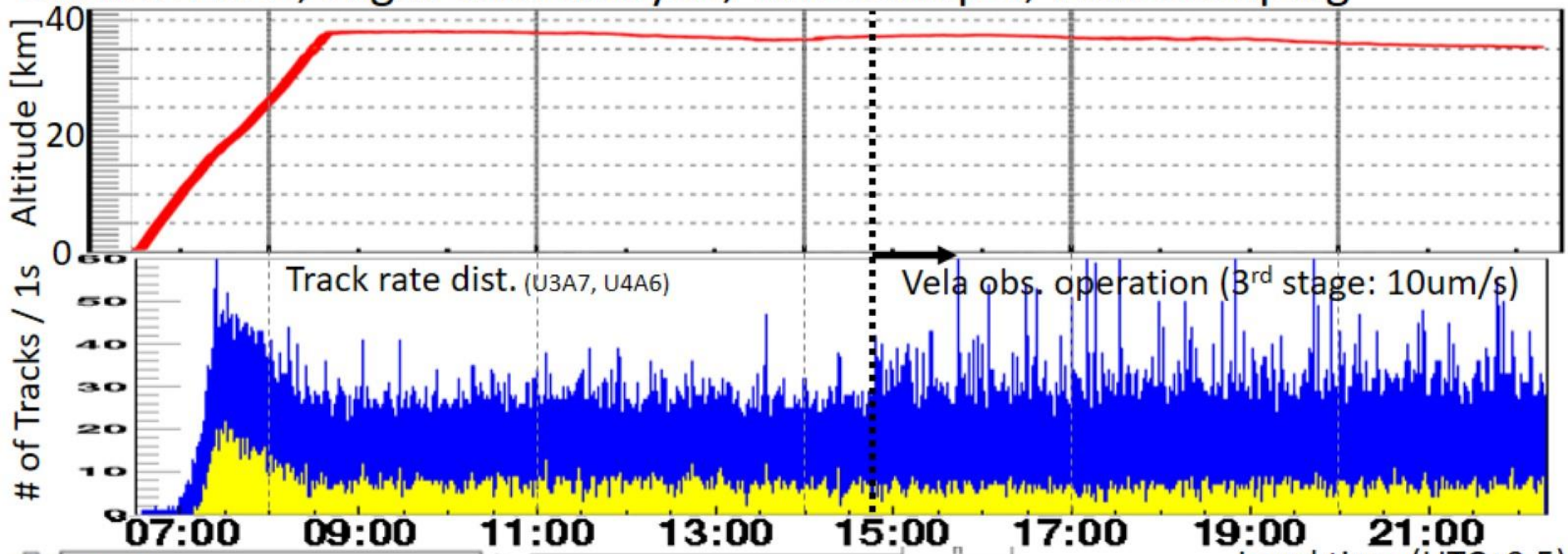


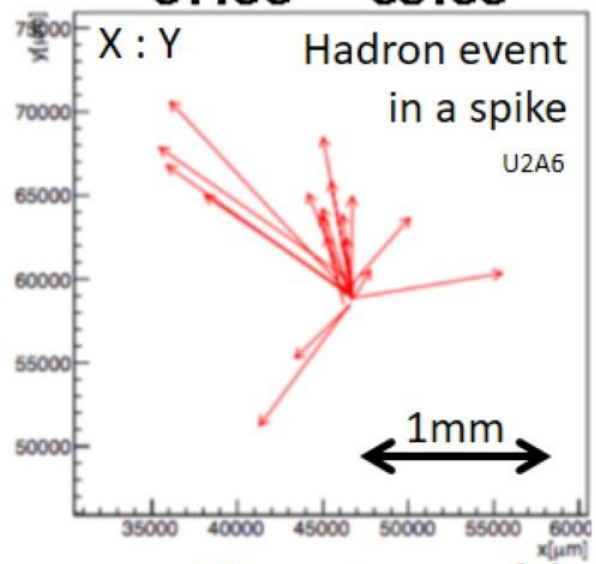


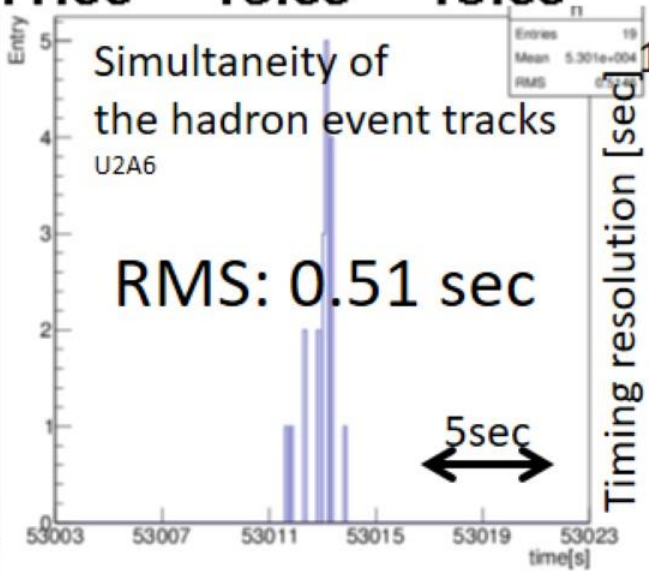


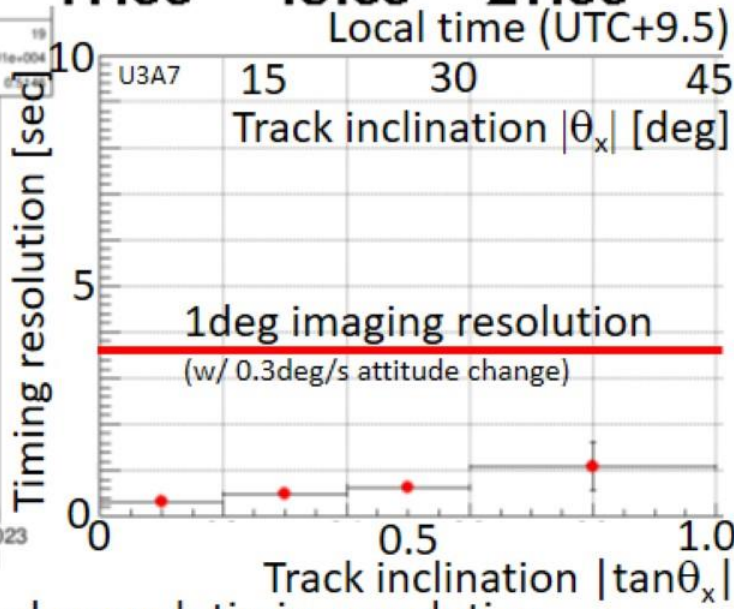


GRAINE 2018, Flight data analysis, Timestamper, Timestamping





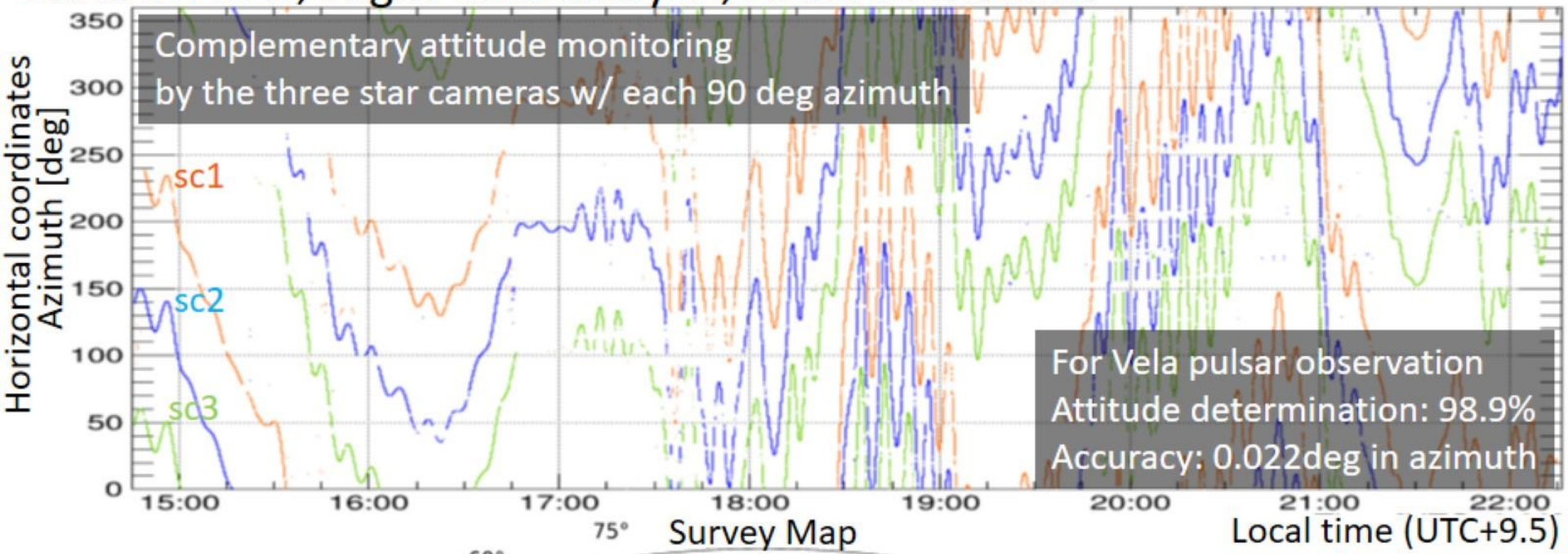




Timestampable
for high resolution γ-ray imaging

