On-ground calibration of the GRB trigger camera SVOM/ ECLAIRs

Olivier Godet

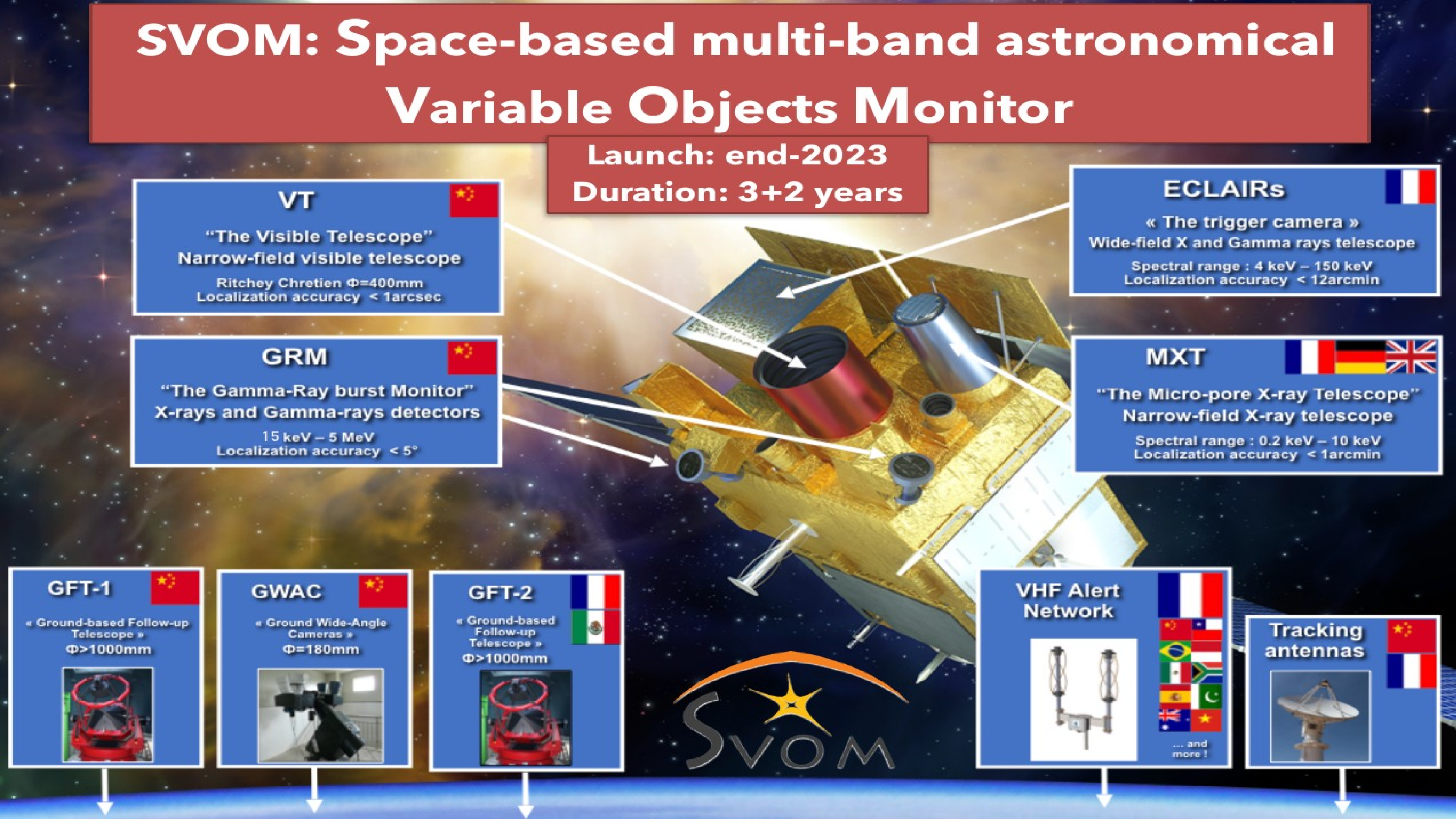
irap
astrophysique & planétologie

On behalf the SVOM collaboration team

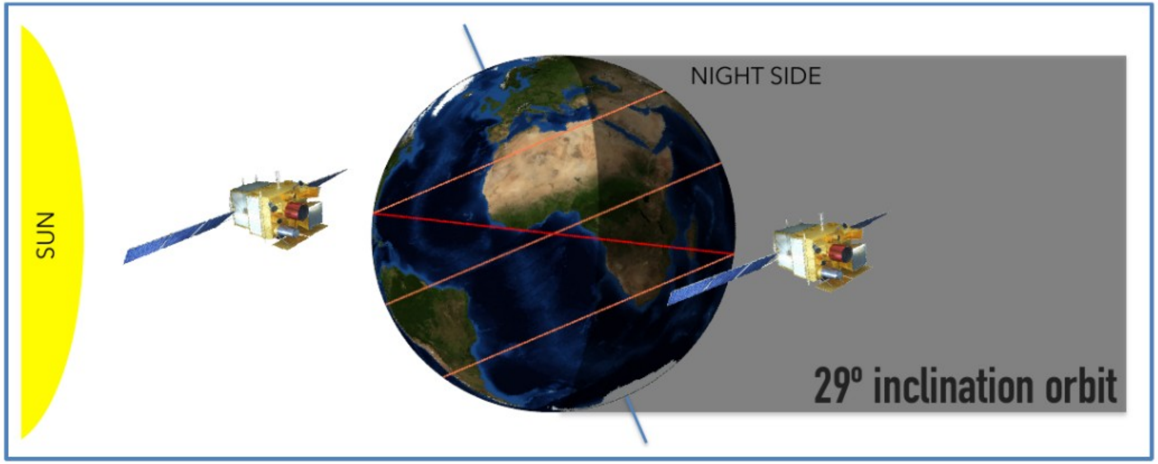
SVOM Consortium

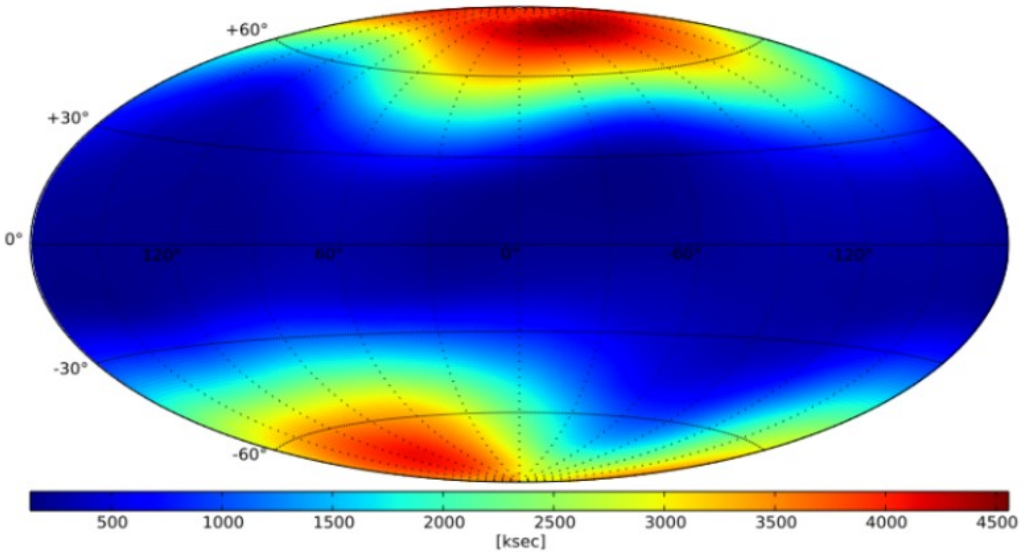
SVOM white paper: arXiv:1610.06892

- **China (PI J. Wei)**
  - SECM Shanghai
  - NSSC Beijing
  - NAOC Beijing
  - IHEP Beijing
  - GuangXi University
- **France (PI B. Cordier)**
  - CNES Toulouse
  - APC Paris
  - CEA Saclay
  - CPPM Marseille
  - GEPI Meudon
  - IAP Paris
  - IJCLab Orsay
  - IRAP Toulouse
  - LAM Marseille
  - LUPM Montpellier
  - ObAS Strasbourg
- **Mexico** UNAM (Colibri)
- **UK** University of Leicester (MXT)
- **Germany** MPE Garching & IAAT Tübingen (MXT)


SVOM: Space-based multi-band astronomical Variable Objects Monitor
Launch: end-2023
Duration: 3+2 years
VT
"The Visible Telescope"
Narrow-field visible telescope
Ritchey Chretien Φ=400mm
Localization accuracy < 1arcsec
GRM
"The Gamma-Ray burst Monitor"
X-rays and Gamma-rays detectors
15 keV – 5 MeV
Localization accuracy < 5°
ECLAIRs
« The trigger camera »
Wide-field X and Gamma rays telescope
Spectral range : 4 keV – 150 keV
Localization accuracy < 12arcmin
MXT
"The Micro-pore X-ray Telescope"
Narrow-field X-ray telescope
Spectral range : 0.2 keV – 10 keV
Localization accuracy < 1arcmin
GFT-1
« Ground-based Follow-up Telescope »
Φ>1000mm
GWAC
« Ground Wide-Angle Cameras »
Φ=180mm
GFT-2
« Ground-based Follow-up Telescope »
Φ>1000mm
SVOM
VHF Alert Network
... and more !
Tracking antennas

Pointing Strategy





- **Optimized for ground follow-up of detected transient events**
  - Nearly anti-solar pointing (with Earth in instrument FOVs each orbit)
  - 65 % duty cycle for ECLAIRs
  - 50 % duty cycle for MXT & VT

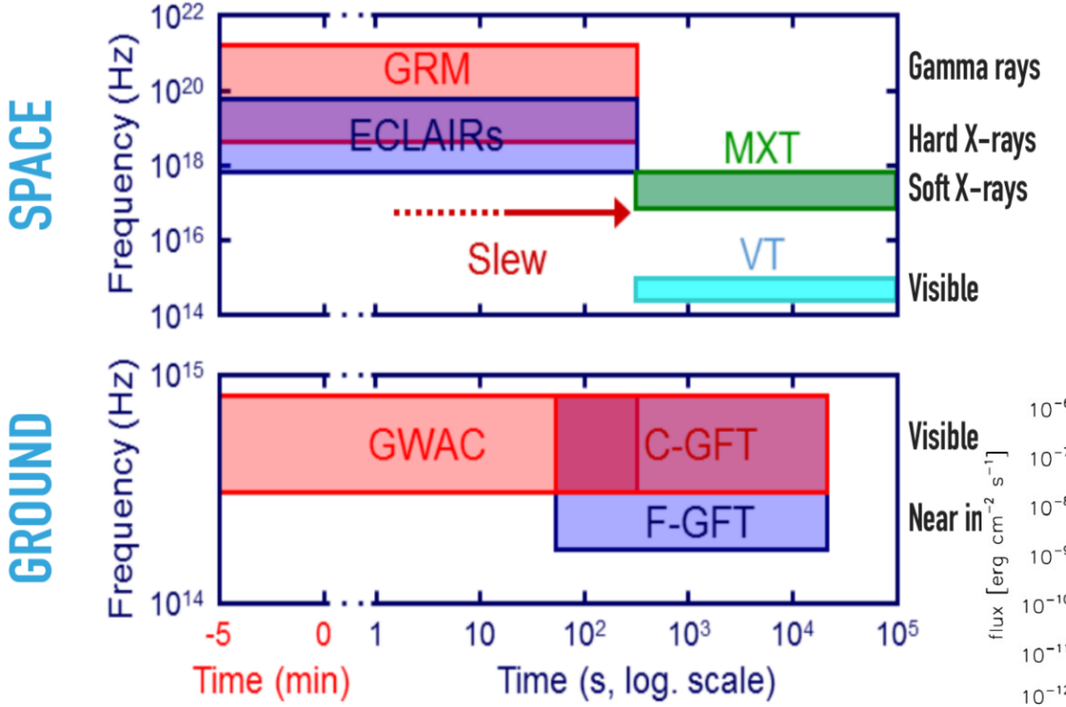
➡ **Redshift measurement for ~2/3 of detected GRBs**

- Avoidance of the Galactic plane + bright sources (e.g. Sco X-1)

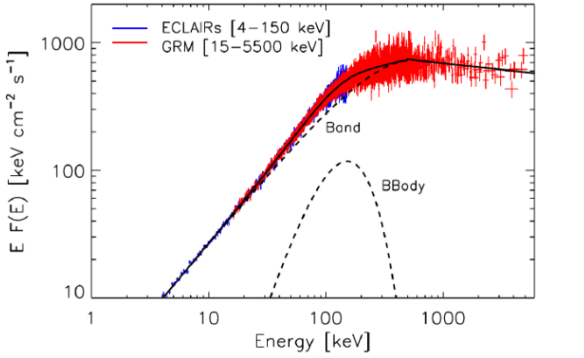
- ECLAIRs annual exposure time
  - ~4000 ks on the Galactic poles
  - ~500 ks on the Galactic plane

Response to a trigger

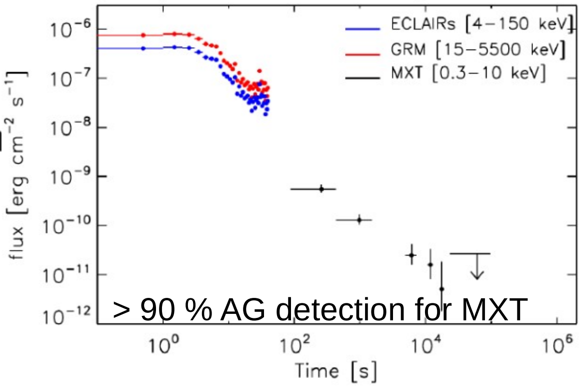
- **Complete coverage of GRB emission over 7 decades in energy from trigger up to the late afterglow phase**



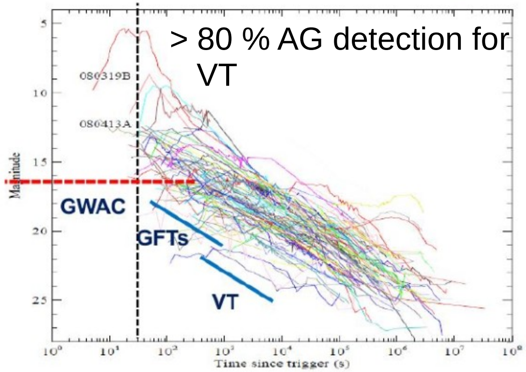
Multi-component spectrum of the Fermi burst GRB 100724B simulated in ECLAIRs and GRM Bernardini+2017



Simulation of GRB 091020 (seen by Fermi/GBM and Swift/XRT)



