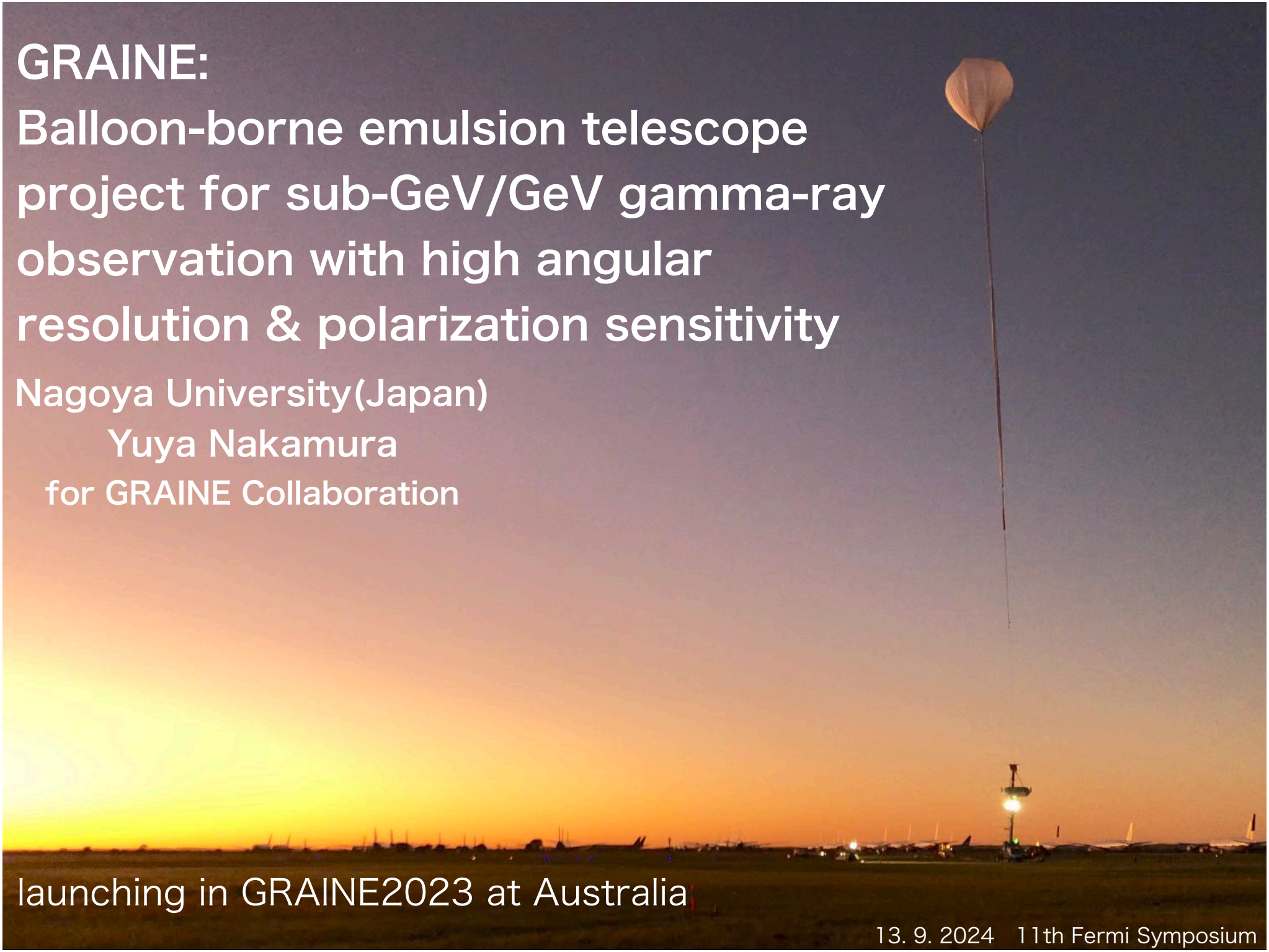
GRAINE:
Balloon-borne emulsion telescope project for sub-GeV/GeV gamma-ray observation with high angular resolution & polarization sensitivity

Nagoya University(Japan)
Yuya Nakamura
for GRAINE Collaboration

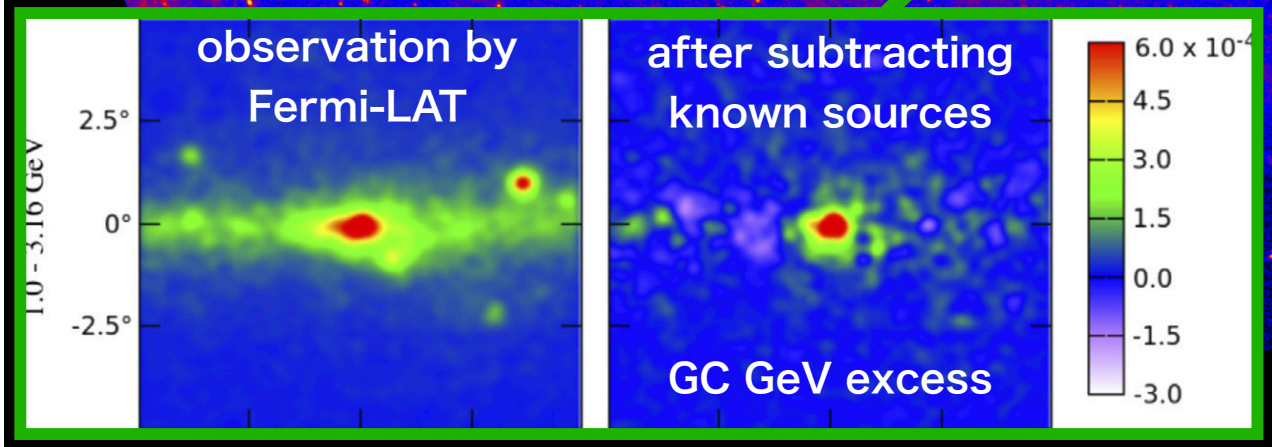


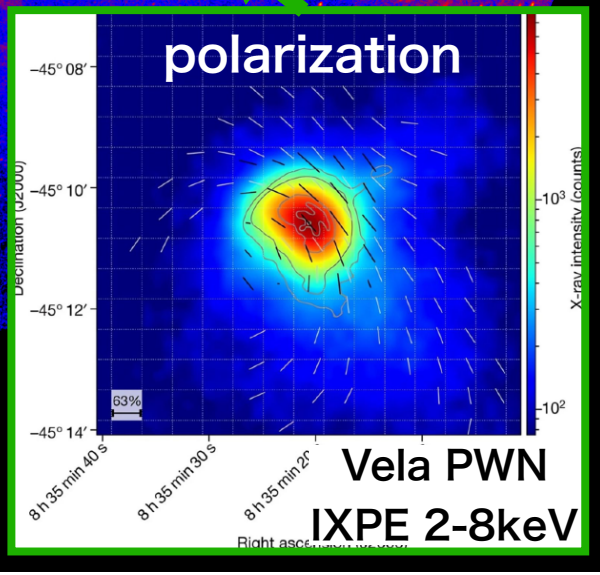
launching in GRAINE2023 at Australia

13. 9. 2024　11th Fermi Symposium

Cosmic Gamma ray(sub-GeV,GeV)

12 years, E>1 GeV





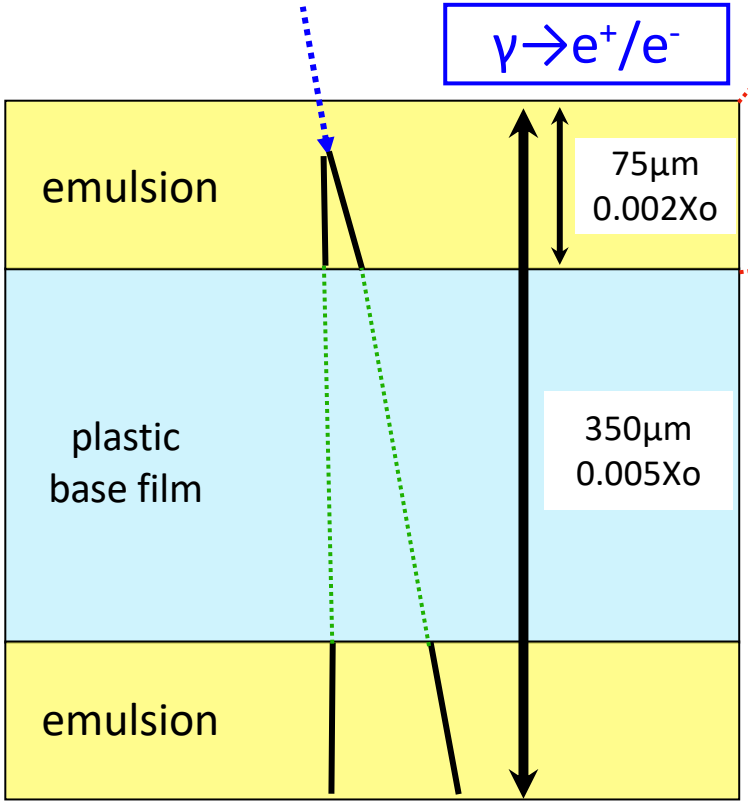
unidentified sources? dark matter?

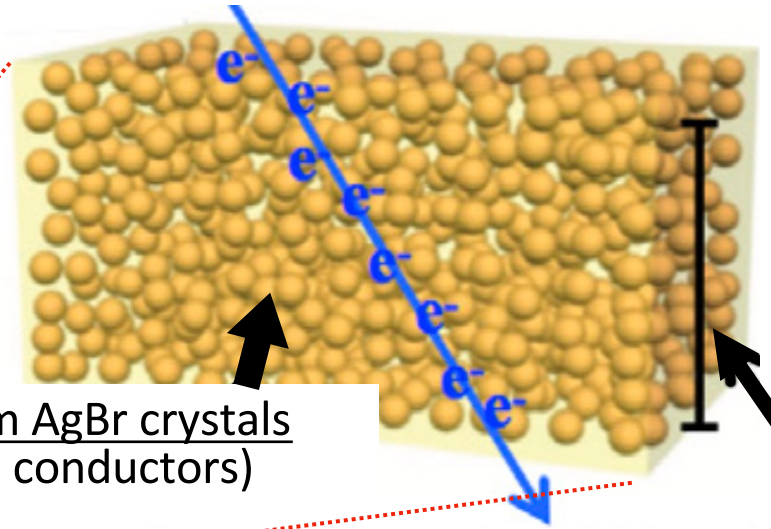
how sub-GeV/GeV band?

-> approach these problems with
higher angular/spatial resolution detector

Detector: Nuclear emulsion film

cross sectional view
of the emulsion film

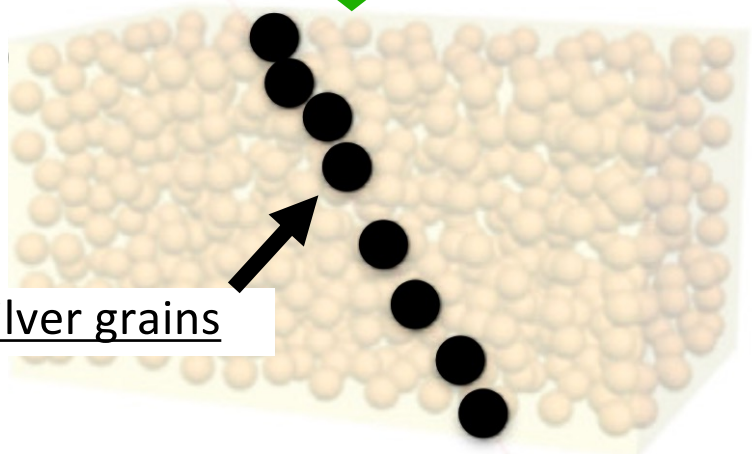




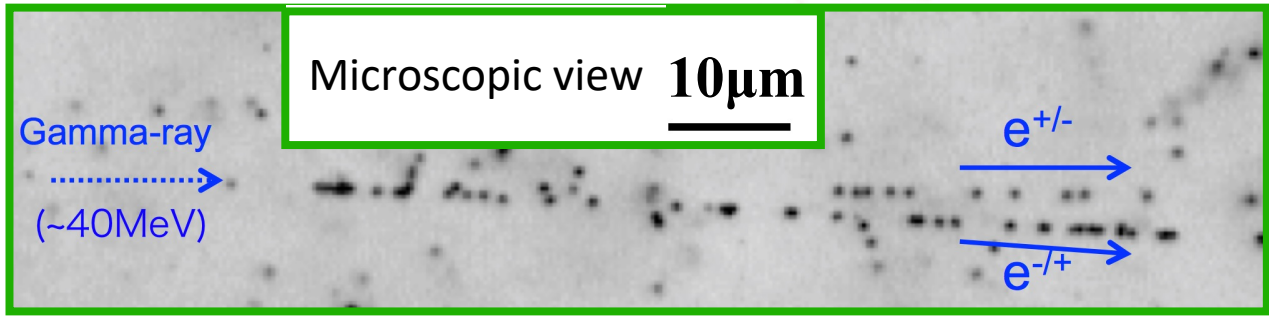
~200nm AgBr crystals
(semi conductors)

gelatin

photo
development

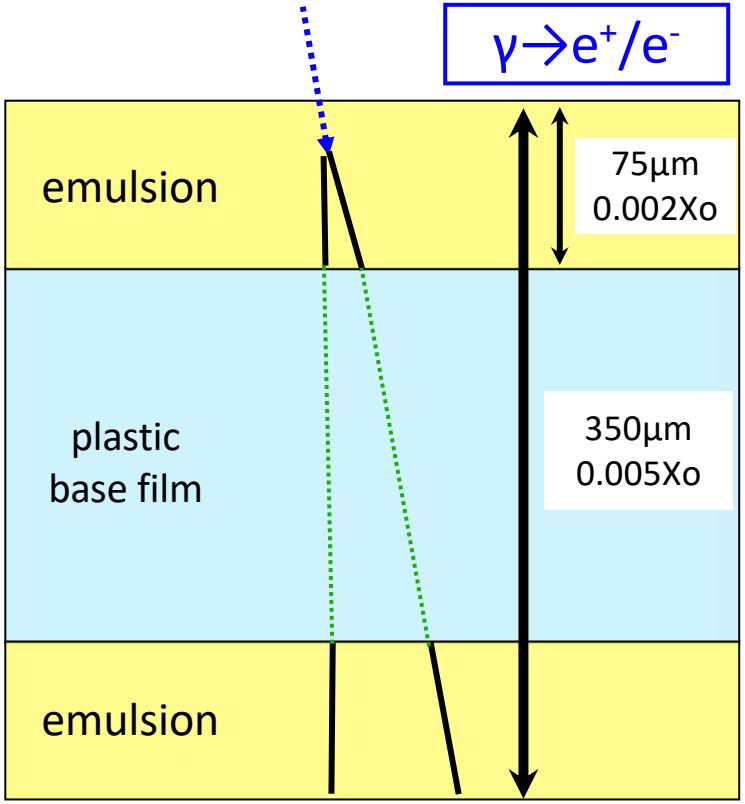


silver grains

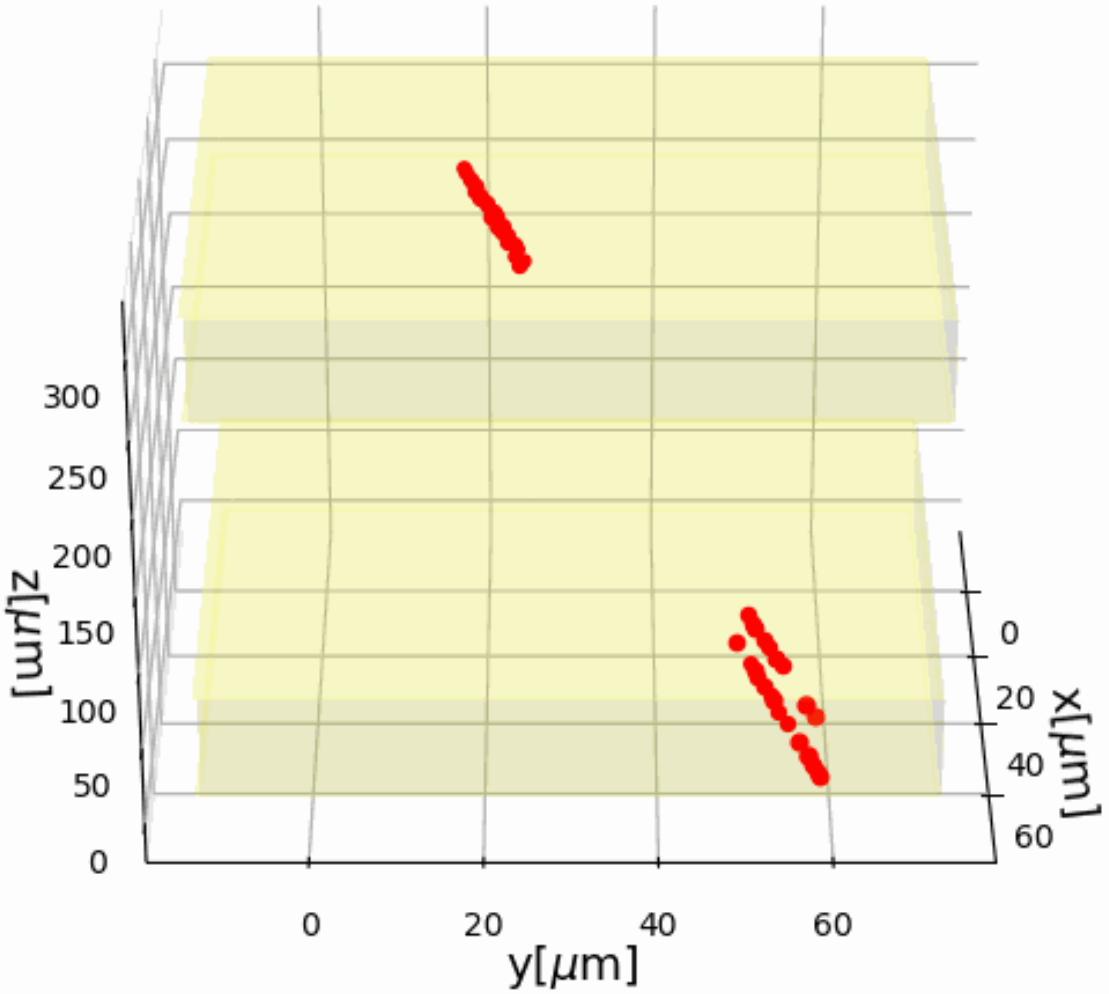


Detector: Nuclear emulsion film

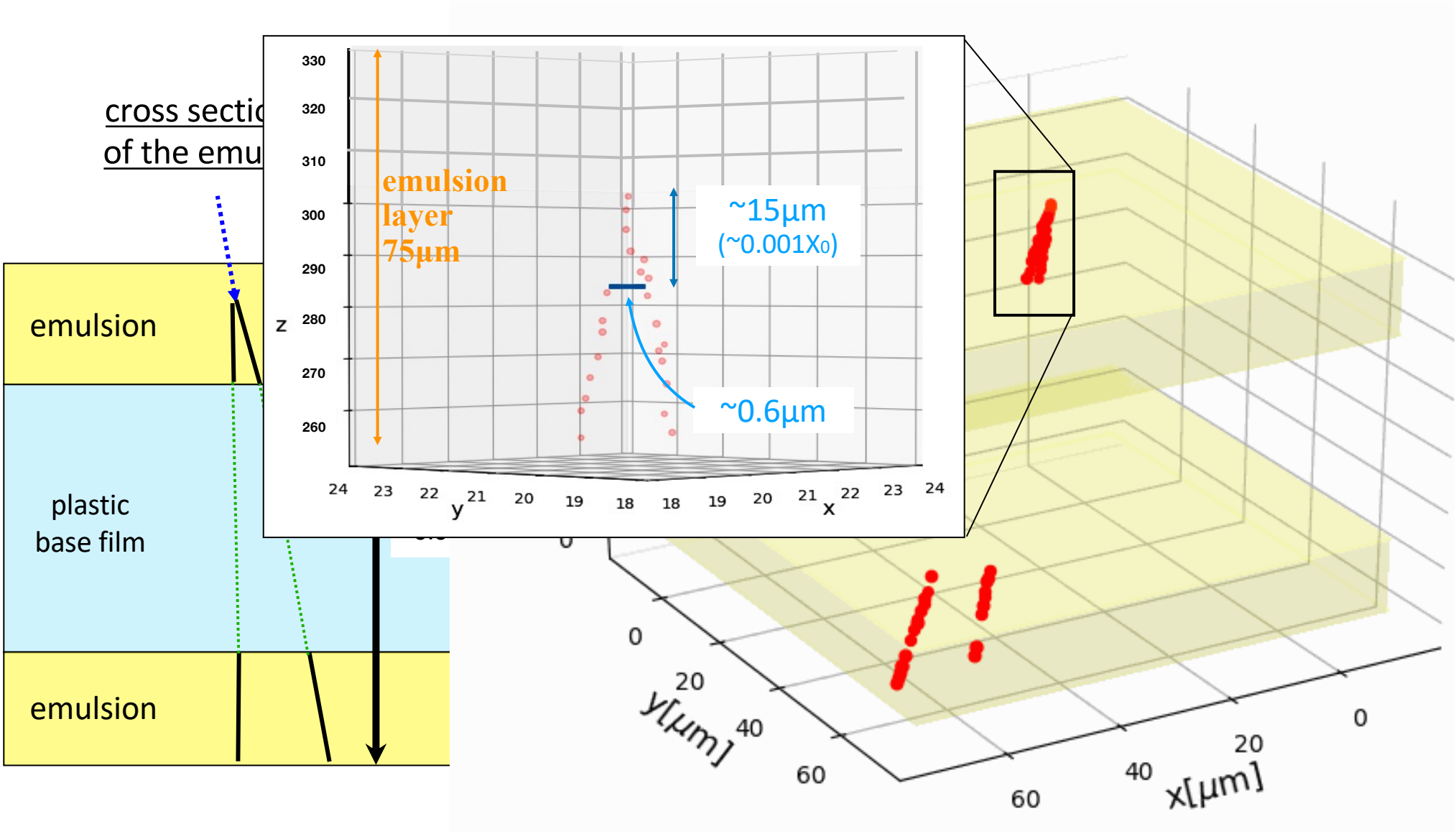
cross sectional view
of the emulsion film



Scanning system: analog to digital
3-D position of silver grains
E_γ:581MeV (E_{e+e-}: 35MeV, 546MeV)

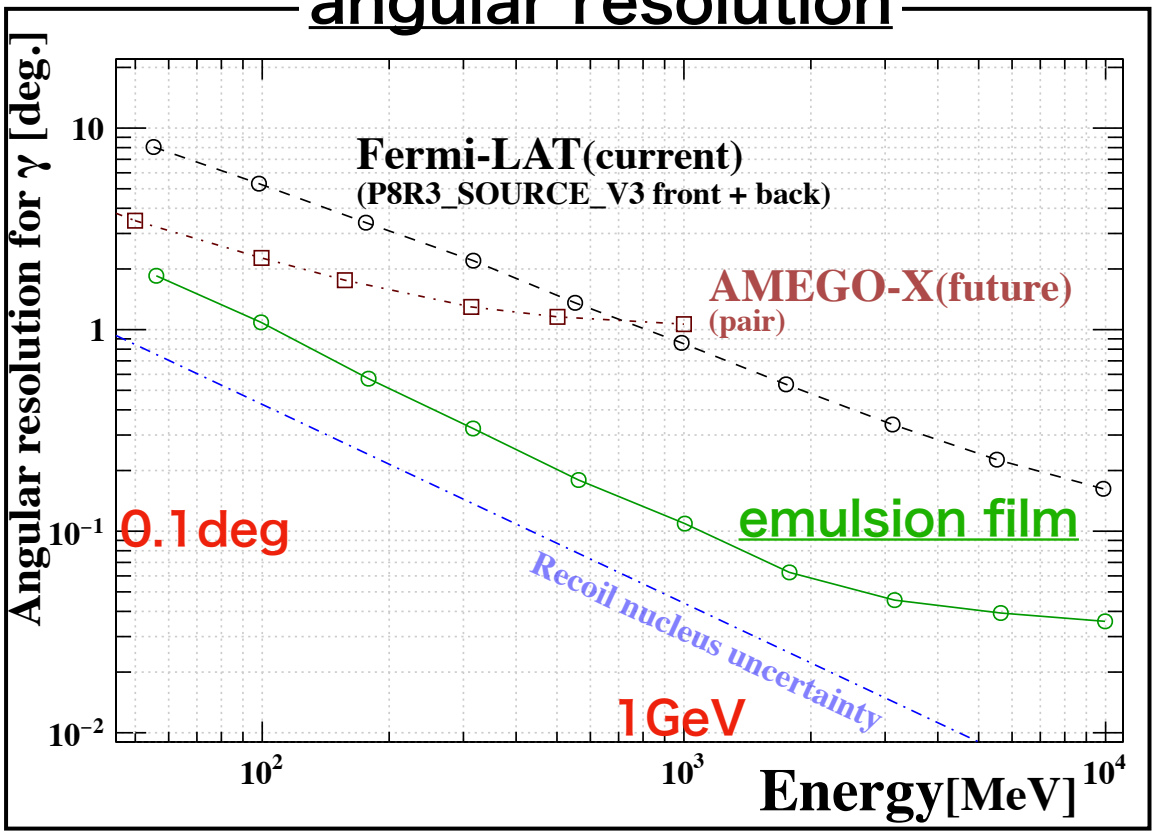


Detector: Nuclear emulsion film



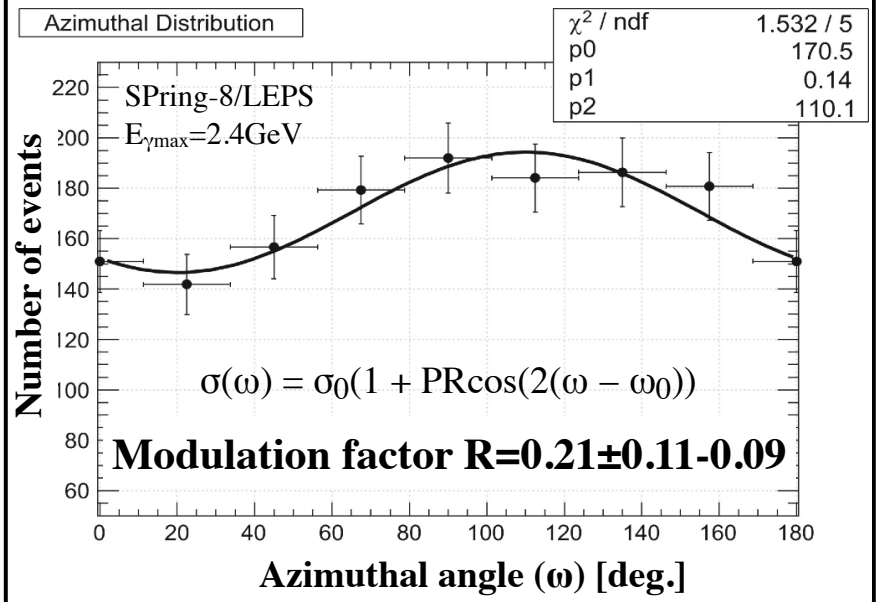
Performance for gamma-rays

angular resolution



polarization sensitivity

(result of a 2.4 GeV beam experiment)



