High-Energy Atmospheric Physics of Lightning and Thunderstorms Observed along the Sea of Japan

Teruaki Enoto
(RIKEN, Extreme natural phenomena RIKEN Hakubi team)

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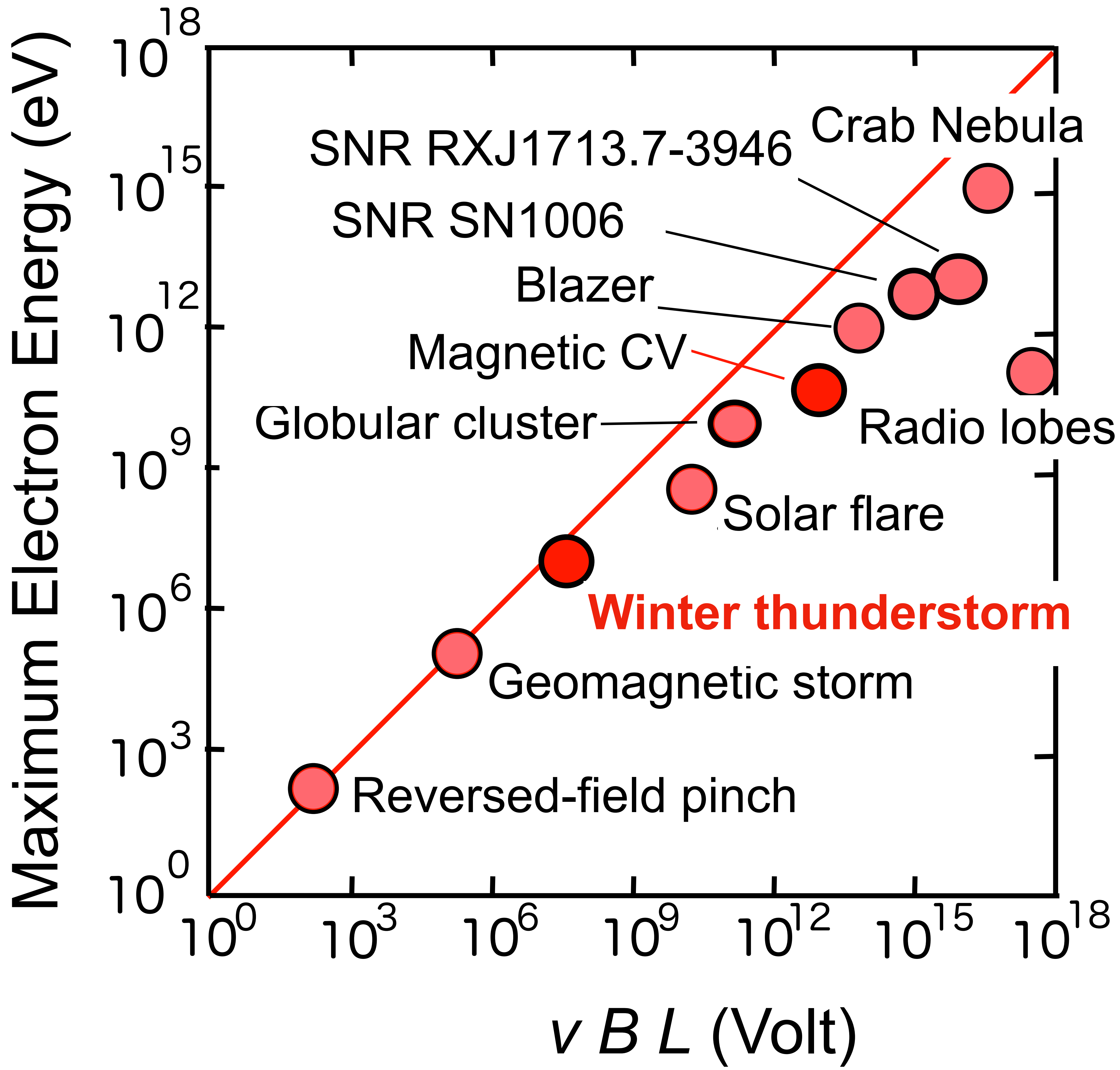
Connecting high-energy astroparticle physics for origins of cosmic rays and future perspectives
15:30-16:00 (25+5), December 8, 2020, Yukawa Institute for Theoretical Physics, Kyoto University

Electron Acceleration by Electric Fields

- *Origin of cosmic rays*? → Acceleration of charged particles needs electric fields, e.g.,
  - Diffusive shock acceleration at supernova remnants (*Motional electric field, E*=*v* x *B*)
  - Reconnection (*Induced electric field*)
  - Pulsar magnetosphere, and wakefield acceleration (*Charge separation*)
- In the astrophysical contexts, magnetic fields are assumed as the source of electric fields.
- Charge neutrality prevent formation of large-scale electric field via charge separation.

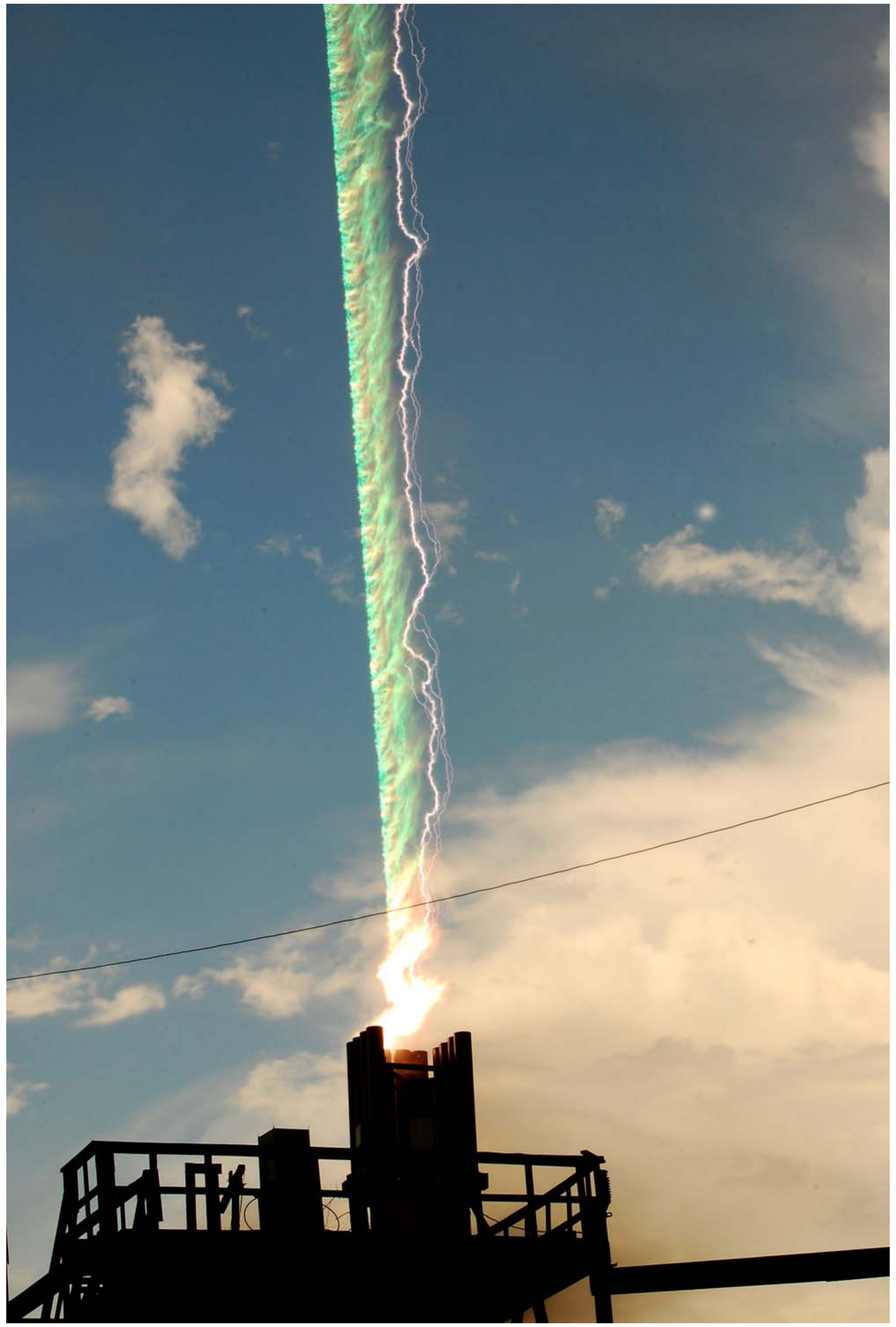


v: typical velocity of the system
B: magnetic field strength
L: size of the system

(Makishima, Journal of the Physical Society of Japan, vol. 63, 8, 2008)

Lightning and Thunderstorms as Accelerators

- Lightning and thunderstorms are revealed to act as natural electron accelerators by “direct” electric fields in the atmosphere.
- Evidence for the electron acceleration: Bremsstrahlung from relativistic electrons
  - Natural and rocket-triggered lightning
  - Terrestrial gamma-ray flash (TGF)
  - Gamma-ray glow
- “High-Energy Atmospheric Physics,” an interdisciplinary field between high-energy physics and atmospheric science.



(Dwyer et al., Geophysical Research Letters, 2004)

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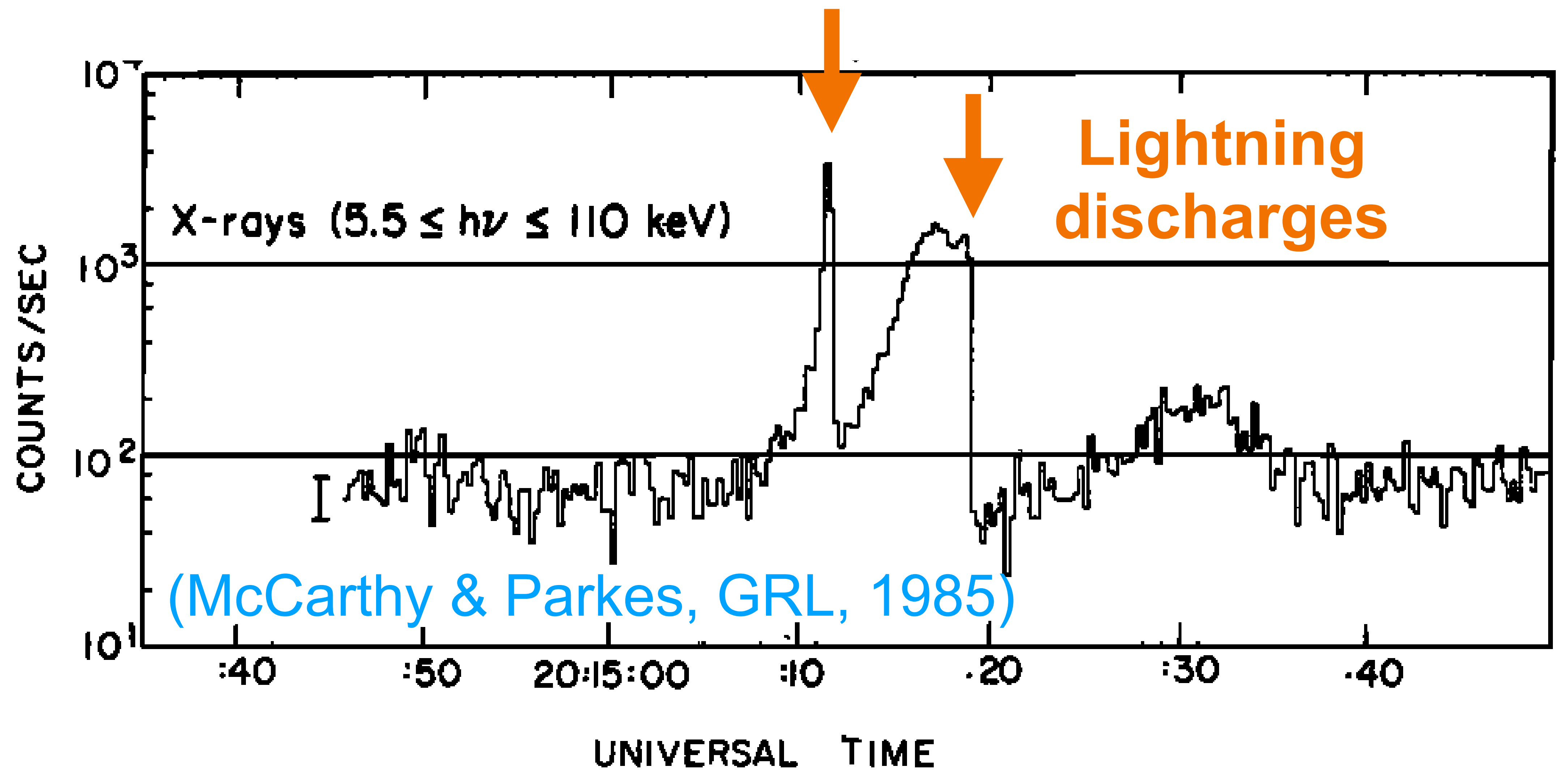
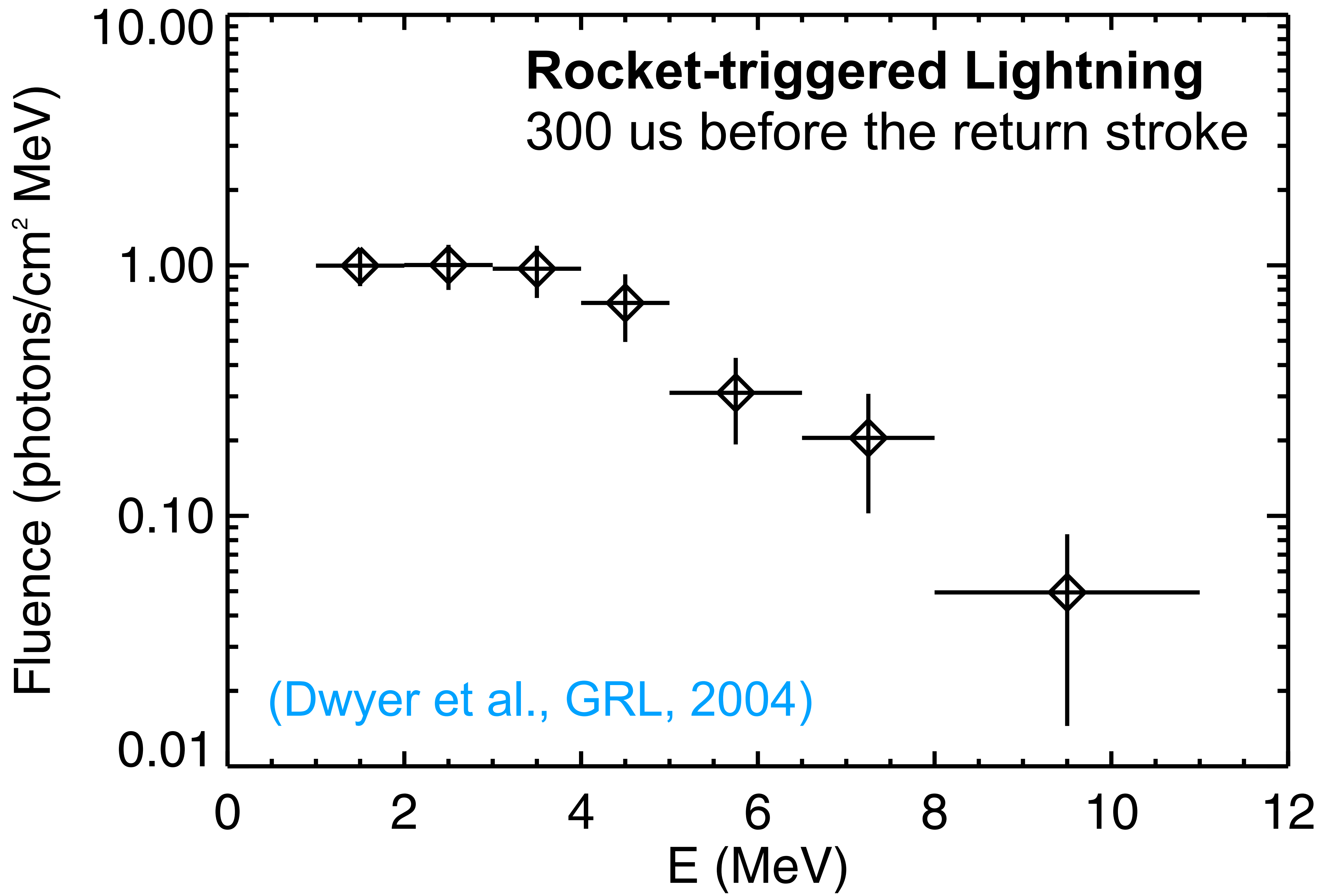




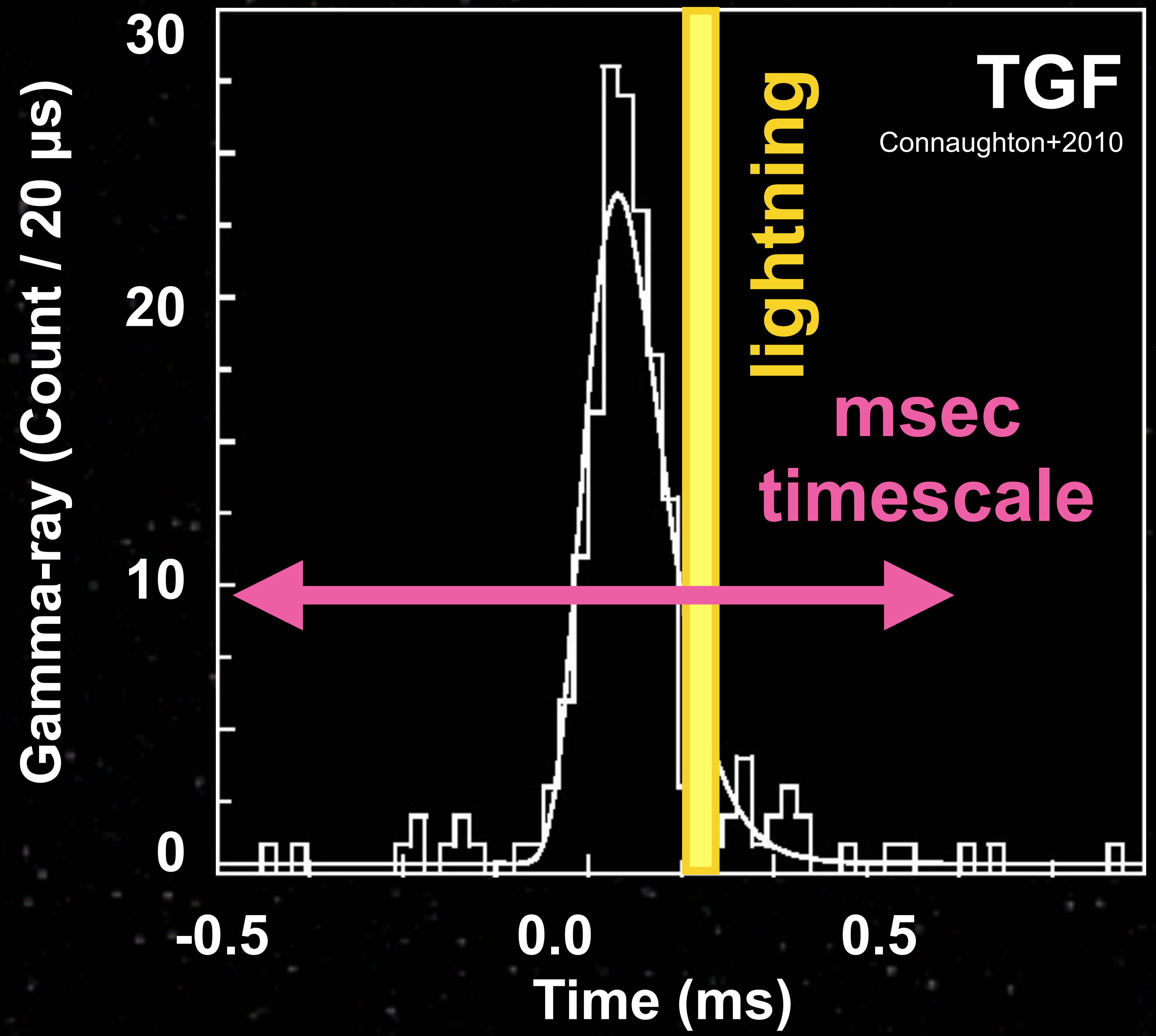
Electron Acceleration at the Stepped Leader?

- Accelerated electrons generate an ionised path of discharge (stepped leader)? As the leader reaches the ground, a huge current run the path (return stroke).