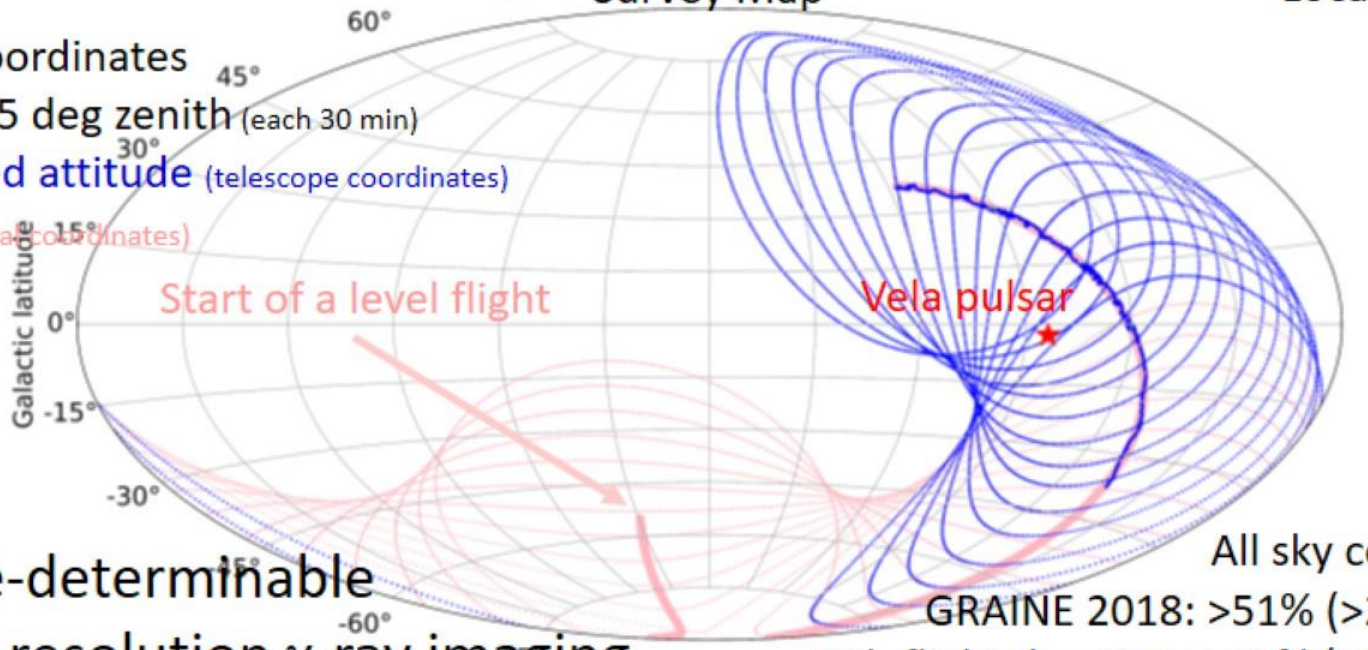
Good enough timing resolution
for 1deg imaging resolution

GRAINE 2018, Flight data analysis, Attitude monitor



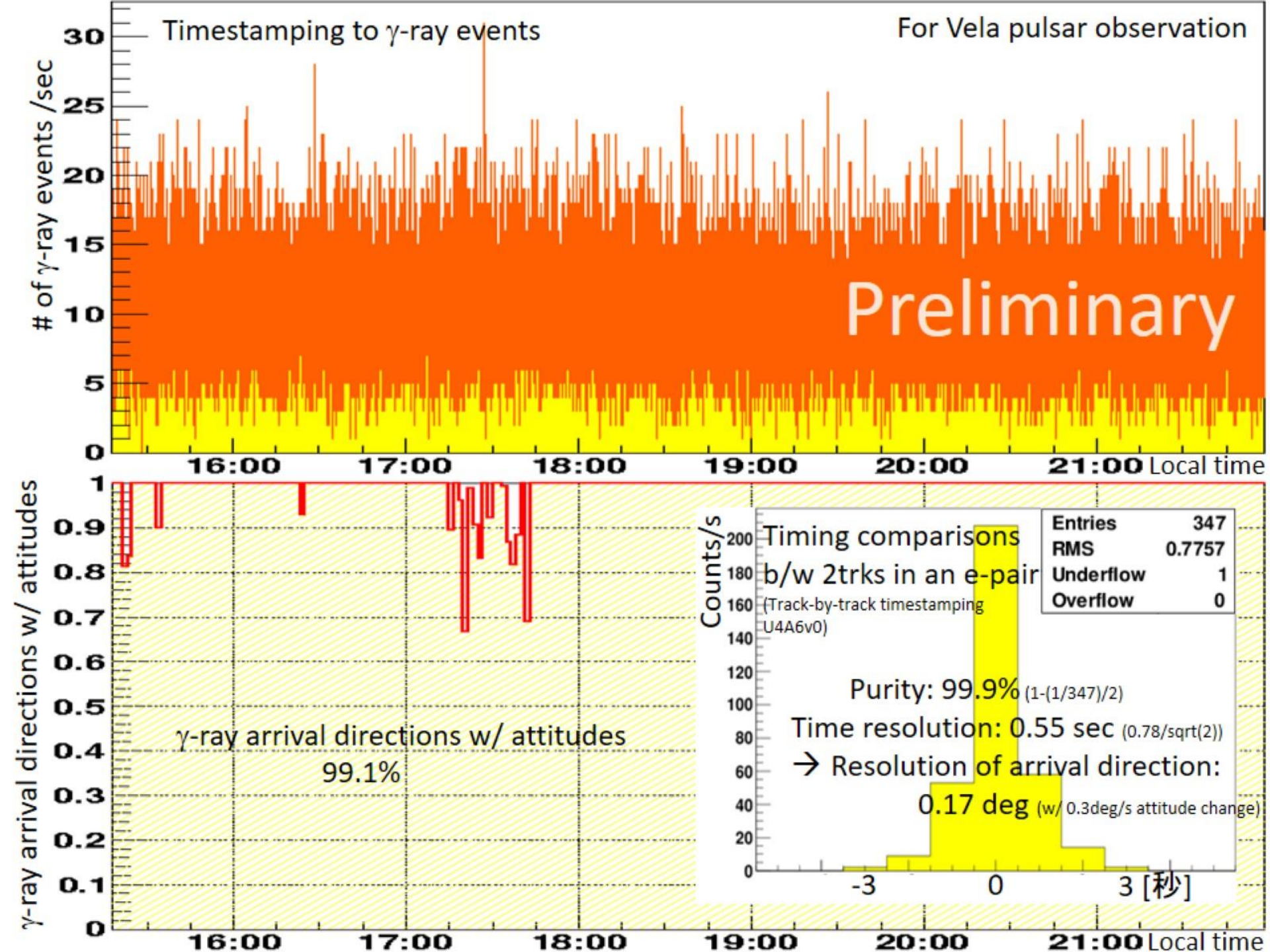
Survey Map

Galactic coordinates
Zenith & 45 deg zenith (each 30 min)
Determined attitude (telescope coordinates)
GPS (horizontal coordinates)