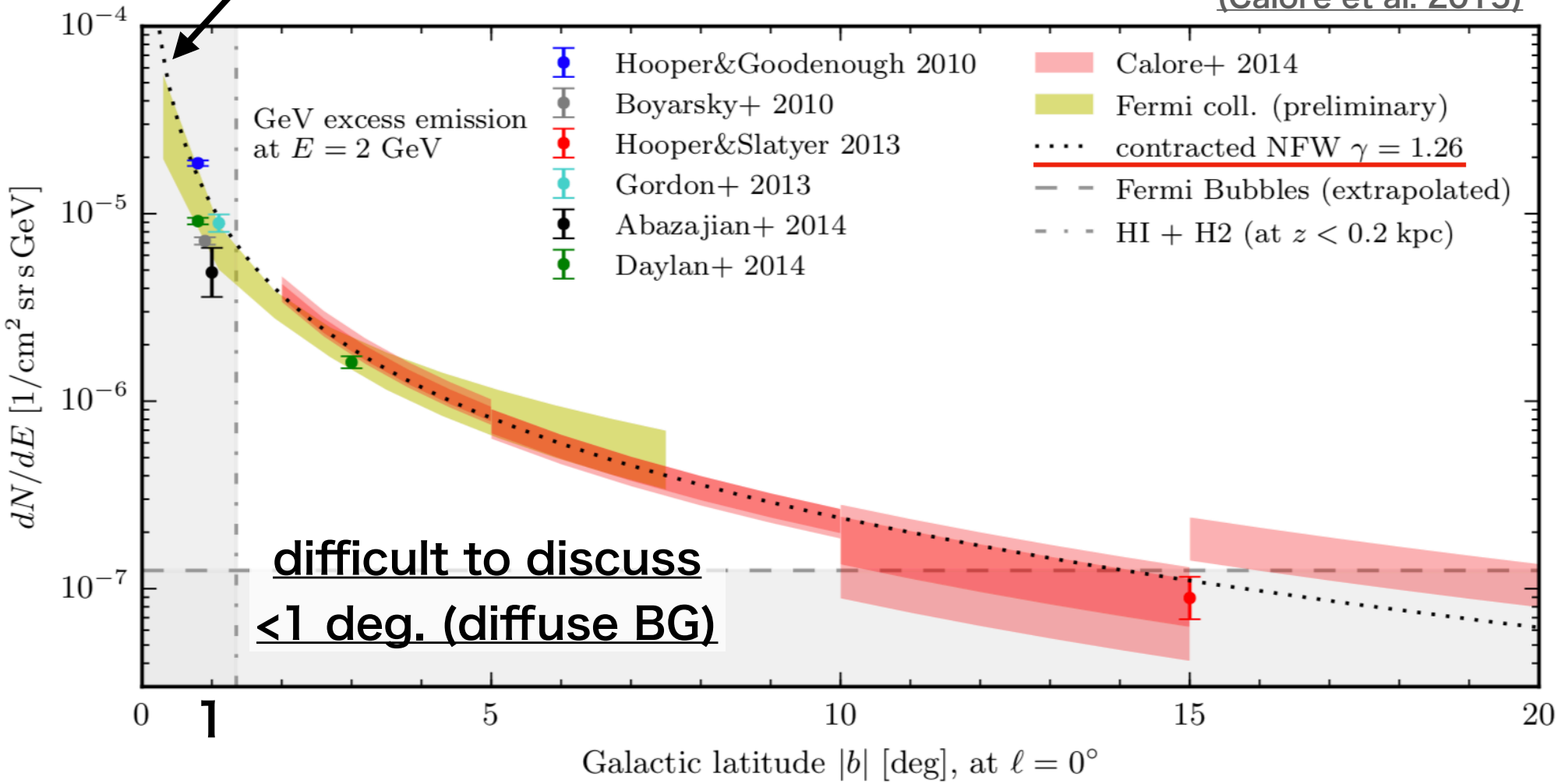
high angular resolution, polarization sensitivity

Galactic Center GeV Excess

Radial profile (latitude dependency of the Excess flux)

DM scenario? (NFW, γ=1.26？)

(Calore et al. 2015)



Galactic Center GeV Excess

? ★ Radial profile (latitude dependency of the Excess flux)

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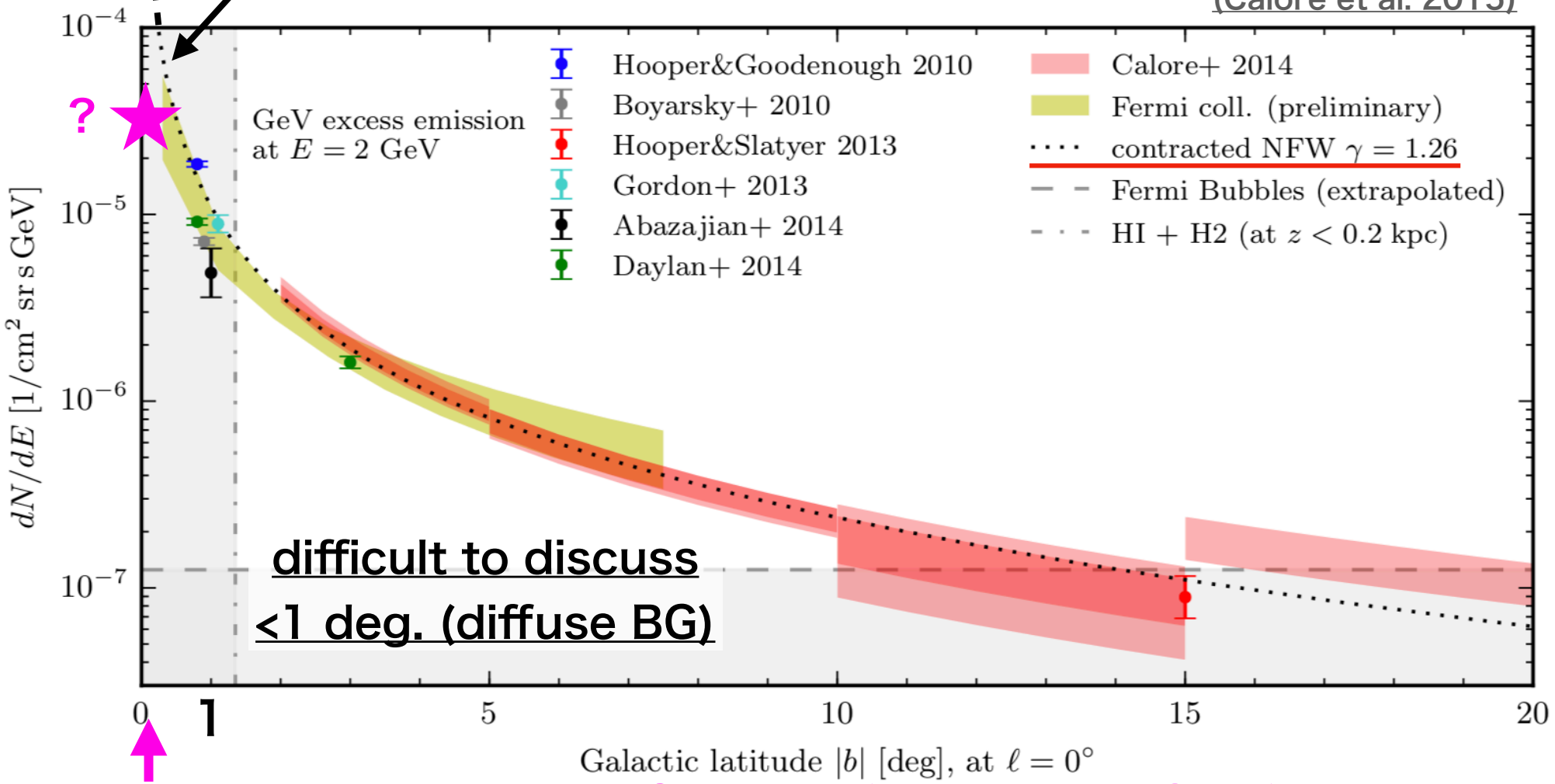
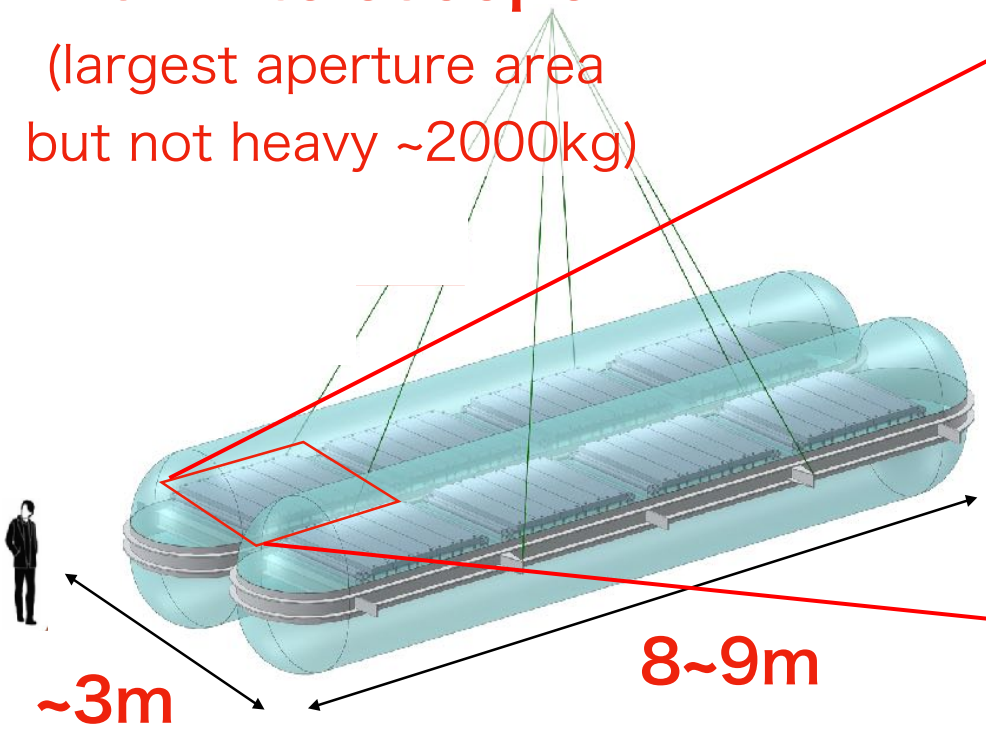


Add the data point at 0.1deg.(emulsion film)

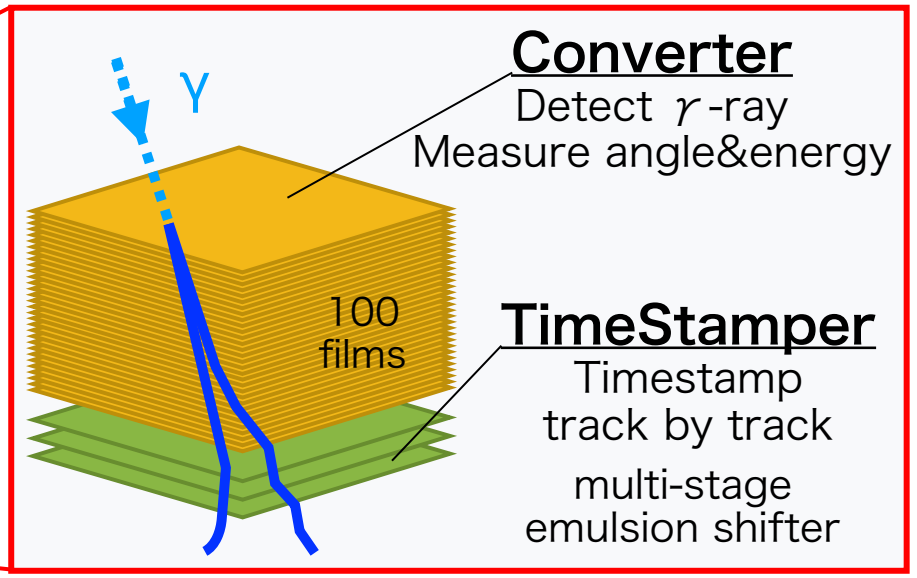
GRAINE project

Cosmic gamma-ray observation
w/ balloon-borne emulsion gamma-ray telescope

Balloon-borne
10m² telescope
(largest aperture area
but not heavy ~2000kg)



emulsion gamma-ray telescope



Altitude Monitor
(star camera)

GRAINE project

Prototype Phase

2004- Technology development

2011 1st Balloon experiment
(0.01m² @Japan w/ JAXA**)**

Demonstration phase

2015 2nd Balloon experiment
(0.38m²@Australia w/ JAXA**)**

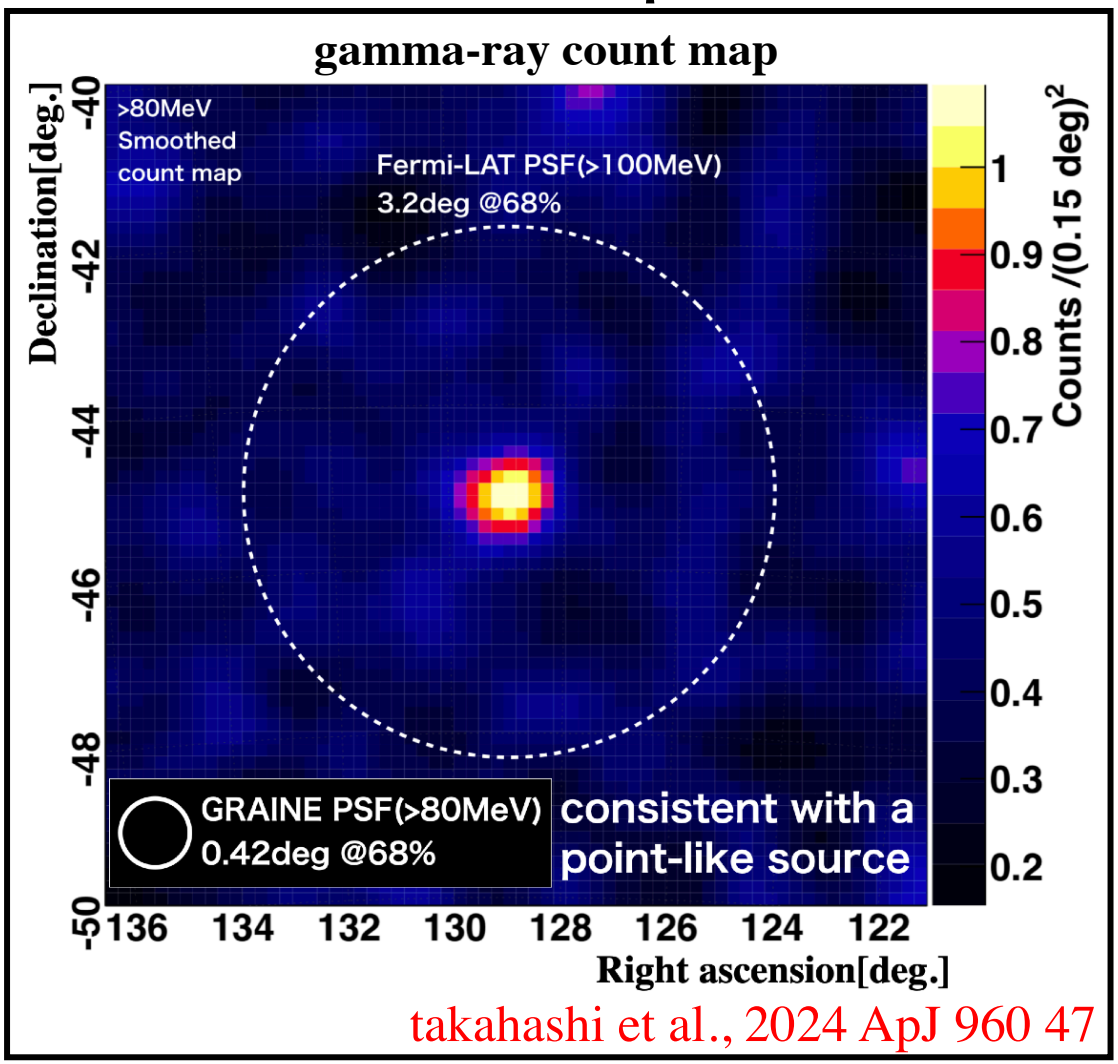
- **2018 3rd Balloon experiment**
(0.38m²@Australia w/ JAXA**)**

Scientific phase

- **2023 4th Balloon experiment**
(2.5m²@Australia w/ JAXA**)**

2027? 5th Balloon experiment

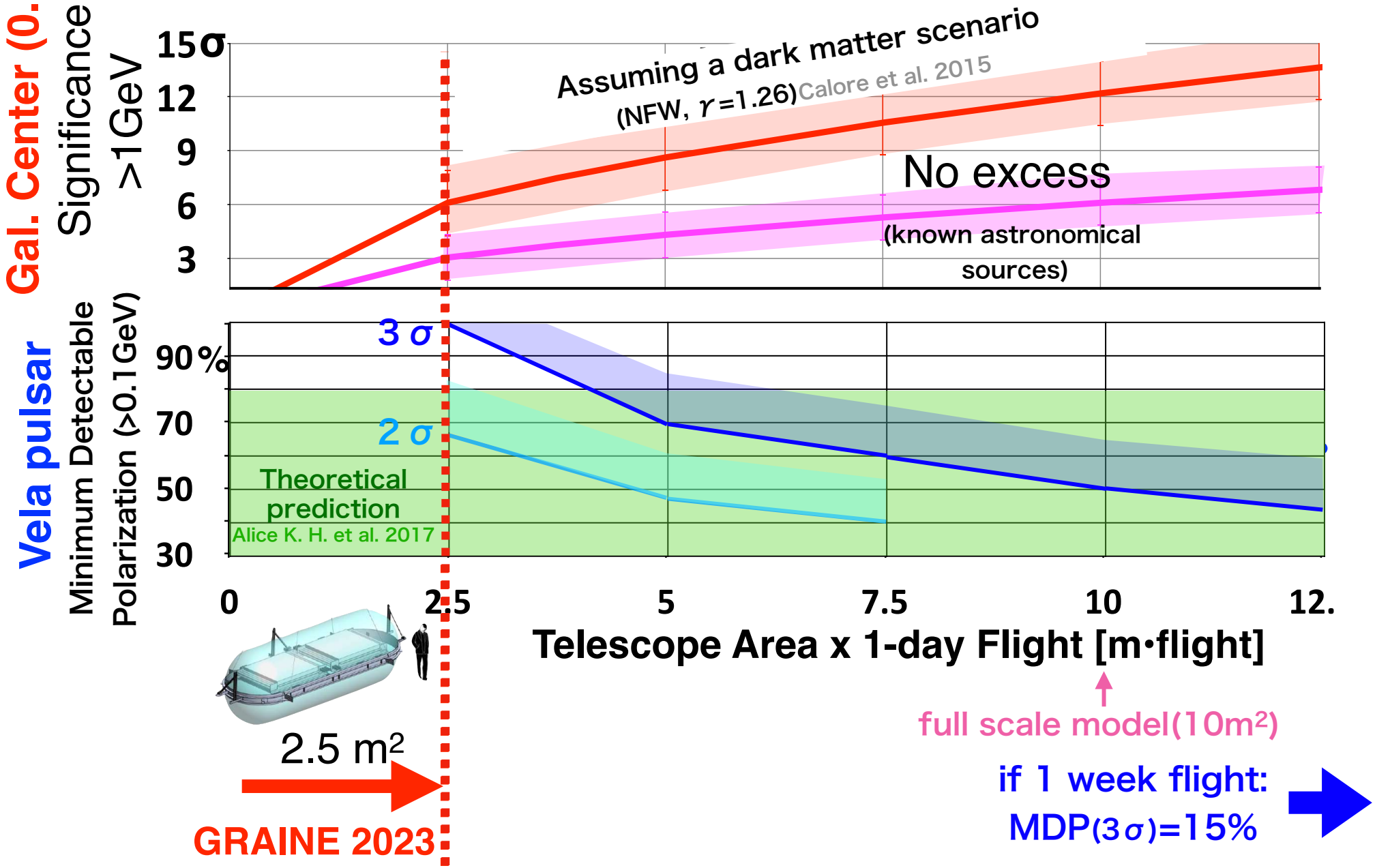
Observation for the Vela pulsar in the 2018 experiment



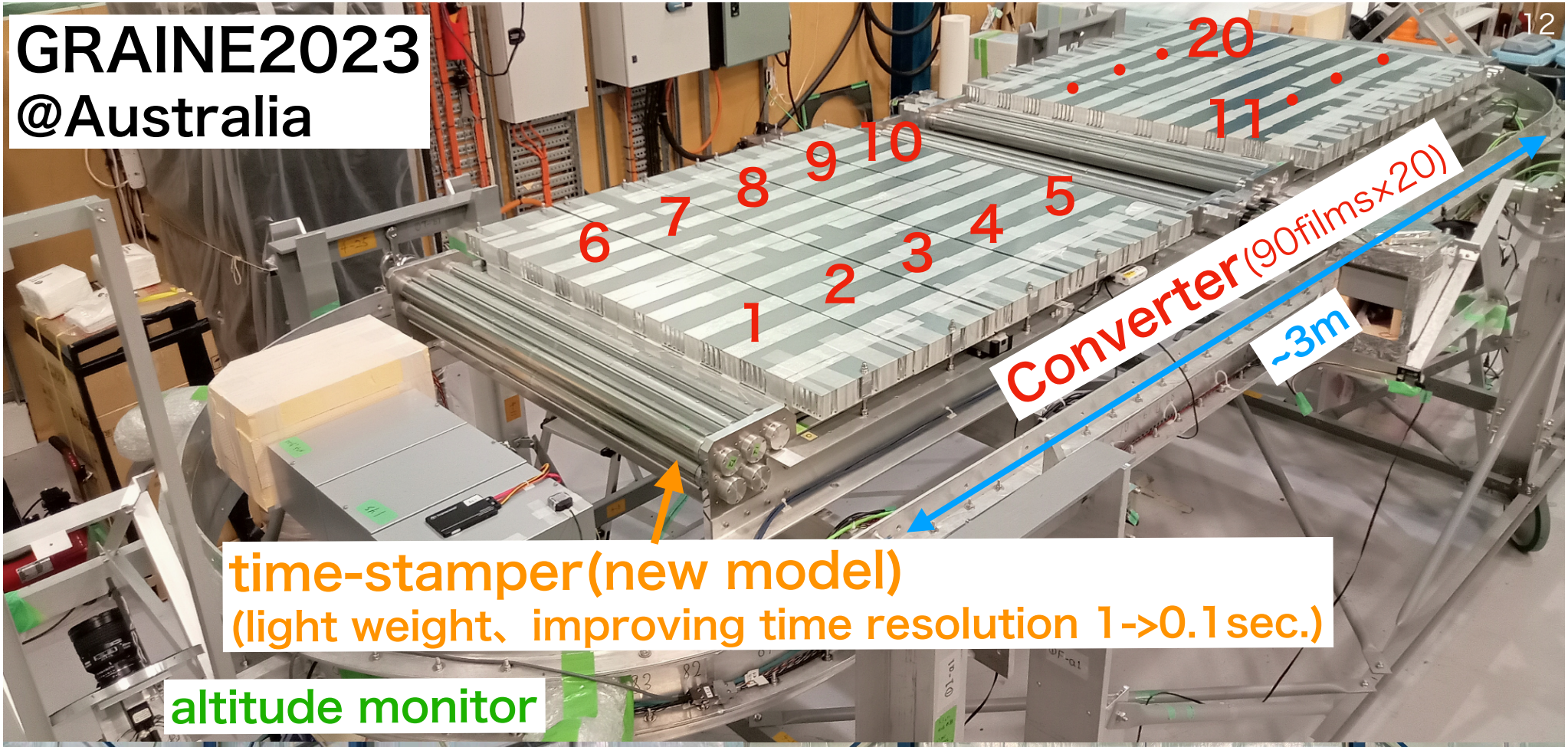
takahashi et al., 2024 ApJ 960 47

Imaging with the highest resolution in sub-GeV

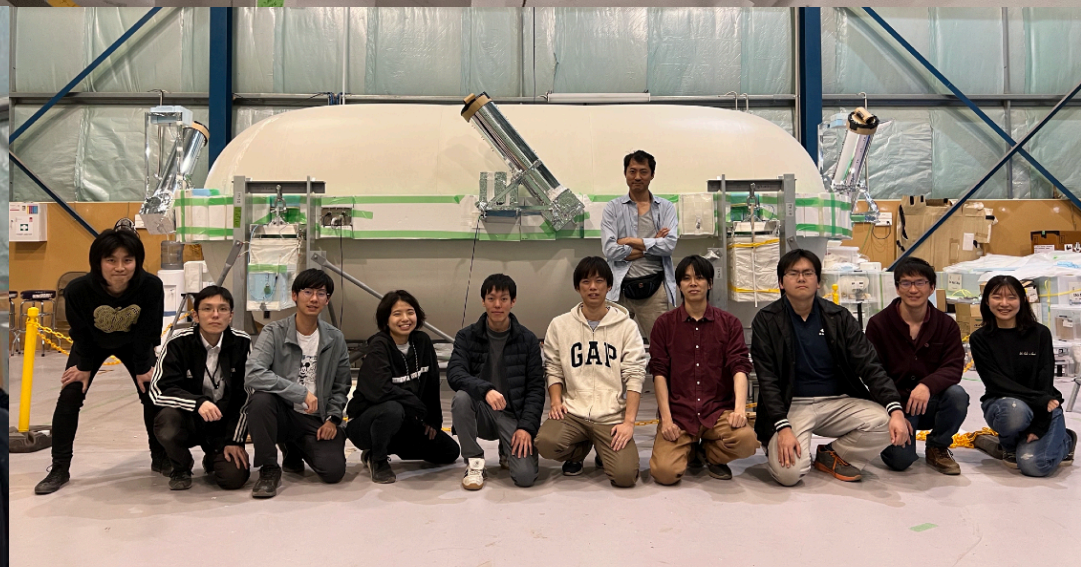
Preliminary predictions for GRAINE2023 observations



