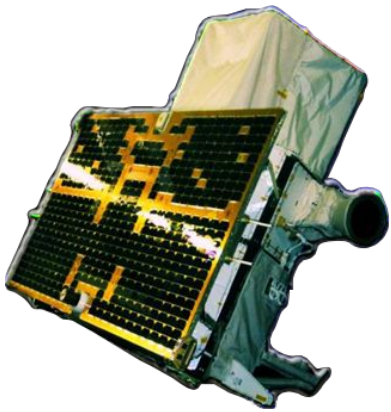
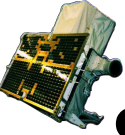




The AGILE Real-Time Analysis in the multimessenger era

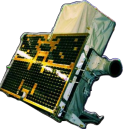
Andrea Bulgarelli
(INAF/OAS Bologna)
on behalf of the AGILE Team

**Low-Latency alerts & Data
Analysis for Multimessenger
Astrophysics Workshop
online, 13-14 Jan 2022**

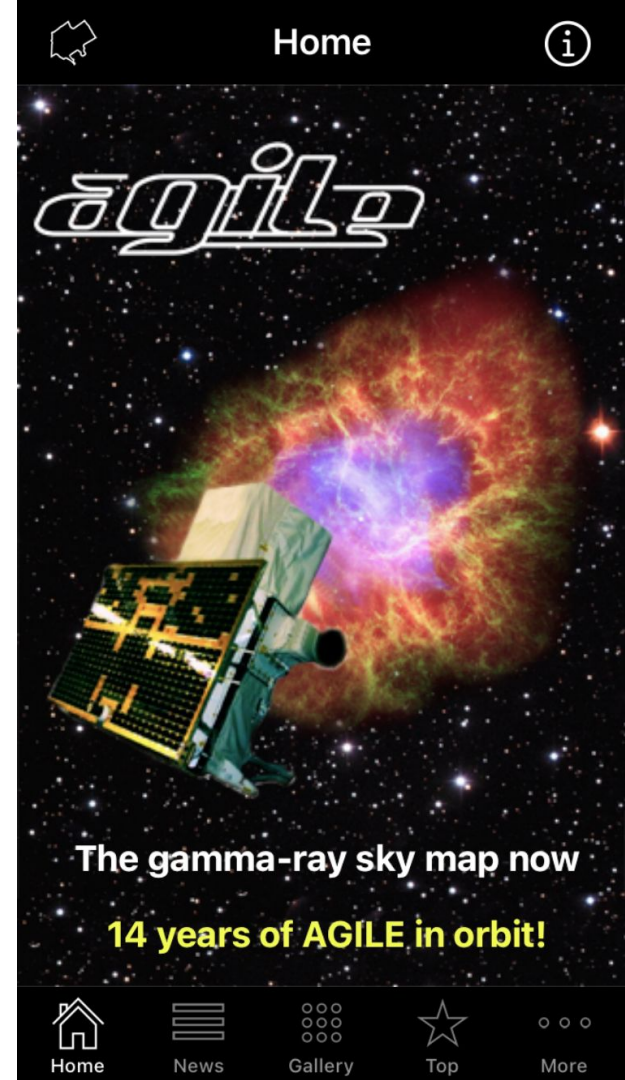


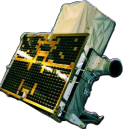
Summary

- The AGILE mission
- Data Flow
- Workflow
- Pipelines
- Current developments



THE AGILE MISSION AND THE DATA FLOW





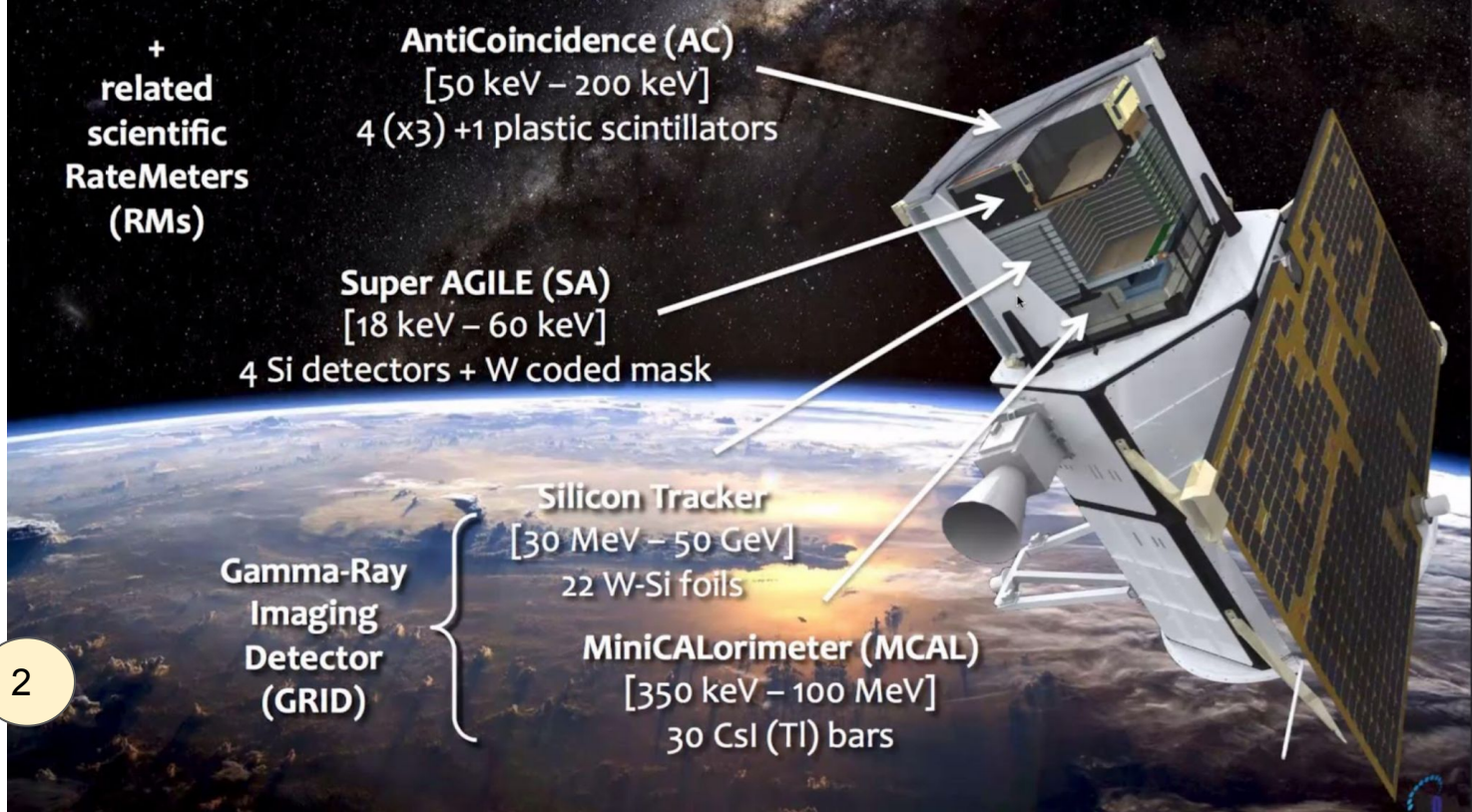
The AGILE satellite

AGILE **unique** combination of two co-aligned X-ray and γ -ray imaging detectors. Excellent for multimessenger counterpart search.

