Precise high-energy gamma-ray observations in GRAINE, latest results on 2018 balloon-borne experiment and next/future experiments

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Aichi U of Education, Gifu U, ISAS/JAXA, Kobe U, Nagoya U, Okayama U of Science

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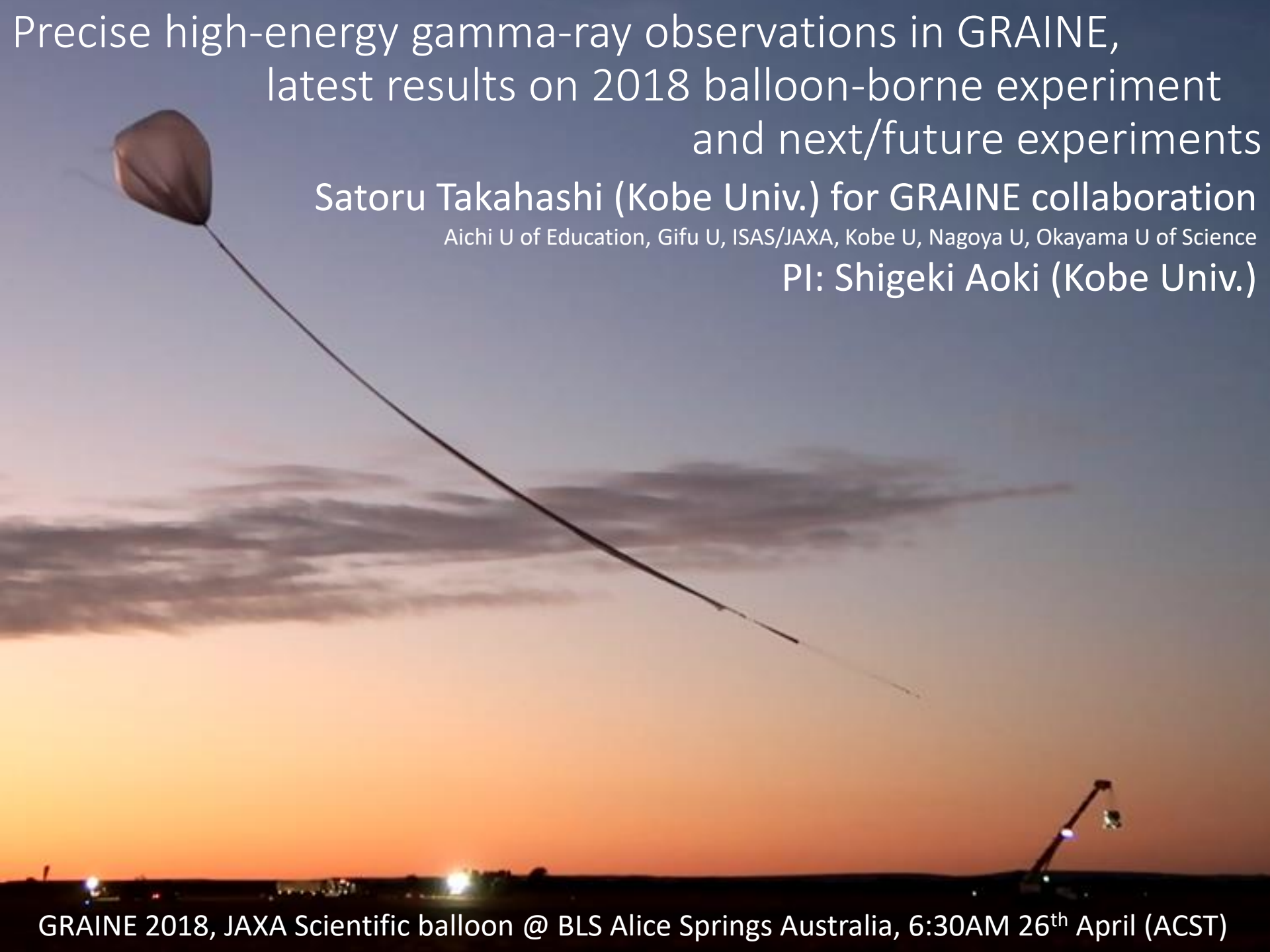


GRAINE 2018, JAXA Scientific balloon @ BLS Alice Springs Australia, 6:30AM 26th April (ACST)

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

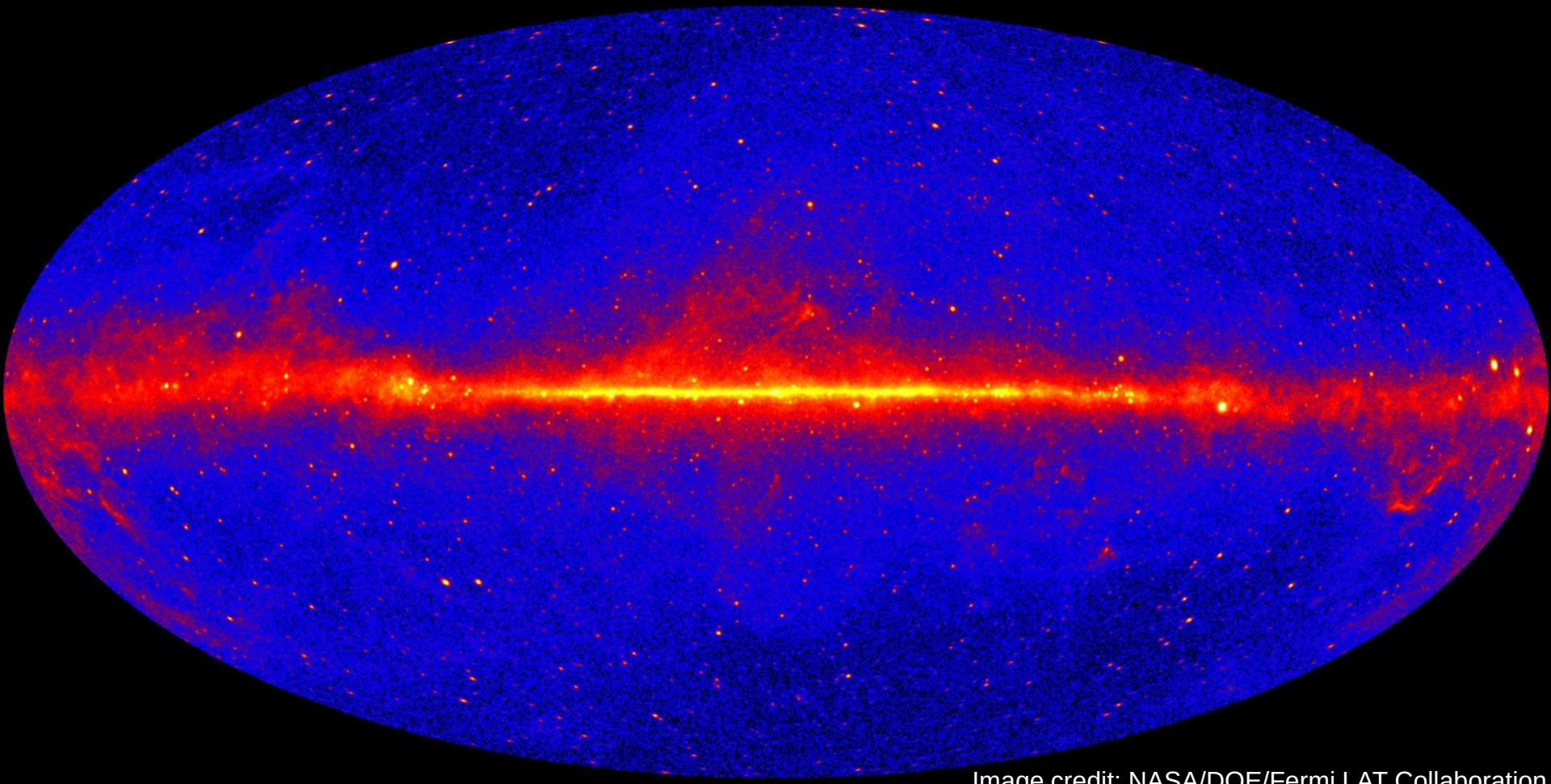


Image credit: NASA/DOE/Fermi LAT Collaboration

5064 sources (4FGL)

Nuclear emulsion

Microscopic view

10 μm

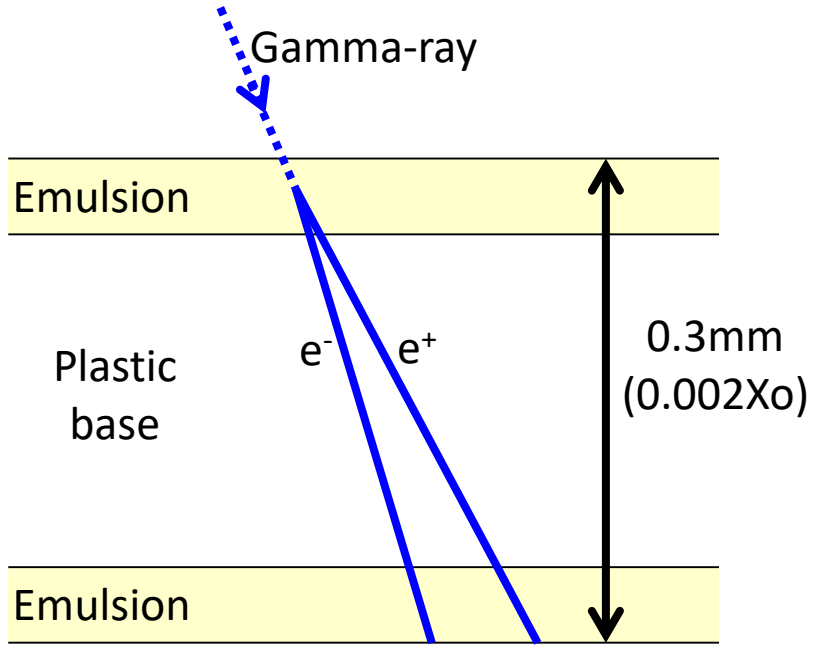
Intrinsic position accuracy of ~50nm

γ-ray

$e^{+/-}$

$e^{-/+}$

Cross sectional view of an emulsion film



Precisely tracking beginning of e-pairs

suppressed multiple Coulomb scattering

→ High angular resolution

→ Polarization sensitive

+Large scalability

+Automatic large-area-analysis technique

+Timestamping technique

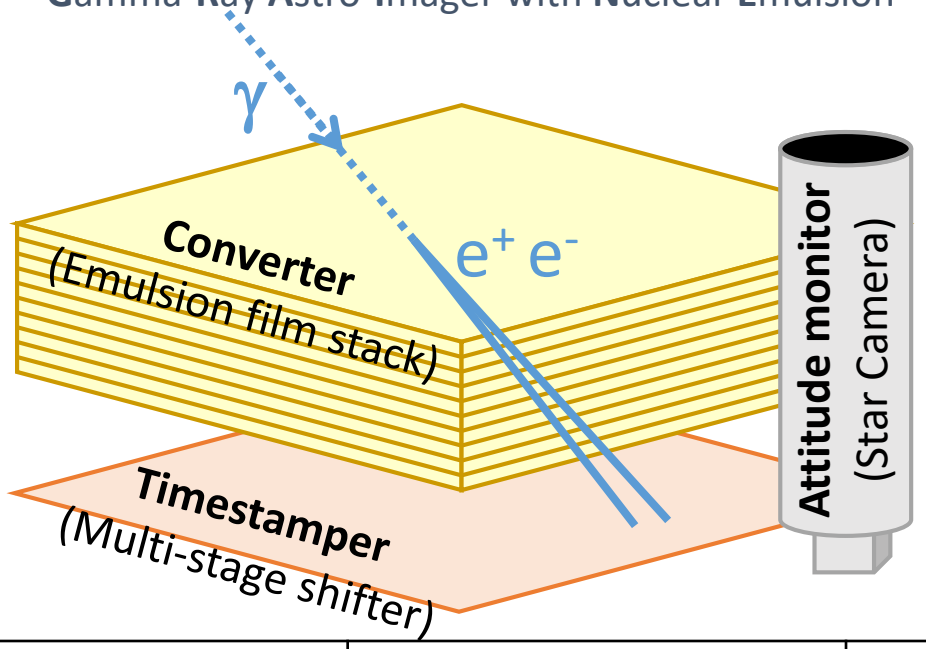
Novel γ-ray telescope

Highest angular resolution
First polarization sensitivity
Largest aperture area

GRAINE

Emulsion γ-ray telescope
Repeated long-duration balloon flights

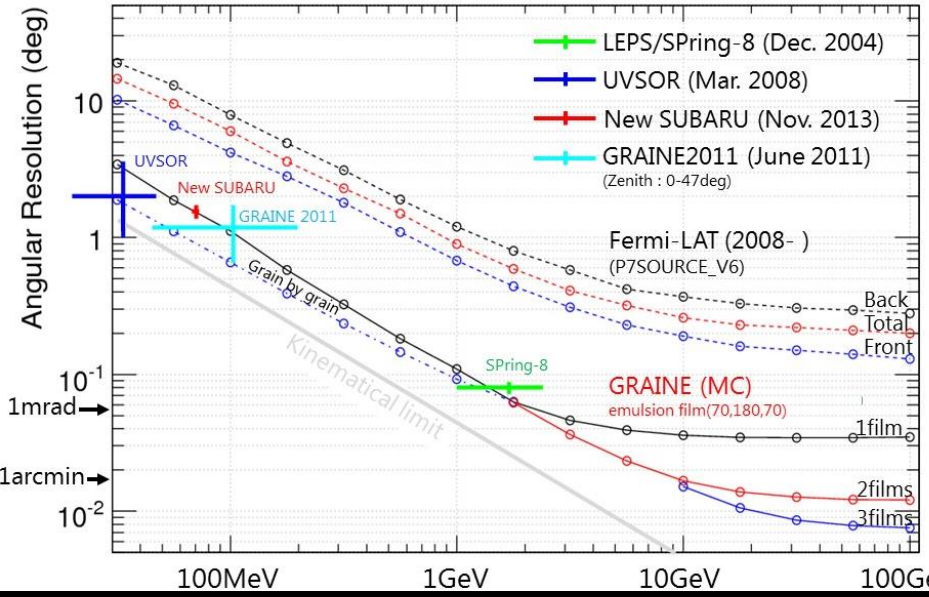
Gamma-Ray Astro-Imager with Nuclear Emulsion