Visible light curves of long GRBs Wang+2013

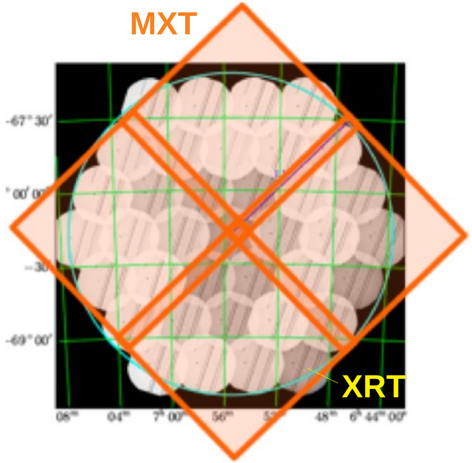


- **A unique sample of ~35 GRBs/year with**
  - Prompt emission over 3 decades with ECLAIRs + GRM (+optical flux/limit: 16% with GWAC)
  - X-ray and Visible / NIR afterglow (VT, C-GFT, F-GFT, …)
  - Redshift

SVOM Reactions to MM event

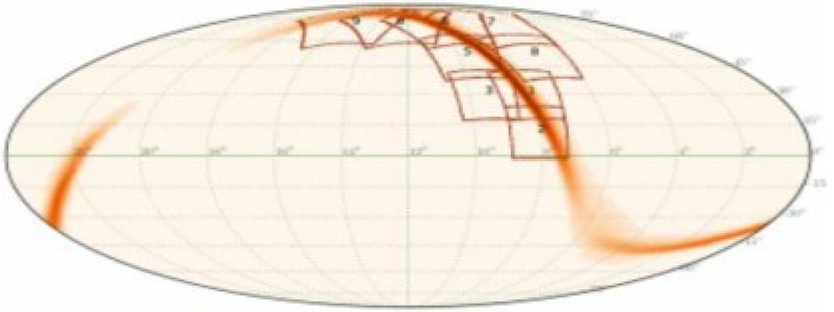
- **Wide FOV HE instruments: ECLAIRs + GRM**
  - Slew if event is above ECLAIRs trigger threshold in less than 5 min
  - Sub-threshold events sent through VHF to SVOM ground segment
  - Otherwise, off-line detection on ground possible within ~6 – 12h

- **Narrow FOV instruments: MXT + VT**
  - Require a decision to slew following the alert (ECLAIRs trigger or ToO)
  - Require a tilling strategy if error box > 1 deg²



- **Wide FOV ground-based instrument: GWAC**
  - Rapid automated response

- **Narrow FOV ground-based instruments: GFTs**
  - Rapid response (robotic telescopes)
  - Need an accurate localization

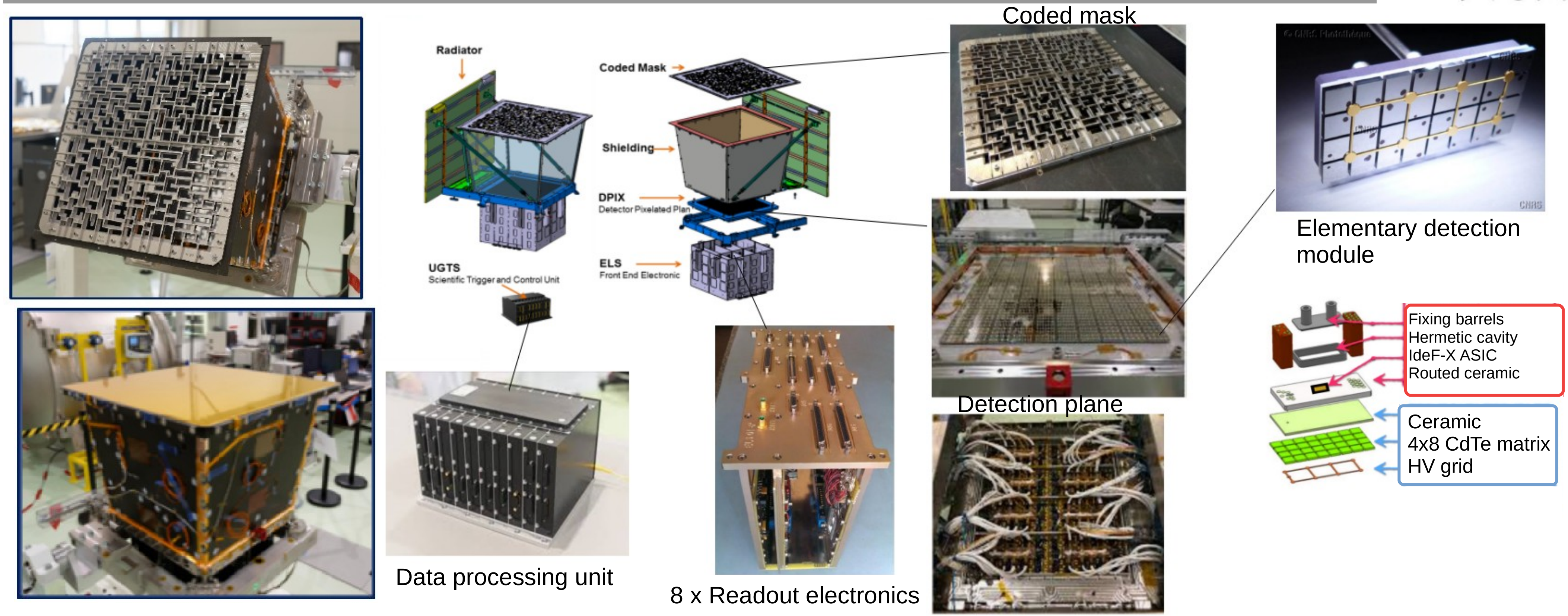


Follow-up of GW170608 with early version of GWAC

- **SVOM preparation to follow GW events from the O4 run (GWAC + C-GFT)**

THE ECLAIRs camera

ECLAIRs in a nutshell



- Mask-to-plane distance = 46 cm // Mask dimension = 54 x 54 cm² // Ti-Ta (0.6 mm)-Ti sandwich
- 40 % mask open fraction // quasi-random pattern
- 80x80 4x4 mm² and 1 mm-thick Schottky-type Pt/CdTe/In detectors from Acrorad Ltd (Japan) operated at –300 V & nominal temperature range of [–25°C ; –18°C]
- Total FOV = 89 x 89 deg² (~2 sr) // Fully coded FOV ~ 22 x 22 deg² (~0.15 sr)

ECLAIRs in a nutshell

Energy range	4 – 150 keV
Detecting area	~950 cm^2
Detectors	6400 CdTe detectors
Total effective area in 10-70 keV	≥340 cm^2
Photopeak effective area @ 6 keV	≥200 cm^2
Field of view	2.05 sr total
Sensitivity to 1 second long GRB	2.5 10^{-8} erg cm^{-2} s^{-1} in [5–50] keV
Source Localization Error	11.5 arcmin for sces with SNR=8
Energy resolution at 60 keV	< 1.6 keV
Time resolution – dead time	20 µs – <5% for 5 10^4 c/s
single/multiple interaction tagging	
Data acquisition mode	Photon mode
Data rate	≤18Gb/day
Energy calibration accuracy	≤0.3 keV below 80 keV

- Detection plane segmented in 8 sectors with an independent electronics each
- Shield made of Pt (0.8 mm) / Cu (0.1 mm)
  - Opacity > 80 % below 150 keV
  - Use for in-flight monitoring of energy scale

- **4 keV energy threshold to increase sensitivity to XRFs & high-z GRBs**
- 3 MLI covers to make sure the camera cavity to prevent optical loading
- **Photon counting mode**
  - All photons transmitted to the ground
  - Readout electronics able to discard particles showers, fluorescence and Compton events as multiple events
- **Automatic software to disable noisy pixels**
- **On-board autonomous detection [count-rate + image triggers] & localisation**
  - ➢ Time scales from 10 ms to 20 min
  - ➢ 4 energy bands, 9 detector zones
  - ➢ **Rate ~ 65 GRBs /year**

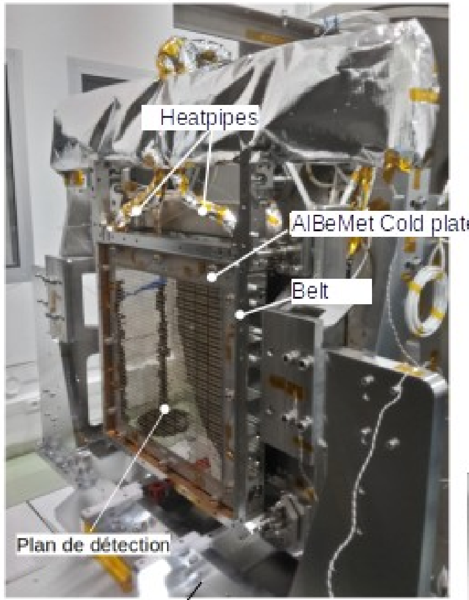
THE ON-GROUND CALIBRATION

Godet et al., 2022, Proceeding of SPIE, 12181, 121815O

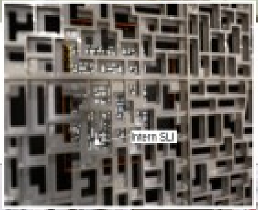
Calibration Sequences

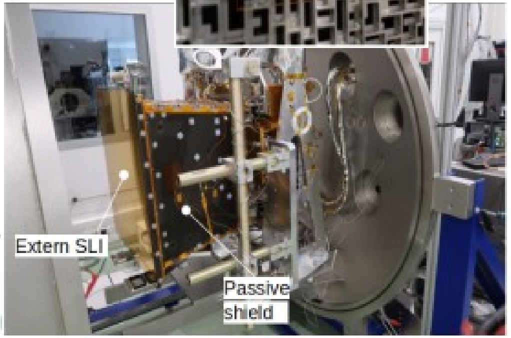
Time

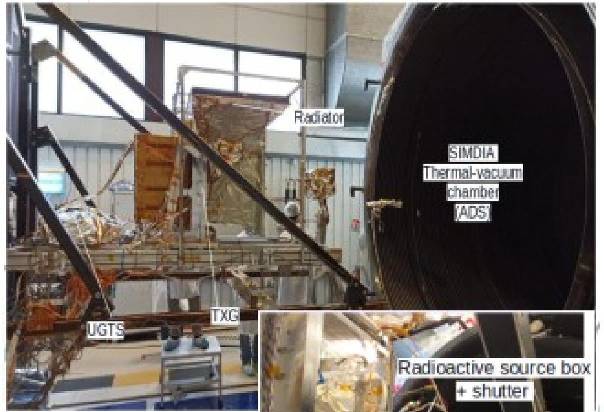
25/01/21	05/03/21	30/04/21	26/05/21	05/10/21	29/10/21	2022 – 2023
Detection Plane (SIGNE-3)	AIT work + Data analysis	**Camera (SIGNE-3)**	AIT work + environment tests + Data analysis	**ECLAIRs (SIMDIA – TVAC)**		Data analysis => 1st version of cal./conf. files Integration, tests, calibration of a ground model (1/4th of the detection plane) at SIGNE-3 // Investigation test

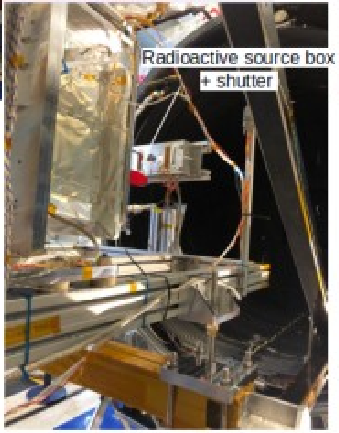


UGTS placed outside chamber



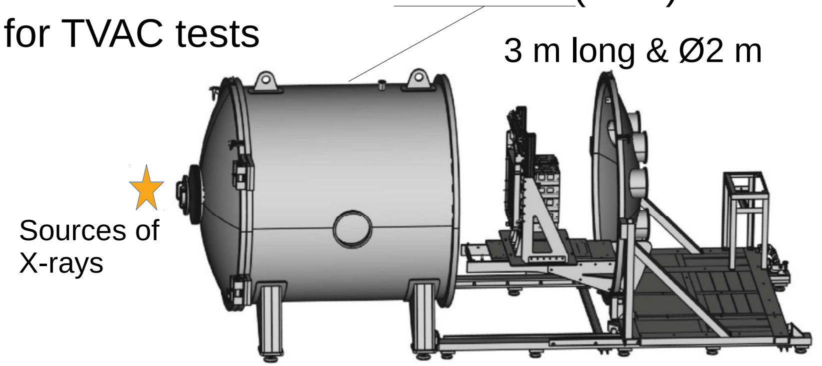






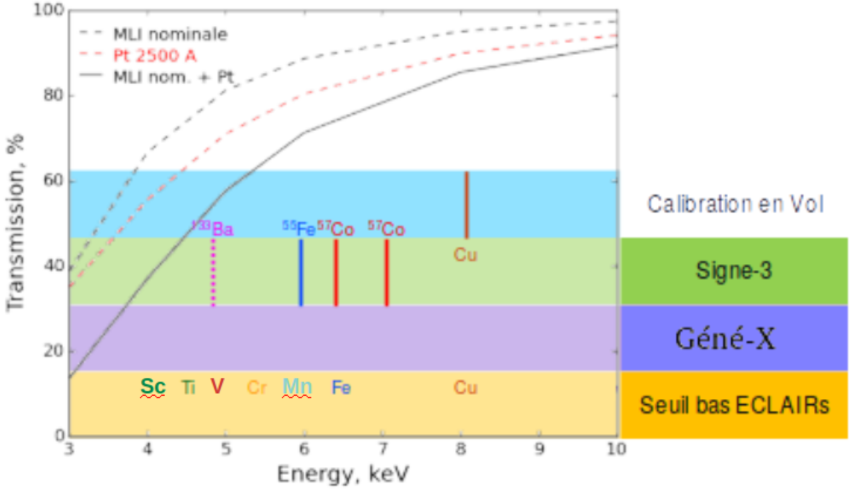
Ground Support Equipments

- Camera operated under flight conditions within a thermal-vacuum chamber located at the SIGNE-3 (CST) clean room and the whole instrument (including UGTS) at ADS (Toulouse) for TVAC tests



- Nominal detector temperature of –20°C or within [–26°C ; –15°C] & Nominal HV = –300 V

- 2 sources of X-ray photons:
  - **Radioactives sources:** Fe-55 (5.9 keV), Zn-65 (8 keV), Am-241 (14 – 60 keV), Ba-133 (4.7 – 81 keV + 356 keV) & Co-57 (6.4 – 136 keV) placed at around 1.1 m from the detection plane so that count rate < 2 cts/s/pixel (negligible dead time).
  - **X-ray generator :** Beam of X-ray fluorescent photons with E ϵ [4 ; 22 keV]
    - Use to refine the measure of the effective area at low energy (< 10 keV) and to create variable events (e.g. bursts, SAA entry with CR > 10^5 cts/s)
    - Intercalibration at 5.9 keV and 8 keV with radioactive sources



