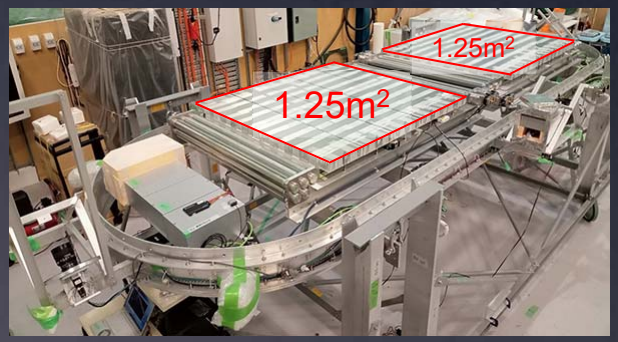
ICMaSS 2023
2023/Dec/1-3

GRAINE* Project:

Balloon-borne Gamma-ray Telescope with Nuclear Emulsion

* Gamma-Ray Astro-Imager with Nuclear Emulsion

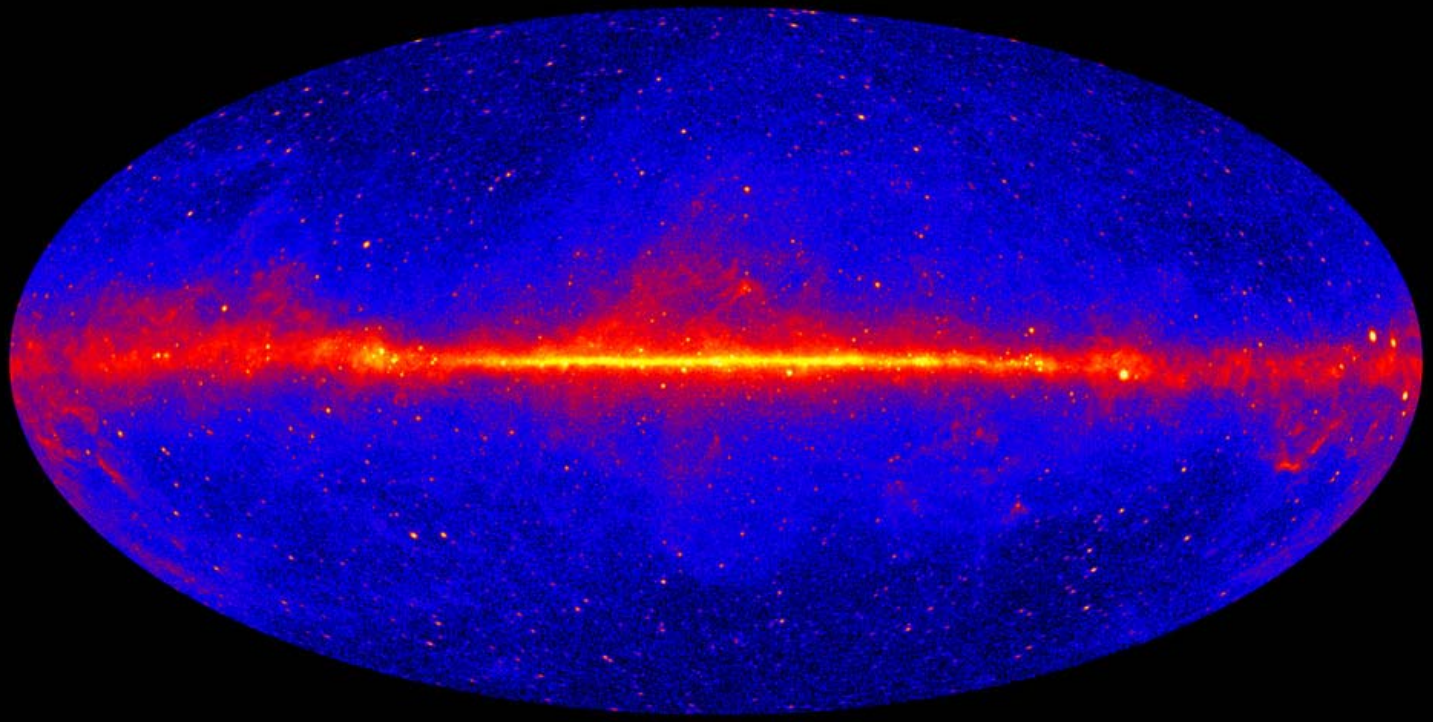


Shigeki Aoki (Kobe University)
for GRAINE collaboration
Kobe University,
Nagoya University,
Okayama University of Science,
Gifu University
Aichi University of Education
and ISAS/JAXA

photo: GRAINE2023
2023/Apr/30 am 6:32
Alice Springs, Australia

All-sky map by Fermi Gamma-ray Space Telescope using 12 years of data collected from 2008 (E > 1GeV)

Image credit:
NASA/DOE/Fermi LAT Collaboration

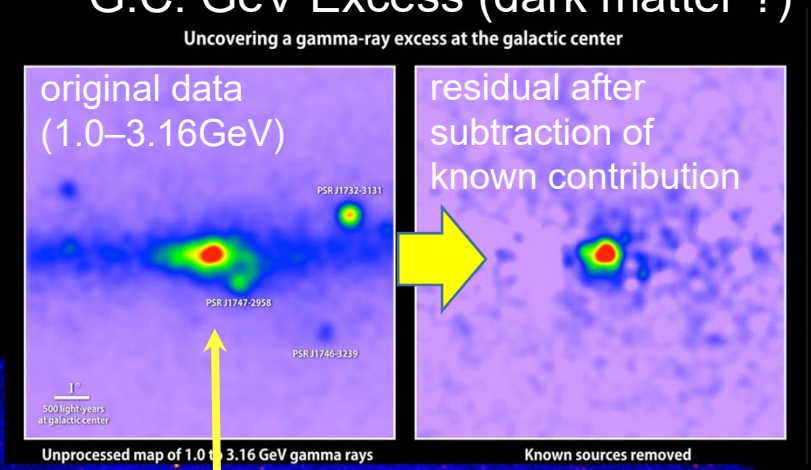


> 6600 sources (4FGL-DR3)

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

Image credit:
NASA/DOE/Fermi LAT Collaboration

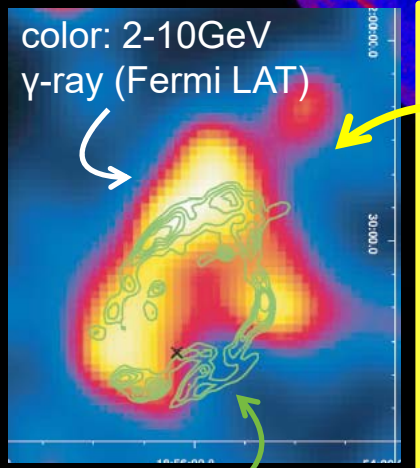
G.C. GeV Excess (dark matter ?)