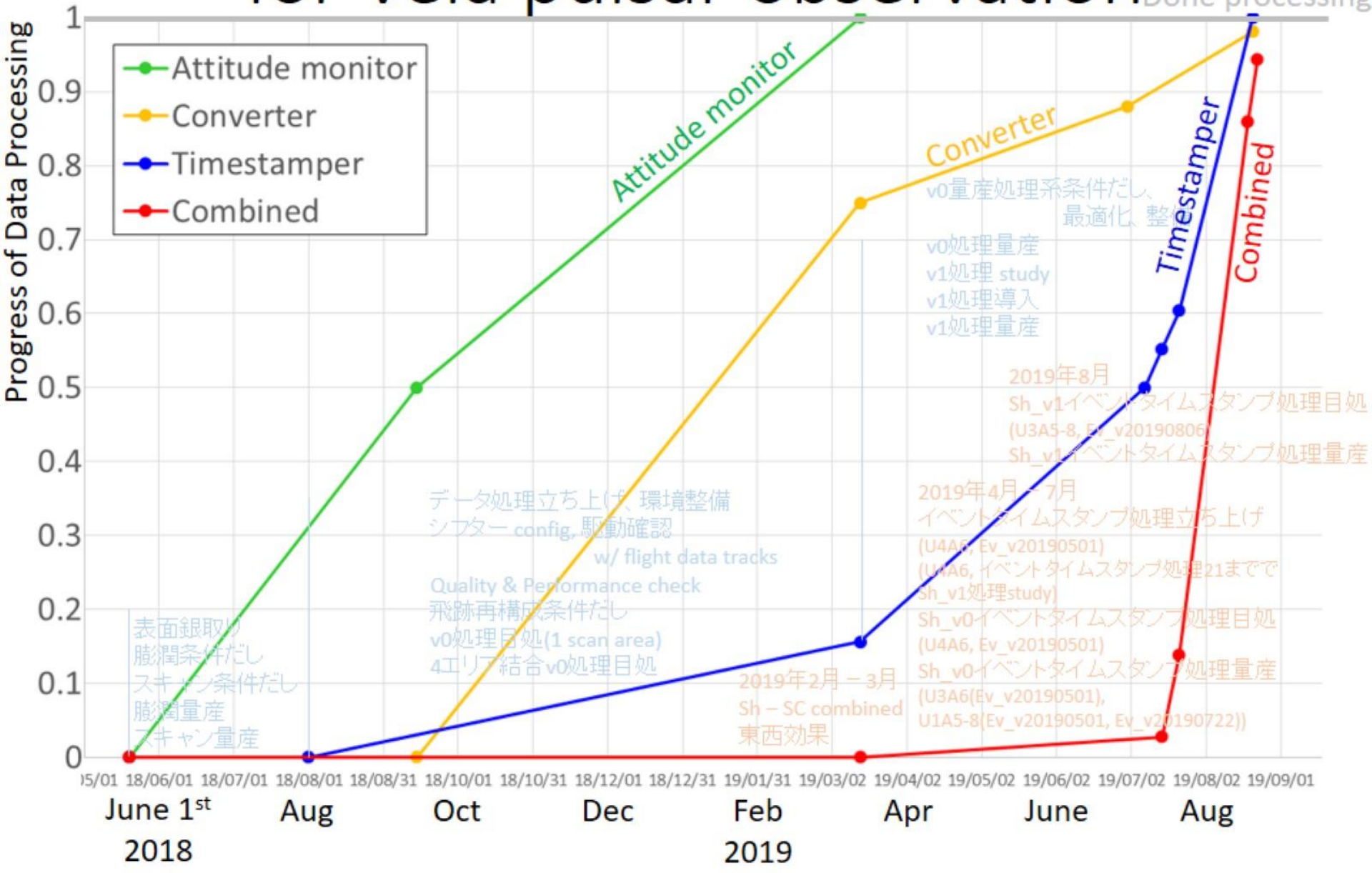
Attitude-determinable
for high resolution γ-ray imaging

All sky coverage
GRAINE 2018: >51% (>2.0π[sr])
24h flight duration: >65% (>2.6π[sr]) incl. GC


Timestamping to γ-ray events
For Vela pulsar observation
# of γ-ray events /sec
Preliminary
16:00
17:00
18:00
19:00
20:00
21:00
Local time
γ-ray arrival directions w/ attitudes
γ-ray arrival directions w/ attitudes
99.1%
Timing comparisons
b/w 2trks in an e-pair
(Track-by-track timestamping
U4A6v0)
Counts/s
Entries 347
RMS 0.7757
Underflow 1
Overflow 0
Purity: 99.9% (1-(1/347)/2)
Time resolution: 0.55 sec (0.78/sqrt(2))
→ Resolution of arrival direction:
0.17 deg (w/ 0.3deg/s attitude change)
-3
0
3 [秒]

