The Fast Gamma ray Spectrometer (FGS): a Multi-mission Instrument to Detect TGFs and Astrophysical Gamma ray Events

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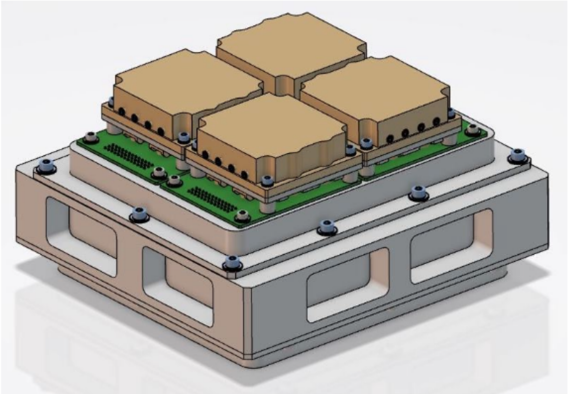

PNST 2024

January 12th, 2024 – Marseille, France

Context: Taranis' launch failure

- Taranis was a microsatellite funded by CNES, which objective was to **study energetic and luminous events produced by Earth thunderstorms**, namely **TGFs and TLEs**

- Taranis' instruments:
  - IDEE: electron detectors
  - MCP: 2 cameras and 4 photometers
  - Electric field low and high frequency antennas
  - XGRE: X-ray and Gamma-Ray scintillation detector

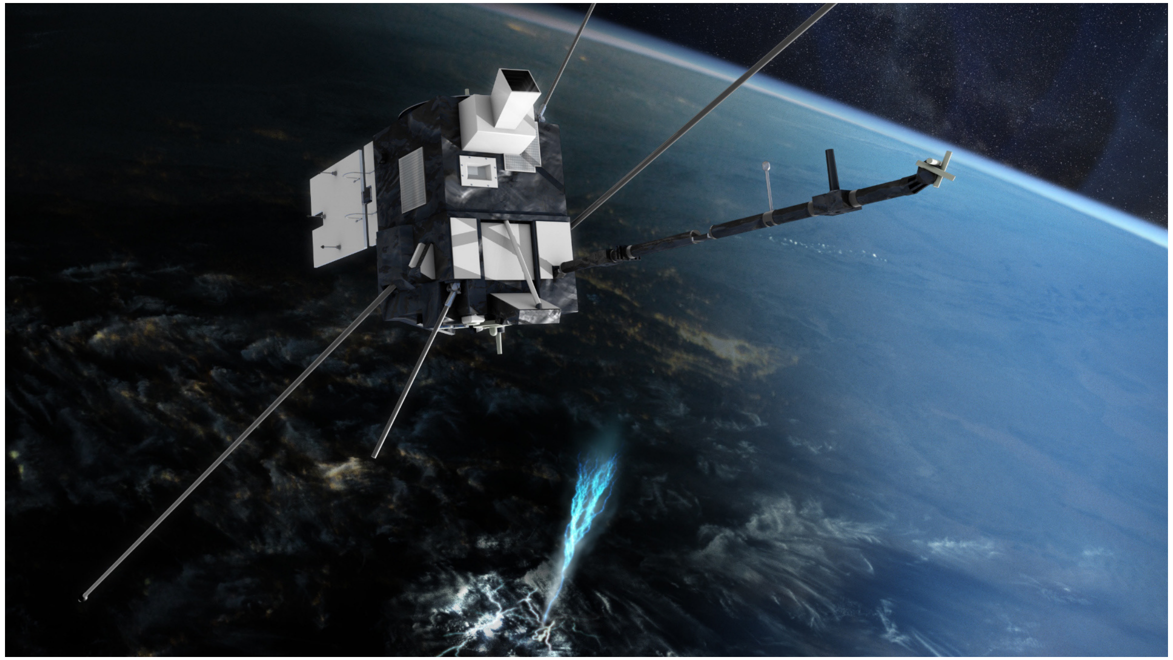

Fig: Illustration of Taranis' satellite

- In November 2020, after tens of years of development, the launch failed

  → **satellite loss**

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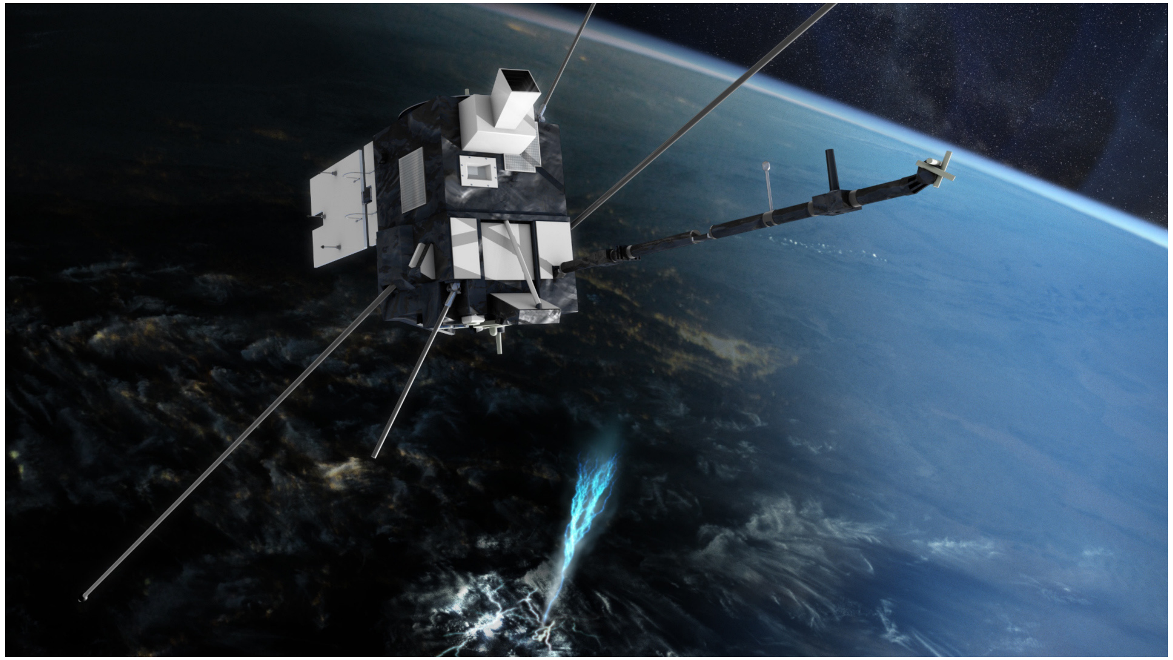

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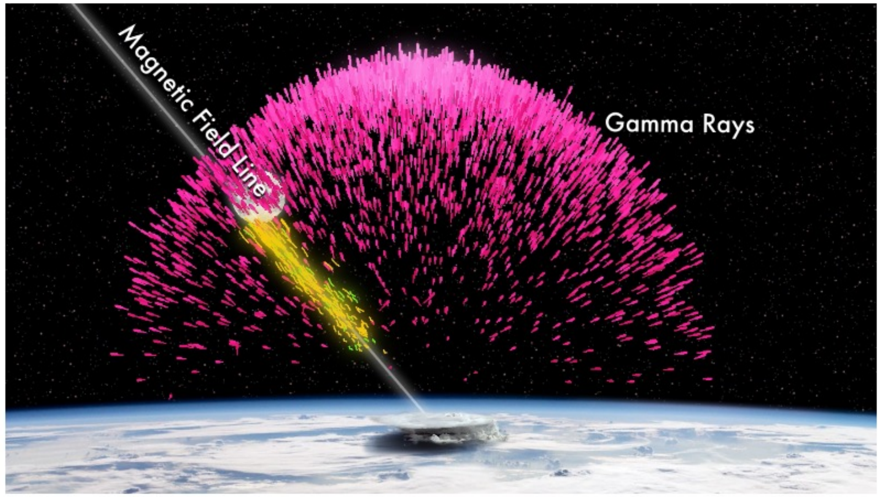
- **Events produced in association with thunderstorms:**

Transient Luminous Events (TLEs)

→ Visible Light

Terrestrial Gamma ray Flashes (TGFs)



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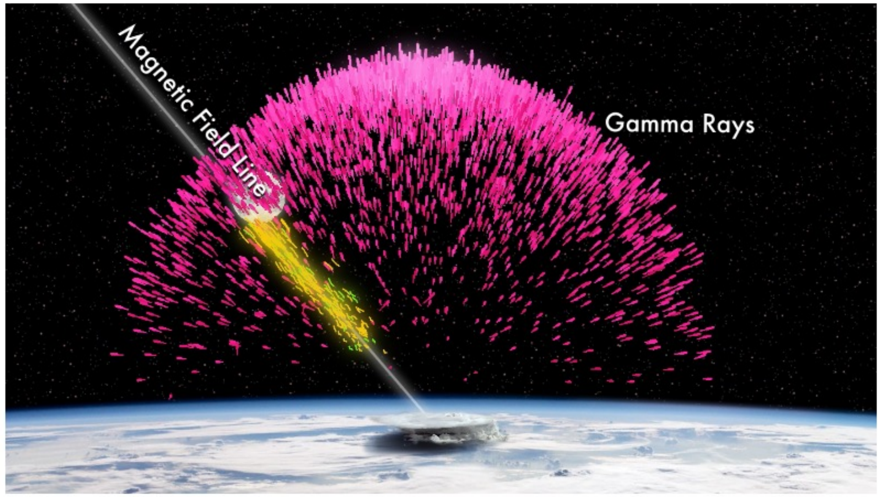