GRAINE2023 @Australia



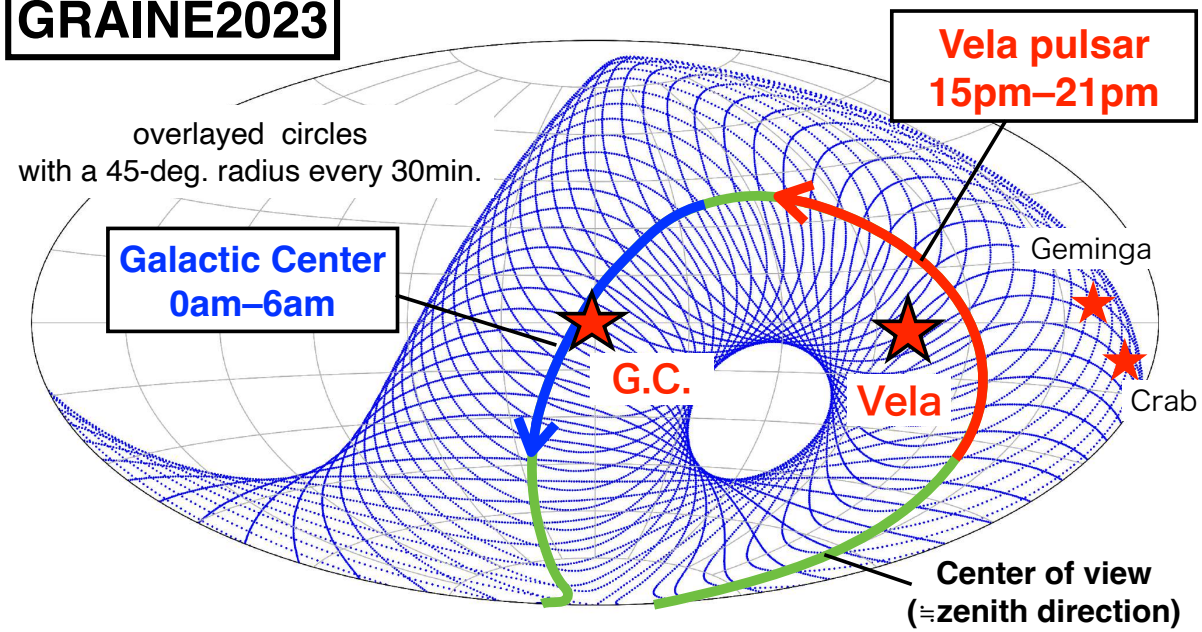
pressure vessel gondola



Launching on Apr. 30th, 6:32am

Balloon was successfully released by the JAXA team

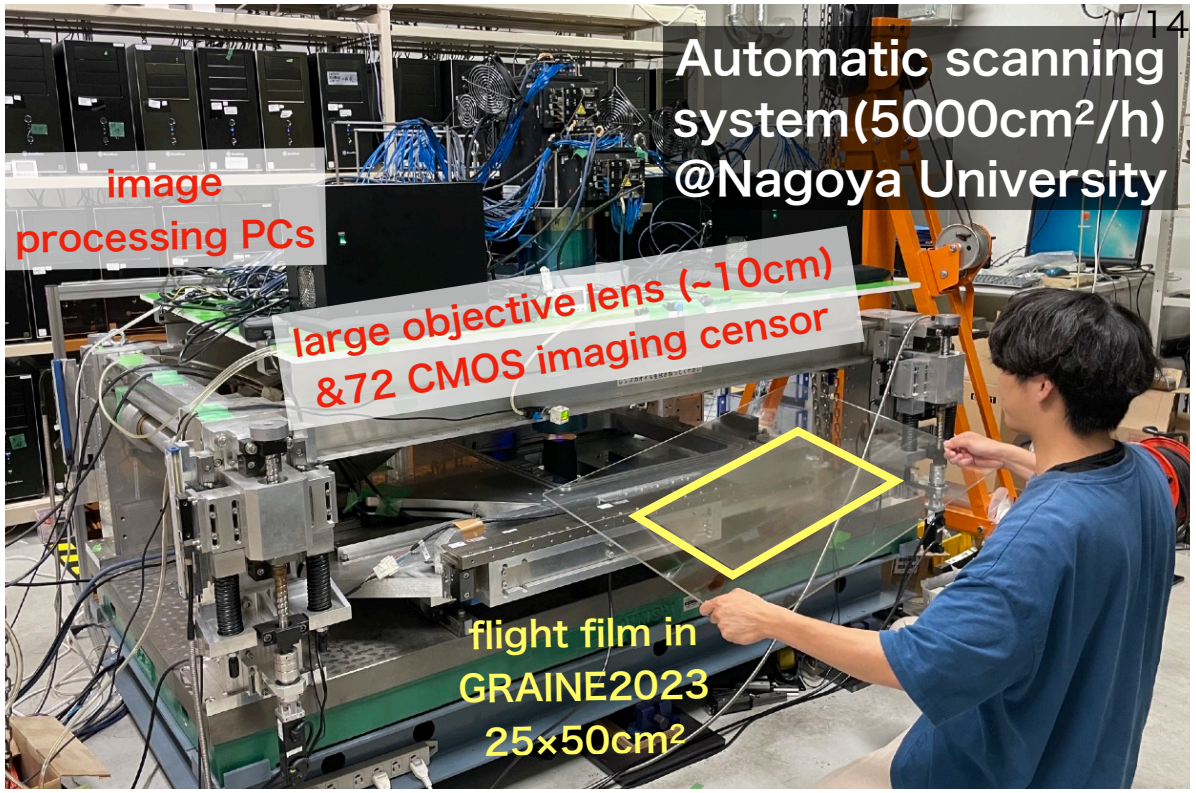
Celestial regions observed by the Emulsion Telescope (FoV ±45°)

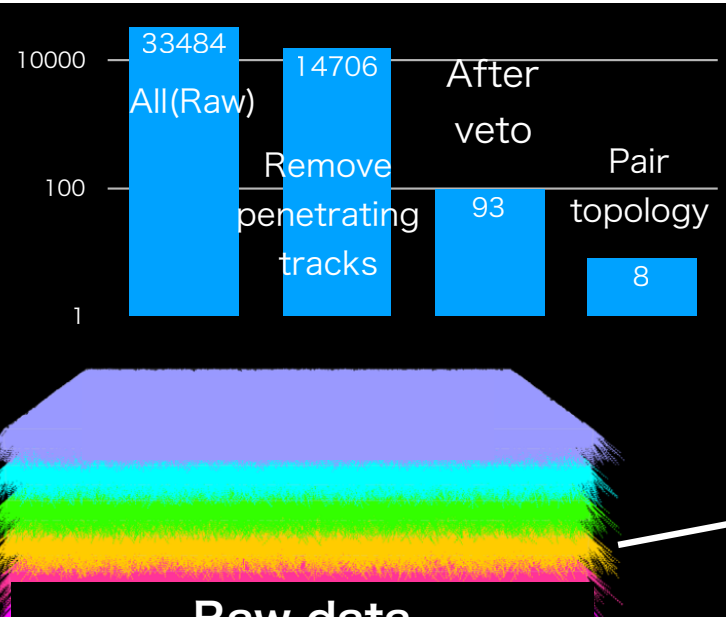


Our gondola

photo by JAXA

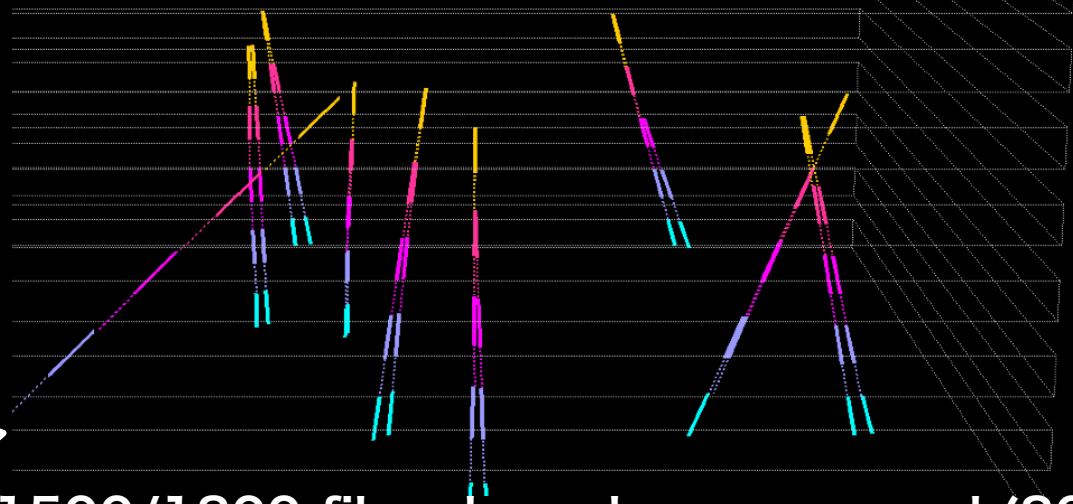
Data taking w/ the high-speed emulsion scanning system





Raw data
~ 2×10⁵ tracks/cm²

scanning & γ-ray detection is ongoing!



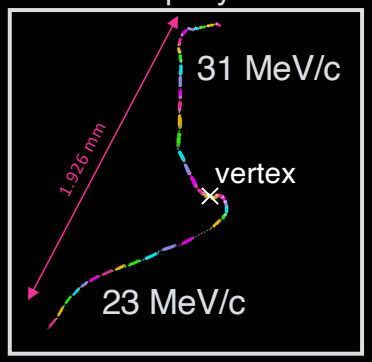
1500/1800 films have been scanned (80%)

>10⁷ γ-ray events have been detected

Detected “e-pair” event topologies

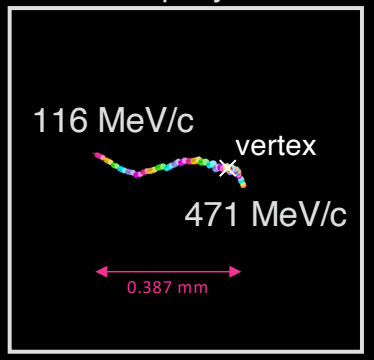
unit 10
start_pl 25
gid 6915973
θ_zenith 29.6°
θ_open 5.17°
E_gamma
$54_{\pm 19}$ MeV

View from γ-ray direction

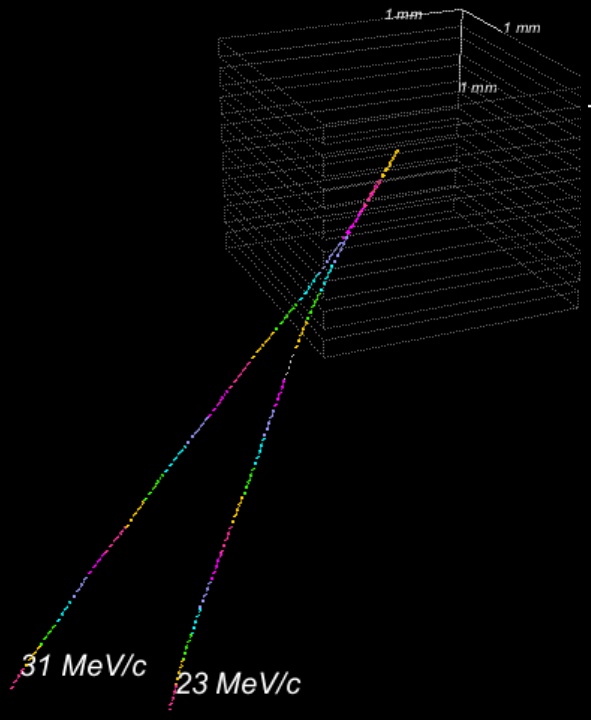


unit 10
start_pl 25
gid 8237284
θ_zenith 30.5°
θ_open 1.36°
E_gamma
$587_{\pm 204}$ MeV

View from γ-ray direction

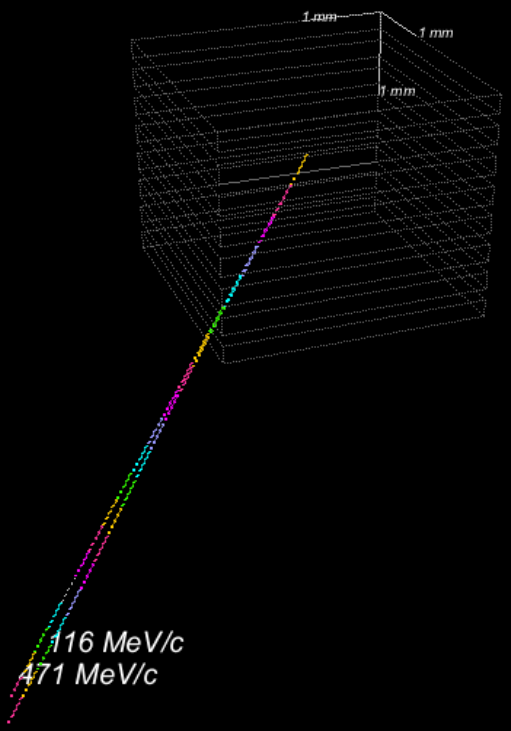


1mm



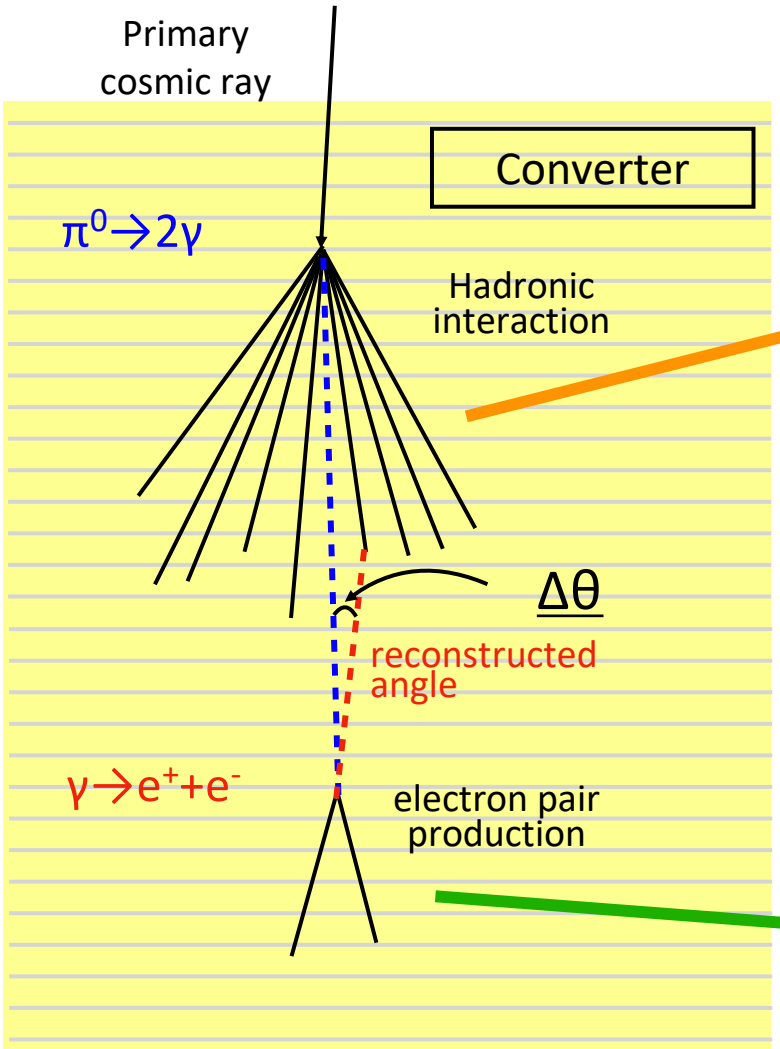
Angular difference
→Track momentum

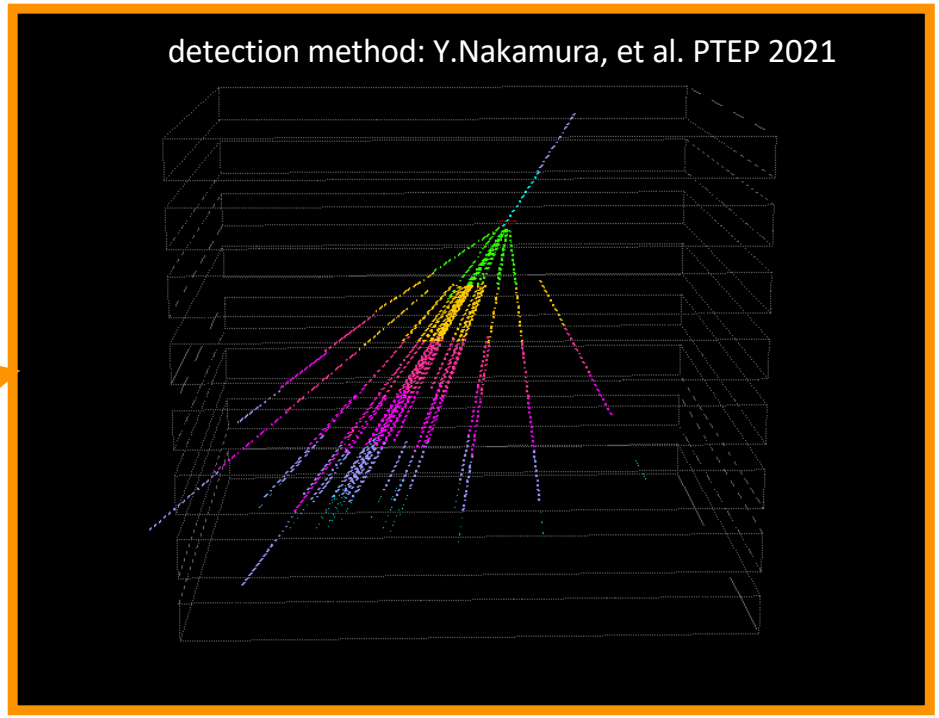
$$\theta_{RMS} = \frac{13.6}{P}\sqrt{x/X_0}$$

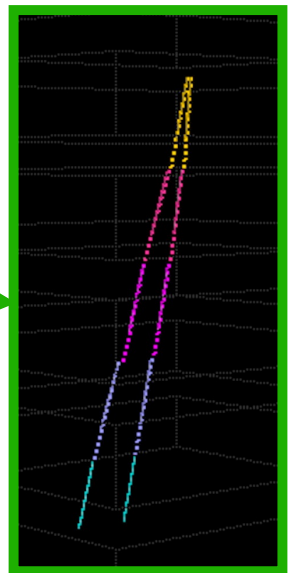


Performance of the angular measurement

① Internal calibration source







multiplicity >10($\tan\theta_\gamma$<1.0)

1.3×10^4 events

(searched with 156 films)

incident angle ($\tan\theta_\gamma$): 0.0-1.0

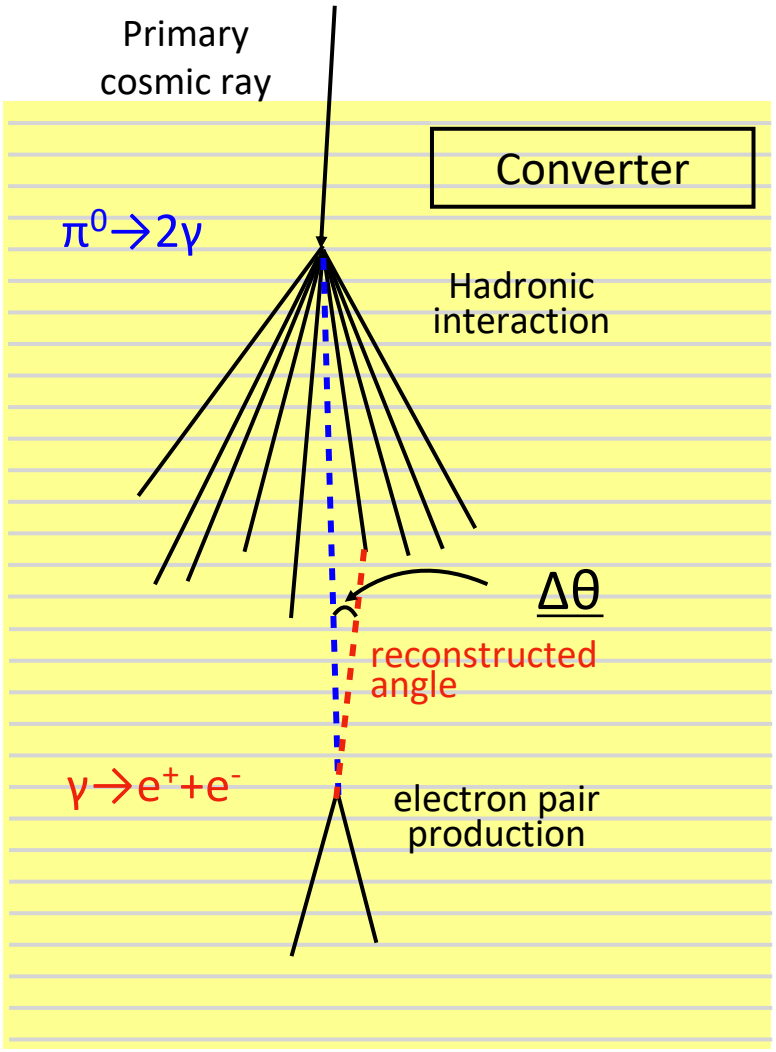
energy range: 100-400MeV

6.8×10^6 events

(searched with 140 films)

Performance of the angular measurement

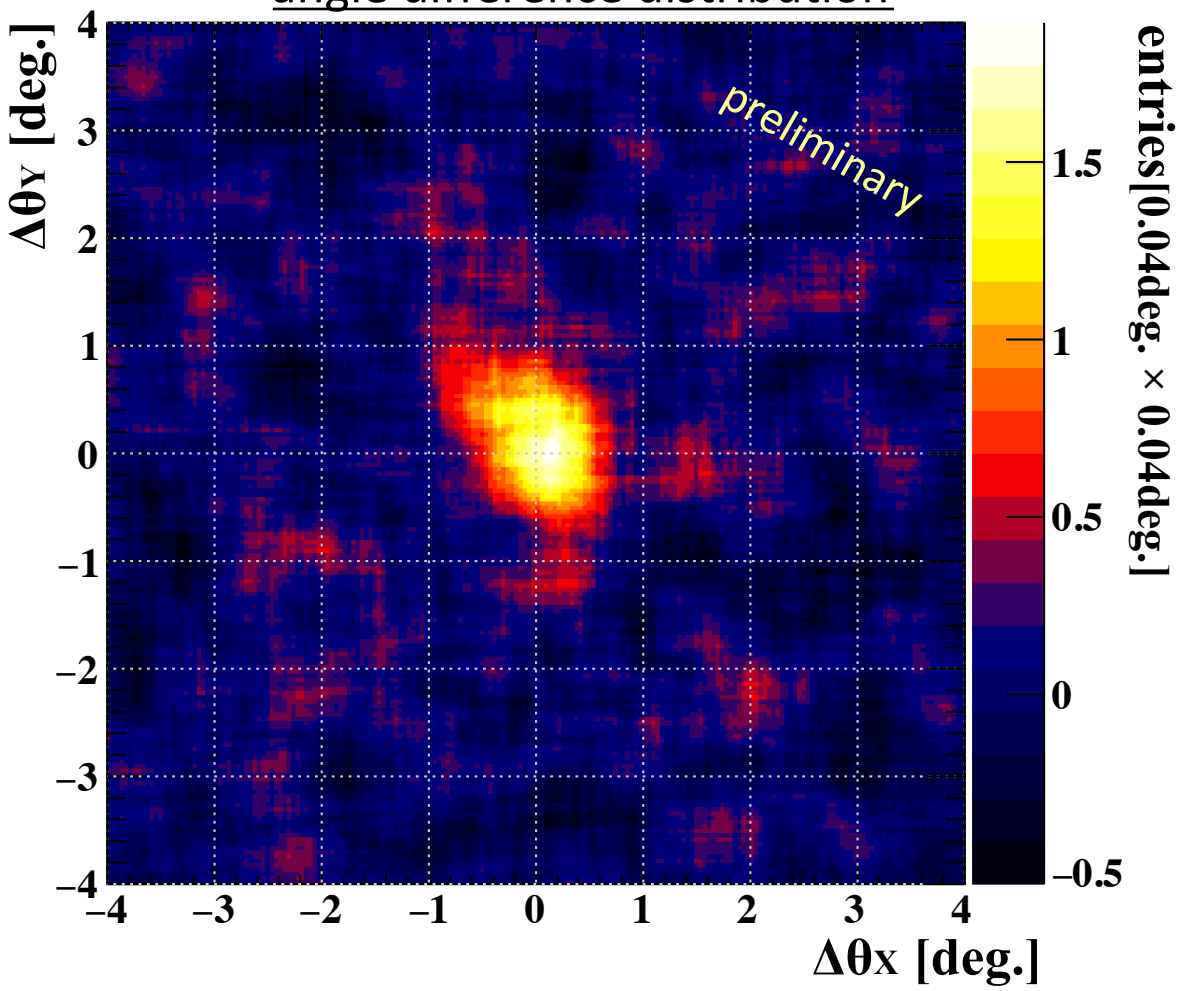
① Internal calibration source



Uncertainty of the expected direction: ~0.3deg.