Progress of data processing for Vela pulsar observation

v0: つなぎの精度× 3σ or 5σ
v1: & 60MeV/c 2σ

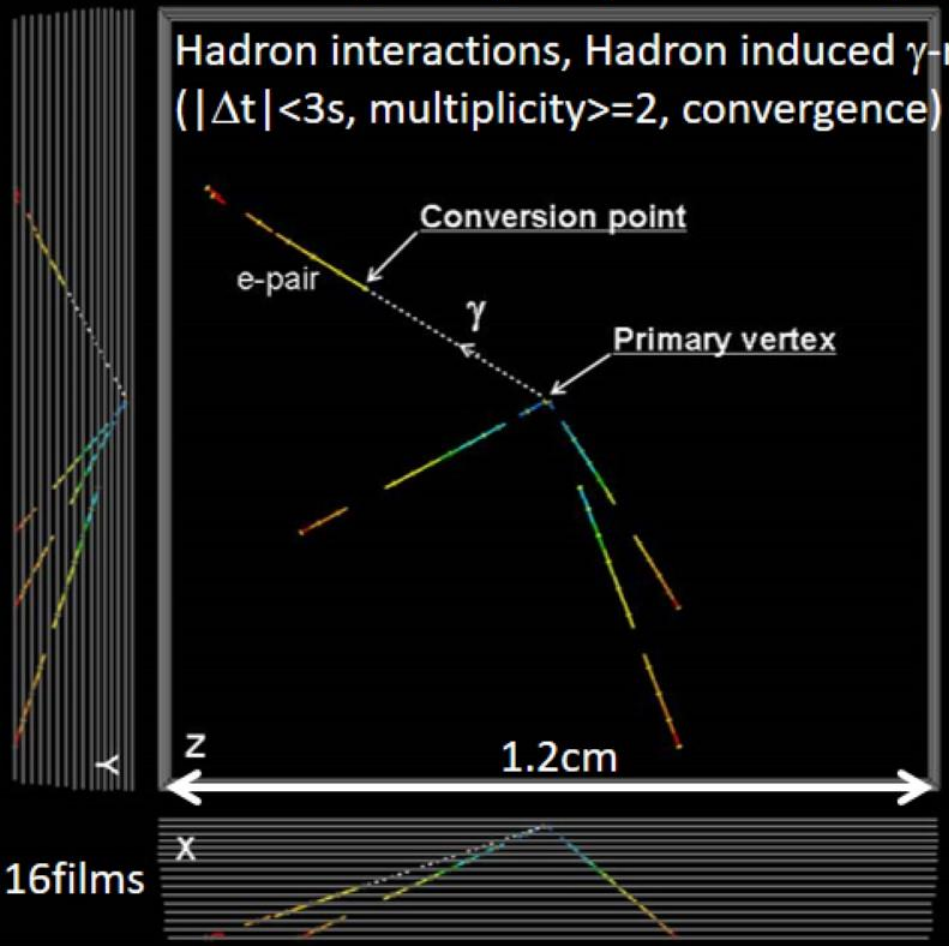


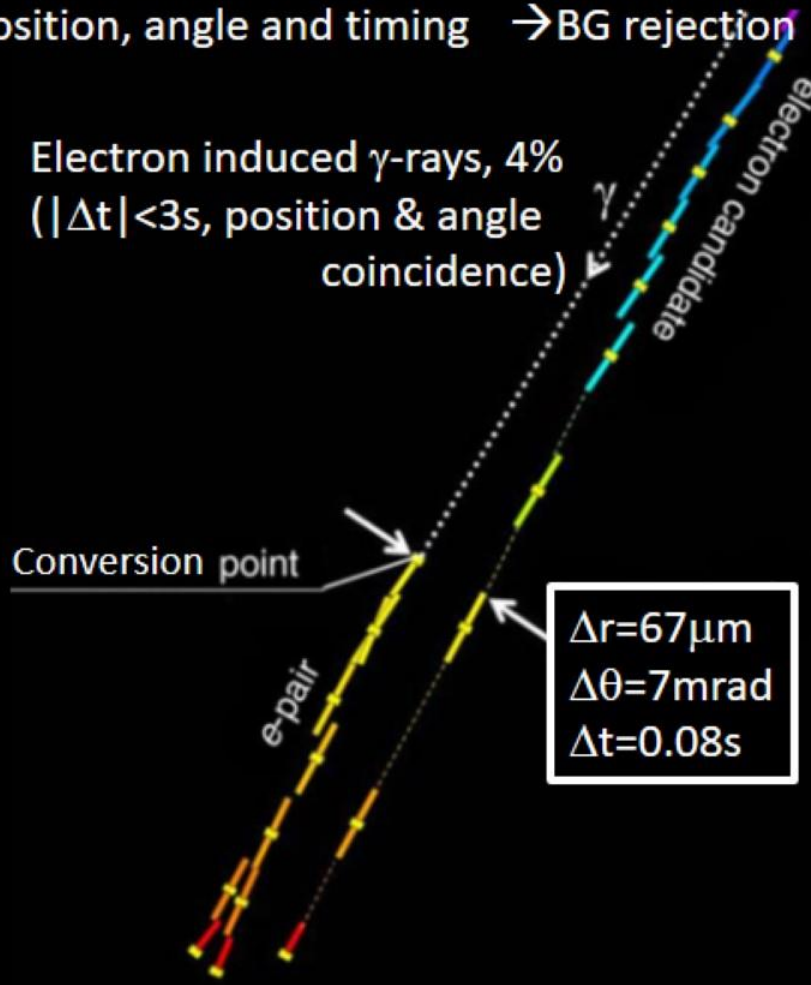
- ✓ Inefficiency recovery (20% increase)
  - —Connection b/w the converter and timestamper, Timestamping, etc.
- ✓ CR induced background rejection (50% reduction)
  - —Hadron int., Hadron induced γ-rays, Electron induced γ-rays
- ✓ Detector axis alignment (w/i 0.1deg)

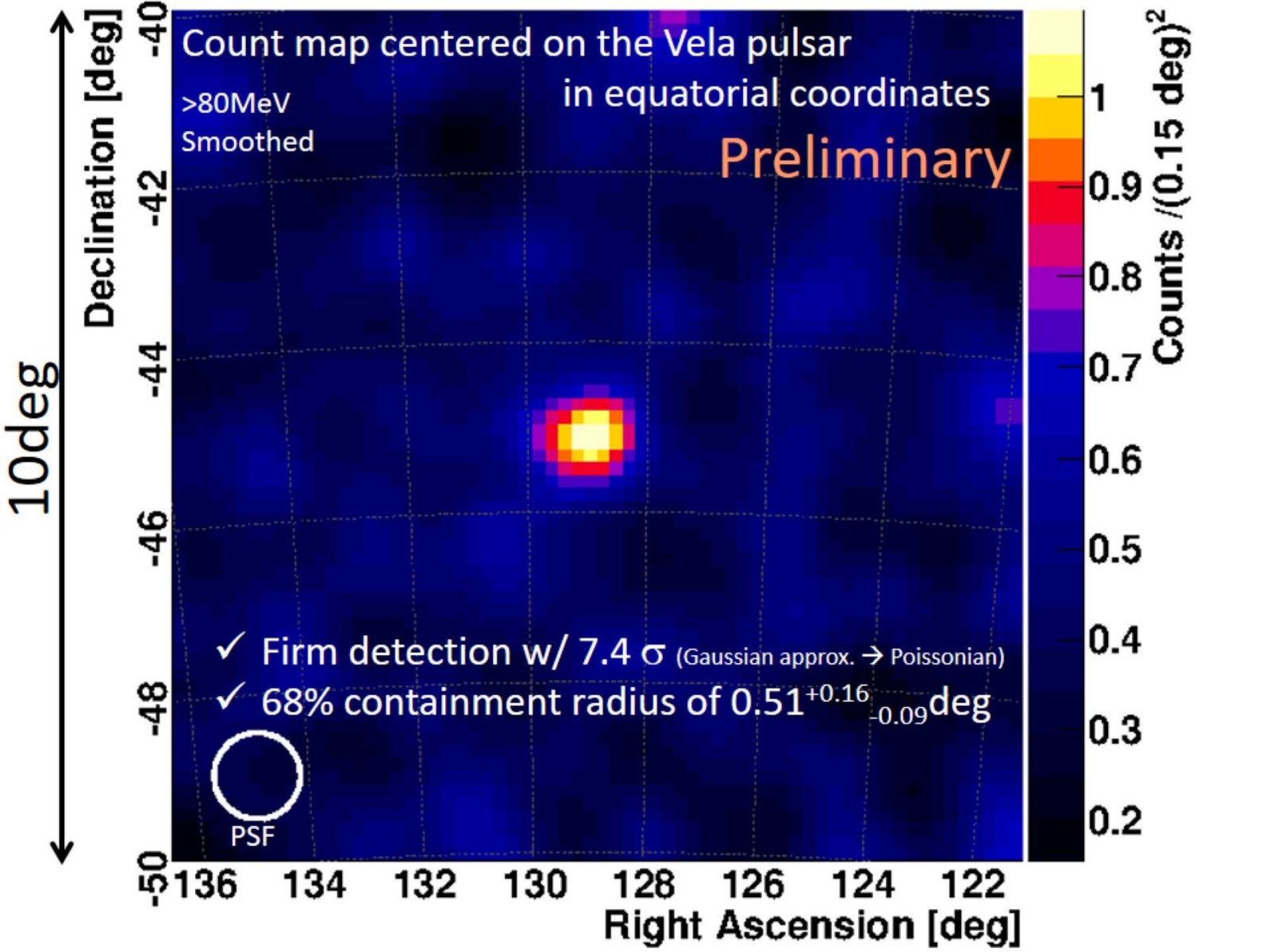
CR induced background discrimination
S. Takahashi et al., PTEP (2015) 043H01

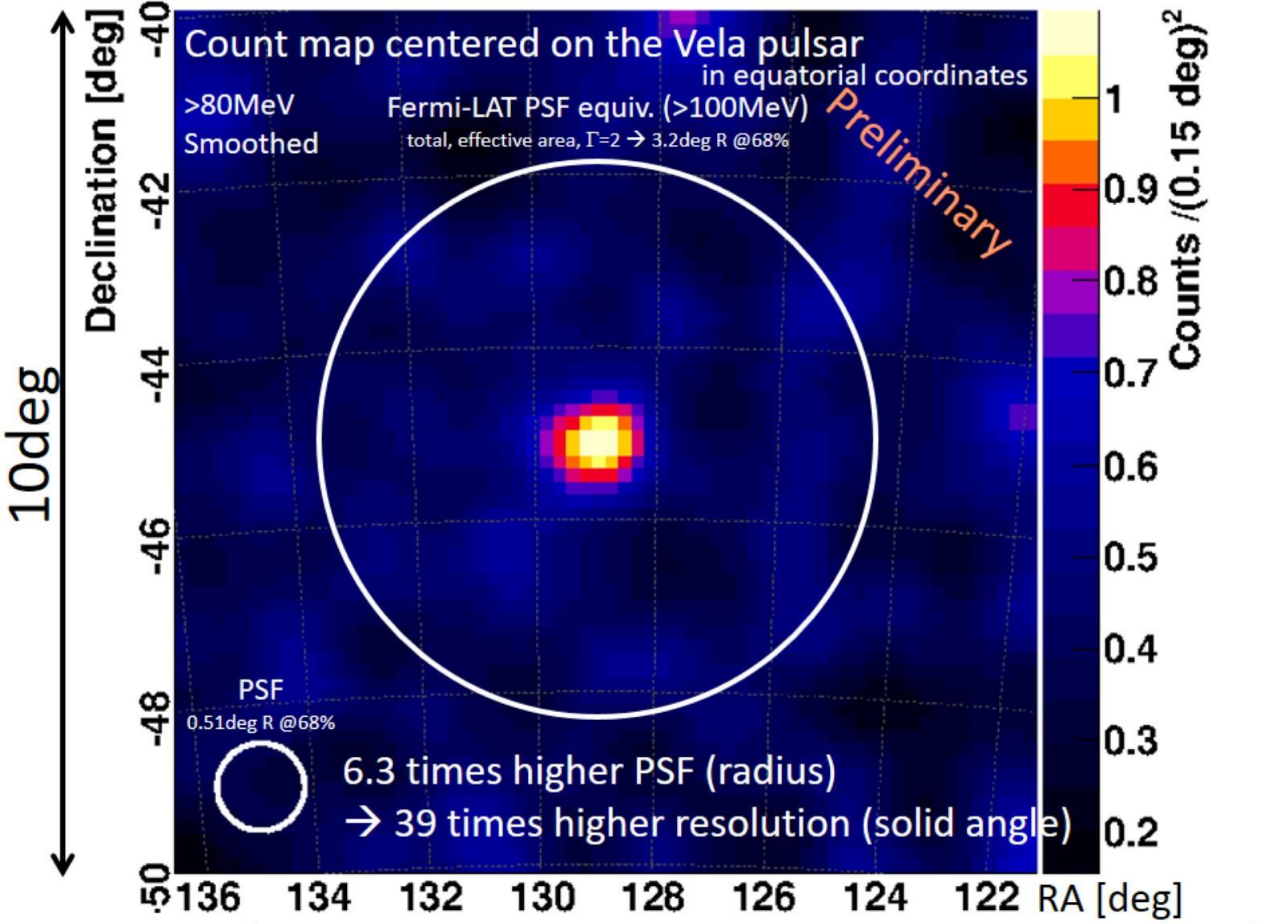
Reconstructable
w/ track position, angle and timing

