

GRAINE project:

High-resolution Imaging and Polarization Measurement of
Sub-GeV/GeV Gamma Rays with Balloon-borne Emulsion Telescopes

Balloon launching on 2023 Apr. 30th
@Australia, Alice Springs Airport

Hiroki Rokujo
(Kyushu Univ./Nagoya Univ. KMI)



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High-resolution Imaging and Polarization Measurement of
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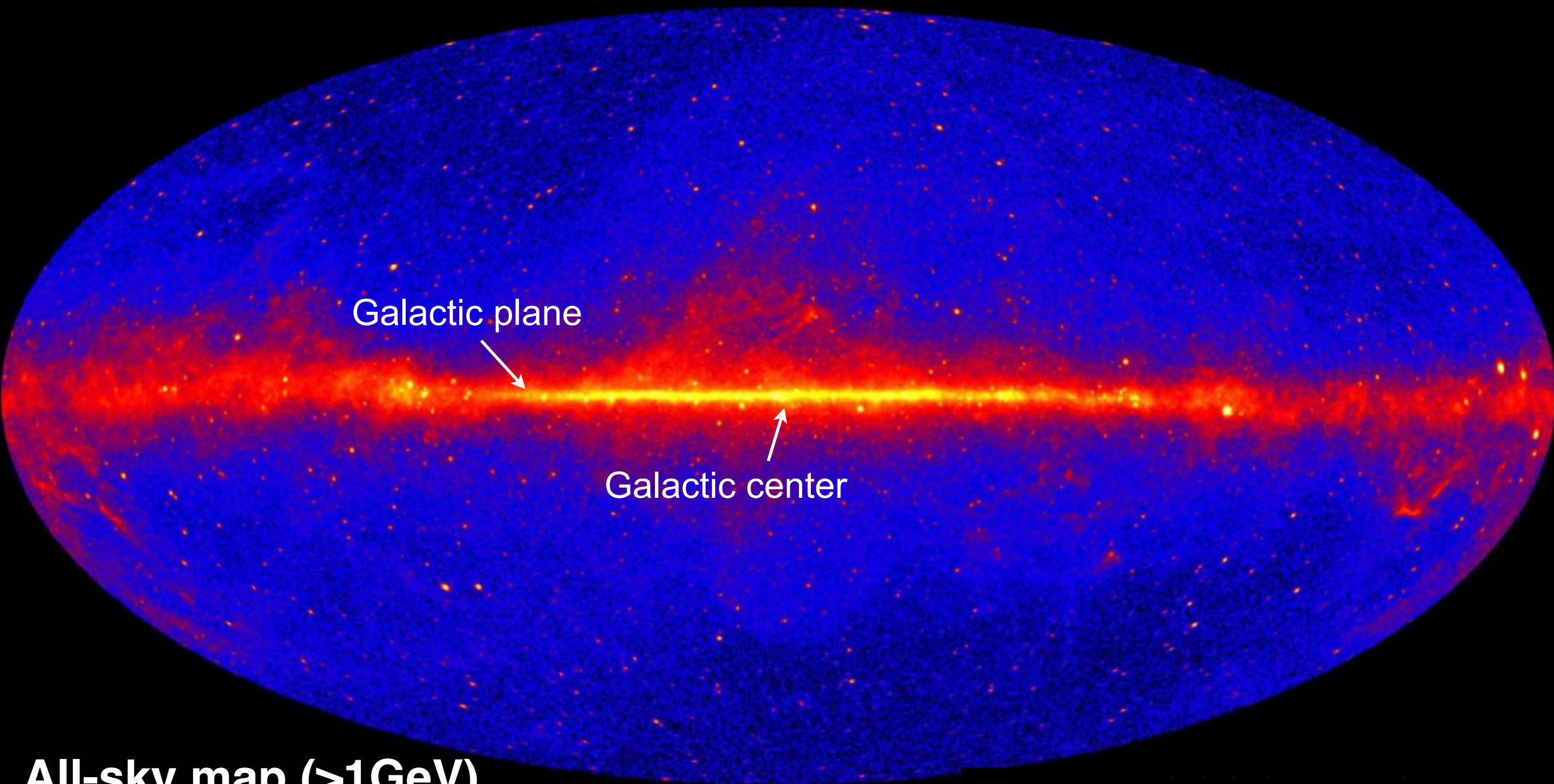
Balloon launching on 2023 Apr. 30th
@Australia, Alice Springs Airport

Hiroki Rokujo
(Kyushu Univ./Nagoya Univ. KMI)



Cosmic Gamma rays (**sub-GeV/GeV**)

This band has been advanced
by Fermi-LAT (2008-)
and AGILE (2007-2024)



All-sky map ($>1\text{ GeV}$)

Cosmic Gamma rays (sub-GeV/GeV)

This band has been advanced
by Fermi-LAT (2008-)
and AGILE (2007-2024)

Cosmic Ray

p (CR) + H (ISM)

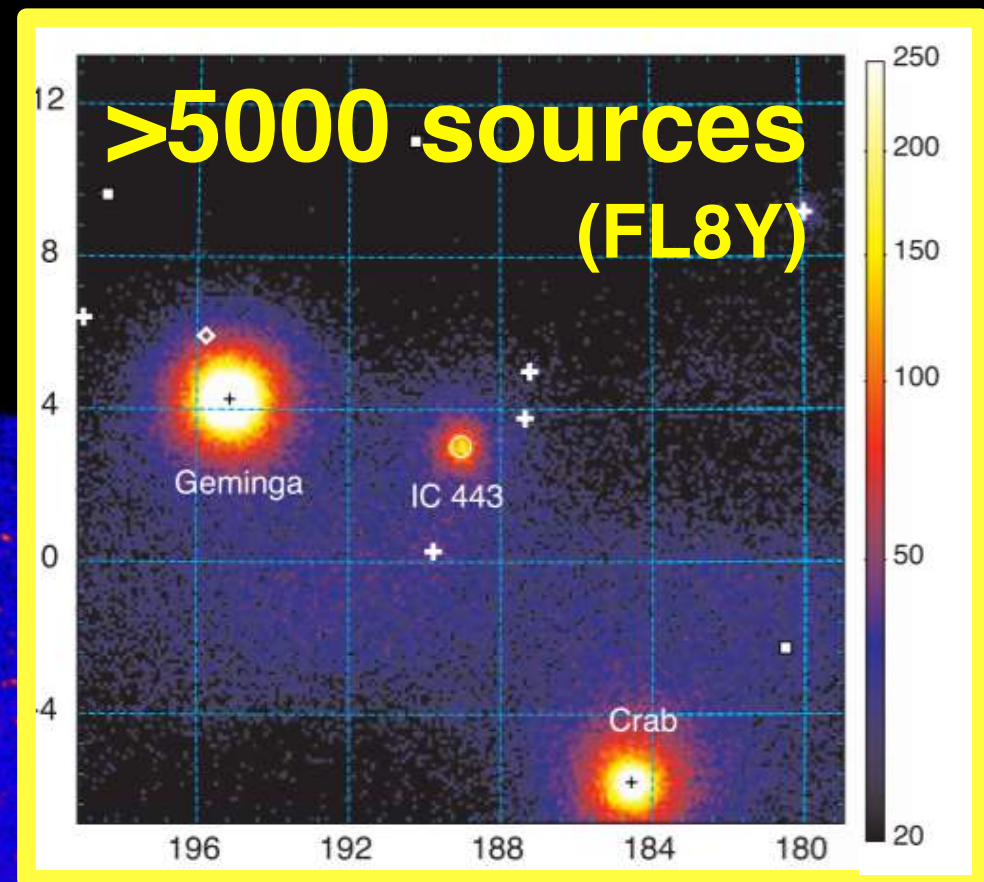
$\rightarrow p, n, \pi^{+/-}, \underline{\pi^0} \dots$

$\pi^0 \rightarrow 2\gamma$

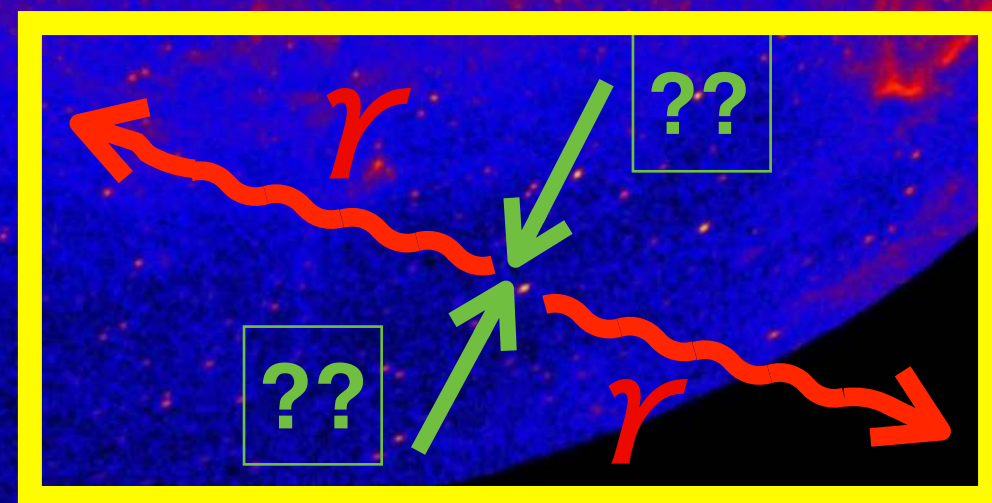
Galactic plane

Galactic center

Cosmic gamma-ray data has
produced scientific results
across a variety of fields.



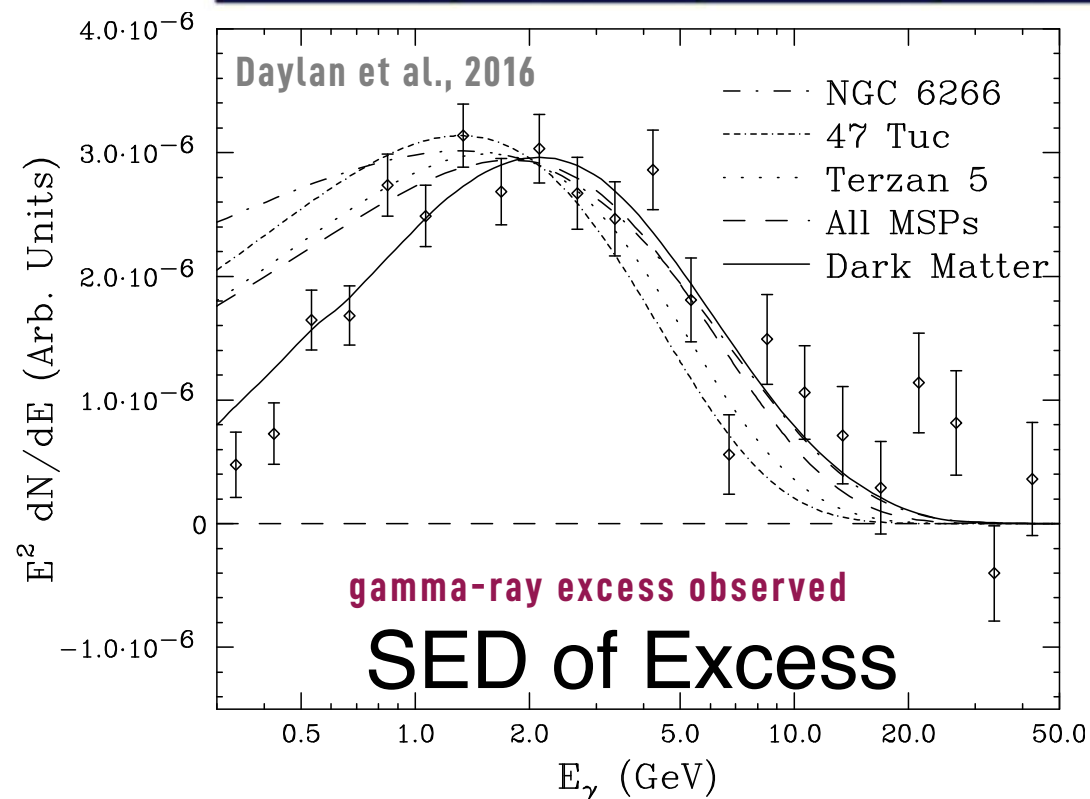
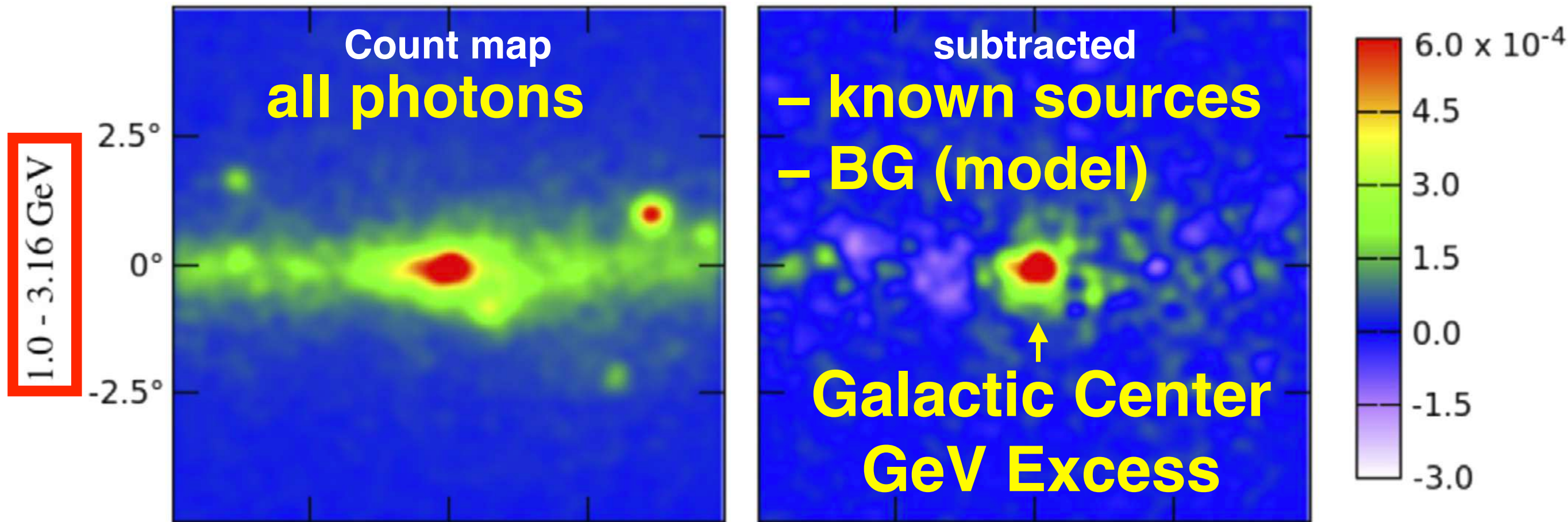
Astronomy



Fundamental/Particle Phys.

Unresolved issues in gamma-ray observation

- Unknown gamma-ray emission in the Galactic center region



Annihilation of WIMPs ?
Unresolved astrophysical object ?

The discussion has been going on
for more than a decade.

One of the known-unknown issues

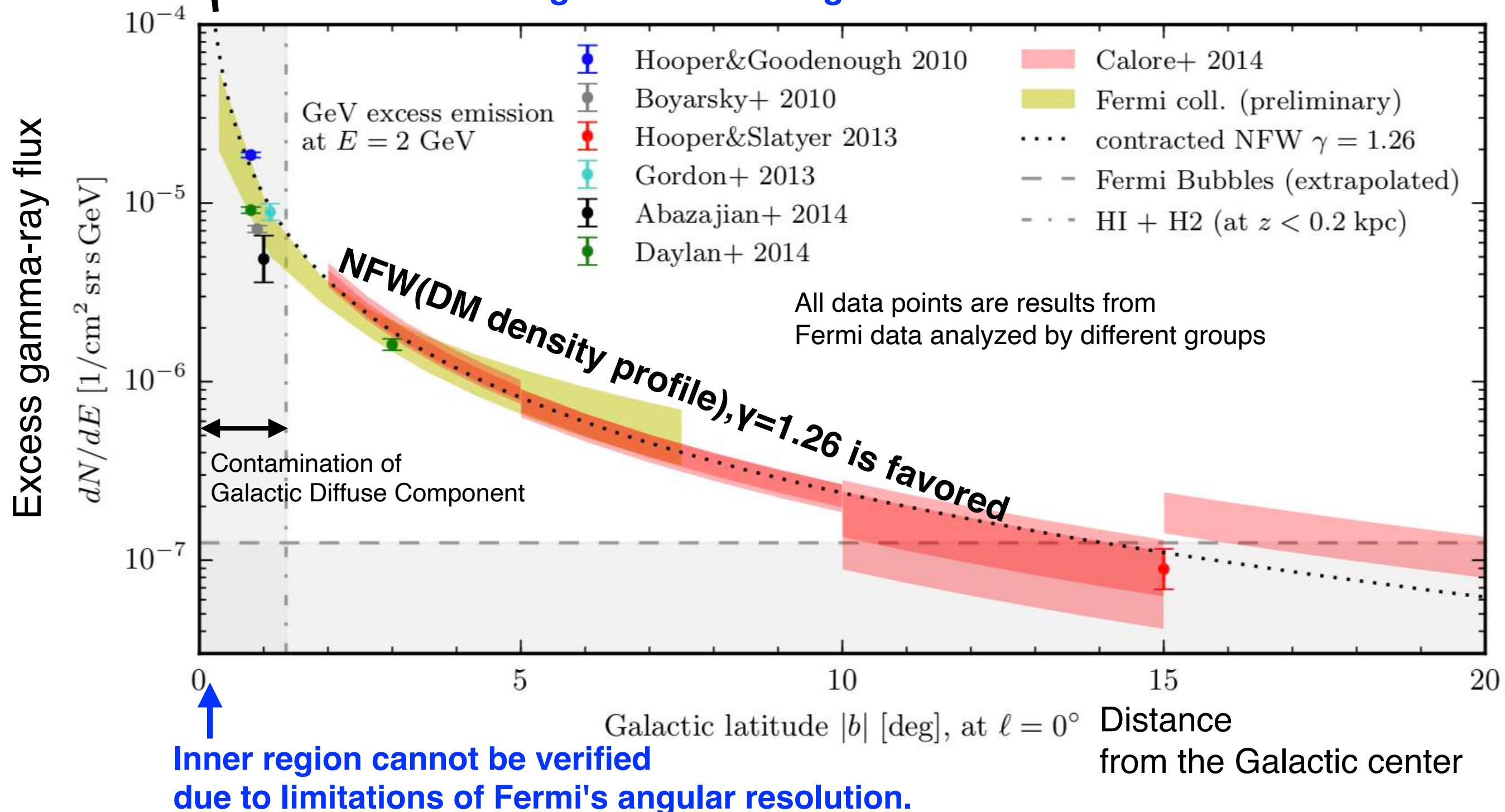
Unresolved issues in gamma-ray observation

• Angular profile of the Galactic Center GeV Excess

Francesca Calore, Ilias Cholis, et al., Phys. Rev. D **91**, 063003

DM Density increases near the center
→ Gamma-ray emissions sharply increase

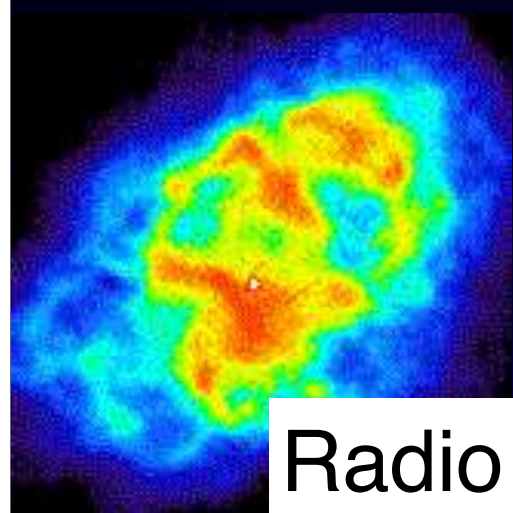
The most central region is interesting to confirm this trend with more reliable



Imaging Performance of Fermi-LAT

γ ray >1 GeV
(Fermi-LAT)

Crab Nebula
(M1:SN1054)