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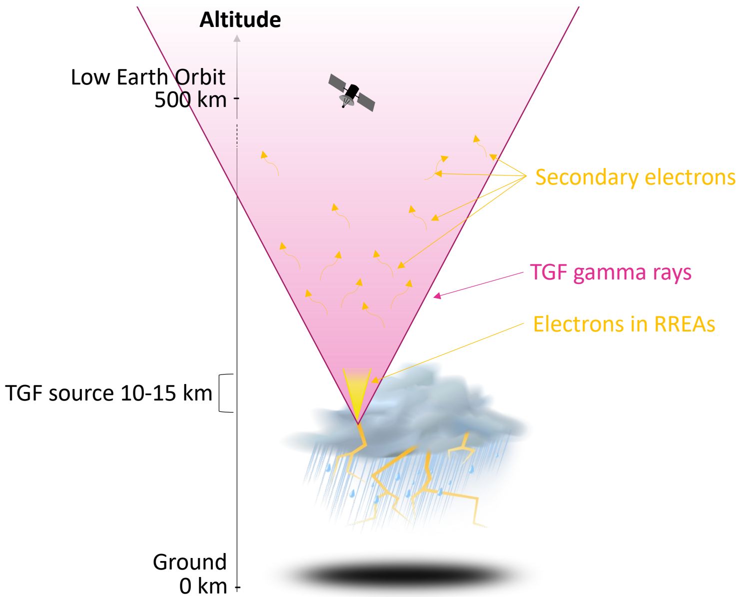

TGFs = Bursts of gamma rays produced in thunderstorms

Characteristics:

- Mostly associated with the first stages of +IC lightning
- Short duration: $< 100\ \mu$s
- High-energy photons: tens of keV to ~40 MeV
- Very bright: $\lesssim$1 ph/cm^2 when observed by satellite
- Occurrence: 400,000 TGFs/year estimated for Fermi-observable TGFs [Briggs et al., 2013]

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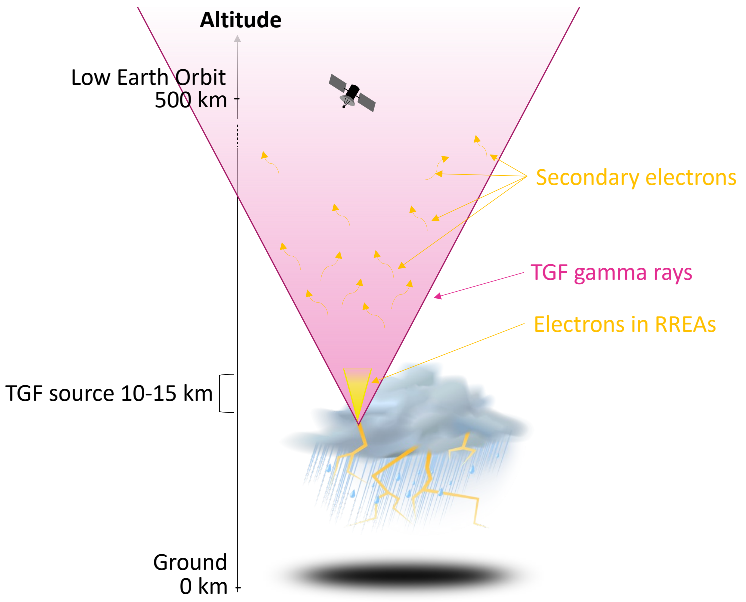
Production mechanism:

- Gamma rays are produced by relativistic electrons accelerated in the electric field of the thunderstorm



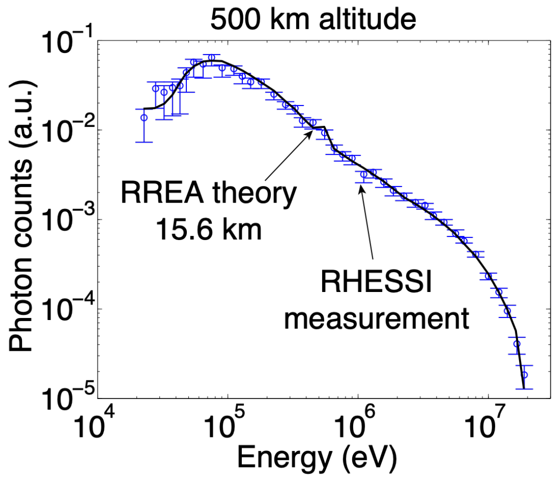


Fig: Accumulated spectrum of 289 TGFs detected by RHESSI [Dwyer and Smith, Geophys. Res. Lett., 32, L22804, 2005]

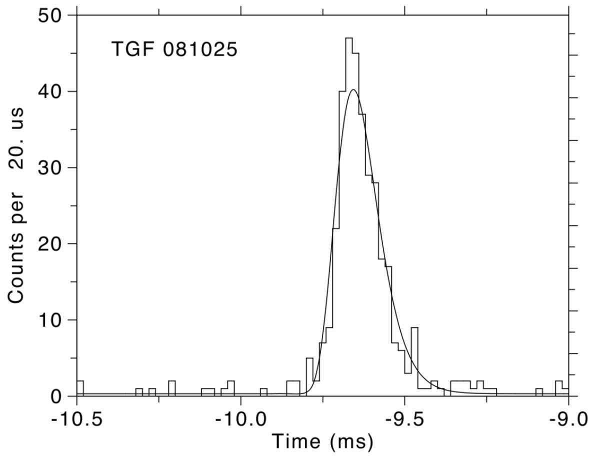
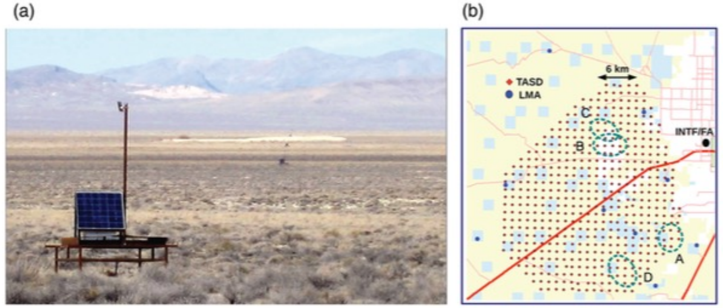


Fig: Light curve of a TGF detected with Fermi-GBM (14 detectors of 5” diameter)

Current TGF detections

- Mostly by satellite:
  - Astrophysics satellites (e.g., Fermi, AGILE, RHESSI)
  - Only few space instruments designed to detect TGFs (e.g., **ASIM on the ISS**)
- Some ground-based detections for downward TGFs (e.g., with the **Telescope Array**)
- Single-point aircraft detections [e.g., Dwyer et al., 2012; Smith et al., 2011; Østgaard et al., AGU, 2023]



+ hundreds of a new type of TGFs, called FGFs (Flickering Gamma ray Flashes), have been very recently detected by aircraft (presented at AGU23, San Francisco)

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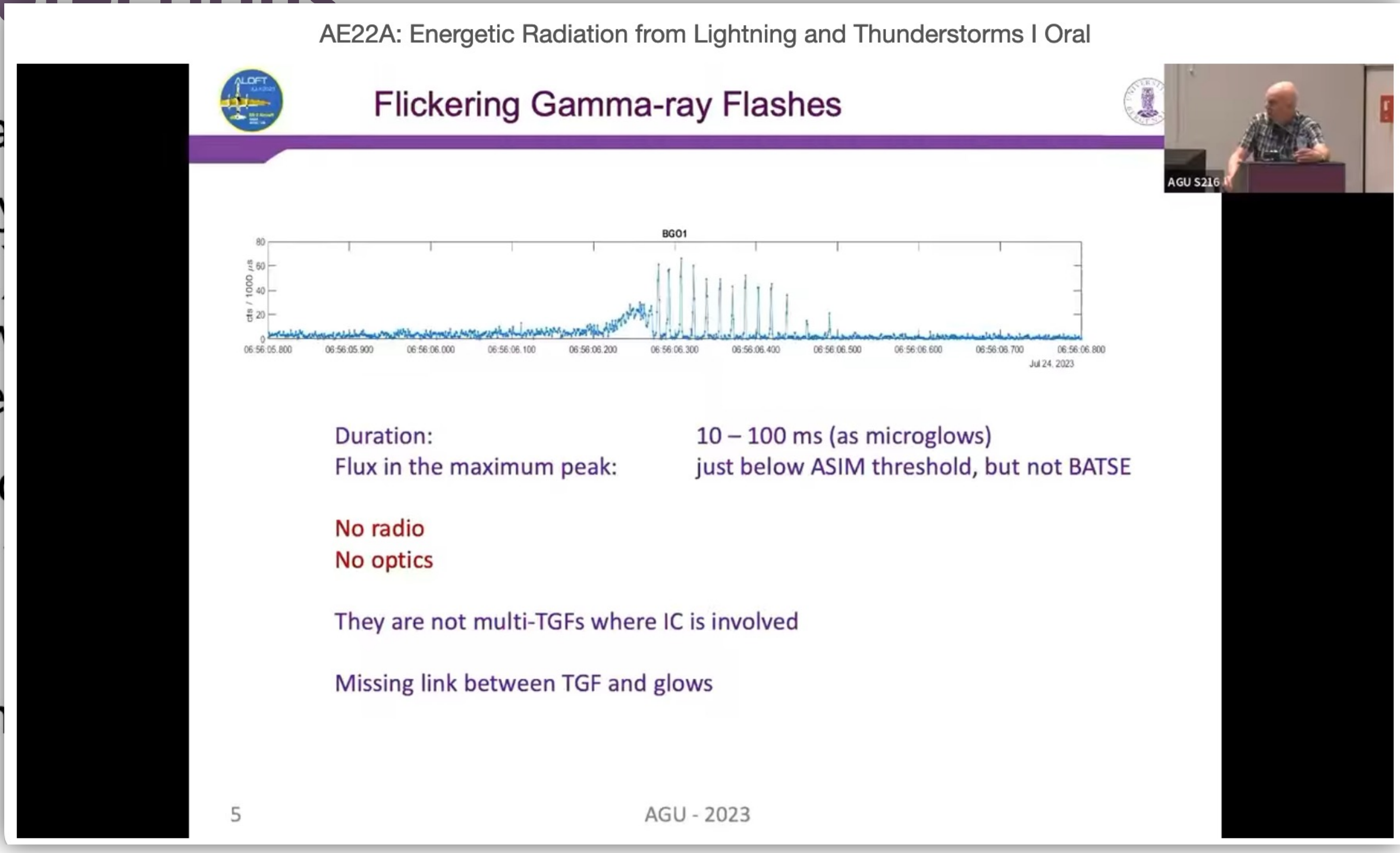