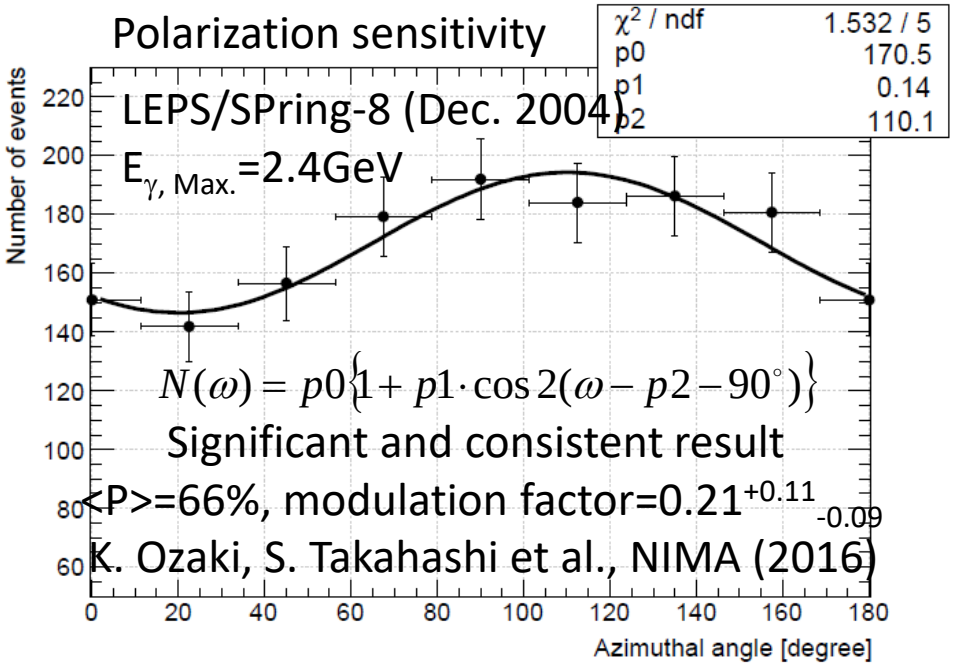
∗ $10m^2 * \varepsilon_{trans} * \varepsilon_{conv} * \varepsilon_{det}$

	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

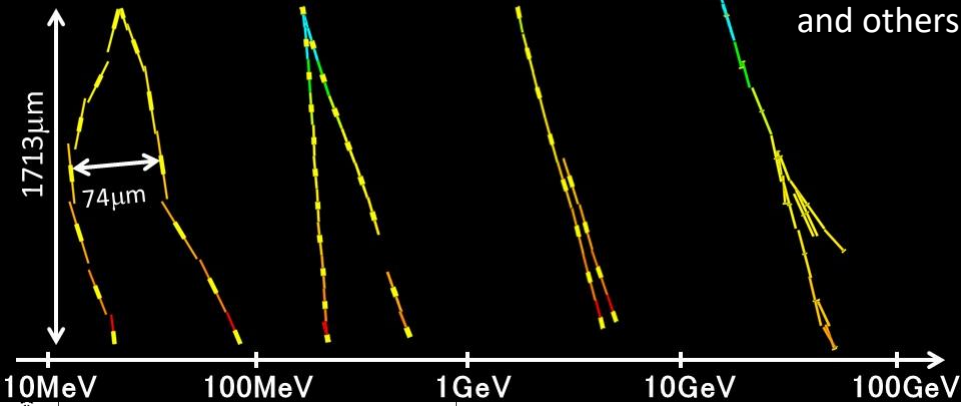


Polarization sensitivity



Energy range

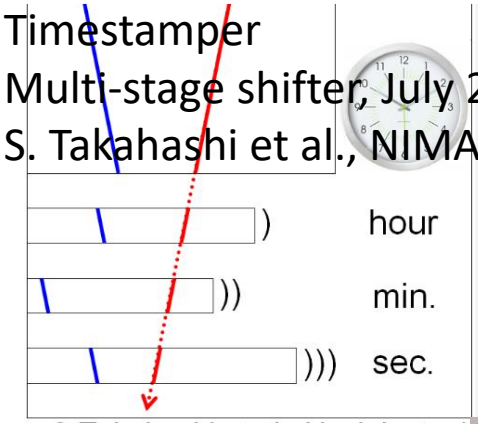
Atmospheric γ-ray @Mt. Norikura (July, Sep. 2007, July 2013), and others

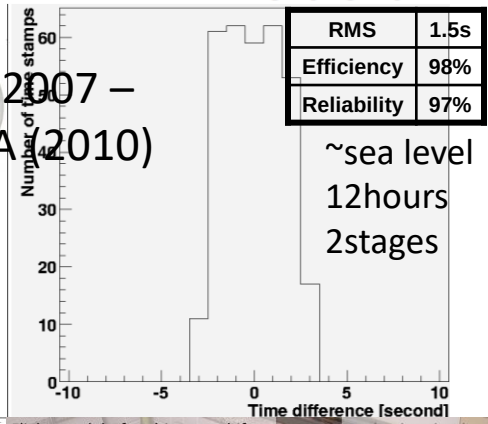


Timestamper

Multi-stage shifter, July 2007 –

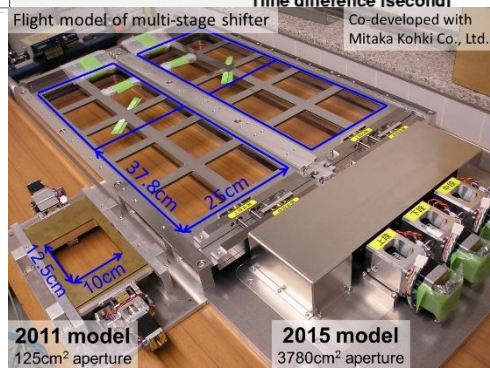
S. Takahashi et al., NIMA (2010)





RMS	1.5s
Efficiency	98%
Reliability	97%

~sea level
12hours
2stages



Momentum w/MCS

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

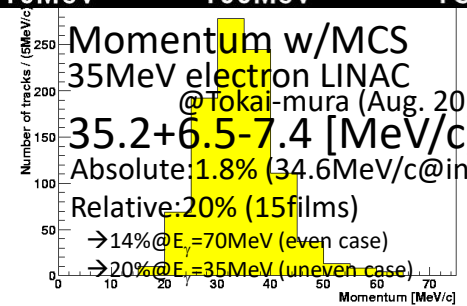
35.2+6.5-7.4 [MeV/c]

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

Relative:20% (15films)

→14%@E_γ=70MeV (even case)

→20%@E_γ=35MeV (uneven case)

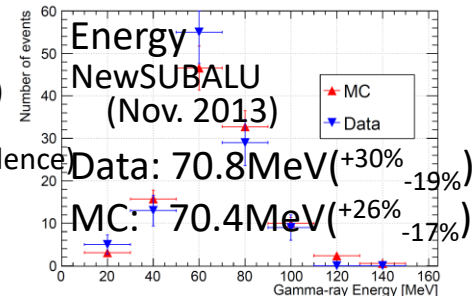


Energy

NewSUBALU (Nov. 2013)

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

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



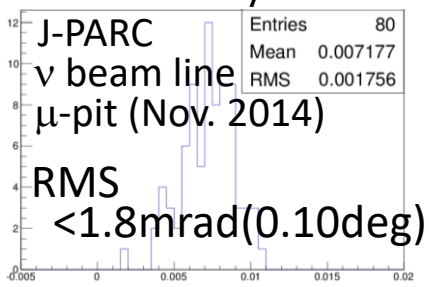
Flatness study

J-PARC

ν beam line

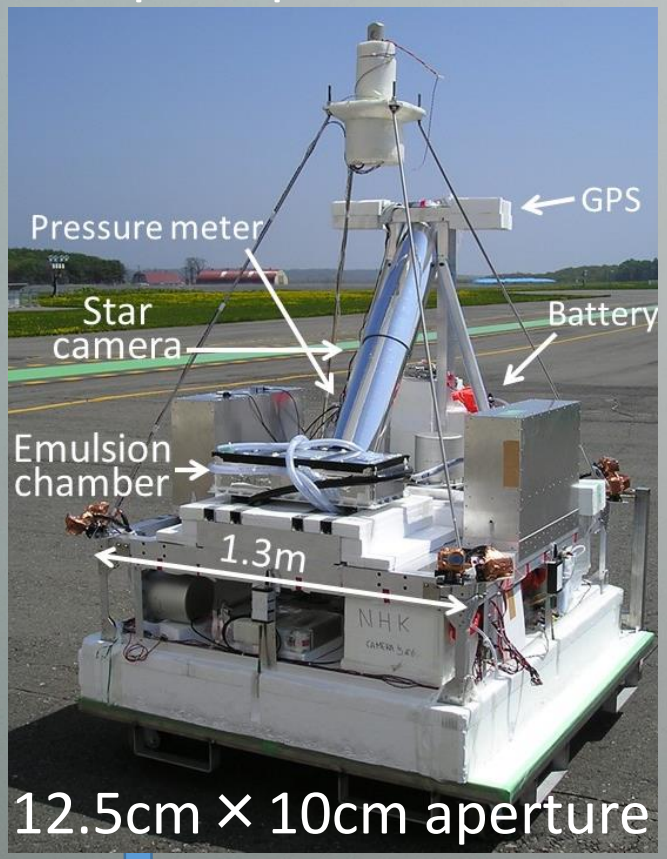
μ-pit (Nov. 2014)

RMS <1.8mrad(0.10deg)



