# Real-Time Follow-Up of Multimessenger Alerts at the Baikal-GVD Telescope

59th meeting of the PAC for Nuclear Physics

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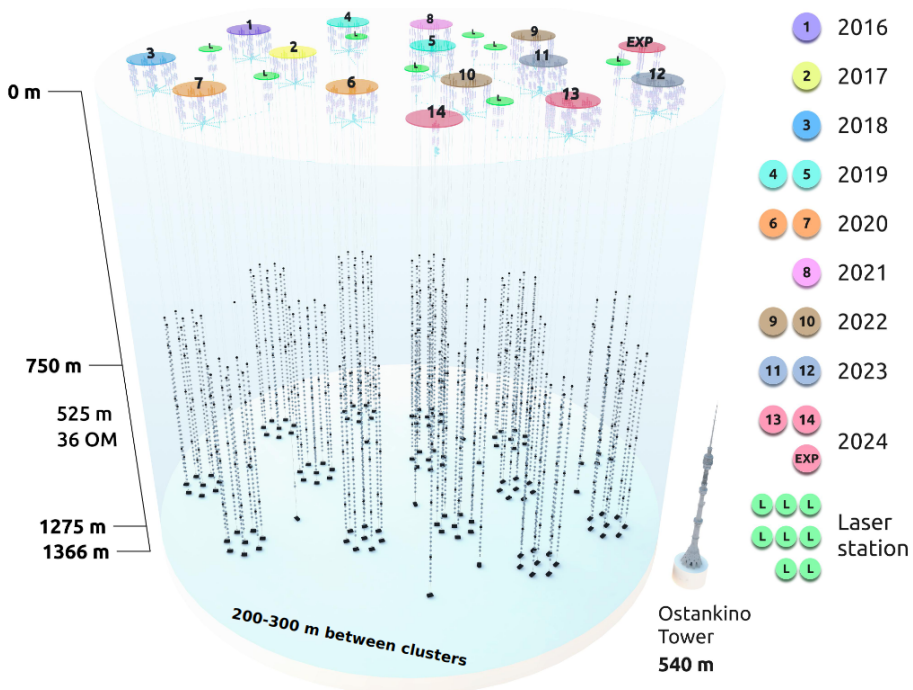
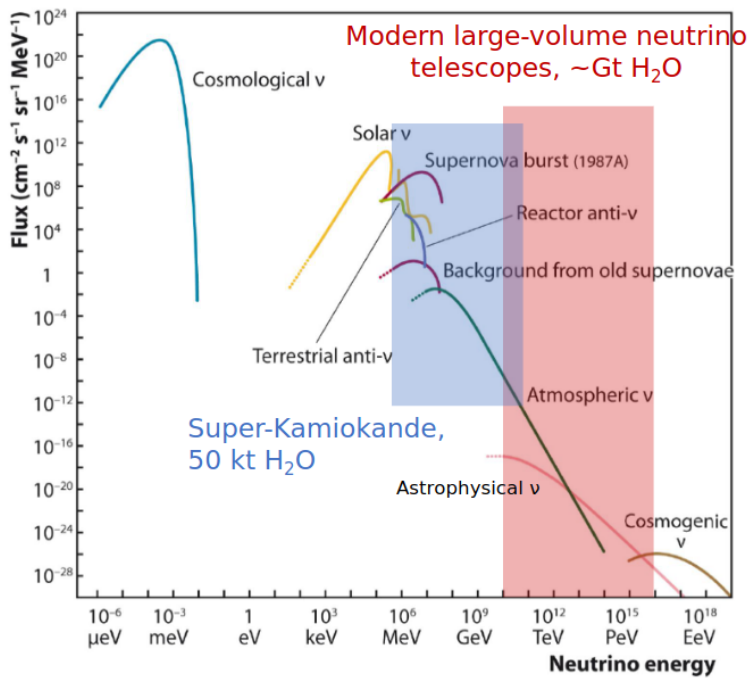
# Status of Baikal-GVD experiment