Radio



Infrared



Visible



X ray



$\updownarrow 0.1^\circ$

$\updownarrow 0.1^\circ$

Same scale

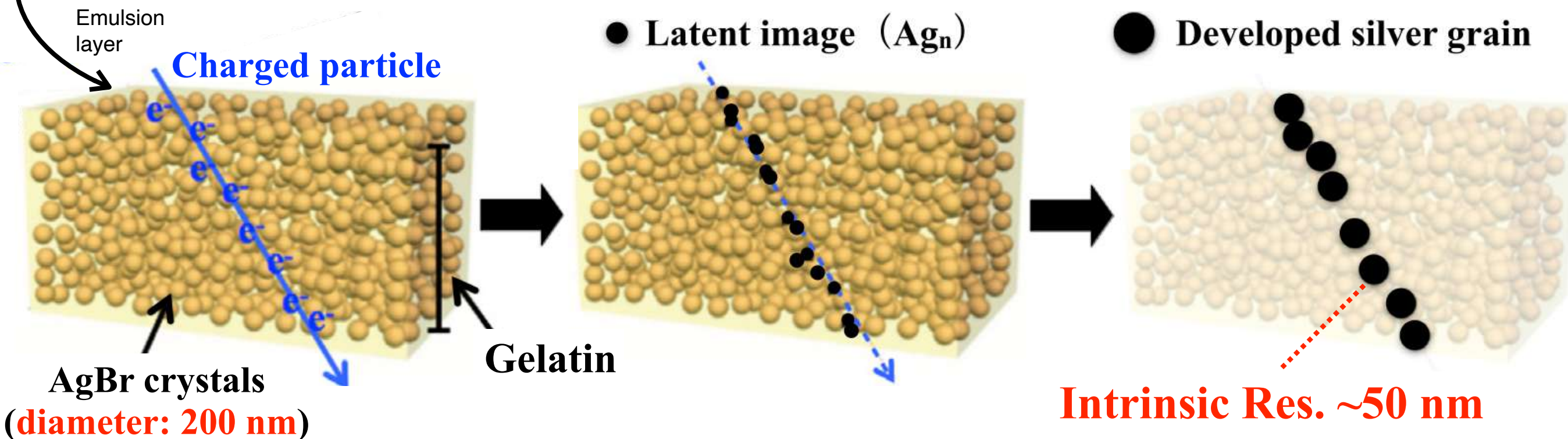
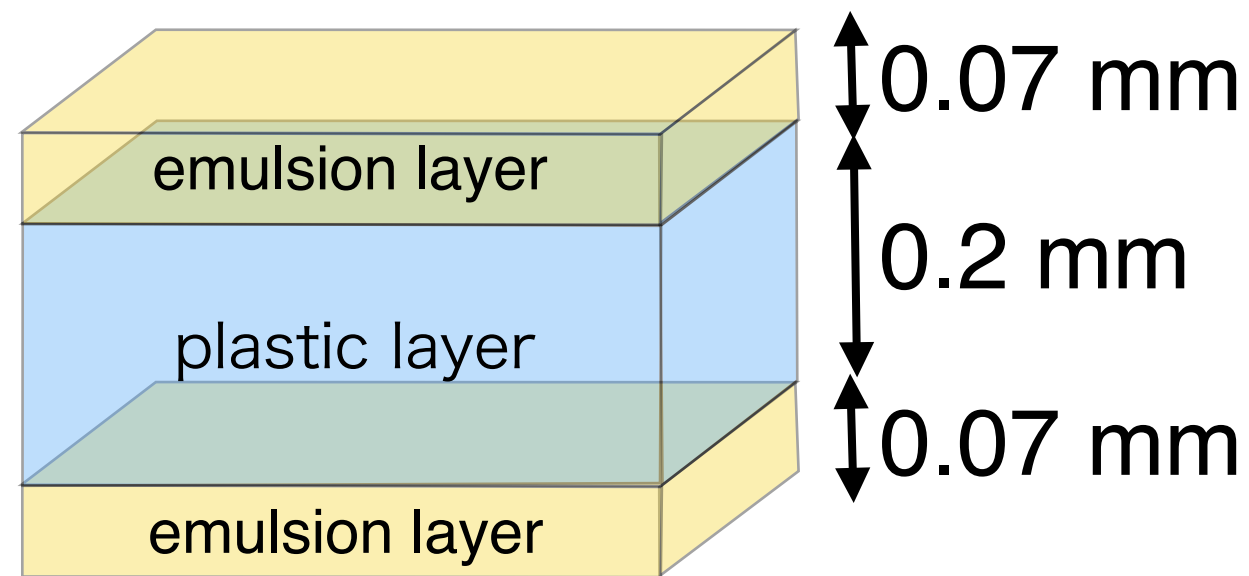
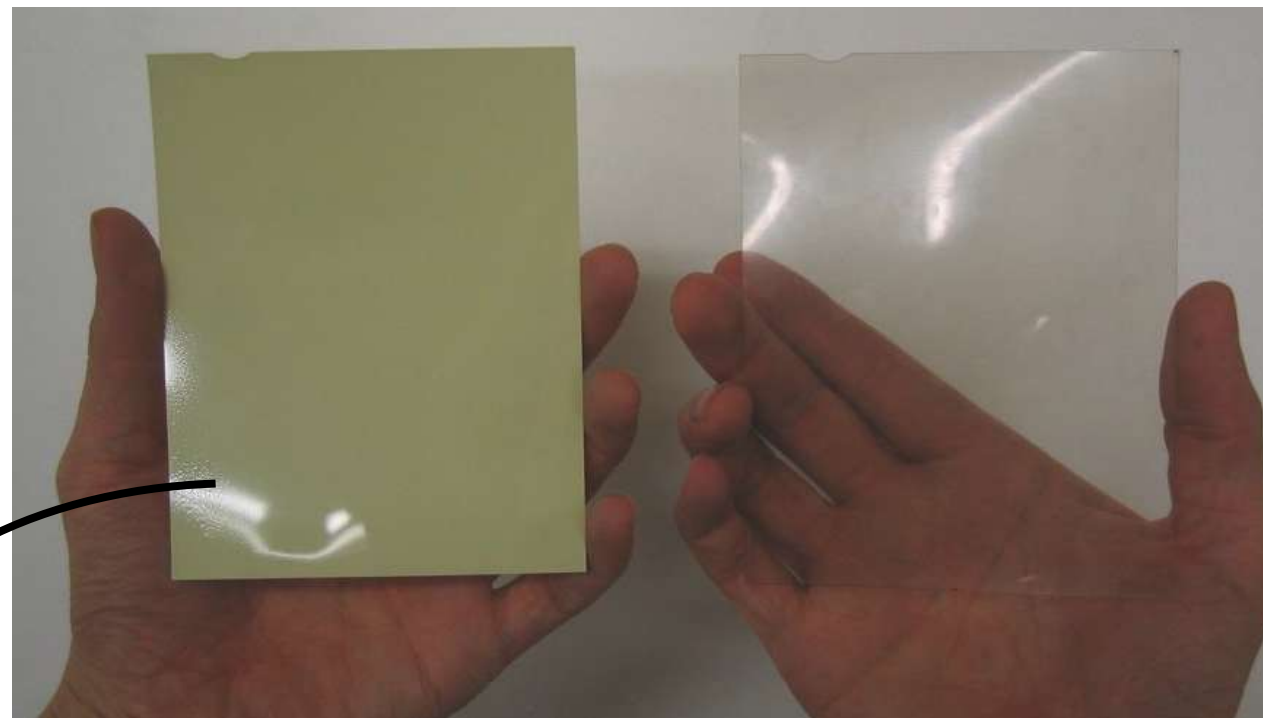
All objects are blurred
with the size of the moon!!

To open the new door
Improvement of Angular res. is needed

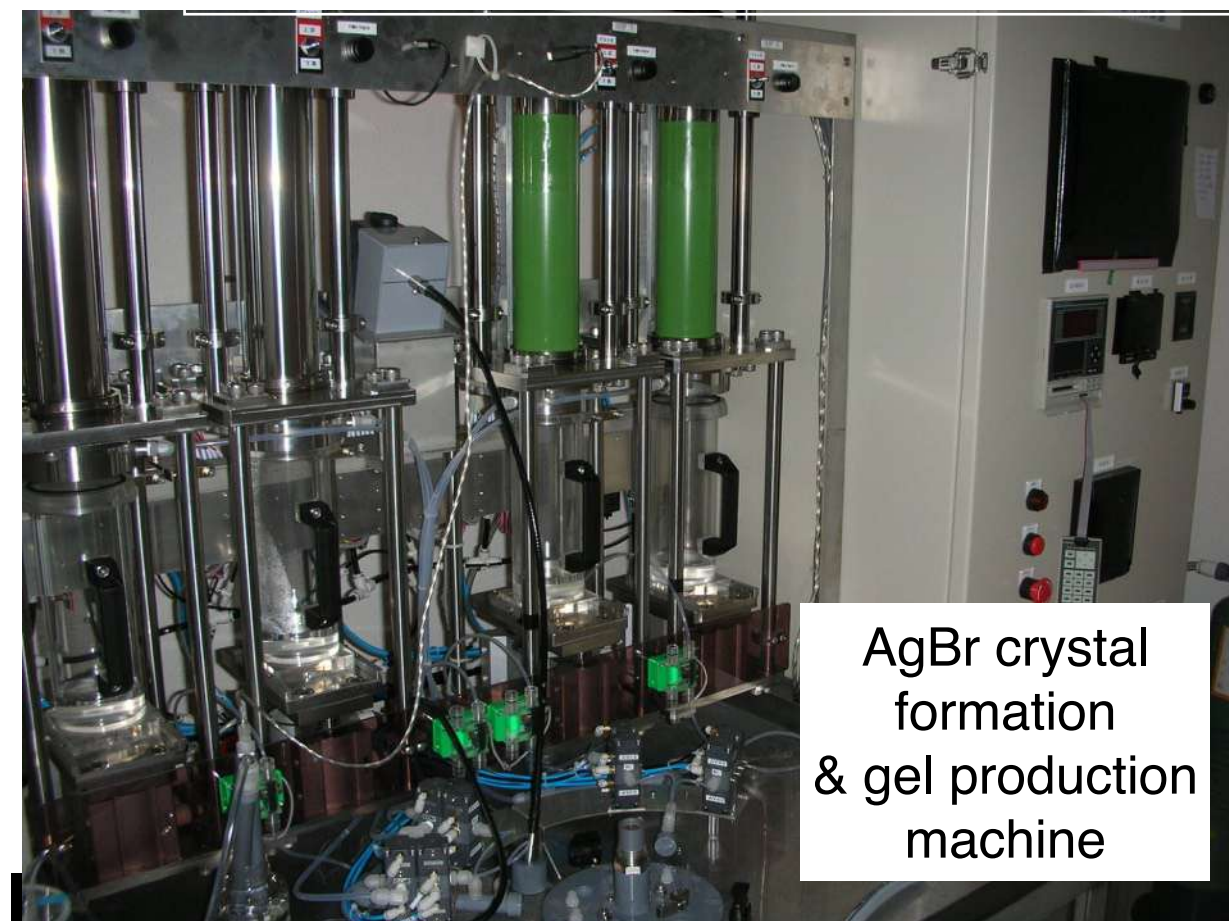


Nuclear Emulsion

A photographic film that can record the trajectories of charged particles **in 3D with high resolution.**



NAGOYA Univ. is the only one institute developing nuclear emulsion in the world.



AgBr crystal
formation
& gel production
machine

Emulsion gel coating (actually in a darkroom)



→
After drying



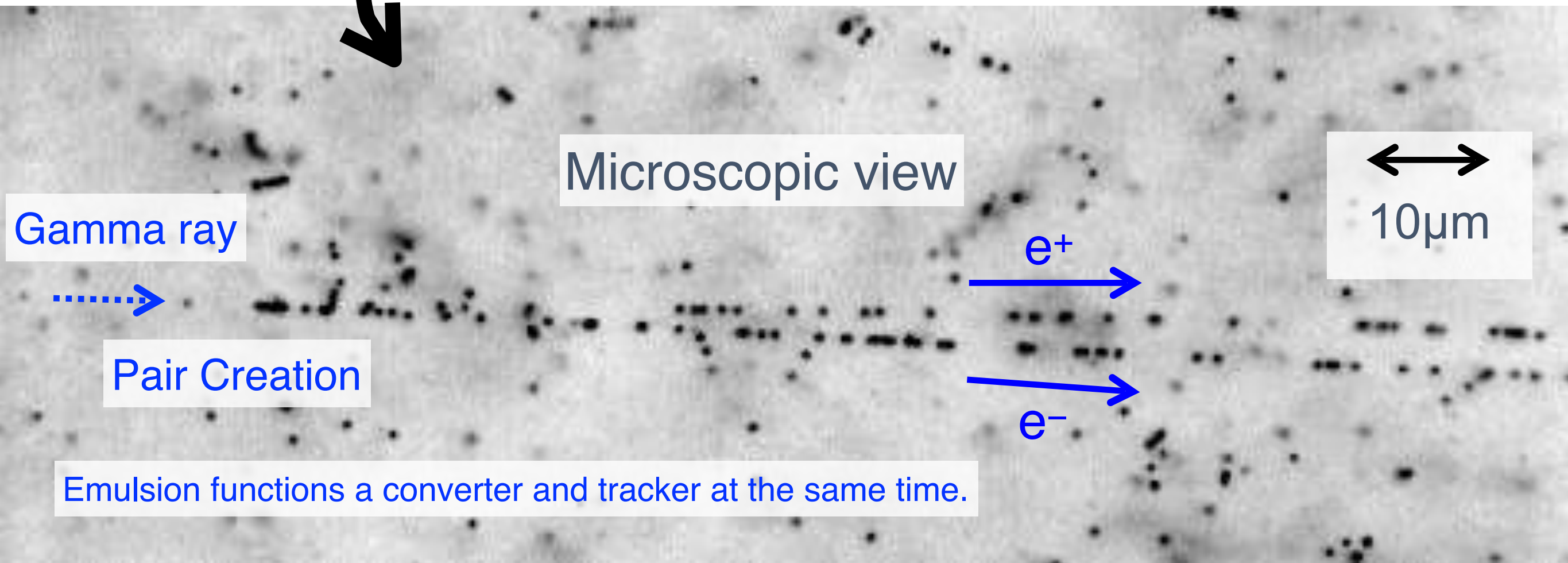
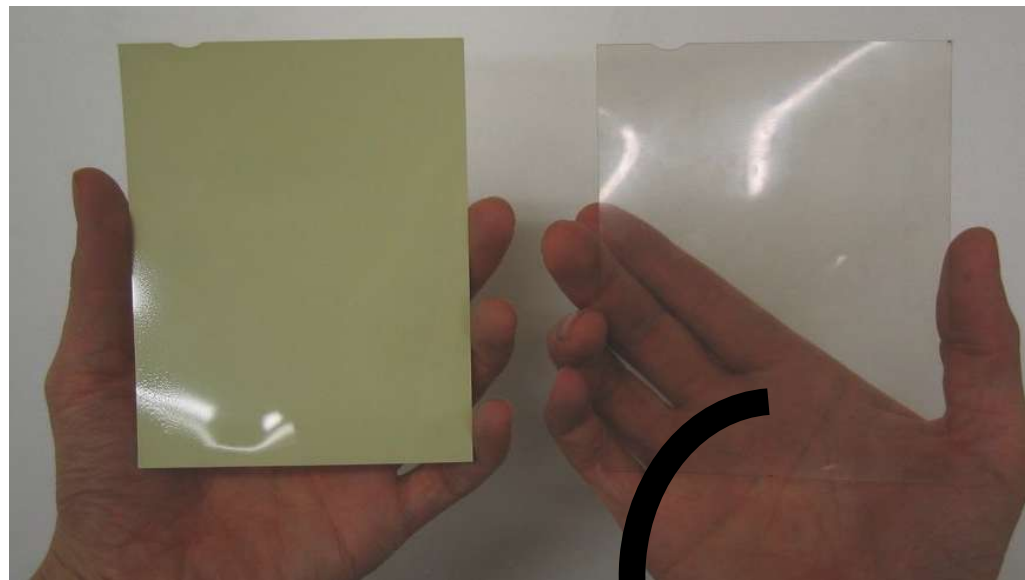
— 100 nm

electron microscopic view

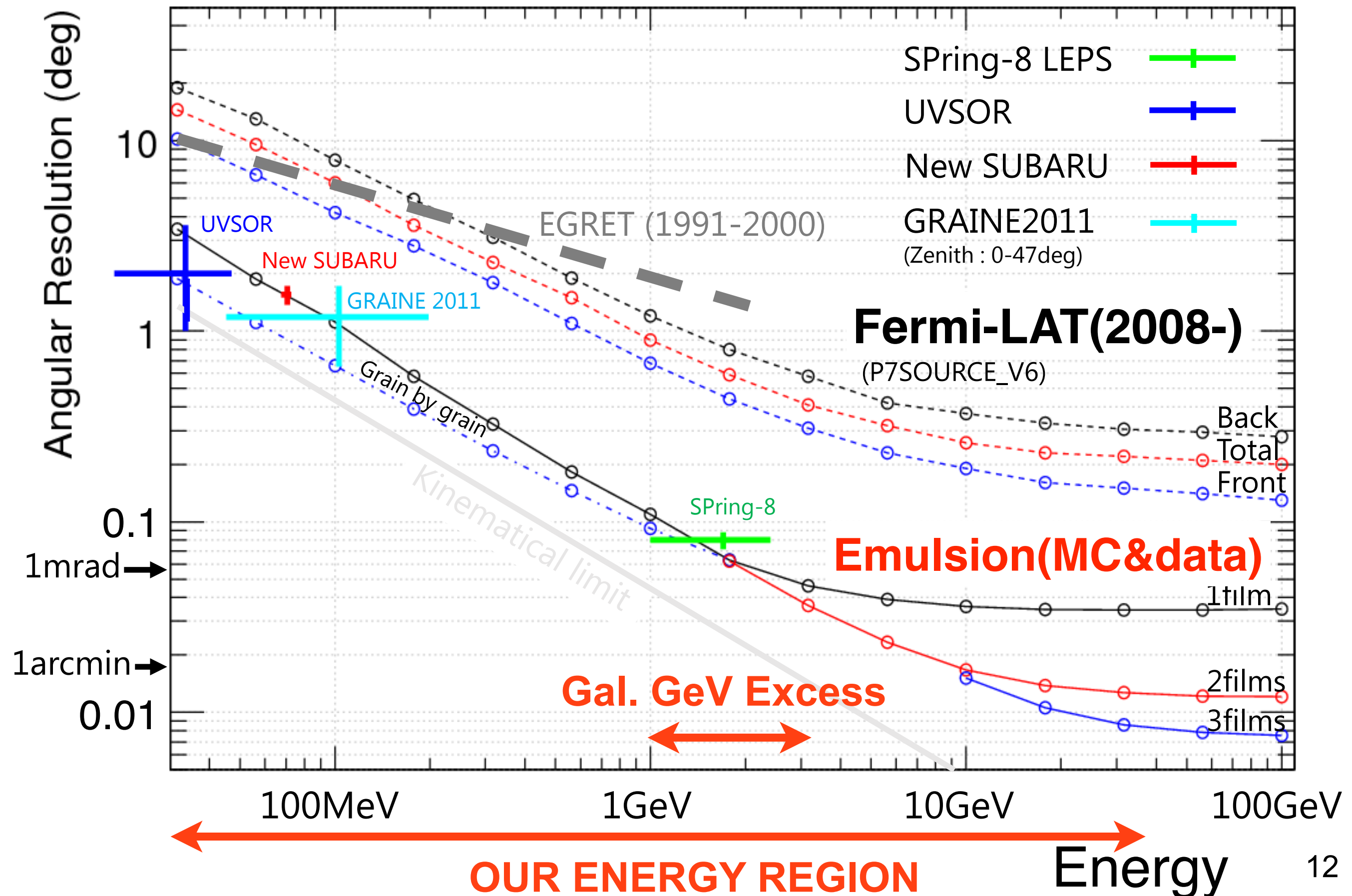
We self-produce nuclear emulsion
to meet our own research requirement.

Nuclear Emulsion

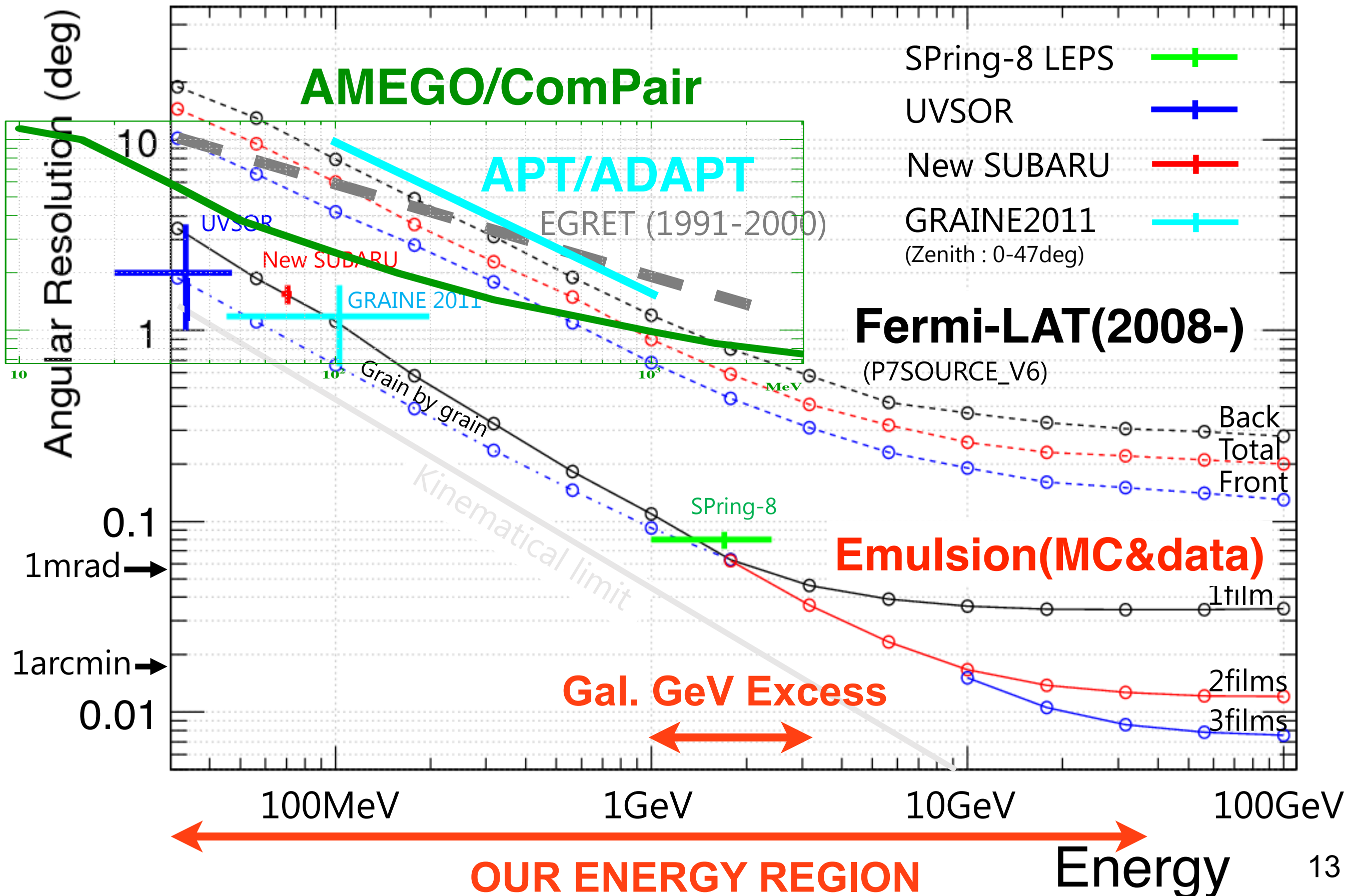
A photographic film that can record the trajectories of charged particles **in 3D with high resolution.**



Angular Resolution for Gamma Ray

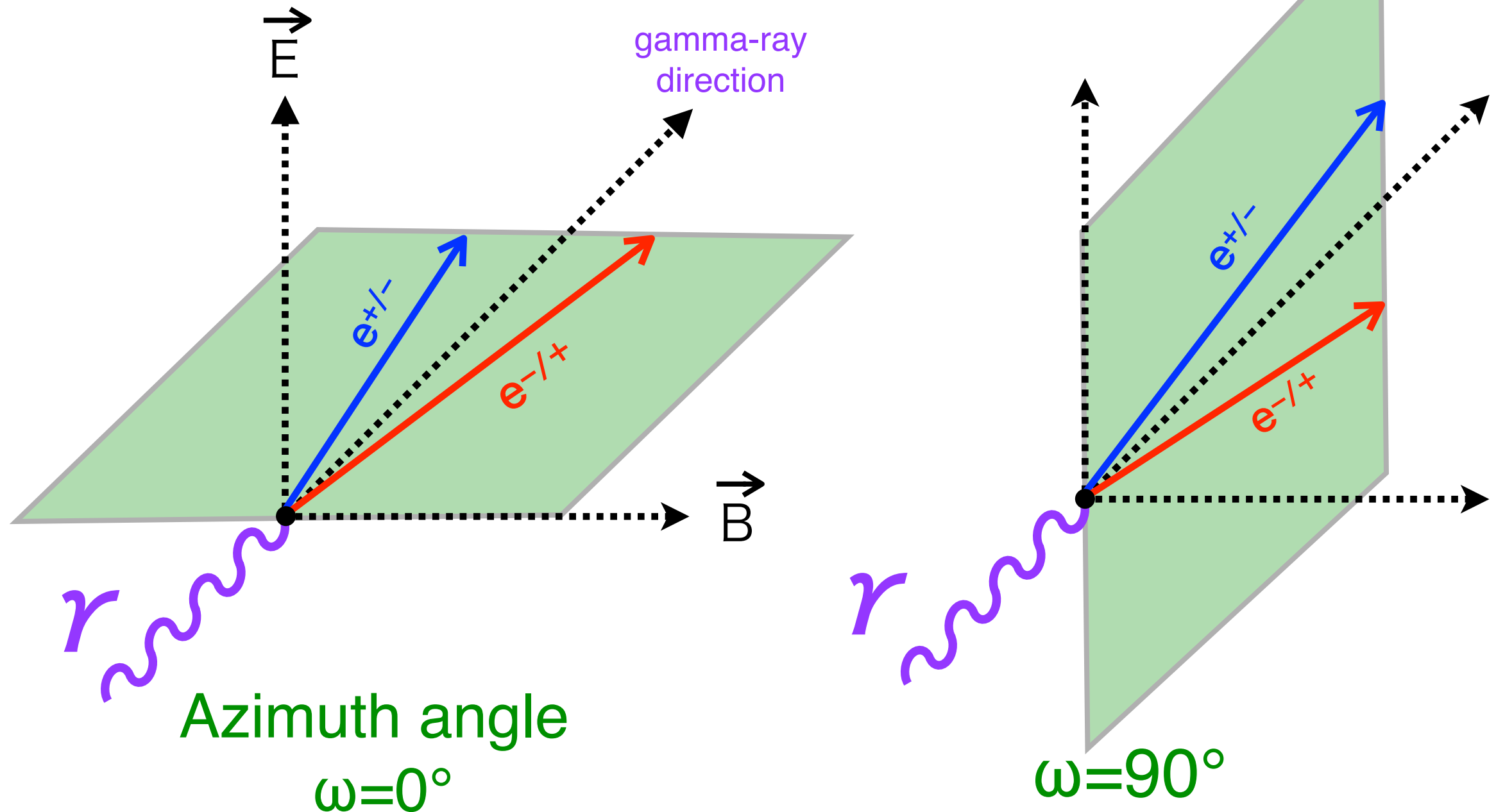


Comparison w/ Post-Fermi (AMEGO/APT)