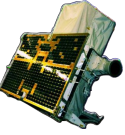
1

Two non-imaging 4π detectors: MCAL (0.3 - 100 MeV), AC (50 keV - 10 MeV)

2



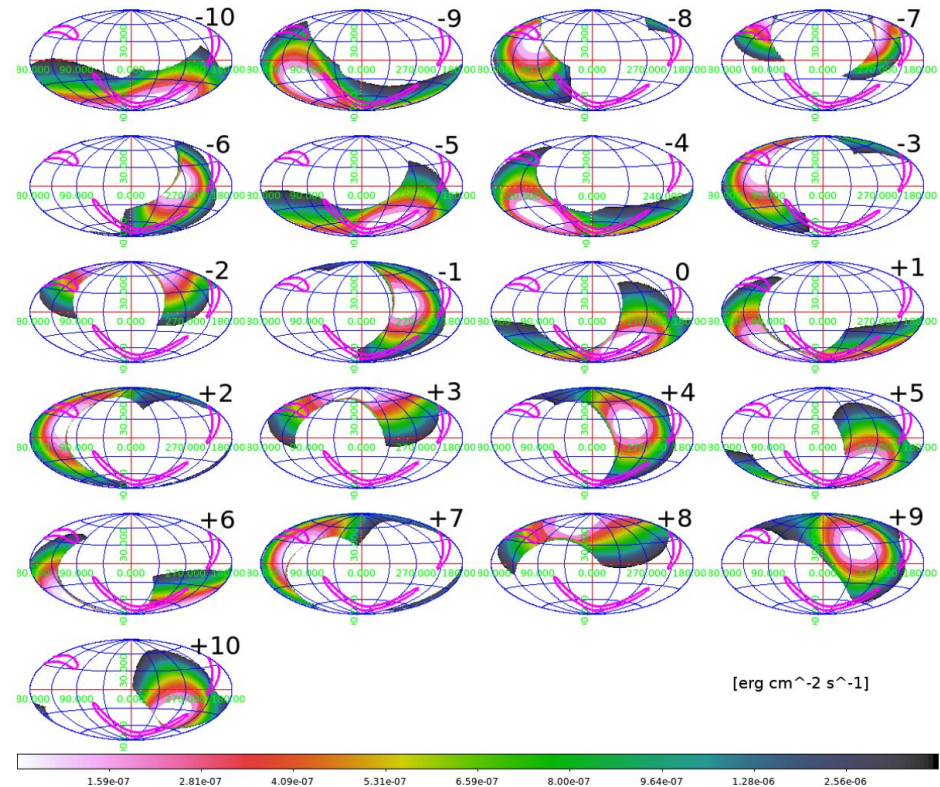
- **Launch: April 23, 2007**
- **Fully operational, nominal status, and active in:**
 - **gamma-ray astrophysics**
 - **terrestrial atmosph. & magnetosph. physics**
 - **search of GRB, GW counterparts, neutrinos, Fast Radio Bursts and other transients**



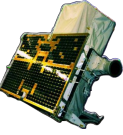
AGILE Mission Configuration

Other capabilities for multimessenger counterpart search:

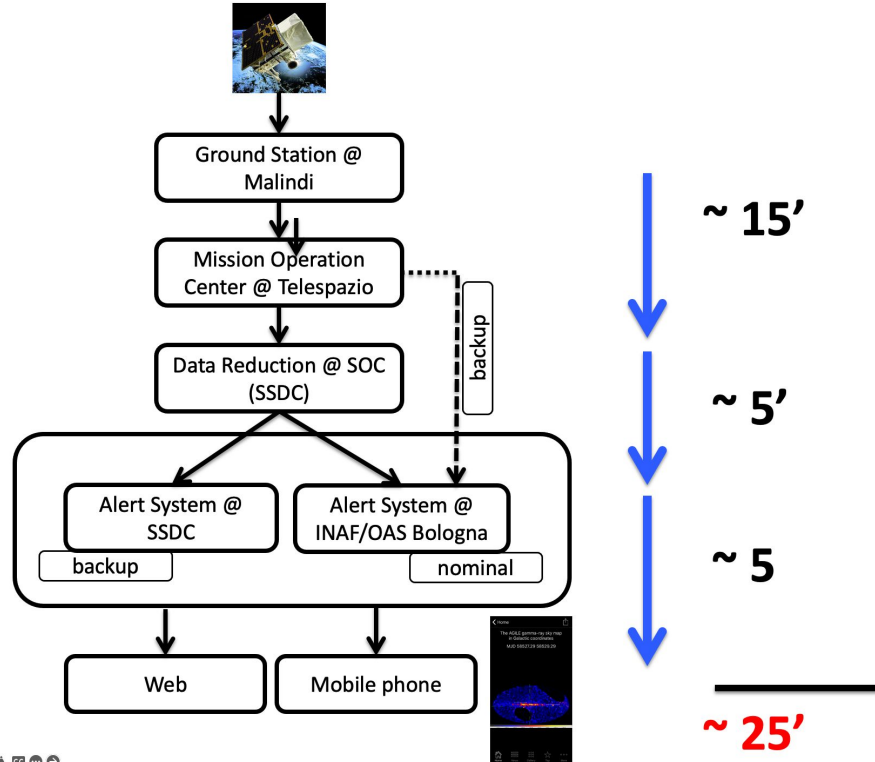
- GRID ($E > 30$ MeV) very large field of view (2.5 sr)
 - Sensitivity $\sim (1-2) 10^{-8}$ erg /cm²s in 100 sec.
- Spinning observation mode:
 - rotation $\sim 0.8^\circ$ /sec
 - **200 passes/day with 70-80% of the sky coverage** (solar panel constraints) →
 - **“almost” full sky coverage every ~ 7 min**



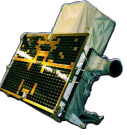
100 s interval sequence of ($E > 50$ MeV) maps in Galactic coordinates showing the AGILE-GRID passes with the best sensitivity (in erg cm⁻² s⁻¹) over the GW170104 obtained during the period (- 1000 s, + 1000 s) with respect to event time.



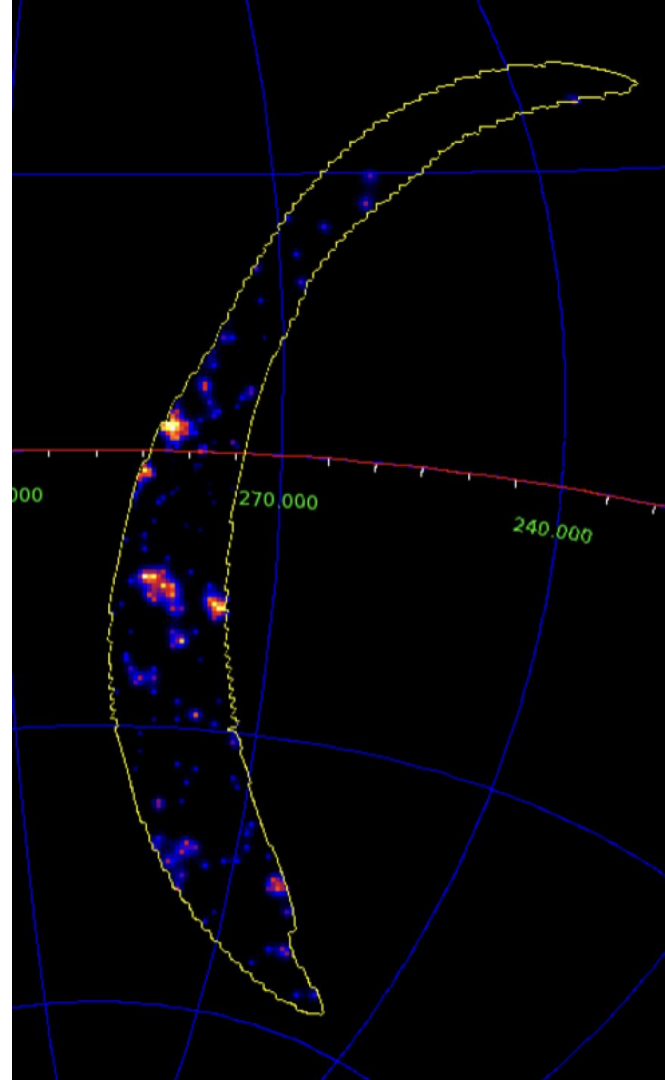
From Ground Station to AGILE Science Team

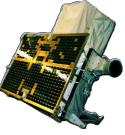


- First scientific results through the Real Time Analysis (RTA) developed by INAF-OAS are **within ~ 25 min from the data downlink** to the ASI Malindi ground station → software optimisation/parallel processing
- The AGILE data flow and **pipelines** are **distributed between the data center at ASI/SSDC and INAF-OAS** in Bologna → redundancy/availability



