GRAINE project and first results on 2018 balloon-borne experiment

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

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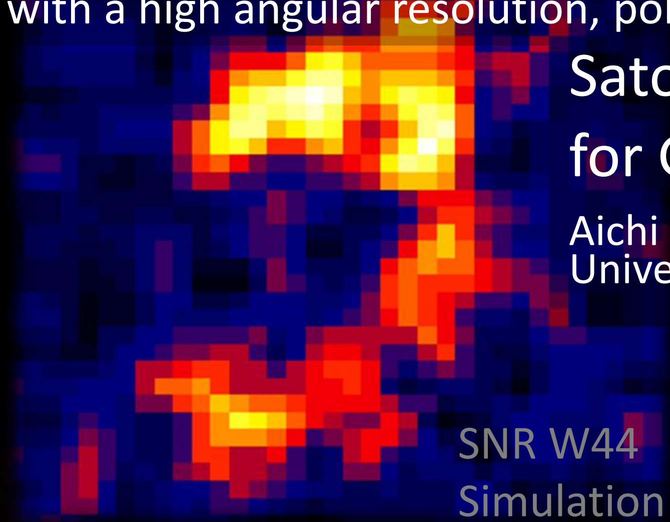
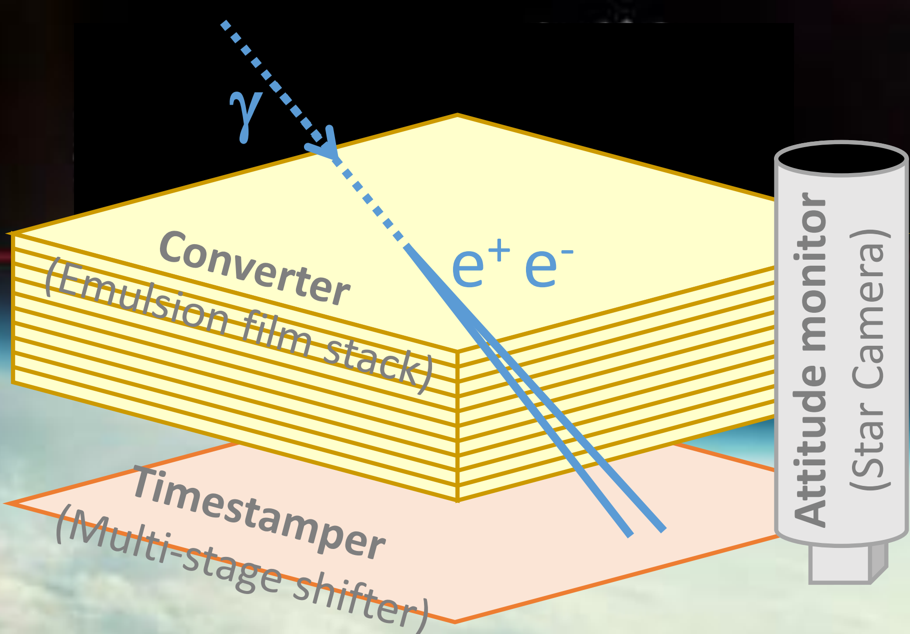
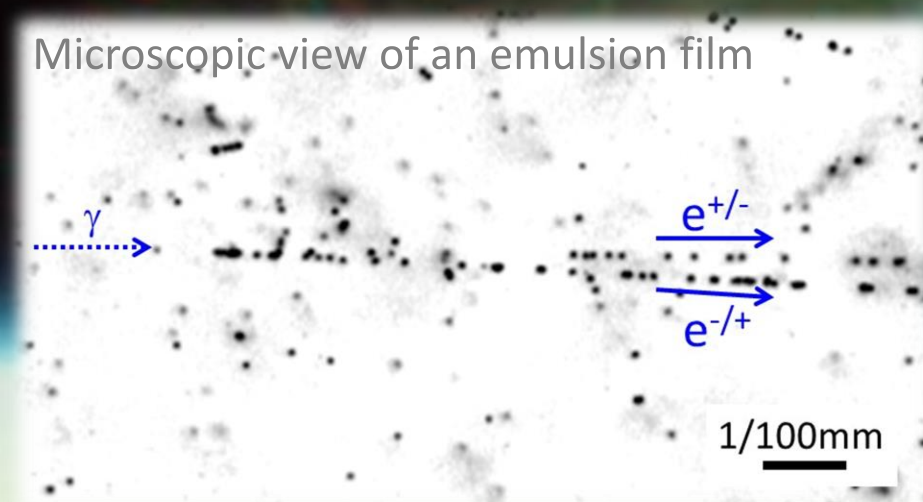
for GRAINE collaboration, PI: S. Aoki (Kobe Univ.)

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







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

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

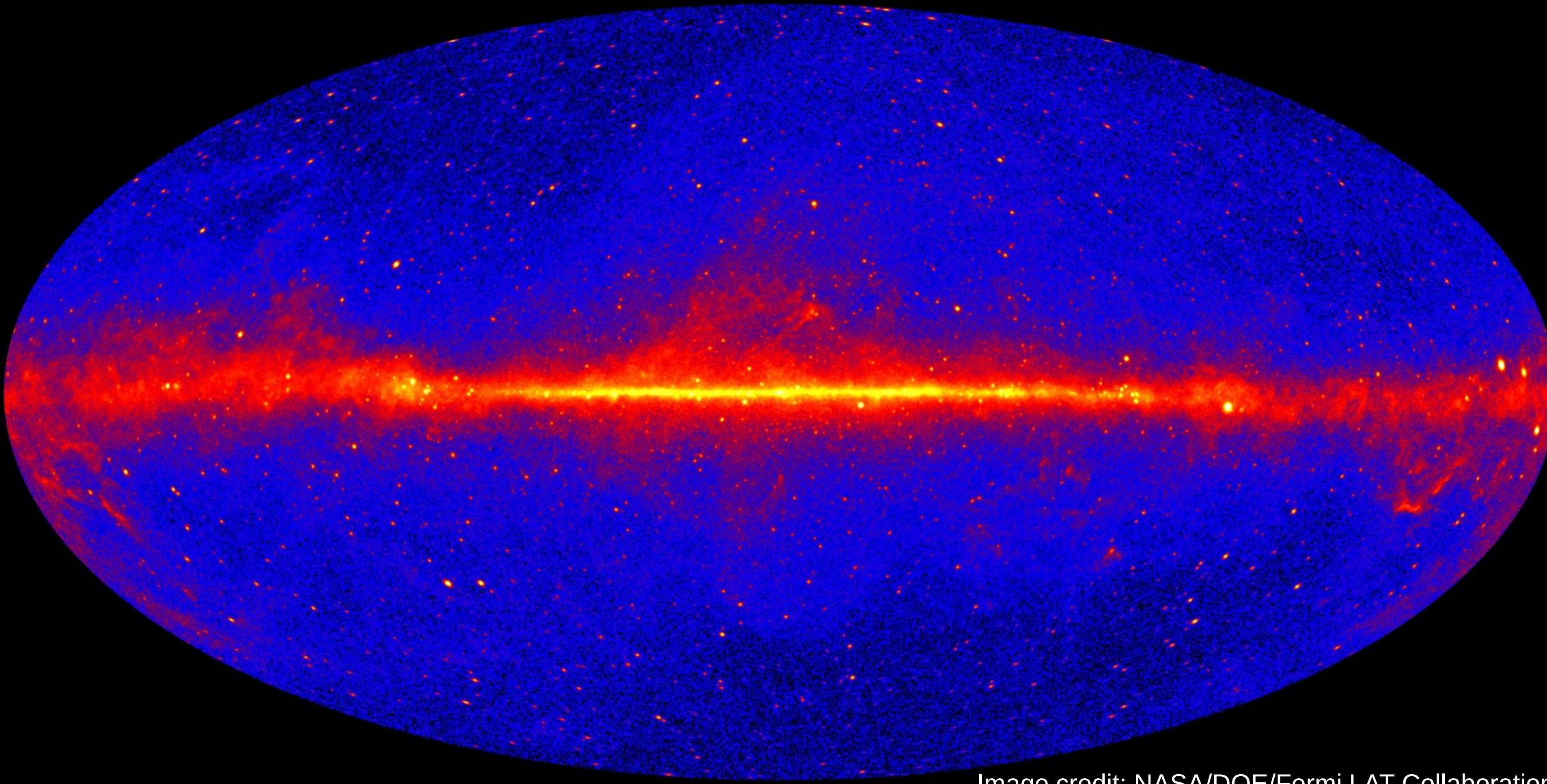
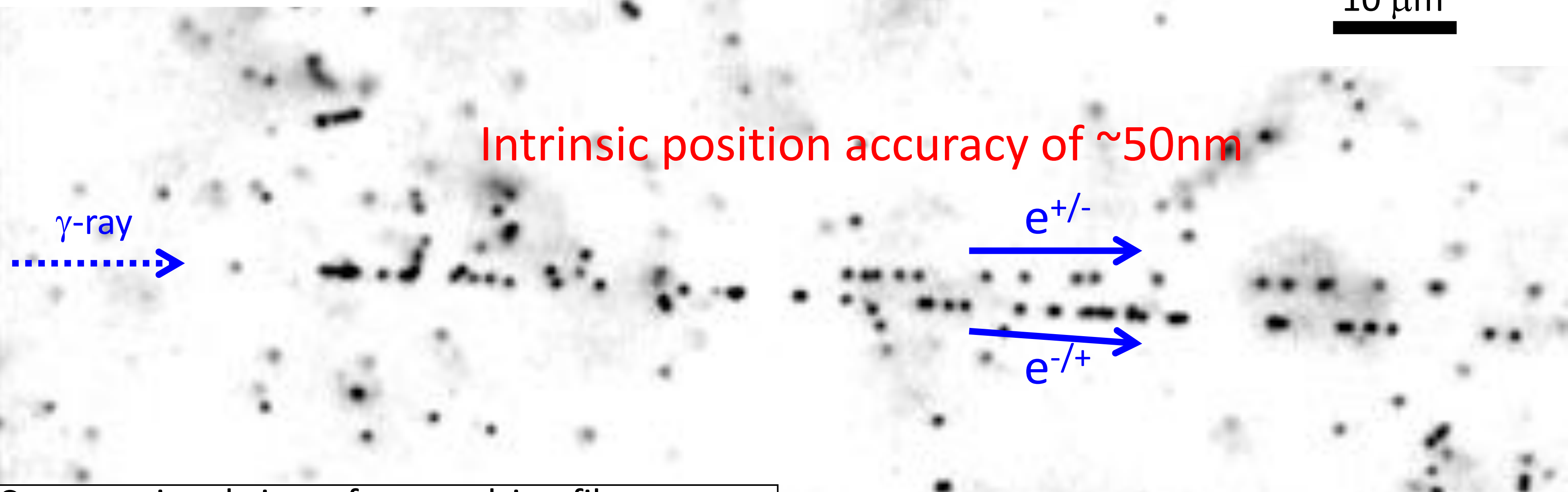


