Recent status of the GROWTH experiment

-Gamma-ray observations at the coastal area of Japan Sea -

(1) Background
(2) GROWTH experiment
(3) Observational results
   1. properties of thundercloud gamma rays
   2. relationship with lightning
   3. photonuclear reaction in lightning

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on behalf of the GROWTH collaboration

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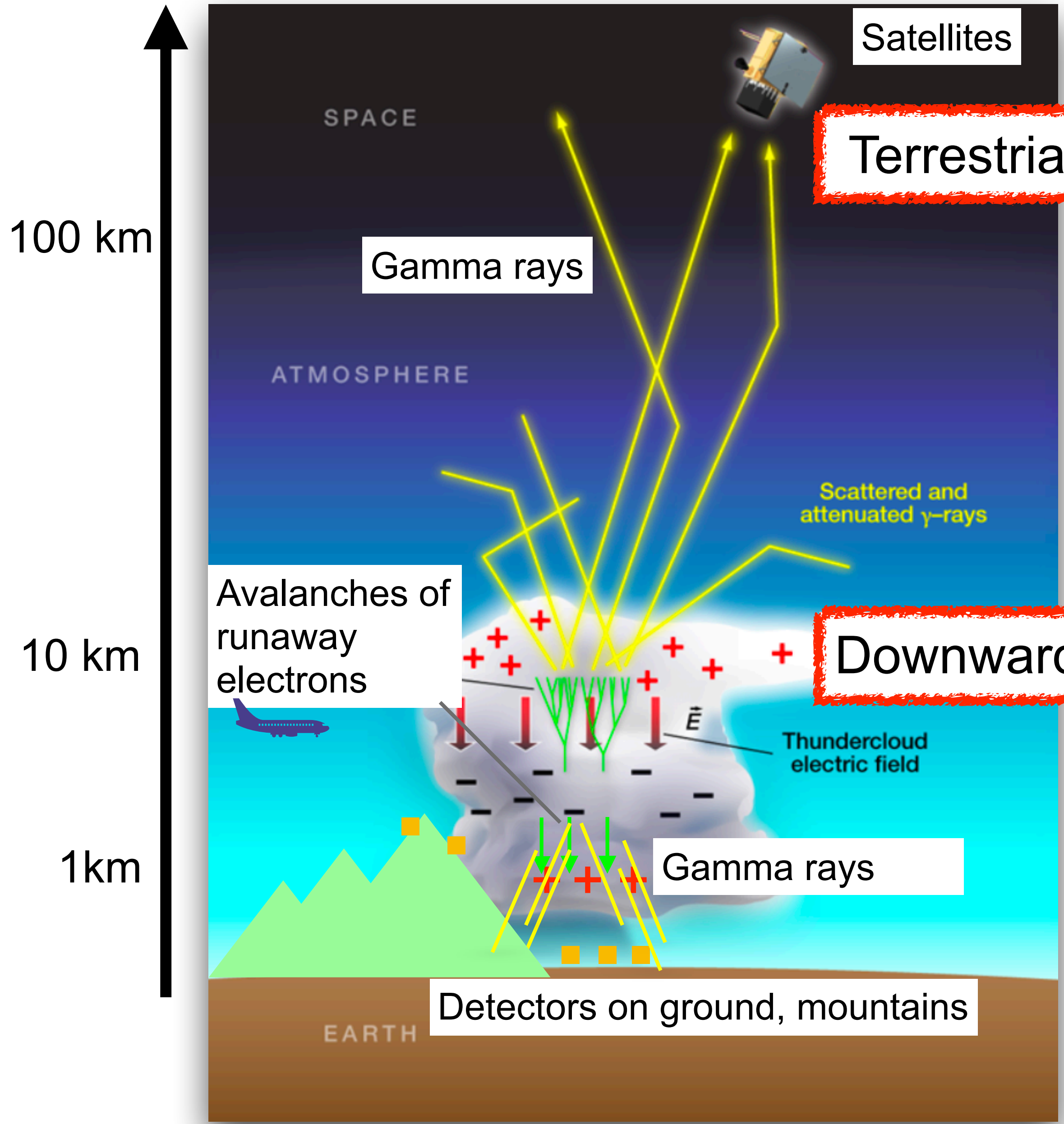
WRMISS in Tsuruga, Sep. 5, 2018

Background

- Radiation enhancement associated with thunderstorms -



Original figure J. Dwyer 2011

Terrestrial Gamma-ray Flashes (TGFs)

Ref: Dwyer et al., SSR (2012)

- ☆BATSE, RHESSI, AGILE, Fermi
- ☆Duration : submilli-second

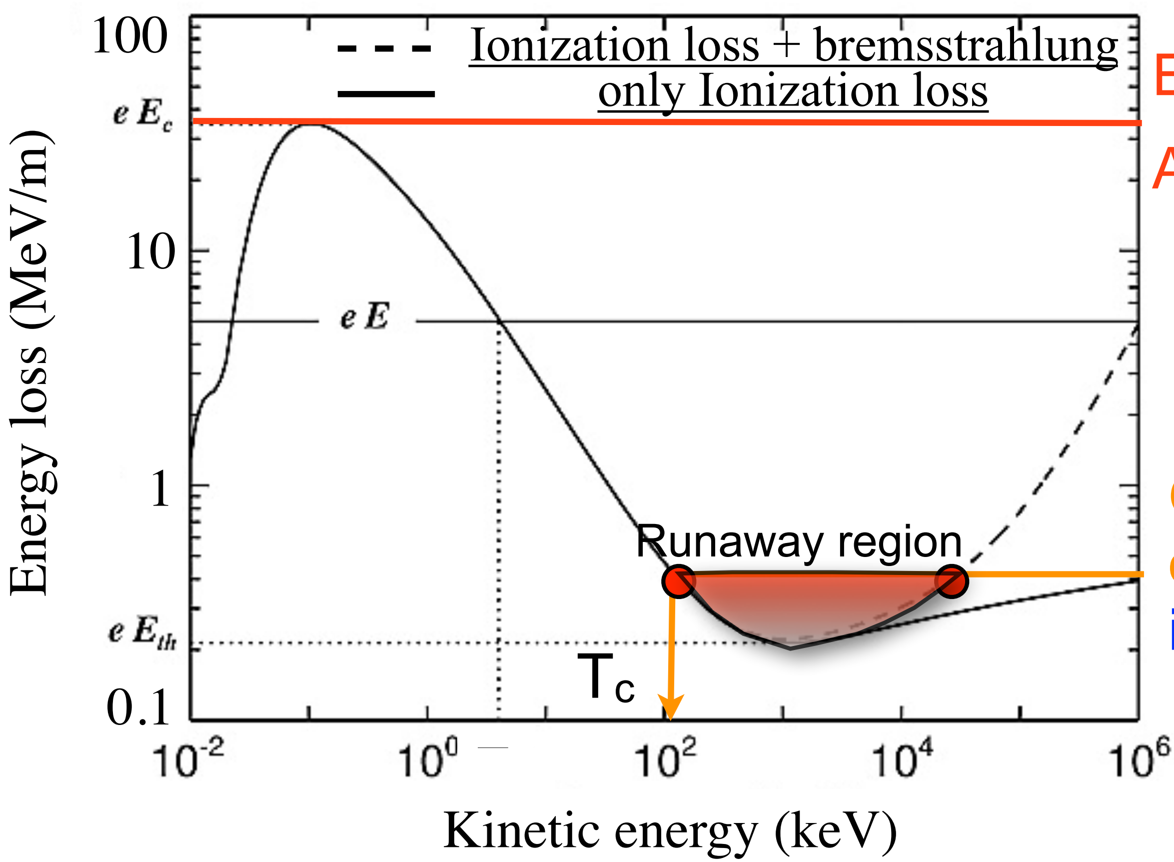
Downward-beamed Radiations

- ☆ Gamma-ray glows
- ☆ Observed by airplane, balloons, high-altitude detectors and the ground-based ones.
- ☆ Duration : submilli-second to a few tens of minute

Background

- How runaway electrons are produced in air? -

Gurevich et al.,PLA 165(1992), Dwyer GRL (2003)



E_D (~30 MV/m)

All electrons become runaway

Observed E :< 0.4 MV/m.

only fast electrons run away

if $T_e > T_c$

Thus, the runaway electron avalanche occurs if

(1) Electric filed *is higher than* $E_c(\text{MV/m}) = 0.28\,P(\text{atm})$

(2) Seed electrons with high energies are present in the atmosphere

Possible sources

Cosmic rays or Radon-decay products

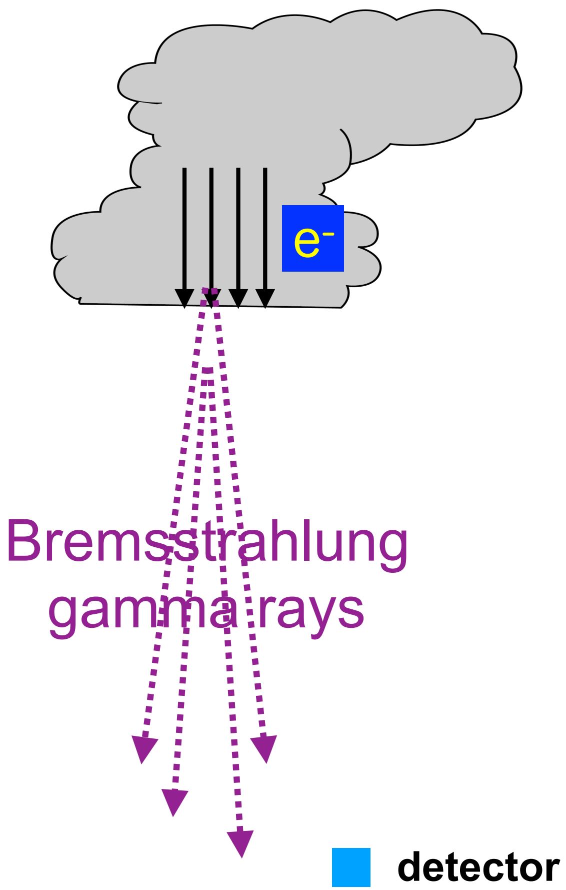
Background

- Radiation enhancement in winter season -

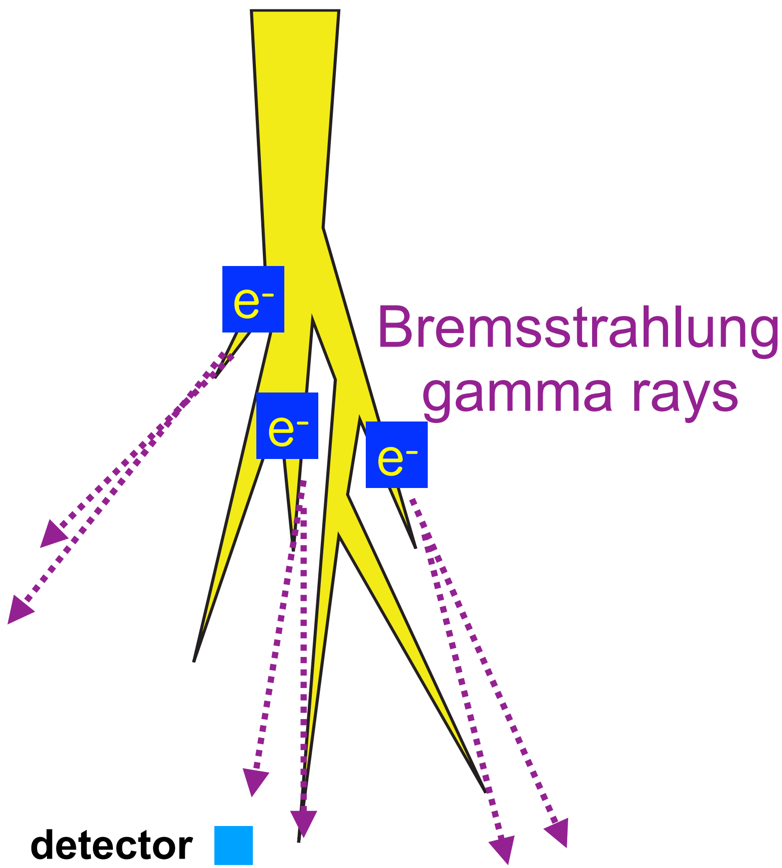
Observations of radiation enhancements only in winter seasons at the coastal area of Japan Sea (Torii+2002,2008, Tsuchiya+2007,2011)