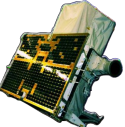
WORKFLOW AND PIPELINES



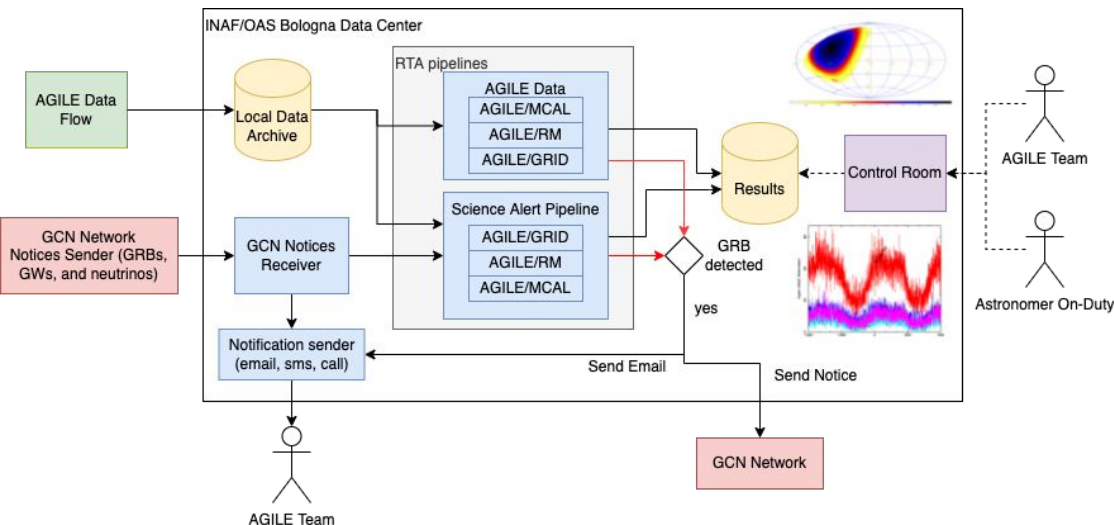


AGILE Team organization

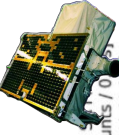
- **The monitoring of the gamma-ray sky is one of the main activities of the AGILE Team**
 - **Flare advocates:** GRID data, daily basis.
 - **Burst advocates:** shifts 24/7 to check results on external trigger, but also the check results on AGILE data.



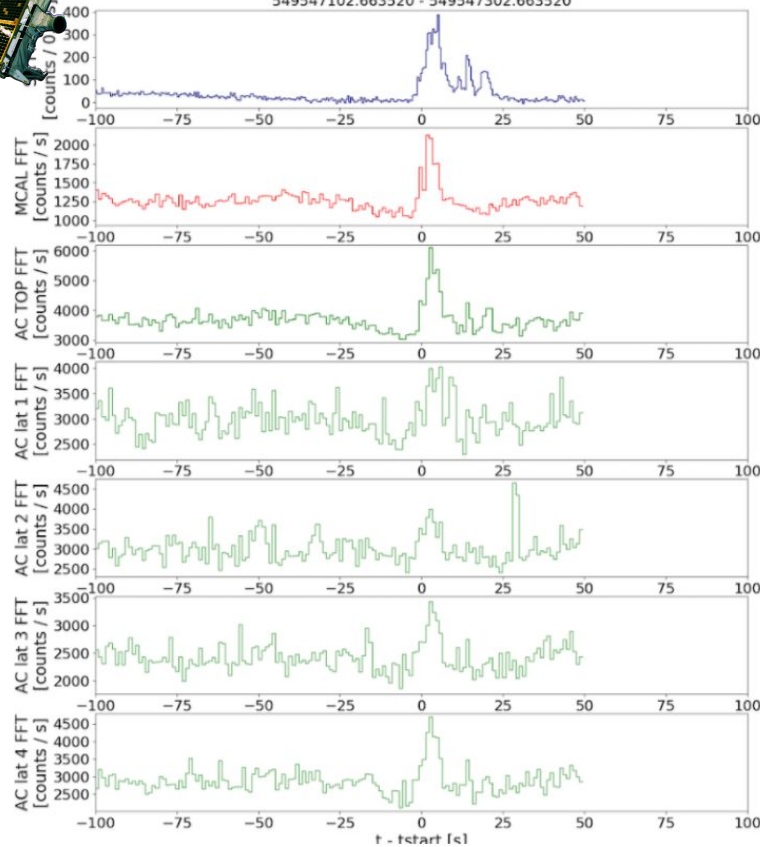
The AGILE Real-Time Analysis workflow



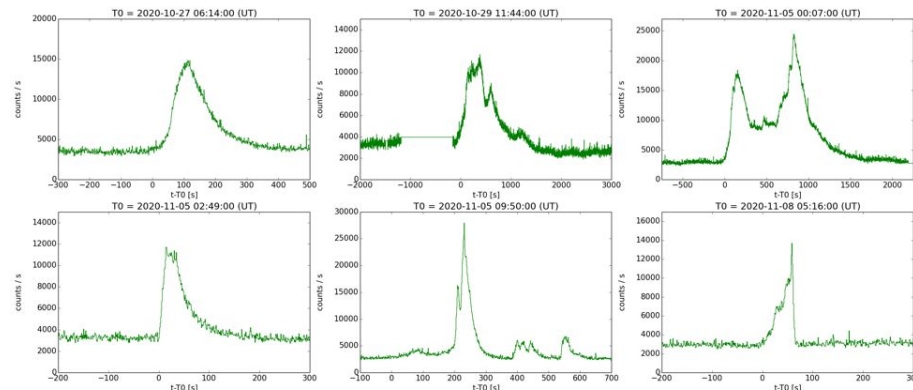
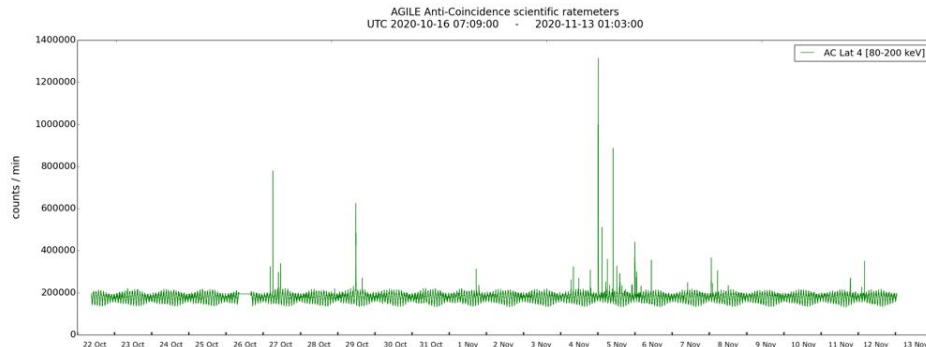
1. The system at INAF/OAS Bologna, with the LV2 data received from SSC.
2. Alerts are received from the GCN network.
3. **GW**: two independent **wakeup systems** call the AGILE Team if a new alert from LIGO/Virgo collaboration is received.
4. **PIPELINES ON REAL-TIME AGILE DATA:**
 - a. AGILE-MCAL pipeline searches GRB and TGFs. In the presence of a GRB identified by MCAL pipeline, an automated GCN notice is submitted to the GCN network.
 - b. AGILE-RM analyses SuperAGILE, MCAL, GRID and AC ratemeters
 - c. AGILE-GRID (SPOT6) search flares at daily basis above 100 MeV
5. **PIPELINES ON EXTERNAL SCIENCE ALERTS:** If new alerts are received, the **science alert pipeline** performs the required scientific analysis of GRID, MCAL and ratemeter data
 - a. The pipeline alerts the AGILE Team (SMS, email and call) preparing two templates for the GCN Circulars that the Astronomer on-duty can use to send an answer to the external science alert.
6. **Control Room**: to monitor both AGILE technical information (data archive, data flow etc.) and scientific results produced by the pipelines.



tstart - tstop
2021-05-31 11:58:22 - 2021-05-31 12:01:42
549547102.663520 - 549547302.663520