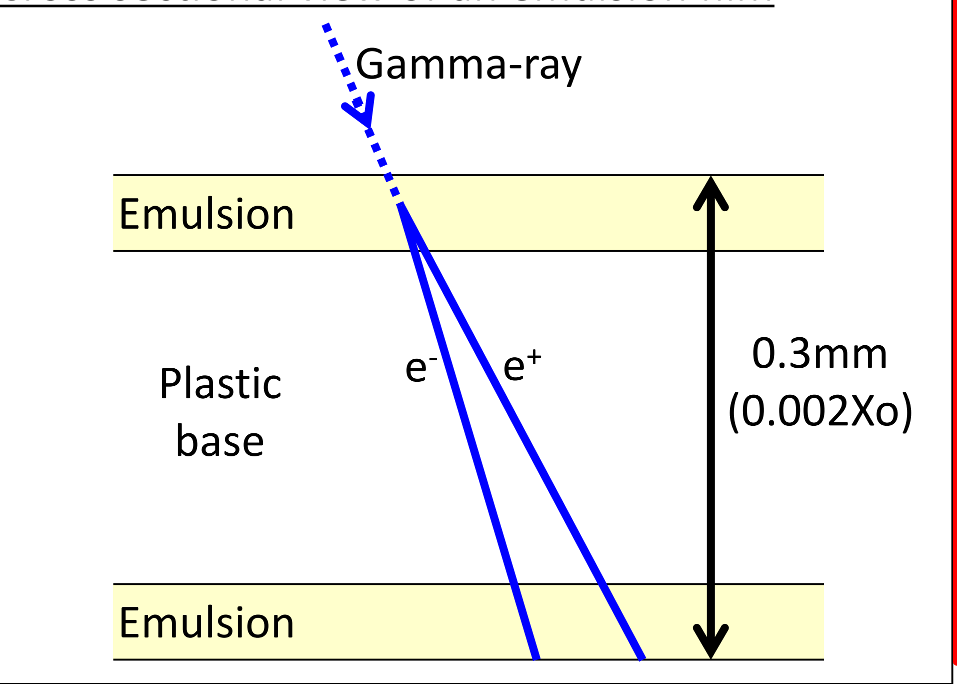
Image credit: NASA/DOE/Fermi LAT Collaboration

>5000 sources (FL8Y)

Nuclear emulsion



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

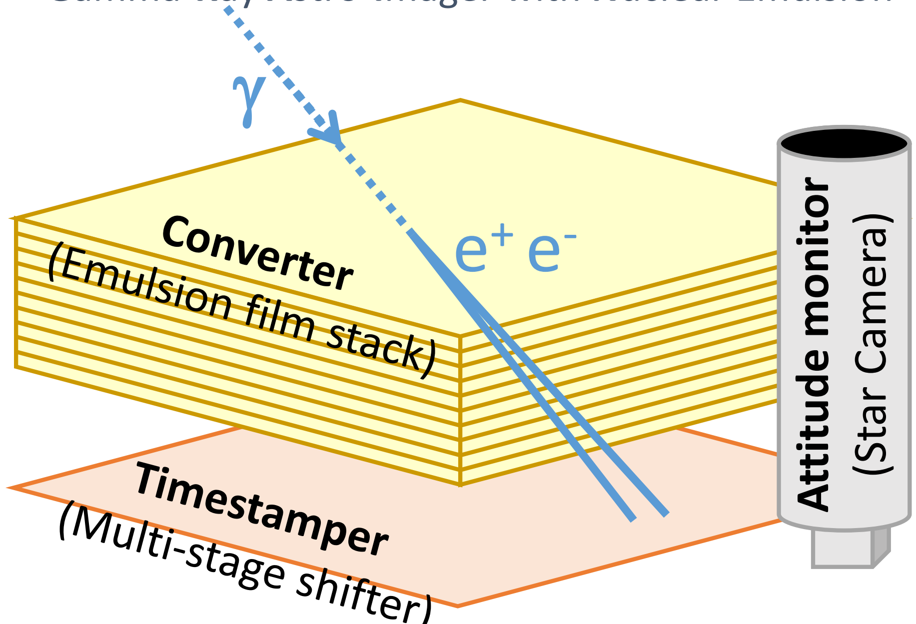
Novel γ-ray telescope

Highest angular resolution
First polarization sensitivity
Largest aperture area

GRAINE

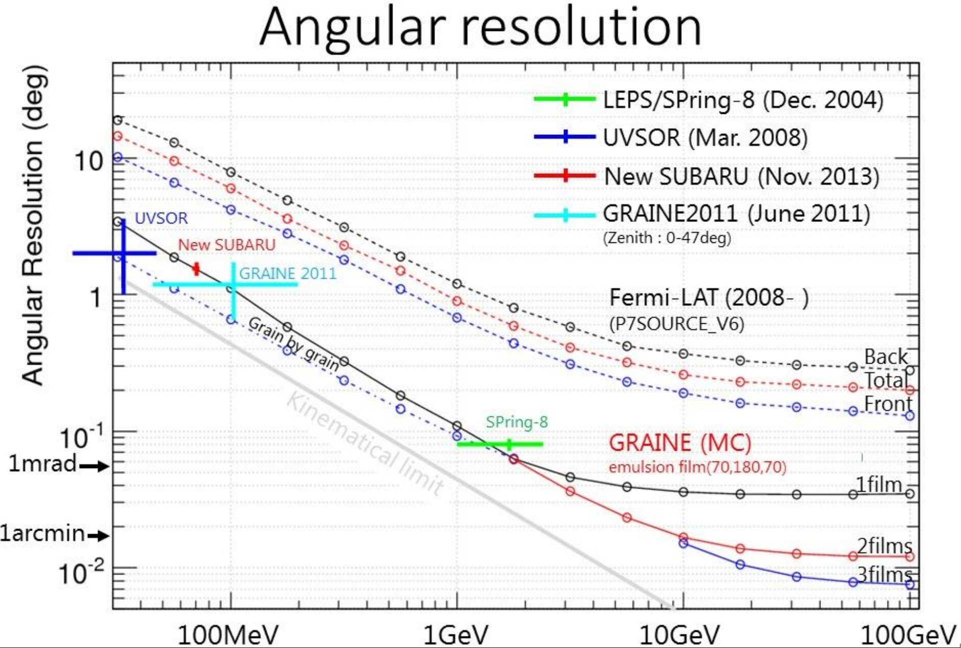
Emulsion γ-ray telescope
Repeated long-duration balloon flights

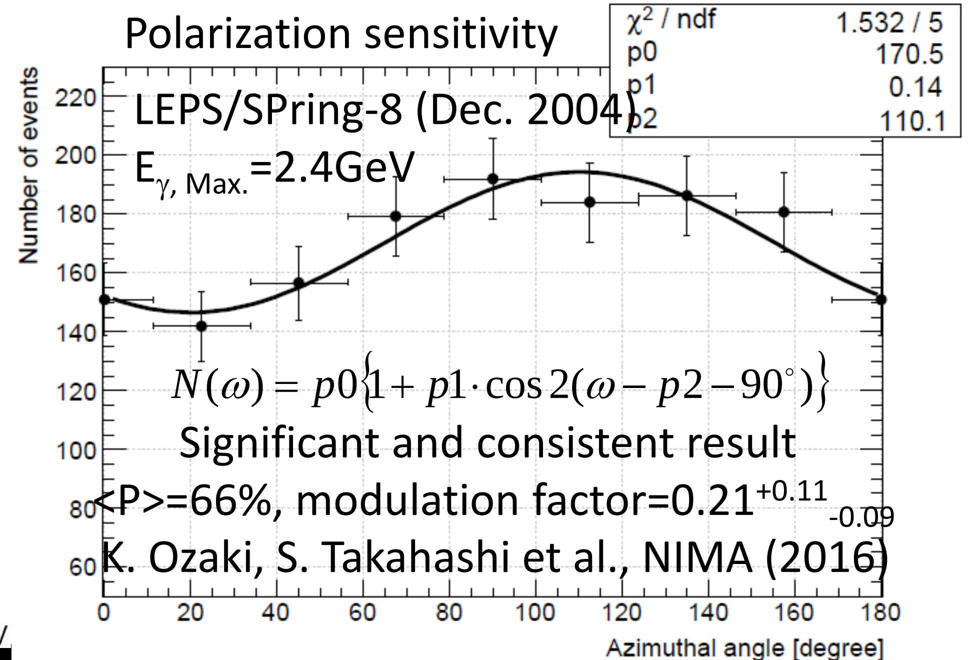
Gamma-**R**ay **A**stro-**I**mager with **N**uclear **E**mulsion

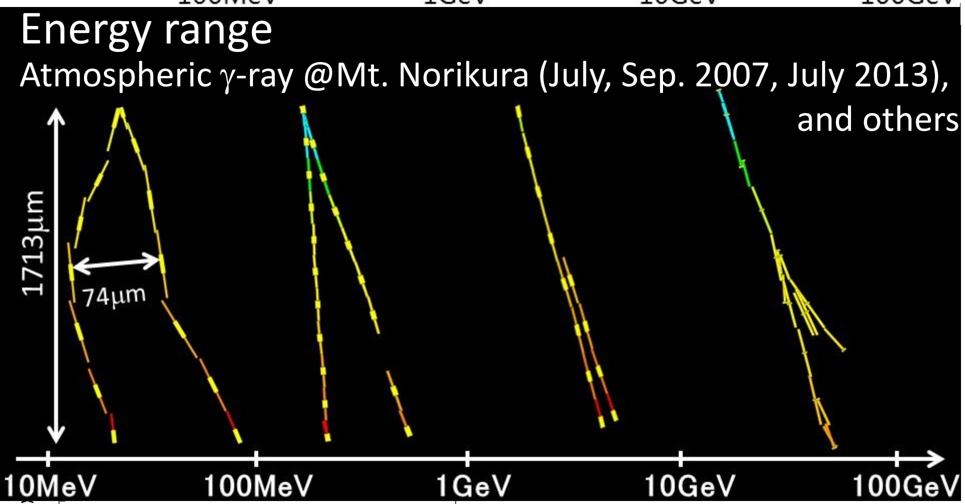


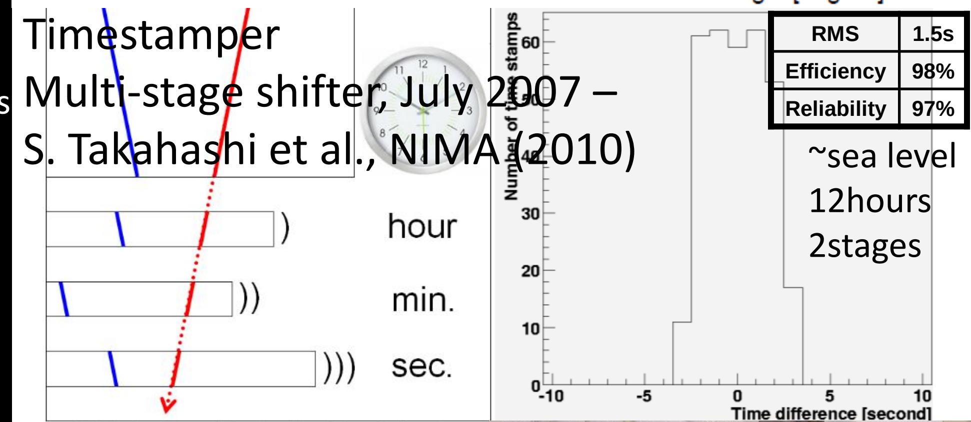
$*$ $10m^2 * \varepsilon_{trans} * \varepsilon_{conv} * \varepsilon_{det}$