Two types of radiation bursts on the ground

☆Long bursts



☆Short bursts



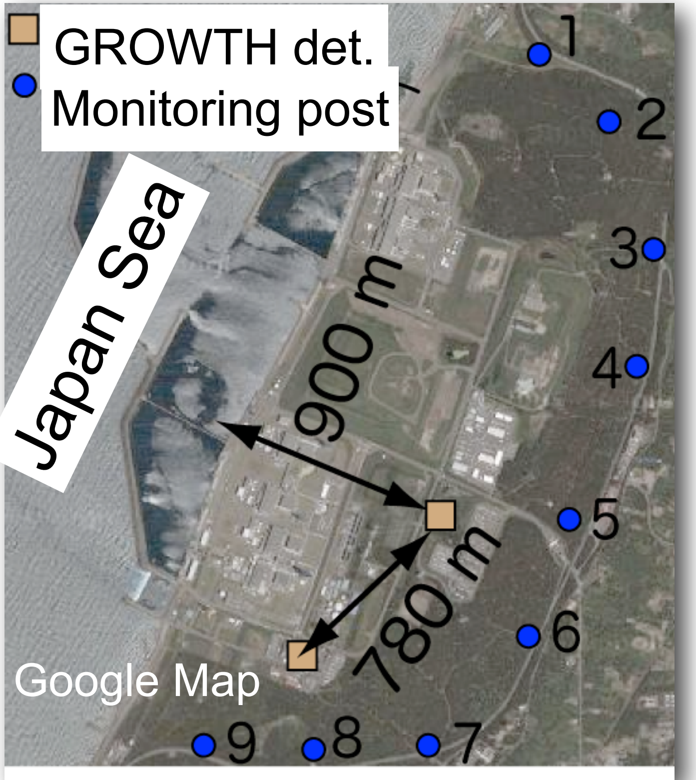
Aim of observations

- How electrons are accelerated to relativistic energies in a dense terrestrial atmosphere?
- How those bursts are associated with lightning/ thunderclouds ?
- How positrons and neutrons are produced in lightning and thunderclouds?
- How lightning is triggered?

GROWTH experiment (-fy2014)

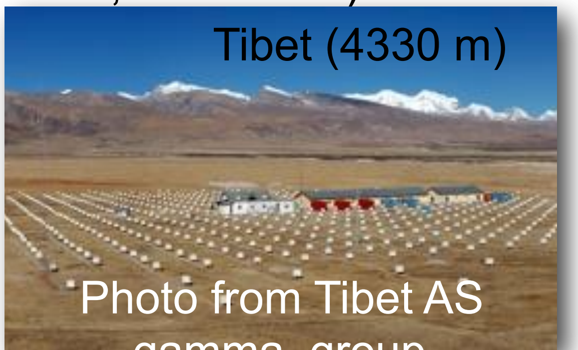
Gamma Ray Observation of Winter Thunderclouds

- Observations at Kashiwazaki-Kariwa power plant (PRL 2007,2013;JGR 2011)



- ☑ Start in 2006
- ☑ NaI, CsI, BGO scintillation detectors and Monitoring posts
- ☑ Low altitude of cloud base : < 1 km

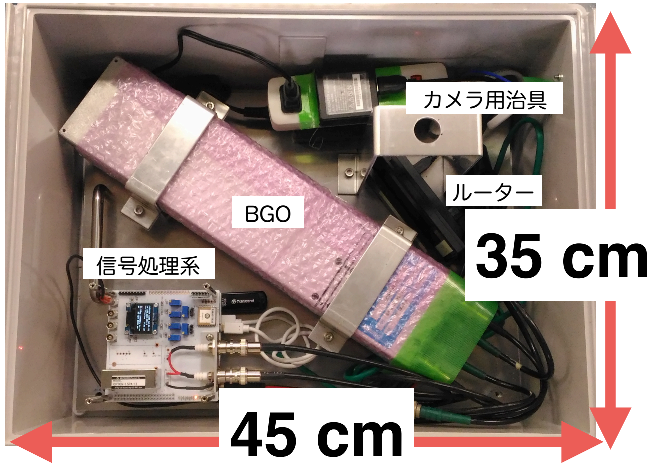
- Observations at high mountains (PRL 2009; PRD 2012)

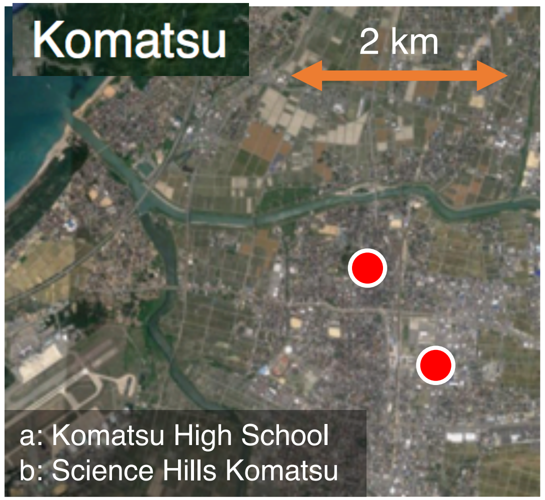


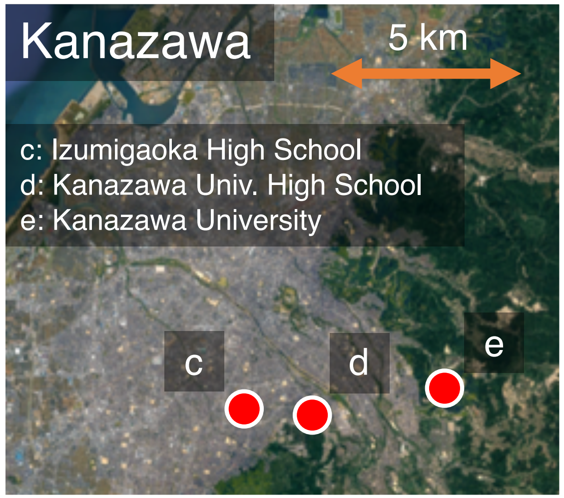
GROWTH experiment (fy2015-)

Gamma Ray Observation of Winter Thunderclouds

- ☑ Kanazawa, Komatsu, Suzu (AS of 2018)(Wada, Master thesis 2017)
- ☑ NaI, CsI, BGO scintillation detectors + Raspberry Pi for downsizing system