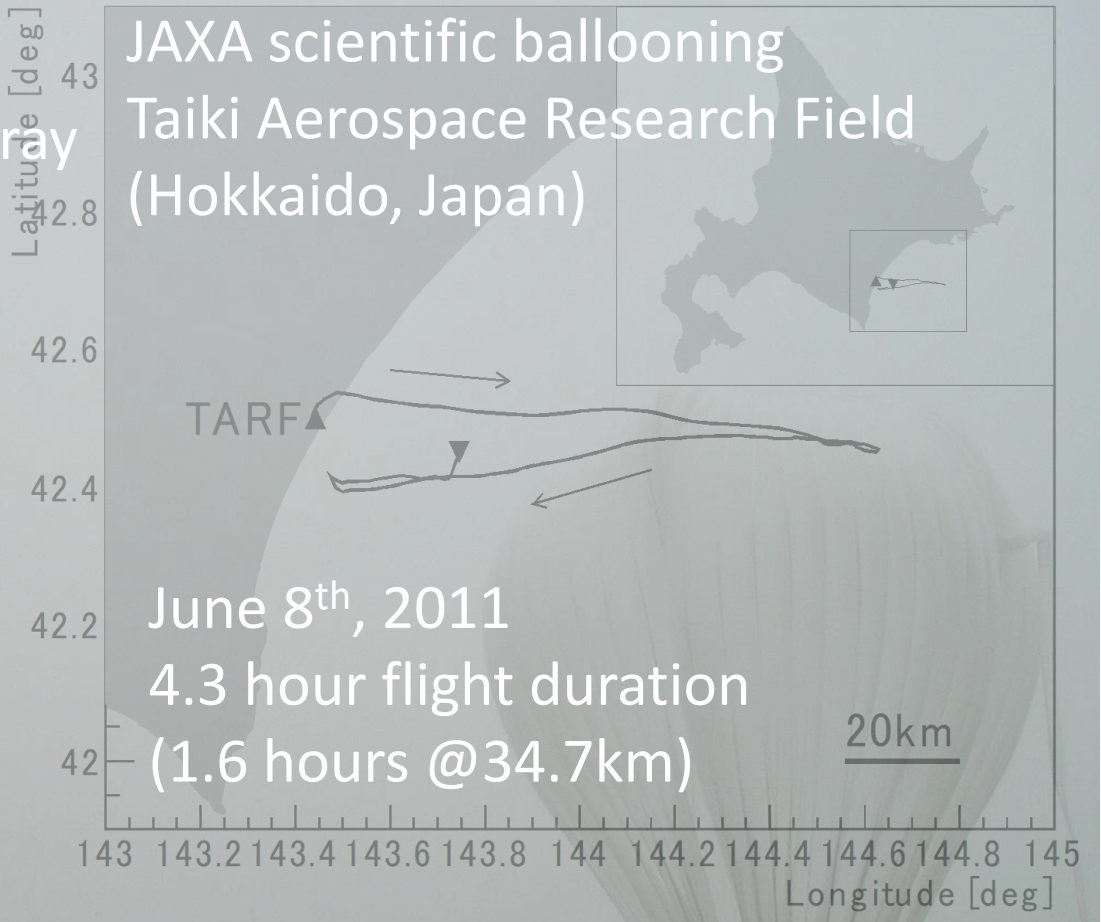
GRAINE 2011

First balloon-borne emulsion γ-ray telescope experiment



12.5cm × 10cm aperture

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

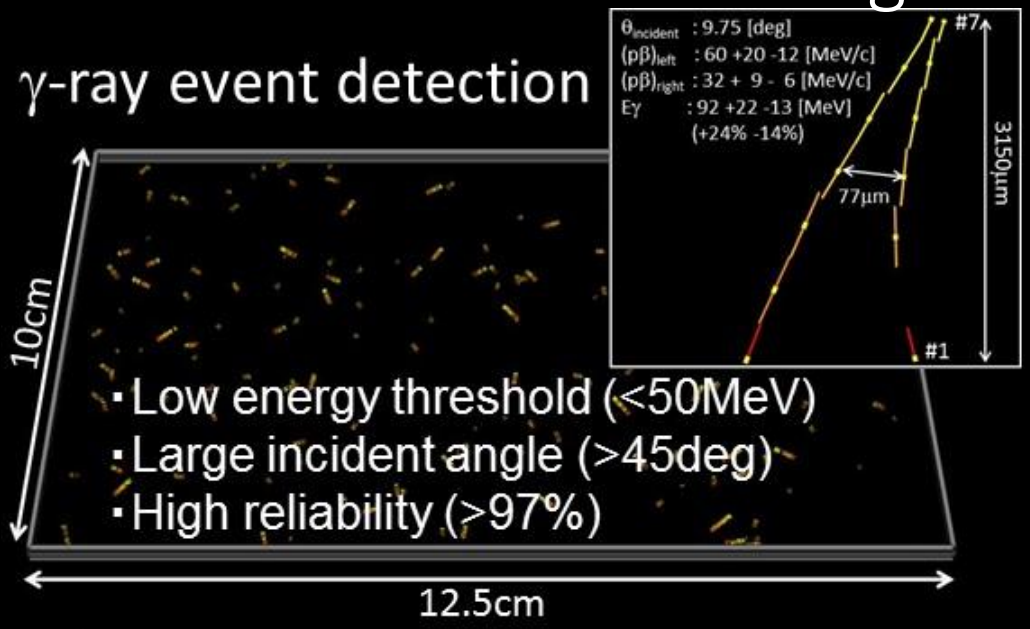


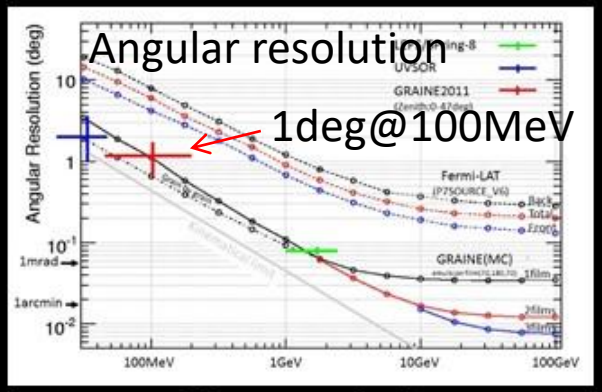
June 8th, 2011
4.3 hour flight duration
(1.6 hours @34.7km)

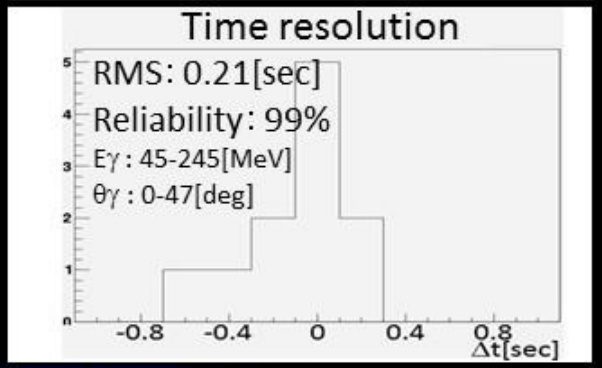
First balloon-borne experiment
Feasibility demonstration

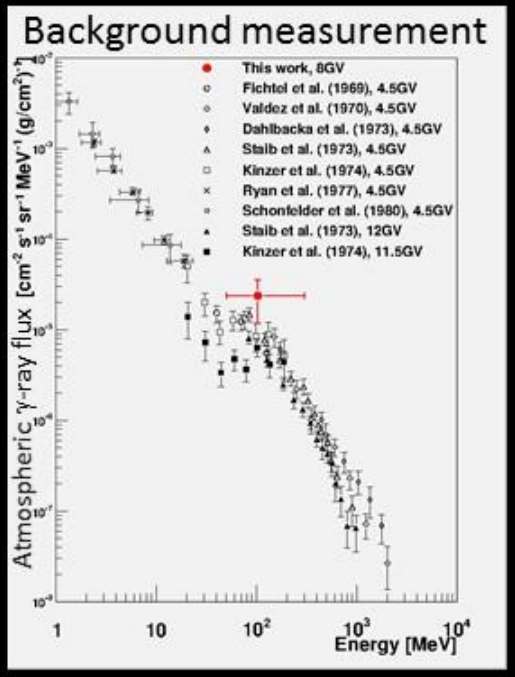
GRAINE 2011 Flight data analysis

γ-ray event detection

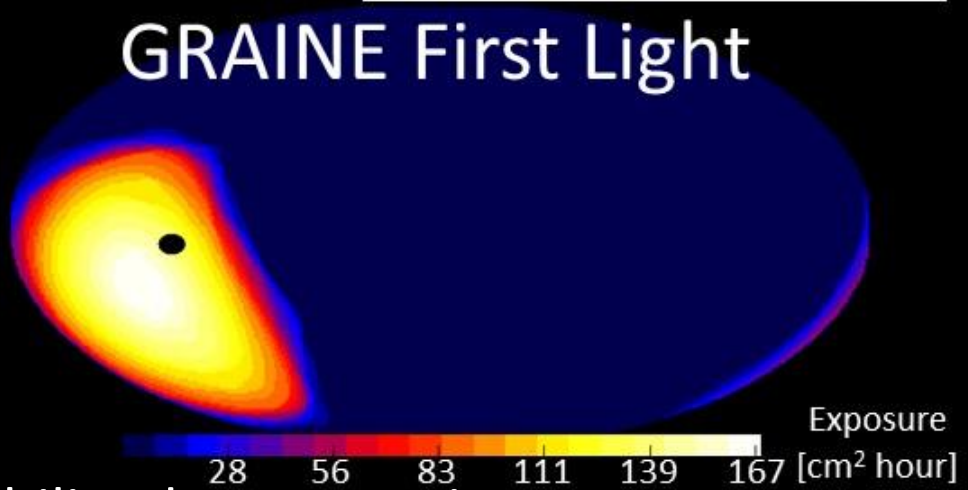








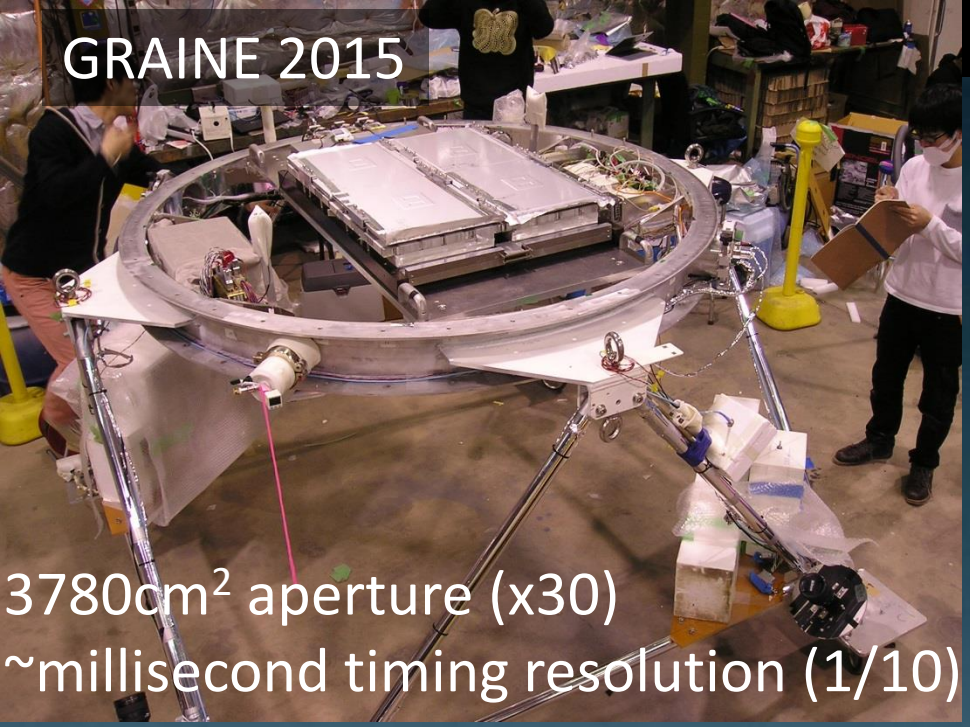
GRAINE First Light



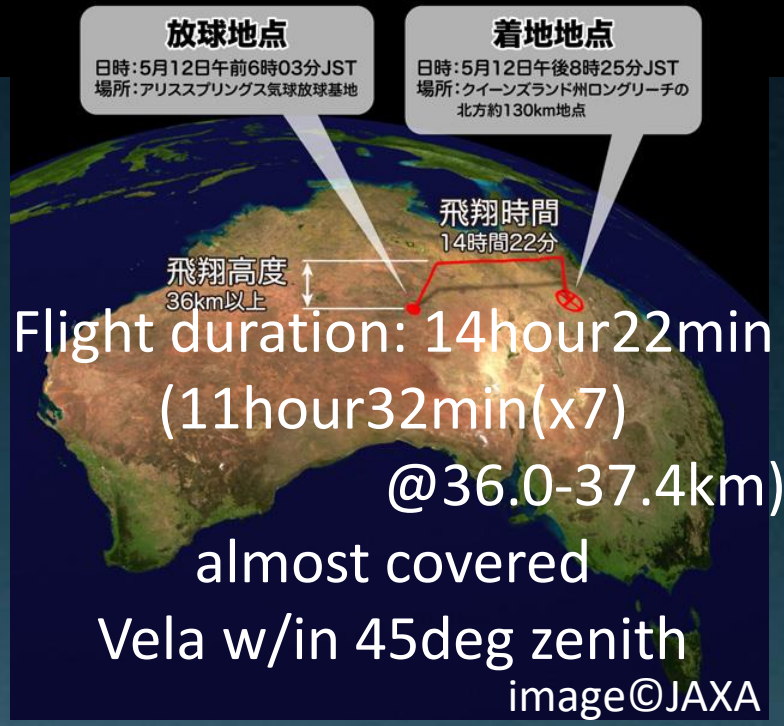
Feasibility demonstration

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

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 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

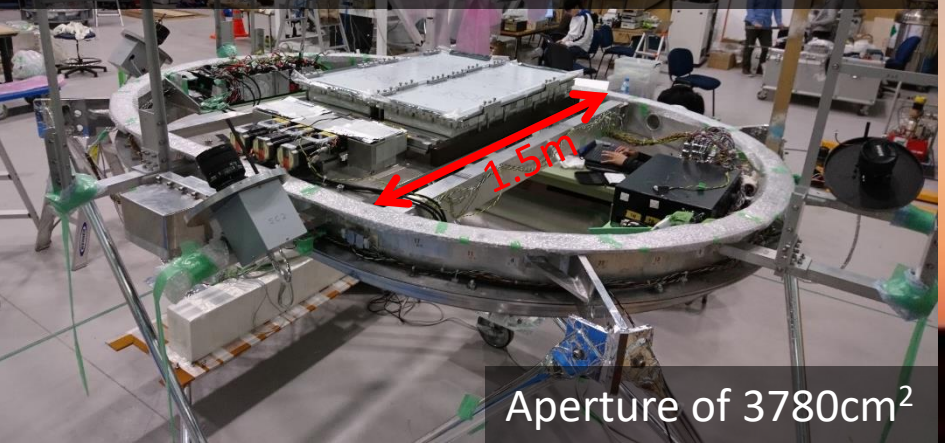
Flight duration: 17.4h (21%↑)

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)

