# Initial results from a multi-point mapping observation of thundercloud high-energy radiation in coastal area of Japan sea

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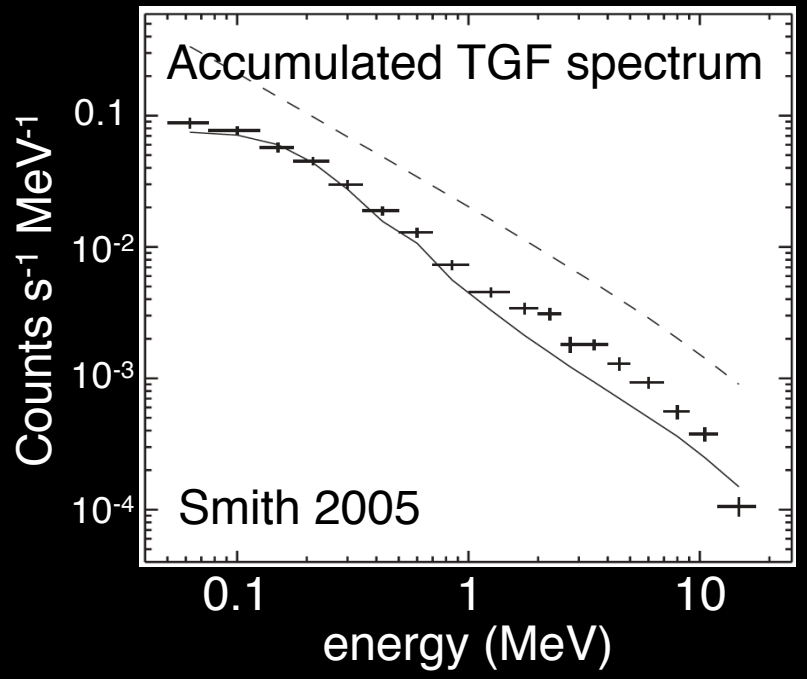
1: Univ. of Tokyo 2: RIKEN 3: Kyoto Univ. 4: Singapore 5: JAEA

AGU Fall Meeting@New Orleans, Atmospheric and Space Electricity, AE31A-03 (2017/12/13 08:40-09:00)

# Energetic Radiation from Thundercloud and Lightning

- Many high energy radiation measurements
  (McCarthy & Parks 1985, Eack et al. 1996, Dwyer 2003, Hare et al. 2016, Tsuchiya et al. 2009, Chilingarian et al. 2010, Torii et al. 2002, Tsuchiya et al. 2007, Fishman et al. 1994, Smith 2005)

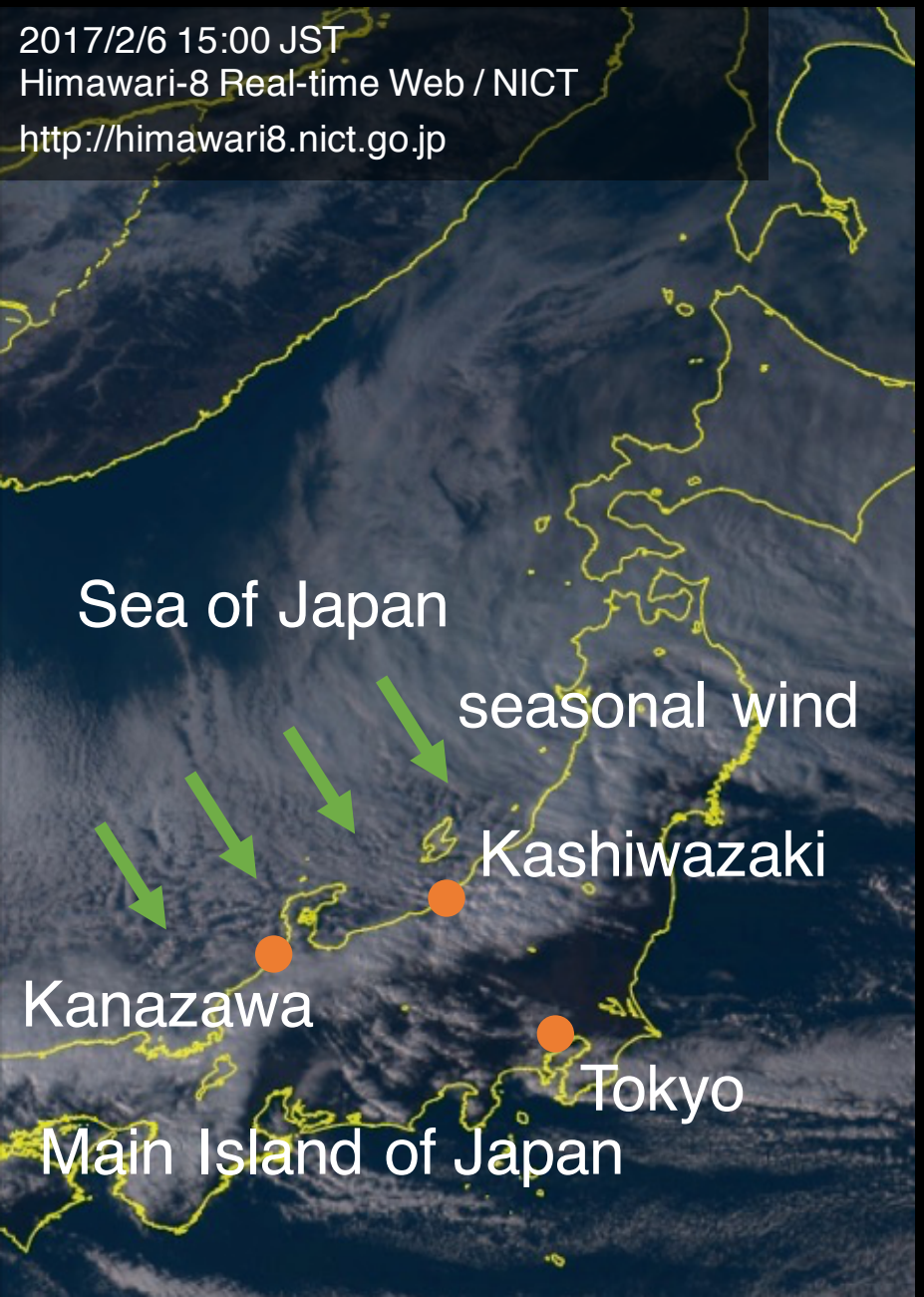


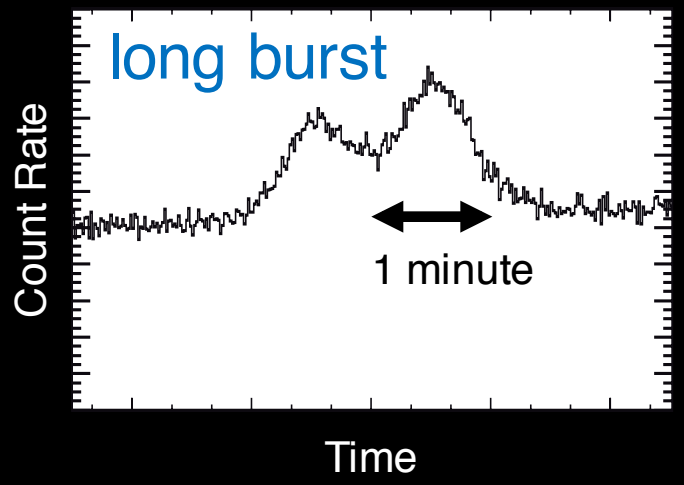

- Relativistic runaway electron avalanches in thundercloud and lightning.
  (Gurevich 1992, Dwyer et al. 2004)

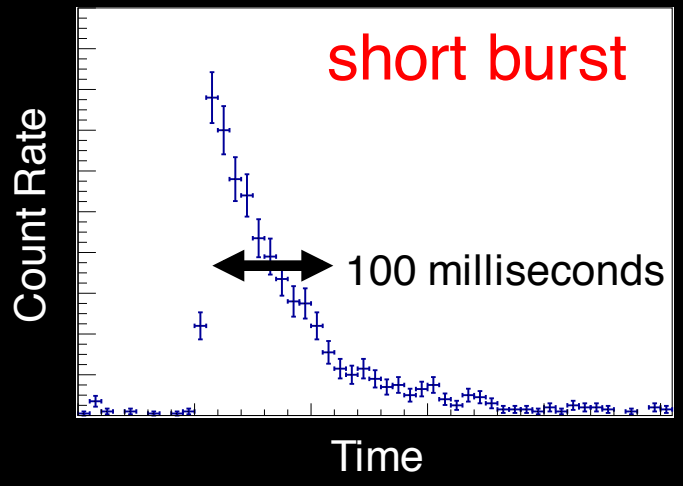
- High energy gamma rays should provoke atmospheric photonuclear reactions.
  (Babich 2006, 2007, Carlson et al. 2010, Babich et al. 2010, 2014)
  - Evidences for neutron detection.
    (Shah et al. 1985, Chilingarian et al. 2010, Gurevich et al. 2012, Bowers et al. 2017)
  - Reports of positron signals. (Dwyer et al. 2015, Umemoto et al. 2016)
  - Simultaneous detection of neutron and positron signals has never been reported.

# Gamma-Ray Observation of Winter Thundercloud (GROWTH)




- Winter thunderstorms along Sea of Japan
  - lower cloud base (< 1 km: Goto & Narita 1992)
  - powerful and frequent lightning
- We have observed long bursts from thundercloud and short bursts from lightning discharge.




- 28 events in 10 years (2006-2015) at Kashiwazaki (Tsuchiya et al. 2007, 2011, 2013, Umemoto et al. 2016)
- We have developed a lot of portable detectors, and deployed for new mapping campaign since 2015.

# Portable Radiation Detector for the Multipoint Observation

Simple configuration

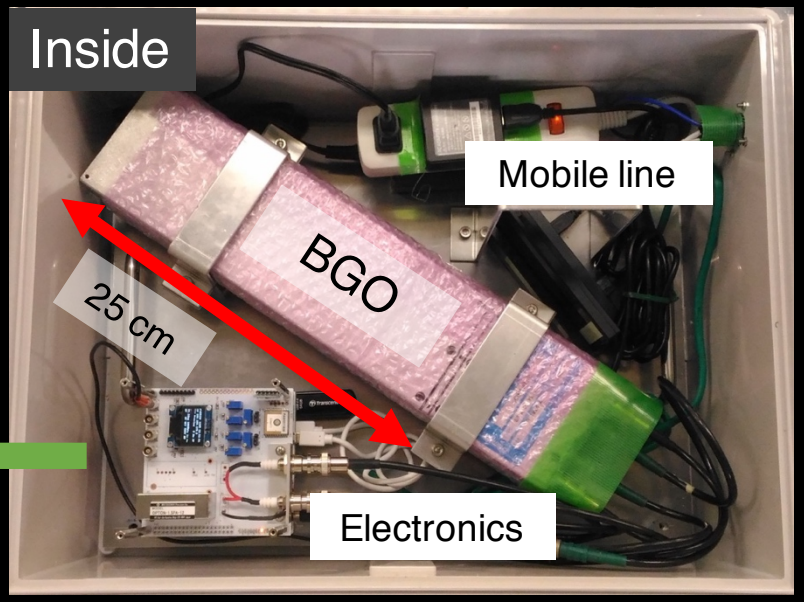
- BGO scintillation crystals for gamma-ray detection
- Compact data acquisition (DAQ) system
- Cellular data connection for monitoring and data transfer
- 10 sets in 2016-2017 winter.

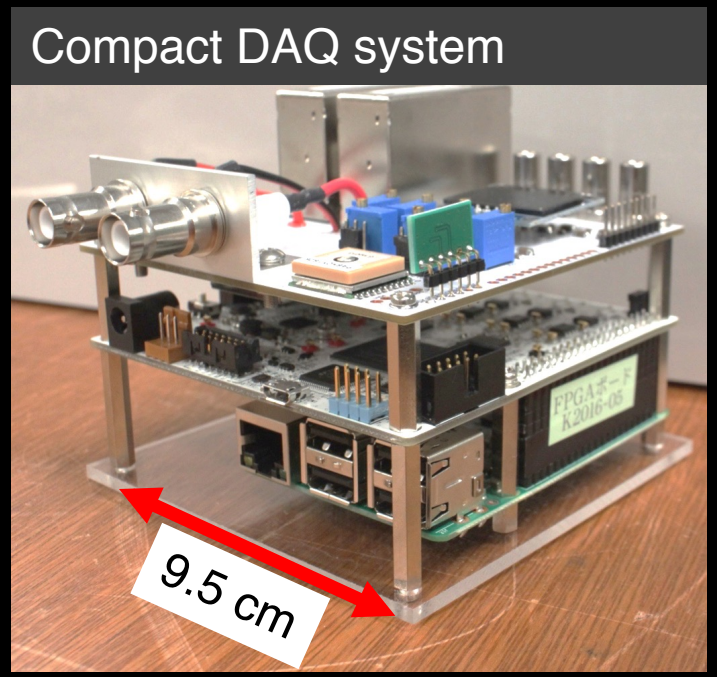
Brand-new compact DAQ system

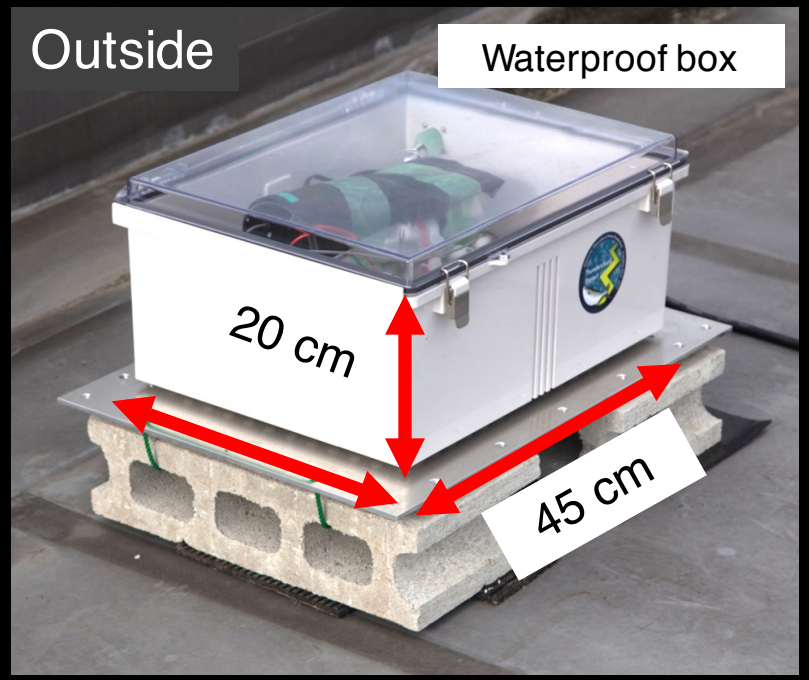
- Photon by photon record with time and energy
- Controlled by Raspberry Pi 3