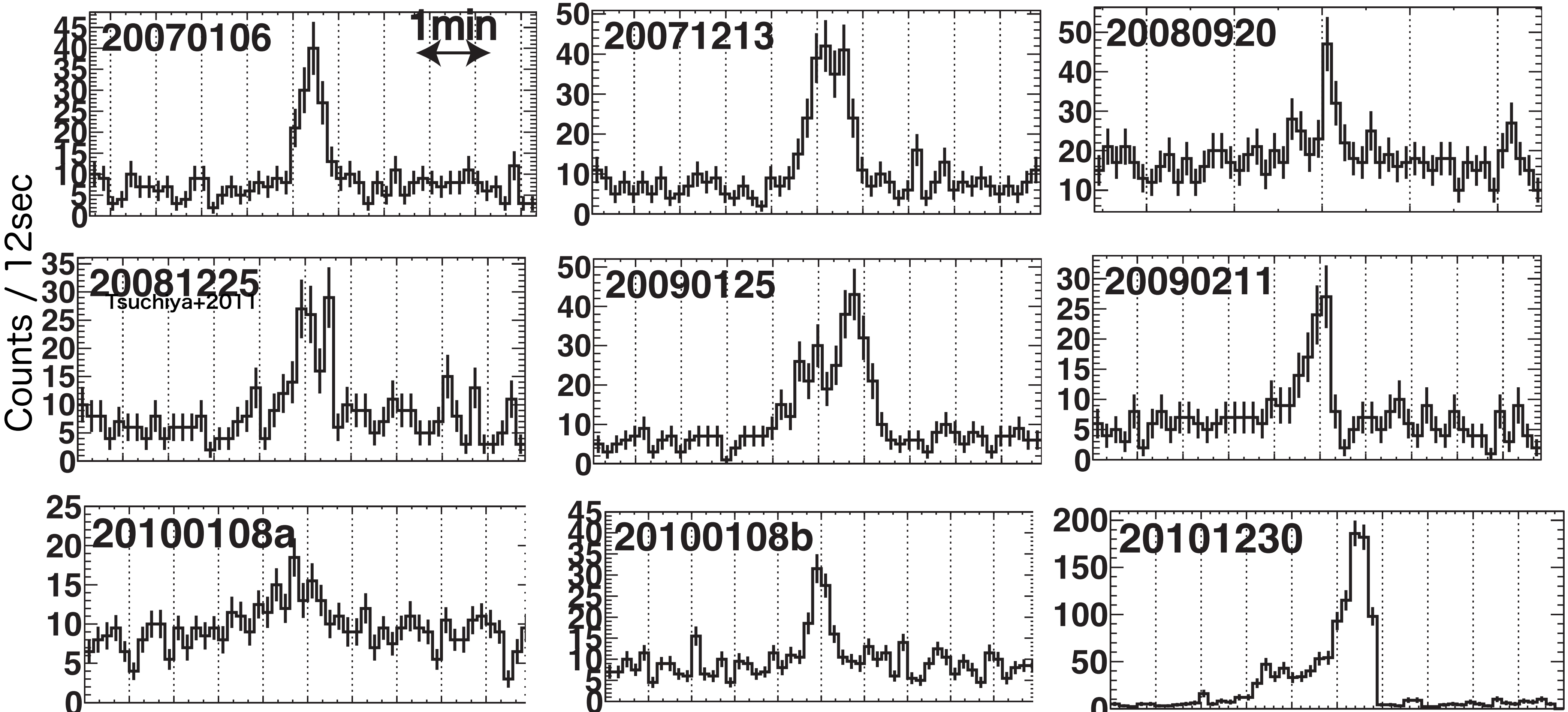
Observational results

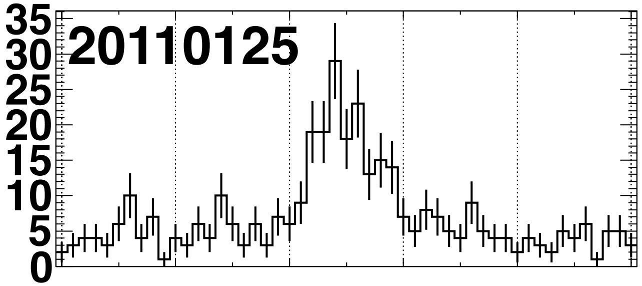
(1) General properties of long bursts

Counts histories of long bursts

Kashiwazaki+Mt. Noikrura

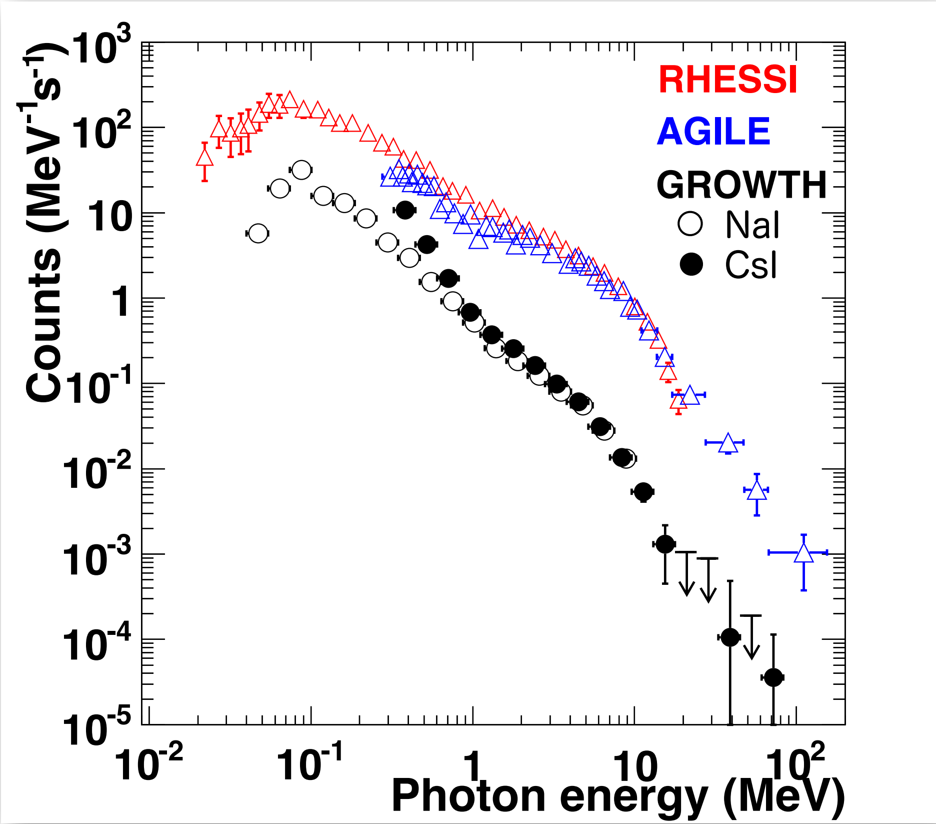
Duration : a few tens of sec to a few minutes





- 10 min or less of mature stage of winter thunderclouds. (Kitagawa & Michimoto,1994)

Energy spectrum
Long bursts vs TGFs



Not corrected for detector response

RHESSI: 289 events(Dwyer&Smith,GRL 2005)

AGILE: 130 events (Tavani et al., PRL 2011)

GROWTH : 5 events Revised Tsuchiya et al., JGR 2011

- Maximum energy

  TGF～100 MeV

  GROWTH～20 MeV

- # of >1 MeV electrons

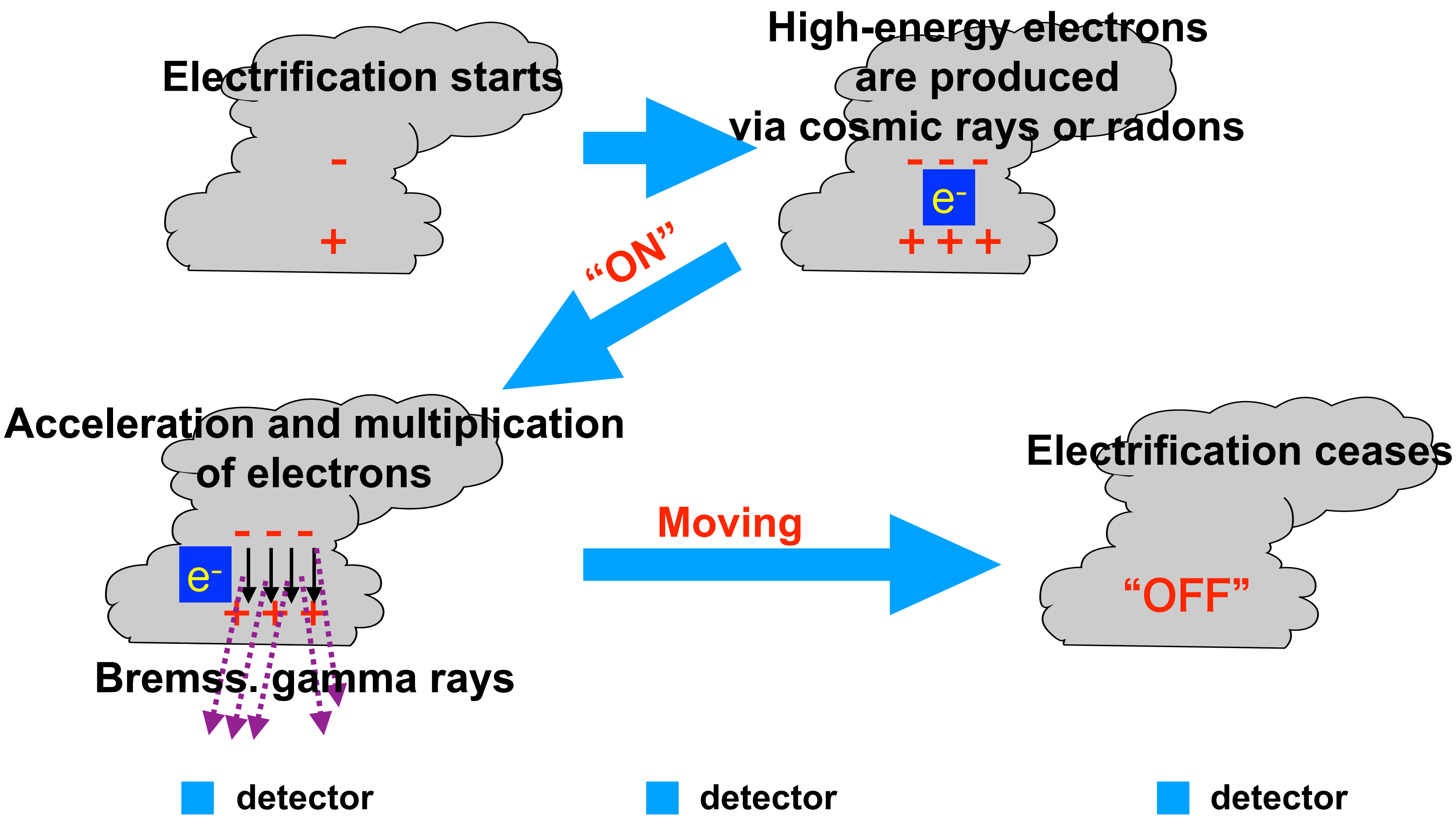
  TGF～10^{16} - 10^{17}

  GROWTH～10^{9} - 10^{11}

Discussions

☑ Long bursts have been observed by airborne detectors, high-mountain ones as well as ground-based ones. They have never been observed by detectors onboard satellites（because primarily of moving of satellites)

☑ It has been thought that long bursts are related to electrification of thunderclouds. We may observe them from the electrification region when it being "ON".



Discussions

- ☑ In order to observe the whole cycle of a long burst, we need to prepare mapping observations such as the GROWTH one. Also air-shower experiments using many detectors would be suitable for those observations. Actually, several air-shower experiments have reported thunderstorms-related enhancements
[Tibet ASg group (Amenomori+, Proc.of ICRC2013), TA group (Abbasi+ PLA, 2017)]

- ☑ Some groups have reported increases or decreases of muon flux during thunderstorms (Alexeenko+2002, Dorman+2003, Muraki+2004).
So far, those muon variations have been observed only at high mountains.

Observational results

(2) Relationship between long bursts and lightning

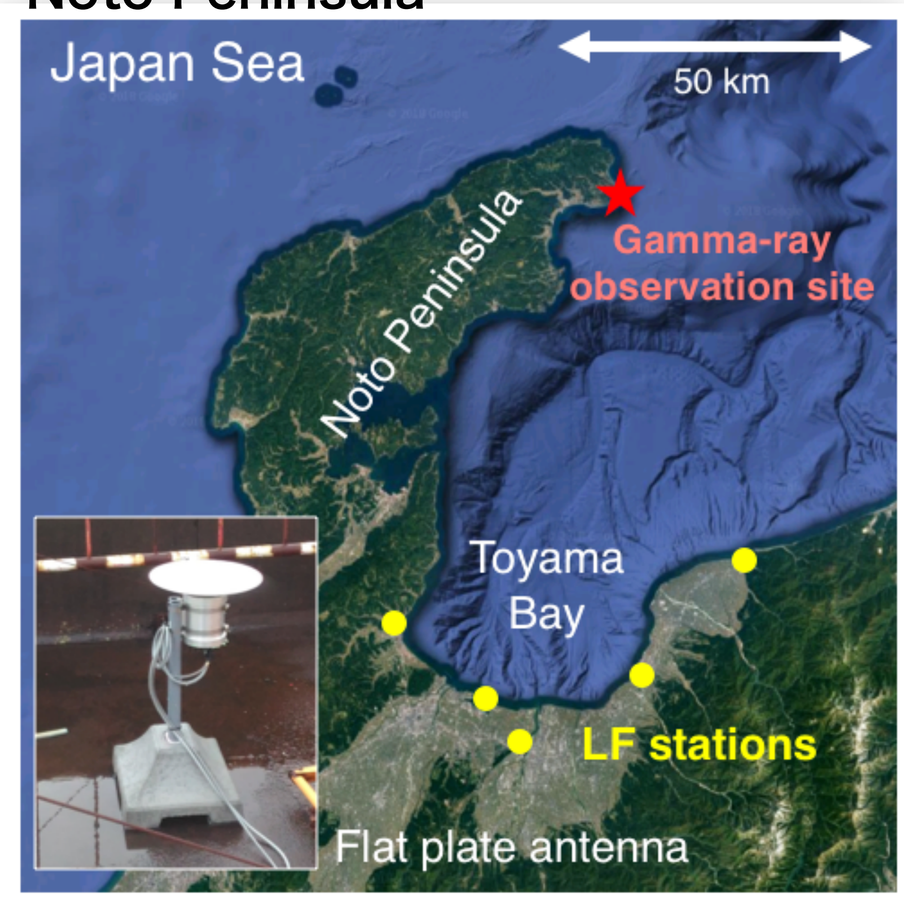
Relation between a long burst and lightning