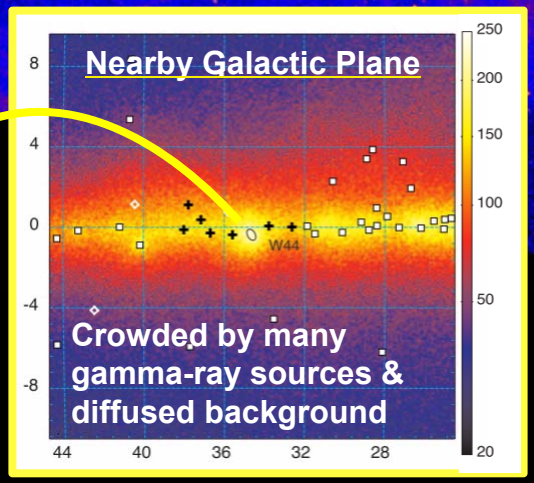


better resolution is needed

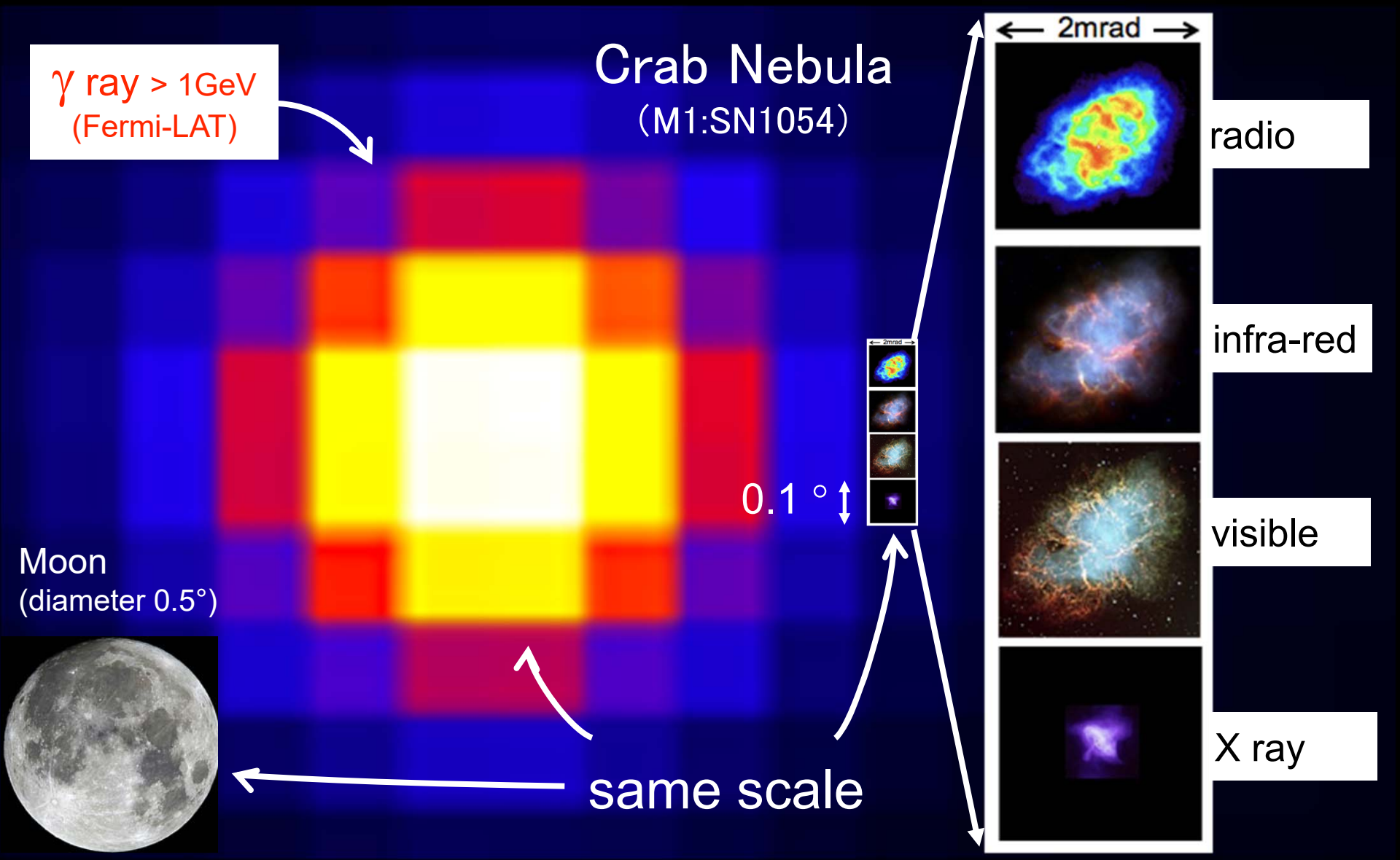
SNR W44

Abdo et al., Science, 2010





Imaging Performance



Nuclear Emulsion

microscope view
10μm

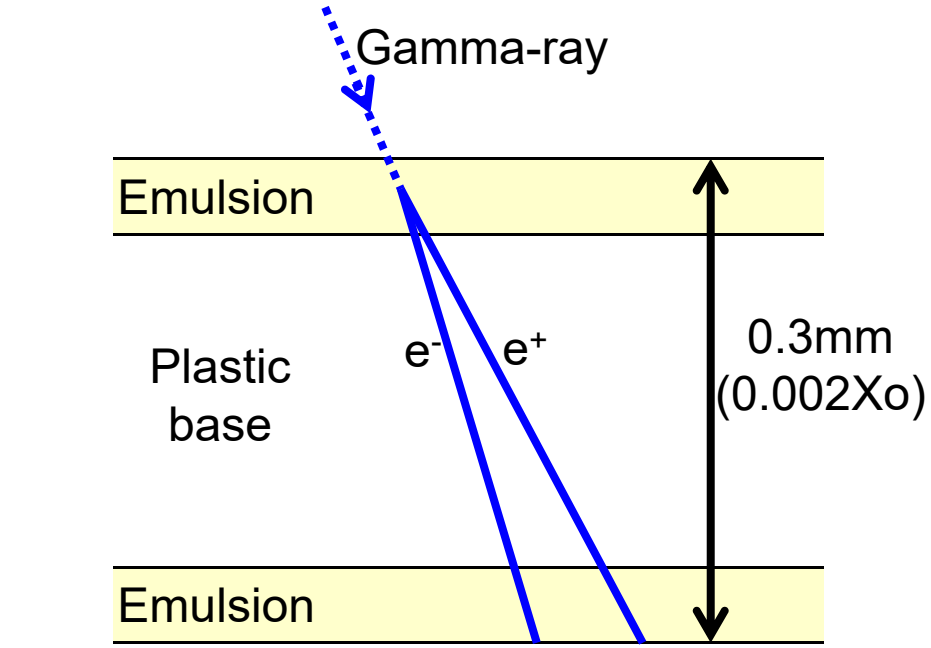
Intrinsic position accuracy of ~50nm

Gamma-ray

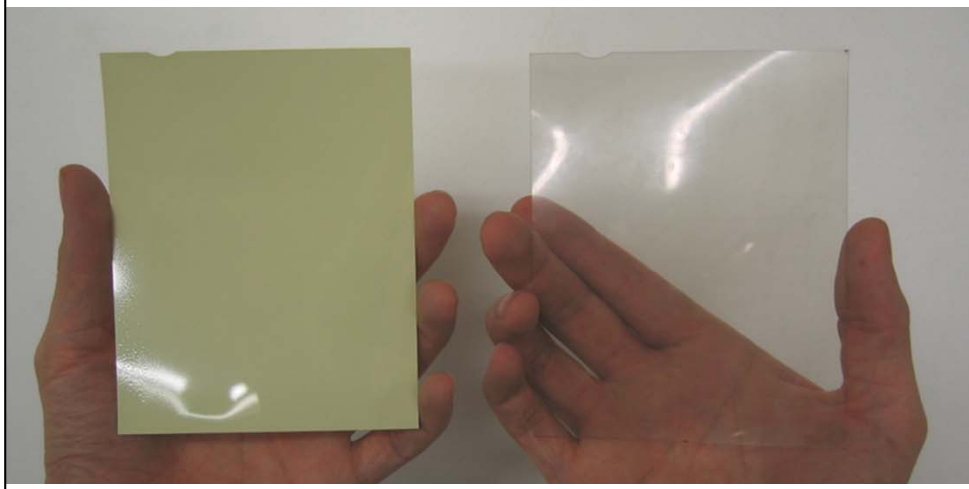
$e^{+/-}$

$e^{-/+}$

Cross sectional view of an emulsion film



Emulsion Film



before and after
development process

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microscope view
10μm

Intrinsic position accuracy of ~50nm

Gamma-ray

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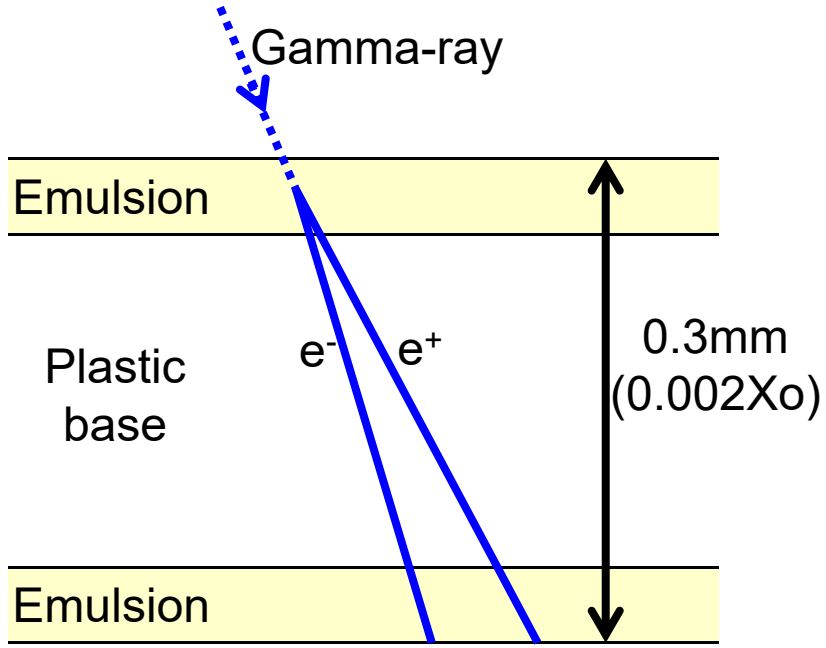
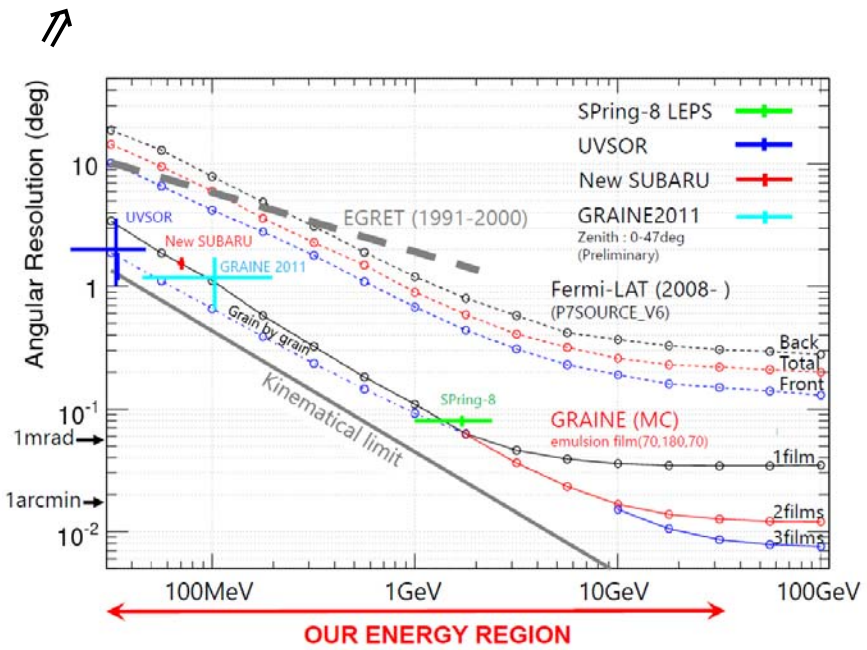
Cross sectional view of an emulsion film



68% containment radius



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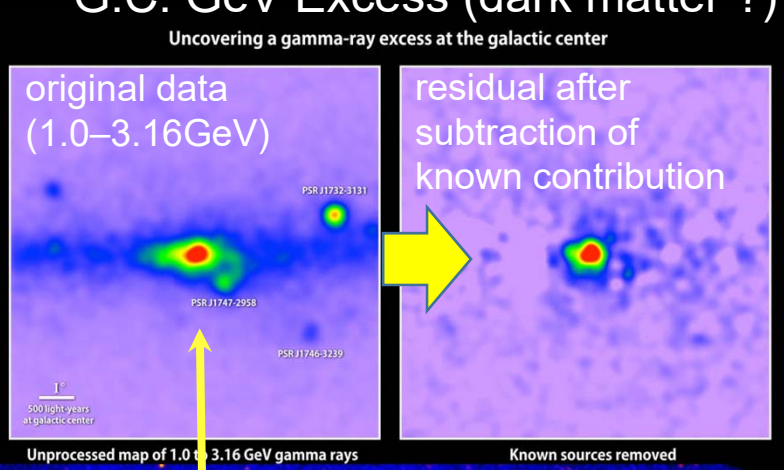

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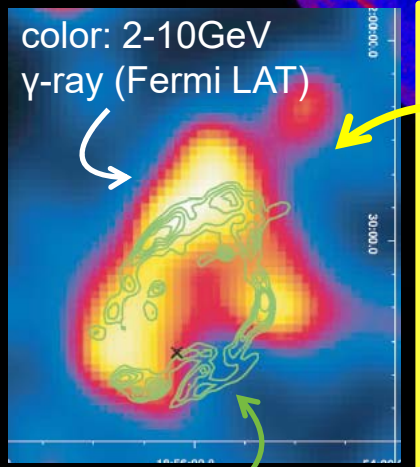
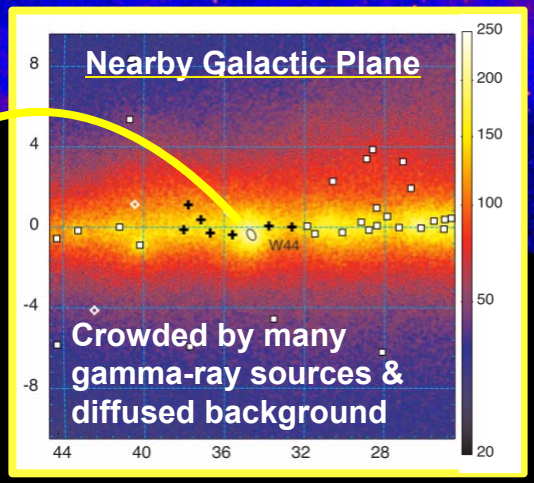
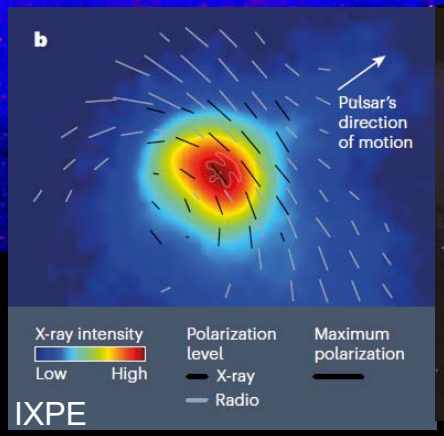
Abdo et al., Science, 2010





Vela



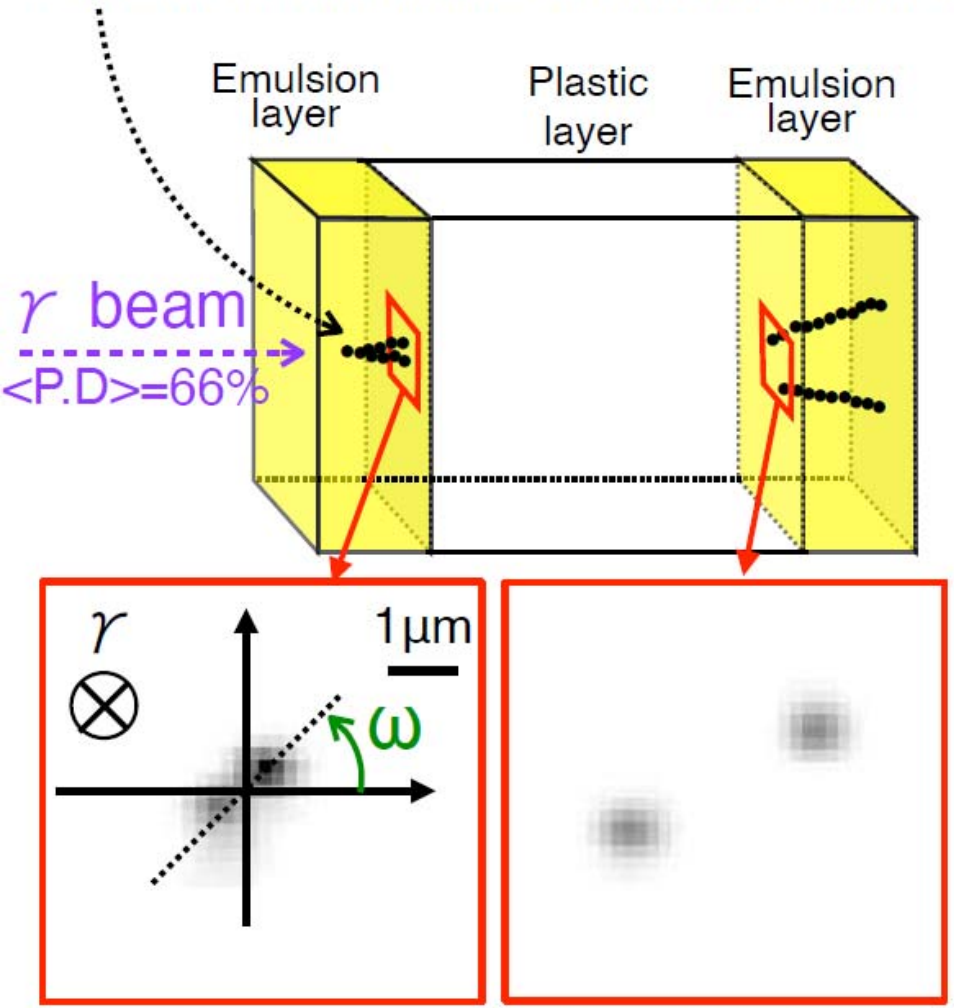
Xie, F. et al. Nature 612, 658,
(adapted in Nature 612, 641)

