The Gamma-Flash Program: High-energy radiation and particles in thunderstorms, lightning, and terrestrial gamma-ray flashes

Paolo Calabretto on behalf of the Gamma-Flash collaboration

in collaboration with:

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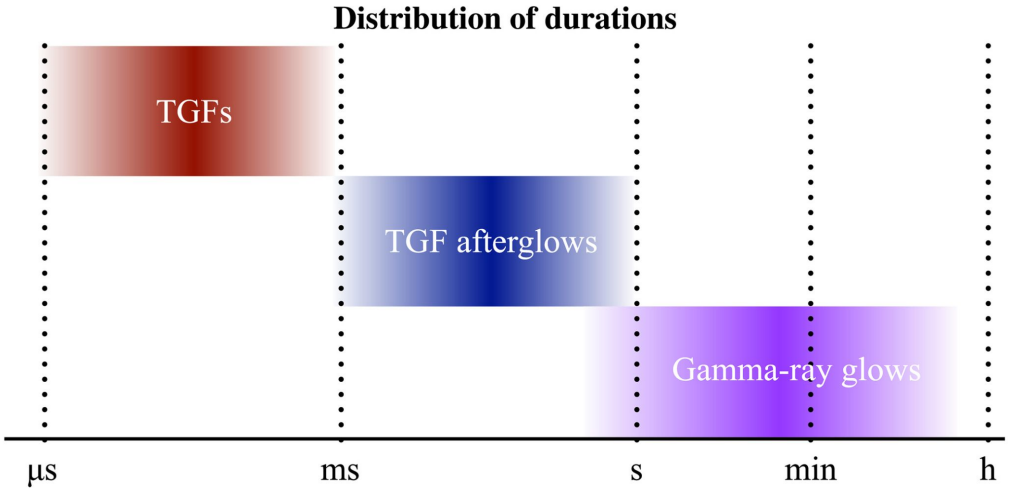
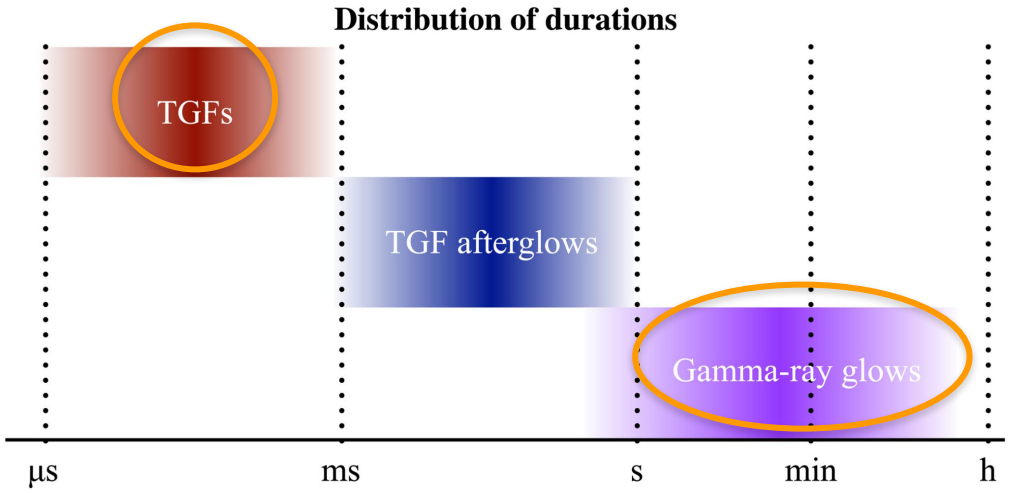
γ-ray emissions: a brief overview



Geophysical Research Letters, Volume: 44, Issue: 20, Pages: 10,702-10,712 (2017) DOI: (10.1002/2017GL075552)

γ-ray emissions: a brief overview



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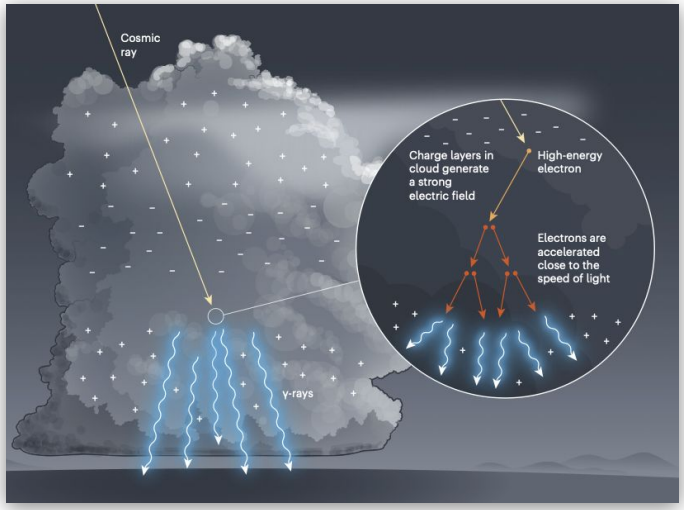
Two main underlying mechanisms:

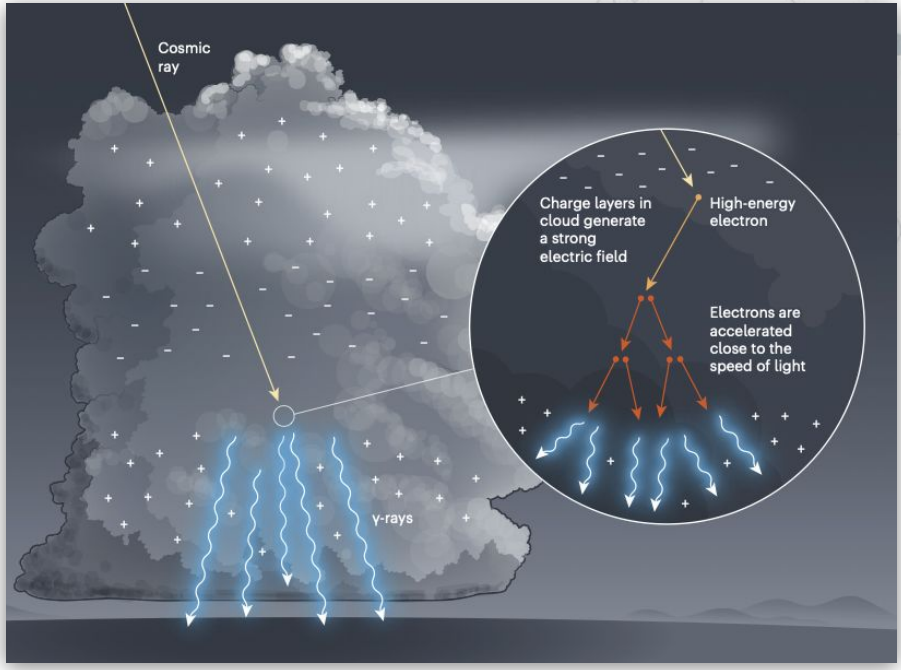
MOS RREA



Adapted from Nature 590, 378-381 (2021)

γ-ray emissions: a brief overview

1. **MOS**: electrons from CR are accelerated in the cloud electric field (but E < Eth)



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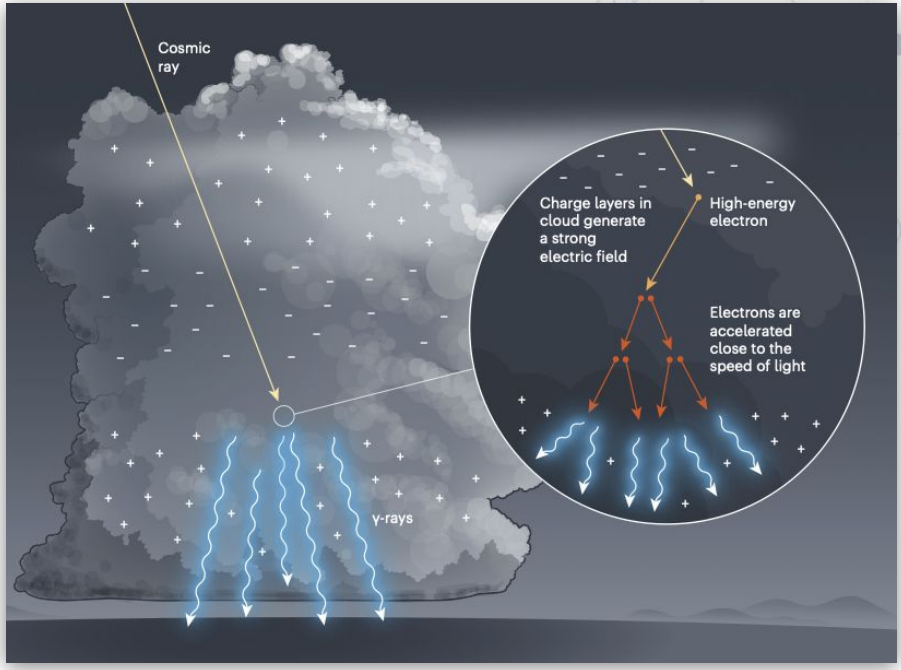

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γ-ray emissions: a brief overview

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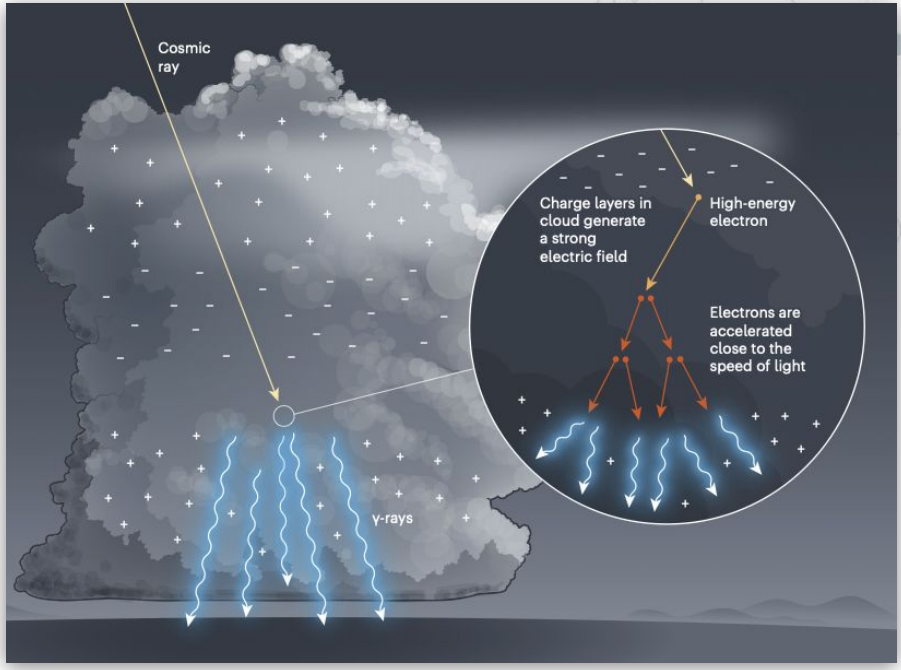
Eth ~ 300 kV/m



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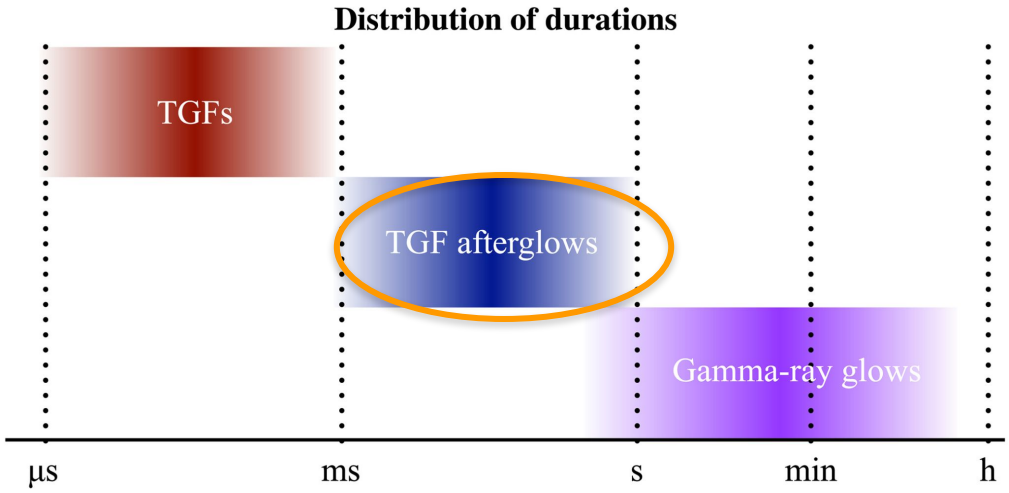