Measurement of gamma-ray polarization in the pair production mode

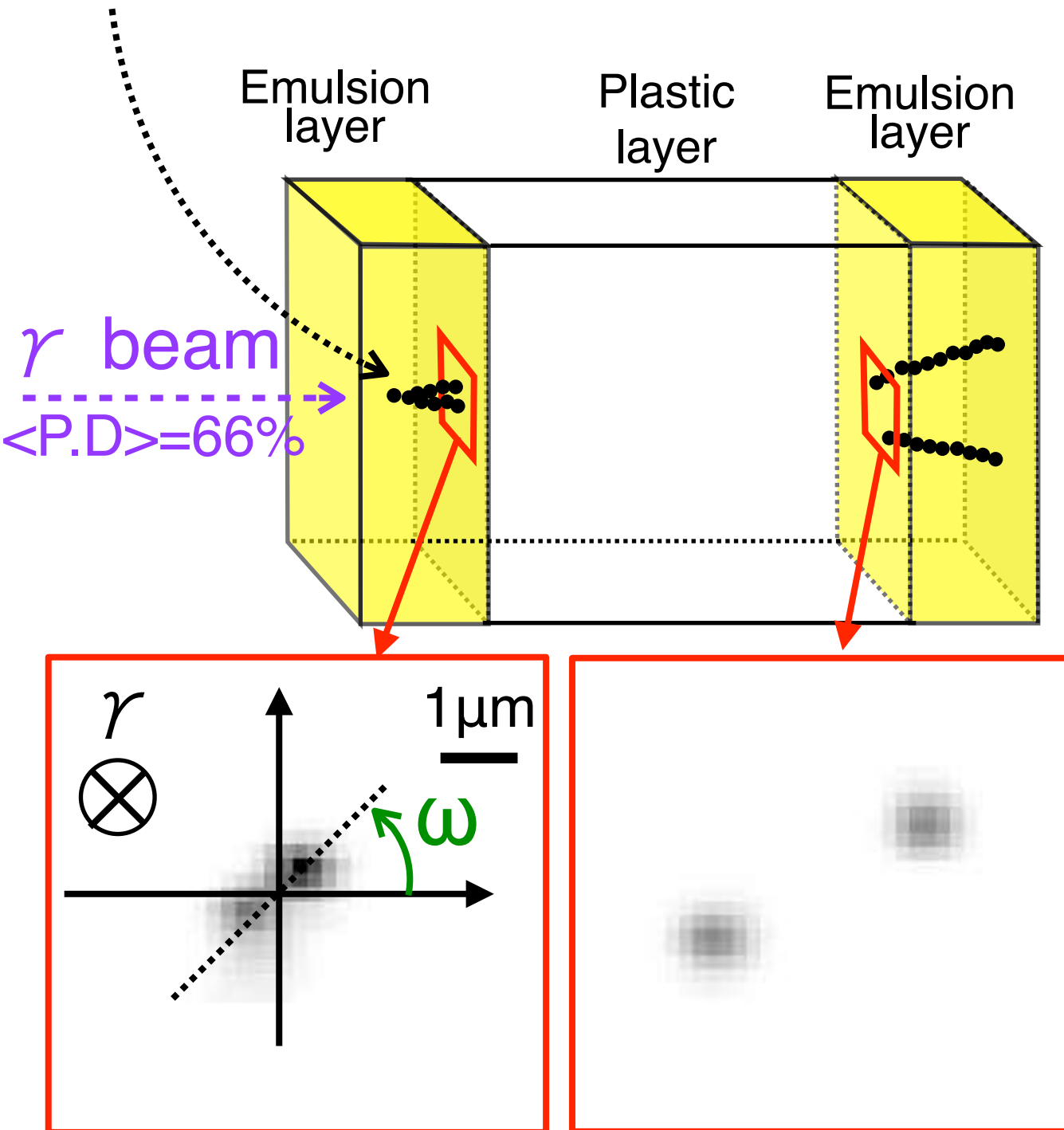
→ Detect a slight bias in the azimuthal angle distribution of the accumulated events



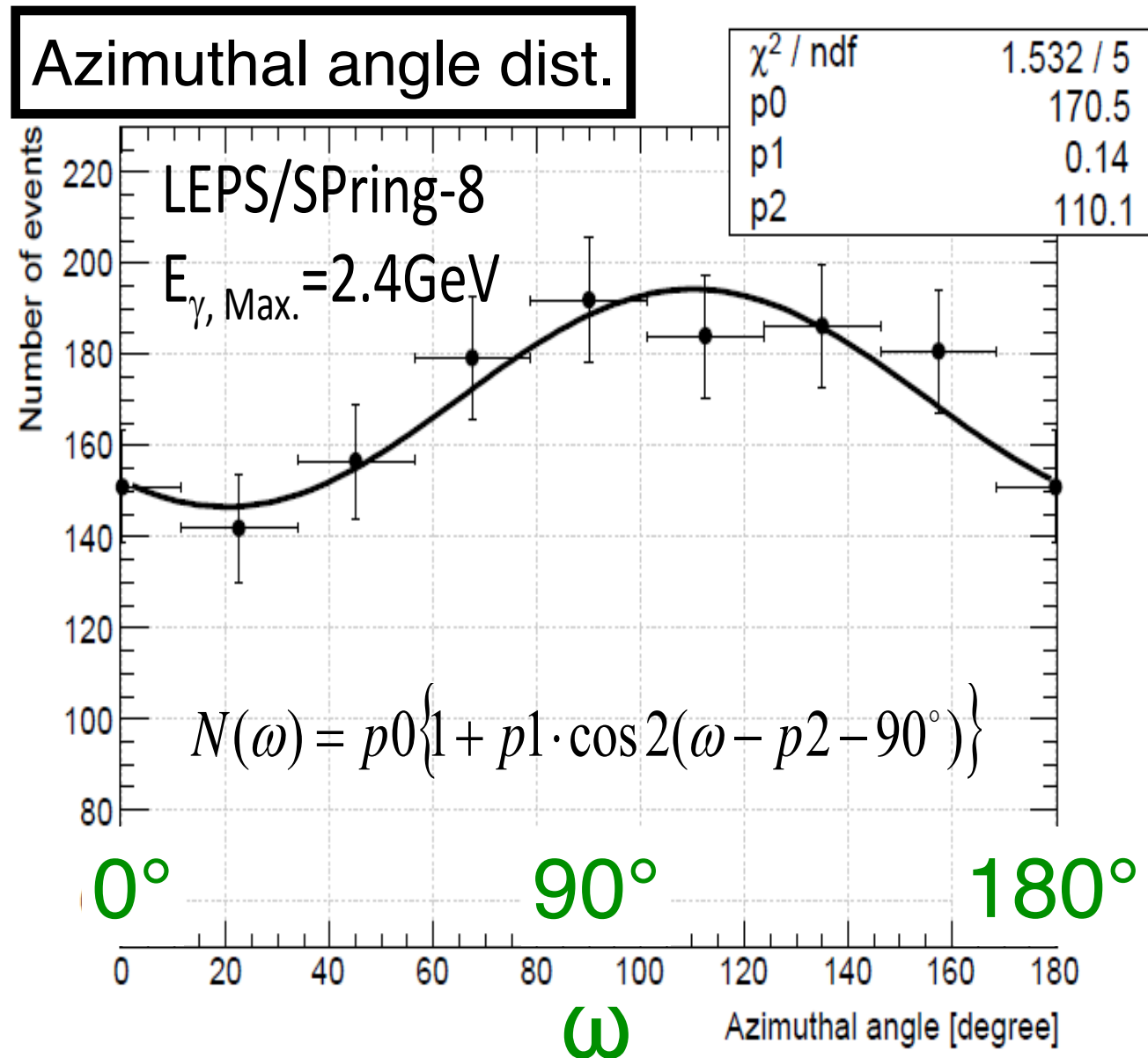
Measuring the azimuthal direction is extremely challenging due to multiple Coulomb scattering in detector

Demonstration of Polarimetry w/ Acc. Beam

Emulsion functions a converter and tracker at the same time.



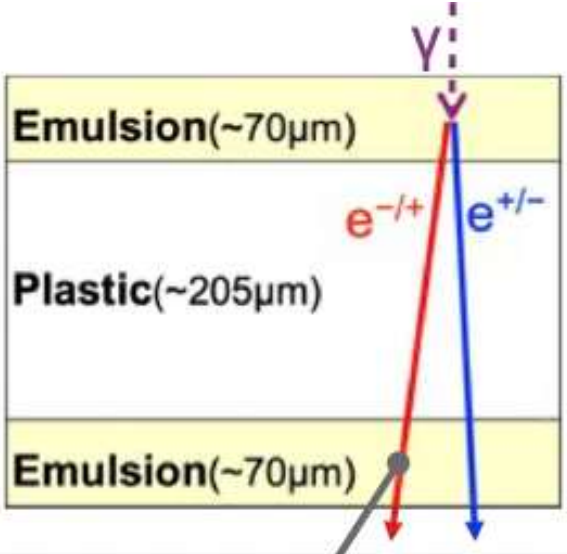
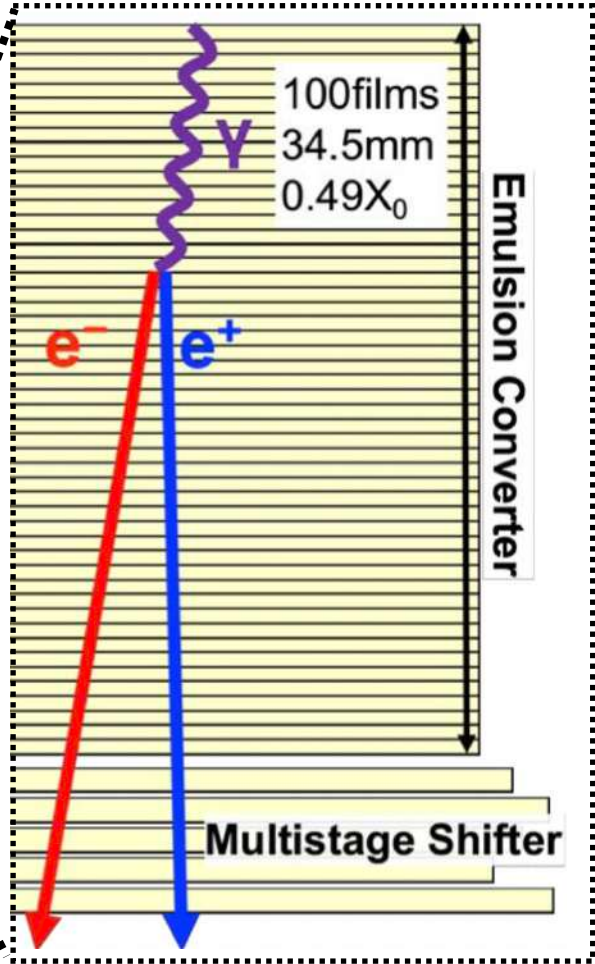
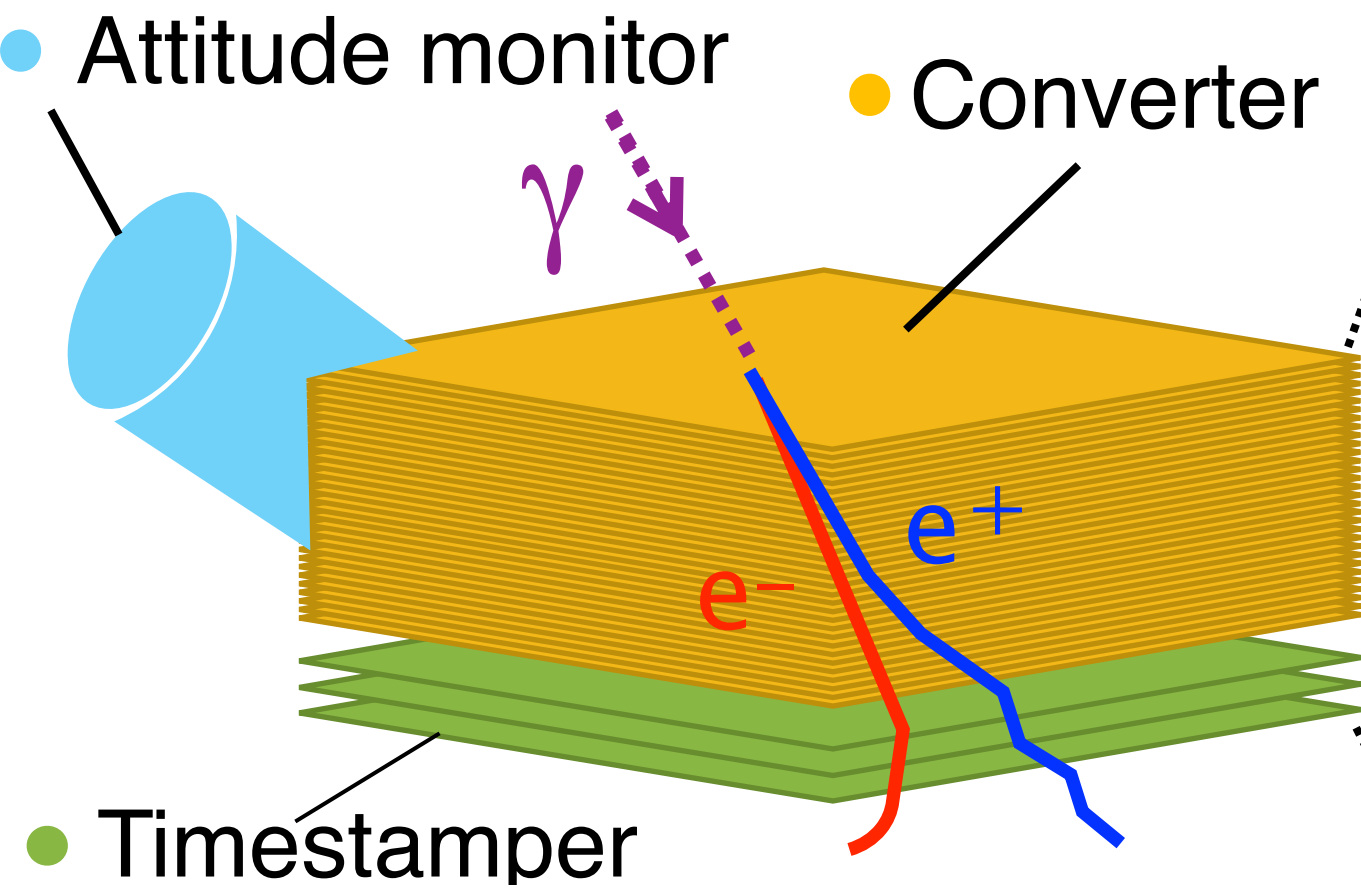
Micrographs(0.13 μm /pixel)



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

Modulation Factor = $0.21^{+0.11}_{-0.09}$
 ($P1=0.14$ at $\langle \text{P.D.} \rangle = 66\%$)

Balloon-borne Emulsion Gamma-ray Telescope



Repeated Balloon Flight
10m², ~2 tons

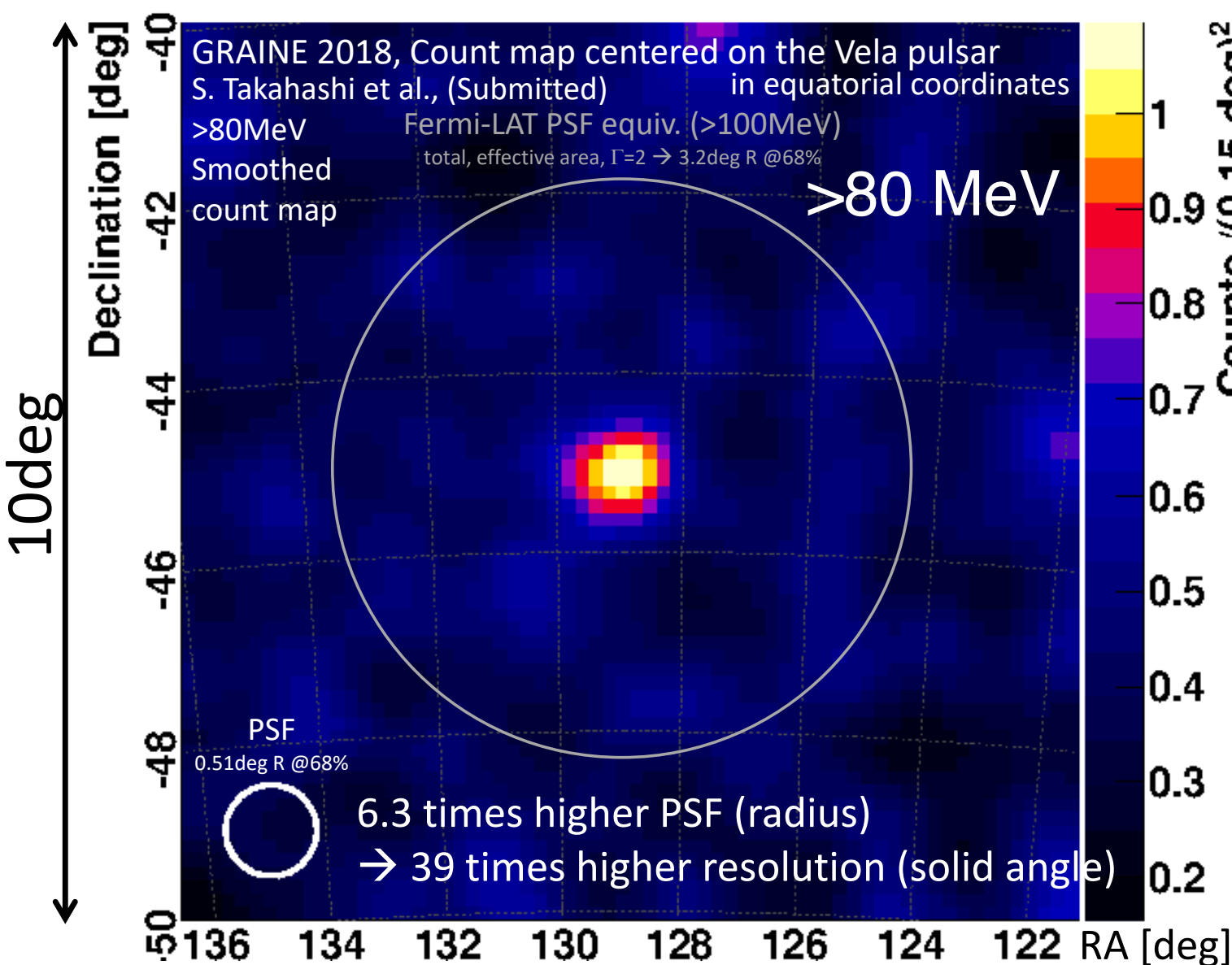
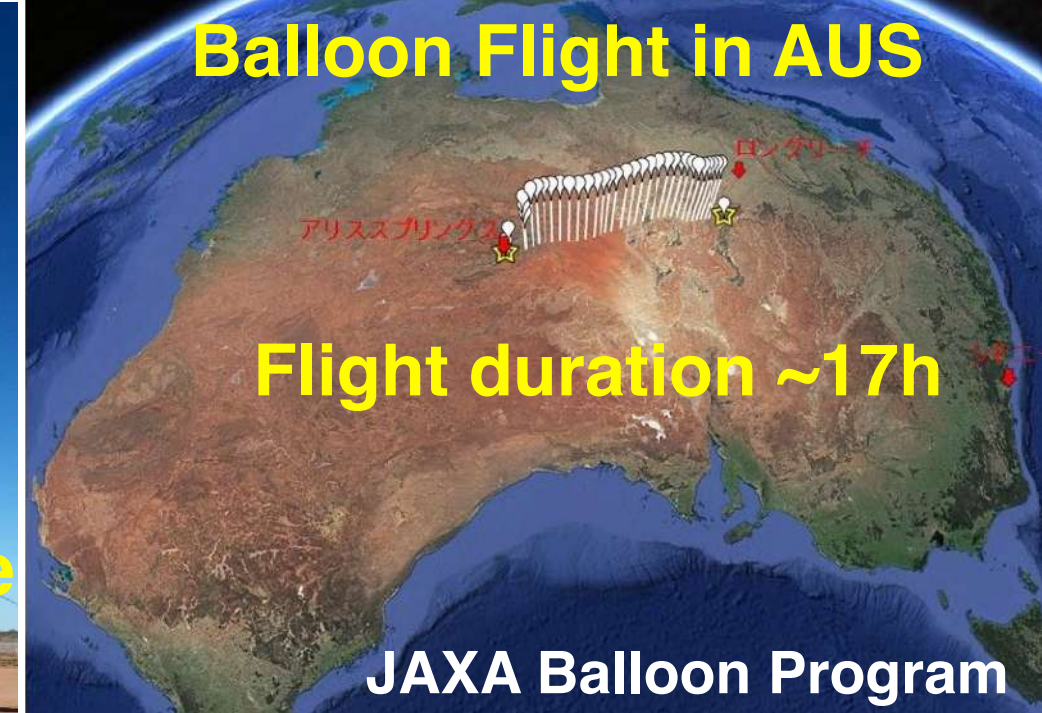
High-angular resolution
Polarization sensitive
Large aperture area

	Fermi LAT		GRAINE
Angular Res. @ 100MeV	6.0 °	x 6 →	1.0 °
@ 1GeV	0.90 °	x 9 →	0.1 °
Polarization Sentivity	—		Yes
Effective Area @ 100MeV	0.25 m²	x 8 →	2.1 m² *
@ 1GeV	0.88 m²	x 3 →	2.8 m² *