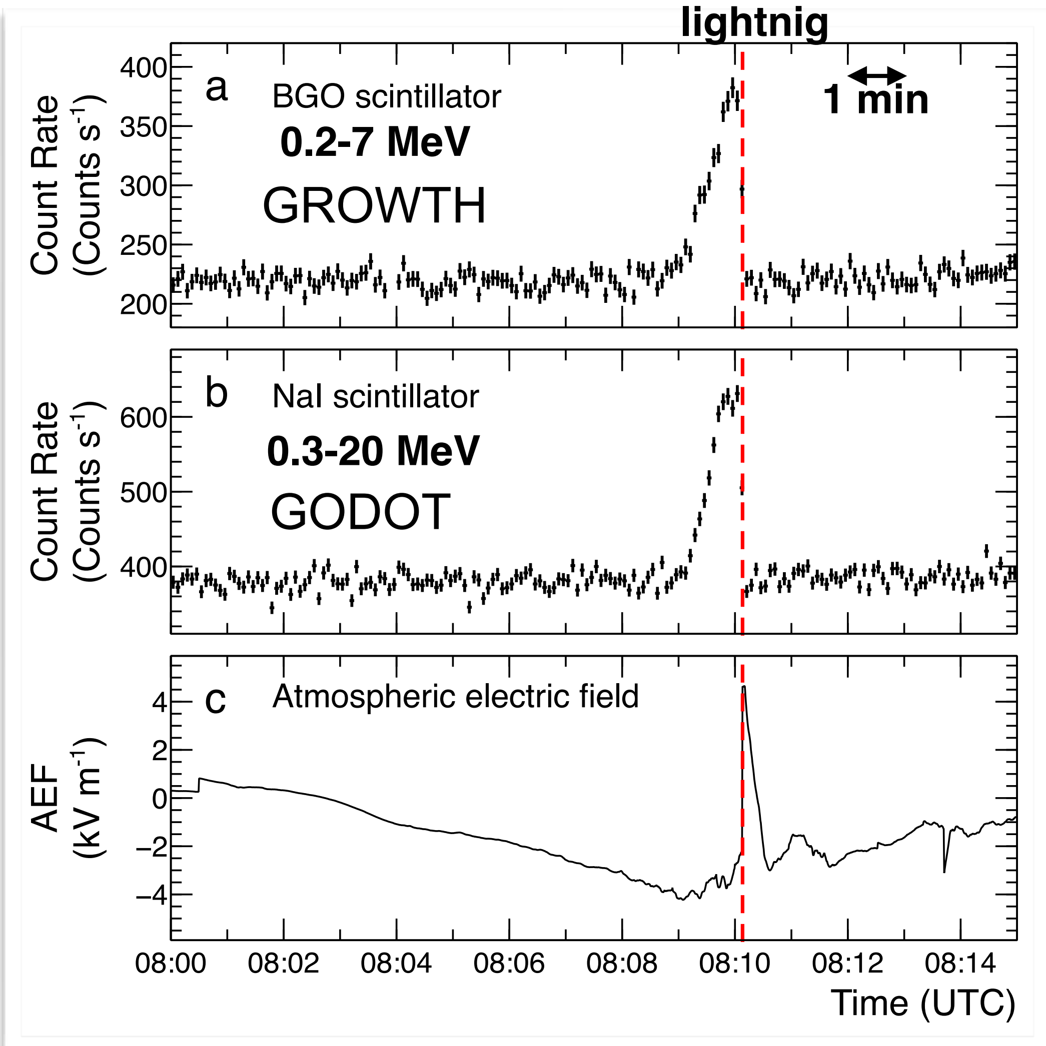
Termination of long bursts just prior to lightning

Y. Wada, G. S. Bowers, T. Enoto et al, GRL **45** 5700 (2018)

- **Simultaneous observations of gamma rays(GROWTH and GODAT), electric field (Kamogawa team) and LF (Morimoto team) were done**

Noto Peninsula

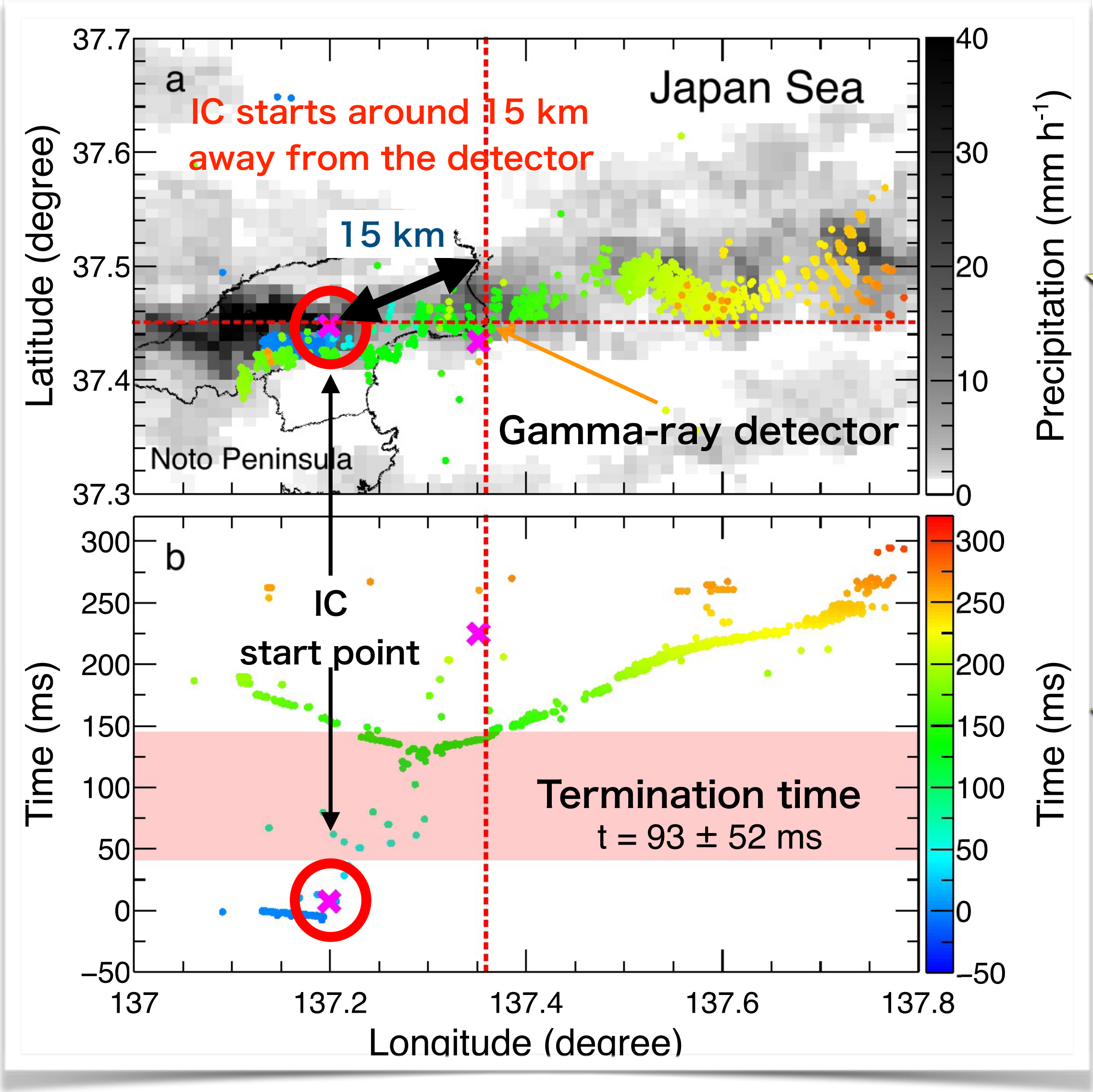




Relation between a long burst and lightning

Termination of long bursts just prior to lightning

LF network detected leader development of an IC*



☆IC started away from the detector.

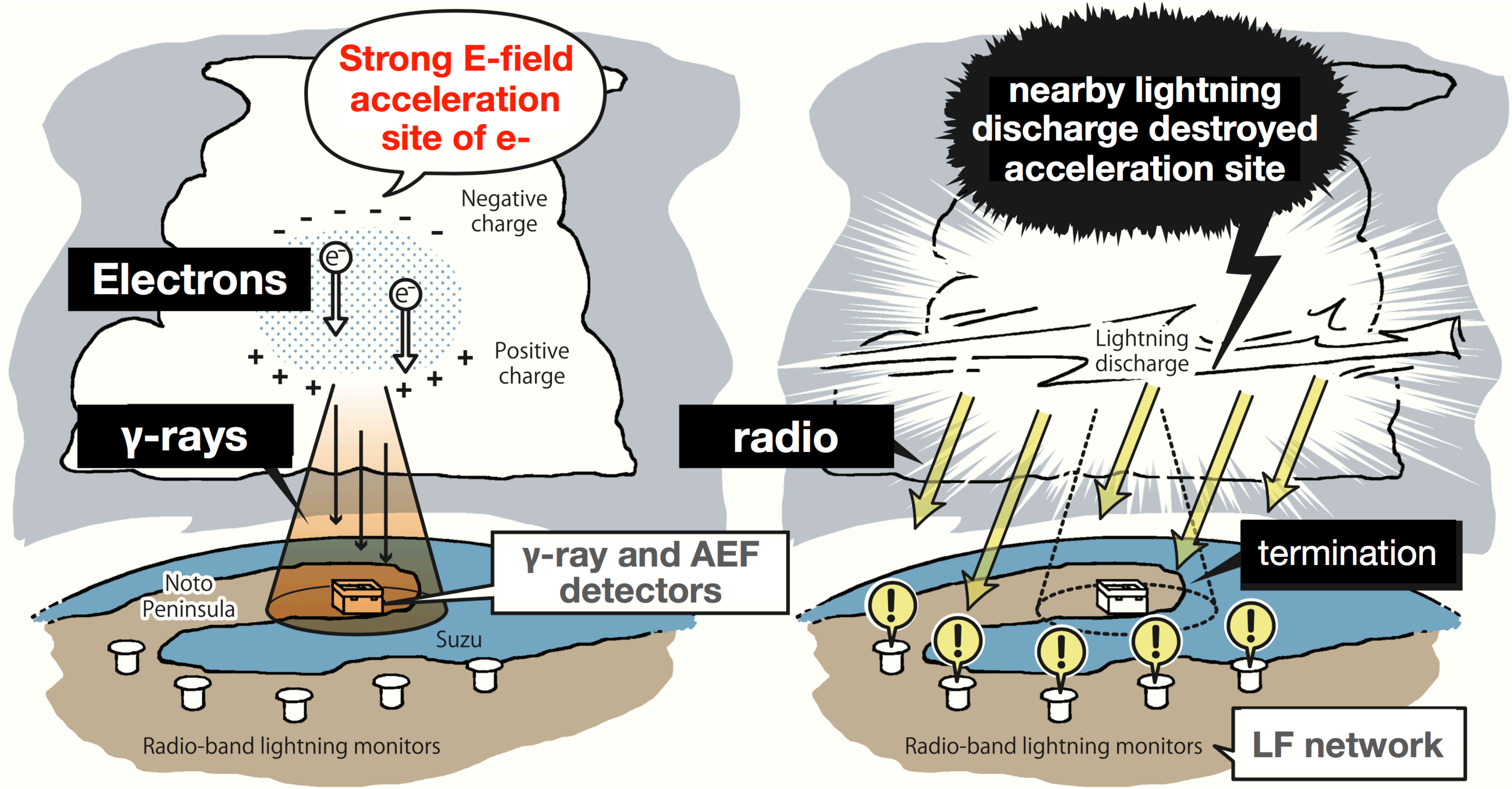
☆IC leader destroyed the gamma-ray emitting region