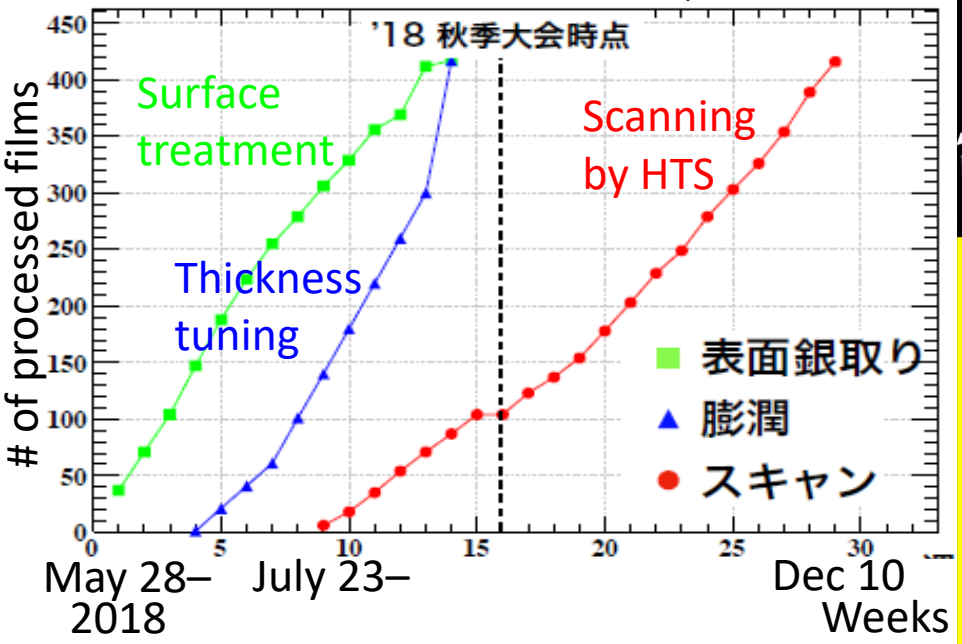
Various developments, improvements, preparations

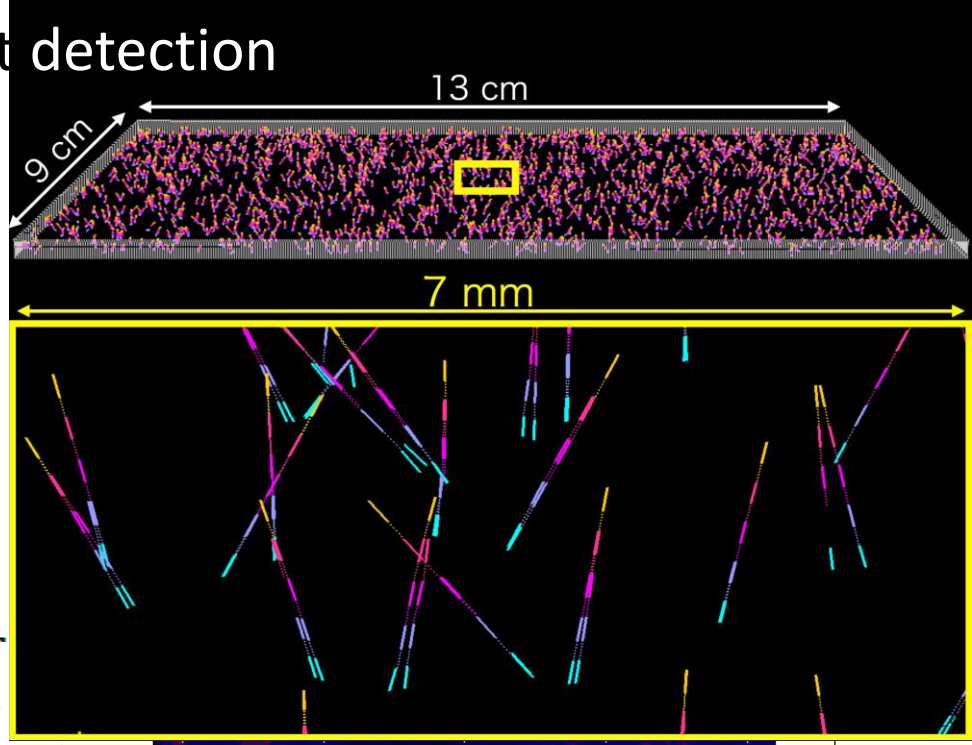


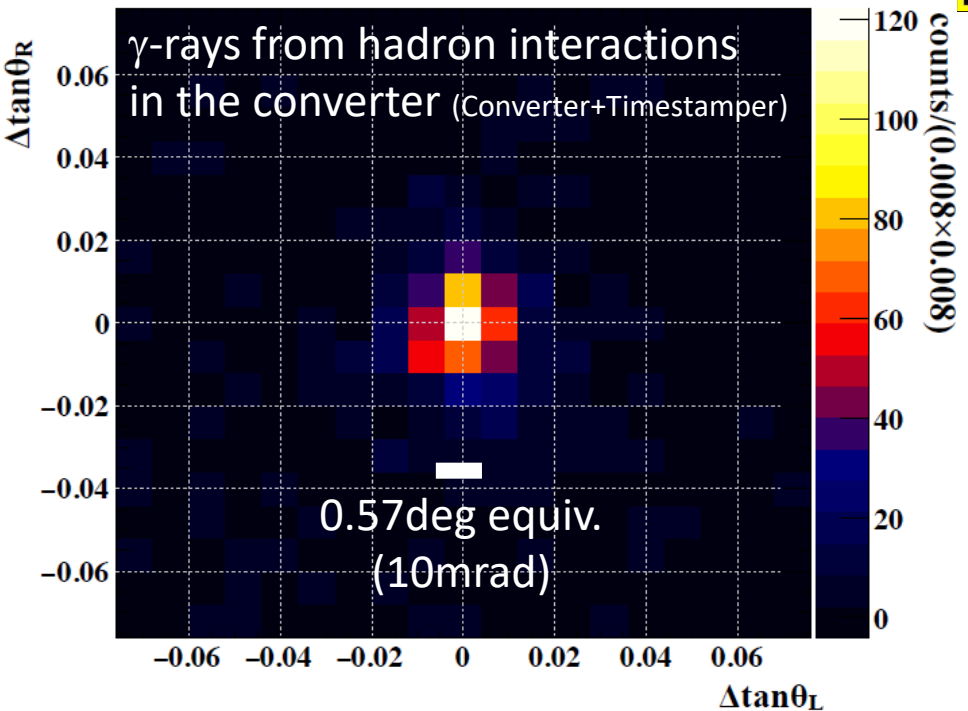
Aperture of 3780cm^2

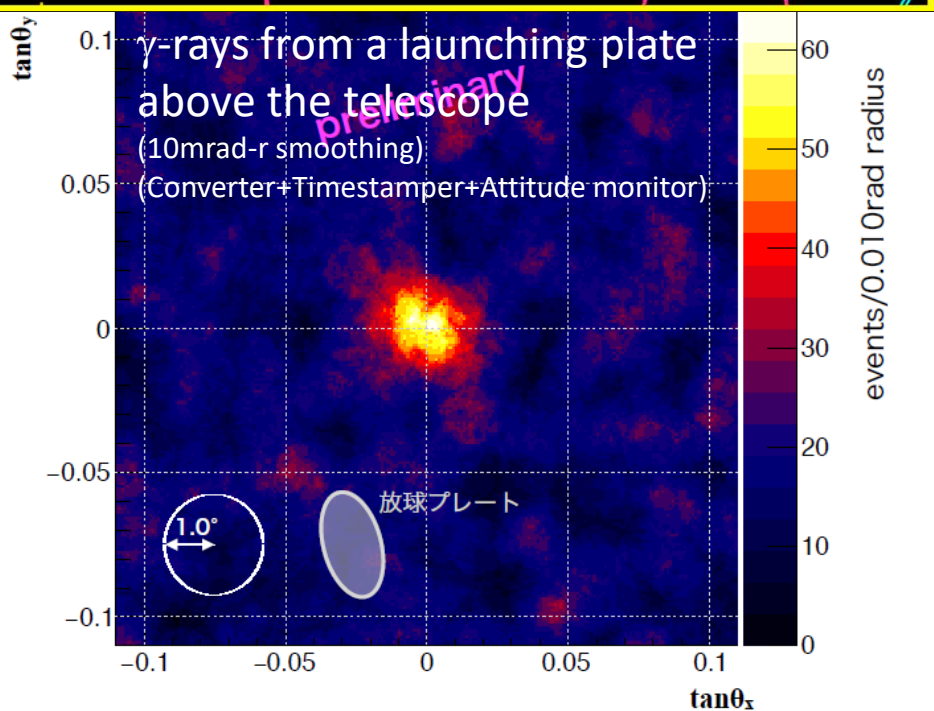
GRAINE 2018, JAXA Scientific balloon
@BLS Alice Springs Australia, 6:30AM 26th April (ACST)