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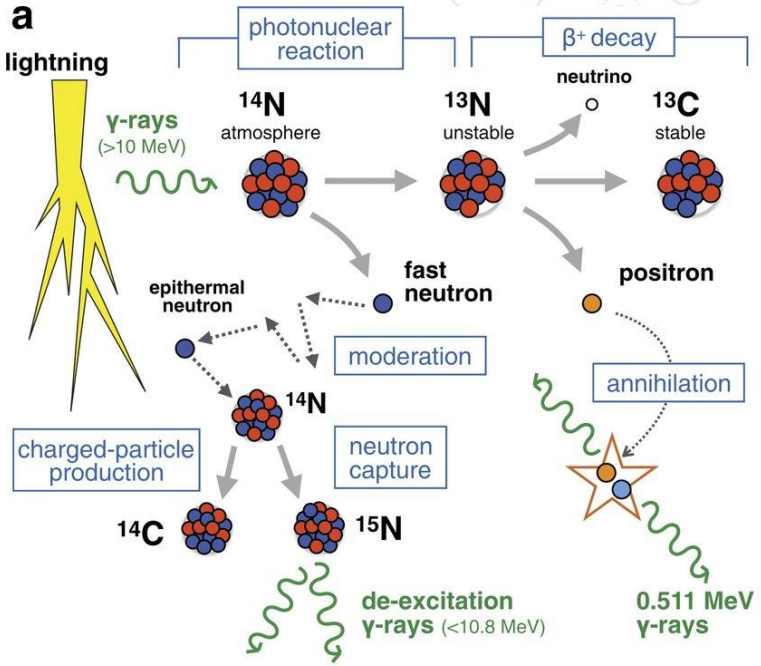
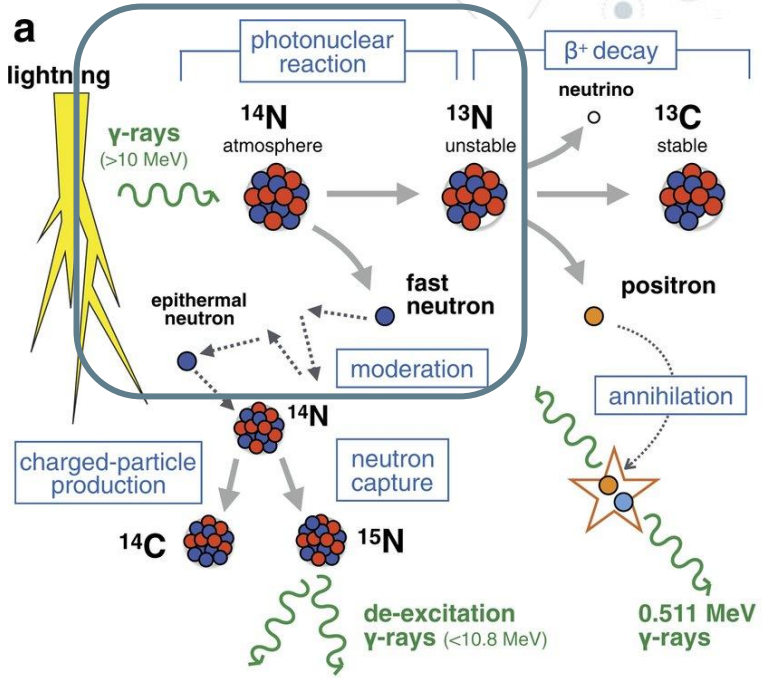


Adapted from Enoto, T., Wada, Y., Furuta, Y. et al. Photonuclear reactions triggered by lightning discharge. Nature 551, 481–484 (2017)

γ-ray emissions: a brief overview

- γ-rays interact with air molecules producing **neutrons**



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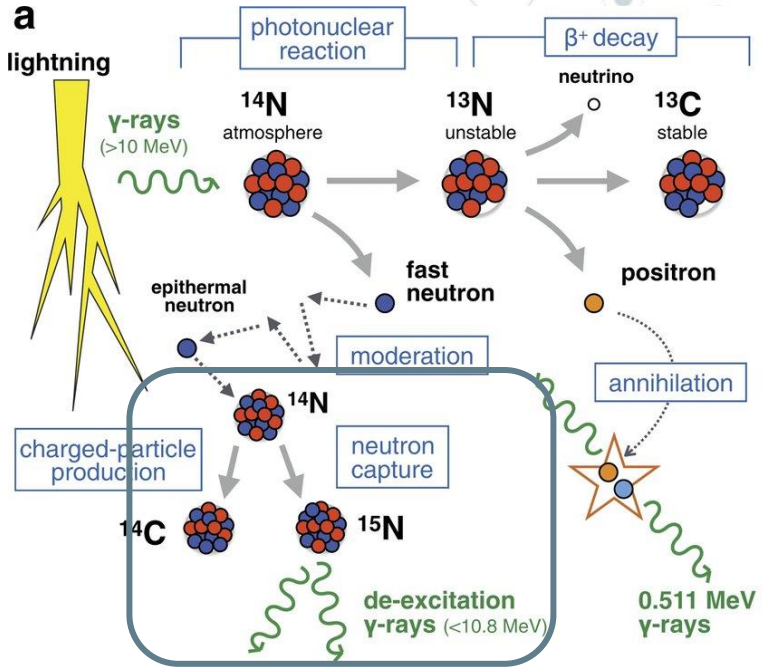
γ-ray emissions: a brief overview

- γ-rays interact with air molecules producing **neutrons**
- Neutron capture can emit further γ-rays (hence the **TGF afterglow**)



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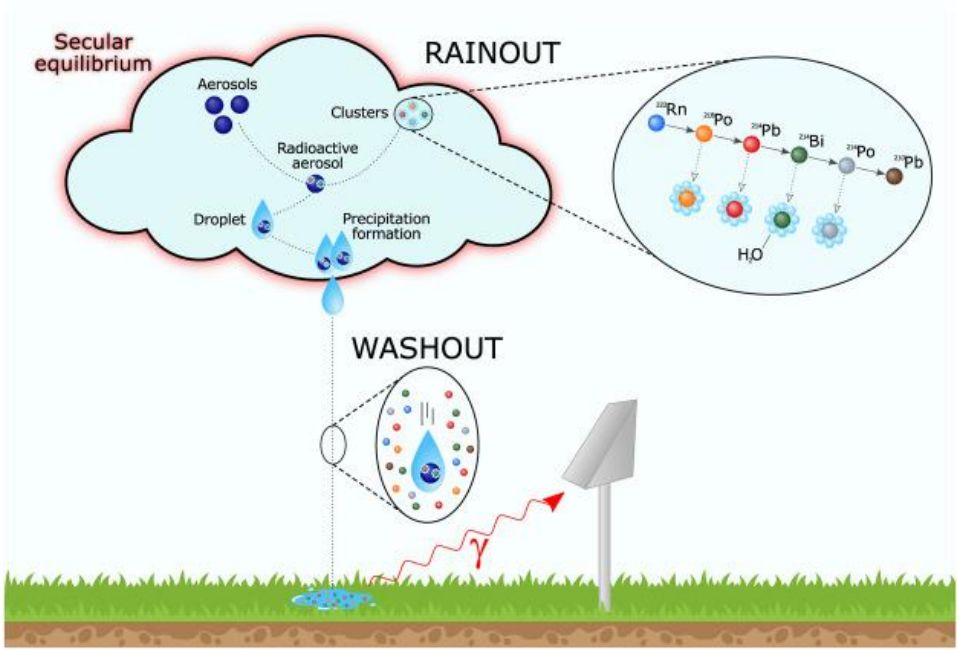
γ-ray emissions: a brief overview

Gamma-ray Enhancements

1. ^{222}Rn daughters (mainly ^{214}Pb & ^{214}Bi) are captured by droplets in a cloud



https://doi.org/10.1016/j.atmosenv.2020.117728

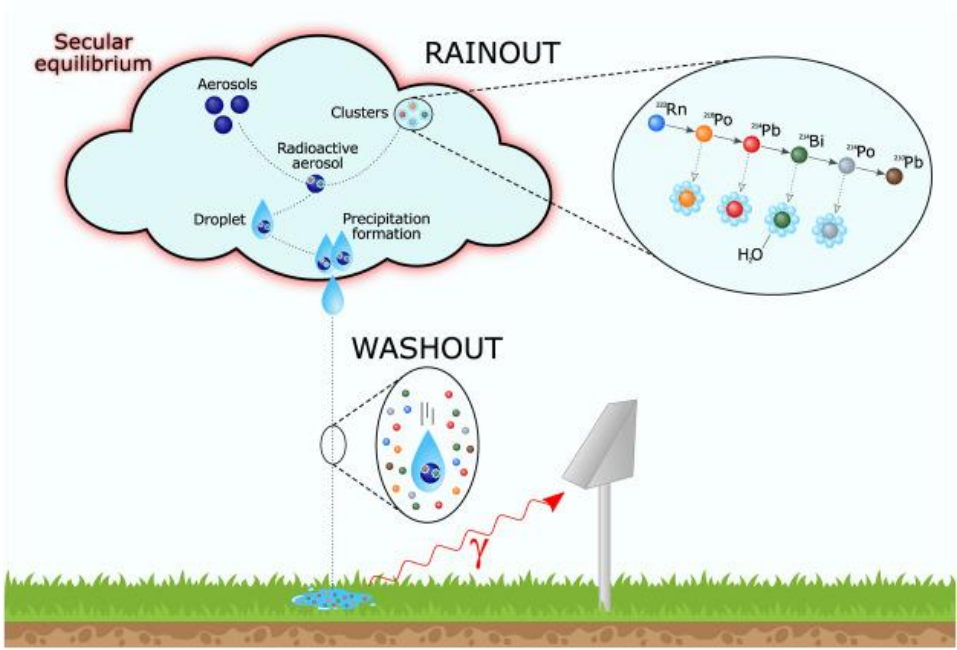
γ-ray emissions: a brief overview

Gamma-ray Enhancements

1. ^{222}Rn daughters (mainly ^{214}Pb & ^{214}Bi) are captured by droplets in a cloud
2. During precipitation, the **rainout-washout** process bring these radionuclides on ground

⬇

Enhanced γ-ray emission lasting for minutes/hours with E ≲ 3 MeV
(not necessarily during electrical activity)



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γ-ray emissions: a brief overview

High altitudes are ideal spots for TGFs and glows detection

γ-ray emissions: a brief overview

High altitudes are ideal spots for TGFs and glows detection

Gamma-Flash program:

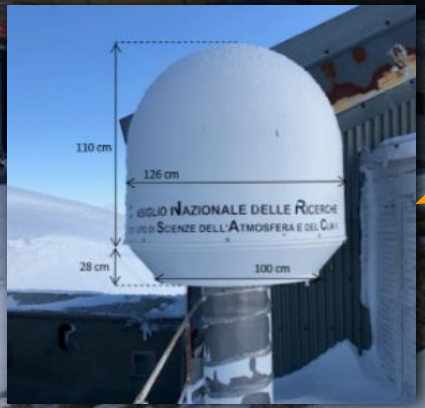
Study high-energy emissions from thunderstorms

+

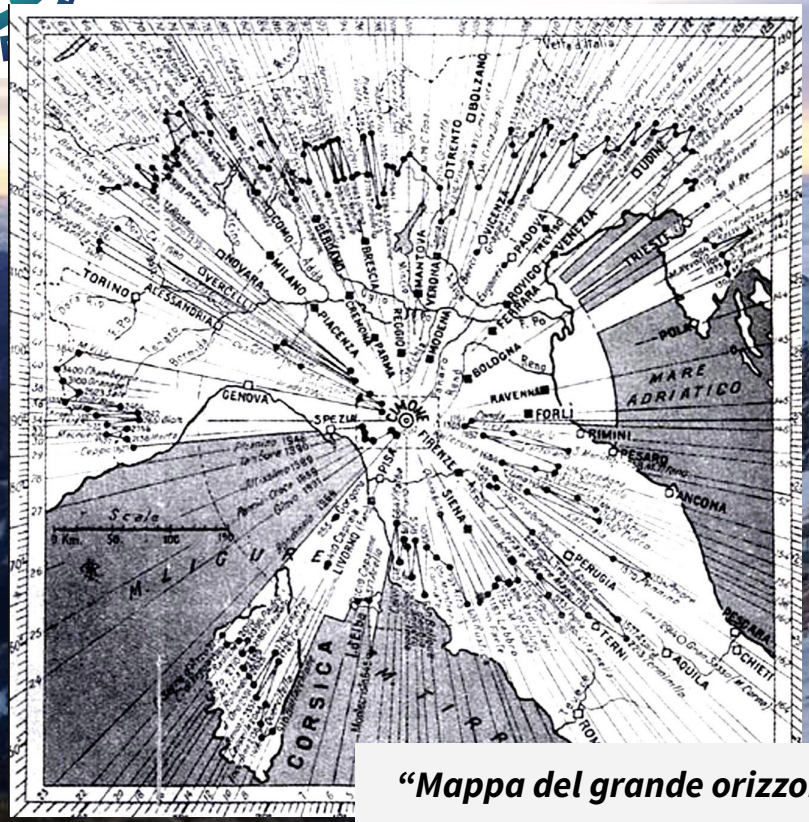
Local lightning and weather monitoring by LINET - CNR

Gamma-Flash program: ground system

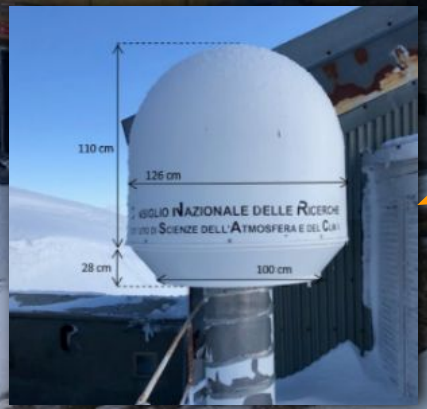
Main on-ground facility at the O. Vittori Observatory on top of Mt. Cimone (**2165** m a.s.l.)