IC : Intra/Inter cloud discharge

Relation between a long burst and lightning

Termination of long bursts just prior to lightning

Schematic view of this event



Y. Wada, G. S. Bowers, T. Enoto et al, GRL **45** 5700 (2018)

Observational results
(3) Photonuclear reactions in lightning

T. Enoto, Y. Wada, Y. Furuta, K. Nakazawa, T. Yuasa,
K. Okuda, K. Makishima, M. Sato, Y. Sato, T. Nakano,
D. Umemoto, H. Tsuchiya, Nature **551** (481) 2017

Lightning and neutron production

- 1970's-1990's : nuclear fusion D + D ->(2.45 MeV) + ^{3}He
  - Possibility of neutron production in lightning Libby & Lukens JGR (1973)
  - "Positive" detections Shah+ Nature(1985), Shyam&Kaushik JGR (1999)

However,

- DD Fusion : Not feasible in normal lightning environment

  Extremely intense electric field would be required for detectable neutron flux (10^{10}-10^{15} n) Babich+ JGR (2007)

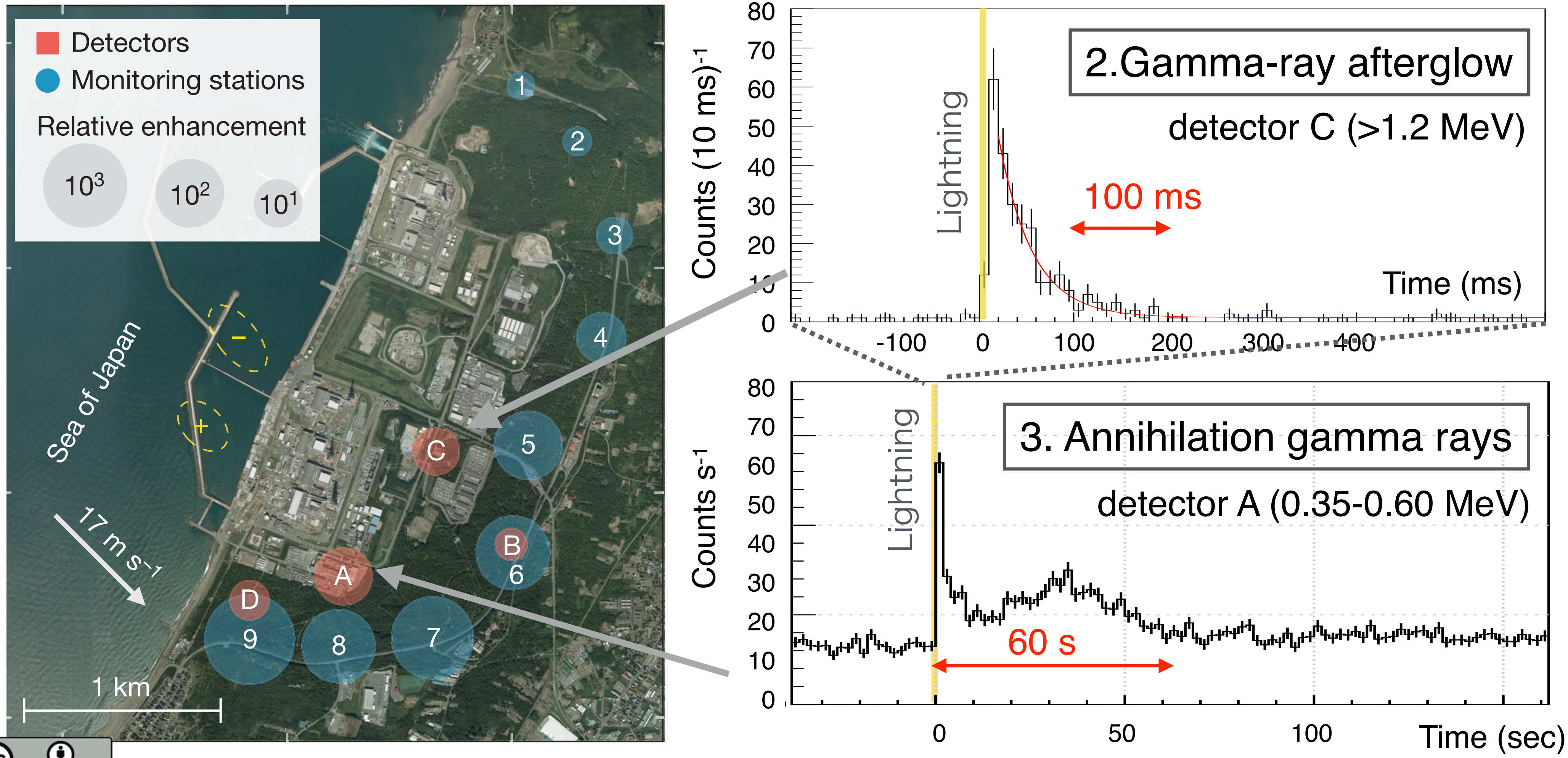
- 2000's : Photonuclear reaction: γ (>10.5 MeV) + ^{14}N → n + ^{13}N
  - Clear detections of >10 MeV gamma rays from lightning
  - Much more feasible than fusion : Babich+ JGR (2007), Carlson+ JGR (2010)

Short burst associated with lightning

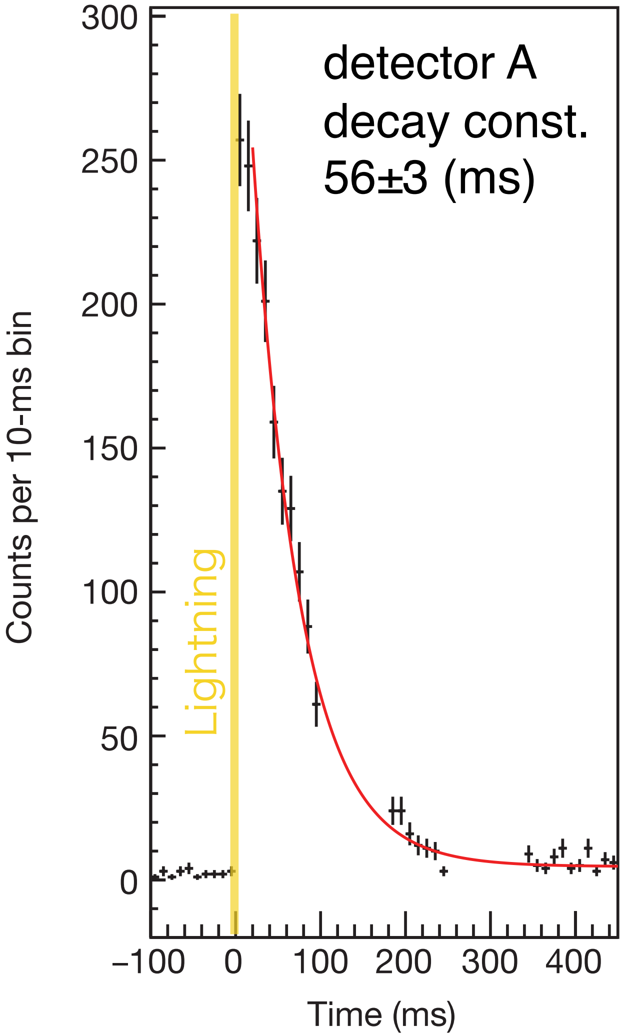
on February 6, 2017, 17:34:06, at Kashiwazaki station

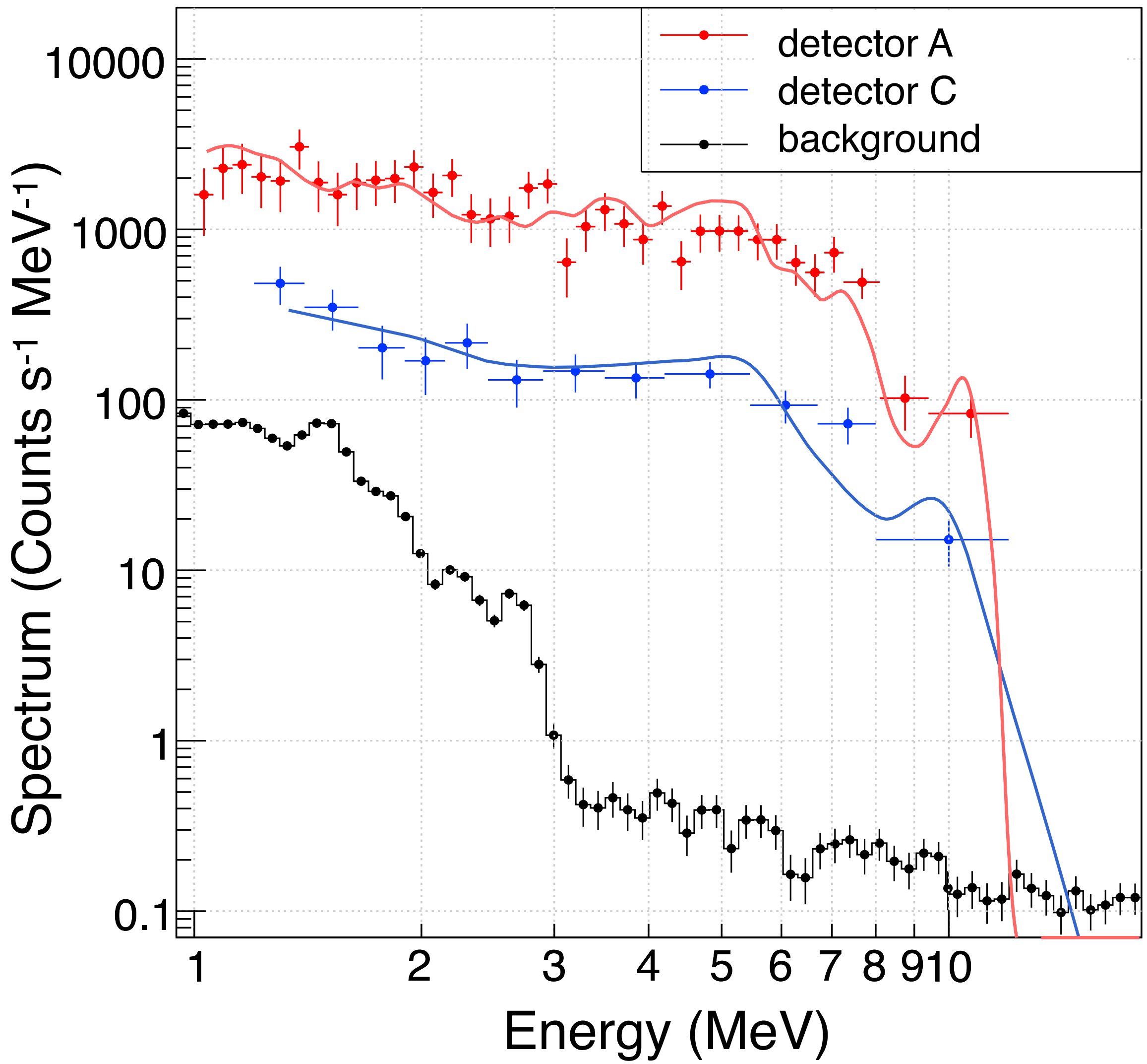
Enoto+ Nature 2017

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)