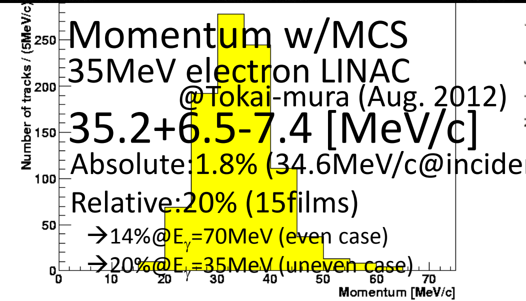
	Fermi LAT		GRAINE
Angular resolution @100MeV	6.0deg (105mrad)	x1/6 →	1.0deg (17mrad)
@1GeV	0.90deg (16mrad)	x1/9 →	0.1deg (1.7mrad)
Energy range	20MeV – 300GeV		10MeV – 100GeV
Polarization sensitivity	---		Yes
Effective area @ 100MeV	$0.25m^2$	x8 →	$2.1m^2$ $*$
@ 1GeV	$0.88m^2$	x3 →	$2.8m^2$ $*$
Dead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

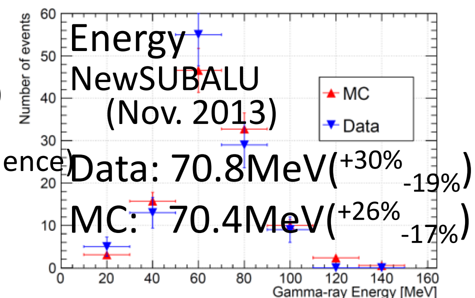

Angular resolution
Angular Resolution (deg)
LEPS/SPring-8 (Dec. 2004)
UVSOR (Mar. 2008)
New SUBARU (Nov. 2013)
GRAINE2011 (June 2011)
(Zenith : 0-47deg)
UVSOR
New SUBARU
GRAINE 2011
Grain by grain
Fermi-LAT (2008-)
(P7SOURCE_V6)
Back
Total
Front
Kinematical limit
SPring-8
GRAINE (MC)
emulsion film(70,180,70)
1film
2films
3films
1mrad
1arcmin
100MeV
1GeV
10GeV
100GeV

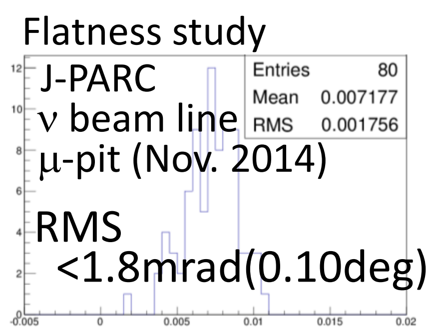

Polarization sensitivity
χ^2 / ndf 1.532 / 5
p0 170.5
p1 0.14
p2 110.1
LEPS/SPring-8 (Dec. 2004)
$E_{\gamma, Max.}$=2.4GeV
Number of events
$N(\omega) = p0\{1 + p1 \cdot \cos 2(\omega - p2 - 90^\circ)\}$
Significant and consistent result
<P>=66%, modulation factor=$0.21^{+0.11}_{-0.09}$
K. Ozaki, S. Takahashi et al., NIMA (2016)
Azimuthal angle [degree]

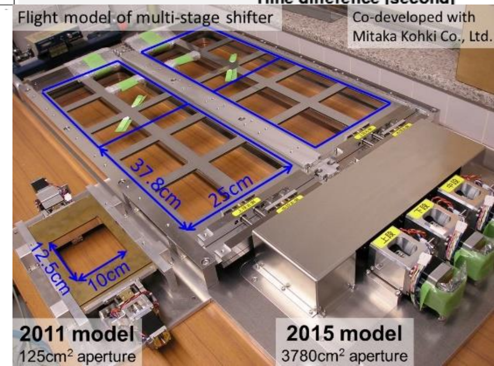

Energy range
Atmospheric γ-ray @Mt. Norikura (July, Sep. 2007, July 2013), and others
1713μm
74μm
10MeV
100MeV
1GeV
10GeV
100GeV


Timestamper
Multi-stage shifter, July 2007 –
S. Takahashi et al., NIMA (2010)
hour
min.
sec.
RMS 1.5s
Efficiency 98%
Reliability 97%
~sea level
12hours
2stages
Time difference [second]


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)
Number of tracks / [5MeV/c]
Momentum [MeV/c]

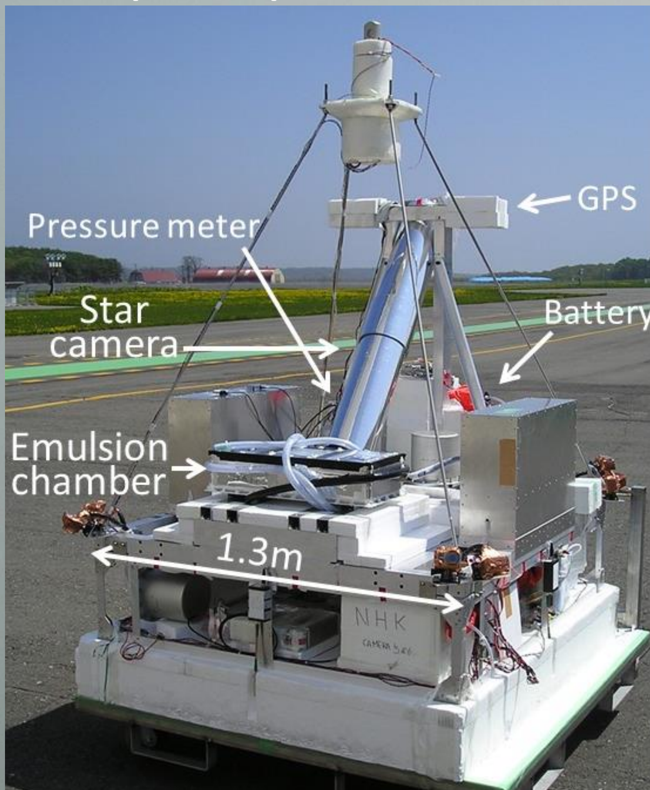

Energy
NewSUBALU
(Nov. 2013)
MC
Data
Data: 70.8MeV($^{+30\%}_{-19\%}$)
MC: 70.4MeV($^{+26\%}_{-17\%}$)
Number of events
Gamma-ray Energy [MeV]


Flatness study
J-PARC
ν beam line
μ-pit (Nov. 2014)
Entries 80
Mean 0.007177
RMS 0.001756
RMS
<1.8mrad(0.10deg)


Flight model of multi-stage shifter
Co-developed with Mitaka Kohki Co., Ltd.
37.8cm
25cm
12.5cm
10cm
2011 model
125cm² aperture
2015 model
3780cm² aperture

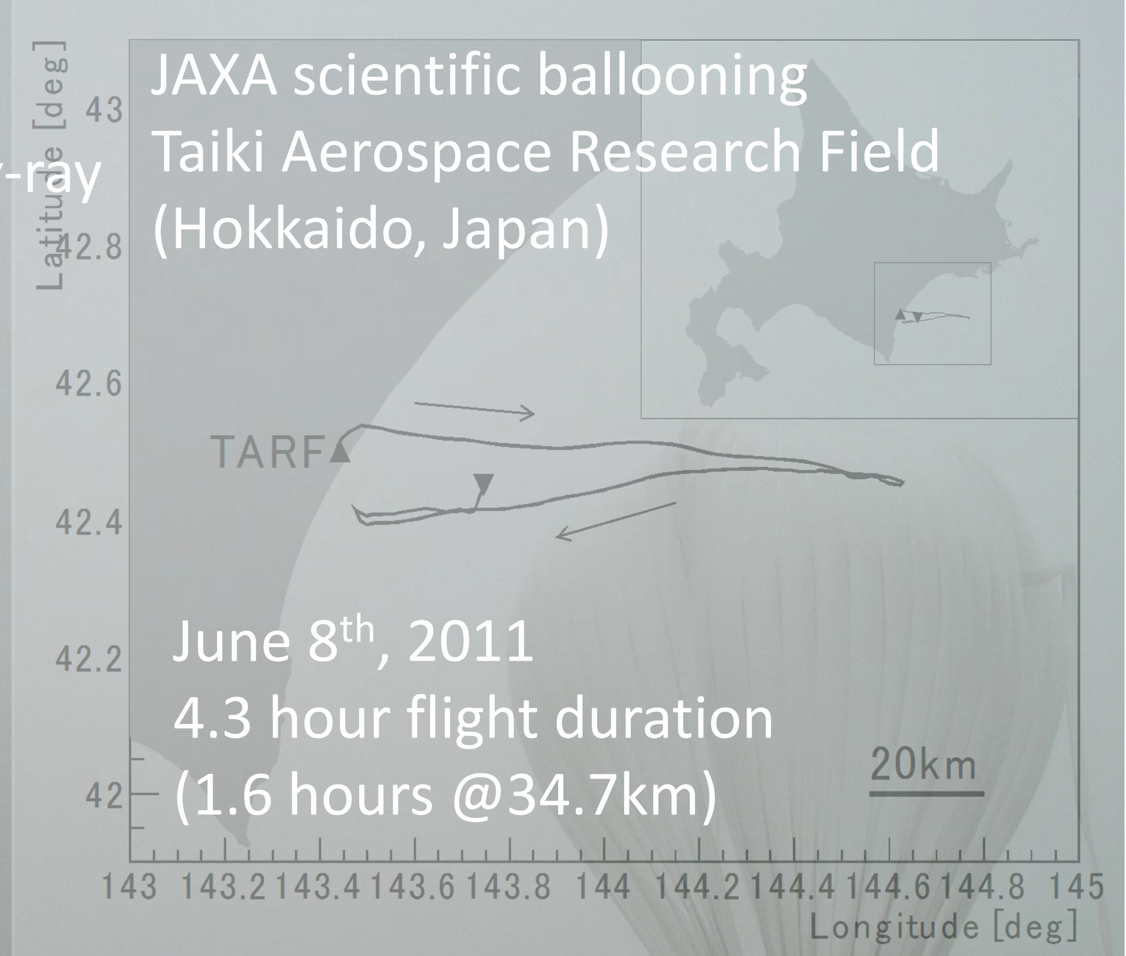
GRAINE 2011

First balloon-borne emulsion γ-ray telescope experiment



12.5cm × 10cm aperture

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

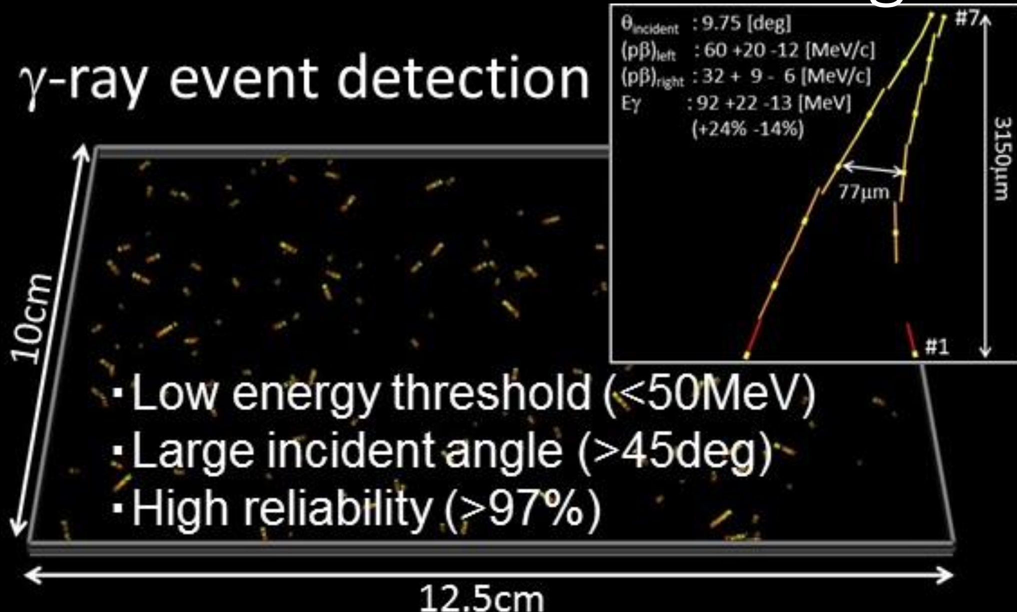


June 8^{th}, 2011
4.3 hour flight duration
(1.6 hours @34.7km)