  - 4 ch 12 bit 50 MHz ADC
  - Charge amplifier
  - High-voltage power supply
  - GPS time tagging
  - Environmental sensor

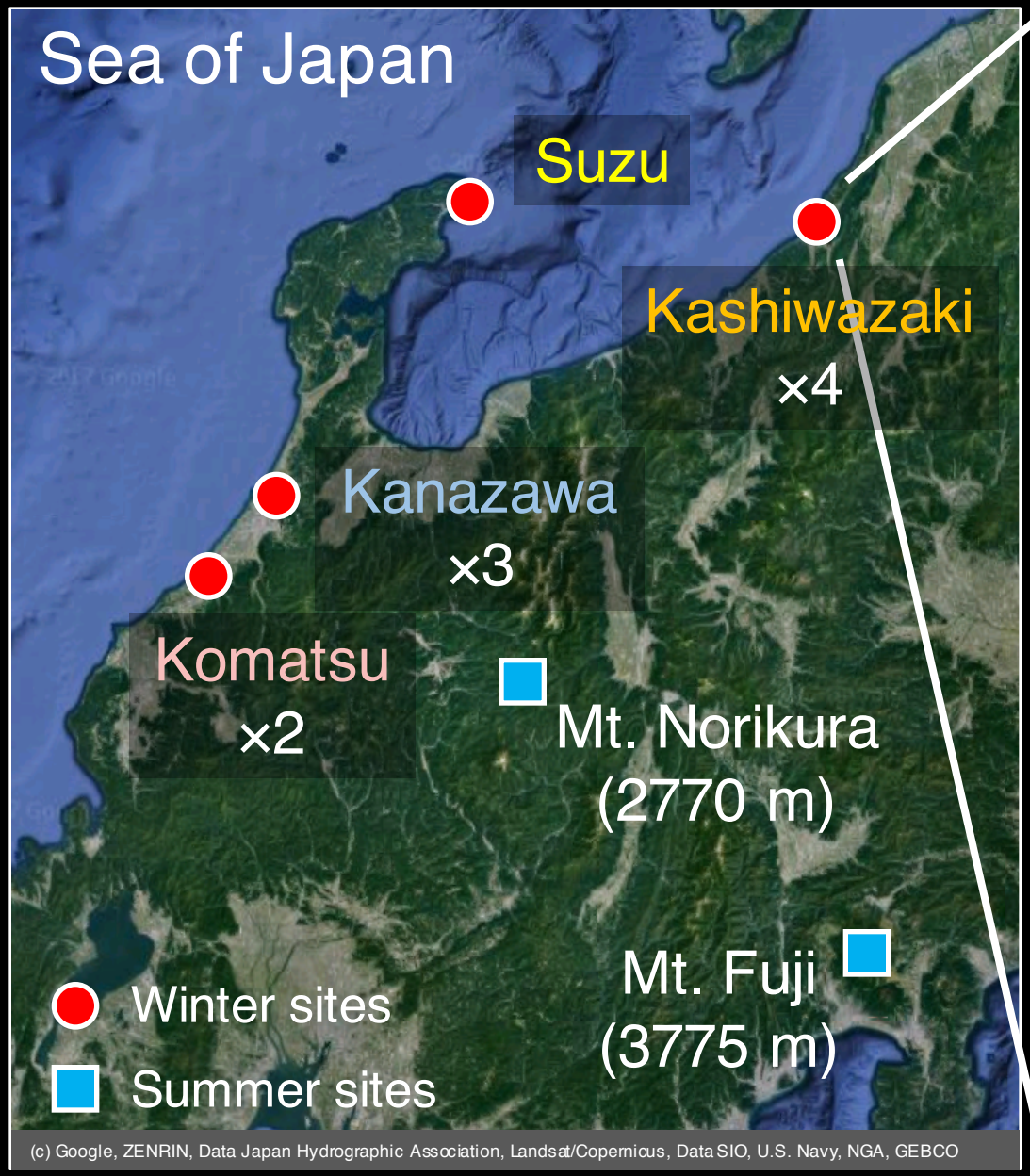
  (Wada, Master Thesis 2017)