Gamma-Flash program: ground system



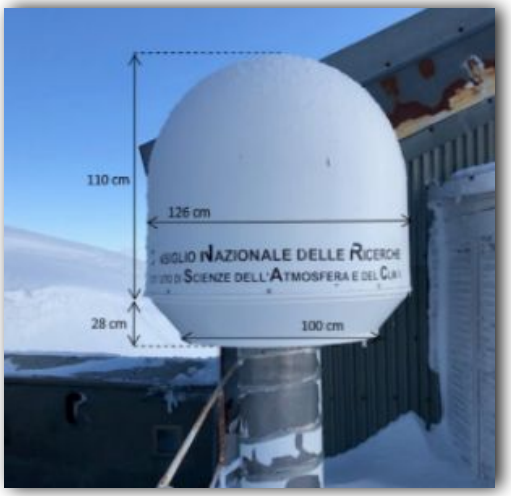
"Mappa del grande orizzonte"

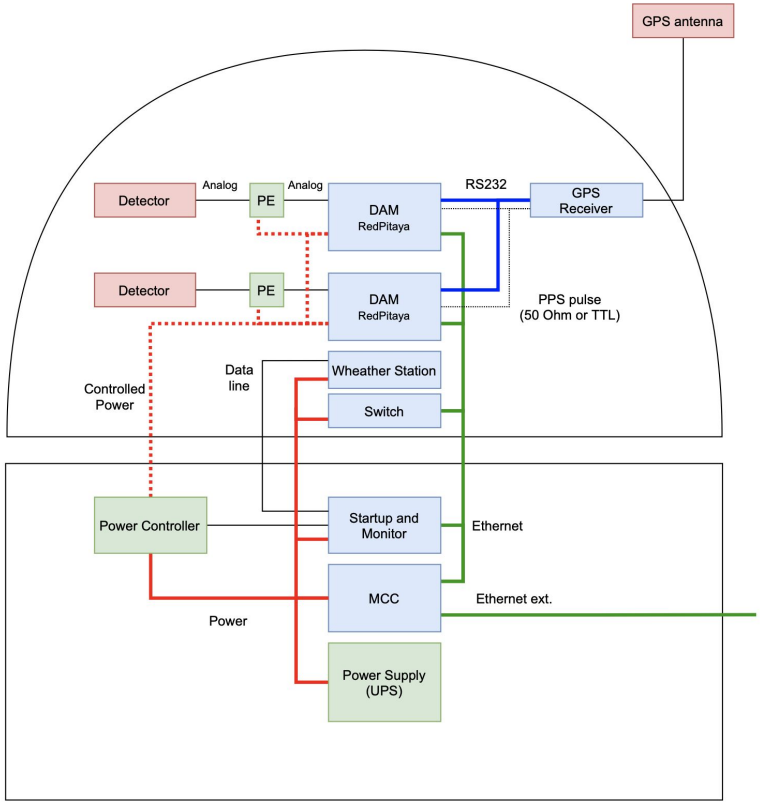


Gamma-Flash program: ground system

Why on top of Mt. Cimone?

- High altitude & free LoS
- Significant clustering in the lightning distribution

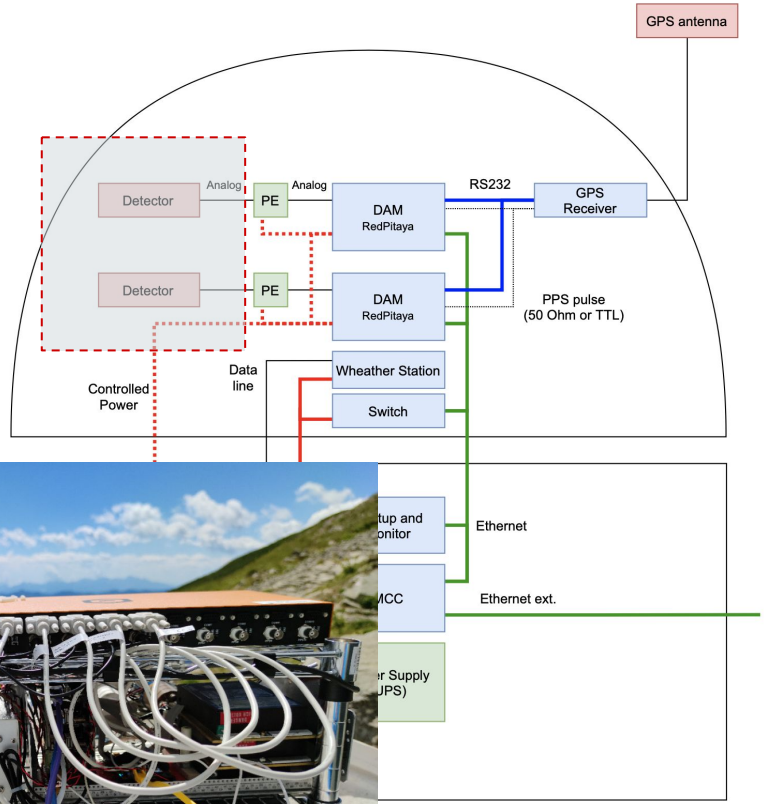


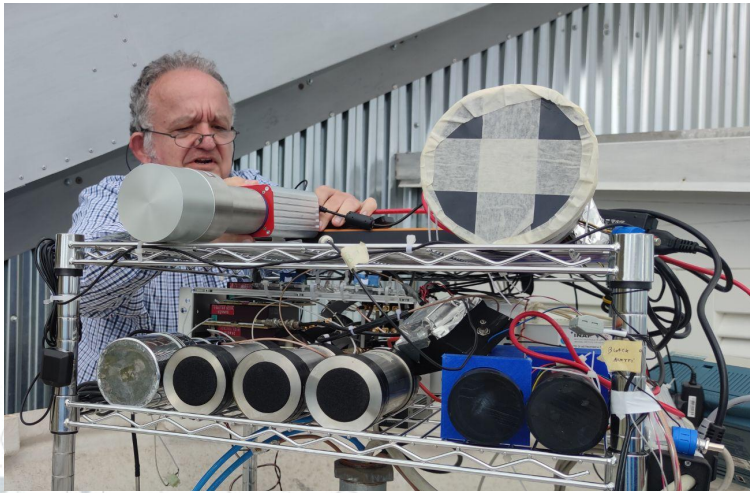


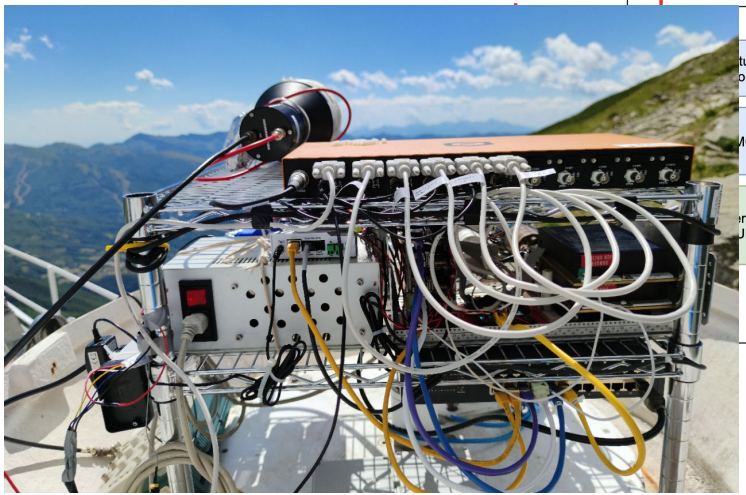
Gamma-Flash program: ground system

5 γ-ray + 3 neutron detectors:

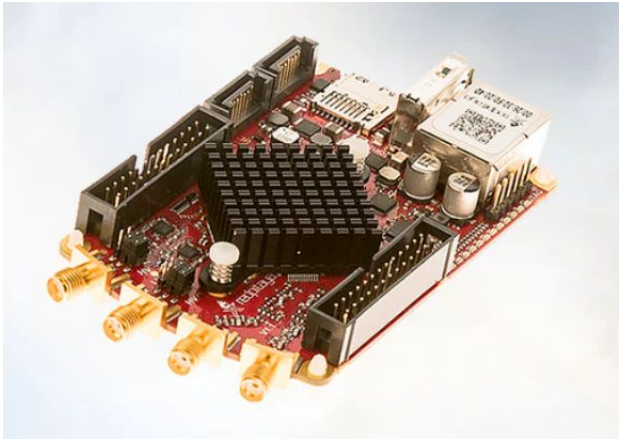
- **γ-ray detectors**: NaI(Tl) scintillator crystals coupled to PMTs (300 keV - 10 MeV)
- **Neutron detectors**: designed for both fast and thermal neutrons (ZnS:Ag & ^{6}Li enriched scintillators + PMT)