GRAINE 2018, Converter, γ-ray event detection

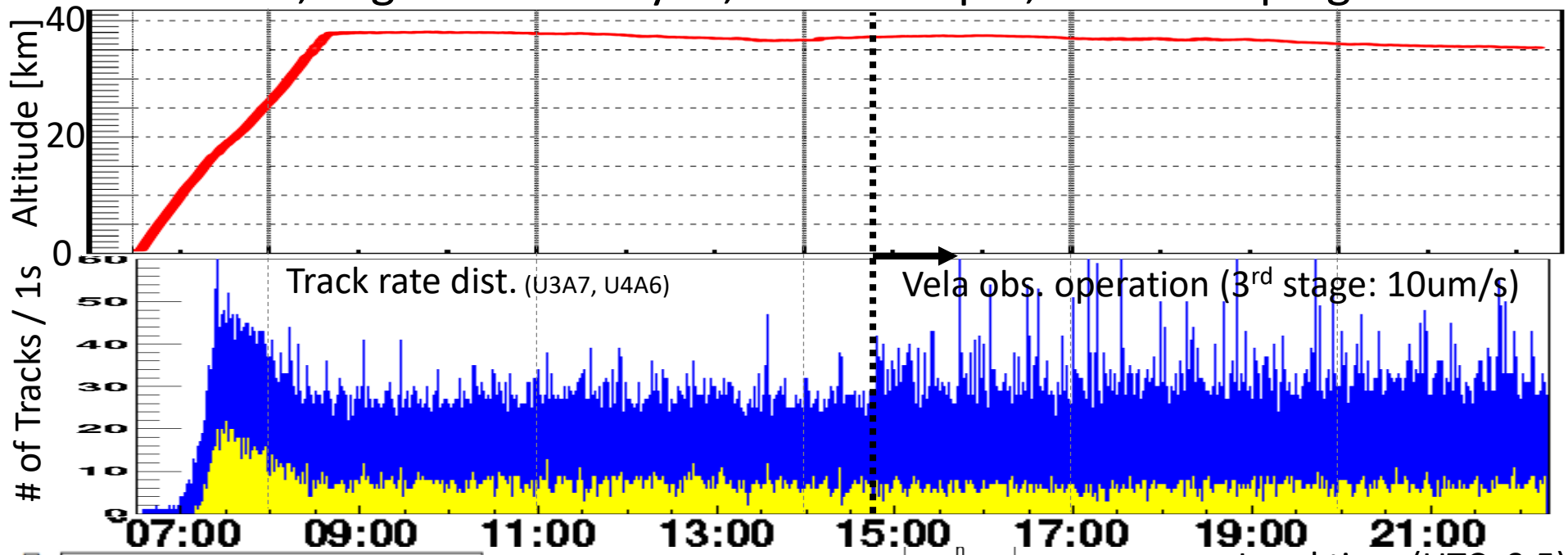


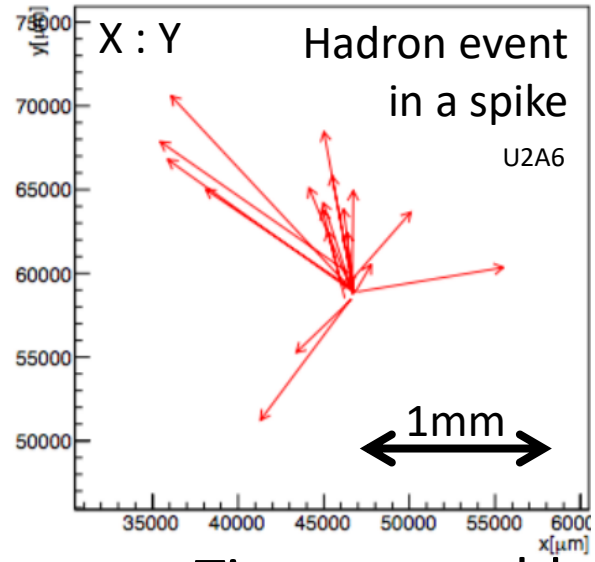


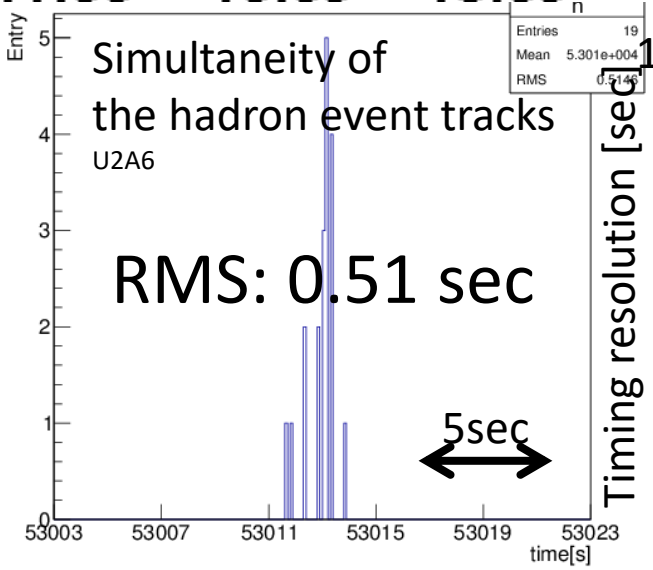


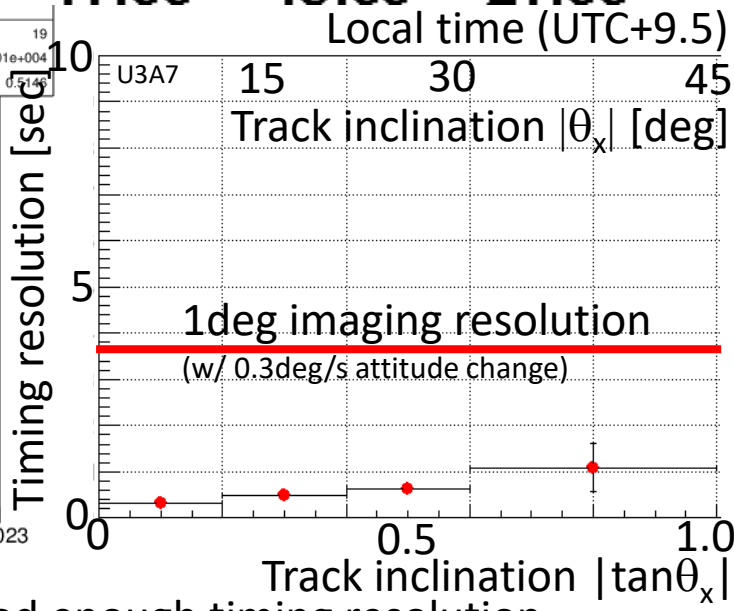


GRAINE 2018, Flight data analysis, Timestamper, Timestamping





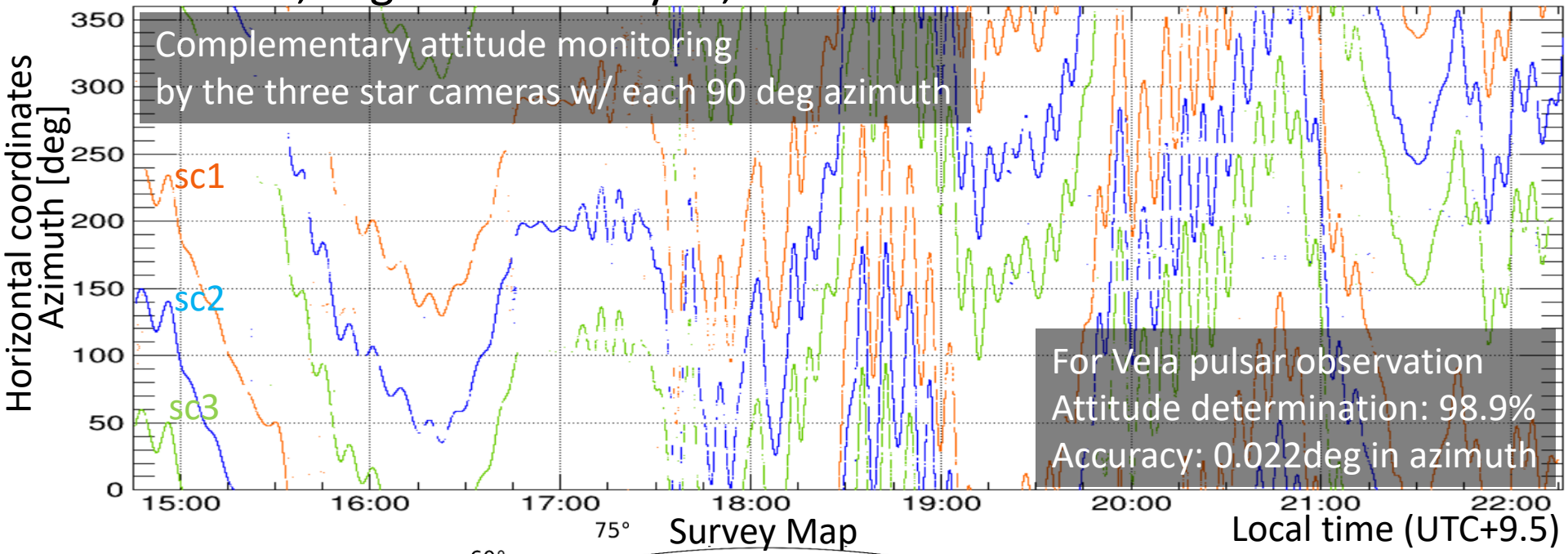




Timestampable
for high resolution γ-ray imaging

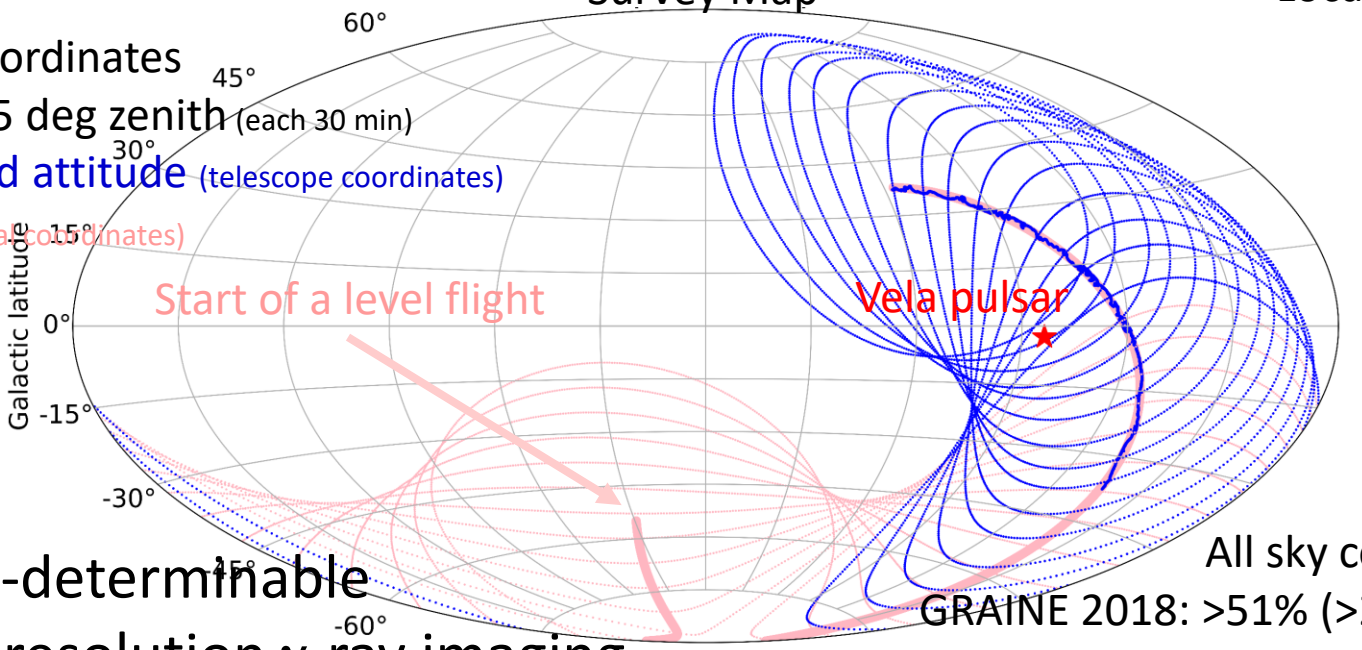
Good enough timing resolution
for 1deg imaging resolution