Calibration Breakdown

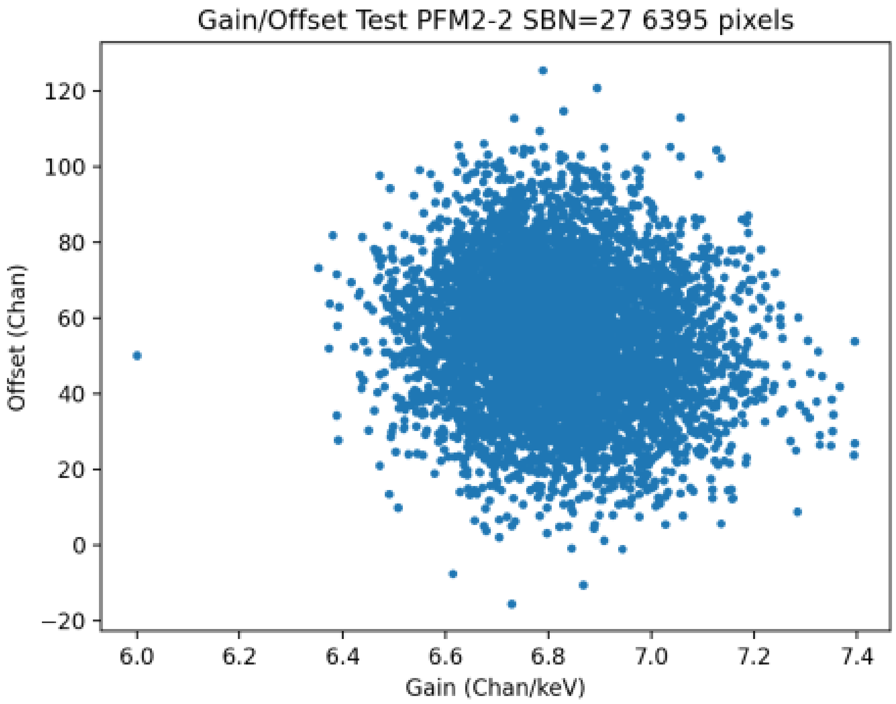
	Prototype & EQM	DPIX FM (Signe-3)	TXG sans masque (Signe-3)	TXG complet (Signe-3)	ECLAIRs (SINDIA)	ECLAIRs (En vol)
Low-energy threshold	X	X				X
Detector efficiency vs energy	X	X	X			X
Spectral response to photon energy	X	X	X			X (Continuum)
Angular Response	X	X				X
Shield efficiency vs energy and photon pitch angles				X		X
Mask stopping power vs energy				X	X	X
Transparency of the FoV vs energy			X (SLI)	X	X	X
Dead time vs photon count rate	X	X	X			X
Level of optical loading		X		X		X
Imaging efficiency and sensitivity vs energy and source position						X
Statistics of dead or noisy pixels	X	X		X	X	X
Cross-talk	X	X		X	X	
Performance stability	X	X		X	X	
Trigger end-to-end test				X	X	X

- Flux calibration at the 10 % level
- Energy scale below 80 keV with an accuracy better than 0.3 keV

Energy Scale

- Calibration of the Channel – Energy relation for active pixels to reconstruct the energy scale

  => Very good homogeneity of the gain/offset coefficients!



Setting of the Low Energy Threshold

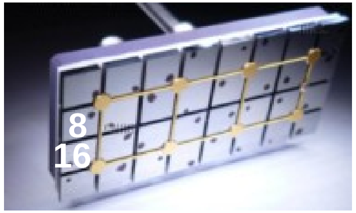
- Calibration of the SBN – E_{thr}(keV) relationship with SBN, a number setting the low-E threshold

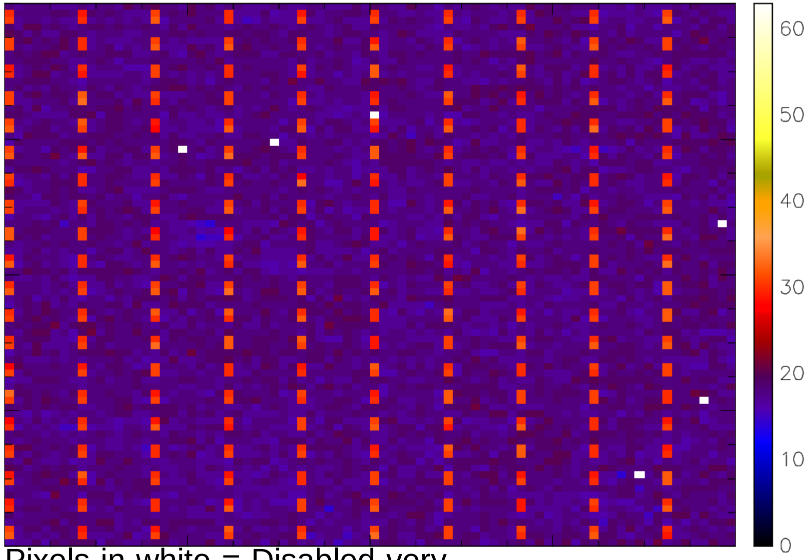
⇒ Building of the SBN table so that E_{thr} = 3.8 keV except for pixels 8 & 16 with E_{thr} = 7 keV to mitigate cross-talk effects (6 % of the 6400 pixels)

⇒ Very good homogeneity of the SBN values

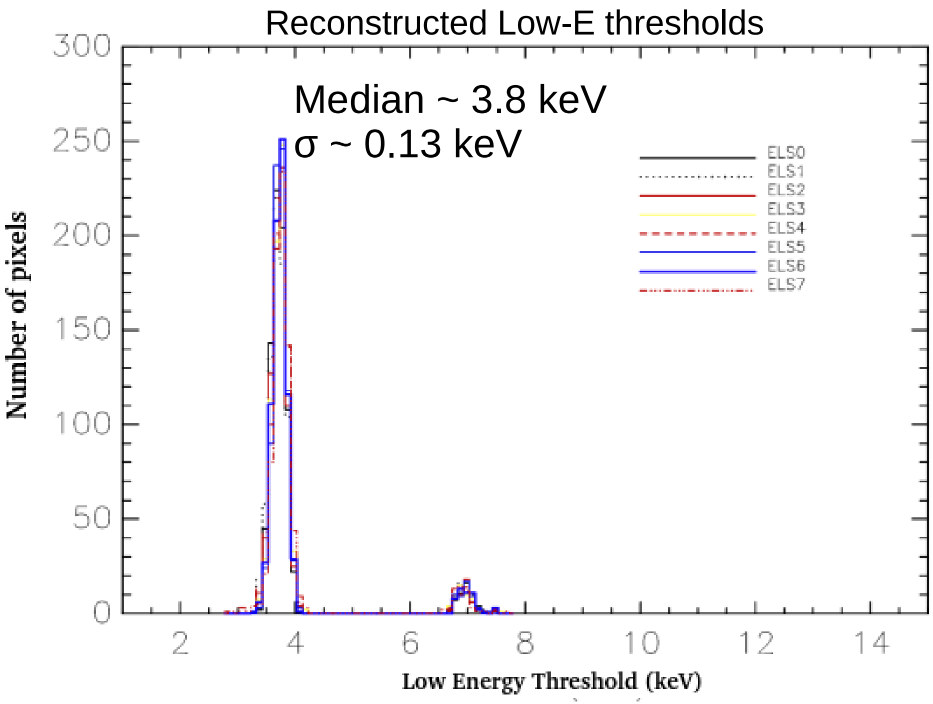
⇒ Very precise setting of the low-energy threshold!

⇒ Only 7 dead pixels (SBN=63) over 6400 detectors!





Pixels in white = Disabled very noisy pixels with CR > 25 cts/s

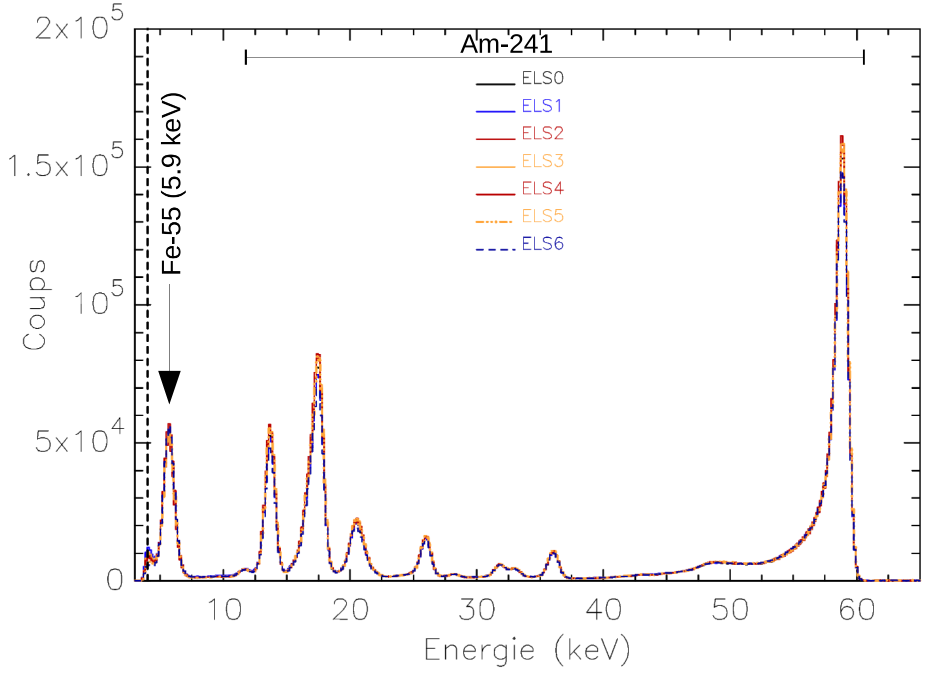


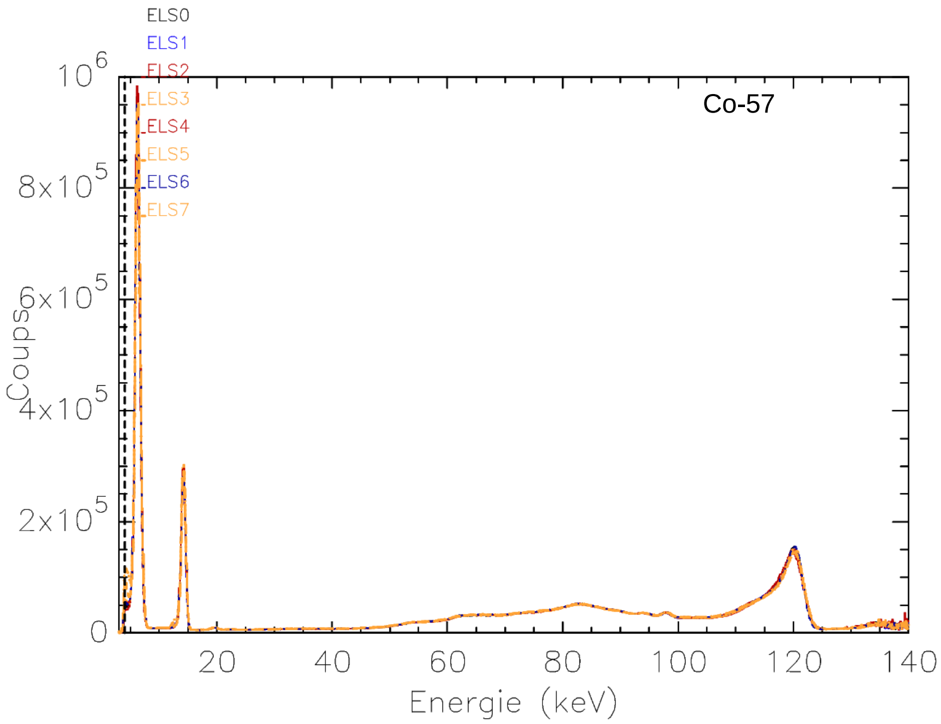
Spectral Response

- On-axis energy-calibrated spectra of ~800 detectors per sector

  => Very good homogeneity of the spectral response and counting

  => FWHM < 1.6 keV @ 60 keV for ~99.5 % of the detectors! (compliant with the science requirement)



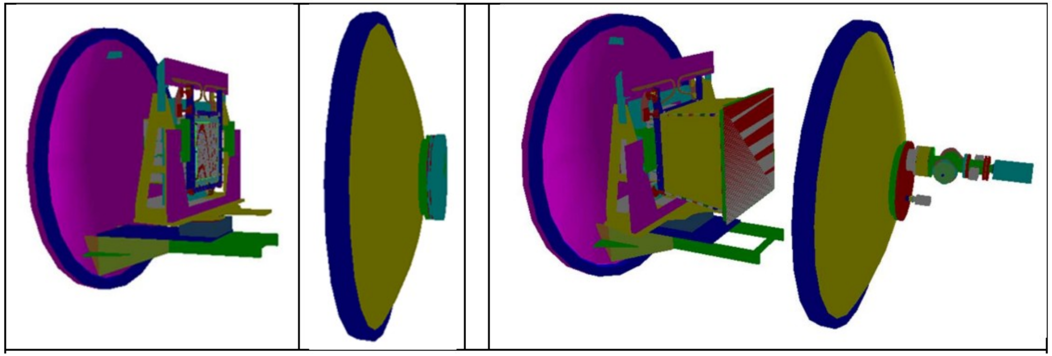


Spectral Response

- Built a GEANT-4-based model to compute the spectral response of ECLAIRs (take into account physical interaction of photons with the detectors)

- Use of the experimental data to calibrate this numerical model to produce RMF, ARF and IRF (angular response) – Yassine et al. in prep.

