

Visualizing high energy particles of extensive air showers with Subaru Hyper Supreme-Cam

HSC project 433, S. Kawanomoto et al., Scientific Reports 13:16091 (2023)

Toshihiro Fujii (OMU, NITEP) toshi@omu.ac.jp

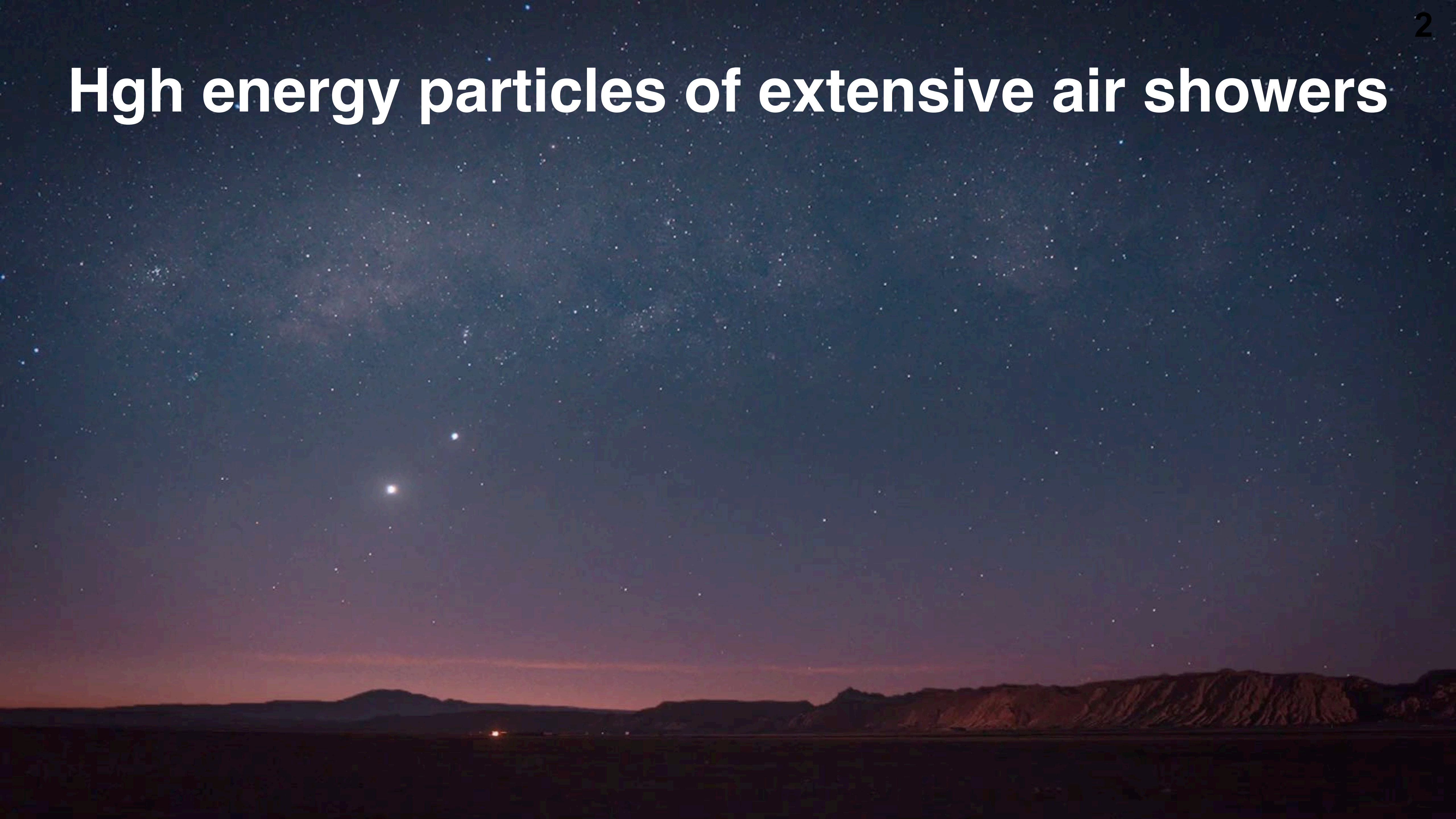
Fraser Bradfield, Ryuichi Kobo, Heungsu Shin (OMU)

Satoshi Kawanomoto, Michitaro Koike, Satoshi Miyazaki (NAOJ)

2024 October 16th, Tohoku University

Workshop on Cosmic Indicators of Dark Matter 2024

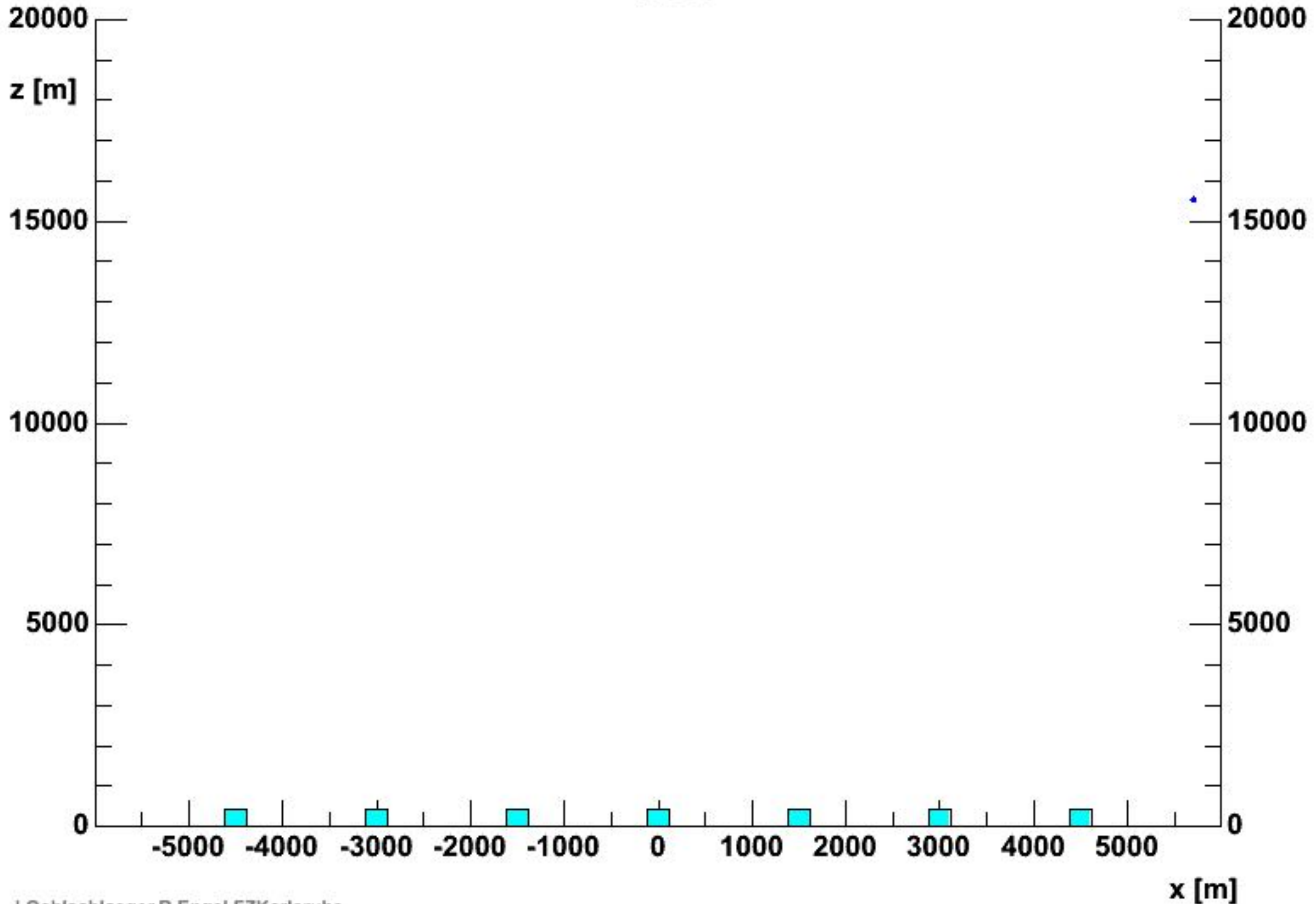
High energy particles of extensive air showers



hadrons muons electrs neutrns

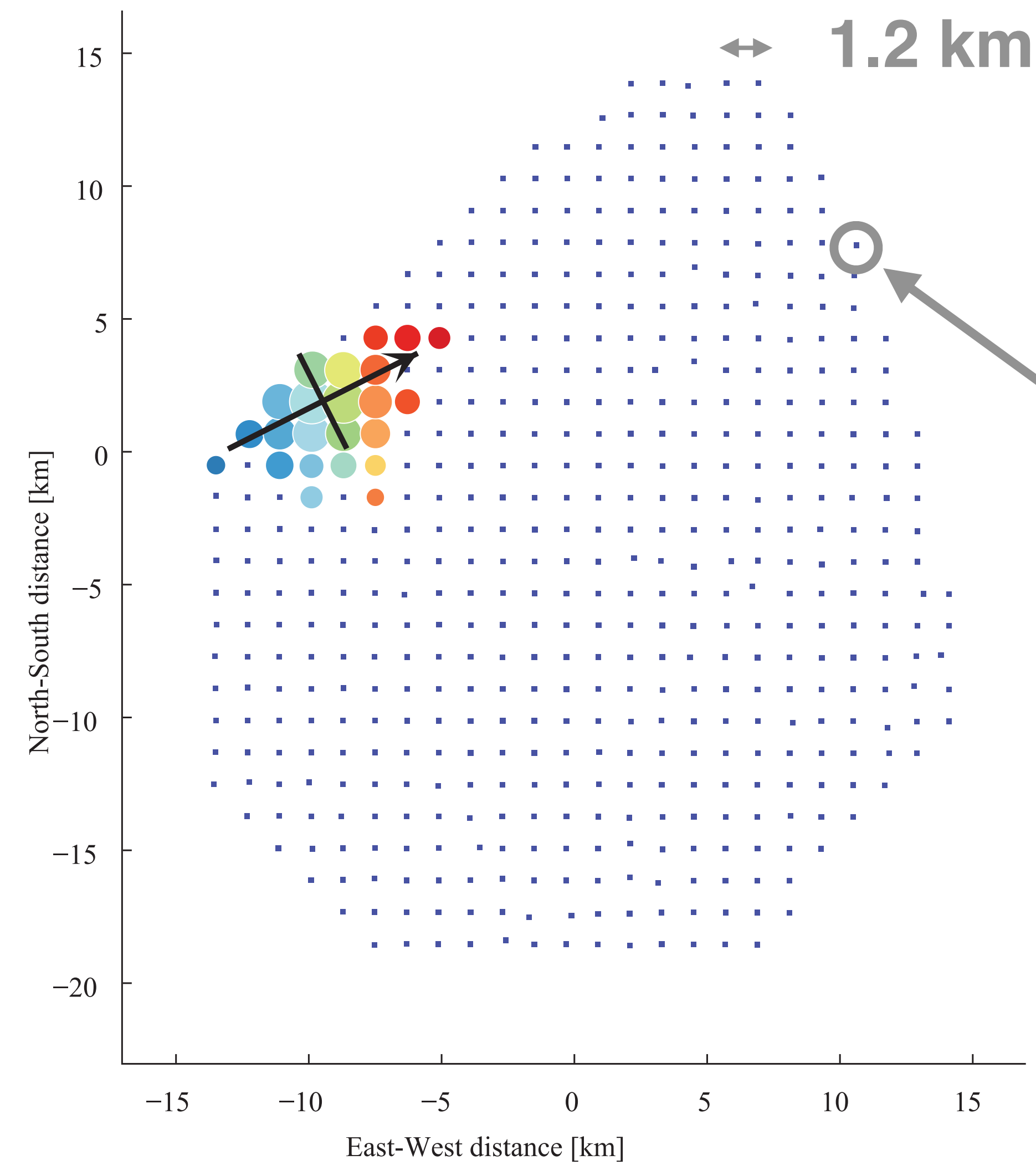
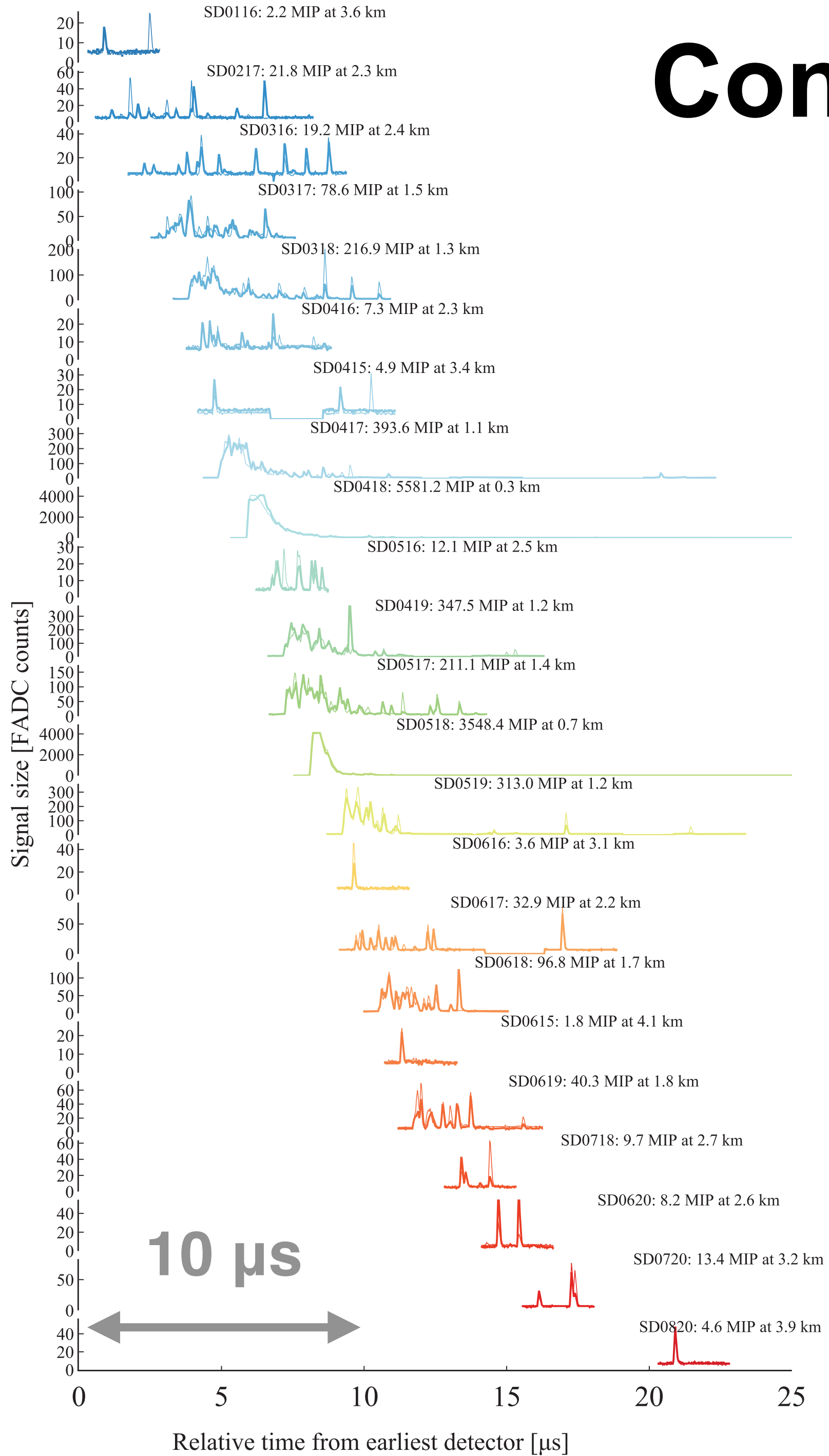
Proton 10^{15} eV