GRAINE 2018, Flight data analysis, Attitude monitor



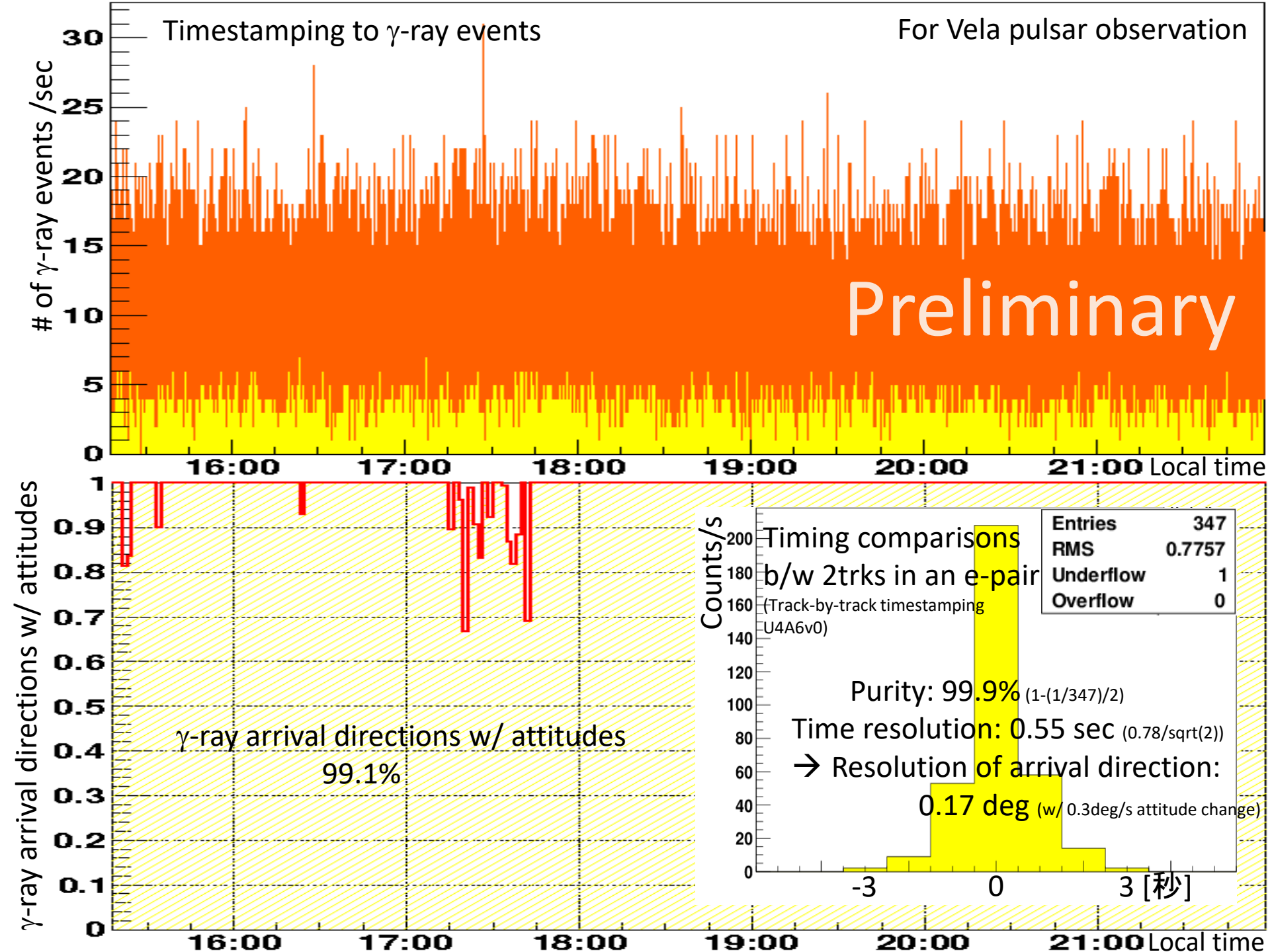
Survey Map

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

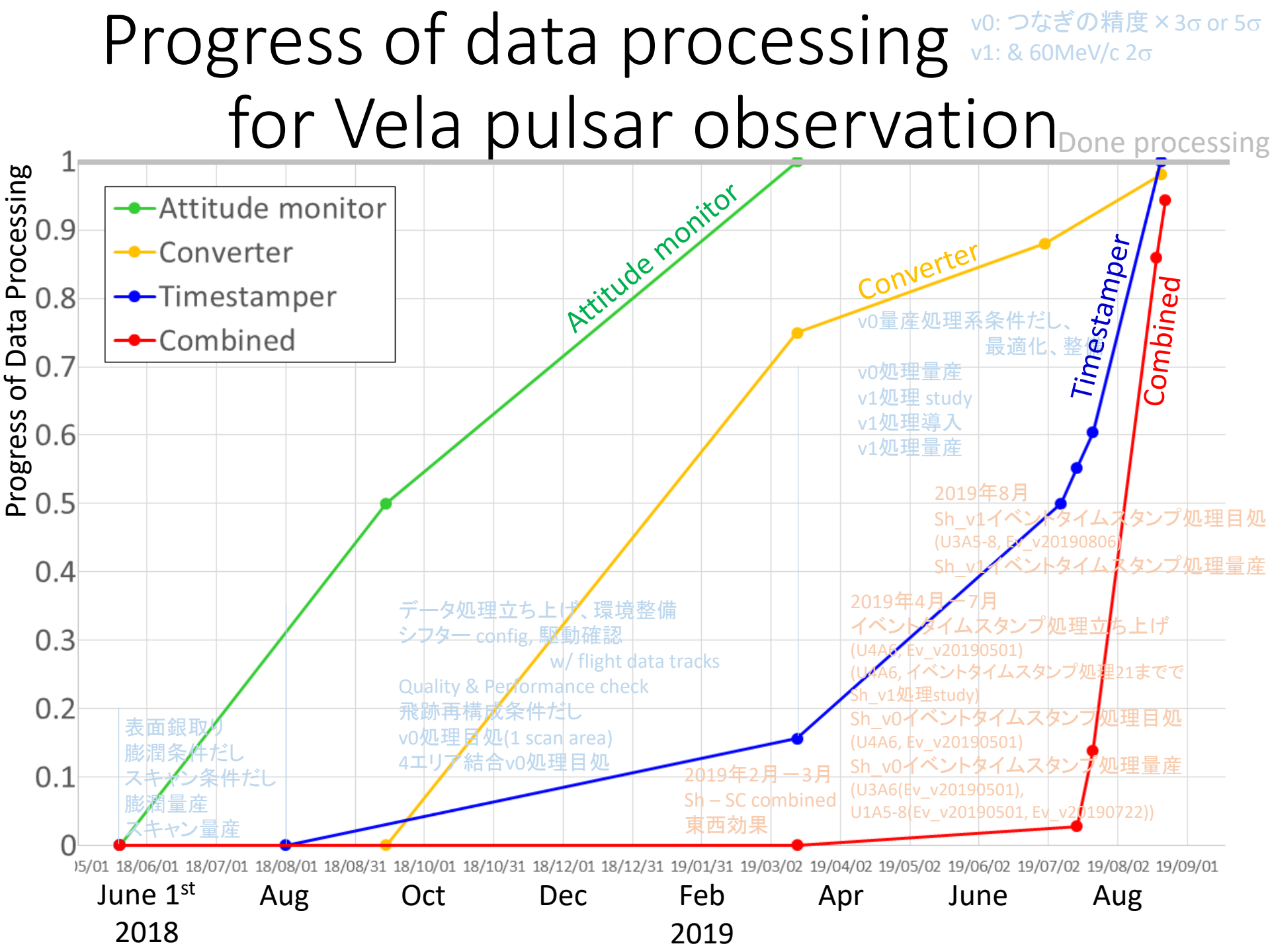


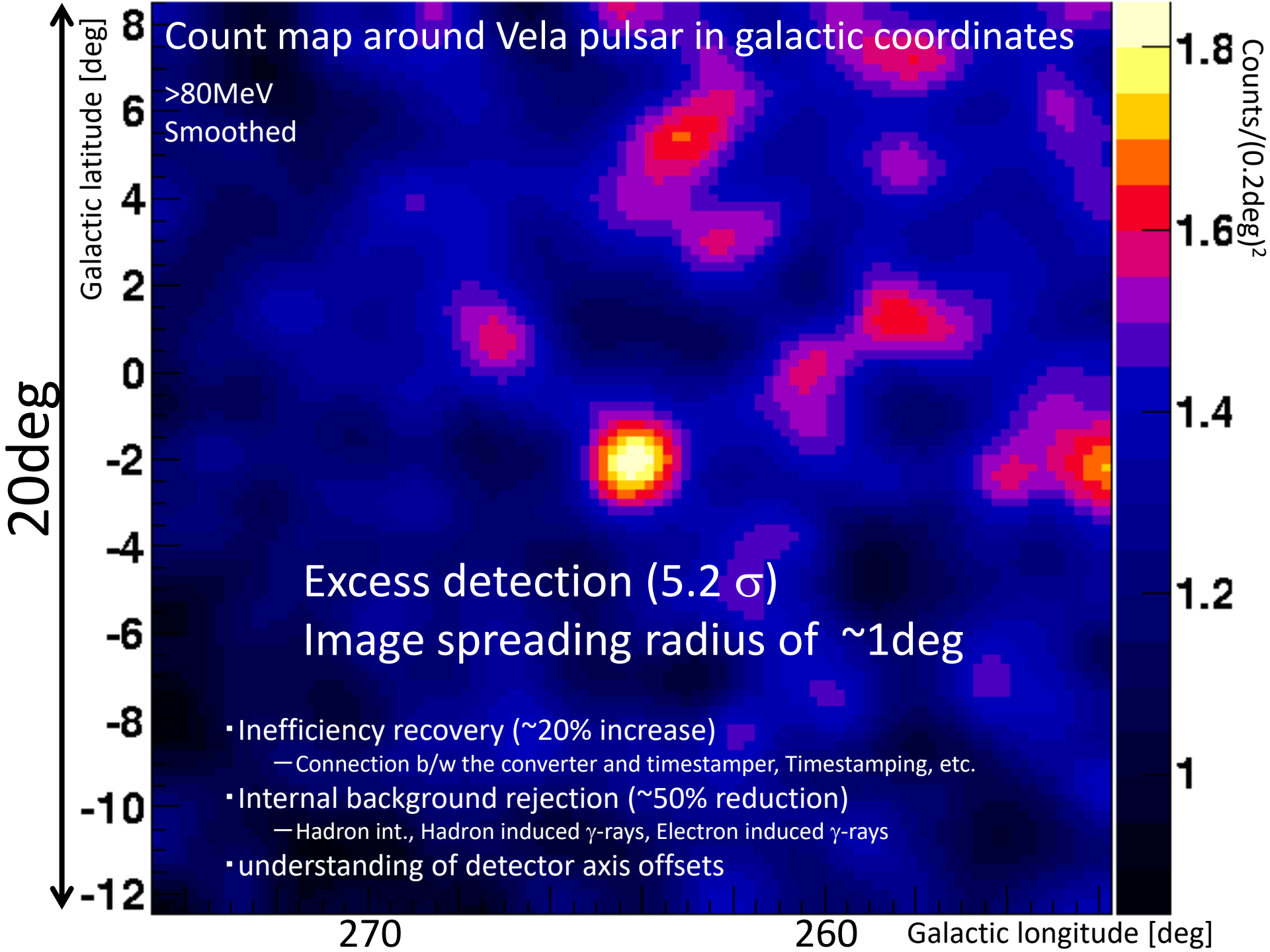
Attitude-determinable
for high resolution γ-ray imaging

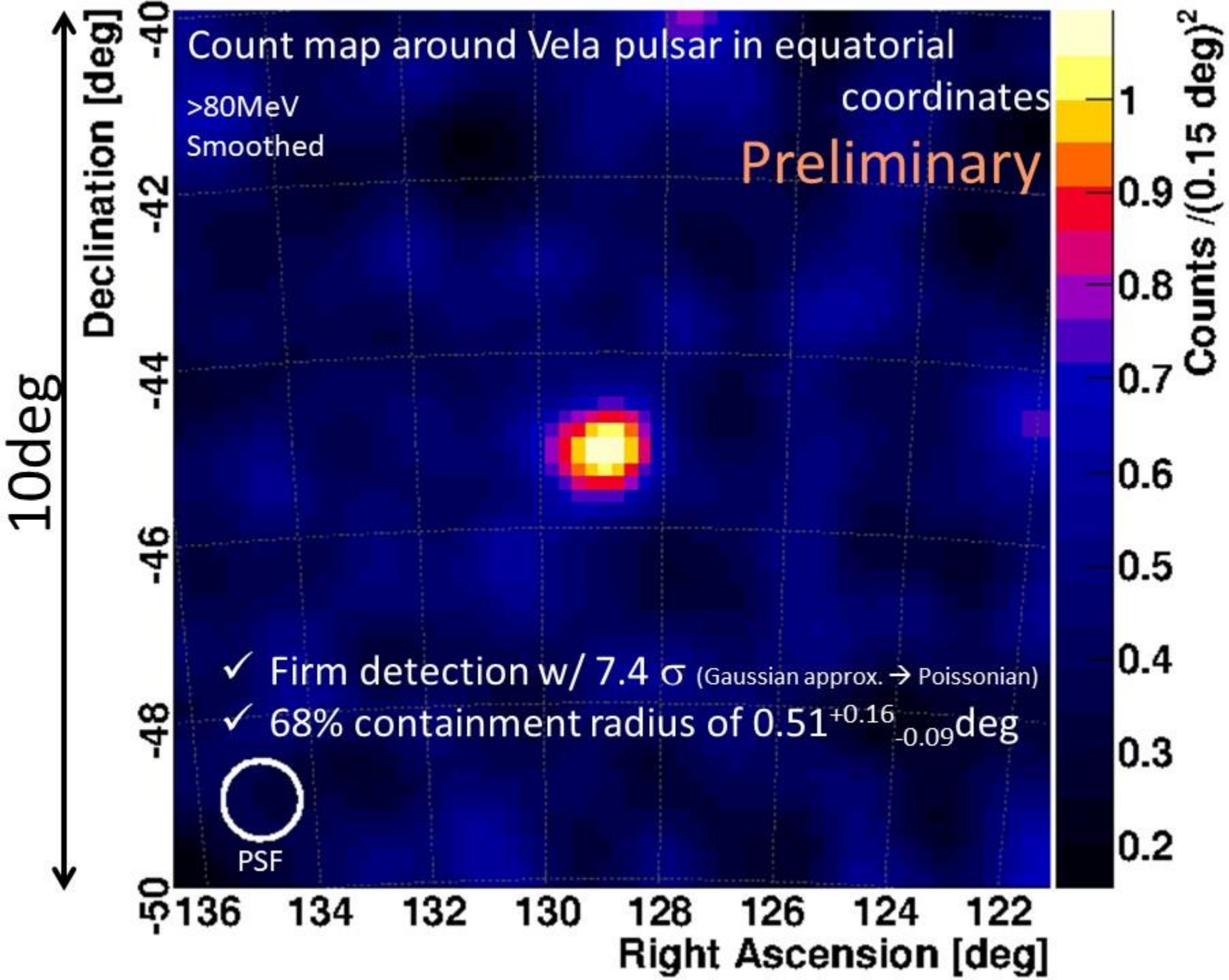
All sky coverage
GRAINE 2018: >51% (>2.0π[sr])
24h flight duration: >65% (>2.6π[sr]) incl. GC


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]

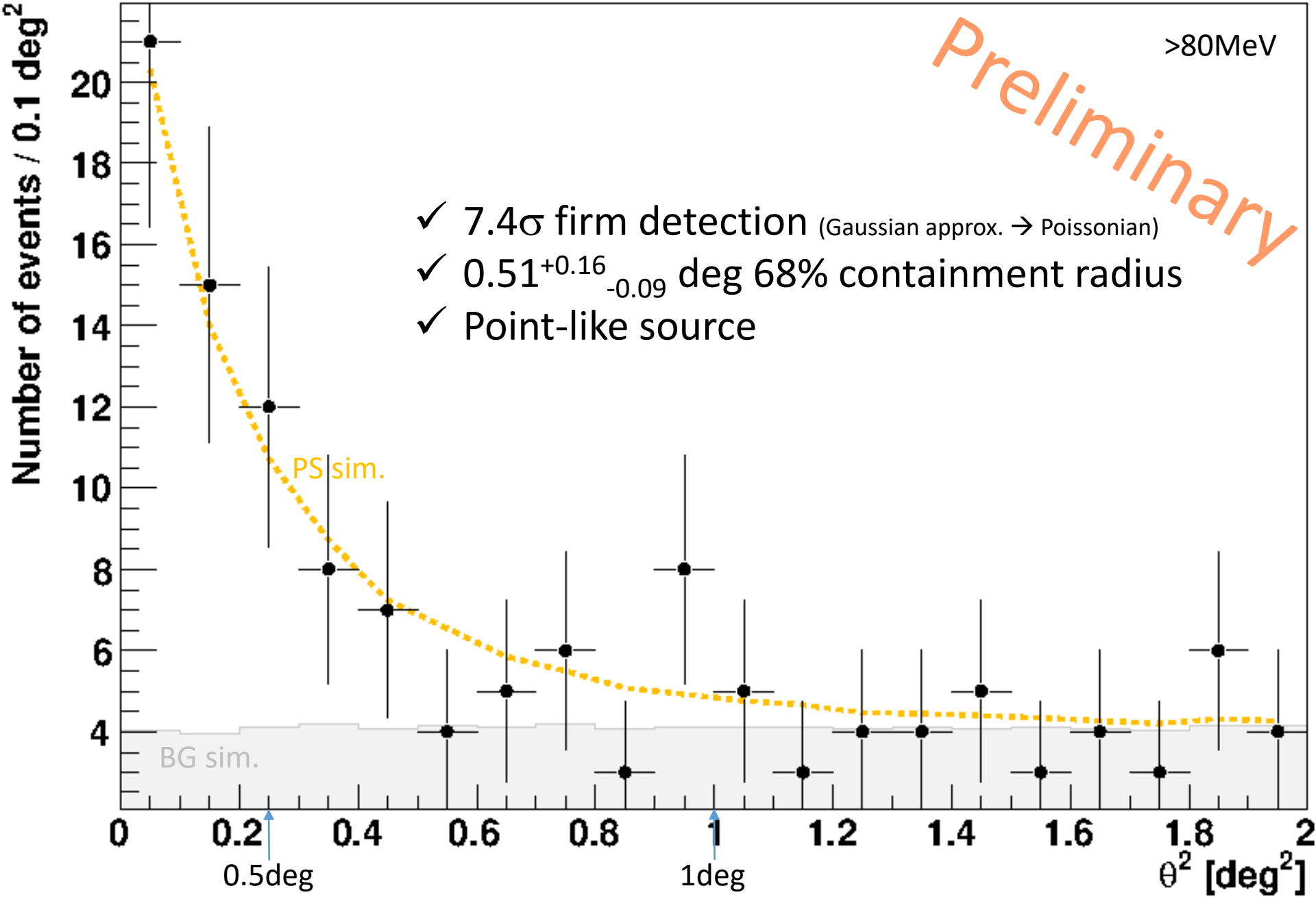
Progress of data processing for Vela pulsar observation