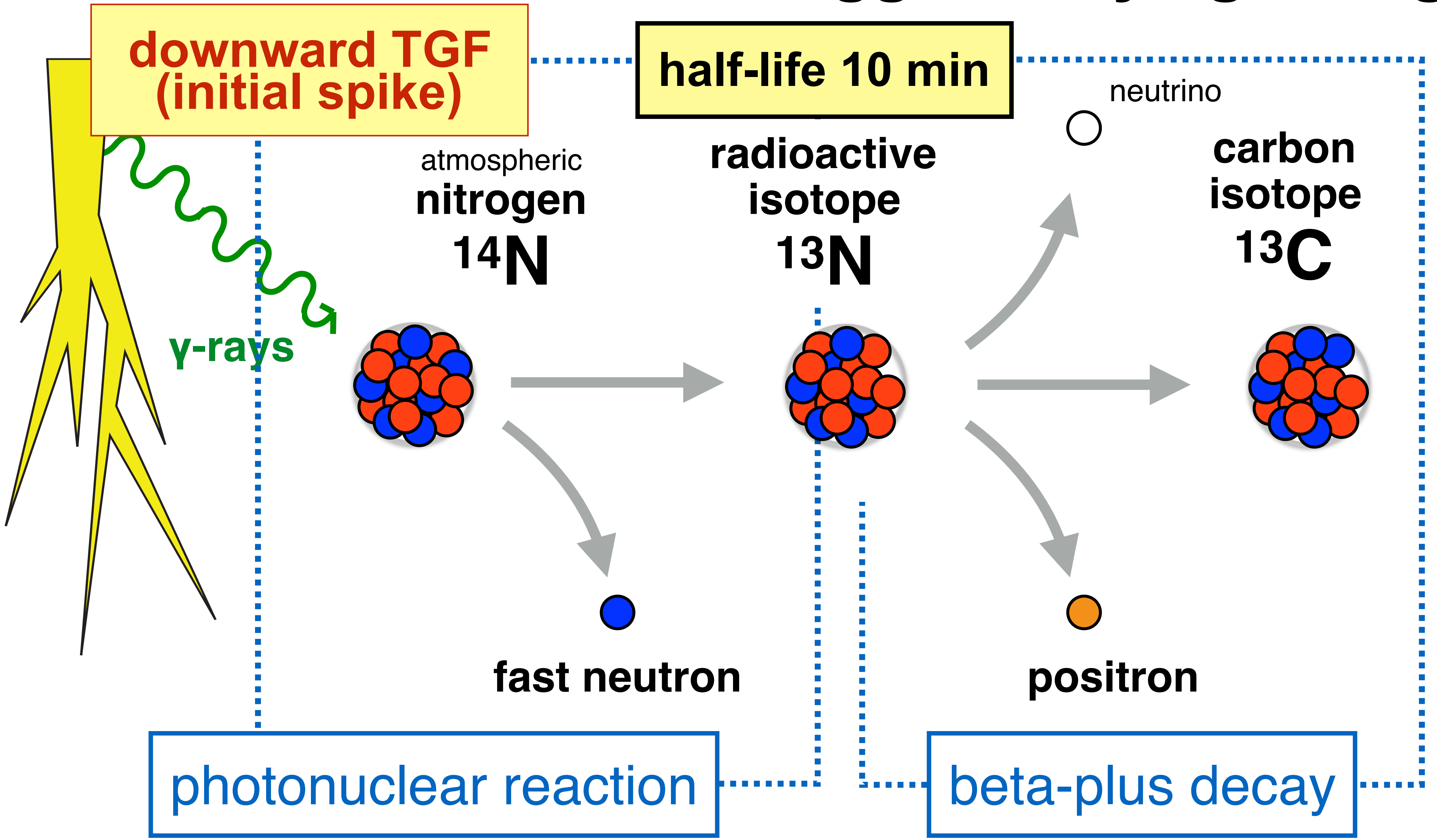
light curves and energy spectra





- Exponential decay constant of the sub-second afterglow is ~56 ms of the neutron thermalization time.
- Spectrum with a sharp cutoff at 10 MeV

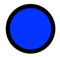
Photonuclear reactions triggered by lightning



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

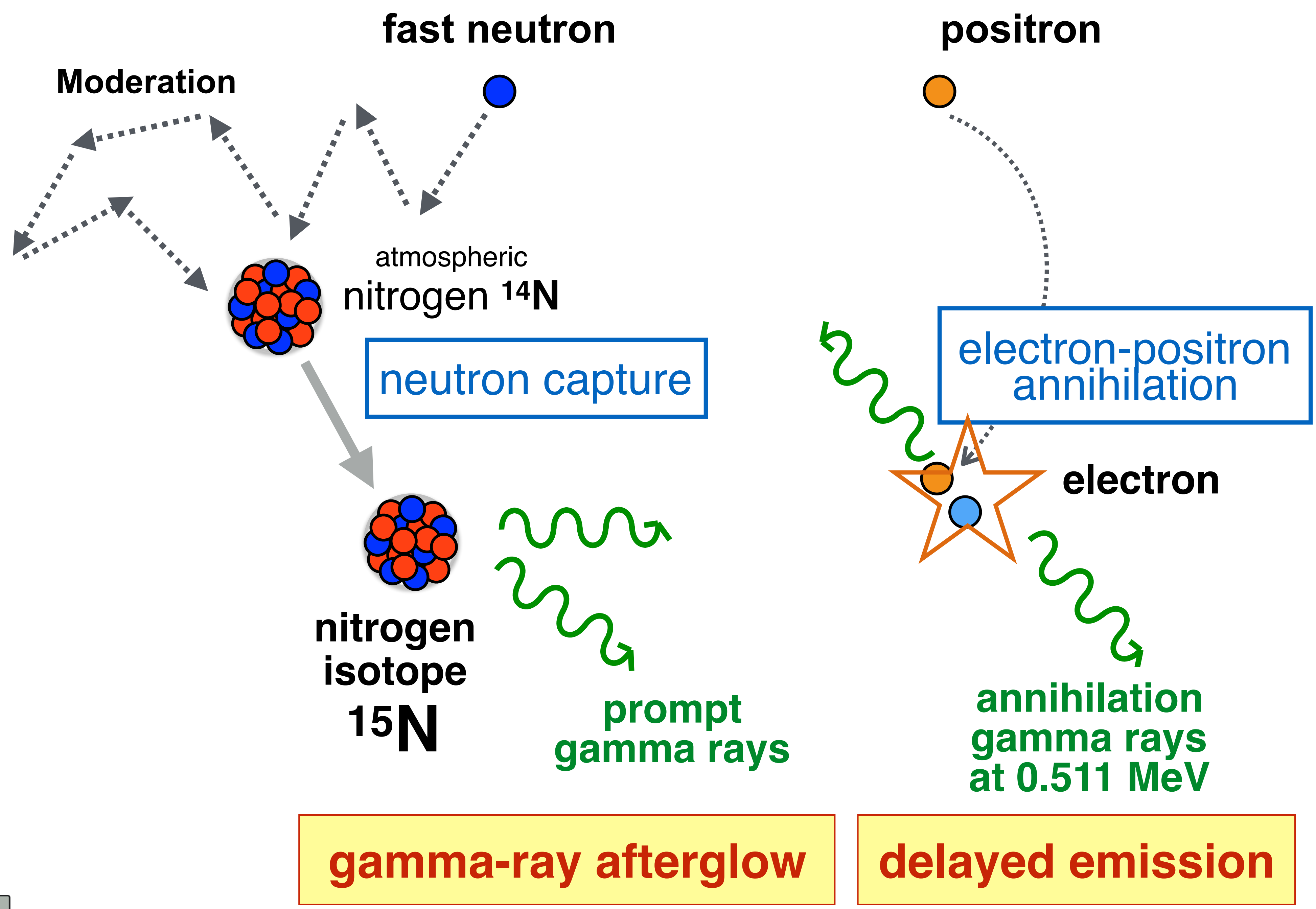
$$ {}^{13}N \rightarrow {}^{13}C + e^{+} + \nu$$
$$(p \rightarrow n + e^{+} + \nu)$$