Dustin Farrell “Transient” (vimeo) https://vimeo.com/245581179

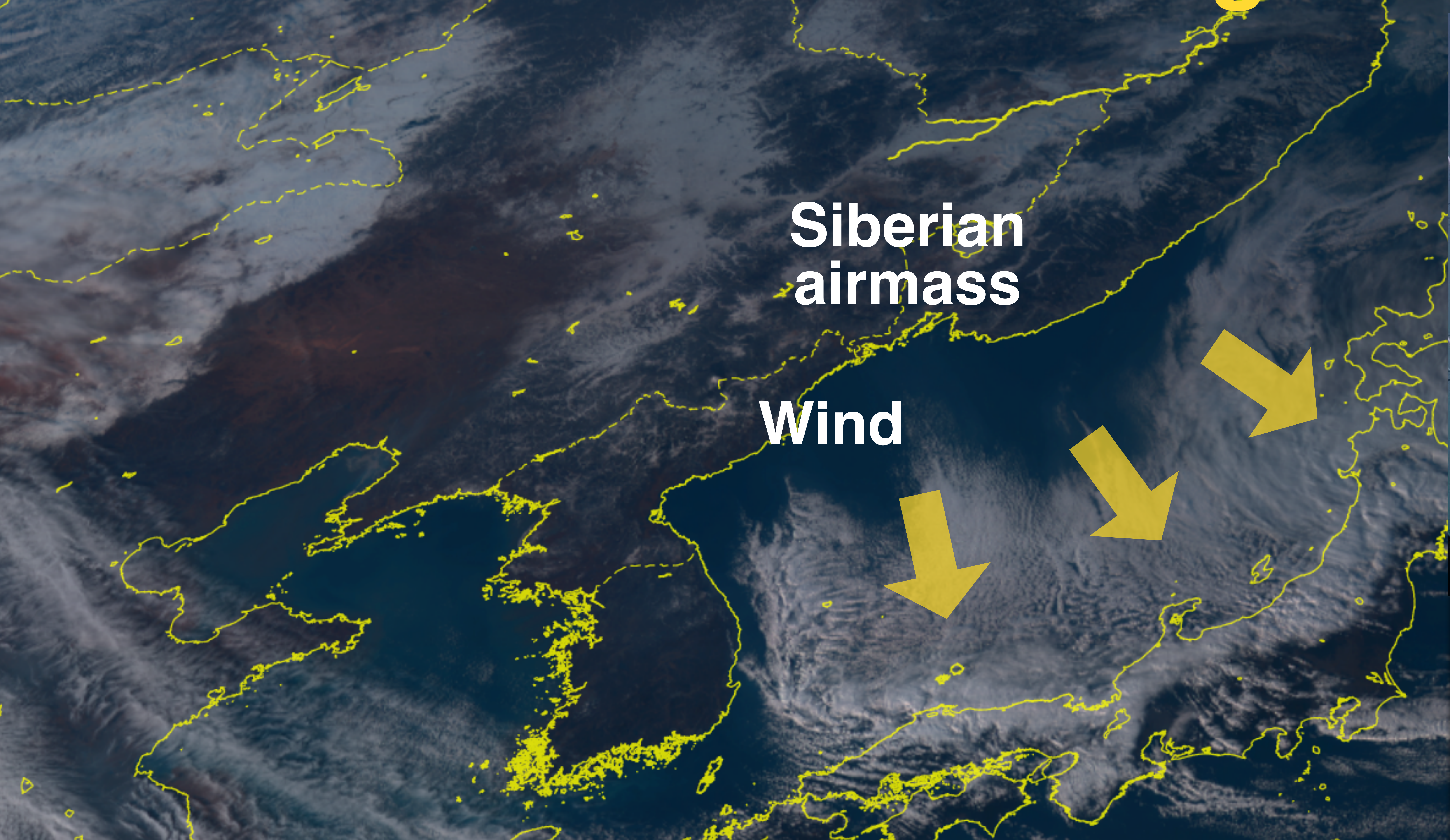
Terrestrial Gamma-ray Flash (TGF)

- Discovered by astronomical satellites above thunderstorm
- Millisecond gamma-ray bursts (<~20 MeV)

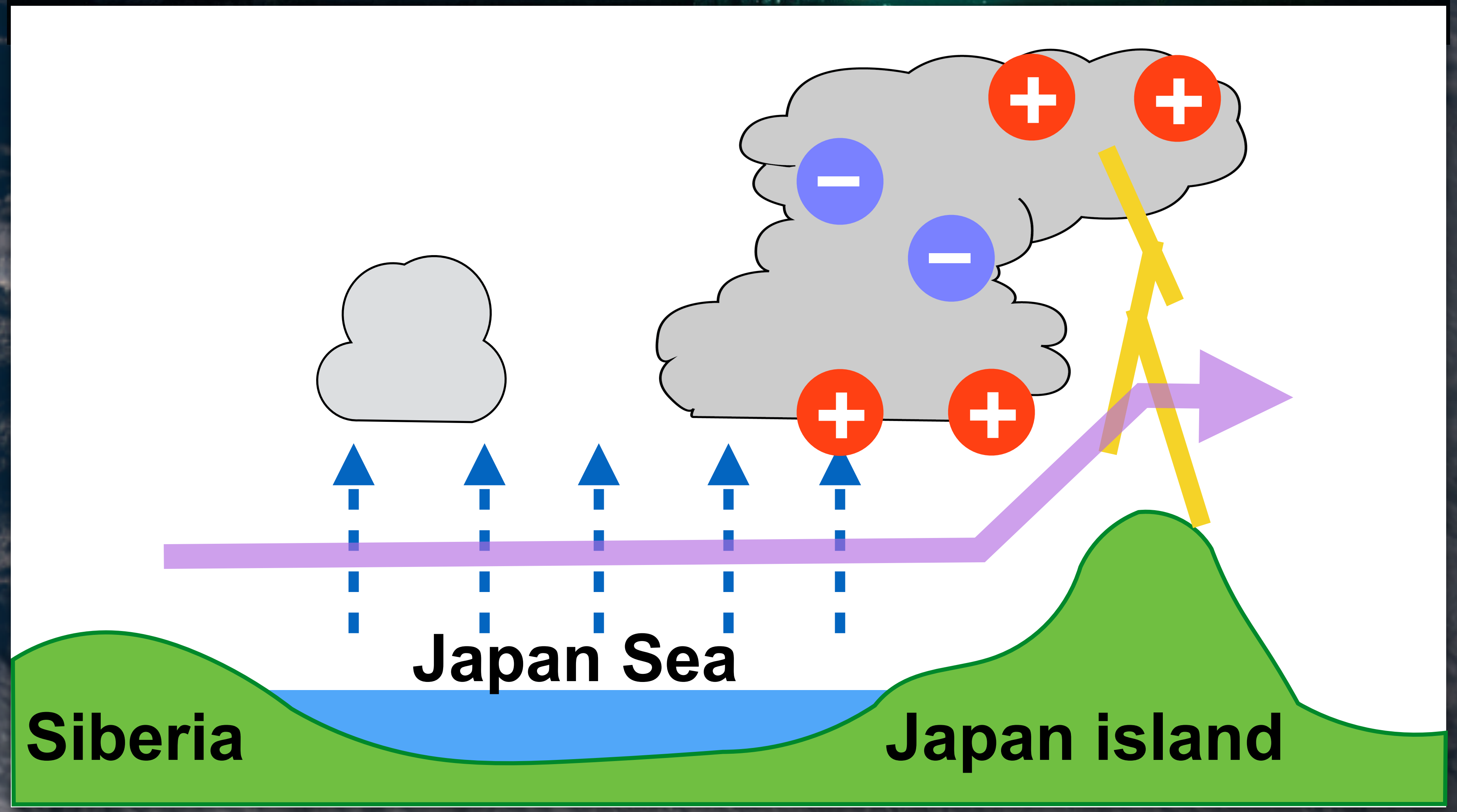


CG Credit: NASA/GSFC

Winter Thunderstorm along the Sea of Japan




A winter lightning discharge in Japan (Fukui, Nov. 20, 2005)
(C) Toshio Yoshioka and Otowa Electric Co., Ltd.

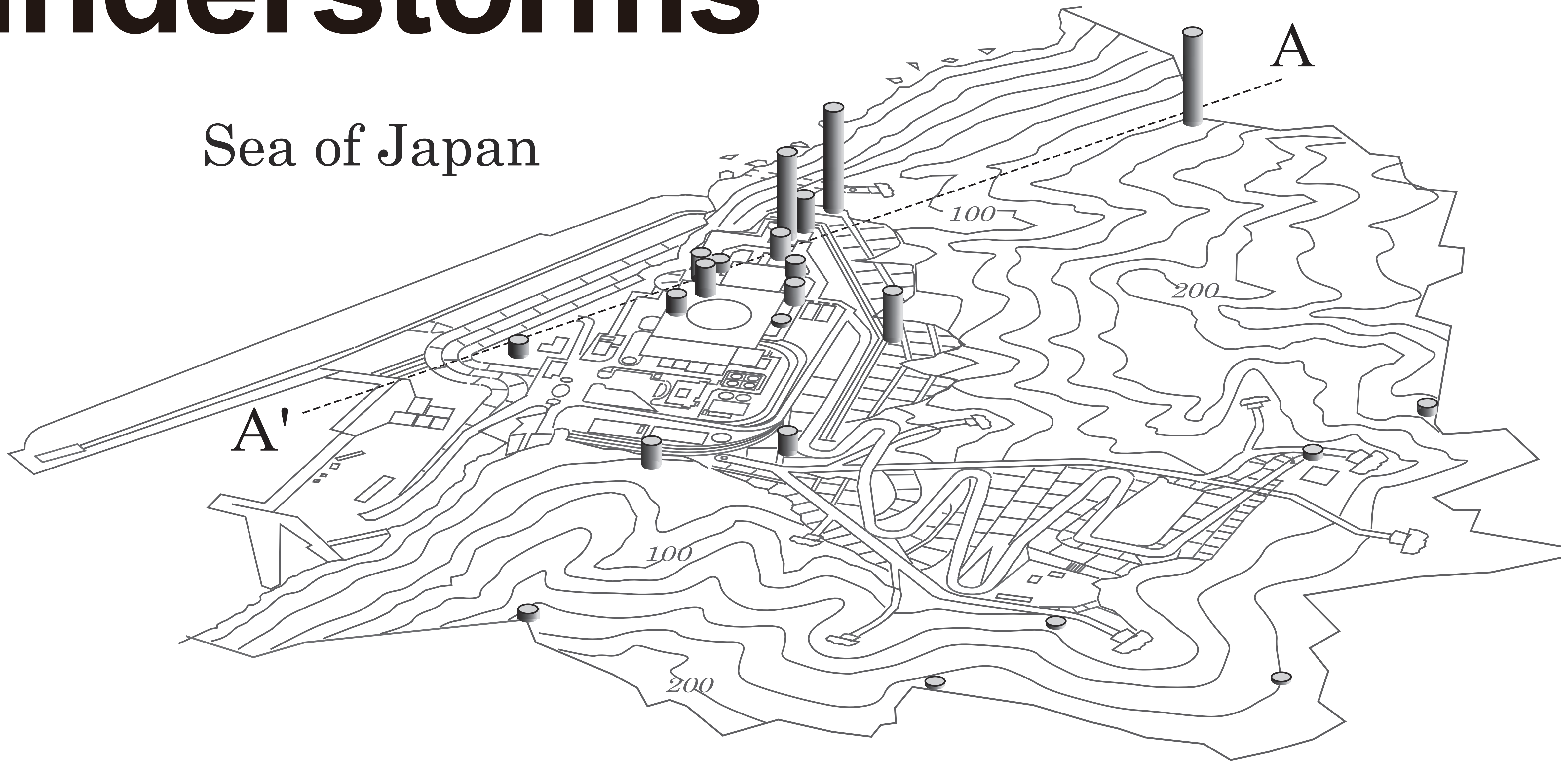


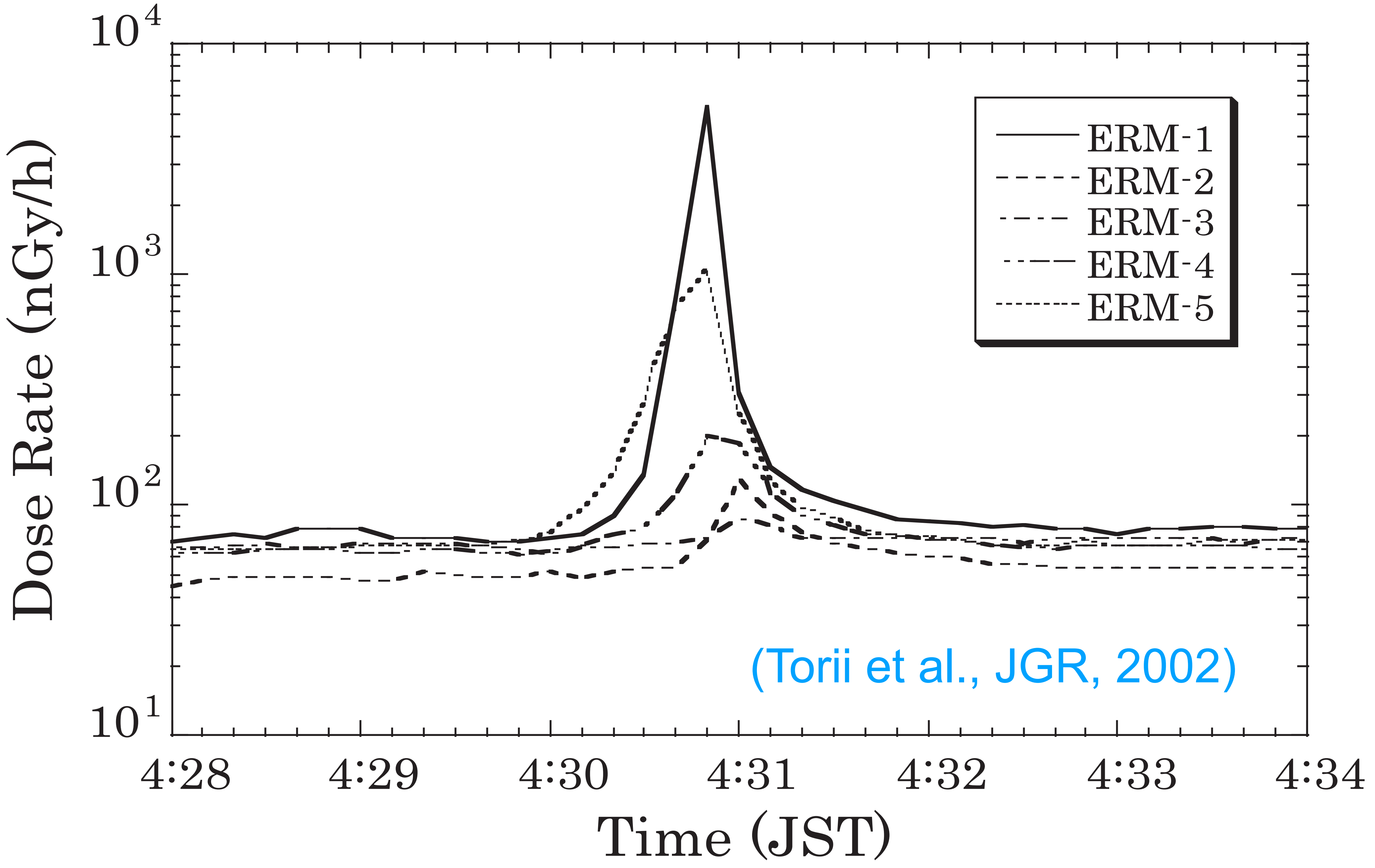
- lower altitude (<1 km) than summer storms
- powerful lightning, frequent positive discharge
- Ideal for observing the high-energy atmospheric phenomena

© Himawari 8 / NICT (Enoto, Wada et al., 2017)
2017/2/6 15:00 JST (http://himawari8.nict.go.jp)

Gamma-ray Glow from Thunderstorms

- Prolonged (a minute or more) high-energy gamma rays (MeV) from thunderstorms
- Radiation enhancements have been detected by safety monitoring at nuclear power plants (initially thought of as noise)





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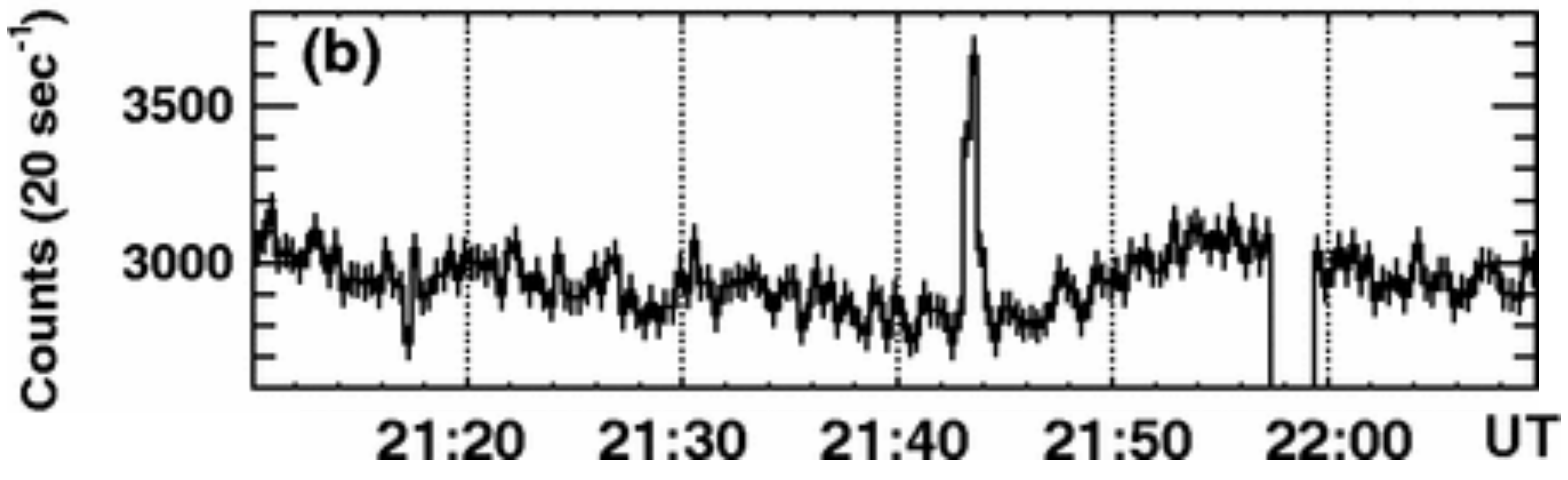
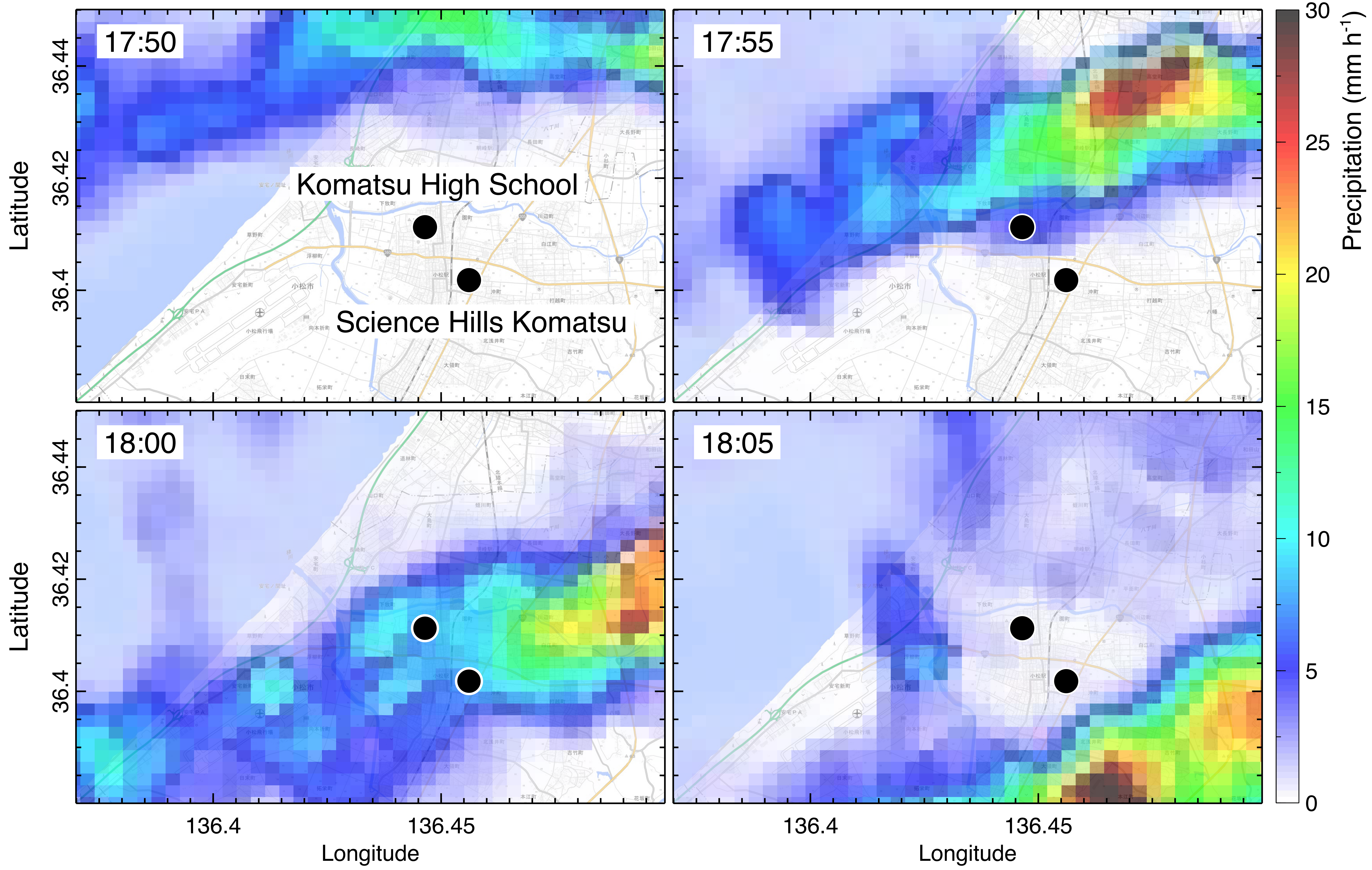
- Radiation enhancements have been detected by safety monitoring at nuclear power plants (initially thought of as noise)
- GROWTH (Gamma-Ray Observation of Winter Thundercloud) collaboration started a new campaign at Kashiwazaki in 2006, and detected a 40-sec lasting gamma ray burst from a thunderstorm.
- Since 2015, we have increased the number of observation sites to perform multi-point measurements.



(Tsuchiya, Enoto et al., PRL, 2007)

Example: Gamma-ray Glow Detected at Kanazawa



(Yuasa, Wada, Enoto et al., PTEP, 2020)

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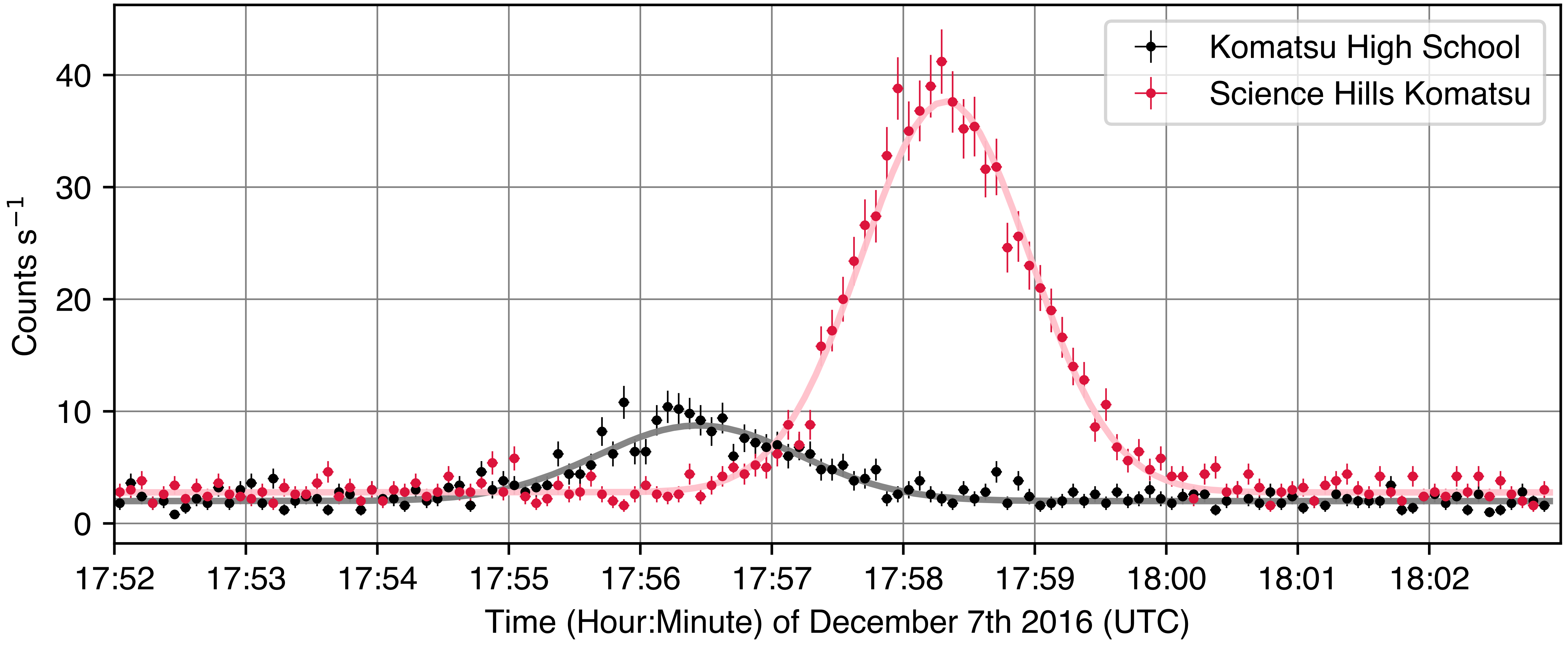