→Calib. source
→BG rejection



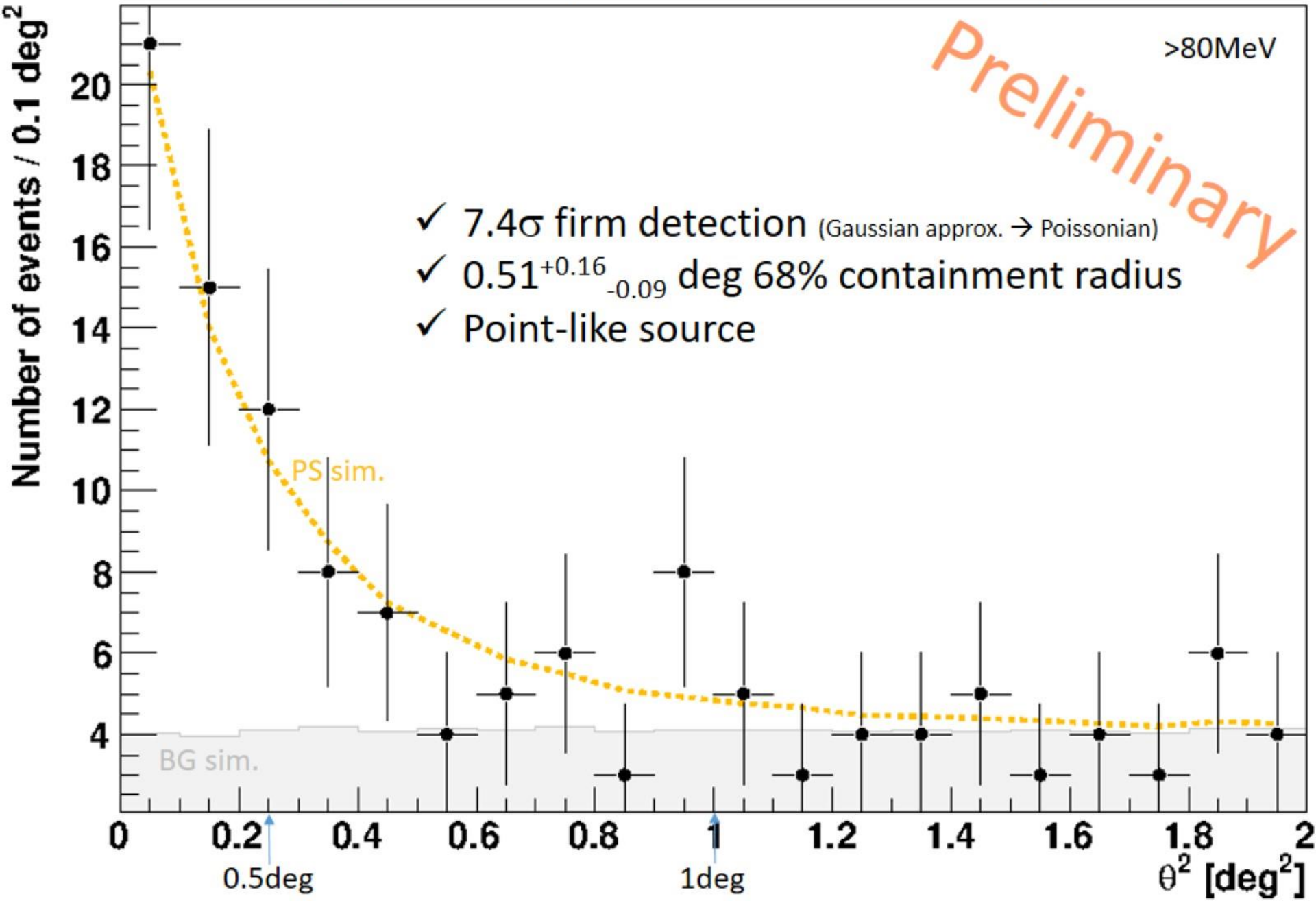



Count map centered on the Vela pulsar
in equatorial coordinates
>80MeV
Smoothed
Preliminary
✓ Firm detection w/ 7.4 σ (Gaussian approx. → Poissonian)
✓ 68% containment radius of $0.51^{+0.16}_{-0.09}$deg
PSF
10deg
Declination [deg]
-40
-42
-44
-46
-48
-50
136
134
132
130
128
126
124
122
Right Ascension [deg]
Counts /(0.15 deg)^2
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2

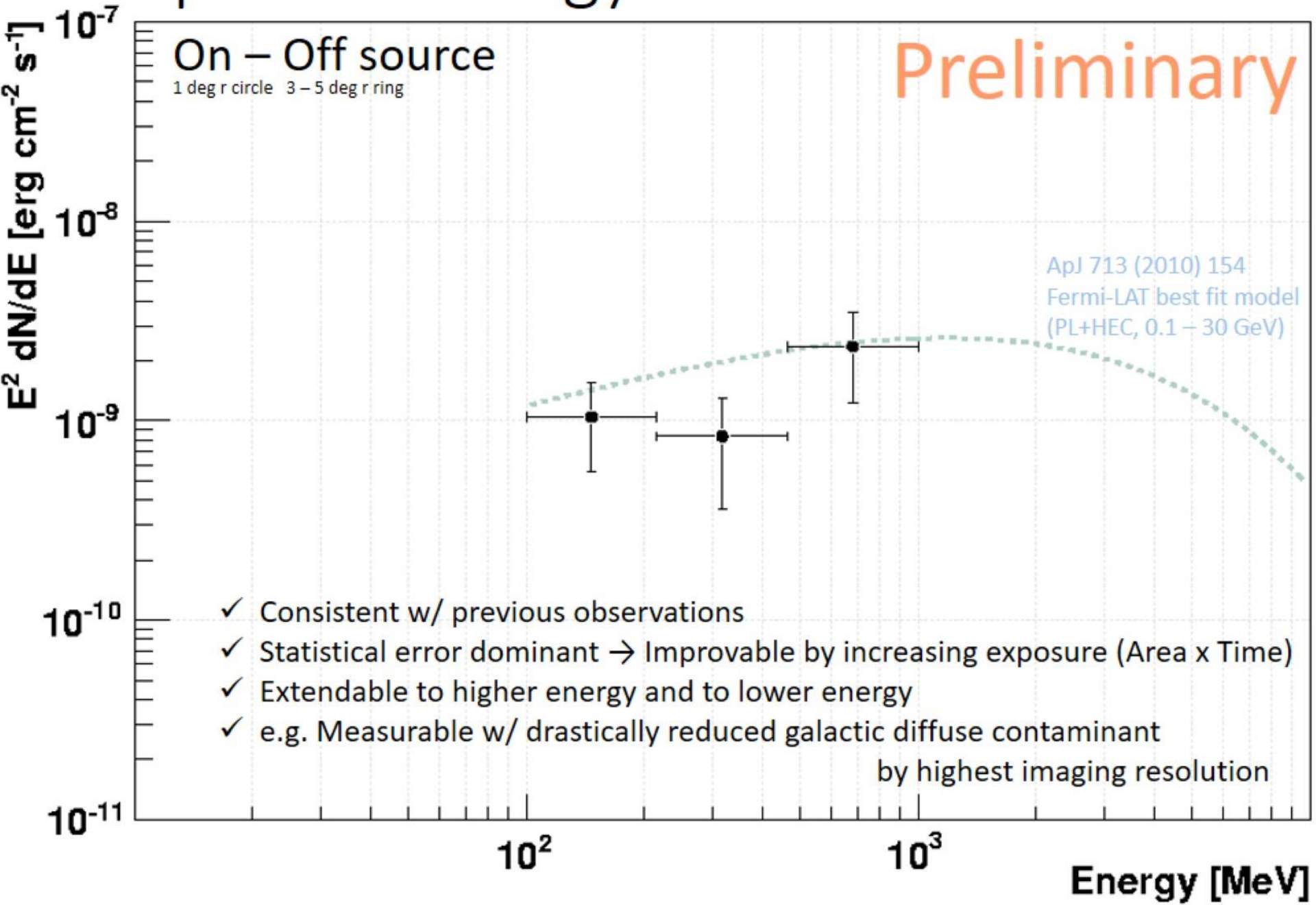


More improvable (possible to be ~10% statistics increase, ~30% BG reduction, ~20% higher PSF)

