International Conference on
the Physics of the Two Infinities
2023/Mar/27-30

GRAINE* project:

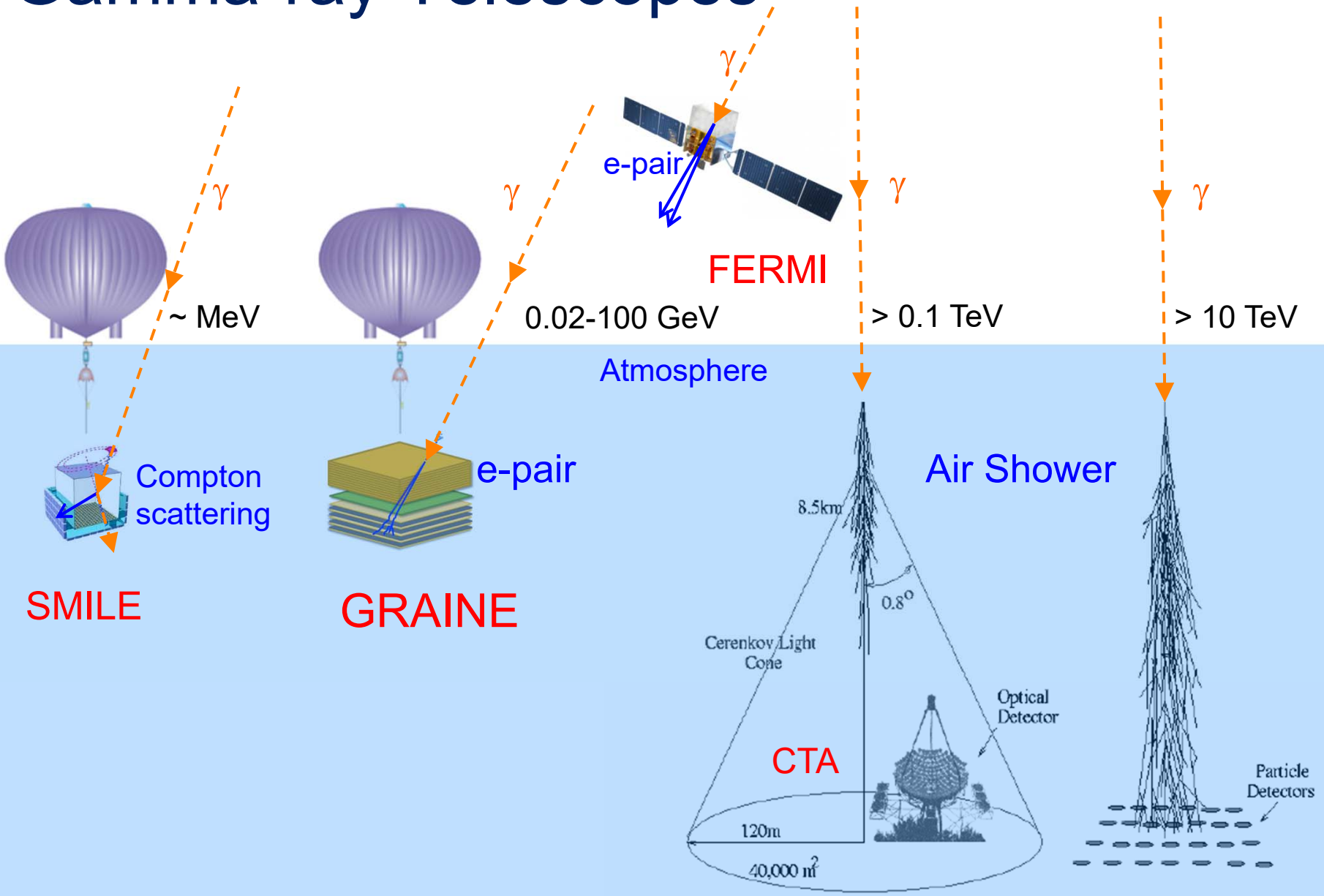
Cosmic Gamma-ray Observation by Balloon-Borne Emulsion Telescope

* GRAINE Gamma-Ray Astro-Imager with Nuclear Emulsion

Shigeki Aoki (Kobe Univ.)
for GRAINE collaboration
Kobe University,
Nagoya University,
Okayama University of Science,
Gifu University,
Aichi University of Education
and ISAS/JAXA

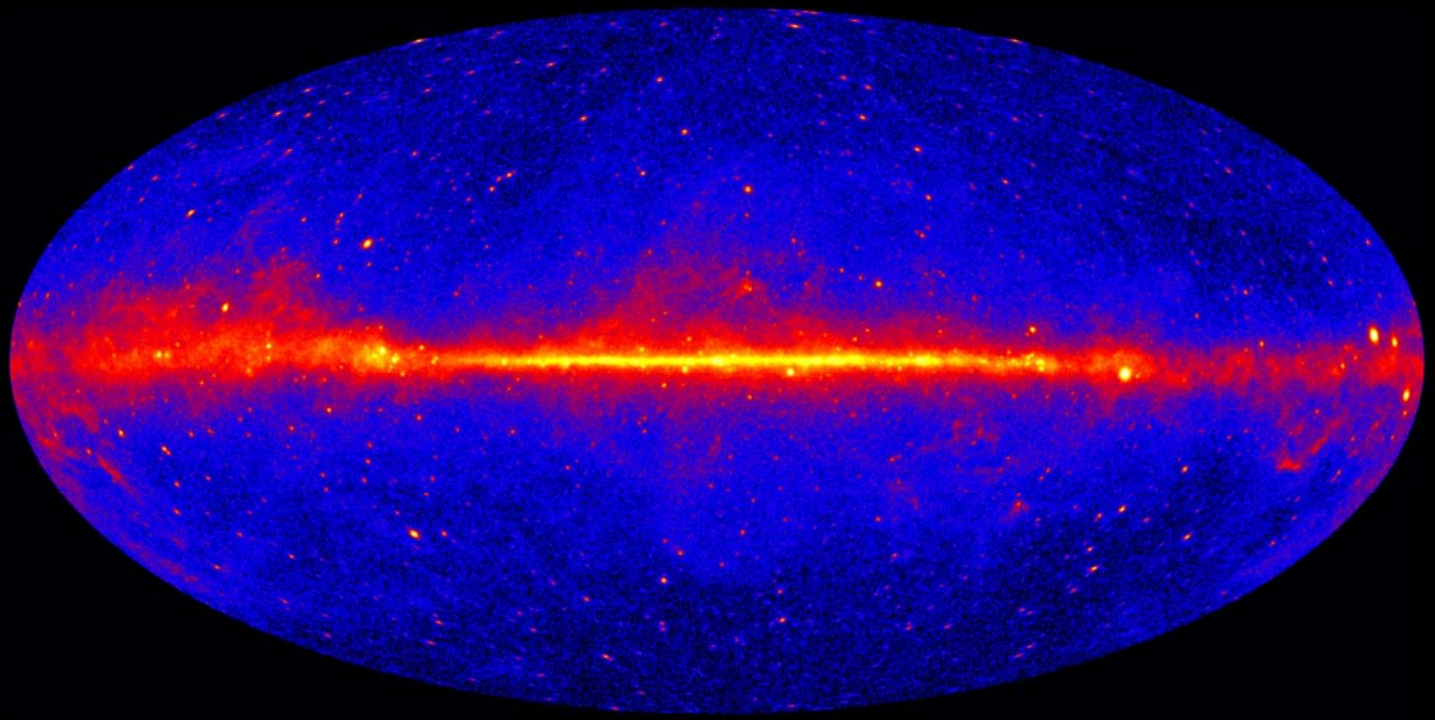
photo: GRAINE 2018
2018/Apr/26 am 6:33
Alice Springs, Australia

Gamma-ray Telescopes



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

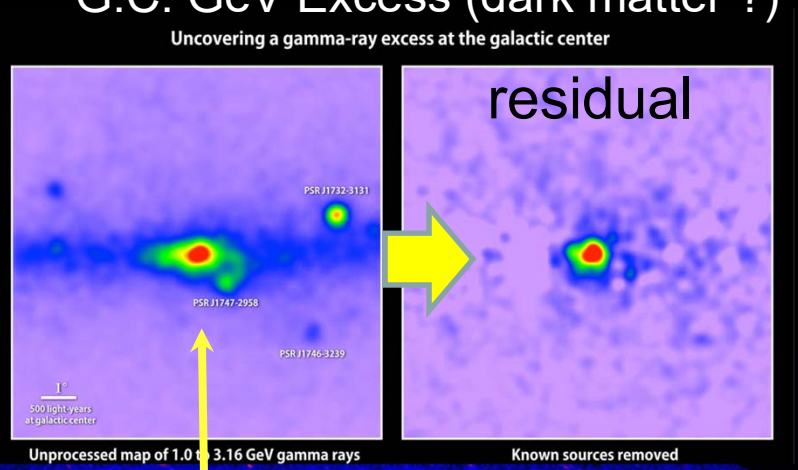


>5000 sources (FL8Y)

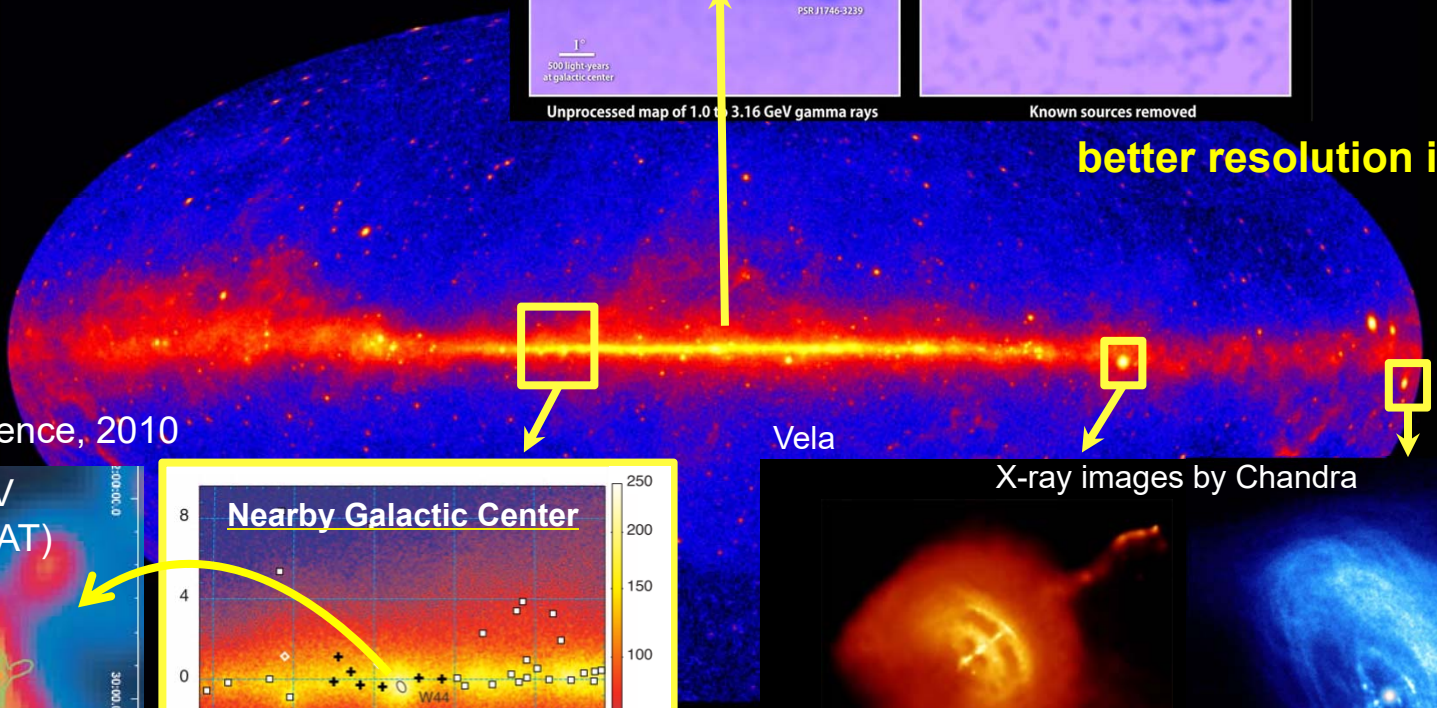
Unresolved issues in cosmic γ-ray bservation （GeV/sub-GeV band）

Image credit:
NASA/DOE/Fermi LAT Collaboration

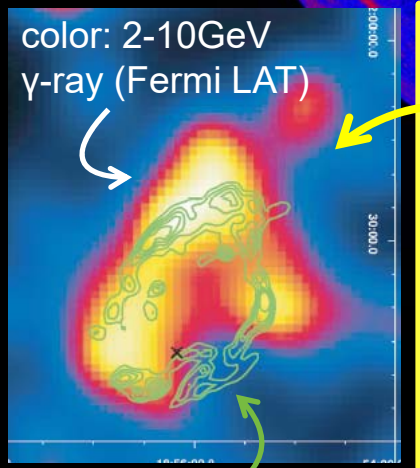
G.C. GeV Excess (dark matter ?)



better resolution is needed



SNR W44
Abdo et al., Science, 2010



Vela

Crab

X-ray images by Chandra

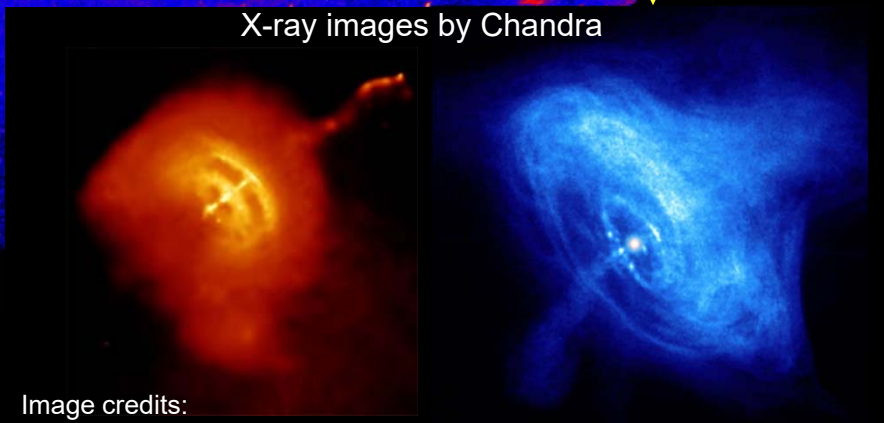


Image credits:
Pavlov, G. G. et al. ApJ. 591, 1157

NASA/CXC/ASU/J. Hester et al.

Unresolved issues in cosmic γ-ray bservation （GeV/sub-GeV band）

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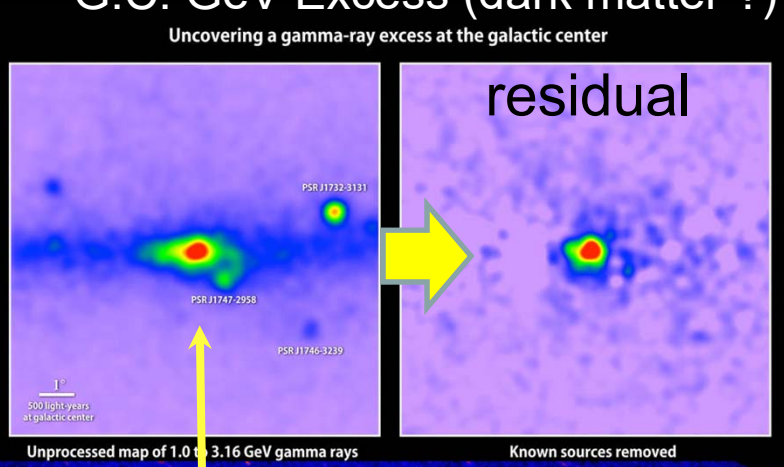

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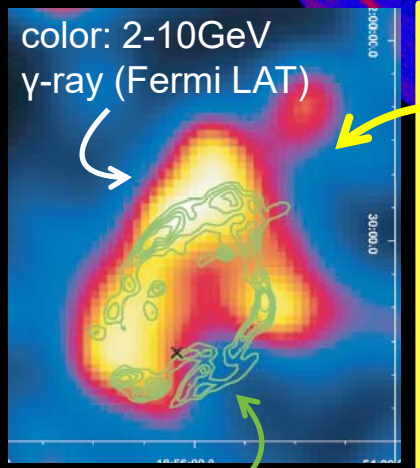
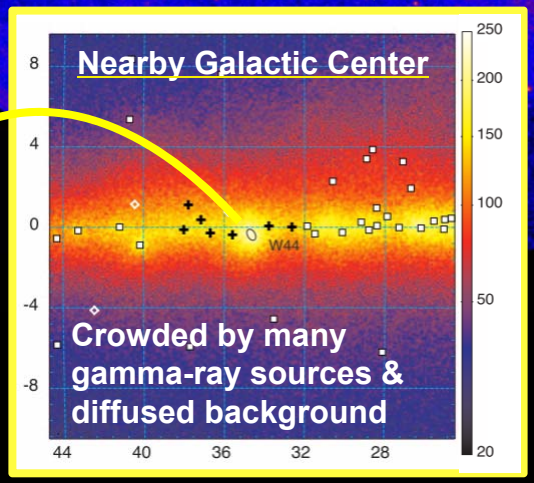
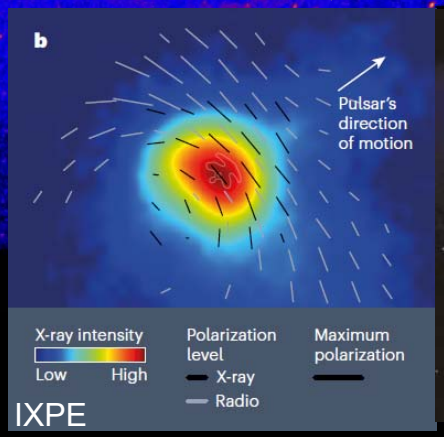
Abdo et al., Science, 2010





Vela



Xie, F. et al. Nature 612, 658,
(adapted in Nature 612, 641)

Crab

for γ-ray polarization, no positive report so far

Nuclear Emulsion

microscope view
10μm

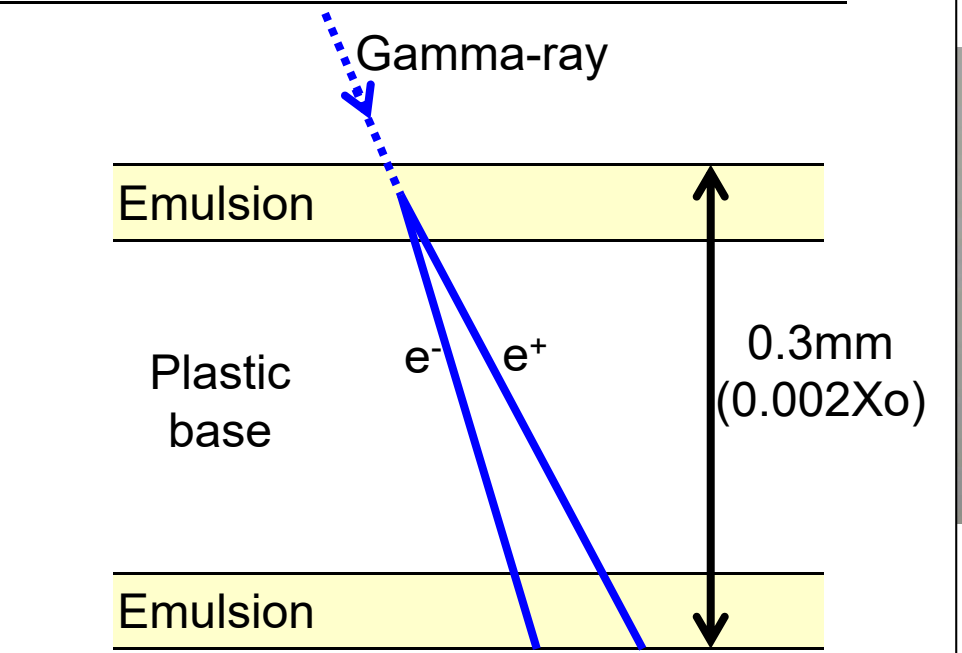
Intrinsic position accuracy of ~50nm

Gamma-ray

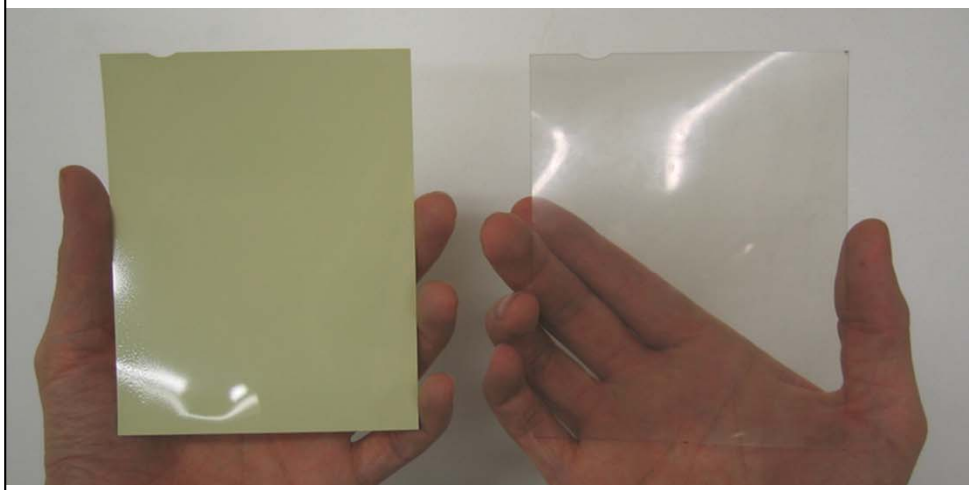
$e^{+/-}$

$e^{-/+}$

Cross sectional view of an emulsion film

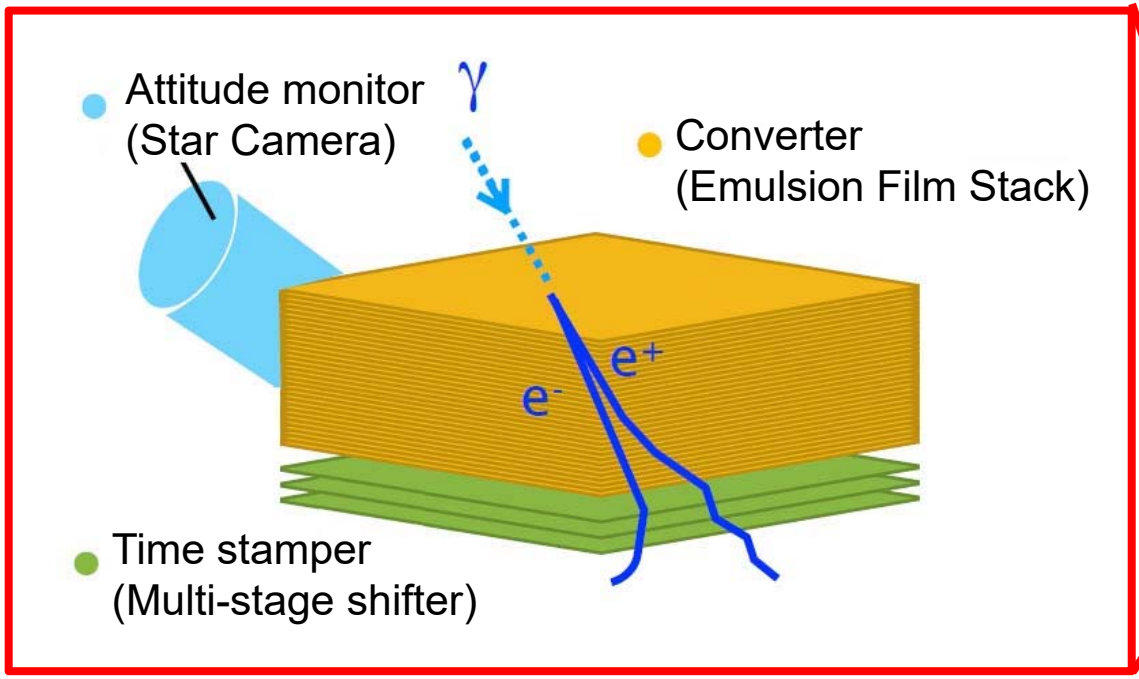


Emulsion Film

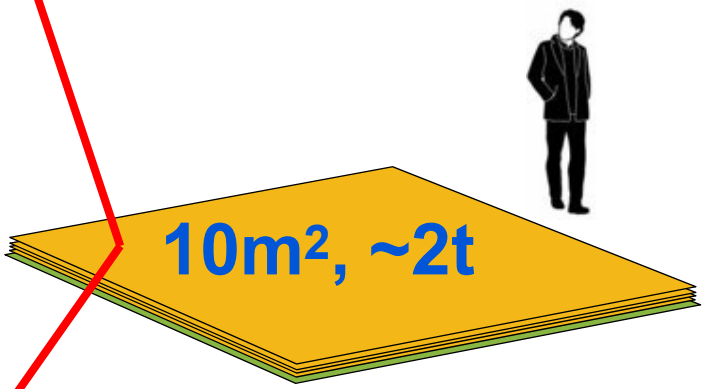


before and after
development process

Balloon-borne emulsion gamma-ray telescope



repeat
long duration flight



	Fermi LAT	GRAINE
Angular resolution @ 100MeV	6.0°	× 6 → 1.0°
Angular resolution @ 1GeV	0.90°	× 9 → 0.1°
Polarization sensitivity	—	Yes
Effective area @ 100MeV	0.25m²	× 8 → 2.1m² *
Effective area @ 1GeV	0.88m²	× 3 → 2.8m² *

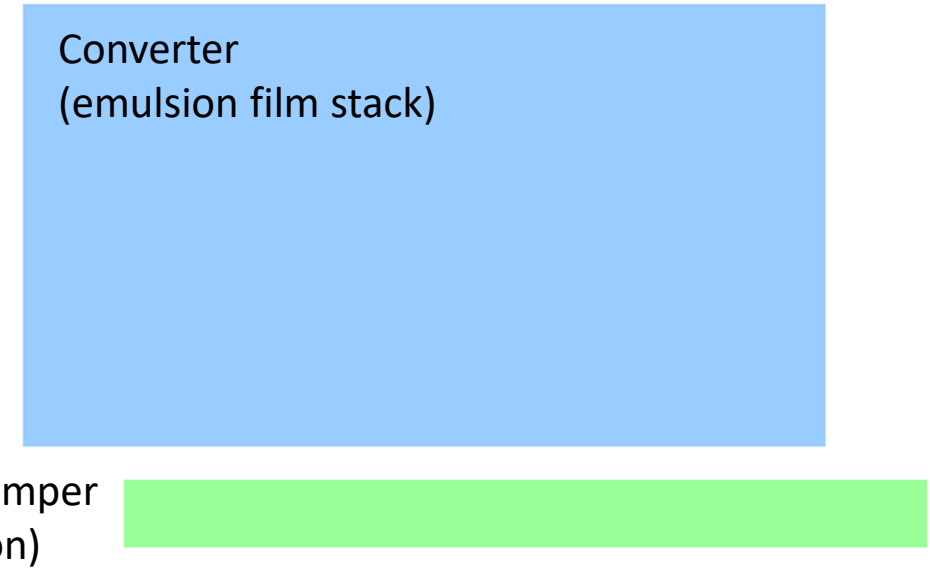
world's highest resolution

world's first in GeV band

world's largest aperture

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

Gondola rotation become
1 deg/sec in bad case.
For pointing in mrad accuracy,
Sub second time resolution required.