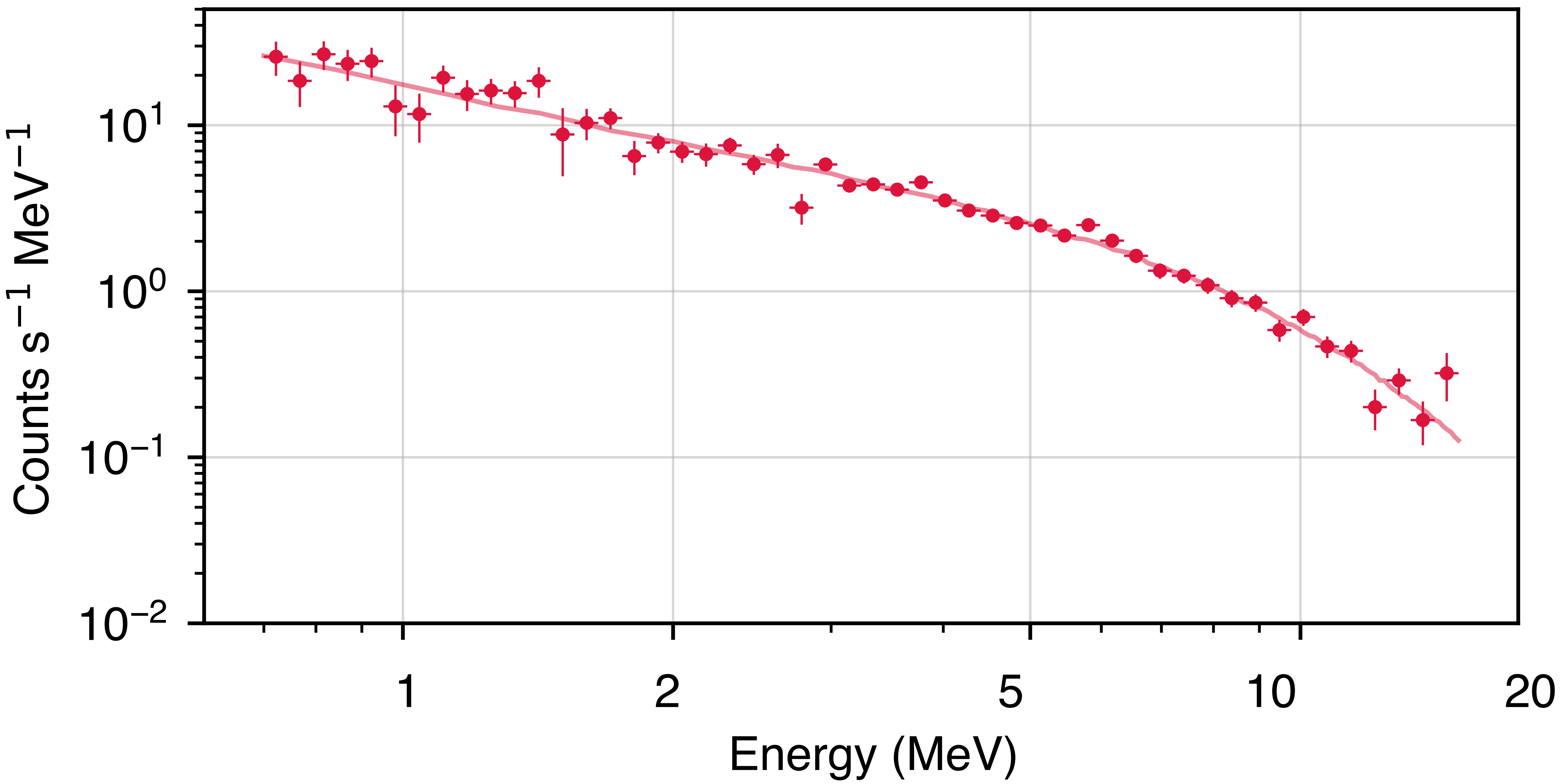

- During a passage of a winter thundercloud, we detected an enhancement of gamma rays at Komatsu on December 8, 2016.
- The burst was detected with two detectors with a delay, which is consistent with a cloud speed.
- The gamma-ray spectrum is fitted by a cutoff power-law model.
  - $F(E) = E^{-\Gamma} \exp(-E/E_{cut})$
  - $\Gamma = 0.26$, $E_{cut} = 4.10$ MeV
  - F_{γ}=1.18 MeV cm^{-2} s^{-1} (3-15 MeV)

(Yuasa, Wada, Enoto et al., PTEP, 2020)

Emission Mechanism of Gamma-ray Glows?

- Charge separation occurs in the collision of ice grains in the updraft.
- Regions of strong electric fields emerge in the clouds.
- Electrons are ejected via passages of cosmic rays. The strong electric field accelerates electrons to relativistic energy and generates avalanche processes.
- Bremsstrahlung gamma rays are radiated from accelerated high-energy electrons.
- We are working on theoretical modeling using Geant4 simulations.

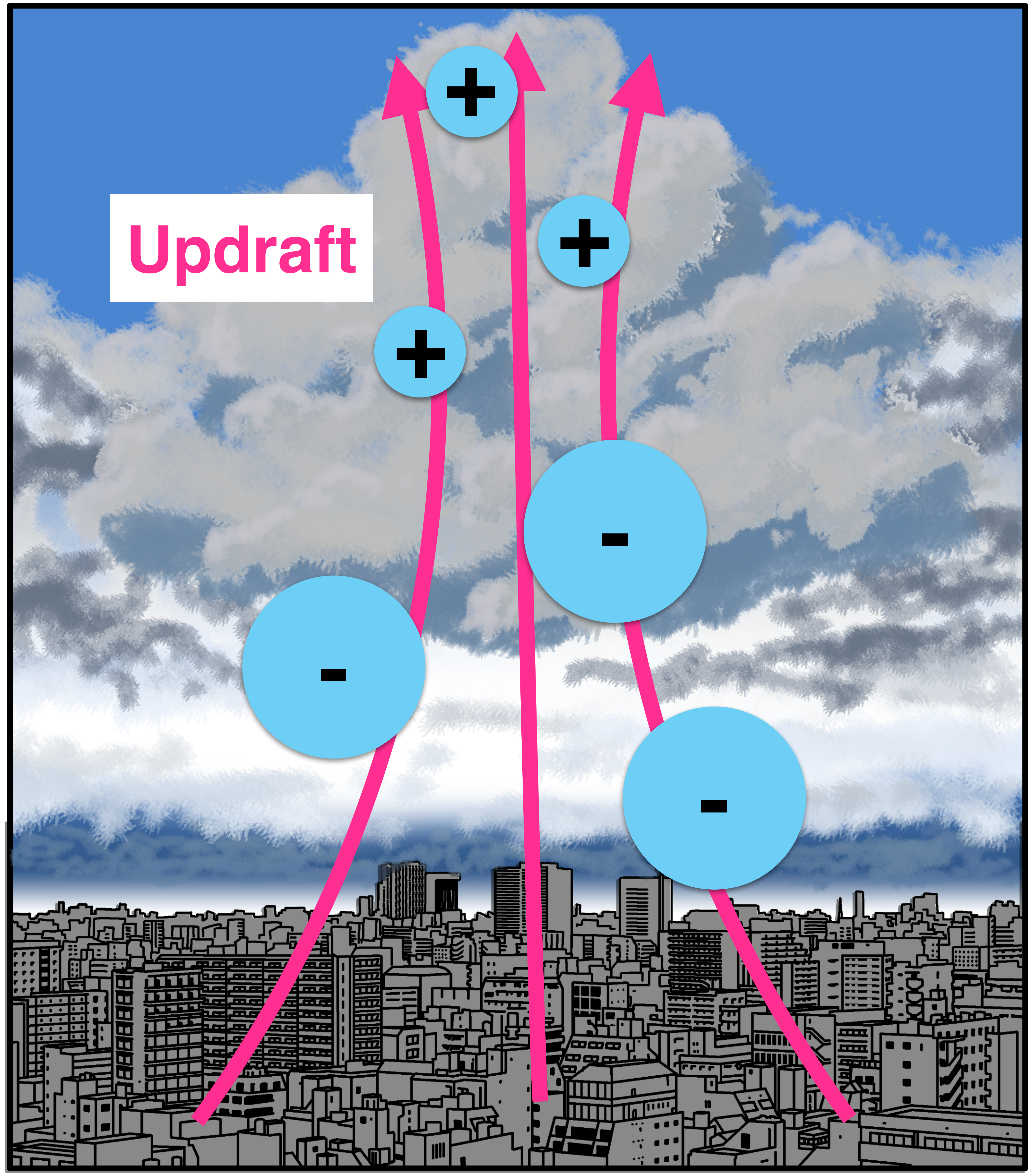

Illustration: Hayanon Science Manga Studio

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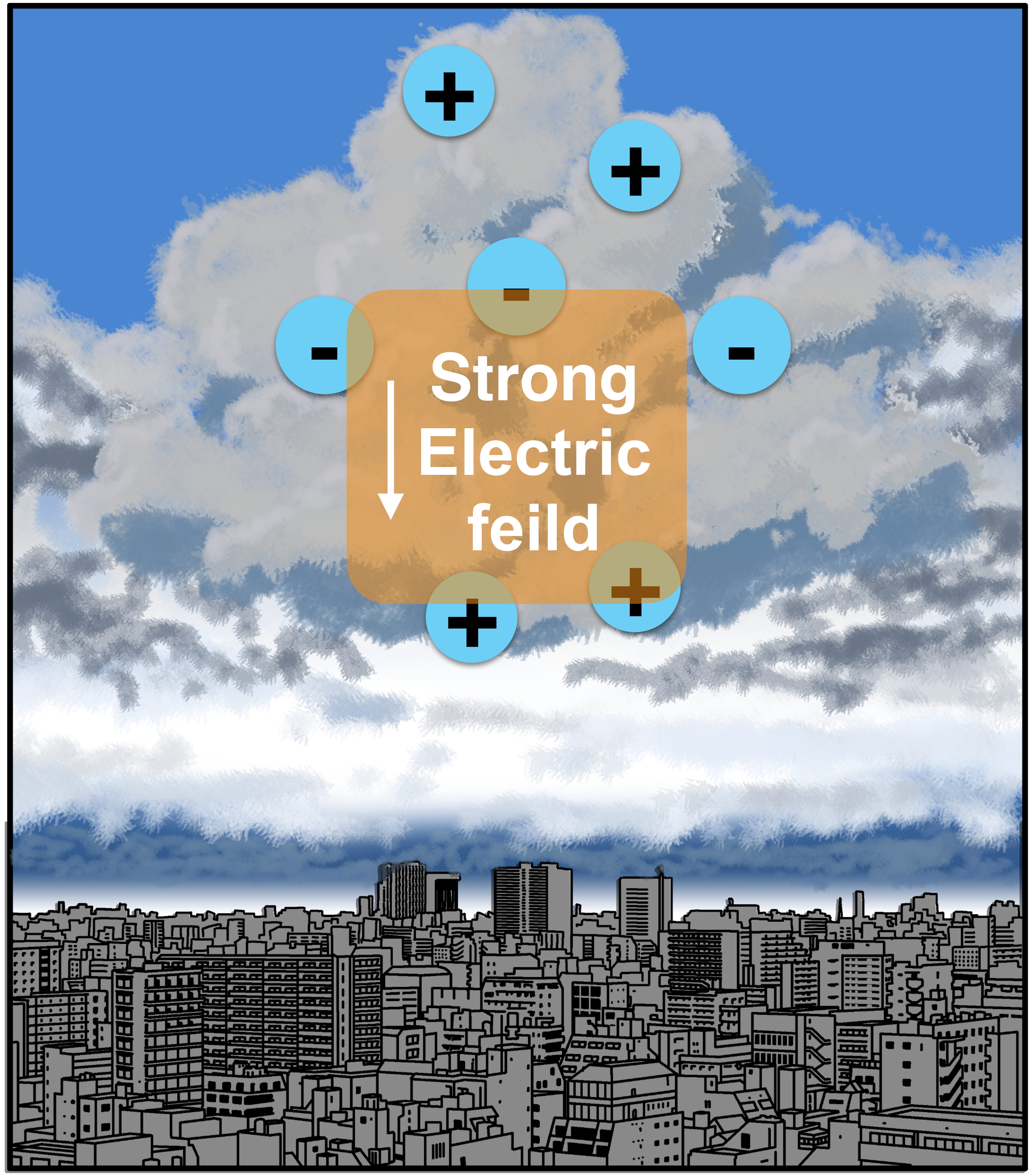

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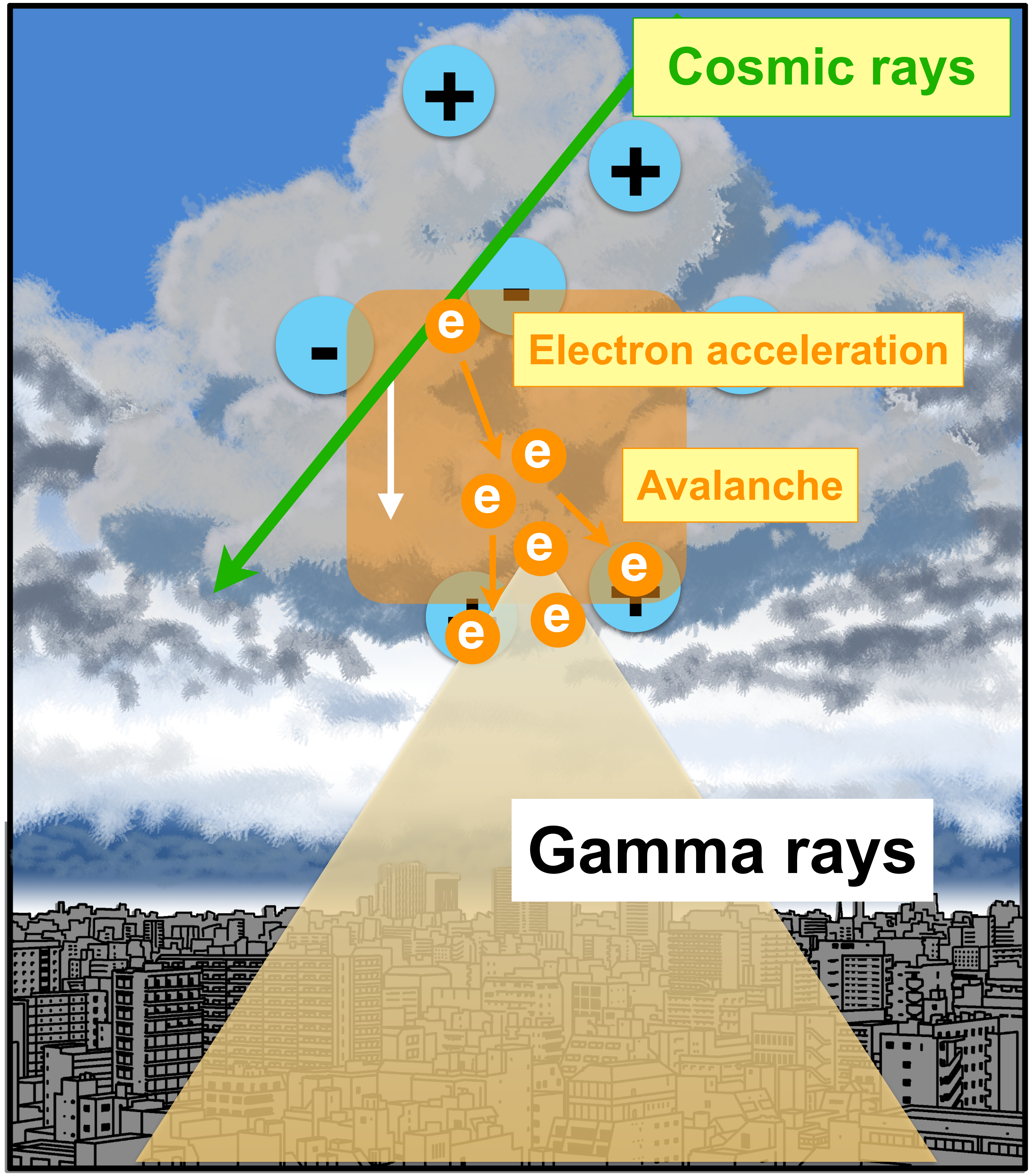

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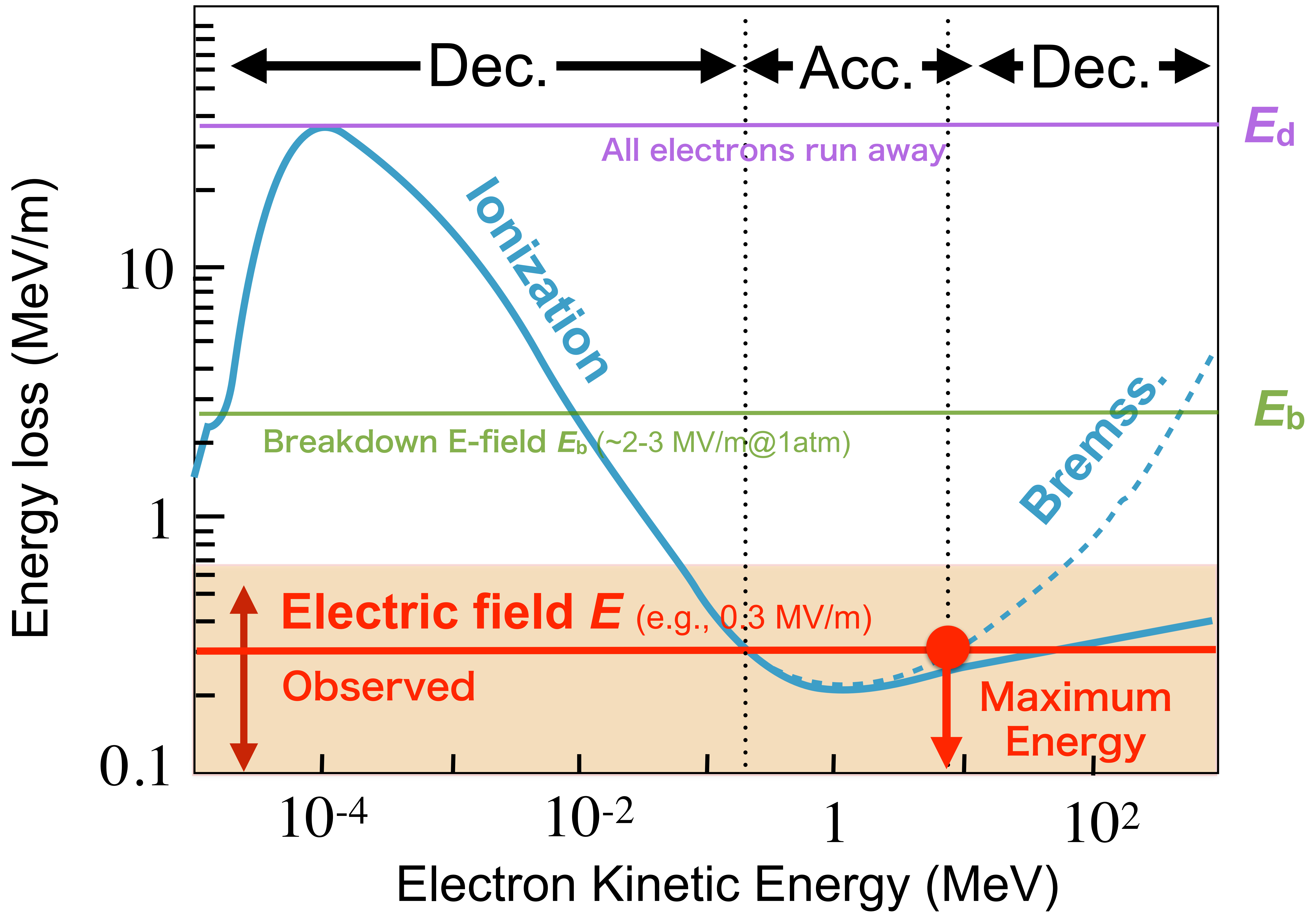
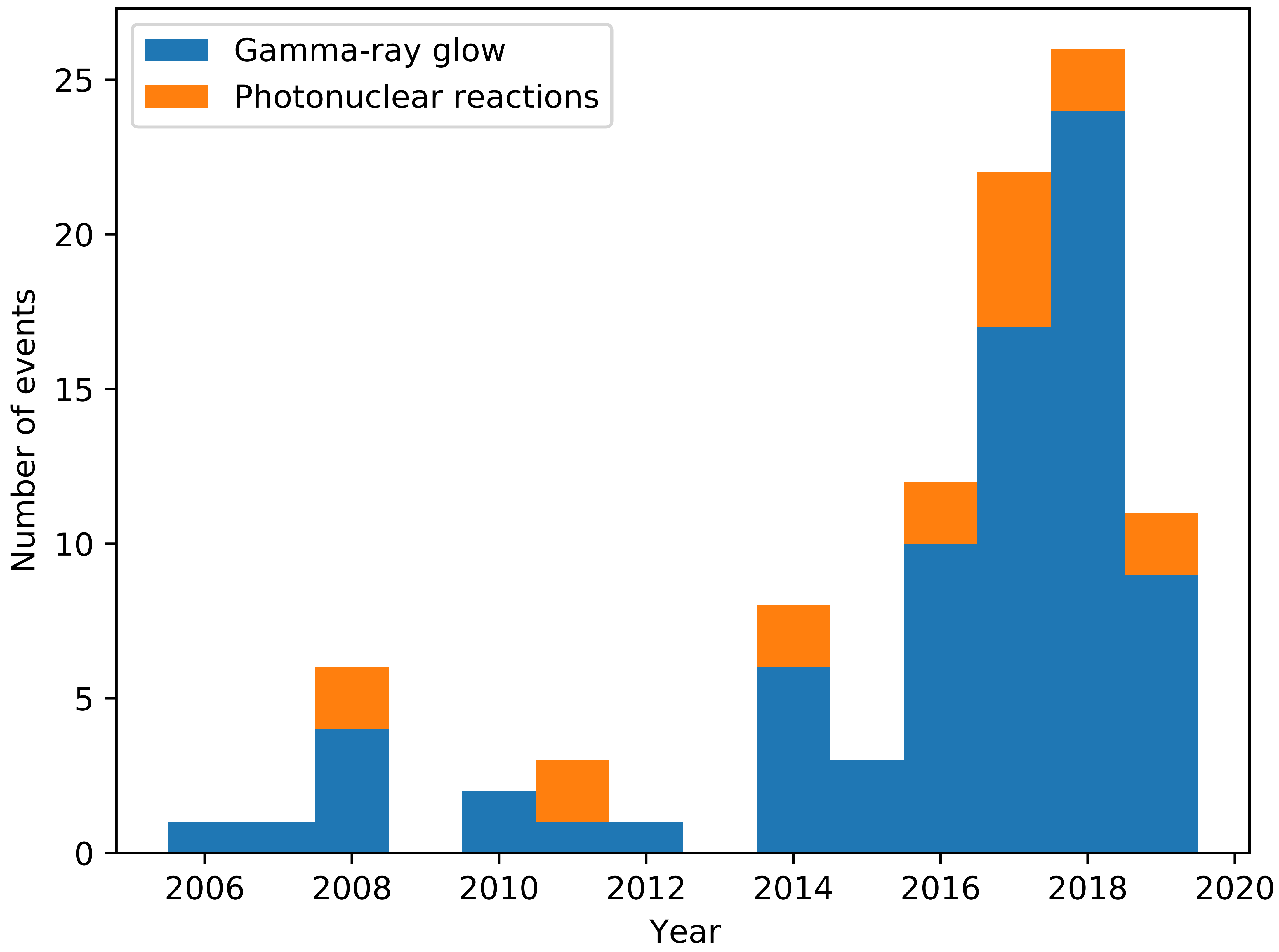
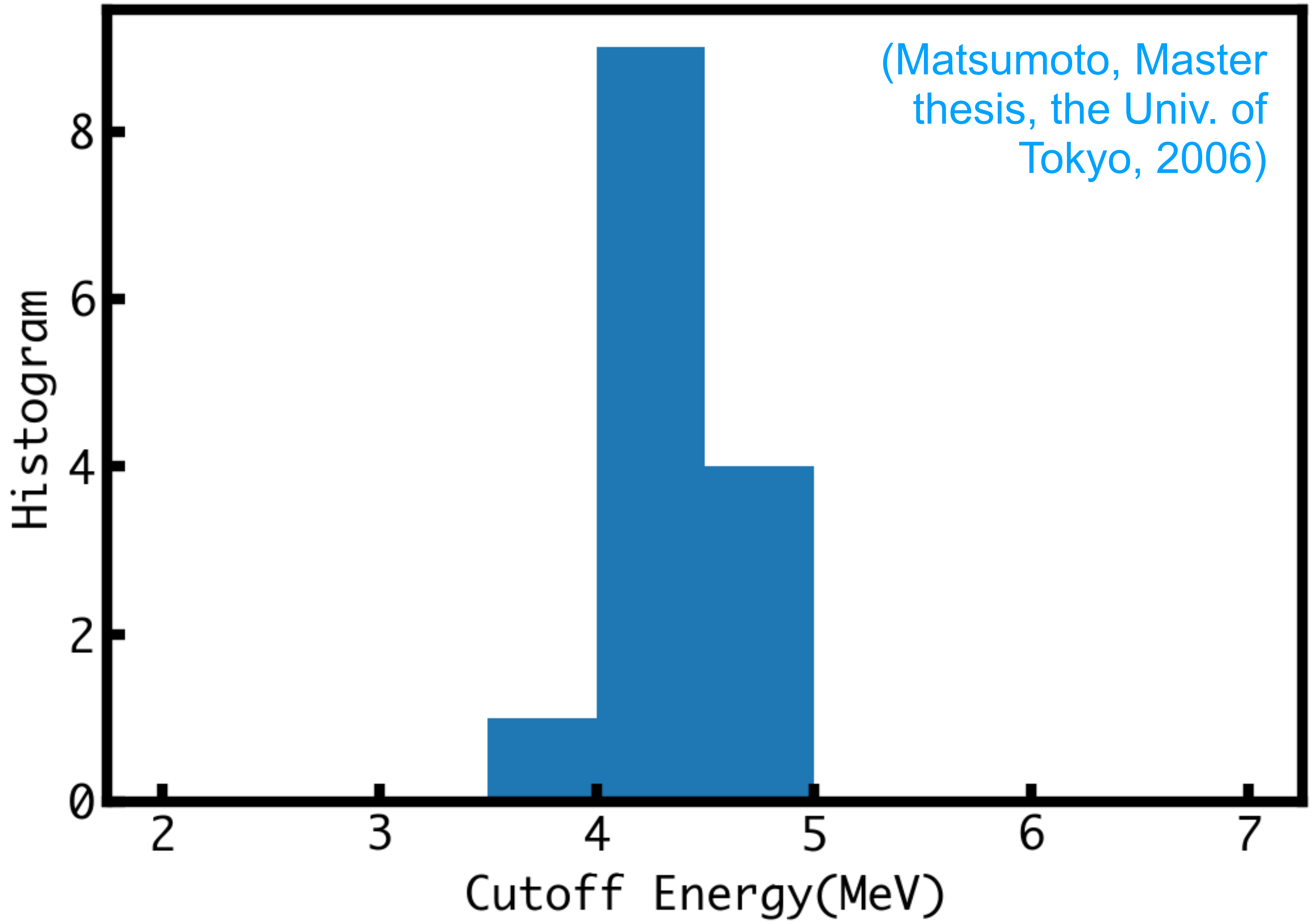


standard atmosphere

(Gurevich et al., Phys. Lett. A, 165, 463, 1992)

Increasing Number of Gamma-ray Glows





- We have about 100 radiation burst events in total detected since 2006.
- Gamma-ray spectral studies show the cutoff energy around ~4-5 MeV, which reflect the maximum energy of electrons accelerated in thunderclouds.