Radial profile (θ^2 distribution)



Spectral energy distribution



First emulsion γ-ray telescope imaging of the Vela pulsar by the GRAINE 2018 balloon-borne experiment

Submitted to PTEP

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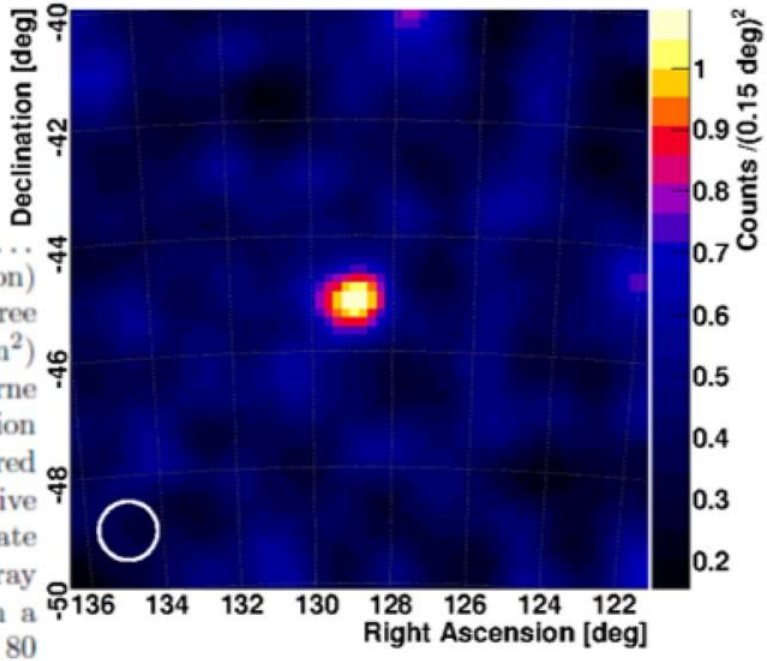
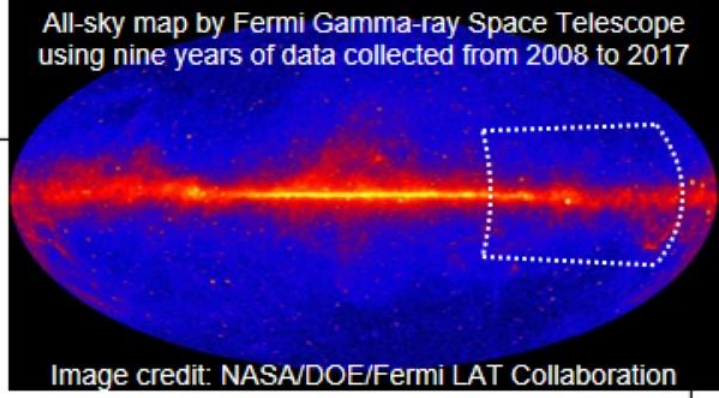


We are developing the GRAINE (Gamma-Ray Astro-Imager with Nuclear Emulsion) project, involving 10 MeV–100 GeV cosmic γ-ray observations with a precise (0.08 degree angular resolution @ 1–2 GeV) and polarisation-sensitive large-area-aperture ($\sim$10 m^2) emulsion telescope for repeated long-duration balloon flights. In 2018, a balloon-borne experiment was carried out in Australia with a 0.38 m^2 aperture and a flight duration of 17.4 hours, including 6.7 hours of Vela operation. Significant improvements compared with a 2015 balloon-borne experiment were achieved, including an increase in effective area$\times$time and a reduction in a background by a factor of 5. We aimed to demonstrate the telescope's overall performance based on detection and imaging of a known γ-ray source, the Vela pulsar. A robust detection of the Vela pulsar was achieved with a 68% containment radius of 0.51 degrees, at a significance of 7.4σ at energies above 80 MeV. The resulting angular profile is consistent with that of a point-like source. We achieved the current-best imaging performance of the Vela pulsar using an emulsion γ-ray telescope with the highest angular resolution of any γ-ray telescope to date.

Galactic diffuse



[Observed] – [BG model*]

*Based on atm. γ-ray East-West effect data

>80MeV, ~300 < l [deg] < ~200

Removed Vela pulsar region

$\theta_{detector\_zenith}$<45deg

Preliminary

- ✓ BG understanding w/i 1%
- ✓ 2.7σ indication at on-plane region (|b|<5deg)
- ✓ Consistent w/ previous observations

- ◆ ~3 times intense around galactic center region
  - ➢ Detectable w/ this aperture
- ◆ By increasing exposure, finer analysis can be performed
  - ➢ e.g. Spatial structure study w/ highest imaging resolution