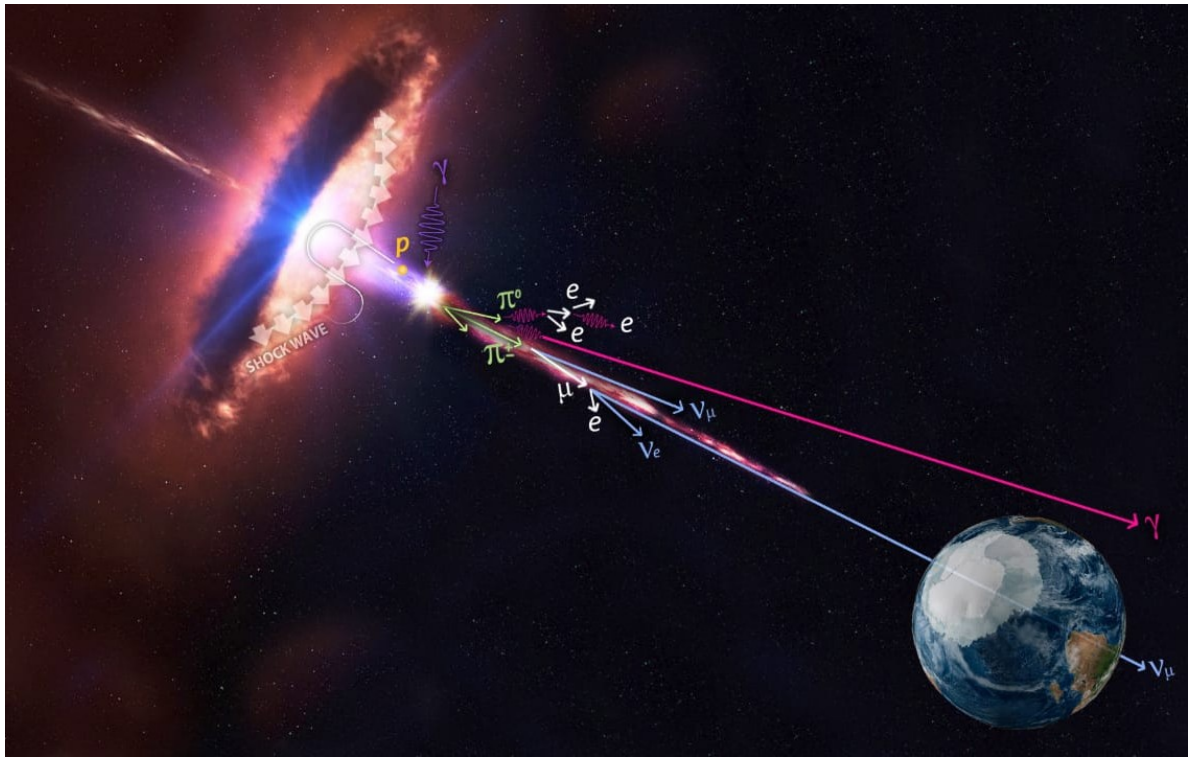
- The Baikal-GVD (Gigaton Volume Detector) is an underwater neutrino detector being constructed in Lake Baikal.
- Currently contains 3960 Cherenkov detecting optical modules with effective volume $> 0.6 km^3$ for cascades E>1PeV.
- The primary goal is the study of high-energy neutrino flux.