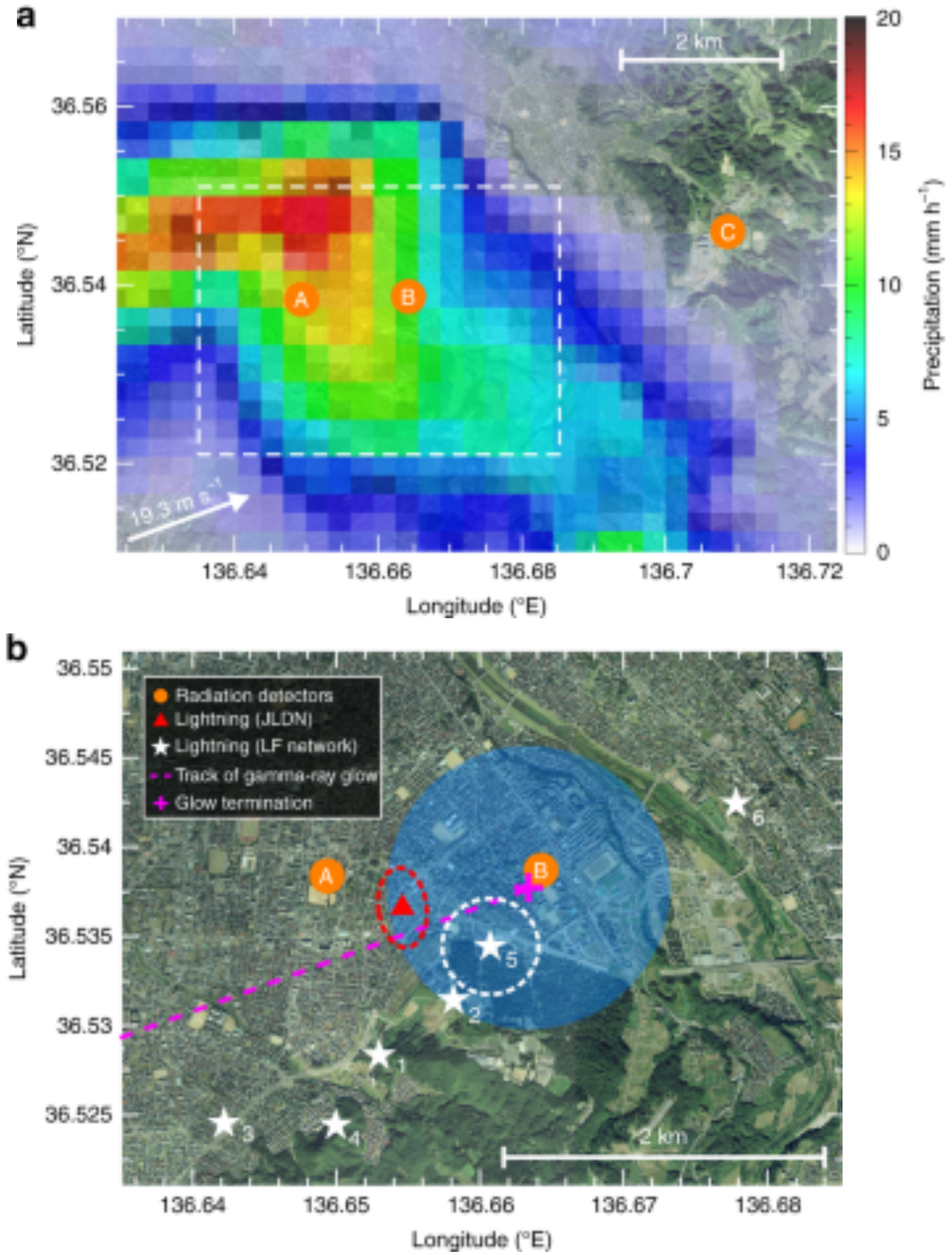
Gamma-ray Glow Terminated by Lightning

- Sudden gamma-ray termination was recorded at Suzu on February 11, 2017.
- This termination was coincided with a passage of a long lightning discharge.
- The lightning discharge, started far away and passing above the detector, destroyed an electron source with strong electric fields.

(Wada, Bowers et al., Geophys. Res. Lett., 2018)

Gamma-ray Glow Triggered Lightning?

- On 9 January 2018, detectors deployed at two high schools at Kanazawa, recorded a gamma-ray glow moving for ~100 s with ambient wind.
- Then, the glow abruptly terminated with a lightning discharge, whose radio pulse was located within ~1 km from where the glow ceased.
- Lightning initiation problem "what triggers lightning discharges?"
- A highly-electrified region producing the glow became a trigger to initiate of this lightning discharge?



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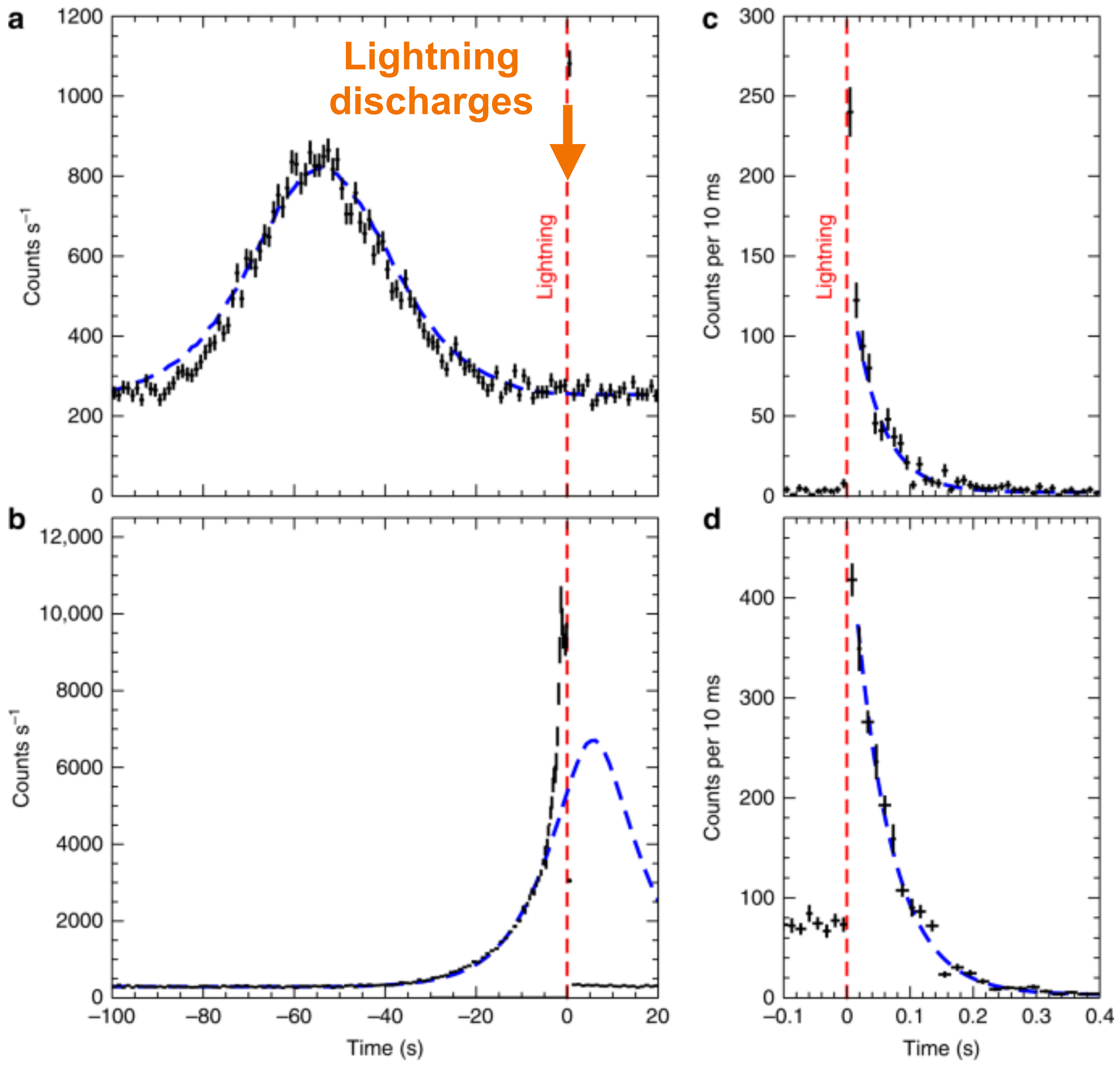

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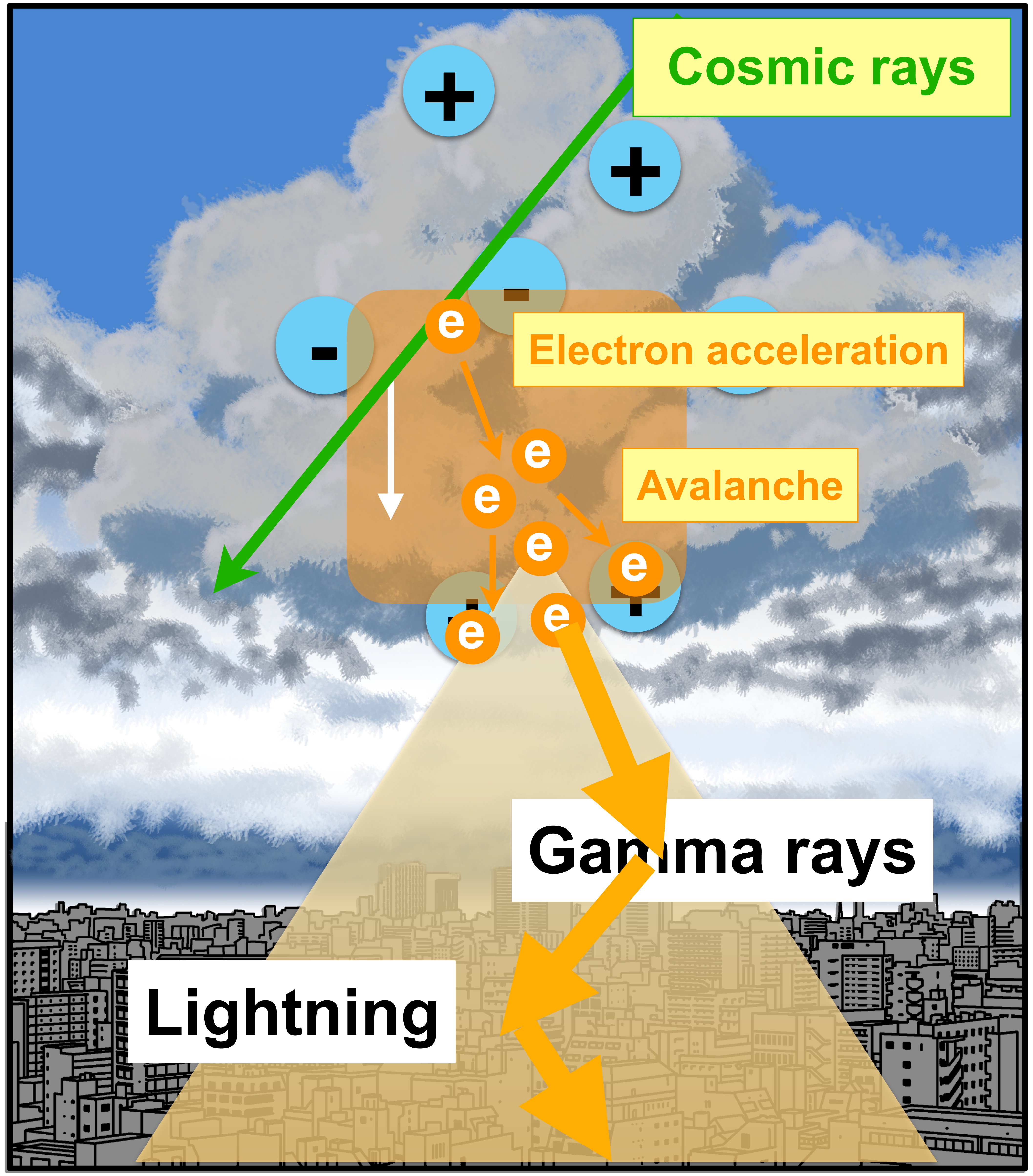


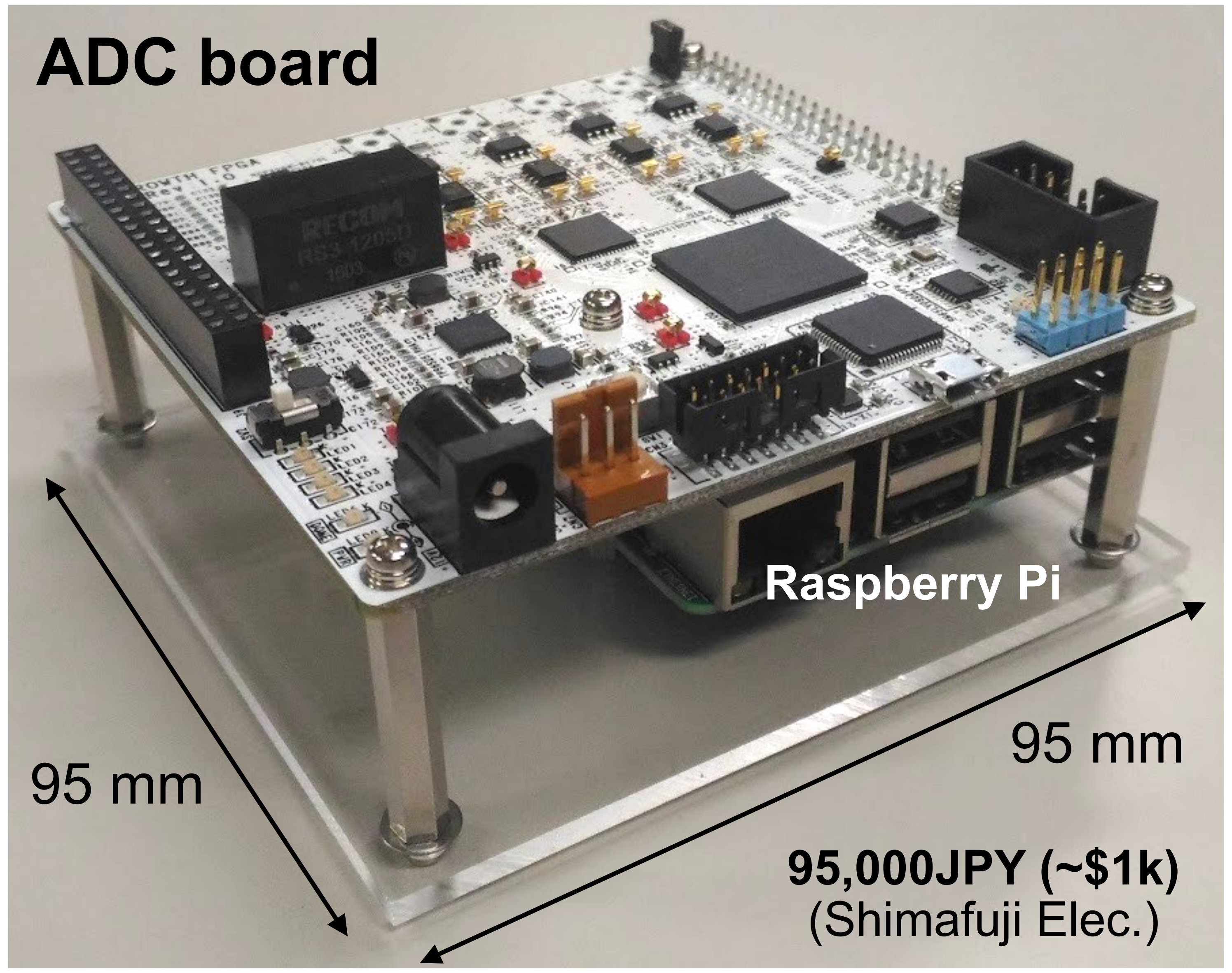
Illustration: Hayanon Science Manga Studio

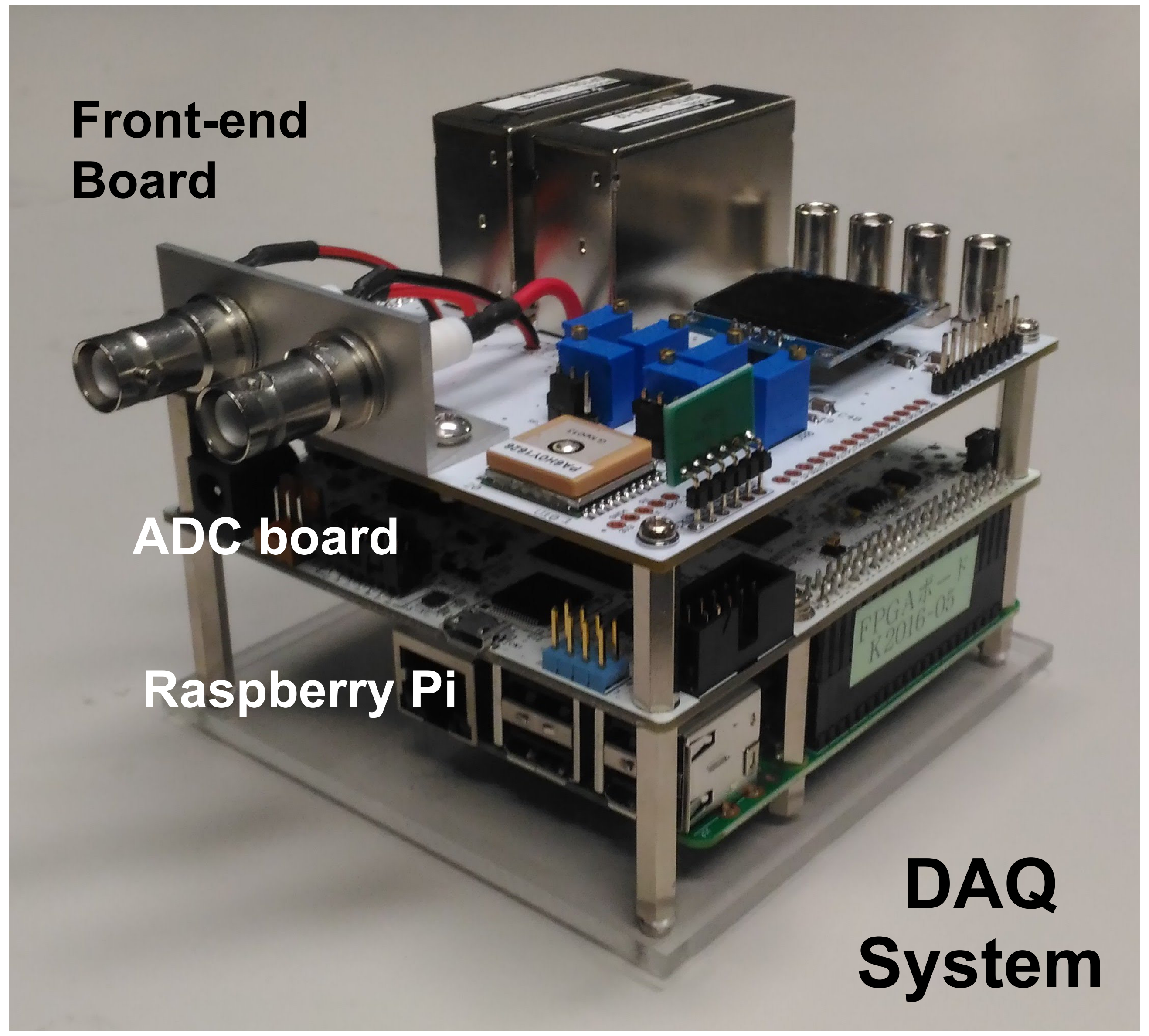
(Wada, Enoto et al., Communication Physics, 2019)