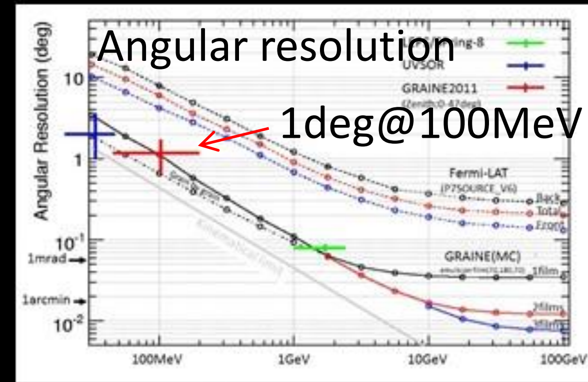
First balloon-borne experiment
Feasibility demonstration

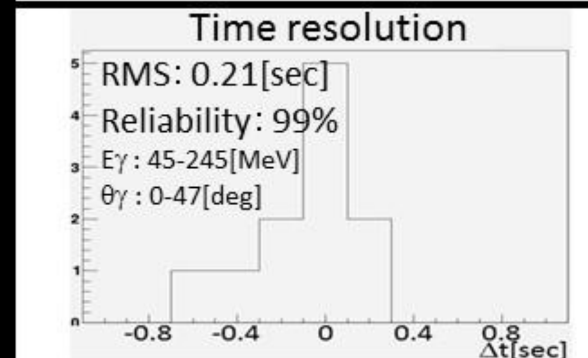
GRAINE 2011 Flight data analysis

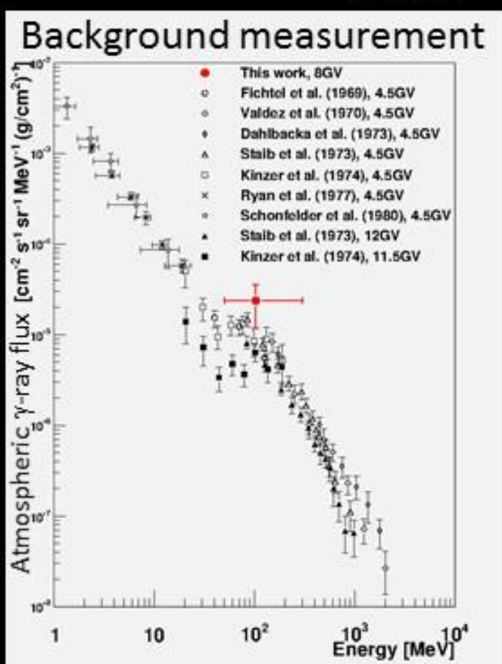
γ-ray event detection



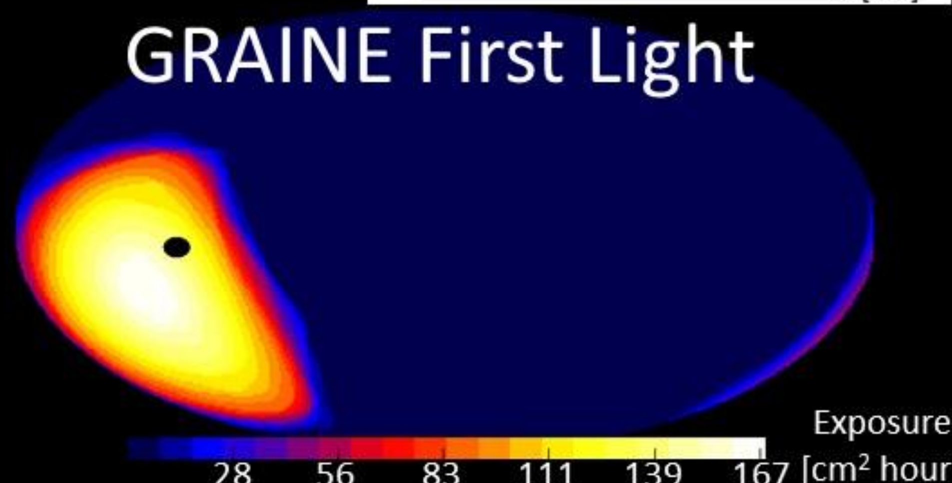
- Low energy threshold (<50MeV)
- Large incident angle (>45deg)
- High reliability (>97%)







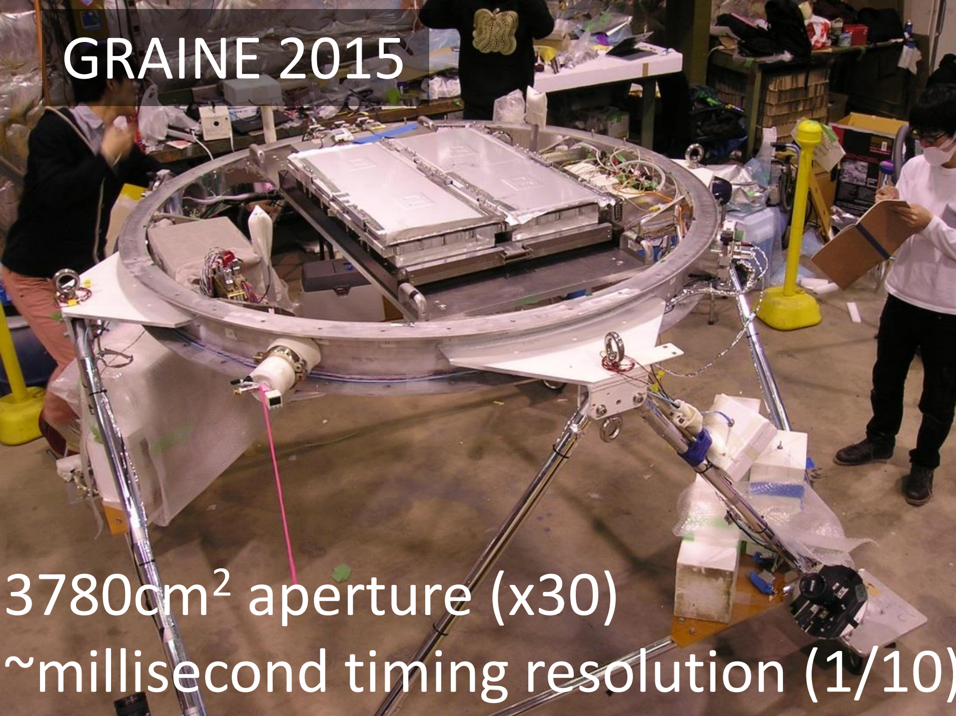
GRAINE First Light



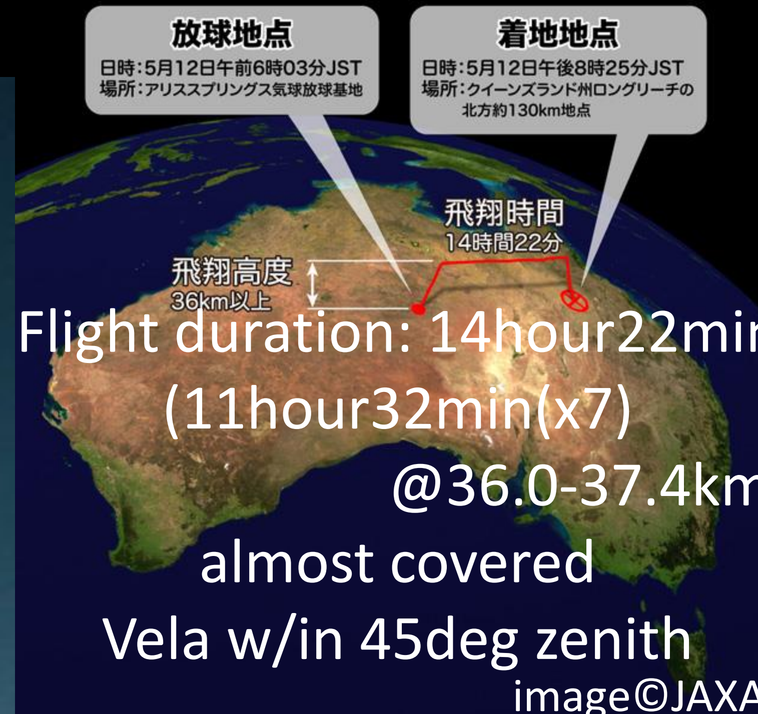
Feasibility demonstration

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

GRAINE 2015

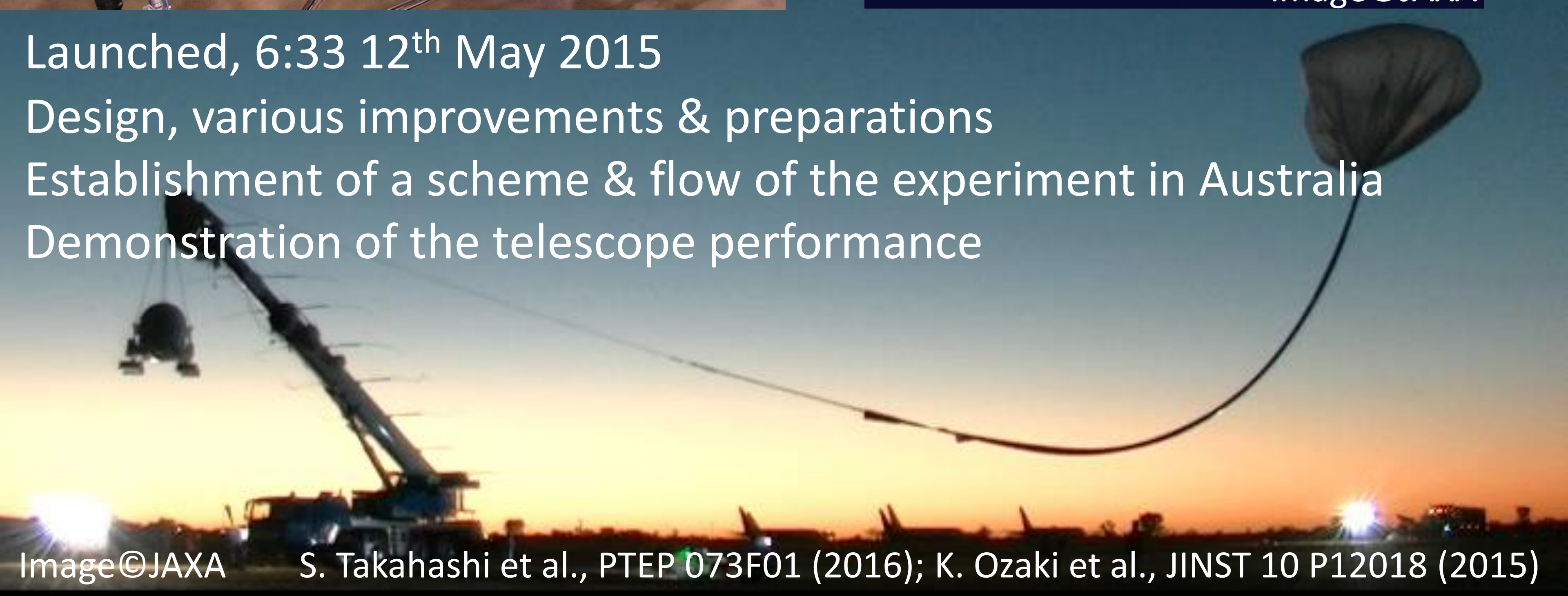


3780cm^2 aperture (x30)
~millisecond timing resolution (1/10)