15514





Conventional air-shower detector

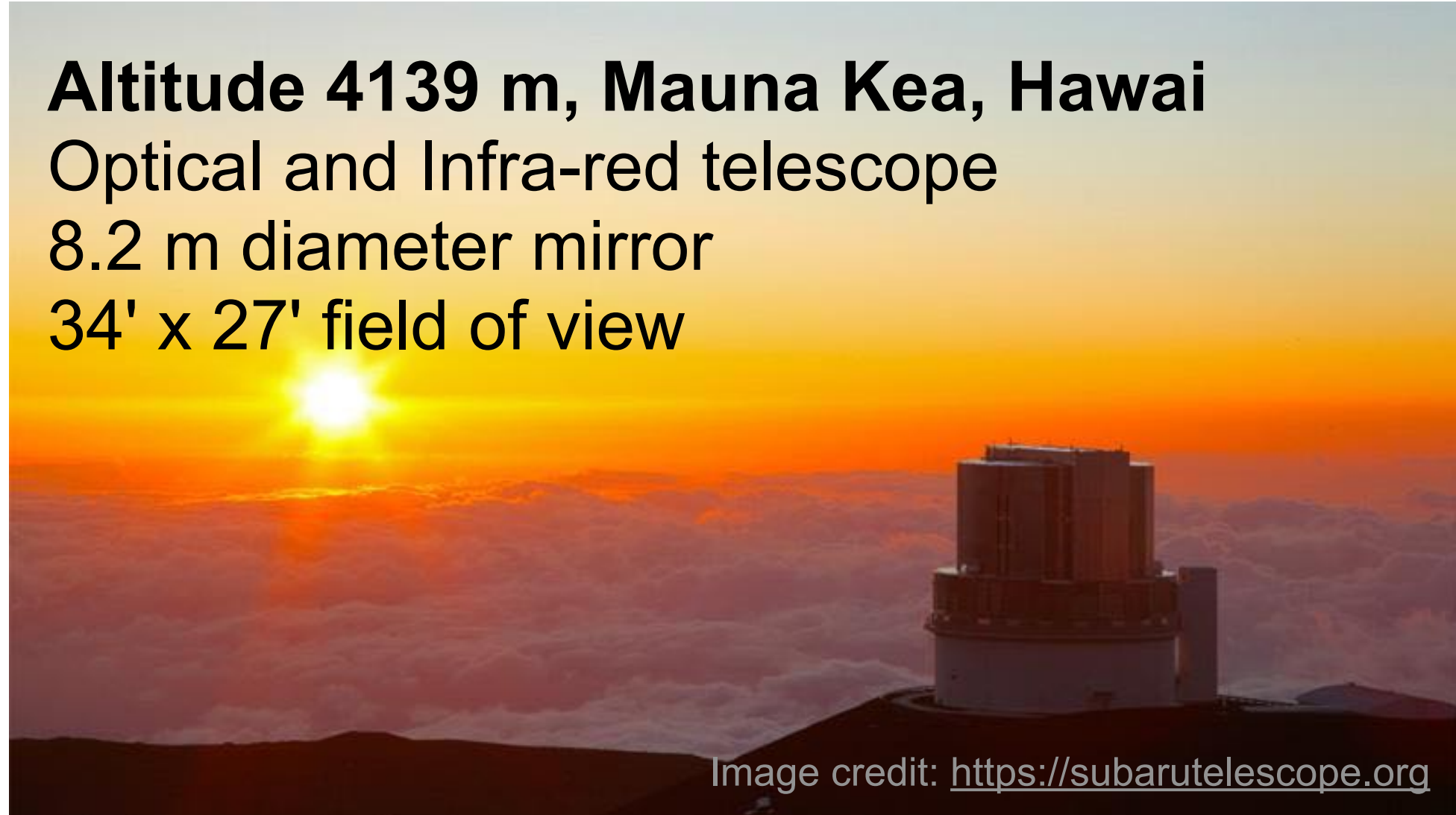


Telescope Array Experiment
 3 m² plastic scintillator
 507 detectors with 1.2 km spacings to cover **700 km²** in Utah, USA

Detection of 244-EeV comic ray reported in Science 382, 903 (2023), dubbed "Amaterasu" particle

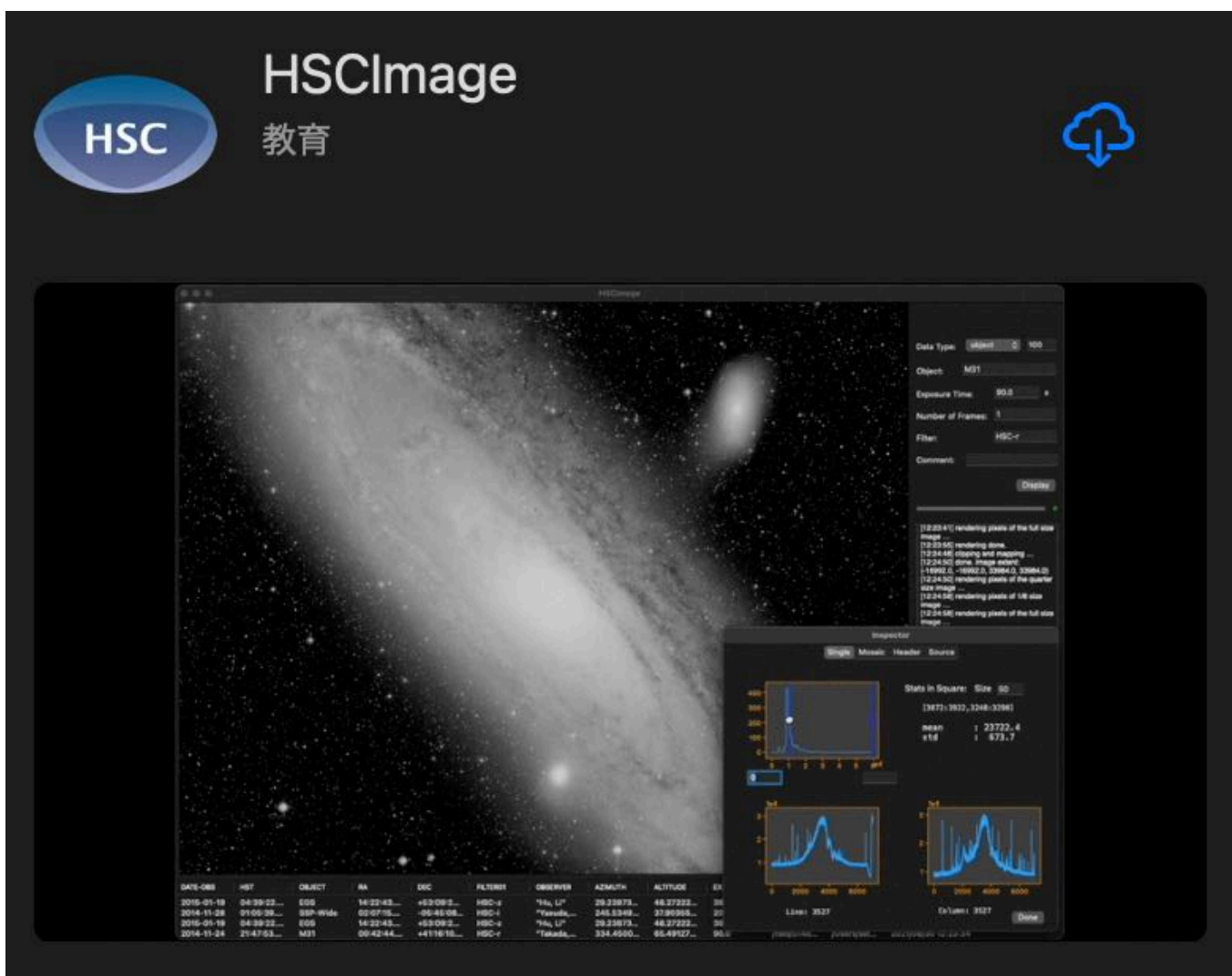
Visualizing high energy particles of extensive air showers with 5 Subaru Hyper Supreme-Cam