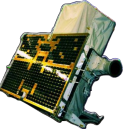


Ratemeters pipeline

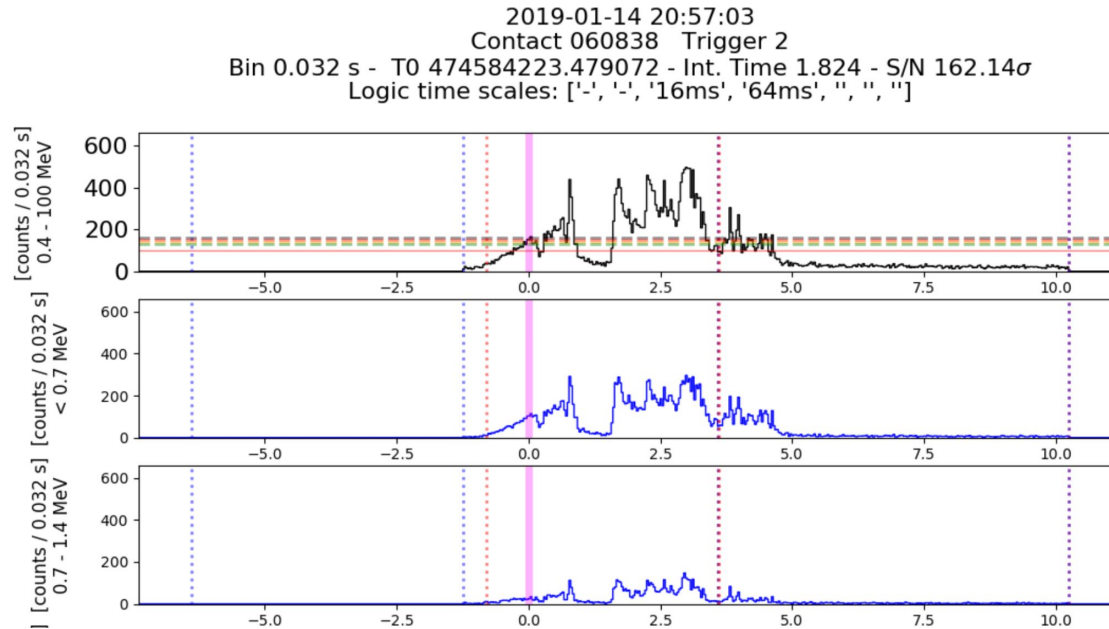


The AGILE RM (ratemeters) pipeline analyses SuperAGILE, MCAL, GRID and AC ratemeters and performs a detrending of the data.

AGILE AC Lat 4: efficient Solar activity X-ray monitor.

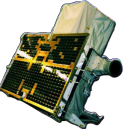


MCAL pipeline - GRB detection

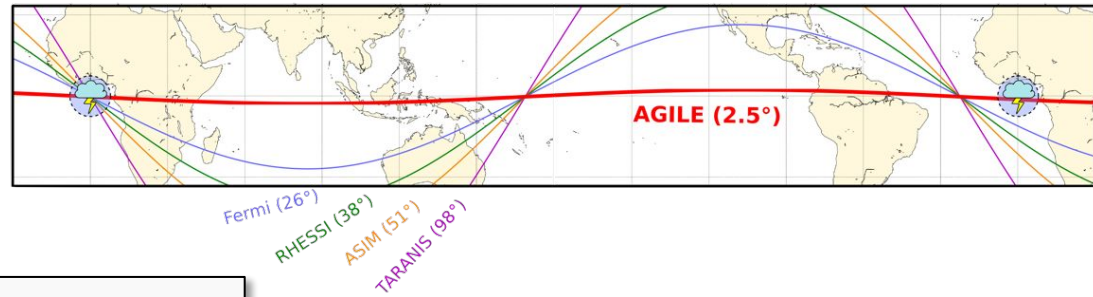


The AGILE MCAL automated pipeline sends notice to the GCN network when a GRB is detected. Since this implementation (2019) more than 60 automatic notices have been sent.

https://gcn.gsfc.nasa.gov/agile_mcal.html



MCAL pipeline - TGF detection



AGILE MCAL

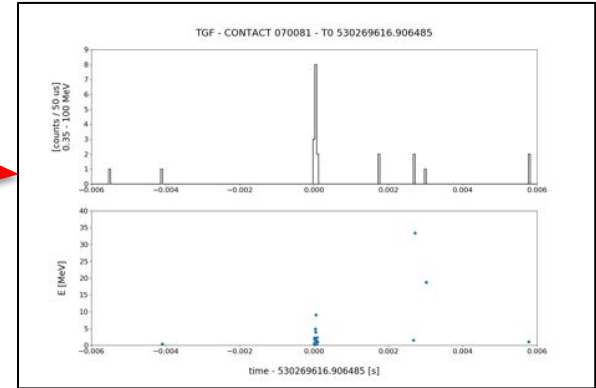
HomeGRBGRBlikeSTETGFControl RoomHelp

Orbit List

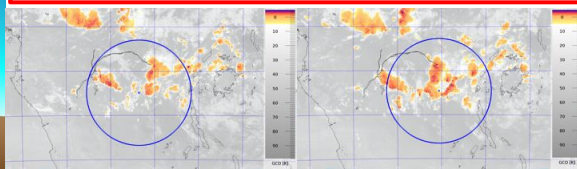
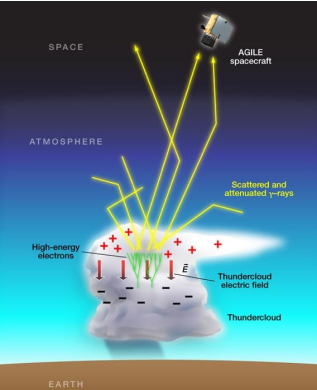
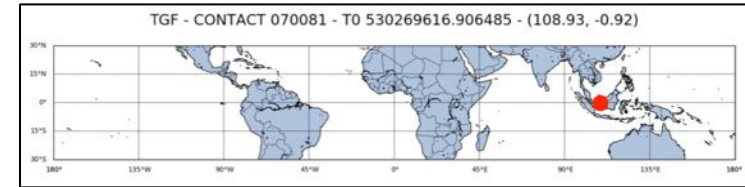
Show50entries

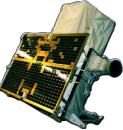
Search:

Orbit Number	First Trigger (UTC)	Last Trigger (UTC)	N of triggers	GRBs	GRBlikes	STEs	TGFs	Actions
070087	2020-10-20 15:34:19	2020-10-20 23:39:41	239	1	1	0	1	Orbit Trend Triggers GRB GRBlike STE TGF
070081	2020-10-20 08:13:13	2020-10-20 15:32:58	226	0	0	0	1	Orbit Trend Triggers GRB GRBlike STE TGF
070077	2020-10-20 00:34:27	2020-10-20 08:13:02	178	0	5	0	0	Orbit Trend Triggers GRB GRBlike STE TGF
070067	2020-10-19 07:25:41	2020-10-19 16:05:26	108	0	3	0	1	Orbit Trend Triggers GRB GRBlike STE TGF
070062	2020-10-19 02:36:25	2020-10-19 07:25:37	164	0	0	0	0	Orbit Trend Triggers GRB GRBlike STE TGF



The AGILE MCAL automated pipeline detect Terrestrial Gamma-Ray Flashes (TGF). From June 2020 about 500 TGF has been detected. Due to its equatorial orbit it is possible to detect multiple TGFs from the same storm.





Science Alert Pipeline

AGILE RT Alert Control Room LIGO Notices Pipes Science Alerts Monitoring GW Team Help 2022-01-13T10:05:22 (UTC)

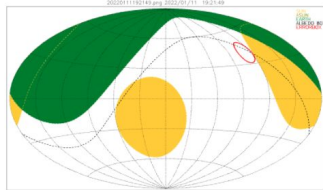
Instrument FERM_GB
Triggerid_seqnum 663621714_0
Coordinates (l,b): 247.783, 40.079
Event T0 (UTC) 2022-01-11T19:21:49.430
Event T0 (MJD) 59592.248228009
Event T0 (TT) 569013709.43

Archive Status

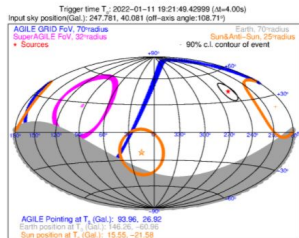
MCAL Coverage COR-3916 2022-01-13 05:57:30.000 UTC -- DeltaT: +124540.57 s
MCAL-3908 last trigger 2022-01-13 05:57:22.305 UTC -- DeltaT: +124532.875 s
GRID-EVT-coverage 2021-12-09 04:06:14.000 UTC -- DeltaT: -2906135.43 s
LOG 2022-01-13 05:57:26.900 UTC -- DeltaT: +124537.47 s
COR-3913 2022-01-13 05:57:29.535 UTC -- DeltaT: +124540.105 s
SA-3905 2021-03-03 22:53:26.367 UTC -- DeltaT: -27116903.063 s
Next MCAL @BO 2022-01-13 11:23:25 UTC
Next GRID @BO 2022-01-13 06:27:43 UTC

Show Contour

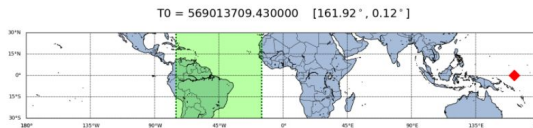
Visibility (Prevision)