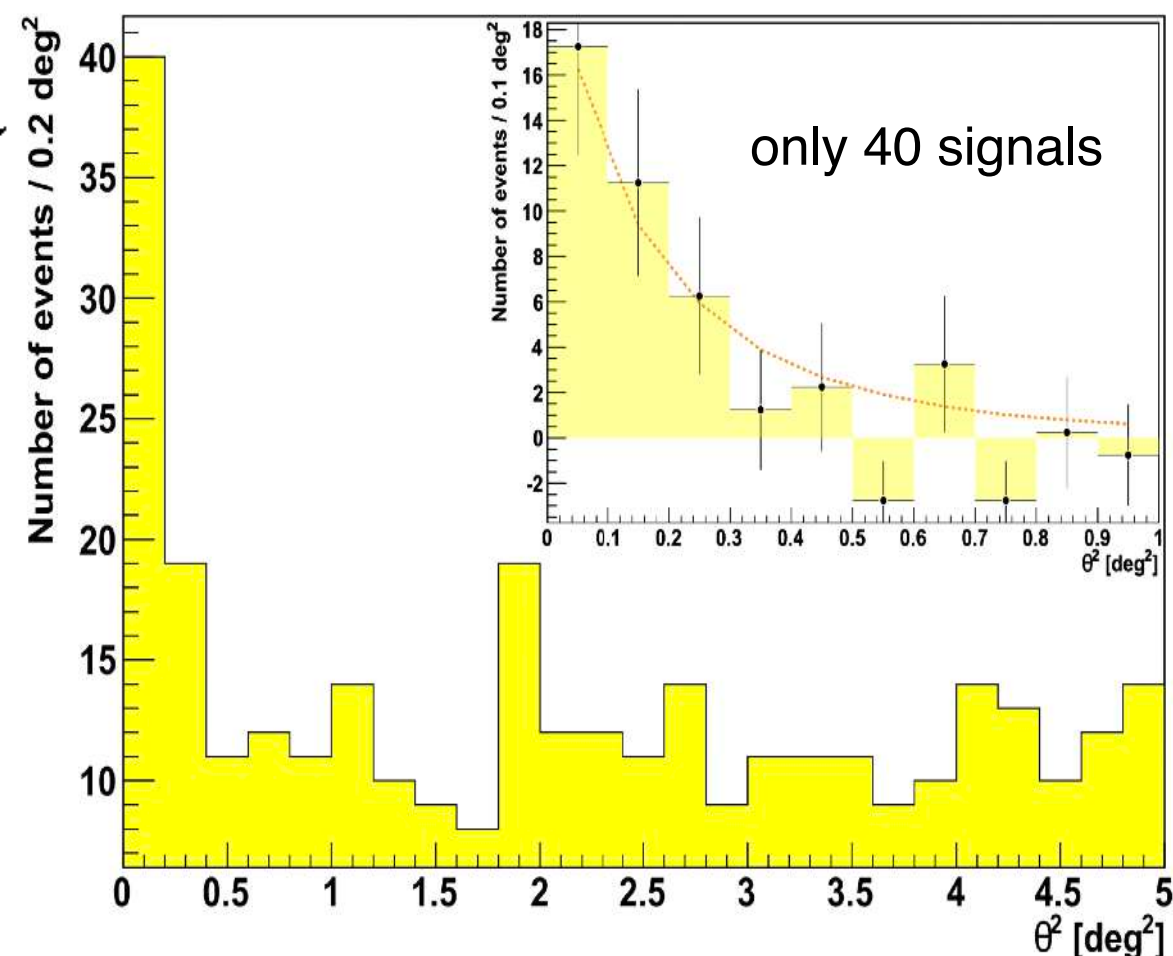
* 10m²×ε_{trans}×ε_{conv}×ε_{det}

GRAINE2018: First Imaging of Vela pulsar

S.Takahashi et al.
ApJ. 960 (2023) 47



Radial profile (θ^2 distribution)



✓ Detection of Vela pulsar (>80MeV)

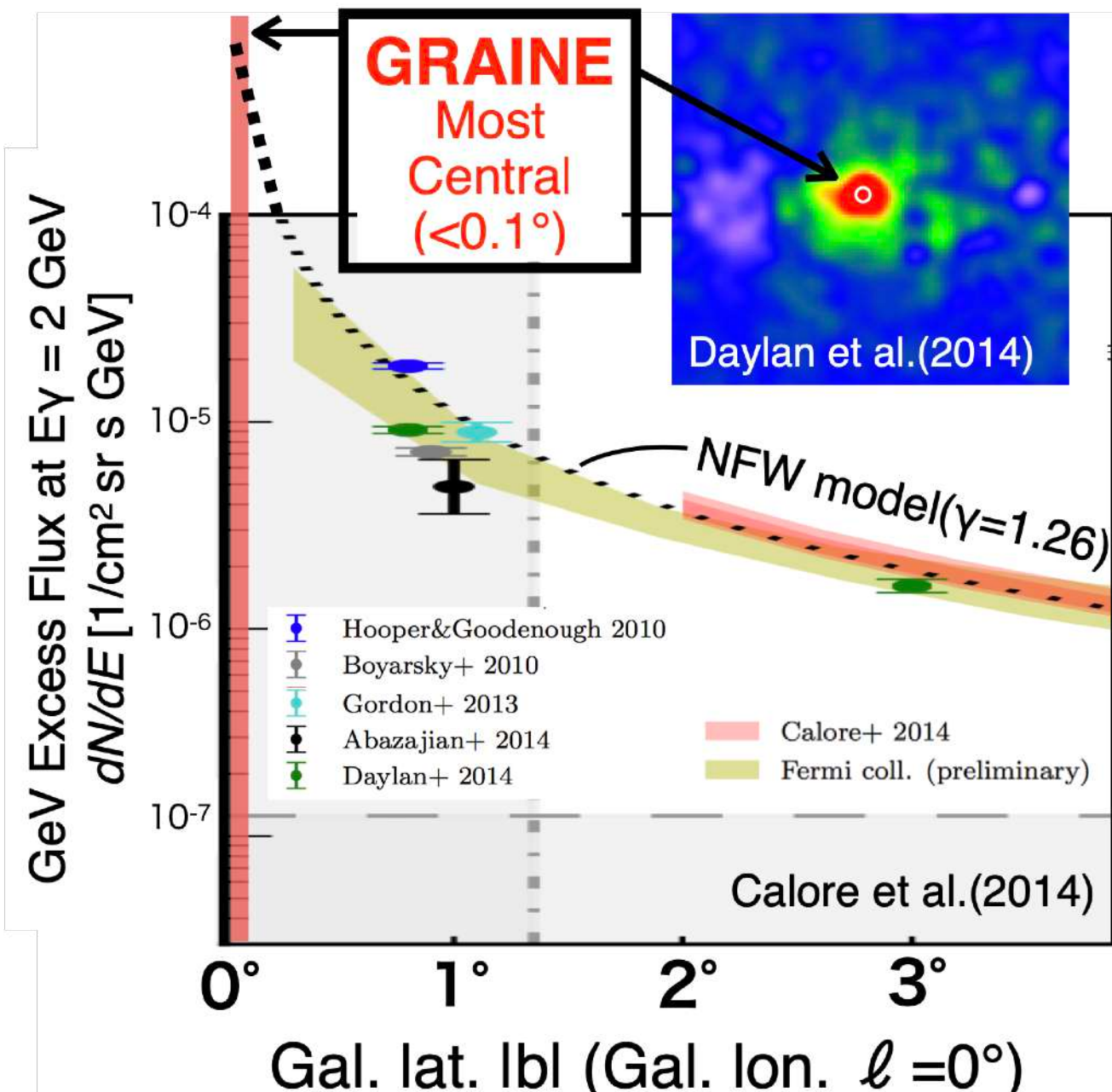
✓ World's Highest imaging
0.4deg 68%radius (>80MeV) 17

Initial Scientific Targets

Bright and southern hemisphere observable sources, and attractive science

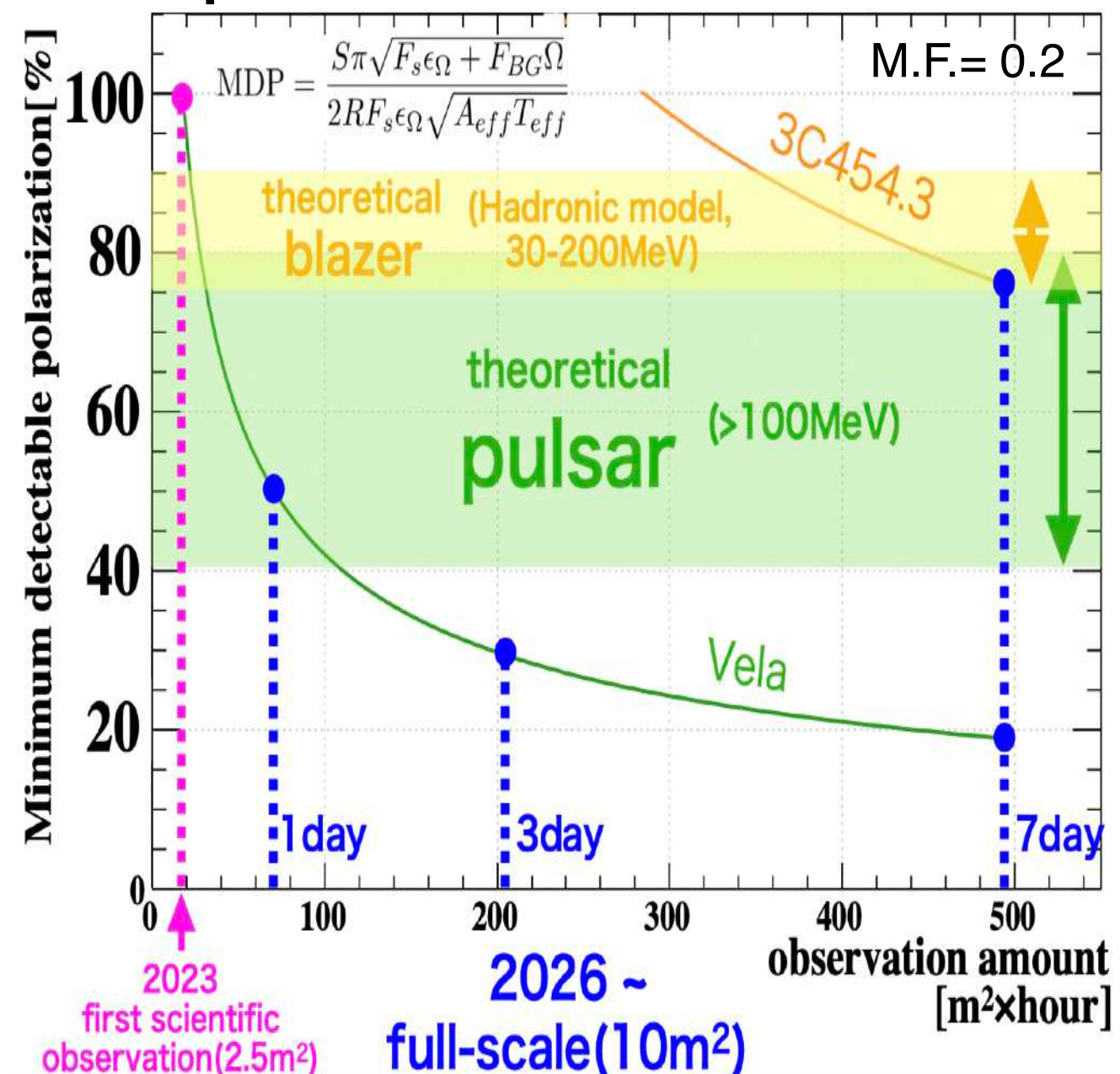
Galactic Center

Precise meas. of excess components
w/ the world's highest angular res. (0.1°)



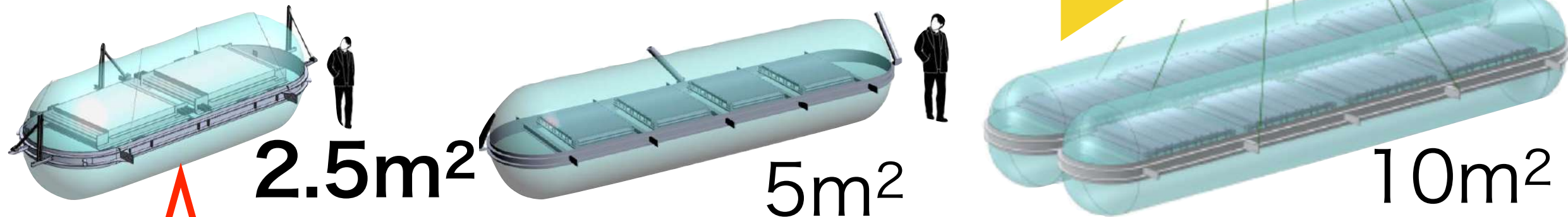
Vela pulsar

The first significant pioneering obs.
of polarization in the 0.1-GeV band.



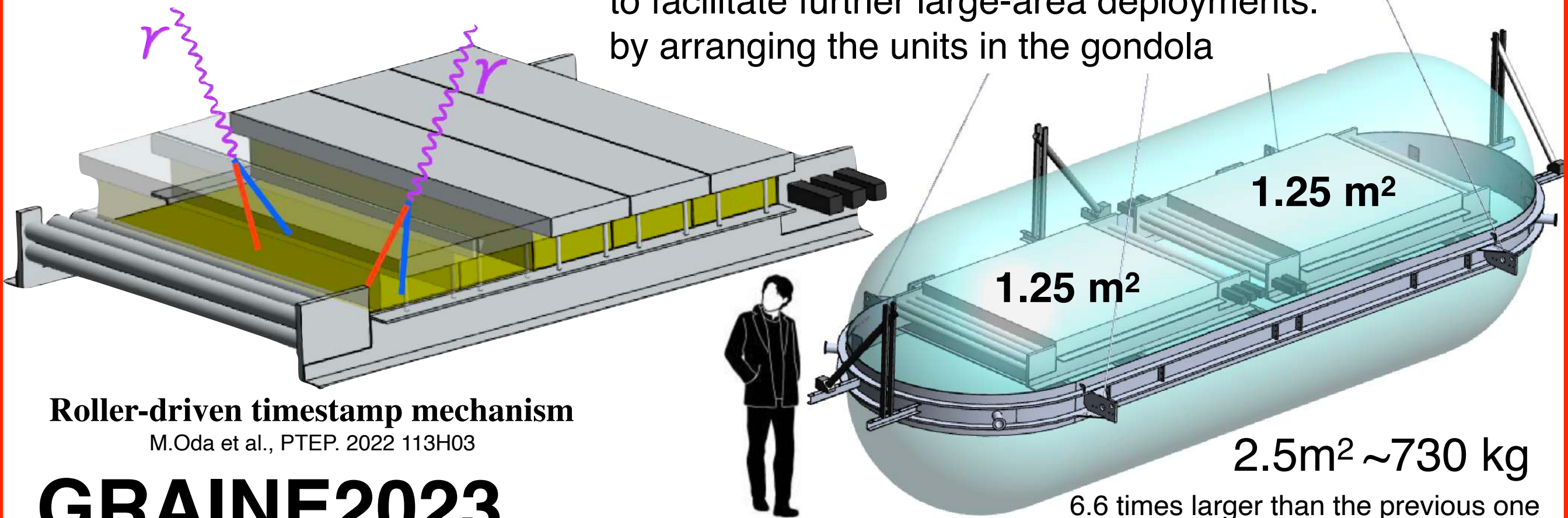
Towards Scientific Observation

Larger aperture area & repeated balloon flights



Unitized emulsion telescope (aperture: 1.25 m^2)

to facilitate further large-area deployments.
by arranging the units in the gondola



Roller-driven timestamp mechanism

M.Oda et al., PTEP. 2022 113H03

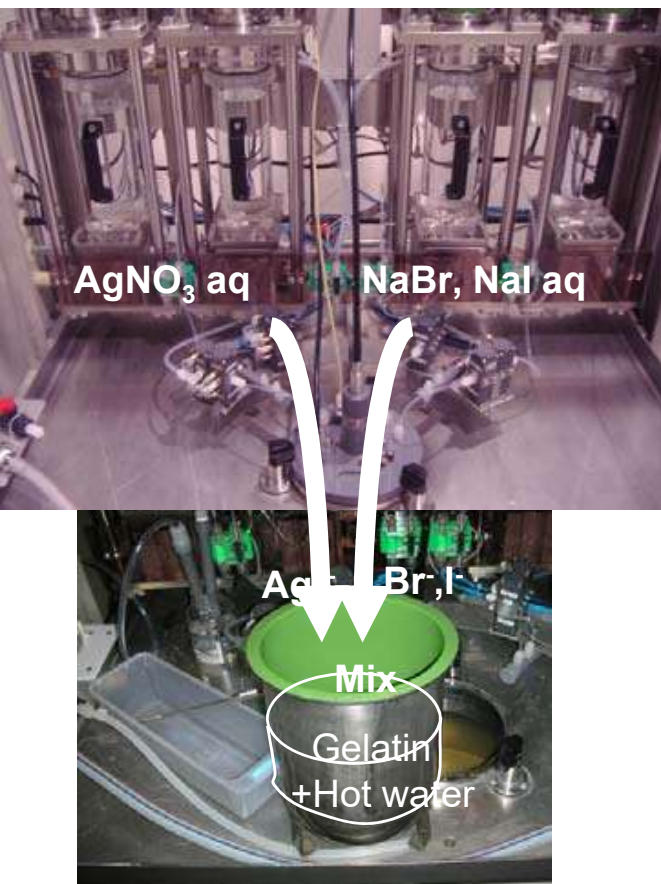
GRAINE2023

starts scientific observation with the newly developed models

Research & Development for GRAINE2023

Day time
Star Camera

Emulsion Gel/Plate
×10 Mass-Pro Facility



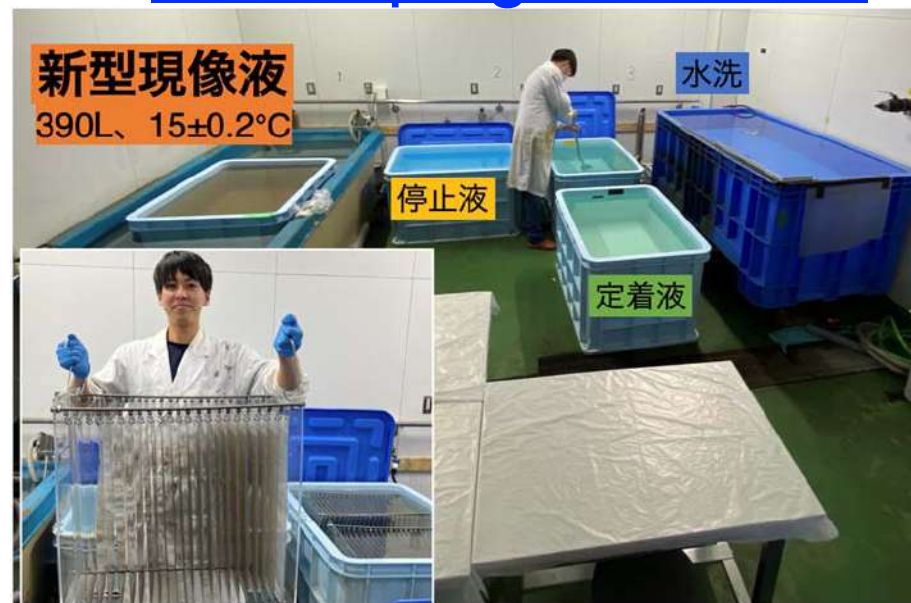
Roller Driven Time stamper



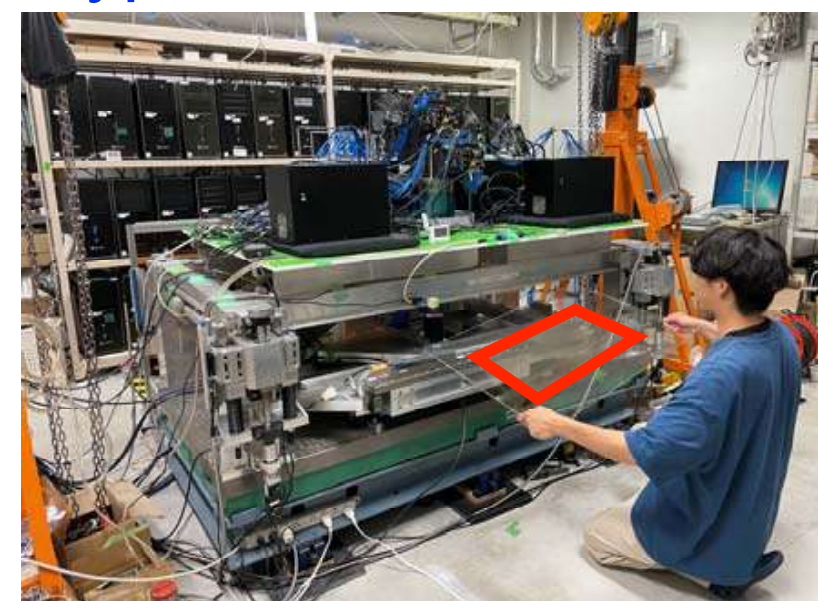
Balloon Vessel & Gondola



New Developing Chemical



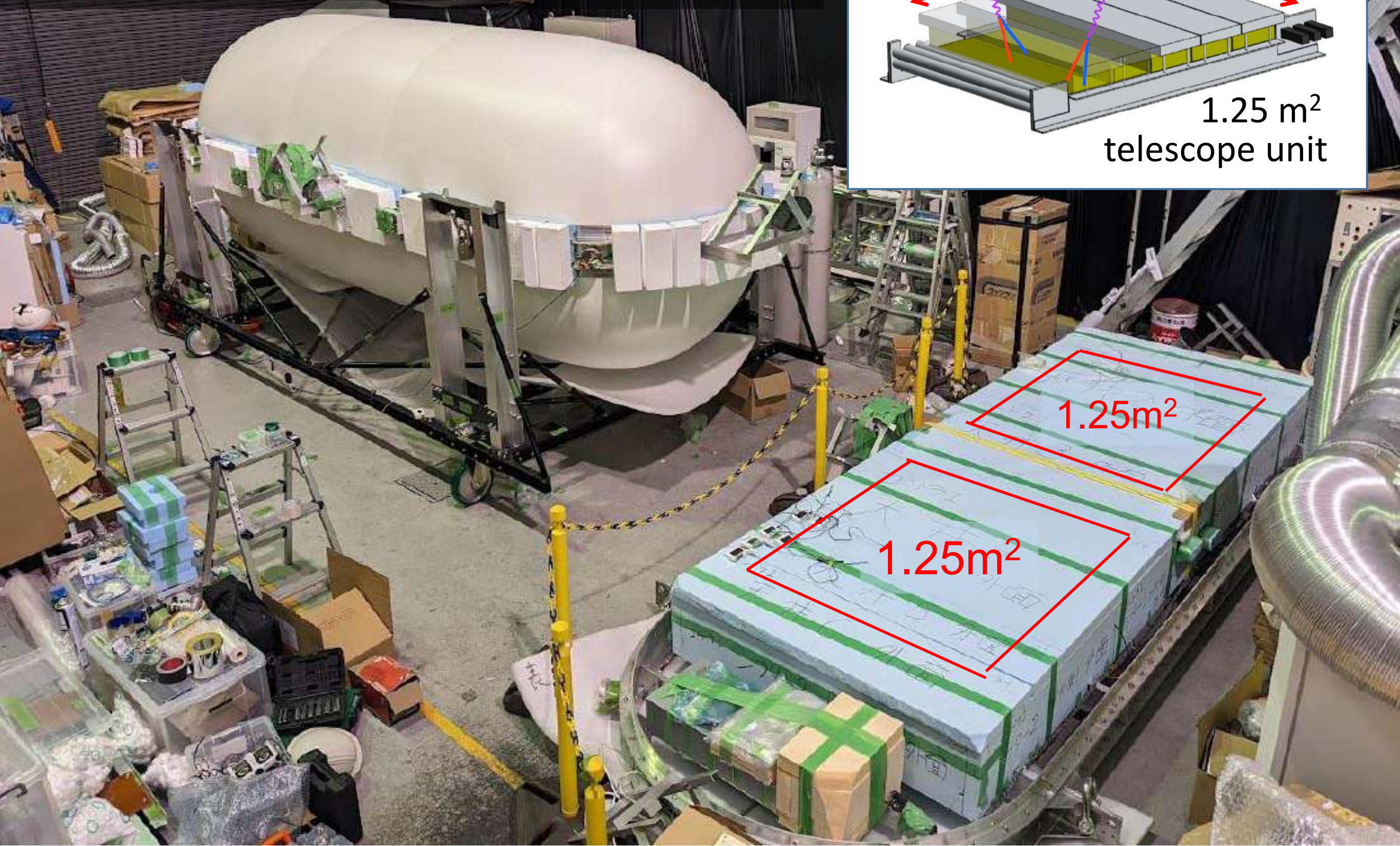
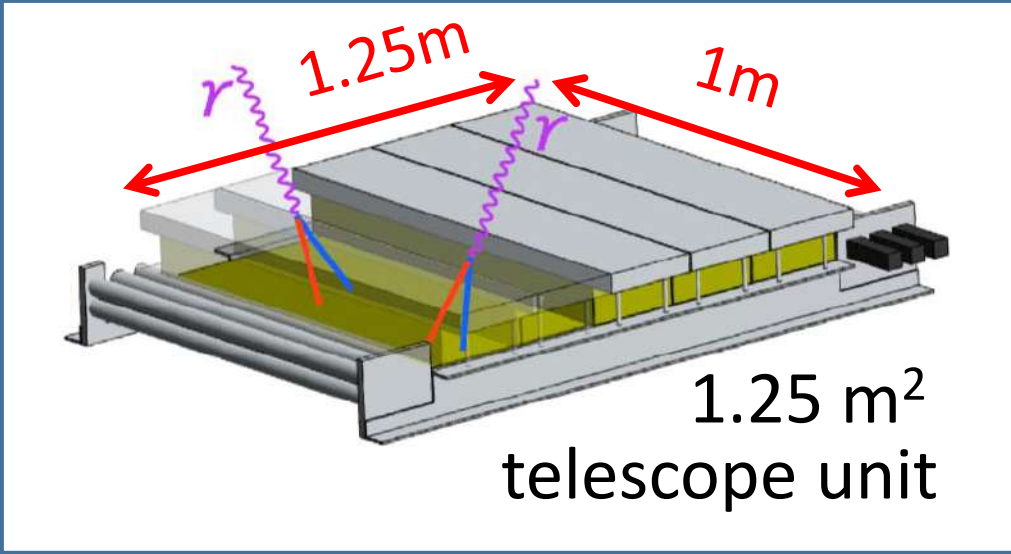
Hyper Track Selector 2