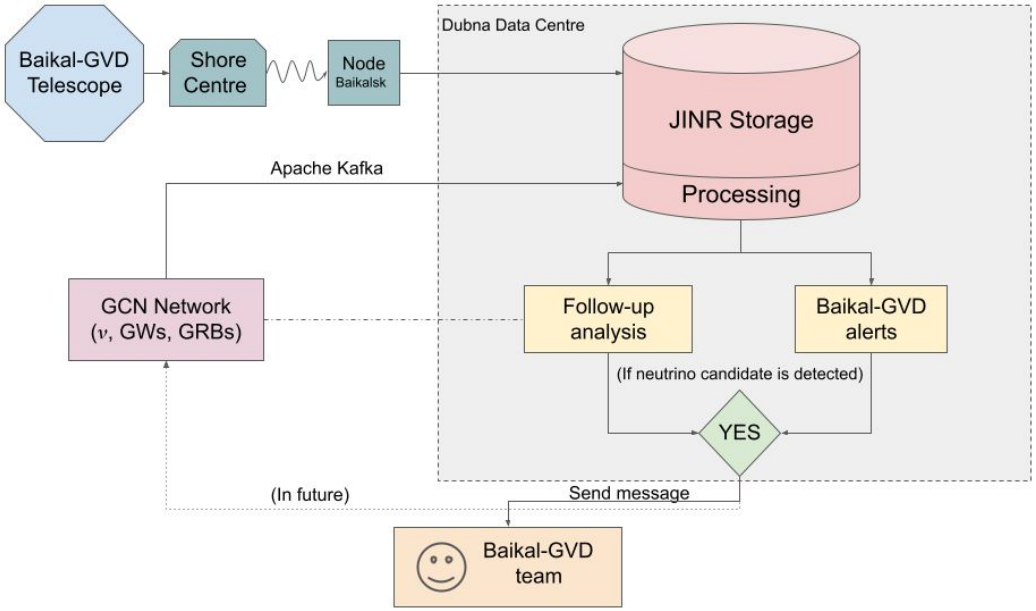



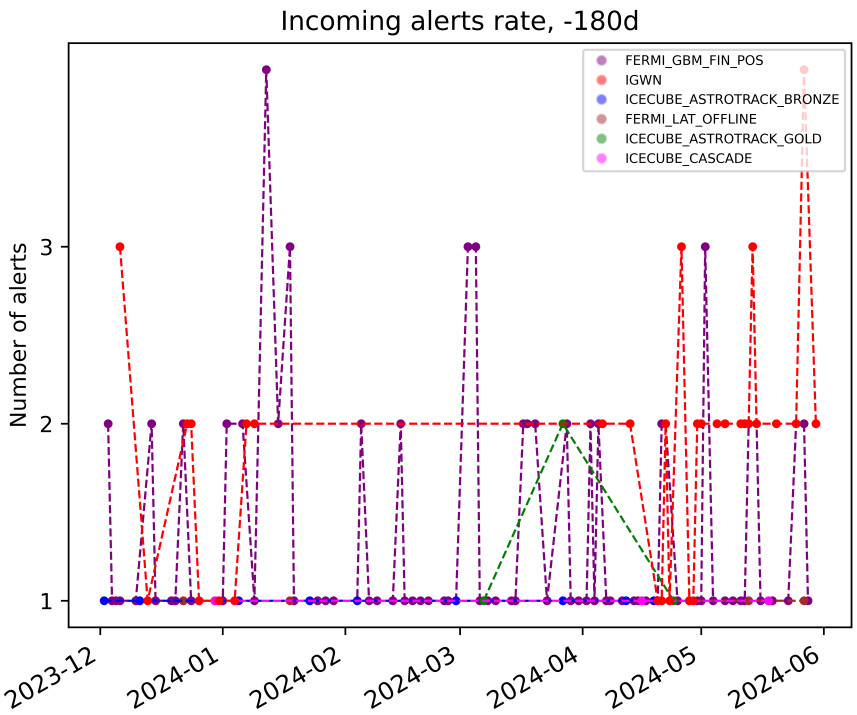
# Multimessenger Astrophysics and Neutrinos

- MM astrophysics involves studying cosmic phenomena using photons, neutrinos, cosmic rays, and gravitational waves.
- Combining data from MM sources helps better understand astrophysical events.
- Neutrinos can travel long distances in space without being affected by magnetic fields.
- MM helps find where HE neutrinos come from in bursts in the EM spectrum or catastrophic events detected through GW.



# Baikal-GVD Real Time Processing and Follow-Up




- BARS C++ programs are managed using PyBARS workflow built on the Luigi package.
- Data is saved with Influx, MariaDB.
- The delay between a Baikal-GVD event and a potential alert message is $\sim$3–10 mins.
- Email in a MM standardized text format, along with a picture showing a potential coincidence, is sent to the Baikal-GVD working group.

# Online Reconstruction

- Less precise coordinates and simplified calibration compared to offline.
- Single cluster reconstruction in parallel tasks, OM hits with charge Q $>$ 1.5 p.e.