Visibility (Data)



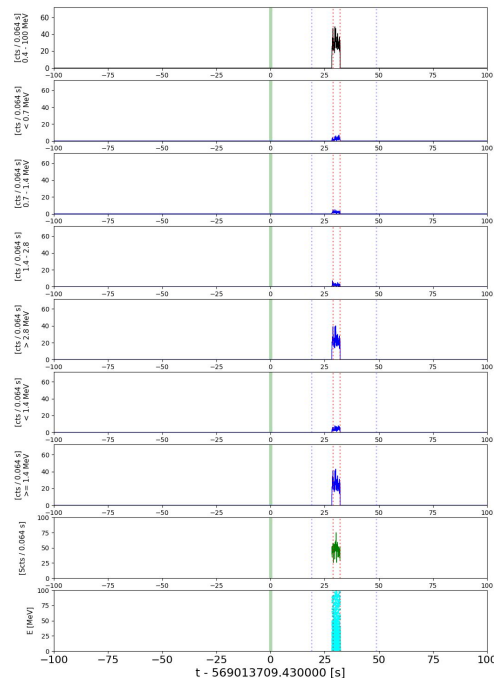
GEO LOC

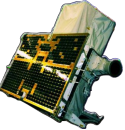


Automated analysis of triggers from
LIGO/VIRGO, Fermi, Swift, Icecube,
Integral, FRB, ...

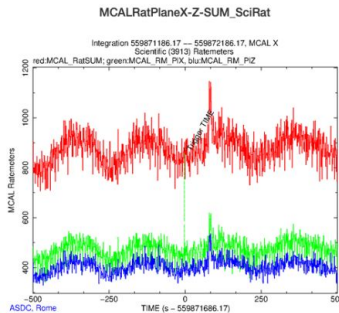
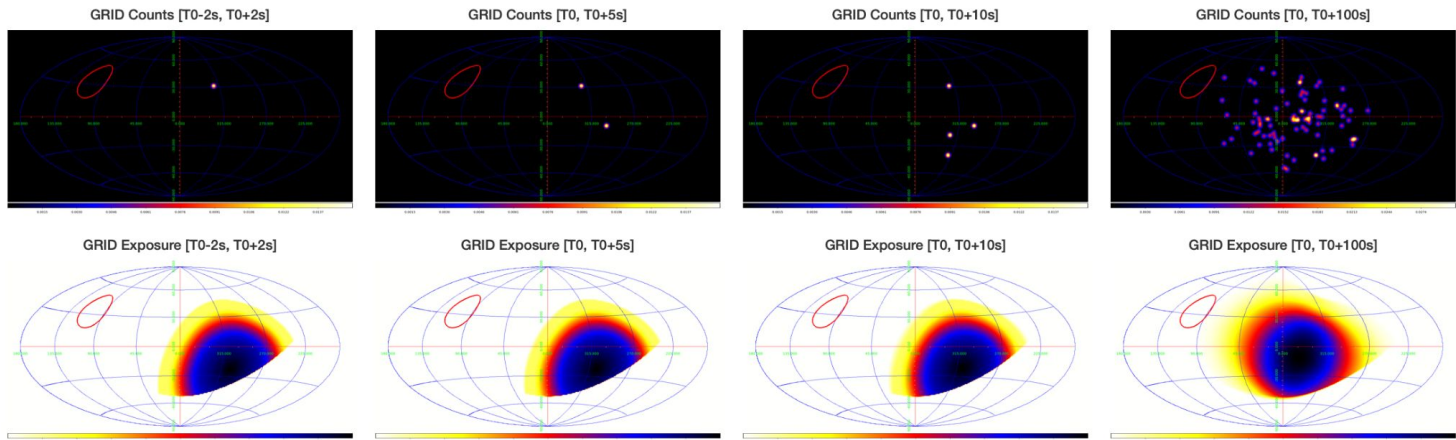
MCAL +/- 100 s