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
- 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
- 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

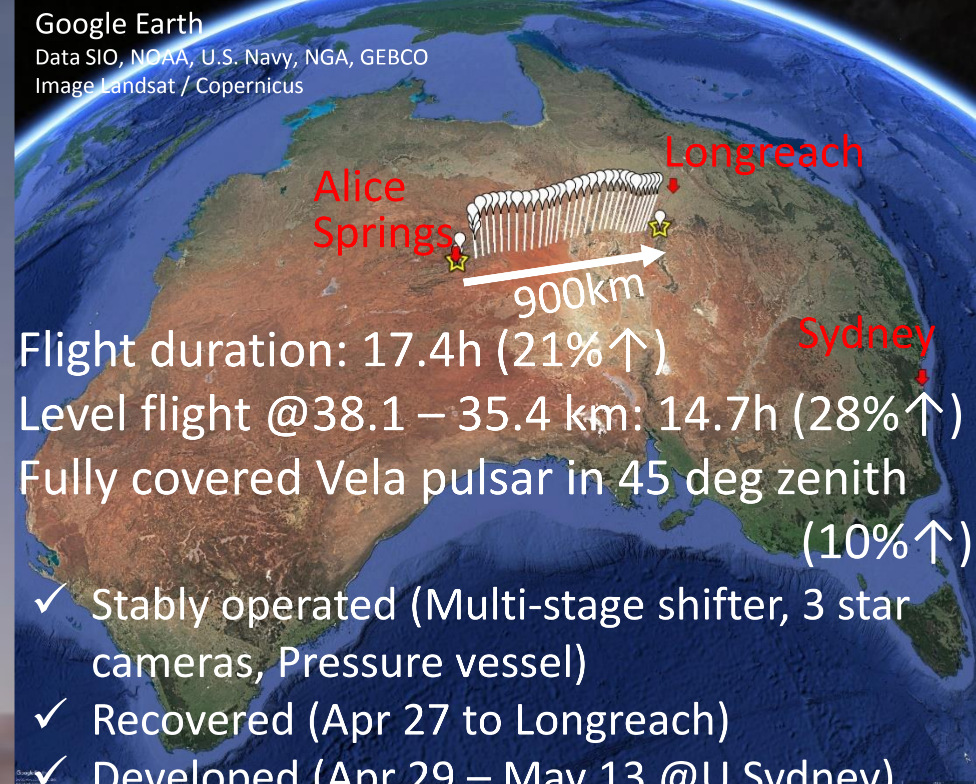
Total x6.3 improvements.

(x5, effectively)

Overall performance demonstration

Imaging resolution aimed w/i 1deg above 100MeV

GRAINE 2018



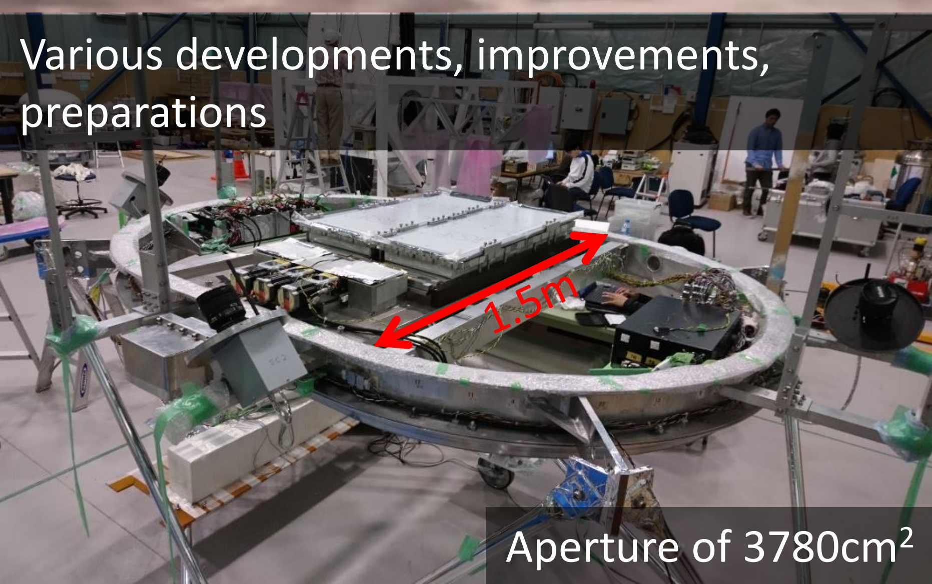
Flight duration: 17.4h (21%↑)

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)

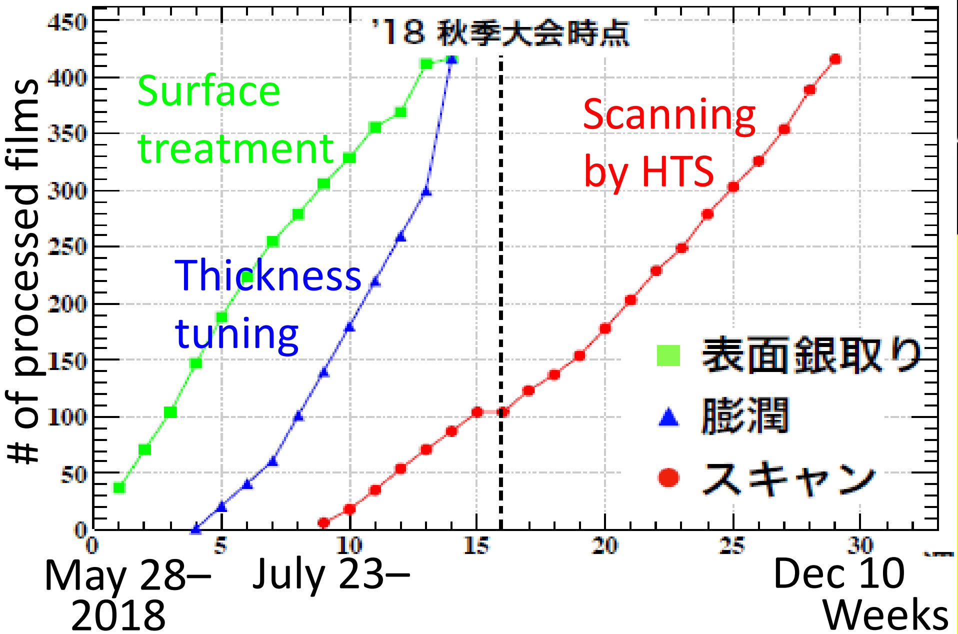
Various developments, improvements, preparations