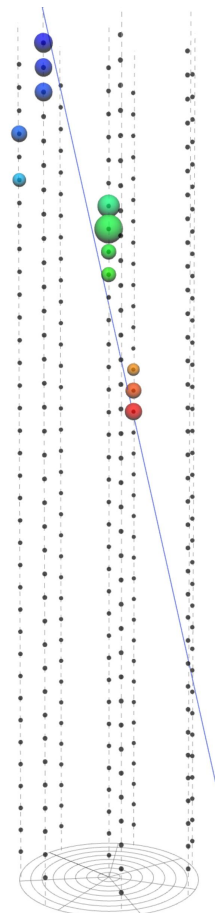
**Tracks upgoing**
(CC, $\nu_\mu$, $\nu_\tau$)
angular resolution is $\sim 0.3^\circ - 0.5^\circ$, energy is 200−300%

- Hit Finding
- Noise Suppression (Fast causally connected pulse search algorithm)
- Direction, Position, Time Evaluation
- Quality Parameter Cuts (BDT)

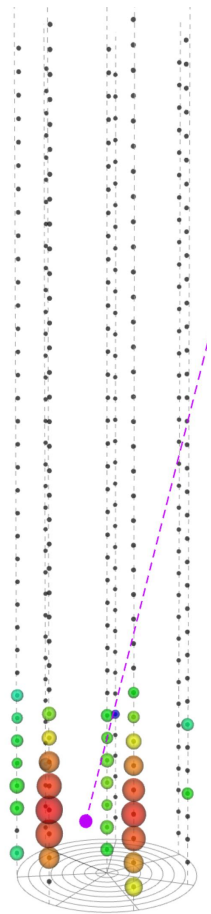
**Cascades all sky**
(CC $\nu_e$, $\nu_\tau$, NC)
angular resolution is $\sim 3^\circ - 5^\circ$, energy is 5−30%

- Event Selection
- Vertex Reconstruction ($\chi^2$ minimization)
- Energy and Direction Reconstruction (max Llh estimation)
- Quality Parameter Cuts (BDT)