Crab

for γ-ray polarization, no positive report so far

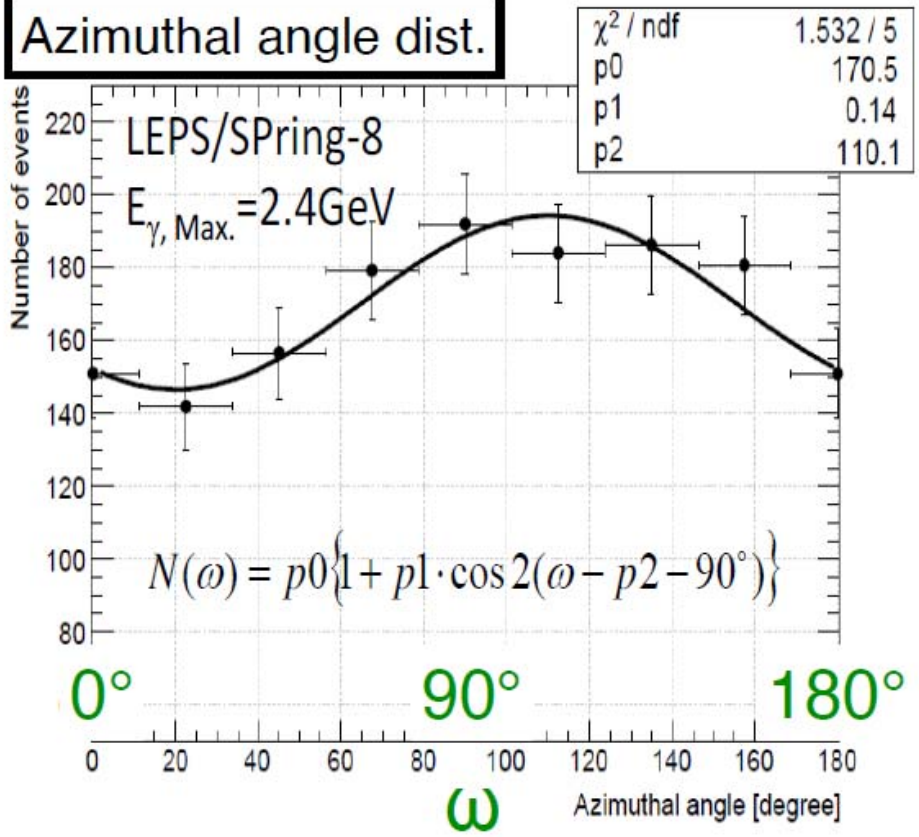
Demonstration of Polarimetry w/ Acc. Beam

Emulsion functions a converter and tracker at the same time.



Micrographs(0.13μm/pixel)

Azimuthal angle dist.

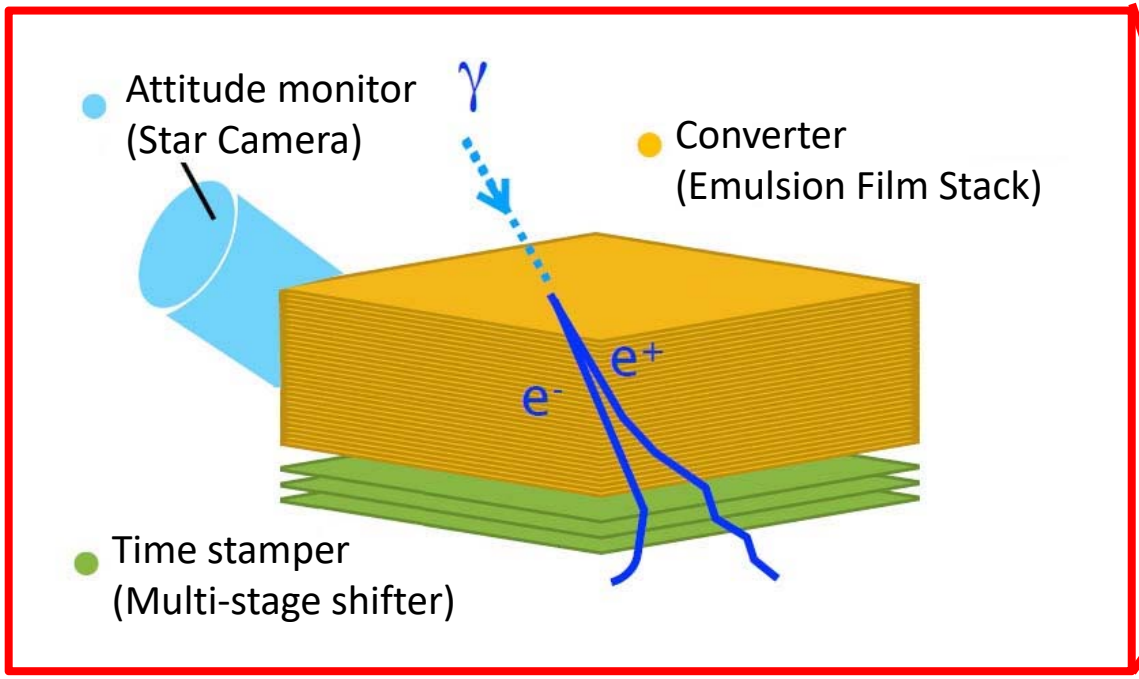


K. Ozaki, et al., NIM A 833, 11(2016)165

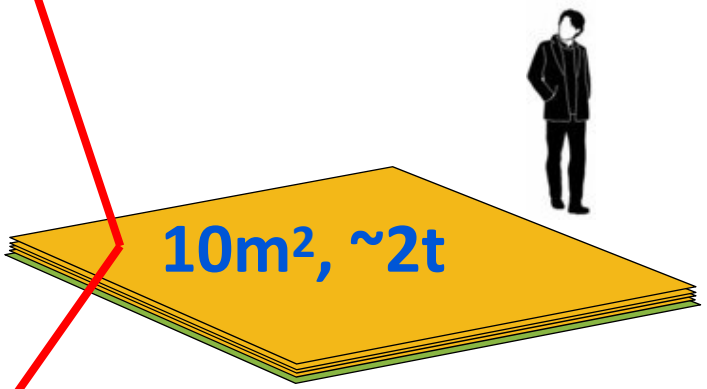
Modulation Factor = $0.21^{+0.11}_{-0.09}$

(*P1*=0.14 at <P.D>=66%)

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

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

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
H. Rokujo et al. PTEP 2018, 063H01
S.Takahashi et al. Adv.Space Res. 62 2945-2953

2018/Apr: 3rd Balloon exp.

- Celestial source detection

H. Rokujo et al. JINST 14, P09009 (2019)
Y. Nakamura et al. PTEP 2021, 123H02
S.Takahashi et al. ApJ, Accepted

2023/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

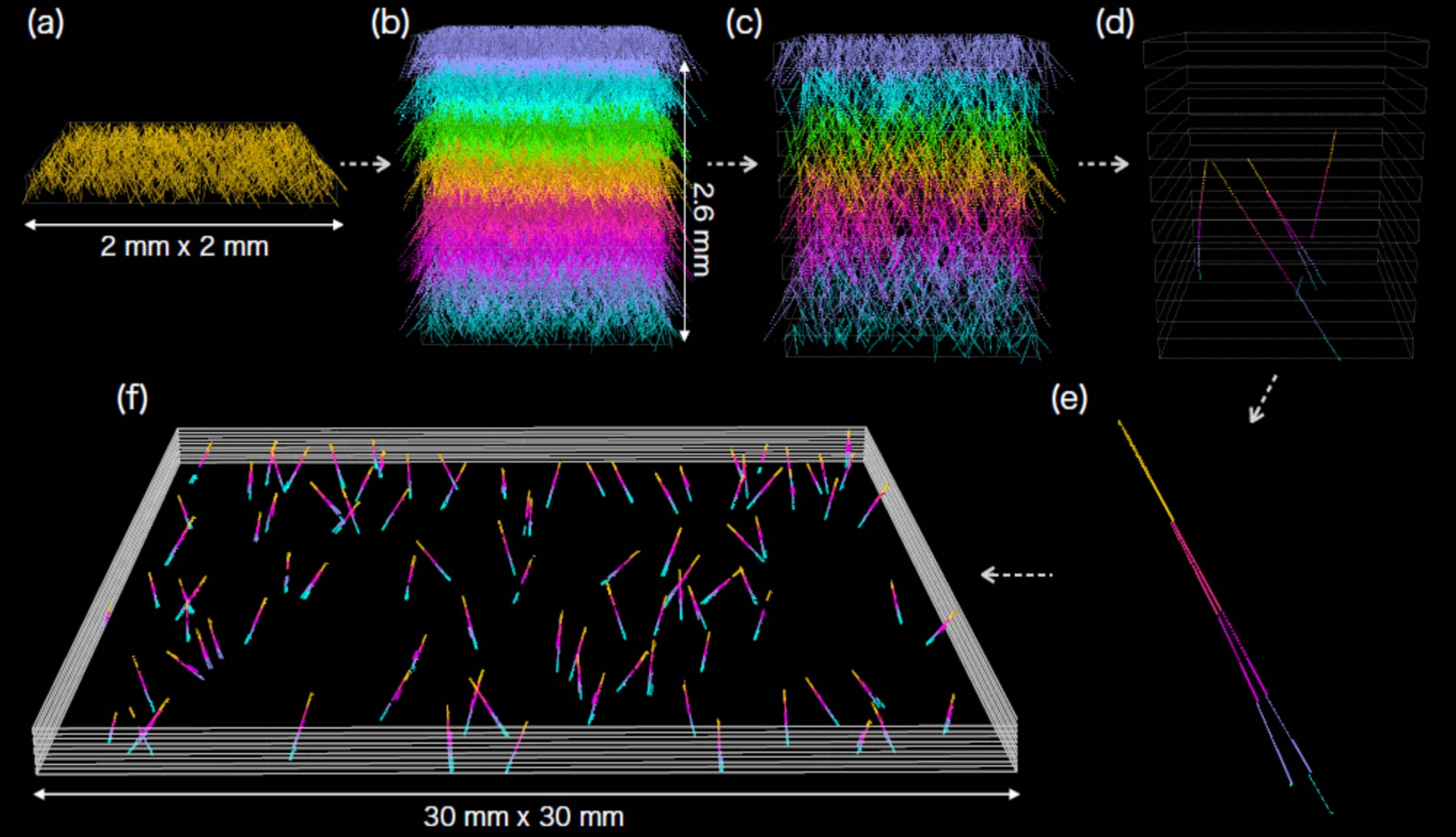
GRAINE 2021→2023

due to COVID-19

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

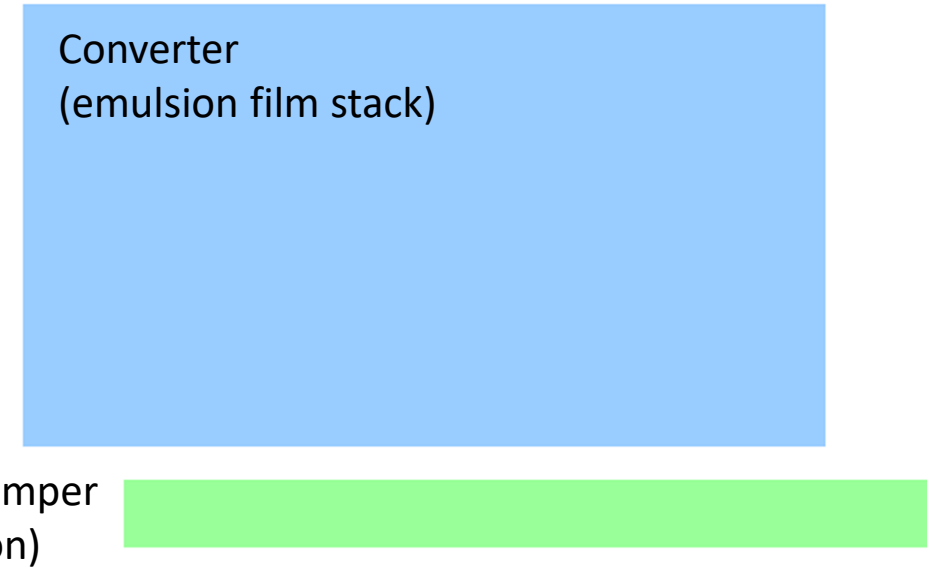
$\gamma \rightarrow e^+ e^-$ Event Selection