Every R&D has been led by student in his/her M&D thesis study

2 sets of 2.5m² telescope for GRAINE2023 (Dec.2022)

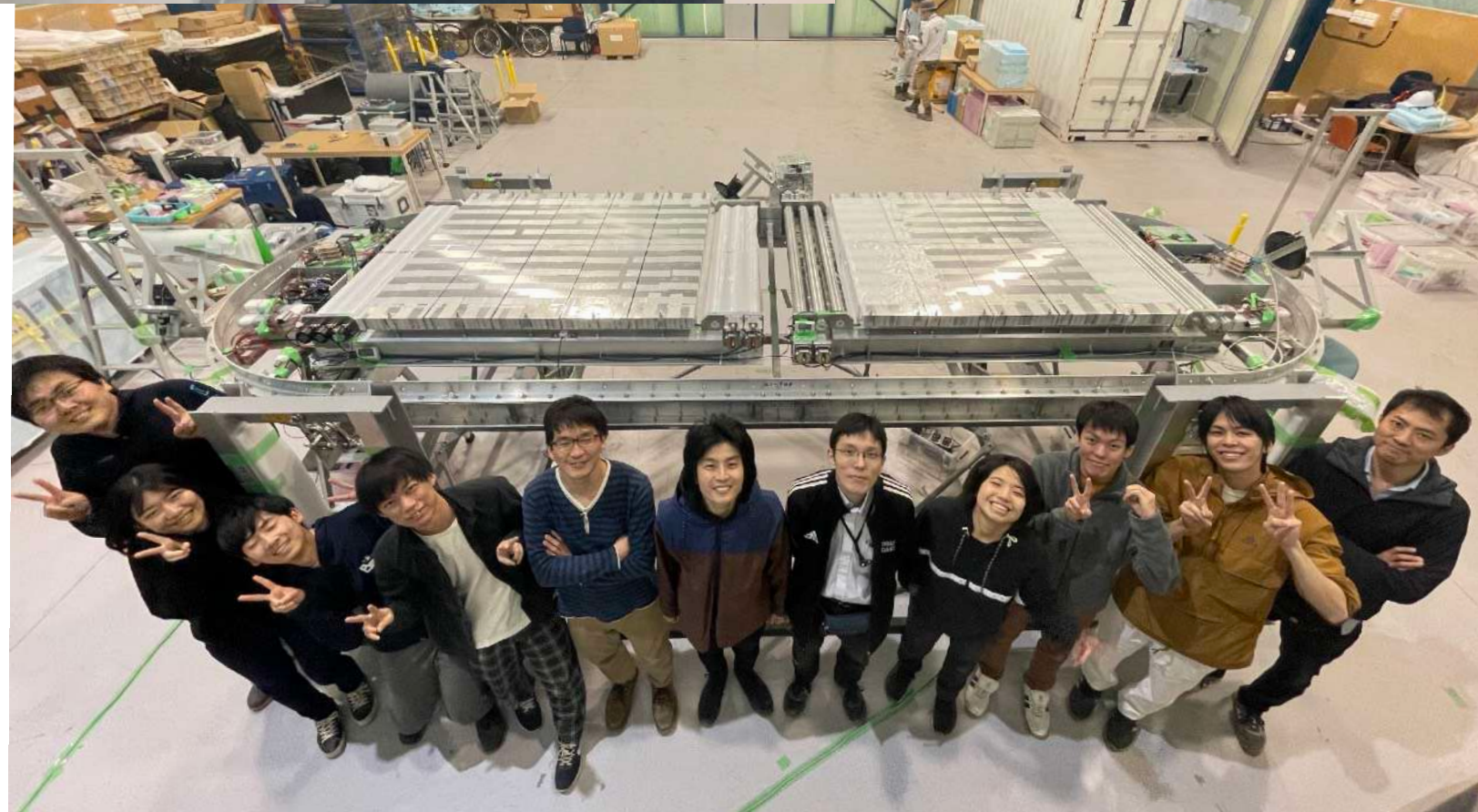
Due to price-up of Helium caused by Ukraine issue,
JAXA couldn't prepare enough gas.
Only 1 set was exported and 1 set was left at Nagoya.



Detector Assembling in Alice Springs, AUS (Feb.-, 2023)



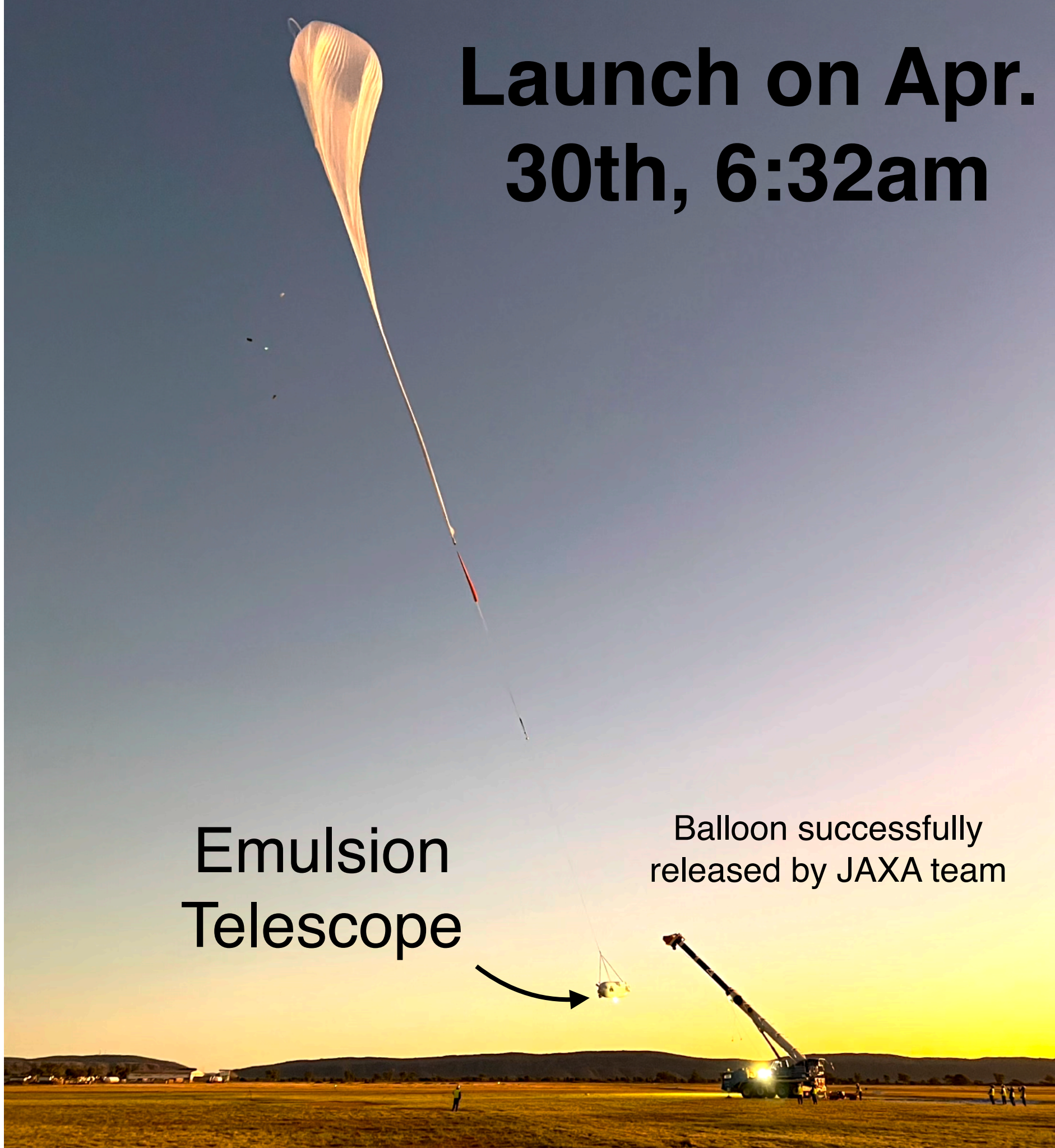
Deploying a part of Emulsion converter ,
90 films in a pack, 1 m x 25 cm, 3 cm thick, 16kg



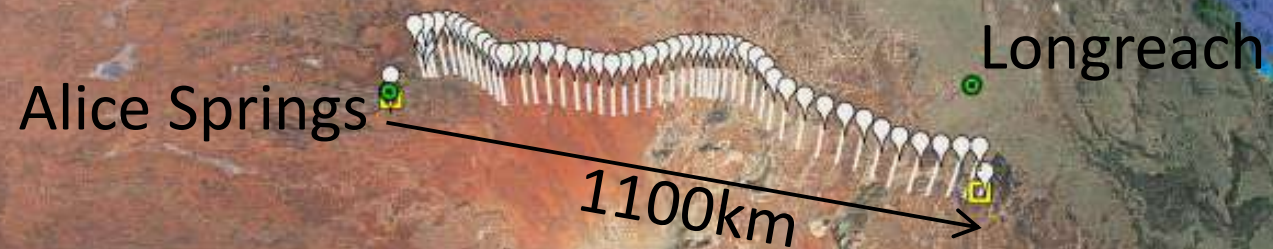
**Launch on Apr.
30th, 6:32am**

**Emulsion
Telescope**

Balloon successfully
released by JAXA team



Flight Path



27 hour flight duration in total (6:32 – 9:25 the next day)
24.3 hour level flight at 36km (8:30 – 8:47 the next day)
Telescope system termination (8:00 the next day)

Google Earth

Data SIO, NOAA, U.S. Navy, NGA, GEBCO

Image Landsat / Copernicus



1600 km

Latitude, longitude, altitude and time taken by JAXA

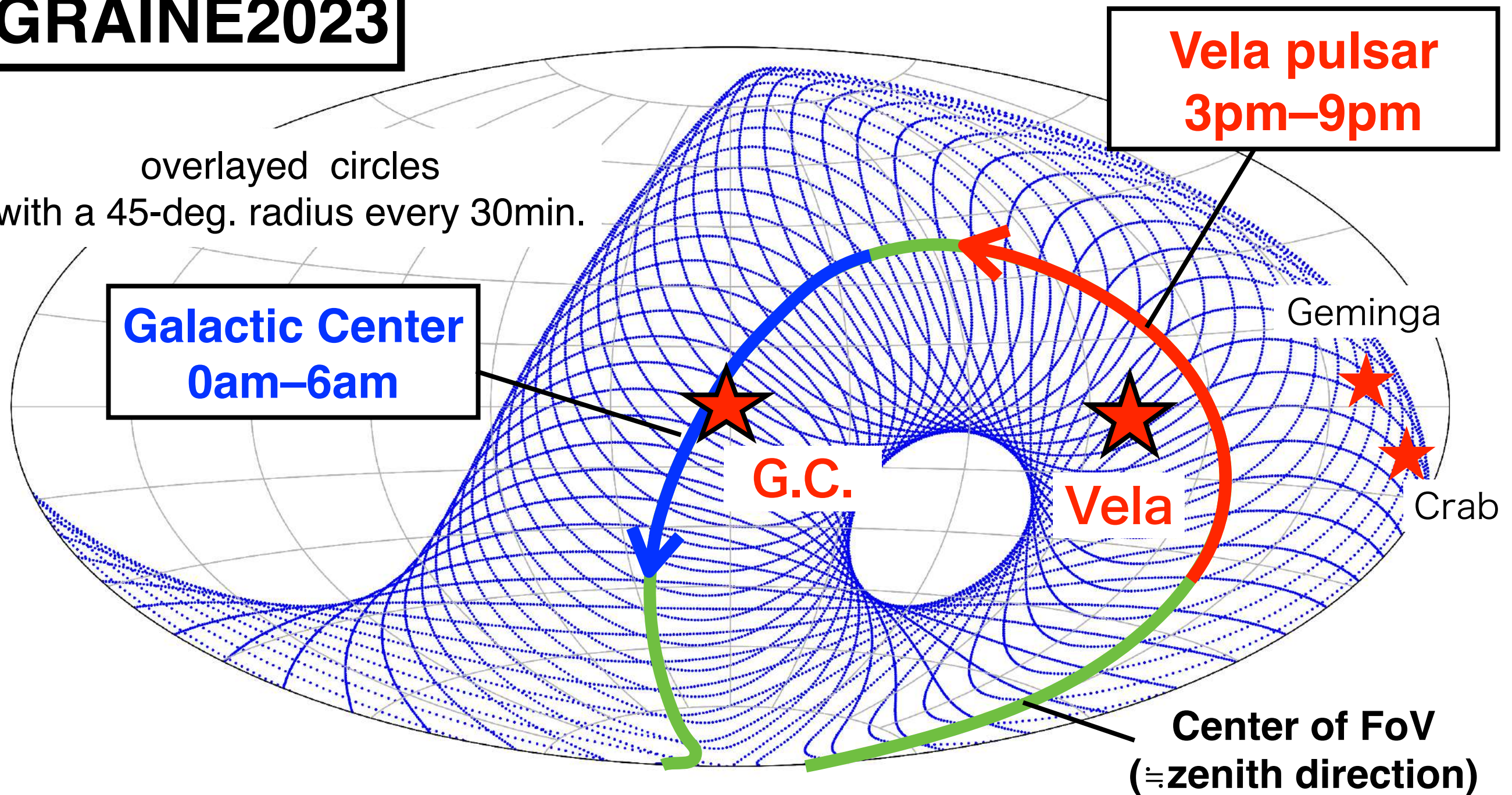
Celestial regions observed by the Emulsion Telescope (FoV $\pm 45^\circ$)

GRAINE2023

overlaid circles
with a 45-deg. radius every 30min.

**Galactic Center
0am–6am**

**Vela pulsar
3pm–9pm**



successfully observed full coverage of the Vela pulsar and G.C.

Recovery on May. 1st 3:30pm

took a helicopter
to search for the payload.



We collected everything
by truck the day after
this.
Three days later, the film
was shipped to Japan via
refrigerated transport.

Emulsion Data Acquisition by Scanning System Converting Analog Tracks into Digital Data

Hyper Track Selector 2 (2023-)

NEW
system

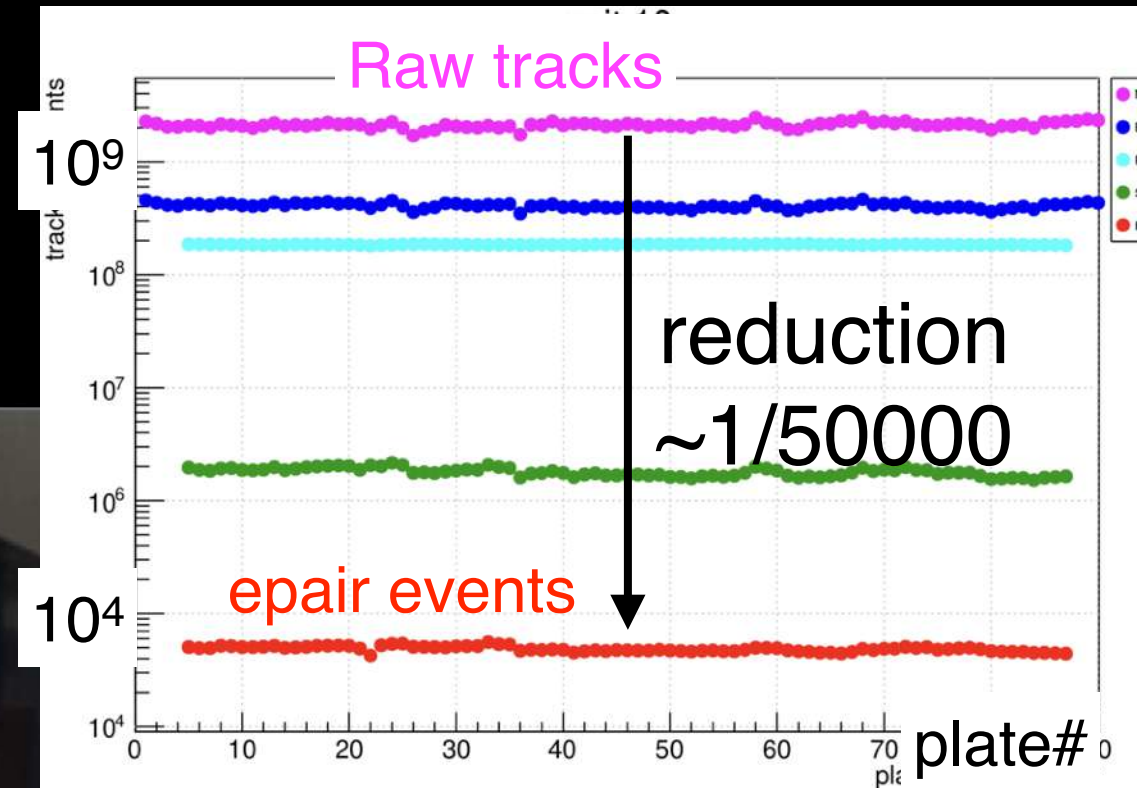
50 cm x 25 cm
1800 plates



Event Selection Analysis

$\sim 4 \times 10^4$ events in each plate

→ Over 7×10^7 events are detected.