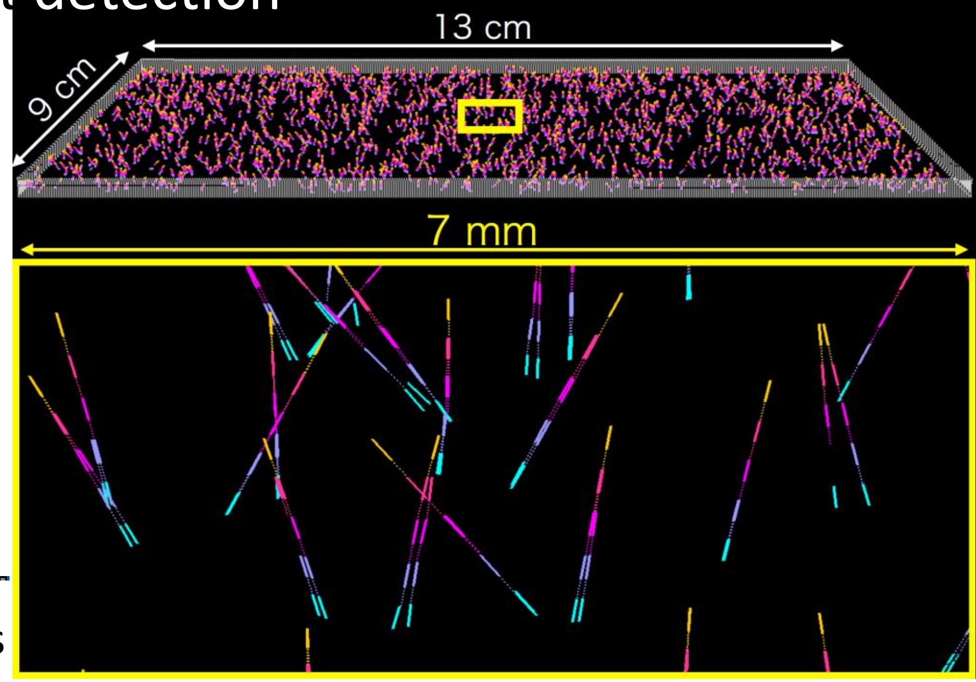


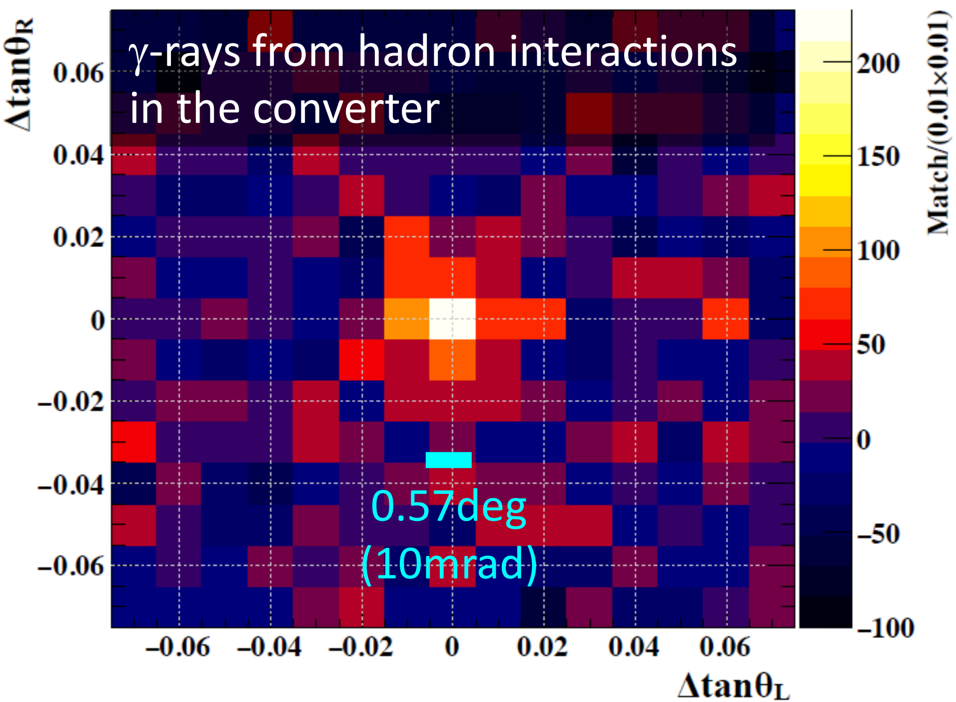
Aperture of 3780cm^2

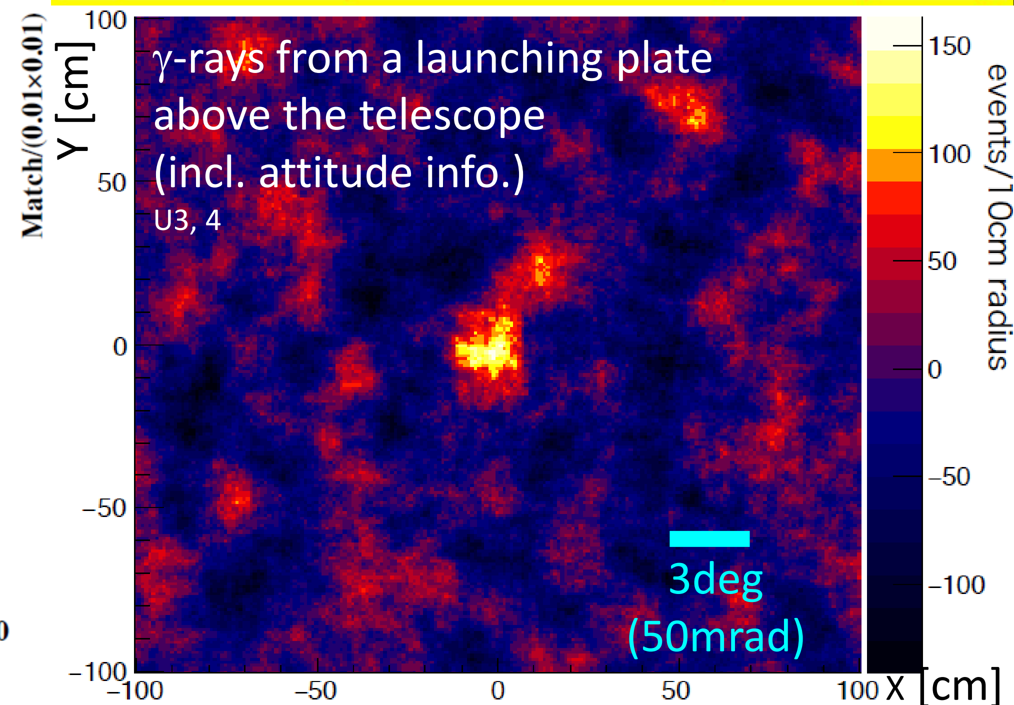
GRAINE 2018, JAXA Scientific balloon @BLS Alice Springs Australia, 6:30AM 26th April (ACST)