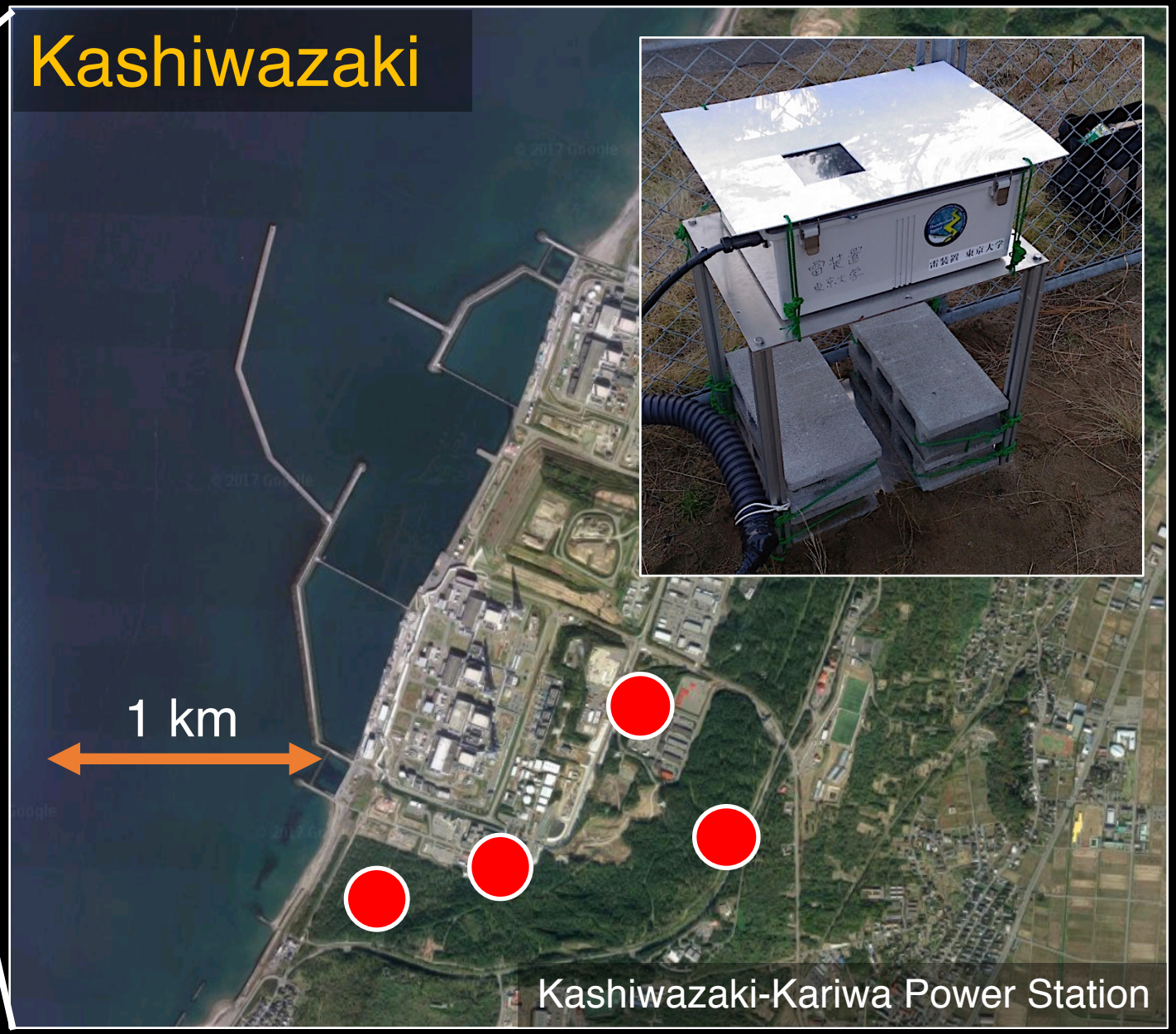


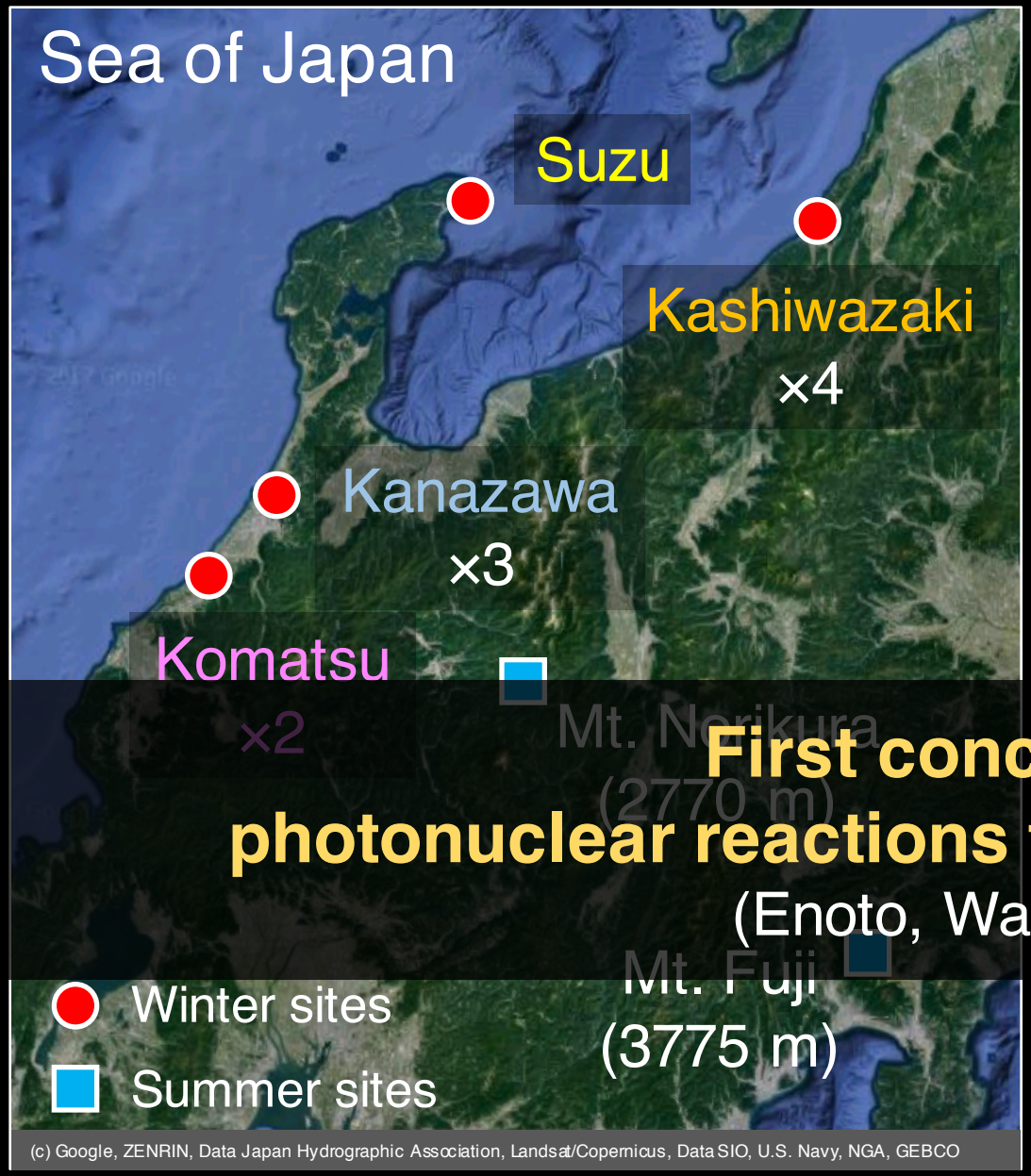



# Observation Sites – 10 Detectors in 4 Areas



# Results of 2016-2017 Winter Campaign



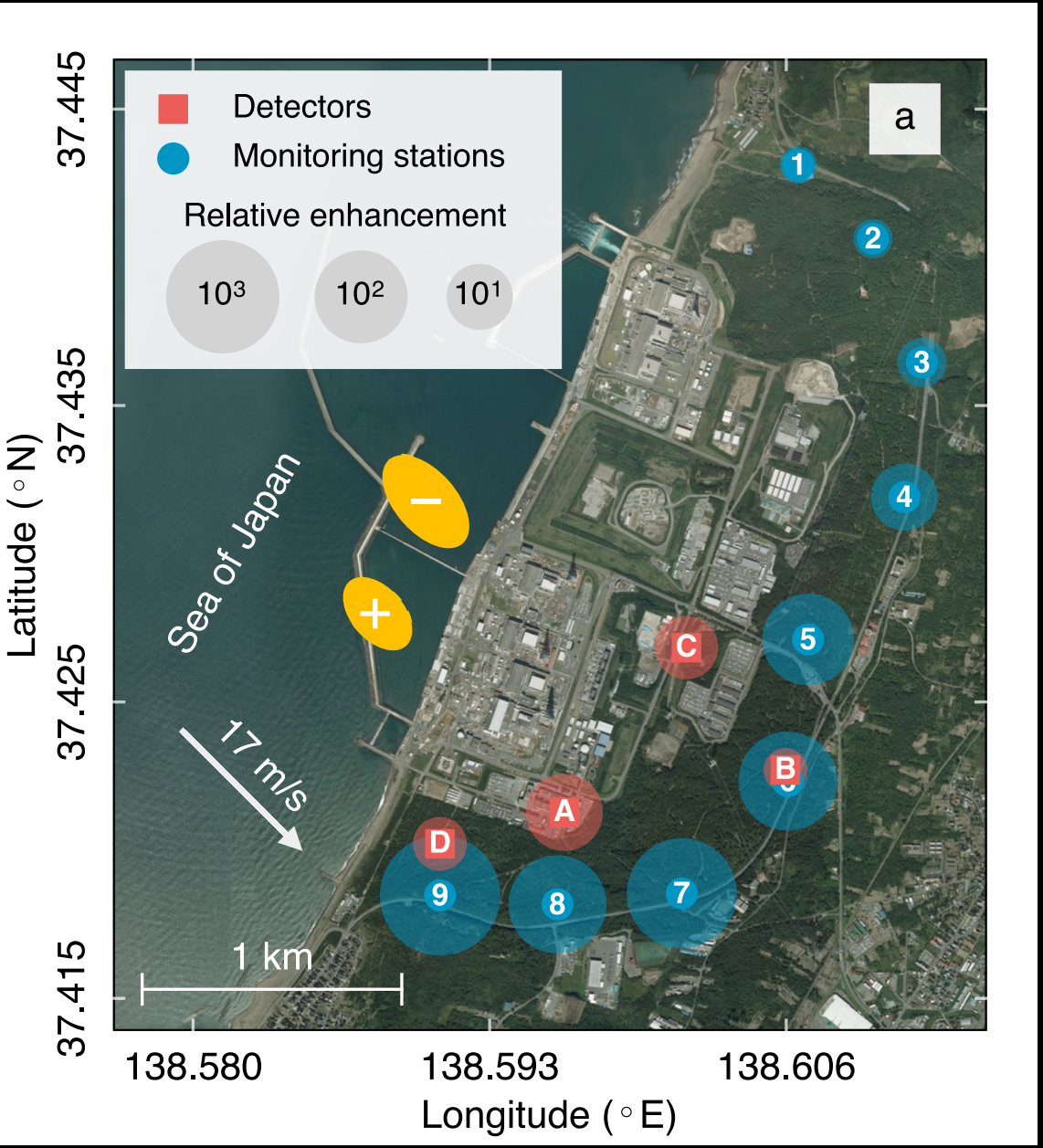

| Date | Time (JST) | Location | Type |
|---|---|---|---|
| 2016-12-08 | 00:14 | Kanazawa | long burst |
| | 02:56 | Komatsu | long burst |
| | 02:58 | Komatsu | long burst |
| 2016-12-09 | 16:29 | Kanazawa | long burst |
| 2017-01-13 | 01:43 | Kanazawa | long burst |
| | 05:05 | Kanazawa | long burst |
| 2017-01-15 | 05:31 | Kanazawa | long burst |
| 2017-01-16 | 12:19 | Kashiwazaki | short burst |
| 2017-02-06 | 05:07 | Kanazawa | long burst |
| | 05:10 | Kanazawa | long burst |
| | 17:34 | Kashiwazaki | short burst |
| 2017-02-11 | 17:10 | Suzu | long burst |

**First conclusive detection of photonuclear reactions triggered by lightning discharge!**

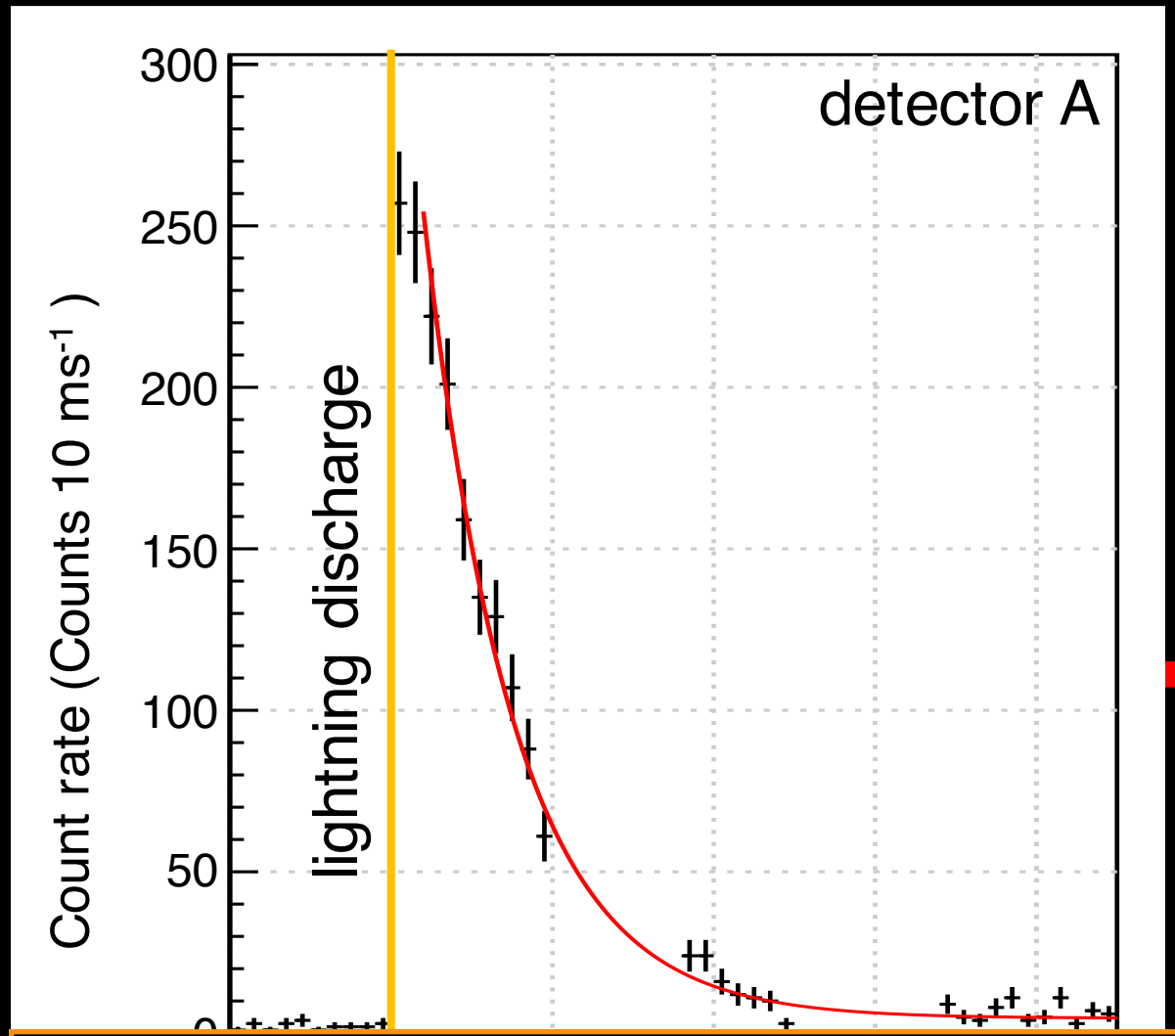
(Enoto, Wada, et al. Nature 2017)

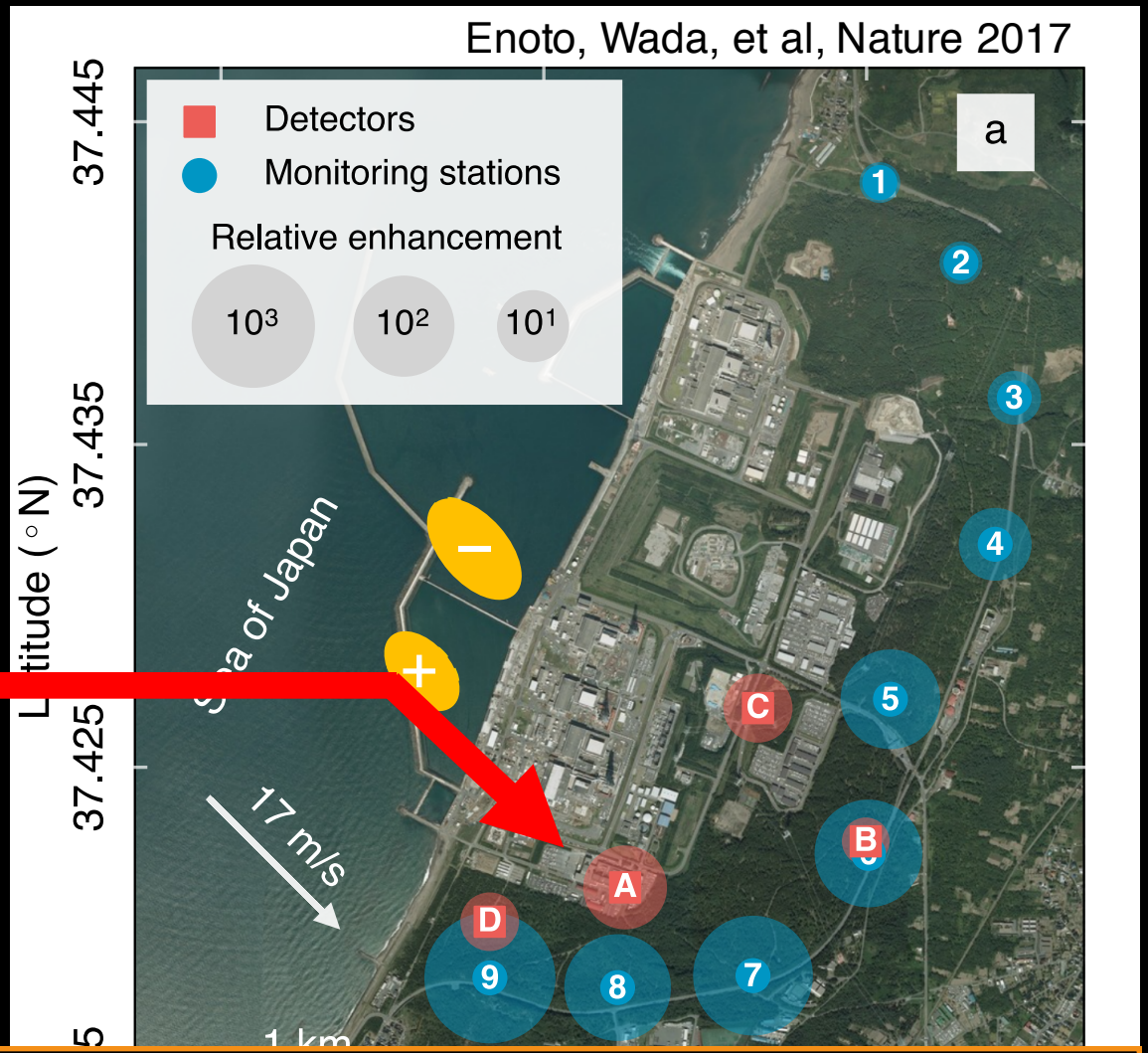
# Detection of Gamma-ray Burst with Lightning

- Lightning discharge occurred at Kashiwazaki at 2017 February 6th 17:34:06 JST.
- Japan Lightning Detection Network and ELF station detected the CG discharge.
- Our 4 detectors and 9 monitoring stations recorded signals with the lightning.