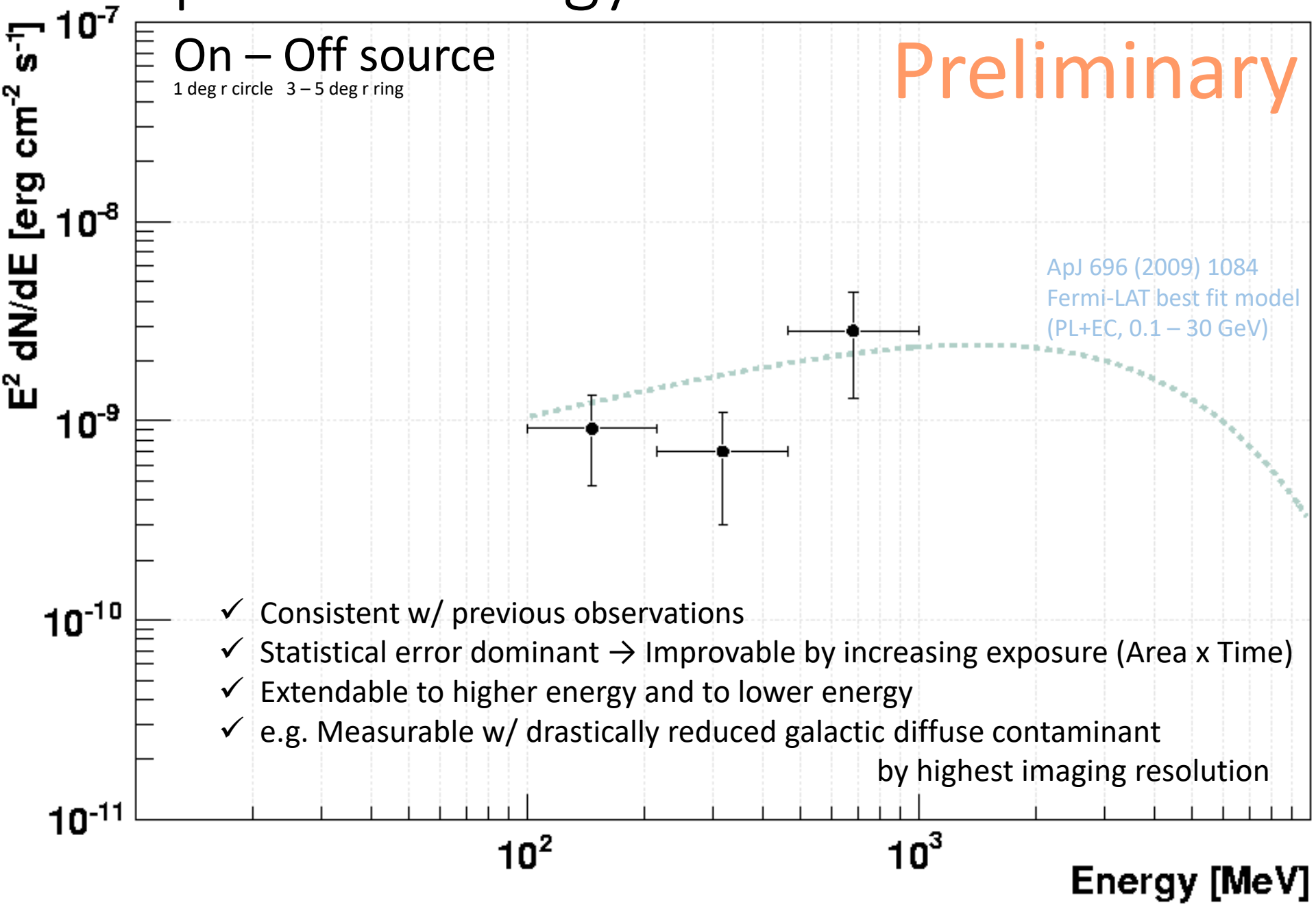

Count map around Vela pulsar in galactic coordinates
>80MeV
Smoothed
Excess detection (5.2 σ)
Image spreading radius of ~1deg
・Inefficiency recovery (~20% increase)
—Connection b/w the converter and timestamper, Timestamping, etc.
・Internal background rejection (~50% reduction)
—Hadron int., Hadron induced γ-rays, Electron induced γ-rays
・understanding of detector axis offsets
20deg
Galactic latitude [deg]
8
6
4
2
0
-2
-4
-6
-8
-10
-12
270
260
Galactic longitude [deg]
Counts/(0.2deg)²
1.8
1.6
1.4
1.2
1


Count map around 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

Radial profile (θ^2 distribution)

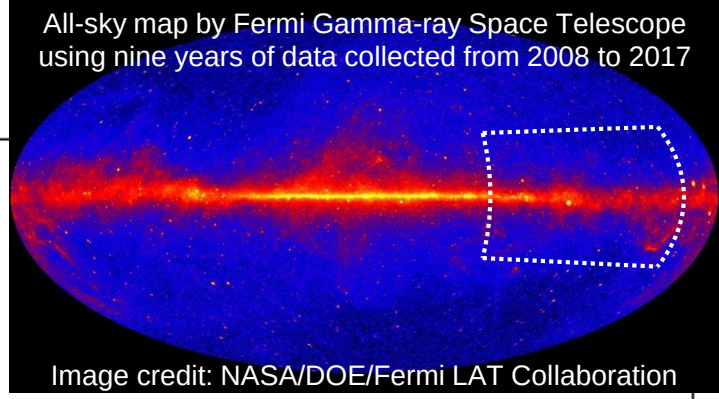


Spectral energy distribution



- ✓ Consistent w/ previous observations
- ✓ Statistical error dominant → Improvable by increasing exposure (Area x Time)
- ✓ Extendable to higher energy and to lower energy
- ✓ e.g. Measurable w/ drastically reduced galactic diffuse contaminant by highest imaging resolution

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

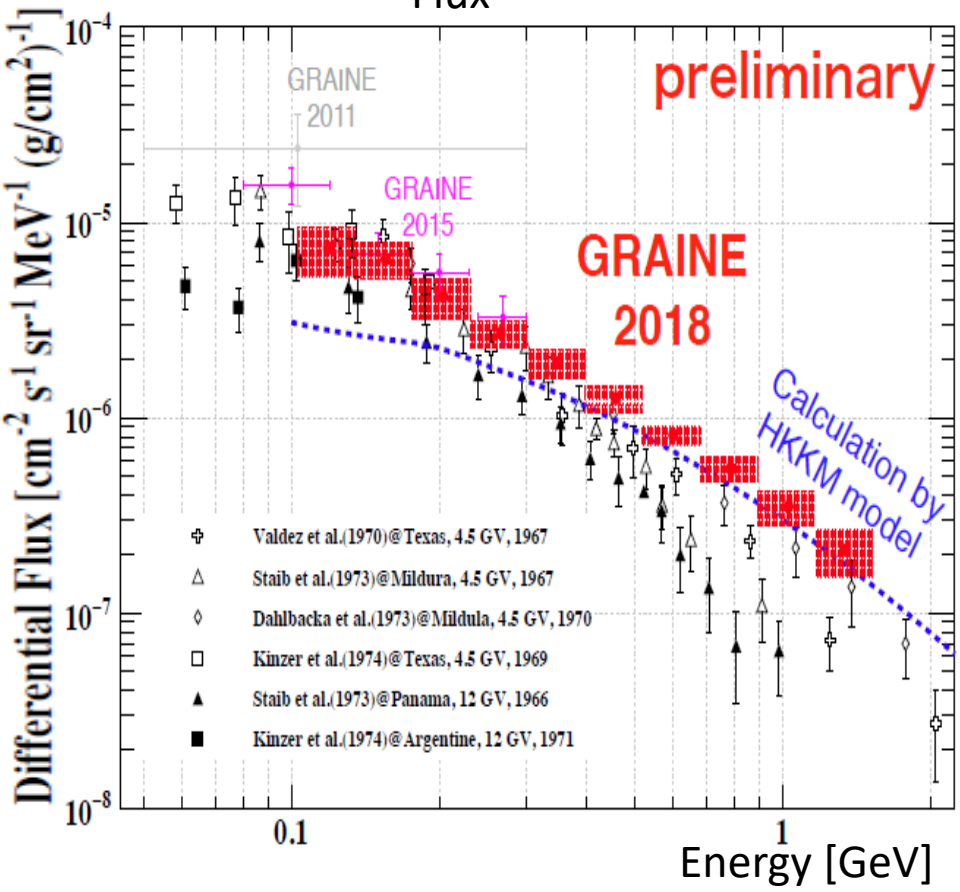
400
300
200
100
0
-100
-200

-30 -20 -10 0 10 20 30

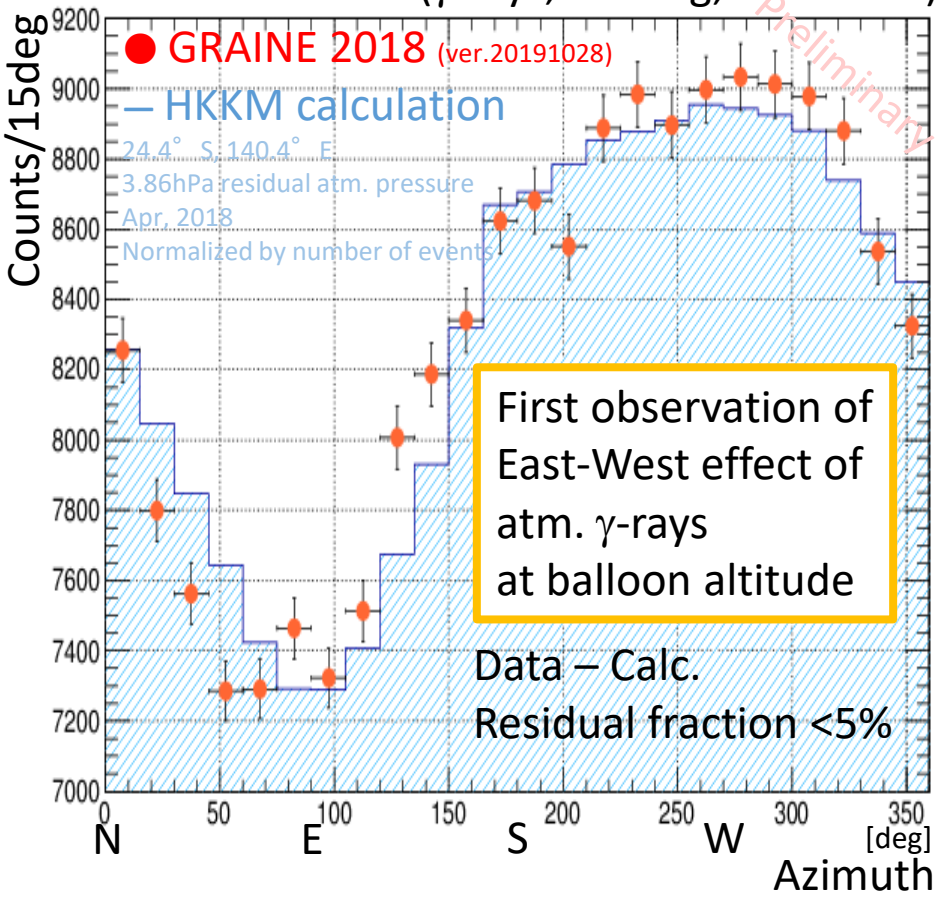
Galactic Latitude [deg]