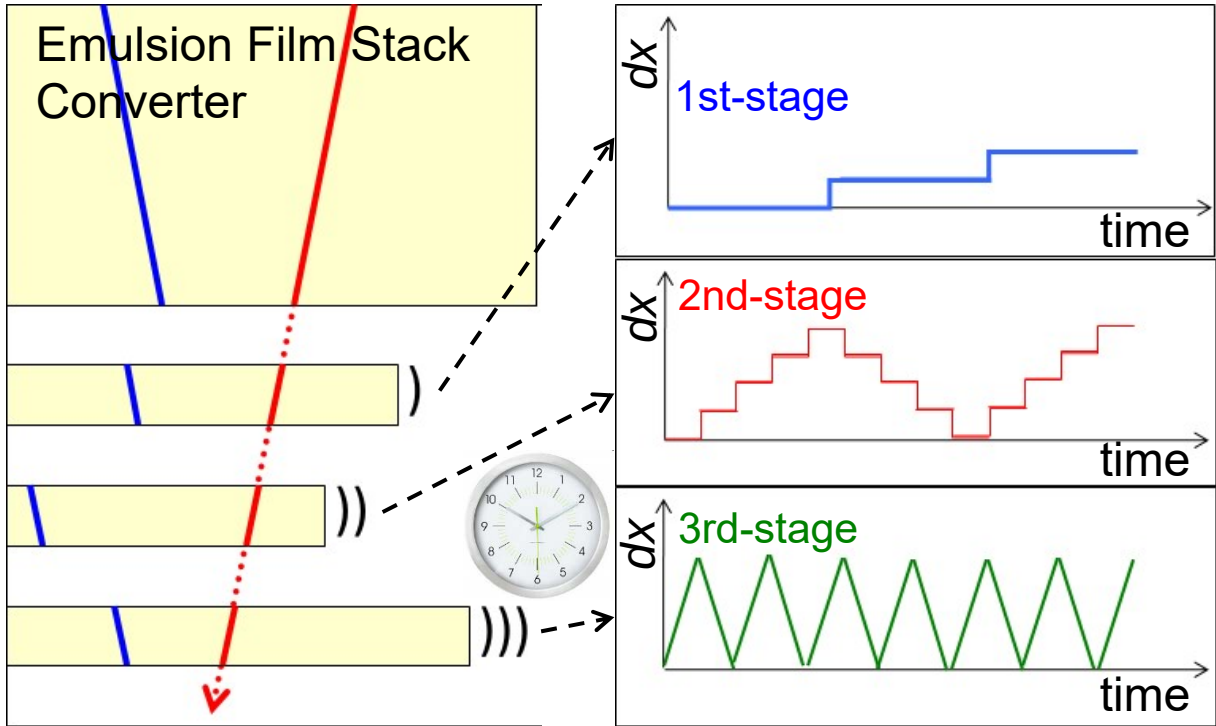


New Technique for GRAINE

Multi-stage Shifter (Time Stamper)

Consisting of emulsion film.
Low momentum threshold ~10MeV/c
High reliability & efficiency
Enlargeable
Simple, compact, light weight, high vol. free
Low power consumption, dead time free

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



GRAINE roadmap

2004- Development on ground

S.Takahashi et al. NIMA 620, 192 (2010)
K.Ozaki et al. NIMA 833, 165 (2016)

2011/Jun: 1st Balloon exp.

- Confirmation of feasibility

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

Demonstration phase w/ 0.38m^2

2015/May: 2nd Balloon exp.

- Establishment of experimental flow
- Demonstration of the detector performance

K.Ozaki et al., JINST 10, P12018 (2015)
S.Takahashi et al. PTEP 2016, 073F01
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S.Takahashi et al. Adv.Space Res. 62 2945-2953

2018/Apr: 3rd Balloon exp.

- Celestial source detection

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Y. Nakamura et al. PTEP 2021, 123H02
S.Takahashi et al. PTEP (2021) submitted

2023/Mar,Apr:

- Commissioning scientific observation
- Approved 2.5m^2 × 2 flights (=5m^2)

→ 10m^2 aperture and longer duration flight (in future)

GRAINE 2011

- 2011/Jun/8
- Hokkaido, Japan
- Aperture 0.013m^2
- 1.6hr@35km

GRAINE 2015

- 2015/May/12
- Alice Springs, Australia
- Aperture 0.38m^2
- 11.5hr@36-37km

GRAINE 2018

- 2018/Apr/26
- Alice Springs, Australia
- Aperture 0.38m^2
- 14.7hr@35-38km

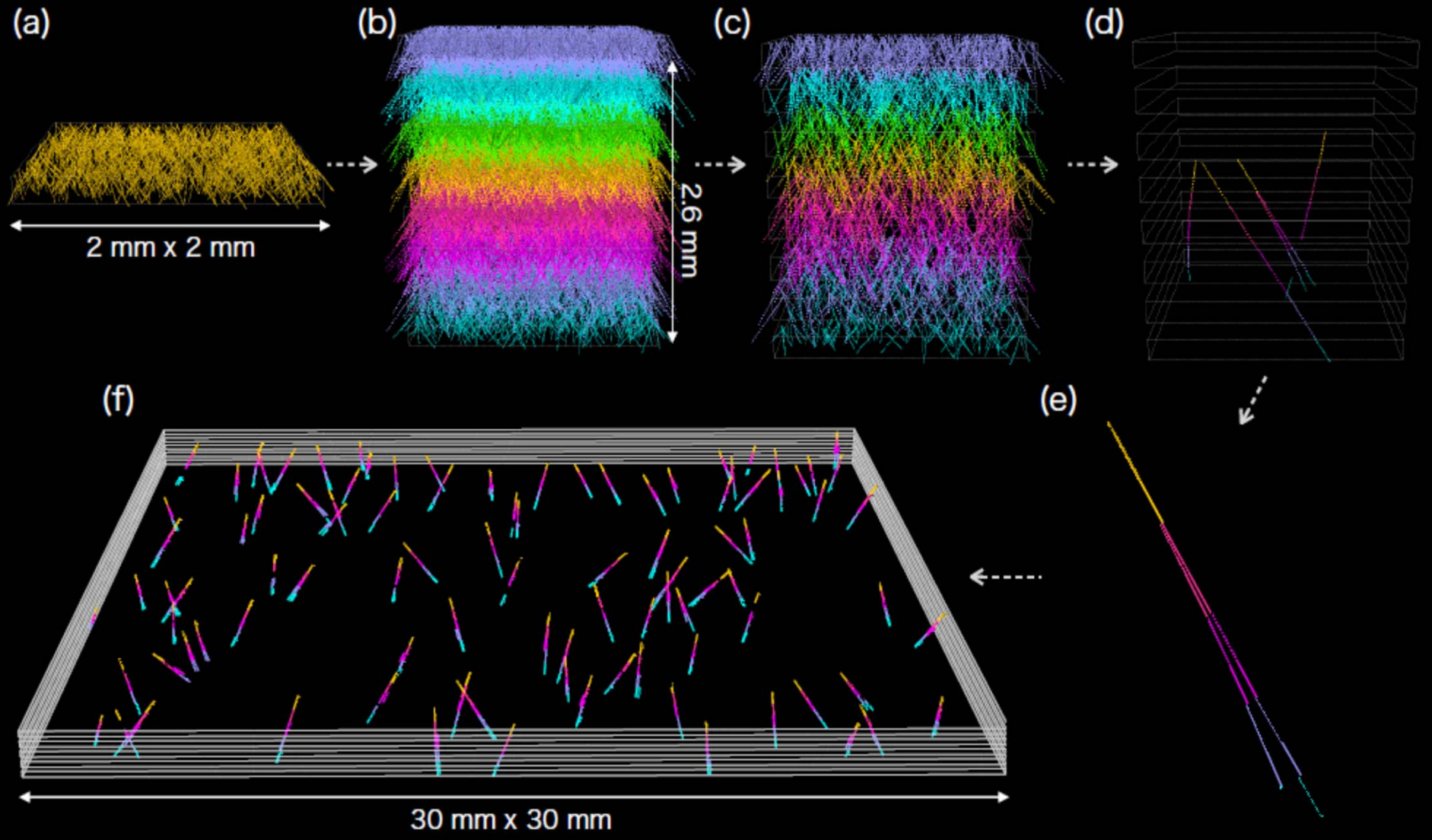
GRAINE 2021→2023

due to COVID-19

- 2023/Mar,Apr/
- Alice Springs, Australia
- Aperture 5m^2→ 2.5m^2
- 24hr to observe Vela and Galactic Center

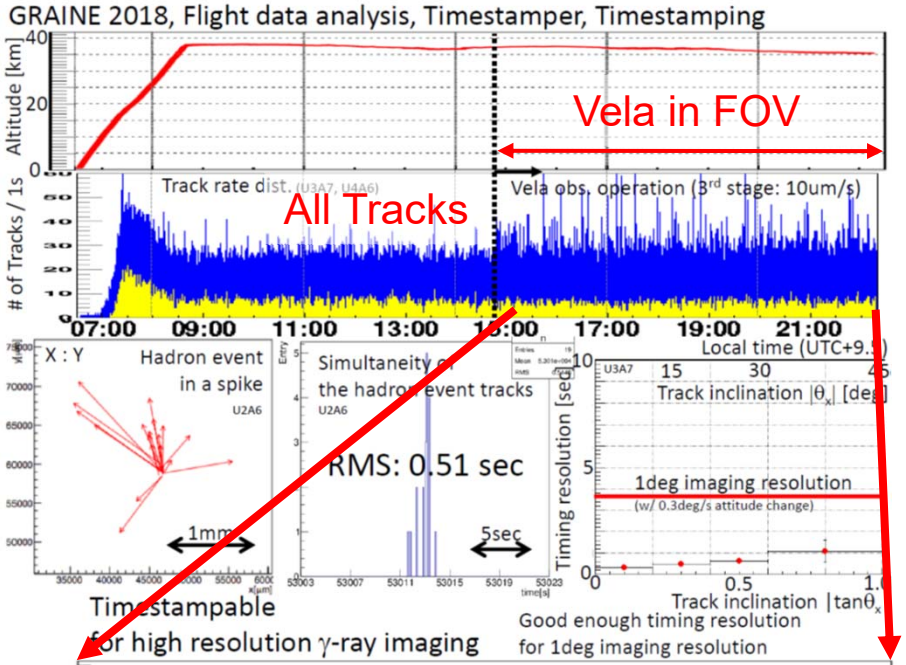
$\gamma \rightarrow e^+ e^-$ Event Selection

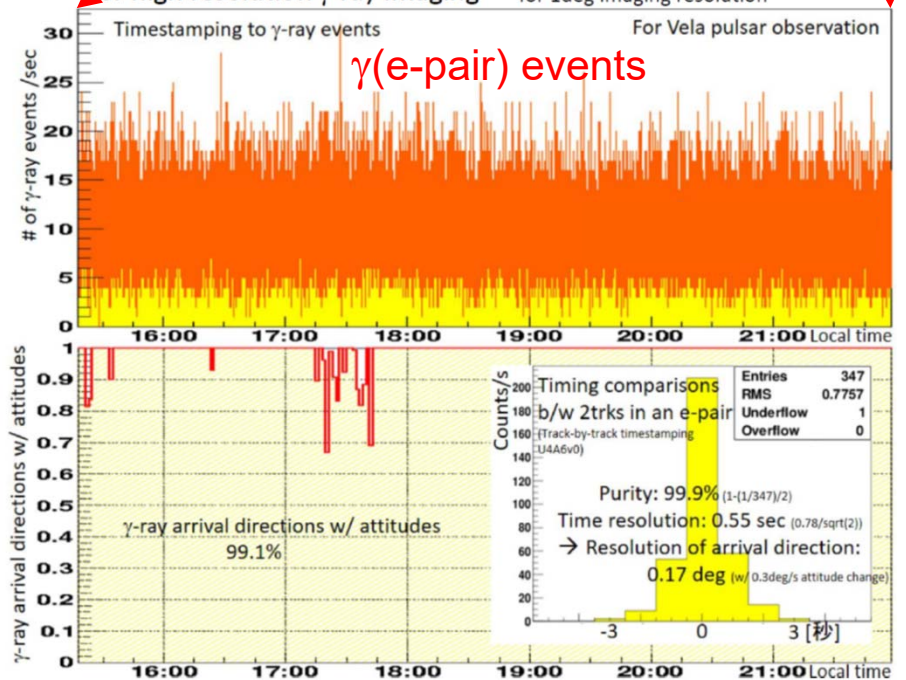
H. Rokujo et al.
PTEP, 2018, 063H01

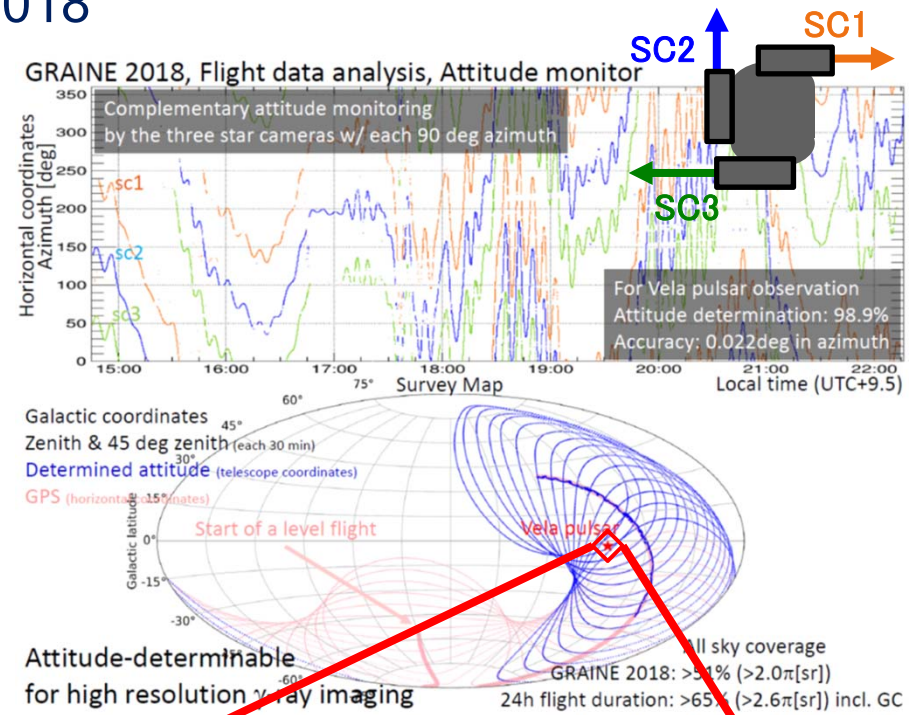


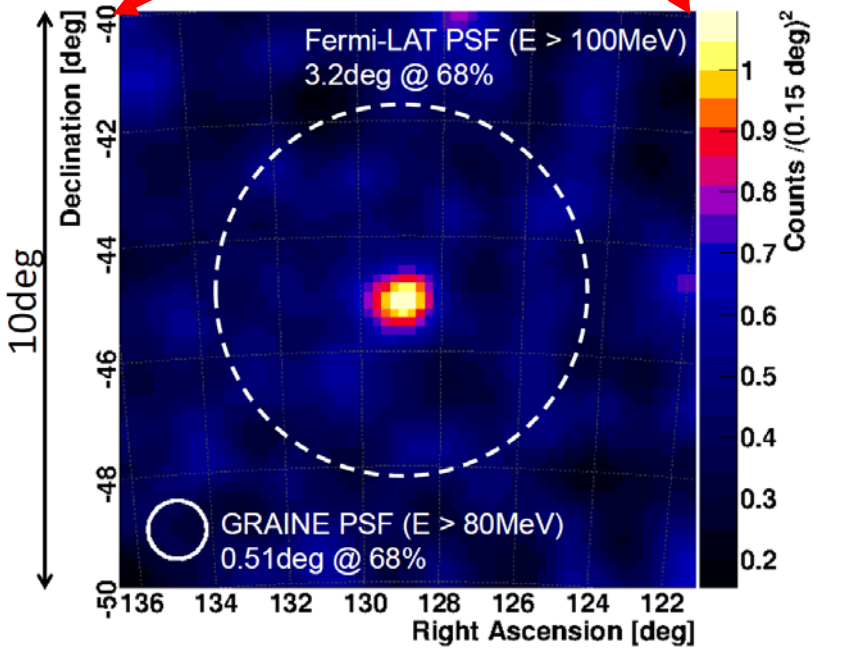
Small area of the real data from GRAINE2015

Vela pulsar imaging @GRAINE2018









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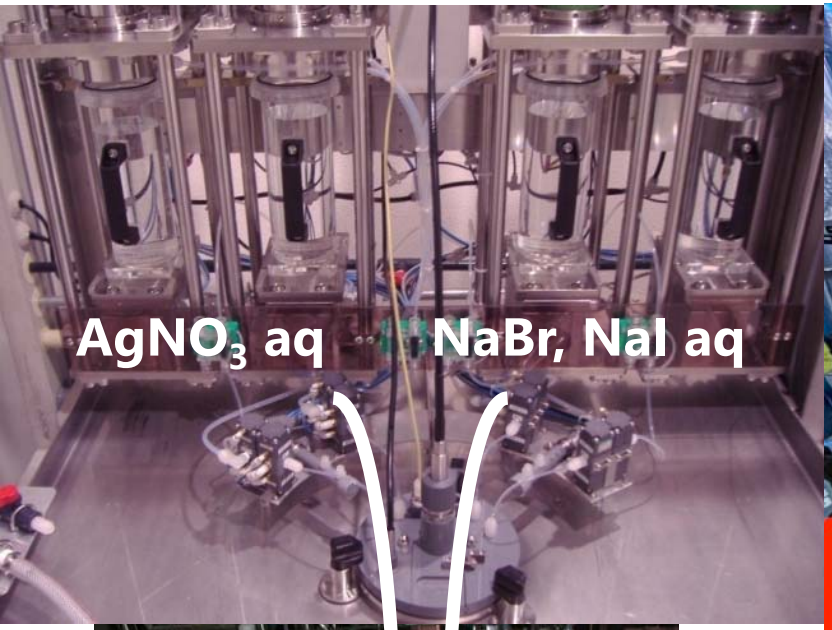
Development of Large Aperture Telescope for Scientific Observation

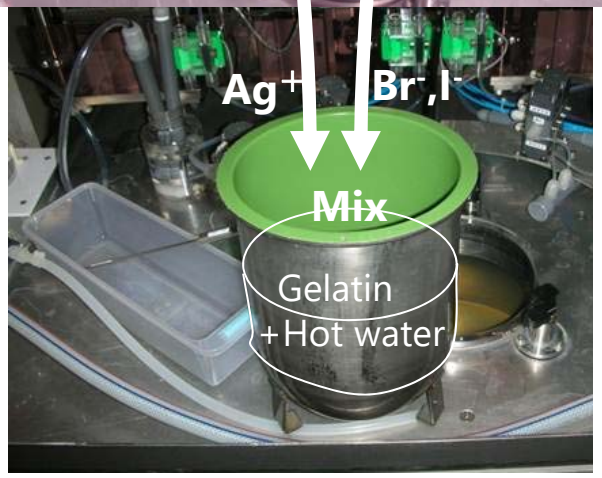
realization of 10m^2 aperture telescope

- Mass-production emulsion gel and film and development process
  (converter film 1000m^2 and shifter film 100m^2)
- Improvement of Hyper Track Selector
- New Pressure Vessel and Gondola
- New Multi Stage Shifter

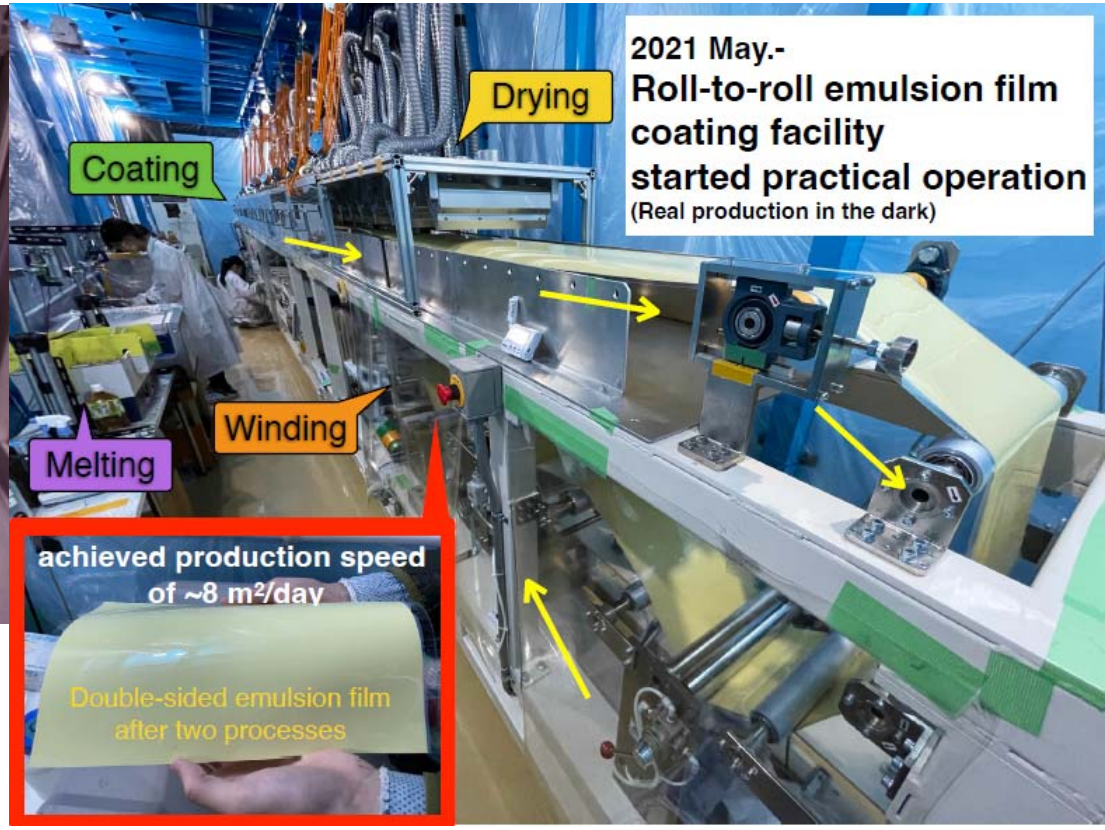
Emulsion film production facility @Nagoya Univ.