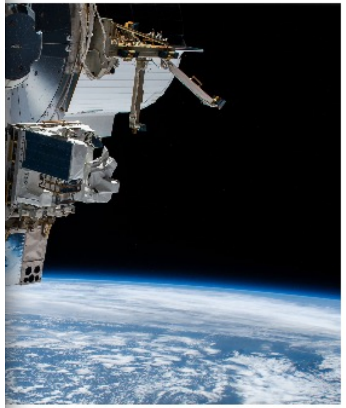

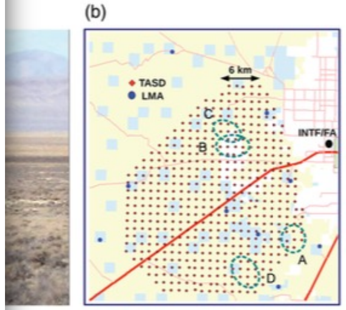

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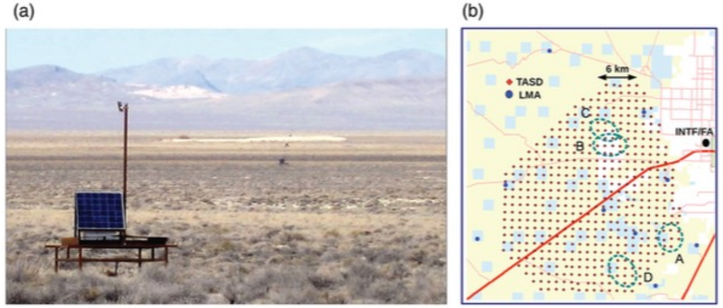

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→ Need to develop instruments designed to detect TGFs

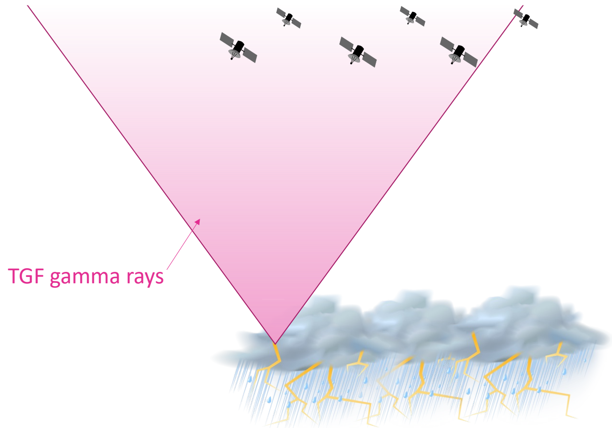
Objective

Develop a new gamma ray spectrometer multi-mission for TGF detections

→ R&T in collaboration with LESIA and CNES

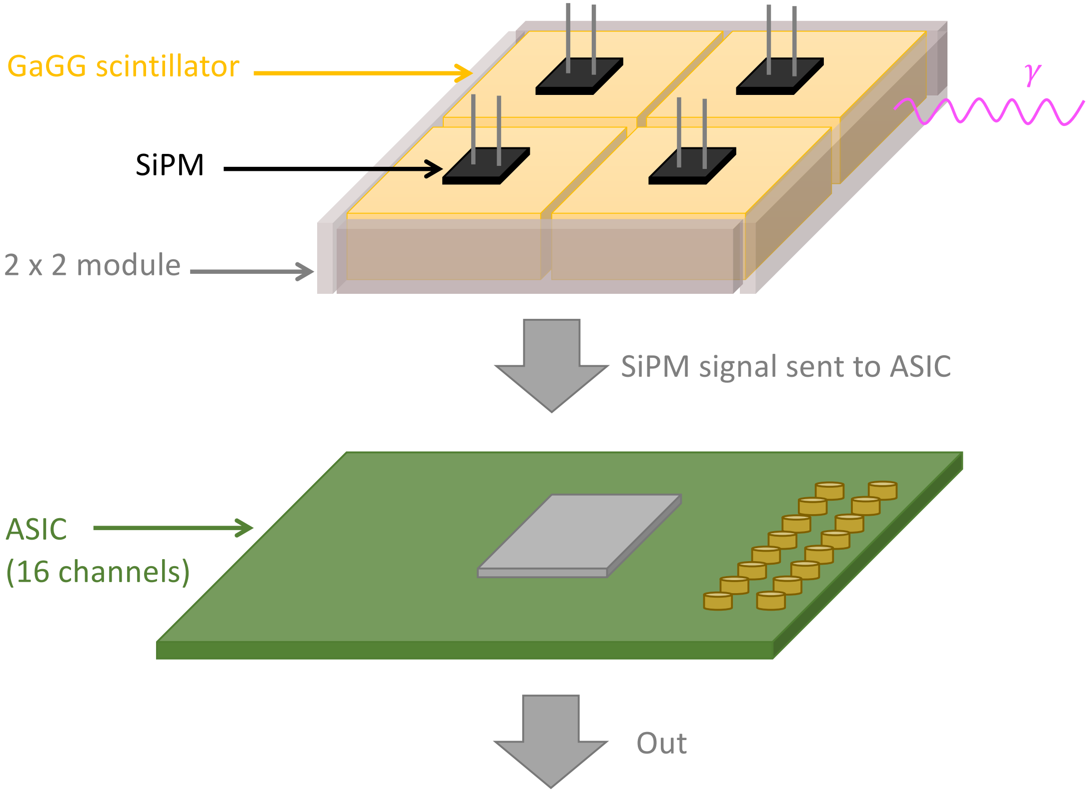
Space multi-mission instrument **Fast Gamma ray Spectrometer (FGS)**:

- To fly on nanosatellites or satellites
- To detect different types of gamma events: TGFs, GRBs, Solar flares
- Scintillators adaptable in types, sizes, ...

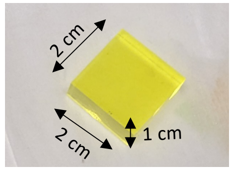


New instrument: Fast Gamma ray Spectrometer (FGS)

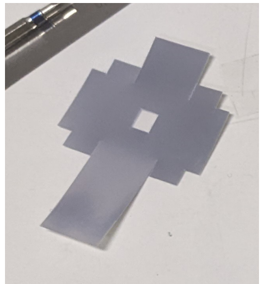
- Components choice: GaGG + SiPM + ASIC
- Electronics development: ASIC/ADC board, power board
- Mechanical structure: for four 2x2-modules



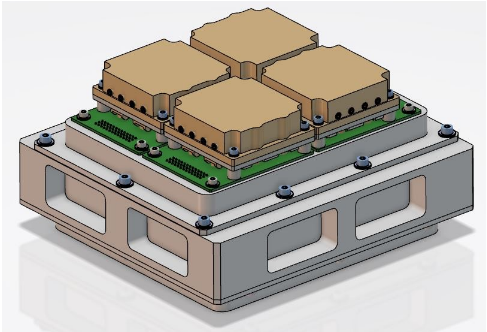
For each photon detected in one of the scintillators:
- Time of the detection
- Energy of the particle



GaGG scintillator



Vikuiti (reflective material)



FGS design composed of four 2 x 2 modules

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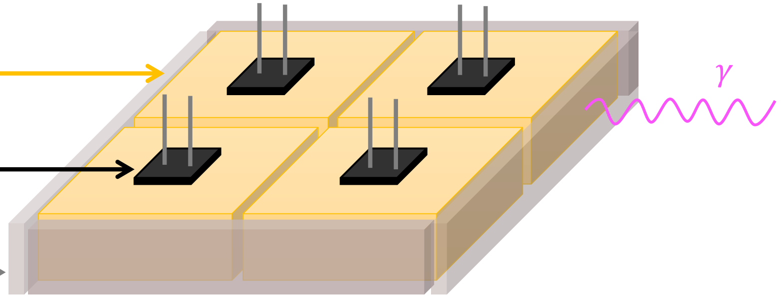
To detect:

- energies between 20 keV – 20 MeV
- flux up to 1 particle/20 us

GaGG scintillator

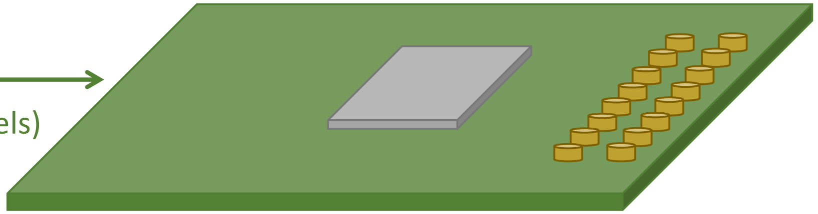
SiPM

2 x 2 module



SiPM signal sent to ASIC

ASIC
(16 channels)



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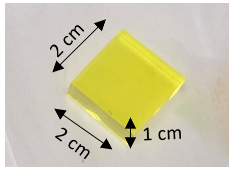

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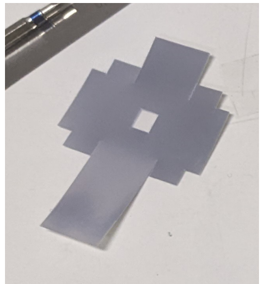

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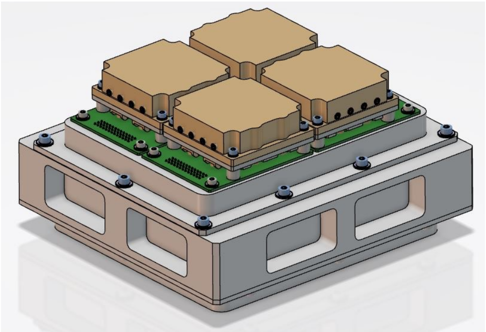

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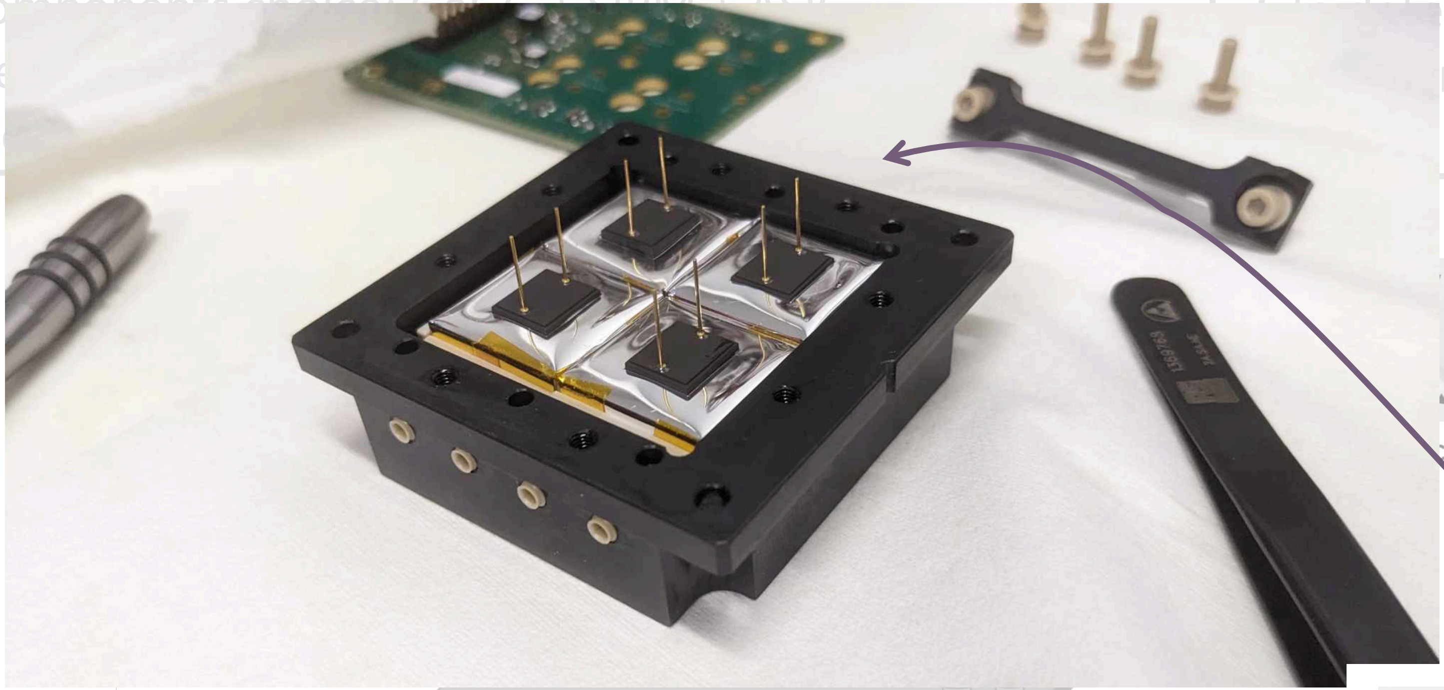

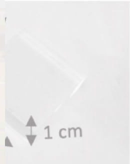

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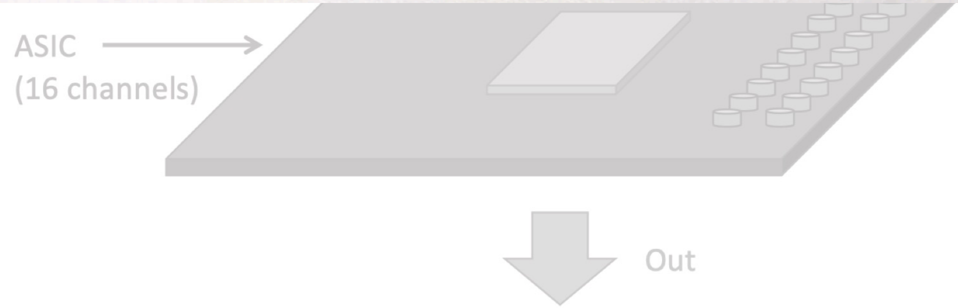

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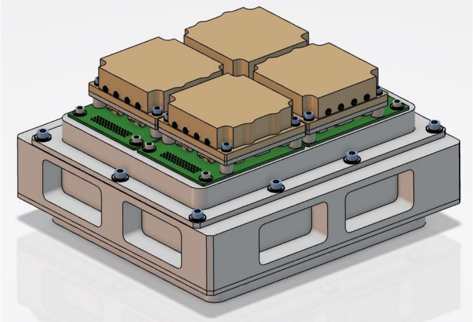

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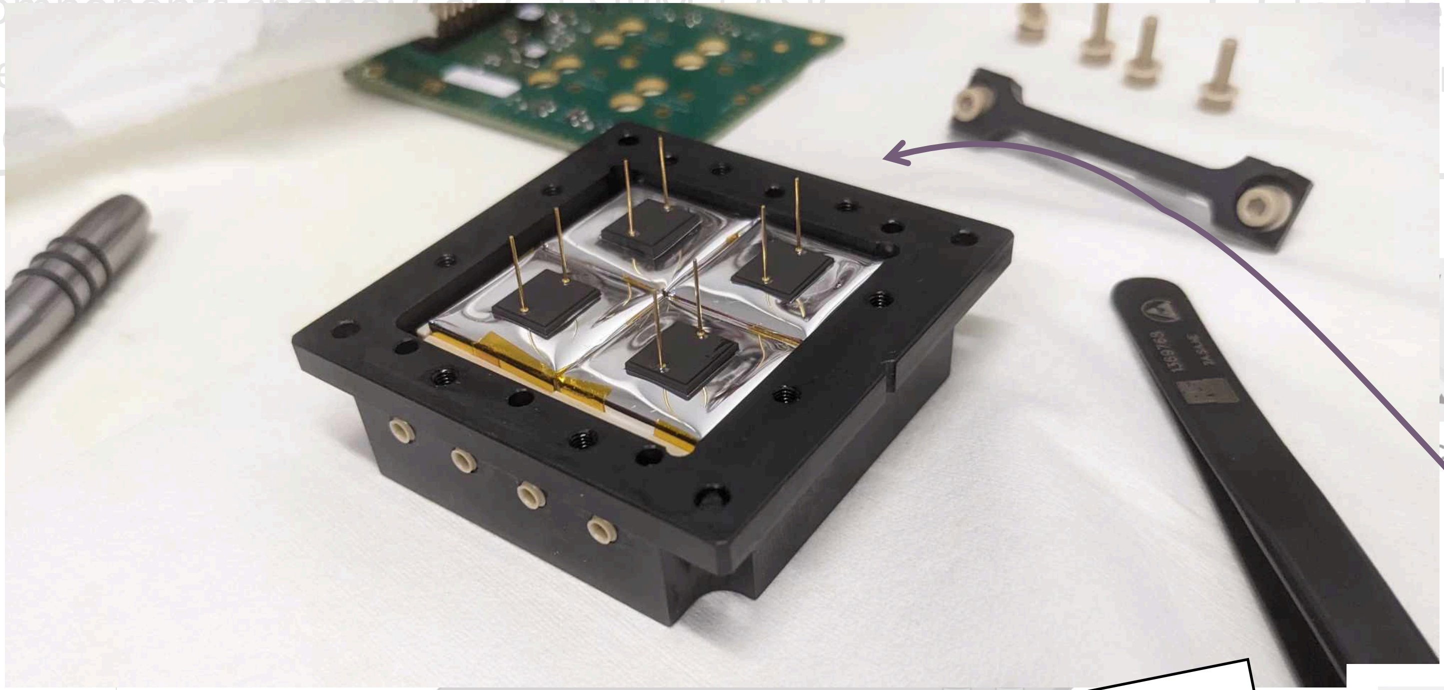