after subtracting random BG
and smoothing

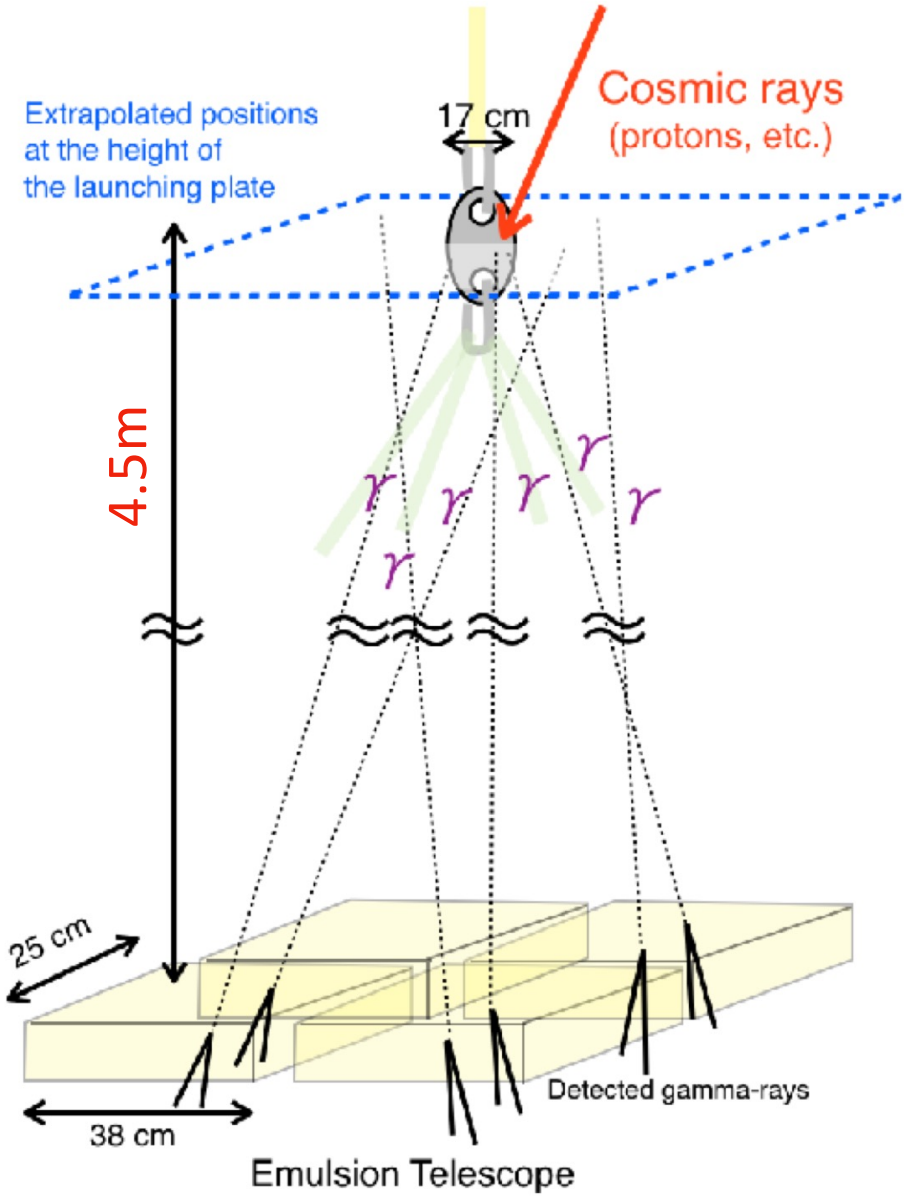
angle difference distribution

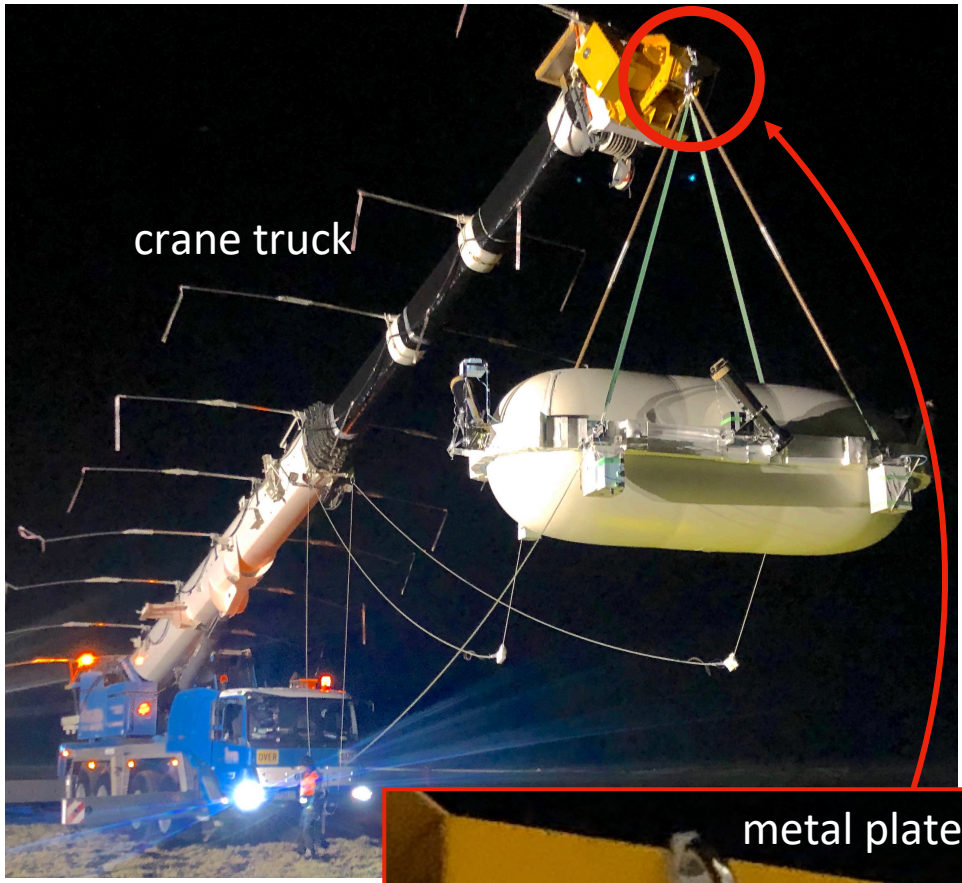


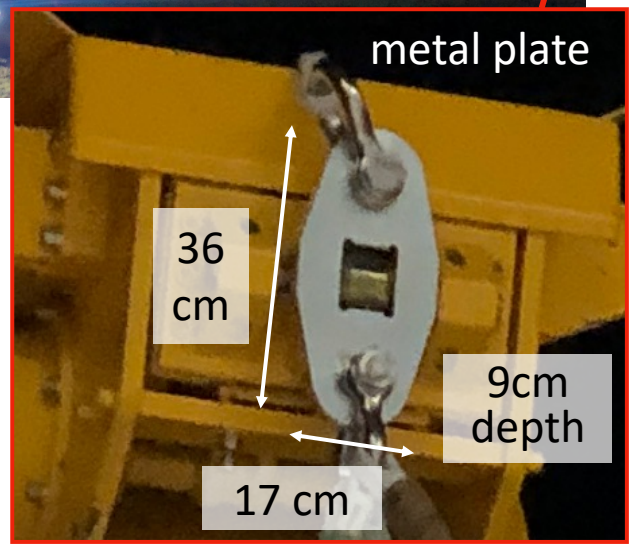
angular resolution:
0.64±0.12deg.($E_{ave.}$ ~250MeV)
(expected value: 0.65deg.)

Performance of the angular measurement

② External calibration source



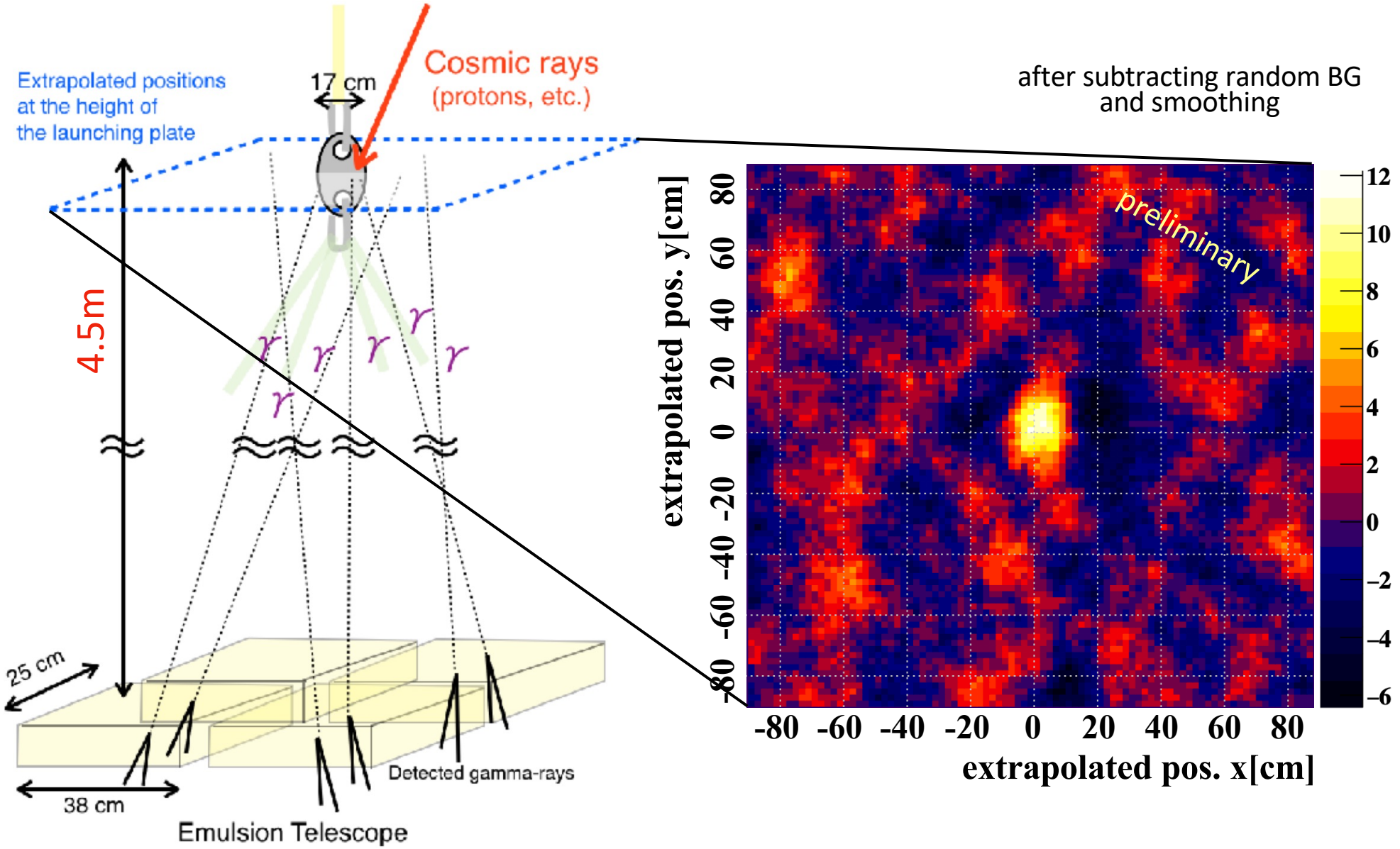




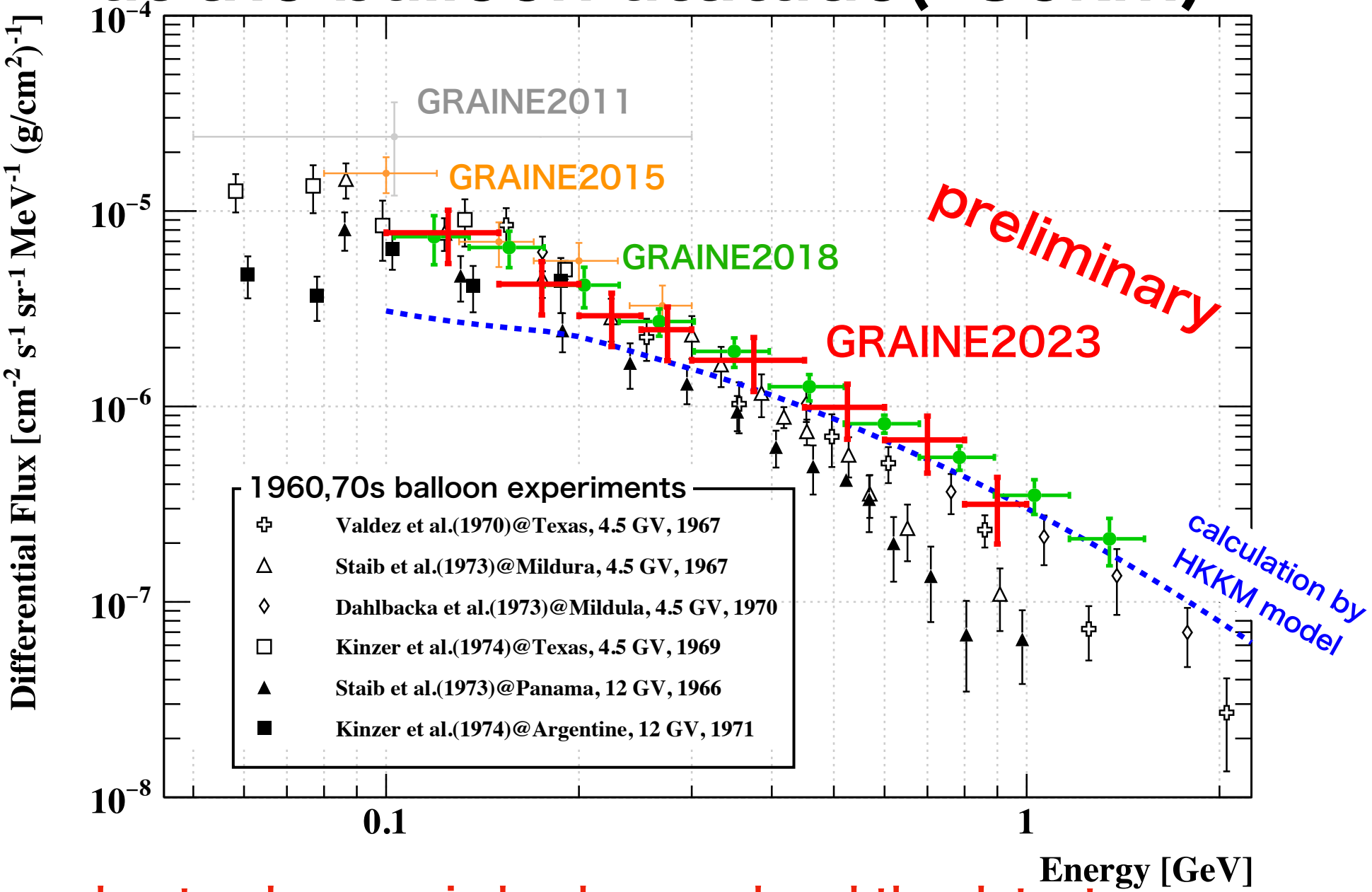
connecting
our gondola and
the balloon

Performance of the angular measurement

② External calibration source



Atmospheric gamma-ray observation at the balloon attitude(~36km)



We understand our main background and the detector response

Summary

Prototype Phase

2004- Technology development

2011 1st Balloon experiment
(0.01m² @Japan w/ JAXA)

Demonstration phase

2015 2nd Balloon experiment
(0.38m²@Australia w/ JAXA)

2018 3rd Balloon experiment
(0.38m²@Australia w/ JAXA)

Scientific phase

2023 4th Balloon experiment
(2.5m²@Australia w/ JAXA)

2027? 5th Balloon experiment

GRAINE project : Cosmic γ-ray observation w/ the high angular resolution & the polarization sensitivity

We conducted 4th balloon experiment in 2023

Starting of the scientific observation

- Observation of the G.C. region w/ the highest resolution
- Trying to measure the polarization of the pulsar

Analysis in GRAINE2023 is ongoing now

-Basic performances are well consistent with the expected values

-Observed atmospheric γ-ray is consistent with the previous experiments

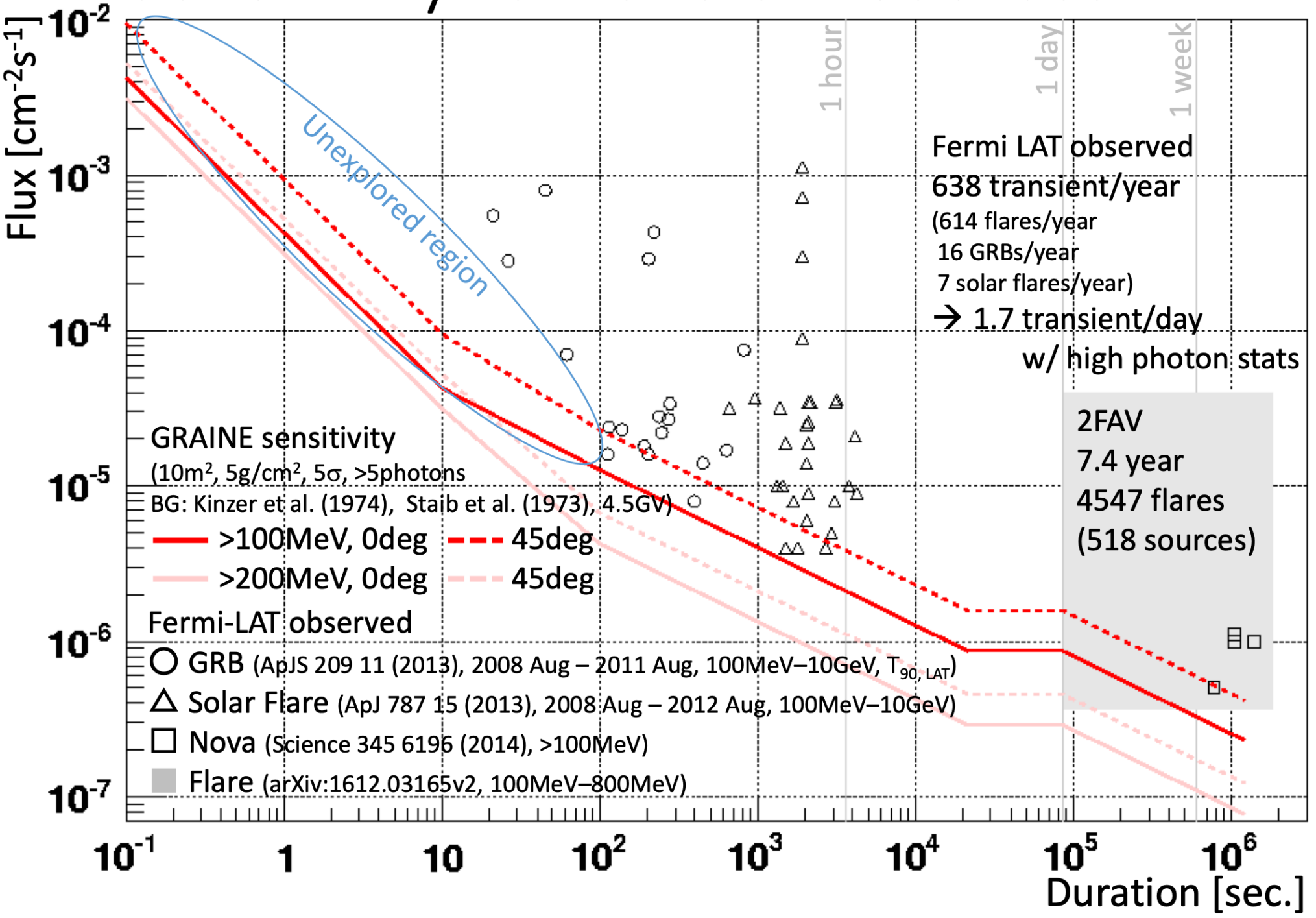
-Analysis for the astronomical sources is ongoing

In the future, we want to conduct repeatedly balloon experiments with larger aperture area / longer flight duration

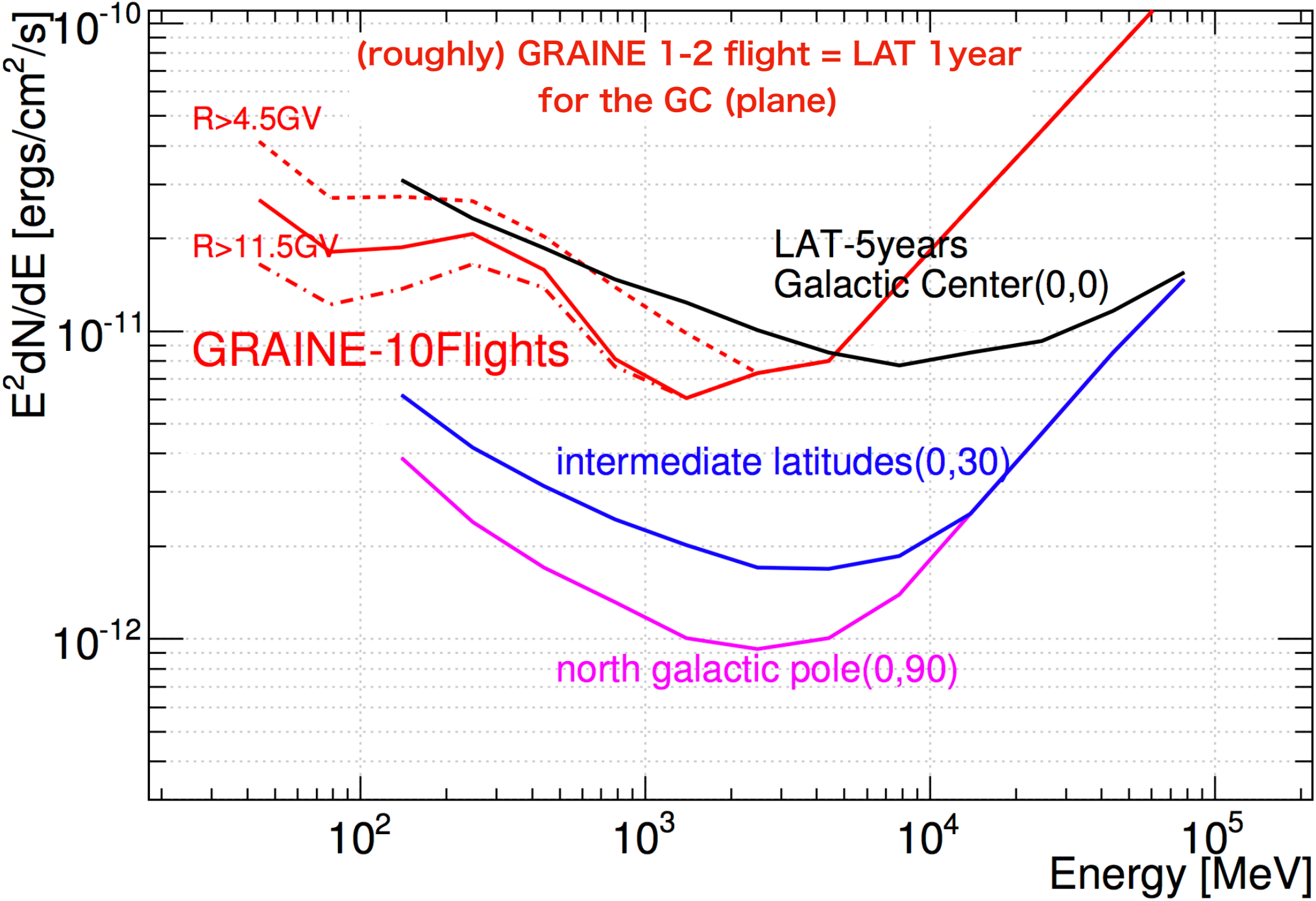
*10m² apperture area

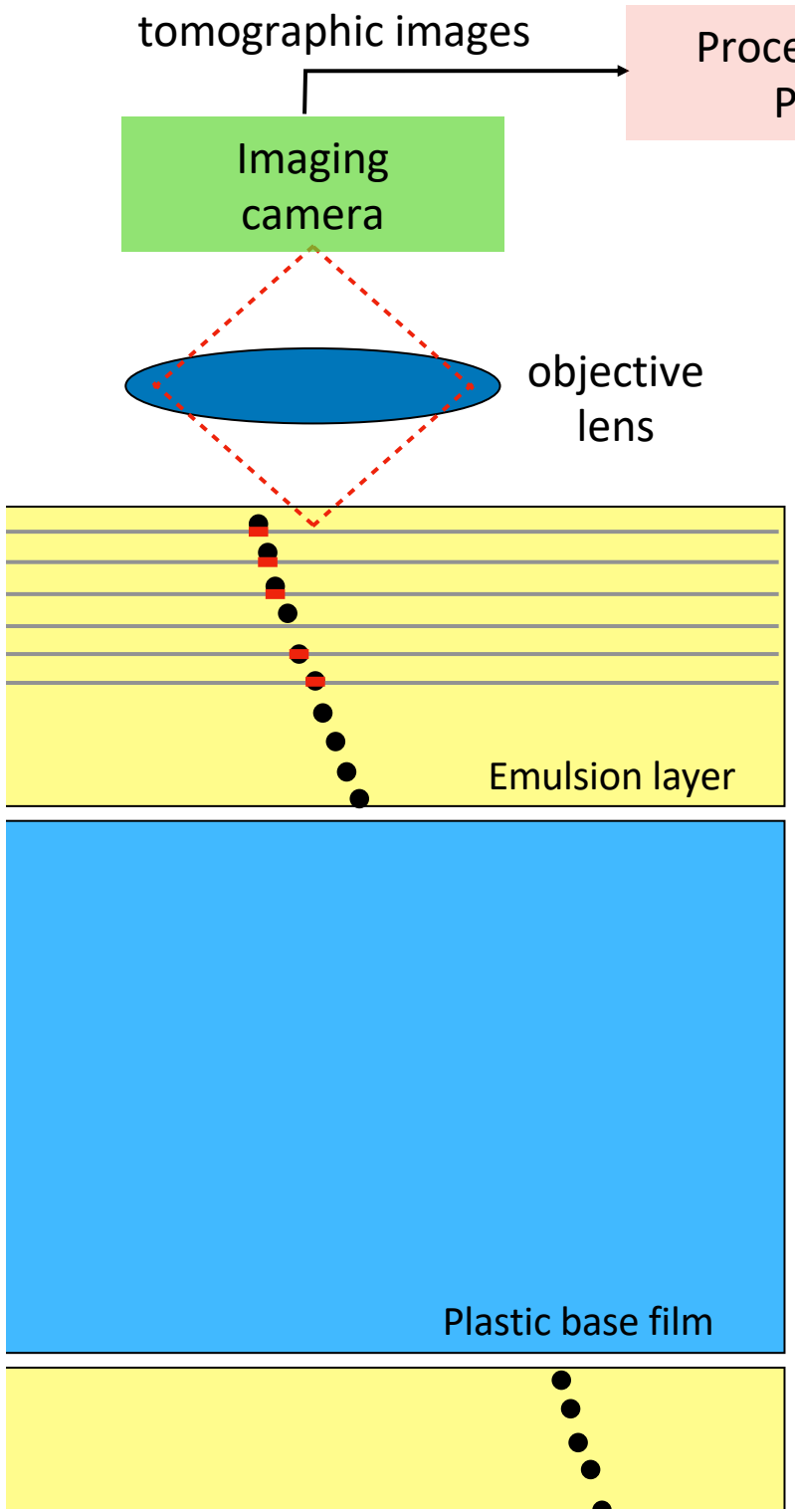
	Fermi-LAT	GRAINE
angular resolution@100MeV	6.0°	1.0°
angular resolution@1GeV	0.80°	0.1°
polarization	-	○
effective area@100MeV	0.25m²	2.1m² *
effective area@1GeV	0.88m²	2.8m² *