2022-01-11 19:21:49
Contact 076515-076515 - T0 569013709.430000

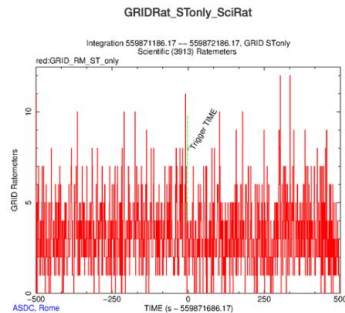




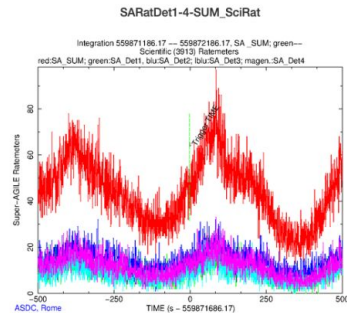
Science Alert Pipeline/2



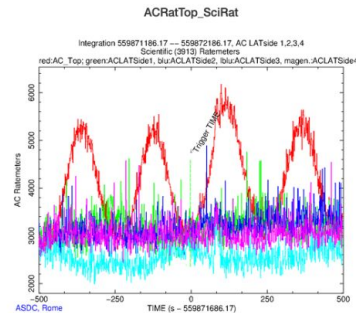
#19-Sep-2017 13:08



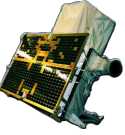
#19-Sep-2017 13:08



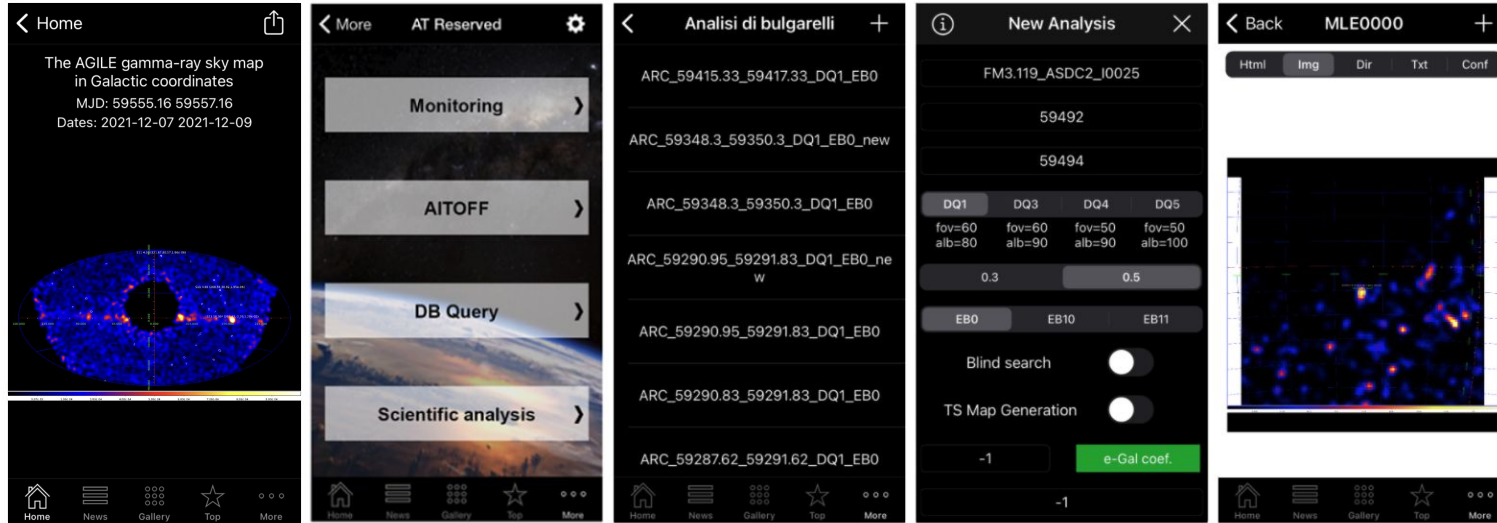
#19-Sep-2017 13:07



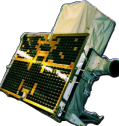
#19-Sep-2017 13:07



AGILEScience App



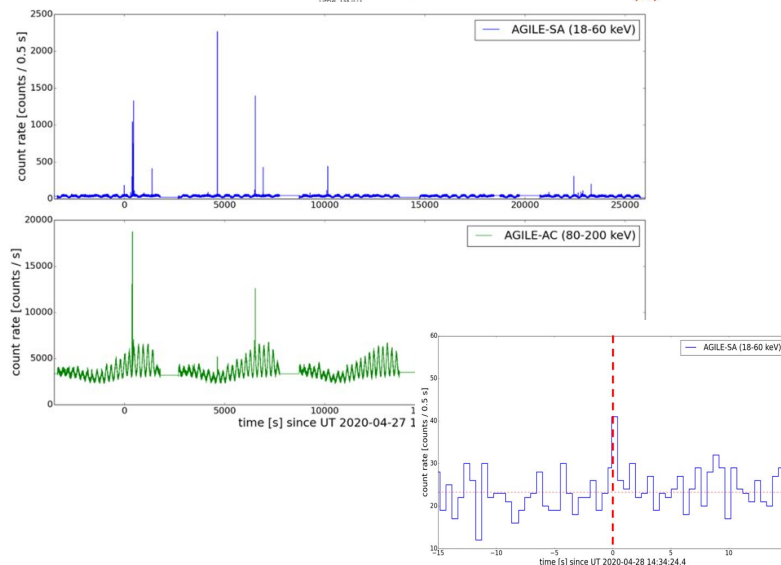
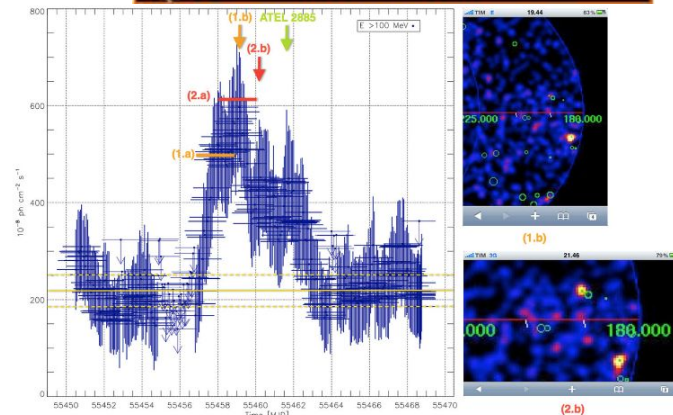
- The Team has developed an App to monitor the results of the AGILE satellite and perform GRID analysis: **AGILEScience - iOS and Android**
- The last available gamma-ray sky maps is available for outreach purposes.
- “Science on the road” with the AGILEScience App. From left to right: (i) the Flare Advocate can check the gamma-ray sky. If a candidate gamma-ray flare is found it is possible to perform a manual scientific analysis to confirm the result. To perform the scientific analysis, (ii) the Flare Advocate goes in the “Scientific Analysis” section, (iii) where it is possible to create a new analysis or select an existing one, (iv) some parameters of the analysis must be inserted (e.g. integration time, position in the sky), and (v) the App shows the final result, analysed with the Maximum Likelihood Estimator, and the sky maps

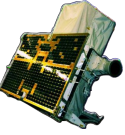


Many important discoveries.

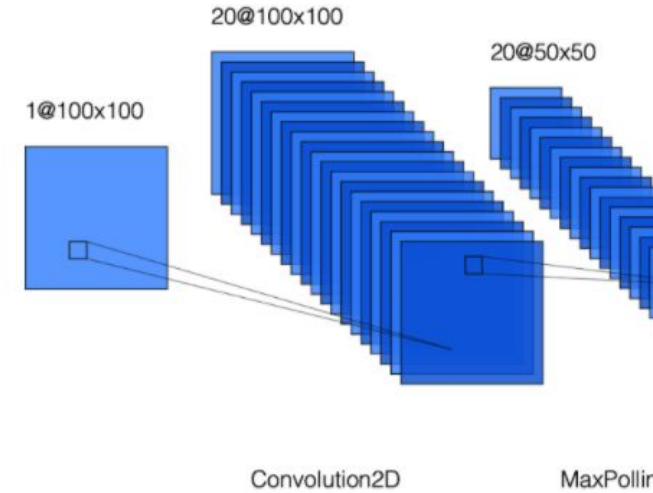
Two examples

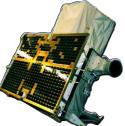
- The first detection of a gamma-ray flare from Crab Nebula in Sept 2010 was performed by these pipelines. AGILE Team was immediately alerted and after few hours the ATEL #2855 was issued. After few hours, the Fermi/LAT confirmed the result
 - **Science, Tavani et al. 2011 → Bruno Rossi Prize 2012**
- AGILE strongly affected by limited ground operations at ASI Malindi due to the COVID-19 pandemic: from March to June 2020 down to 3 pass/day (over ~14 pass/day) → new automatic ratemeter analysis pipeline and burst identification →
 - AGILE as a solar flare monitor
 - FRB science: **very important discovery** on April 28, 2020 (ATEL #13686) published in **Nature Astr., Tavani et al. 2021** (2021NatAs...5..401T), it shows for the first time that **a magnetar (SGR 1935+2154) can produce X-ray bursts in coincidence with FRB-like radio bursts**





DEEP LEARNING METHODS



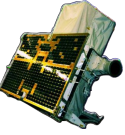


CNN evaluation with real data

- We developed a **Convolutional Neural Network** (CNN) to detect GRBs from the AGILE/GRID counts maps to overcome the limits of the Li & Ma methods
 - We tested the CNN using the Fermi-LAT, Fermi-GBM, and Swift-BAT GRB catalogues.
 - These maps are analyzed with both the CNN and the standard Li&Ma methods.
 - **The CNN detected 21 GRBs with a sigma > 3 from the list of GRBs obtained with Fermi and Swift catalogues. The Li&Ma on the same list and with the same parameters detected only two sources.**
 - This CNN is implemented into the AGILE GRID real-time analysis pipeline that reacts to external science alerts.
- **In progress: deep learning methods on ratemeters.**

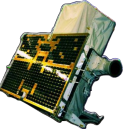
Table 2. List of GRBs detected with CNN and Li&Ma methods.

GRB	CNN			Li&Ma		
	T_{on}	N_{on}	sigma	T_{on}	N_{on}	sigma
100724B	200	9	5	200	11	4.4
110530A	200	3	3			
120711A	200	2	3			
121202A	200	2	3.5			
130427A	200	5	5			
130518A	200	2	3.5			
130828A	200	5	5			
131108A	200	11	5			
141012A	200	3	4			
141028A	200	4	3			
160325A	200	4	4			
160804A	200	2	3.5			
160912A	200	8	4			
170115B	200	4	4			
170127C	200	3	4.5			
170522A	200	5	5			
170710B	200	4	3.5			
180418A	200	2	3.5			
180720B	200	13	5	200	13	4.7
190324B	200	5	3			
190530A	200	6	4.5			



Conclusions

- The **monitoring** of the gamma-ray sky with a rapid and efficient alert system led to the publication of **231 ATels** and **114 GCNs circulars**.
 - AGILE follow-up of all GW events resulted in **96 GW-AGILE type GCNs**.
- From May 2019 automatic **GCN notices** on **MCAL**: more than 60 notices have been sent to the GCN network about GRBs without human intervention.
- Many **lessons learned** after 15 years of operation on team experience, mission configuration, software optimization, team organisation that are available to the overall community.
 - Some part of the system will be reused for the development of the CTA/Science Alert Generation System (see Monica Seglar-Arroyo's talk).
- AGILE team is producing **new tools** available at <https://agile.ssdsc.asi.it/> and Agilepy (see backup slides) **to make easier as possible the use of AGILE data**, that is publicly available.
- **Coordination is mandatory. Enhance cooperation with the community**, e.g. on sub-threshold events.
- THE AGILE SKY SCANNING GOES ON!



References

Pittori, C. The AGILE data center and its legacy. *Rend. Fis. Acc. Lincei* **30**, 217–223 (2019).

<https://doi.org/10.1007/s12210-019-00857-x>

Bulgarelli, A. The AGILE Gamma-Ray observatory: software and pipelines, [Experimental Astronomy](#), 2019.

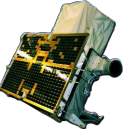
Tavani, M., et al., Science, Volume 331, Issue 6018, pp. 736- (2011).

Tavani, M., et al., Nature Astronomy, Volume 5, p. 401-407

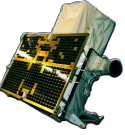
F. Verrecchia et al 2017 ApJL 847 L20

Parmiggiani, N., Bulgarelli, A. et al. The AGILE real-time analysis pipelines in the multi-messenger era, [ICRC 2021](#).