1 cm
cintillator

Vikuiti (reflective material)

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Instrument specifications published in: Pailot et al., **FGS, a multi-mission space gamma-ray spectrometer: Design optimization and first results**, 2023, https://doi.org/10.1016/j.nima.2023.168076

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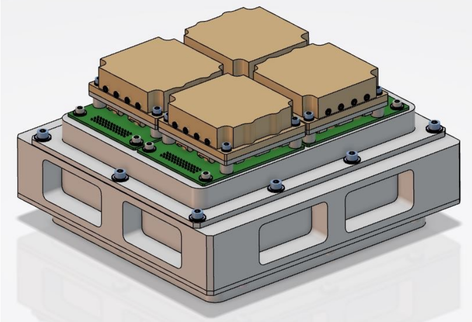

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Development: crystal comparison

- 2 suppliers (EPIC, C&A)
- 3 types of GaGG (normal, fast, high-resolution)
- Surface state (polished/unpolished)
- Size of the Vikuiti window

Development: crystal comparison

Comparison of gain and **resolution** for:

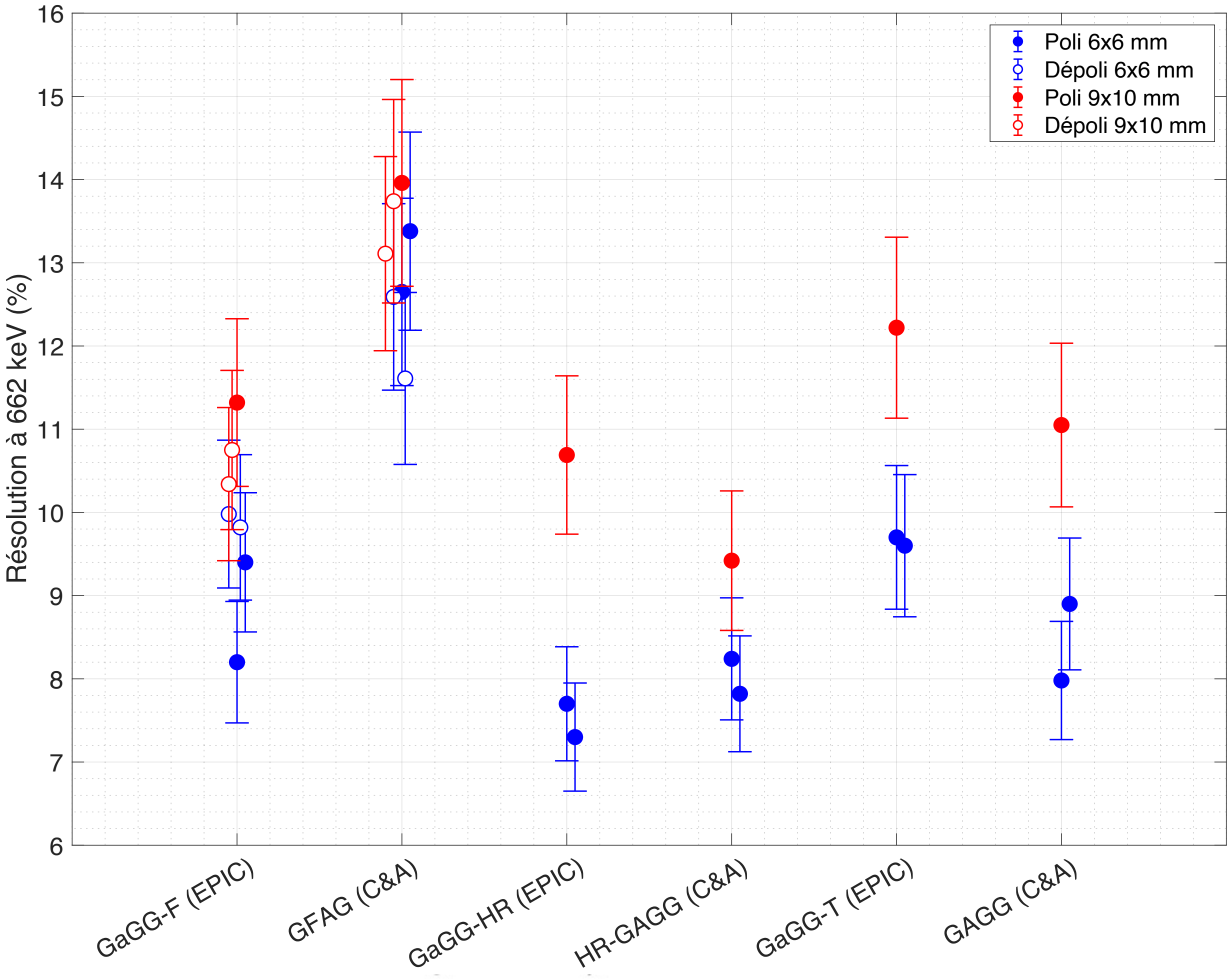
- 2 suppliers (EPIC, C&A)
- 3 types of GaGG (normal, fast, high-resolution)
- Surface state (polished/unpolished)
- Size of the Vikuiti window

→ **GaGG-F (EPIC), unpolished**

Because:

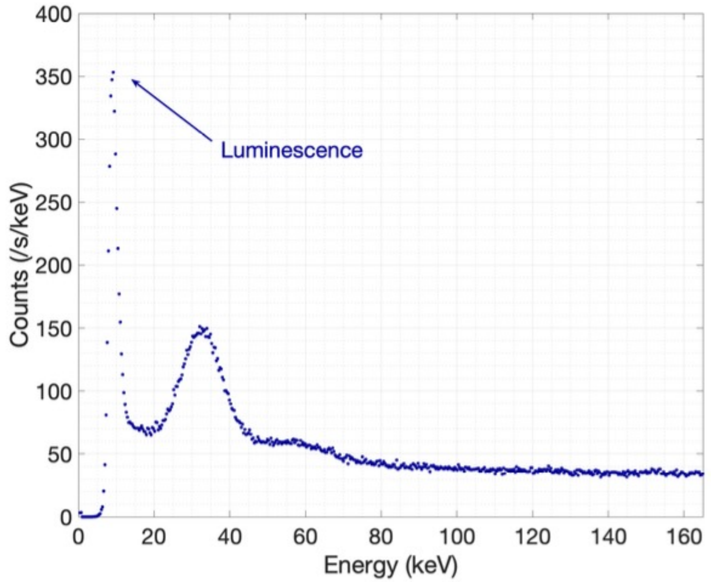
fast and good gain and resolution

Resolution @662 keV

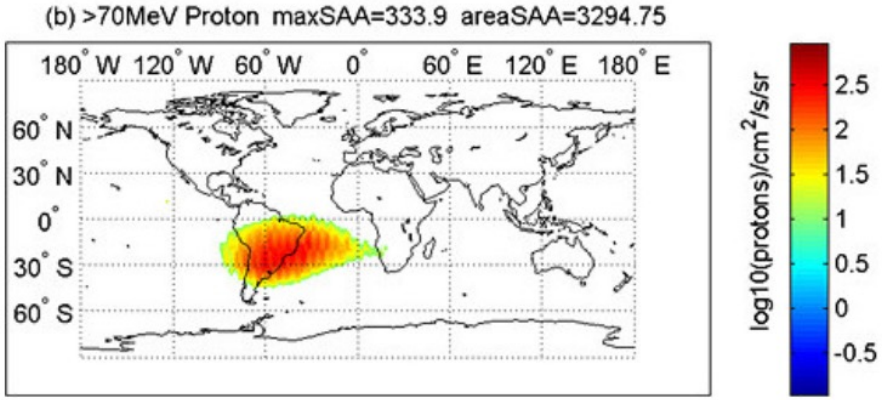


Development: luminescence

- Phenomenon of **luminescence** discovered with GaGG scintillators:
  When GaGG crystal exposed to visible light
  → luminescence produced by the GaGG crystals
  → SiPM sees lots of light
  → seen as a high number of low energy counts in the energy spectrum
  → detector gain is reduced because of the current involved