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



Small area of the real data from GRAINE2015

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

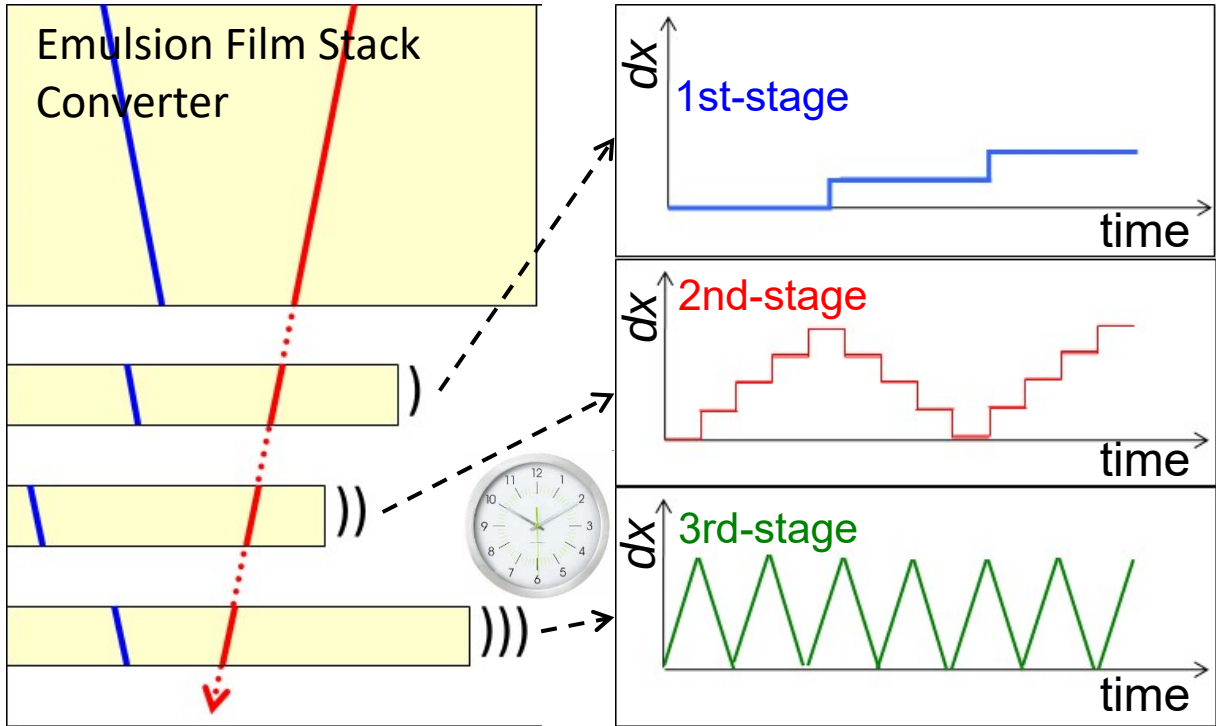


New Technique for GRAINE

Multi-stage Shifter (Time Stamper)

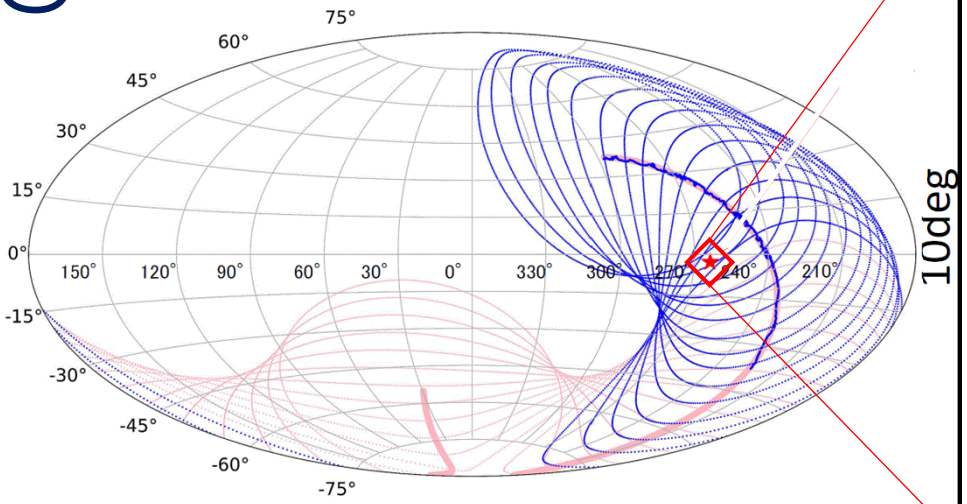
Consisting of emulsion film.
Low momentum threshold ~10MeV/c
High reliability & efficiency
Enlargeable
Simple, compact, light weight, high vol. free
Low power consumption, dead time free

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

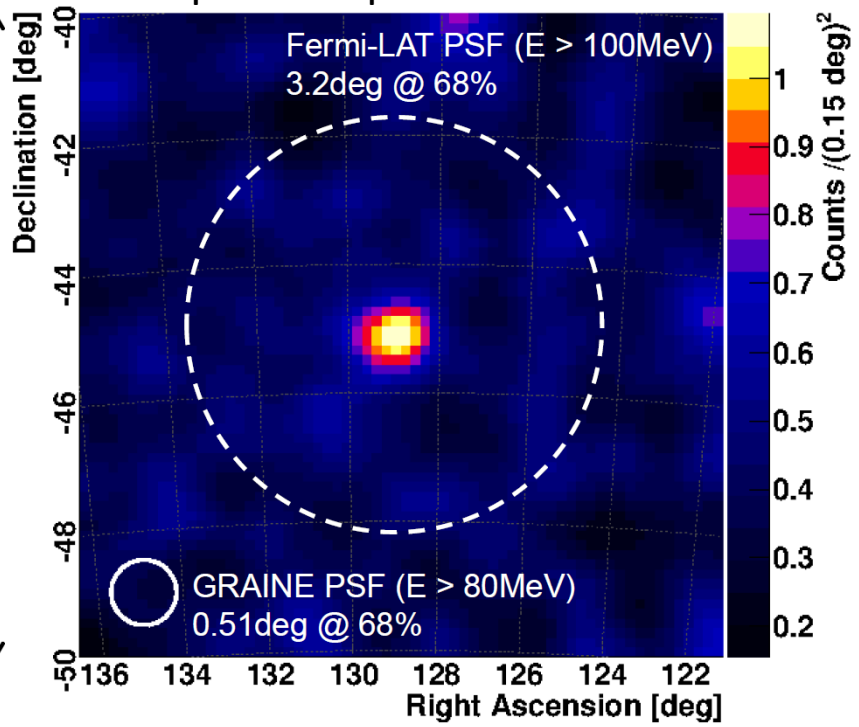


Vela pulsar imaging @GRAINE2018

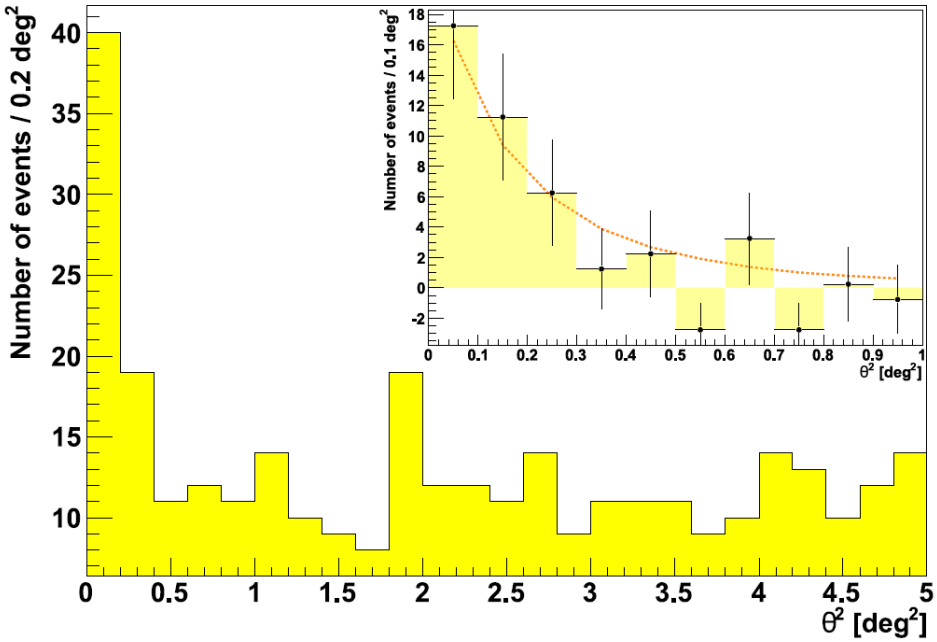
Accepted in ApJ



10deg



radial profile (θ^2 distribution)



6.3 times higher PSF (radius)

⇒ 39 times higher resolution (solid angle)

World's Highest Imaging

0.4deg 68% radius (E > 80MeV)

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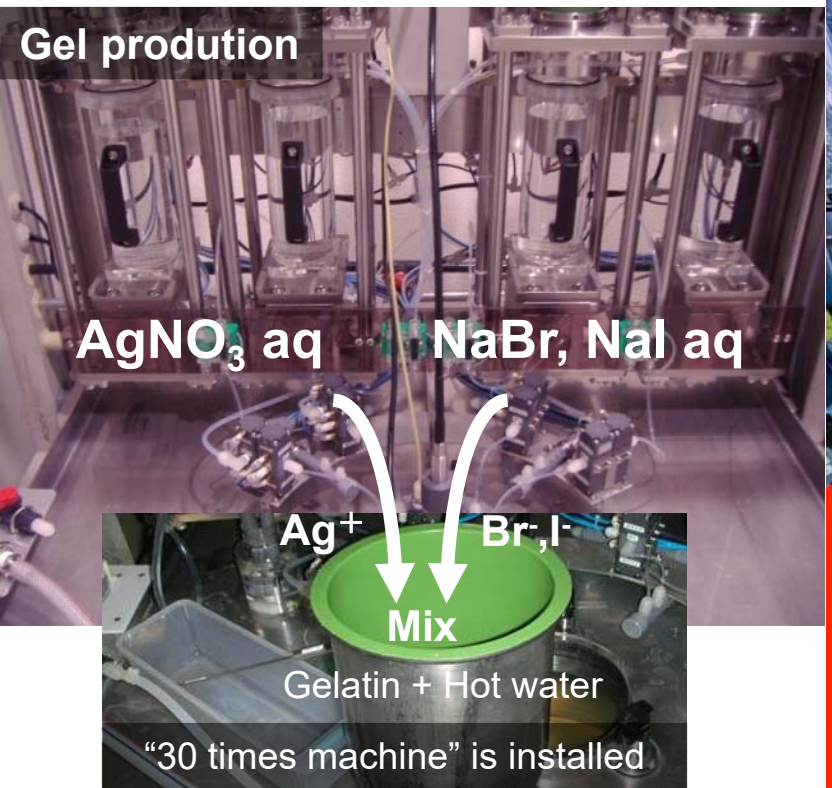
Development of Large Aperture Telescope for Scientific Observation starting from GRAINE2023

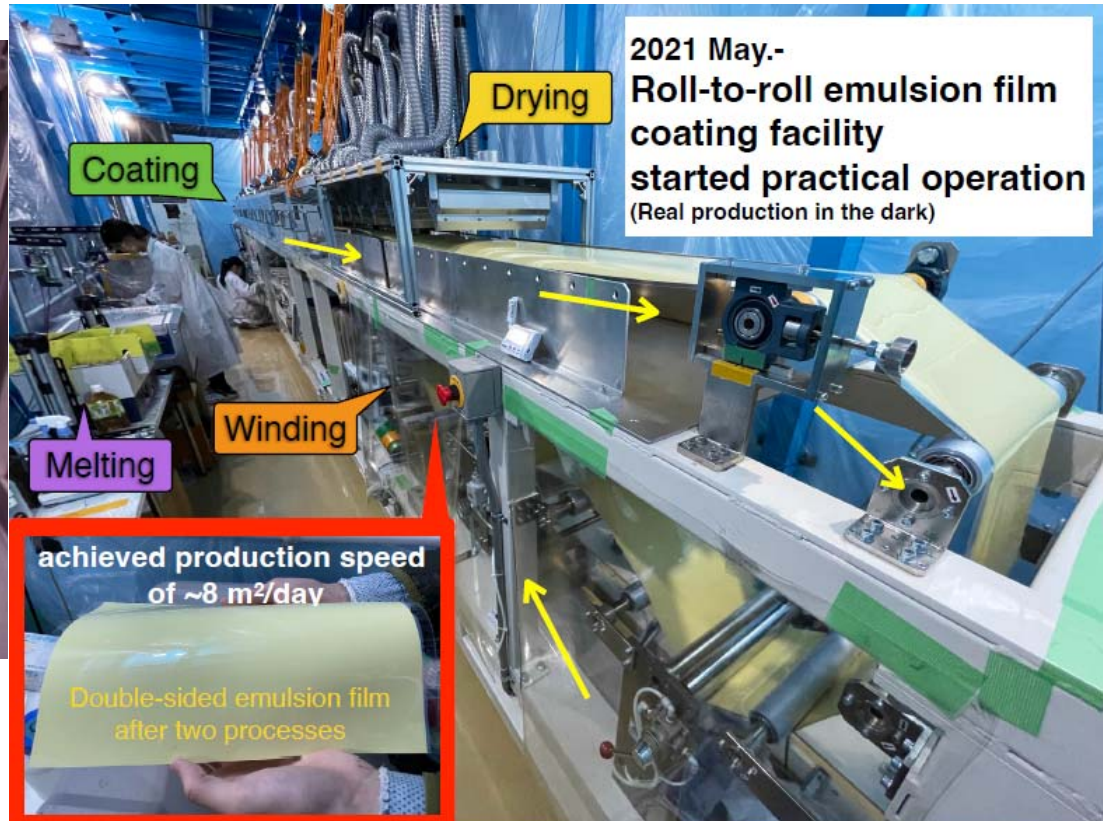
- Mass-production emulsion gel and film and development process