Parmiggiani N., Bulgarelli A., Fioretti V. et al. A Deep Learning Method for AGILE/GRID Gamma-ray Bursts detection, [Astrophysical Journal](#), Volume 914, Issue 1, id.67, 12 pp (2021)



Backup slides



AGILE two "lives": pointing and spinning

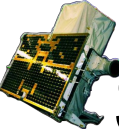
AGILE	POINTING	SPINNING
time period	Jul.07 – Oct.09	Nov. 2009 - today
attitude	fixed	variable (rotation $\sim 0.8^\circ/\text{sec}$)
sky coverage	1/5	$\sim 70\text{-}80\%$
1-day exposure (≤ 30 deg off-axis, @ 100 MeV)	$\sim 2 \times 10^7$ ($\text{cm}^2 \text{ sec}$)	$(0.5 - 1) \times 10^7$ ($\text{cm}^2 \text{ sec}$)

Agilepy

- Agilepy is an open-source Python package developed at INAF/OAS Bologna to analyse AGILE/GRID data built on top of the command-line version of the AGILE/GRID Science Tools.
- The main purpose of the package is to provide an easy to use high-level Python interface to analyse AGILE/GRID data by simplifying the configuration of the tasks and ensuring straightforward access to the data.
- Agilepy provides the last version of the available Science Tools (BUILD25), the H0025 instrument response functions (IRFs), and the latest version of the diffuse Galactic emission model.
- **Released in 2020**
- **In progress: new data access from SOC@SSDC**



3C454.3 Oct 2010 flare



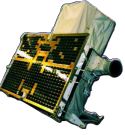
SSDC Tools

- <https://www.ssdsc.asi.it/mmia/index.php?mission=agilelv3mmia>
- <https://www.ssdsc.asi.it/mcal2grbcat/>

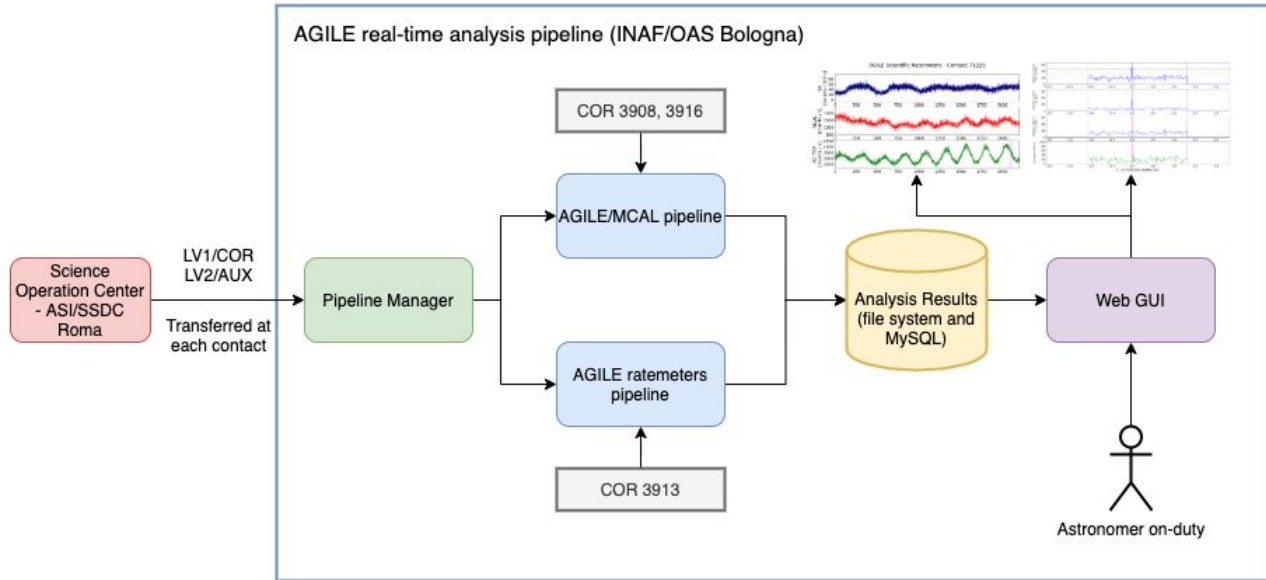


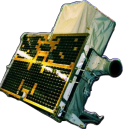
- Bulgarelli+, ADASS Conference, 2021



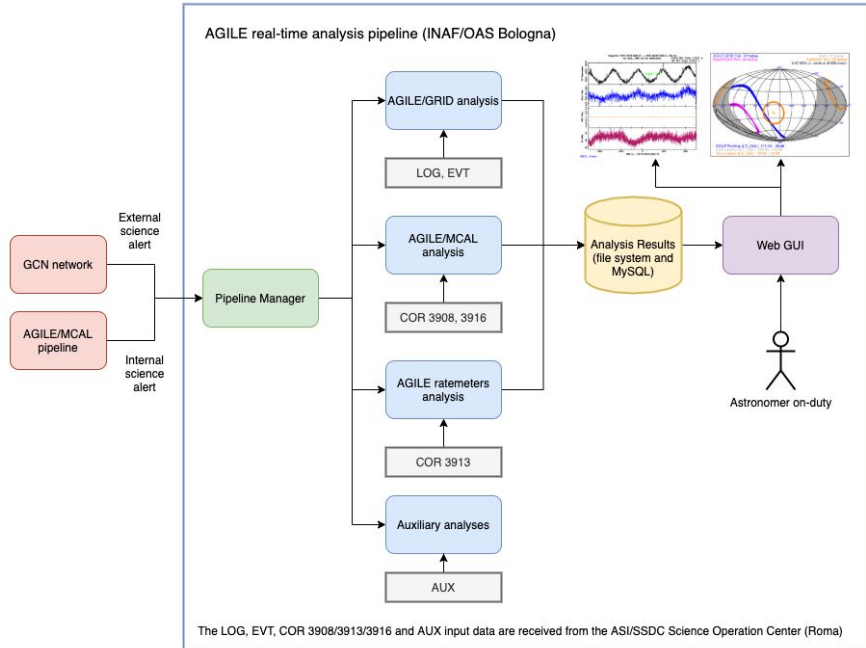


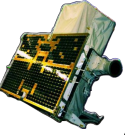
RTA pipeline to generate internal science alerts (GRBs and TGFs)





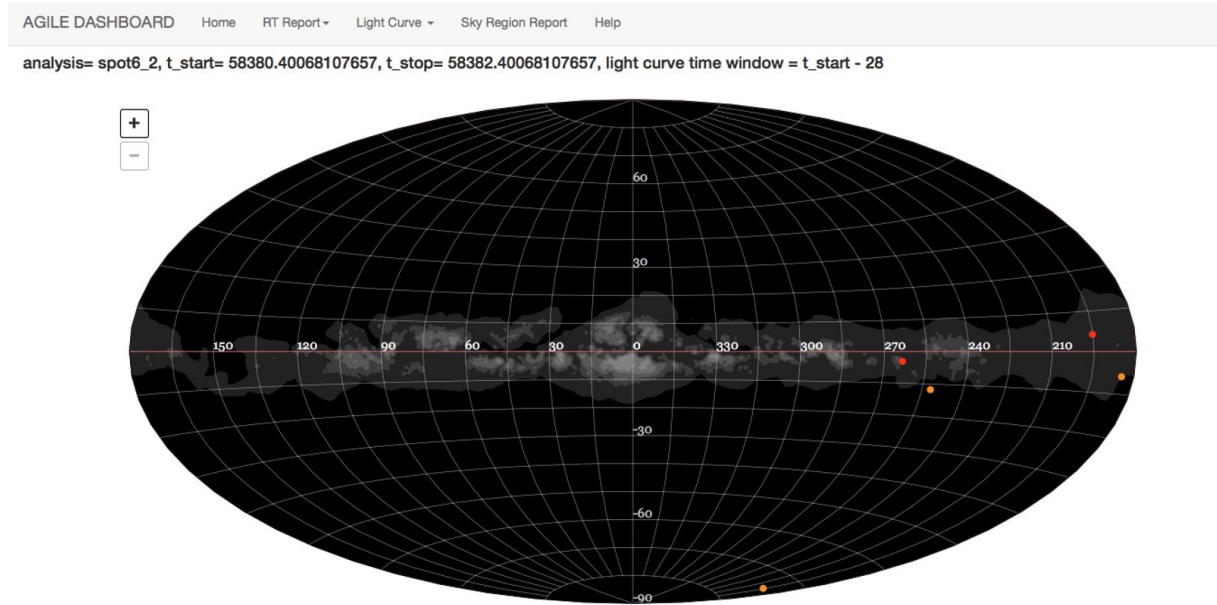
RTA pipeline for external science alerts (GW, GRBs Neutrinos)