- Response files used to prepare commissioning phase activities as well as to perform some tests on the data reduction and analysis pipeline



GEANT-4 mass models

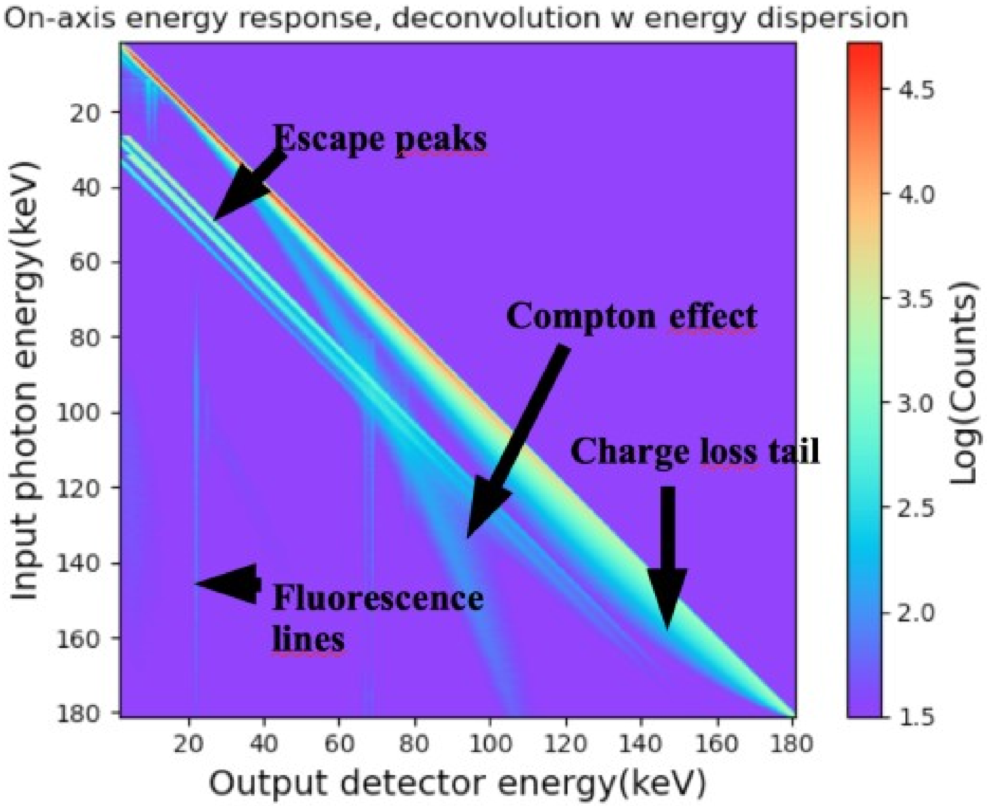
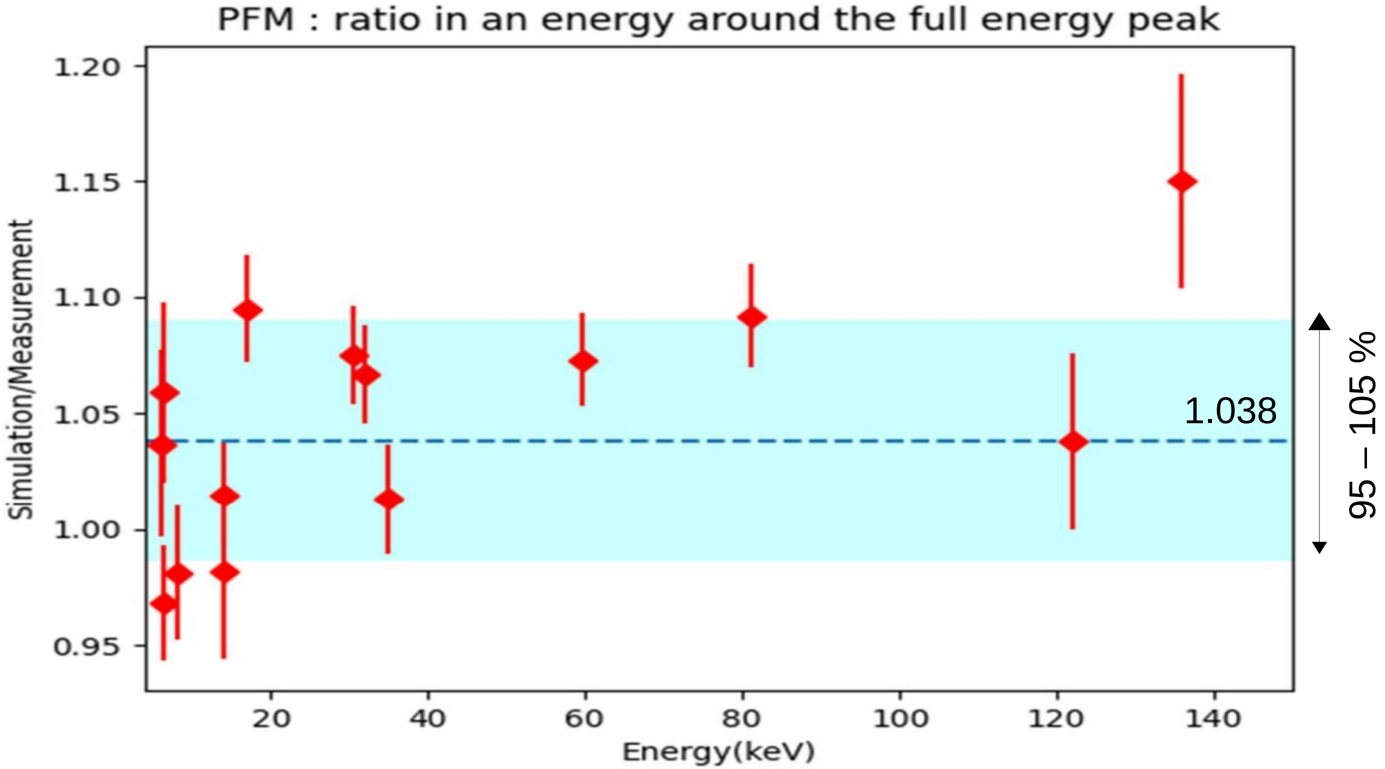


Photo-Peak Effective Area of the camera

- Making use of the data collected using radioactive sources + X-ray generators

  => Very good agreement between measures and numerical model! (Compliant with scientific requirement)

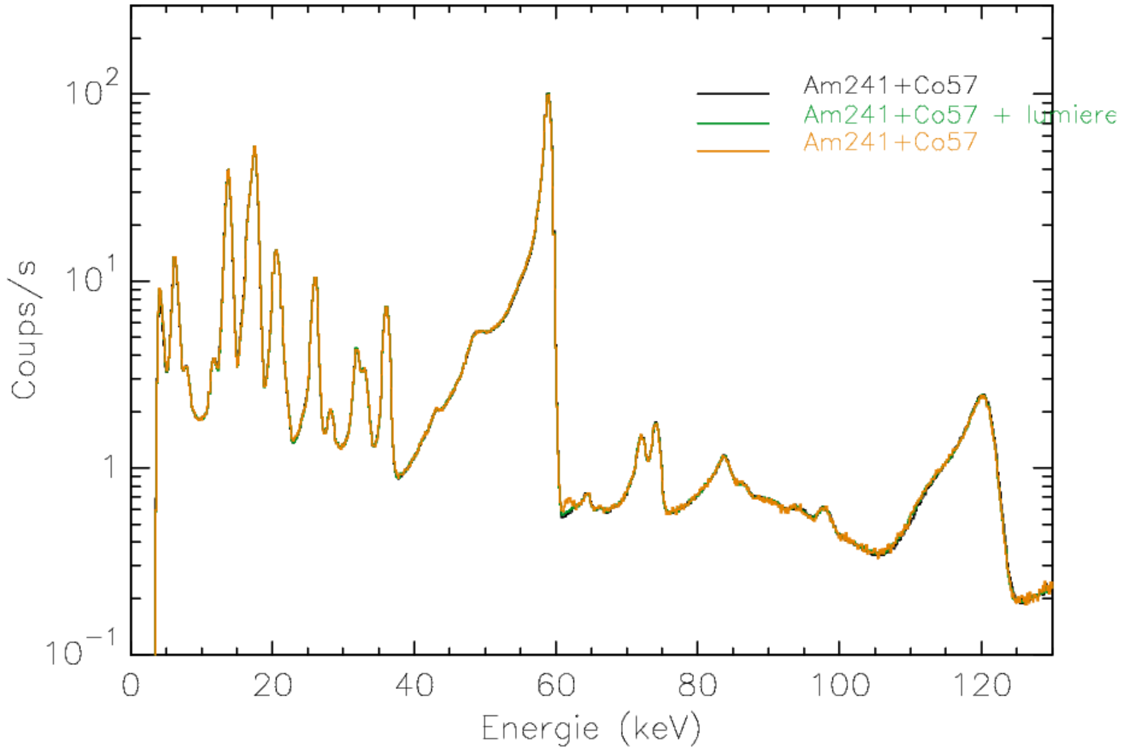


Optical Loading

- Made use of optical light with a 10 kLux intensity roughly mimicking the Earth Albedo (passage of the Earth in the ECLAIRs FoV) + Radioactive sources

- Below energy-calibrated spectra over the whole detection plane illuminated by X-ray photons (Am-241+Co-57) without optical light (black curve), with optical light (green curve) and without optical light (orange curve)

⇒ Camera cavity fully opaque to optical light



Take away

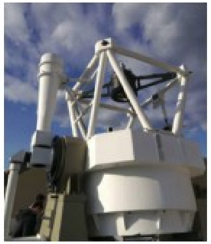
- The calibration performed with the camera and the full instrument in 2021 have demonstrated that ECLAIRs has the expected performances.
- Some minor issues do not affect the overall performances.
- Building of a 1st version of the camera onboard configuration and auxillary files
- Building, testing & calibration of a on-ground spare model of the detection plane (1/4th of the FM) in 2022
- The French instruments (ECLAIRs & MXT) have been delivered to China mid-March 2023.
- Integration on satellite just finished, MXT will follow soon. So far no delay on the AIT schedule.
- Present Launch date: End of 2023

BACK-UP SLIDES

SVOM from the ground

- Ground Follow-up Telescopes permit the fast identification and measure of early optical/NIR afterglows using the ECLAIRs positions, while the spacecraft is slewing to the source.
  - C-GFTs is located at Weihai observatory (Jilin province)
  - F-GFT will be located at San Pedro Martir (Mexico)

Ground Wide Angle Cameras
2 x 20 camera units
Ø = 180 mm // Total FOV ~ 5000 deg²
500 – 800 nm
Limitting mag ~ 16-17 (10 s)



C-GFT

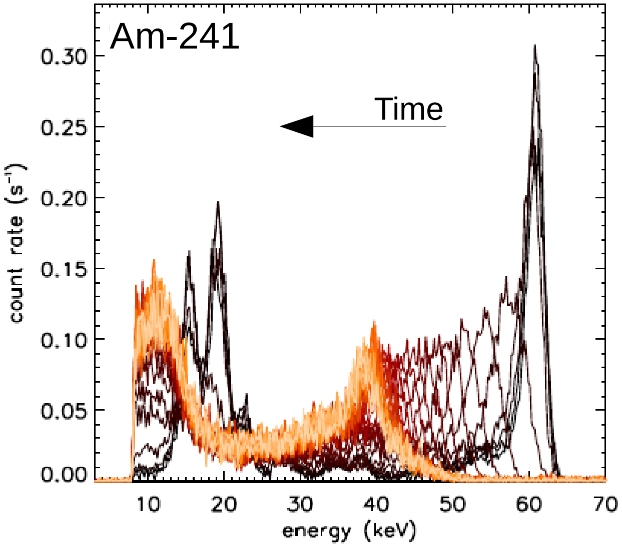
F-GFT(Colibri)
Diameter : 130 cm
FOV : 26 x 26 arcmin
400 – 1700 nm → **nIR capabilities (CAGIRE, IRAP)**
Limiting mag ~ 22 (R, 300 s)

Diameter : 120cm
FOV : 90 x 90 arcmin
400 – 900nm
Limiting mag ~ 20 (R, 300 s)

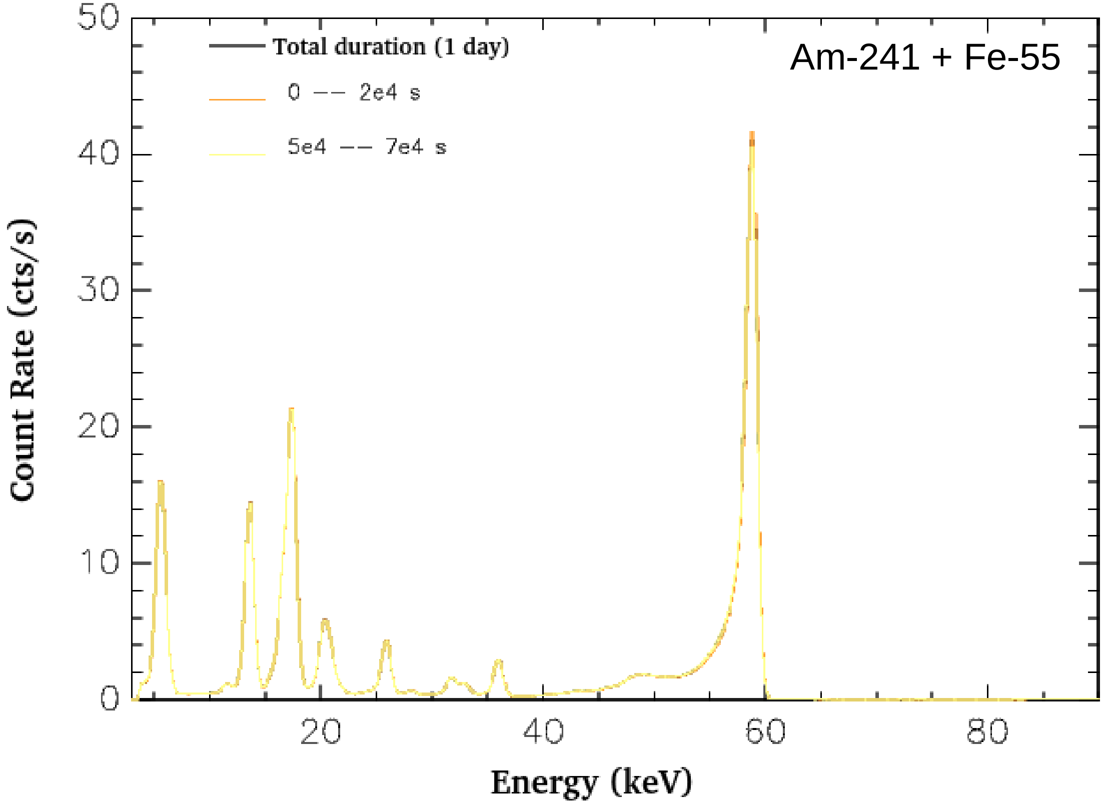
- Agreement to use the LCOGT network through NAOC guaranteed time (2000 h/yr)
- **> 75 % of ECLAIRs GRBs immediately visible by one of the ground telescopes**

Polarization effect

- Measure over 1 day on the calibration plane alone to investigate for possible effect induced by polarization effect (Cola+07). In-flight detectors depolarized when S/C passing through SAA – Longest duration between 2 SAA passages ~ 15 h
- Detectors operated at –15°C and HV = –300 V
  ⇒ No sign of any spectroscopic and counting degradation over 1 day