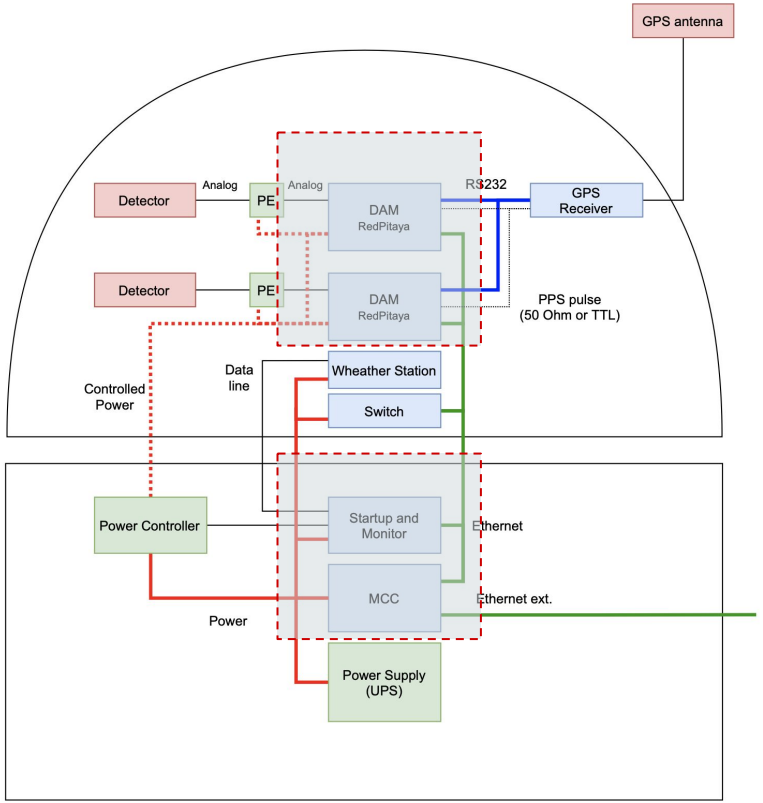






Data Acquisition Module (**DAM**) running on **RedPitaya**'s boards

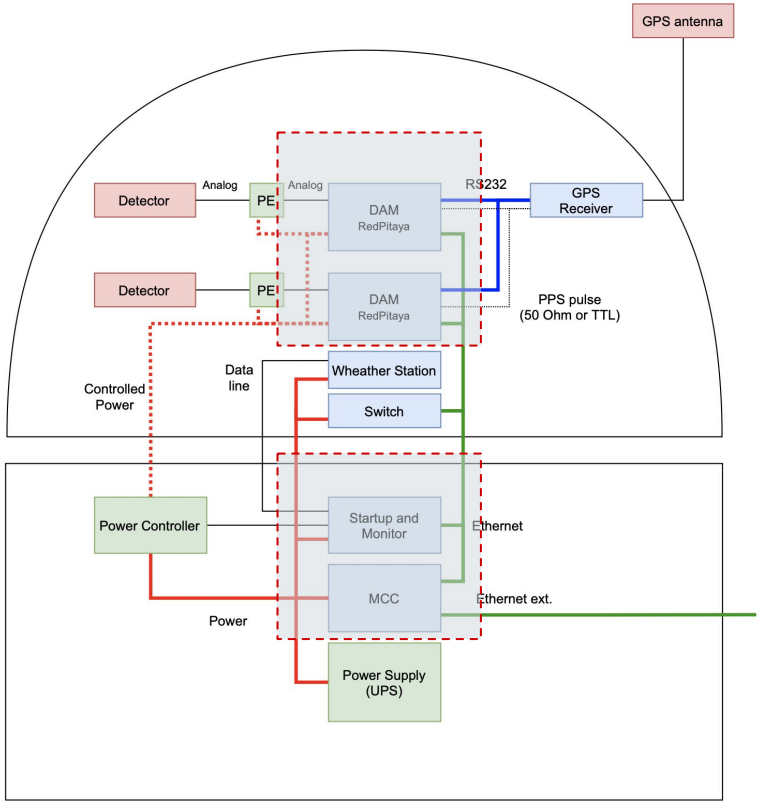




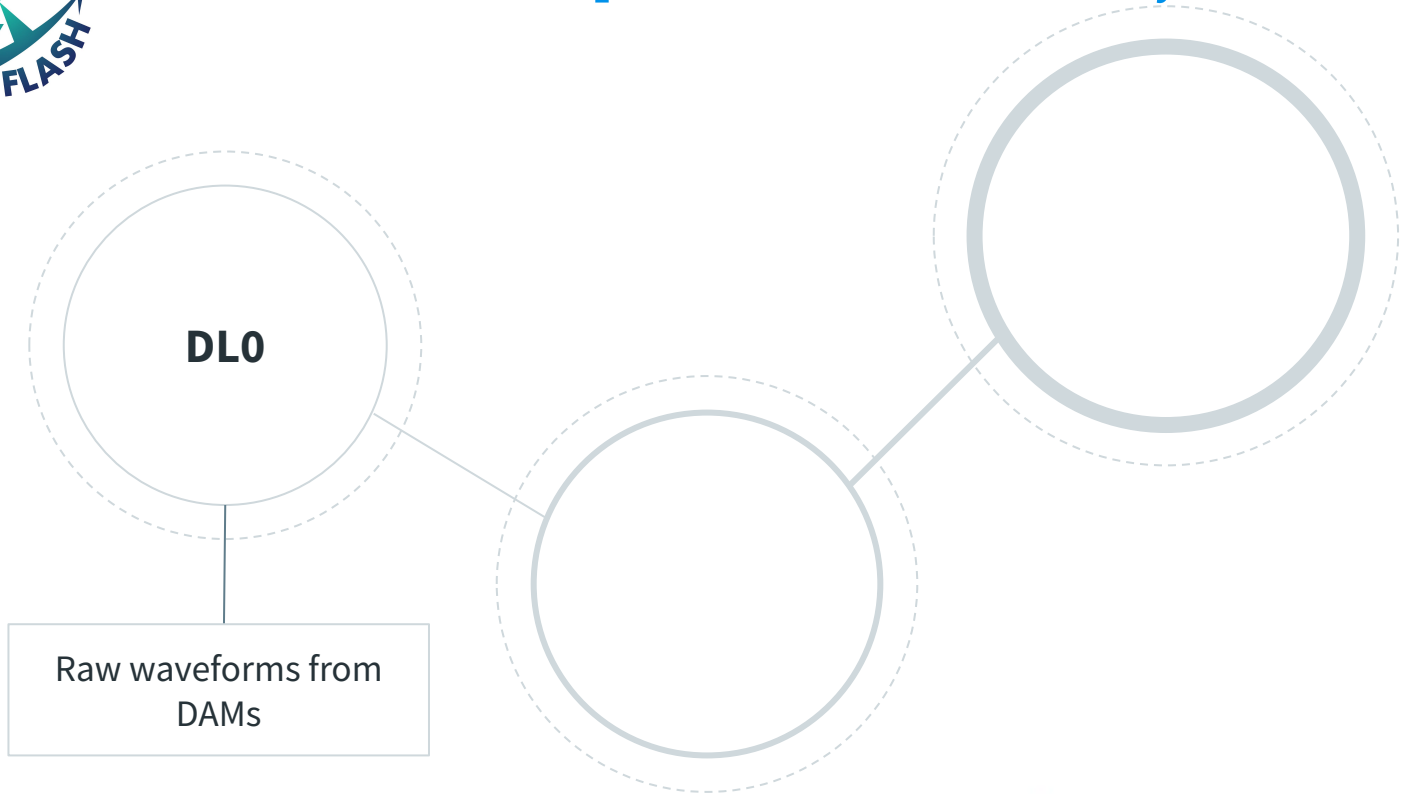
Gamma-Flash program: ground system

Data Acquisition Module (**DAM**) running on **RedPitaya**'s boards

Acquisition period: **July 2022 - October 2023**
Global acquisition time: **259 days**
Total amount of thunderstorm hours: **260** (**4%** total time)



DACS - Data Acquisition and Control System



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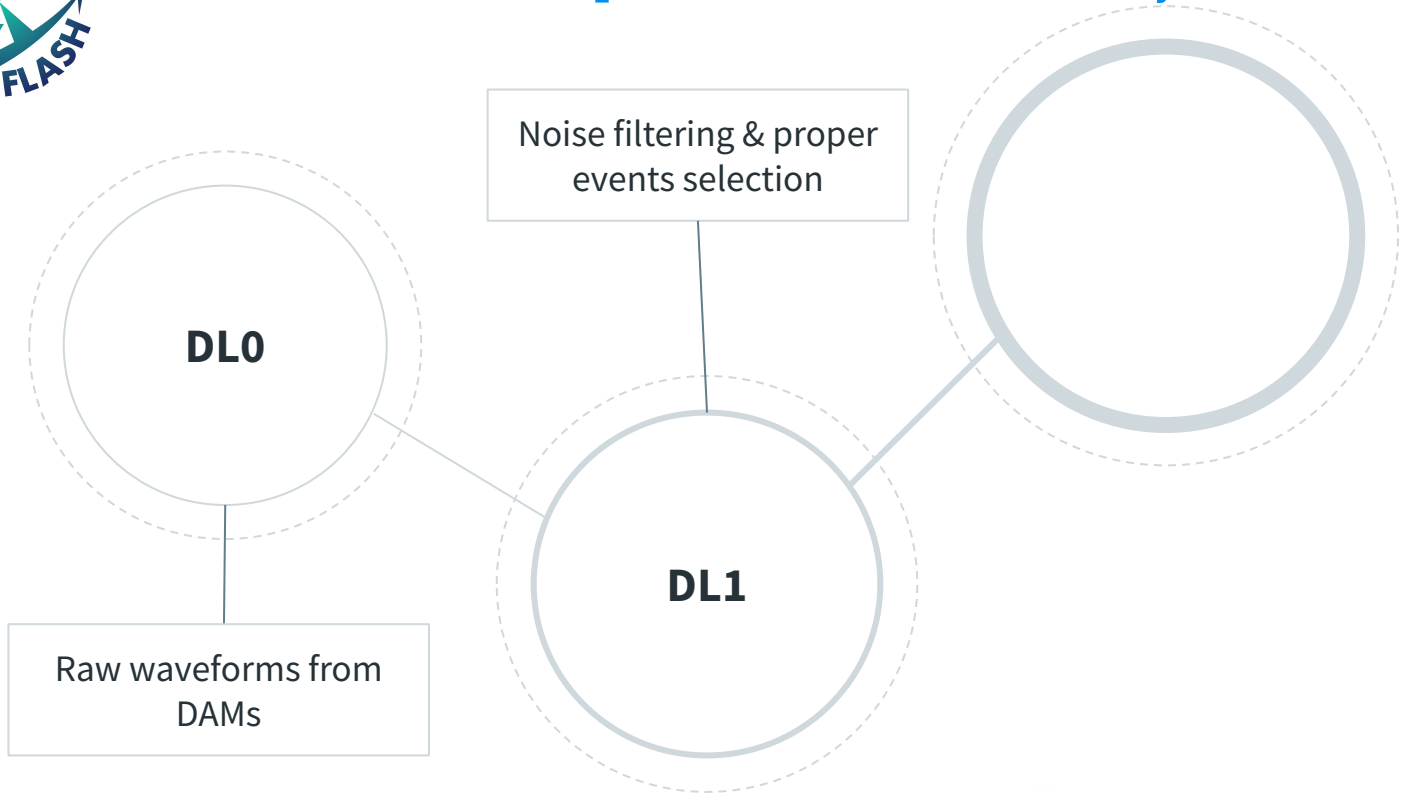

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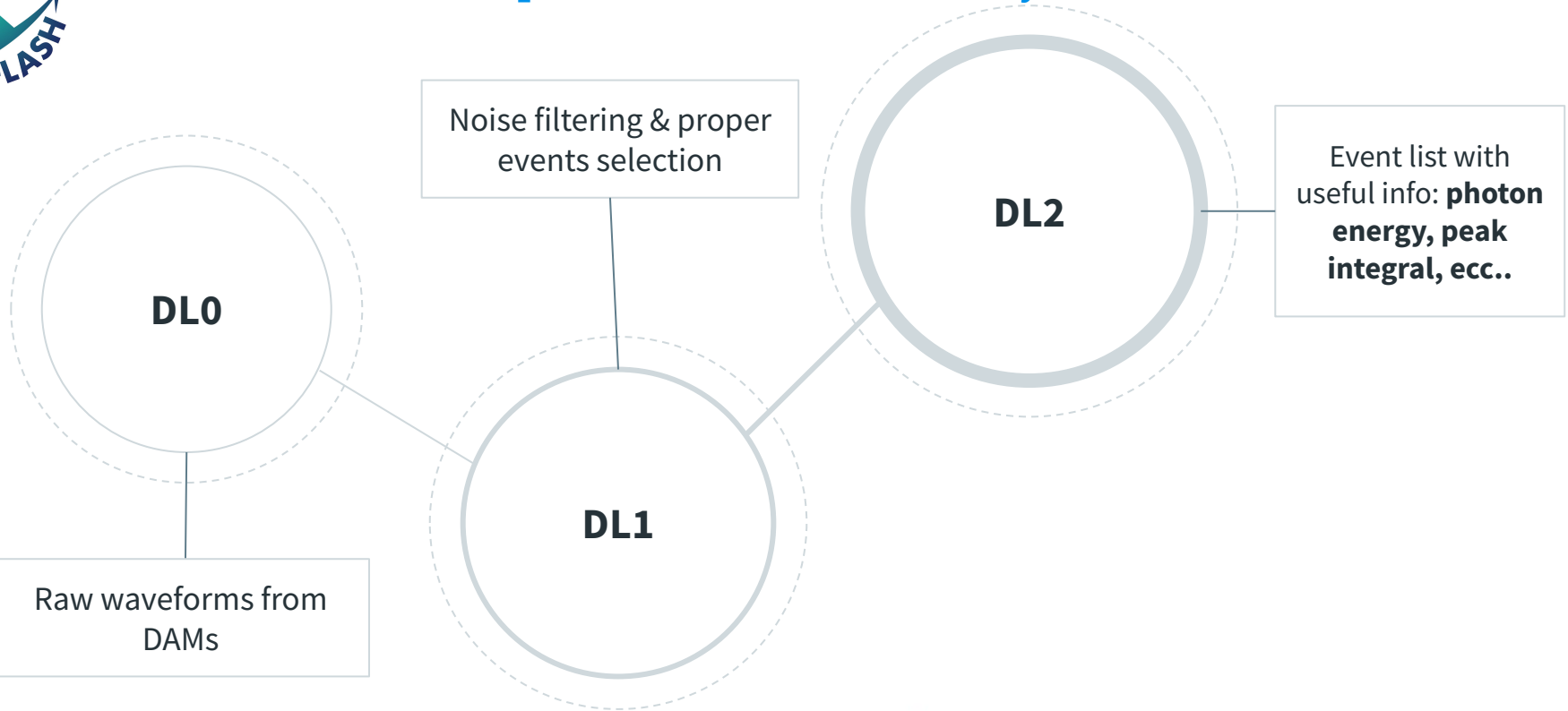