fast neutron

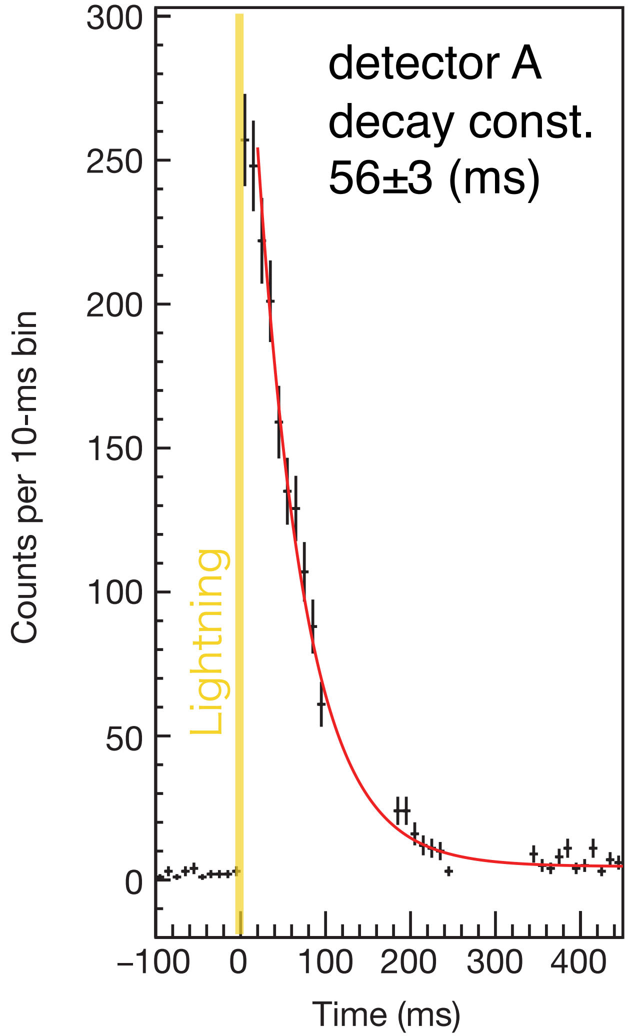


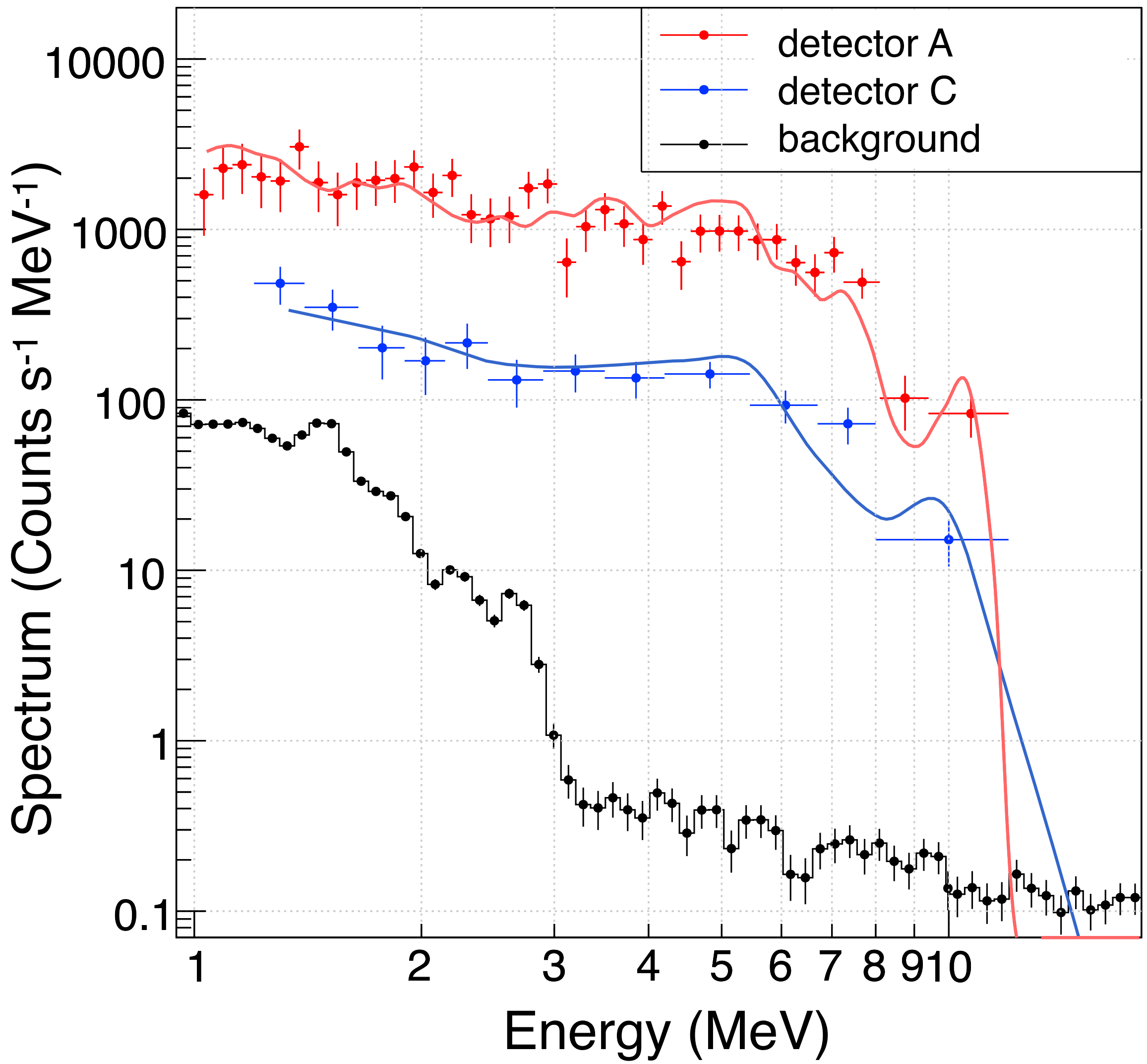
positron

Gamma rays from neutrons and positrons



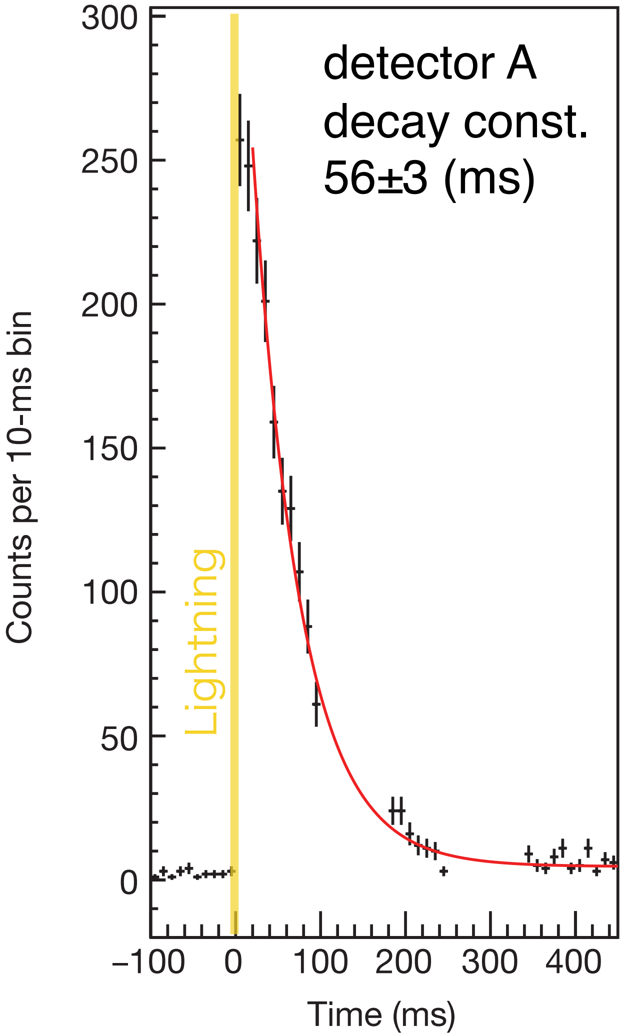
Neutrons make the gamma-ray afterglow

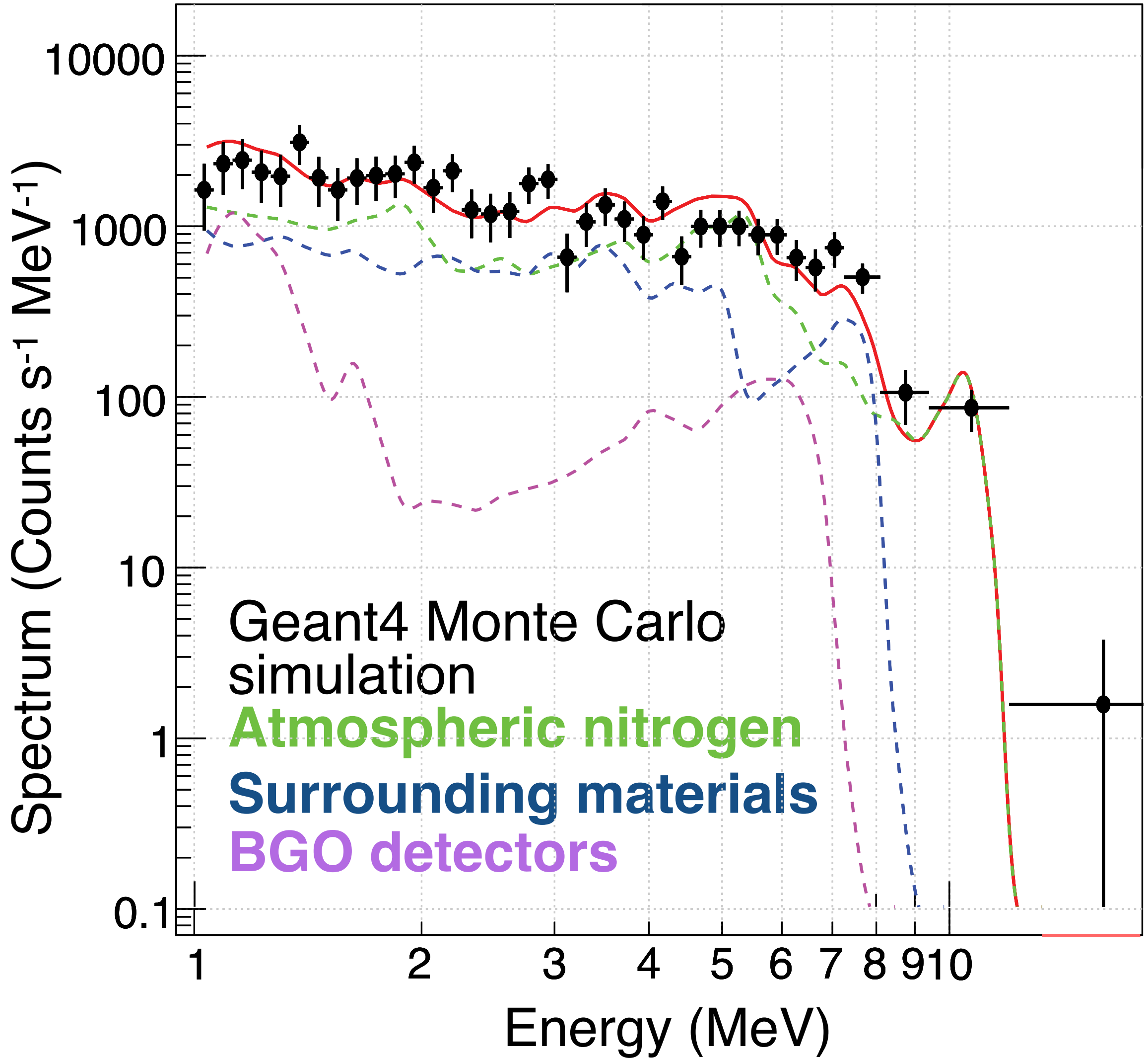




- Exponential decay constant of the sub-second afterglow is consistent with the theoretical prediction ~56 ms of the neutron thermalization time.

Neutrons make the gamma-ray afterglow

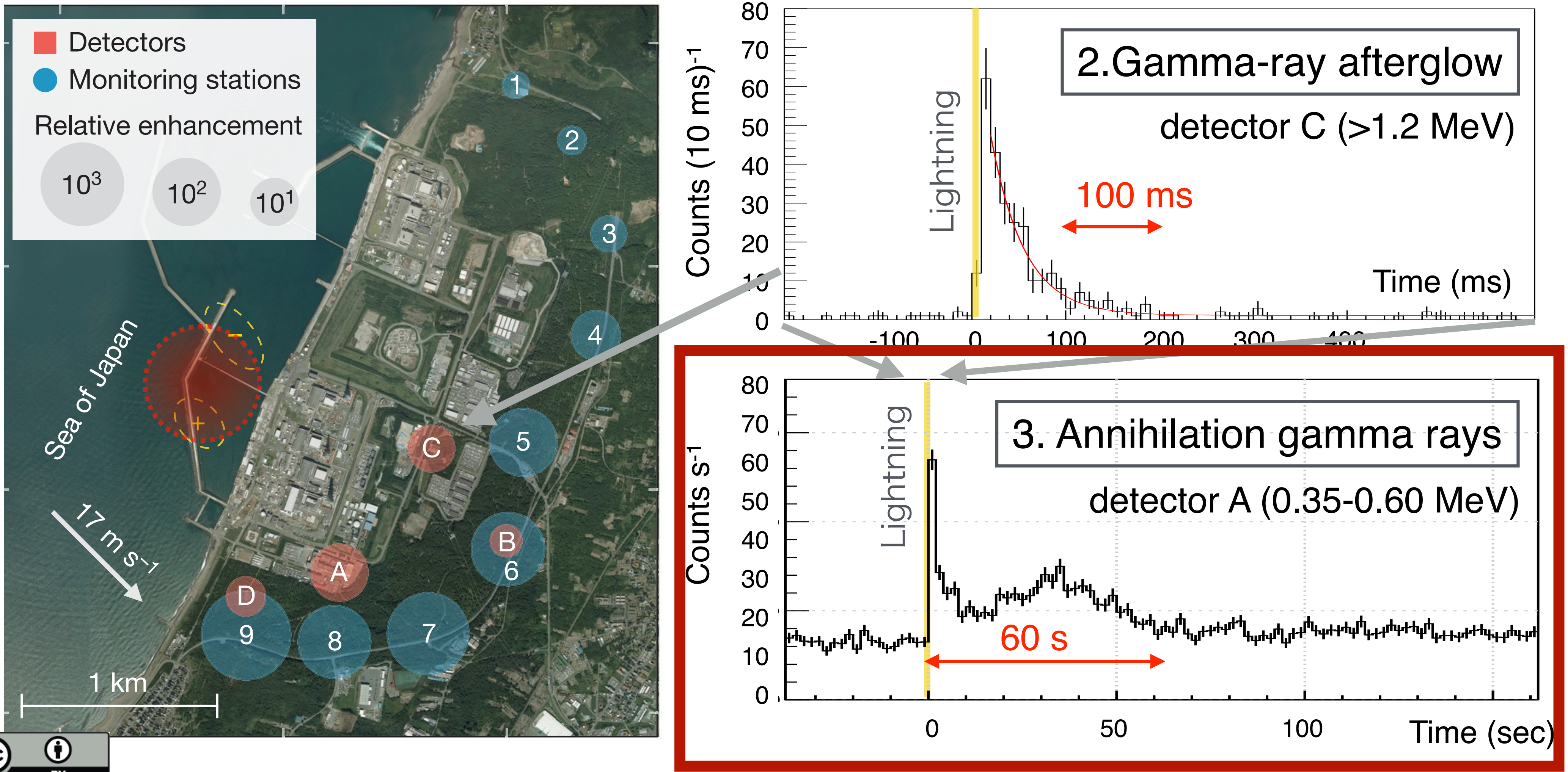




- Exponential decay constant of the sub-second afterglow is consistent with the theoretical prediction ~56 ms of the neutron thermalisation.
- Spectrum with a sharp cutoff at 10 MeV is well explained by prompt gamma rays from atmospheric nitrogens and surrounding materials.