Direct detection of Subaru HSC CCDs

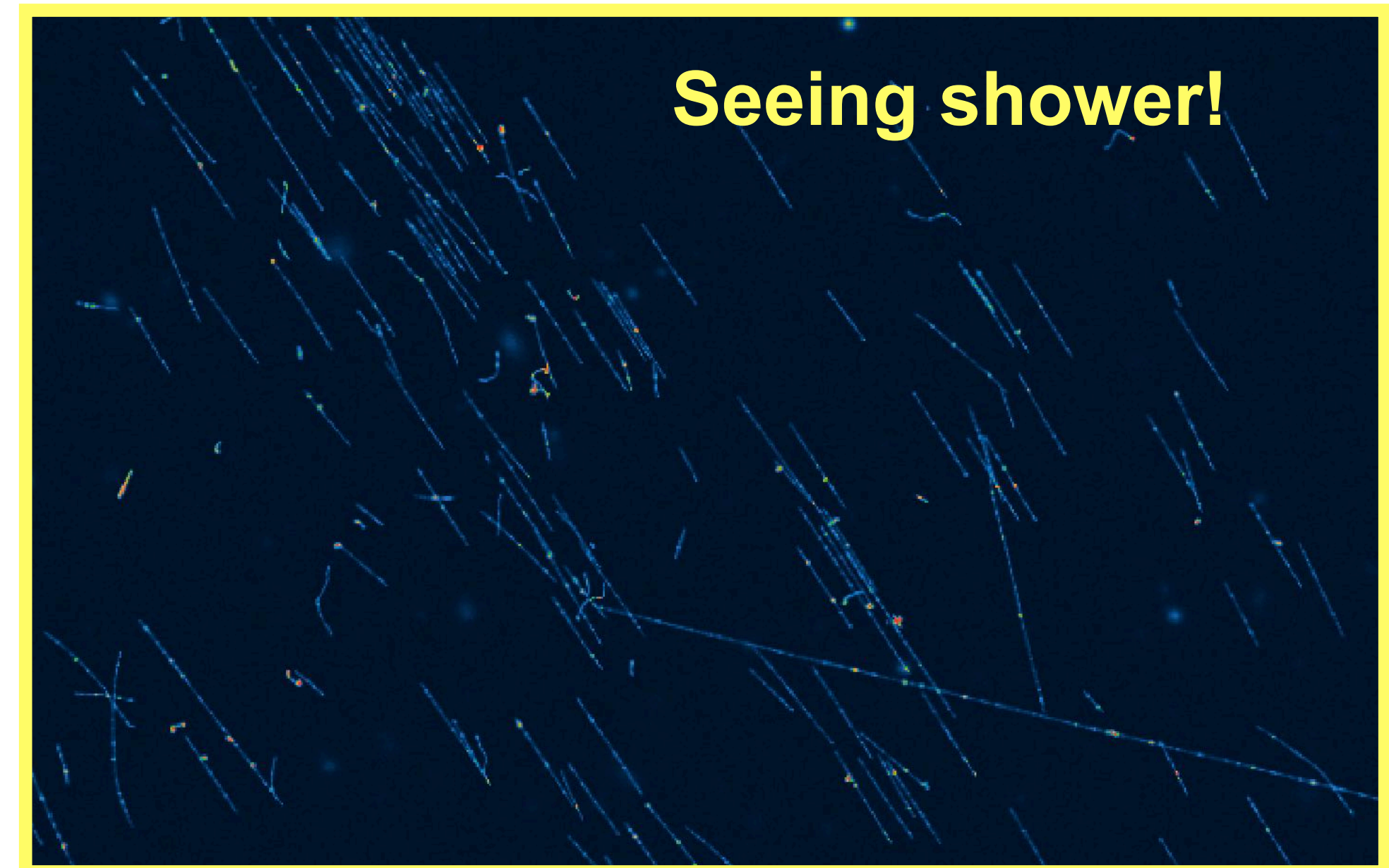
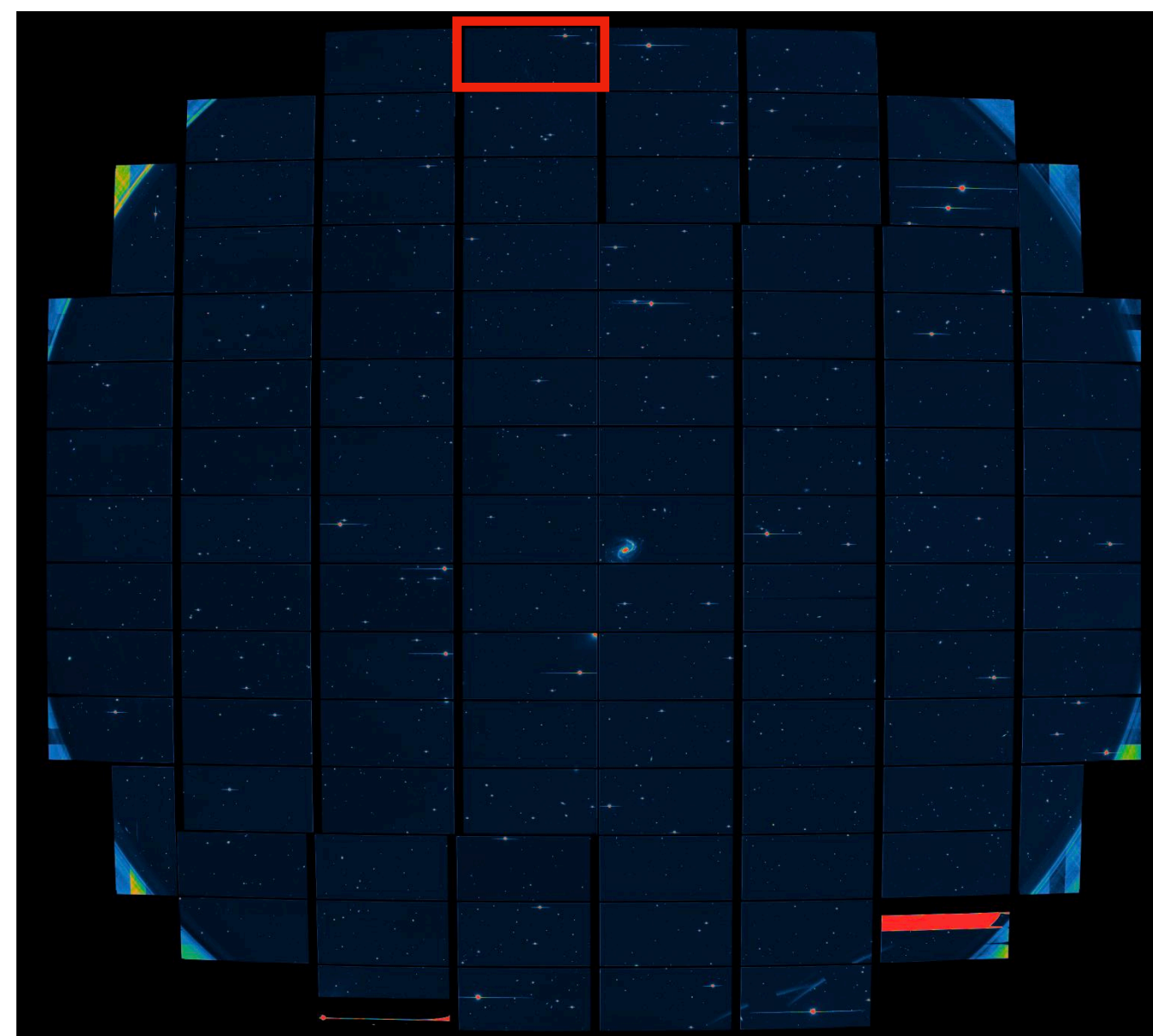


CCD size
30 mm x 60 mm
0.2 mm thickness
150 sec. exposure

116 CCDs



App Store (Mac)

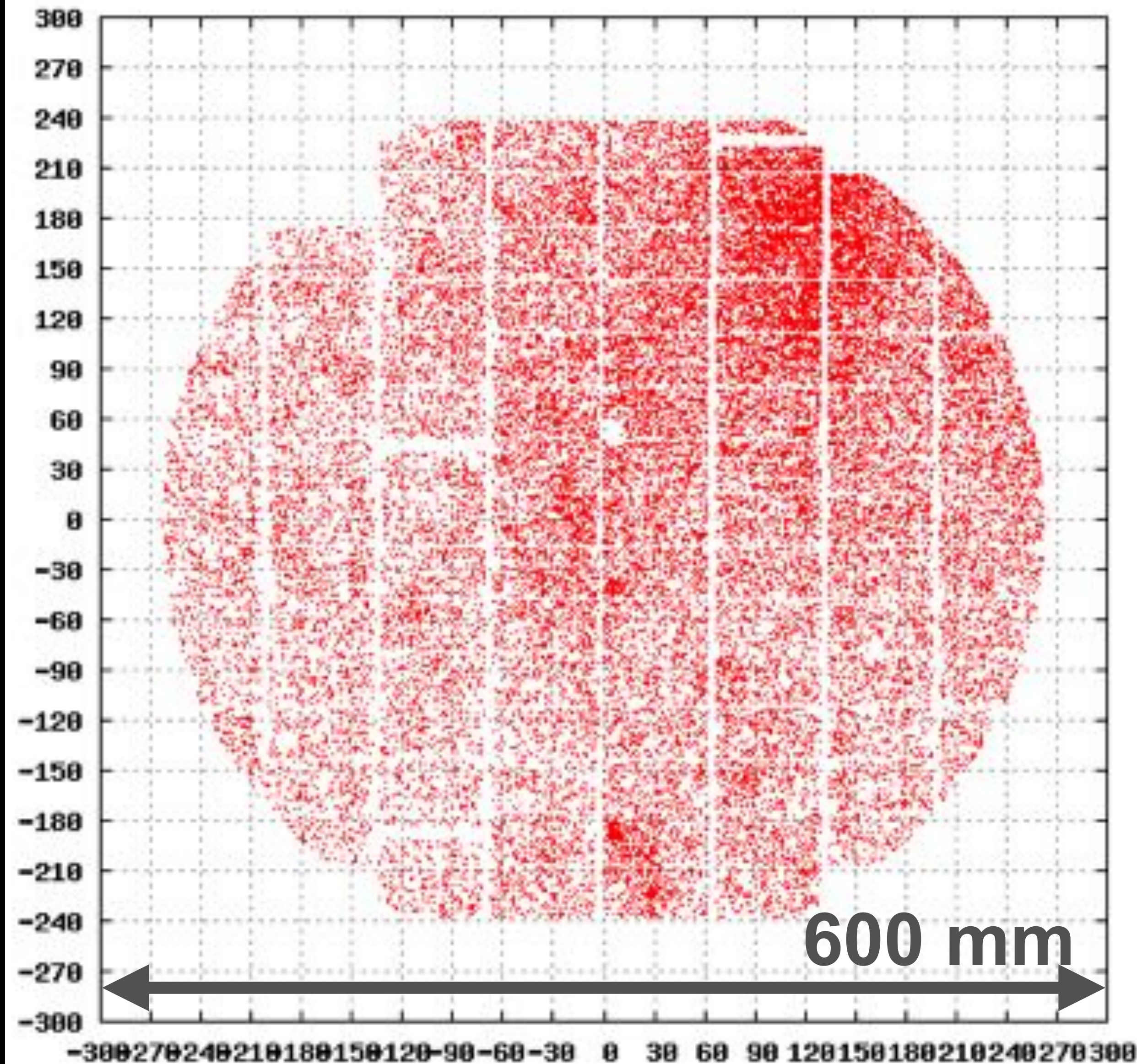
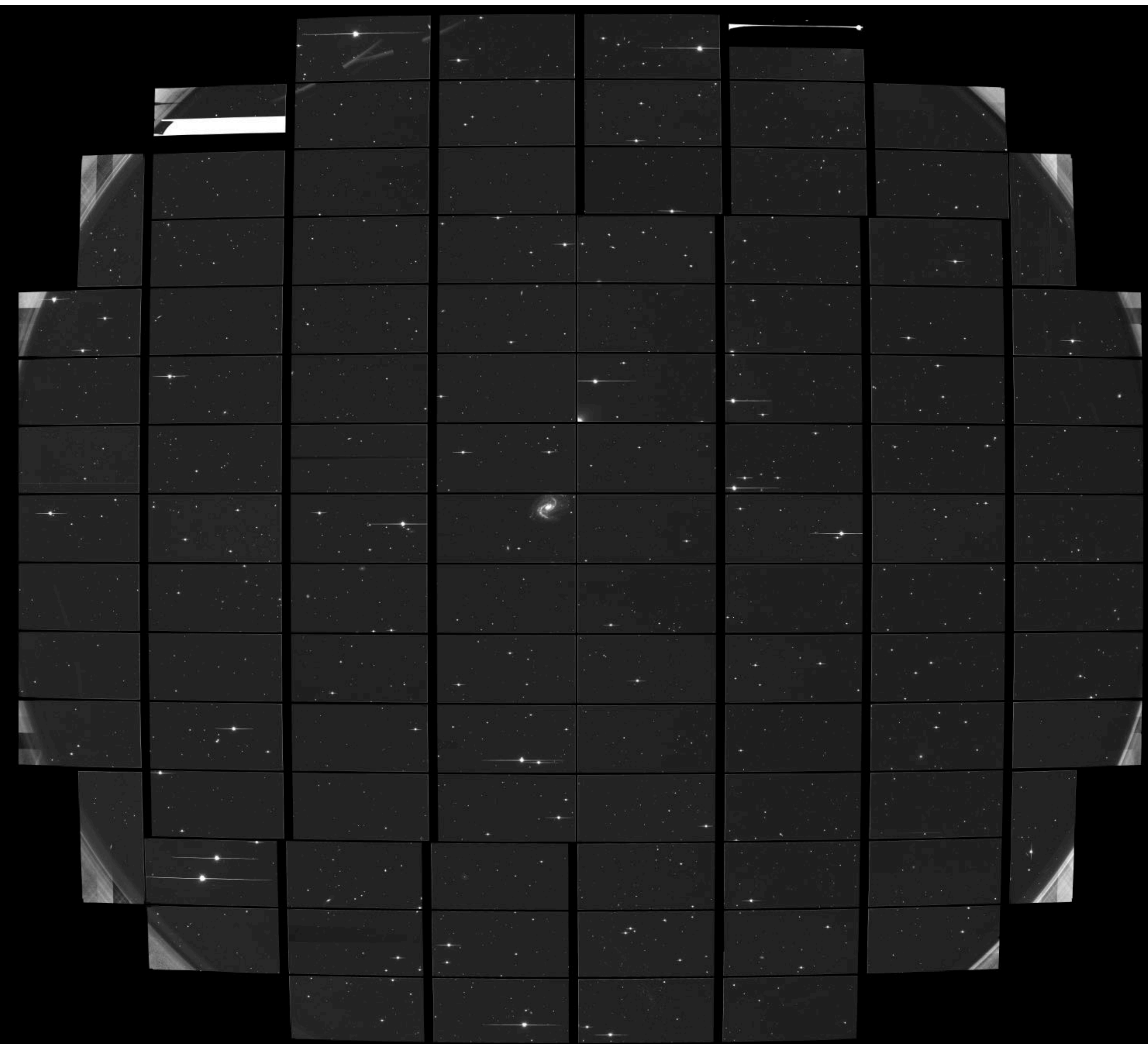