GRAINE 2018, Converter, γ-ray event detection

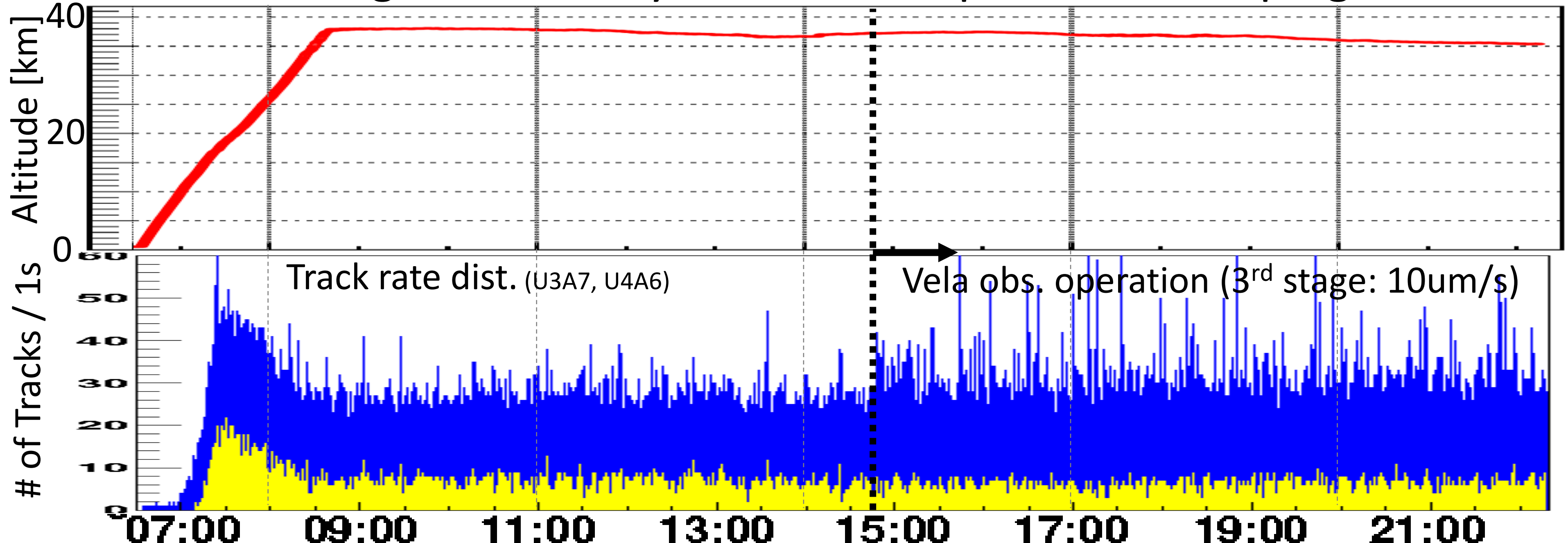


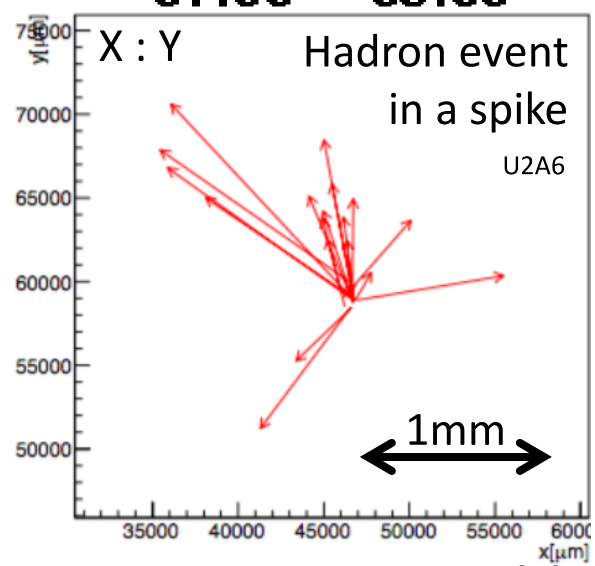


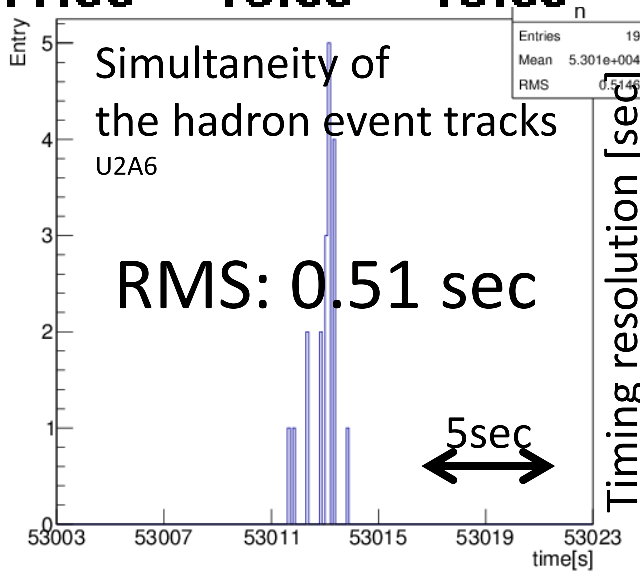


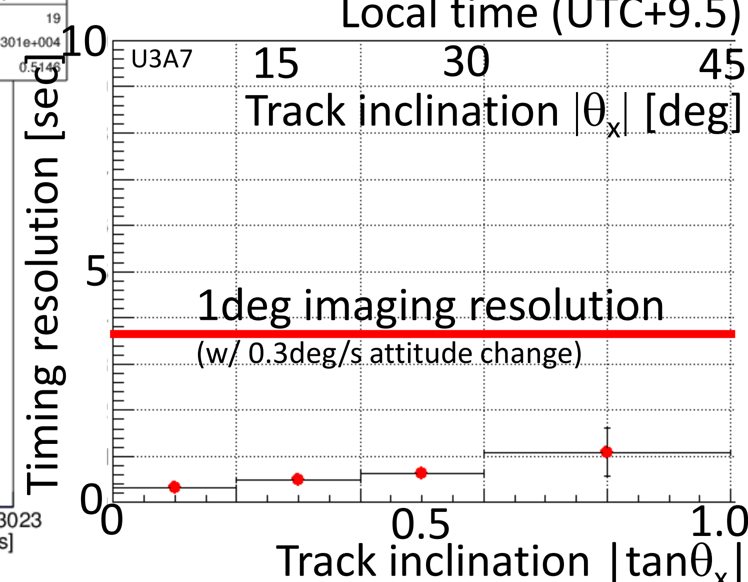


GRAINE 2018, Flight data analysis, Timestamper, Timestamping





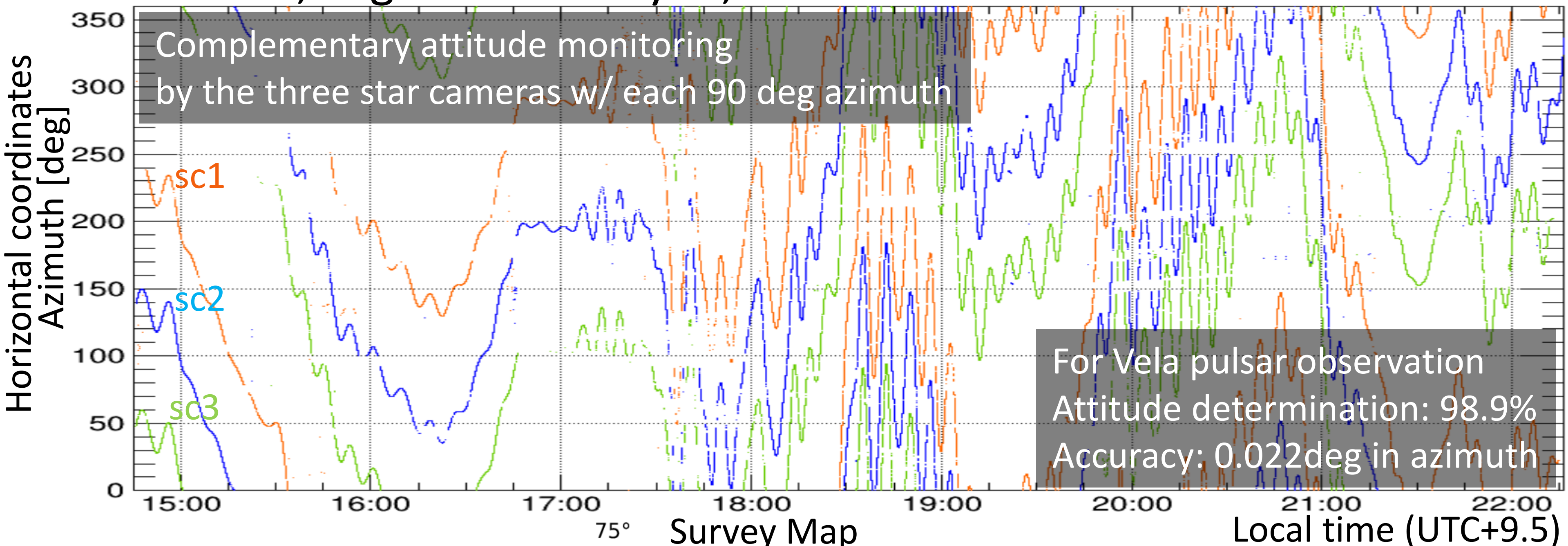




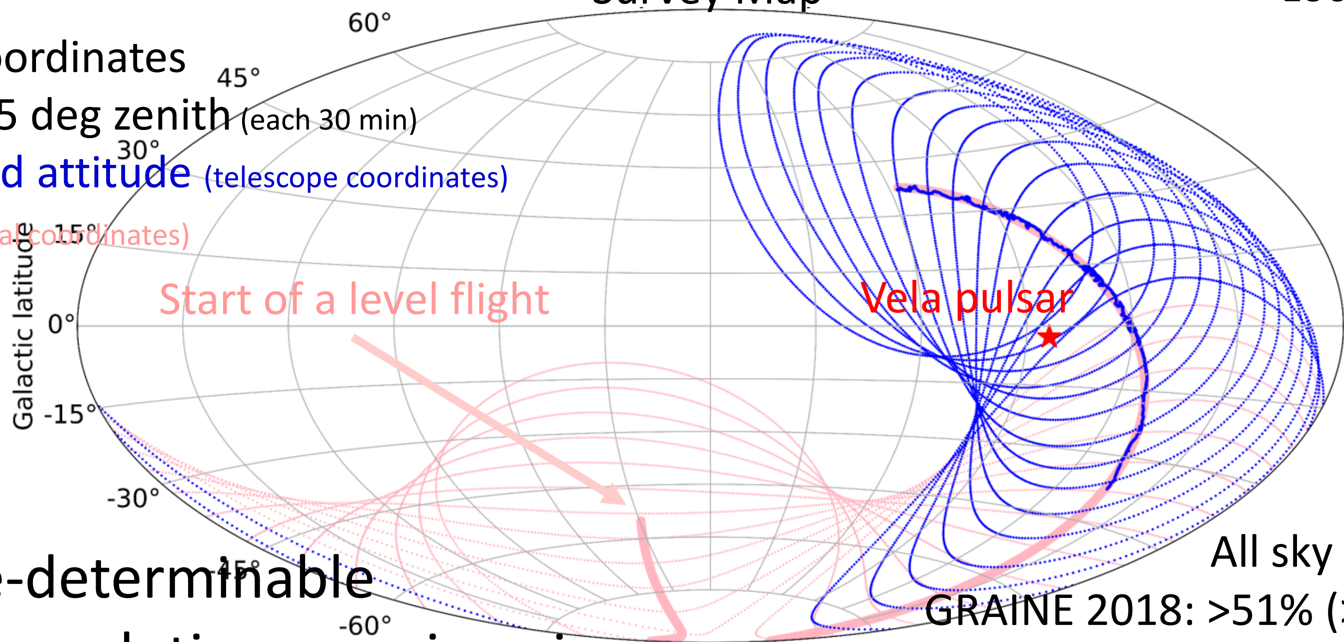
Timestampable
for high resolution γ-ray imaging

Good enough timing resolution
for 1deg imaging resolution

GRAINE 2018, Flight data analysis, Attitude monitor



Survey Map

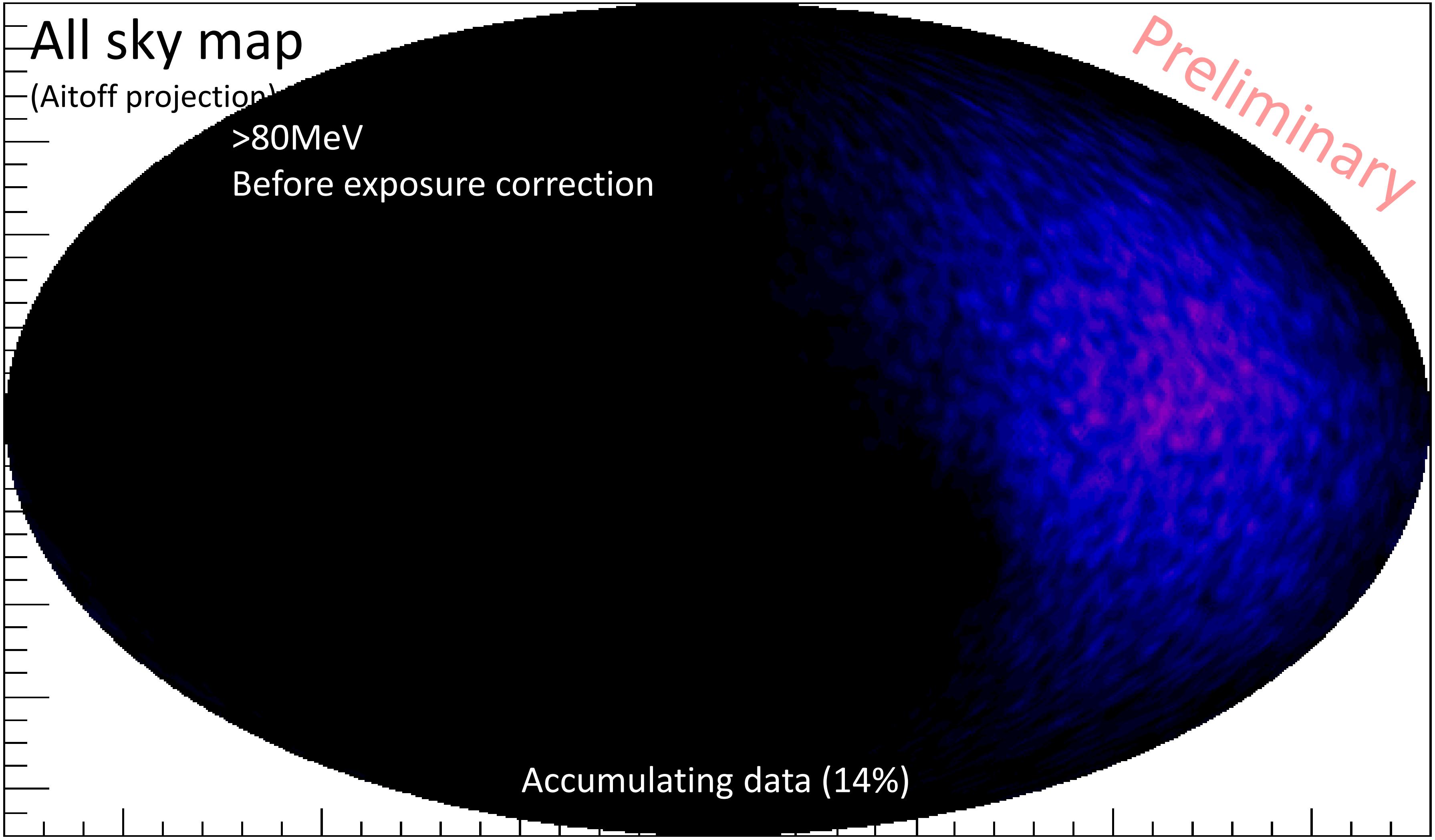


Attitude-determinable
for high resolution γ-ray imaging

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

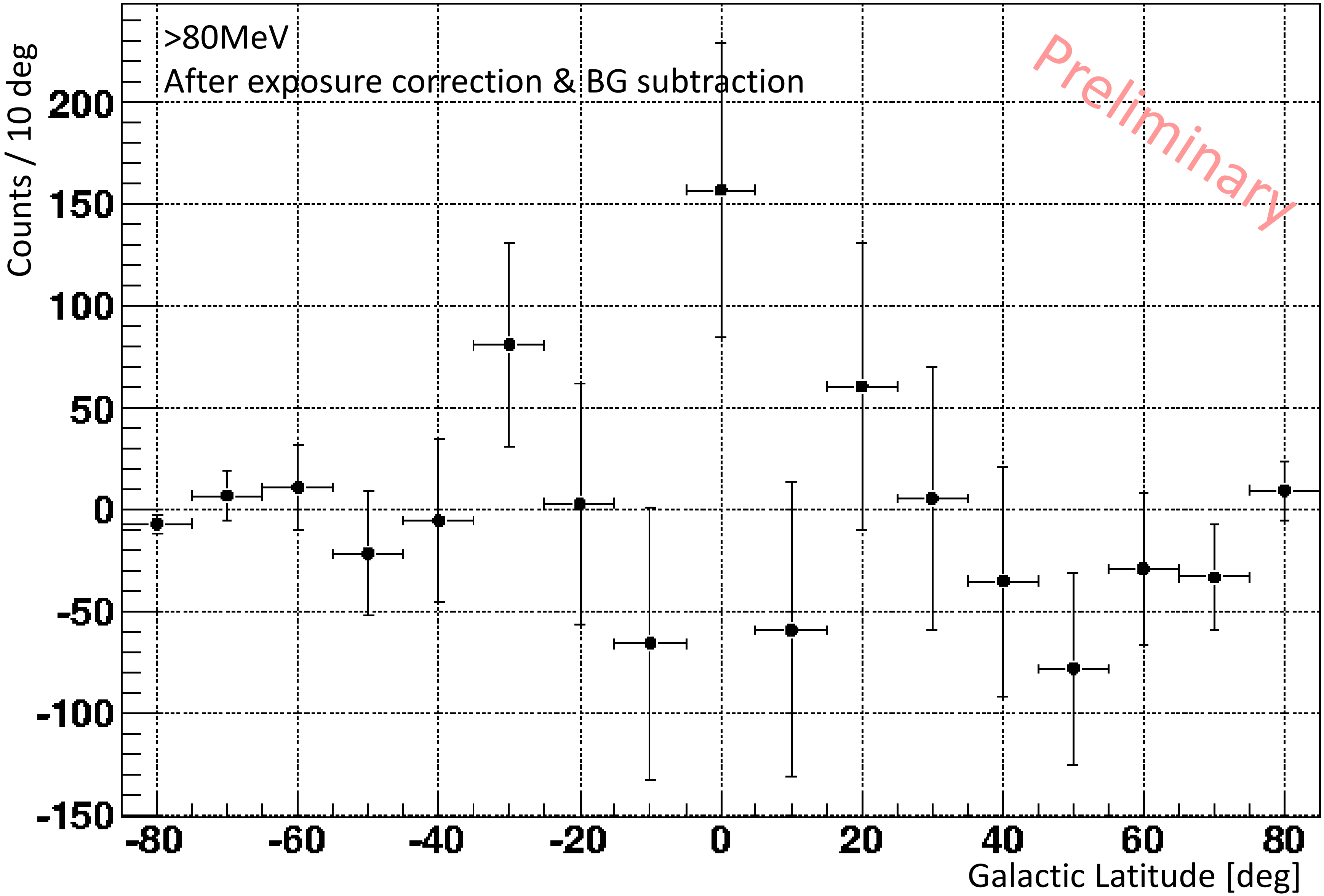
GRAINE 2018, Converter+Timestamper+Attitude monitor