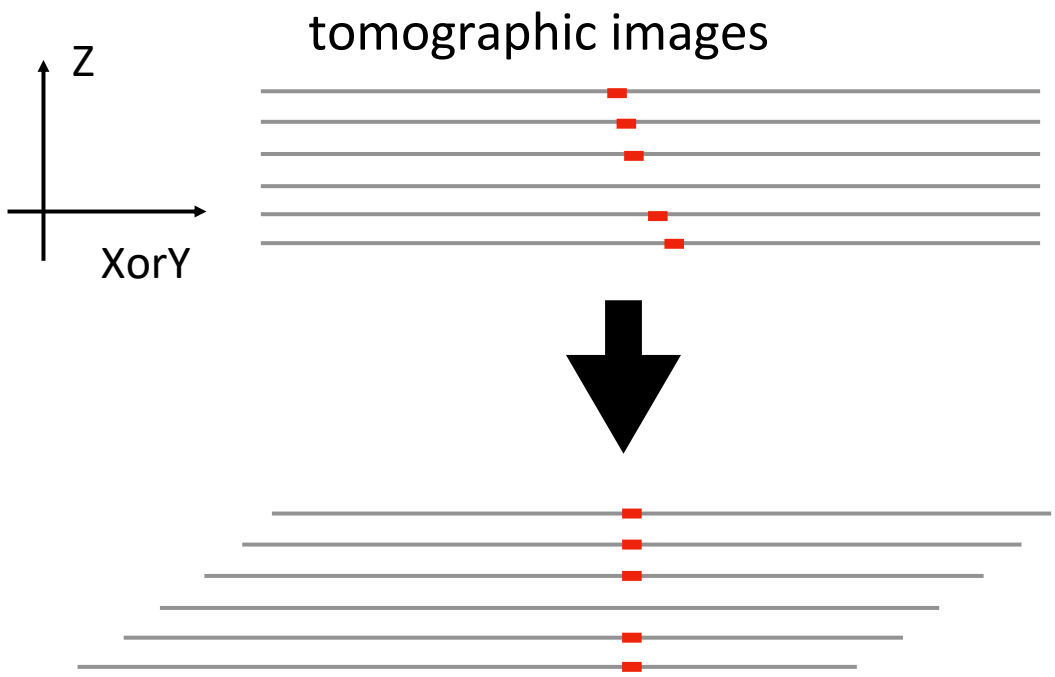
Sensitivity to transient sources



Differential Sensitivity

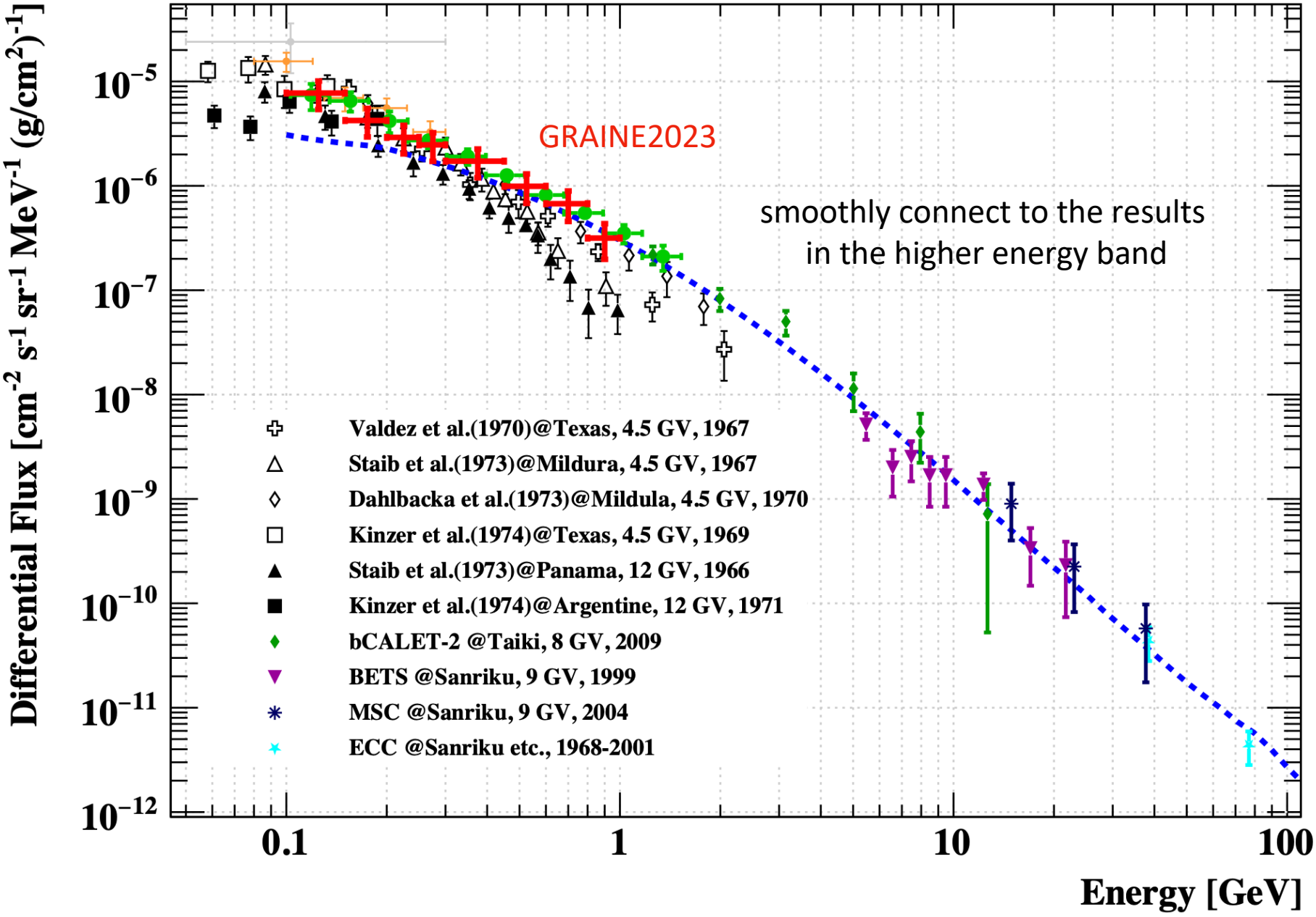






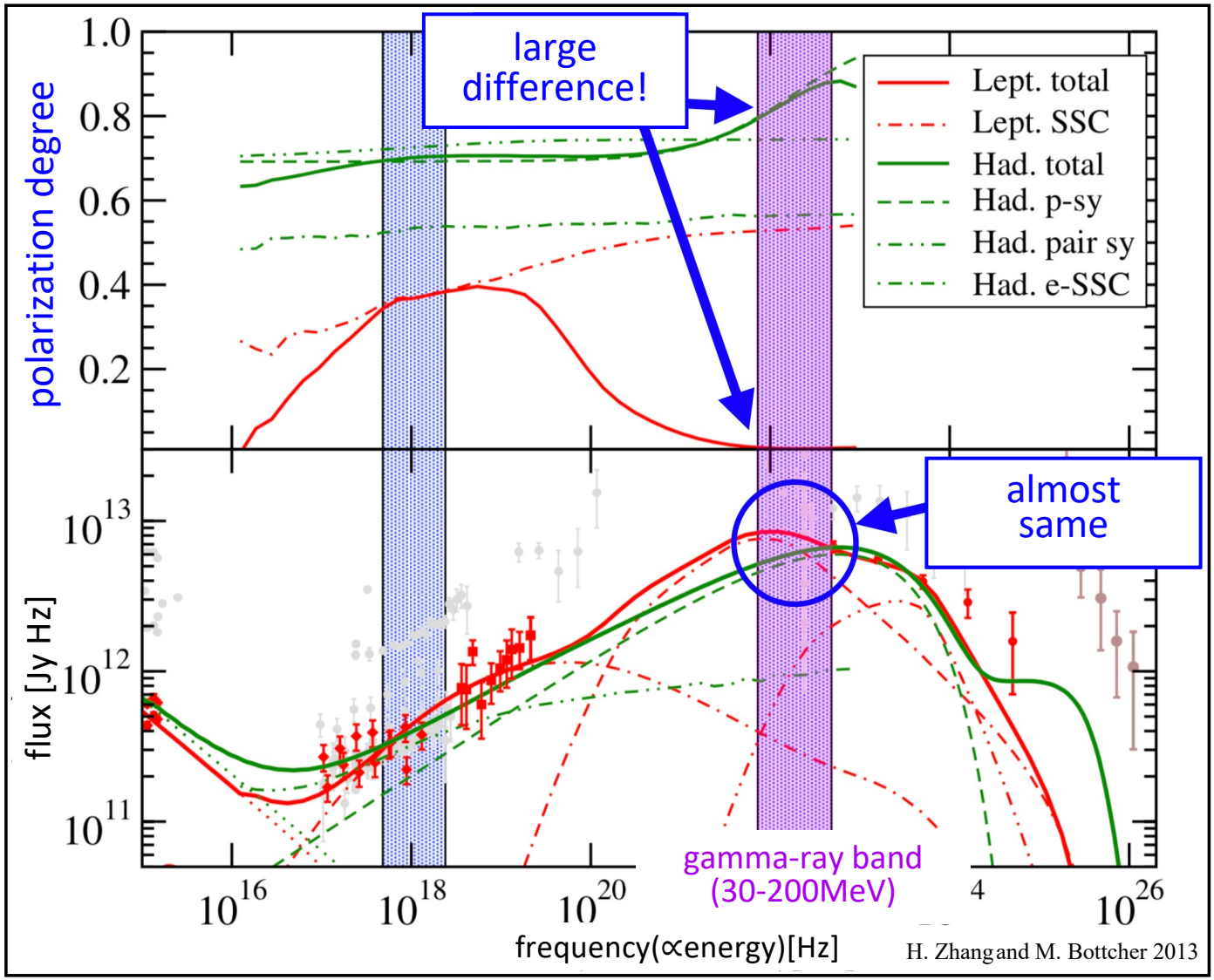
Shift the tomographic images
and sum up the hit pixels
Searching for straight lines

Atmospheric gamma-ray flux



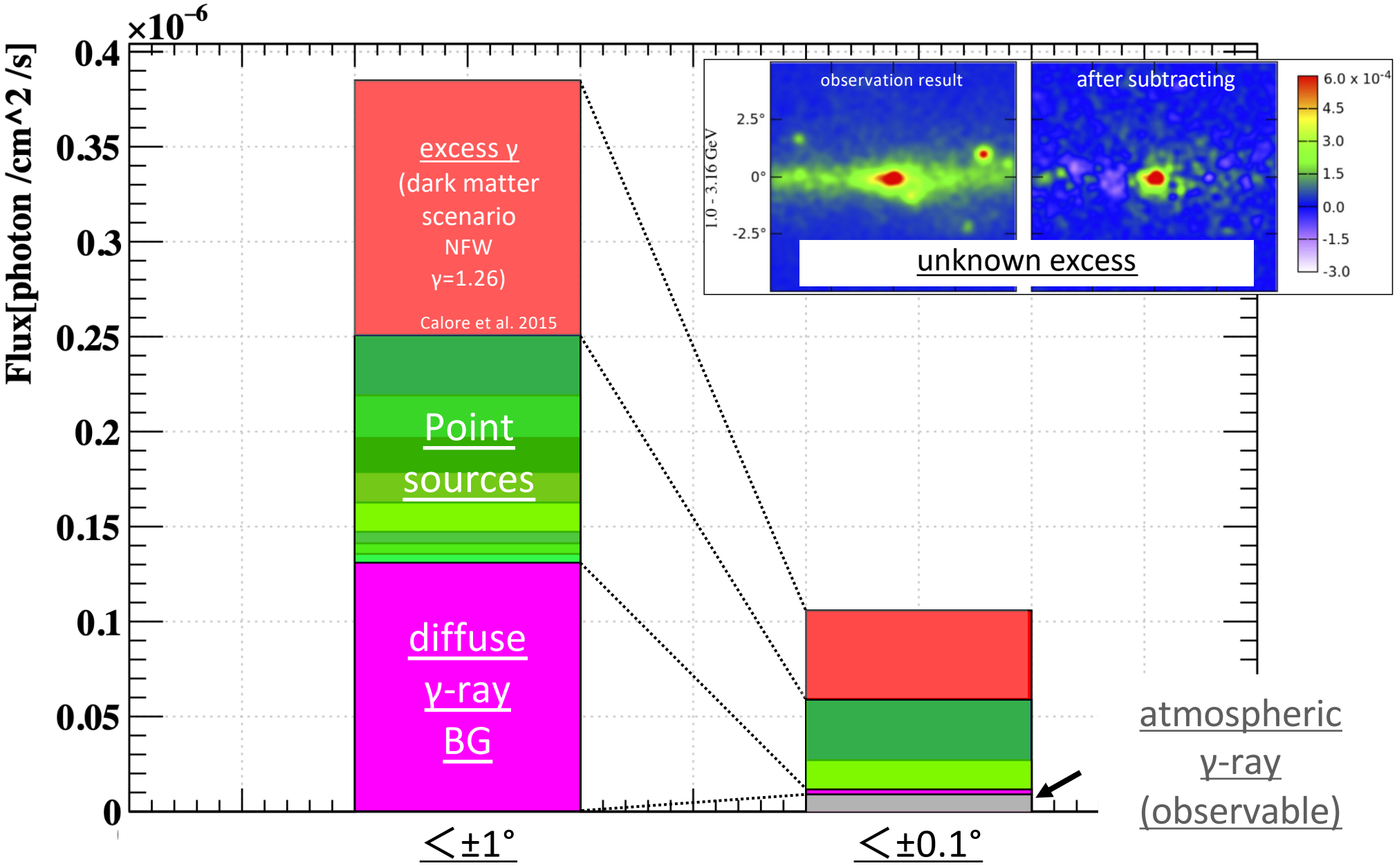
Effect of the polarization measurement

Expected for the FSRQ blazer(3C279)



completely new information !

unknown γ excess in the G.C.