10 mm

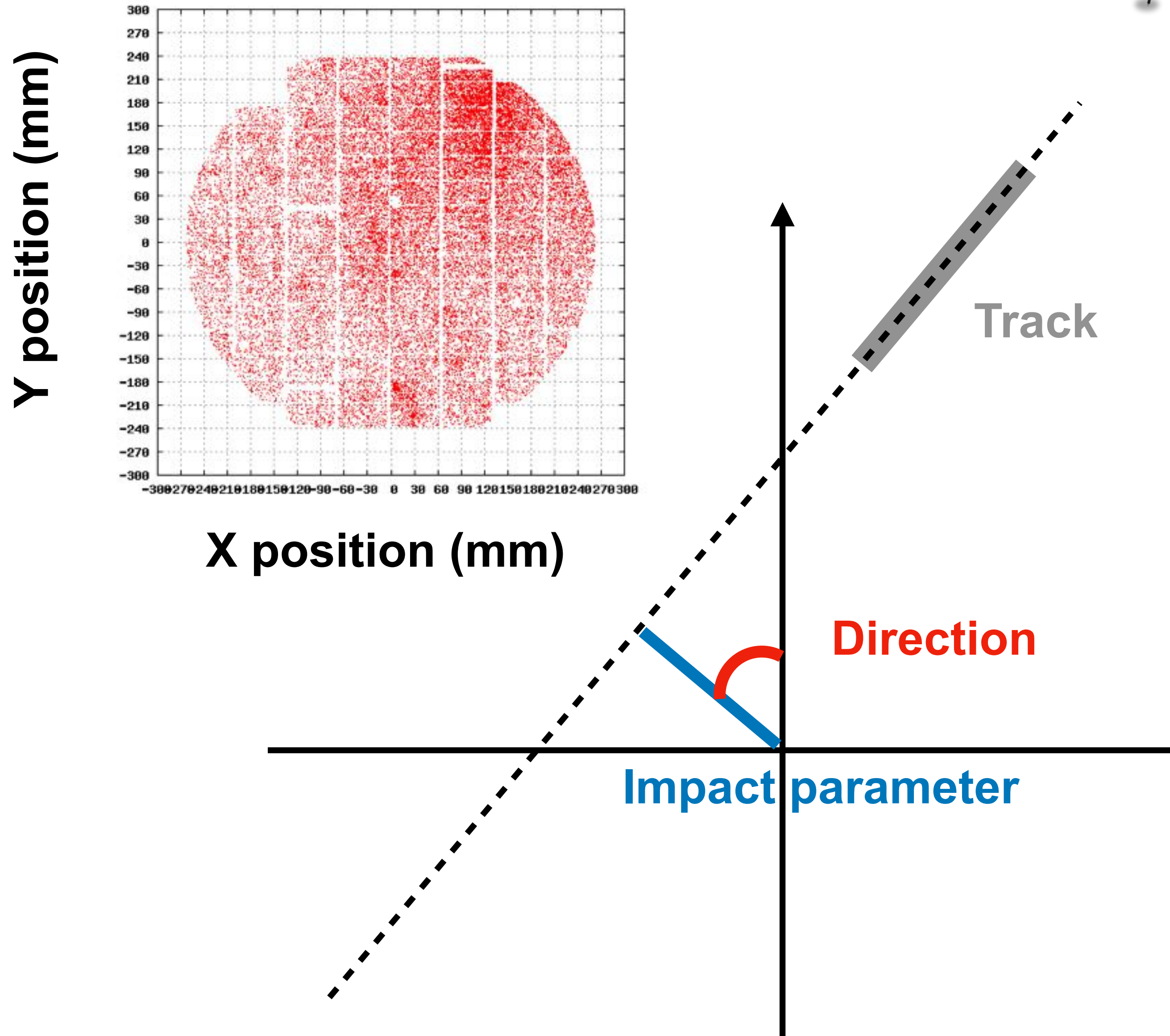


Particle densities detected by Subaru HSC



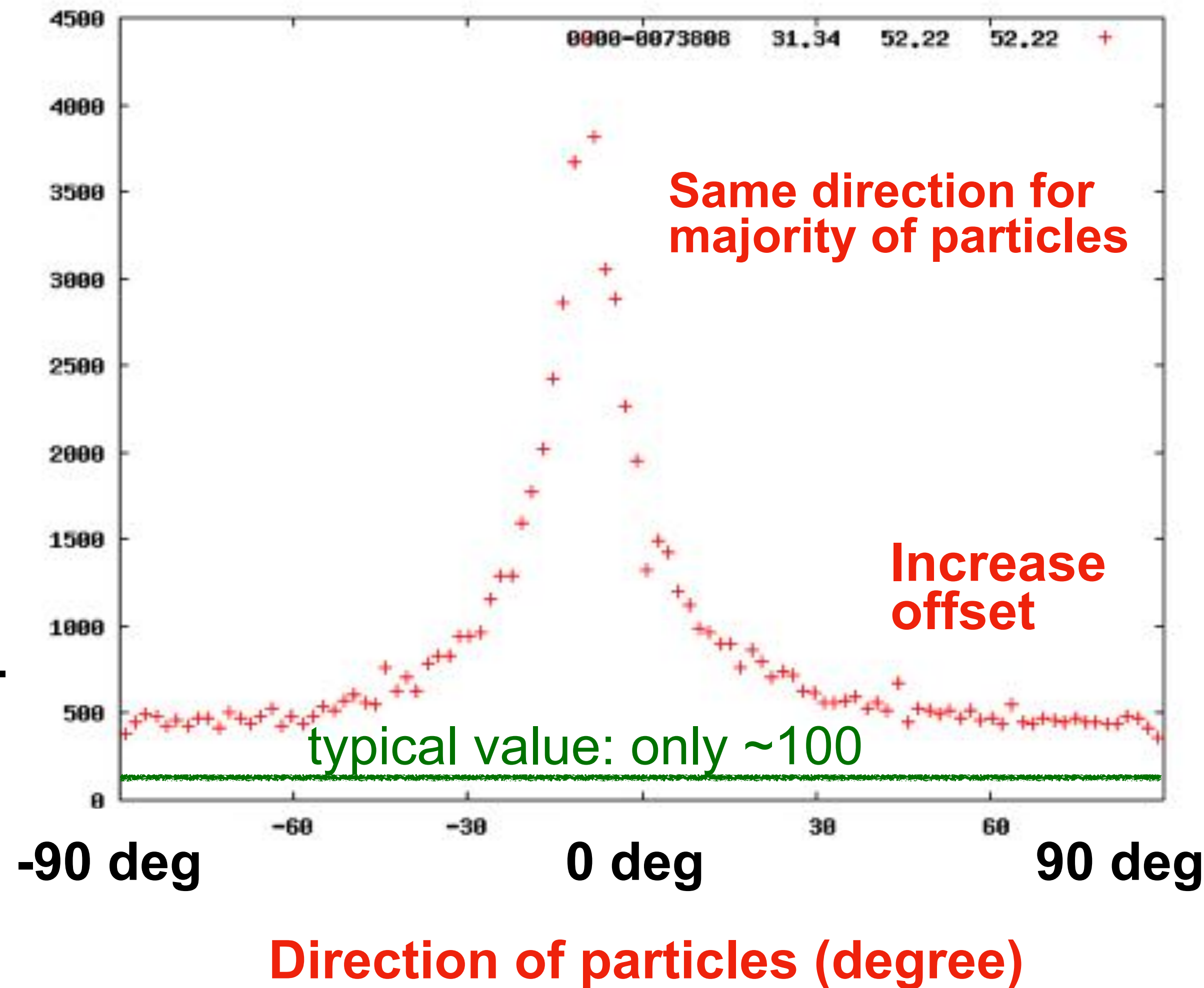
Directional analysis of cosmic-ray shower particles

Position of particles

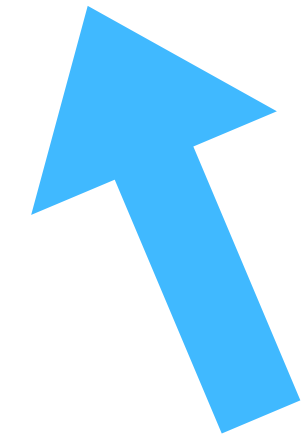


Result of directional analysis

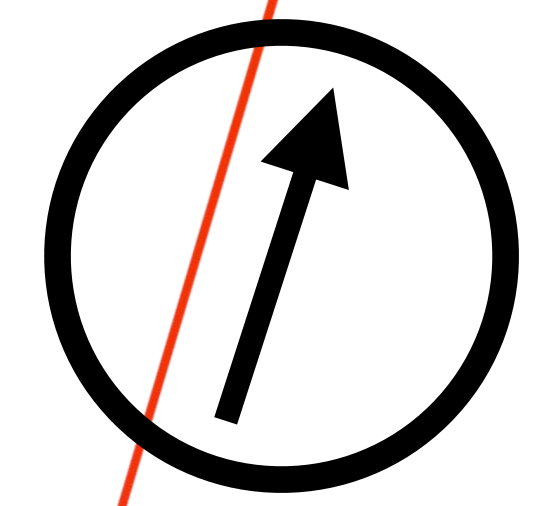
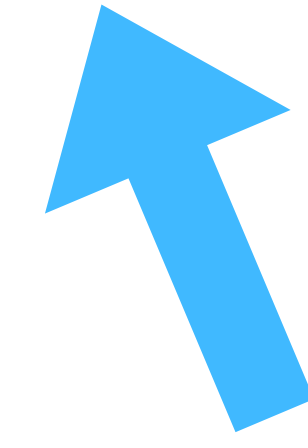
Number of excess particles, $N_{cr} \sim 75,000$