Gel prodution





"30 times machine" is installed

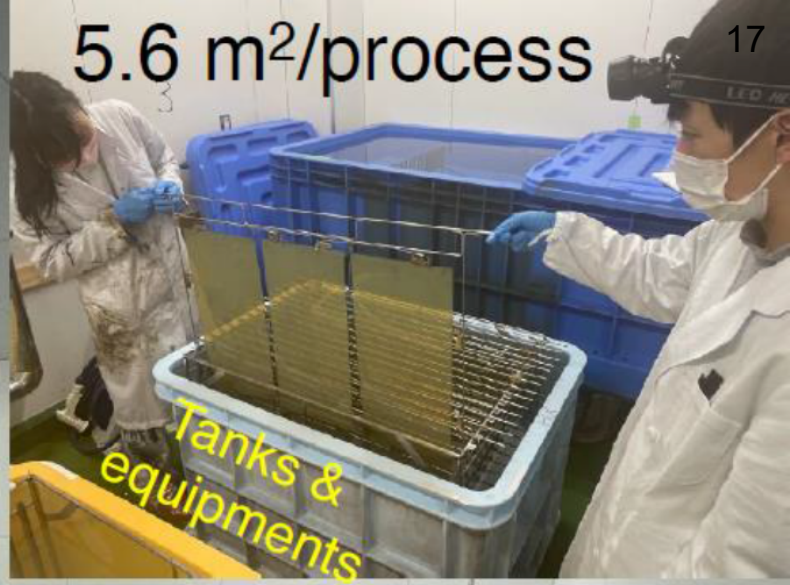


Particle physics, muon radiography, gamma-ray telescope etc.

Next balloon-borne experiment
total emulsion film surface area ~600m^2
Oct 2021, Converter rehearsal @Mt. Norikura
May 2022, Started mass-production

Large Scale Development Facility

@ Gifu University



Large space

Water bath with cooling

Dev. 390L

Stop

Fix

Wash

Waste water system

Drain

Drywel

GRAINE next, 4500 emulsion films equiv. (4000+500)
15 hanger, 120 cycle (90+30) → Developing for 1 – 2 months

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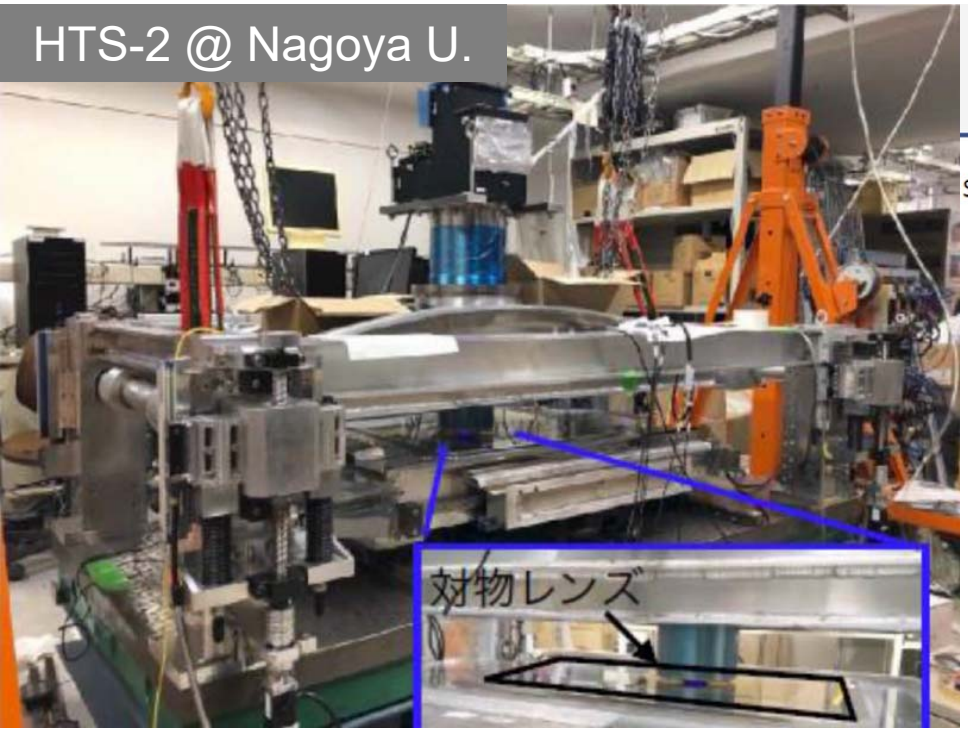
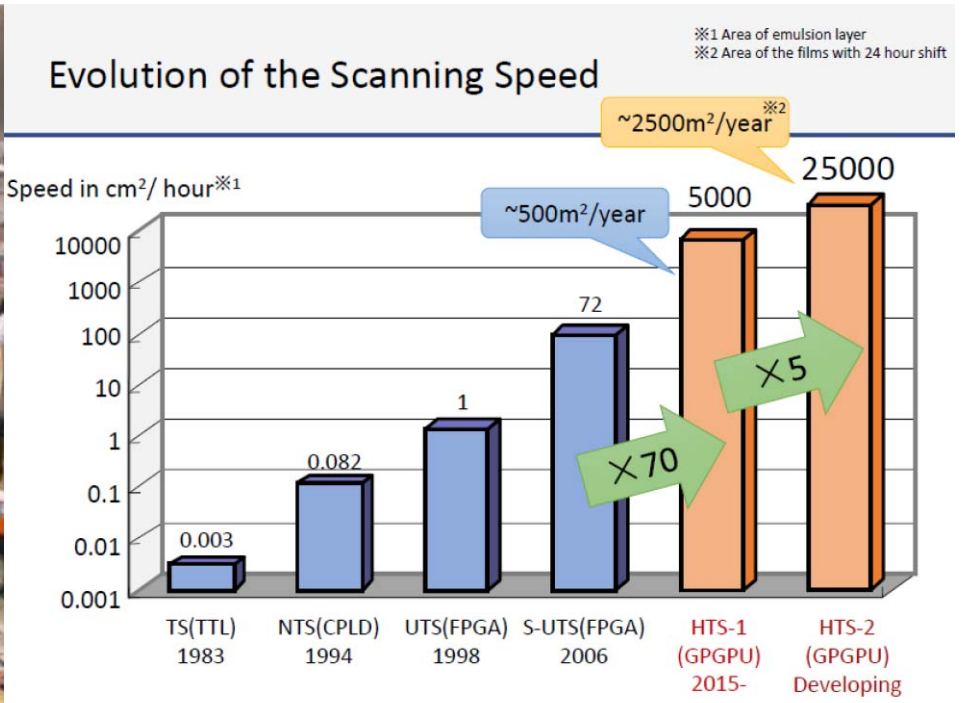
HTS-2 @ Nagoya U.





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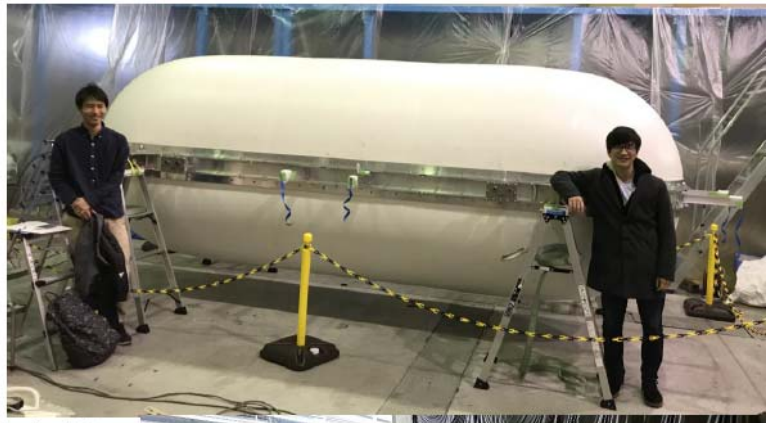
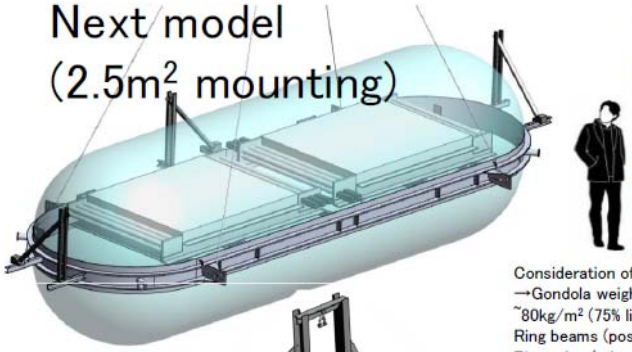
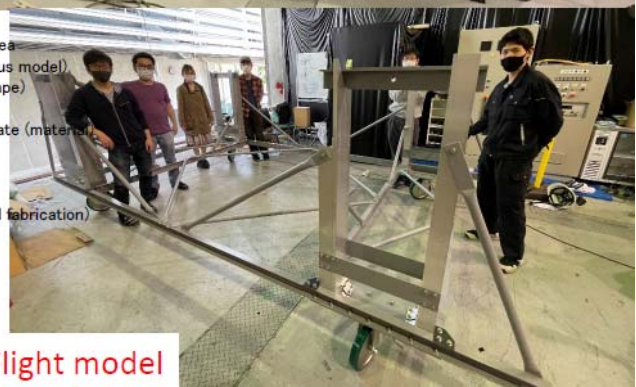
Large, Light, Thin
(<0.3 atm)



Next model
(2.5m^2 mounting)



Consideration of various factors
→Gondola weight per aperture area
~80kg/m^2 (75% lighter than previous model)
Ring beams (position, number, shape)
Ring edge (edge cutting)
Suspension point (shape), strip plate (material)
Bolt (diameter, number of bolts)
Trusses (elimination, carting)
Shell membrane (configuration)
Airtight membrane (shape, original fabrication)



Gondola carrying cart

1st Flight model

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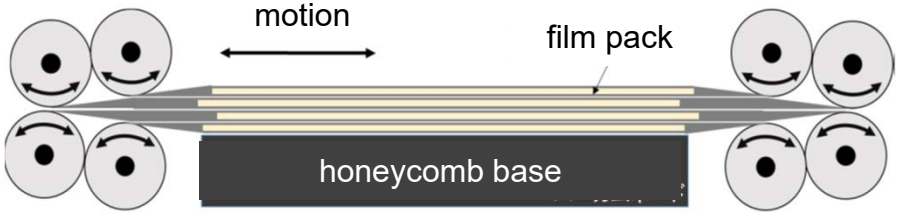
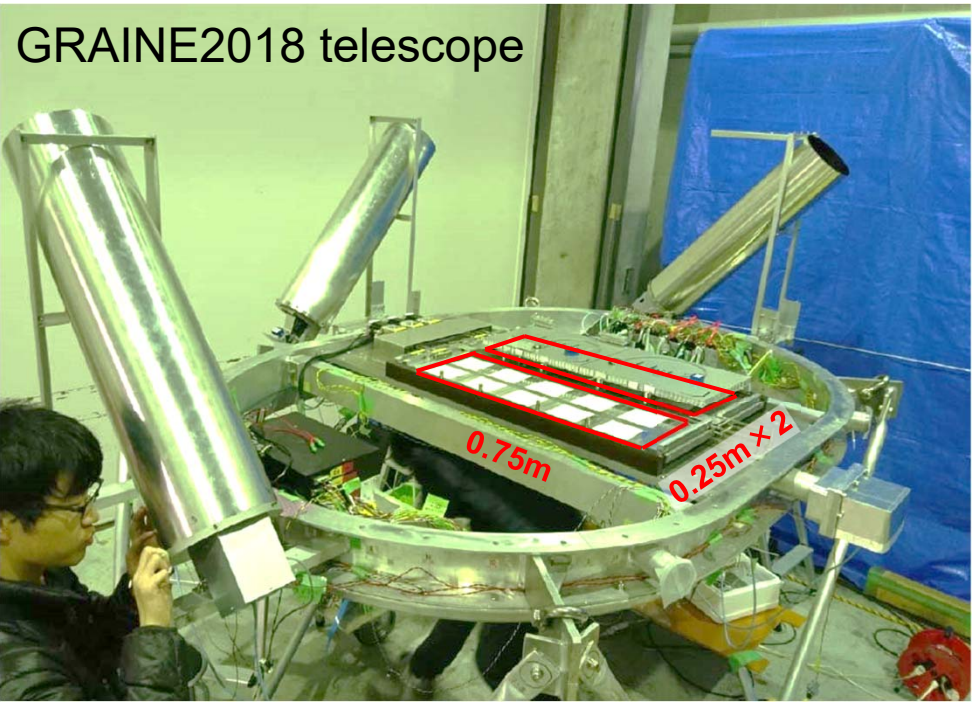
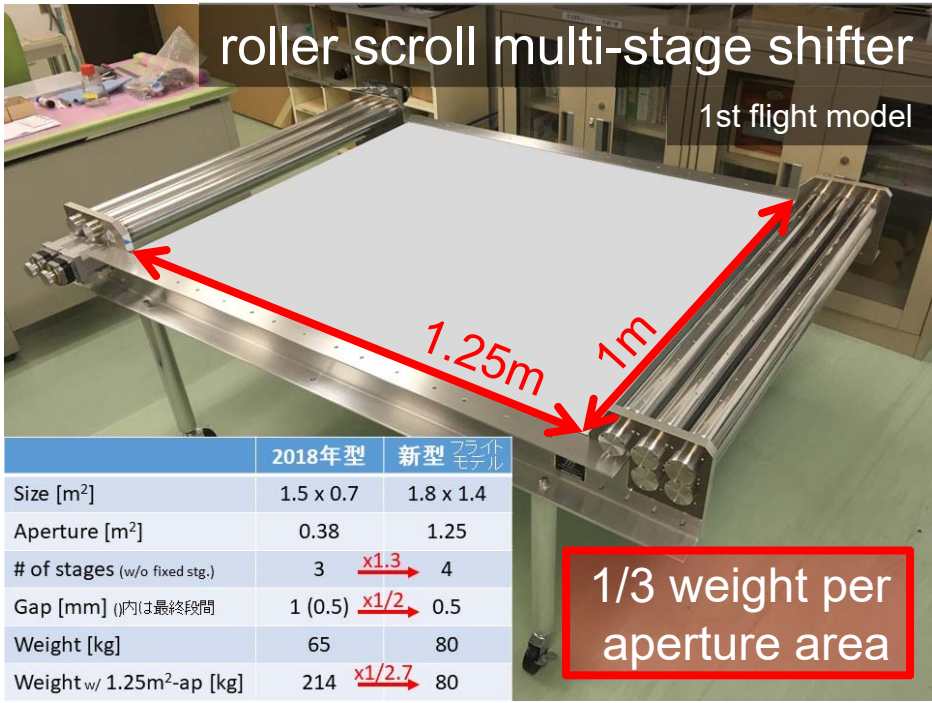




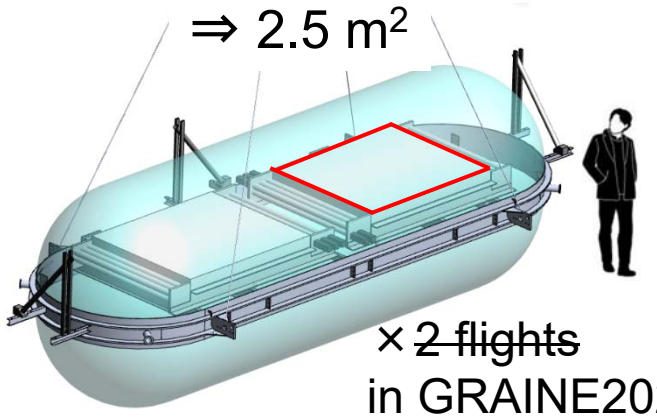


	2018年型	新型 フライトモデル
Size [m^2]	1.5 x 0.7	1.8 x 1.4
Aperture [m^2]	0.38	1.25
# of stages (w/o fixed stg.)	3 x1.3	4
Gap [mm] ()内は最終段間	1 (0.5) x1/2	0.5
Weight [kg]	65	80
Weight w/ 1.25m^2-ap [kg]	214 x1/2.7	80

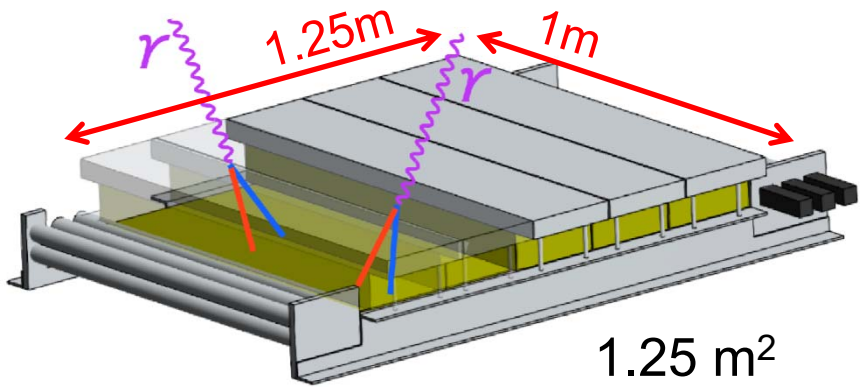
1/3 weight per aperture area

Scalable telescope assembling identical units

2 units
⇒ 2.5 m^2

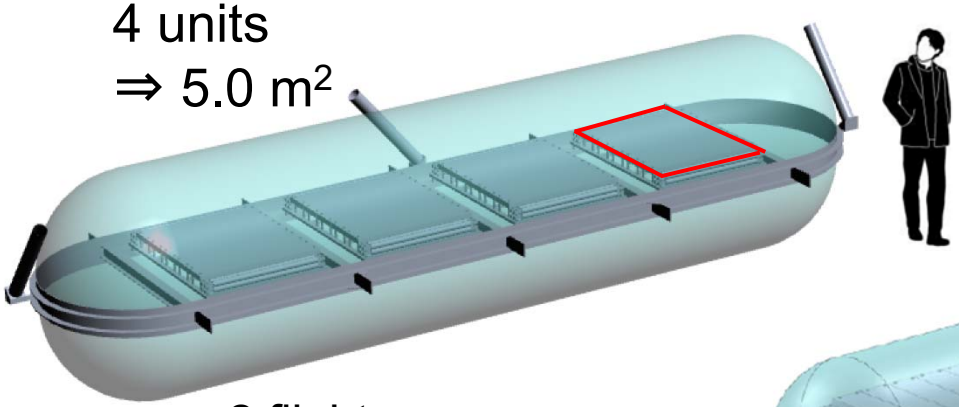


× ~~2 flights~~ → 1 flight
in GRAINE2023



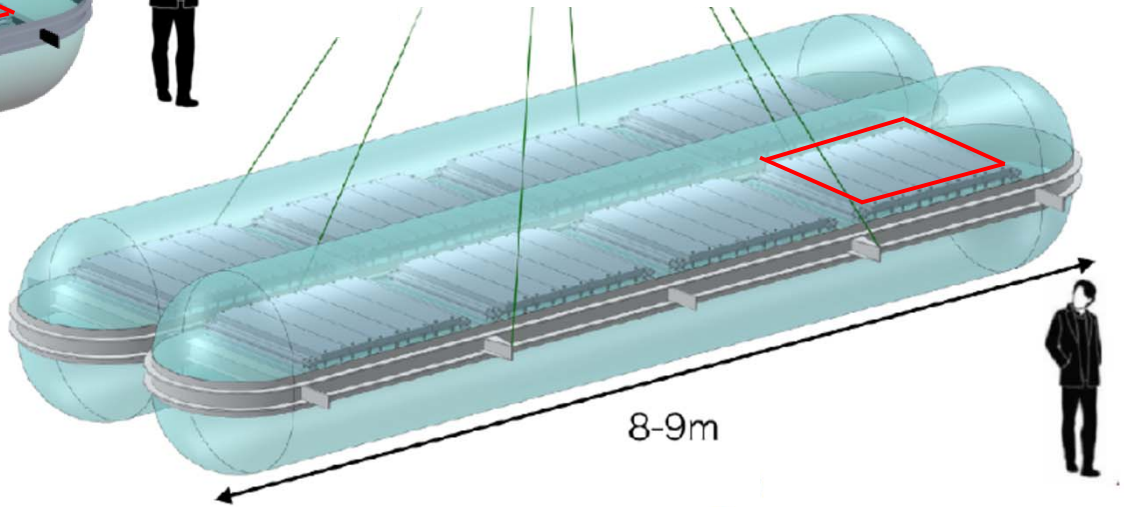
1.25 m^2
telescope unit

4 units
⇒ 5.0 m^2



× 2 flights
in GRAINE2026?

8 units
⇒ 10.0 m^2



GRAINE2023 is now on going

JAPAN

2022 Dec: export Gondola and parts by Sea Container

2023 Jan: export Emulsion films by Air Cargo

June: Large Scale Scanning @ Nagoya Univ.

May: Large Scale Development Process @ Gifu Univ.