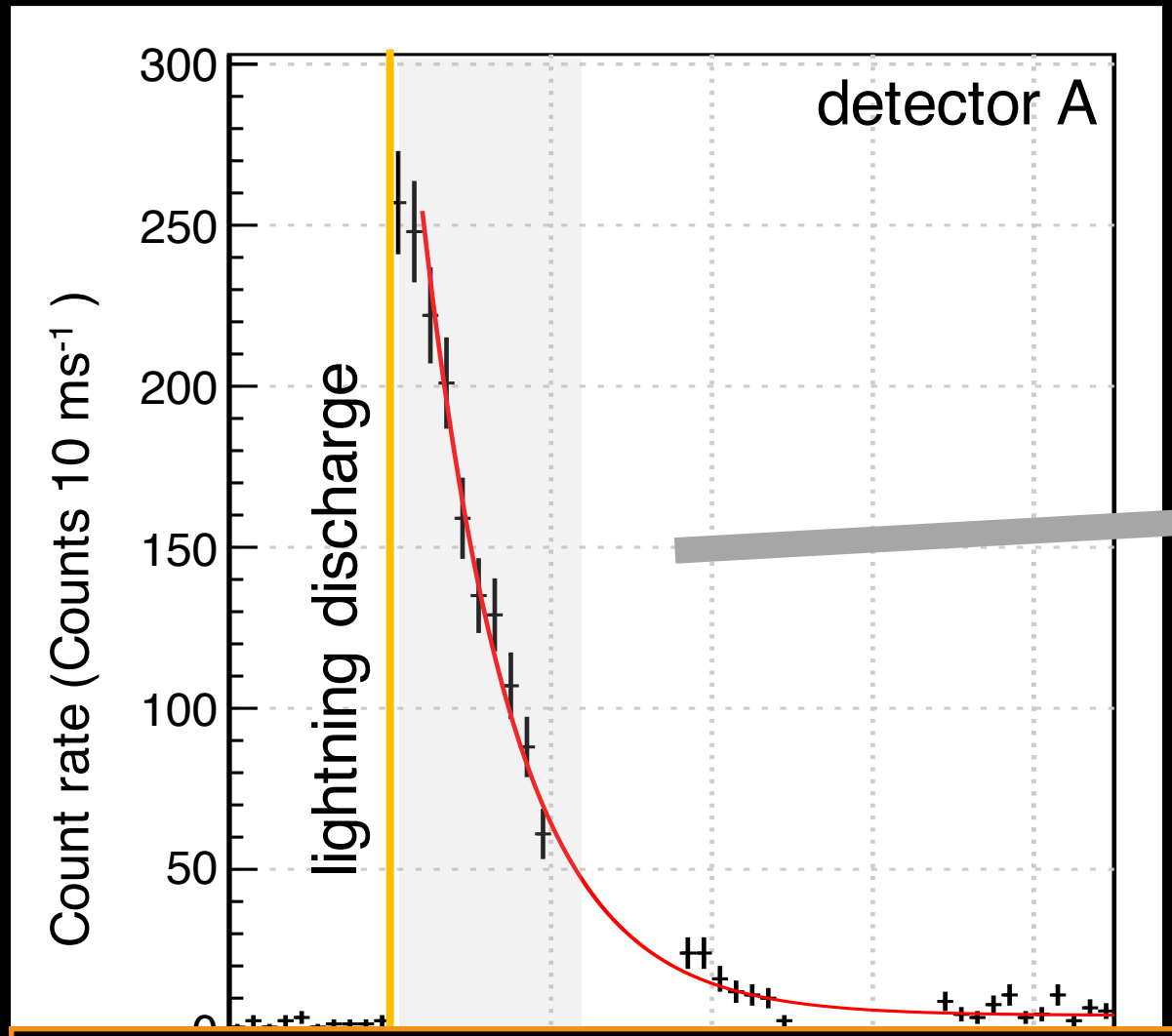
# Detection of Gamma-ray Burst with Lightning

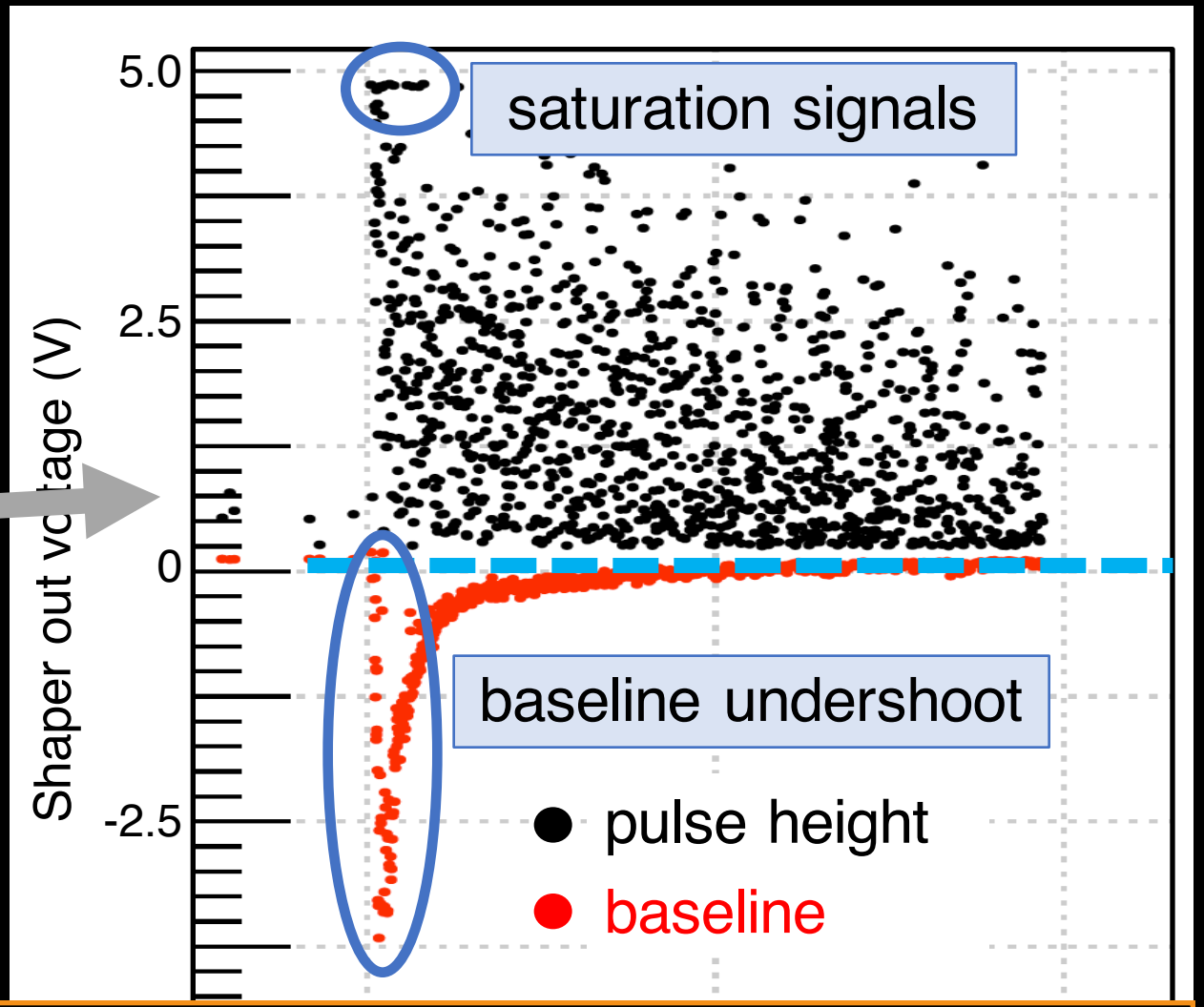



Our four detectors recorded a sub-second gamma-ray burst decaying with ~50 ms time constant.

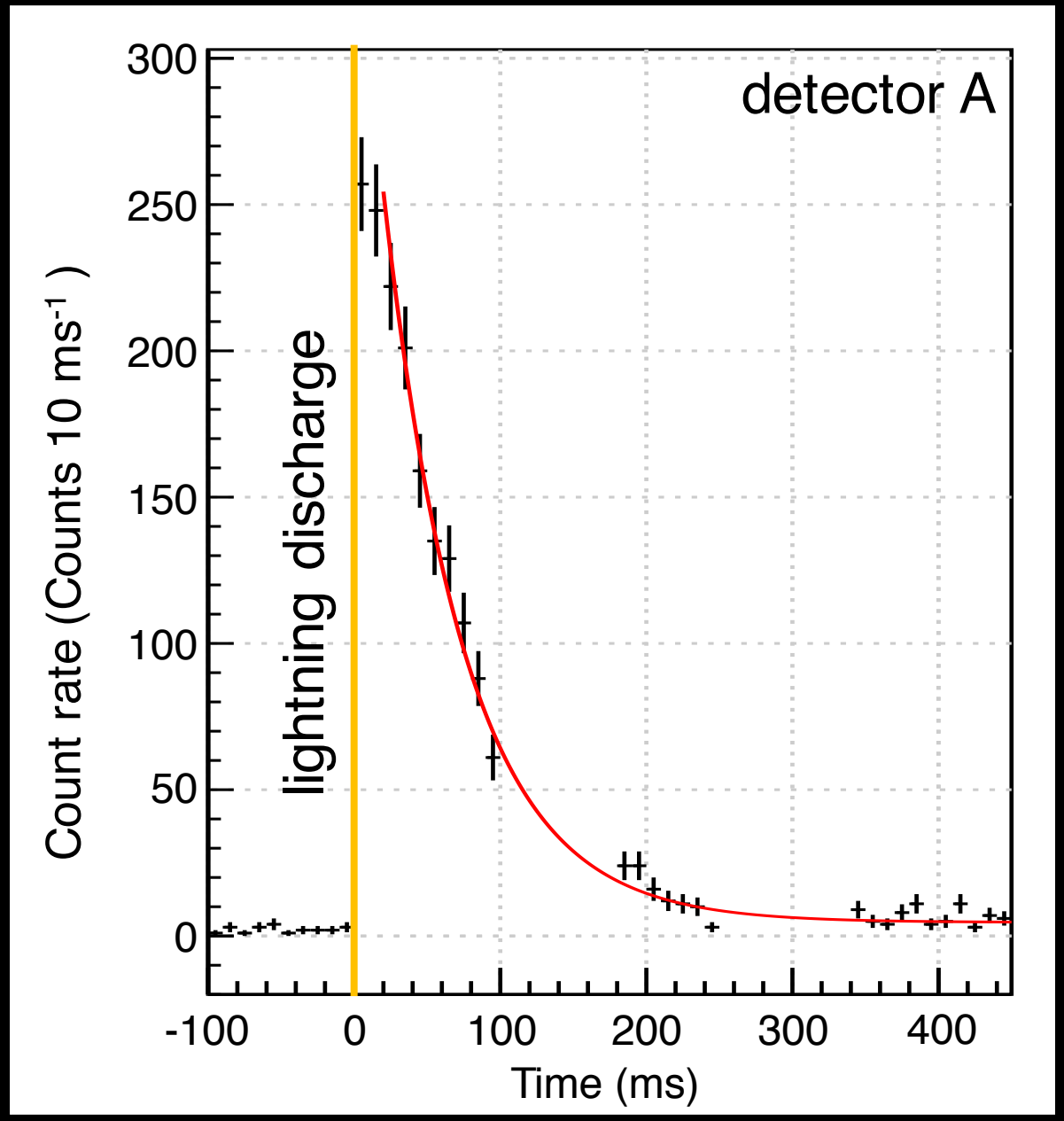
# Detector Saturation at the Beginning of the Burst

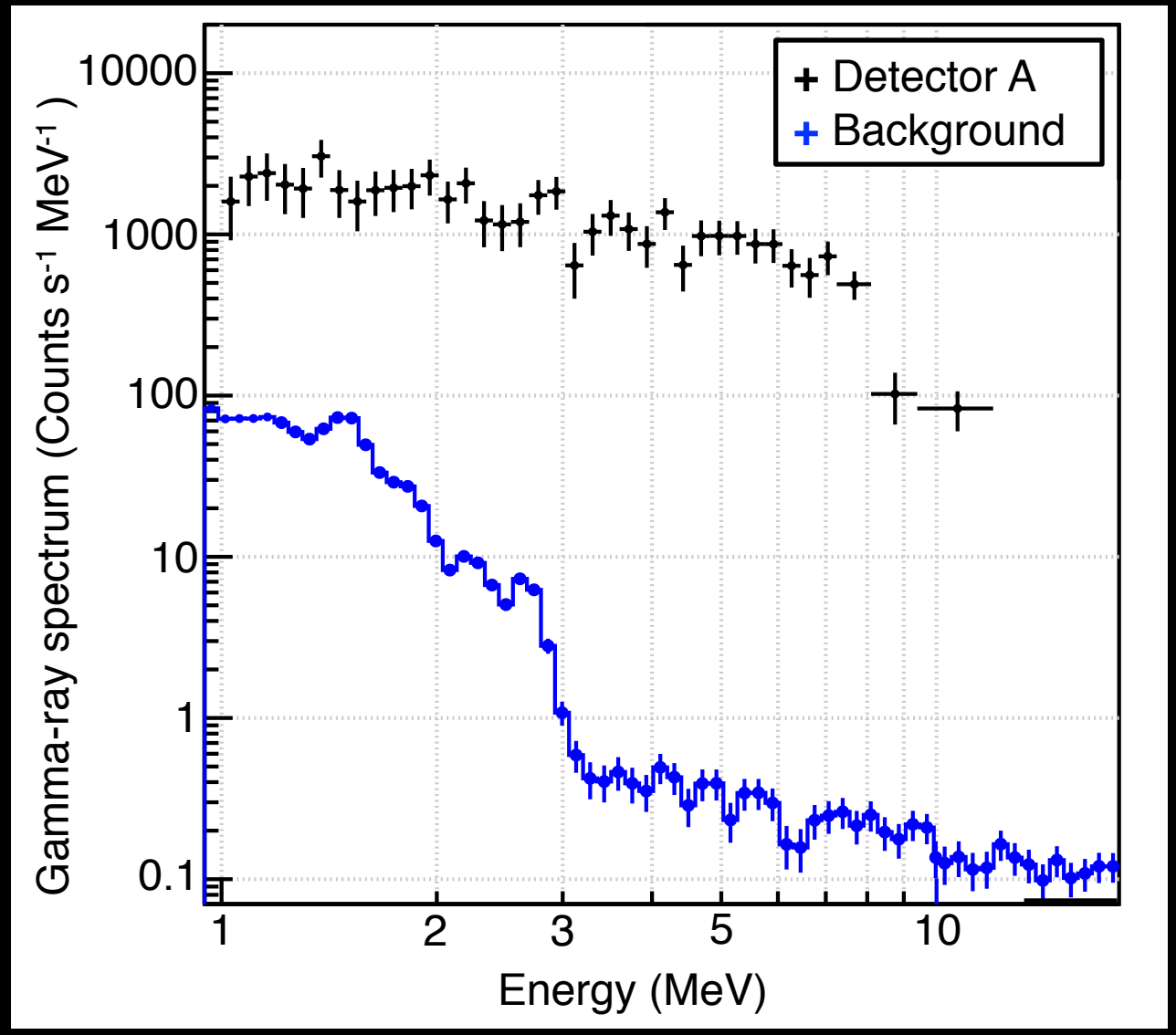



Initial large energy deposit in the scintillation crystal.
→ Sub-millisecond strong gamma-ray flash.