(converter film 1000m^2 and shifter film 100m^2 for 10m^2 aperture telescope as final goal)

- Large scale “refresh” facility, packing system and development facility
- Upgrade of Hyper Track Selector
- New Pressure Vessel and Gondola
- New Multi Stage Shifter

A1-I-1 H.Rikujo





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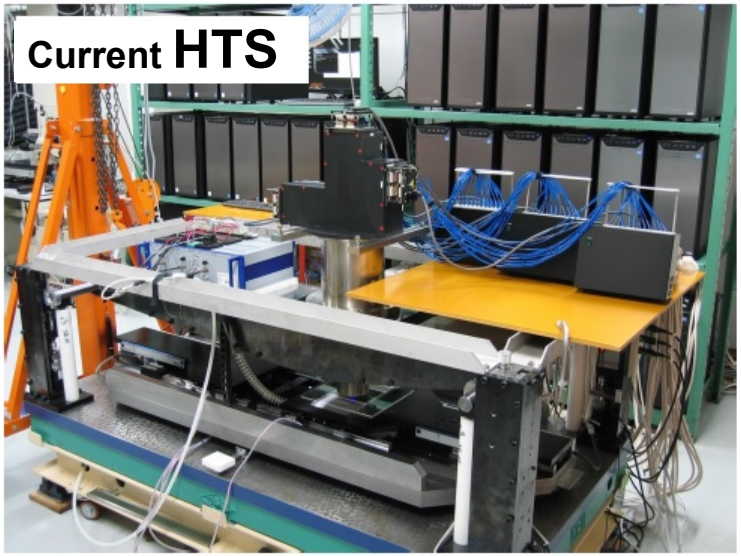
A1-I-2 T.Nakano
A1-P-4 H.Minami



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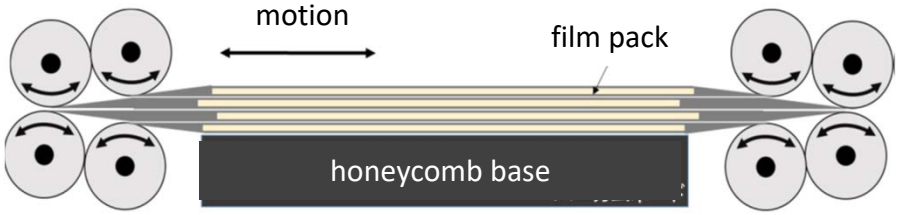
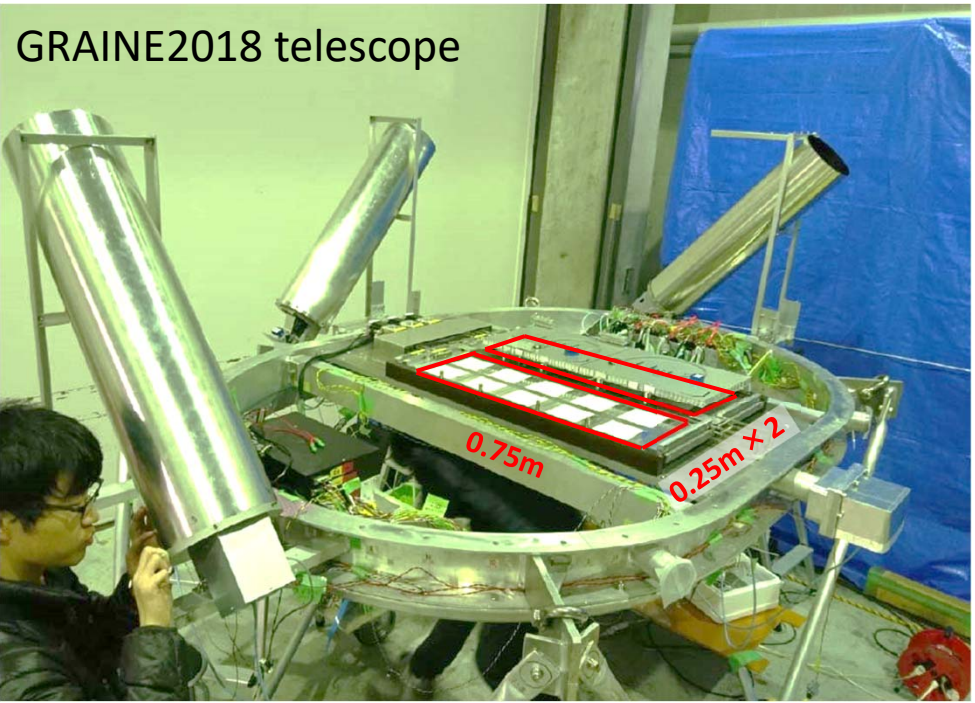
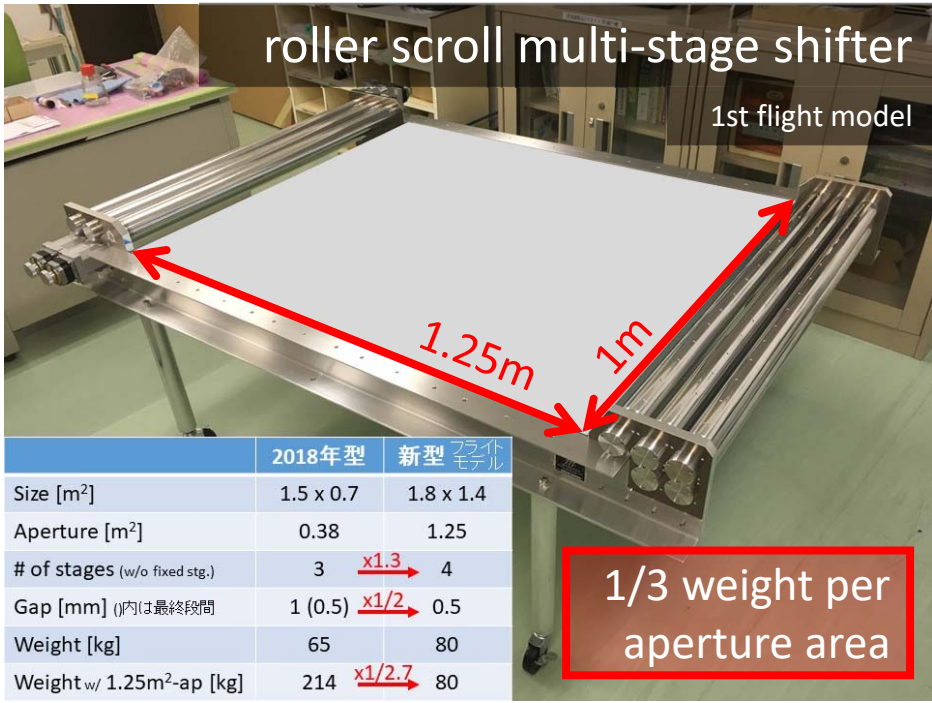
A1-I-4(next) S. Nagahara







	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

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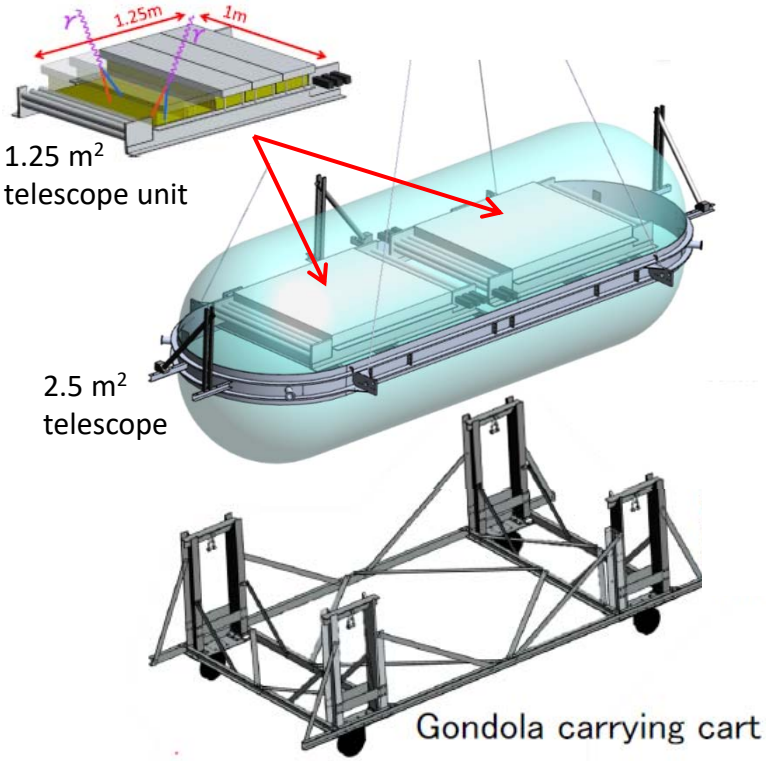
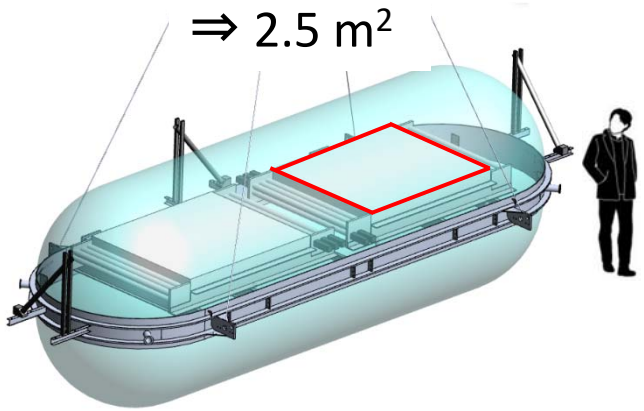
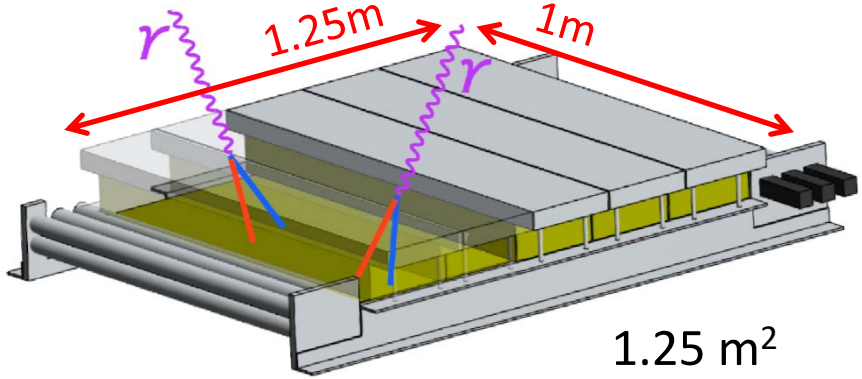