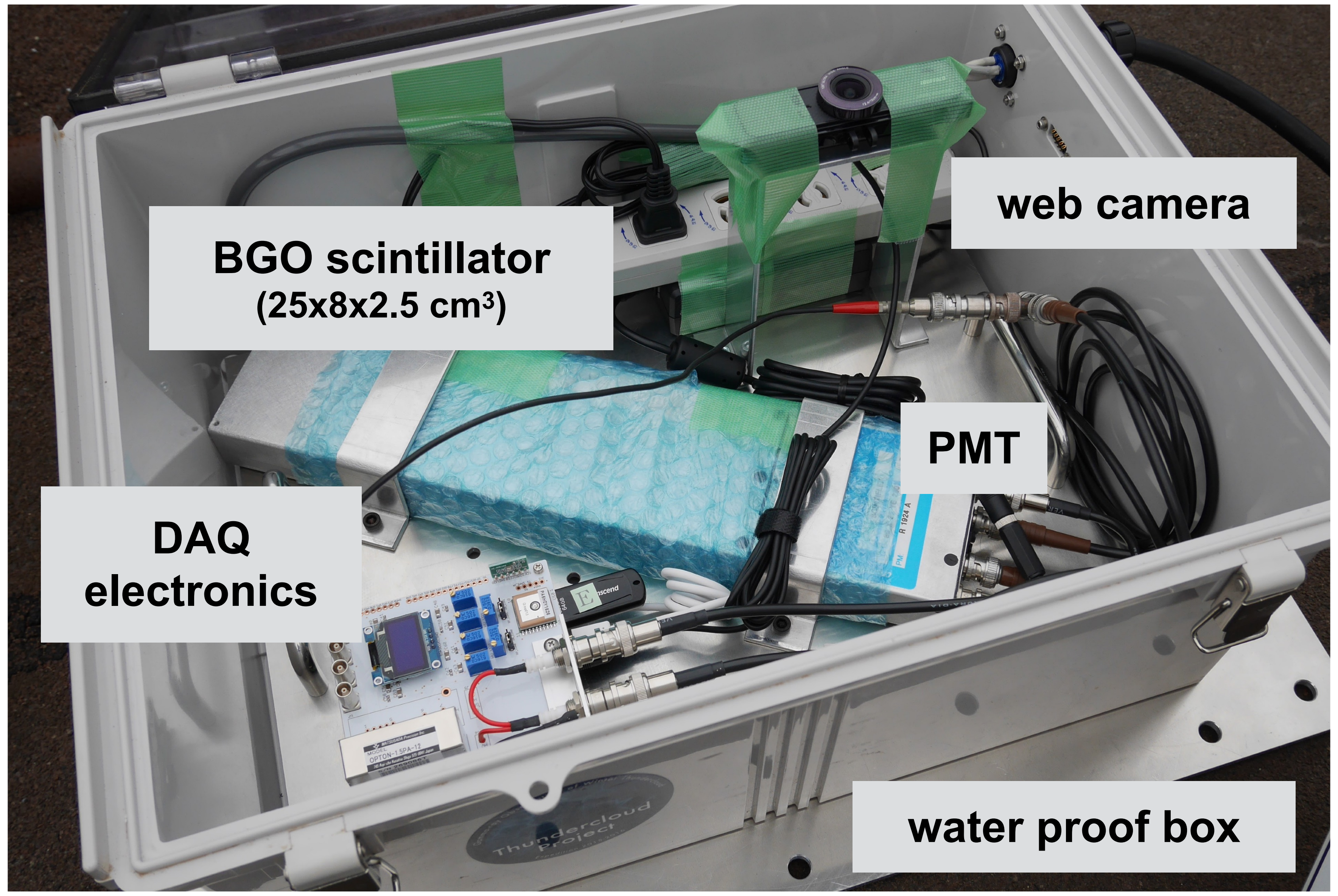
Supported by Academic Crowdfunding

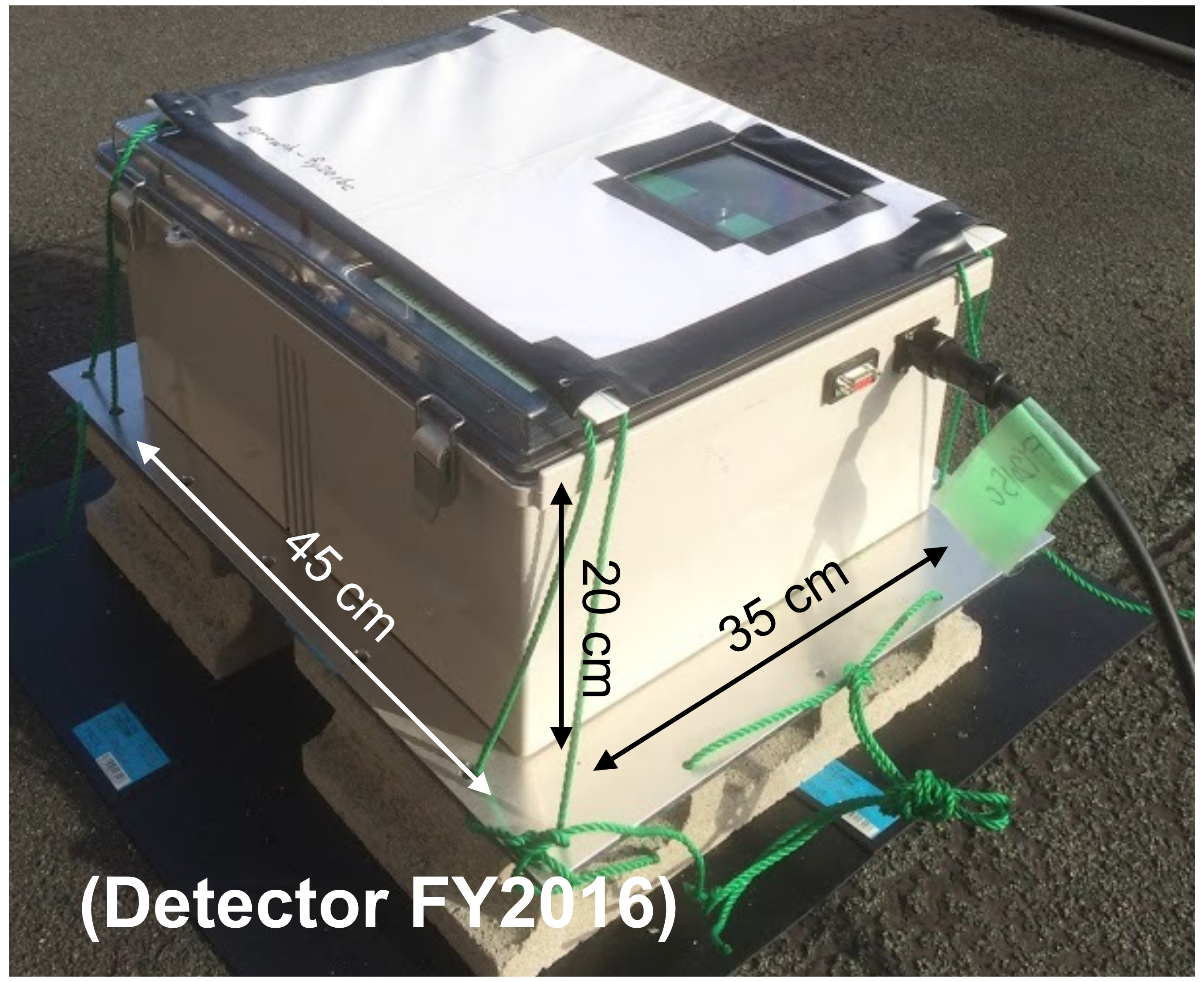
(Academies: カミナリ雲からの謎のガンマ線ビームを終え！)

Small, Low-cost, and High-performance Detector









- BGO, CsI scintillators + PMTs
- New FPGA board of 4 channel 50 MHz, 12 bit ADC
- GPS-tagged Event data and house keeping monitor data
- GPS, remote control & upload

(Wada, Master thesis of the Univ. Tokyo, 2017) (Yuasa, Wada, Enoto et al., PTEP, 2020)

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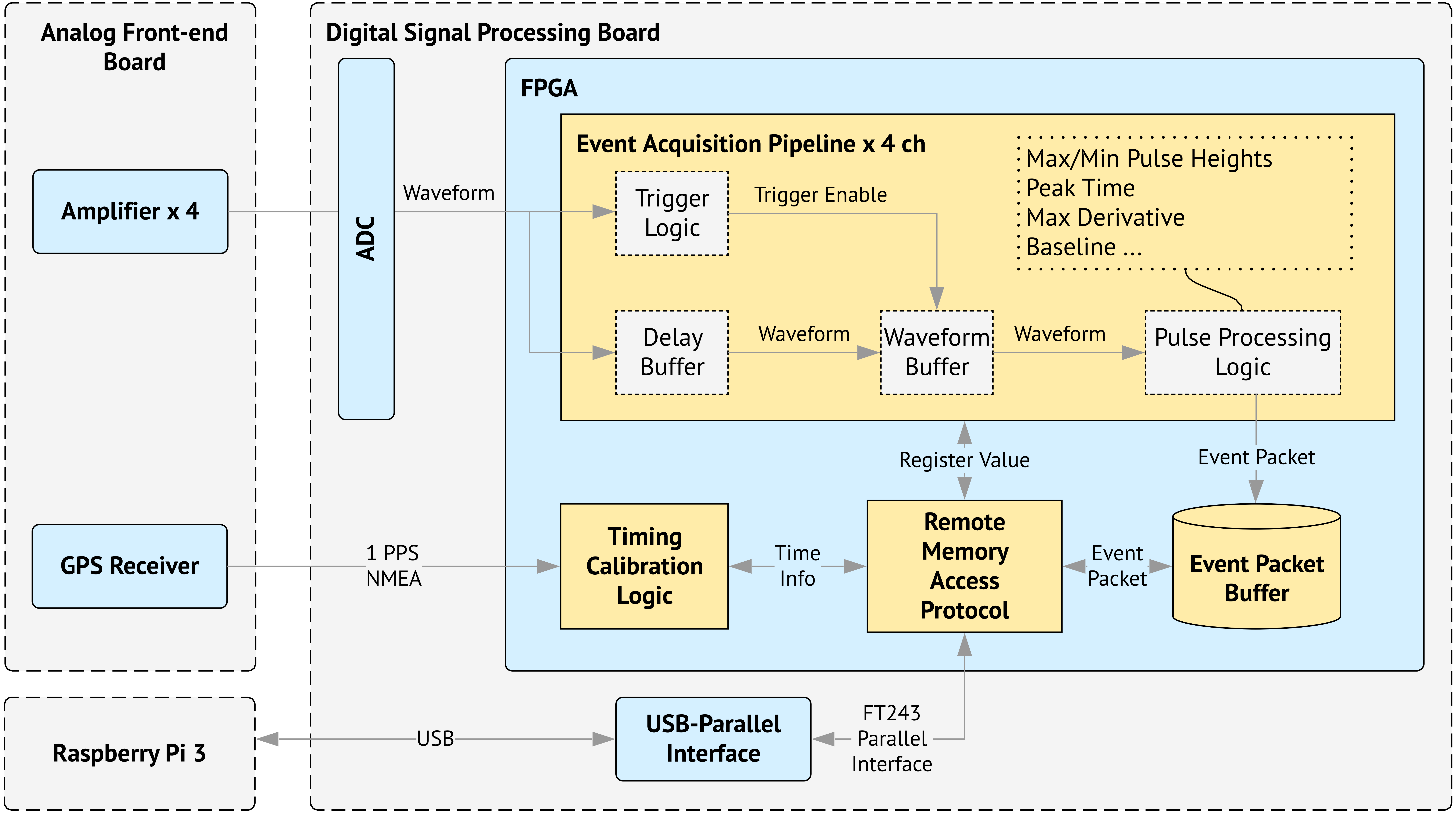

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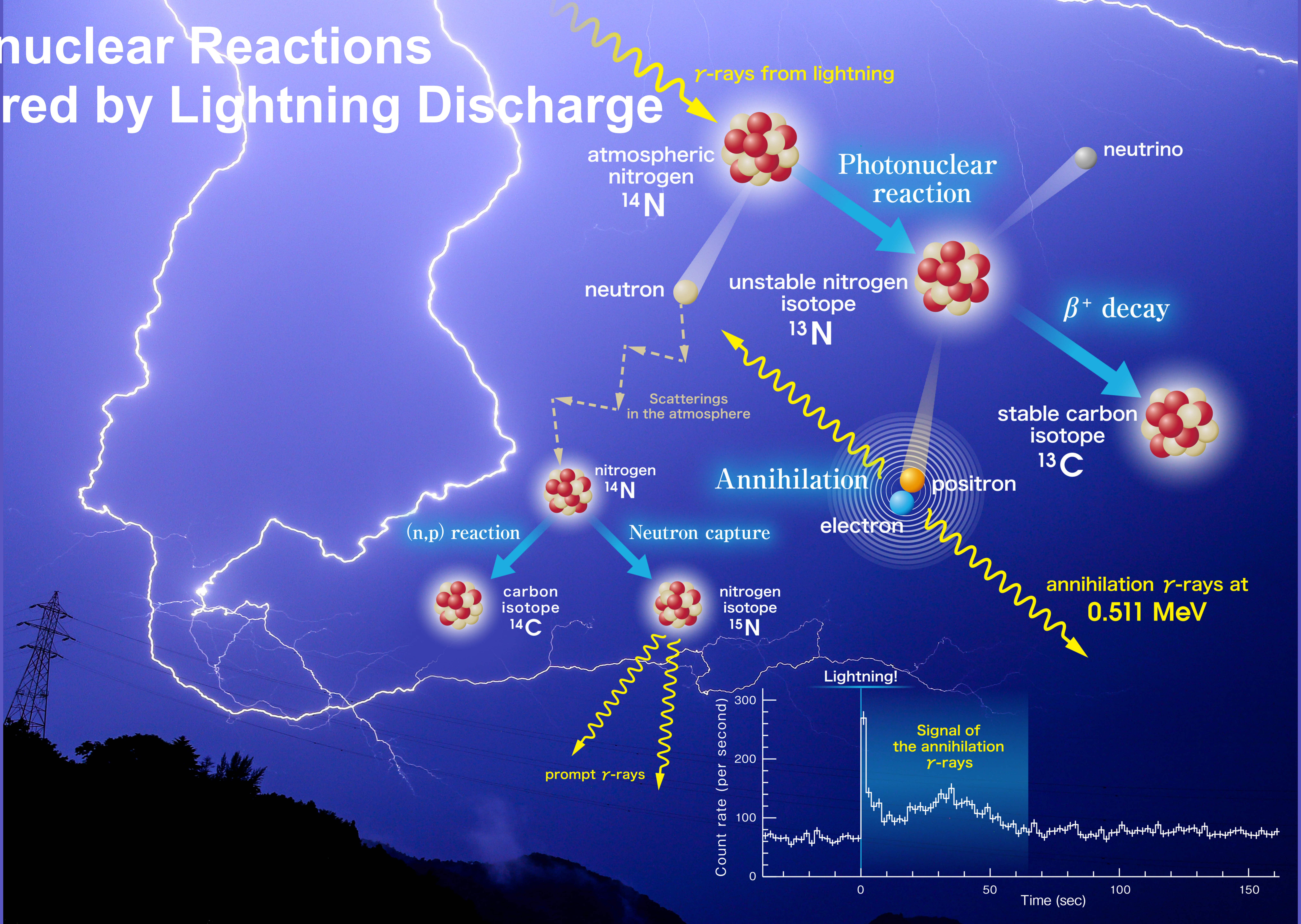
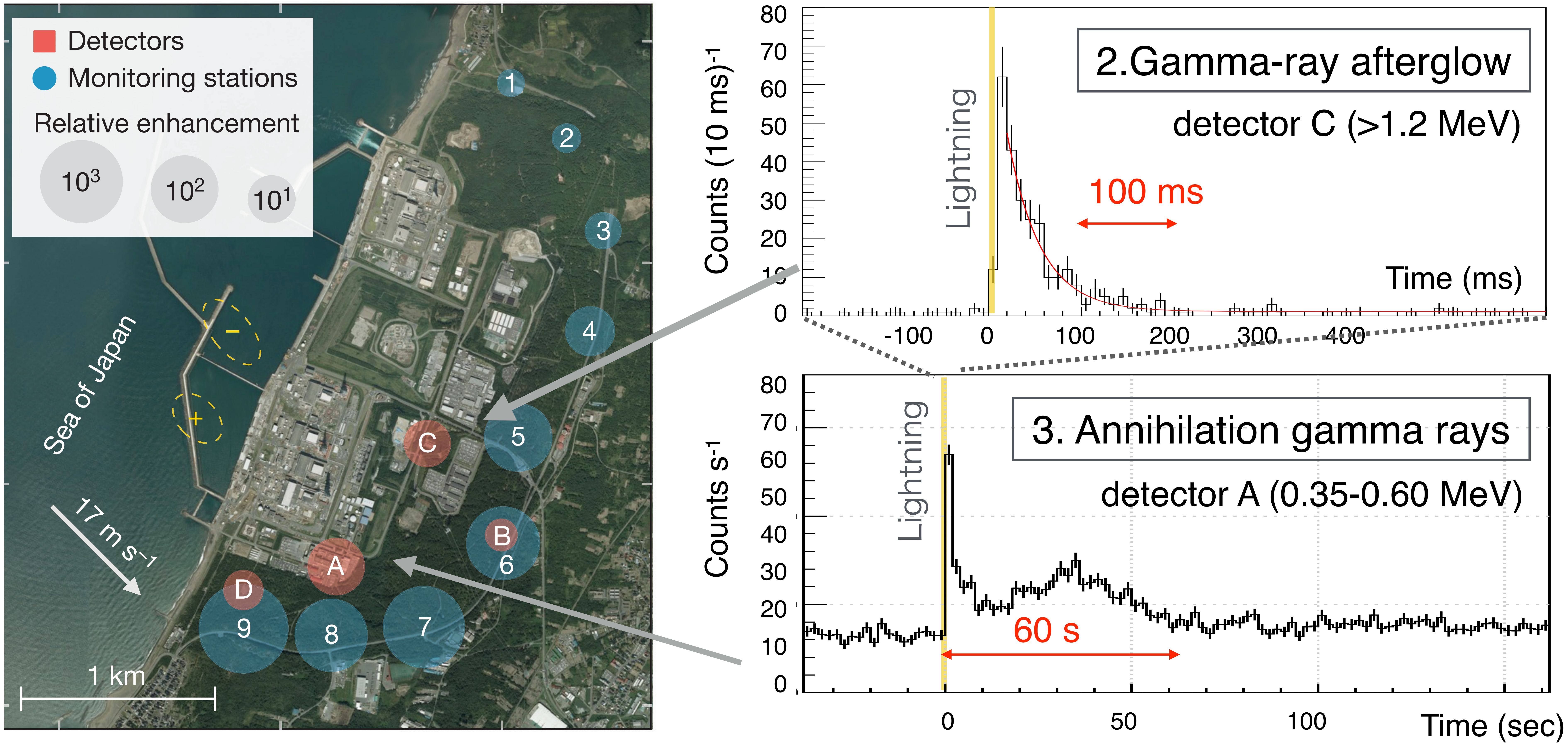
Photonuclear Reactions Triggered by Lightning Discharge



Short-duration burst associated with lightning



- on February 6, 2017, 17:34:06, at Kashiwazaki

1. Intensive initial spike (<~a few milliseconds, exceeds 10 MeV)
2. Gamma-ray afterglow (<~100 ms, <10 MeV)
3. Delayed annihilation gamma rays (~minute, at 0.511 MeV)

(Enoto, Wada et al., Nature, 2017)

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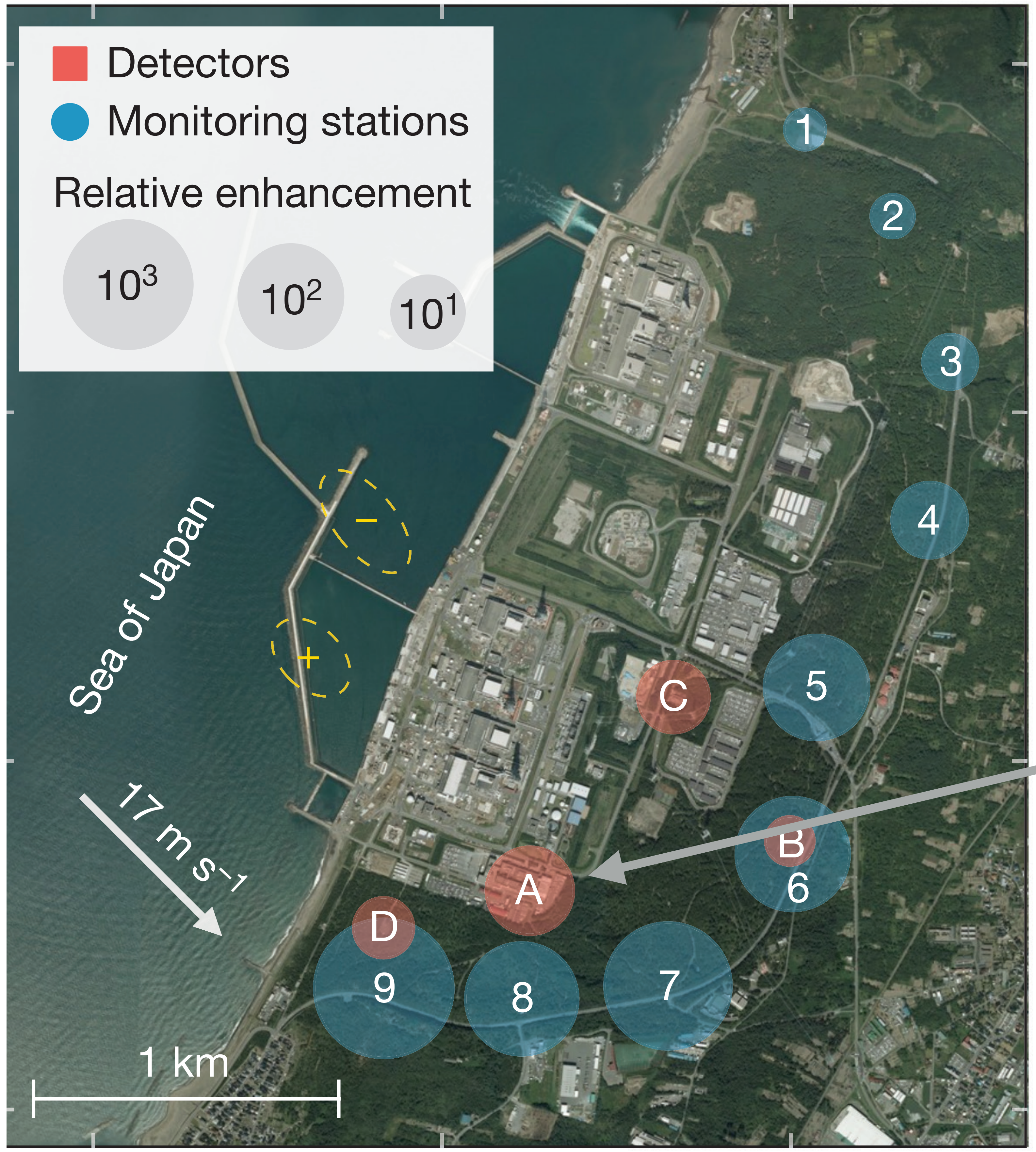

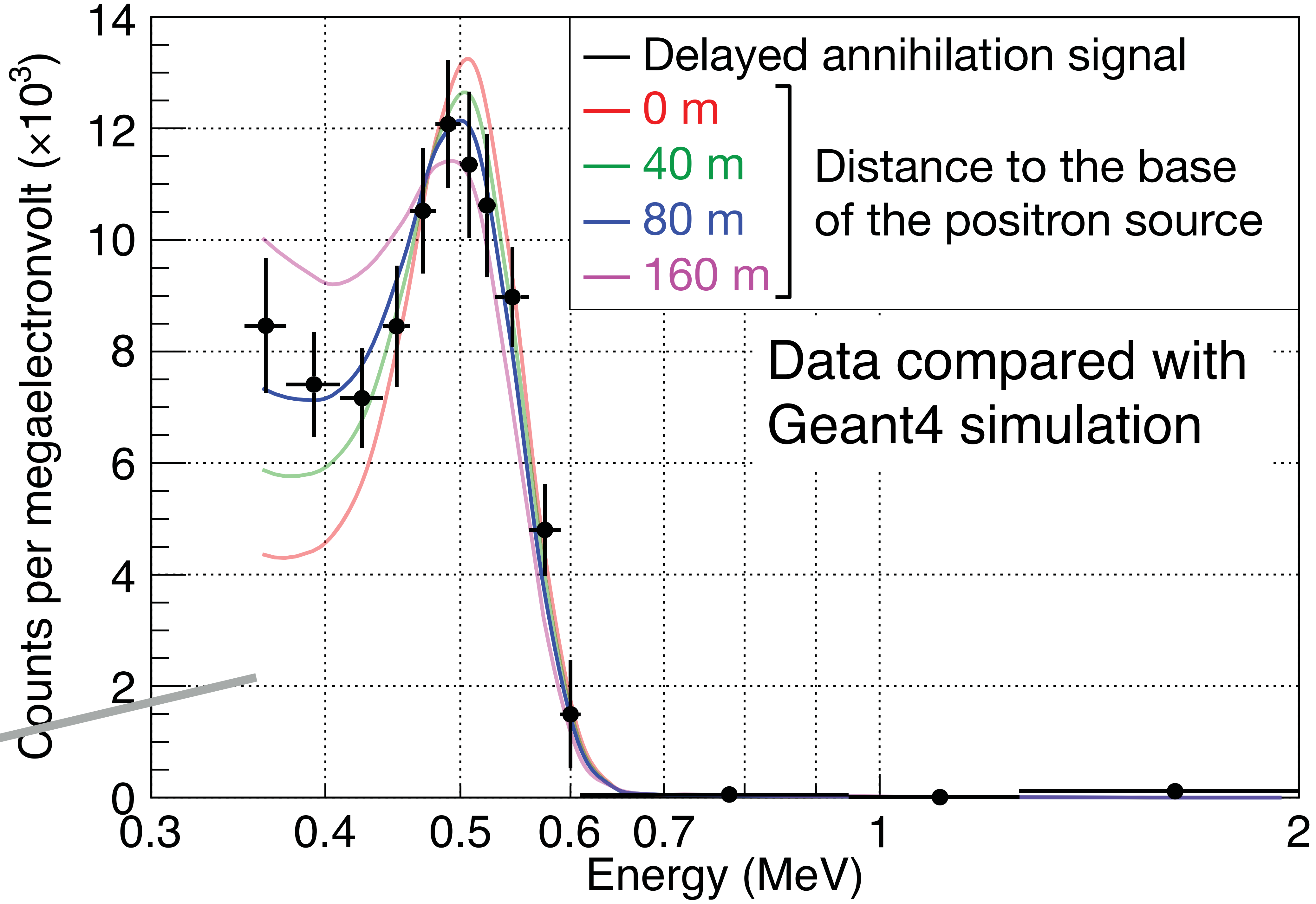

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We detected evidence for the annihilation signals at 0.511 MeV ~35 sec after the lightning!