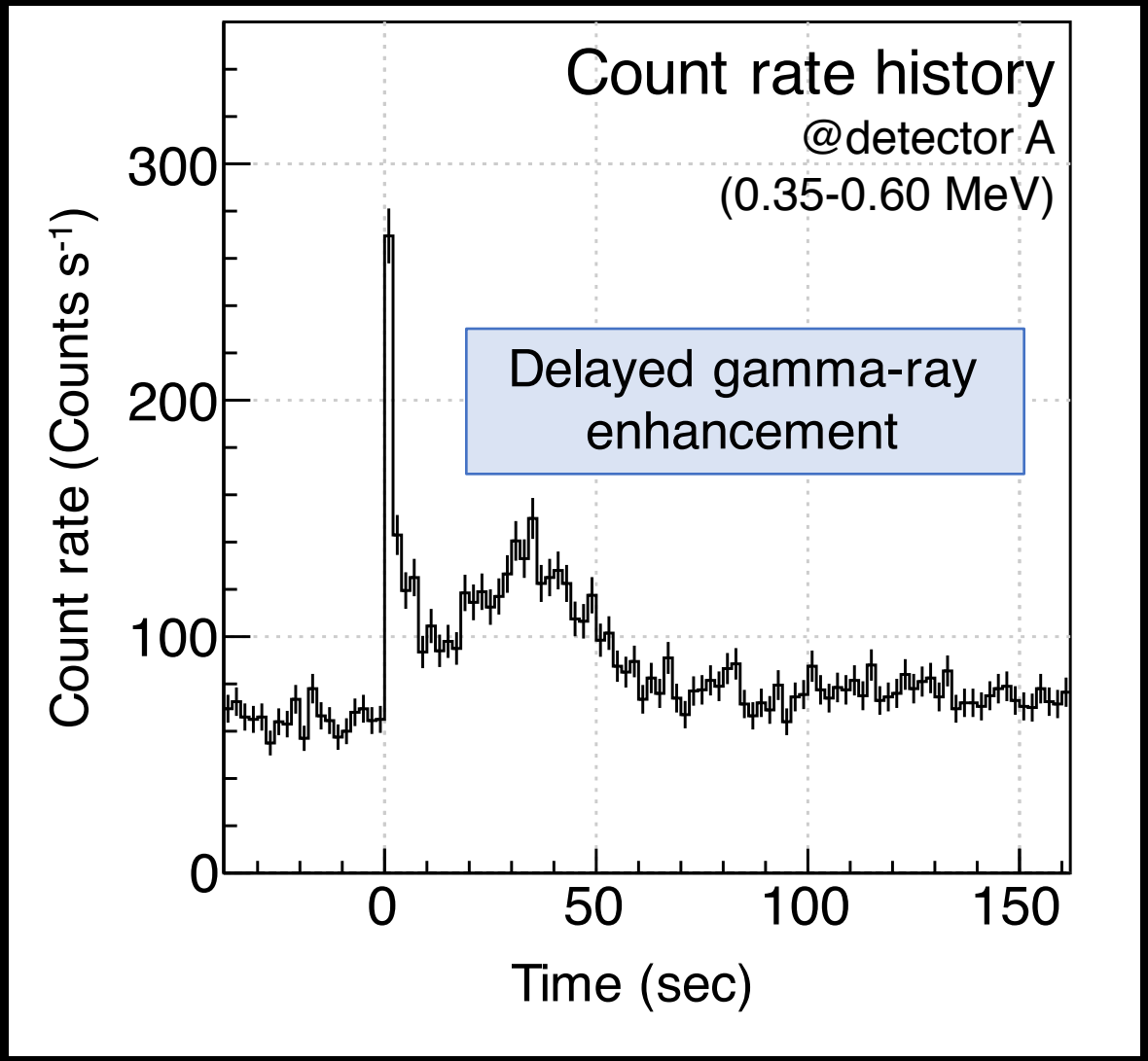
# Burst Gamma-ray Spectrum up to 10 MeV

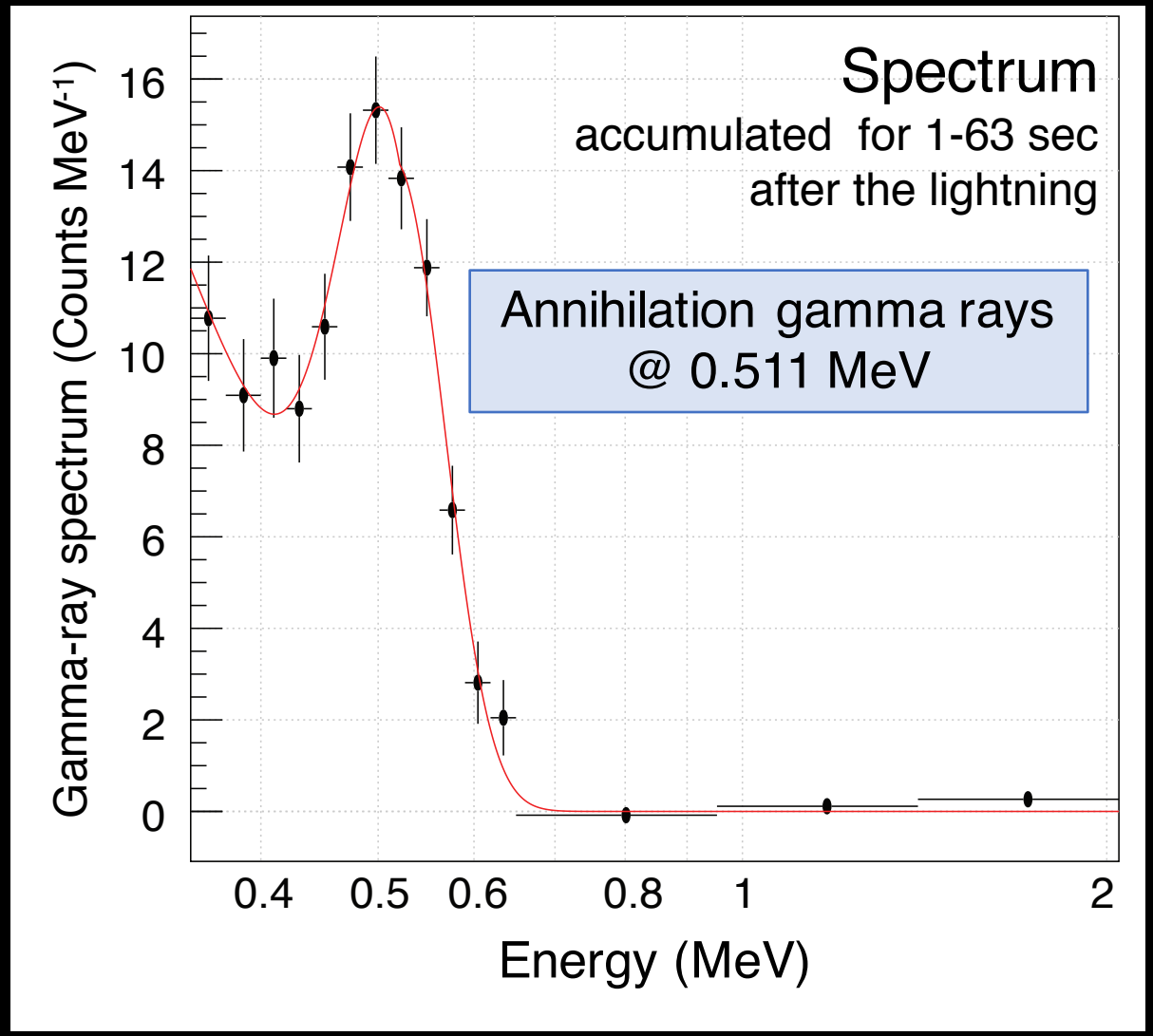



Sharp cut-off of spectrum at ~10 MeV.

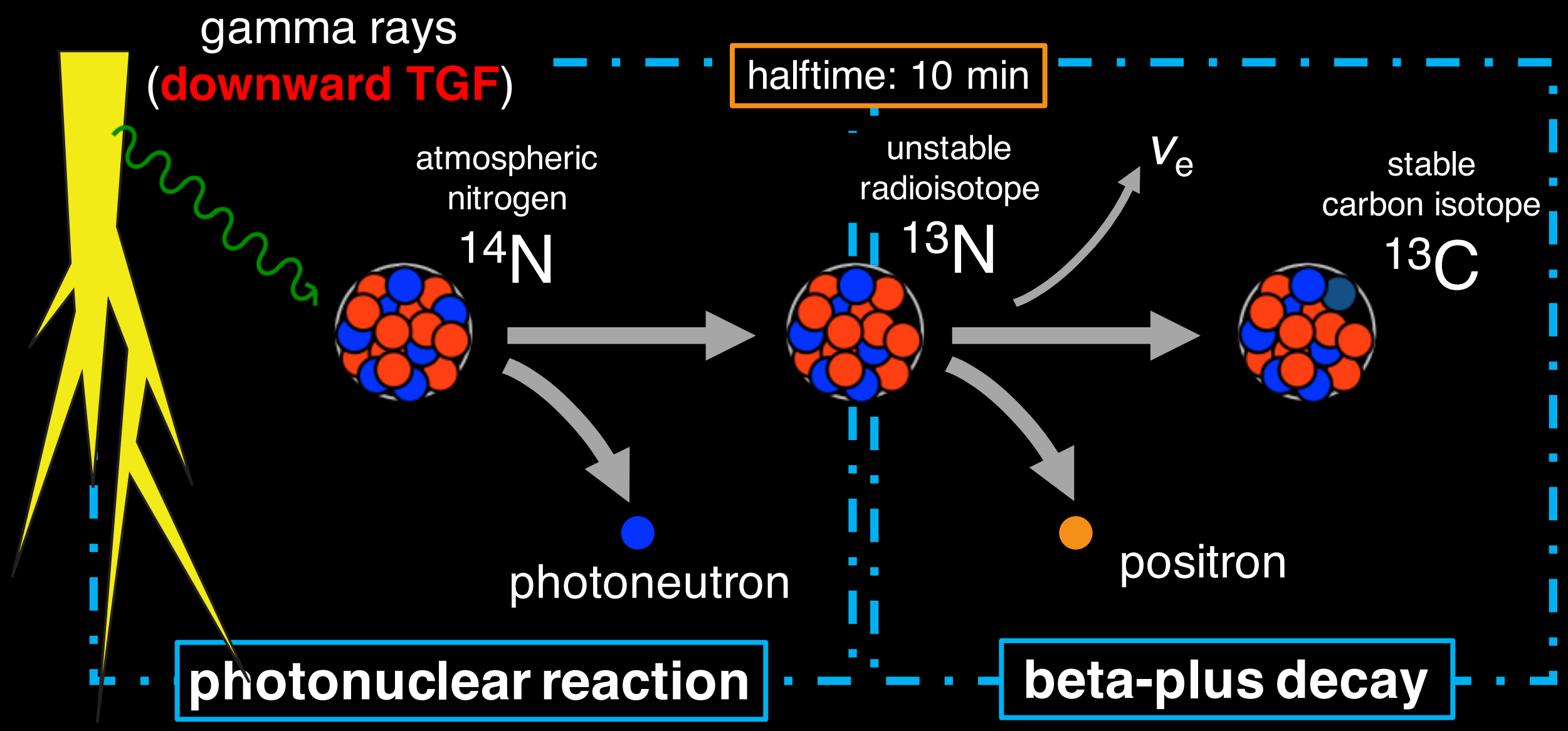
# Delayed Annihilation Signals Lasting for 1 minute




Annihilation gamma-ray signal peaking at ~35 sec and lasting for 1 min.
(without significant high energy photons)