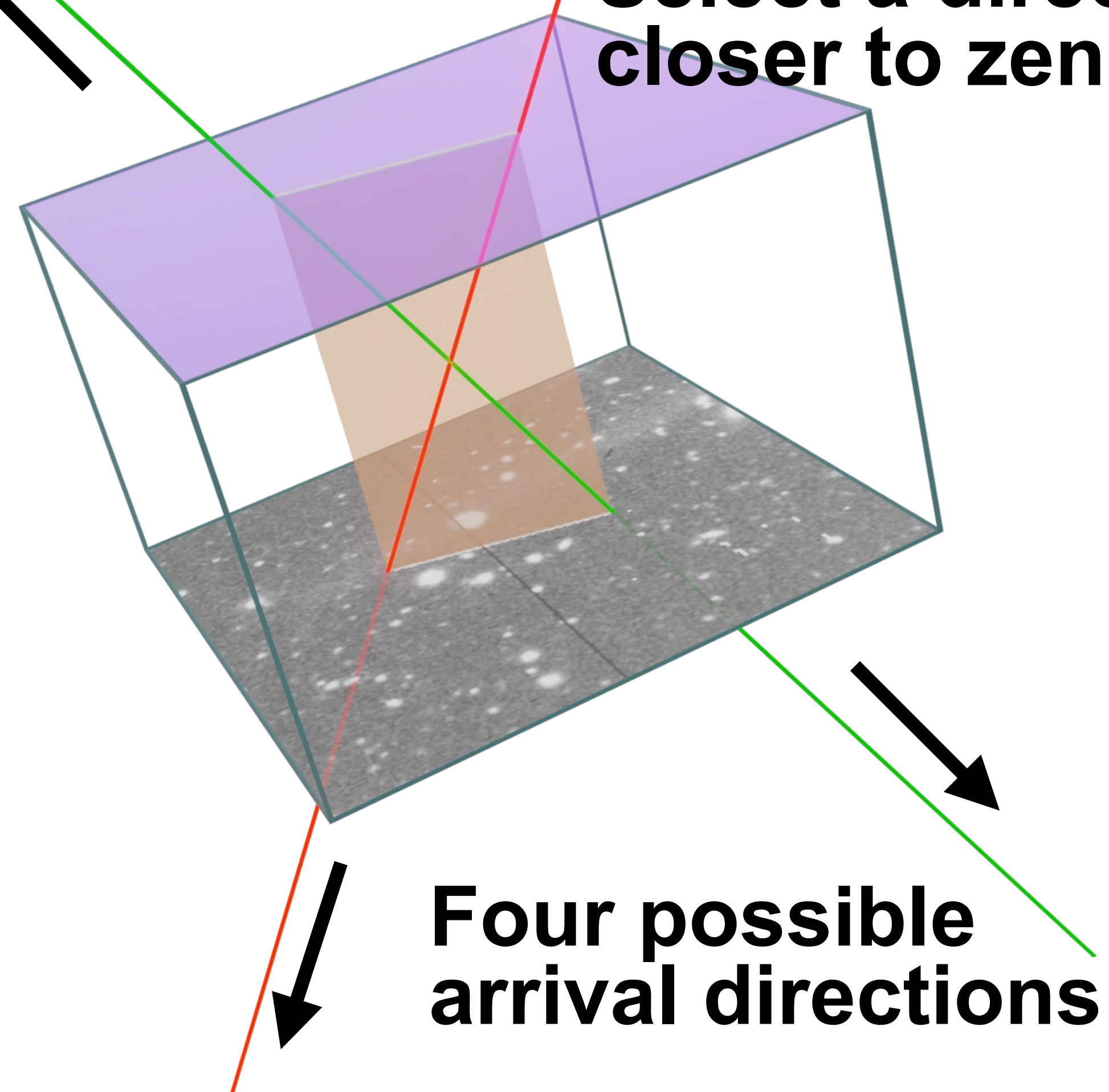
3-D projection of the arrival directions



Telescope pointing



Select a direction closer to zenith



Four possible arrival directions

Subaru HSC data set and search result

- 📌 Subaru HSC data set between March 2014 and January 2020, total 875 hours exposure.
- 📌 Formulate the "background model" of single electromagnetic and/or muonic particles
- 📌 Select "significant" excess events with $>20\sigma$ compared to background fluctuation \rightarrow **13 events**

Visit	Date	UT	Filter	ψ_{tel}	ϕ_{tel}	B_{sky}	N_{track}	N_{model}	N_{excess}
034298	2015-07-14	09:17:32	HSC-g	54.2	138.9	413	24745	16685	8060
034480	2015-07-14	13:28:20	HSC-g	72.7	1.4	423	28276	18760	9516
034814	2015-07-15	14:47:34	HSC-r	64.7	45.5	1559	35124	19424	15700
039340	2015-10-06	14:08:04	HSC-y	43.3	63.4	6209	36354	22328	14026
069450	2016-04-15	10:55:54	HSC-y	55.5	54.3	7843	38513	24810	13703
073808	2016-06-11	09:42:43	HSC-i2	59.0	57.1	2880	99476	25113	74363
146672	2018-04-22	09:42:33	HSC-r2	63.2	50.7	2845	32509	18302	14207
161642	2019-01-07	15:31:21	HSC-g	57.4	55.0	358	40683	17182	23500
162680	2019-01-11	05:20:15	HSC-z	66.0	37.0	1874	33089	23908	9181
163754	2019-02-02	15:35:37	HSC-g	51.7	68.7	367	23441	16365	7076
190348	2019-11-01	10:00:11	HSC-g	60.7	61.1	418	26593	17657	8936
202364	2020-01-03	12:39:19	HSC-g	51.1	-67.2	396	24279	15839	8440
203690	2020-01-20	14:27:54	HSC-r2	67.3	-48.5	1017	27180	18166	9014