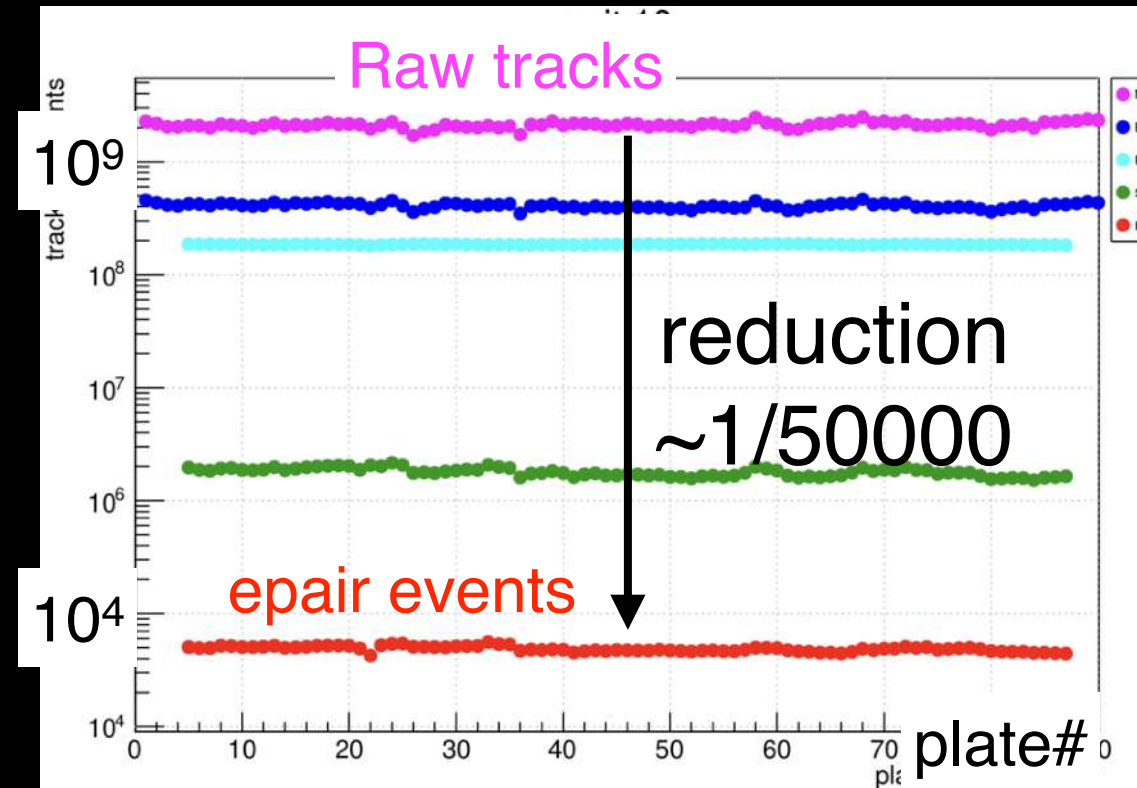
25 cm

50 cm

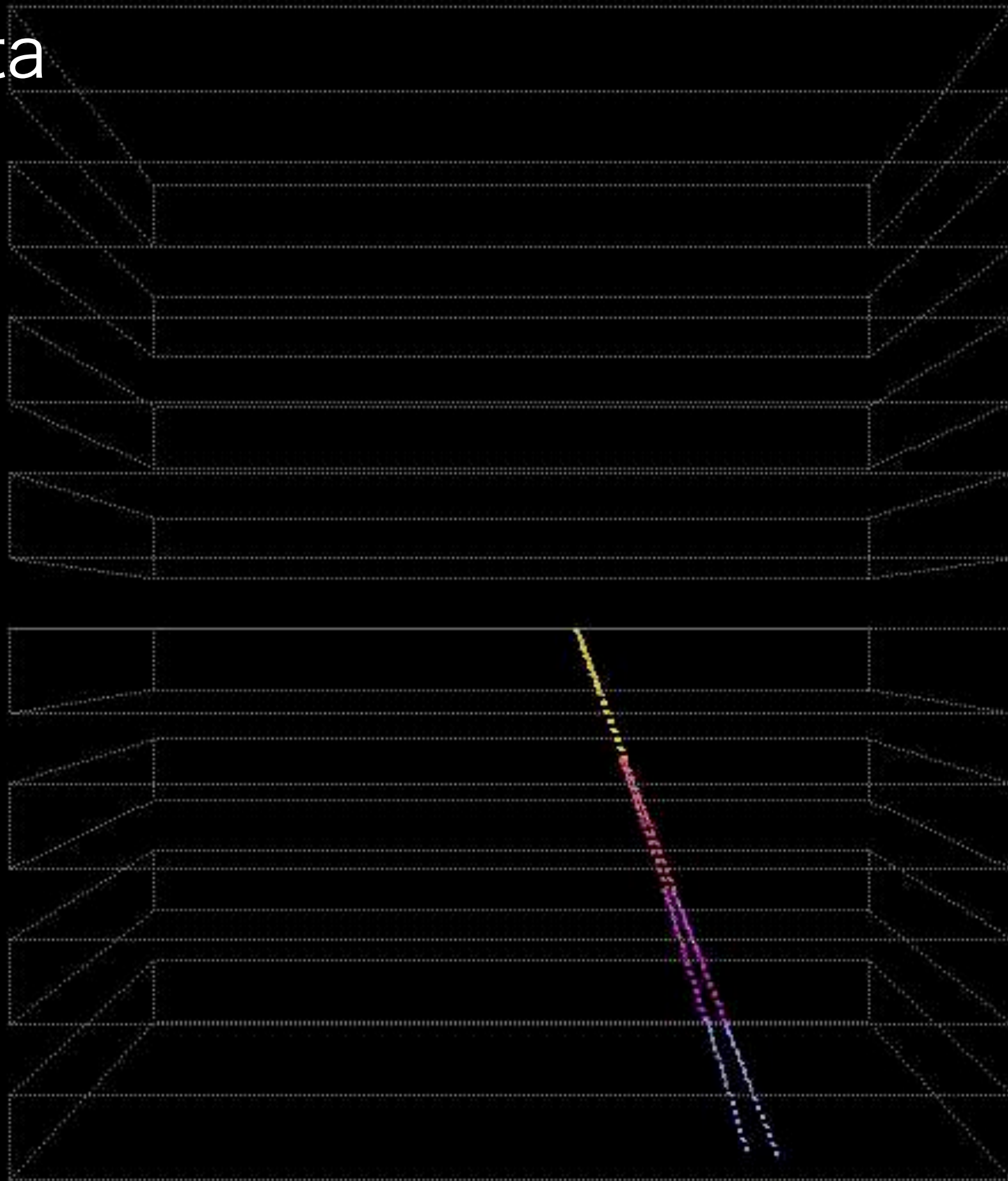
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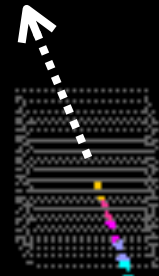


Flight data



Full reconstruction in the converter (90 plates)

Flight data



Gamma-ray Direction

Track 1

Momentum:

46 MeV/c (Recon.)

Track 2

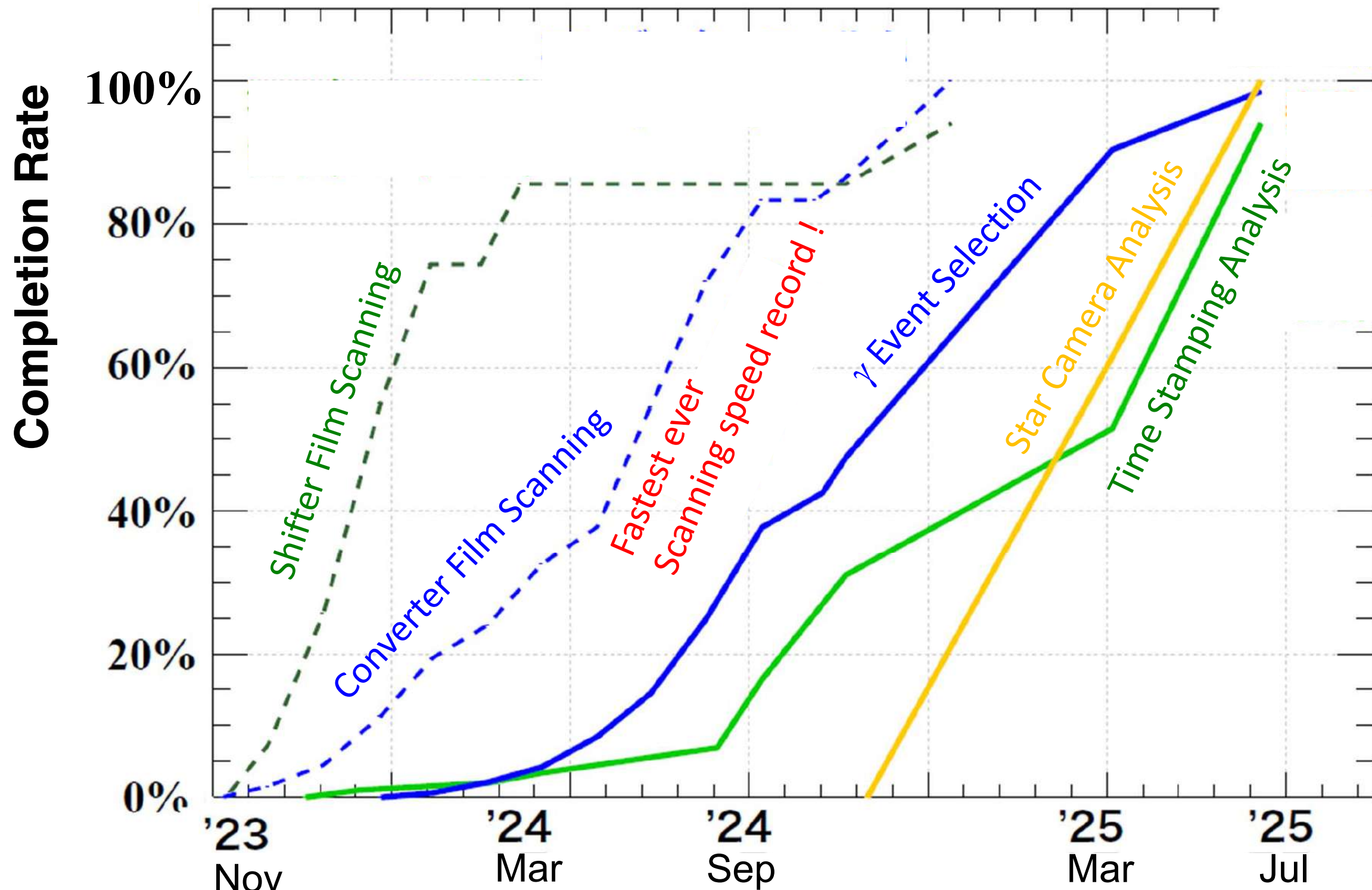
Momentum:

129 MeV/c (Recon.)

Gamma-ray Energy:
176 MeV (Recon.)

Progress of GRAINE2023 data taking and analysis

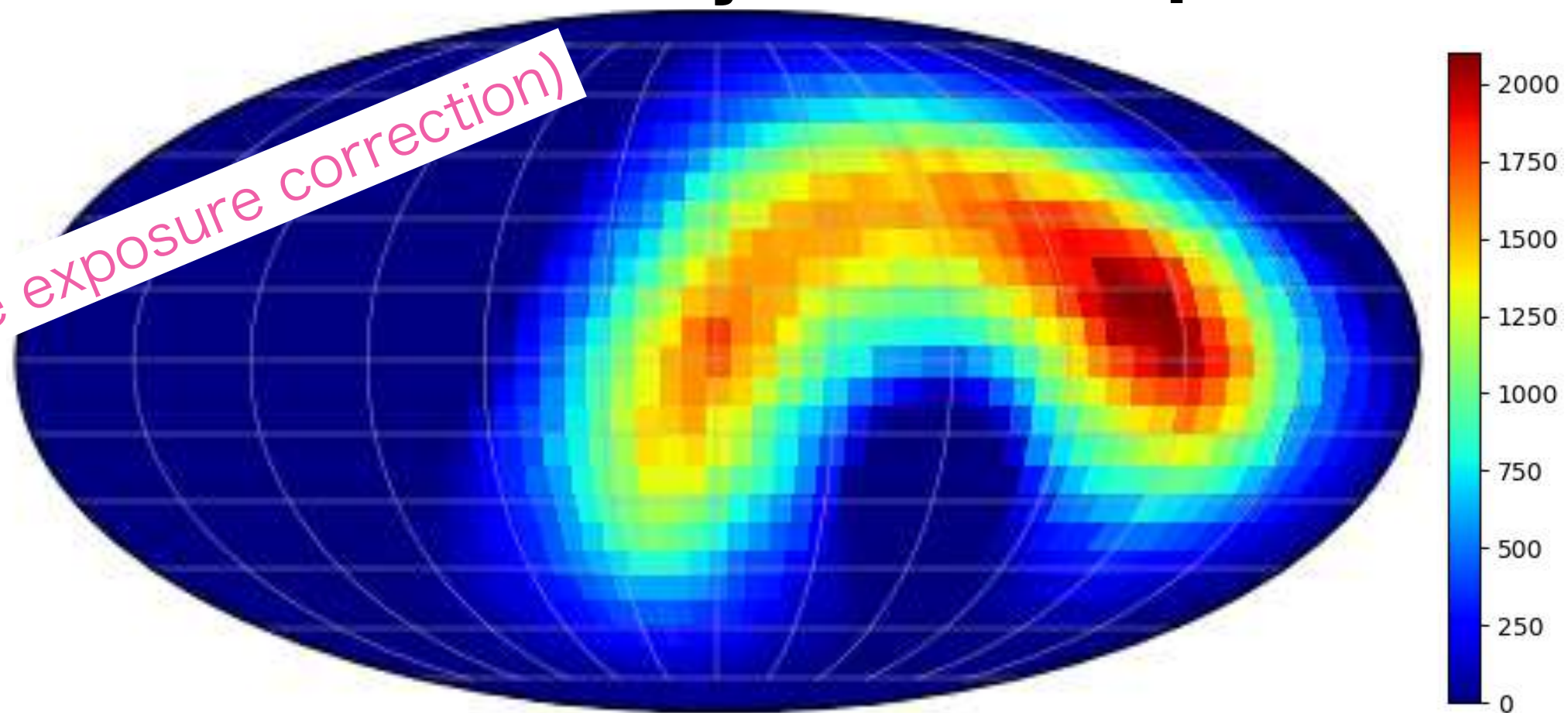
Converter Film : $0.125\text{m}^2 \times 1800 = 225\text{m}^2$
Shifter Film : $0.158\text{m}^2 \times 160 = 25\text{m}^2$ } 250m² Massive Volume Scan



Data processing for gamma-ray pointing has been completed.

Gamma-ray count map

(before the exposure correction)



GRAINE2023

overlaid circles
with a 45-deg. radius every 30min.

**Galactic Center
0am–6am**

**Vela pulsar
15pm–21pm**

Geminga

Crab

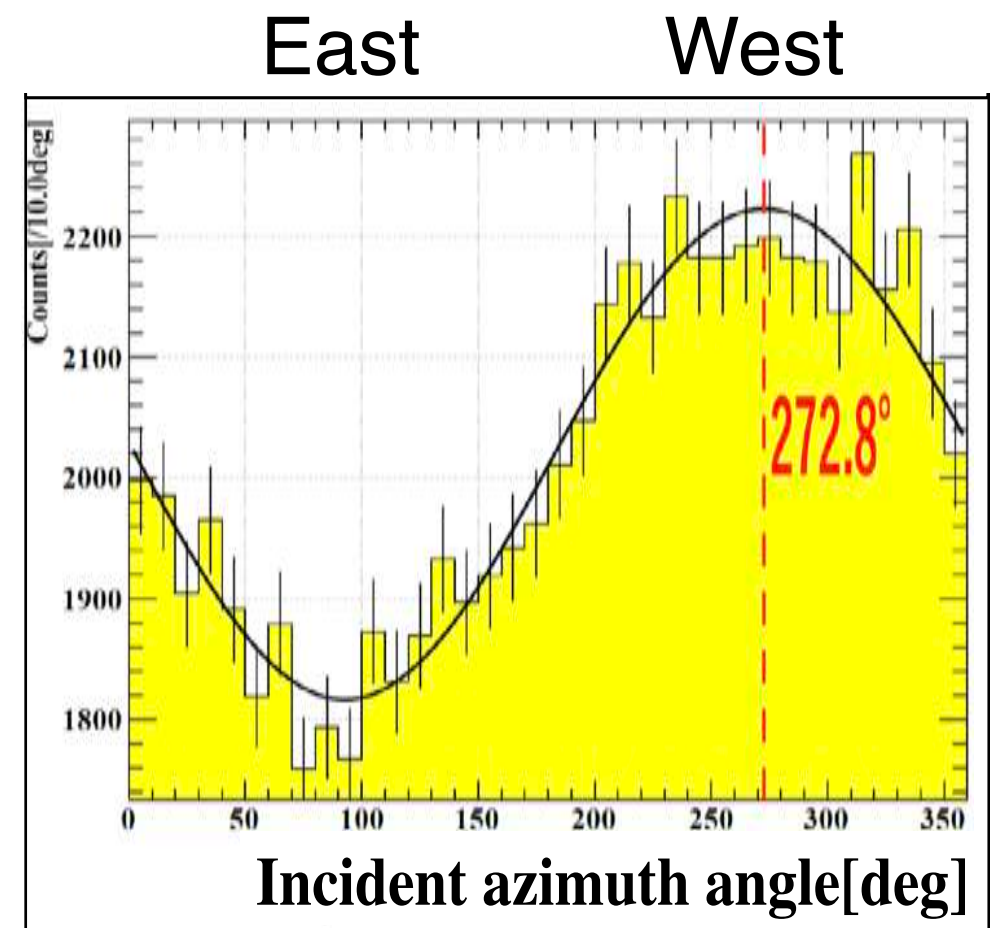
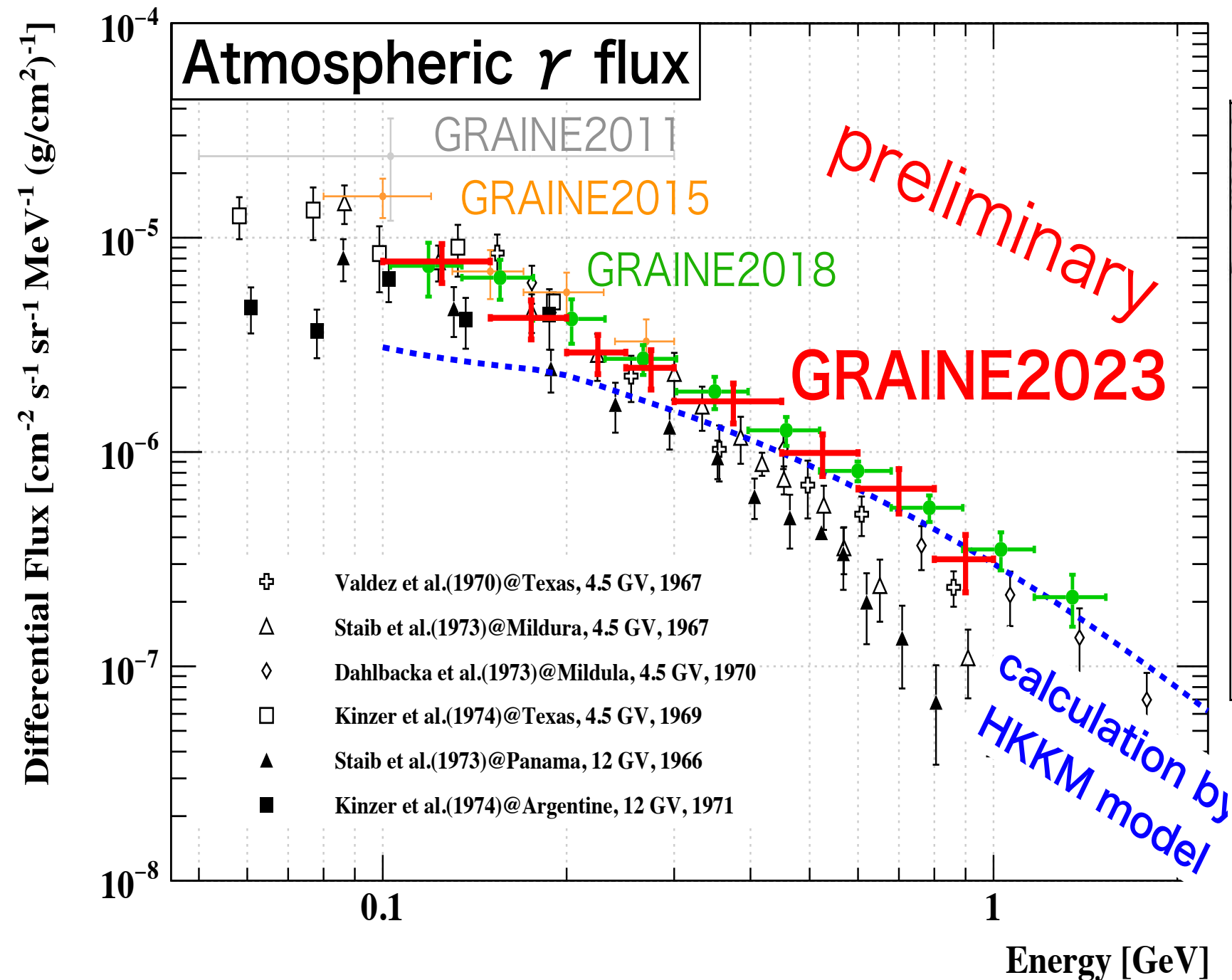
G.C.

Vela

**Center of view
(≡zenith direction)**

BG Measurement Results

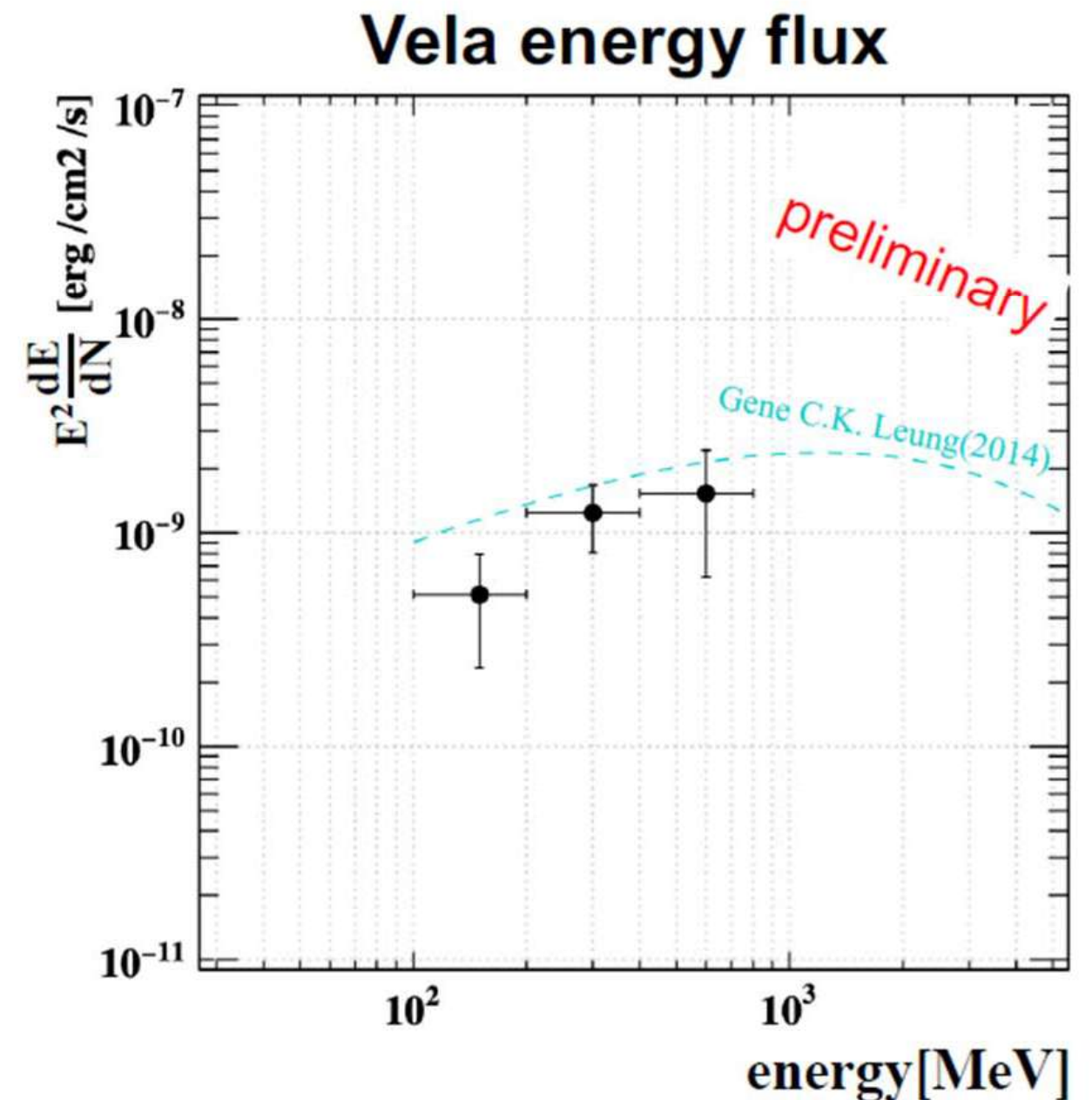
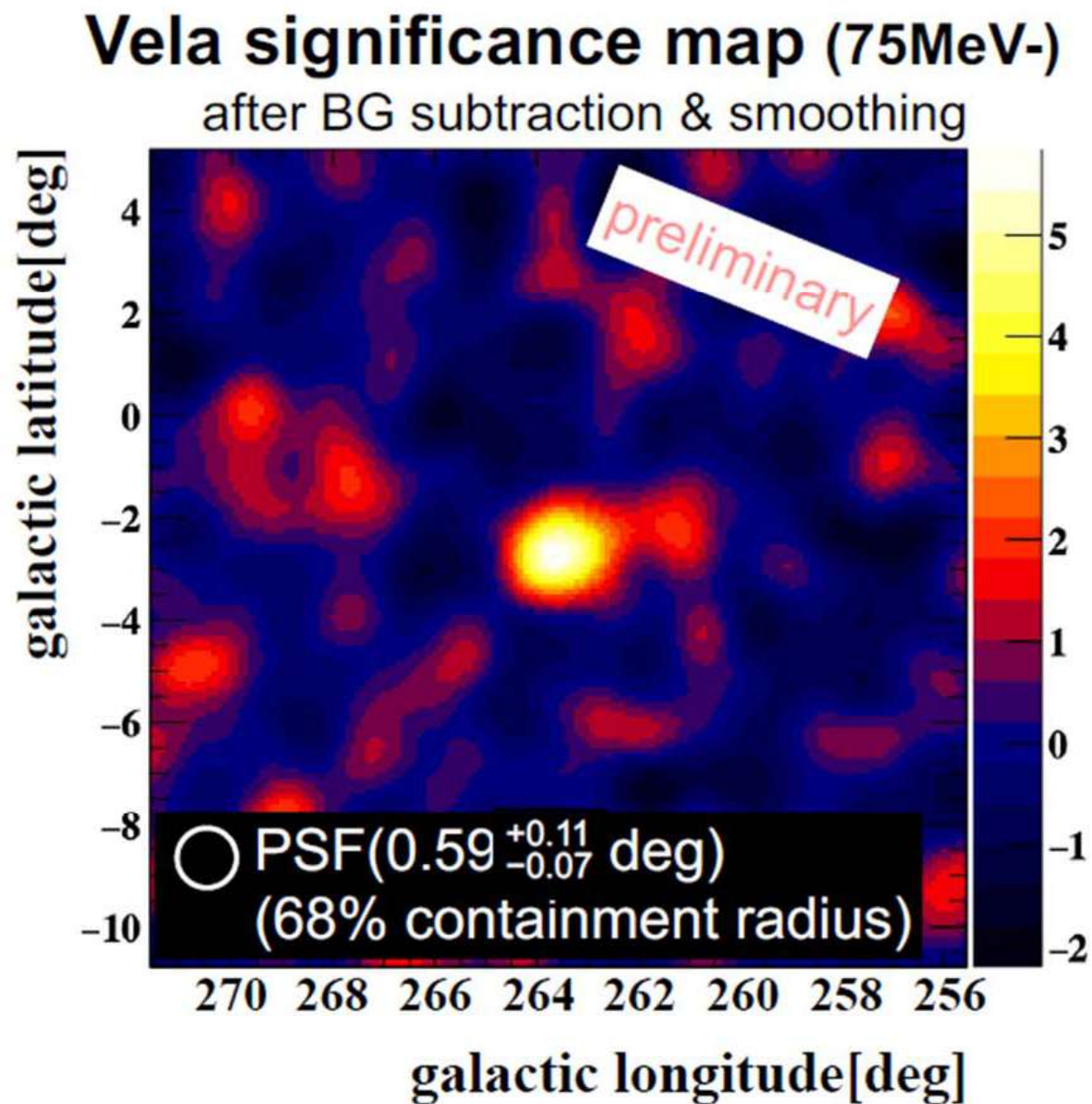
(atmospheric gamma rays)