Alice Springs

Mid Feb: Installation & Construction

↓

Mid Mar: Compatibility Test Rehearsal

↓

Early Apr: Waiting for Good Wind Launch

April:

Recovery @ Alice Springs

or

Recovery @ Long Reach

Long Reach

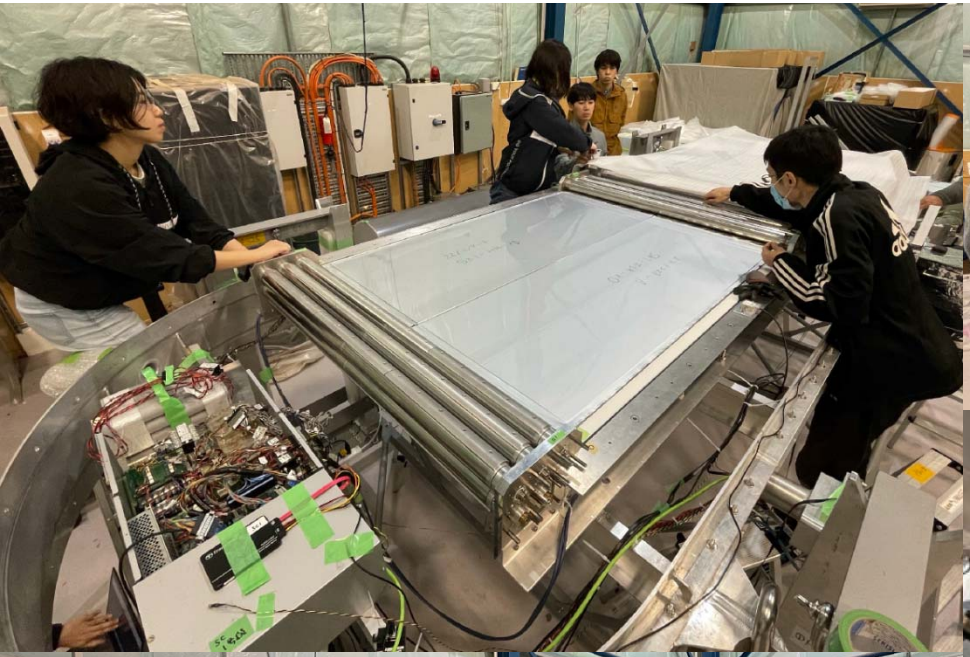
Alice Springs

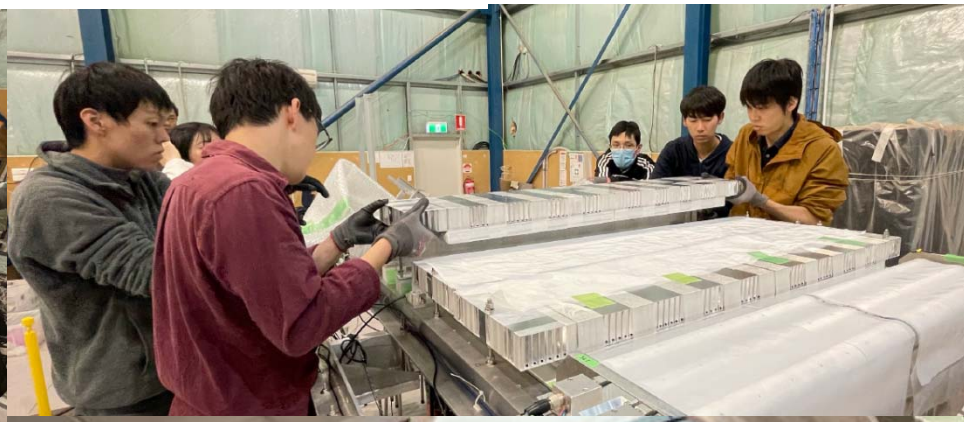
Hangars in Balloon Launching Station at Alice Springs, Australia

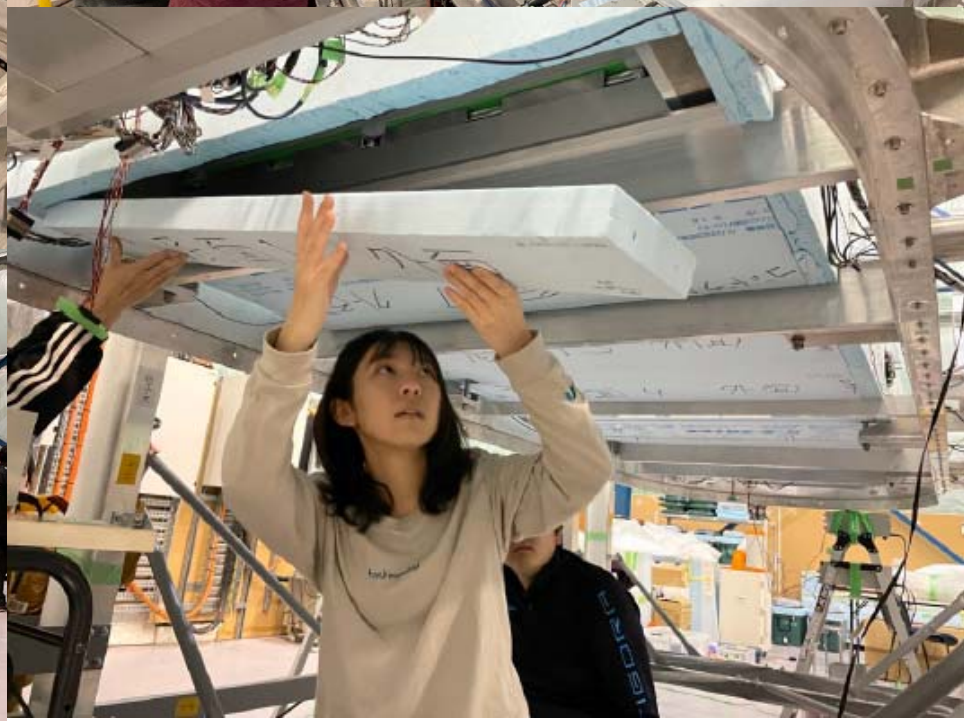
Gondora and main parts in Sea Container and transshipped to Railroad

Emulsion films via Air cargo & Cooling track

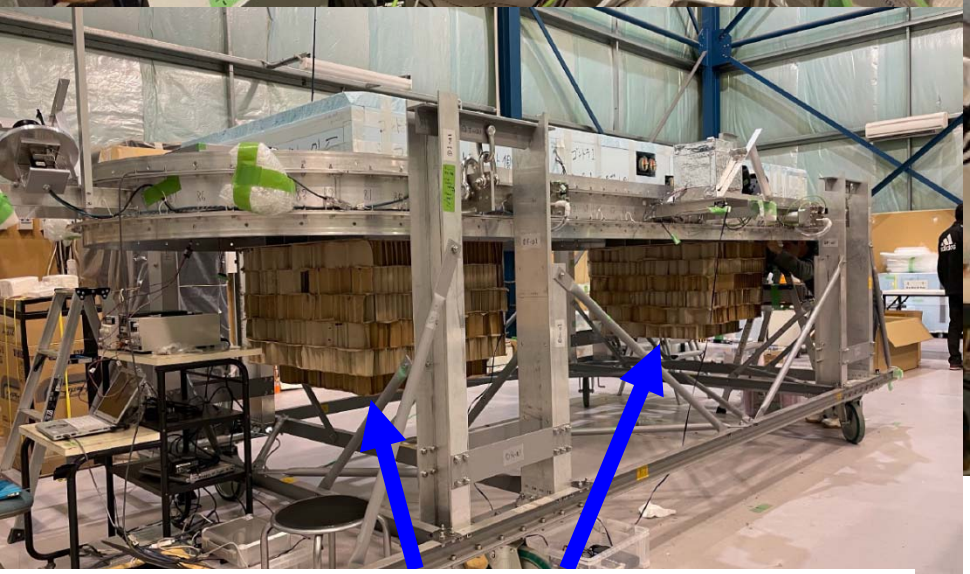
Film Installation (Shifter & Converter)







Thermal Insulation



Crush Pad (paper honeycomb)

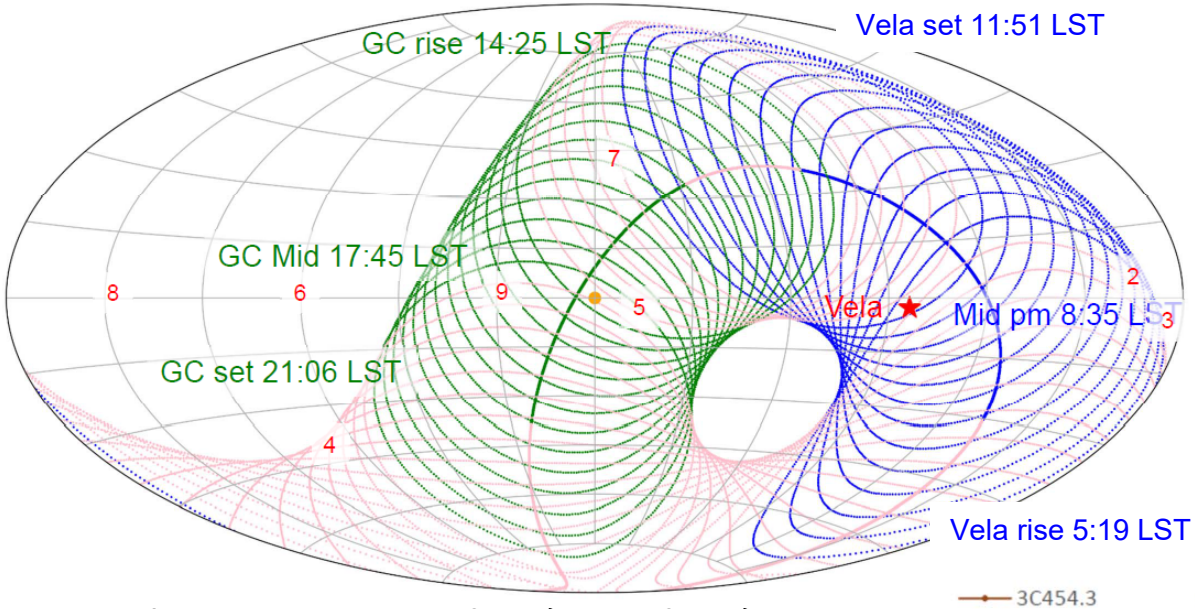
Pressure Vessel & Outside Components

Attitude Monitor (Star Camera)

Hanging & Radio Test with Launching Crane

GRAINE Payload is Almost Ready for Launch

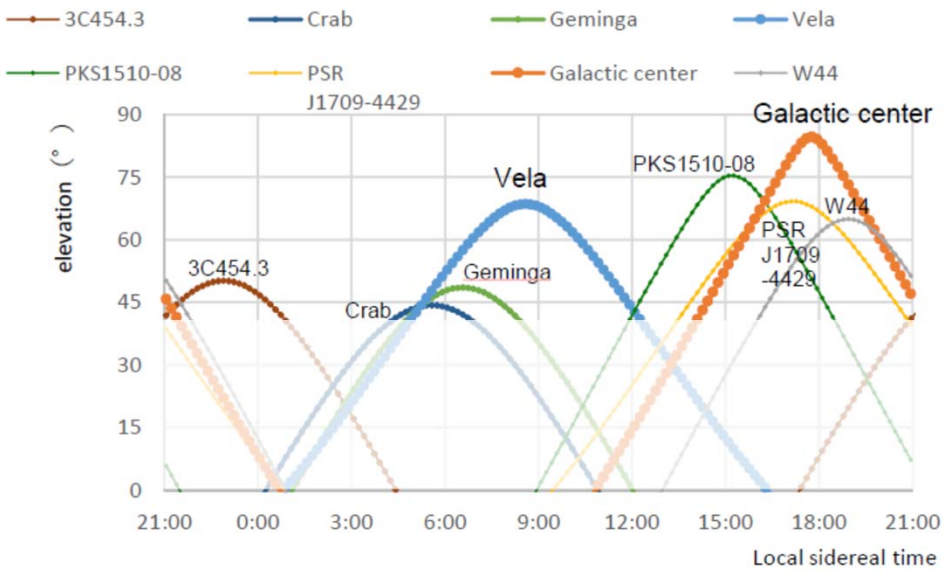
Field of view transition in 24 hours



@Alice Springs: 133° 50′ E 23° 40′ S

>100MeV Flux (2FGL)			
1	Vela	1.0	PSR
2	Geminga	0.389	PSR
3	Crab	0.254	PSR
4	3C454.3	0.219	BZQ
5	J1709-4429	0.144	PSR
7	PKS1510-08	0.091	BZQ
9	W44	0.073	SNR
10	GC	0.066	spp

Elevation Angle



local time (NT)				Vela			Galactic Center		
date				rise	mid	set	rise	mid	set
4/1	8:54	11:54	14:54	17:54	20:54	23:54	2:54	5:54	8:54

24hours

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
>~30 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

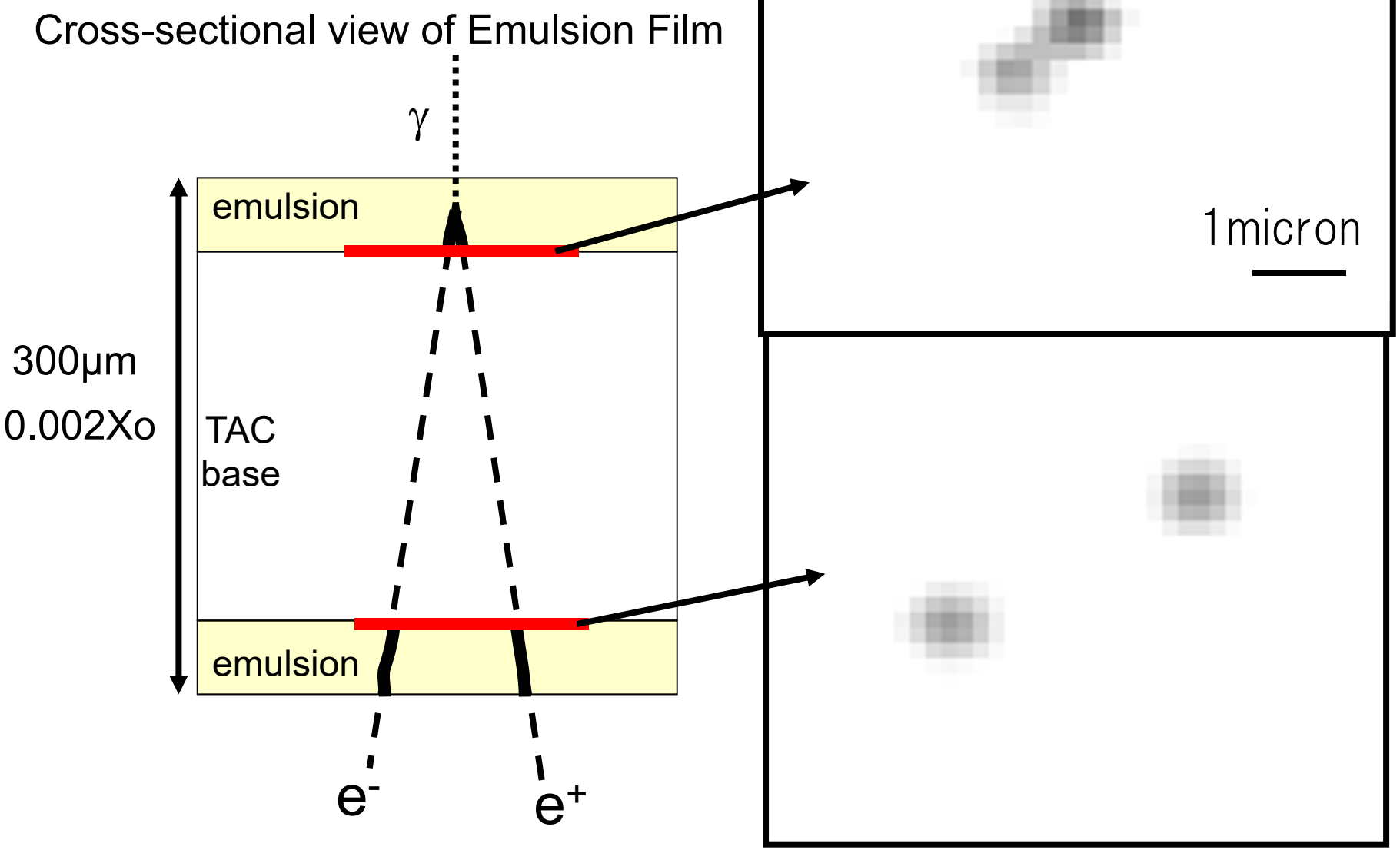
Test of fundamental symmetries beyond the Planck scale

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

Polarization Measurement

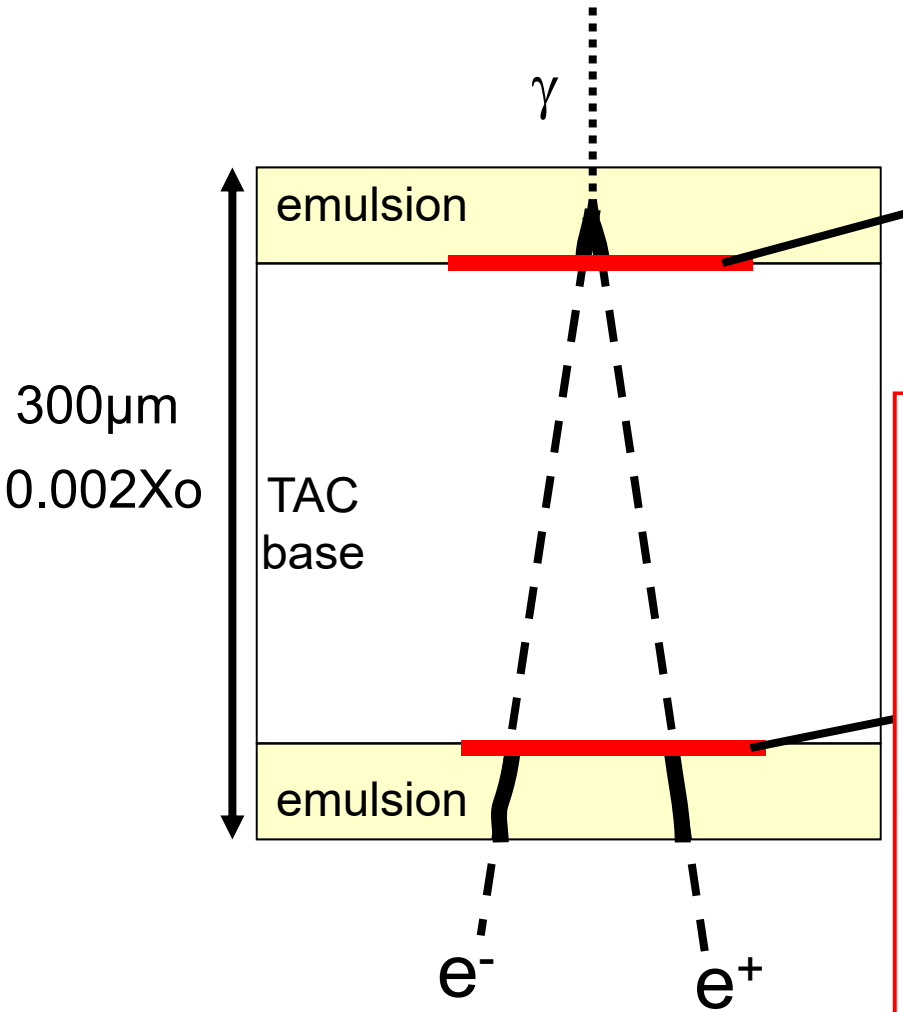
(Beam Test @ LEPS of Spring-8)

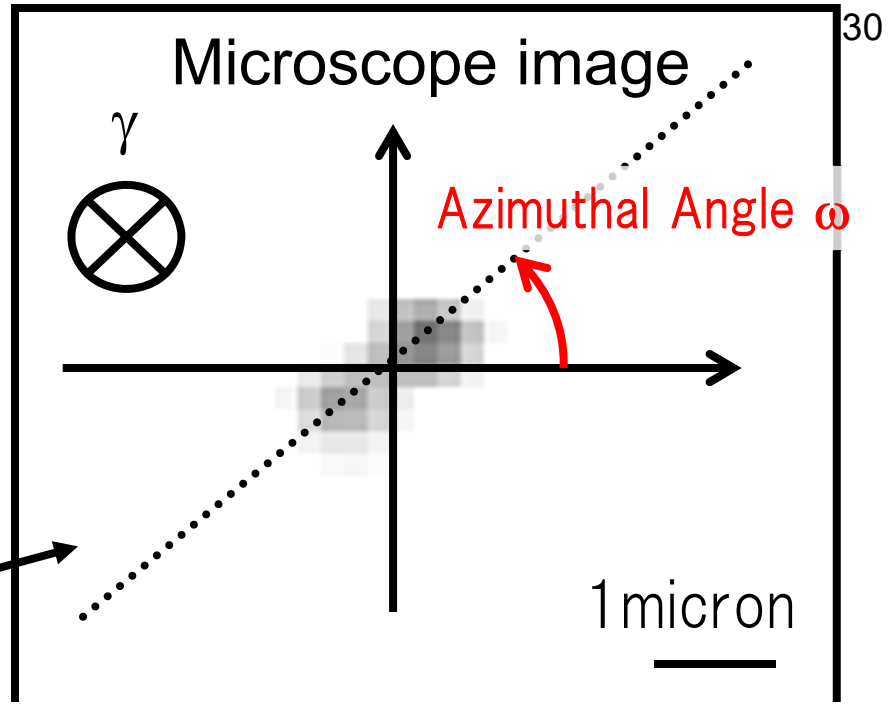


Polarization Measurement

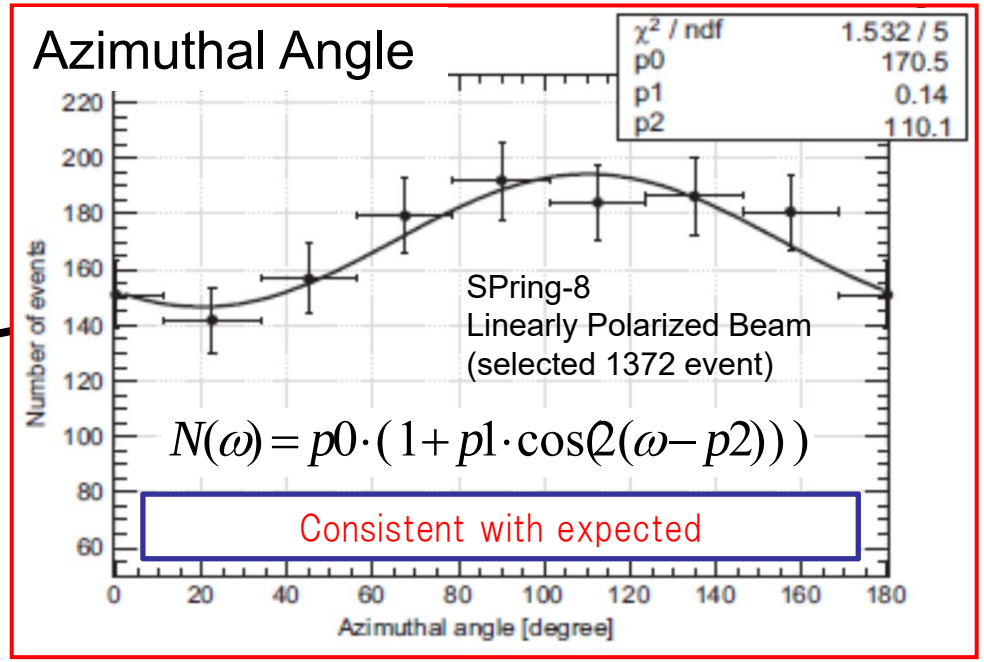
(Beam Test @ LEPS of Spring-8)