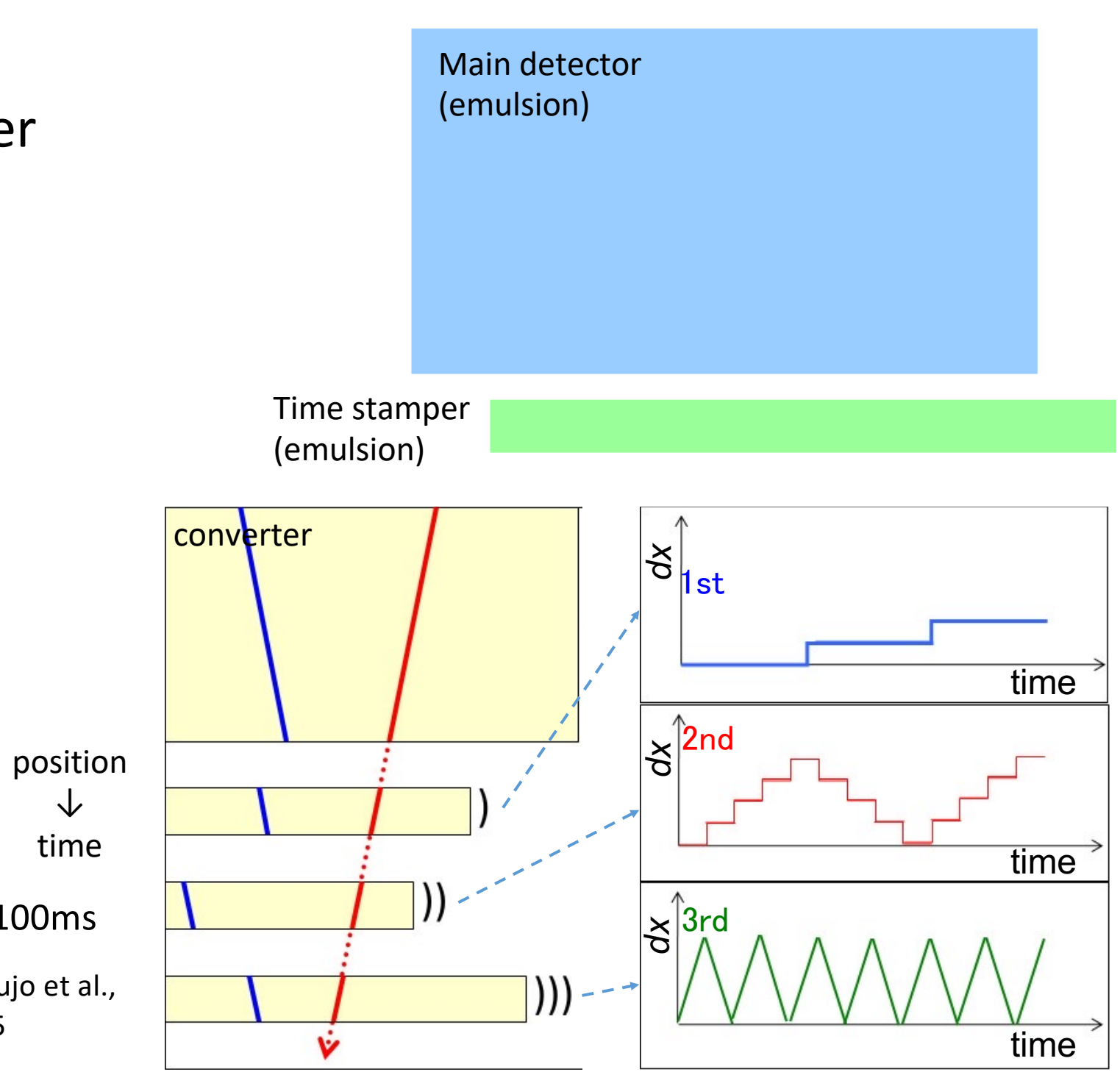


lower contamination of the BG uncertainty

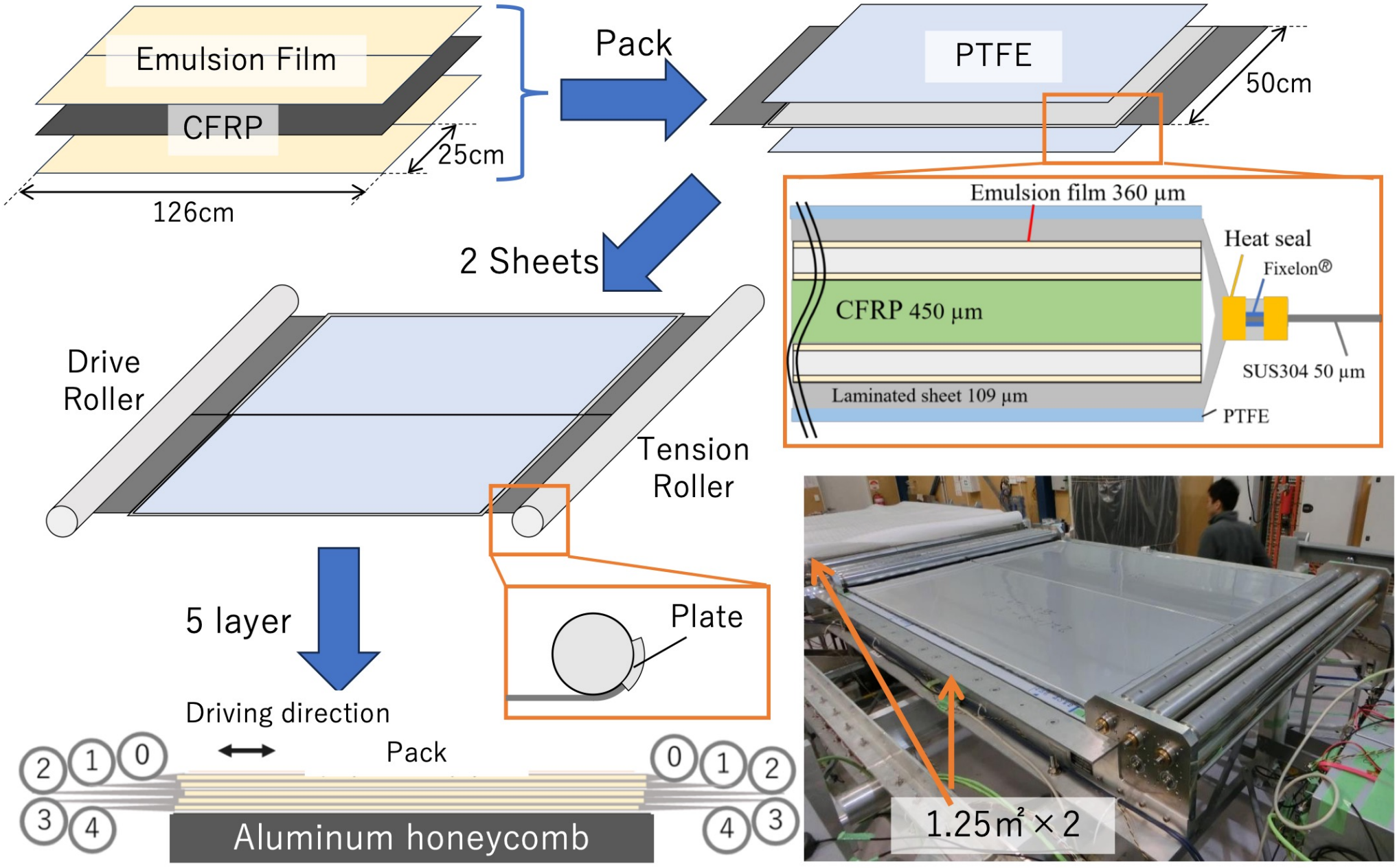
Time stamper emulsion shifter

Time resolution < 100ms

S.Takahashi, S.Aoki, H.Rokujo et al.,
NIM A, 620 (2010) 192-195

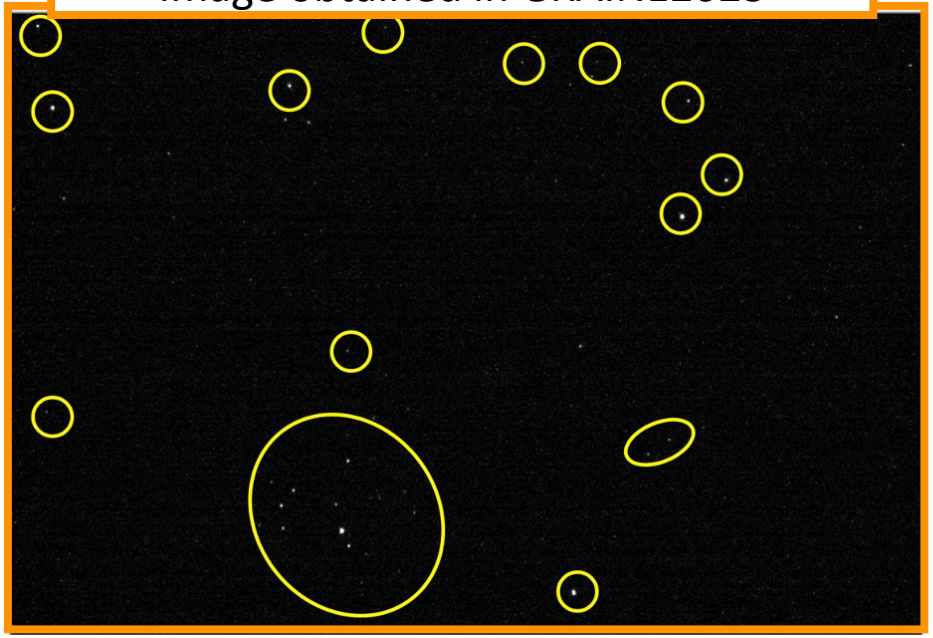


TimeStamper

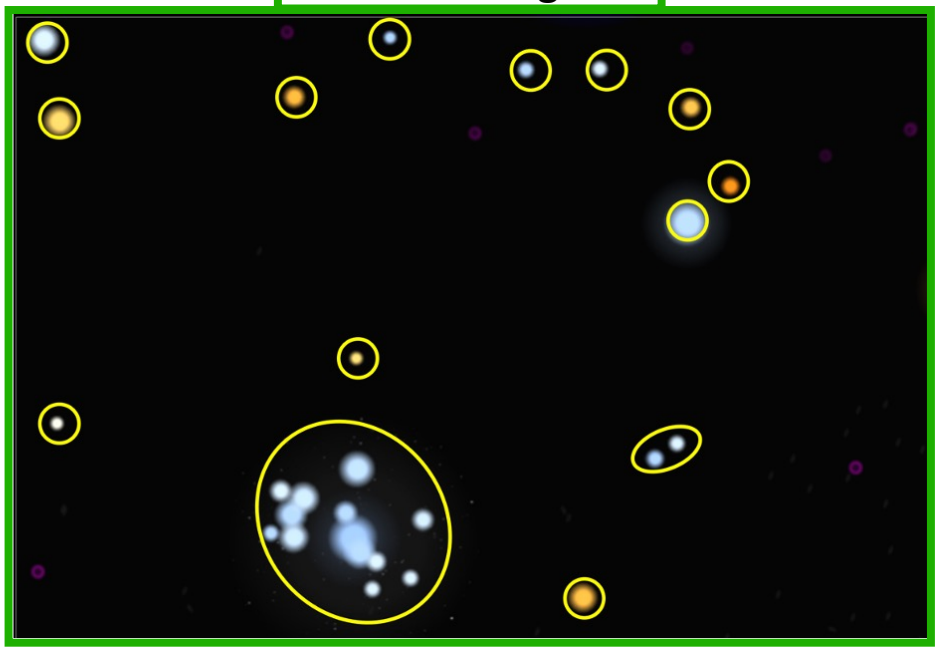


Star camera in GRAINE2023

Image obtained in GRAINE2023

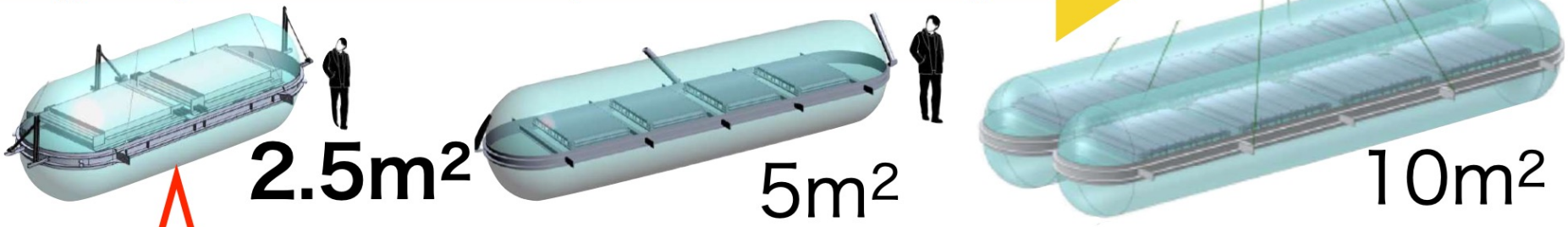


Star catalogue



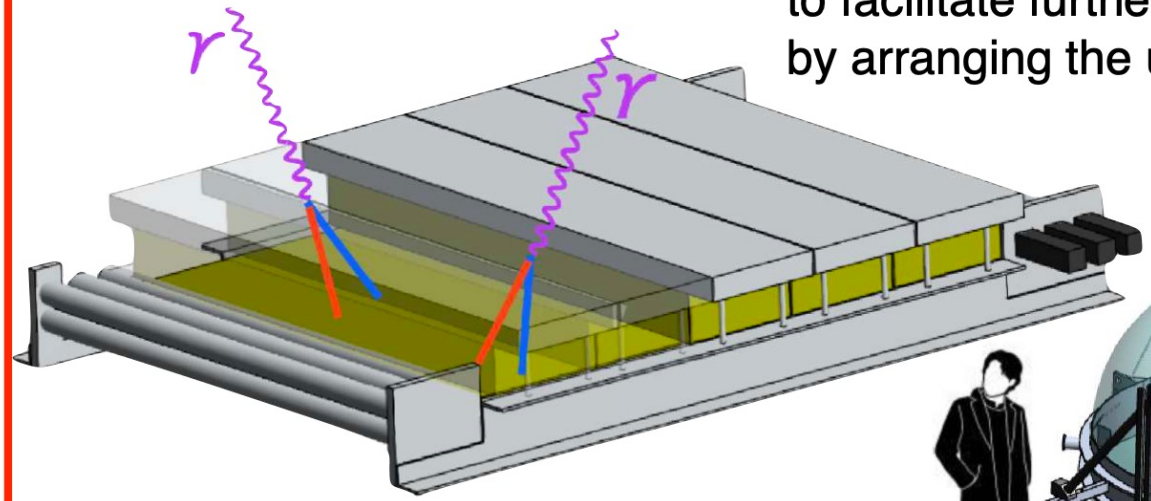
Towards Scientific Observation

Larger aperture area & repeated balloon flights

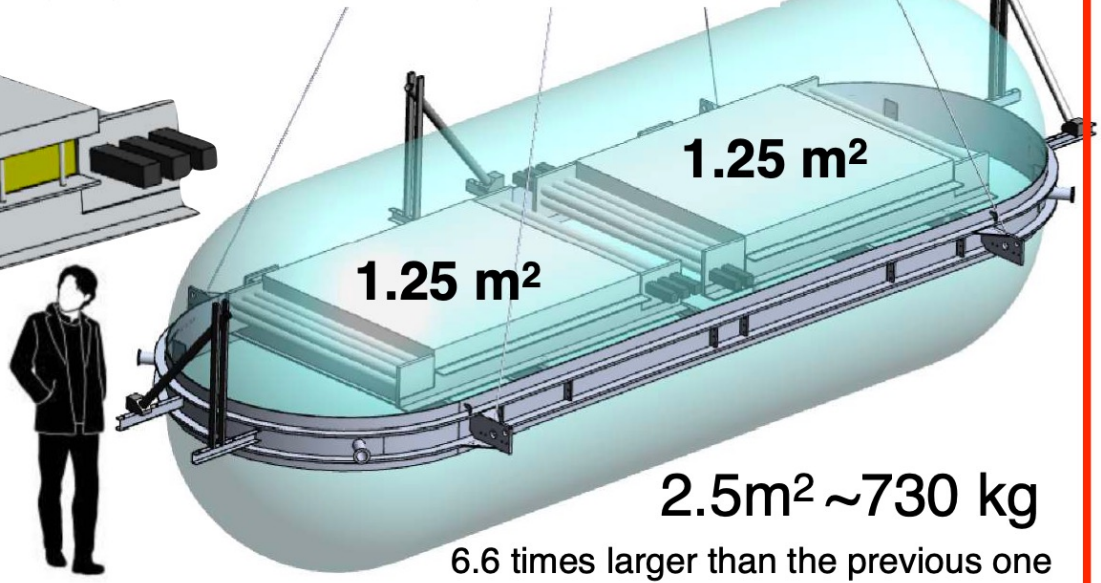


Unitized emulsion telescope (aperture: 1.25 m²)

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



Roller-driven timestamp mechanism
M.Oda et al., PTEP. 2022 113H03

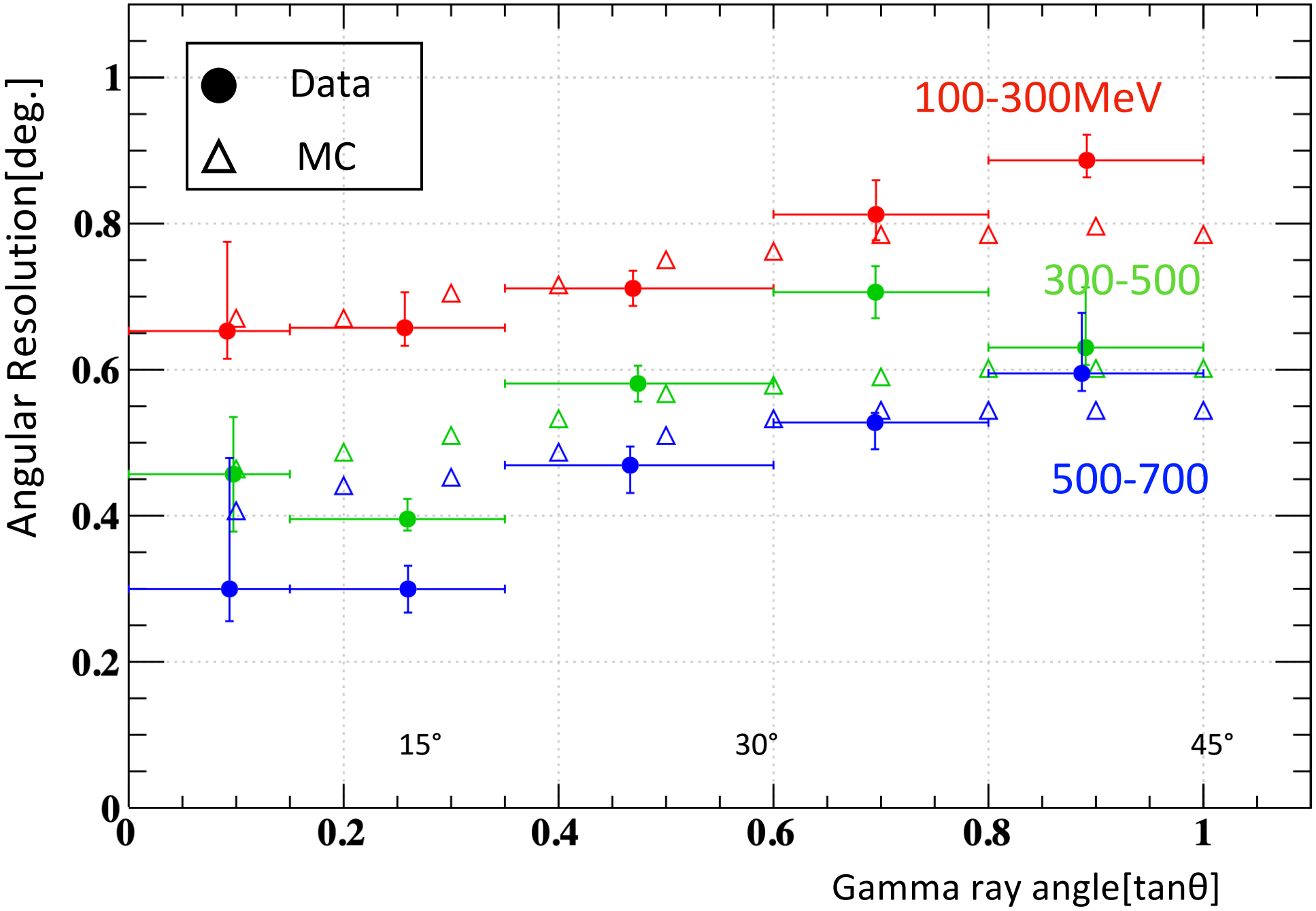


2.5m² ~730 kg
6.6 times larger than the previous one

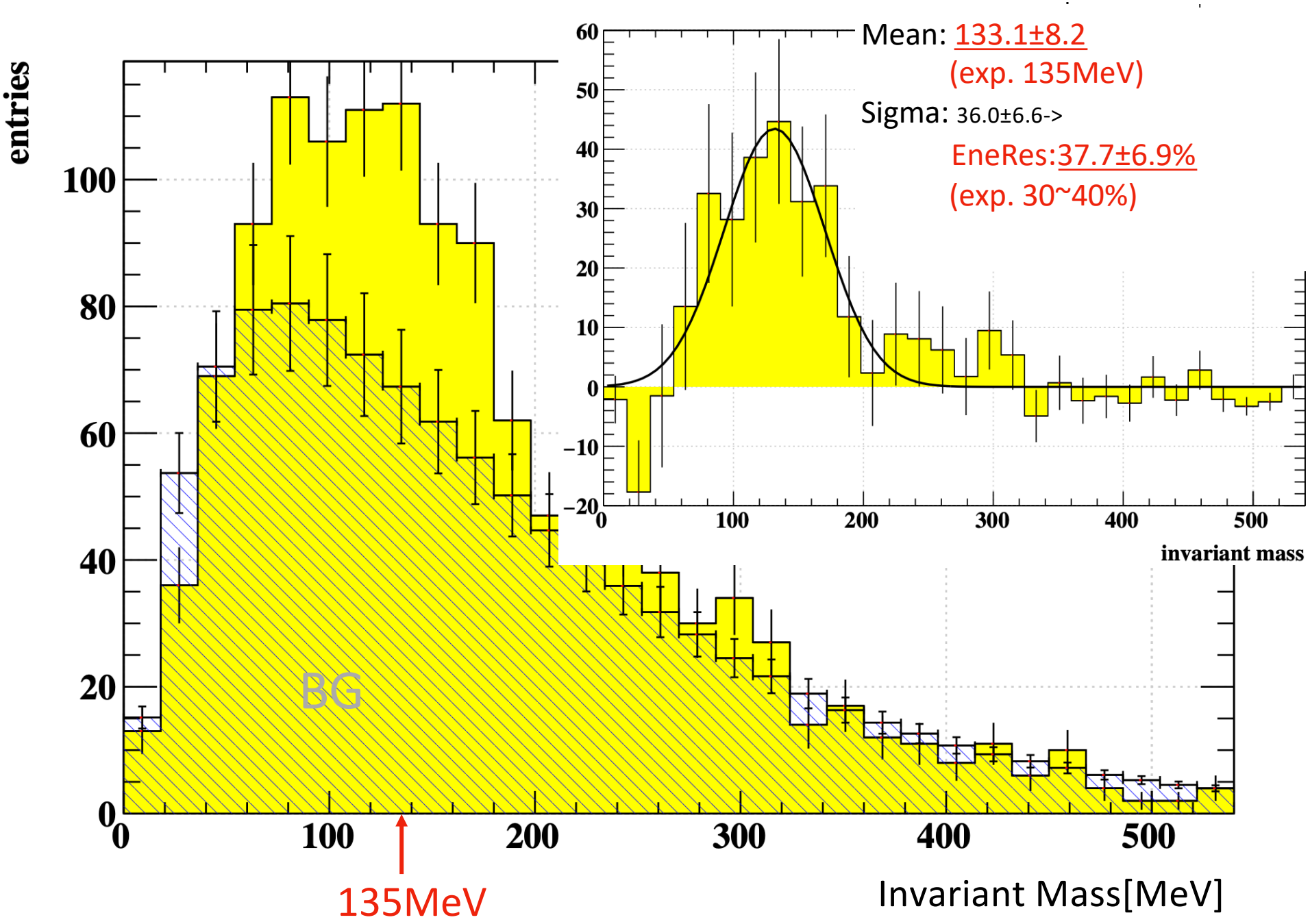
GRAINE2023

starts scientific observation with the newly developed models

Evaluation of the angular resolution

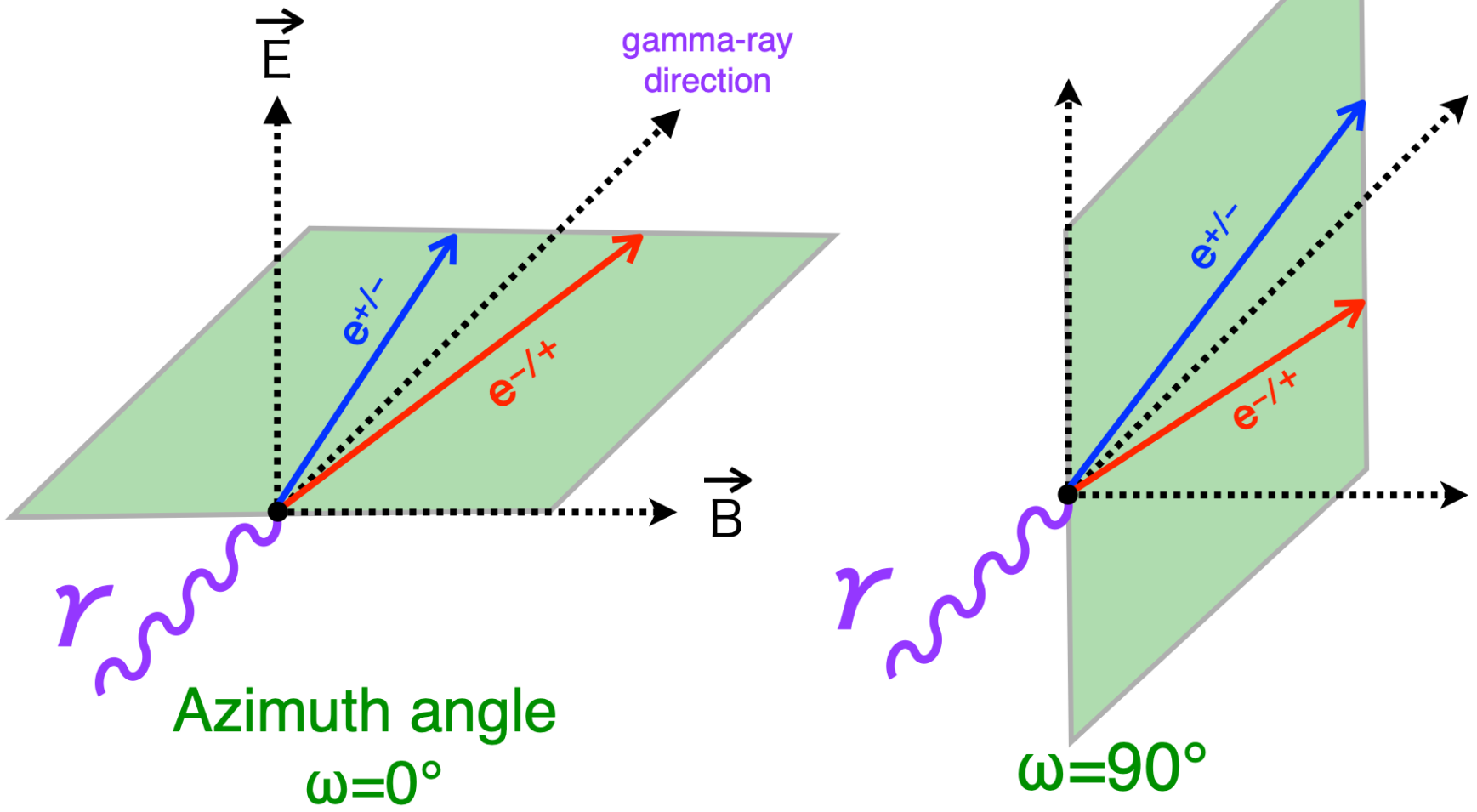


Evaluation of the energy measurement



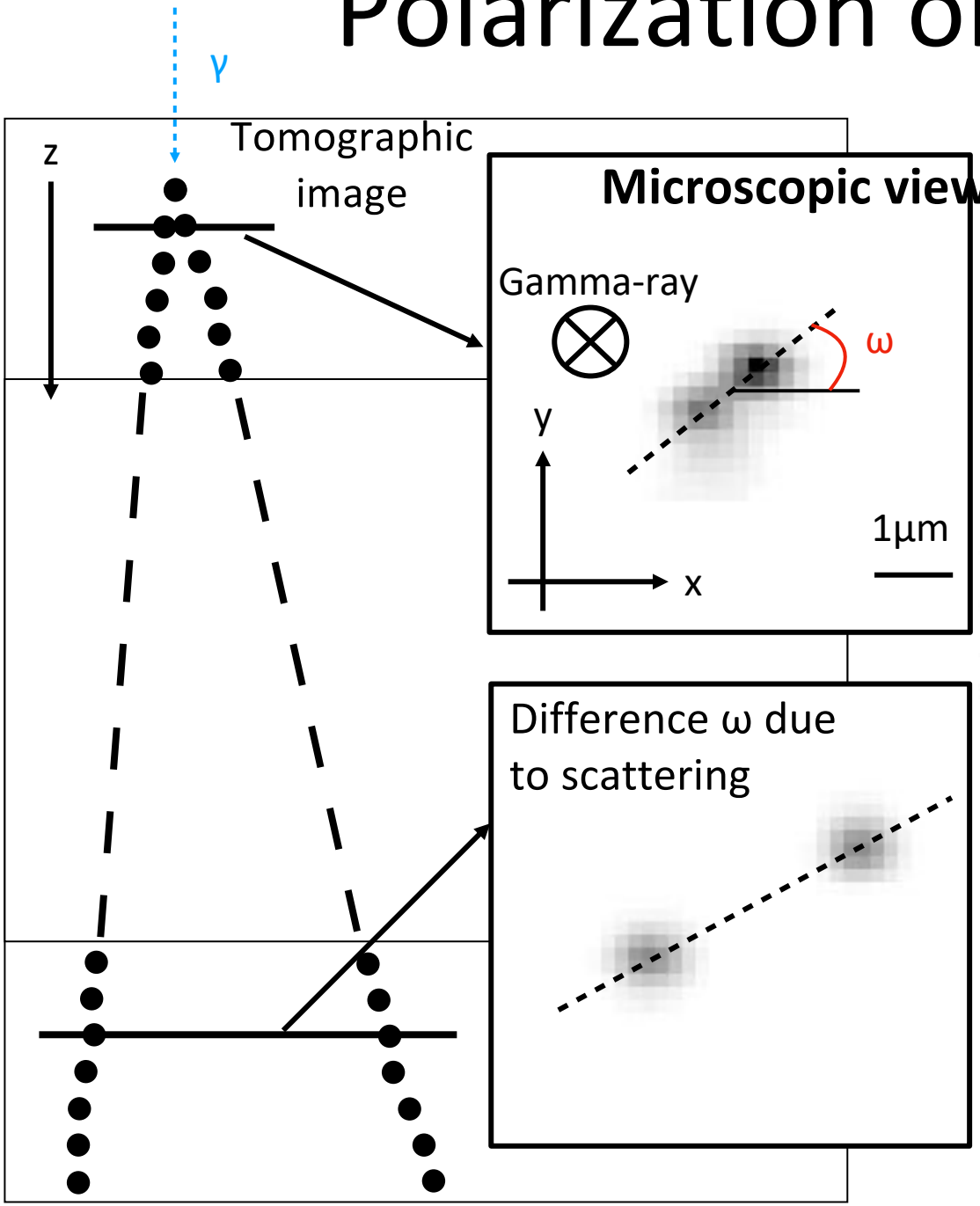
Measurement of gamma-ray polarization in the pair production mode

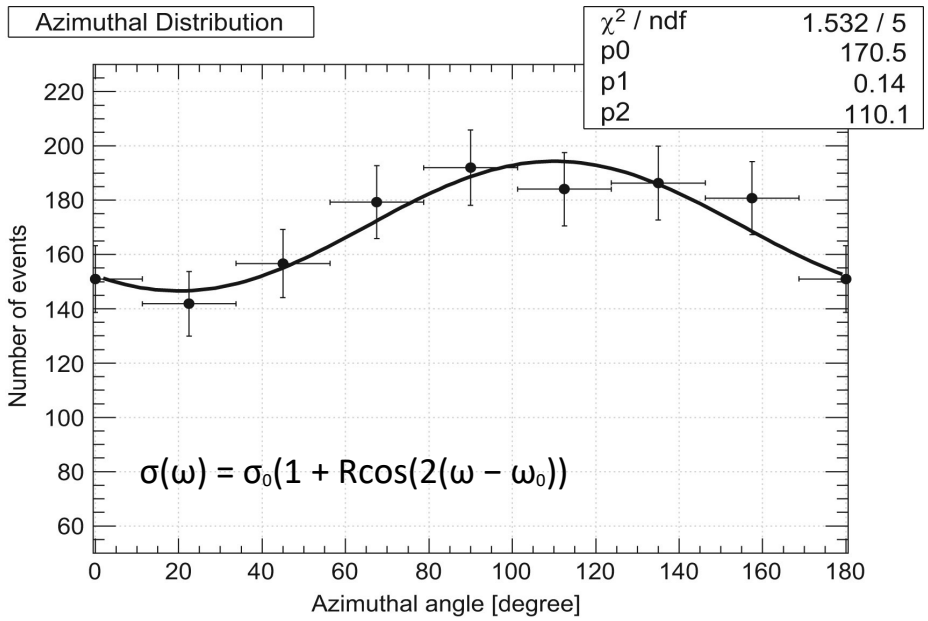
→Detect a slight bias in the azimuthal angle distribution of the accumulated events