East-West asymmetry
by the earth's geomagnetic field
(Atm. gamma rays is produced by
primary proton or He)

We can measure these trends using flight data.
Subtracting as background in the astrophysical analysis

GRAINE2023 Result①: Vela Pulsar

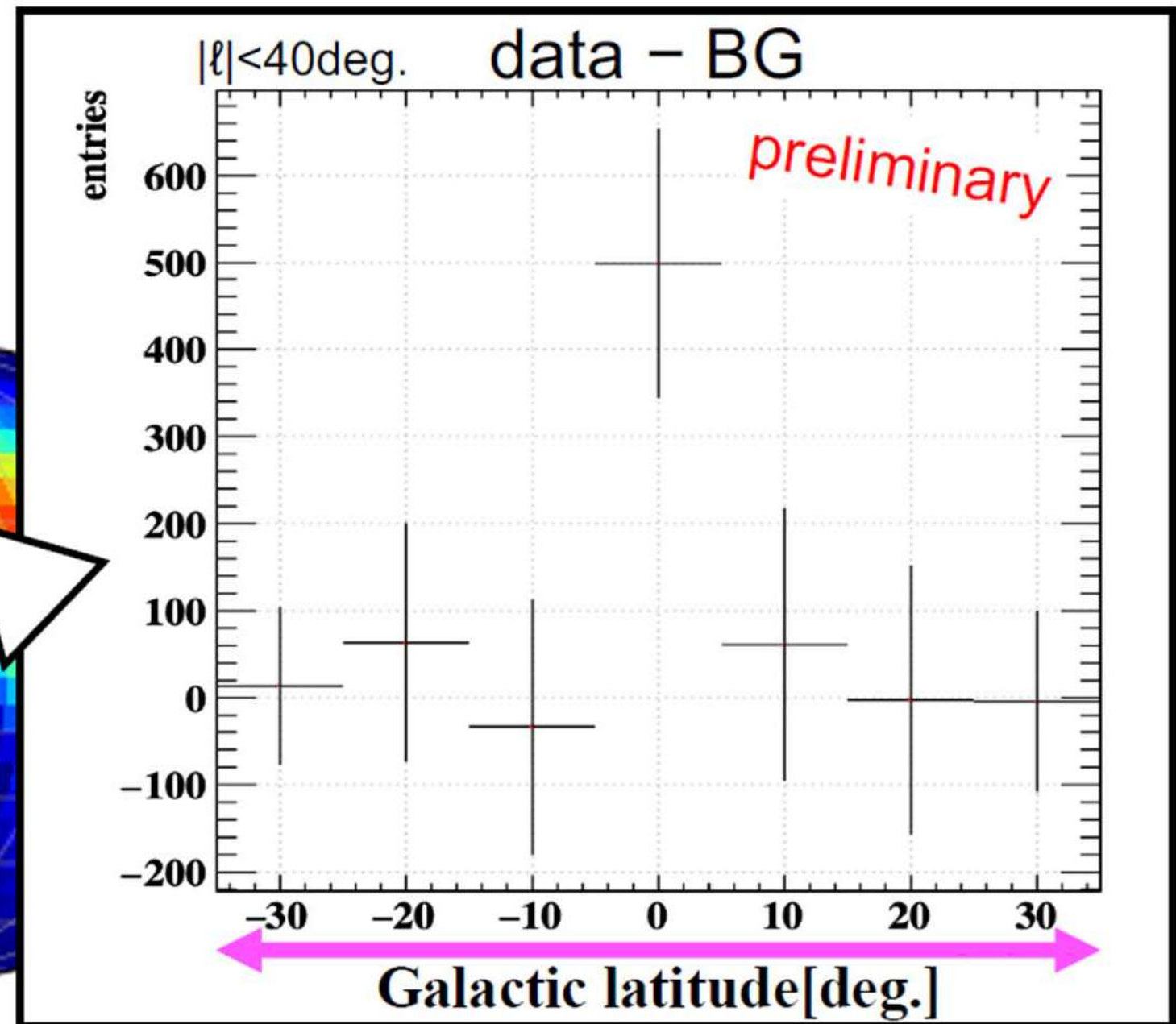
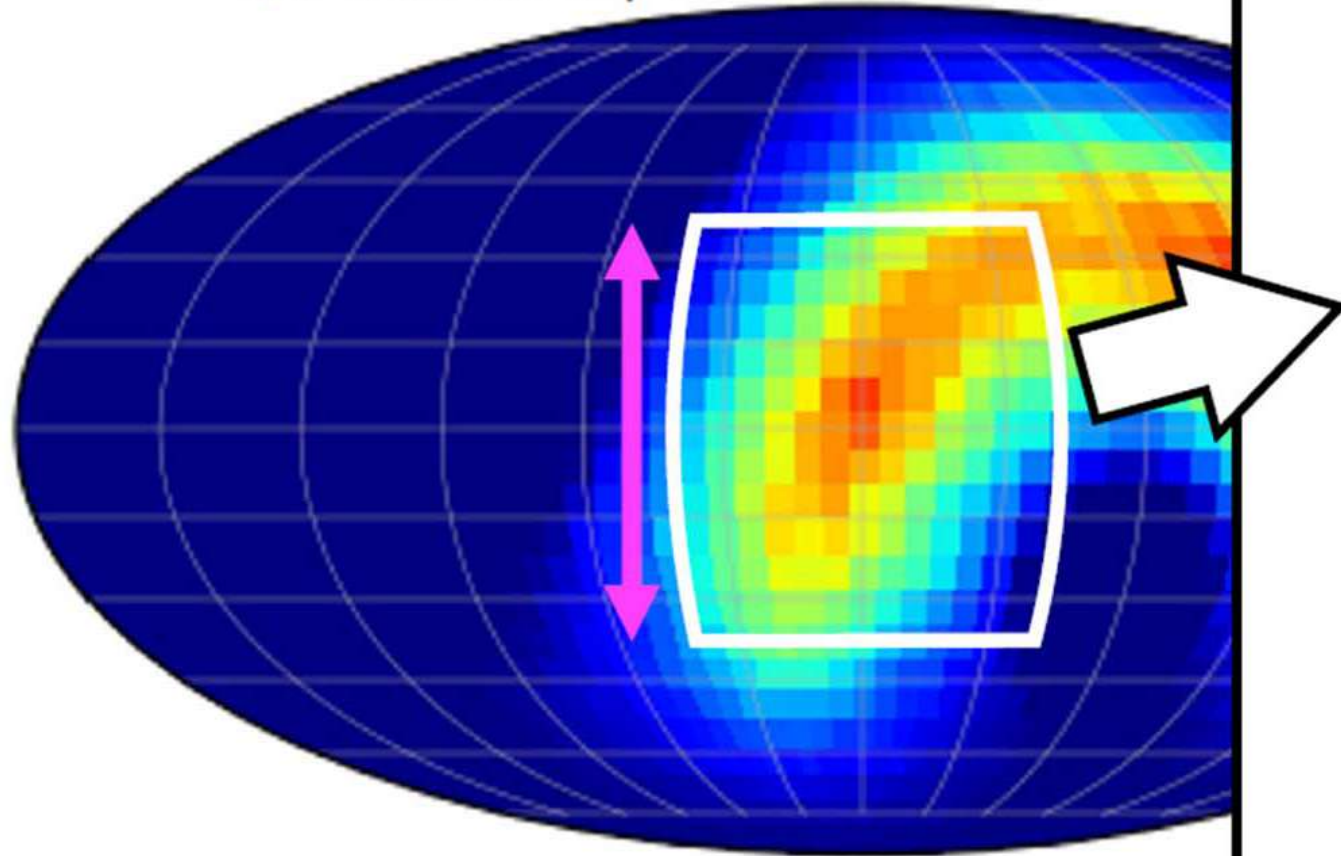


(Before internal BG reduction analysis)

**Detection of the Vela pulsar was
achieved with our new large telescope**

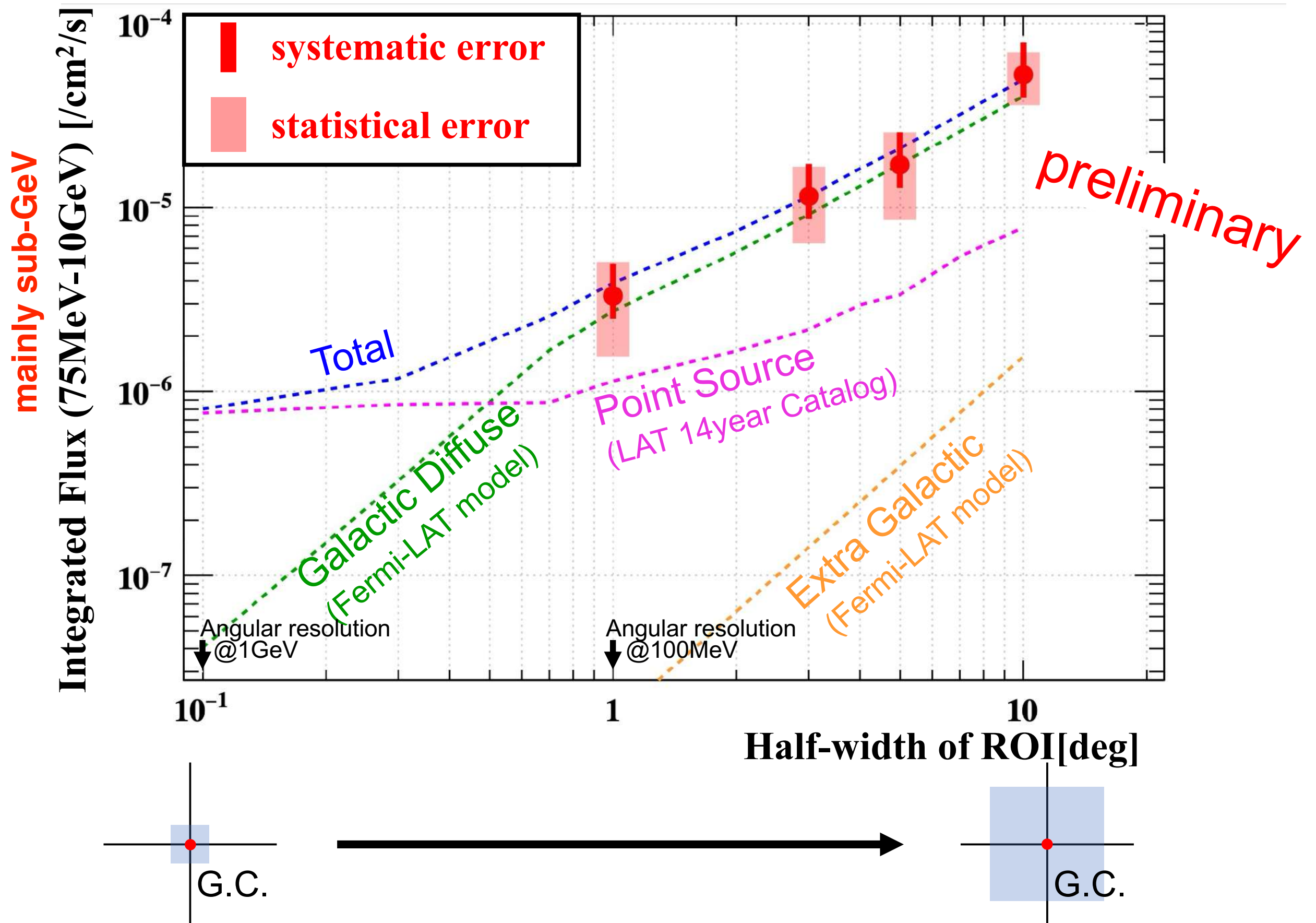
GRAINE2023 Result②: Galactic Plane

Gamma ray count map
✕before the exposure correction

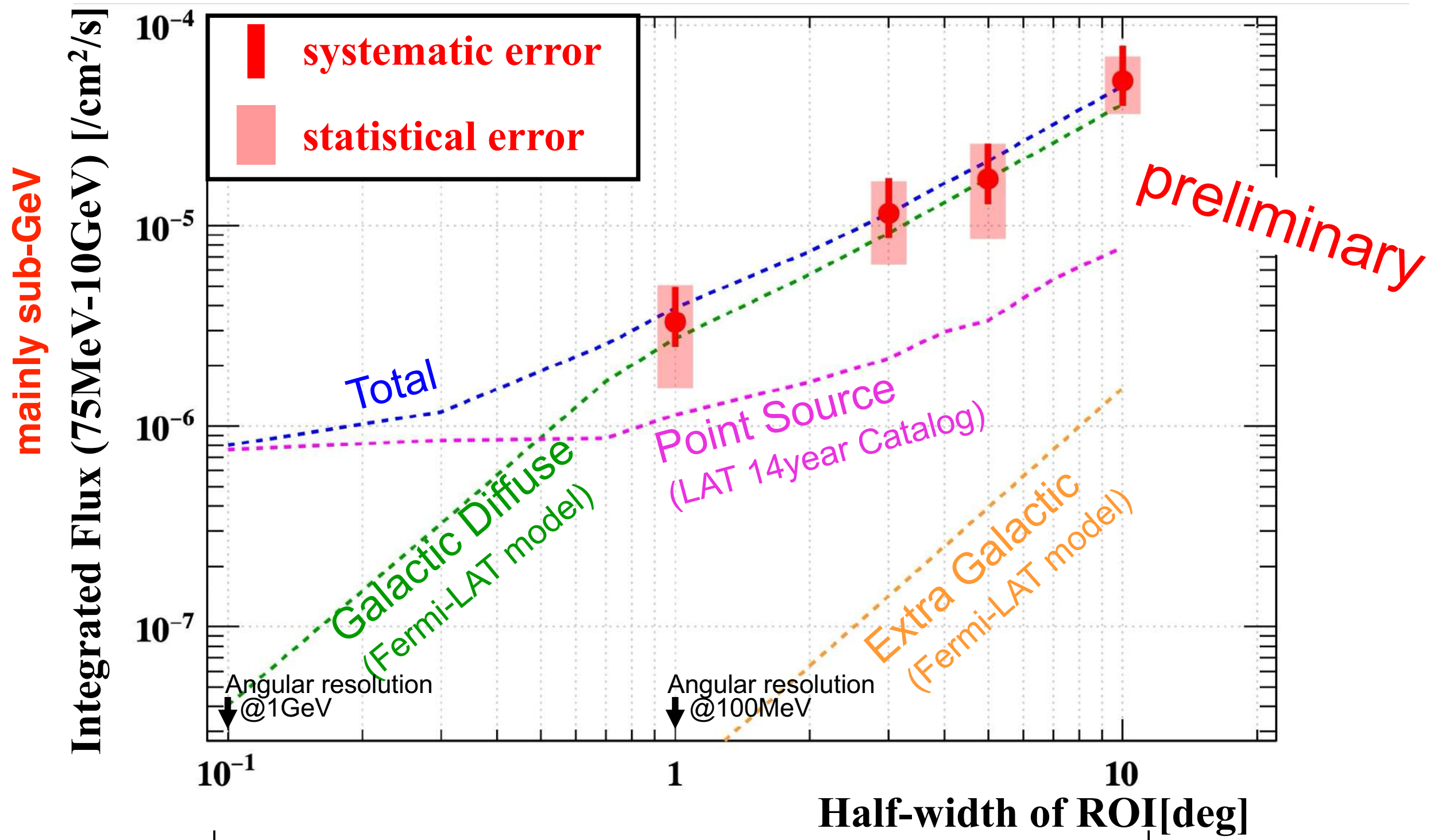


For the first time in the GRAINE experiment,
we succeeded in detecting
a significant cosmic gamma-ray signal in the GC region (3.2σ).

GRAINE2023 Result③: Galactic Center

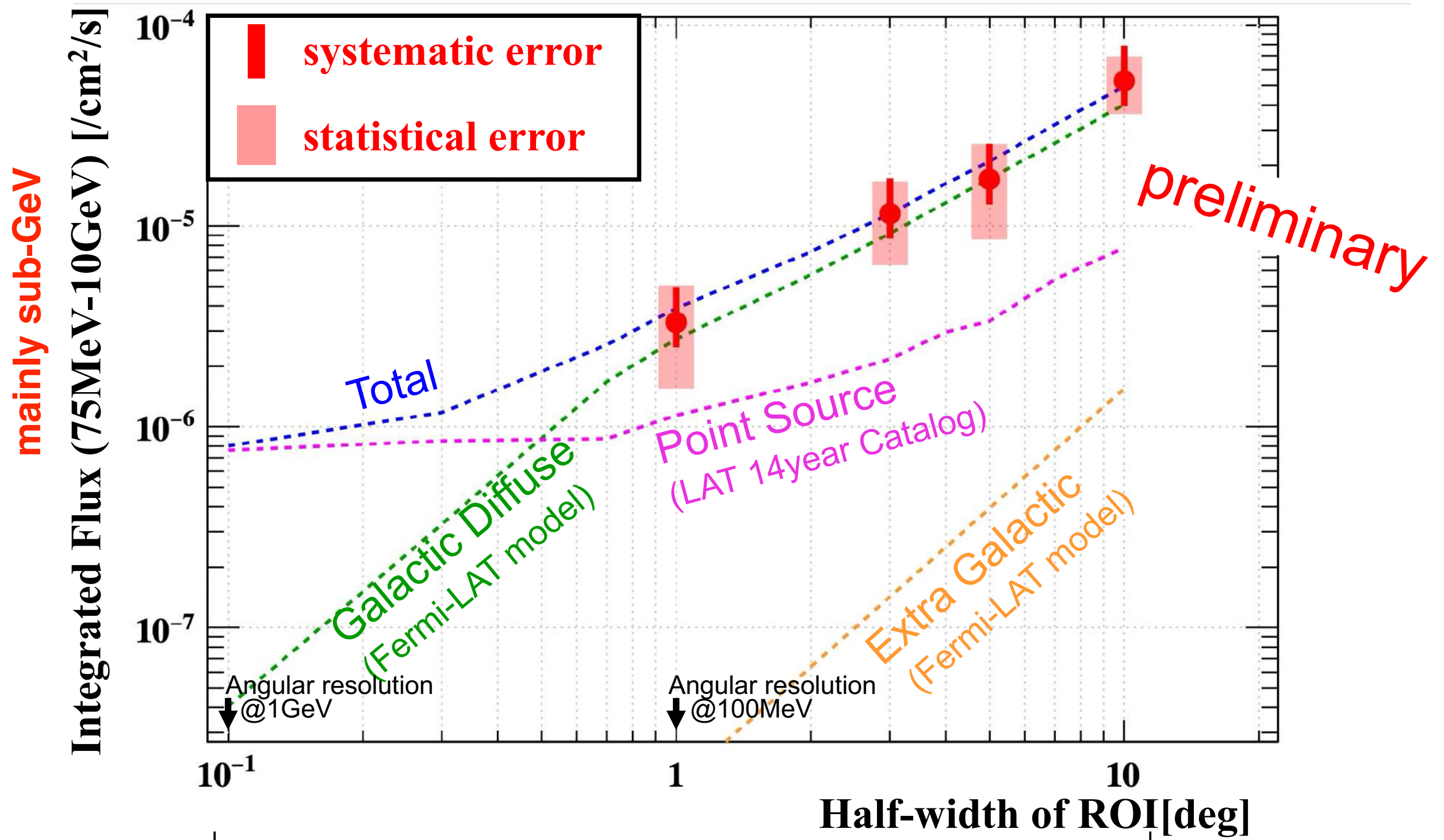


GRAINE2023 Result③: Galactic Center



- We successfully measured the sub-GeV cosmic gamma-ray flux within 1° of the Galactic center with the highest angular resolution.
- This measurement is independent of Fermi-LAT and model-independent.