For comparison, evolution of the spectral response of one CdTe detector operated at +25°C & –300 V over 160 min
In orange, lastest measured spectrum

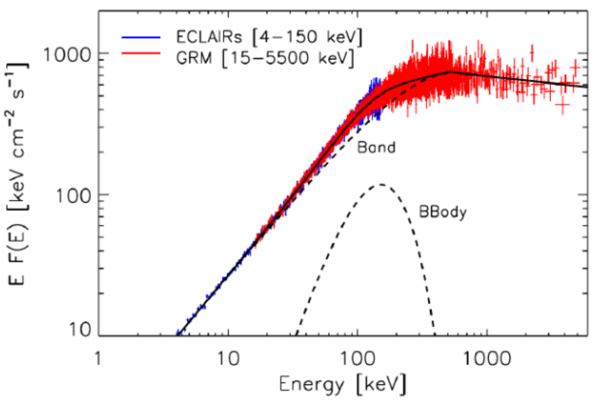


GRB Outputs

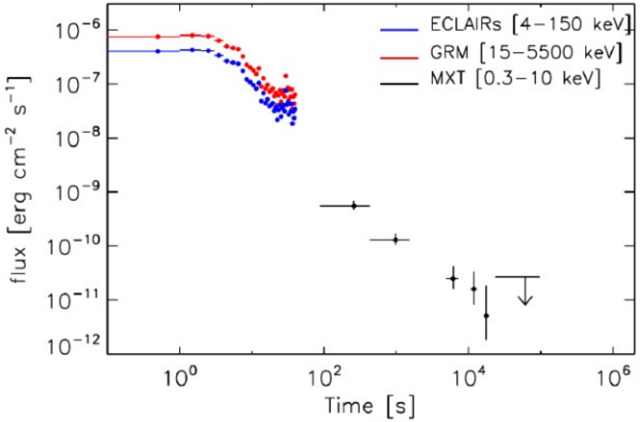
- **A unique sample of ~35 GRBs/year with**
  - Prompt emission over 3 decades with ECLAIRs + GRM (+optical flux/limit: 16% with GWAC)
  - X-ray (MXT ; **> 90 % AG detection**) and Visible / NIR afterglow (VT **[> 80 % AG detection]**, C-GFT, F-GFT, …)
  - Redshift

	Swift	Fermi	SVOM
Prompt	Poor	Excellent 8 keV -100 GeV	**Very Good 4 keV - 5 MeV**
Afterglow	Excellent	> 100 MeV for LAT GRBs	**Excellent**
Redshift	~1/3	Low fraction	**~2/3**

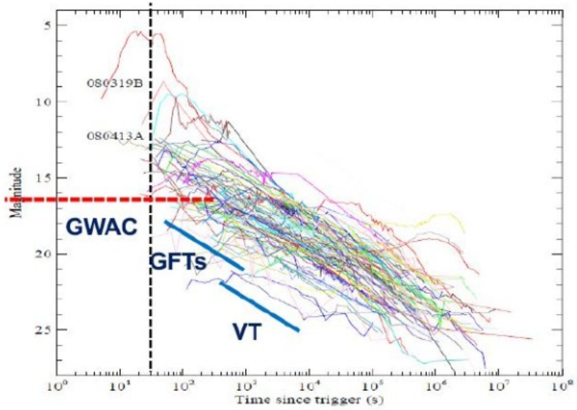
Multi-component spectrum of the Fermi burst GRB 100724B simulated in ECLAIRs and GRM Bernardini+2017



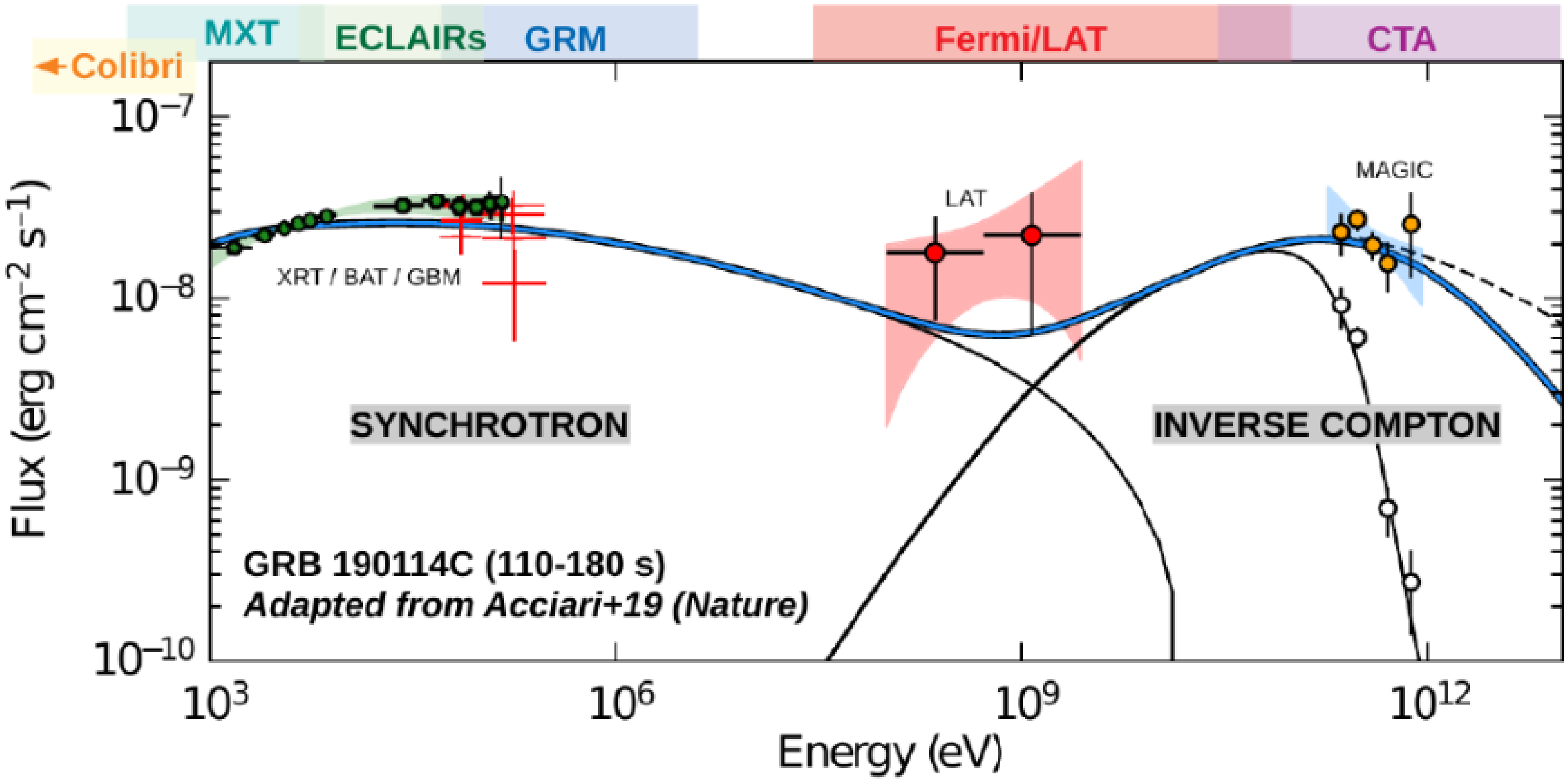
Simulation of GRB 091020 (seen by Fermi/GBM and Swift/XRT)



Visible light curves of long GRBs Wang+2013



Synergy with HE & VHE instruments

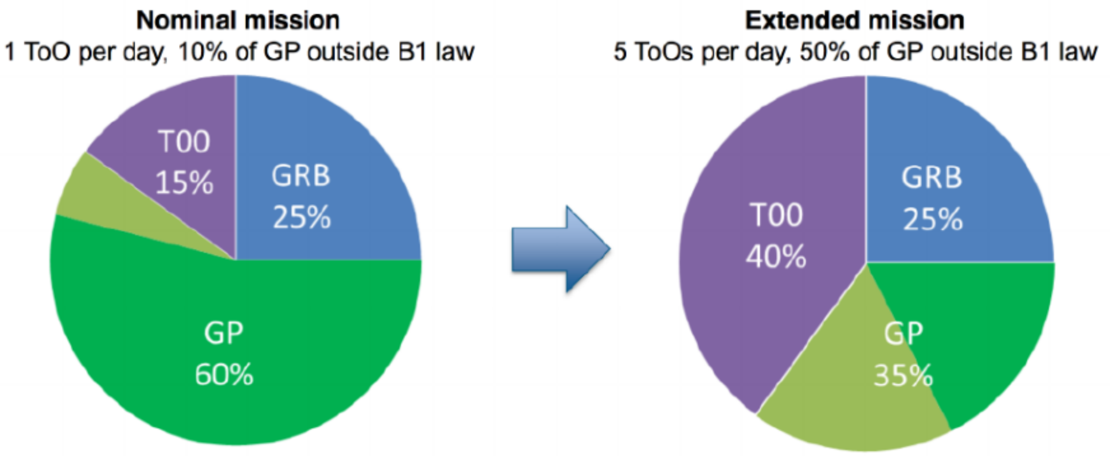


SVOM Scientific Programs

- **Core Program (CP):** GRB science (25% of time, with the highest priority)

- **General Program (GP)** or SVOM as an open observatory: observations will be awarded by a TAC for astrophysical targets (a SVOM co-I needs to co-sign your proposal)
  - -10% of the time can be spent on low Galactic latitude sources during nominal mission
  - -Up to 50% during mission extended phase

- **Targets of Opportunity (ToO) Program:** alerts sent from the ground to the satellite
  - -Initially 1 ToO per day focused on TDA and multi-messengers
  - -Devoted time will increase during mission extended phase



SVOM Data Policy

Core Program (GRB)

Real-time VHF scientific products (under the supervision of the Burst Advocates) will be **public as soon as they are available** => similar to Swift or Fermi-GBM.

All the **scientific products are public six months** after the data production.

General Program (GP)

Semester Call for proposal (**in association with a SVOM Co-I**), it can include ToO.

All the SVOM data will be distributed to the Responsible Co-I.

One year of proprietary period before all the scientific products become public.

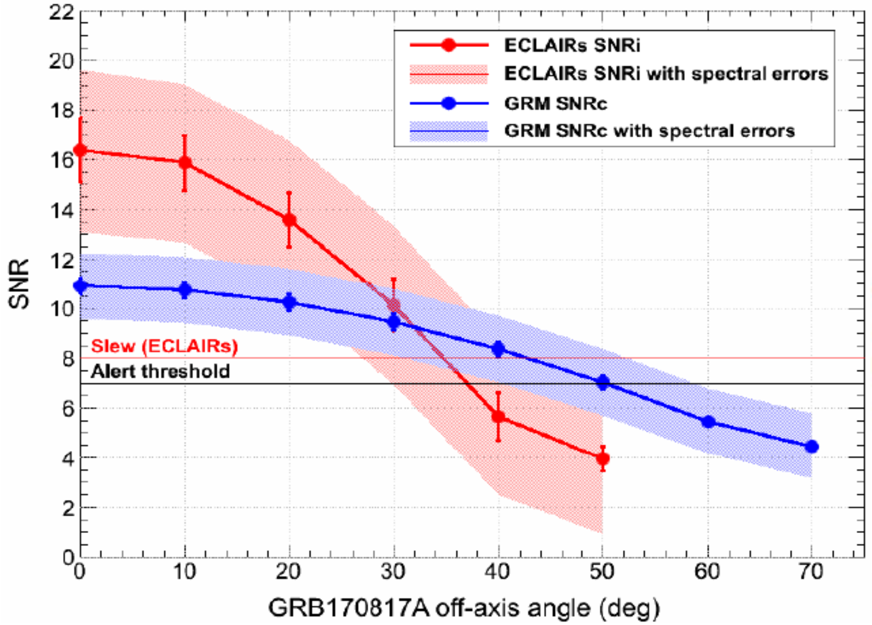
ToO Program (still under discussion)

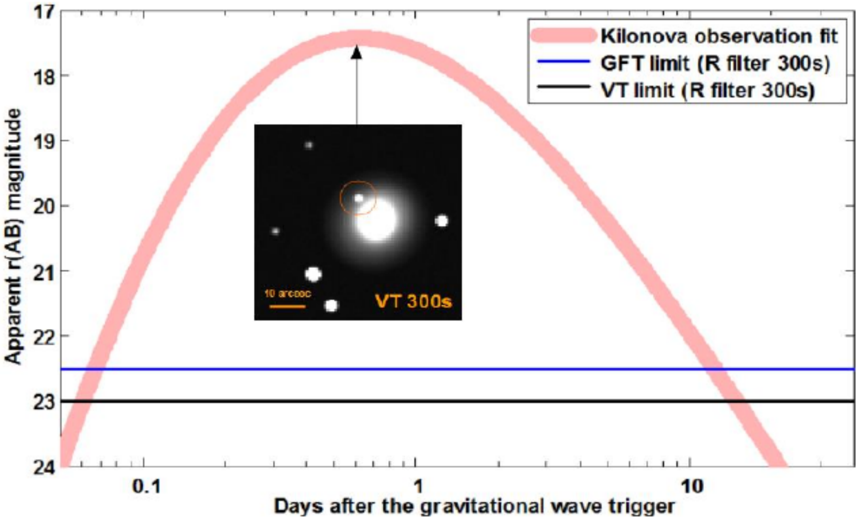
ToOs triggered by the SVOM CO-Is => we will make **publicly available as soon as possible** any scientific product that is relevant to perform follow-up observations. The number of products to be publicly released will be addressed case by case.

ToOs triggered by non SVOM CO-Is => **all the scientific products will be public** as soon as they are available.