# Photonuclear Reactions and Consecutive Processes



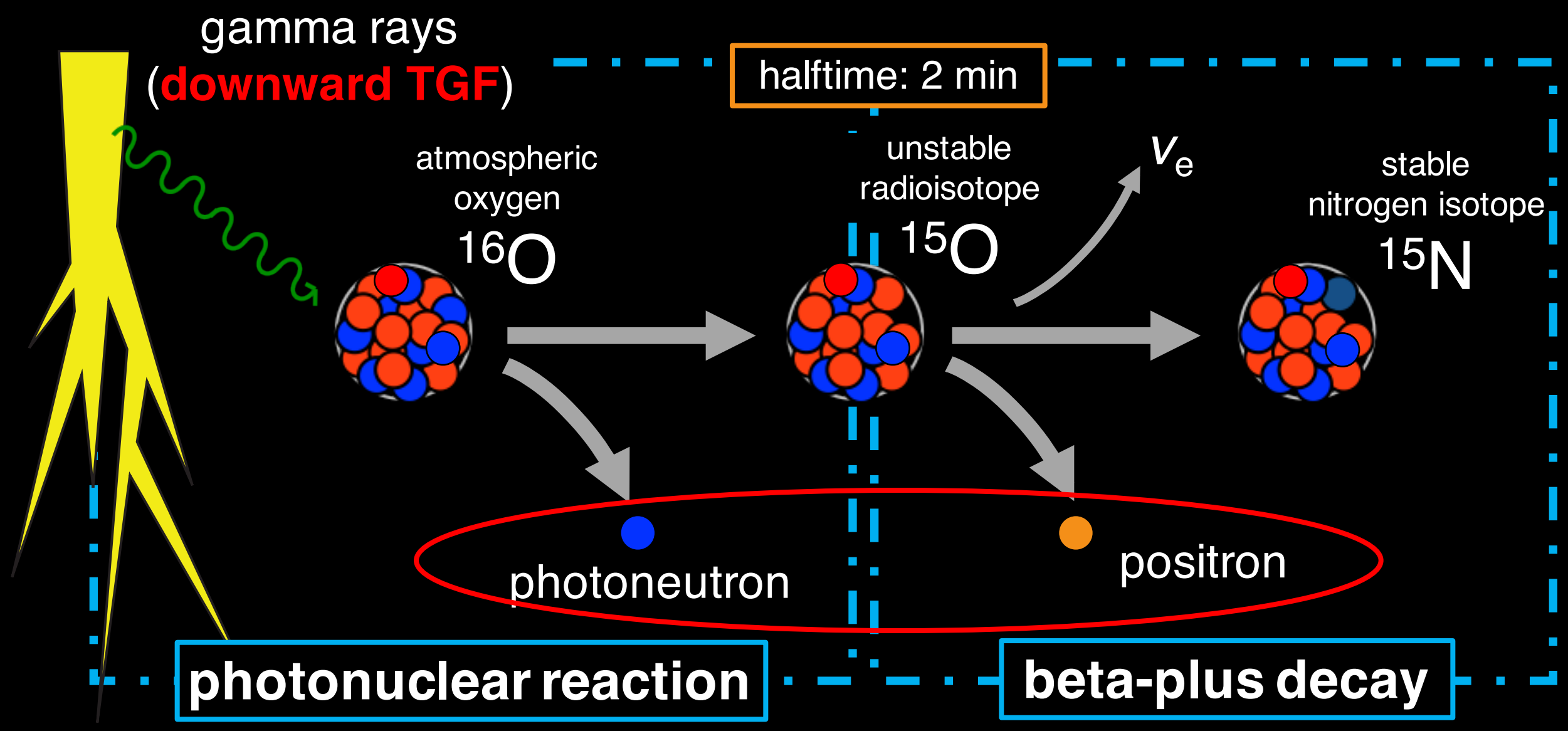

**photonuclear reaction**

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

**beta-plus decay**

$${}^{13}N \rightarrow {}^{13}C + e^{+} + \nu_e$$

# Non-negligible contribution of Oxygen-16



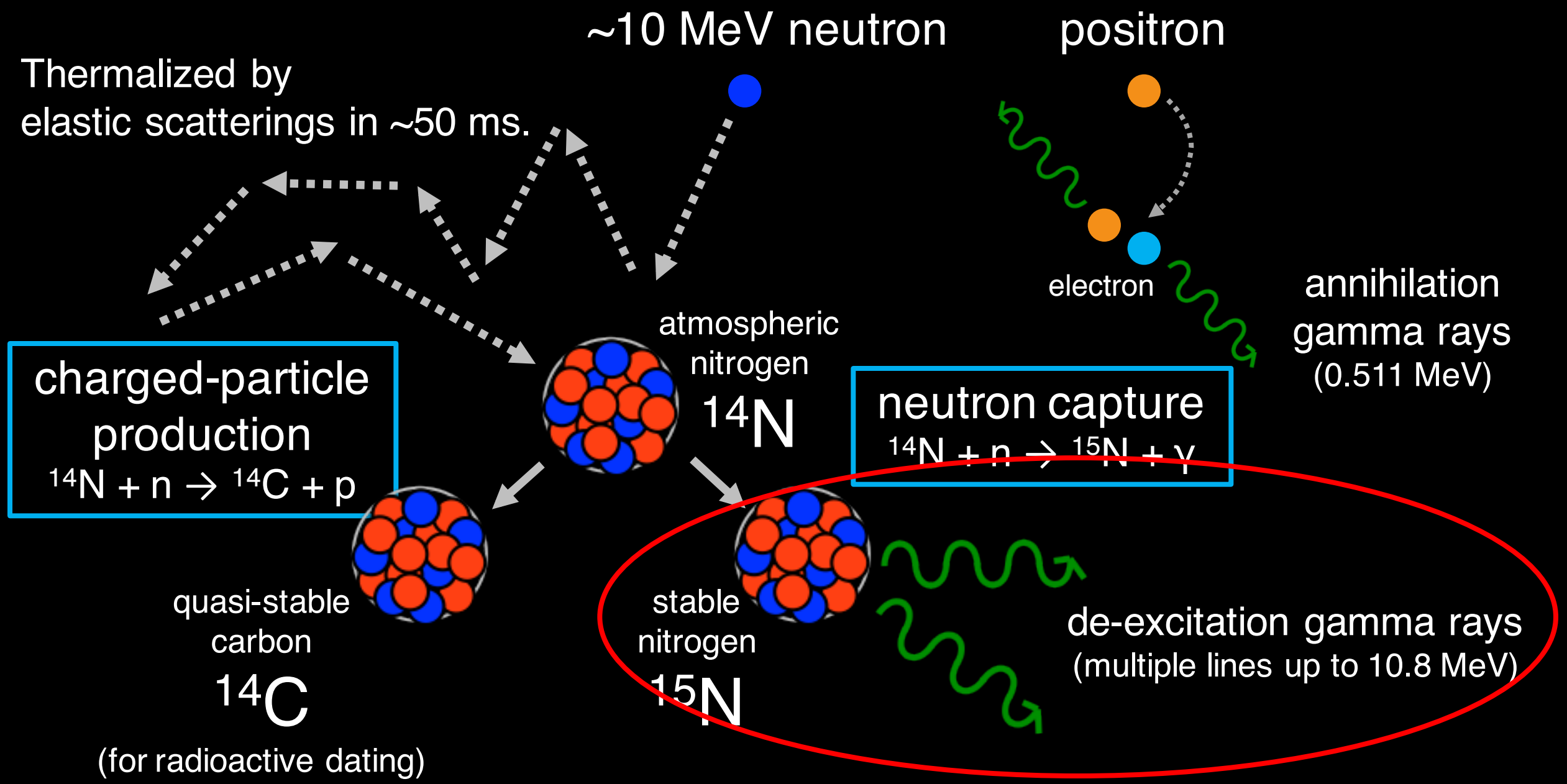

**photonuclear reaction**

$$\gamma + {}^{16}O \rightarrow {}^{15}O + n$$

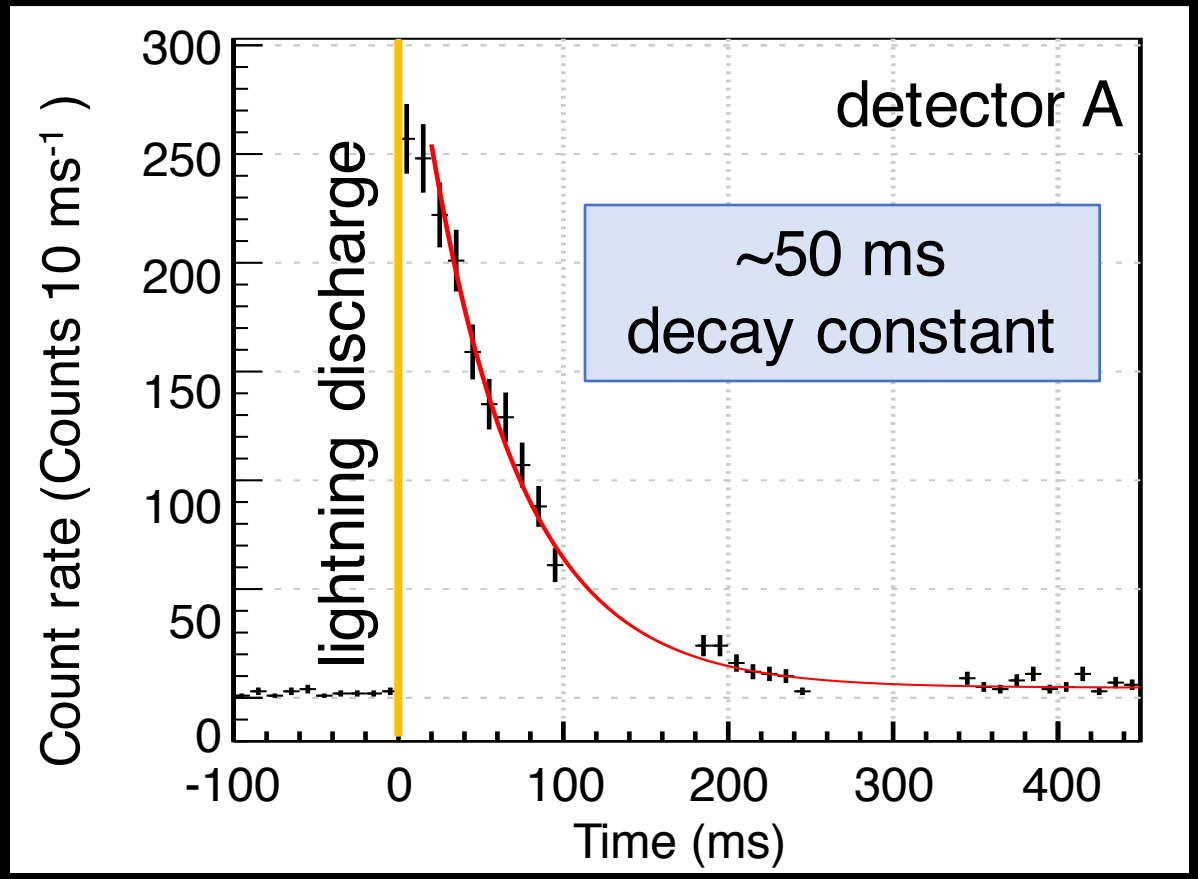
**beta-plus decay**

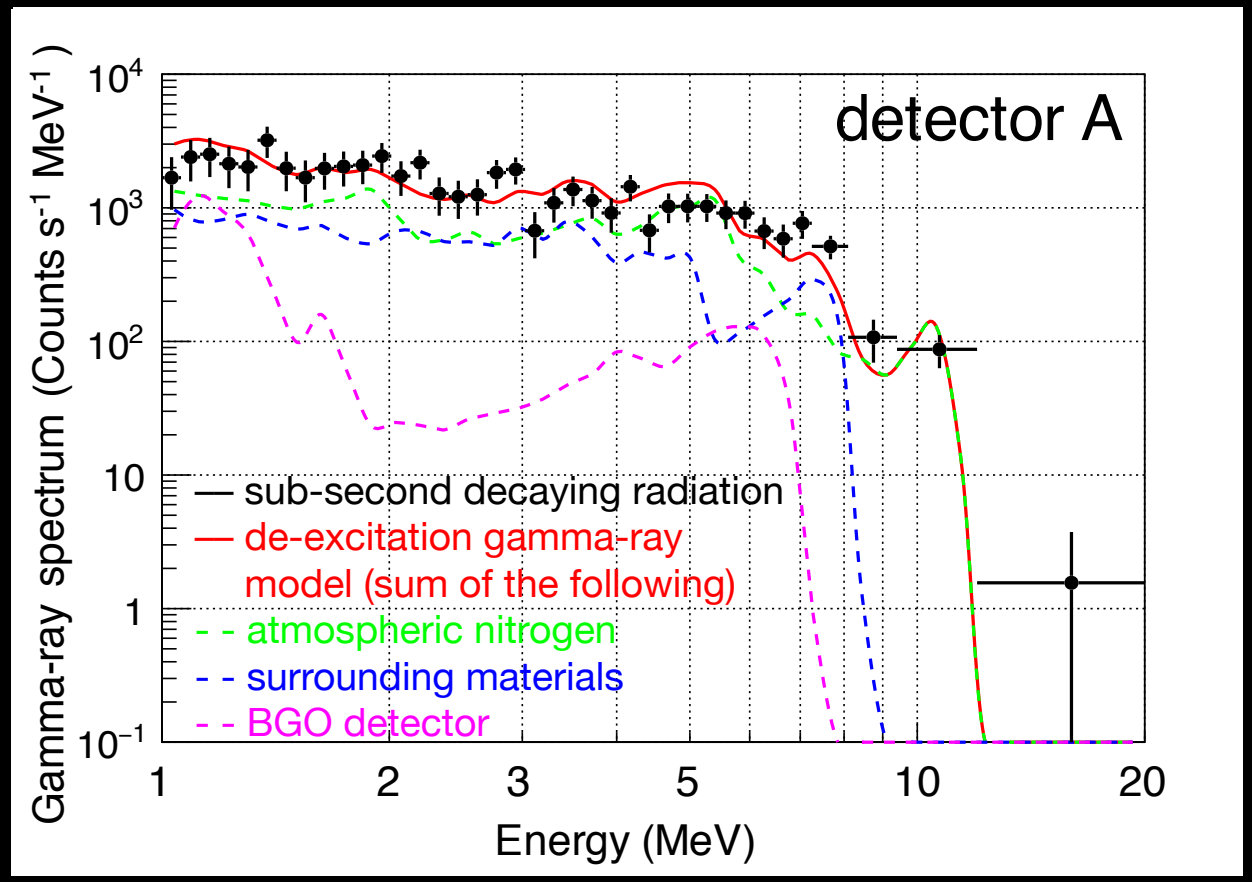
$${}^{15}O \rightarrow {}^{15}N + e^{+} + \nu_e$$