Expandable telescope assembling identical units

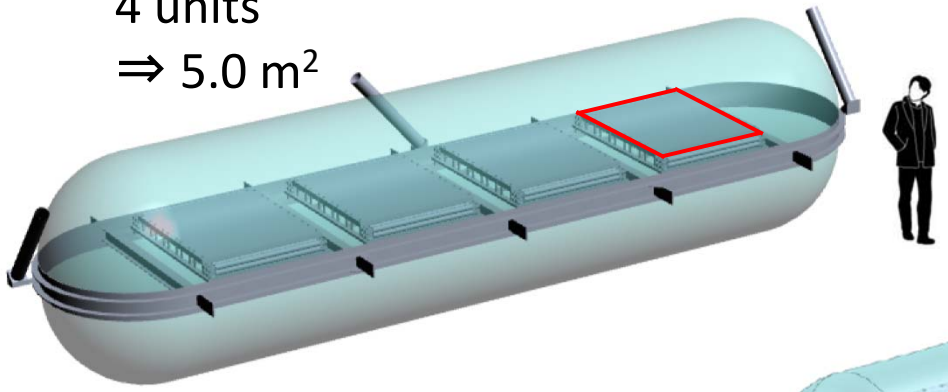
2 units
⇒ 2.5 m²



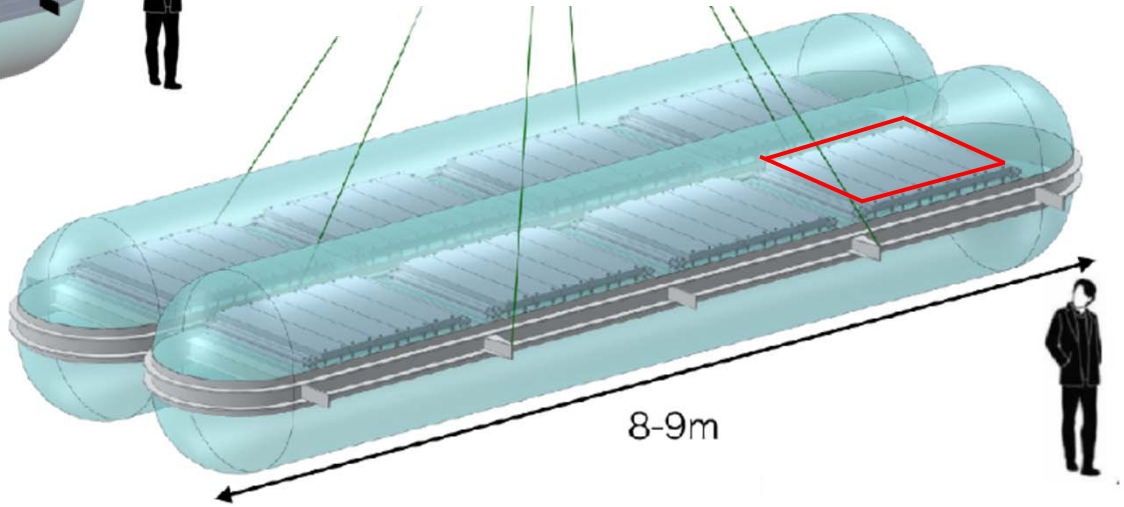


1.25 m²
telescope unit

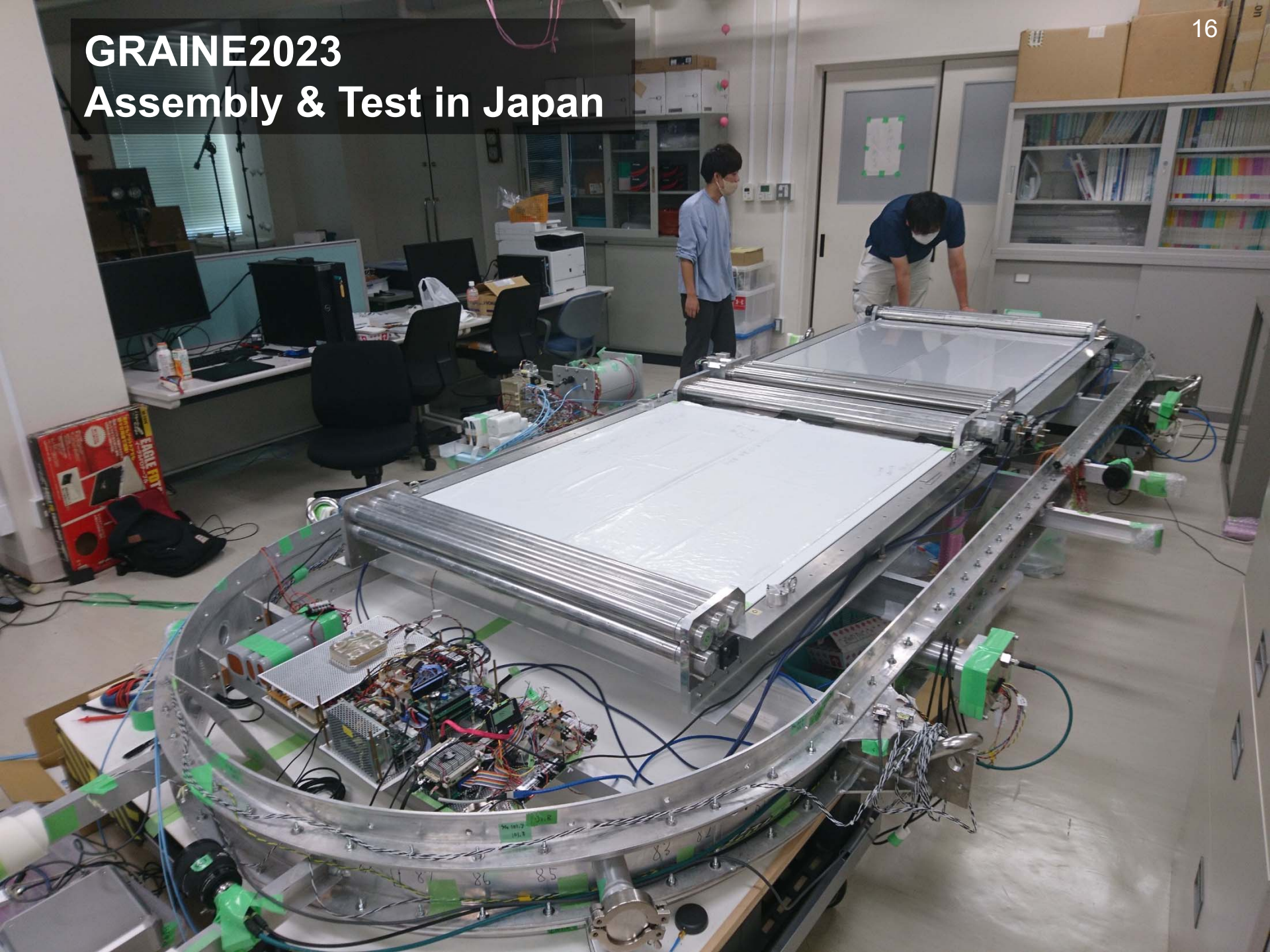
4 units
⇒ 5.0 m²



8 units
⇒ 10.0 m²

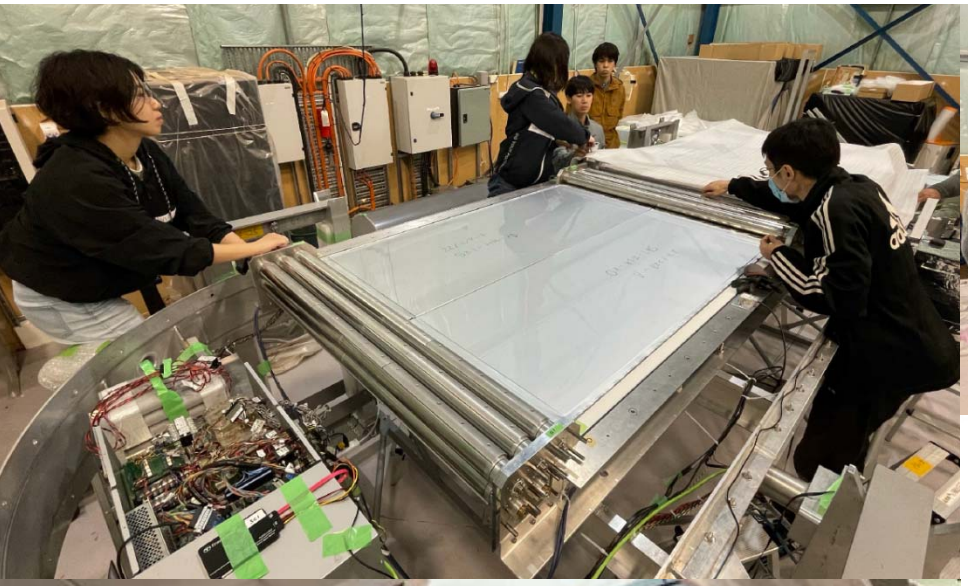


GRAINE2023
Assembly & Test in Japan

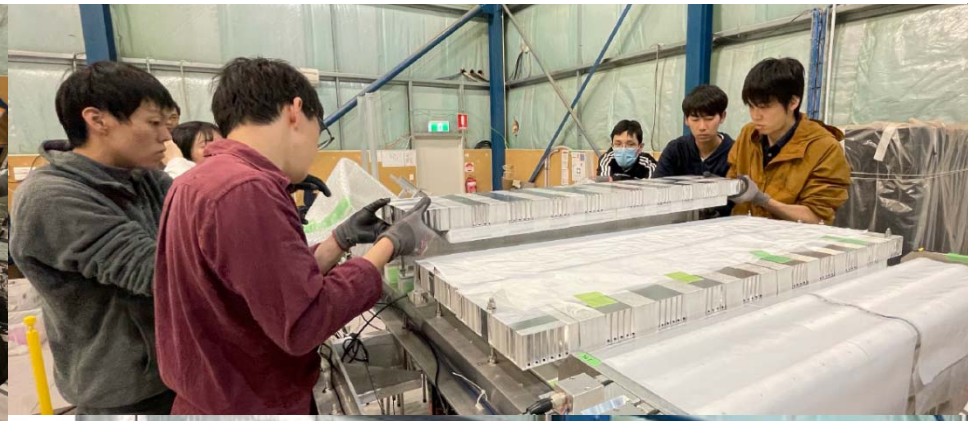


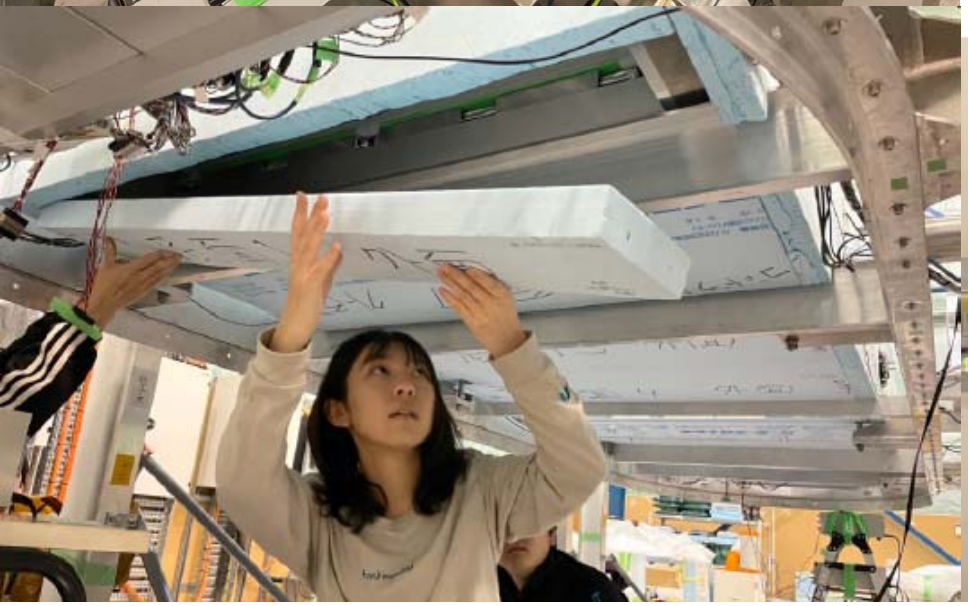
GRAINE2023 Final Installation @ Australia

Shifter Film



Converter





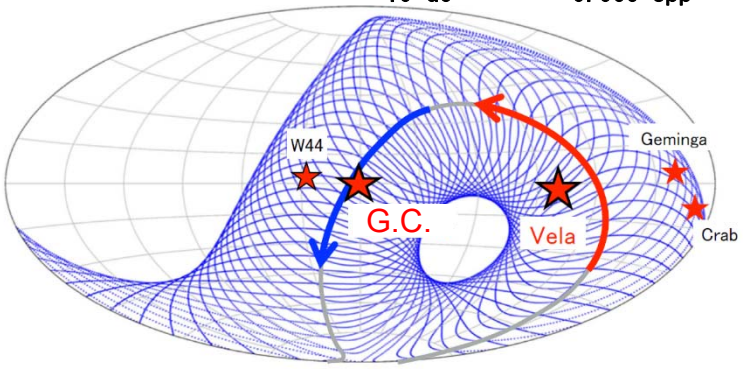
Thermal Insulation

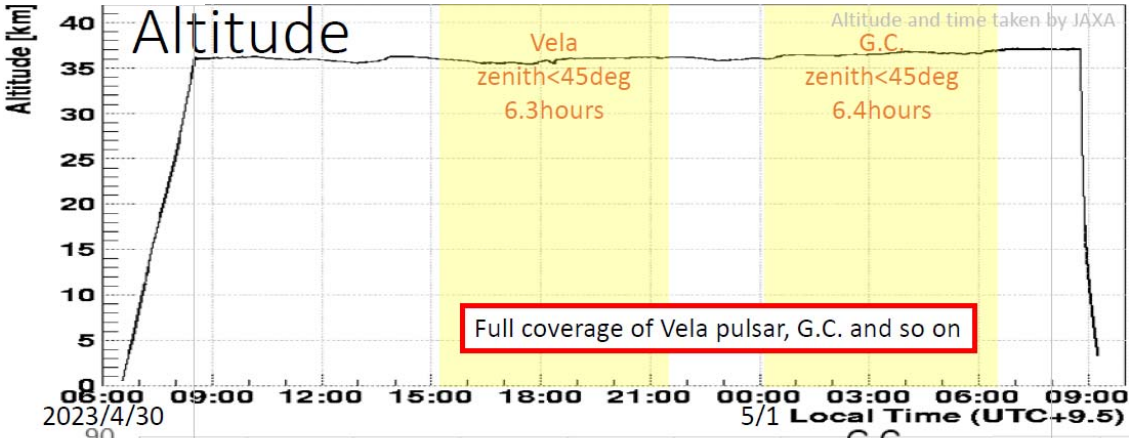
Attitude Monitor (Star Camera)