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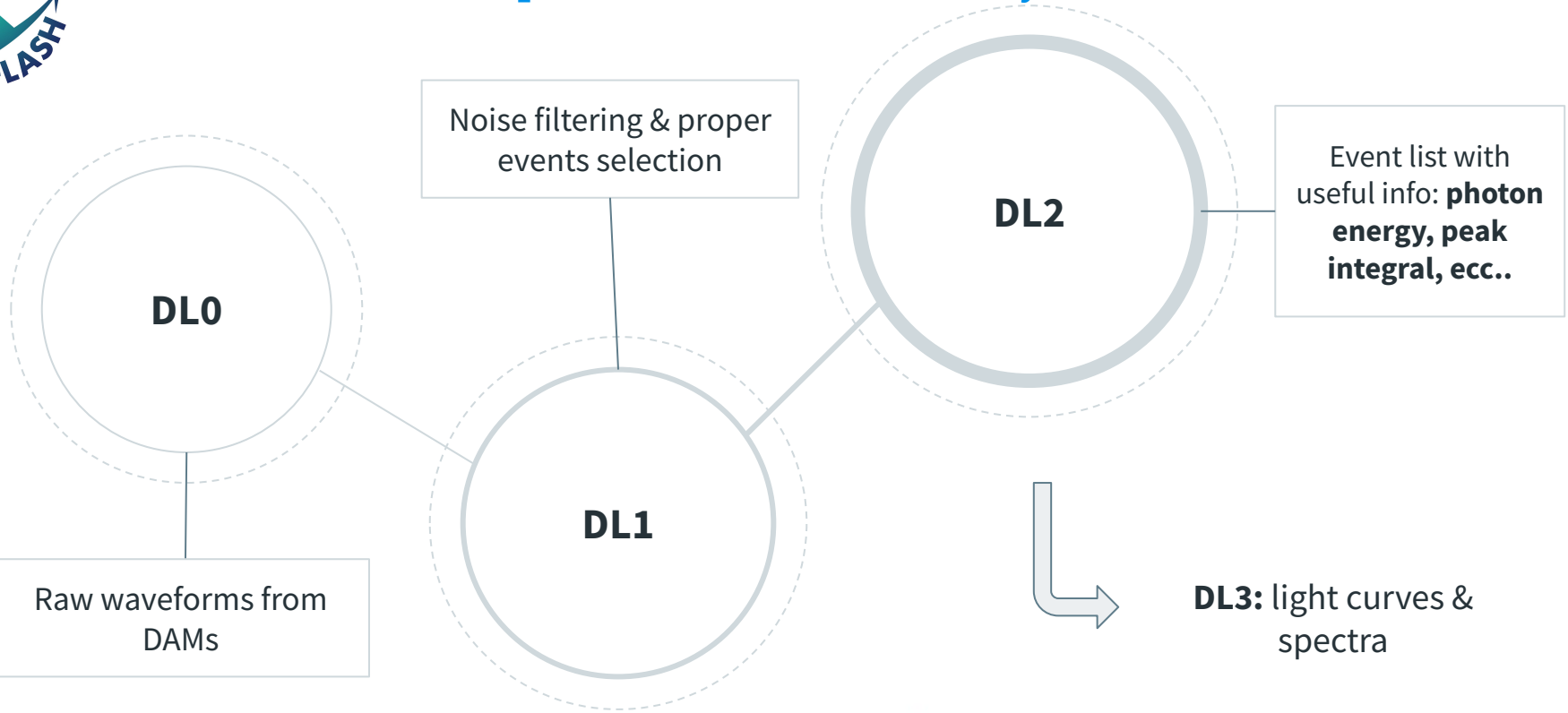
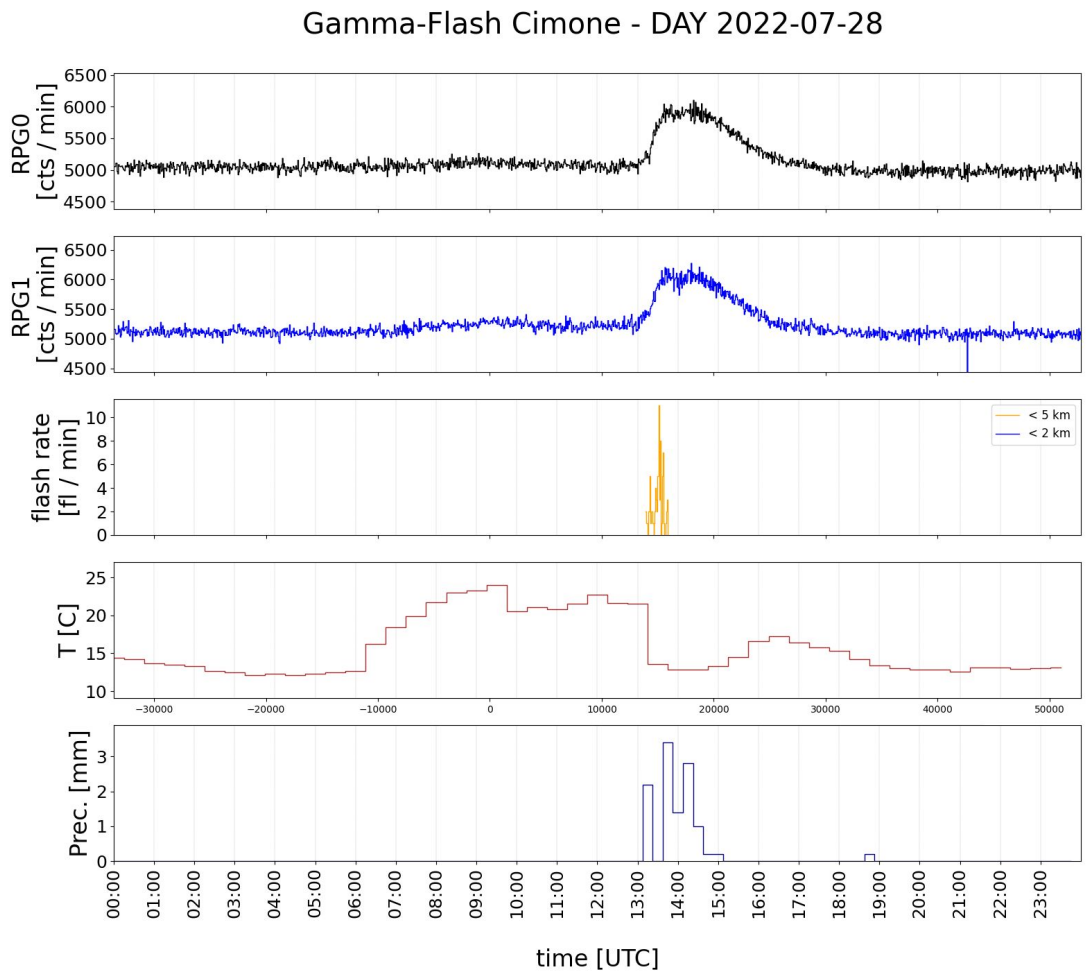


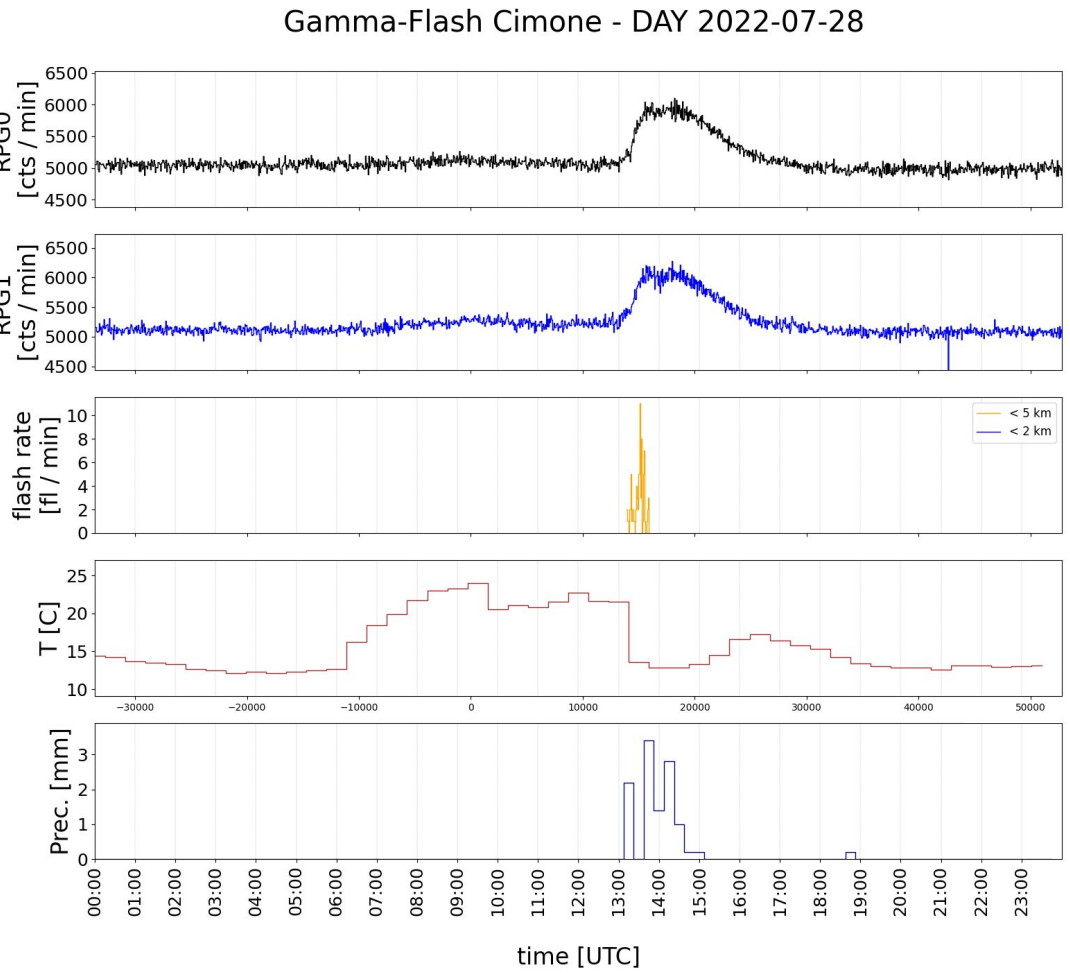

Gamma-Flash Cimone - DAY 2022-07-28
RPG0 [cts / min]
RPG1 [cts / min]
flash rate [fl / min]
< 5 km
< 2 km
T [C]
Prec. [mm]
time [UTC]

Daily **light curves**

Lightning activity

Temperature

Precipitation rate



Gamma-Flash program: flight system

- Collecting additional data by flying nearby convective systems

Gamma-Flash program: flight system

- Collecting additional data by flying nearby convective systems

- Flights provided by **Sky Services** with a Cessna Citation Mustang

Gamma-Flash program: flight system

Main payload:

1. 6 ***Scionix*** NaI(Tl) scintillator detectors for γ-rays (200 keV - 12 MeV) + *Redpitaya STEMlab* modules
2. 2 neutron (fast & termal) detectors + *CAEN* digitalizer