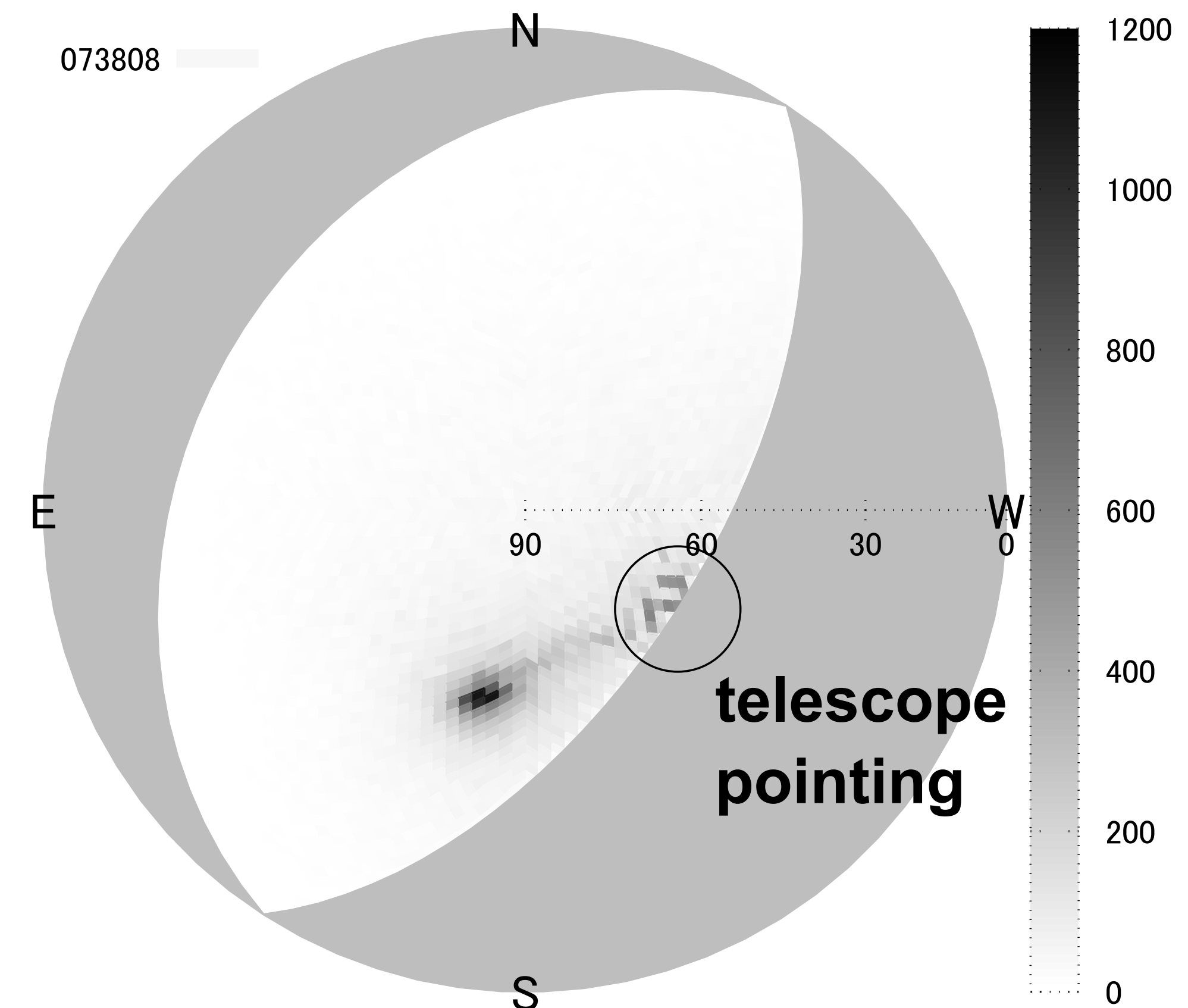
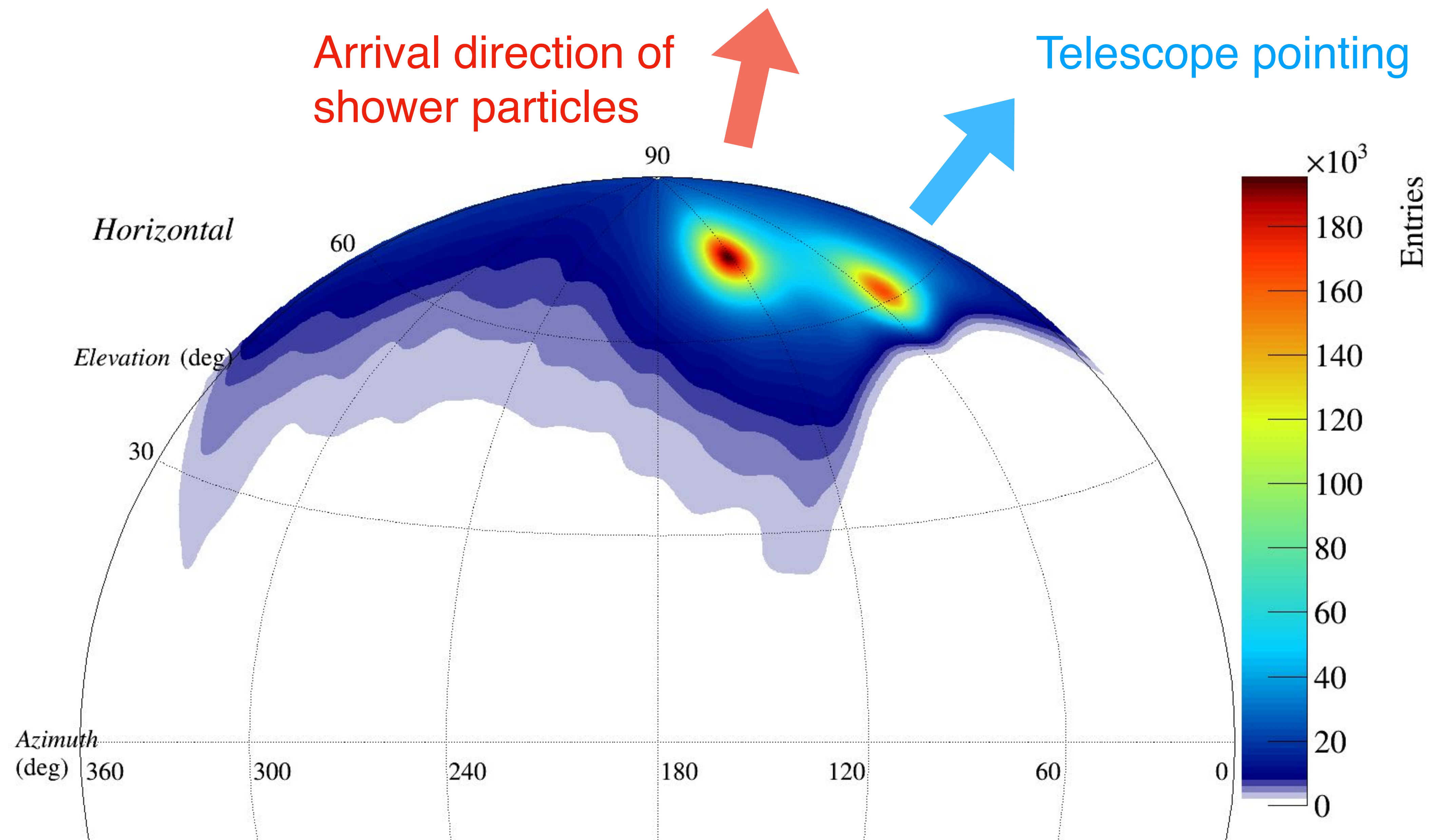
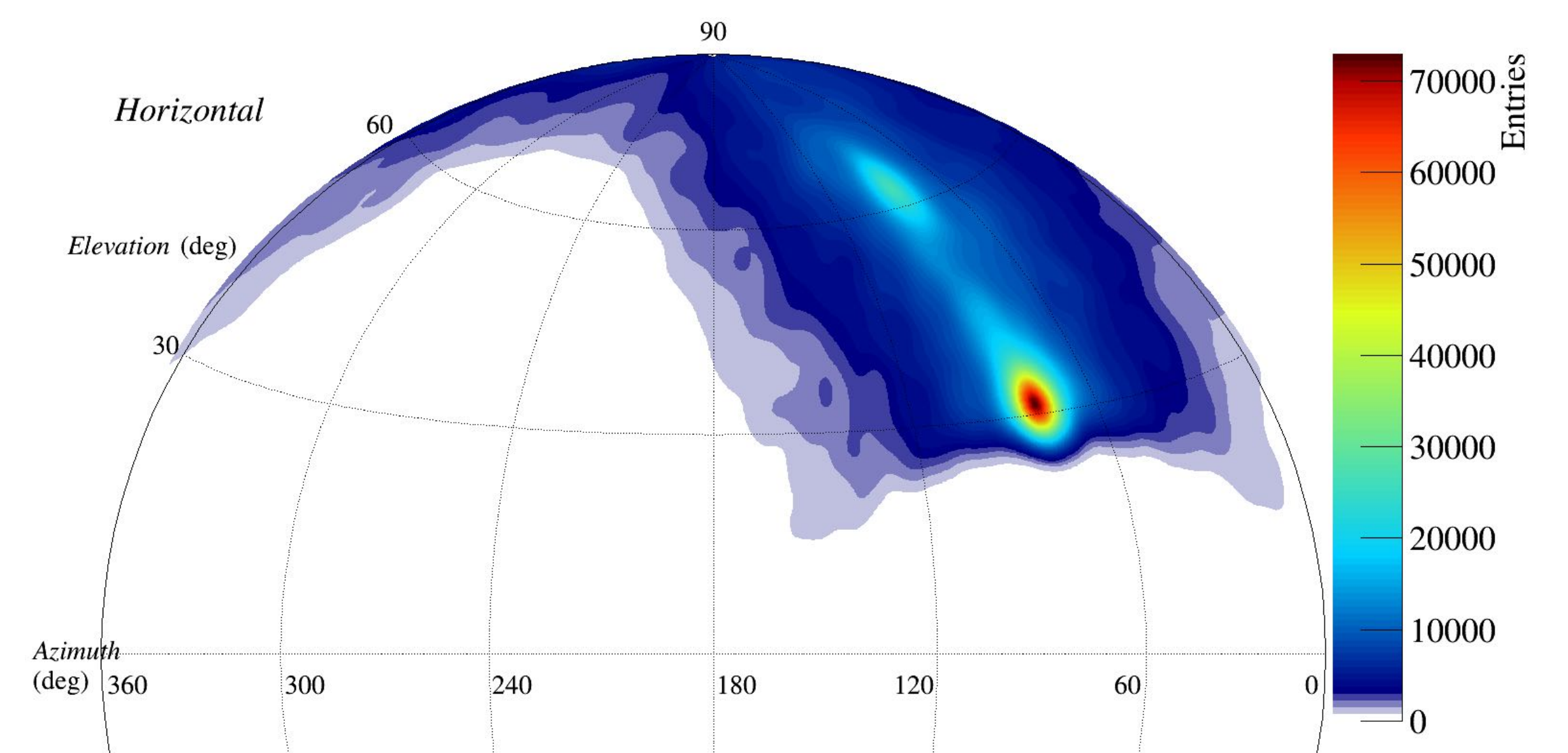
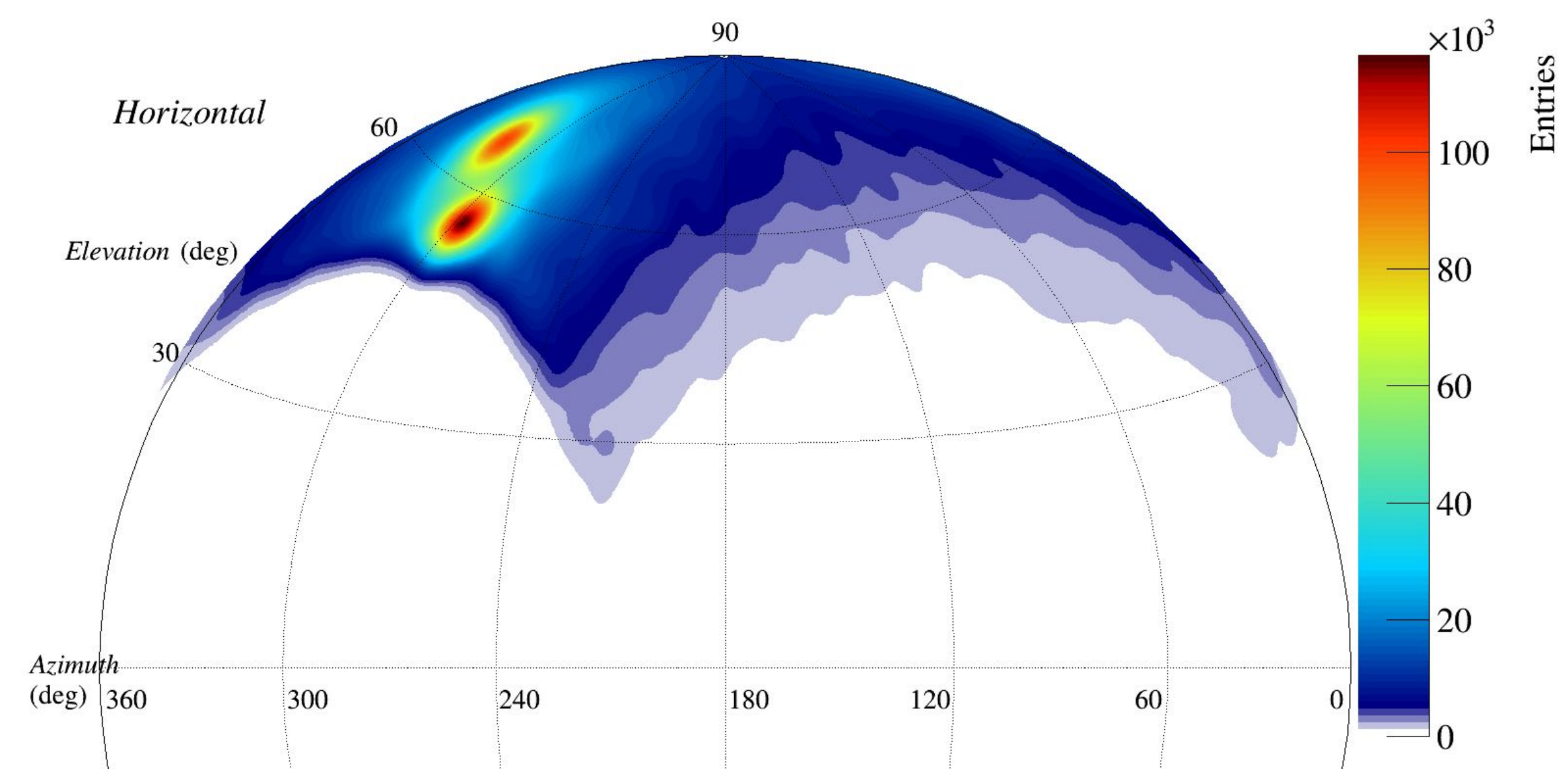
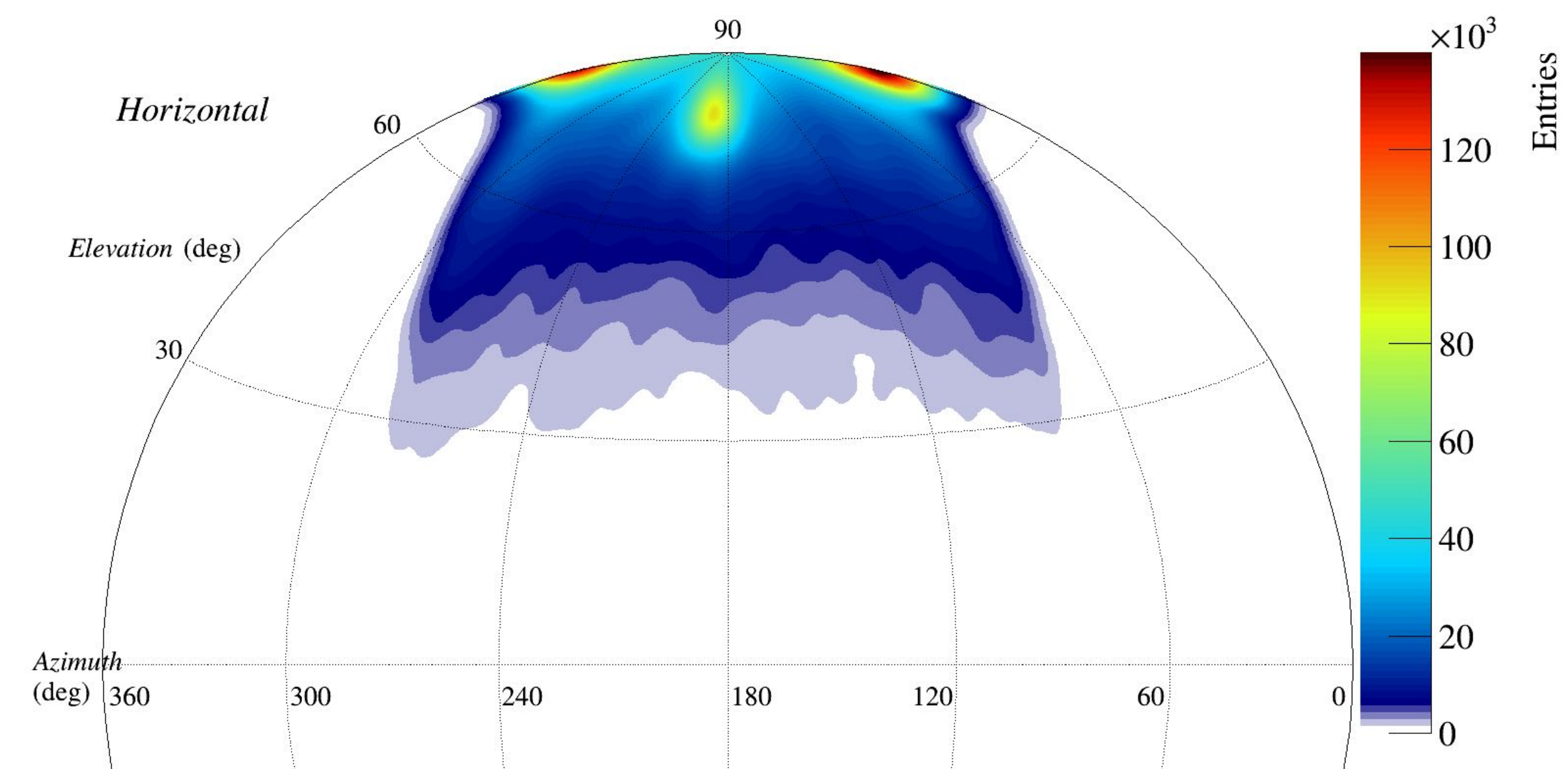
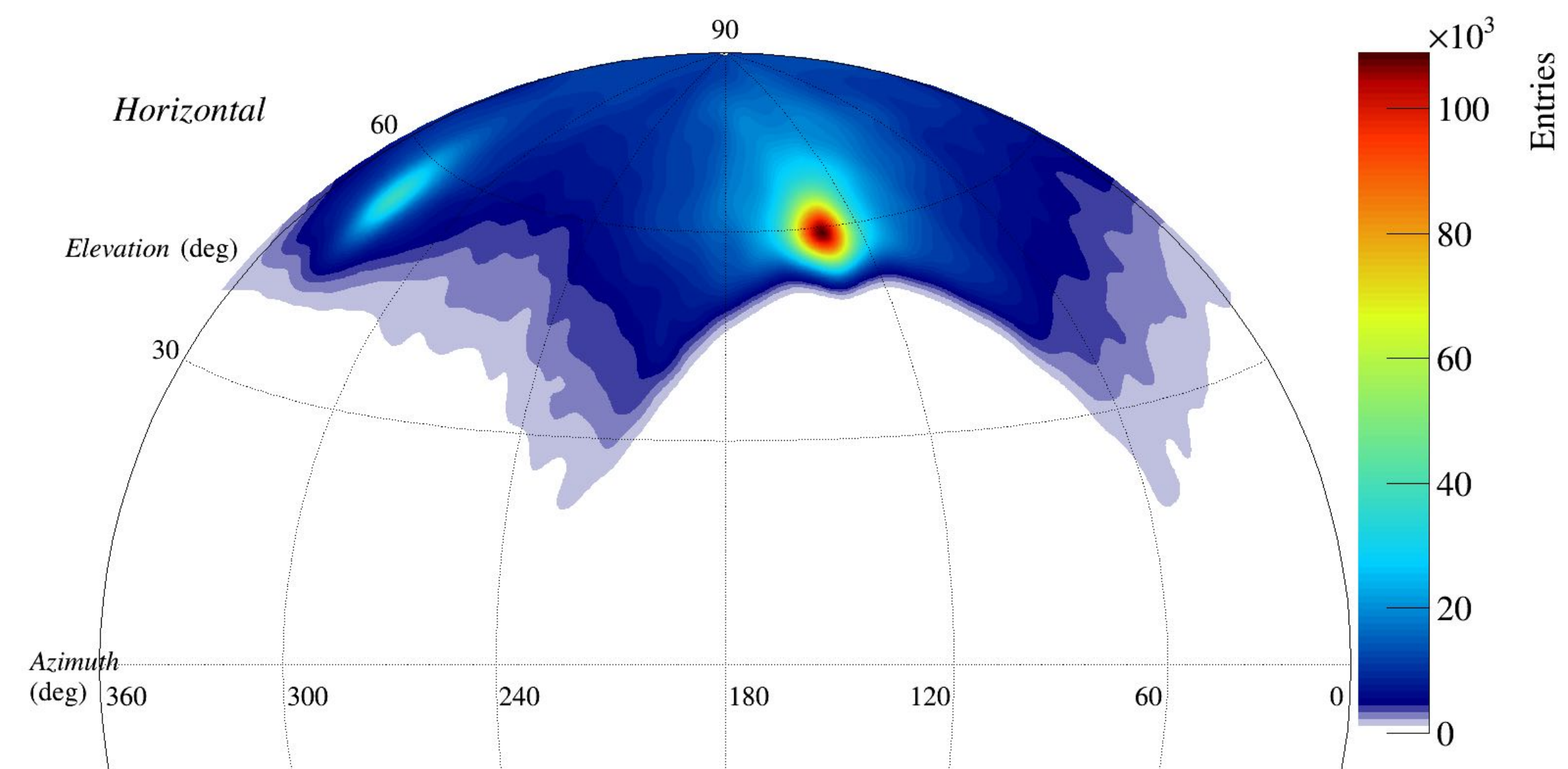