# Reactions of Photoneutron / Positron in the Atmosphere



# De-excitation Gamma Rays from Neutron Capture

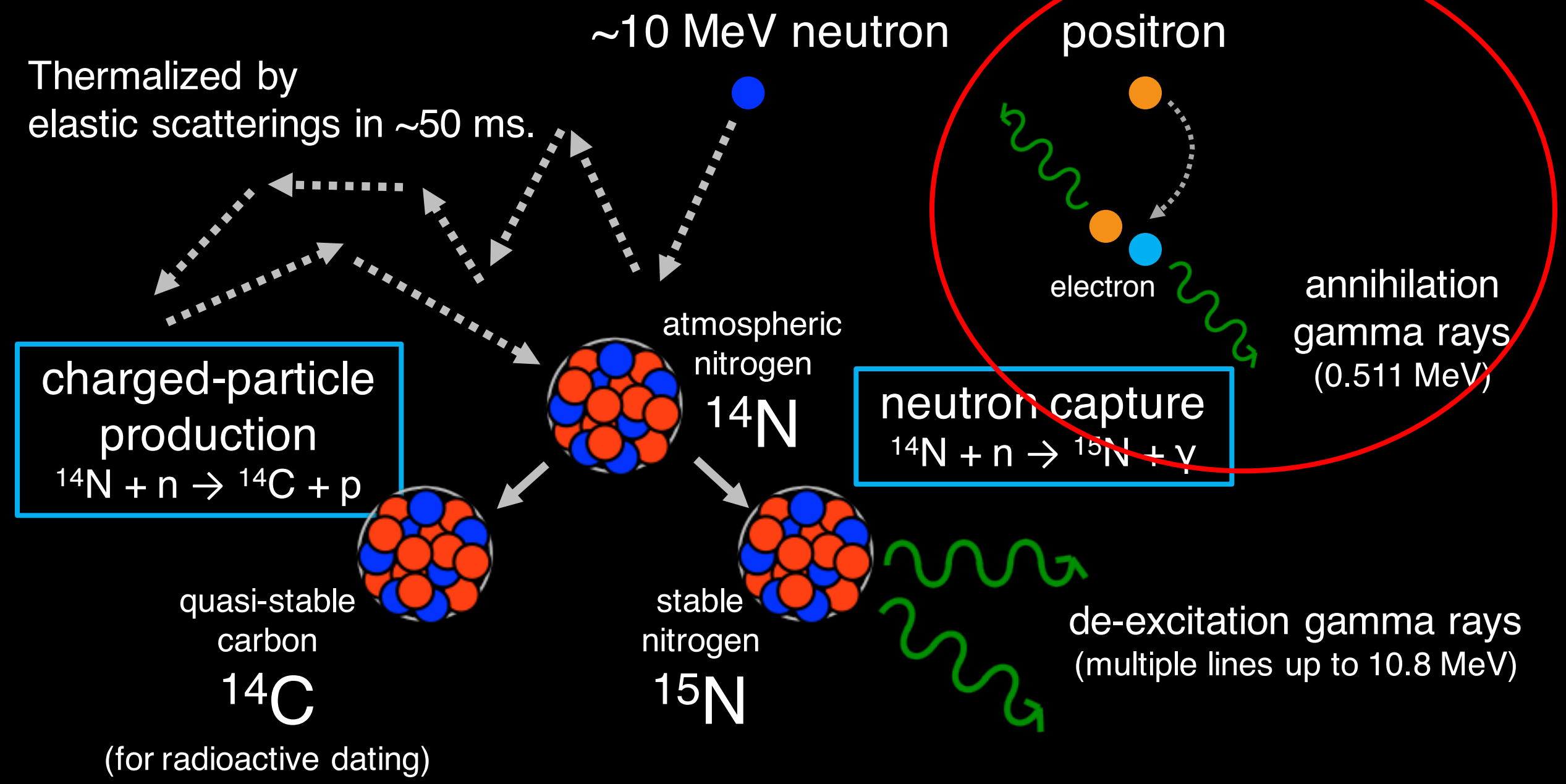


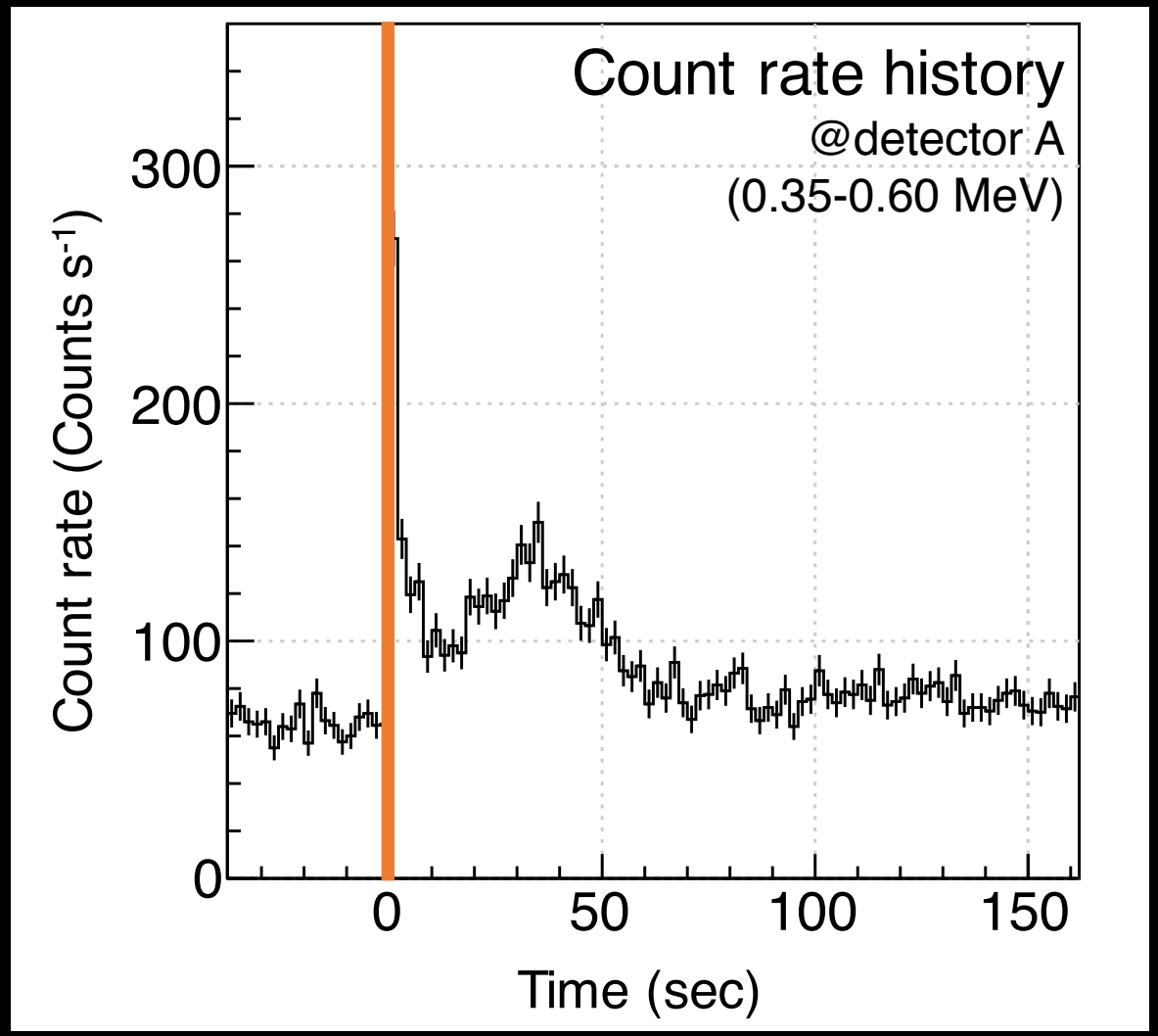

Consistent with thermalization time scale (~50 ms).

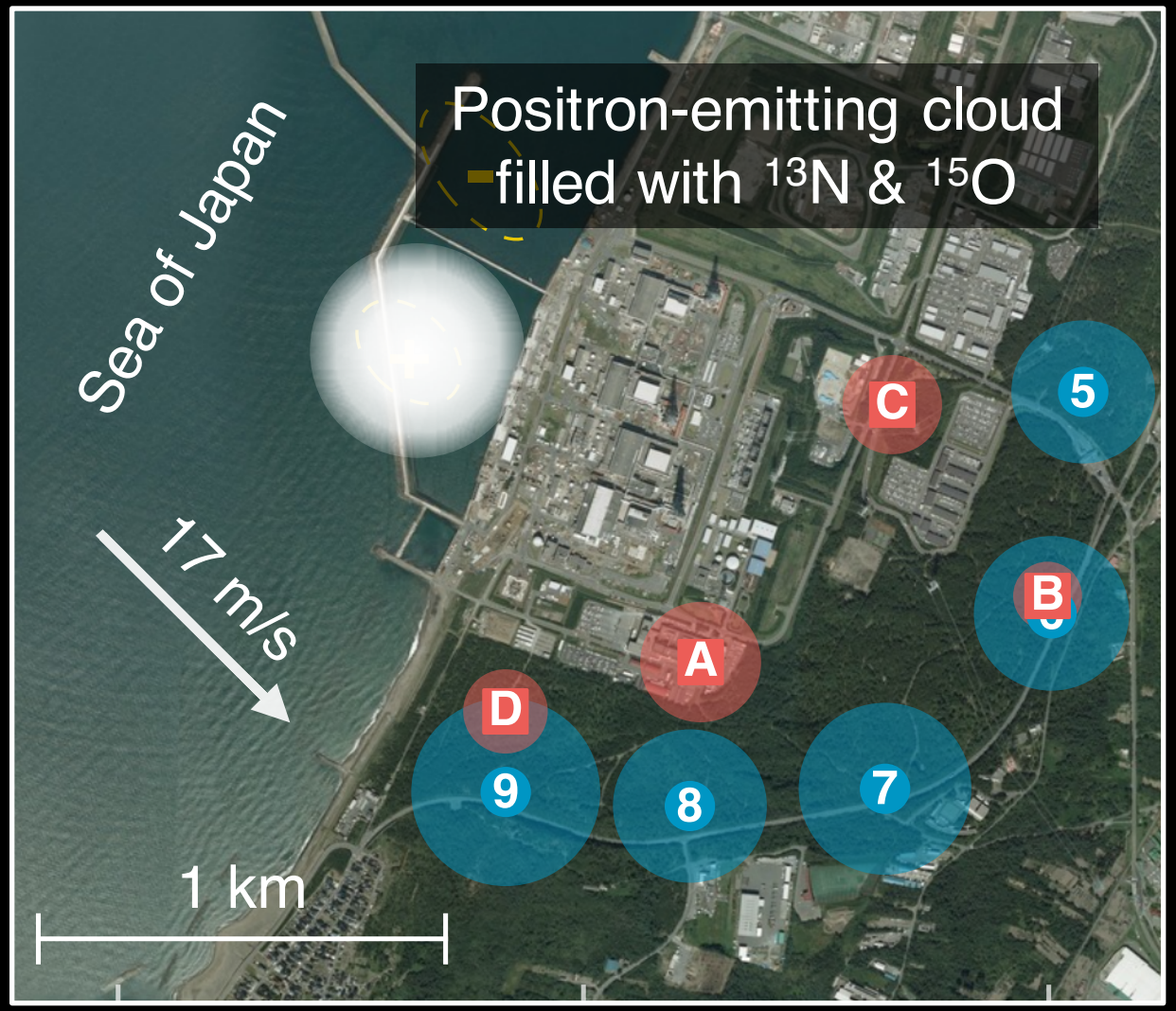
Many lines of de-excitation gamma rays from neutron capture.