γ-ray arrival direction reconstruction in galactic coordinates



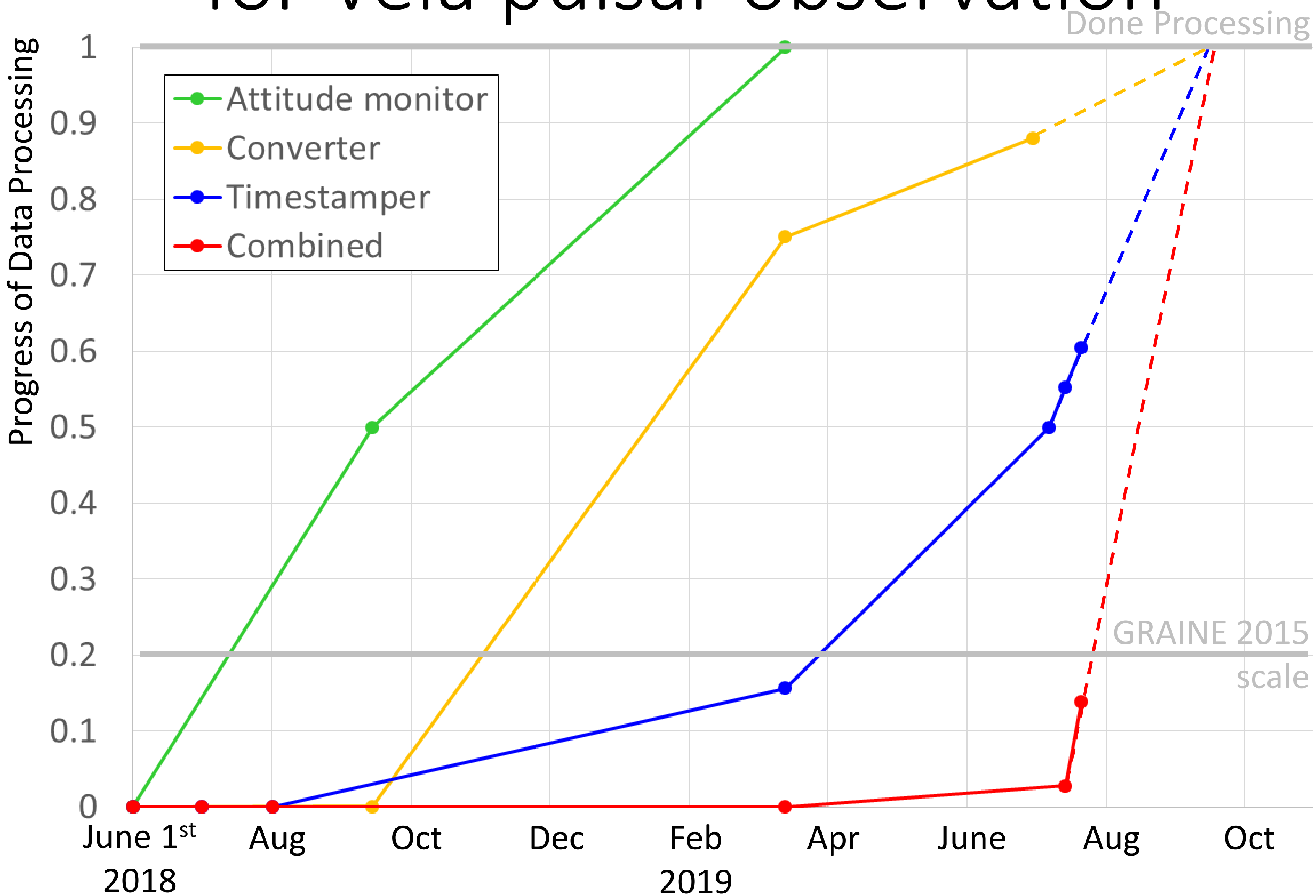
GRAINE 2018, Converter+Timestamper+Attitude monitor

Search for galactic diffuse emmision



First indication of astrophysical gamma-rays for the emulsion gamma-ray telescope

Progress of data processing for Vela pulsar observation



GRAINE Scientific observation roadmap

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

Apr 2018, Demonstration

Done by JAXA balloon

Alice Springs
0.39m^2 aperture
17.3hours flight duration
3 – 5 g/cm^2 altitude
Improvements

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

Imaging resolution
aimed w/i 1deg above 100MeV

PS3-255: Gamma-ray Imaging Performance of Nuclear Emulsion Telescope in GRAINE-2018 Balloon Experiment
Hiroki Rokujo

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

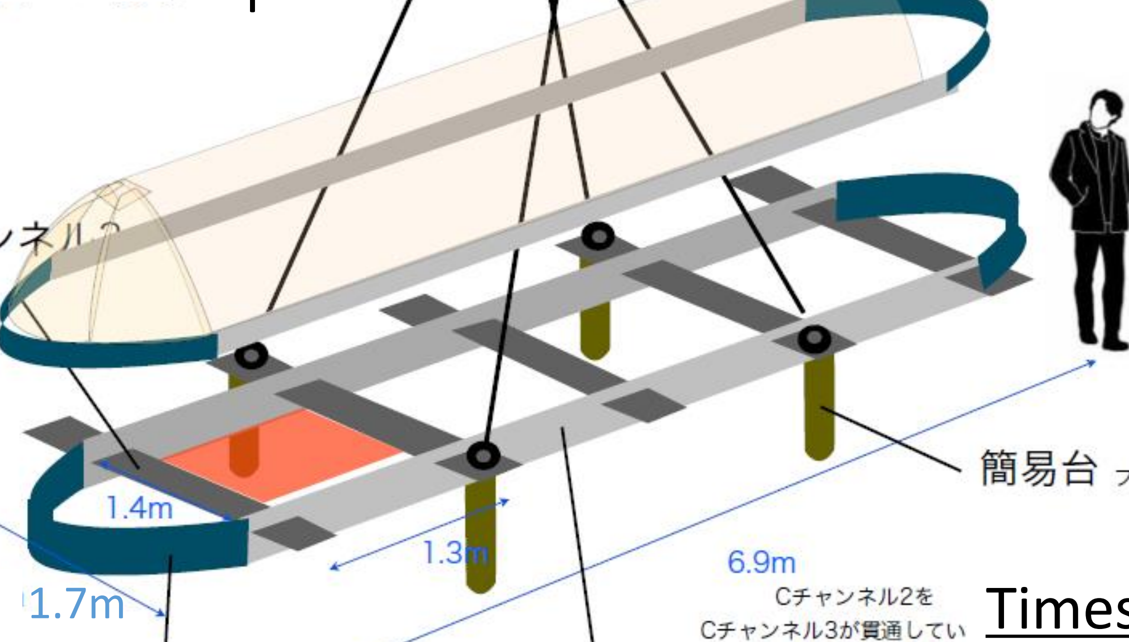
Galactic Center
Obs. with ~arcmin resolution
→ Resolving GeV γ-ray excess at galactic center

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

Developments for scientific balloon-borne experiments

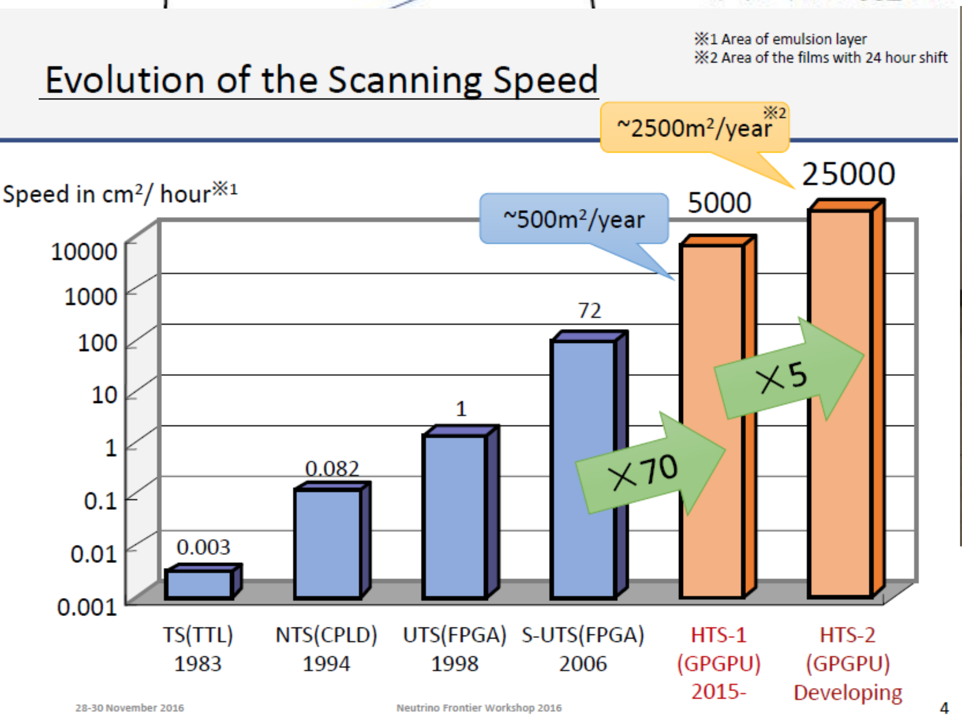


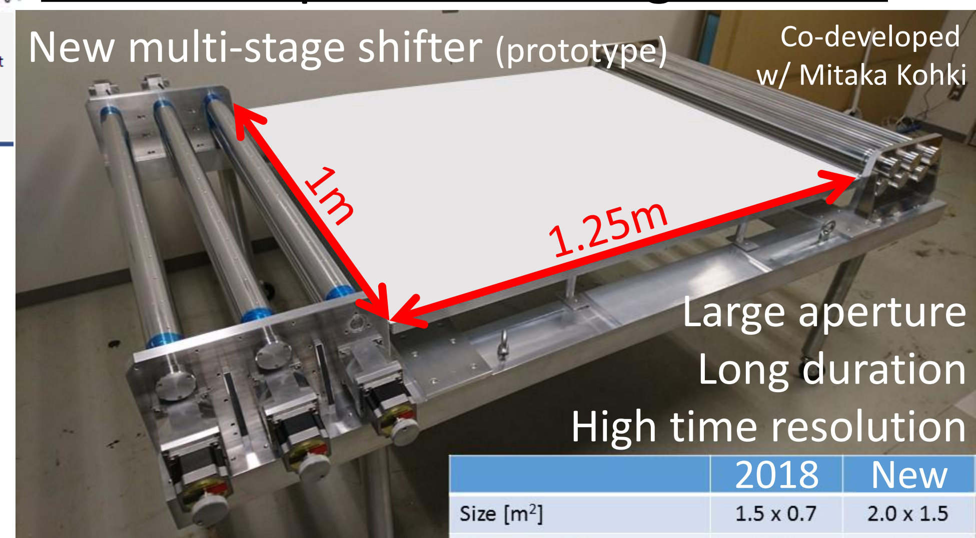
Pressure vessel gondola

Conceptual design
Light, Thin, 0.3atm
5m² (4units) aperture area
w/ a single pressure vessel gondola
(~0.3ton weight)

< ~2 ton payload (aimed)
w/ a 10 m² aperture

Timestamper, Multi-stage shifter





A 1/2 weight of conventional model per aperture

	2018	New
Size [m²]	1.5 x 0.7	2.0 x 1.5
Aperture [m²]	0.38	1.25
# of stages (w/o fixed stg.)	3 x1.7	5
Gap [mm] ()内は最終段間	1 (0.5) x1/2	0.5
Weight [kg]	65	107
Weight w/ 1.25m²-ap [kg]	214 x1/2	107