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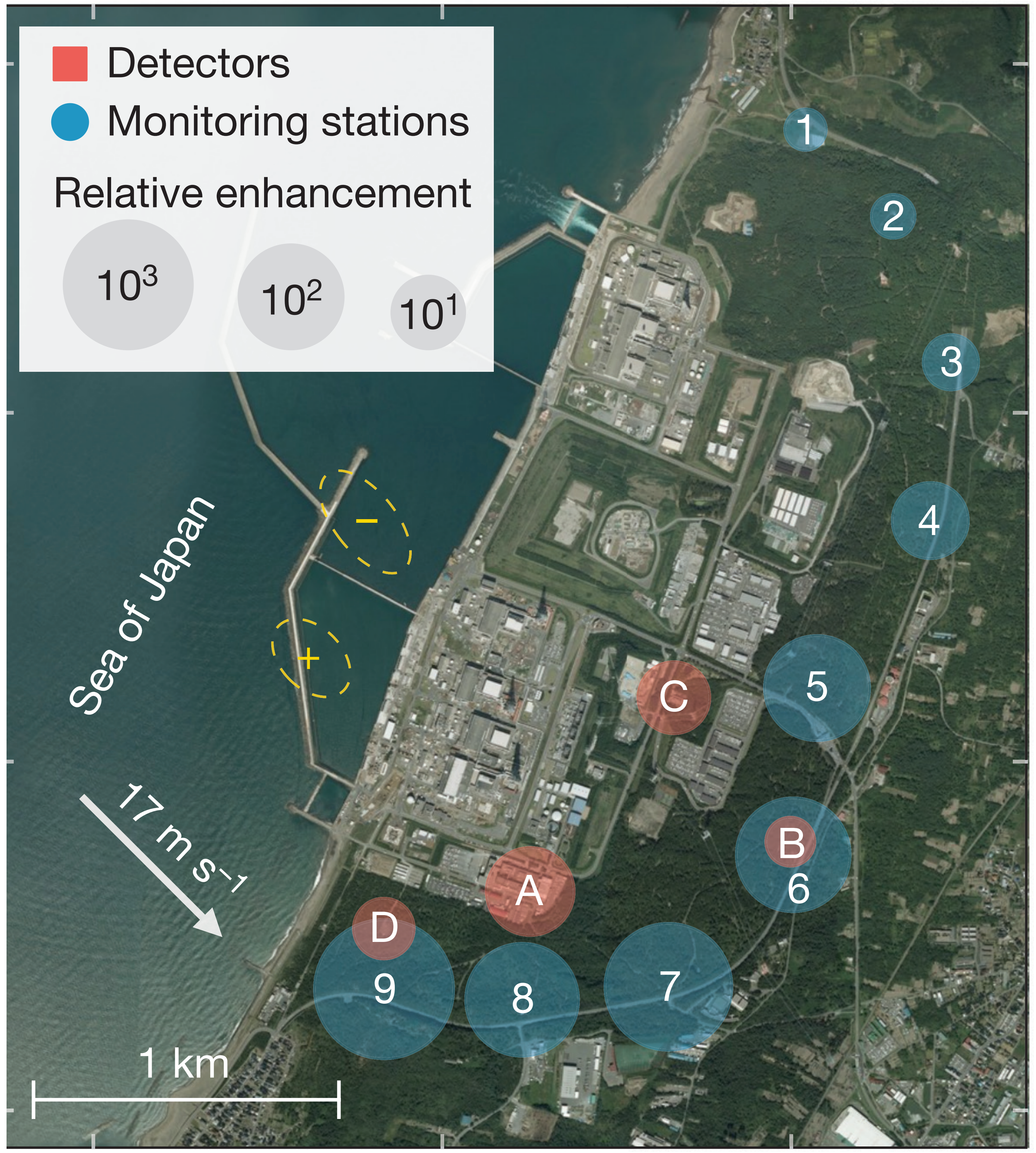

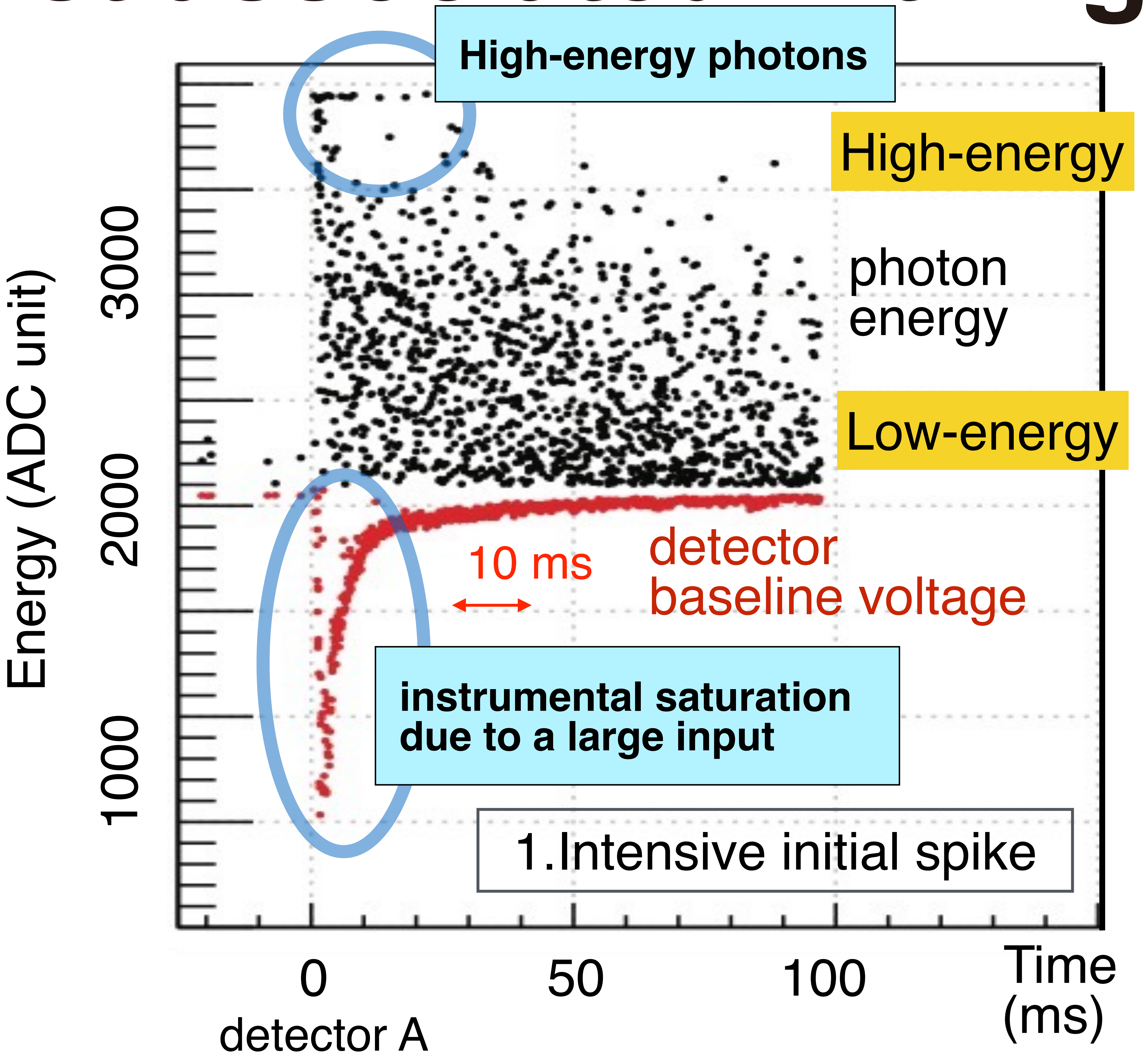

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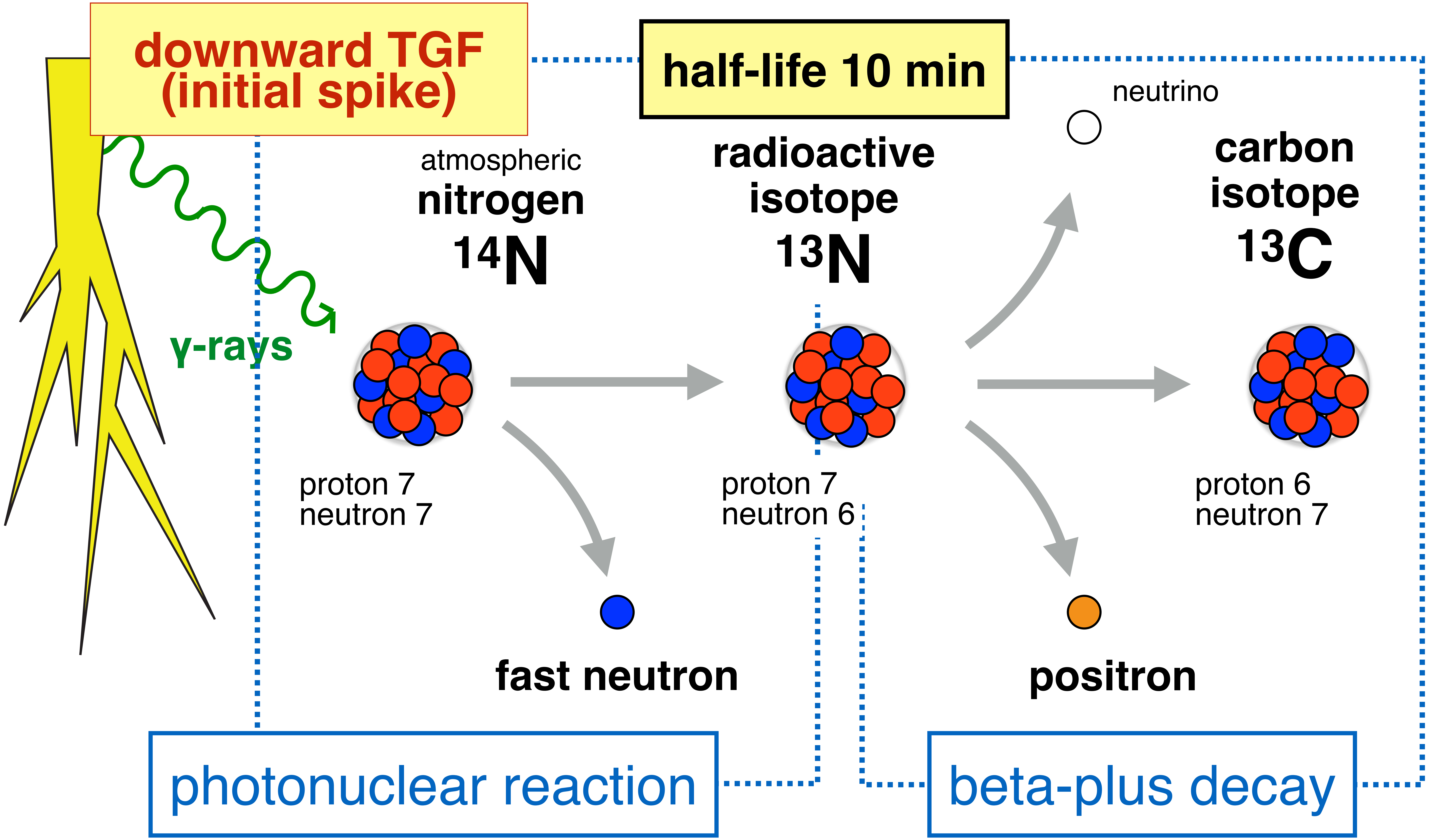
Photonuclear Reactions Triggered by Lightning



$$\gamma + {}^{14}N \rightarrow {}^{13}N + n$$

$$^{13}N \rightarrow {}^{13}C + e^{+} + \nu$$
$$(p \rightarrow n + e^{+} + \nu)$$

(Enoto, Wada et al., Nature, 2017)

Photonuclear Reactions Triggered by Lightning

fast neutron

positron

(Enoto, Wada et al., Nature, 2017)

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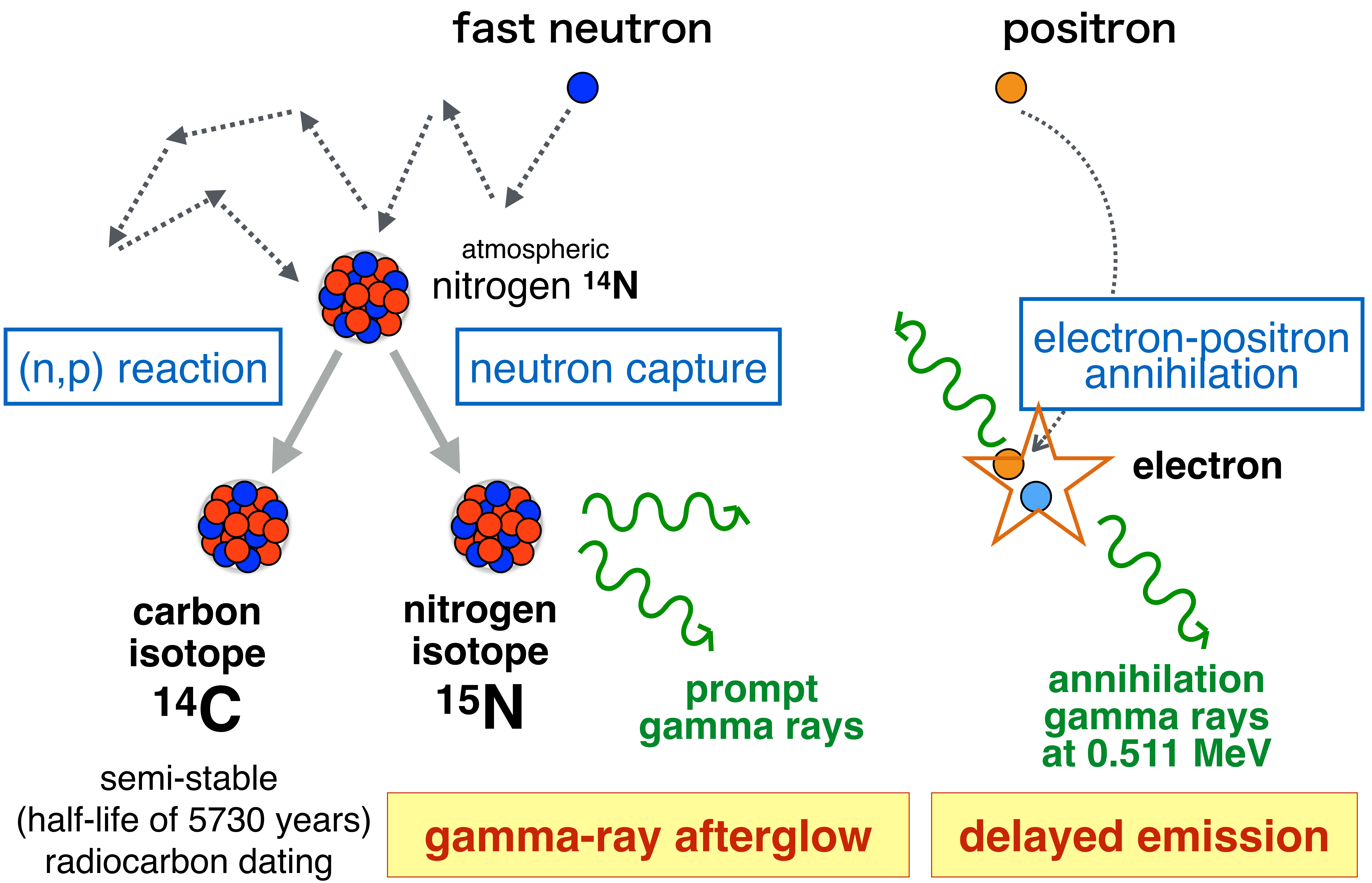
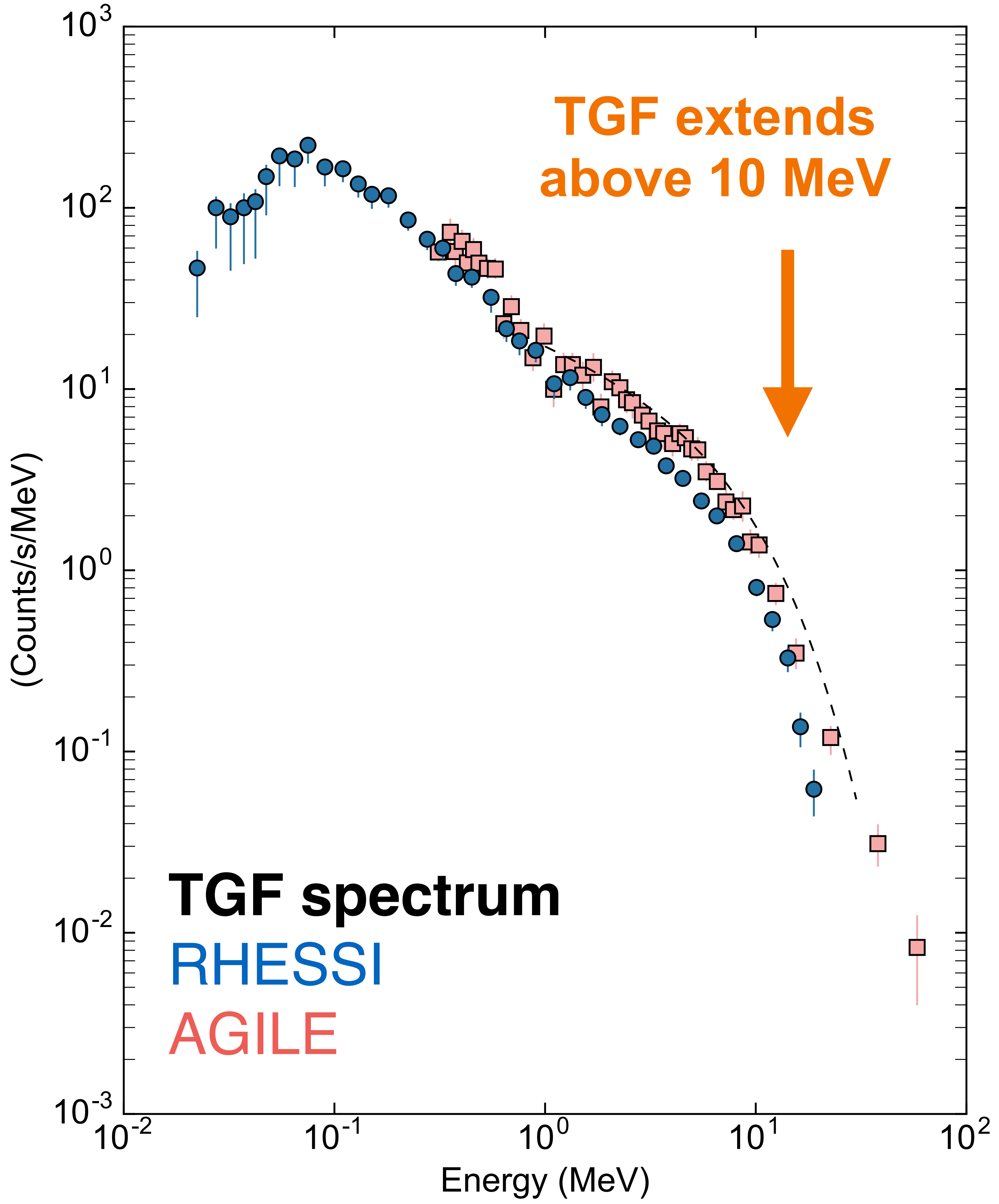
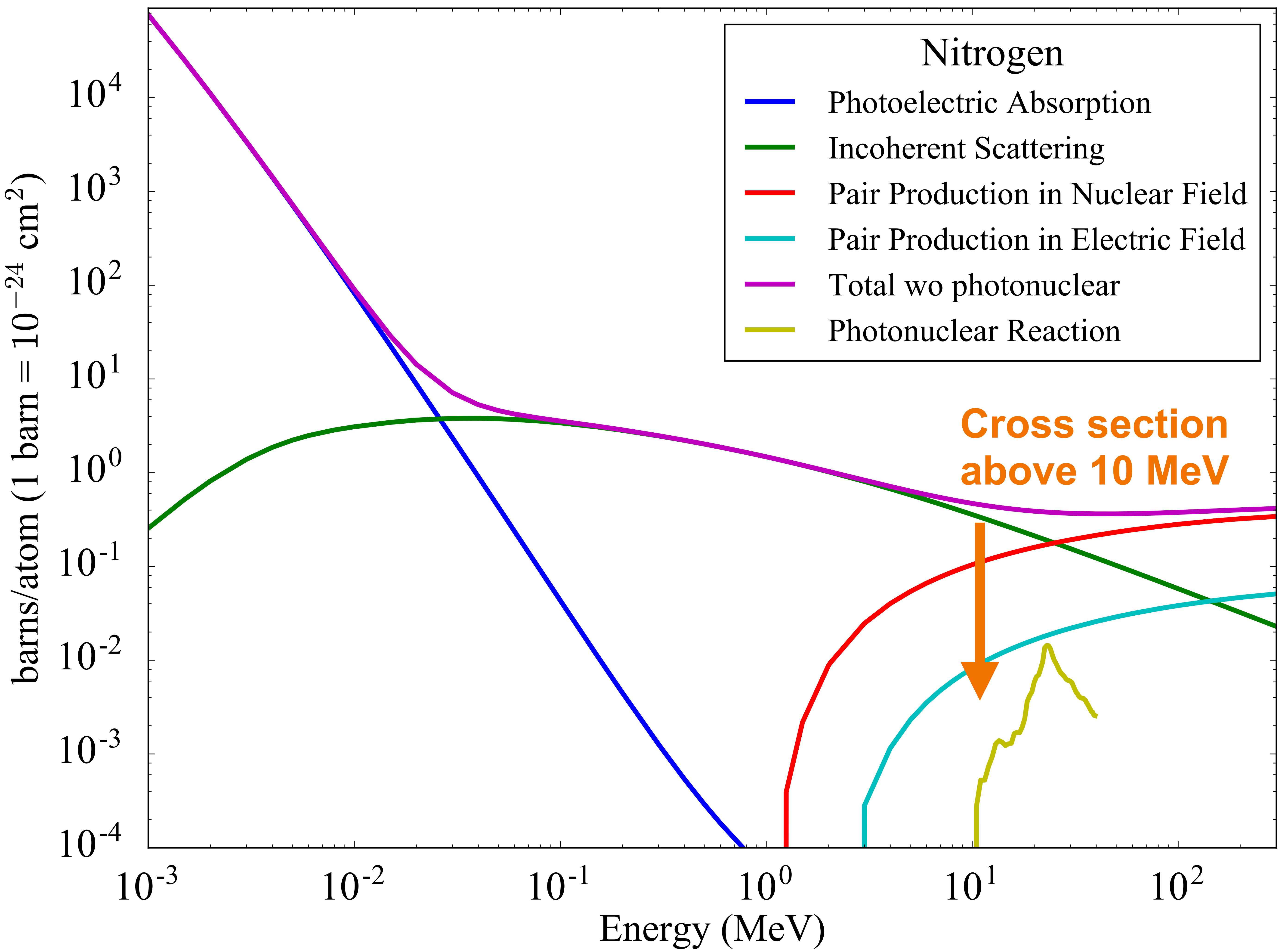