SVOM Reactions to MM event

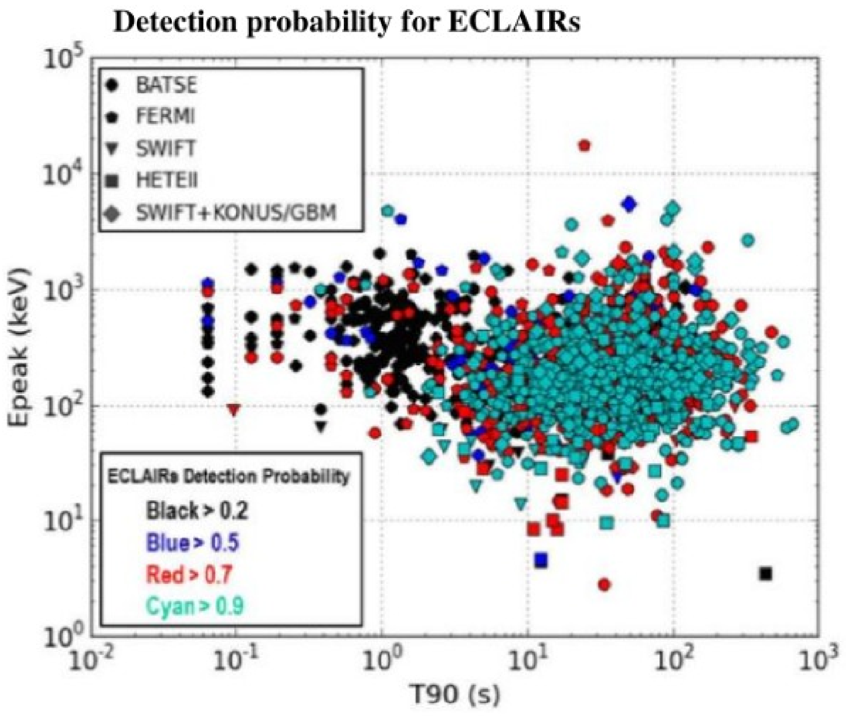
- **It the GRB appeared in ECLAIRs or GRM field of view**
  - ECLAIRs & GRM detection with high probability → slew request sent by ECLAIRs
  - MXT and VT follow-up observations → kilonova easily detected by the VT
- **If not in ECLAIRs and GRM field of view**
  - LIGO-Virgo alert received at the French scientific center → GFT observations triggered, nearby galaxy targeting within the GW error contour (several observation cycles)
  - Thanks to its NIR channel, Colibri would certainly have detected the kilonova

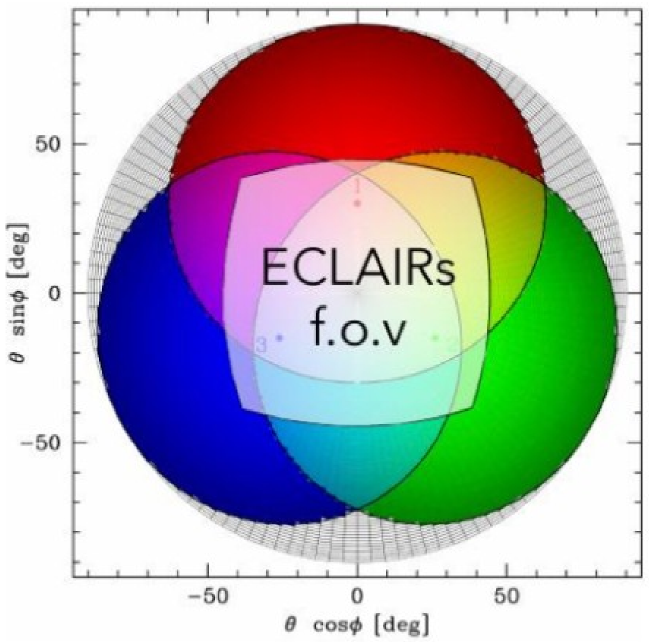




GRB Outputs

- **ECLAIRs sensitive to all classes of GRBs**
- **Rate ~ 65 GRBs/yr including a few GRBs with z > 5**





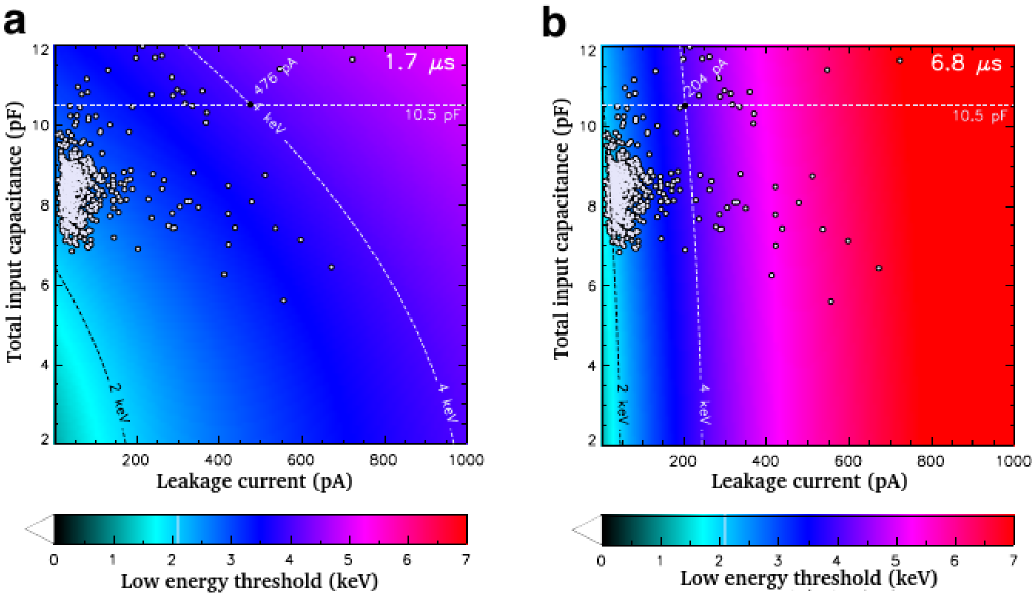
- **GRM FOV wider than ECLAIRs one**
- **Rate ~ 90 GRBs/yr** – poorer localization (5-10 deg with 3 GRD)
- ECLAIRs sensitivity to short GRBs can be improved when combined with GRM.

Schottky-type CdTe detectors

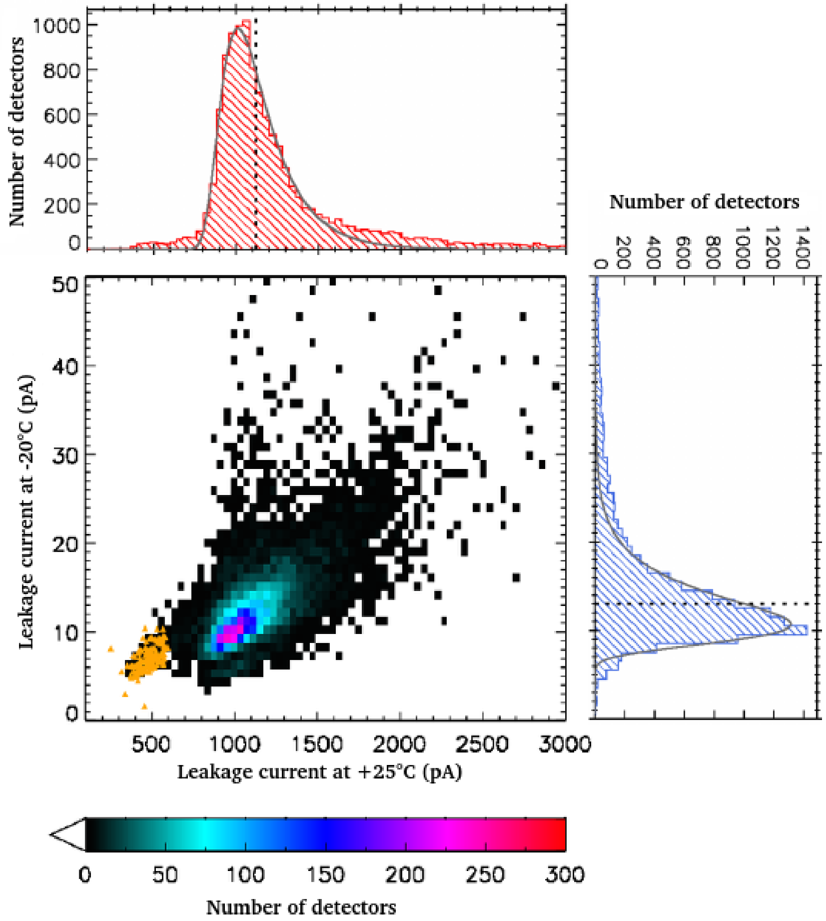
- To reach a 4 keV low-energy threshold, we needed to limit the electronic noise by making use of
  - Schottky-type CdTe detectors known to have low leakage currents (< 150 pA at –20°C & –600 V)

    ⇒ Selection of 8000 detectors over a sample of > 14000 detectors

  - Low-noise and low-consumption ASIC IdeF-X produced by C



For two values of the peaking time

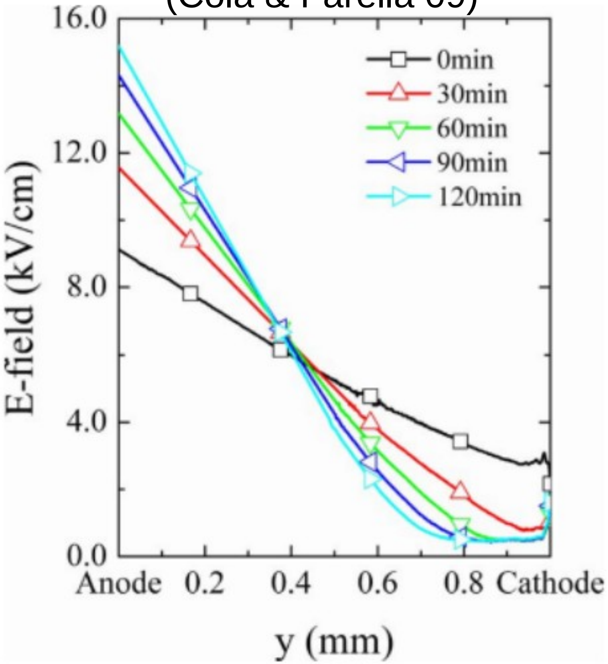


Detectors polarized at –600V

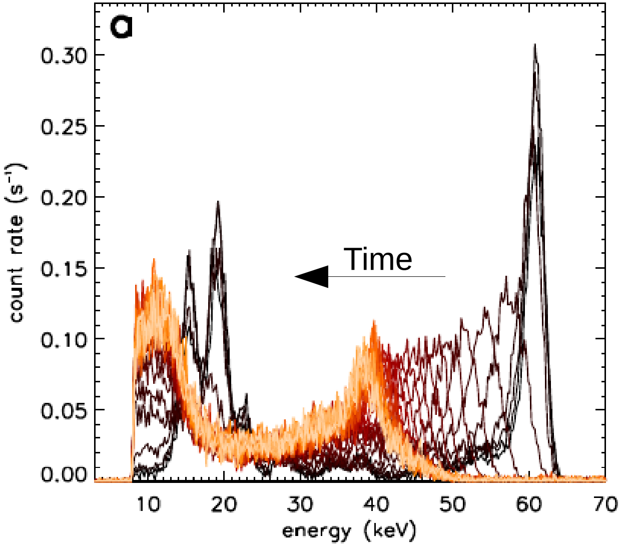
Schottky-type CdTe detectors

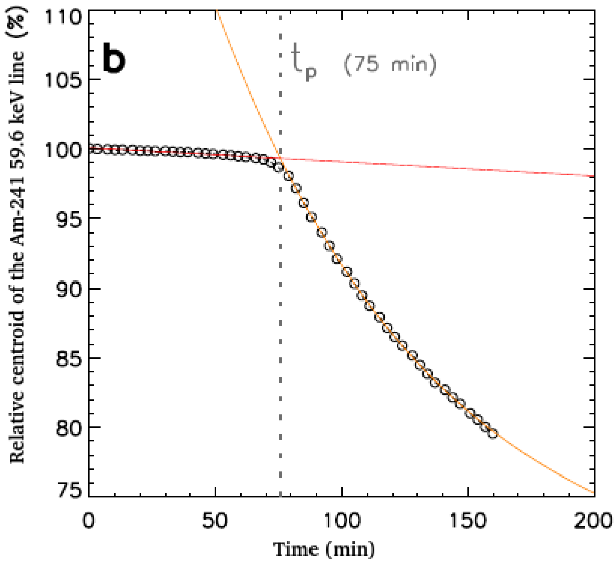
- However, such detectors suffer from the polarization effect (Cola+07) ⇒ degradation of the spectroscopic and counting performance of the detectors once polarized

(Cola & Farella 09)



Spectra measured at +25°C & HV = –300 V



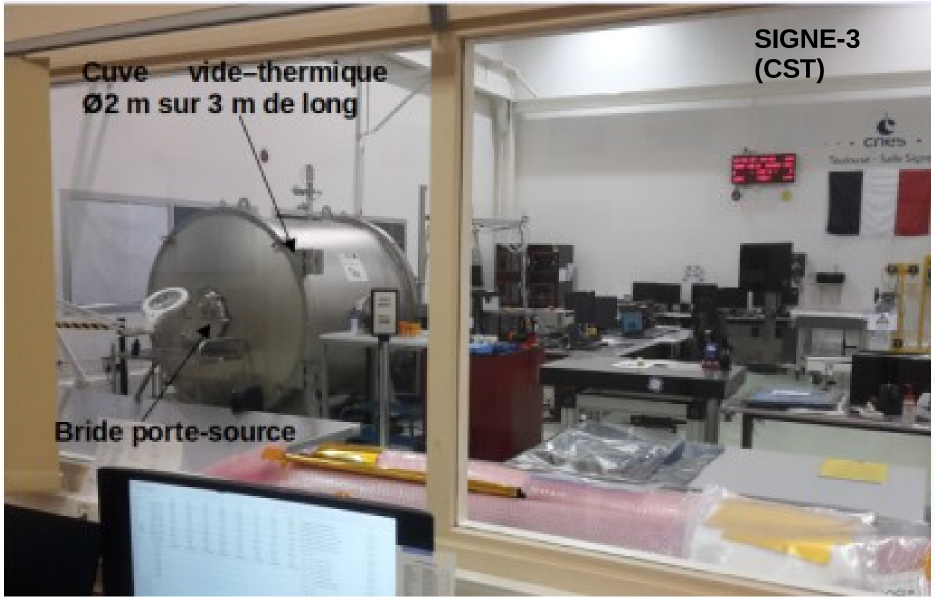


- Polarization time (t_p) depends strongly on the detector temperature (and the HV-value applied)