Cross-sectional view of Emulsion Film





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



Summary & Prospects

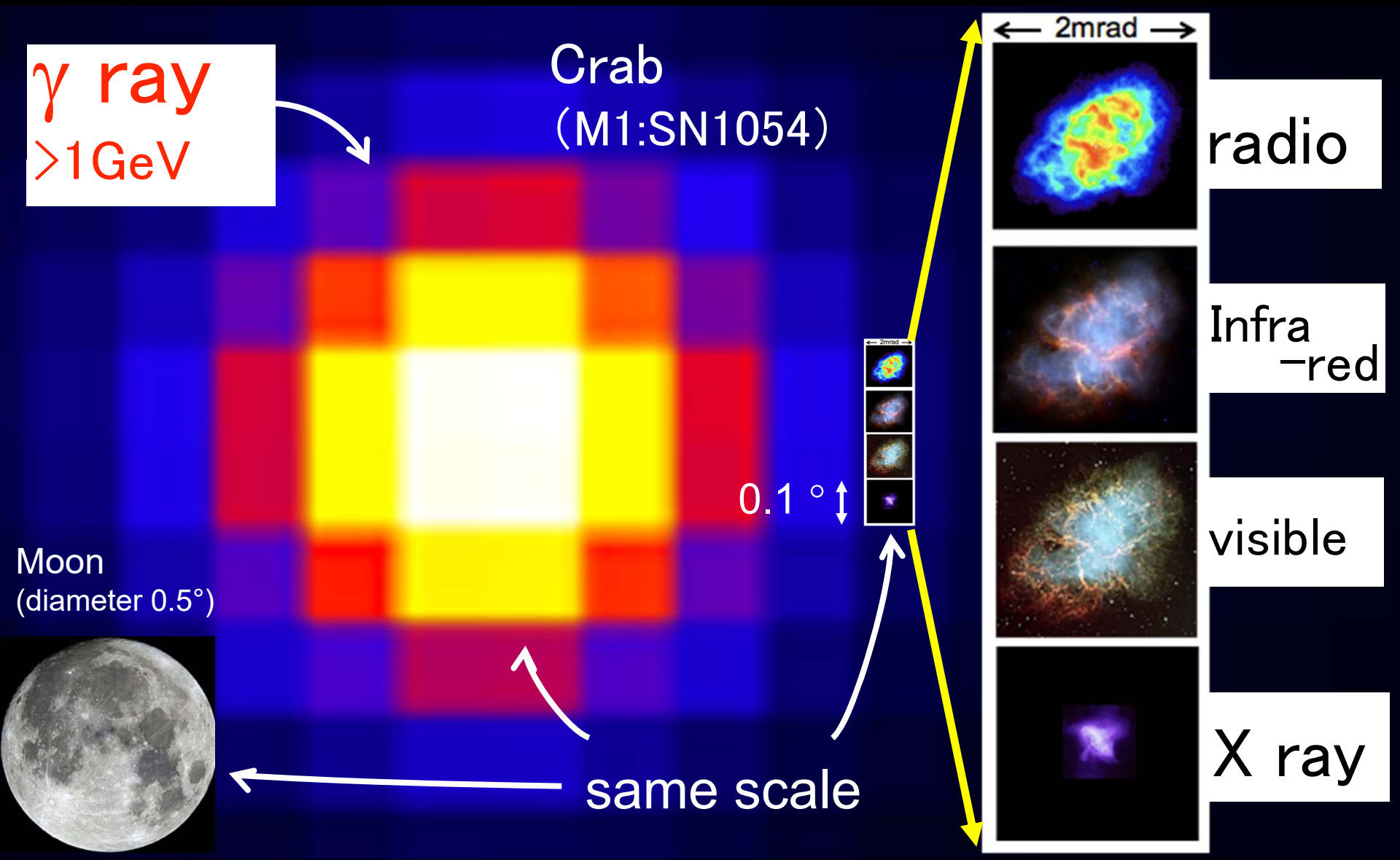
- **GRAINE project**
  - Precise observation by balloon-borne emulsion gamma-ray telescope
  - High angular resolution, Polarization sensitive, Large effective area

- **2018 Balloon experiment in Australia**
  - Confirmed overall performance by imaging Vela pulsar
  - 6.3 times better PSF radius, 39 times better solid angle than Fermi-LAT

- **2023 Balloon experiment in Australia**
  - Start scientific observation by 2.5m^2 (6.5 times of GRAINE2018)
  - higher statistics of Vela pulsar and detection of Galactic Center

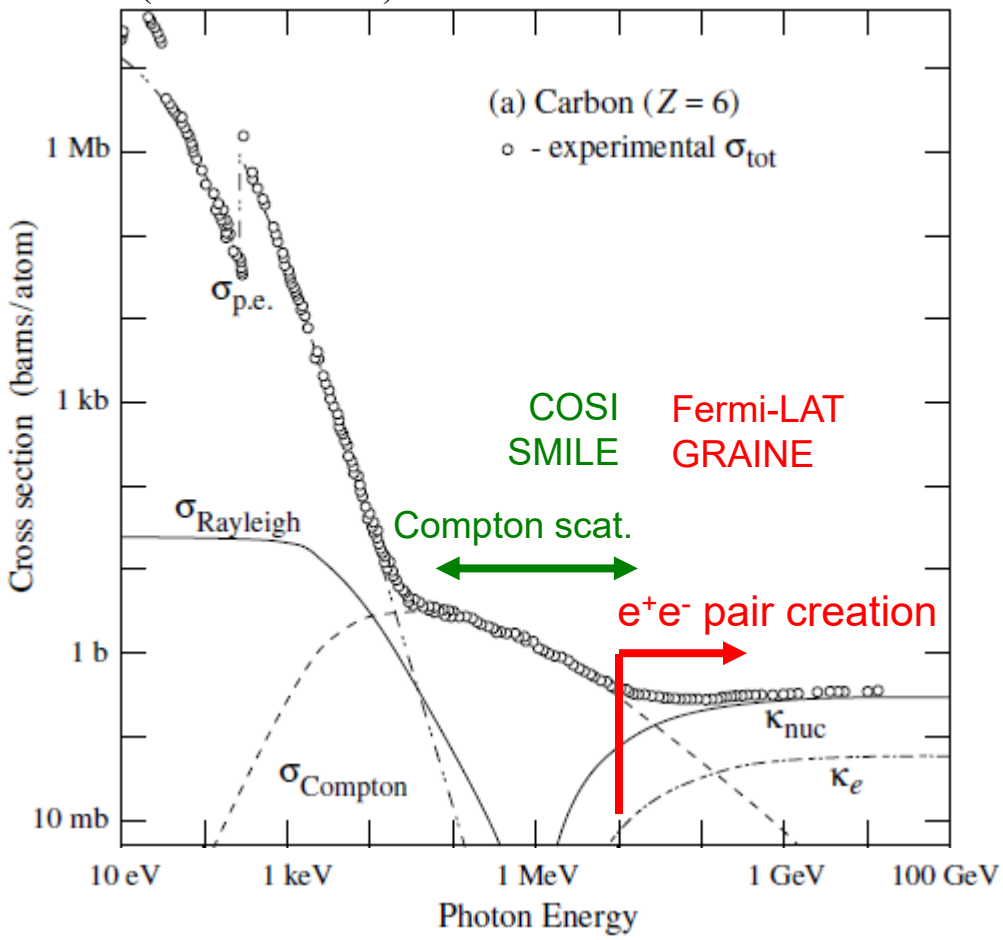
- **Full scale scientific flight with 10m^2 aperture telescope**
  - Looking for longer duration flight @middle latitude
  - SNR, Galactic center/plane, un-ID sources, Polarimetry, Burst events

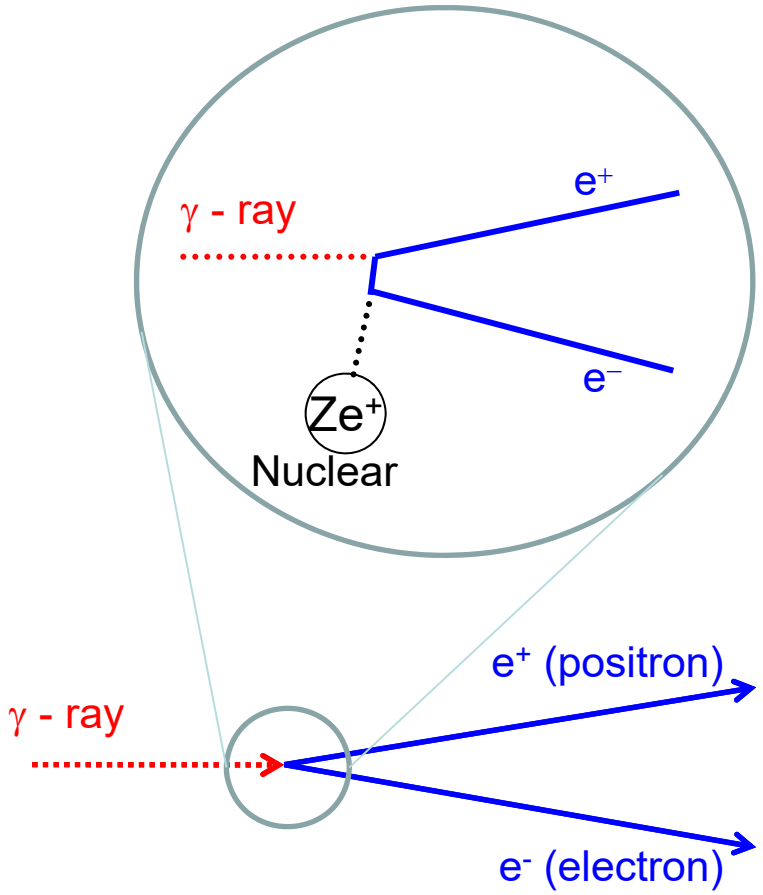
backup

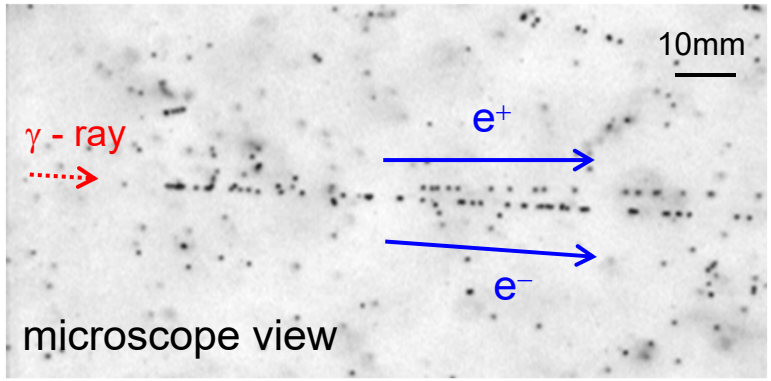

γ ray
>1GeV
Crab
(M1:SN1054)
0.1 °
Moon
(diameter 0.5°)
same scale
2mrad
radio
Infra
−red
visible
X ray

Detection principle

photon total cross sections as a function of energy
(from PDG2022)

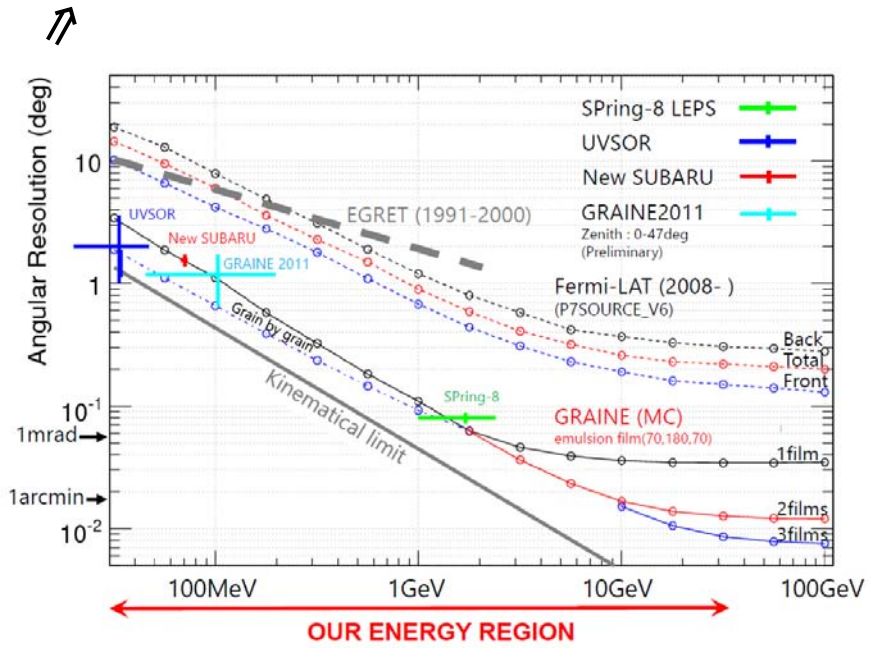






Angular Resolution

68% containment radius



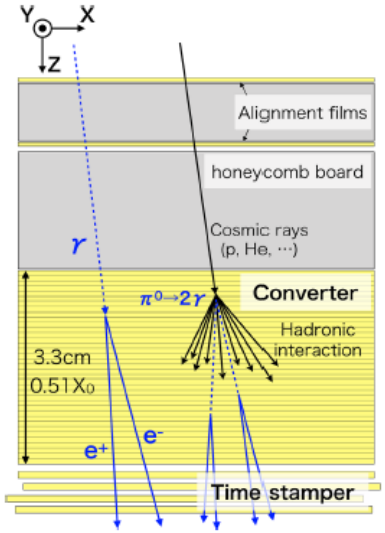


Fig. 1. Cross-sectional view of the emulsion chamber used in GRAINE2018.

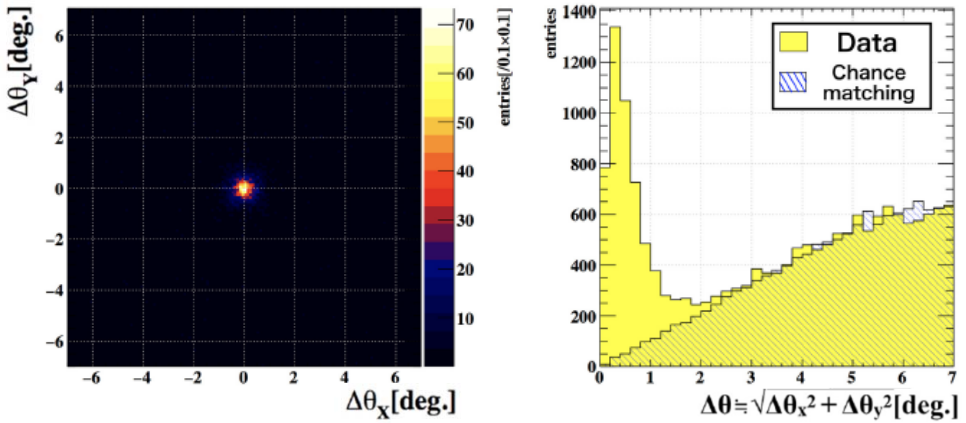
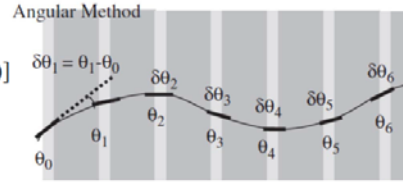


Fig. 6. Distribution of the angle difference between the expected and reconstructed gamma-ray directions.

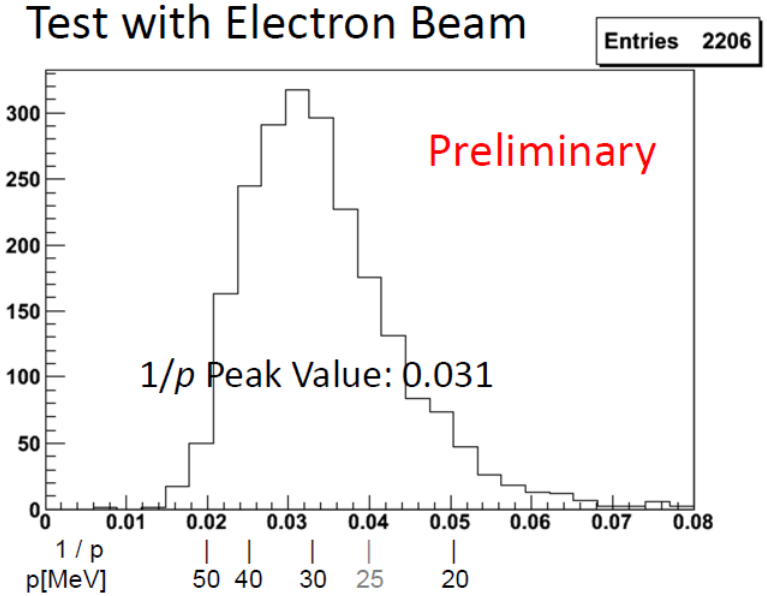
Energy Resolution

Momentum Measurement by MCS

$$(\delta\theta)_{RMS} = \frac{13.6MeV}{\beta cp}\sqrt{x/Xo}[1+0.038\ln(x/Xo)]$$



Test with Electron Beam



Reconstructed momentum

$32.1\ ^{+7.6}_{-8.8}$ [MeV/c]

(preliminary)

PTEP 2021, 123H02 Y. Nakamura et al.

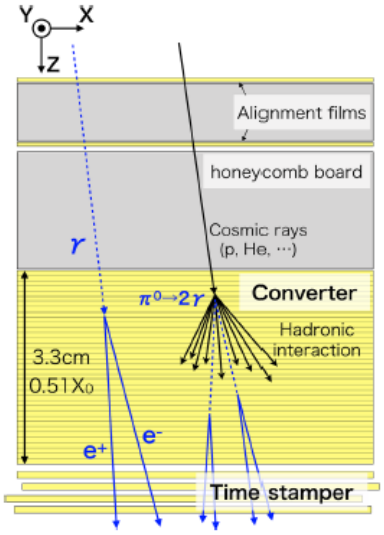


Fig. 1. Cross-sectional view of the emulsion chamber used in GRAINE2018.

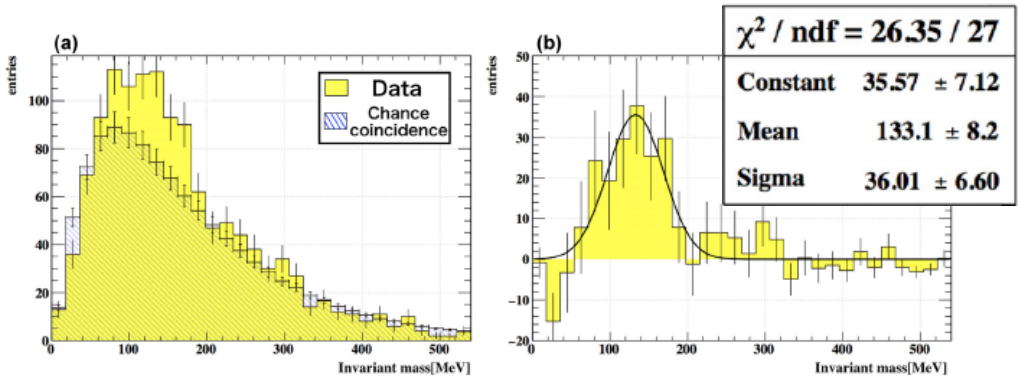
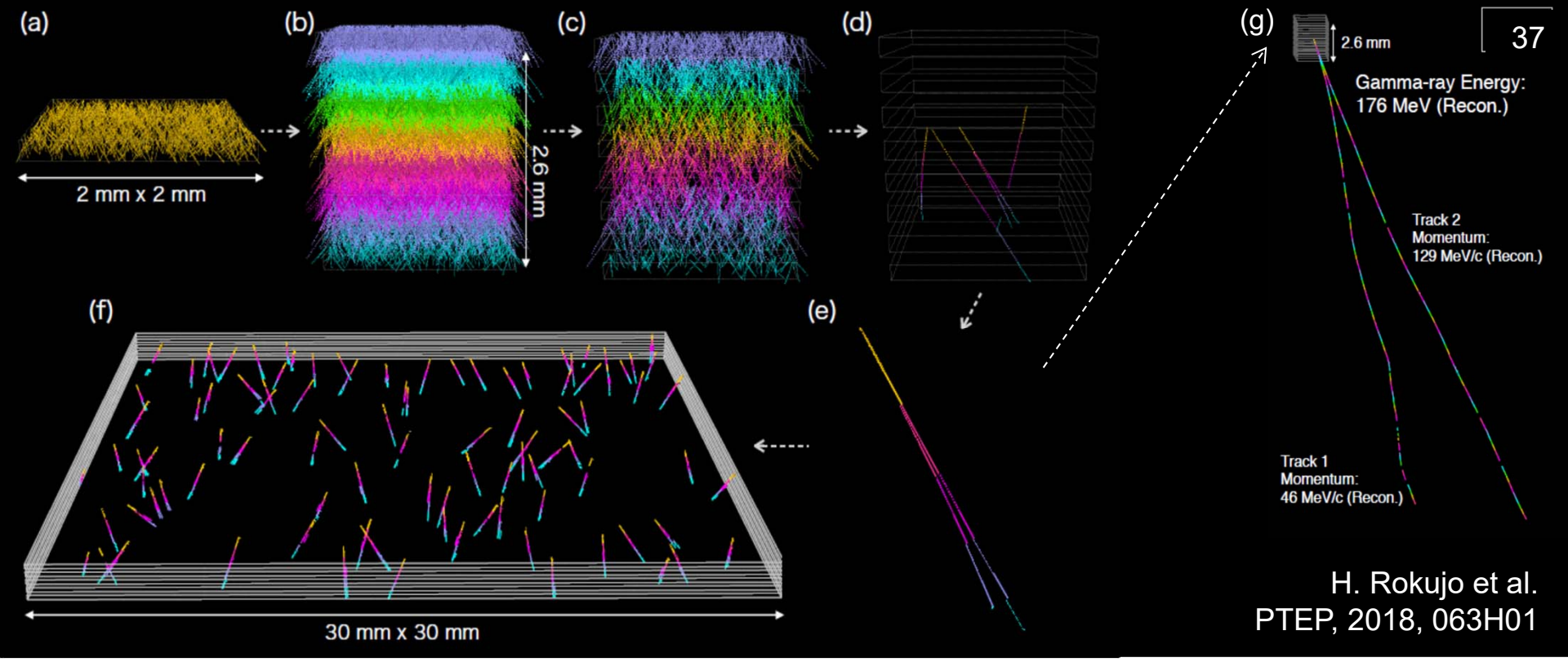


Fig. 8. (a) Invariant mass distribution of matched two gamma rays. (b) Distribution of the data subtracting the chance coincidence background and the Gaussian fitted curve.