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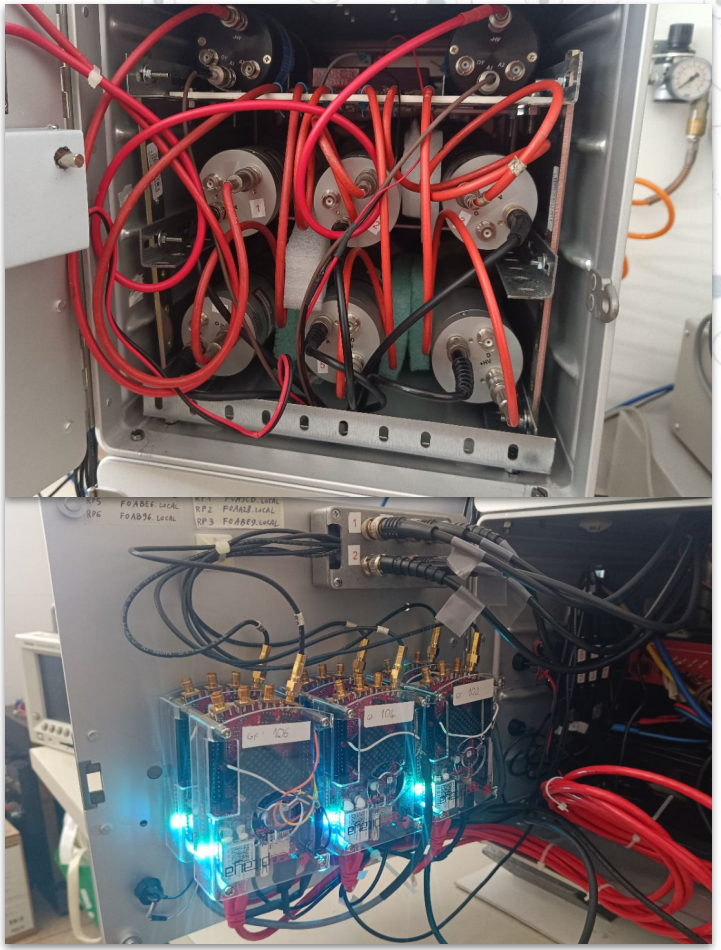
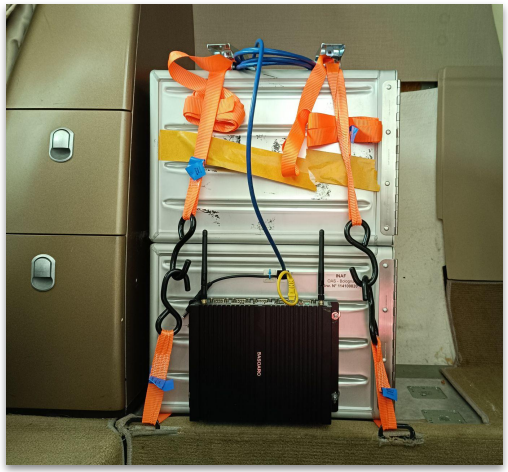
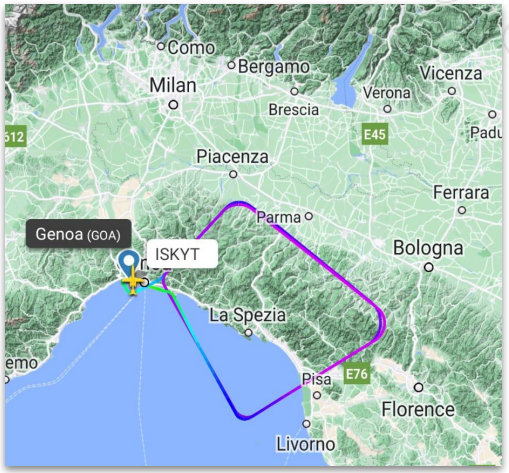


Gamma-Flash program: flight system

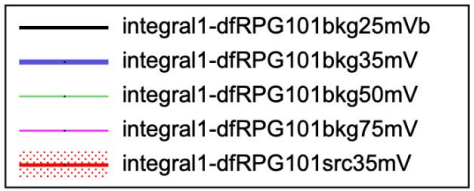
Test flight: 22 December 2023 → Verify the correct performance of the setup under good weather conditions

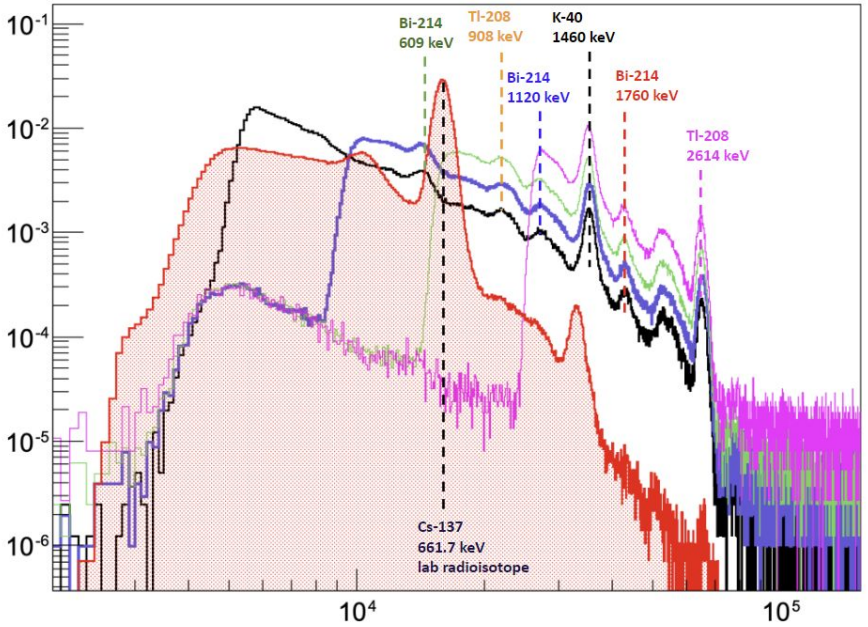




Gamma-Flash program: flight system

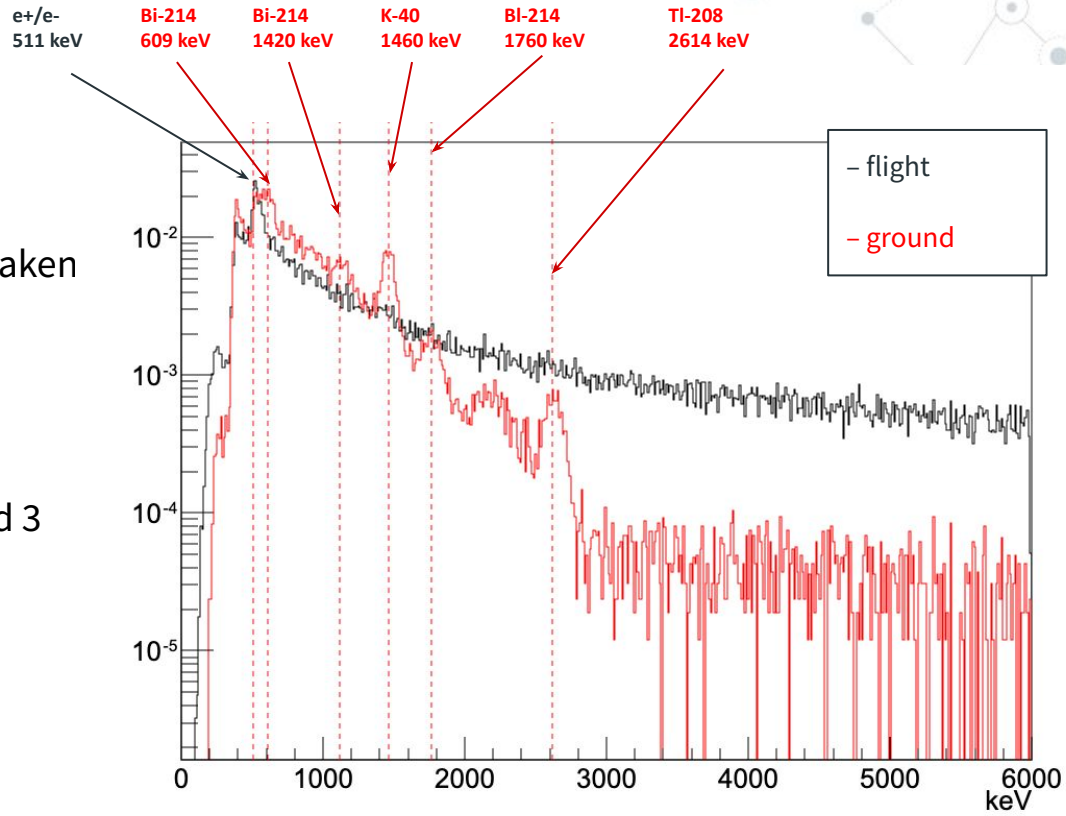
Tuning of lower threshold in order to be able to detect the 511 keV emission





Gamma-Flash program: flight system

- In **red**, calibrated spectrum taken on ground
- In **black**, flight spectrum integrated on 2 detectors and 3 altitudes (10, 11, 12 km)

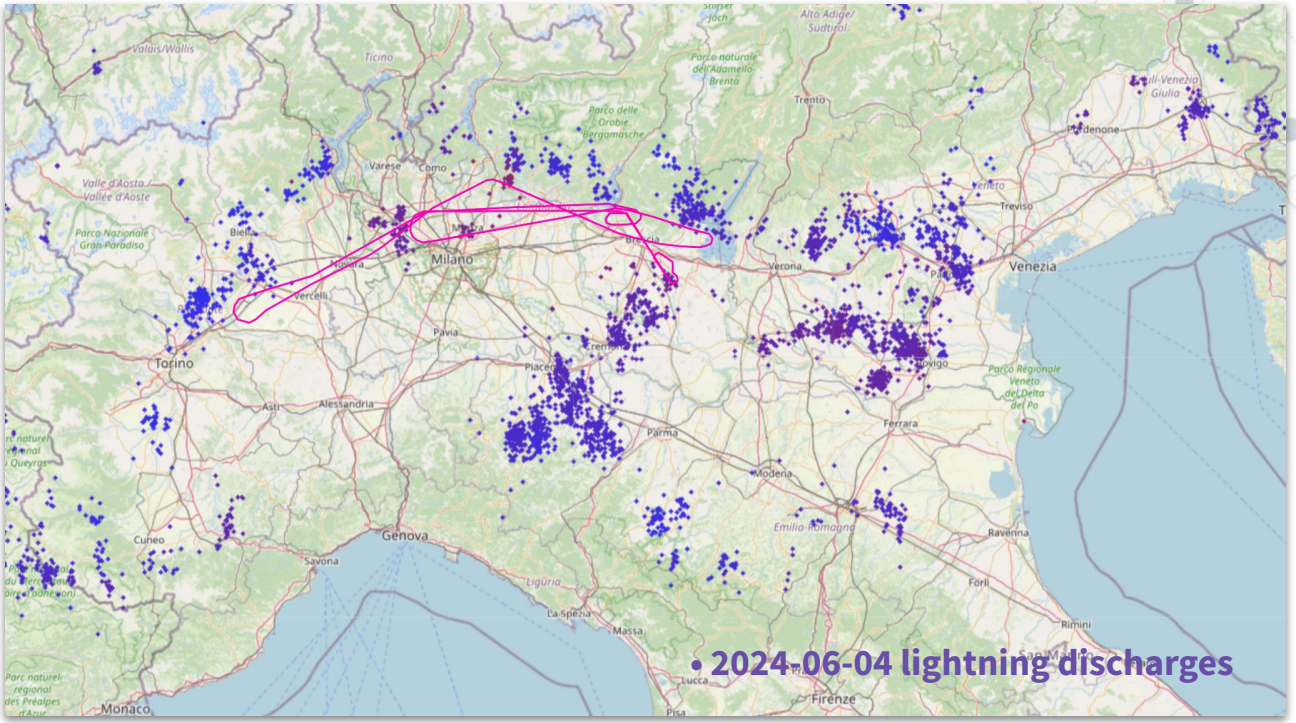


Gamma-Flash program: flight system

1st operational flight:
4 June 2024

Duration: 2.5 h
Average altitude: 10 km
Travelled distance: 800 km

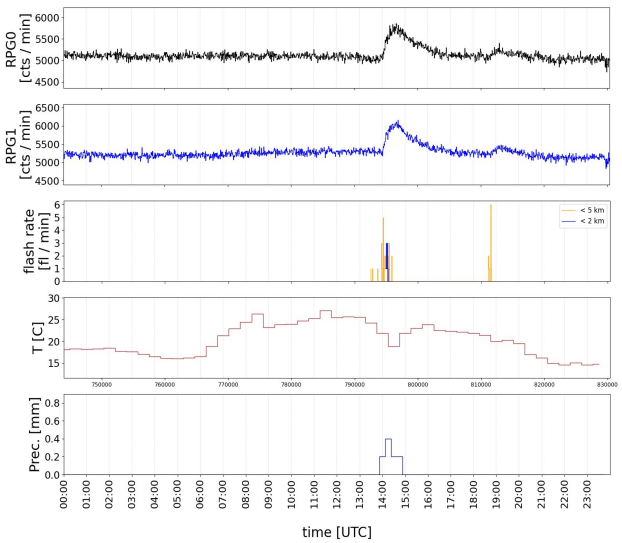
Data analysis in progress…



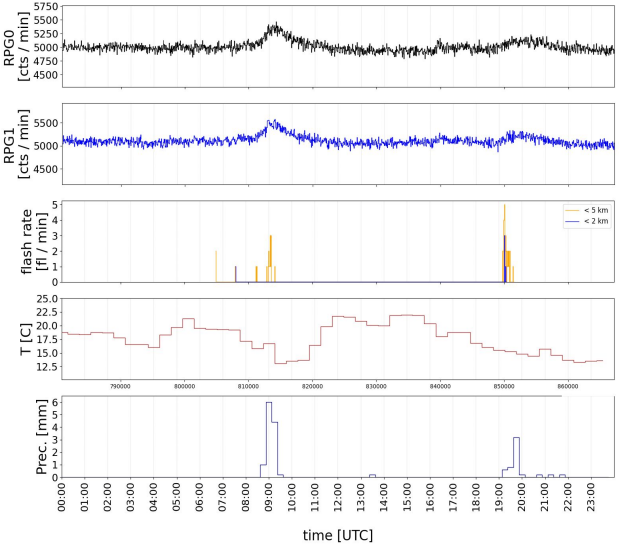
Detection of gamma-ray emissions

55 gamma-ray enhancements (18 during thunderstorms; 37 during standard precipitations)