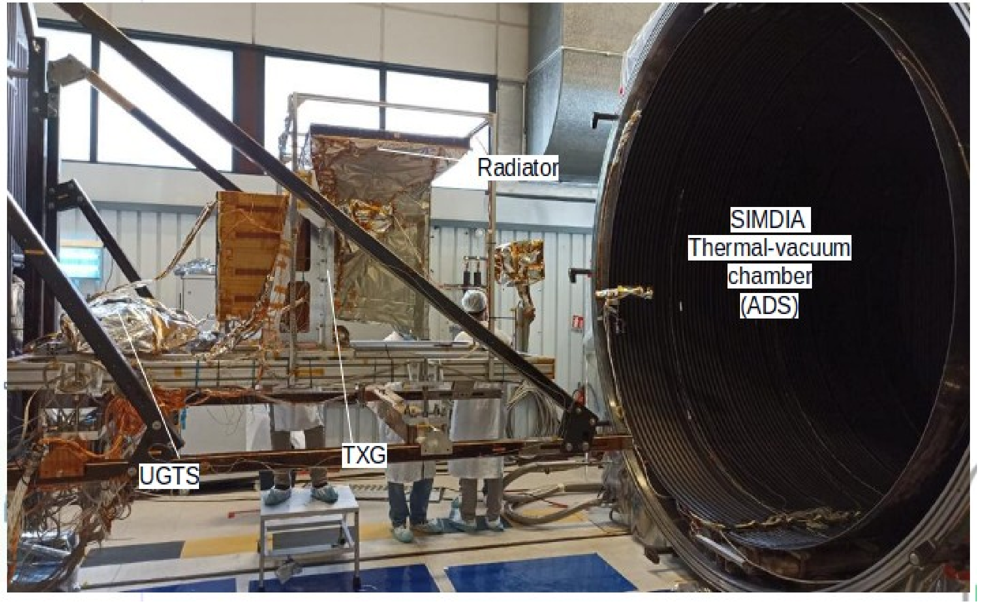
- **Necessity to depolarize the detectors regularly in-flight when passing through the SAA** (longest time between SAA passages ~ 15 h) since no observations could be done

Ground Support Equipments

- Camera operated under flight conditions within a thermal-vacuum chamber located at the SIGNE-3 (CST) clean room and the whole instrument (including UGTS) at ADS (Toulouse) for TVAC tests
- Nominal detector temperature of –20°C or within [–26°C ; –15°C]



SIGNE-3 CNES clean room
(Toulouse, FR)



Airbus clean room
(Toulouse, FR)

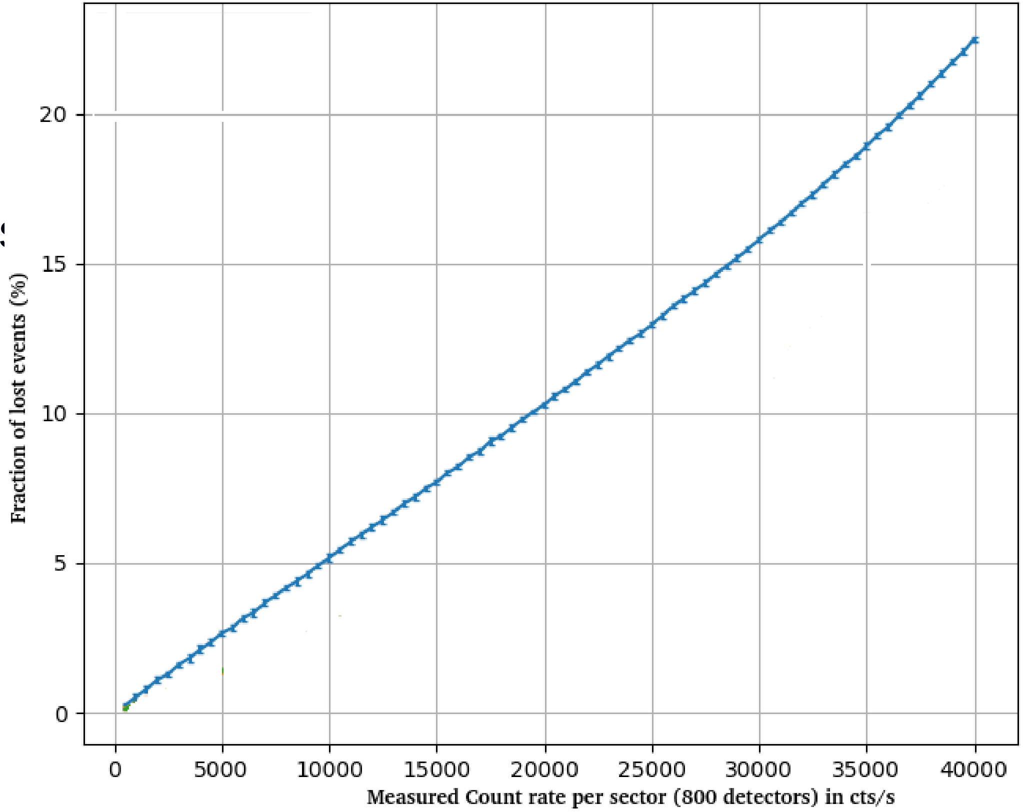
Dead Time

- An on-axis source with Crab intensity will produce in the 4 – 150 keV band around 800 cts/s over the entire plane in addition to the background noise (~4500 cts/s)

- Dead time has to be computed at the sector level.

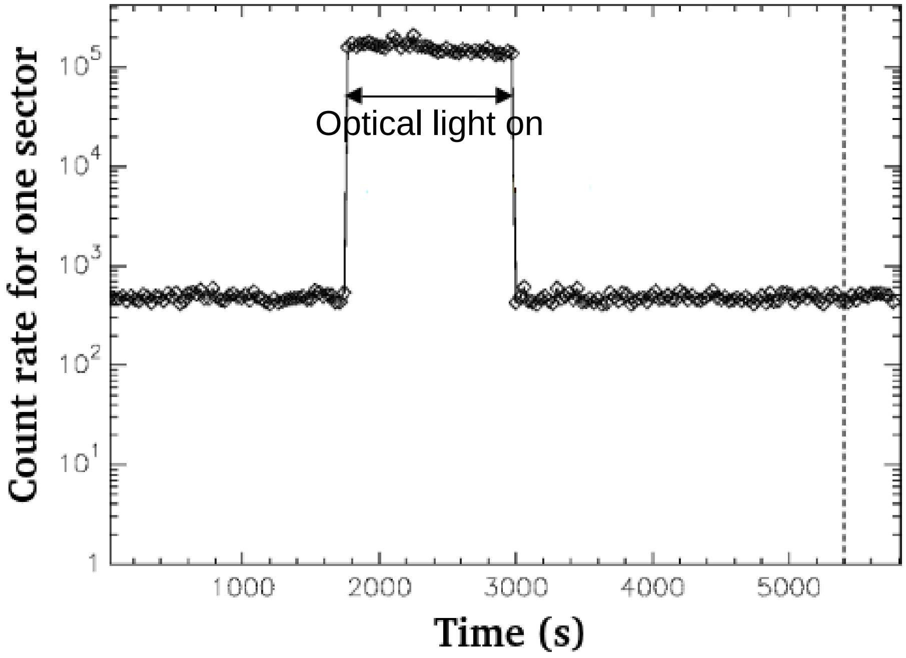
- Simulations with real hardware show that the dead time is:
  - ~7% for counts rates of 10^5 cts/s (12500 cts/s
  - over a sector) over the plane (< 0.1% of GRBs
  - ~4% for count rates of 5×10^4 cts/s over the plane (< 0.5% of GRBs).

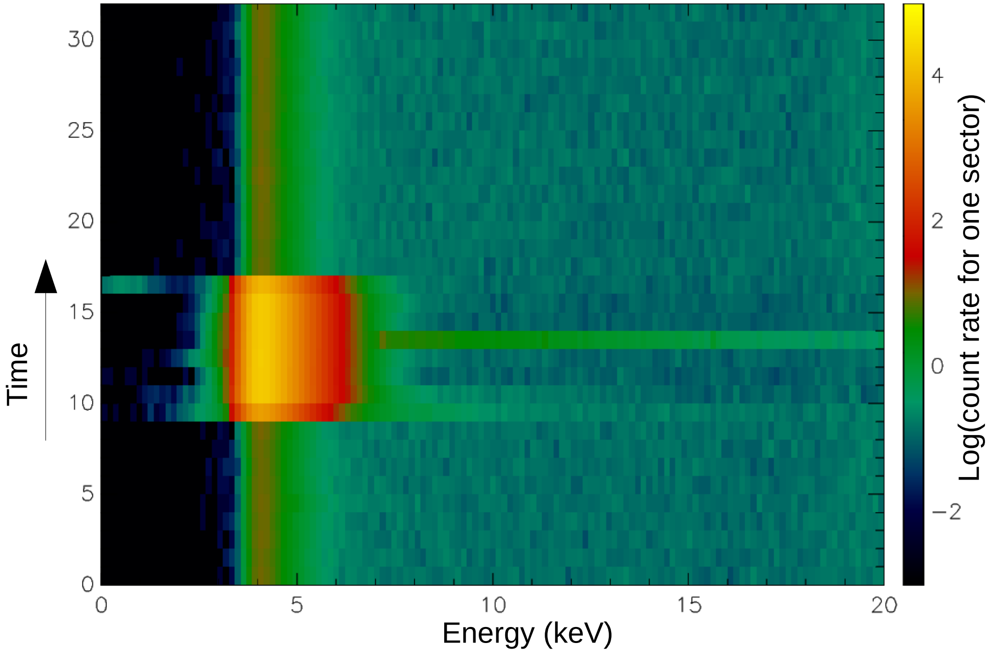
- We consider that this is acceptable, because we can reconstruct the original flux for dead times up to 15 – 20%.



Optical Loading

- Tests done with and without optical light within the thermal-vacuum chamber to investigate for any afterglow effect on the detector performances

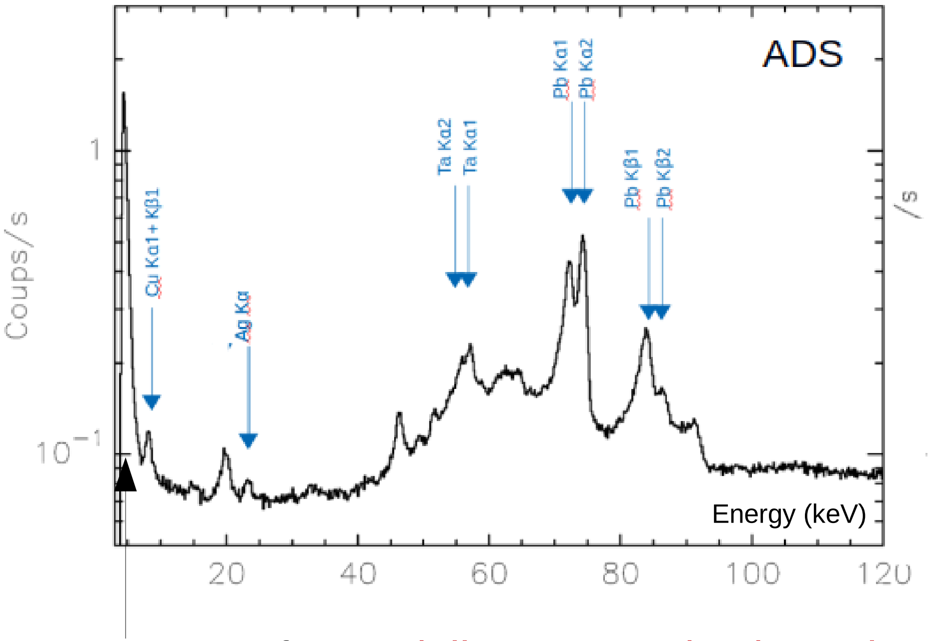


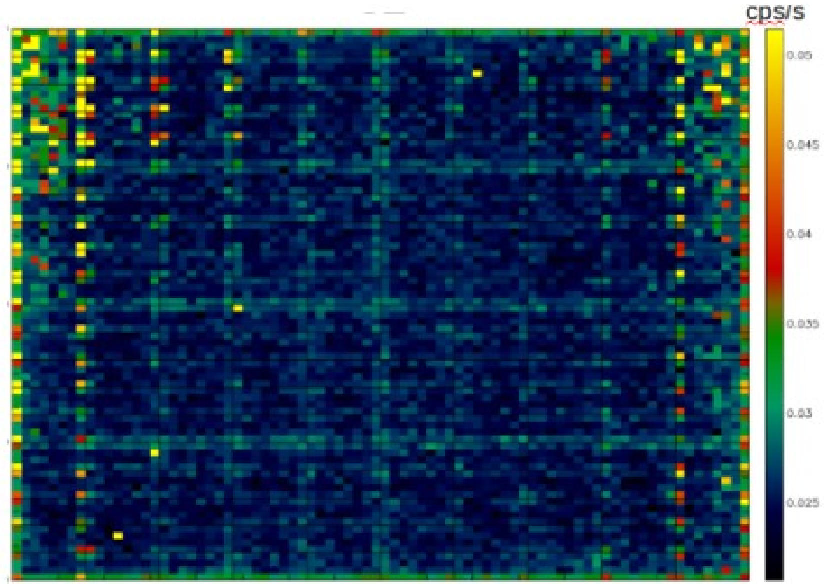


- After switching off the optical light, X-ray spectral response + counting not affected
- Readout electronics enabled to process very high count rates (> 10^5 cts/s)

Minor issues

- Background measures without any X-ray sources within the thermal-vacuum chambers at T_{det} = –20°C



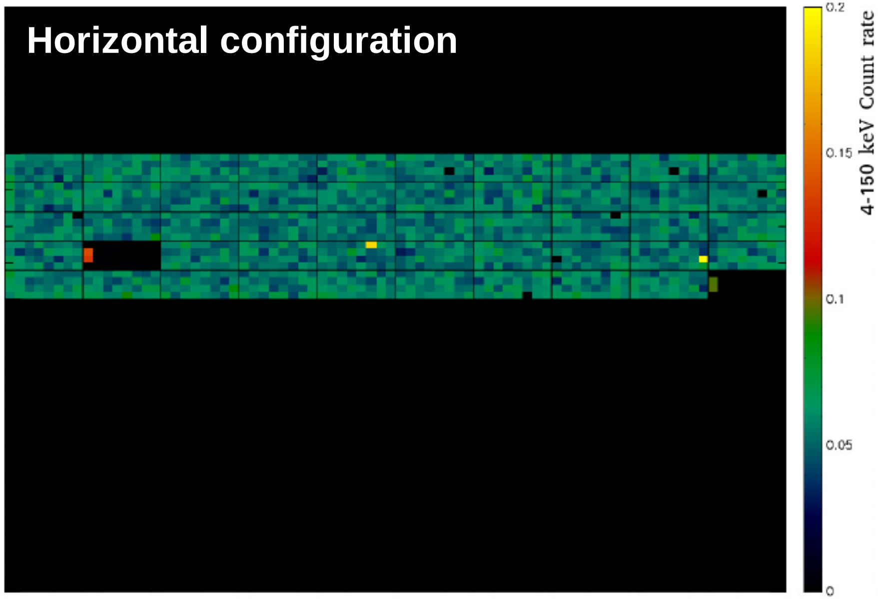


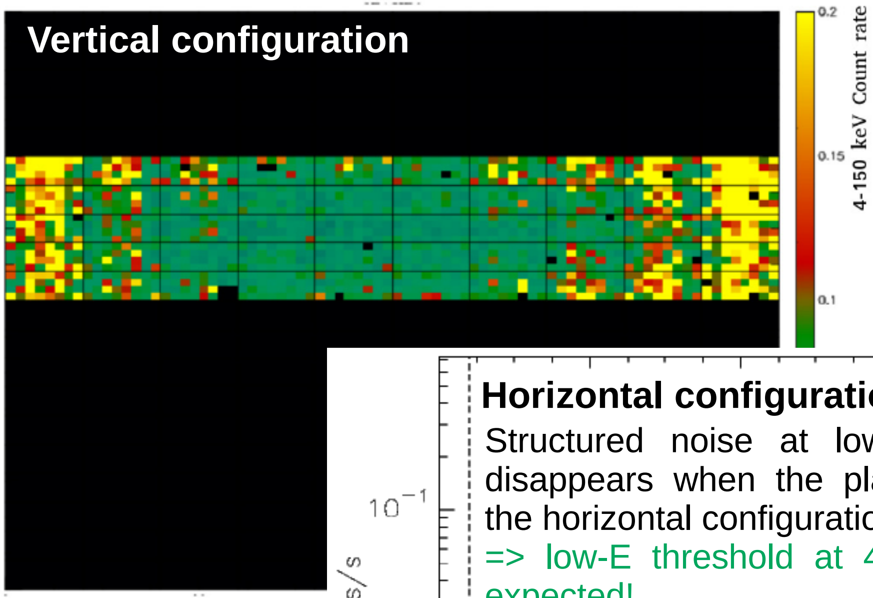
- Presence of a spatially-structured noise at low energy (< 7 keV) produced when the heatpipes work
- Noise count rates (CR) vary from ~4 to ~50 cts/s. To be compared to CR_{CXB}(4–5 keV) ~ 260 cts/s (wo Earth in FoV)
- Deep investigation of this phenomenon, but origin still unclear