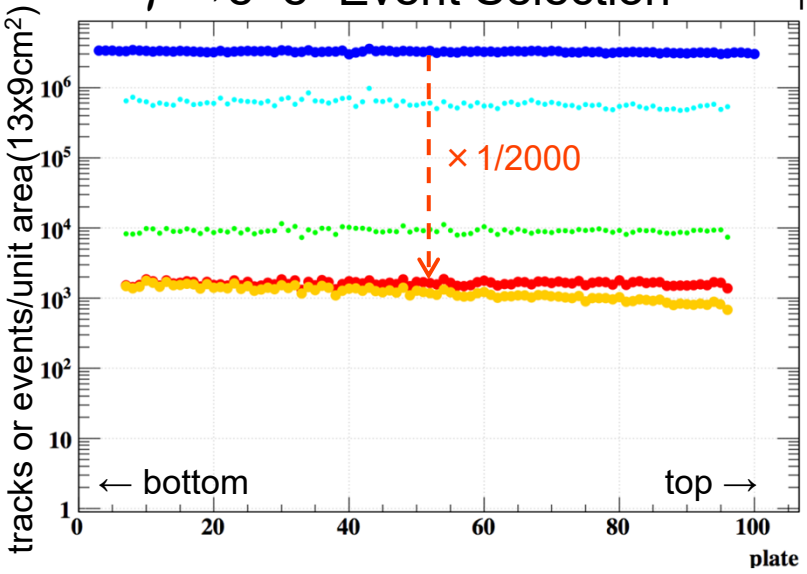
26% error for 32 MeV/c electron

27% error for π^0 mass peak



H. Rokujo et al.
PTEP, 2018, 063H01

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



|tanθ|<1.0

(b) all tracks

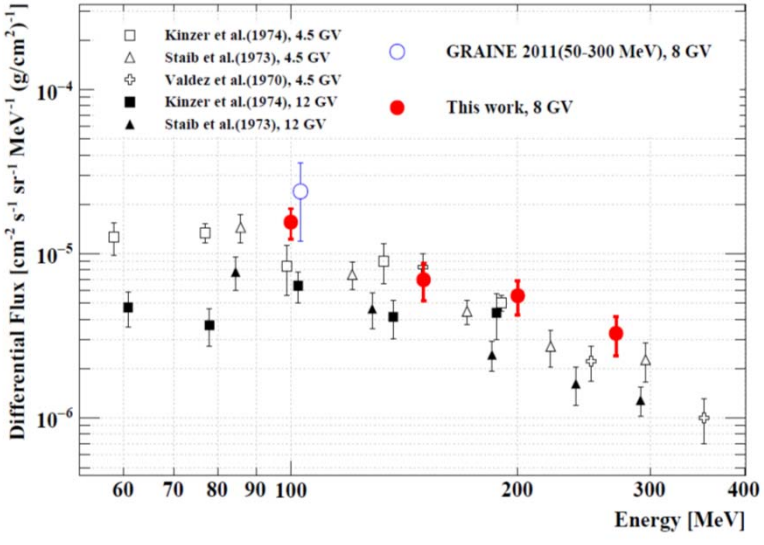
(c) eliminate penetrating tracks

(d) starting from middle

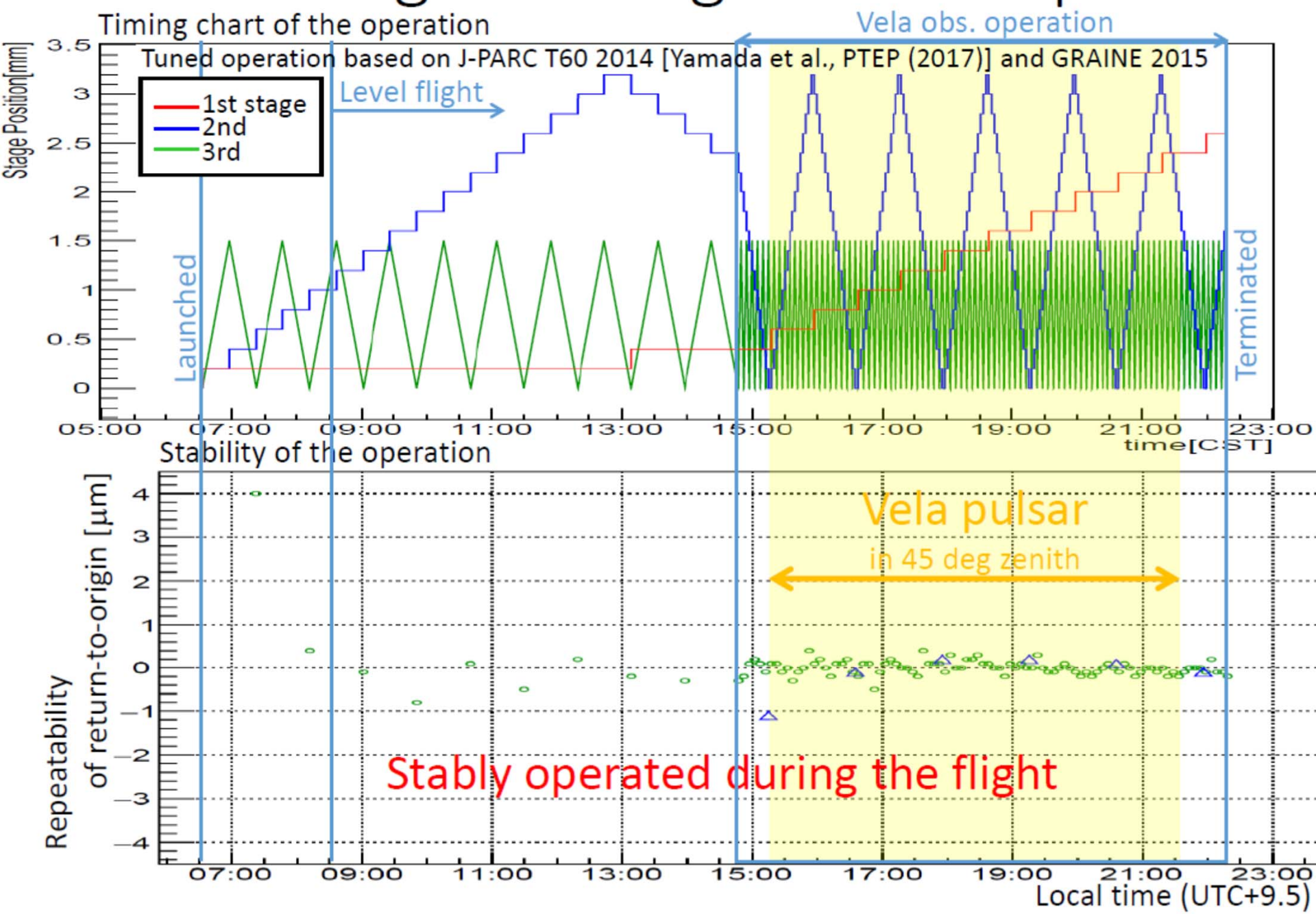
(e) e-pair candidates with partner track

(g) connect to time stamper

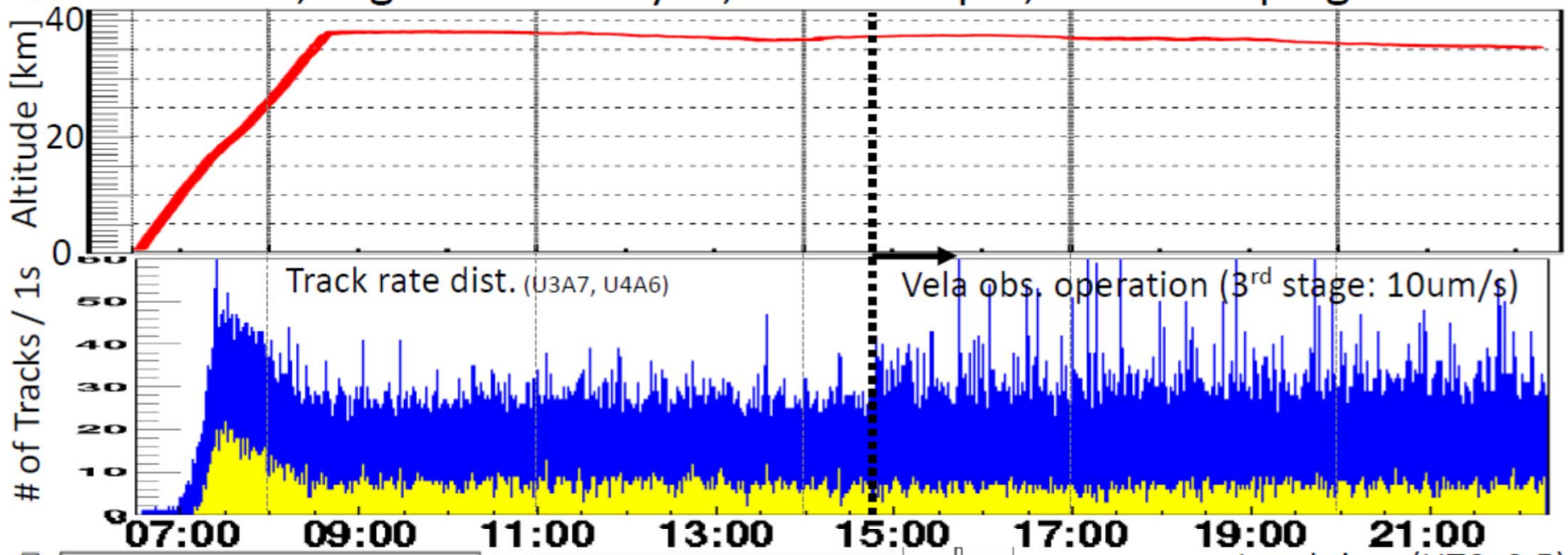
BG Flux(atm. γ)Measurement

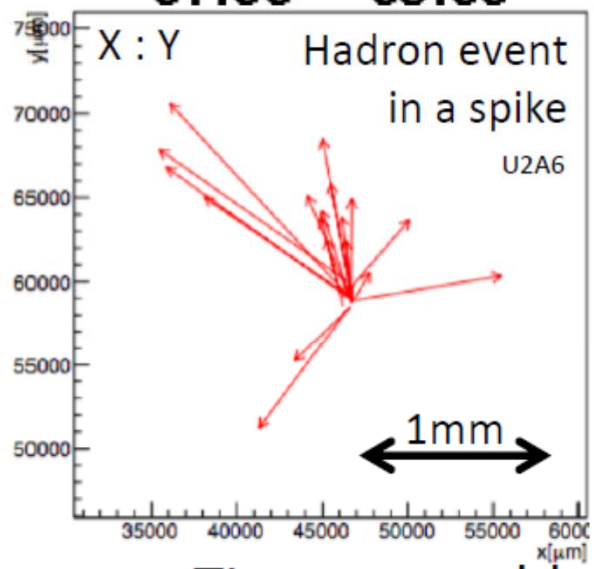


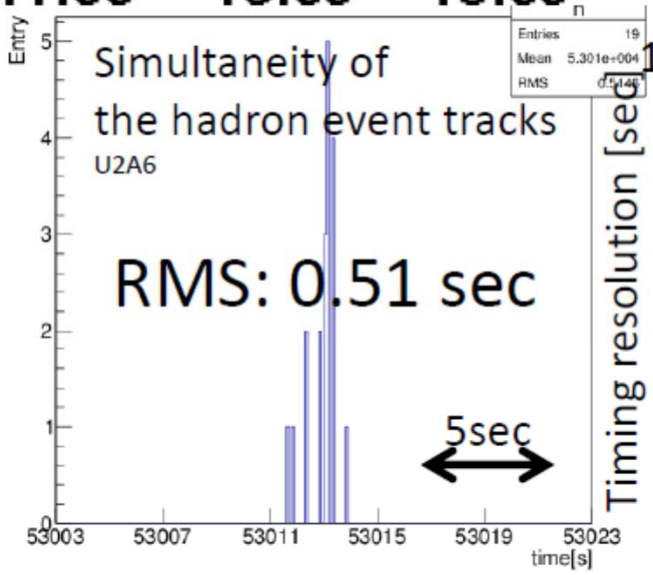
Multi-stage shifting timestamper

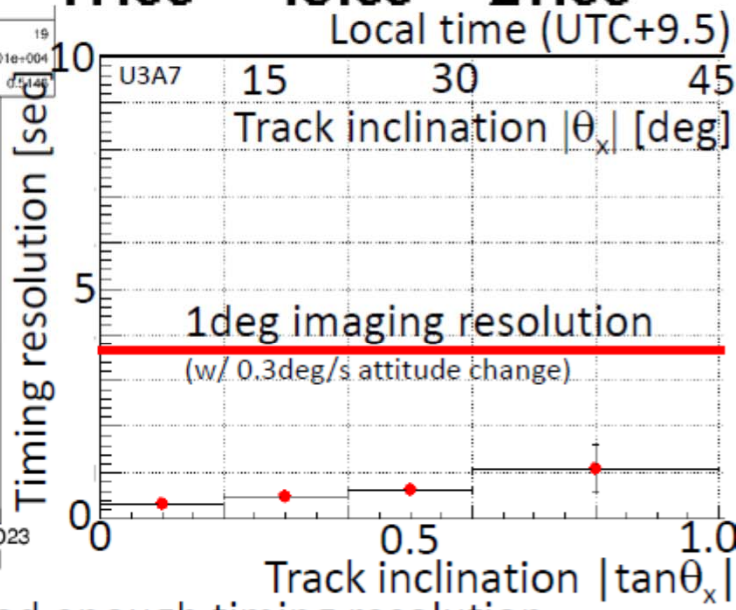


GRAINE 2018, Flight data analysis, Timestamper, Timestamping



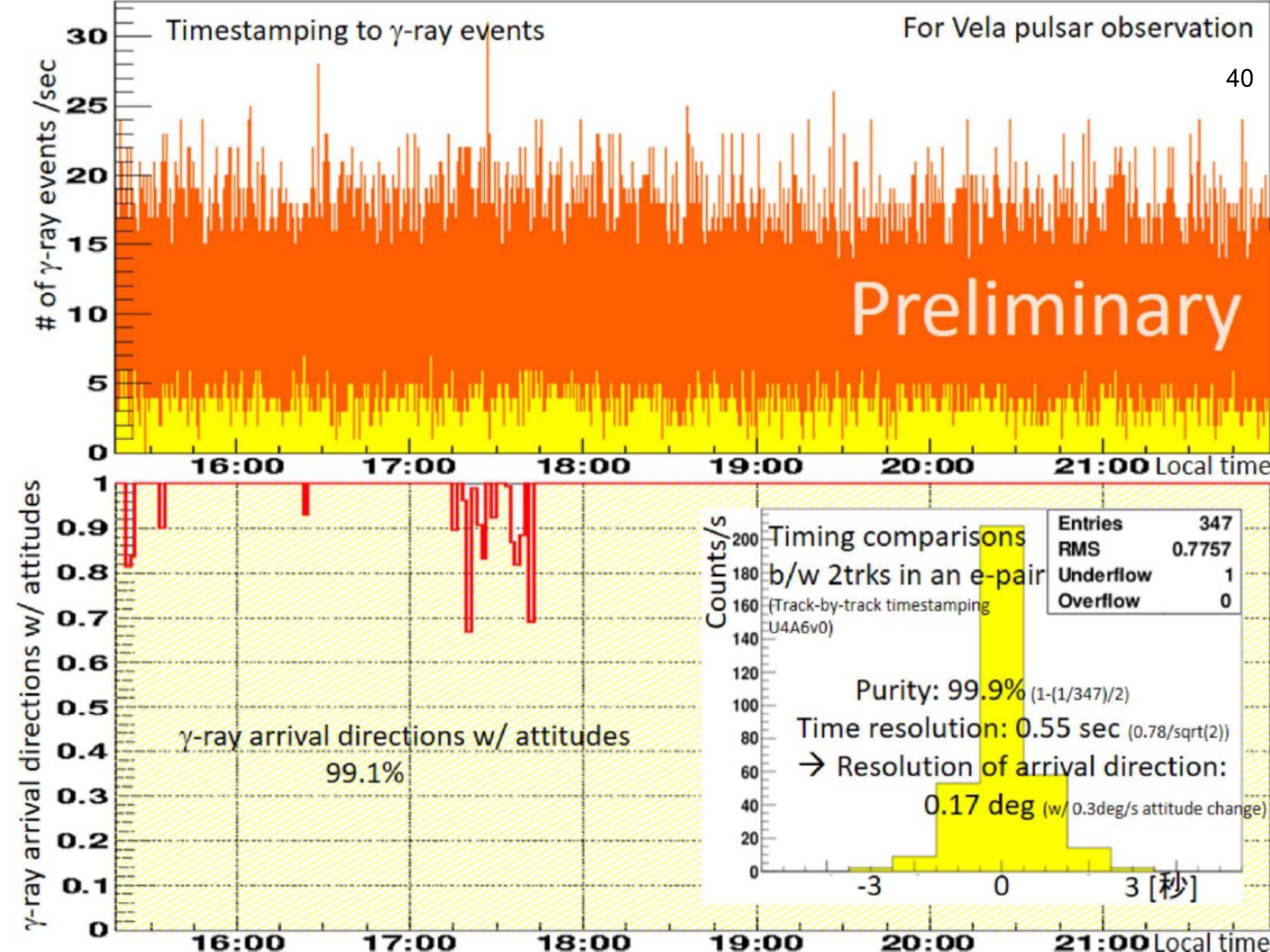




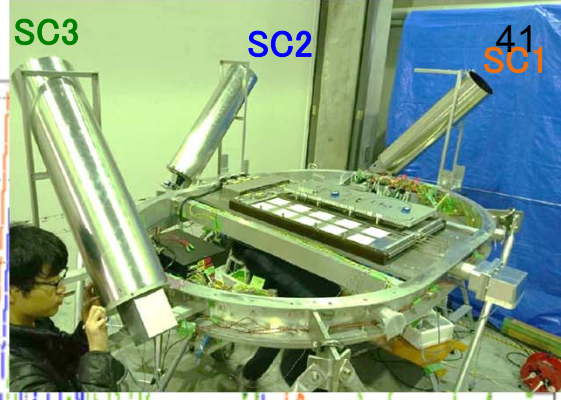


Timestampable
for high resolution γ-ray imaging

Good enough timing resolution
for 1deg imaging resolution


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%
Counts/s
Timing comparisons
b/w 2trks in an e-pair
(Track-by-track timestamping
U4A6v0)
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]

GRAINE 2018, Flight data analysis, Attitude monitor



Complementary attitude monitoring
by the three star cameras w/ each 90 deg azimuth

Horizontal coordinates
Azimuth [deg]

sc1
sc2
sc3

For Vela pulsar observation
Attitude determination: 98.9%
Accuracy: 0.022deg in azimuth

Local time (UTC+9.5)

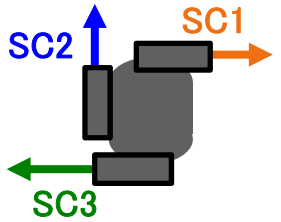
Survey Map

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

Galactic latitude

Start of a level flight

Vela pulsar

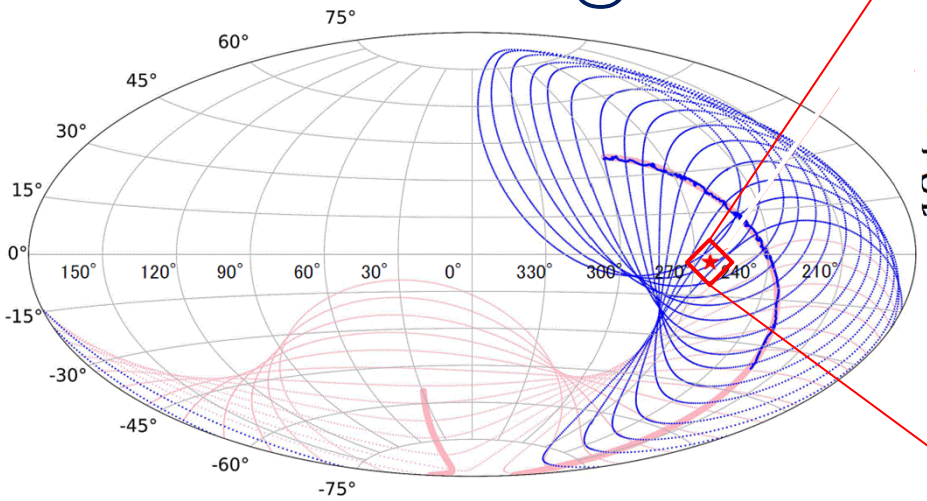


Attitude-determinable for high resolution γ-ray imaging

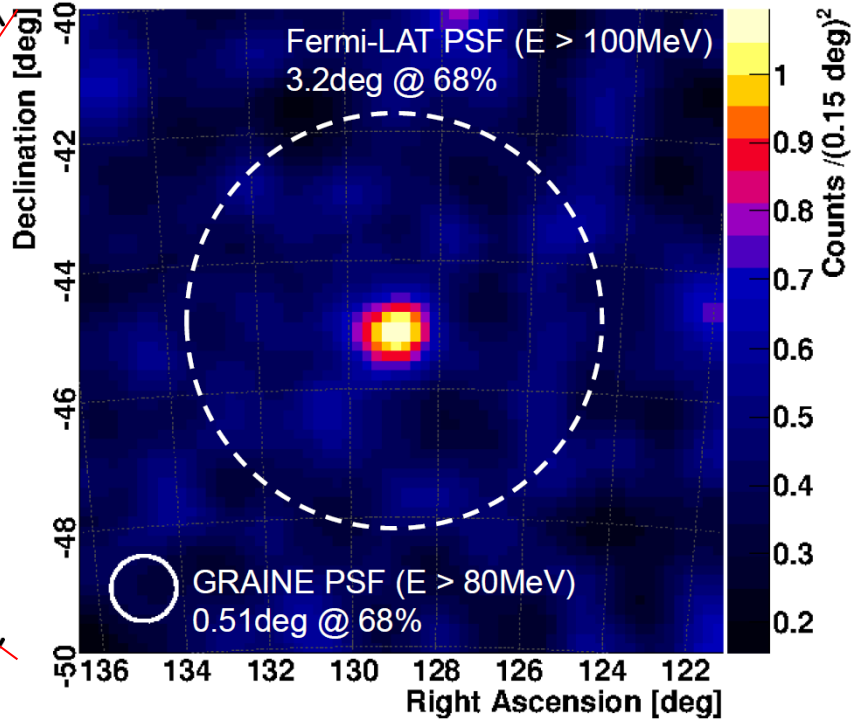
All sky coverage
GRAINE 2018: >51% (>2.0π[sr])
24h flight duration: >65% (>2.6π[sr]) incl. GC

Vela pulsar imaging

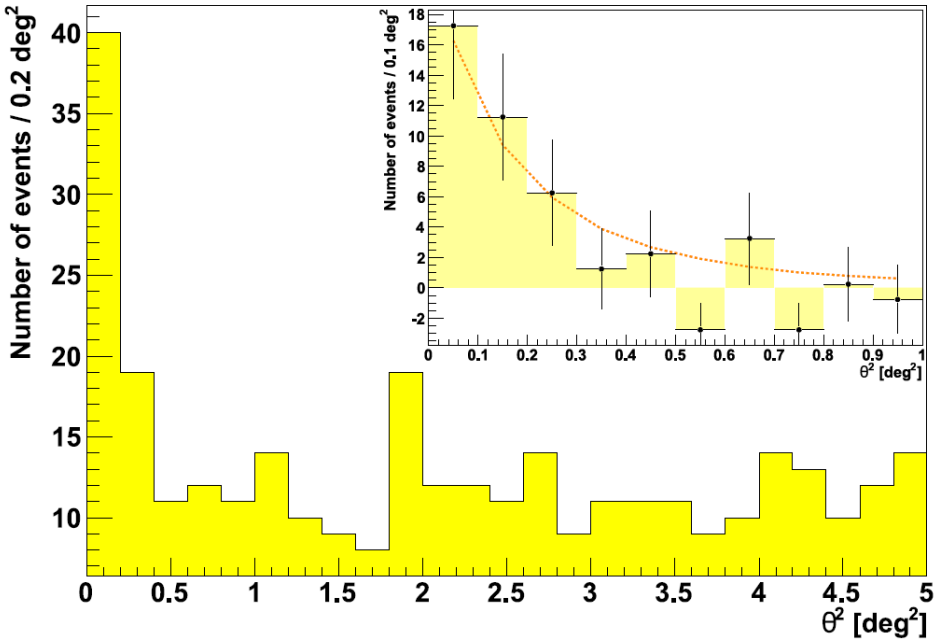
@GRAINE2018



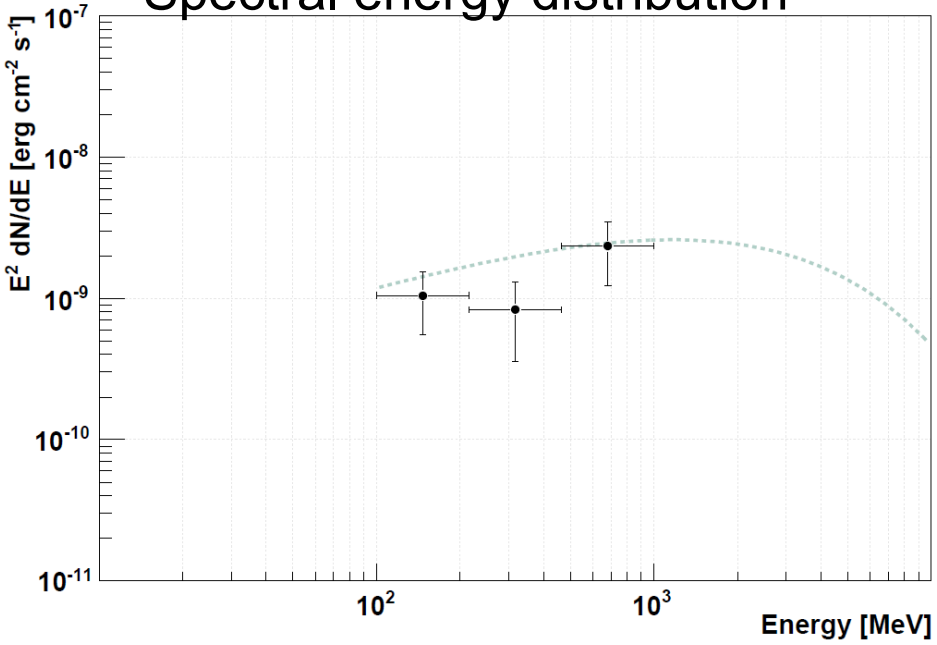
10deg



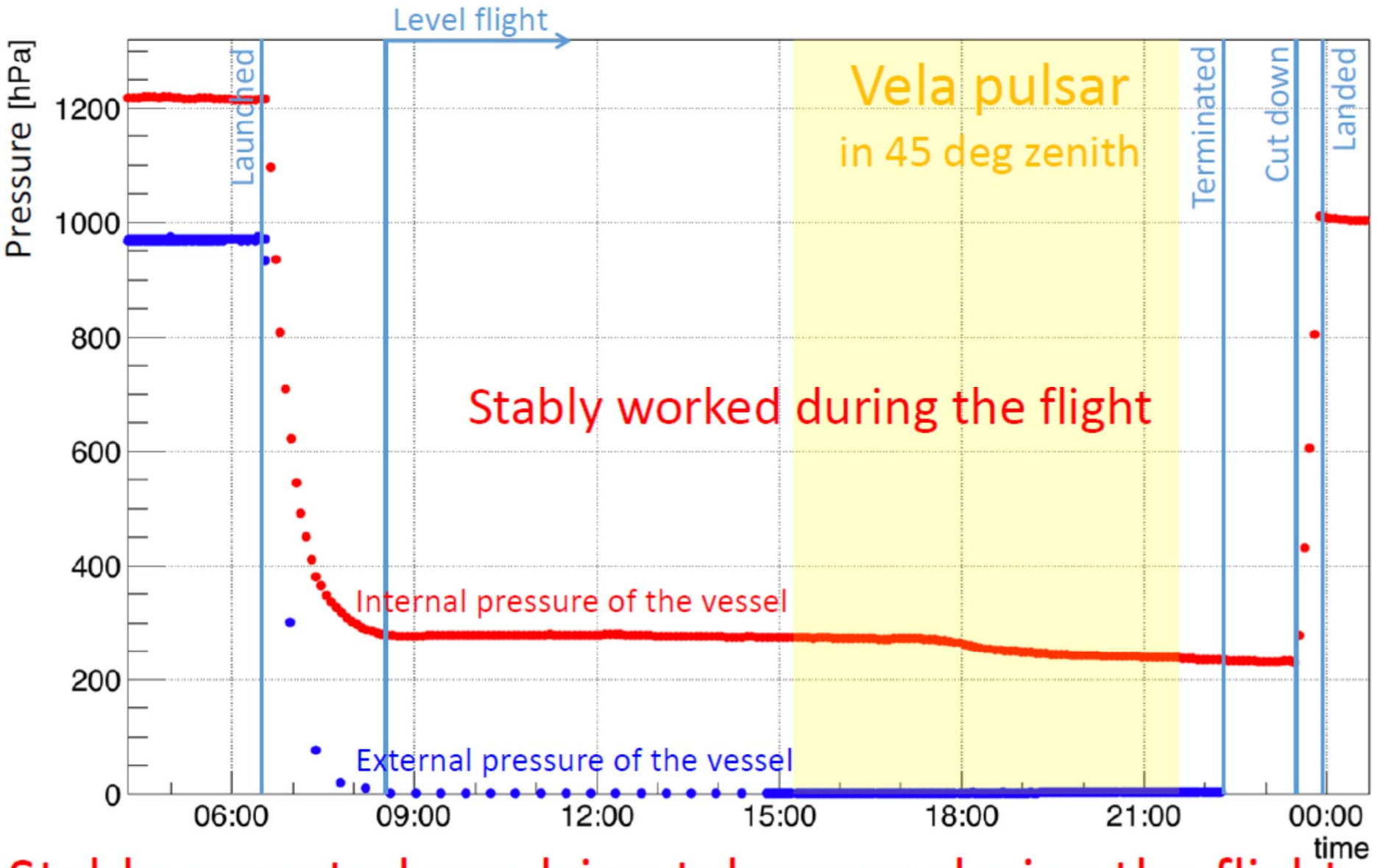
radial profile (θ^2 distribution)