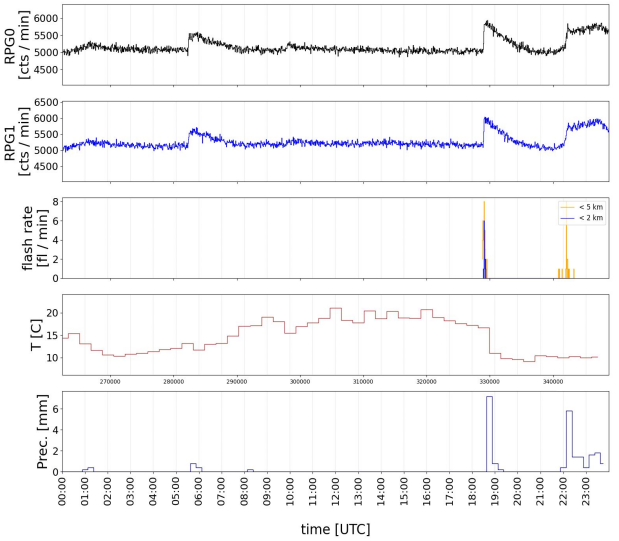
Gamma-Flash Cimone - DAY 2022-08-06



Gamma-Flash Cimone - DAY 2022-08-18



Gamma-Flash Cimone - DAY 2022-08-12



analysis in progress…

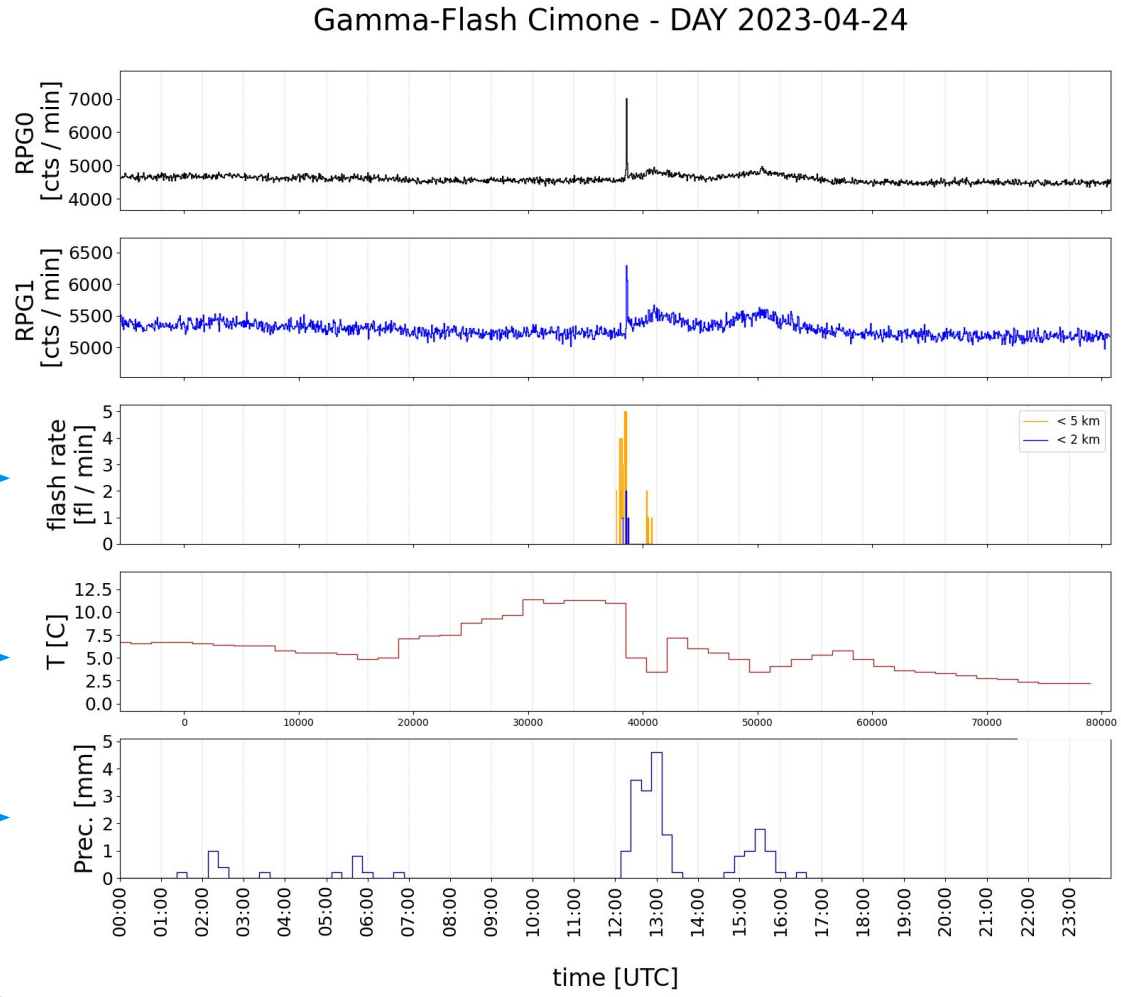
Detection of a gamma-ray glow

Daily **light curves**

Lightning activity →

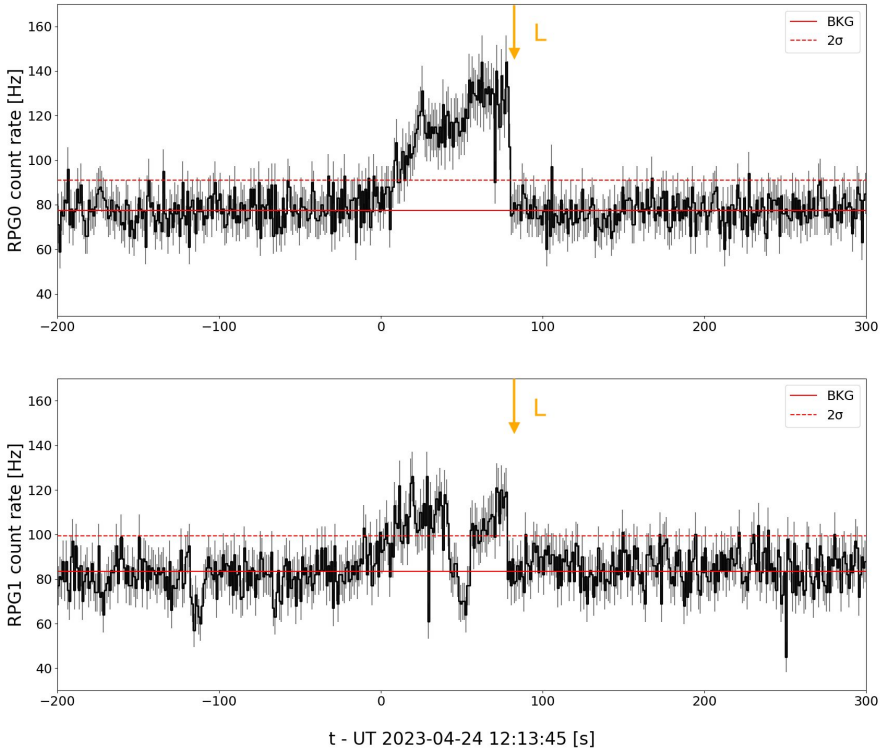
Temperature →

Precipitation rate →



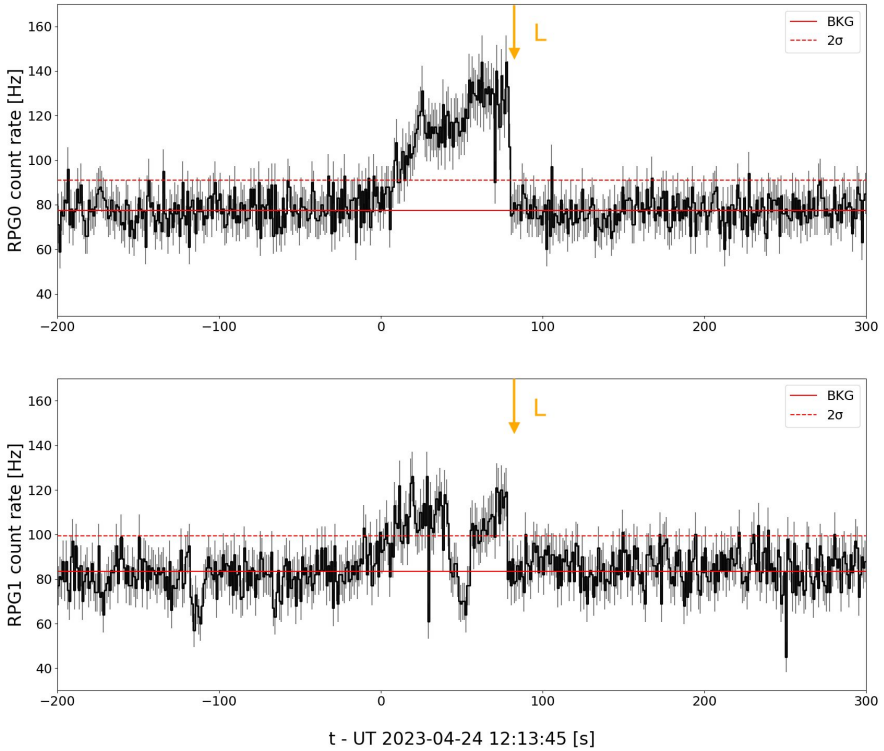
Detection of a gamma-ray glow

- Duration of the glow: **84s**



Detection of a gamma-ray glow

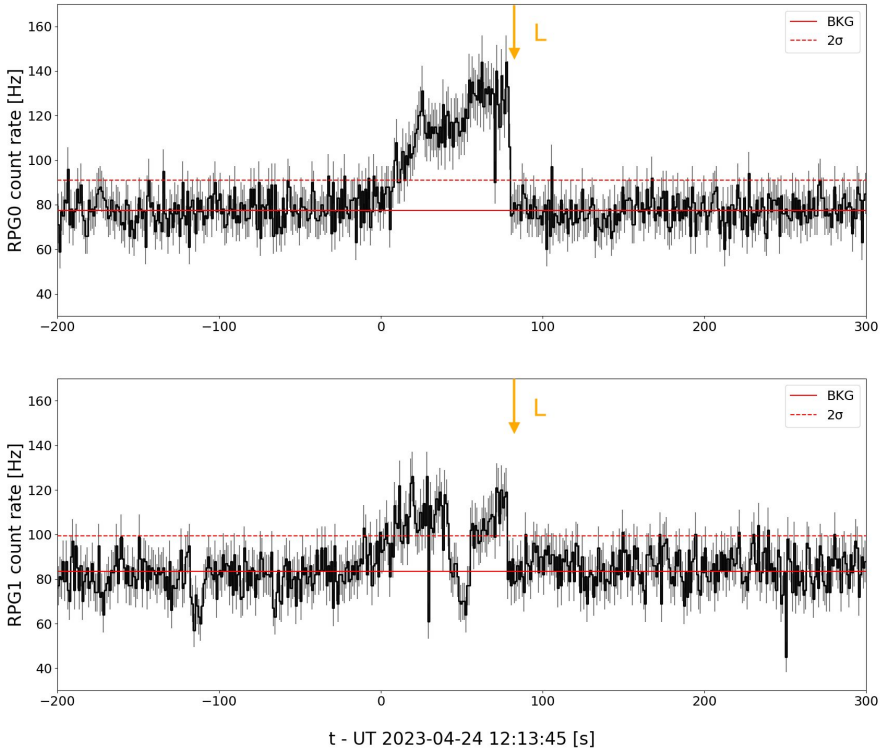
- Duration of the glow: **84s**
- ~**2200** counts above background