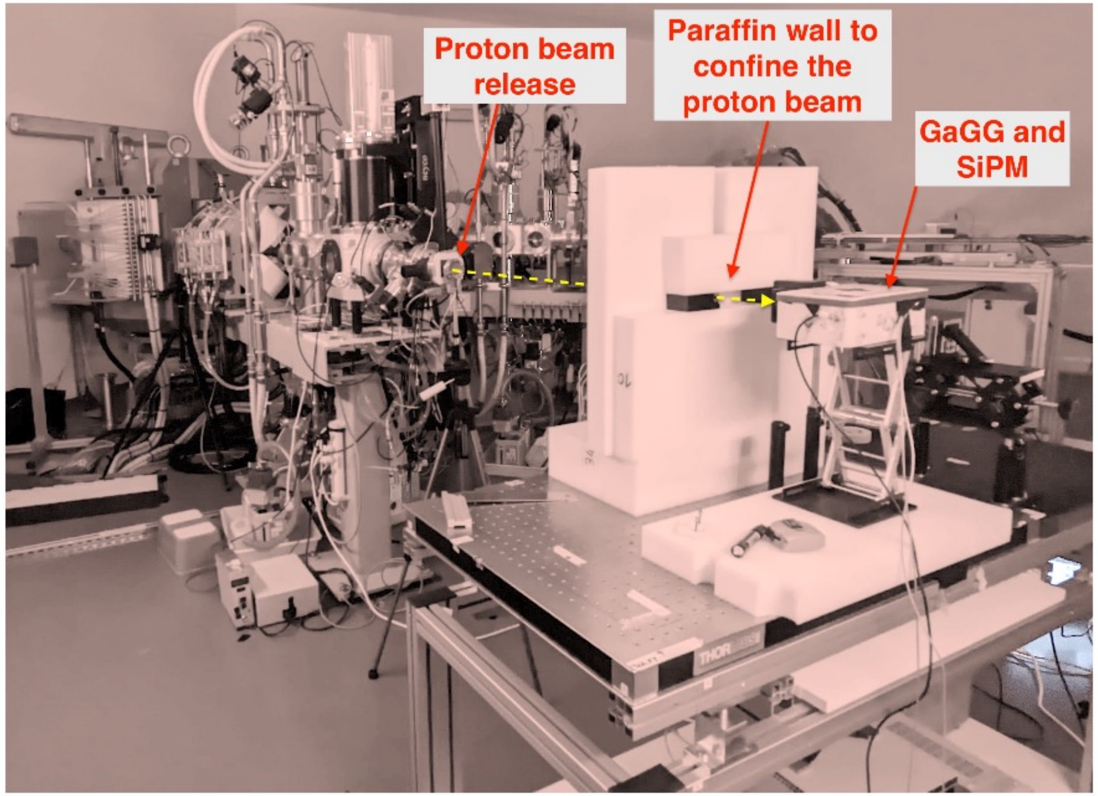


→ **Question of the impact of protons in space (South Atlantic Anomaly) on GaGG performances**



Development: proton irradiation

→ **GaGG measurements in proton accelerator performed in March:**

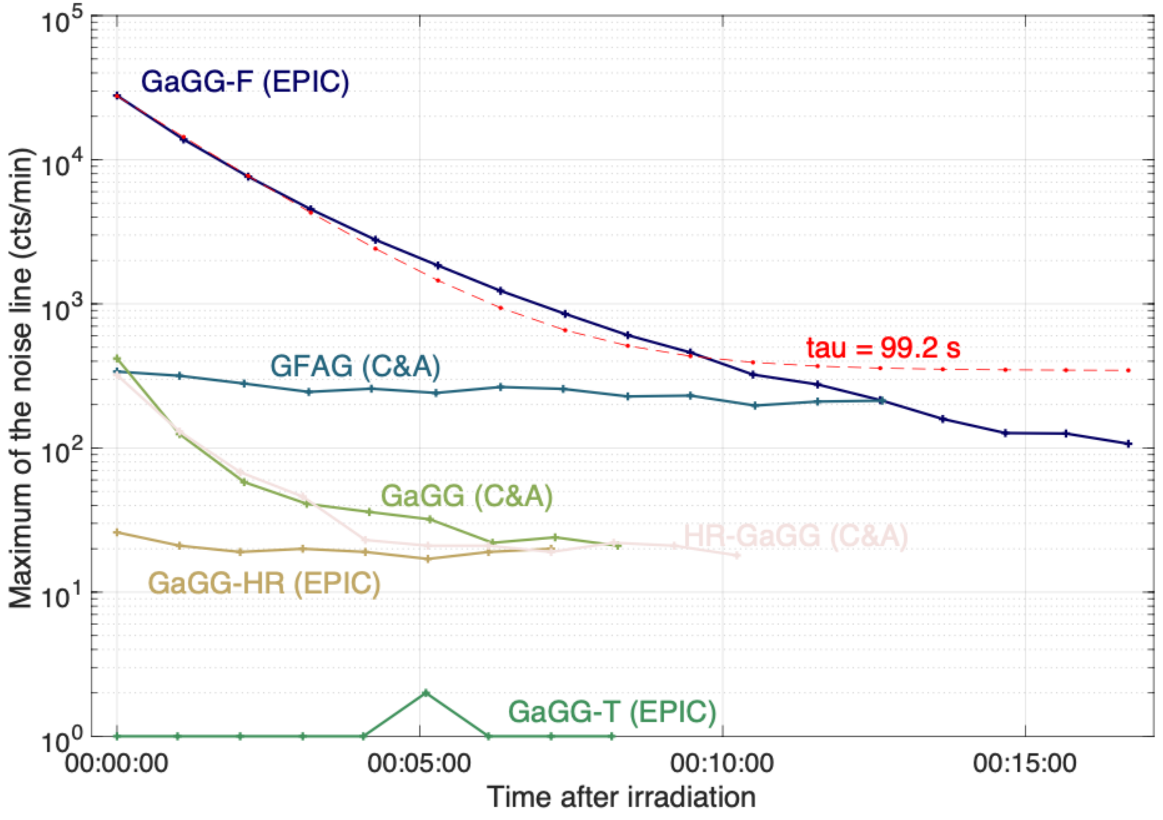


ARRONAX proton accelerator (in Nantes)

Proton beam maximizing the proton flux in the SAA:

- Flux: 10,000 pr/cm^2/s
- Energy: 70 MeV
- Duration: ~15 min

Development: proton irradiation



Results:

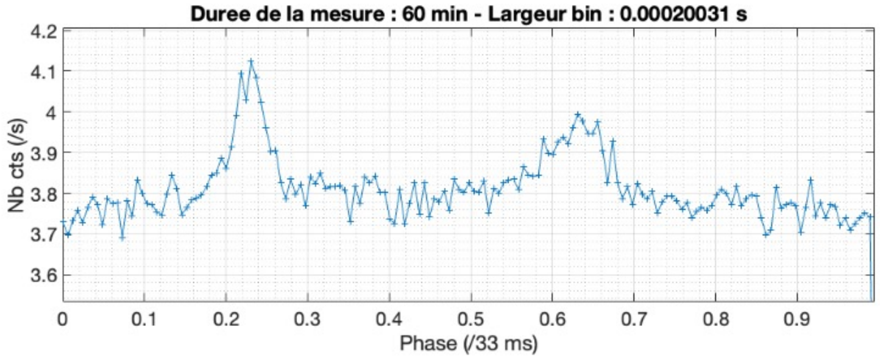
- Fast GaGG (EPIC) is subject to luminescence after proton irradiation
- Luminescence decay time is estimated to be low: ∼1 min 30

→ Luminescence << an orbit duration decay time (∼ 1h30)

→ These results and others will be published in Pallu et al. (in preparation)

Future of FGS: balloon flight in June 2024

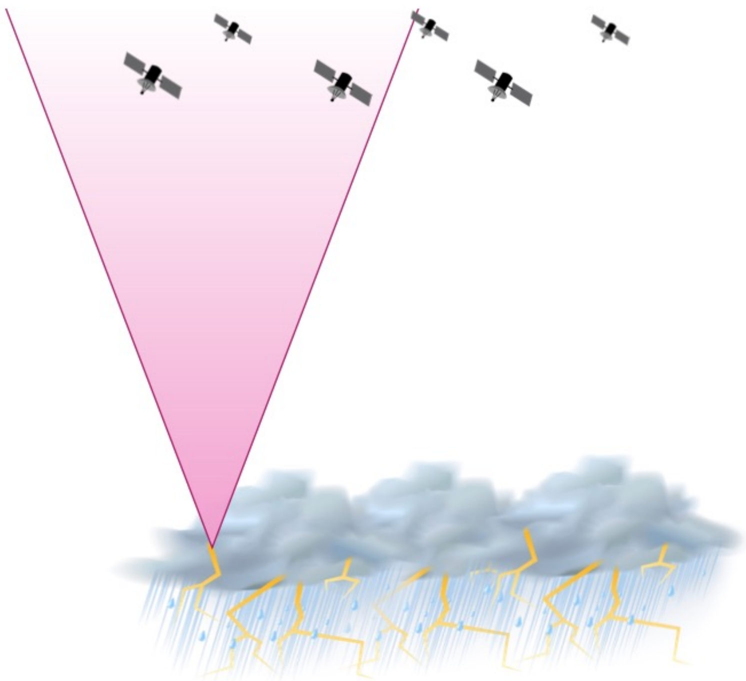
- Very convenient to validate instrument working in conditions close to space conditions
- CNES proposes balloon flights with stratospheric balloons: ∼10 h of flight at ∼30 km of altitude, in Kiruna, Sweden (high latitude)
- Scientific objective: no TGF or GRB expected, but we should detect Crab pulsar, see simulation:



Future of FGS: possible future missions

BEES (Bursty Energetic Events in Space):

- Project proposed at CNES/PASO
- Nanosatellite constellation in formation flight
- To detect TGFs and GRBs
  → help to determine TGF parameters (nb of photons, beam angle, tilt,...)