Spectral energy distribution



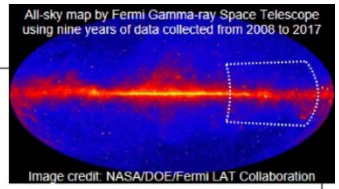
Pressure vessel



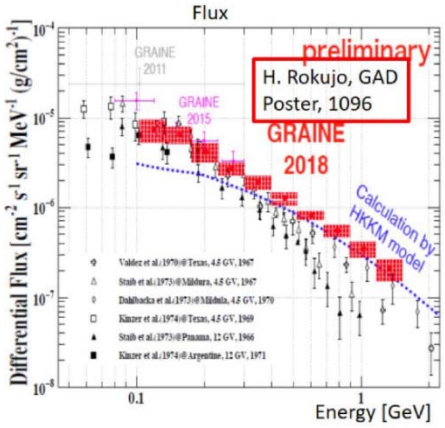
Stably operated emulsion telescope during the flight

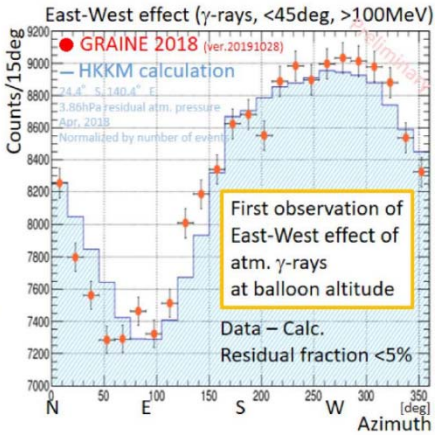
Other observation @GRAINE2018

Galactic diffuse



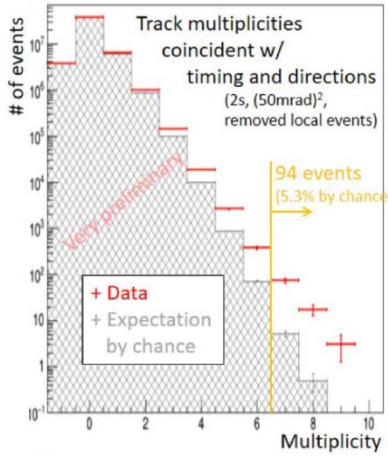
Atmospheric γ-ray measurements



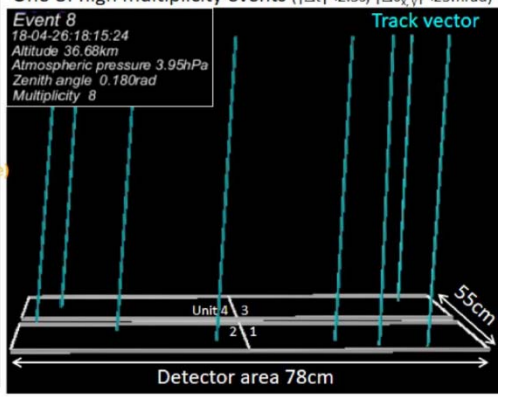


✓ BG and detector response understanding
✓ Atm. γ-ray physics (Primary, Solar activity, Geomagnetism, Atmosphere, Interaction, Secondary)
- ➢ Flux and East-West effect in Sub-GeV
- ➢ Comparison w/ atm. ν flux calculation
  - Contribution to Neutrino physics
- ➢ Advantage by balloon-borne experiments

Search for hadron showers over the detector area

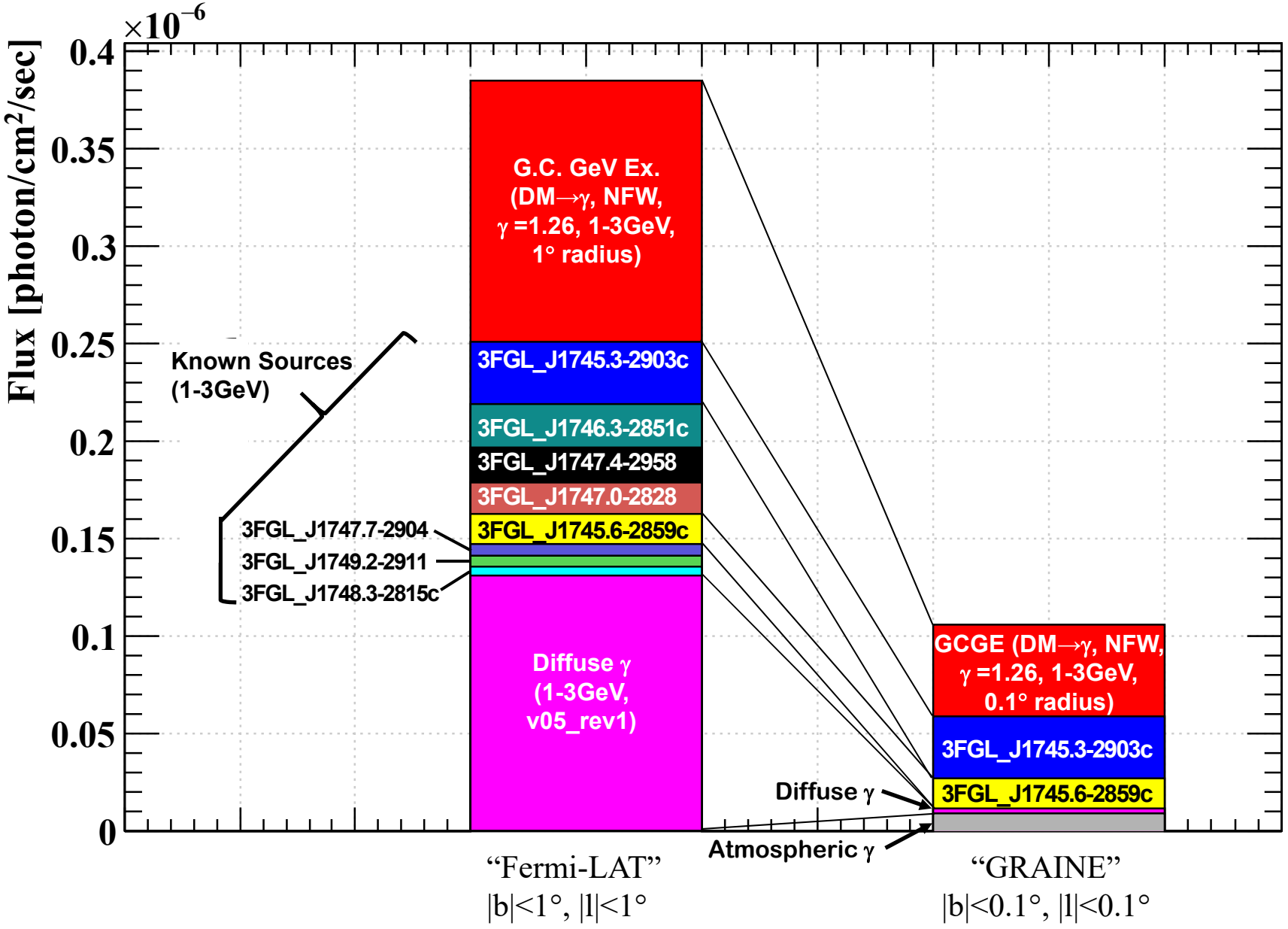


Excess detection beyond the expectation by chance



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

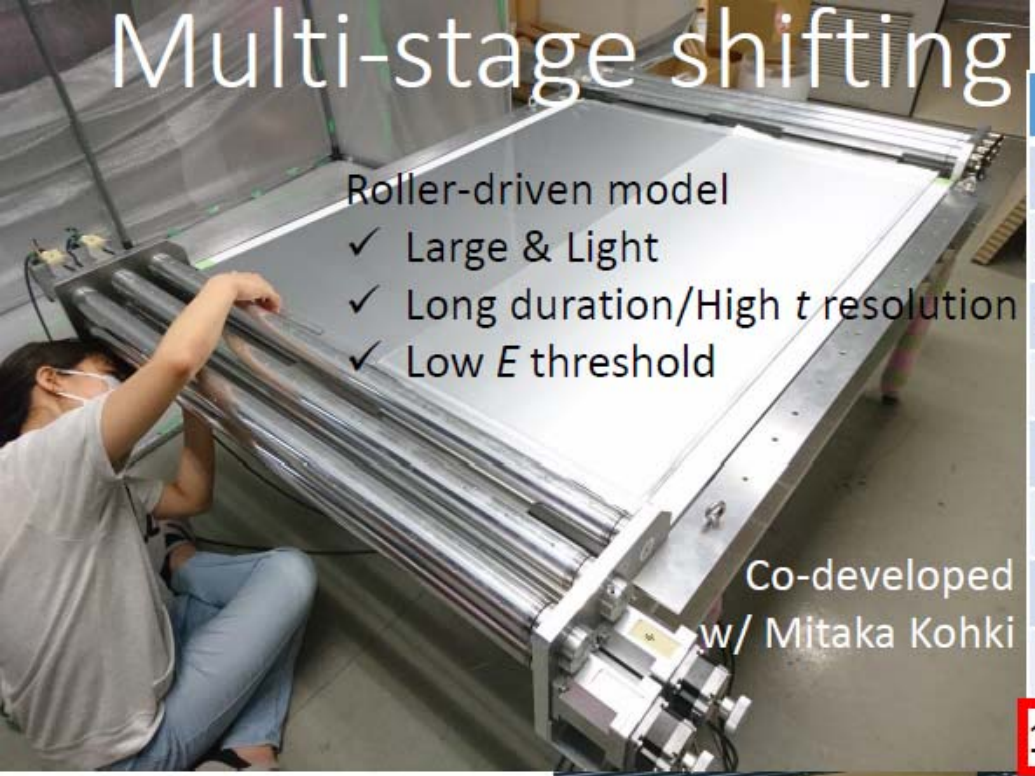
Galactic Center GeV Excess



Missions @ sub-GeV/GeV band

	Fermi-LAT	GRAINE	ASTROGAM	AMEGO	HARPO
Converter & Tracker	W (0.03/0.18Xo) & SSD	Emulsion	Double-sided SSD	Double-sided SSD	Gas TPC
Energy Range	20 MeV – 300 GeV	10 MeV – 100 GeV	10 MeV – 3 GeV (pair)	10 MeV – 5 GeV(pair)	MeV – GeV
Angular Reso. @100MeV	6.0°	1.0°	1.5° (requirement)	2°	0.4°
Angular Reso. @1GeV	0.9°	0.1°	0.2° (requirement)	1°	out of study
Polarization	under study	Yes	?	?	Yes
Apparture Size	1.96m^2 (eff. 0.25m^2@100MeV)	10m^2 (eff. 2.1m^2 @100MeV)	0.9m^2	0.9m^2	? (eff. 0.03m^2 w/ 10kg Ar)
Launch	2008	2023	Not Yet Approved (2037～)	Not Yet Approved (2028～)	No plan
Flight by	NASA	JAXA balloon	ESA?	NASA?	No plan

Multi-stage shifting timestamper

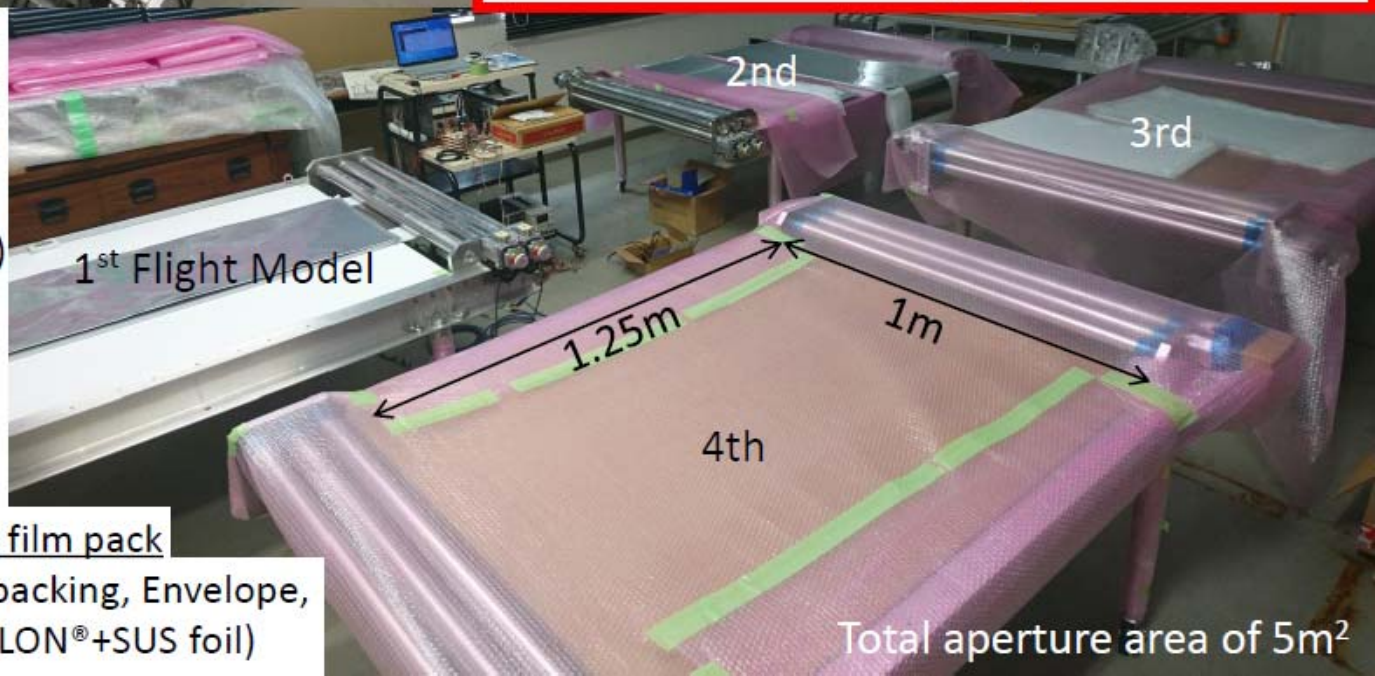


	2018	Next
Size [m²]	1.5 x 0.7	2.0 x 1.5
Aperture area [m²]	0.38	1.25
# of stages (w/o IF)	3	→ 4
Gap b/w stages[mm](Final stages)	1 (0.5)	x1/2 → 0.5
Weight [kg]	65	80
Weight w/ 1.25m²-ap [kg]	214	x1/2.7 → 80
Consumption [W]	25	20
CN w/ 1.25m²-ap [W]	82	x1/4 → 20

1/3 of conventional weight per aperture area

<u>Development history</u>

Aug. 2014, Started
Mar. 2015, Prototype(1-stage)
Feb. 2017, Pipe-roller
Feb. 2019, Prototype(5-stages)
Mar. 2020, 1st Flight Model
Feb. 2021, 2nd & 3rd FMs
Jul. 2021, 4th FM



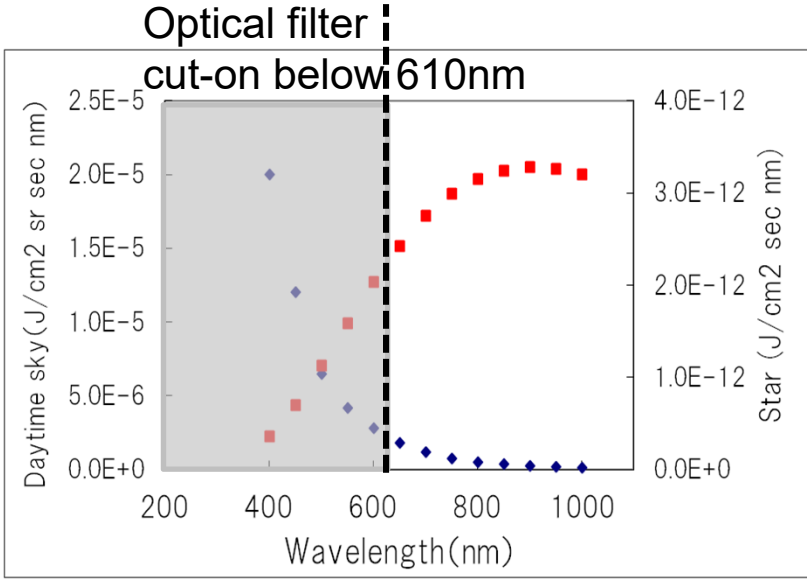
<u>Developments of the emulsion film pack</u>

CFRP backing, L-sized vacuum packing, Envelope, Friction(PTFE), Elongation(FIXELON®+SUS foil)

Attitude monitor (Day Time Star Camera)

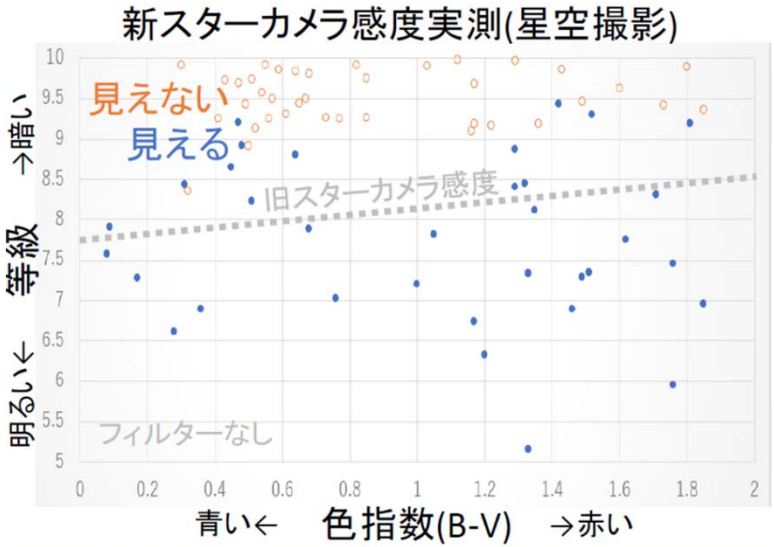
- **Optical Filter**
  Schneider Optics B+W091 (690nm)
- **Camera Lens**
  Nikon AF Nikkor 85mm F1.4D
  diameter：77mm
  focal length：85mm
- **CMOS Camera**
  TRI028-MC (near-IR camera)
  2/3 inch (11mmϕ)
  pixels：1936×1464, 2x2 binning

- **CPU board**
  ADVANTECH PCM-3365EW
  - CPU:Intel Atom E3845
- **SSD (1TB)**
  Transcend SSD370S (MLC NAND)

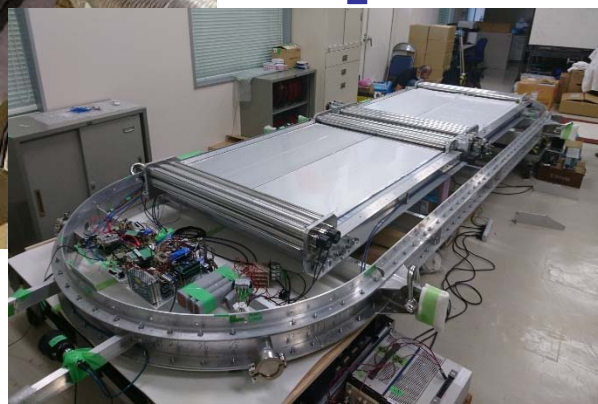


◆:Daytime sky BG(Dietz et al., 2002)