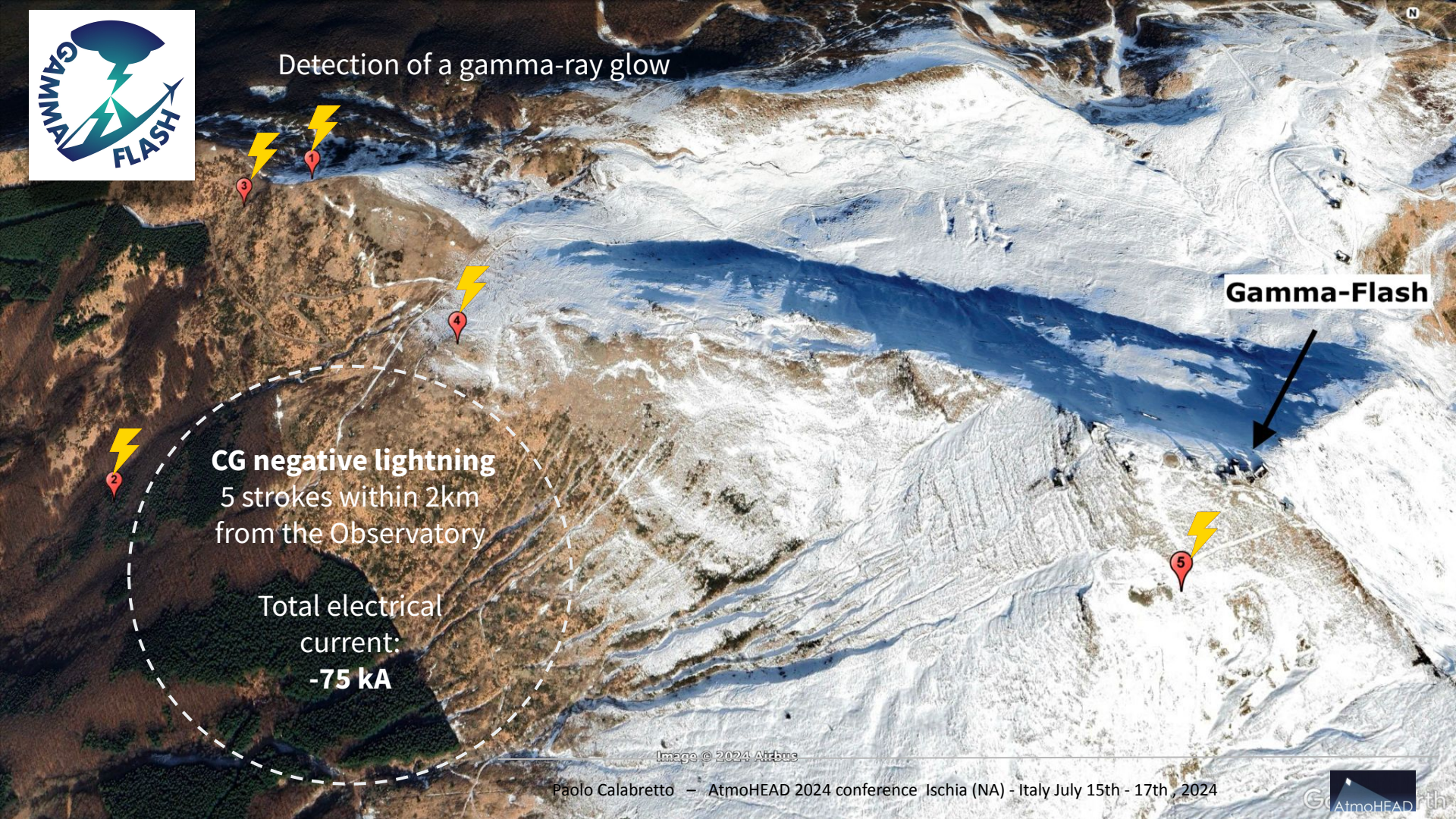


Detection of a gamma-ray glow

CG– lightning strike

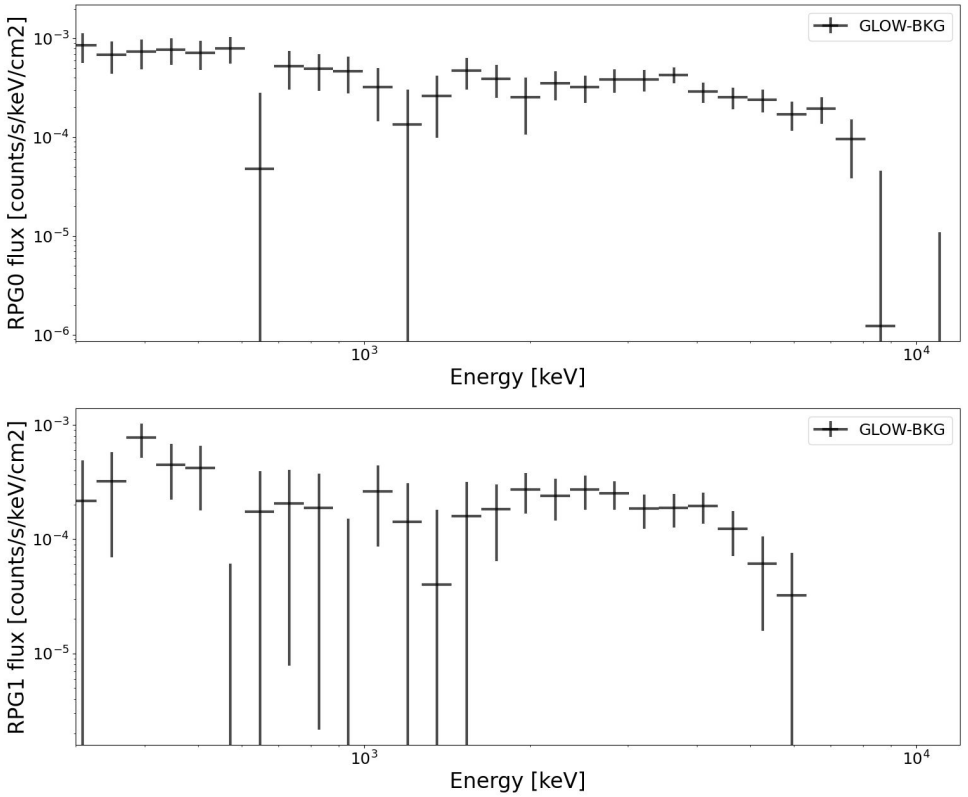
- Duration of the glow: **84s**
- ~**2200** counts above background
- Sharp decrease in count rates in conjunction with a lightning discharge




GAMMA FLASH
Detection of a gamma-ray glow
1
2
3
4
5
Gamma-Flash
CG negative lightning
5 strokes within 2km
from the Observatory
Total electrical
current:
-75 kA
Image © 2024 Airbus

Spectral analysis

Substantial component above ~2.6 MeV
(not compatible with background)



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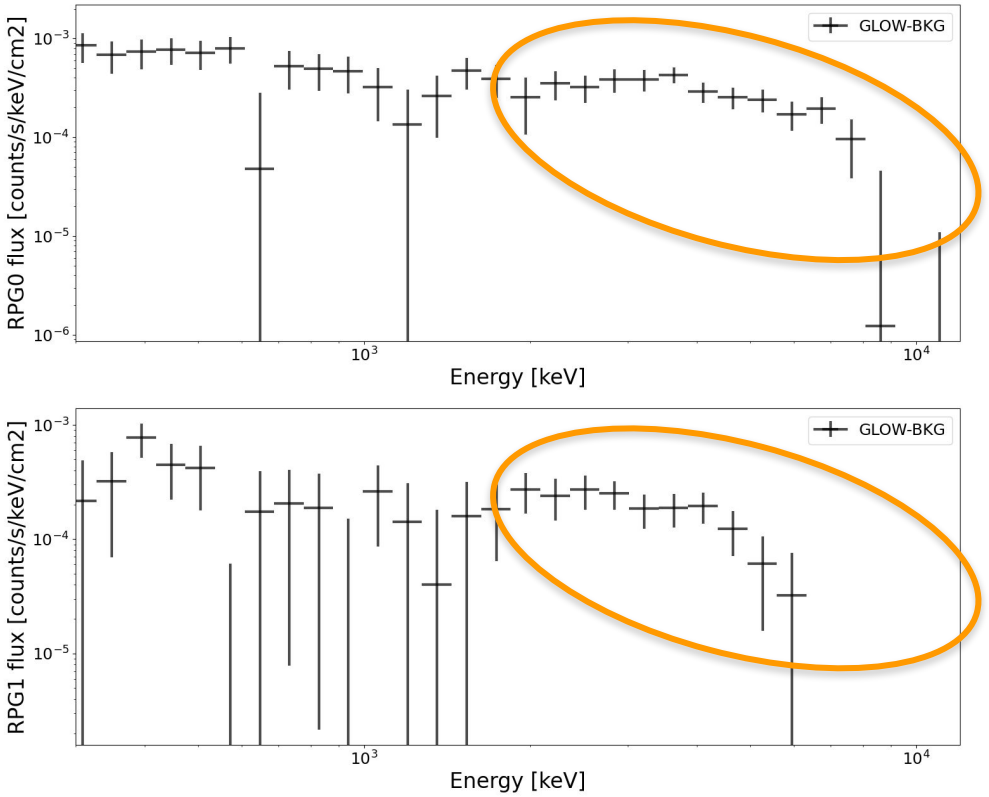
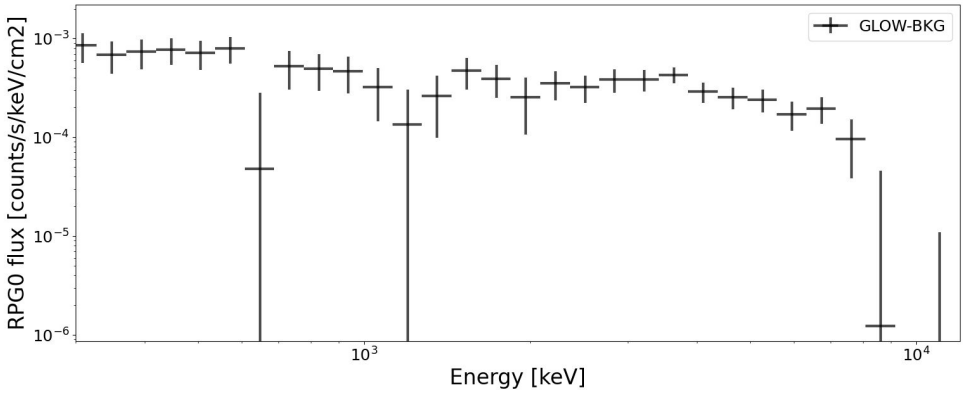


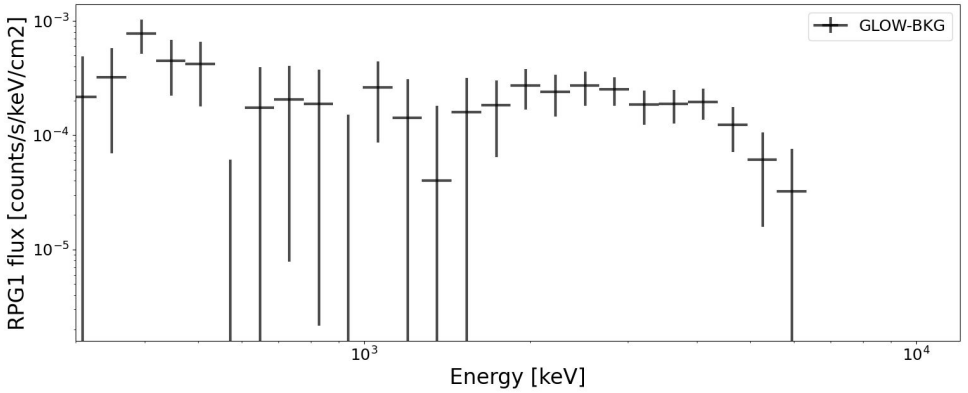
Spectral analysis

In the range 300 keV - 10 MeV, best fit with an exponential cut-off power-law

$$kE^{-\alpha}e^{-E/E_c}$$

$$\alpha = 0.4^{+0.1}_{-0.1} \qquad E_c = 6092^{+421}_{-211}\ keV$$





Future developments

- Increase effective area of the ground-based detection system
- 9 hours of flight available during summer/fall 2024