# Reactions of Photoneutron / Positron in the Atmosphere



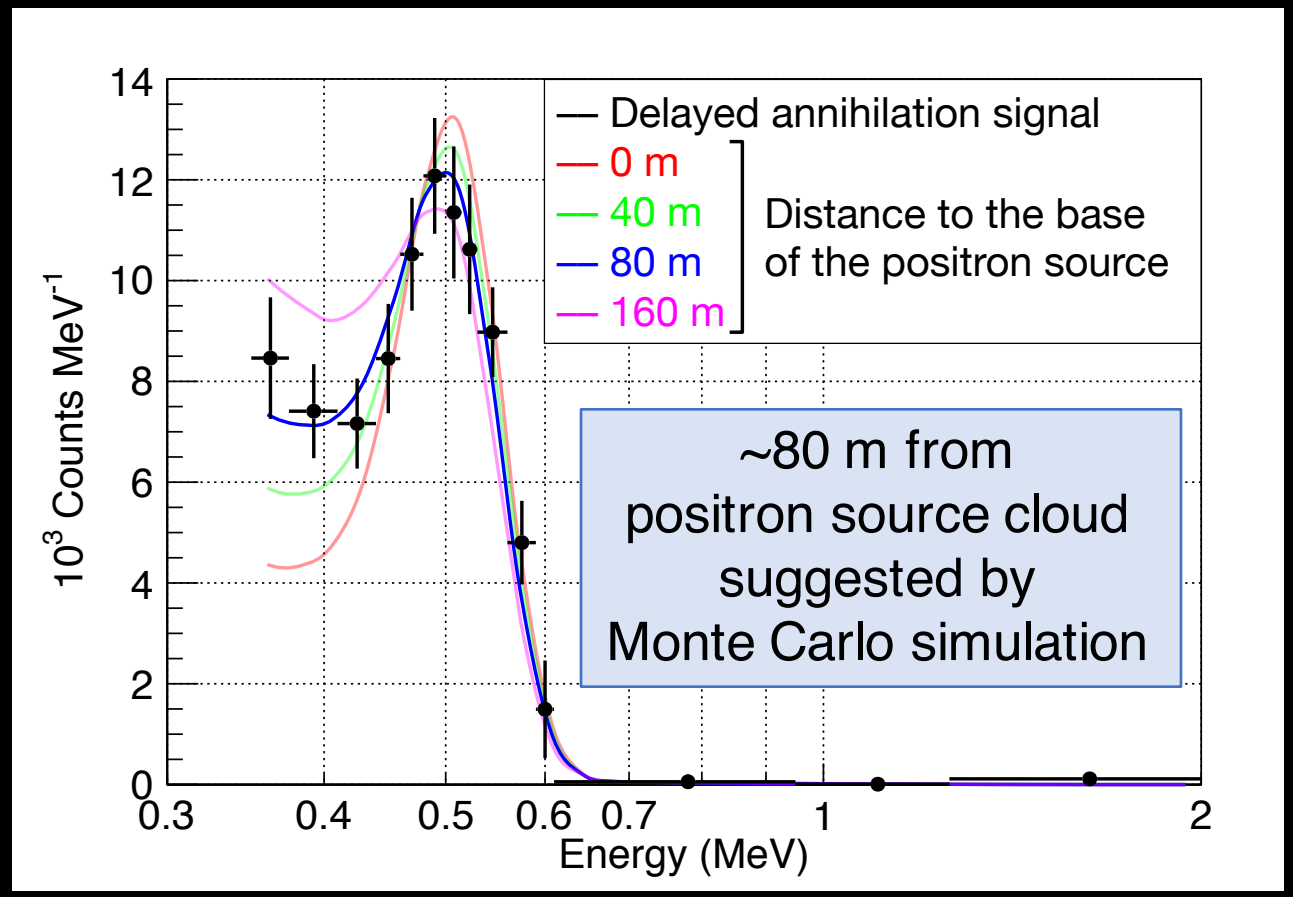
# Emergence of Positron-emitting Cloud

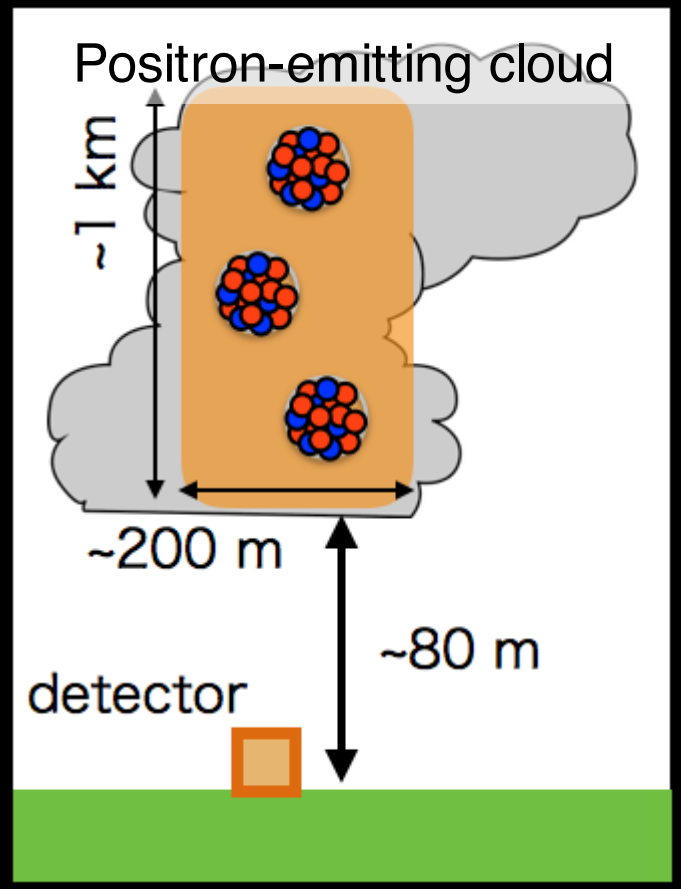



Cloud of $^{13}N$ and $^{15}O$ moved with ambient wind flow, and passed over detector A.
→ Delayed annihilation signal

# Number of produced neutrons



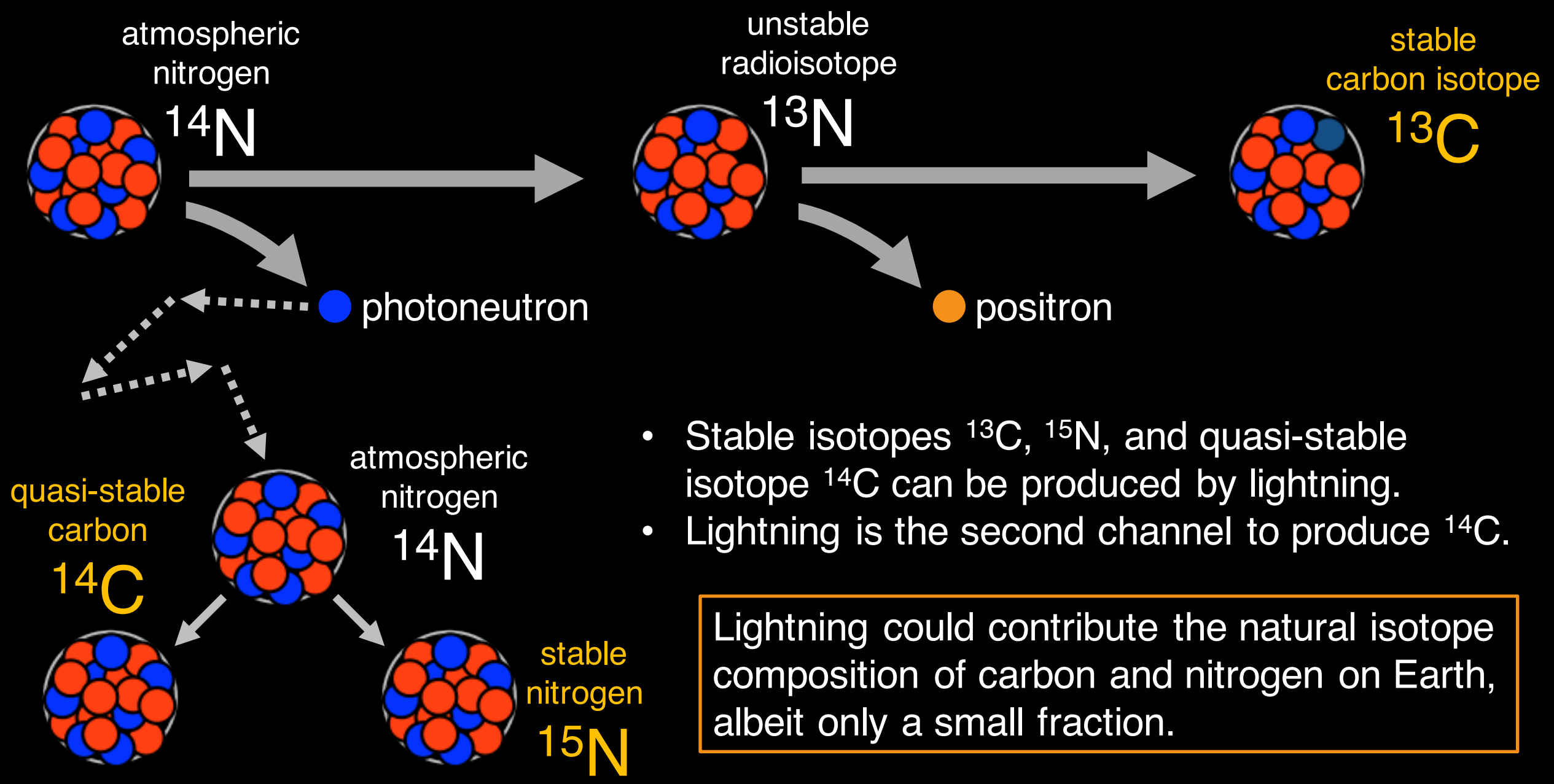




Monte Carlo simulation and a simplified cylindrical geometry derived the lightning produced $4\times10^{12}$ neutrons via photonuclear reactions.

Consistent with theoretical predictions and recent neutron observation.

($10^{11\text{-}15}$: Carlson et al. 2010, Babich et al. 2010) ($10^{12\text{-}13}$: Bowers et al. 2017)

# Nitrogen and Carbon Isotopes Produced by Lightning




- Stable isotopes $^{13}C$, $^{15}N$, and quasi-stable isotope $^{14}C$ can be produced by lightning.
- Lightning is the second channel to produce $^{14}C$.

Lightning could contribute the natural isotope composition of carbon and nitrogen on Earth, albeit only a small fraction.

# Conclusion

- GROWTH project started the mapping campaign of high energy radiation from winter thundercloud and lightning in the coastal area of Japan Sea.

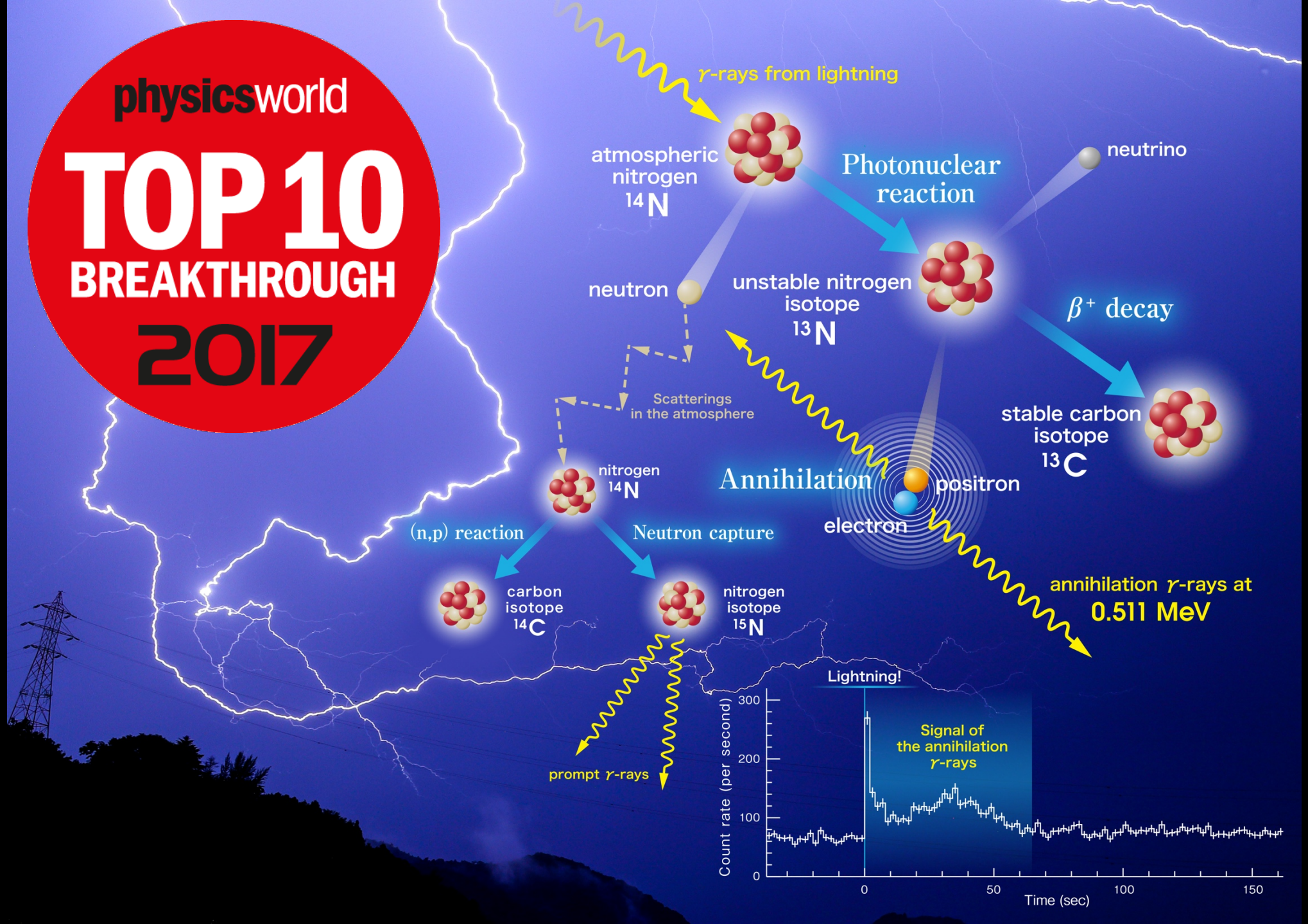
- In 2017 February, we detected signals of neutron and positron after lightning, which is the first conclusive detection of photonuclear reactions triggered by lightning discharge.

- The lightning produced $4\times10^{12}$ neutrons, which is consistent with theoretical predictions and other neutron observation.

- Lightning can produce stable and quasi-stable isotopes $^{13}C$, $^{14}C$, $^{15}N$, and could make a small contribution to the natural isotope composition on Earth.

See also Enoto, Wada, et al., *Nature* 551, 481-484 (2017)

**Winter thunderstorms in Japan are fruitful for high energy atmospheric physics. We welcome collaborators for winter thunderstorm research!**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TOP 10
BREAKTHROUGH
2017
γ-rays from lightning
atmospheric nitrogen $^{14}N$
Photonuclear reaction
neutrino
neutron
unstable nitrogen isotope $^{13}N$
$\beta^+$ decay
Scatterings in the atmosphere
stable carbon isotope $^{13}C$
nitrogen $^{14}N$
Annihilation
positron
electron
(n,p) reaction
Neutron capture
carbon isotope $^{14}C$
nitrogen isotope $^{15}N$
annihilation γ-rays at 0.511 MeV
prompt γ-rays
Lightning!
Signal of the annihilation γ-rays
Count rate (per second)
300
200
100
0
0
50
100
150
Time (sec)