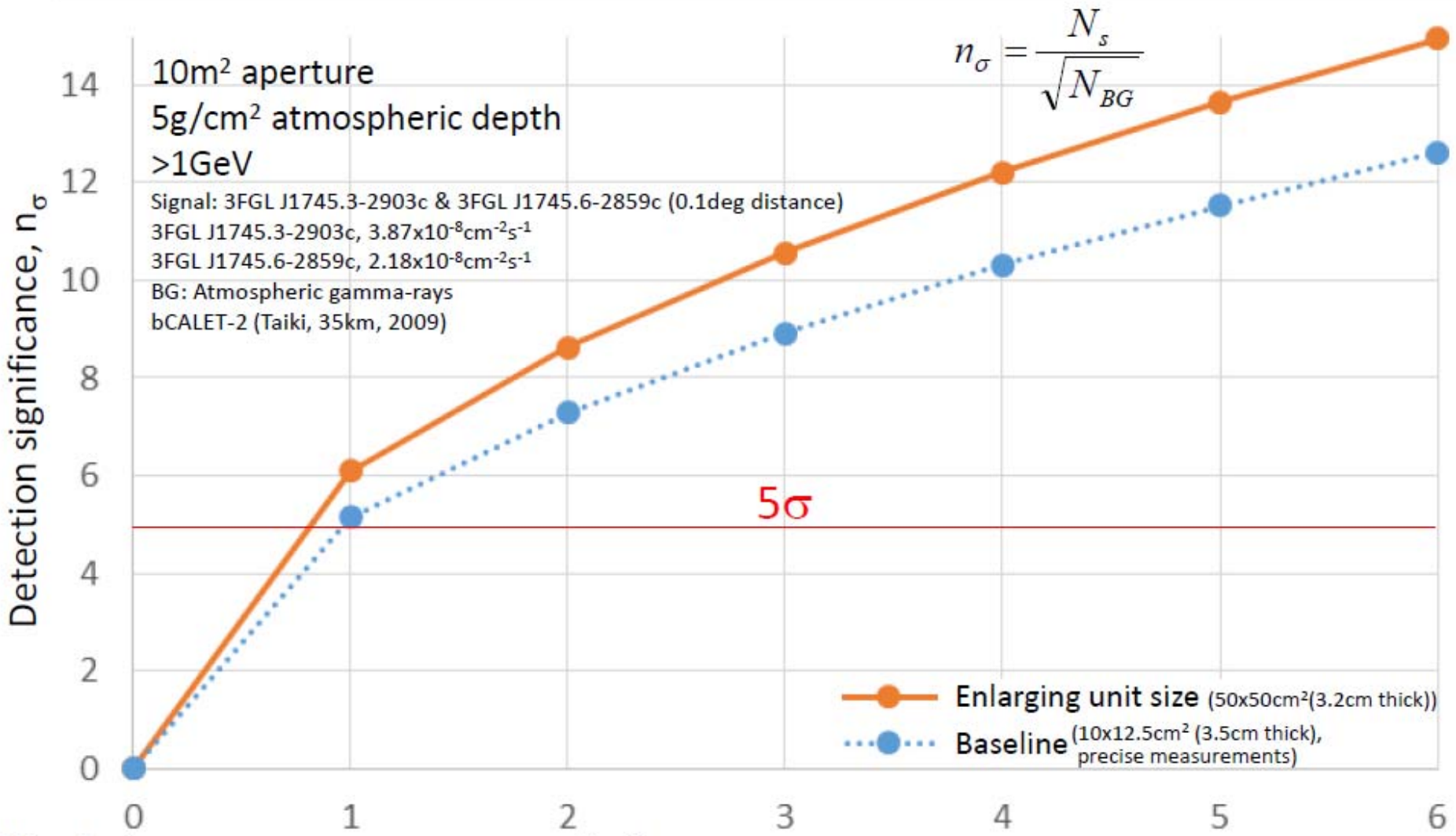
■:Star spectrum(M-type:3200K)



2.5m^2 telecope × 2 were ready to export



Galactic center region, detection sensitivity



Alice Springs

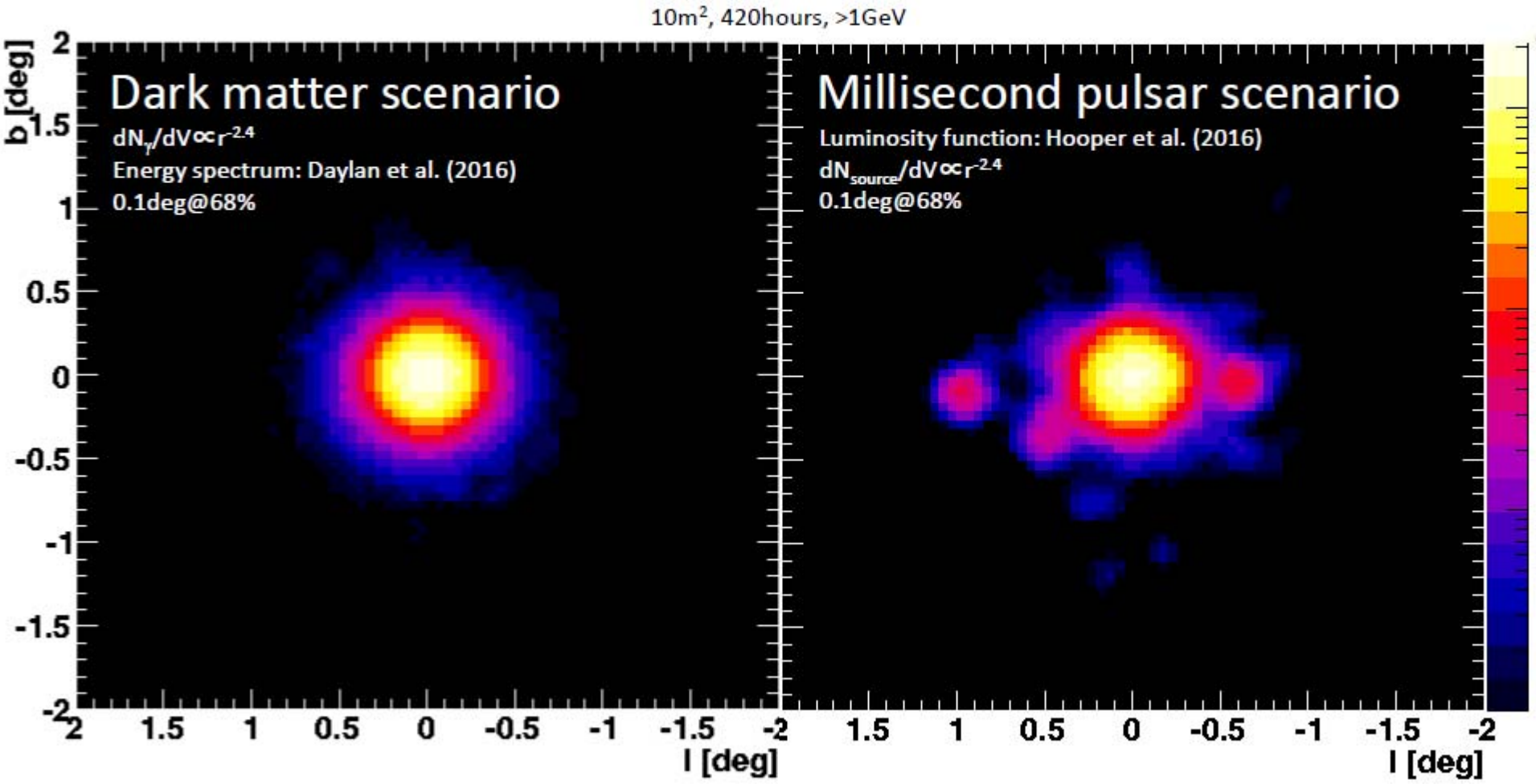
Apr. 15th, 4:53(ACST) culmination, 5.3deg zenith

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

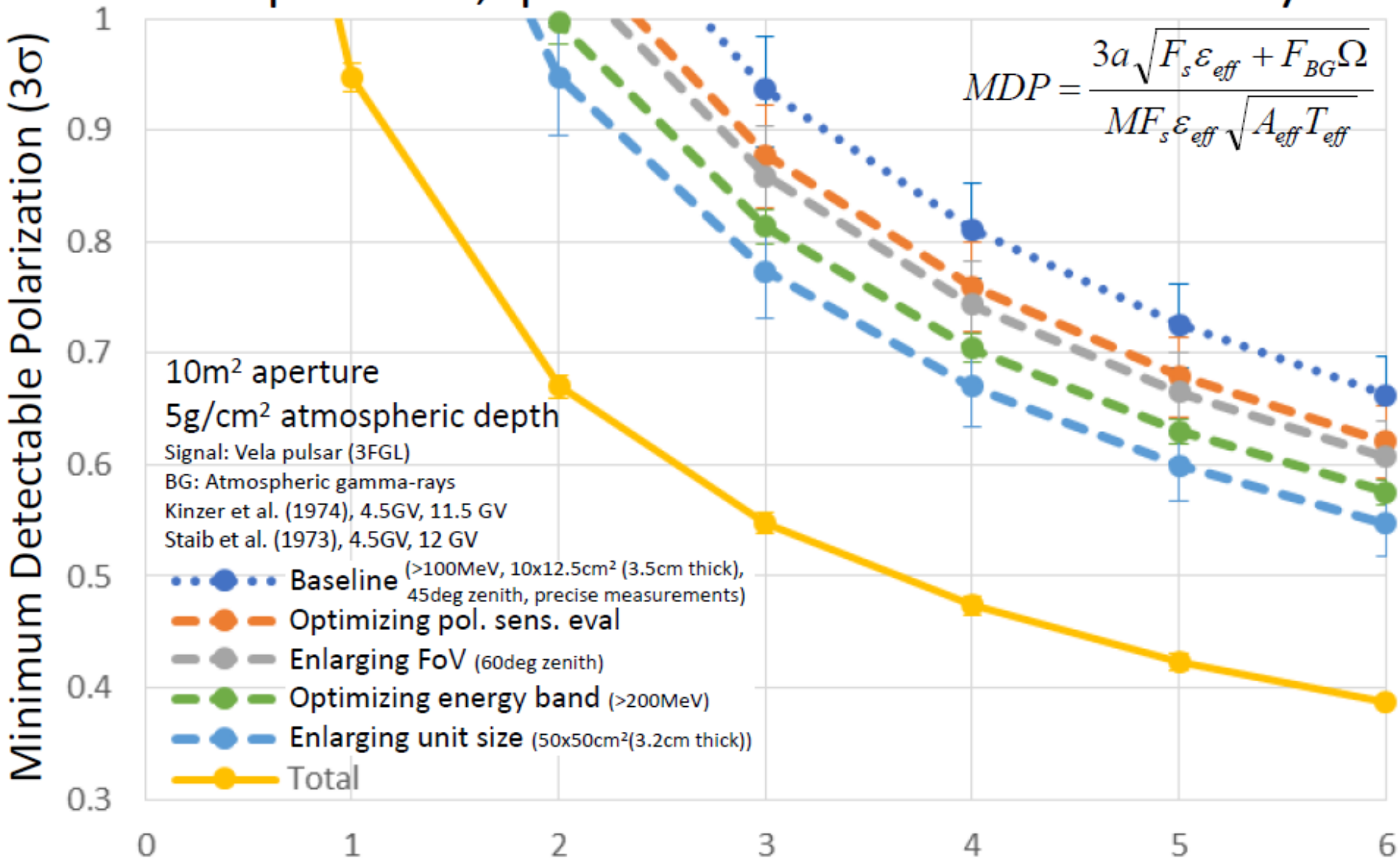
of a source in a field of view of the telescope with diurnal rotation (roughly corresponding to flight days)

N_{signal}=132, N_{BG}=78 @ 6 crosses

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



Vela pulsar, polarization sensitivity



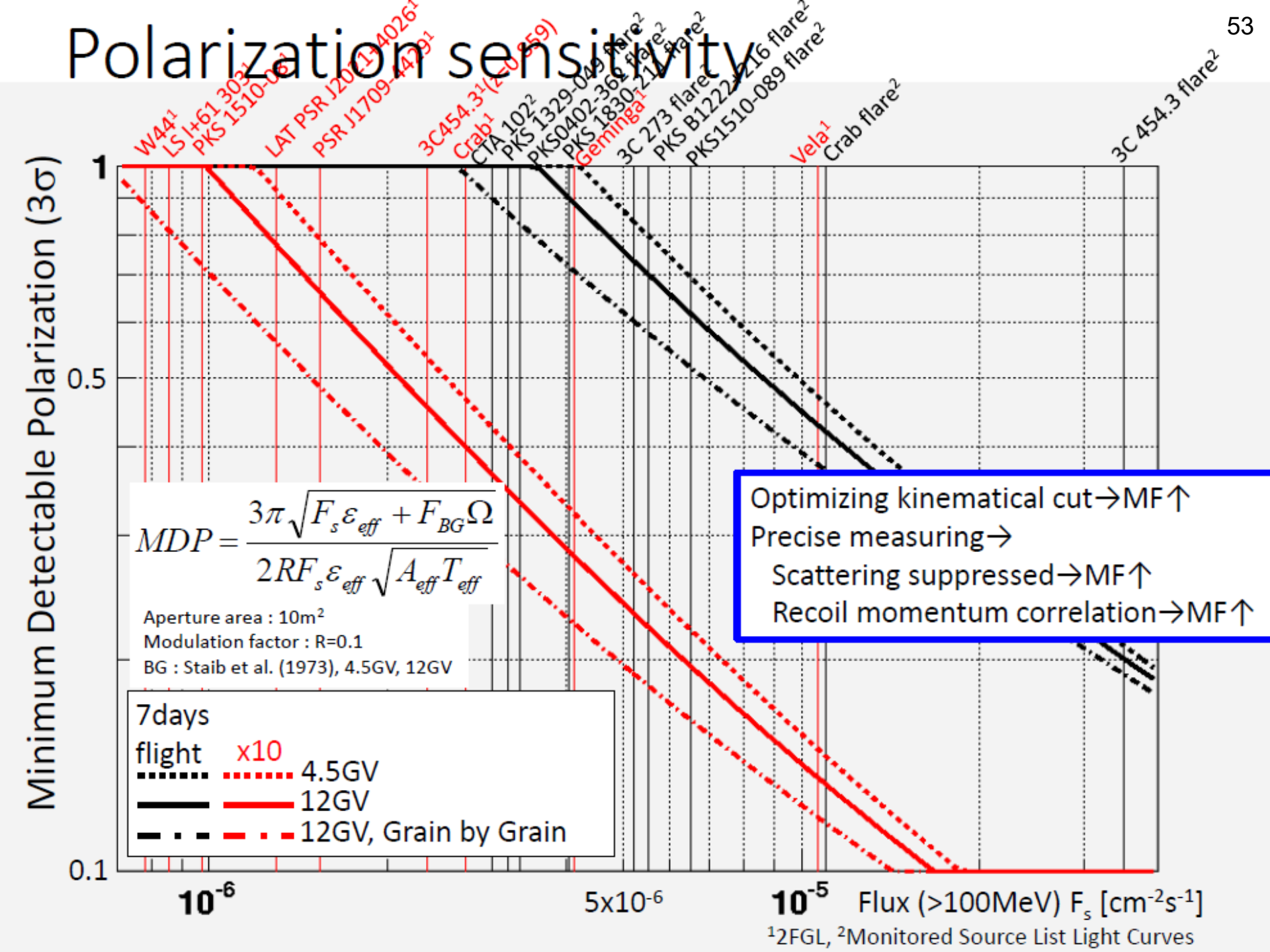
Alice Springs

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

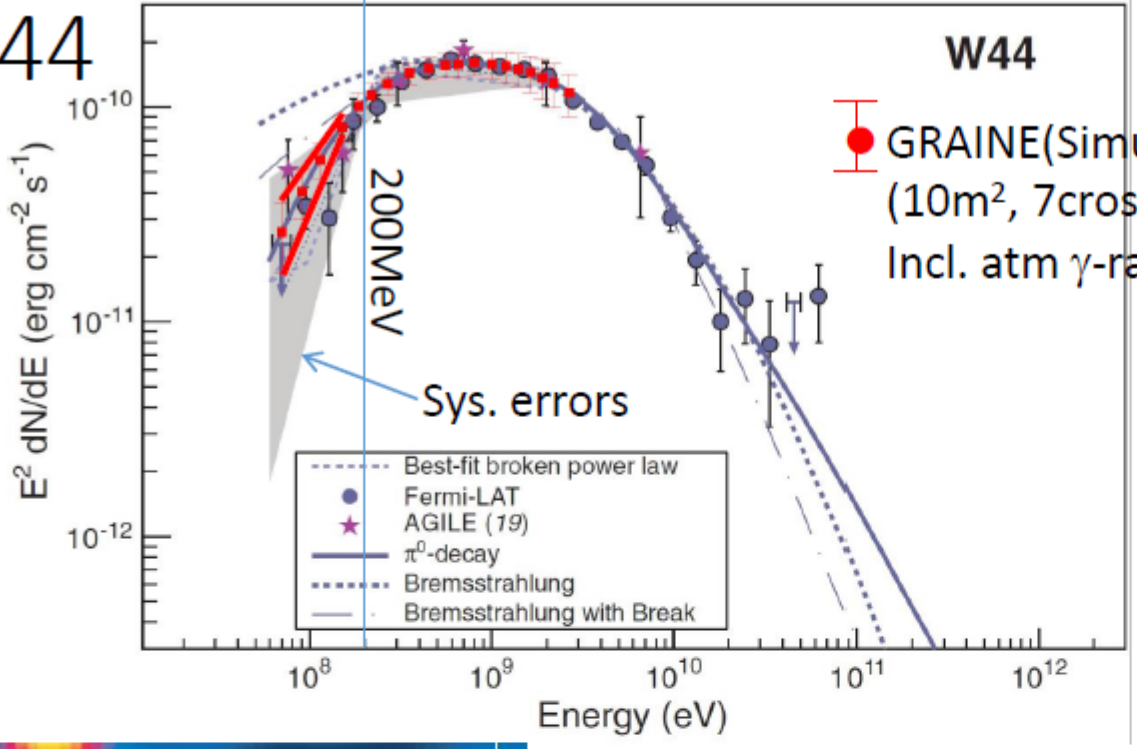
# of crosses of a source in a field of view of the telescope with diurnal rotation (roughly corresponding to flight days)

Polarization sensitivity

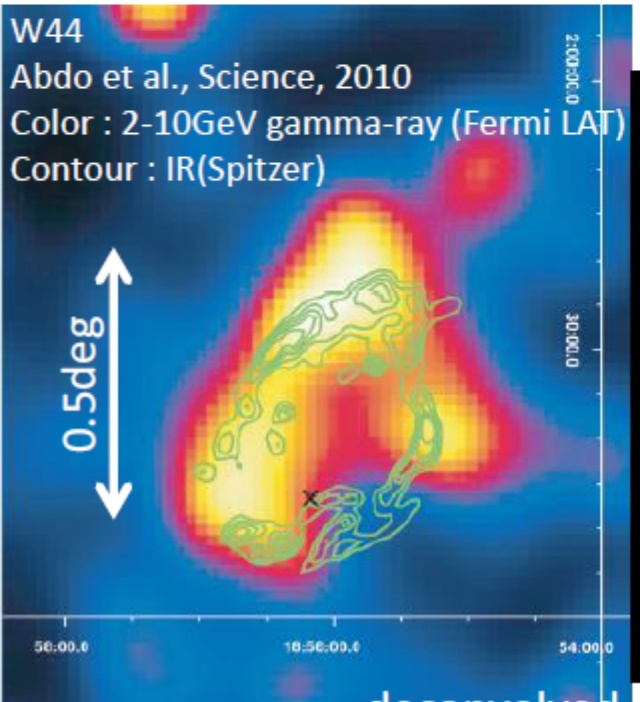


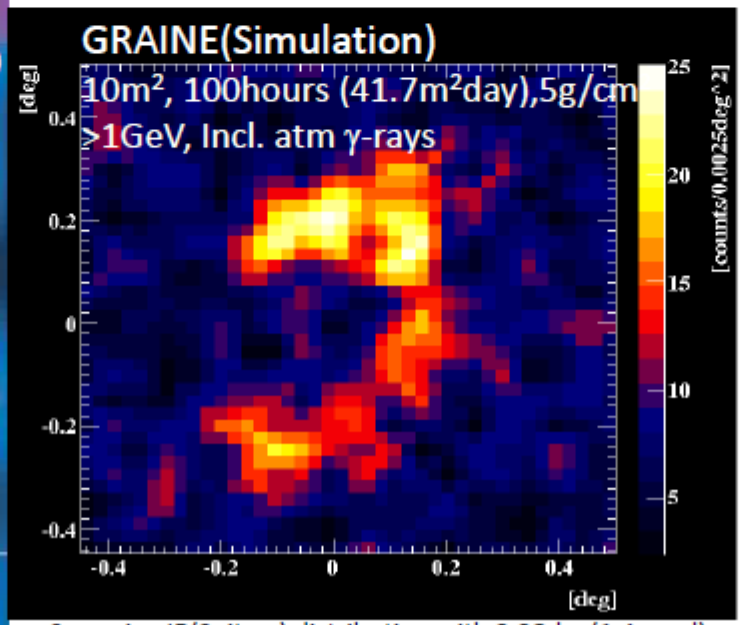
[1]2FGL, [2]Monitored Source List Light Curves

W44



<200MeV
Precise spectral measuring
with suppressed systematic error



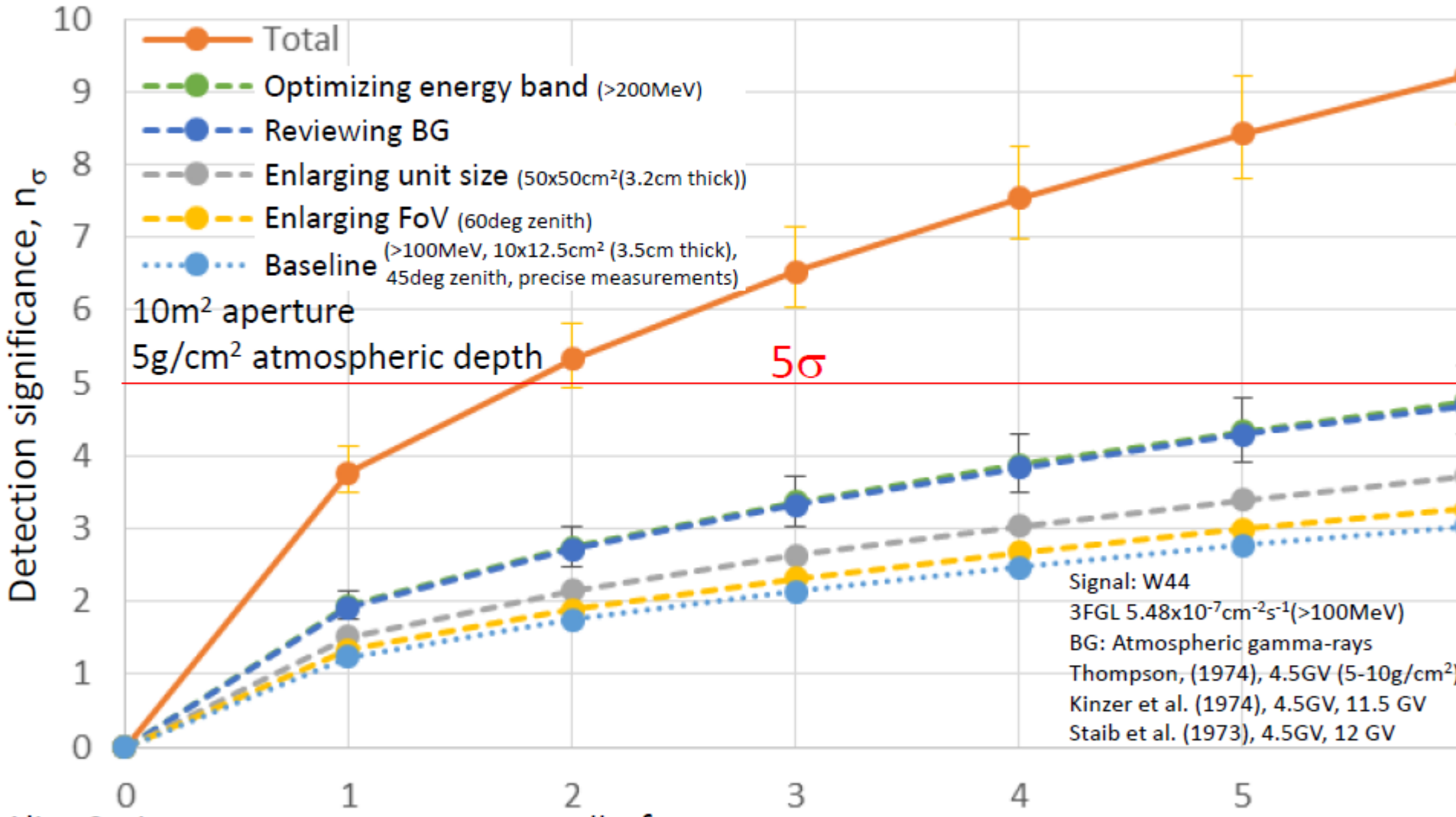


>200MeV
Investigating spatial structu

Smearing IR(Spitzer) distribution with 0.08deg(1.4mrad)

W44 detection sensitivity

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



Alice Springs

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

of a source in a field of view of the telescope

with diurnal rotation (roughly corresponding to flight da

Sensitivity to transient sources