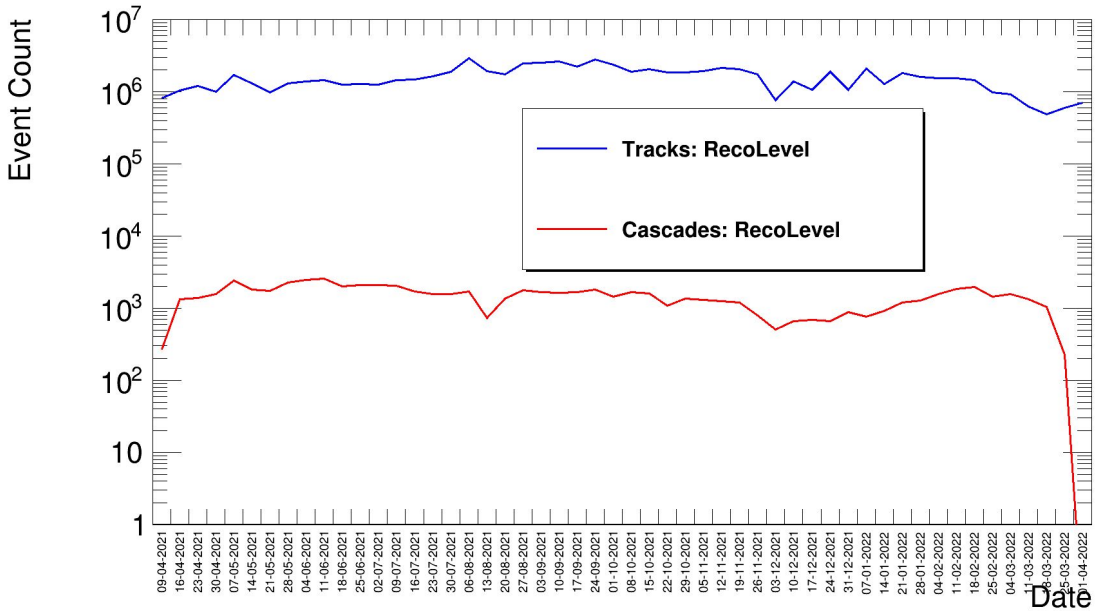
Track-like, data 2019

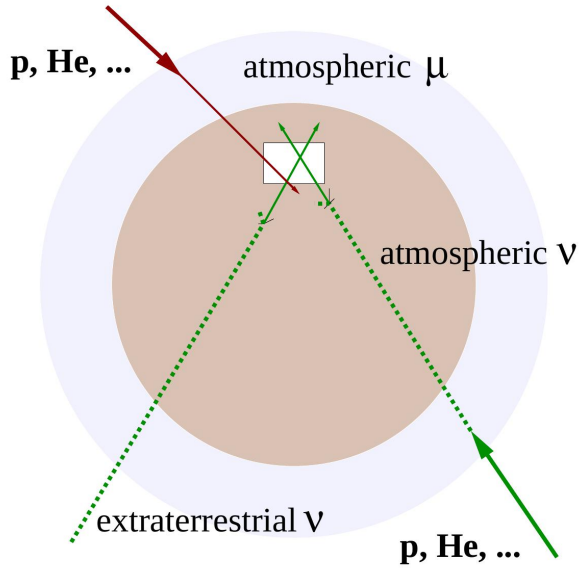


Cascade-like, data 2022



# Reconstructed Events in Processing




Baikal-GVD 2021 season

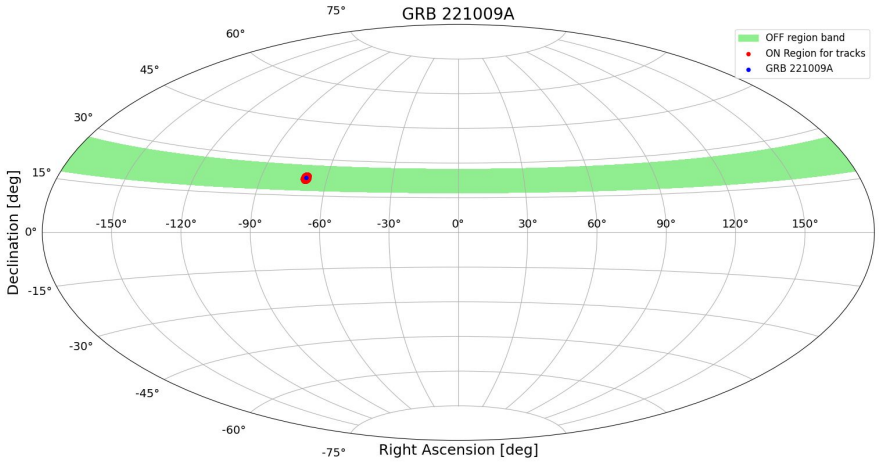
Majority of the reconstructed events is background atmospheric muons and muon groups.
The goal of selection is the suppression of muon backround.

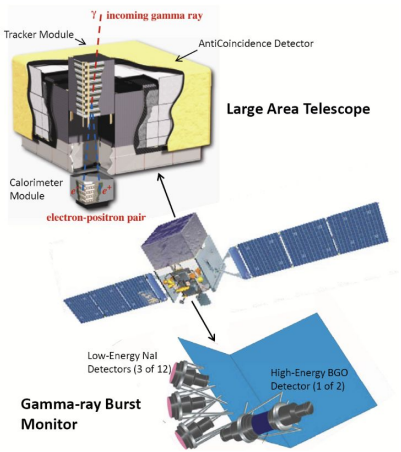
- V.M. Aynutdinov et al. PoS ICRC2023 (2023) 1001 - tracks
- V.M. Aynutdinov et al. PoS ICRC2023 (2023) 986 - cascades

# Baikal-GVD and Follow-Up with GCN Kafka

**Search for online coincidences:**

- ON/OFF method
- ON region includes 90% localization errors
- OFF is extended within a $\pm$ 5 dec band
- OFF is evaluated using real data from previous seasons




Fermi-GBM/LAT:

- $[T0 - 1\text{d}, T0]$
- $[T0 - 1\text{d}, T0 + 12\text{h}]$
- $[T0 - 1\text{d}, T0 + 1\text{d}]$

LIGO-Virgo-KAGRA:

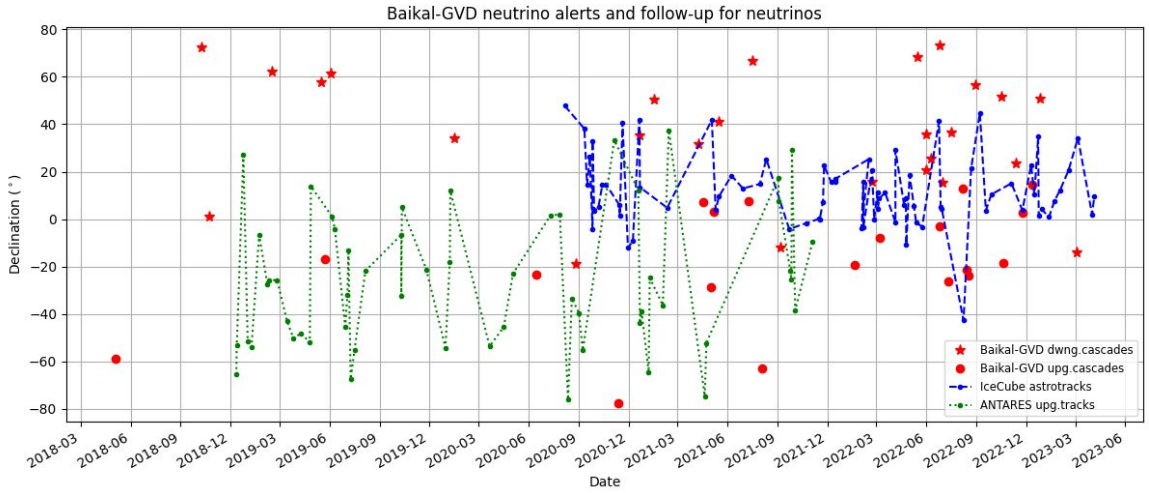
- $[T0 - 1000\text{s}, T0 + 1000\text{s}]$
- $[T0 - 1000\text{s}, T0 + 14\text{d}]$

IceCube:

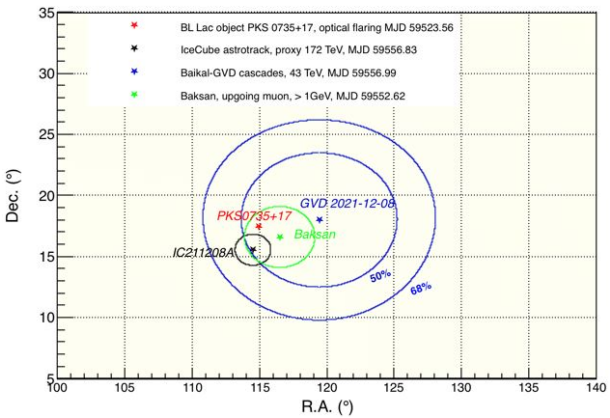
- $[T0 - 1\text{h}, T0 + 1\text{h}]$
- $[T0 - 1\text{d}, T0 + 1\text{d}]$

# Neutrino Follow-Up

- 2018 - 2 cls
- 2019 - 3 cls
- 2020 - 5 cls
- 2021 - 8 cls
- 2022 - 10 cls
- 2023 - 12 cls

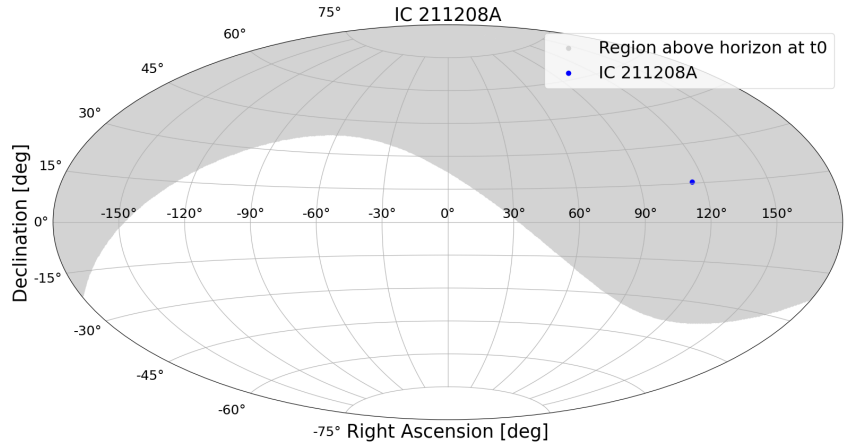



Upgoing events: $E > 15$ TeV, Downgoing: $E > 60$ TeV




**GVD211208A** & **PKS0735+17**

**Astrotelegram # 15112**




IC211208A localization for Baikal

Upper limits on the neutrino fluence $E^2 \cdot \Phi_\nu(E)$ for one cluster for $1\text{TeV} < E < 10\text{PeV}$ in cascade mode are found to be from 1 to 3 GeV/cm$^2$ within $\pm 12$ hours.


Thank you for your attention!