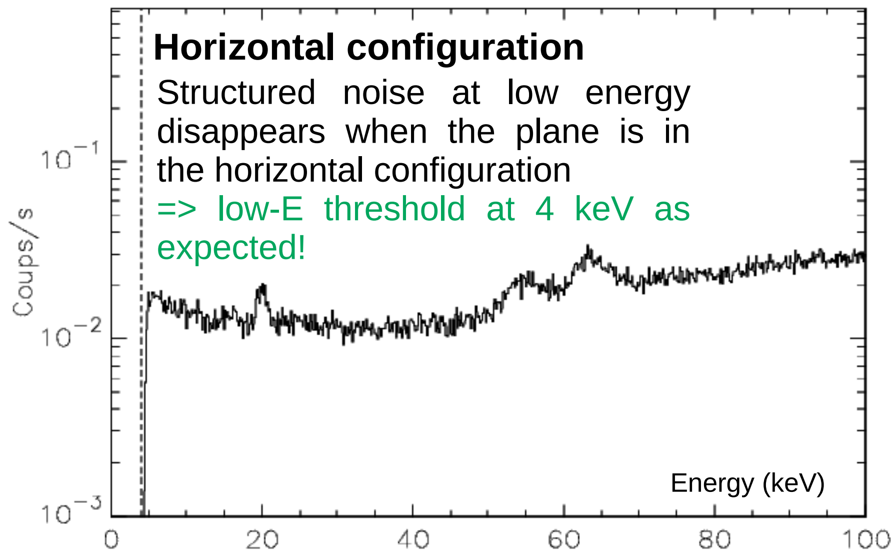
- Development of several analysis methods to mitigate the effects of this noise for ground analysis

Minor issues

- Investigation of this noise origin for different configurations of our ground model of the detection plane (i.e. 1/4th of the flight model) in 2022







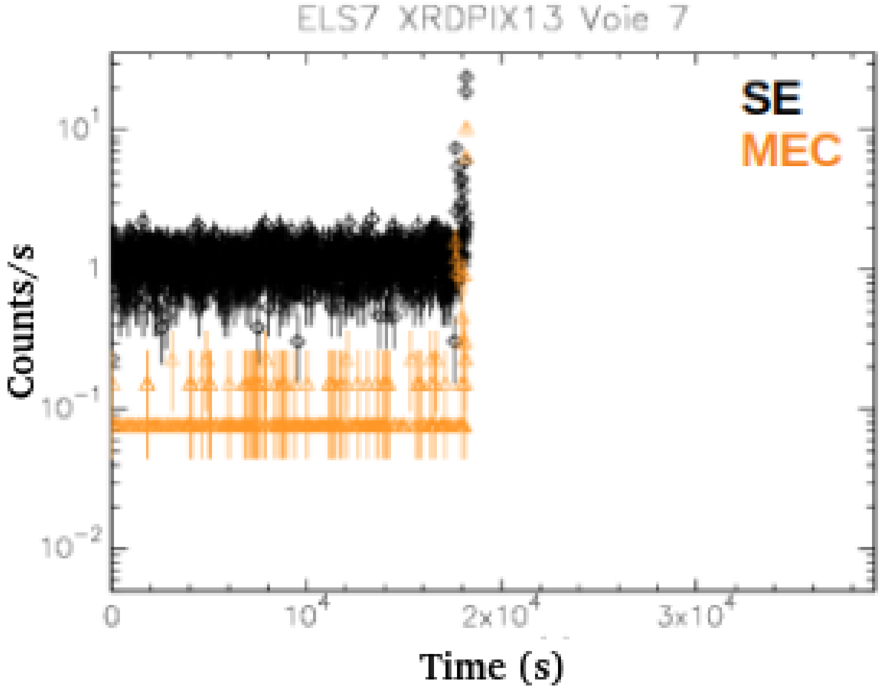
- Most tests on the flight model performed with a vertical position of the detection plane

- In the vertical position, heatpipes do not work in a nominal way. Horizontal position better mimicks micro-gravity conditions.

Noisy Pixels

- Automatic software to disable noisy pixels by putting SBN=63 once CR > 25 cts/s (i.e. 200 cts over 8 s) in order to ensure valid event counting
  ⇒ Software works well
  ⇒ Noisy pixels disabled are rare

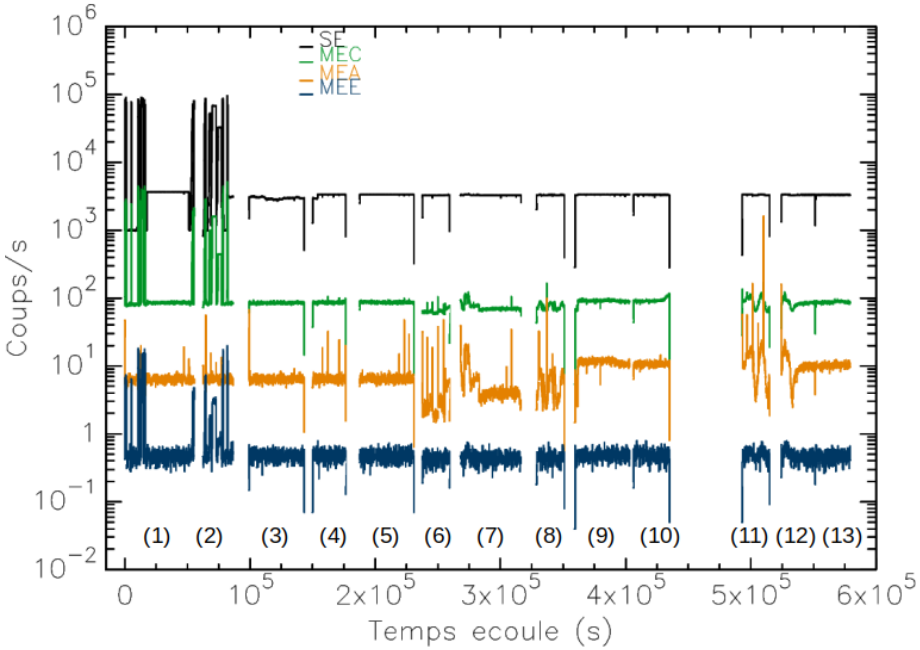
- At the end of the calibration sequence, only 7 dead pixels (SBN = 63)

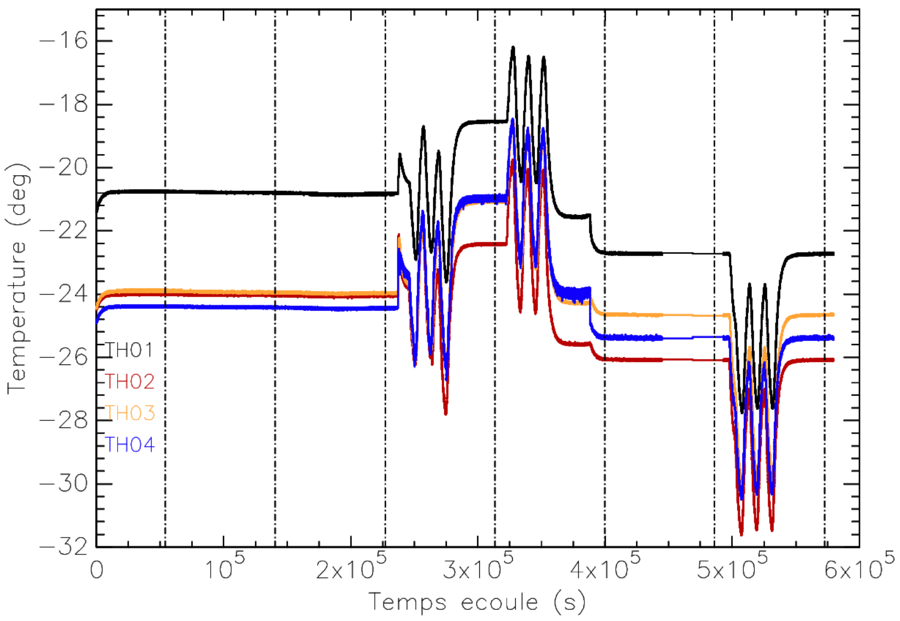


Example of a disabled noisy pixels

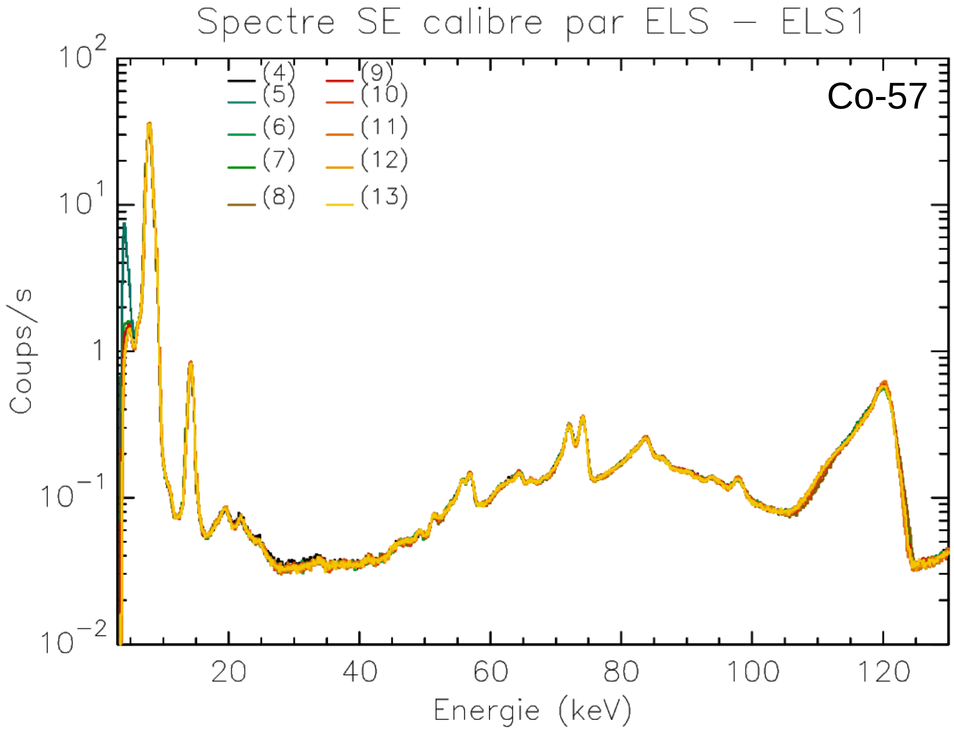
Performance Stability

- Test over 7 days simulating realistic SAA passages using Co-57 + X-ray generator
- Generation of bursts with X-ray generator during phases (1) & (2). After, photon flux stable
  => System robust for counting reaching up to 10^5 cts/s over the detection plane
- Thermal cycles with amplitudes of ± 3°C around 3 temperature steps (see Figure on the right)
  => Counting varies due to structured noise at low energy – >7–8 keV count rates stable

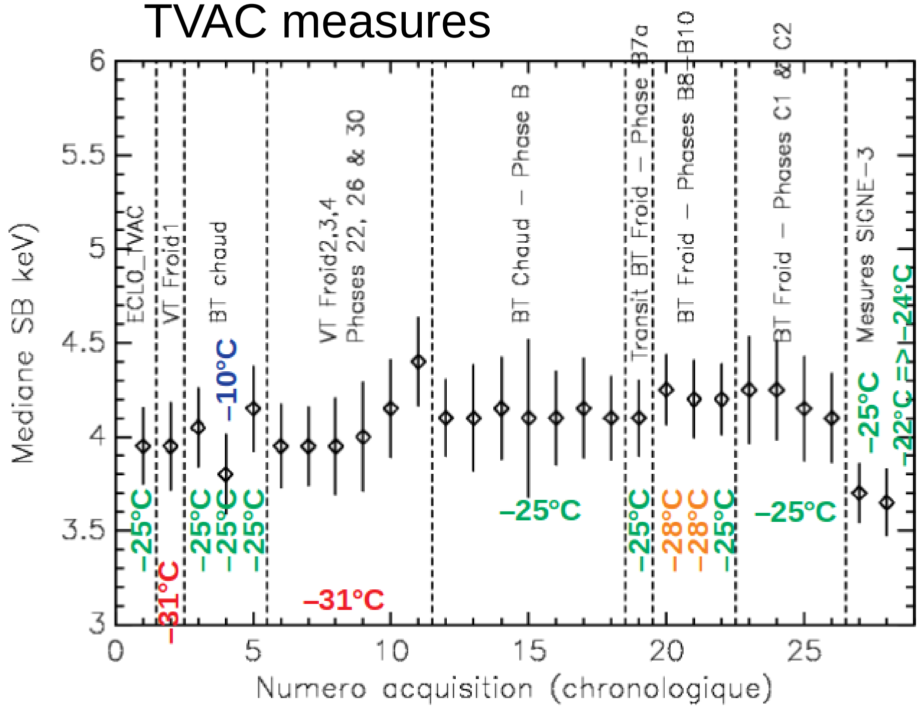




Performance Stability



TVAC measures



- Spectral response and low-energy threshold very stable over time and as a function of the detector temperature