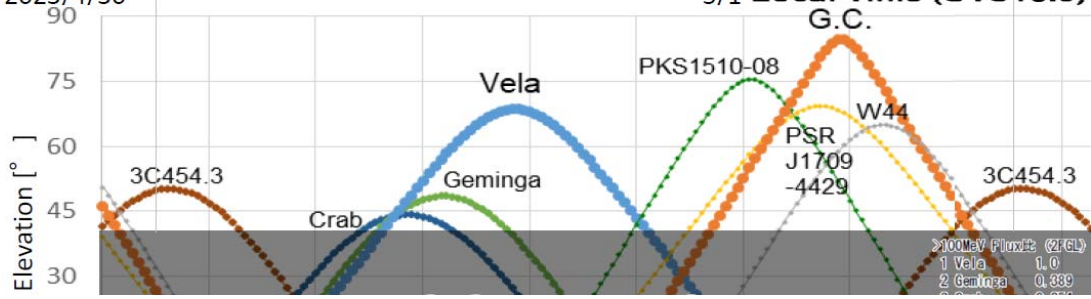
GRAINE2023

Latitude, longitude, altitude and time taken by JAXA

>100MeV Flux (2FGL)			
1	Vela	1.0	PSR
2	Geminga	0.389	PSR
3	Crab	0.254	PSR
4	3C454.3	0.219	BZQ
*	PKS 0402-362 (flare)		
5	J1709-4429	0.144	PSR
7	PKS1510-08	0.091	BZQ
9	W44	0.073	SNR
10	GC	0.066	spp

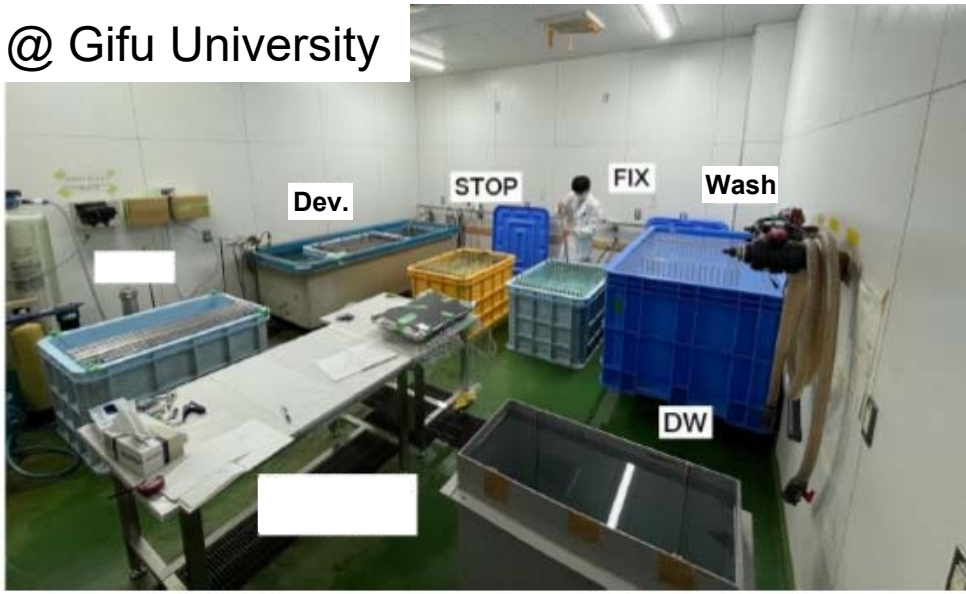




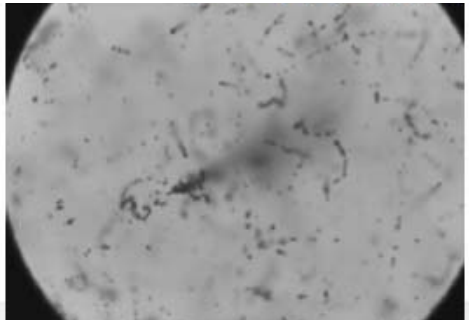


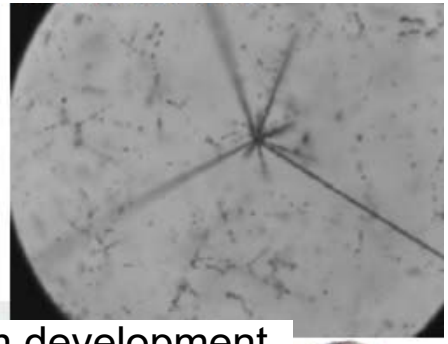
GRAINE2023 Photo Development Process of Recovered Films

Large scale development facility @ Gifu University

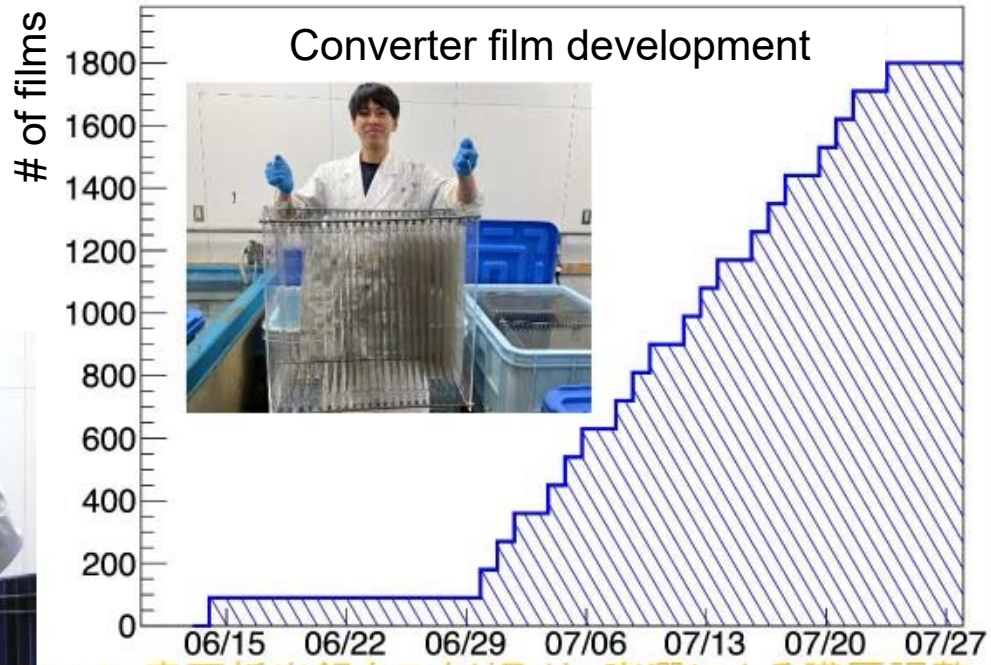


Microscopic views of the flight film



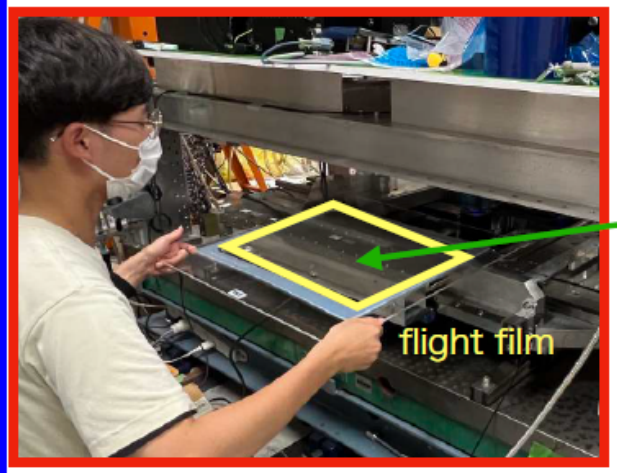


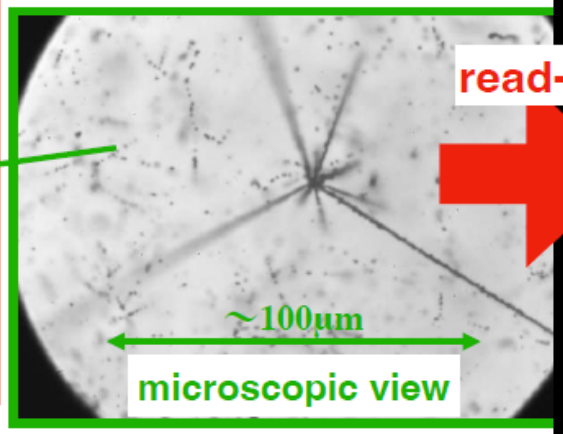
6/14-17 timestamper film development



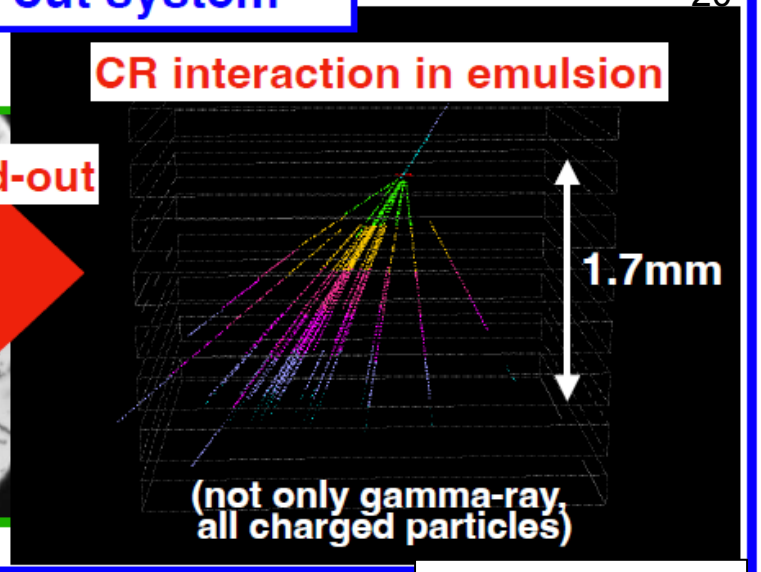
現像処理枚数2000枚(1800+160+α)、表面析出銀をこすり取り、膨潤による膜厚調整