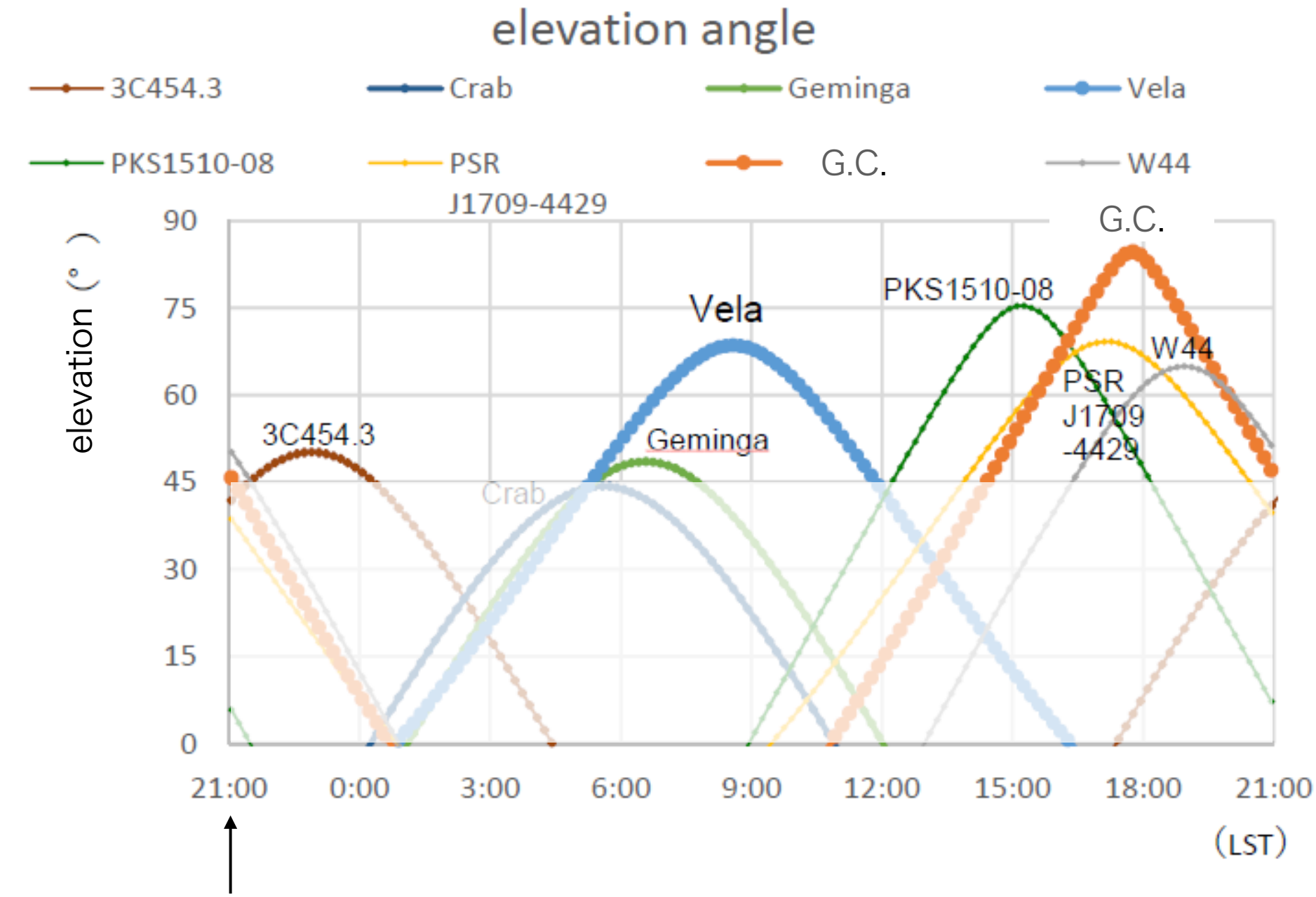


Measuring the azimuthal direction is extremely challenging due to multiple Coulomb scattering in detector

Polarization observation

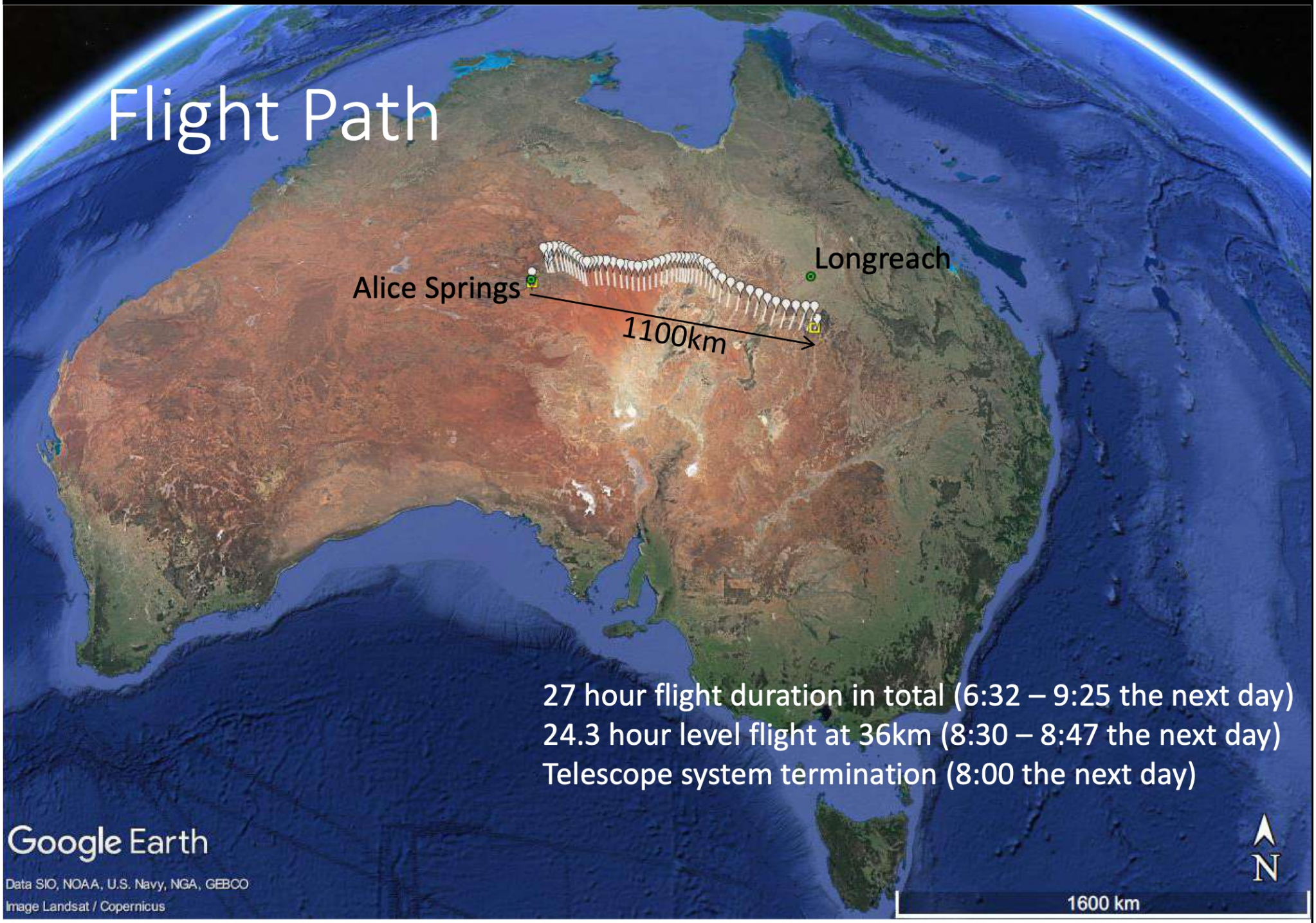






flight on Apr.(@Australia)
starting the level flight

Flight Path

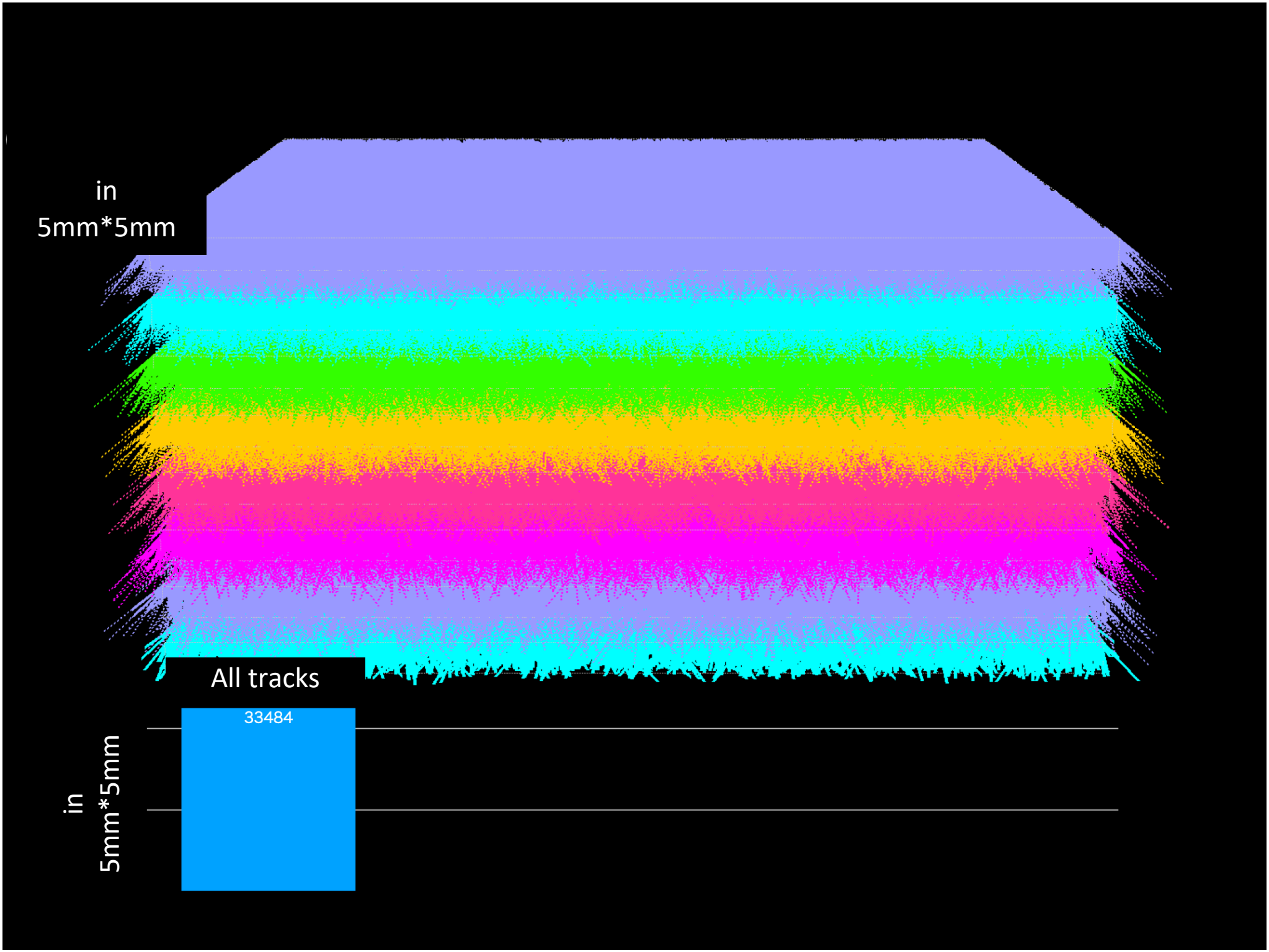


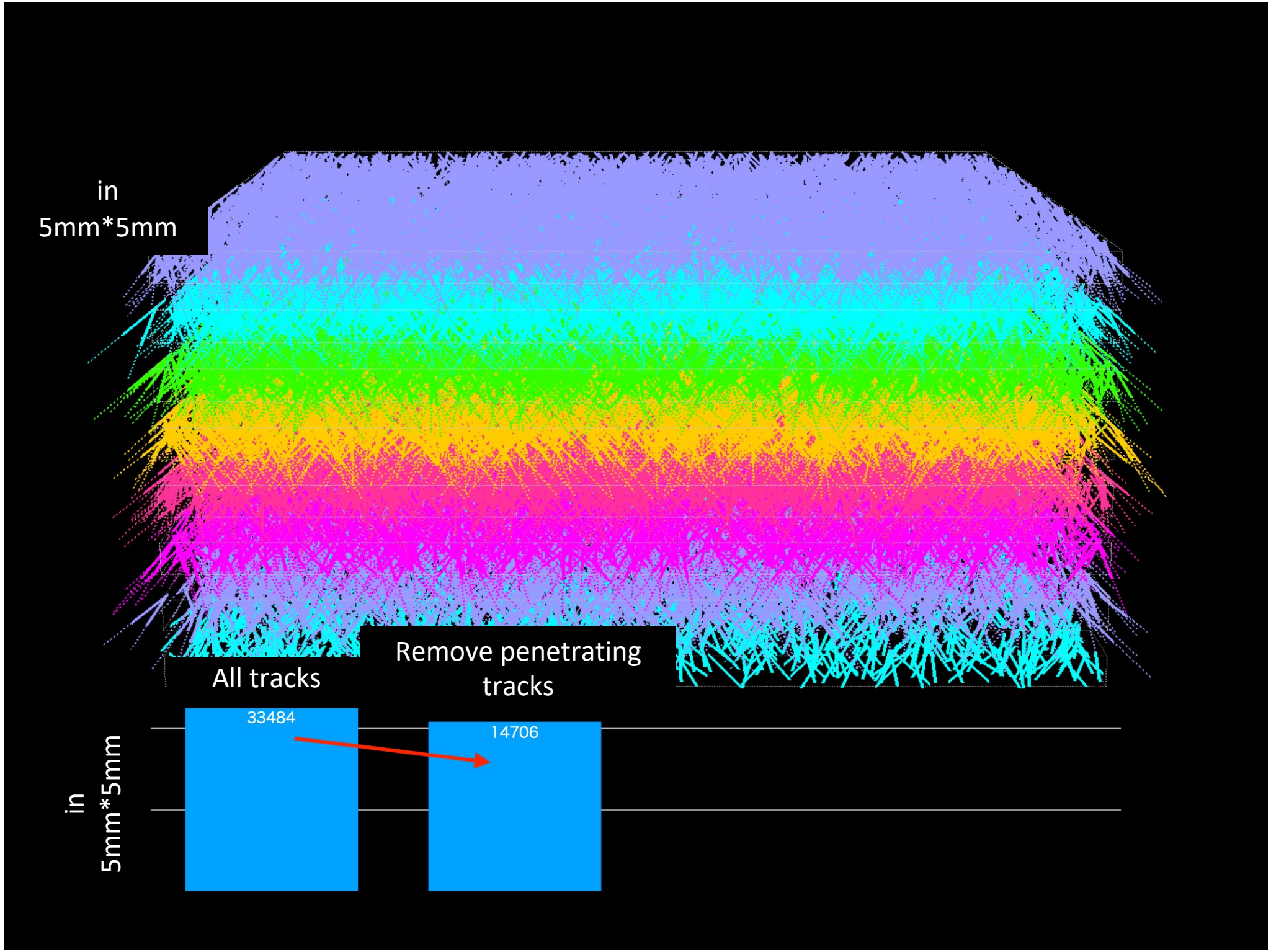
Latitude, longitude, altitude and time taken by JAXA

Recovery on May. 1st 3:30pm

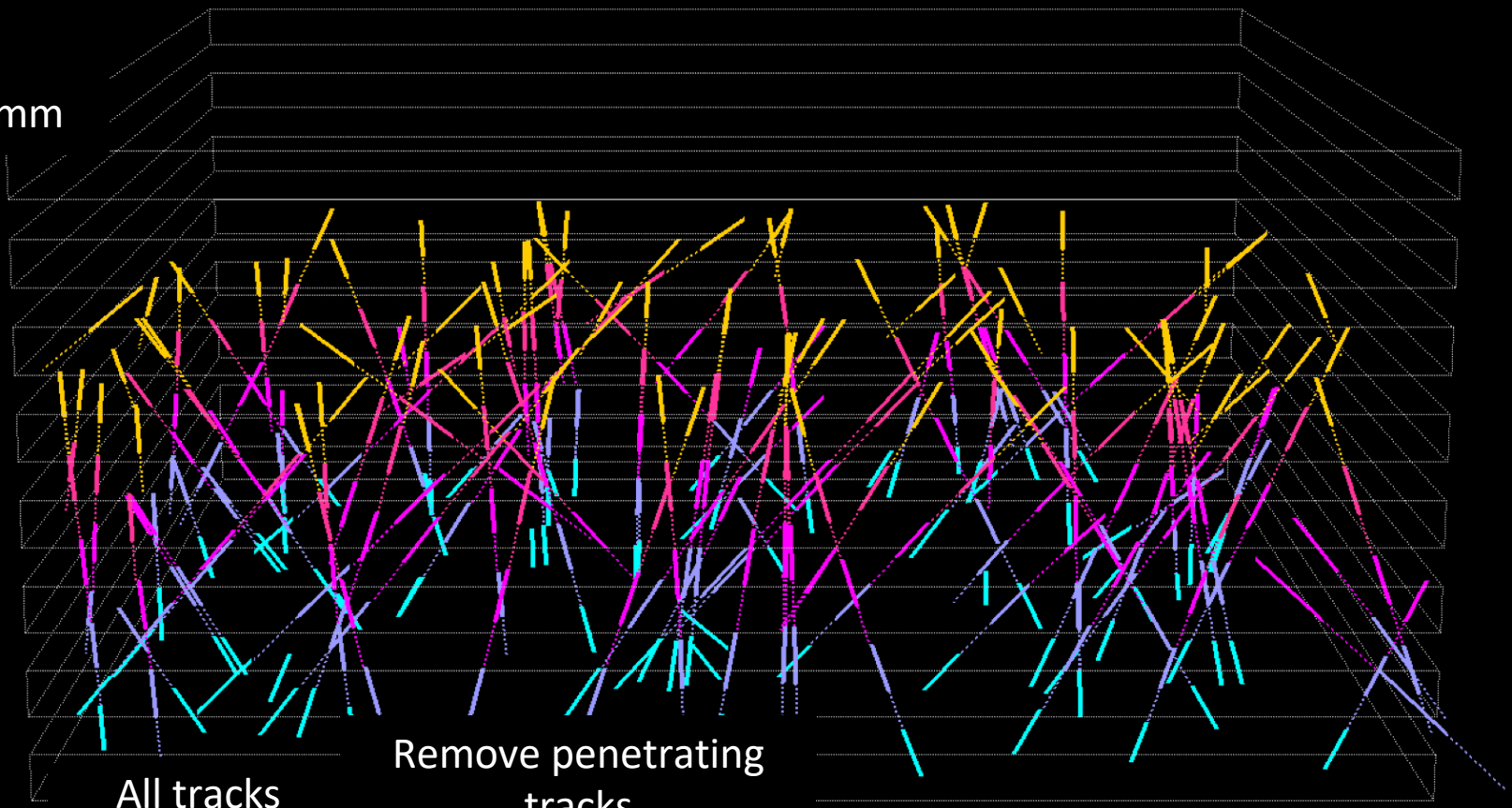
took a helicopter
to search for the payload.