- BEES will also detect Gamma-Ray Bursts (GRBs)

The flux measurement done by the different nanosats of the constellation will give us an estimate of the GRB location, with a precision of few degrees (TBC)

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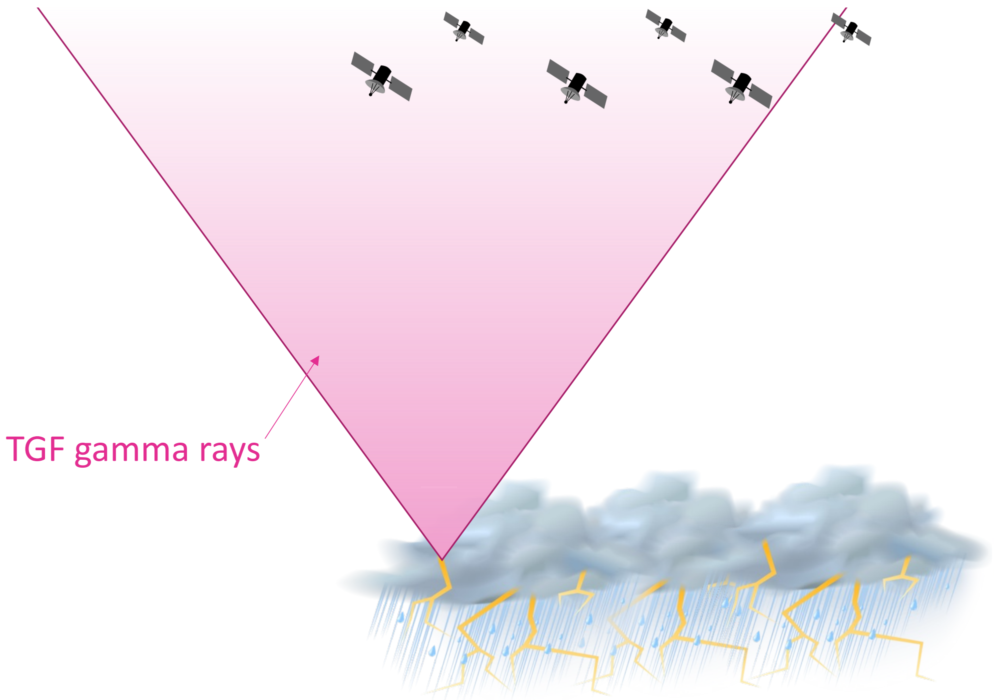

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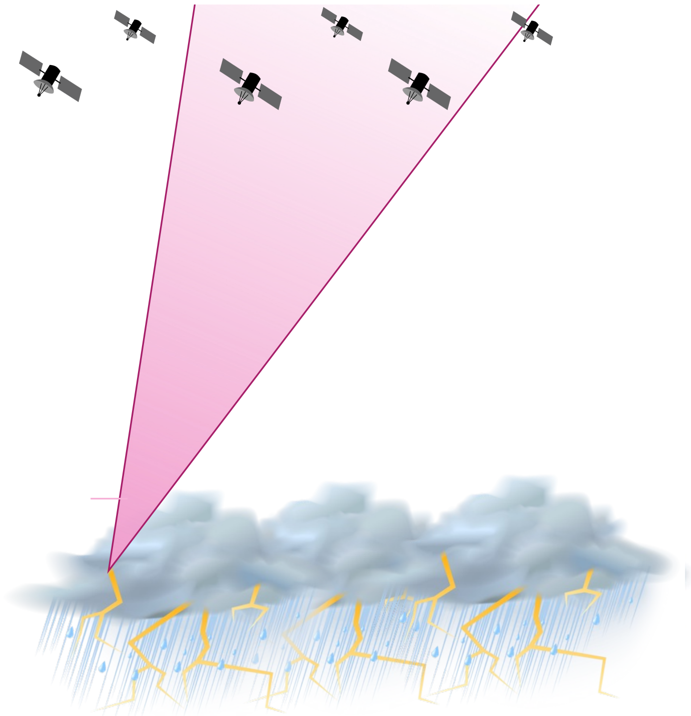

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Our work on FGS may also be used for **the gamma-ray instrument of the solar SPARK mission, called LISSAN**:

- SPARK is a high energy mission proposed for M7 for the study of solar flares
- SPARK has not been selected but the consortium goes on to search for new flight opportunities with ESA or NASA
- The LISSAN high energy detector is based upon our work on GAGG + SiPM detectors. It is similar to FGS, with GAGG crystals of 2.5×2.5×10 cm size

see: Ryan, D.F.; et al. **The Large Imaging Spectrometer for Solar Accelerated Nuclei (LISSAN): A Next-Generation Solar γ-ray Spectroscopic Imaging Instrument Concept**. *Aerospace* **2023**, *10*, 985. https://doi.org/10.3390/ aerospace10120985

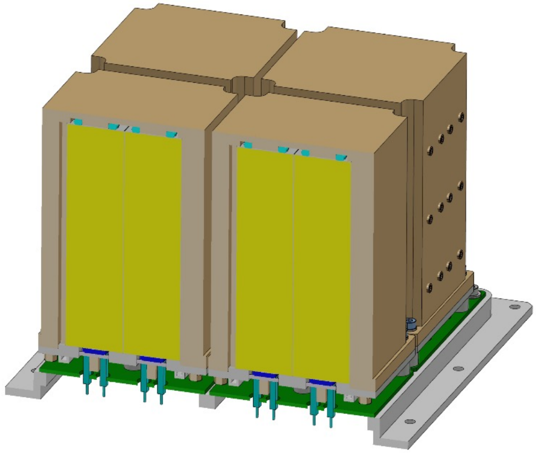

Figure: FGS detector adapted for LISSAN and proposed for SPARK

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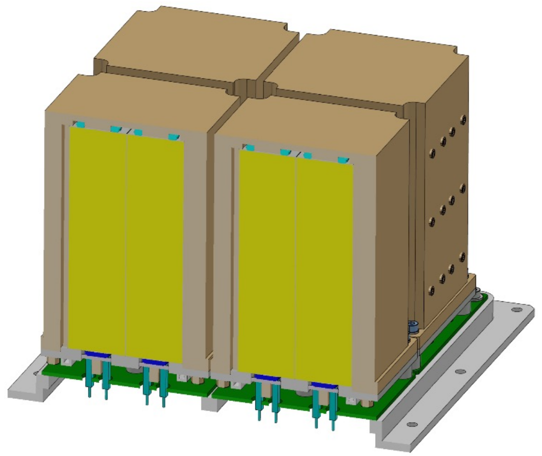
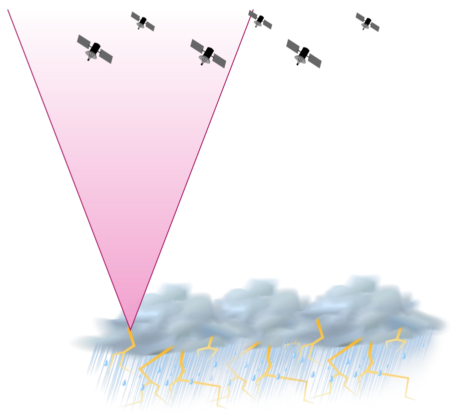


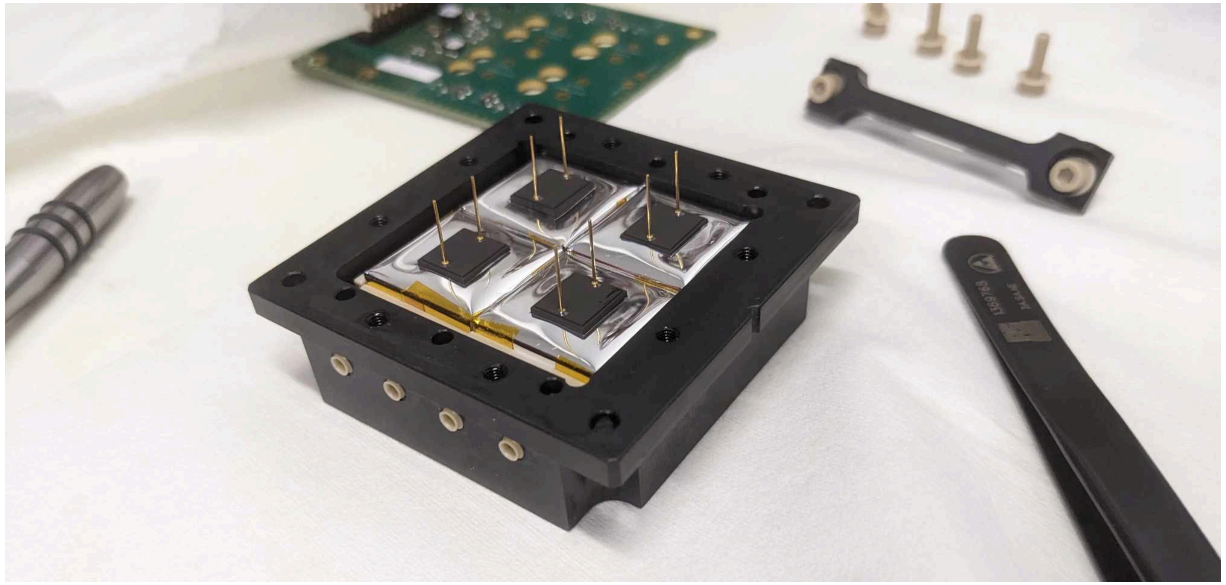
Figure: FGS detector adapted for LISSAN and proposed for SPARK

Our FGS spectrometer may also be used for **a future Compton telescope**:

- We can imagine putting spectrometers on 5 sides out of 6 of a cube and look for Compton events between two faces
- These will enable us to make Compton images of the MeV sky in a near 2π field of view

Thank you!