Automatic emulsion read-out system



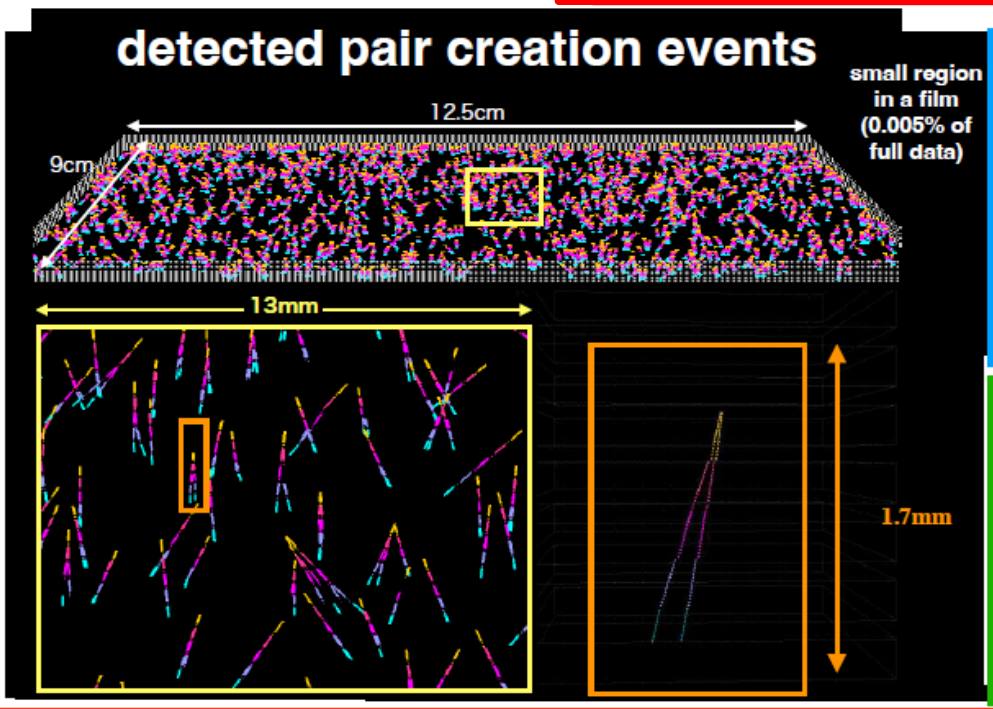


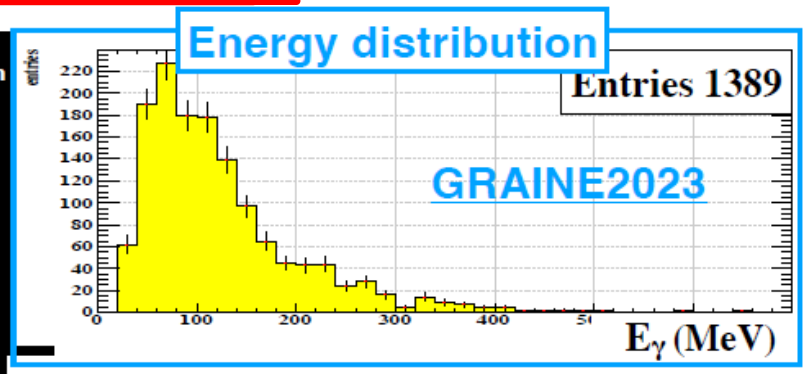
read-out

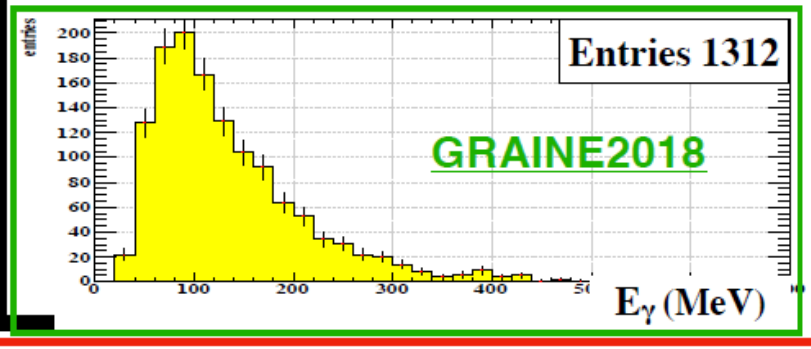


A1-P-5 I.Usuda

Pilot Analysis of Gamma-ray

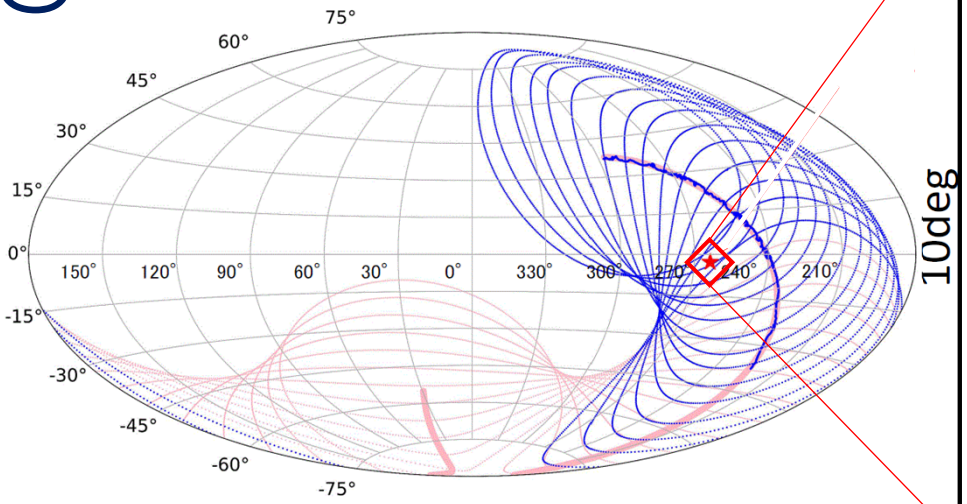




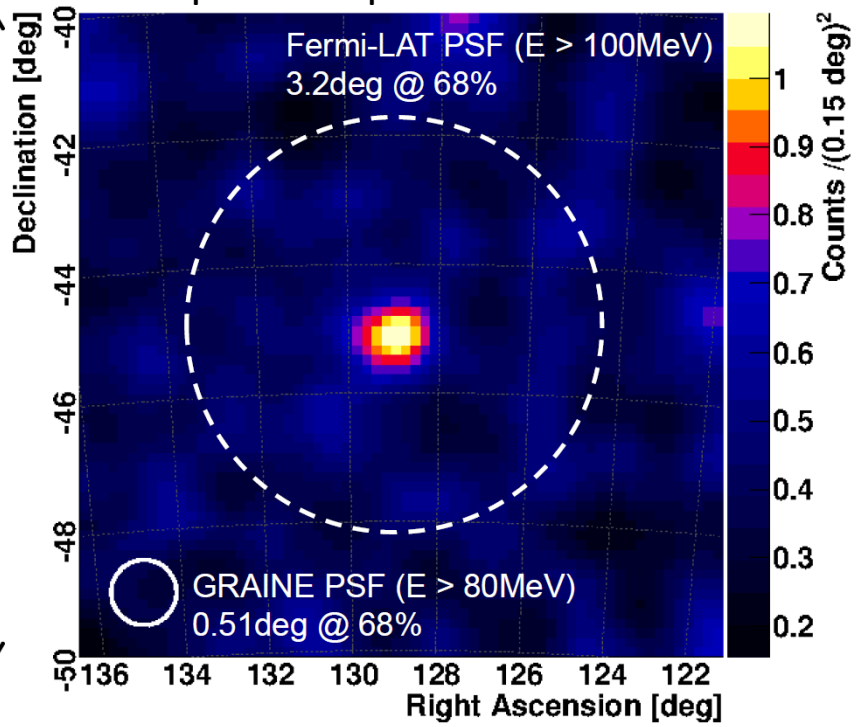


Vela pulsar imaging @GRAINE2018

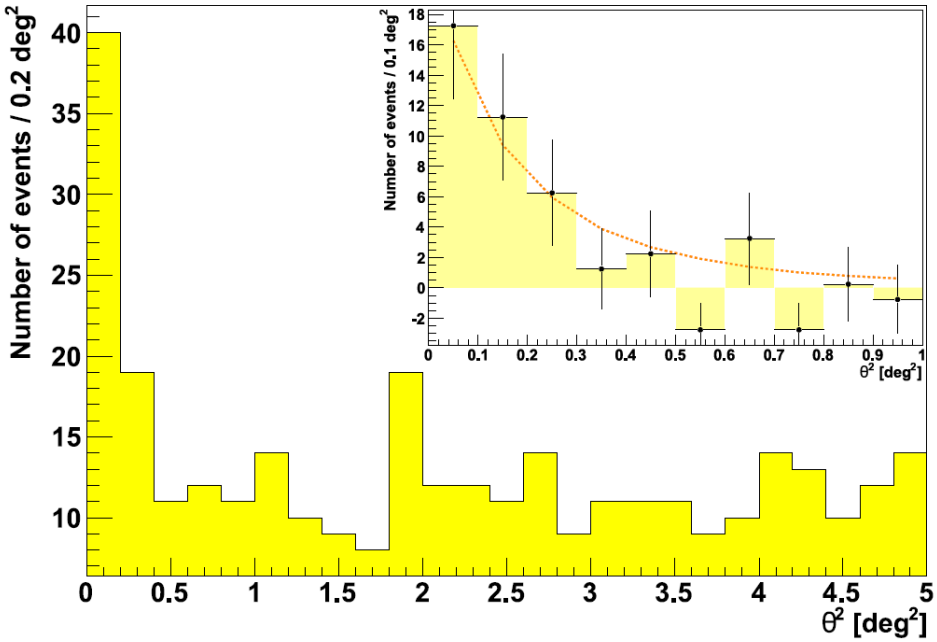
Accepted in ApJ



10deg



radial profile (θ^2 distribution)



6.3 times higher PSF (radius)

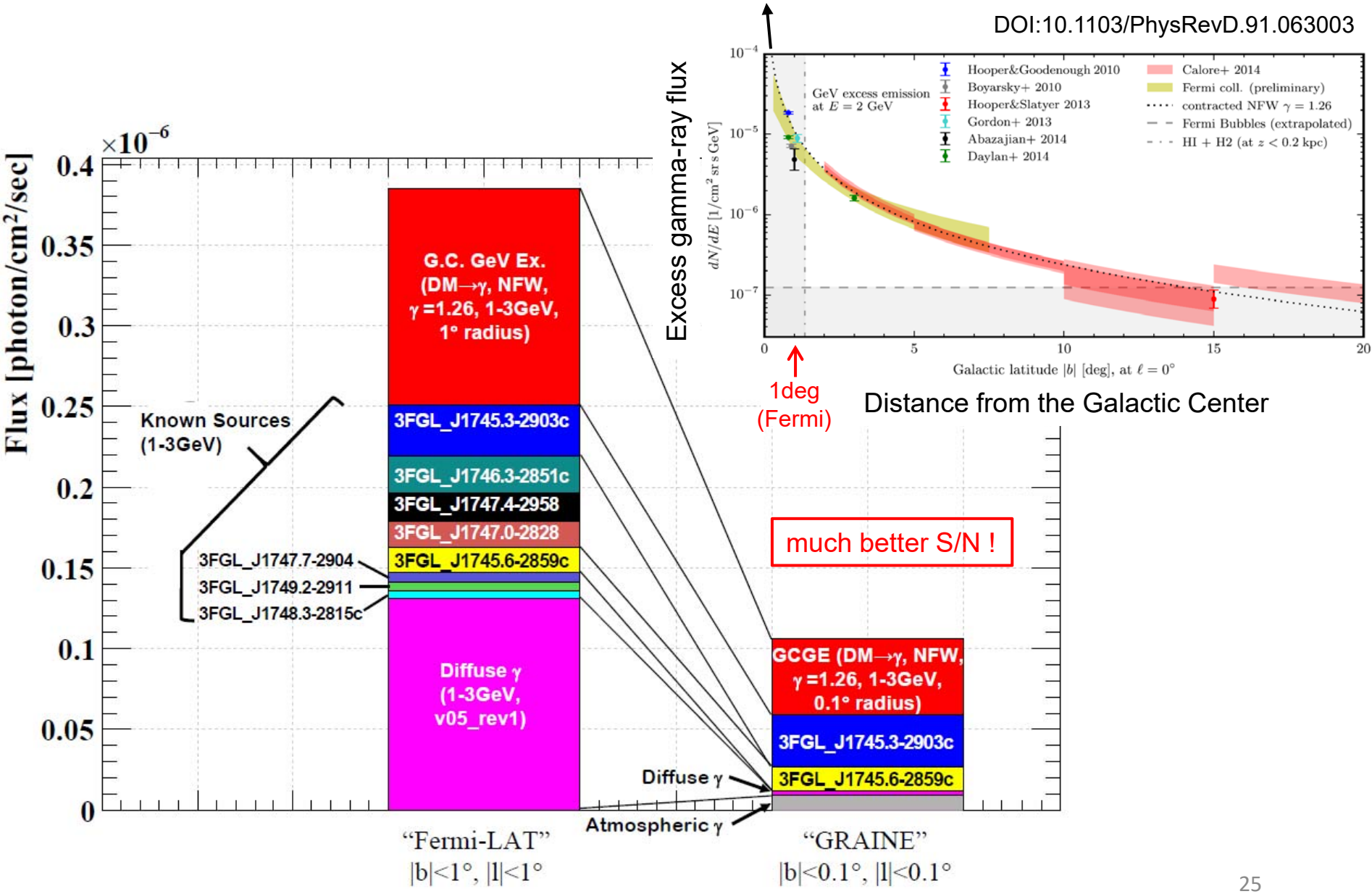
⇒ 39 times higher resolution (solid angle)

World's Highest Imaging

0.4deg 68% radius (E > 80MeV)

Galactic Center GeV Excess

DOI:10.1103/PhysRevD.91.063003



GRAINE Scientific observation roadmap

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

2023, Commissioning

Done by JAXA balloon

Alice Springs
2.5m^2 aperture (x6.6 2018)
27 hour flight duration (x1.6 2018)
<5g/cm^2 altitude

Full scale

Alice Springs, North. hemisphere
10 m^2 aperture
>~30 hour flight duration } repeated
<~10 g/cm^2 altitude

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