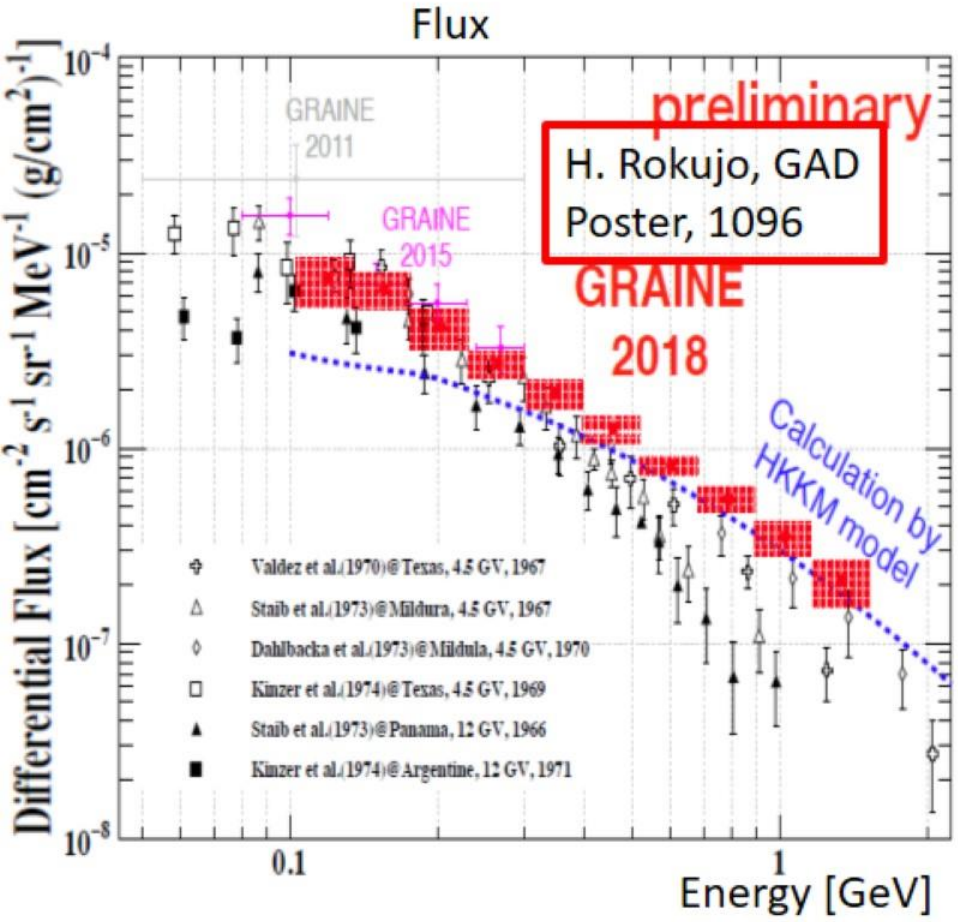
Number of Events /10 deg

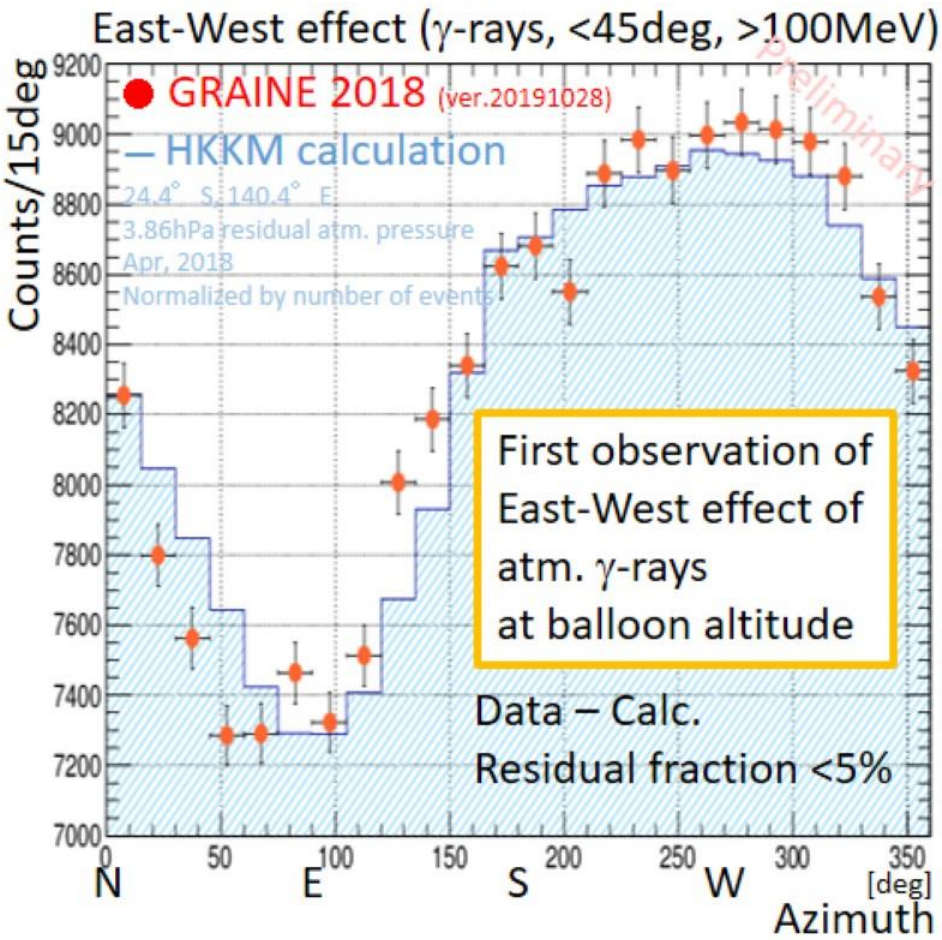
400
300
200
100
0
-100
-200

-30 -20 -10 0 10 20 30

Galactic Latitude [deg]

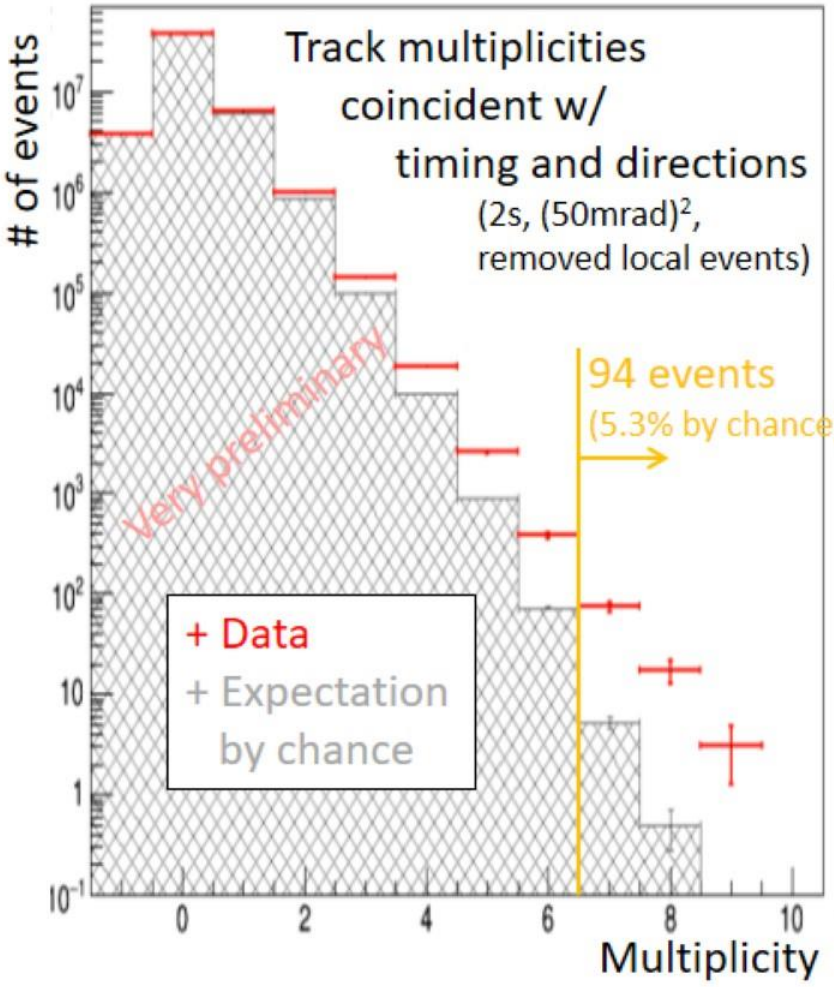
Atmospheric γ-ray measurements



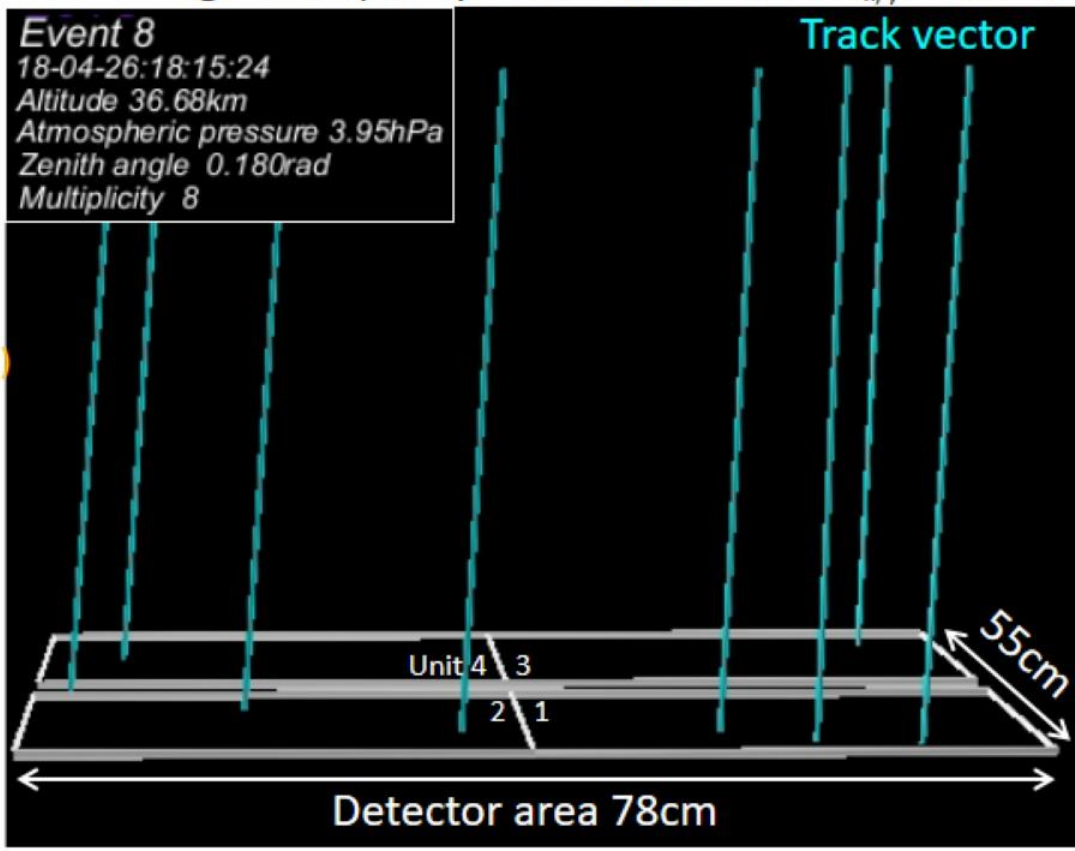


- ✓ BG and detector response understanding
- ✓ Atm. γ-ray physics (Primary, Solar activity, Geomagnetism, Atmosphere, Interaction, Secondary)
  - ➢ Flux and East-West effect in Sub-GeV
  - ➢ Comparison w/ atm. ν flux calculation
    - Contribution to Neutrino physics
  - ➢ Advantage by balloon-borne experiments