Atmospheric γ-ray measurements

Flux

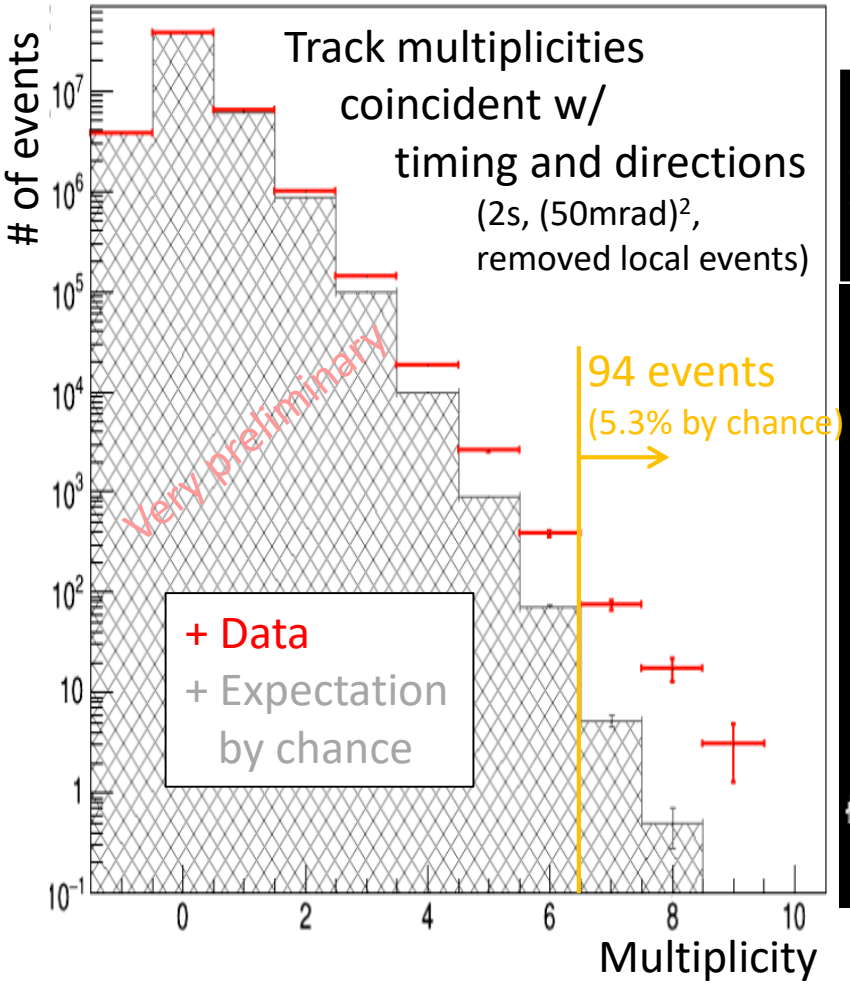


East-West effect (γ-rays, <45deg, >100MeV)

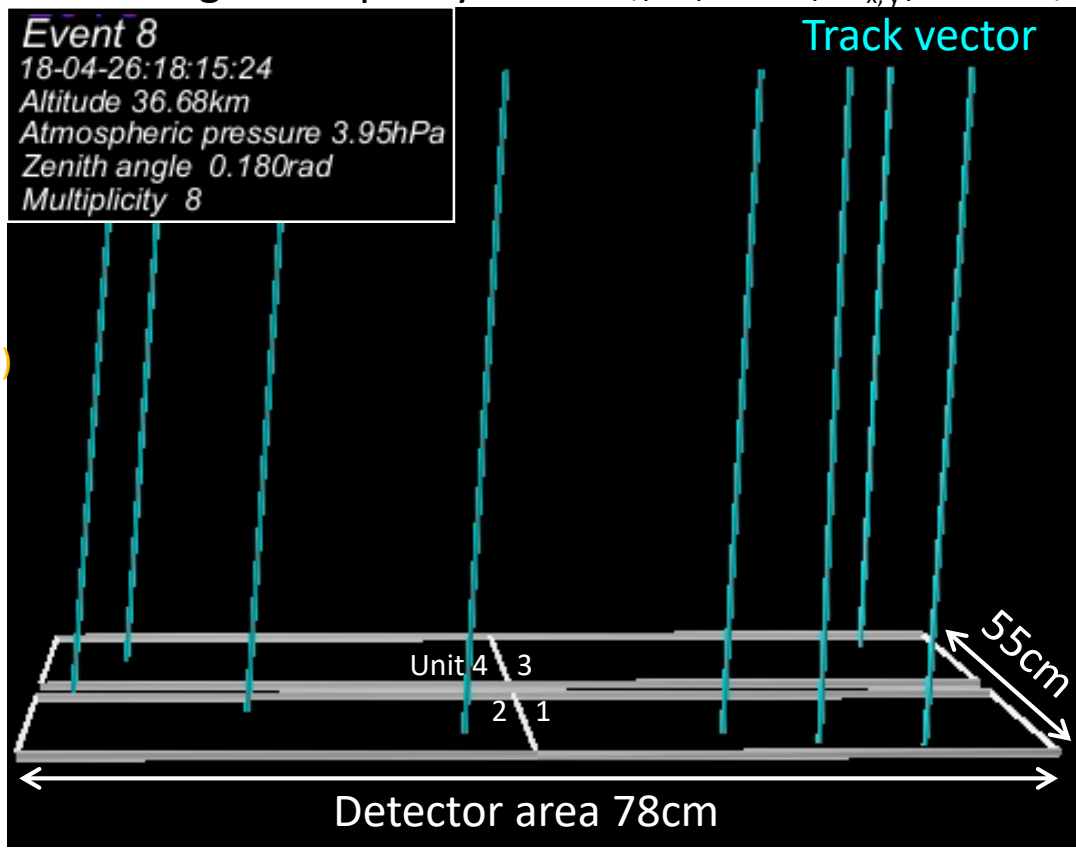


- ✓ BG and detector response understanding
- ✓ Atm. γ-ray physics (Primary, Solar activity, Geomagnetism, Atmosphere, Interaction, Secondary)
  - ➢ Flux and East-West effect in Sub-GeV
  - ➢ Comparison w/ atm. ν flux calculation
    - Contribution to Neutrino physics
  - ➢ Advantage by balloon-borne 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 for Vela pulsar
7.4σ detection
0.51deg 68%radius (>80MeV)

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

2021–, Scientific flight

Alice Springs etc. incl. North. Sky
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

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

~~2021~~

2022, Commissioning

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

JAXA balloon approved

Full scale

Alice Springs, etc. incl. North. Sky
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

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

For GRAINE 2022

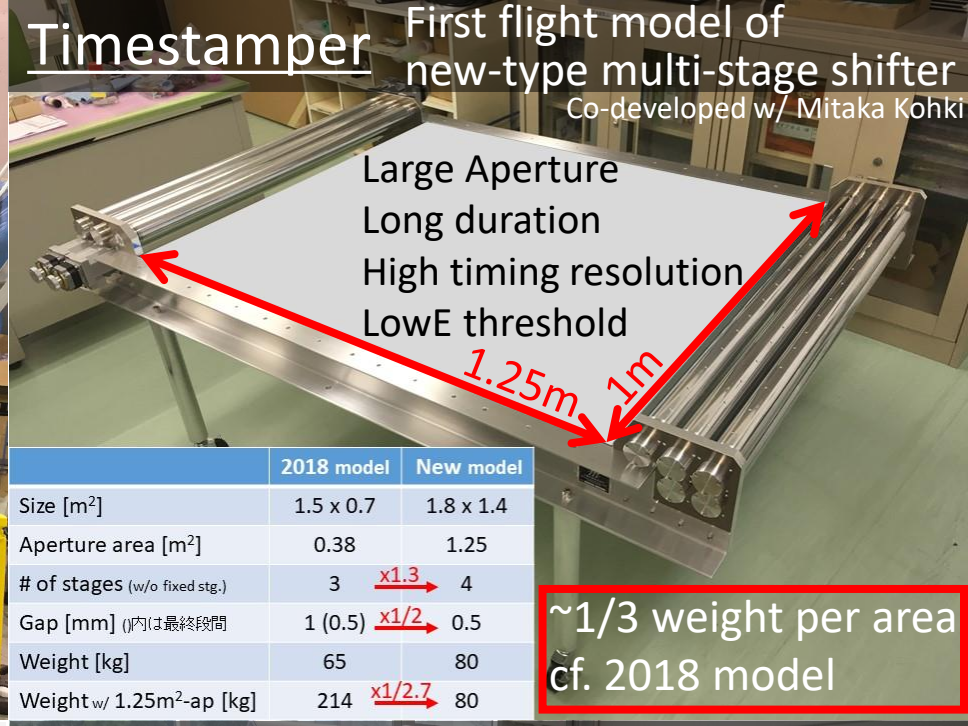
Pressure vessel gondola 2.5 m² (2 units)

Light, Thin, 0.3atm 700kg payload

Timestamper

First flight model of new-type multi-stage shifter

Co-developed w/ Mitaka Kohki



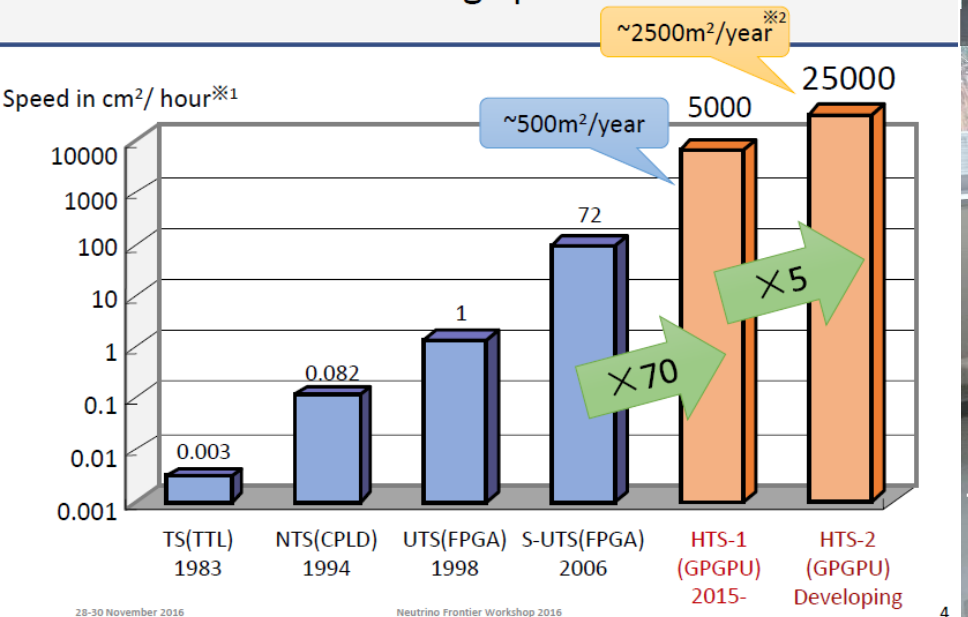
	2018 model	New model
Size [m²]	1.5 x 0.7	1.8 x 1.4
Aperture area [m²]	0.38	1.25
# of stages (w/o fixed stg.)	3	x1.3 → 4
Gap [mm] ()内は最終段間	1 (0.5)	x1/2 → 0.5
Weight [kg]	65	80
Weight w/ 1.25m²-ap [kg]	214	x1/2.7 → 80

~1/3 weight per area cf. 2018 model

Emulsion scanning system

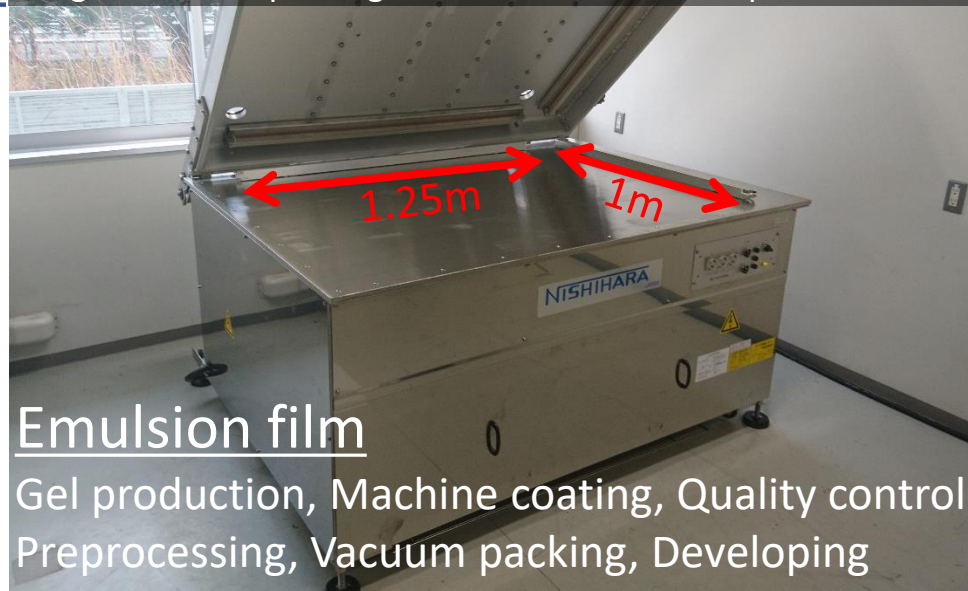
※1 Area of emulsion layer
※2 Area of the films with 24 hour shift

Evolution of the Scanning Speed



Large vacuum packing machine

Largest vacuum packing in the balloon-borne experiments



Emulsion film

Gel production, Machine coating, Quality control
Preprocessing, Vacuum packing, Developing