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


in
5mm*5mm
All tracks
33484
in
5mm*5mm

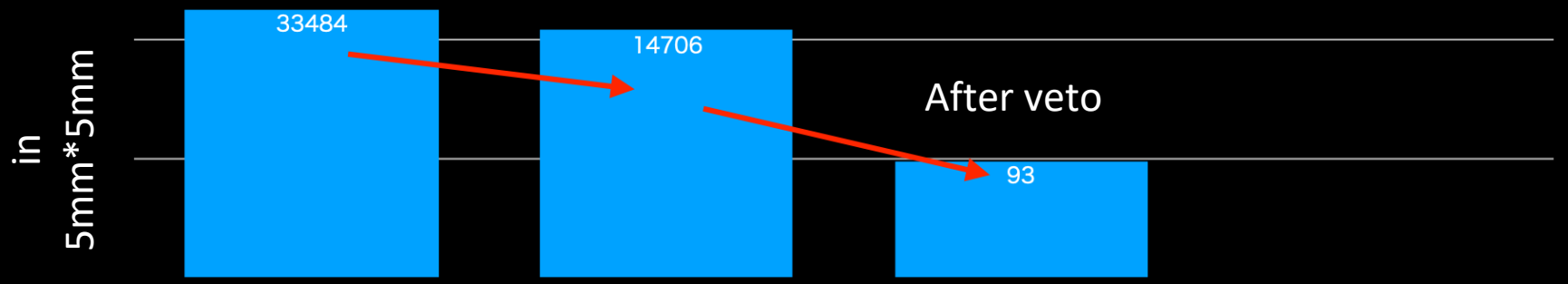

in
5mm*5mm
All tracks
Remove penetrating tracks
33484
14706
in
5mm*5mm

in
5mm*5mm

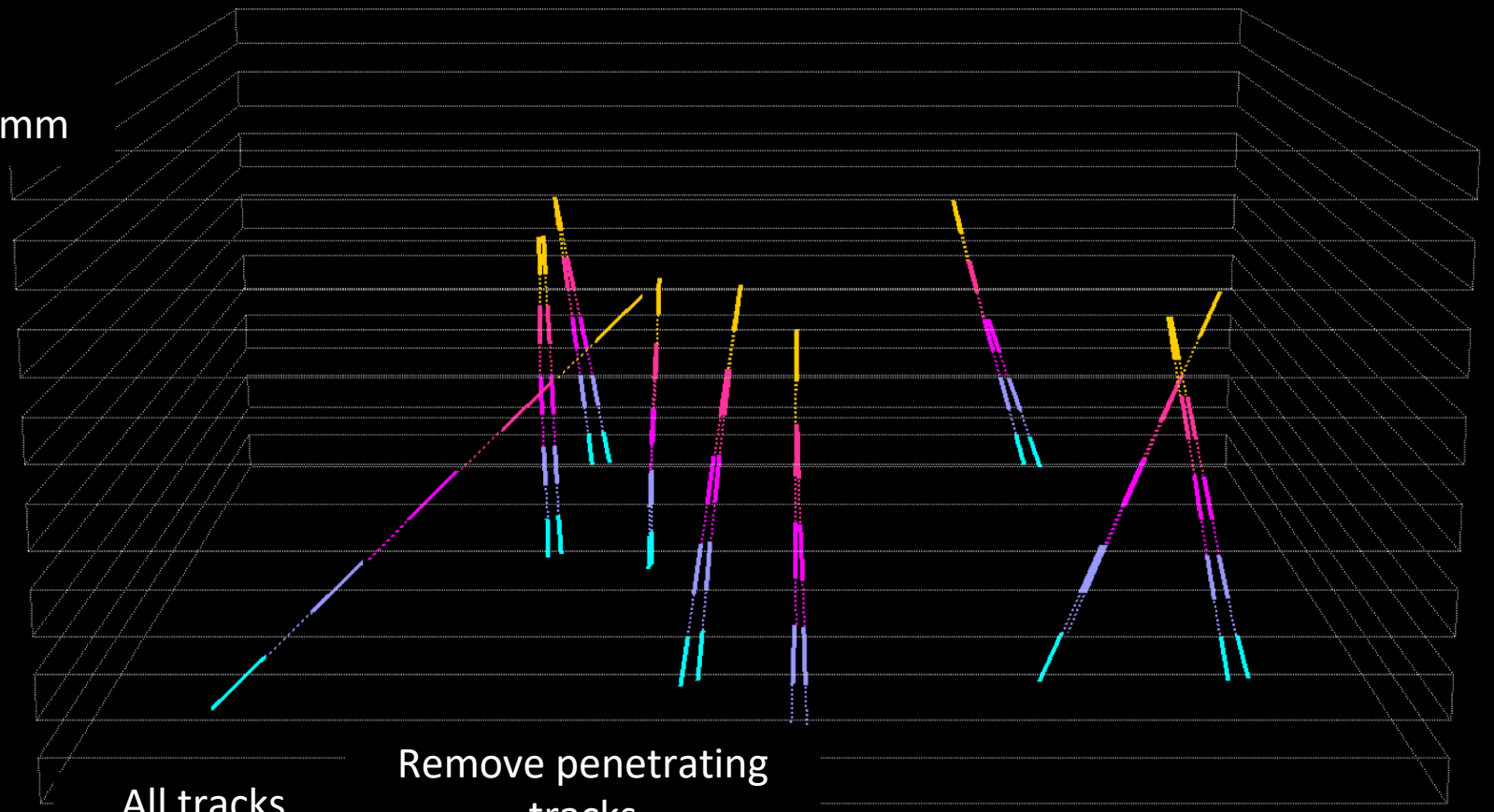


All tracks

Remove penetrating tracks



in
5mm*5mm



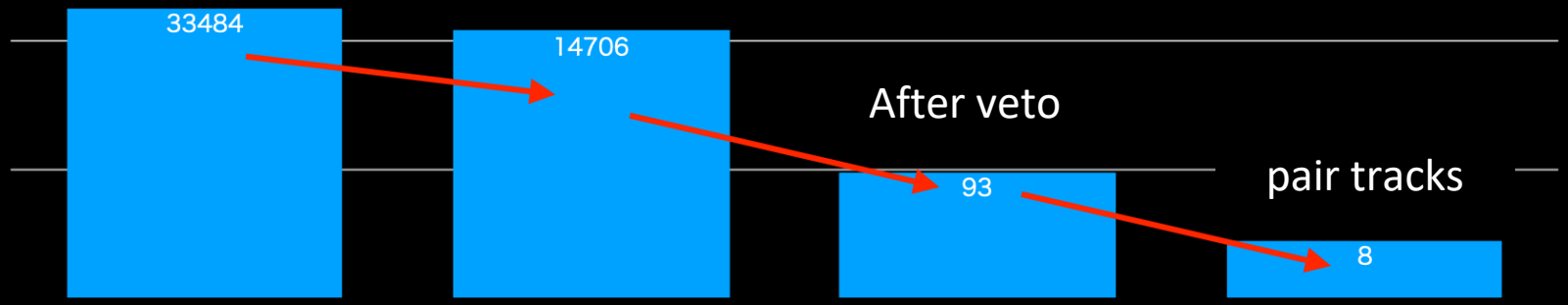
All tracks

Remove penetrating tracks

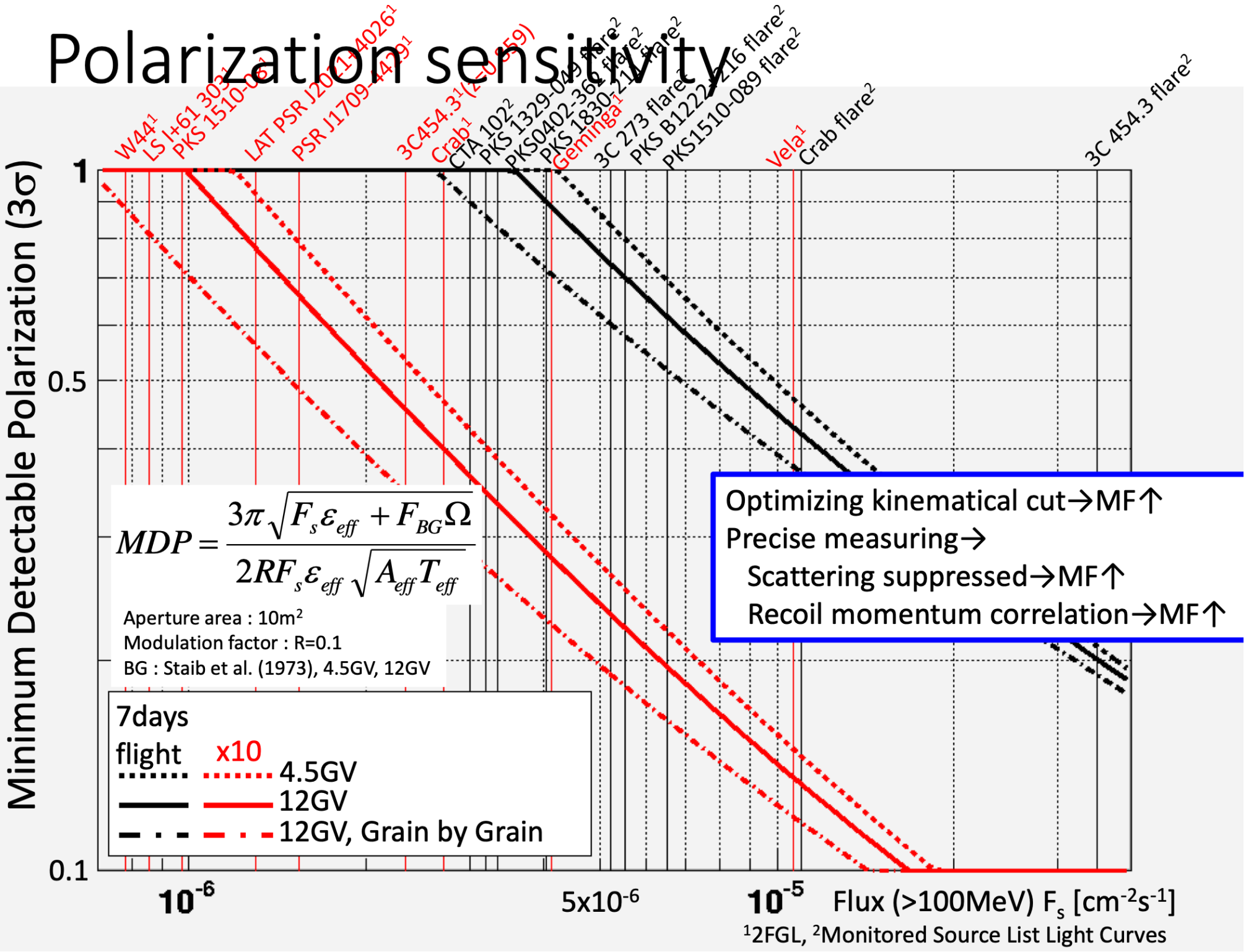
After veto

pair tracks

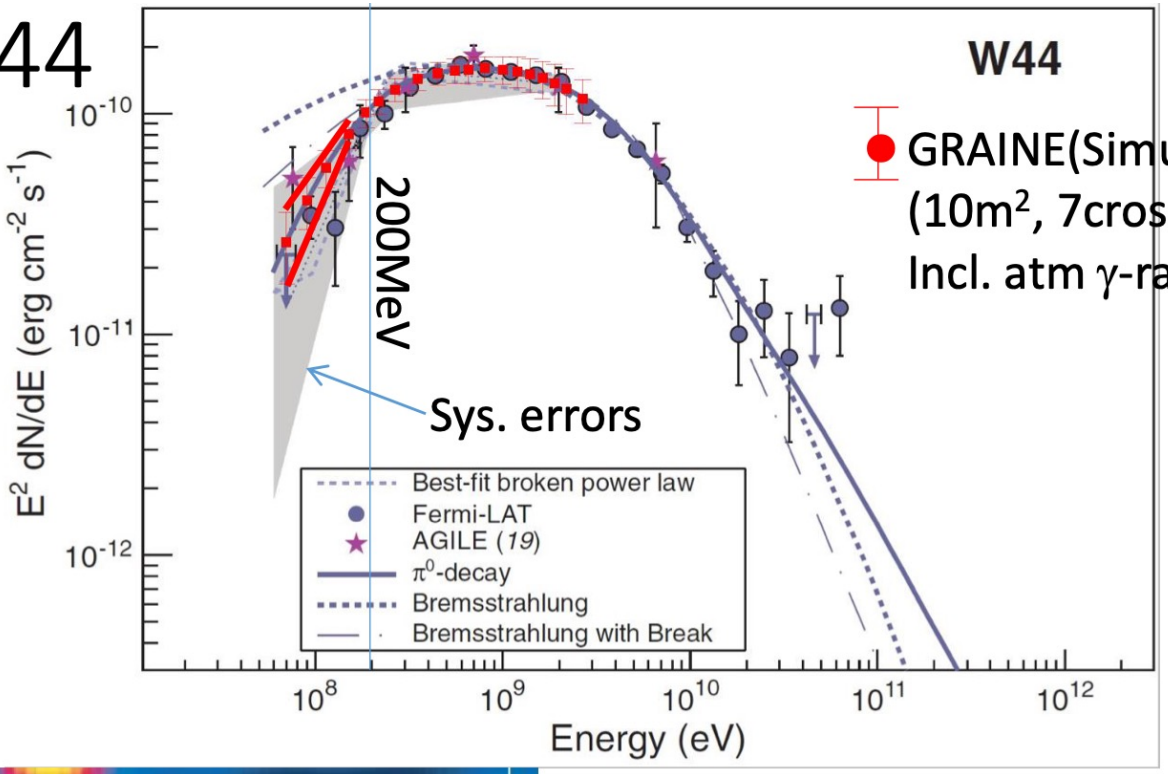
in
5mm*5mm

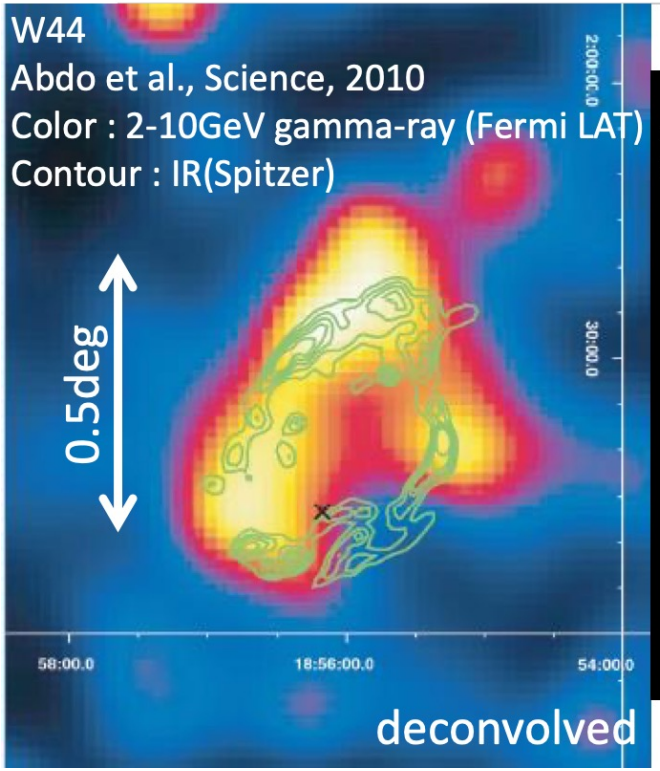


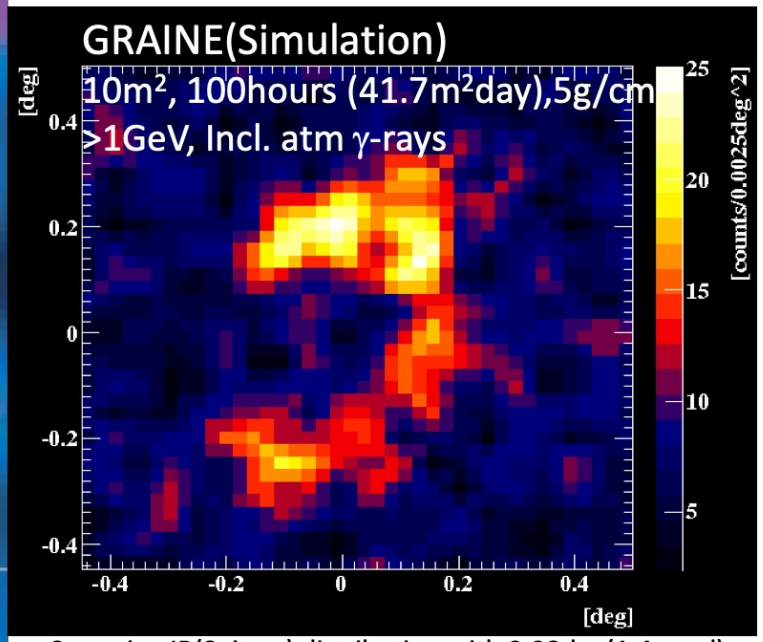
Polarization sensitivity



W44

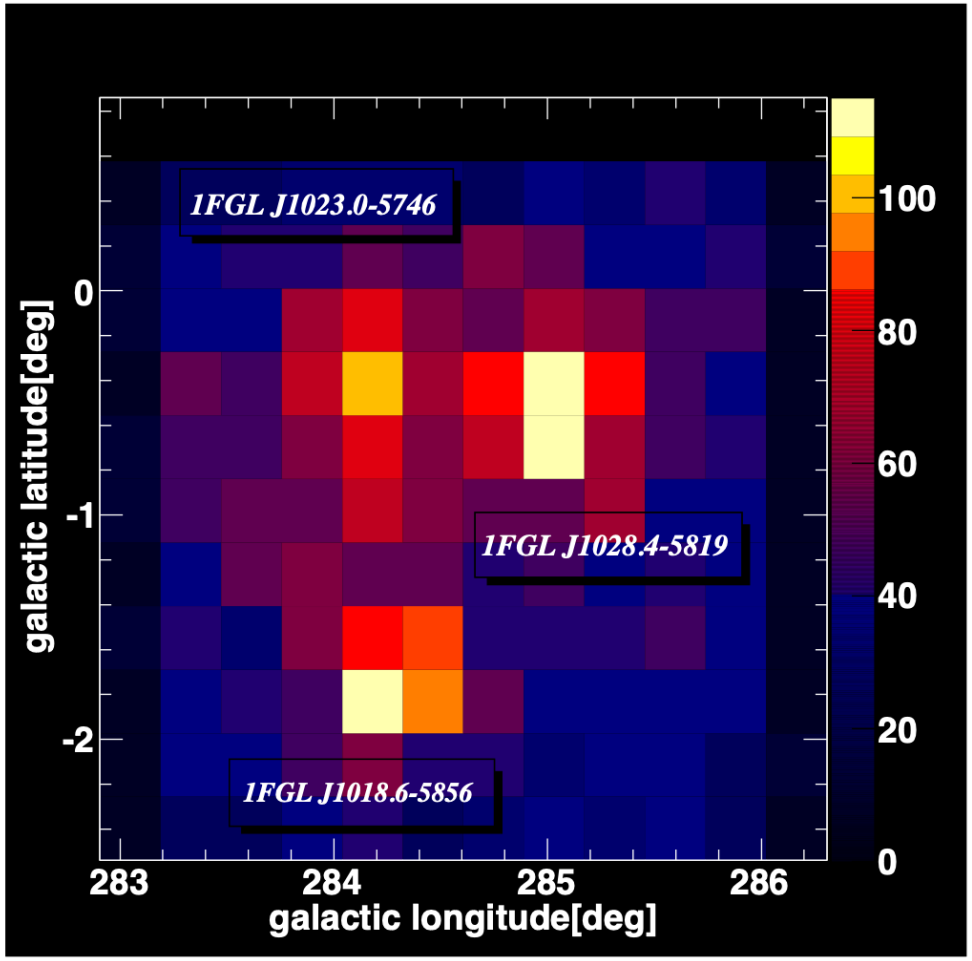




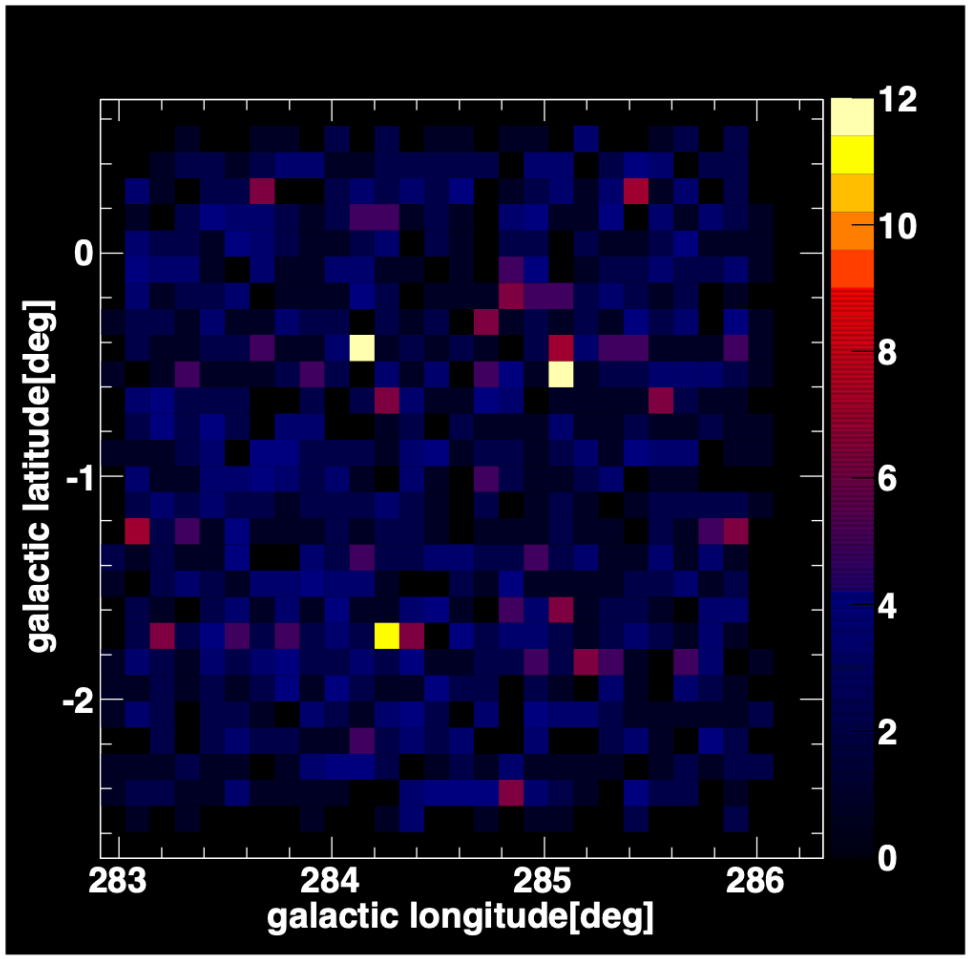


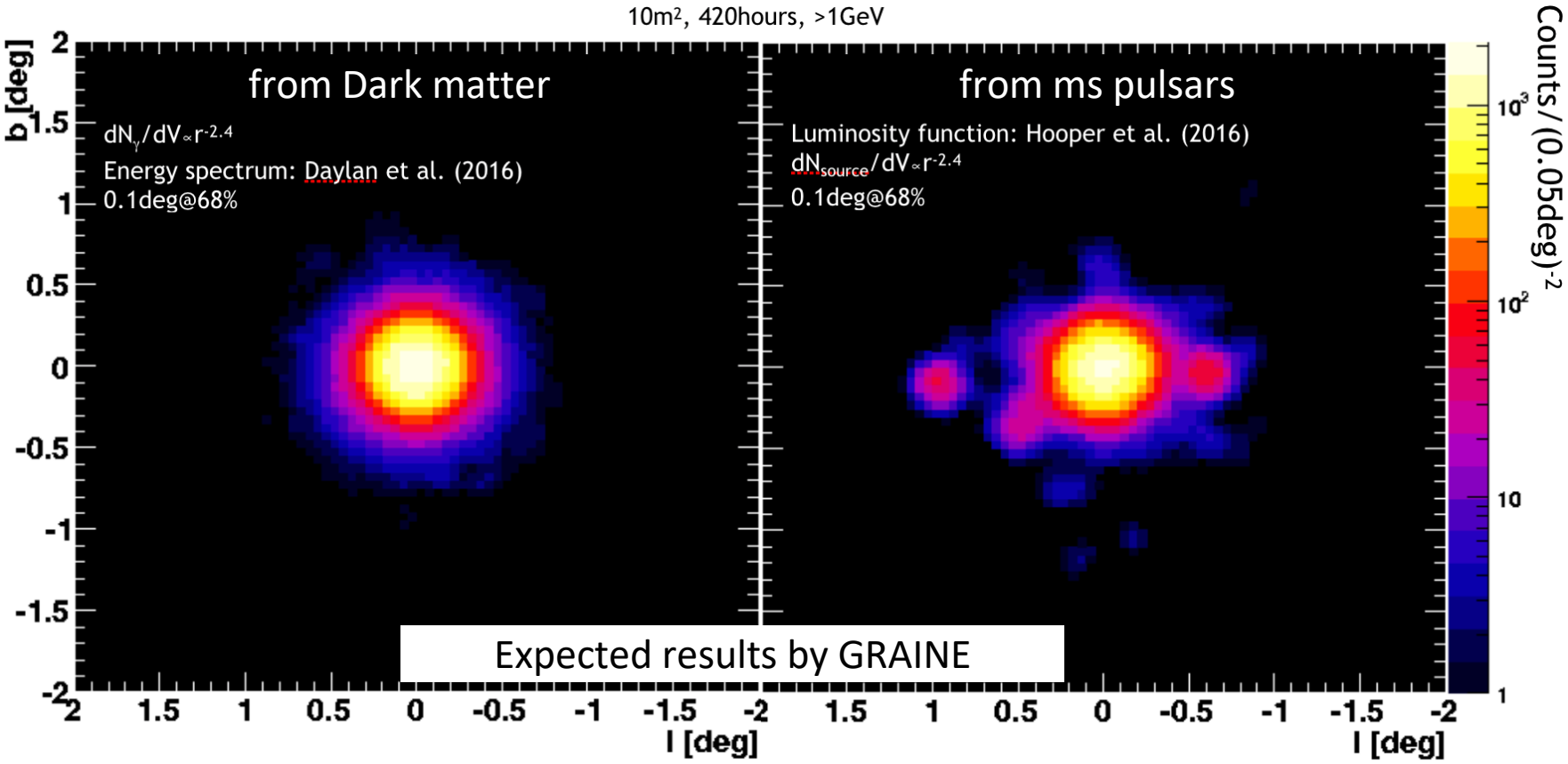
Smearing IR(Spitzer) distribution with 0.08deg(1.4mrad)
Considering atmospheric gamma-ray(>1GeV) as BG

Fermi-LAT(DATA)

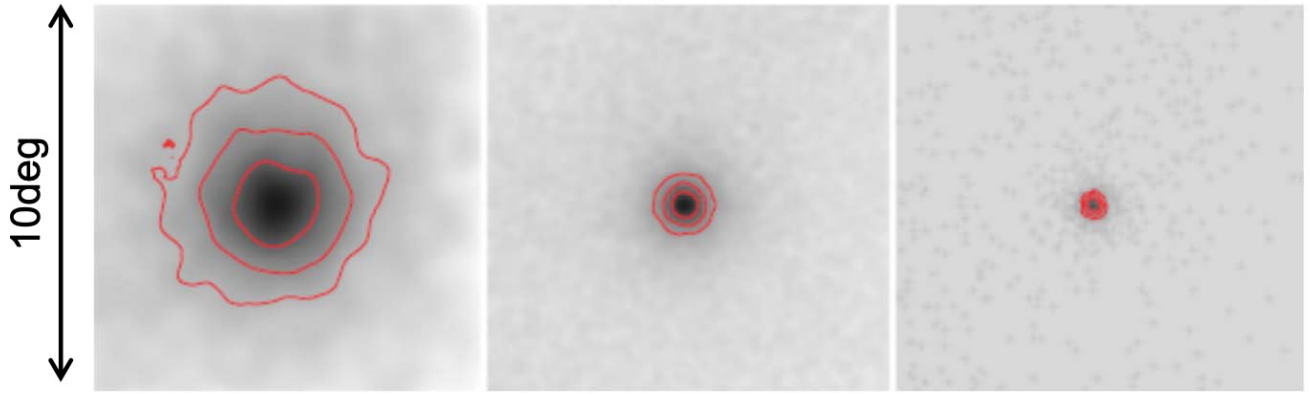


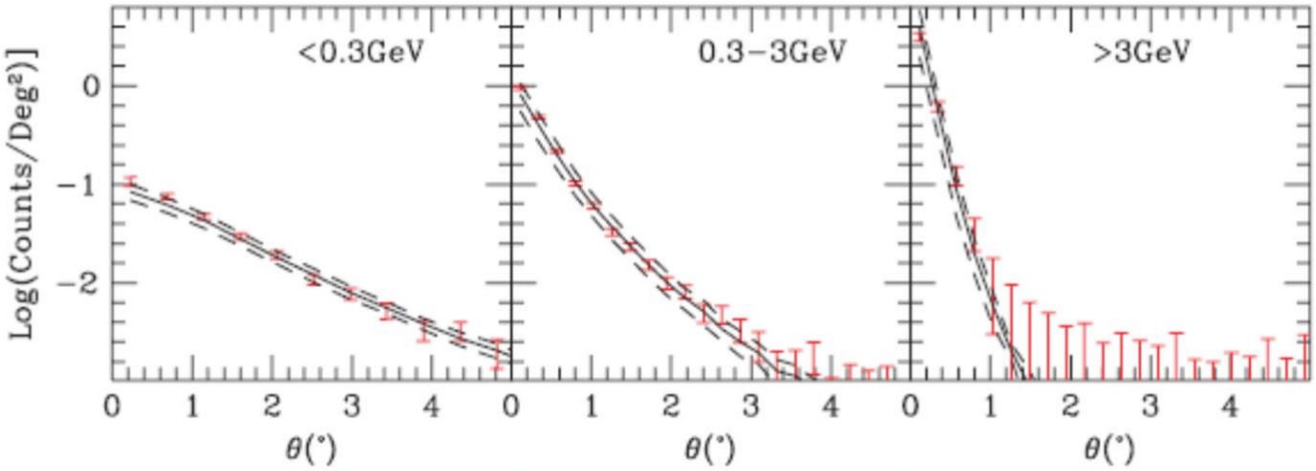
GRAINE(MC)

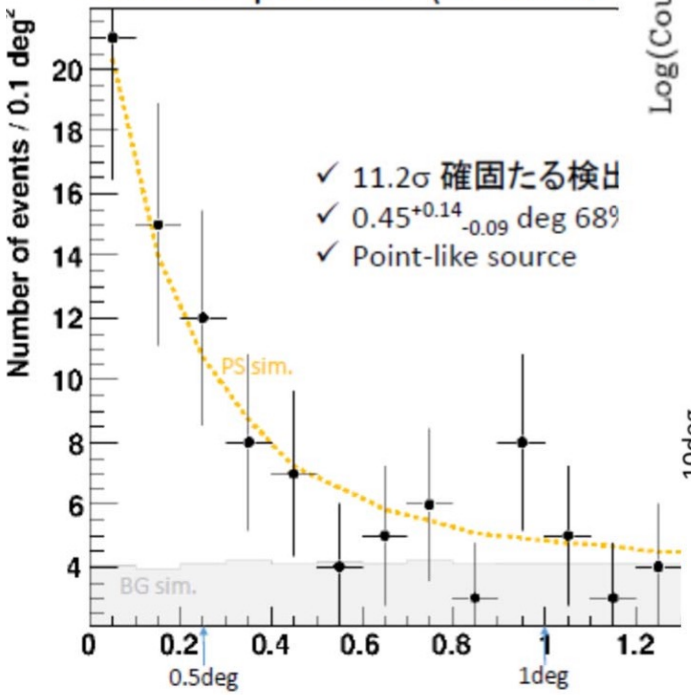


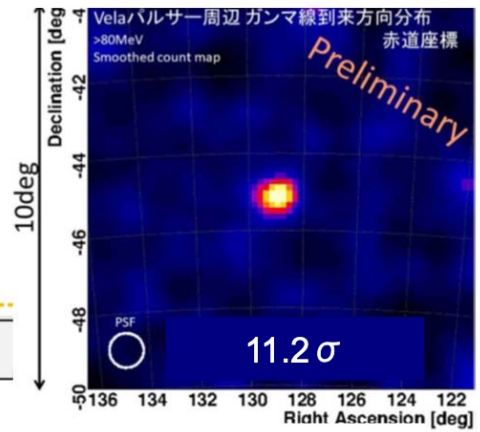

10m², 420hours, >1GeV
from Dark matter
dN_γ/dV∝r^-2.4
Energy spectrum: Daylan et al. (2016)
0.1deg@68%
from ms pulsars
Luminosity function: Hooper et al. (2016)
dN_source/dV∝r^-2.4
0.1deg@68%
Expected results by GRAINE
b [deg]
l [deg]
l [deg]
Counts/(0.05deg)^-2
2
1.5
1
0.5
0
-0.5
-1
-1.5
-2
10^3
10^2
10
1

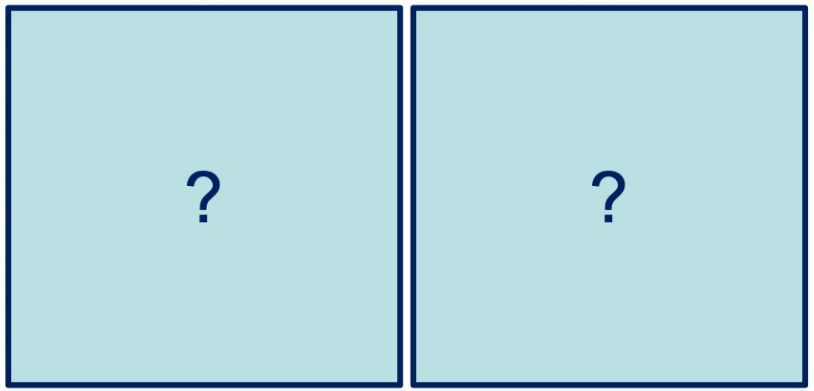
Fermi-LAT (A.A. Abdo et al.)
Astrophysical J., Vol.696, pp.1082-1093, (2009)











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