Table 3. Event information of the possible extensive air showers detected by Subaru HSC.

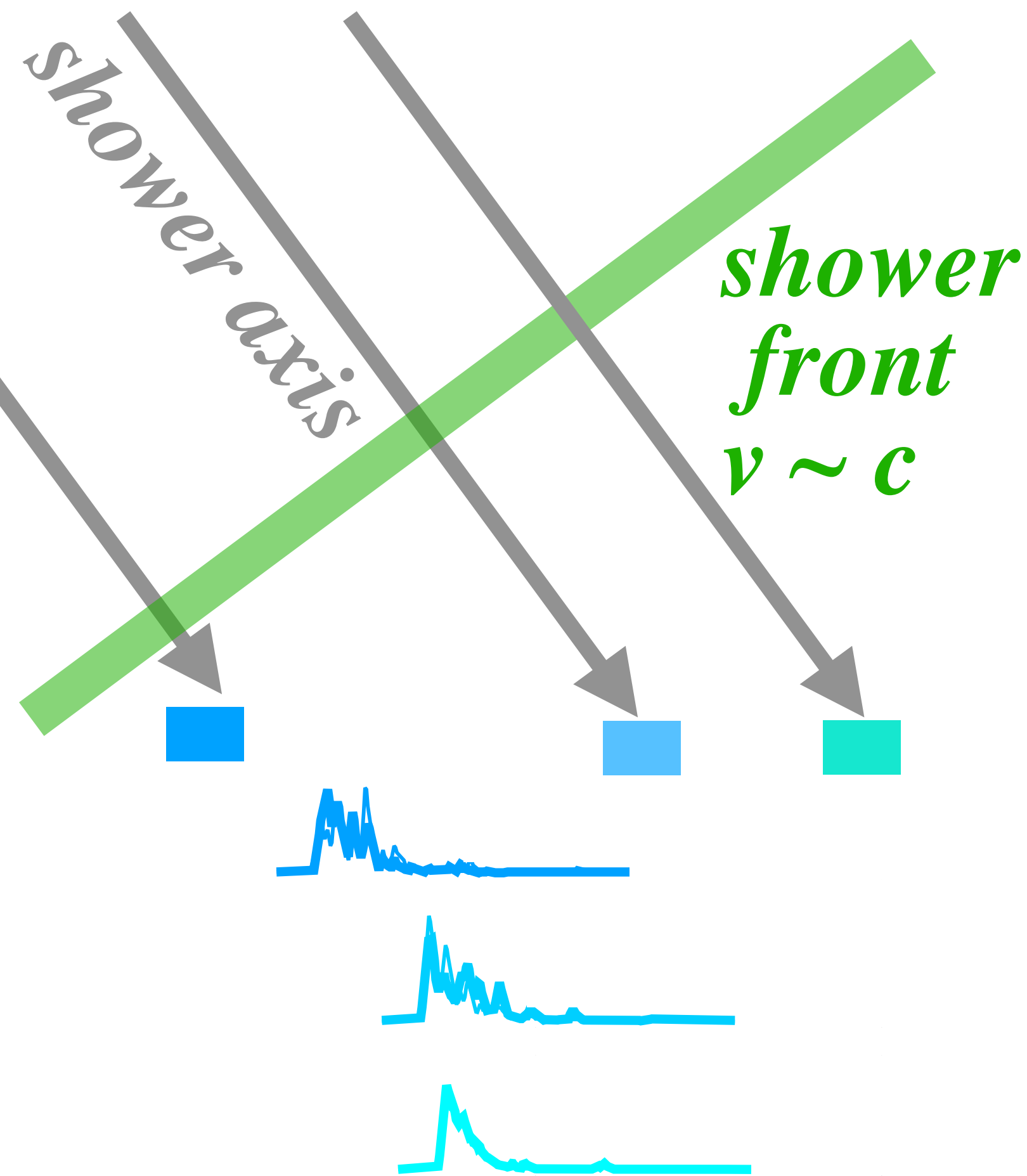
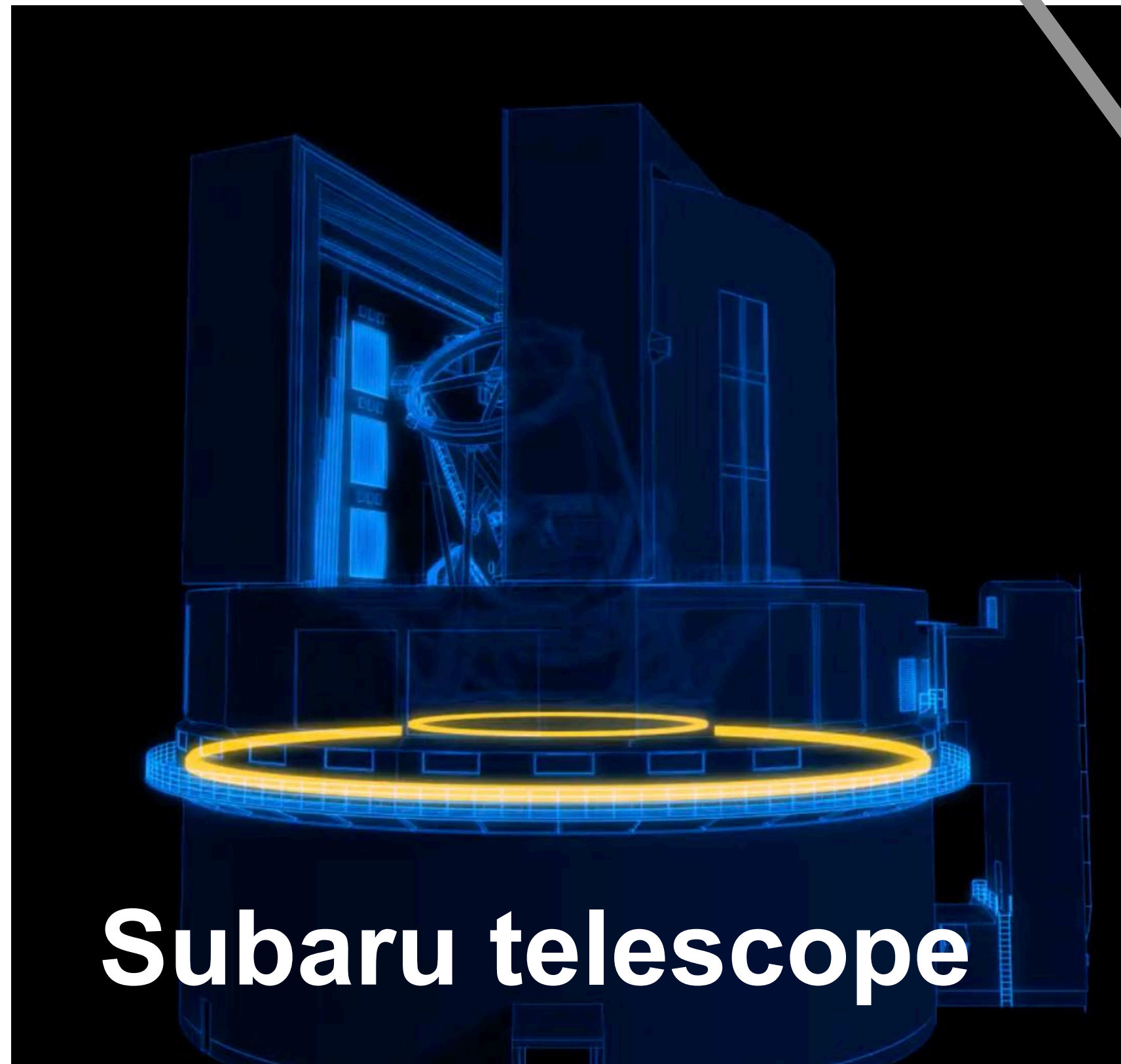
Reconstructing arrival direction of shower particles



Results of other extensive air shower events



Future plan to install surface detector array in Subaru



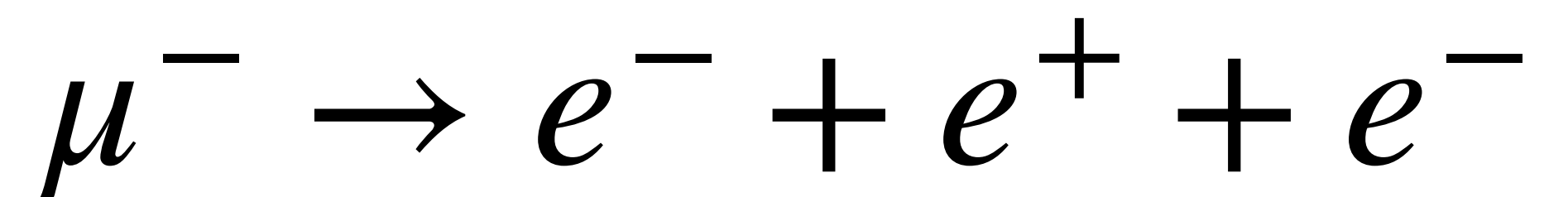
1 m² scintillator



- 📌 Discussion to install surface detector array **at ventilation room**
- 📌 4 x 1 m² plastic scintillators with 20 m spacing
- 📌 A new "hybrid" detection with surface detector array and silicon imaging detector

Application for "Dark Matter" or new physics search

- 📌 Unprecedented detailed measurements for cosmic ray extensive air showers
- 📌 Possibility on proton, He, Li, Be Fe identification by separating electrons and muons
- 📌 Understanding air-shower physics and hadron interaction models
- 📌 **Search for dark matter signal in CCD of Subaru HSC?**
- 📌 **Potential on new physics search?** (Discussed with M. Yamanaka)
- 📌 Search for Lepton flavor violating decay?