Short-duration burst associated with lightning

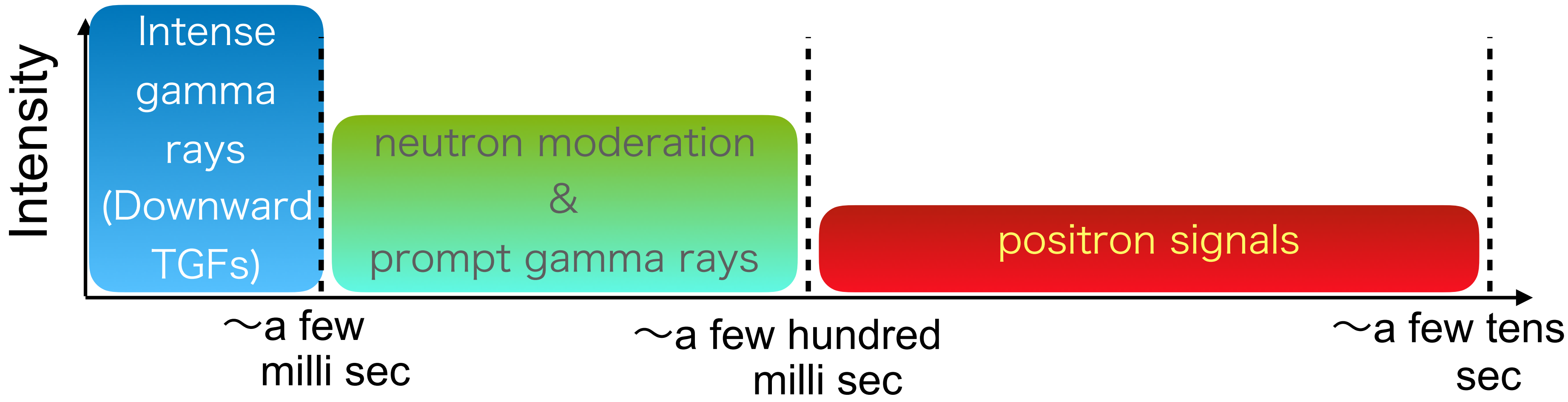
1. **Intensive initial spike** (<~a few milliseconds, exceeds 10 MeV)
2. **Gamma-ray afterglow** (<~100 ms, <10 MeV)
3. **Delayed annihilation gamma rays** (~minute, at 0.511 MeV)



Discussions

☑We have confirmed that photonuclear reactions occur in a lightning discharge. It is noted that Bowers et al., (GRL, 2017) also detected photonuclear neutron signals at the same coastal area of Japan sea.

☑Time structure of this event is consistent with that proposed by Rutjes et al. (GRL,2017).

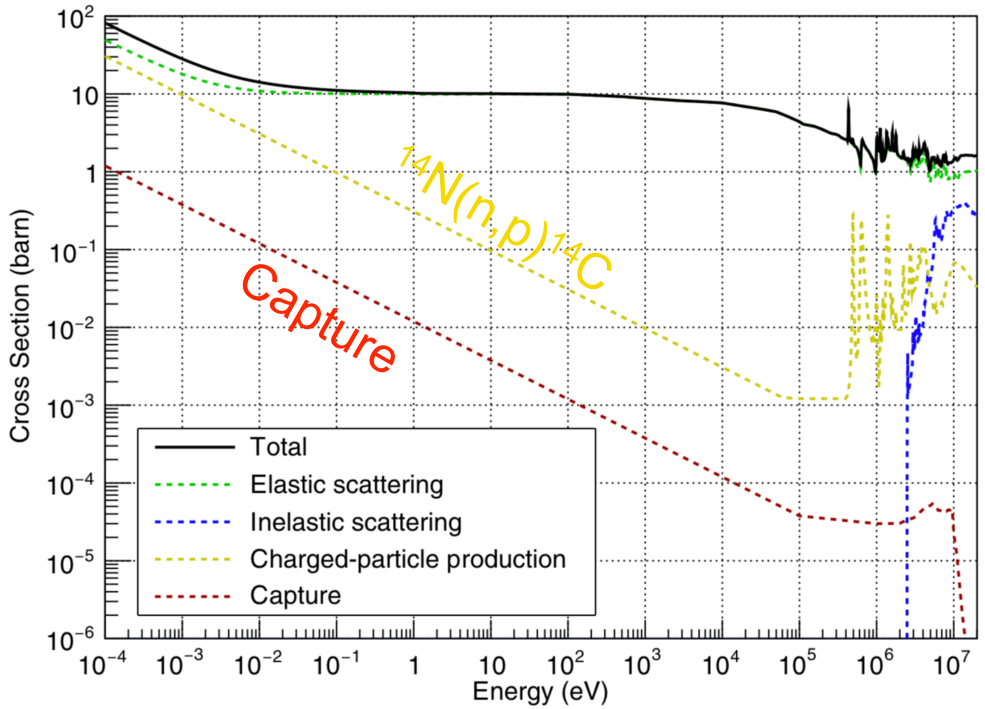


Discussions

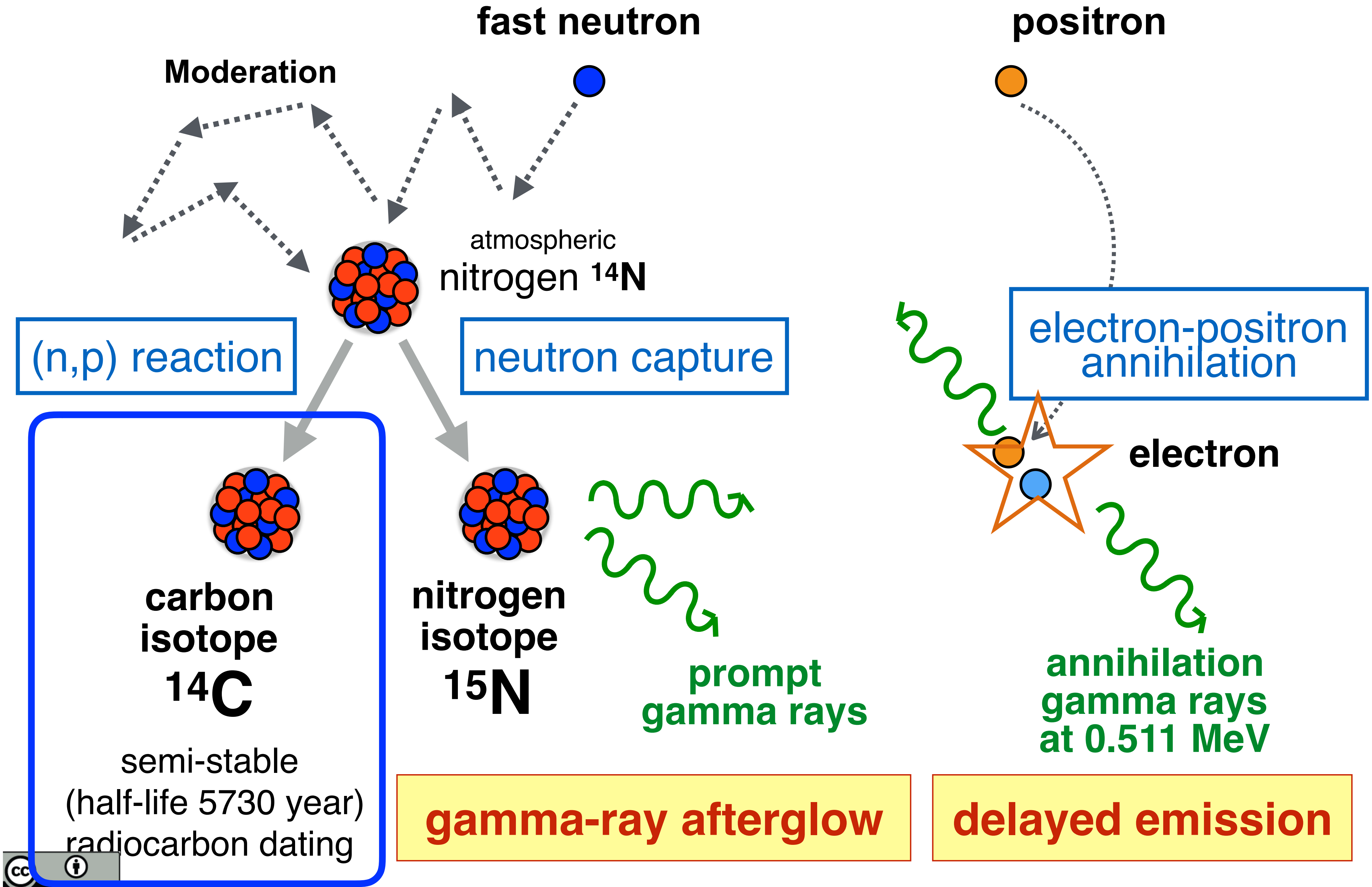
- ☑ This observation showed that radioactive isotopes such as ^{13}N and ^{15}O were produced.

- ☑ ^{14}C would be also produced via $^{14}N(n, p)^{14}C$. This means that lighting may be an additional source of ^{14}C in the atmosphere as reported by Libby & Lukens (JGR,1973) and Babich (GRL, 2017).

Cross sections of ^{14}N (JENDL 4, Shibata et al., 2009)



Discussions



Summary

☑ The GROWTH experiment has so far observed two types of bursts;

Long burst & Short burst

☑ Long burst :

Bremsstrahlung gamma rays emitted from electrons accelerated in thunderclouds

(occasionally) annihilation gamma rays, muons

☑ Short burst :

Bremsstrahlung gamma rays emitted from electrons accelerated in lightning

(occasionally) prompt gamma rays emitted from a de-excitation nucleus

☑ Photonuclear reactions are triggered by lightning

neutrons, positrons and radioactive isotopes (^{13}N, ^{15}O, ^{14}C)