GRAINE2023 Result③: Galactic Center

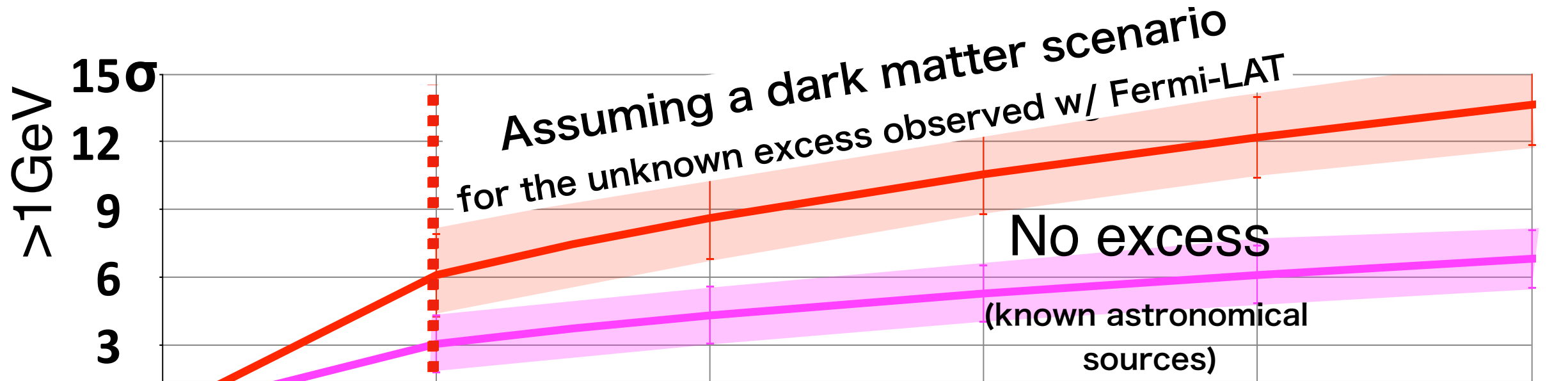


- A crucial first step toward measuring the flux of the Galactic Center GeV Excess!!
- Multi-GeV event analysis is in progress.
- We also promote the next balloon observation (in 2028).

Further Promotion of GRAINE Scientific Observations

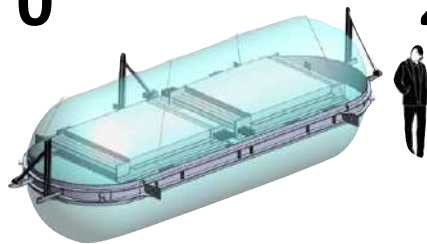
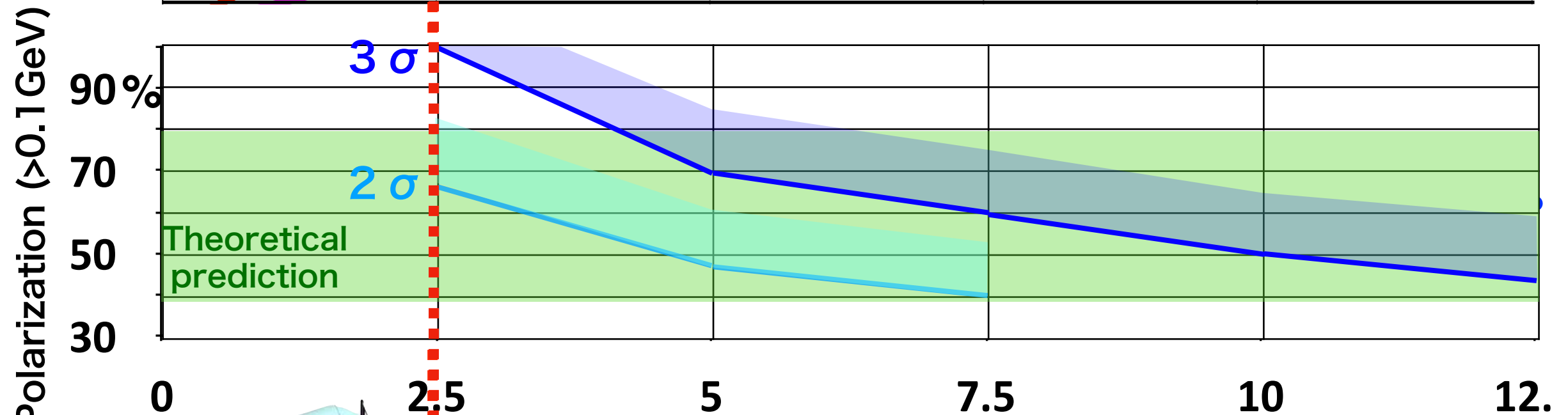
Gal. Center (0.1°)

Significance



Vela pulsar

Minimum Detectable



~700kg

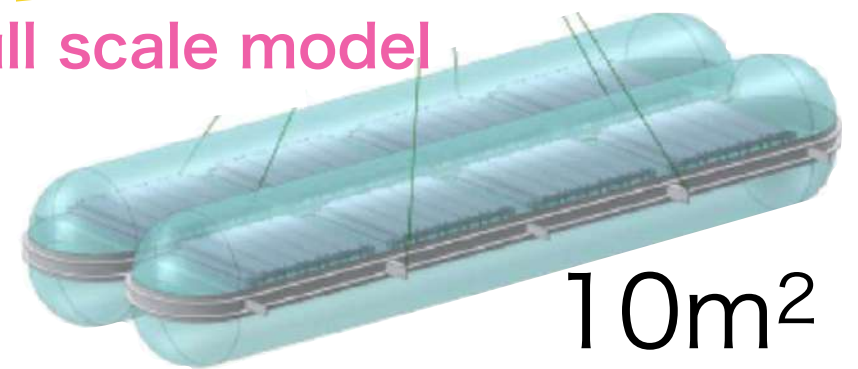
2.5 m²

GRAINE 2023

Telescope Area x 1-day Flight [m²·flight]

Next flight in 2028 is pre-selected!!

full scale model



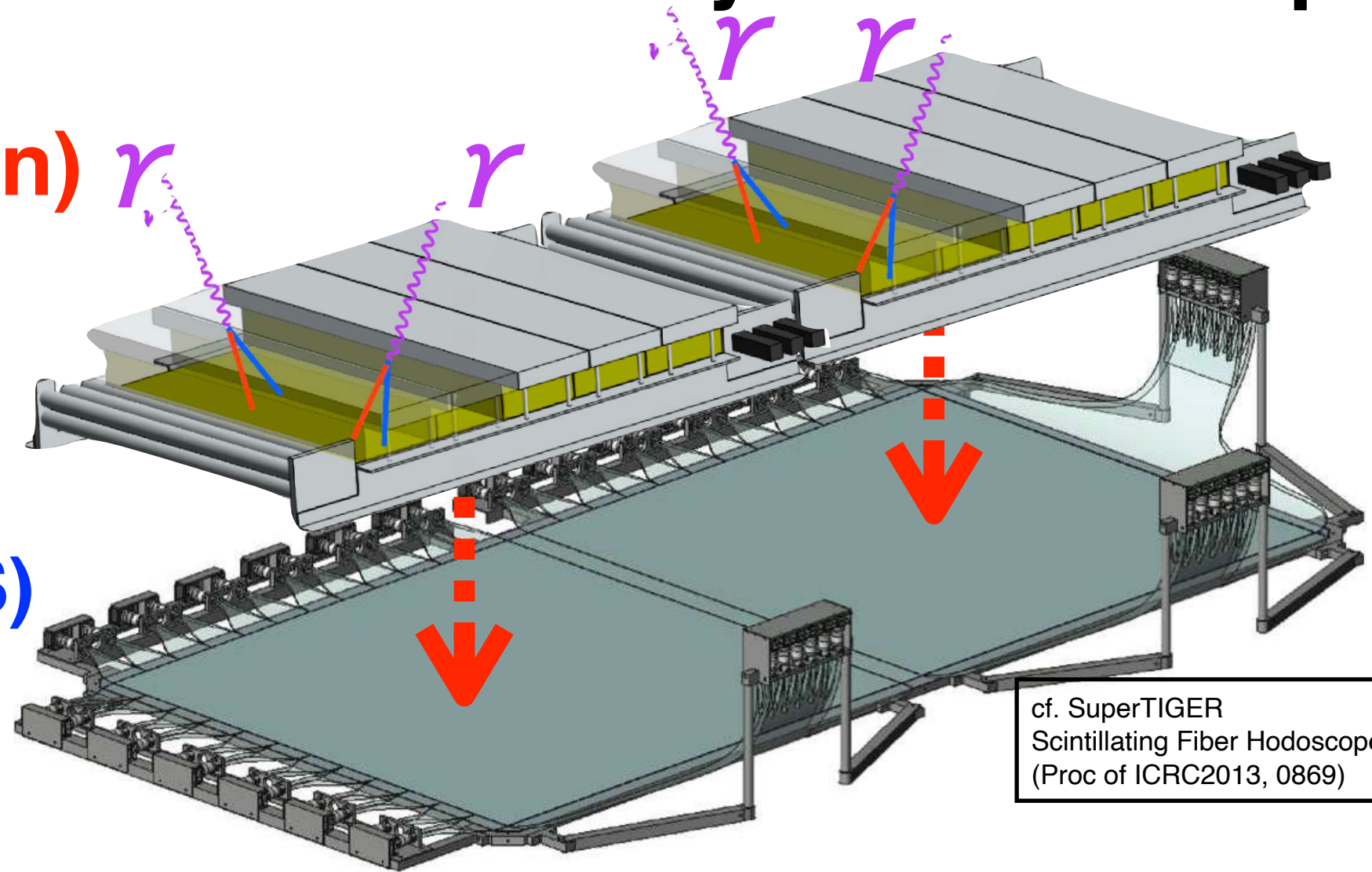
10m²

Future Upgrade Plan (under discussing): Idea of Emulsion-Electronics Hybrid Telescope

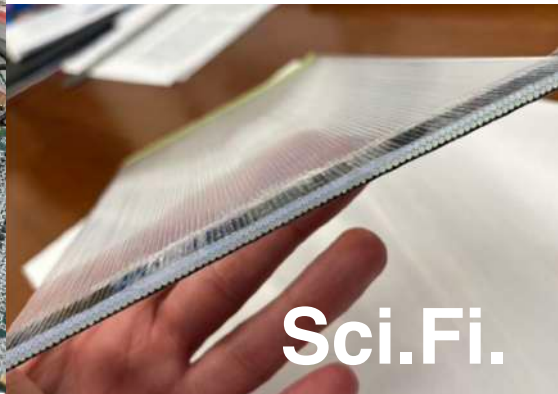
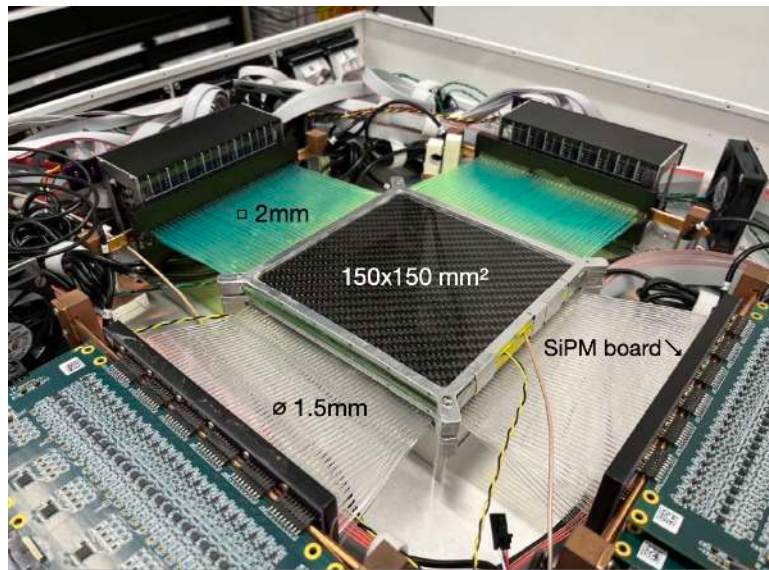
Emulsion (Japan)

gamma-ray detection
and rough timestamp

Sci.Fi. Tracker (US)
precise timestamp



cf. SuperTIGER
Scintillating Fiber Hodoscope
(Proc of ICRC2013, 0869)



**Washington U
St Louis**

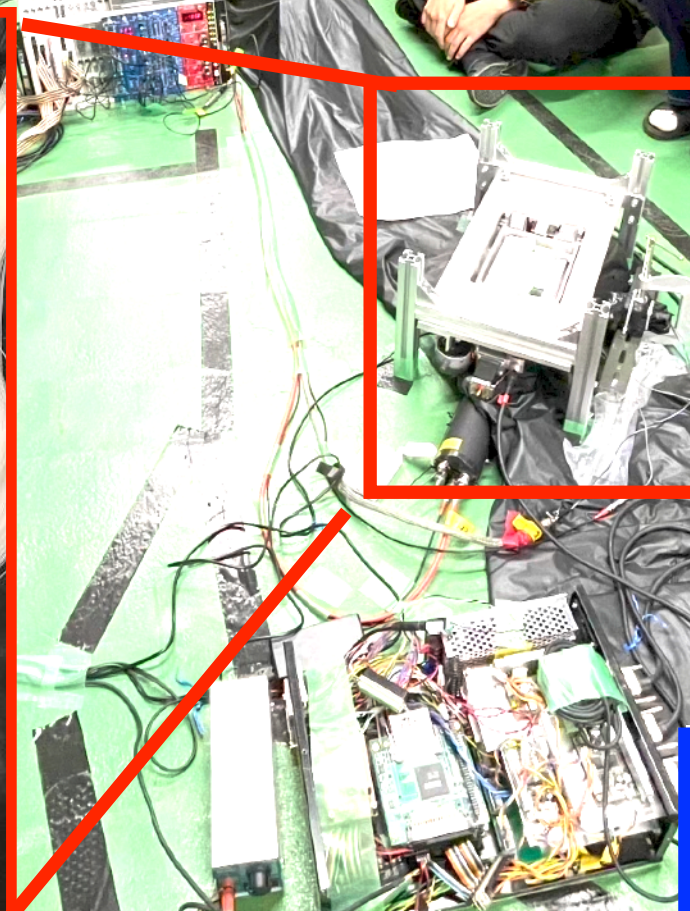
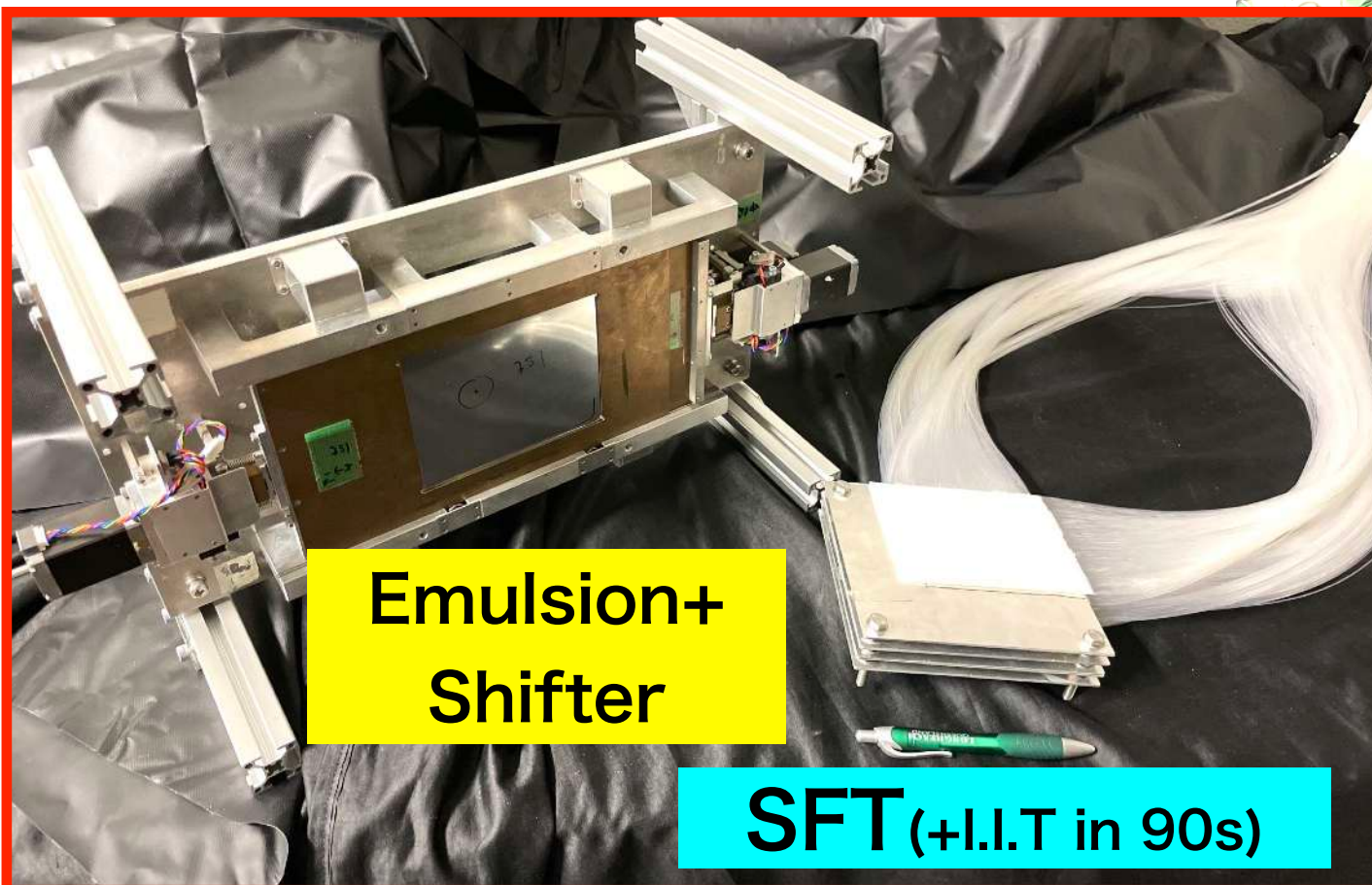
Large
Balloon
(NASA)

We would promote a larger telescope (more than twice the size)
and longer observation flights. (e.g. 7 days from Kiruna, Sweden)

Hybrid Telescope Test Observation

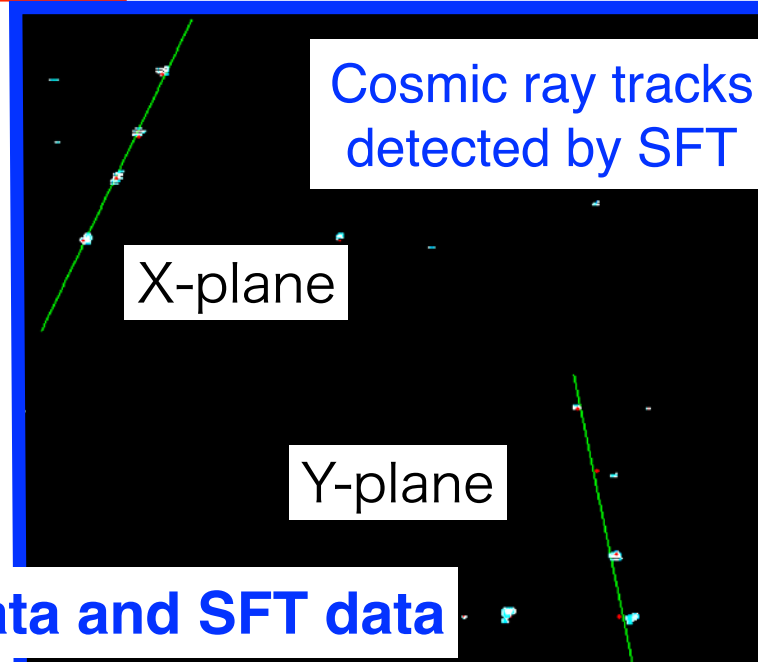
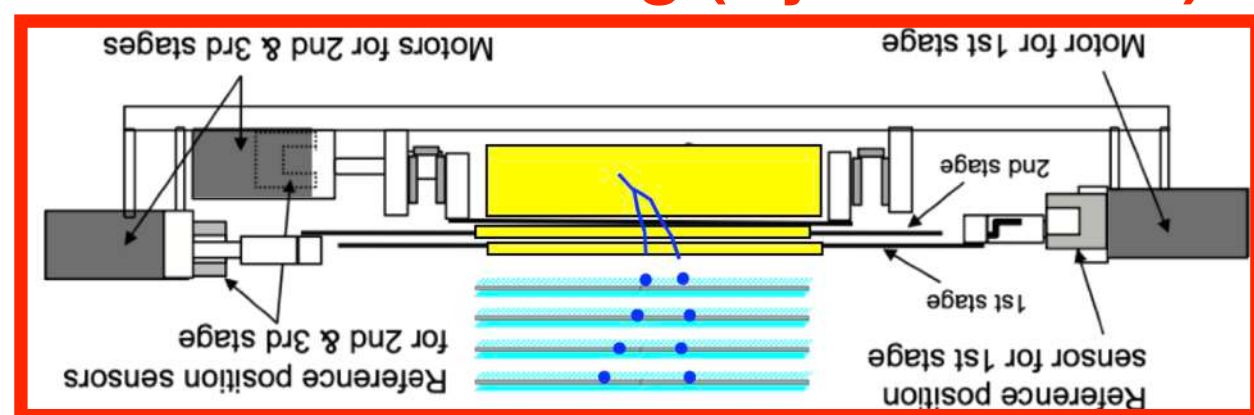
@ Mt. Norikura CR Observatory
2025/8/18-21

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~50MeV
Electron/Gamma rays
@Elevation 2700m

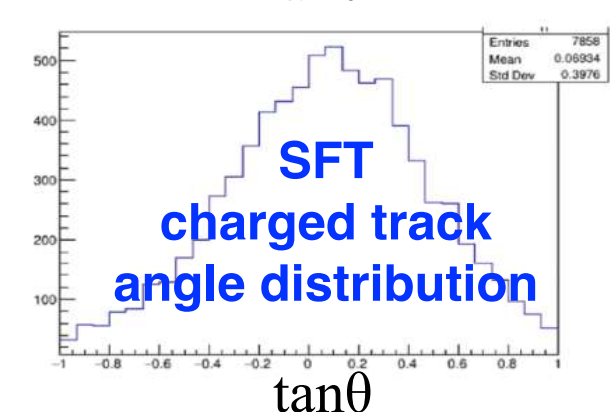
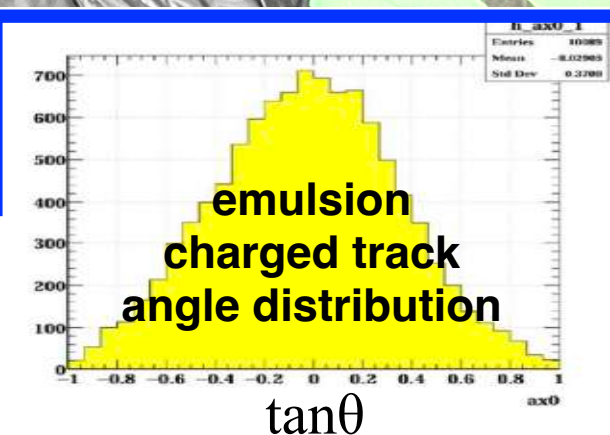
Detector Docking (Hybridization)



Cosmic ray tracks
detected by SFT

X-plane

Y-plane



Conducting joint analysis of emulsion scan data and SFT data

Summary

- **GRAINE** (Gamma-Ray Astro-Imager with Nuclear Emulsion)
 - Frontier of high-resolution imaging at GeV (e.g G.C.)
 - Pioneer of gamma-ray polarimetry at sub-GeV (e.g Vela)
 - Will provide unique and impactful science that cannot be achieved by current and future satellite missions.
- **GRAINE2023:**
 - Started scientific observation w/ 2.5 m² telescope.
 - Measured gamma ray flux in the vicinity of the Galactic Center with the highest angular resolution in sub-GeV band.
- **Next Balloon Exp. in 2028 is pre-selected by JAXA**
- **Upgrade GRAINE:** discussing hybrid telescope with JP-US collaboration towards further observations and physics.

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