μ^- DECAY MODES

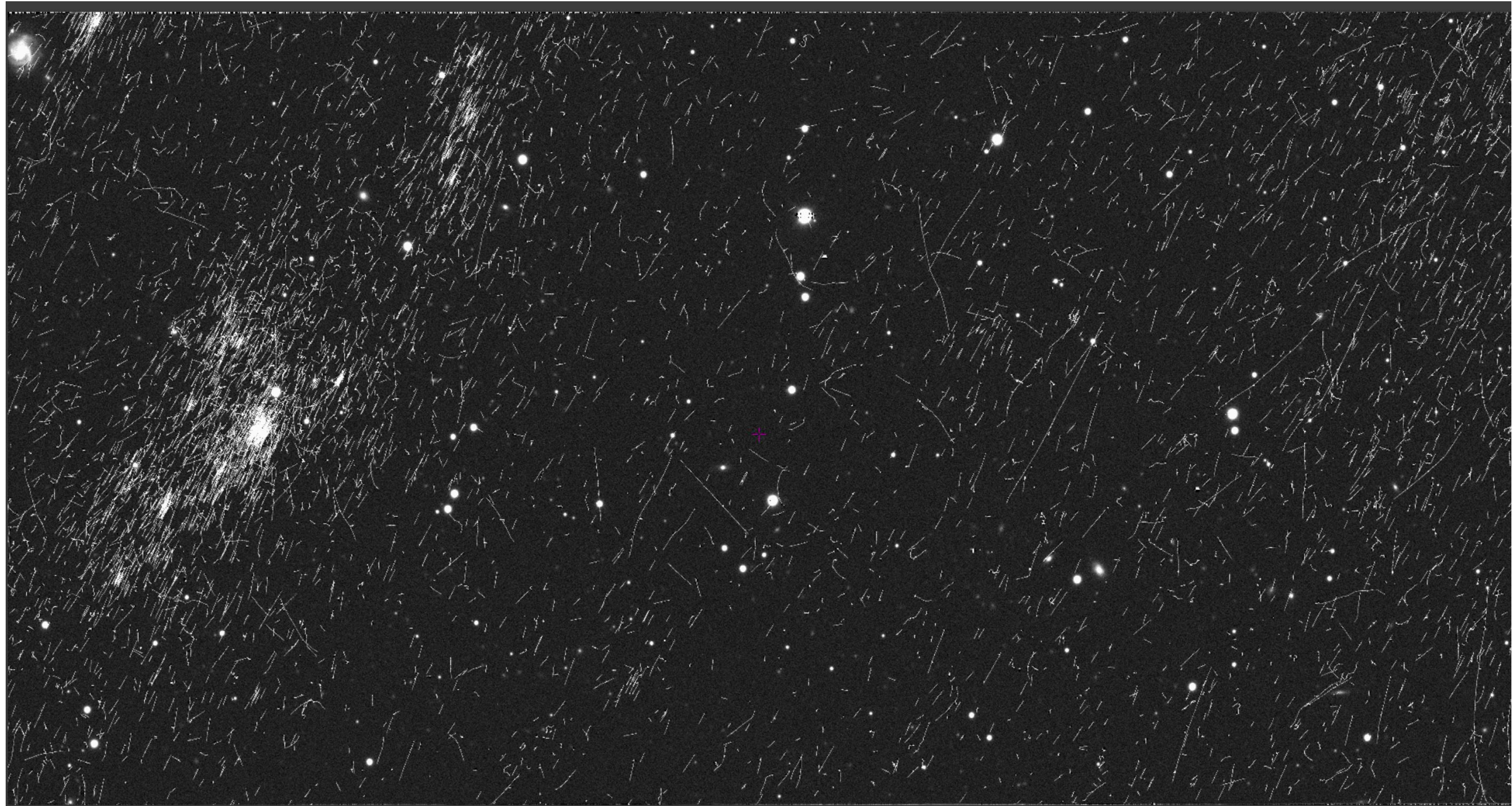
μ^+ modes are charge conjugates of the modes below.

Mode	Fraction (Γ_i/Γ)	Confidence level
Γ_1 $e^- \bar{\nu}_e \nu_\mu$	$\approx 100\%$	
Γ_2 $e^- \bar{\nu}_e \nu_\mu \gamma$	[a] $(6.0 \pm 0.5) \times 10^{-8}$	
Γ_3 $e^- \bar{\nu}_e \nu_\mu e^+ e^-$	[b] $(3.4 \pm 0.4) \times 10^{-5}$	

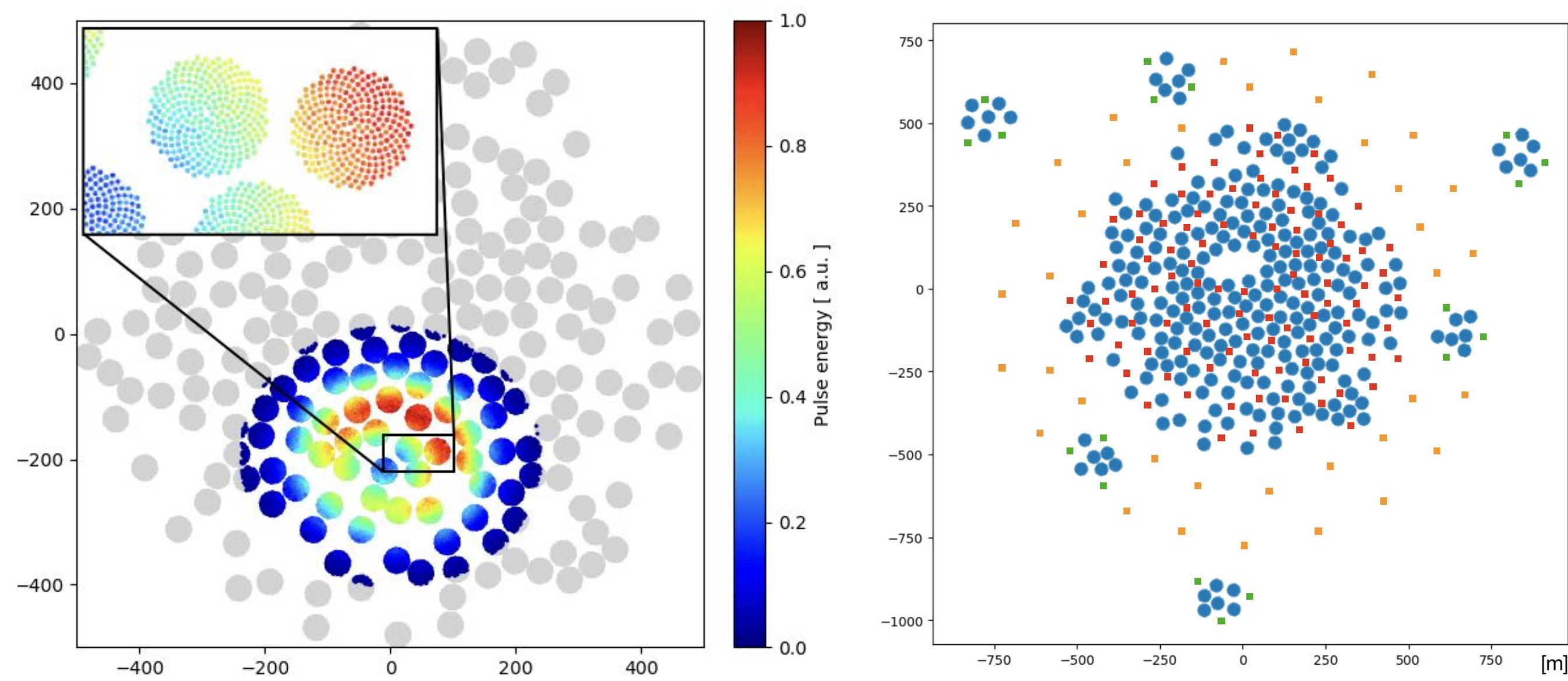
Lepton Family number (LF) violating modes

Γ_4	$e^- \nu_e \bar{\nu}_\mu$	LF	[c] < 1.2	%	90%
Γ_5	$e^- \gamma$	LF	< 4.2	$\times 10^{-13}$	90%
Γ_6	$e^- e^+ e^-$	LF	< 1.0	$\times 10^{-12}$	90%
Γ_7	$e^- 2\gamma$	LF	< 7.2	$\times 10^{-11}$	90%

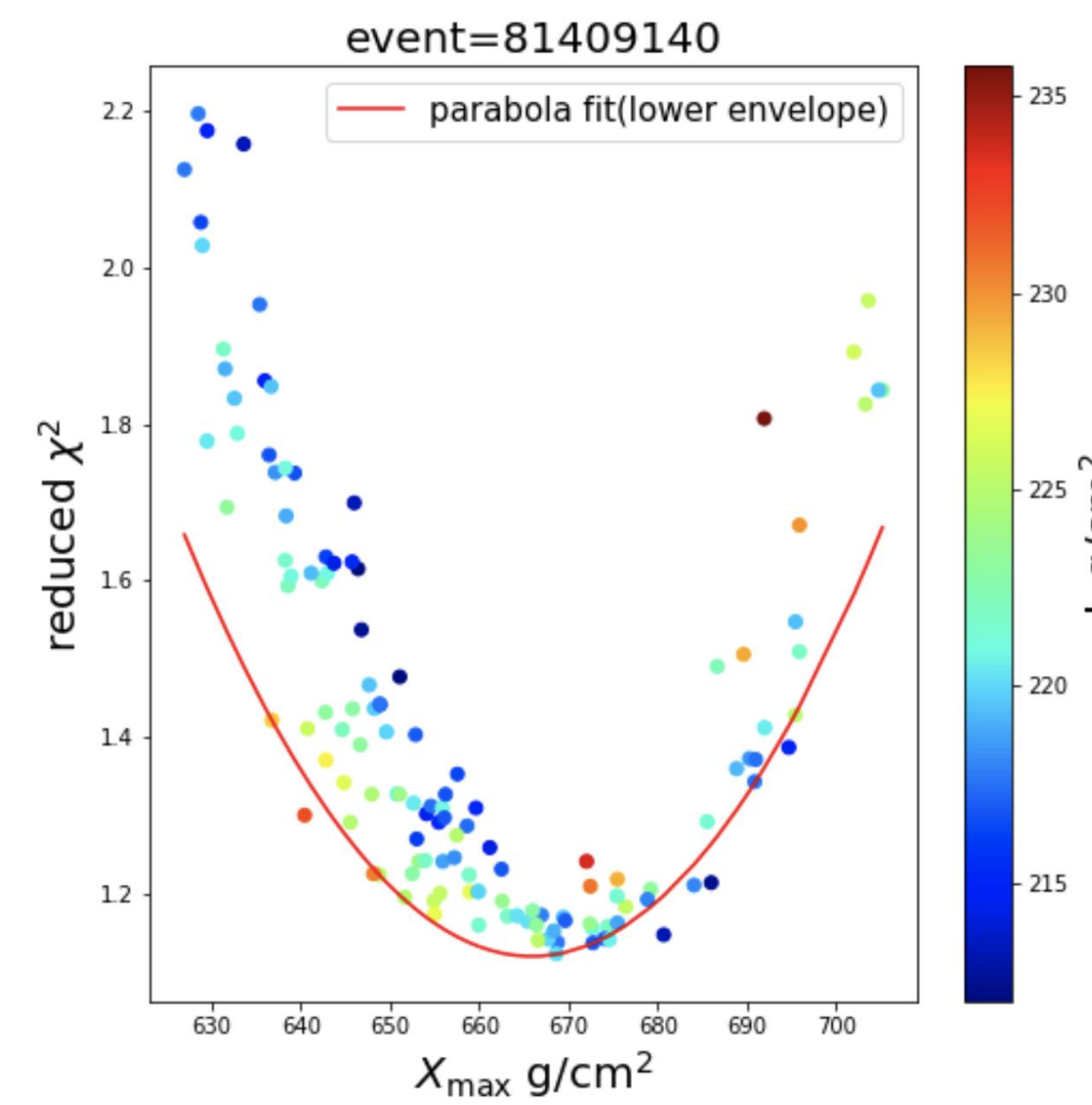
Dark Energy Survey (DES)



Square Kilometer Array (SKA)



<https://www.darkenergysurvey.org/>



"Inverse" multi-messenger observations by astronomical telescopes for cosmic rays

- 8 g/cm² on X_{\max}
- 3% in Energy

Summary and future plans

- 📌 Visualizing cosmic-ray extensive air showers with Subaru Hyper Supreme-Cam
- 📌 Your insightful suggestions are highly welcome for possible application
 - 📌 Search for exotic physics; Dark matter, WIMP, Monopole, Q-ball?
 - 📌 Search for lepton flavor violating decay? $\mu^+ \rightarrow e^+ e^- e^+$
- 📌 Future plans and ideas
 - 📌 Further data analysis of Subaru HSC
 - 📌 Being prepared for an installation of surface detector array
 - 📌 Data taking of dark images in daytime as a cosmic ray detector?