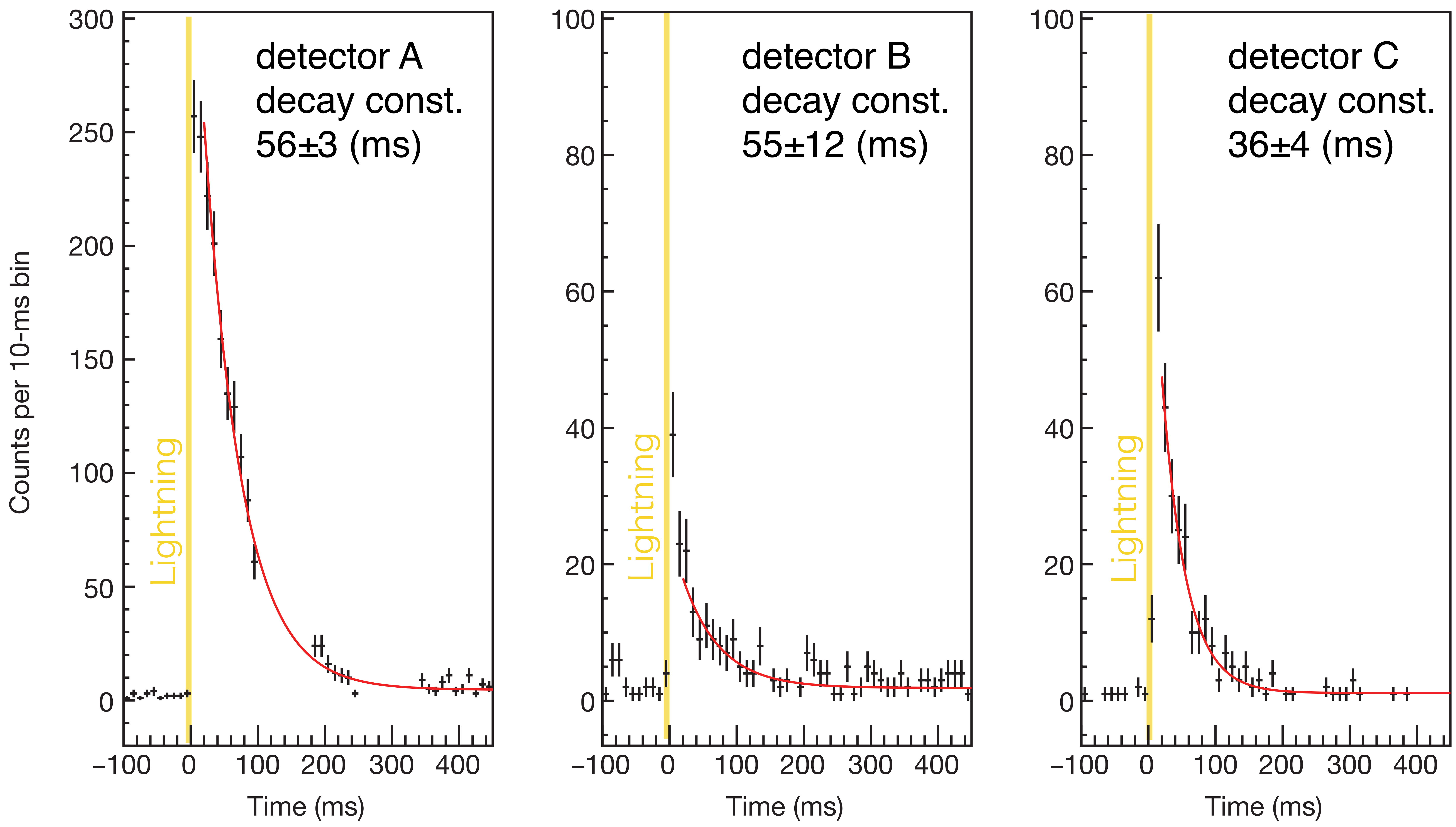
Photonuclear Reactions above 10 MeV





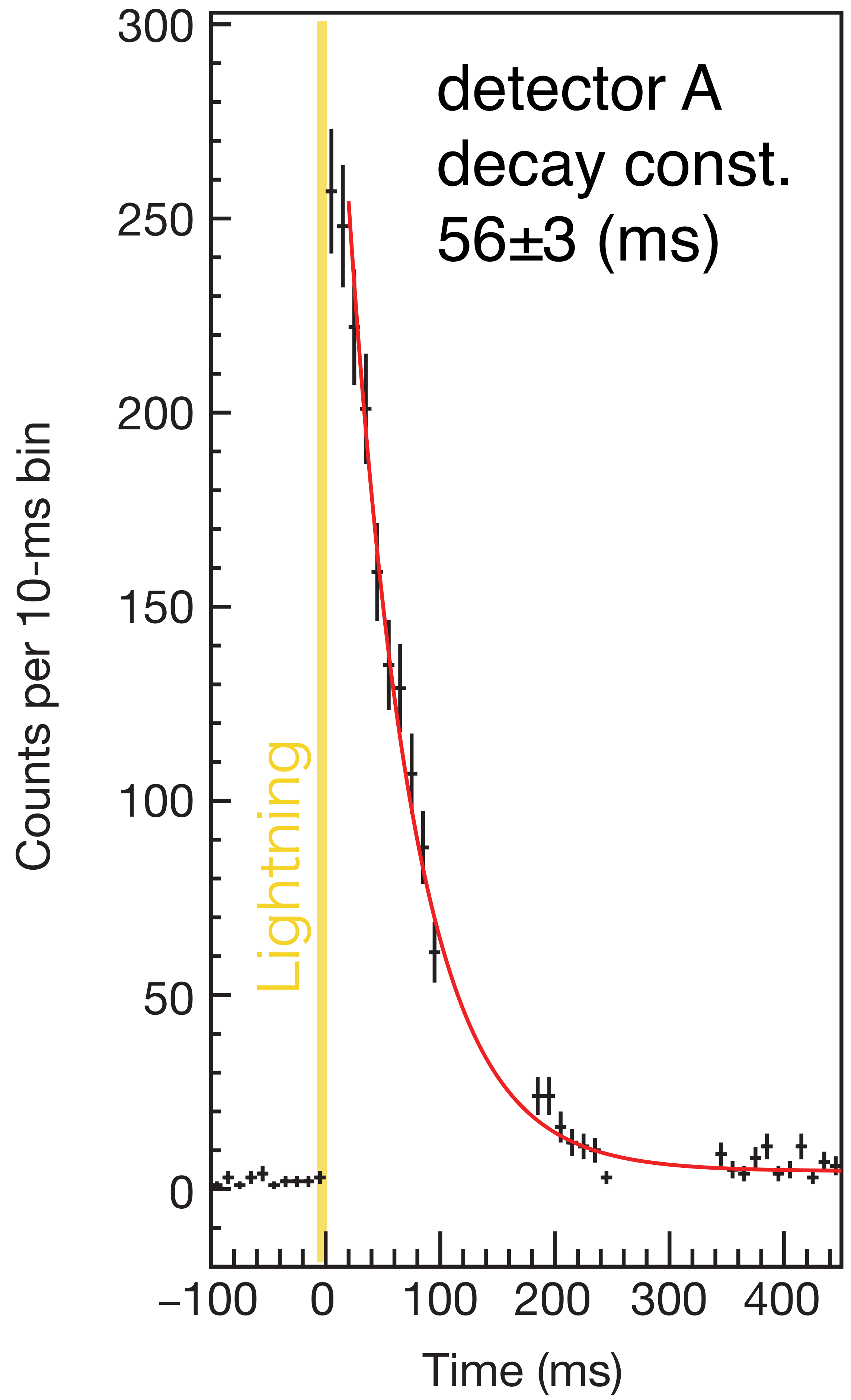
- Cross section of the photonuclear reactions is one order of magnitude smaller than that of the pair production. Downward TGFs can provide enough photons.

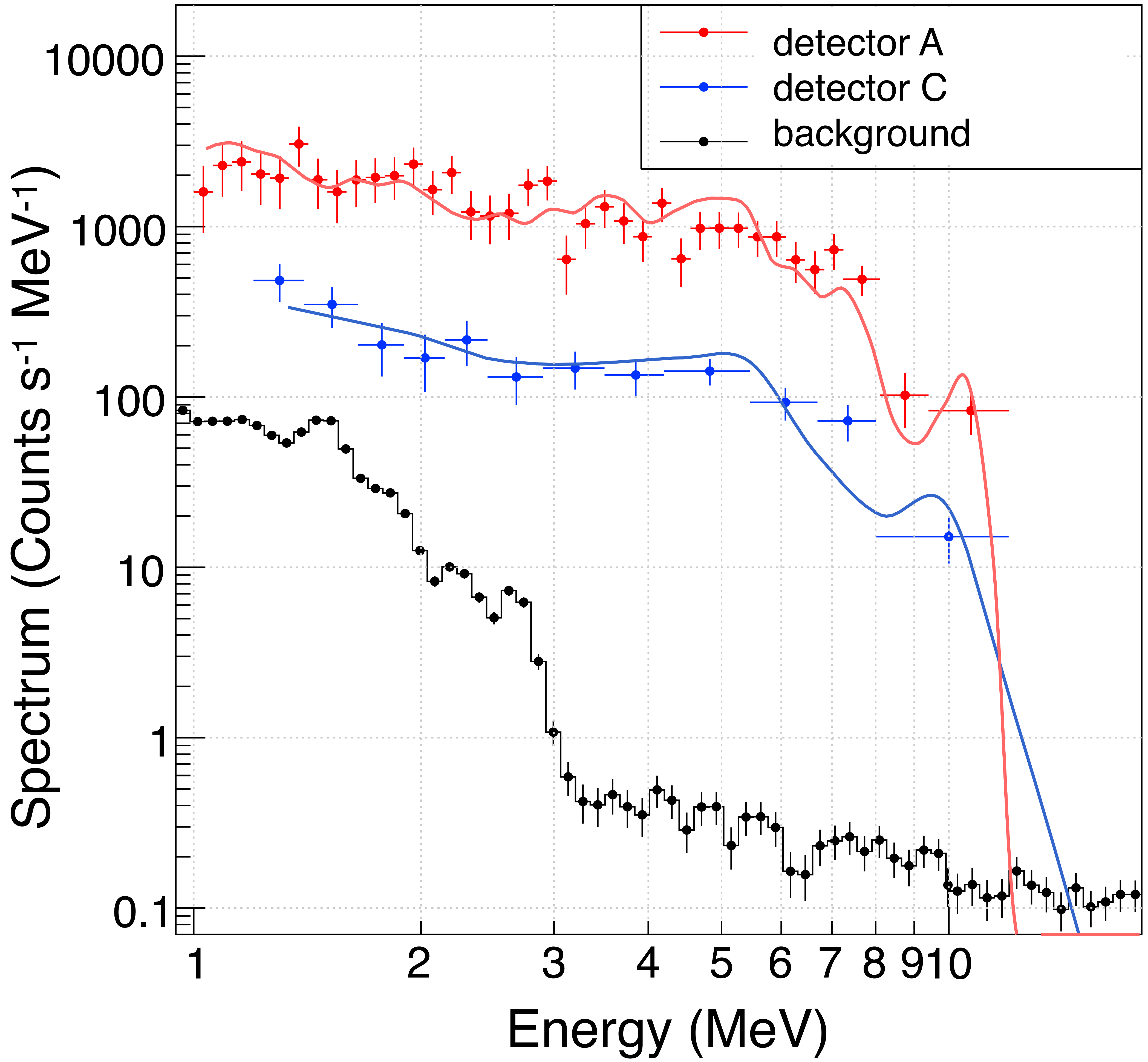
Gamma-ray Afterglow from Neutron Captures



- Exponential decay constant of the sub-second afterglow is consistent with the theoretical prediction ~56 ms of the neutron thermalization.
- Spectrum with a sharp cutoff at 10 MeV is well explained by prompt gamma rays from atmospheric nitrogens and surrounding materials.

Gamma-ray Afterglow from Neutron Captures





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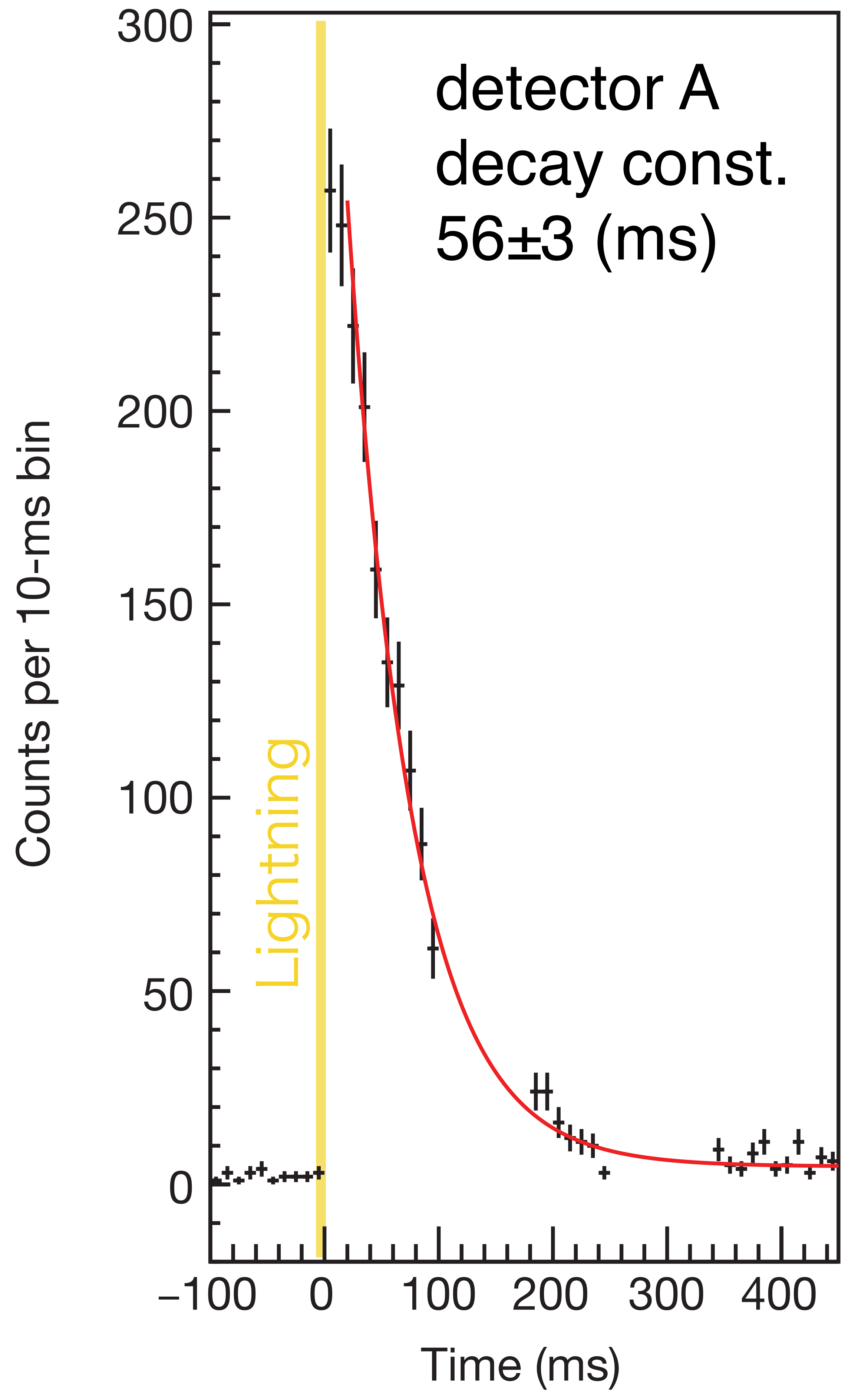