Search for hadron showers over the detector area



One of high multiplicity events ($|\Delta t|$<2.5s, $|\Delta\theta_{x,y}|$<25mrad)



Excess detection
beyond the expectation by chance

- ✓ Novel calibration source over the detector area
- ✓ Atmospheric γ-ray discriminable
  w/ charged particle coincidence

GRAINE Scientific observation roadmap

Takahashi, Aoki et al., ASR 62 (2018) 2945

Apr 2018, Demonstration

Done by JAXA balloon

Alice Springs
0.38m^2 aperture
17.3hours flight duration
3 – 5 g/cm^2 altitude

Highest imaging of the Vela pulsar
(>80MeV, x6.3@radious
→x39@solid angle)
→Highest angular resolution
emulsion γ-ray telescope

Galactic diffuse
- BG understanding w/i 1% level
- 2.7σ indication

Atmospheric γ-ray physics
- Flux and EW effect in Sub-GeV
- Comparison w/ atm. ν flux calculation
  - Contribution to ν physics
- Advantage by balloon-borne exp.

Hadron shower
over the detector area
- Calib. source over the detector area
- Atm. γ-ray discriminable

Chemical Composition Study
A. Iyono, CRD, Poster, 869

2023–, Scientific flight

Alice Springs, North. hemisphere
10m^2 aperture
>~36hours flight duration } repeated
<~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

Test of fundamental symmetries beyond the Planck scale

Transient sources
Obs. w/ high sensitivity
& high photon stats
→ Studying transient sources & w/ ones

Search for γ-ray correlation with Giant Radio Pulses from pulsars
Search for GeV γ-ray Pair Halo → Constraints on IGMF

GRAINE Scientific observation roadmap

Takahashi, Aoki et al., ASR 62 (2018) 2945

2023, Commissioning

Alice Springs
2.5m^2 aperture
>15 hour flight duration
<5g/cm^2 altitude
} x2

JAXA balloon approved

Full scale

Alice Springs, North. hemisphere
10 m^2 aperture
>~36 hour flight duration
<~10 g/cm^2 altitude
} repeated

Largest aperture in γ-ray telescopes

Vela pulsar in GeV range for highest imaging (& down to ~10MeV)

Diffuse & Point sources around Galactic Center

Transient sources (~2 flares)

Other sources
- Galactic diffuse (on the plane)
- Geminga
- PSR J1709-4429
- 3C 454.3
- Crab
- Moon, PKS 1510-08, W44, Sun etc.

Vela pulsar
Polarization observation (<50%)
→ Pioneering polarization observation for high energy γ-rays

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Precise spectrum measurement
High resolution imaging
→ Studying cosmic ray sources

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Search for γ-ray correlation with Giant Radio Pulses from pulsars

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For GRAINE next

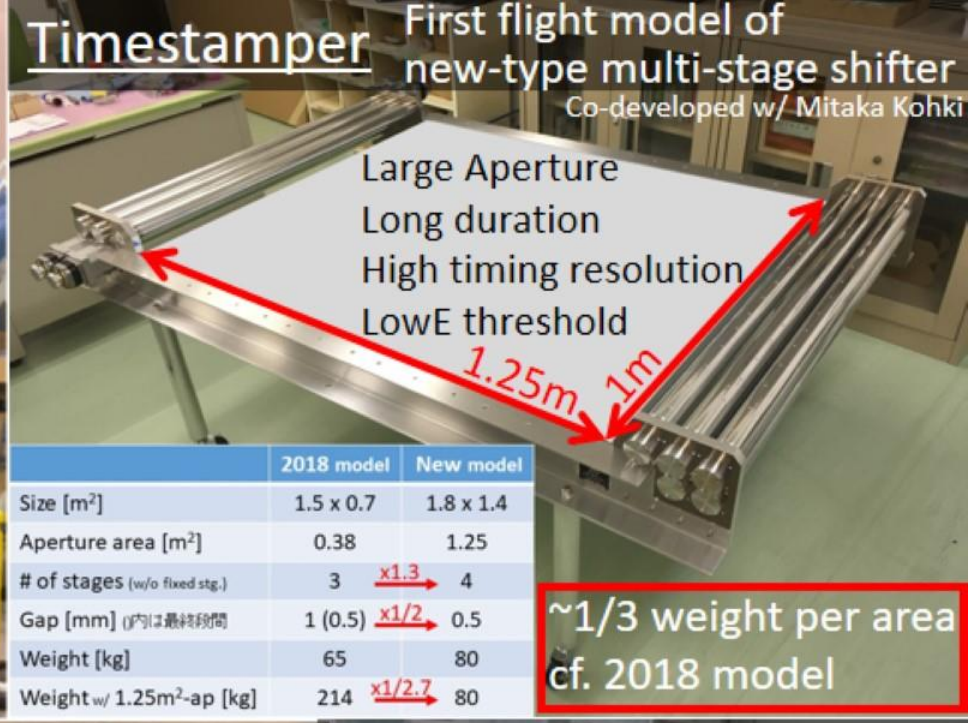
Pressure vessel gondola 2.5 m² (2 units)

Light, Thin, 0.3atm 700kg payload

Timestamper

First flight model of new-type multi-stage shifter

Co-developed w/ Mitaka Kohki

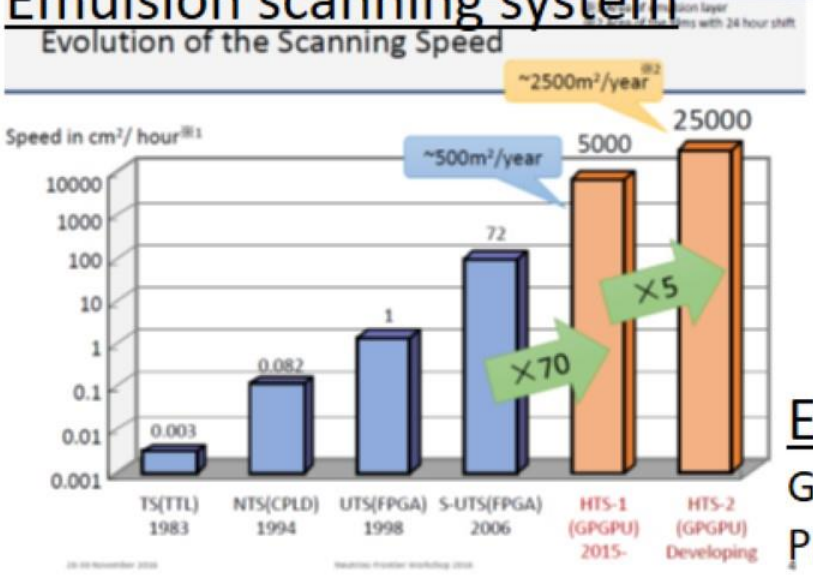


	2018 model	New model
Size [m²]	1.5 x 0.7	1.8 x 1.4
Aperture area [m²]	0.38	1.25
# of stages (w/o fixed stg.)	3 x1.3	4
Gap [mm] (()内は最終段間	1 (0.5) x1/2	0.5
Weight [kg]	65	80
Weight w/ 1.25m²-ap [kg]	214 x1/2.7	80

~1/3 weight per area cf. 2018 model

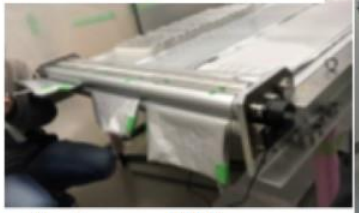
Balloon exp. system (prototype)

Emulsion scanning system



Envelope R&D

FIXELON® introduction



Large vacuum packing machine

Largest vacuum packing in the balloon-borne exp.

Emulsion film

Long-term stability test, Fading test

Gel production, Machine coating, Quality control

Preprocessing, Vacuum packing, Developing