The Fast Gamma ray Spectrometer (FGS): a Multi-mission Instrument to Detect TGFs and Astrophysical Gamma ray Events

Thanks to the FGS team:
APC team: Philippe Laurent, Damien Pailot, Éric Bréelle, Sylvie Blin, Claude Chapron, Ronan Oger, Kévin Biernacki, Stéphane Dheilly, François Lebrun
LESIA team: Nicole Vilmer, Denis Perret, Daniel Dias, Moustapha Dekkali, Pierre-Luc Astier
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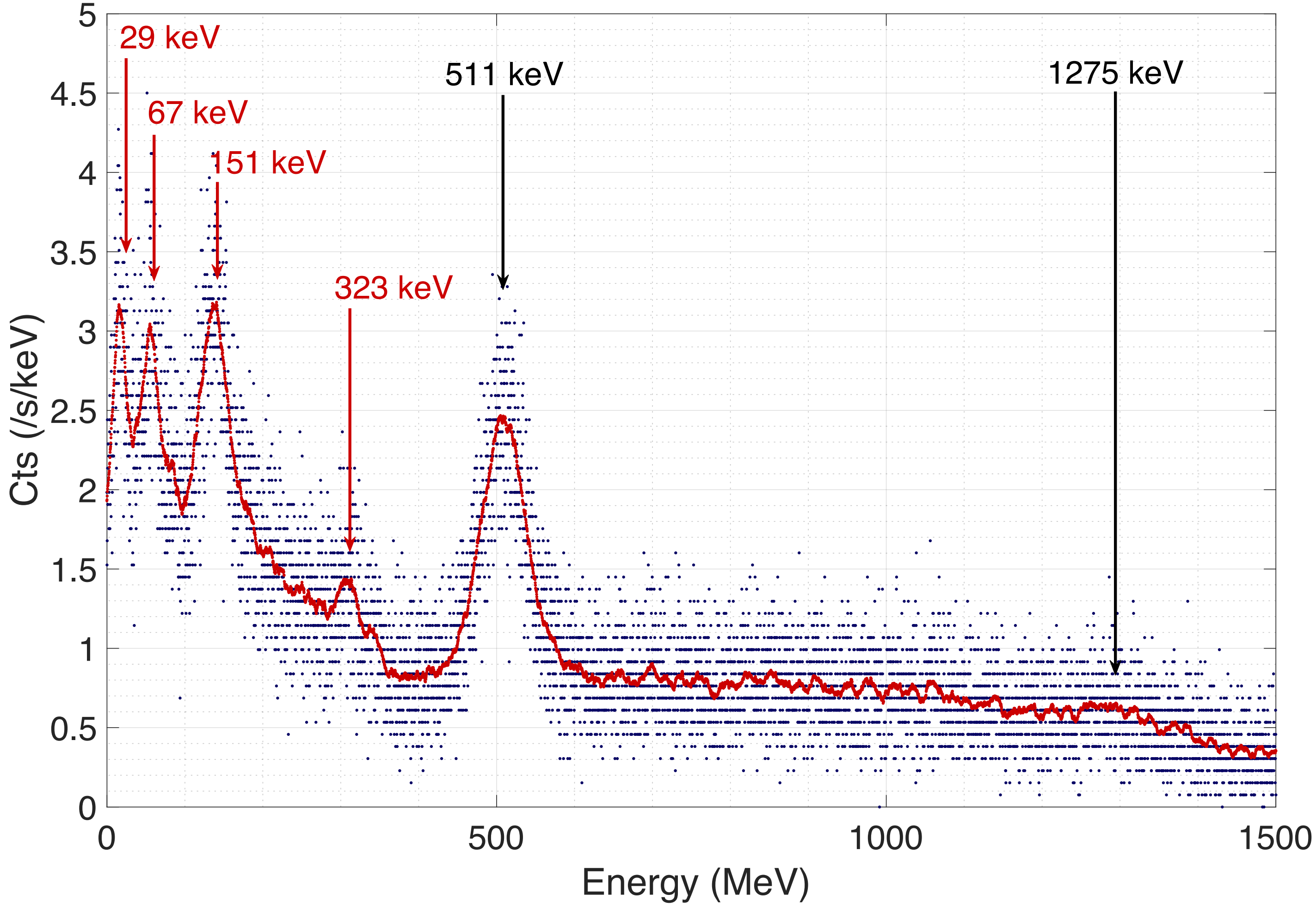
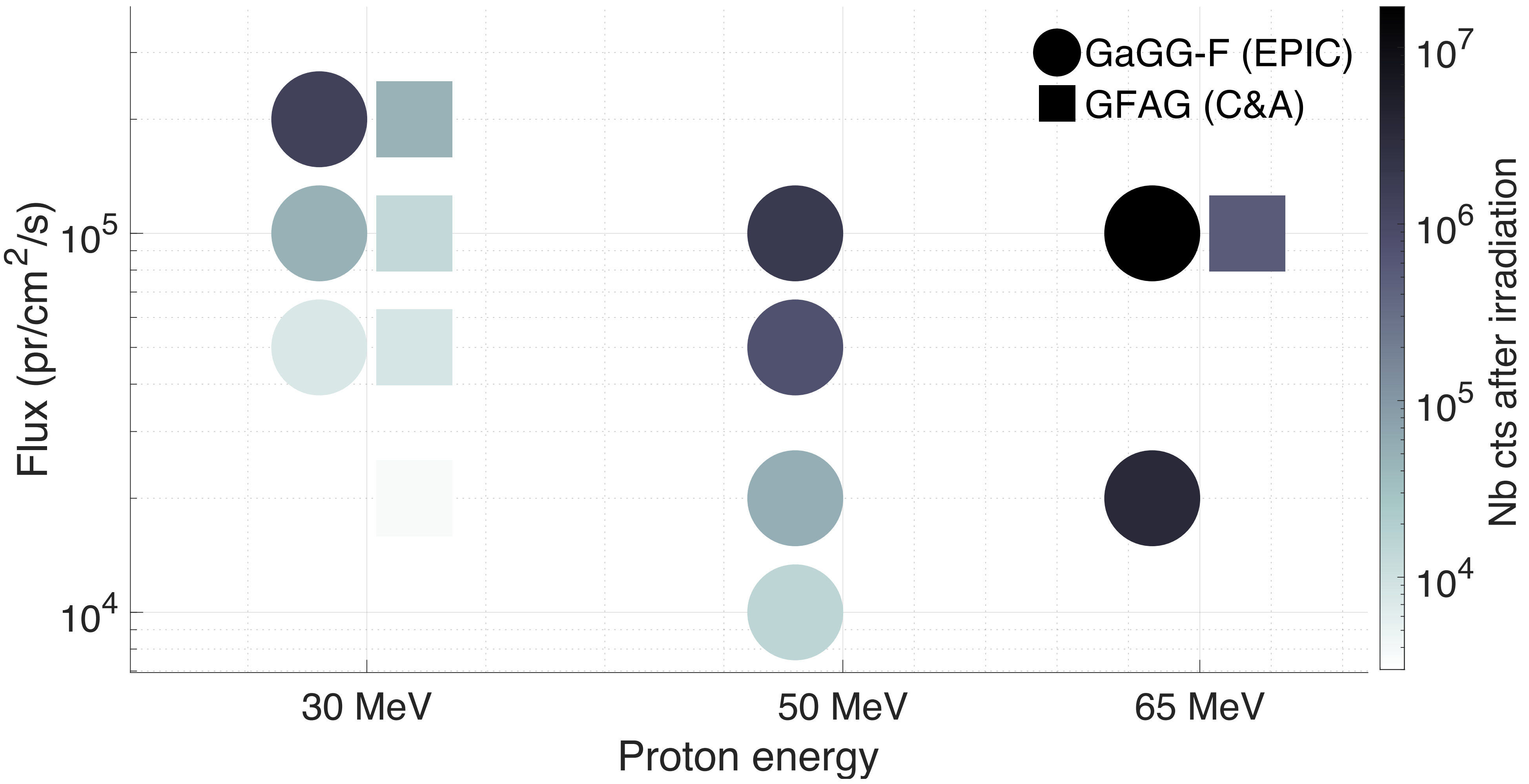
Back up 1

Raies activées lors de l'irradiation proton sur un cristal de GaGG :



Back up 2

Luminescence en fonction de l’énergie et du flux de proton :



Back up 3

Allure des spectres avant/pendant/après irradiation :