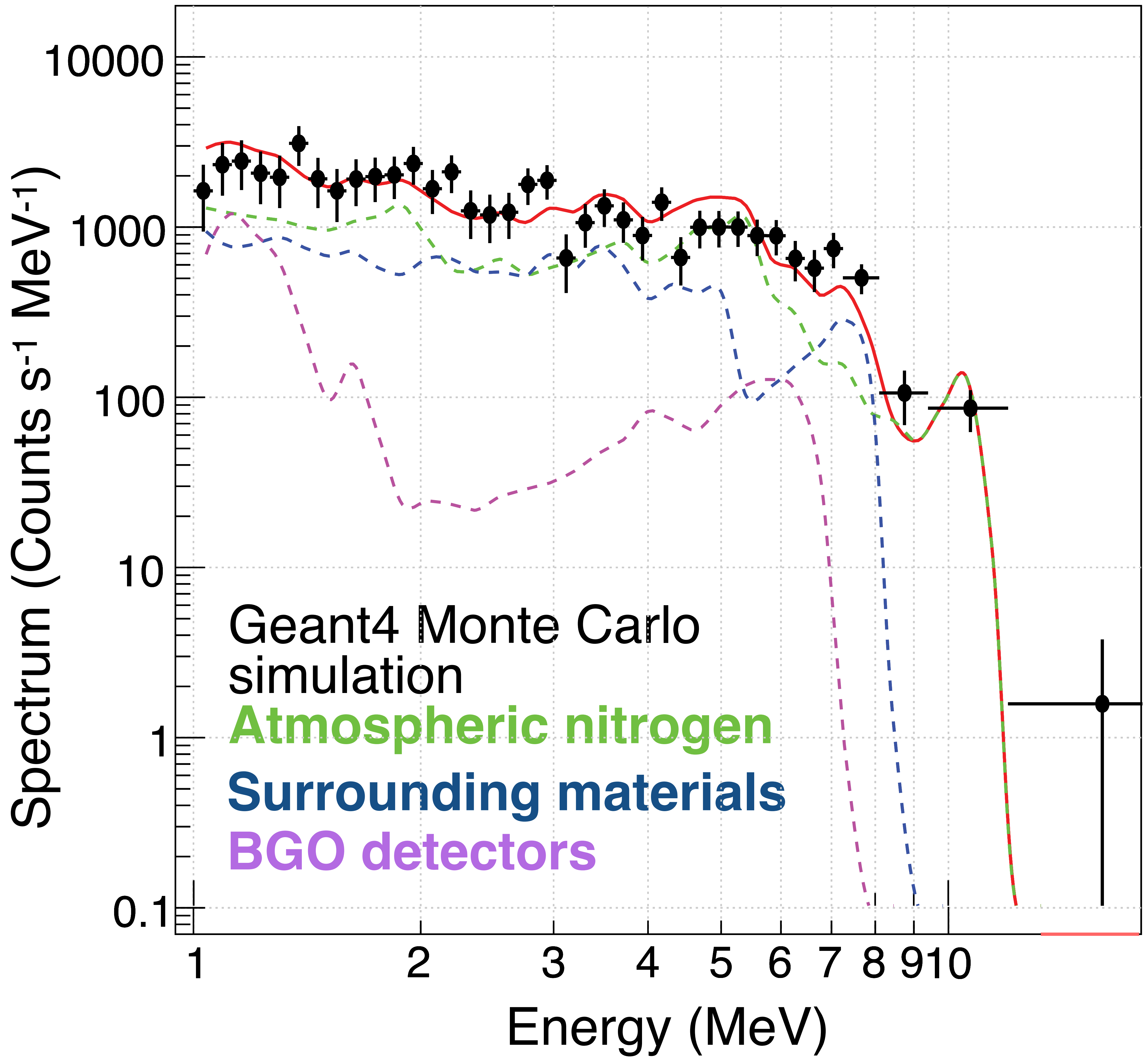

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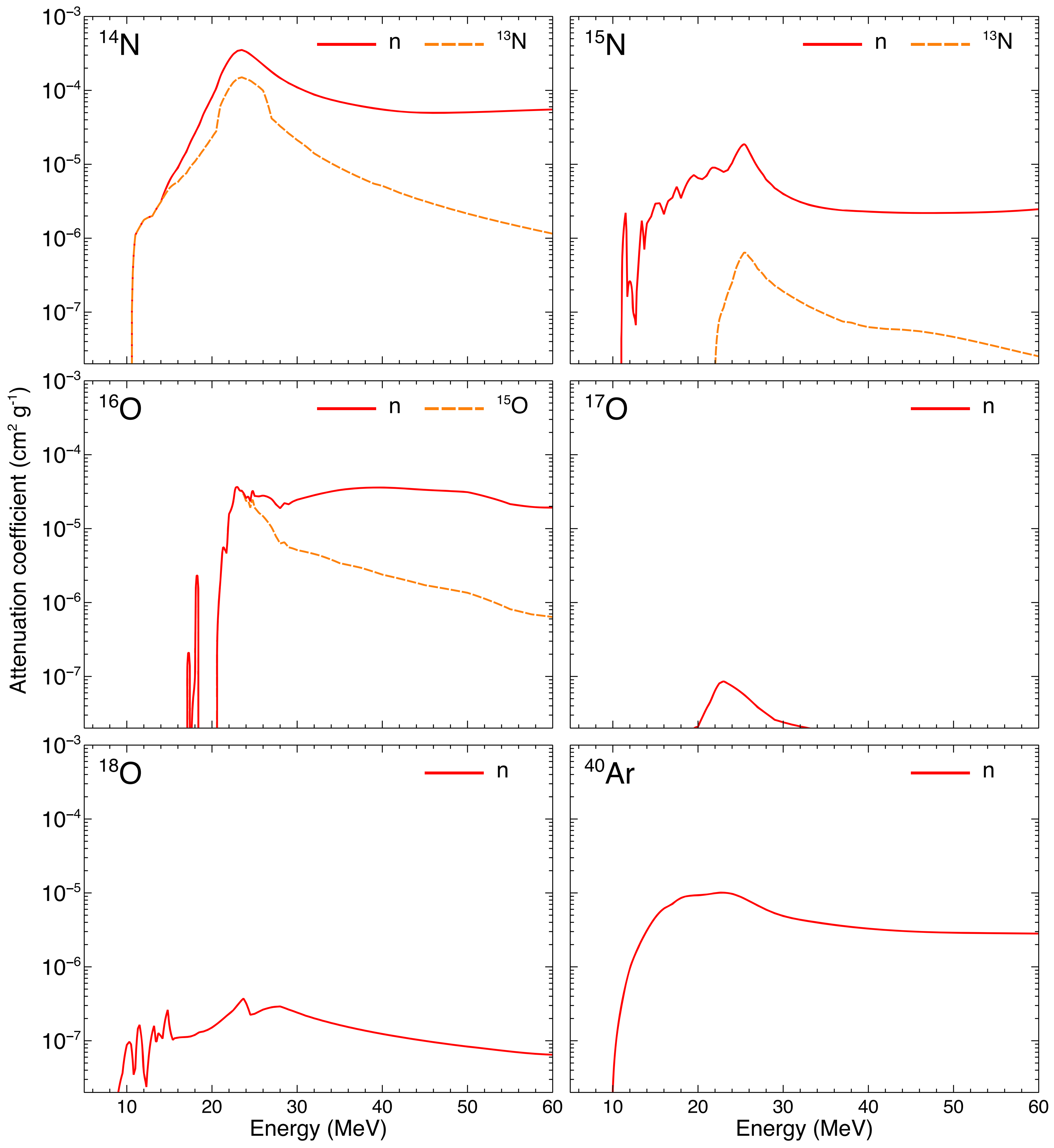
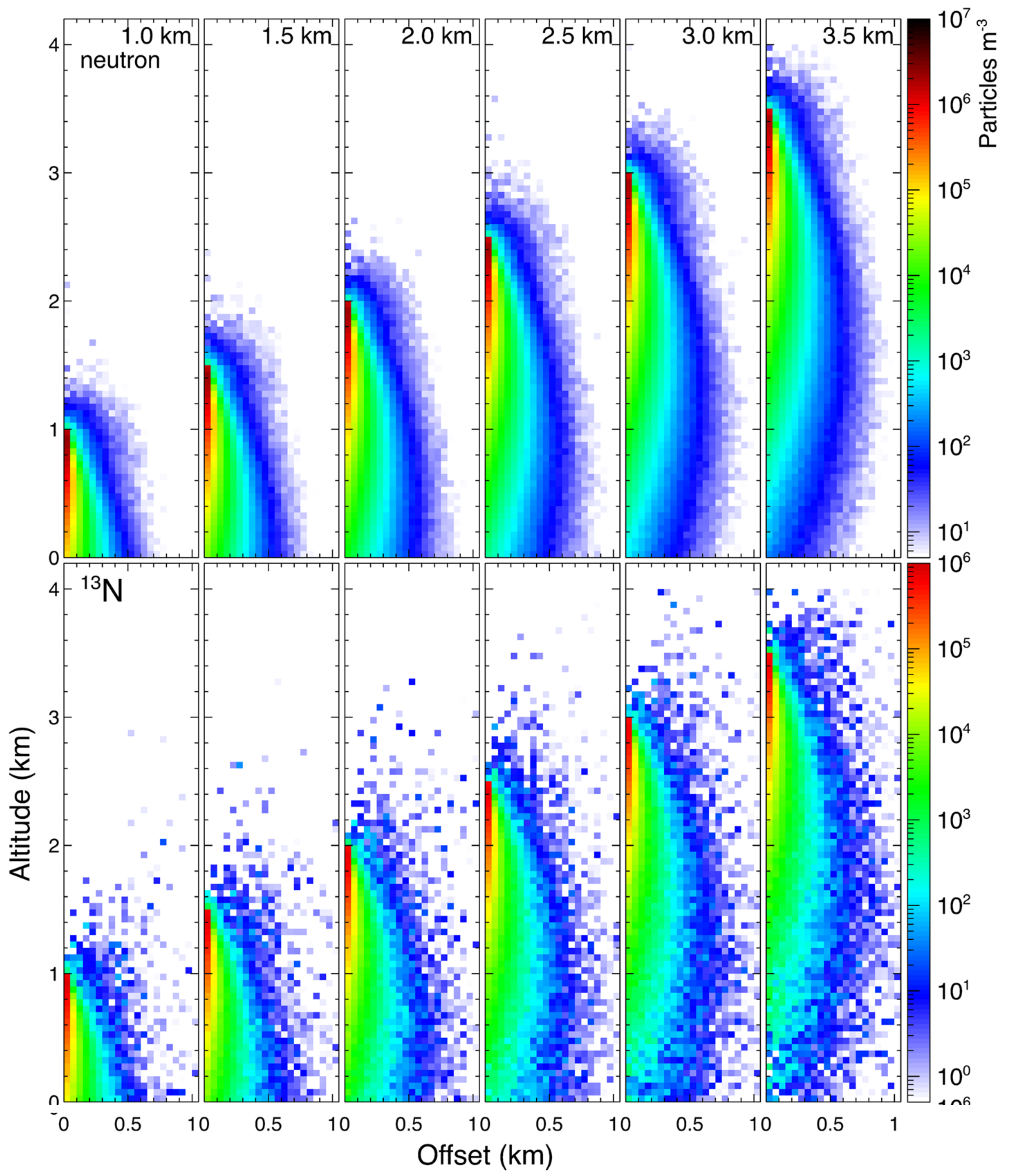
Theoretical Modeling Compared with Observations



Cross section



Geant4 simulation

(Wada Ph.D thesis 2019, the University of Tokyo; Wada et al., JGR Atmosphere 2020a, Wada et al., JGR Atmosphere 2020b)

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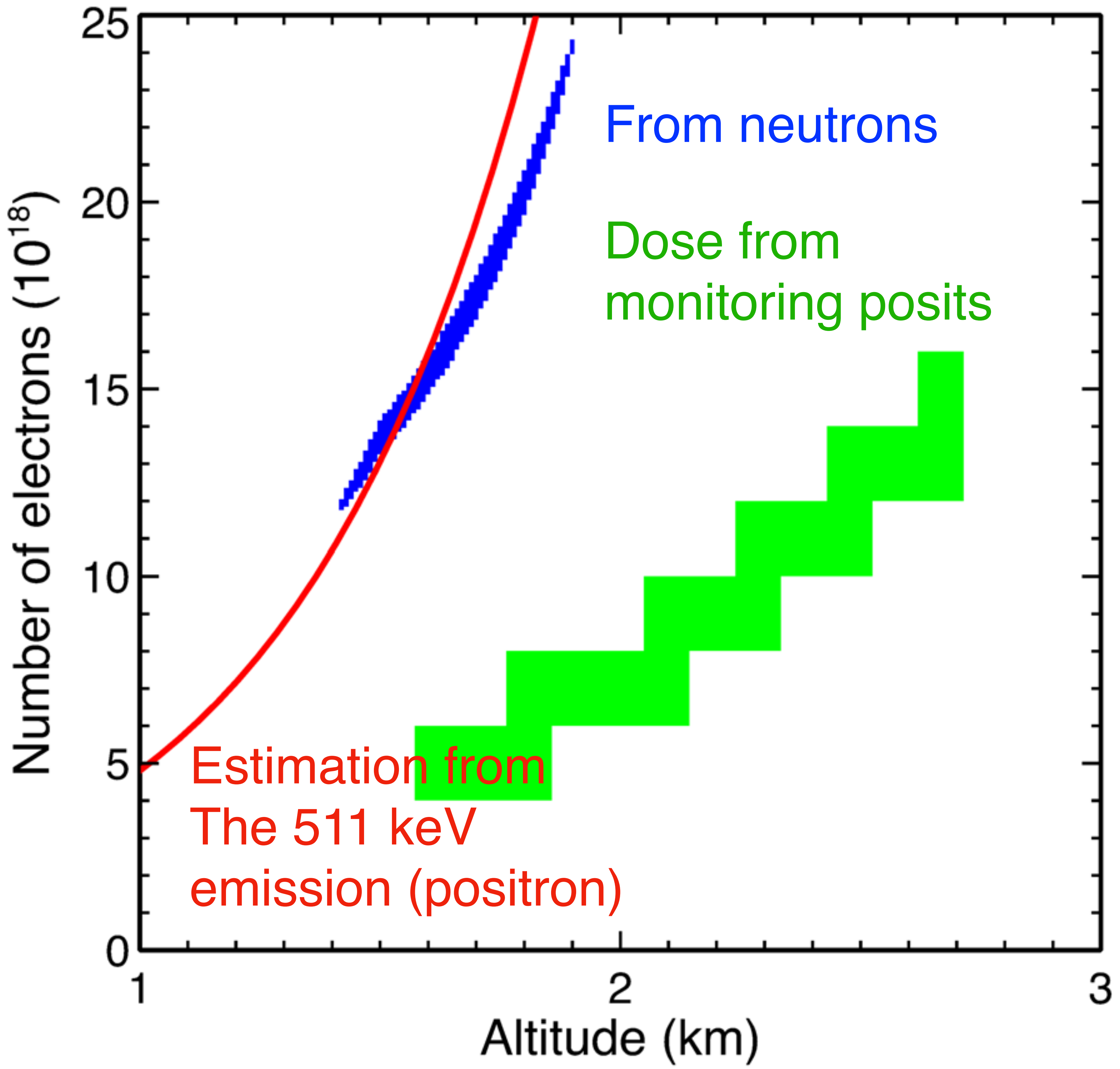
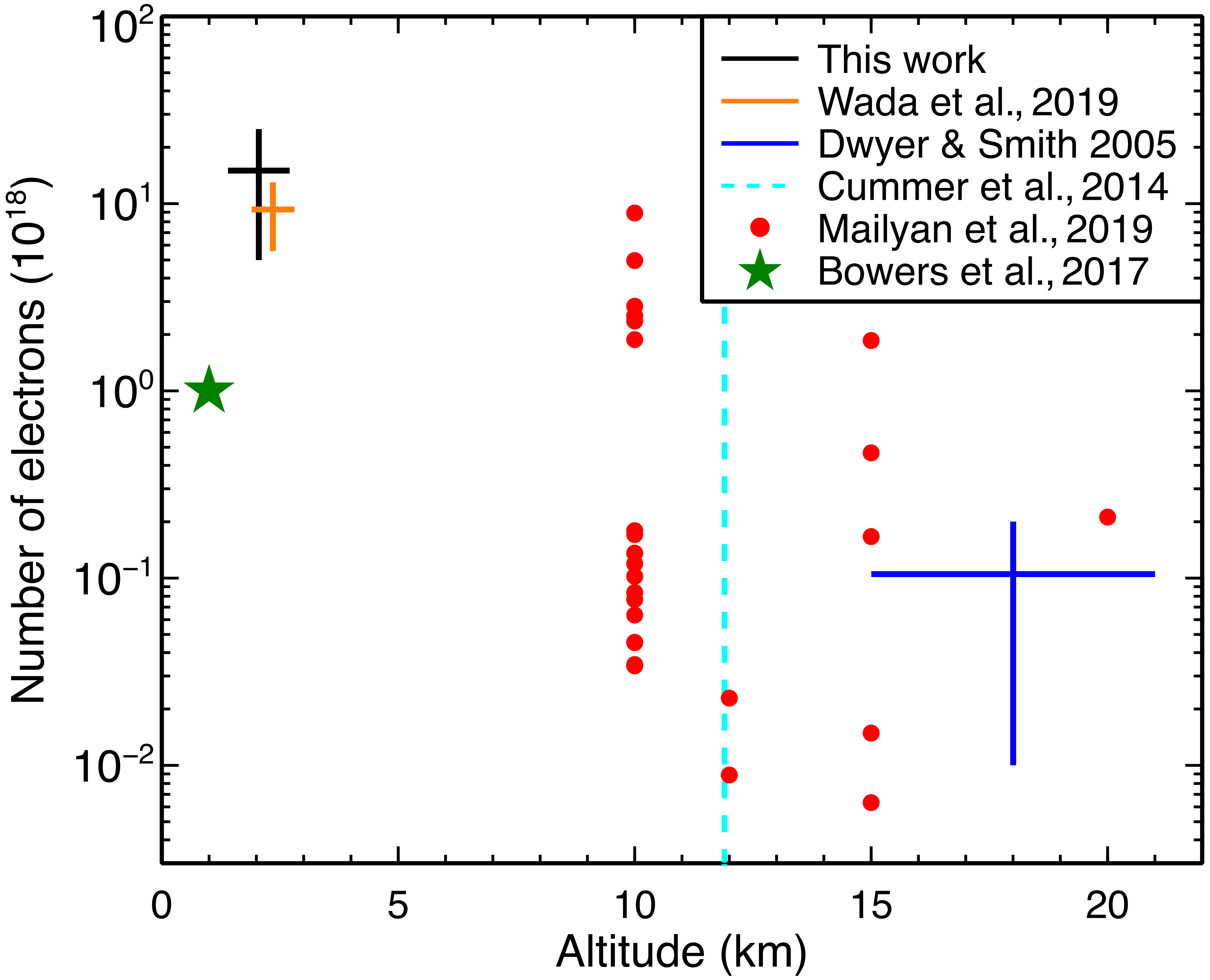




- Simulation vs. Data: Neutron, positron annihilation, and radiation dose.
- Downward TGF: (0.5-2.5)x10^{19} avalanche electrons above 1 MeV at an altitude of 1.4-2.7 km, compared with upward TGFs observed by satellites.

(Wada Ph.D thesis 2019, the University of Tokyo; Wada et al., JGR Atmosphere 2020a, Wada et al., JGR Atmosphere 2020b)

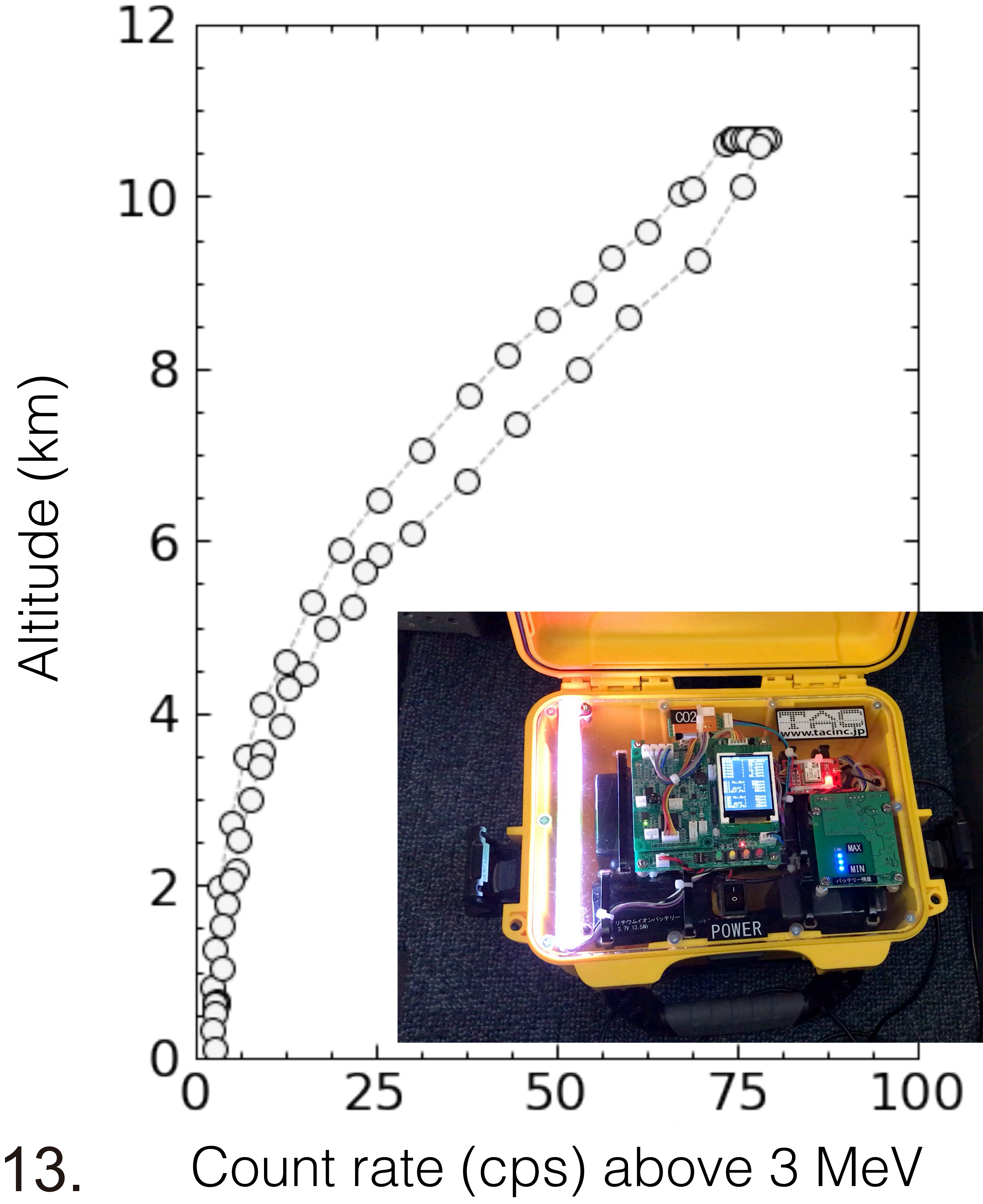

Illustration: Hayanon Science Manga Studio
negative charge
positive charge
Terrestrial gamma-ray flash
Satellites
strong electric field
lightning
relativistic electron acceleration
Photonuclear reactions
Neutron detectors
Gamma-ray glow
Radio antena network
Radiation detector network

Citizen Science “Thundercloud Project”

- Gamma rays can fly up to a few 100 m in the atmosphere.
- Multipoint measurement is essential, with lightning radio monitor, radio later, and electricity observations.
- We are aiming to ask citizen supporters to deploy our radiation detectors at their yards and balconies. Real-time alert of gamma-ray glows for supporters to take photos.

- CsI (Tl) scintillation 5 x 5 x 15 cm3 + MPPC
- Sending data via IoT devices (Sakura internet)
- Only a single “ON-OFF” button to operate everything!!

Portable Radiation Detector for Citizen Science



- Flight measurement up to 11 km similar to the historical experiment by V. Hess in 1911 and 1913.

Collective Power of Science (共創型サイエンス)

- Not a single huge telescope, but using collective power of multiple simple detectors
- Not only by professional researchers, but also by collaborating with citizen scientists.

Summary

- We are opening a new interdisciplinary field, “High-Energy Atmospheric Physics” of lightning and thunderstorms.
- Gamma-ray glows are bremsstrahlung emission from high-energy electrons accelerated by strong electric fields in thunderstorms.
- Photonuclear reactions have been detected from downward TGF-associated lightning discharges along the Sea of Japan.
- We are aiming to establish a citizen science “Thundercloud Project” for multi-point radiation measurement campaign.

    - Publications of the GROTH collaboration [ADS Library]
    - 日本語の記事:「雷放電が開く高エネルギー大気物理学」日本物理学会誌 2019年4月号

Question from Organizers

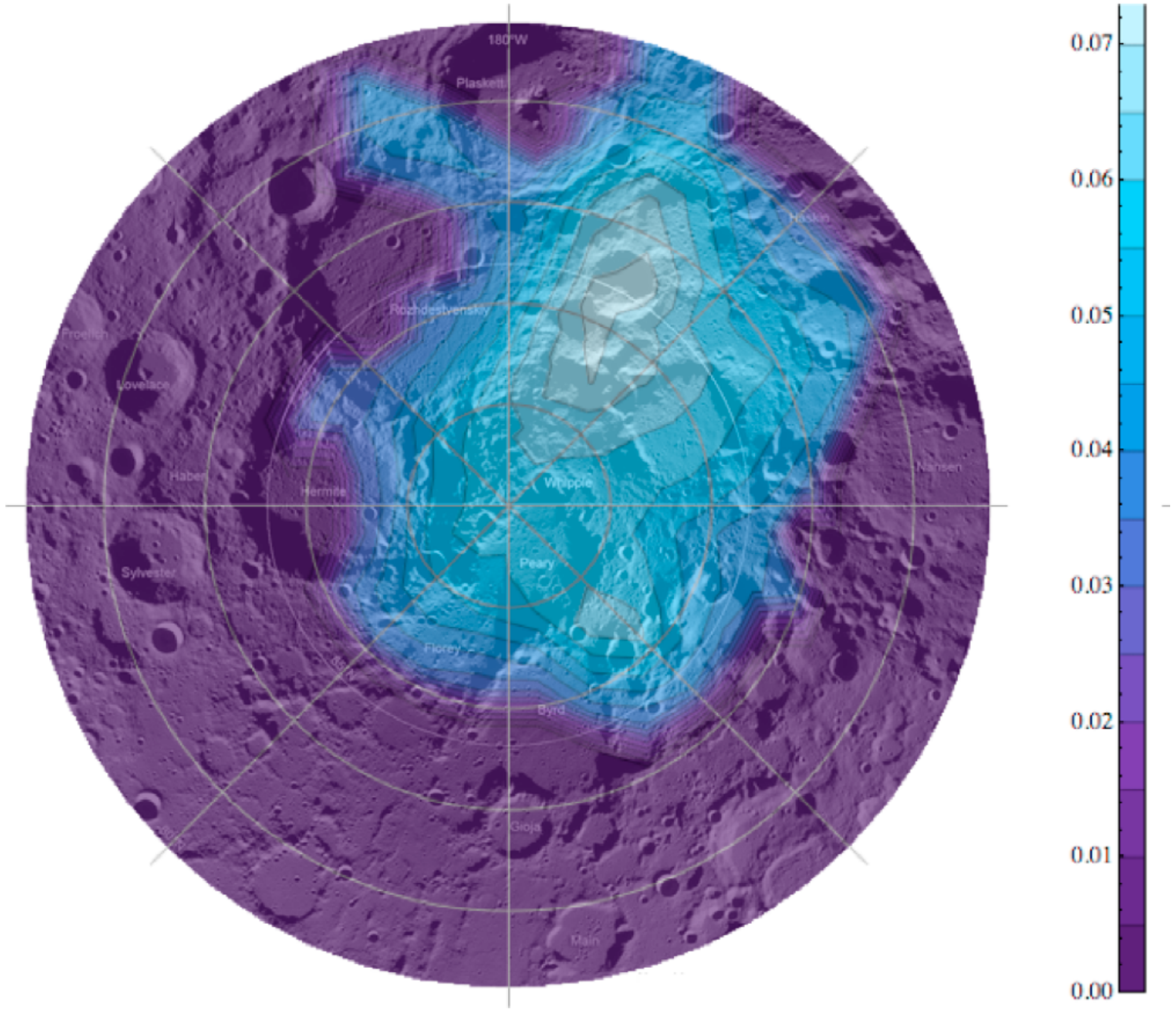
- To invited speakers, we would like to request your personal opinion at your final slide,
  - What's your targeted physics in next decades?
  - What we need to accomplish?
  - and take-home messages (optional)
- These descriptions will be addressed in the Summary session.

Developments of New Neutron Detectors

- Photonuclear reactions of lightning produced neutrons. In addition to gamma-ray afterglow of neutron capture signals in the atmosphere, Wada et al., (2020) reported direct detection of neutron signals in GSO scintillator.

- Our team has been developing new neutron sensors, which can discriminate thermal neutrons, fast neutrons, and gamma rays for our citizen science “Thundercloud Project”

- By the way, we are entering a new era of lunar exploration and space exploration. Searching for water on the lunar surface is one of the primarily targets of projects.



(Miller et al., JGR, 2012)

Distribution of water equivalent hydrogen (WEH) of the lunar north pole (>80°)

(Wada et al., PRD, 2020)

Lunar Exploration using Neutron Signals

- Starting from collaboration with planetary scientists, eventually I want to try astronomy from the moon in the next decade. Need collaborators to consider this together!