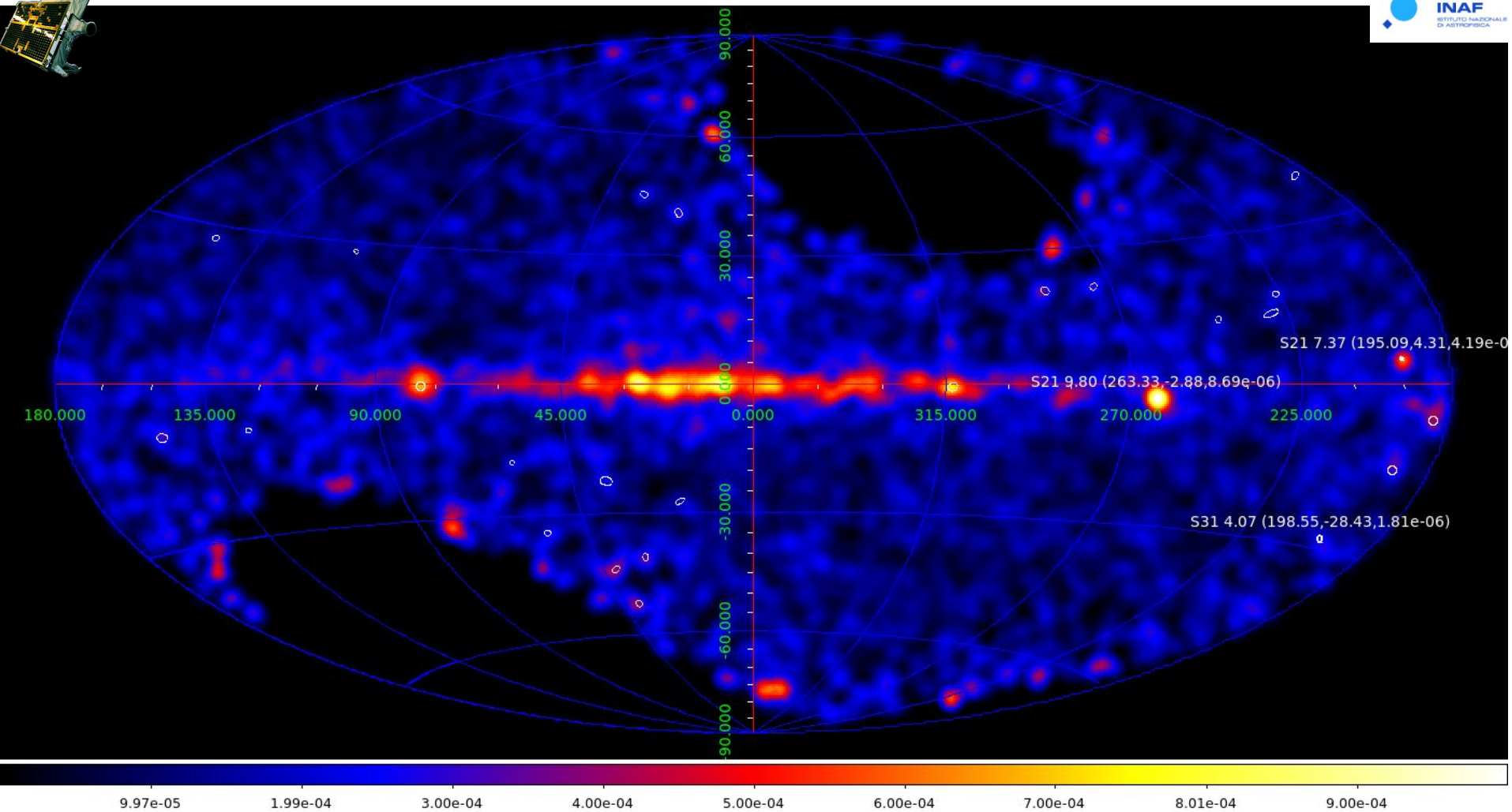
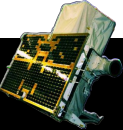


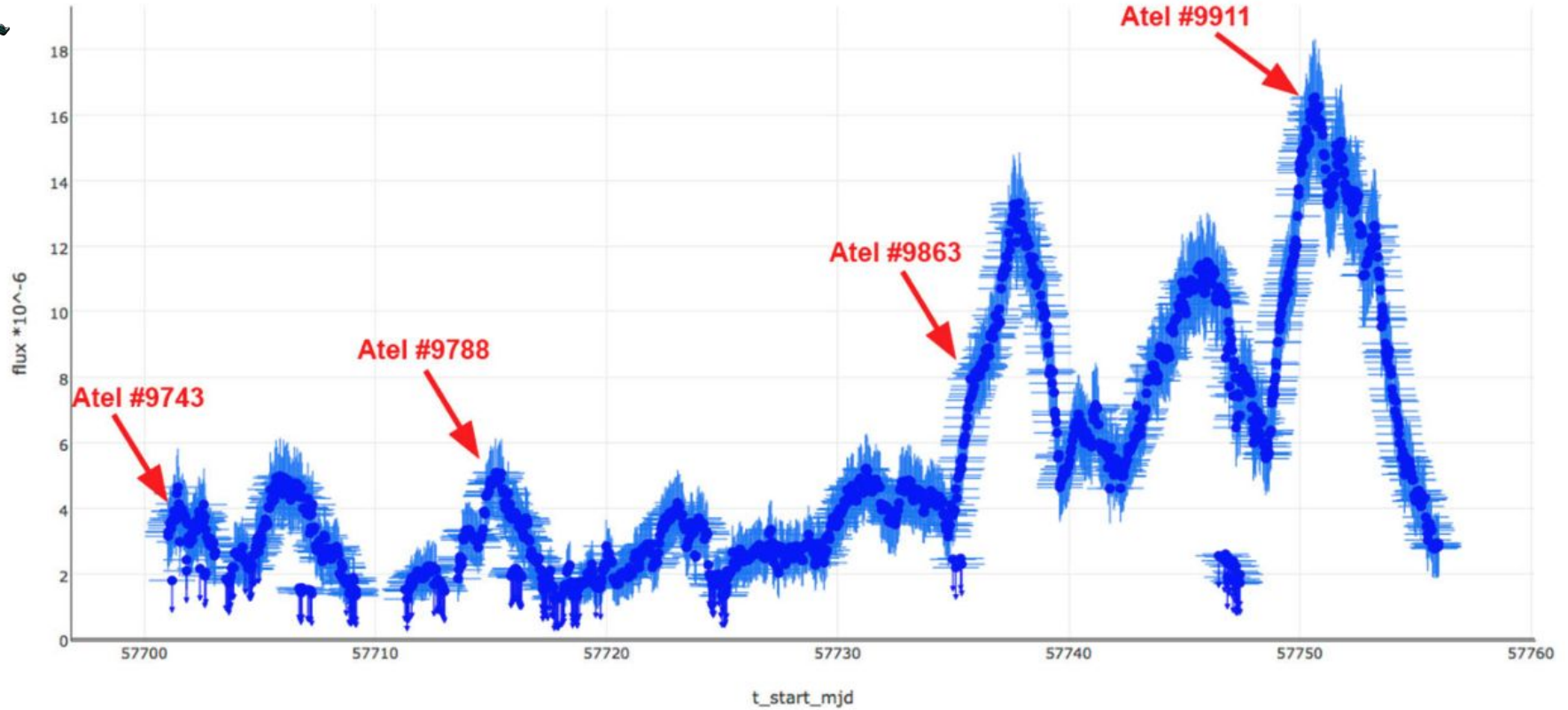
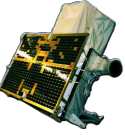


AGILE-GRID Science Alert (SPOT6)

- **Fast data processing** and use a list of known sources and blind search methods **to detect known or serendipitous astrophysical sources**.
- Analysis of the output of the data processing in order to **select the best transient candidates and generate science alerts** to provide a fast and automatic communication to AGILE Team and, after a manual and more refined recheck, to astronomical community via Astronomical Telegram

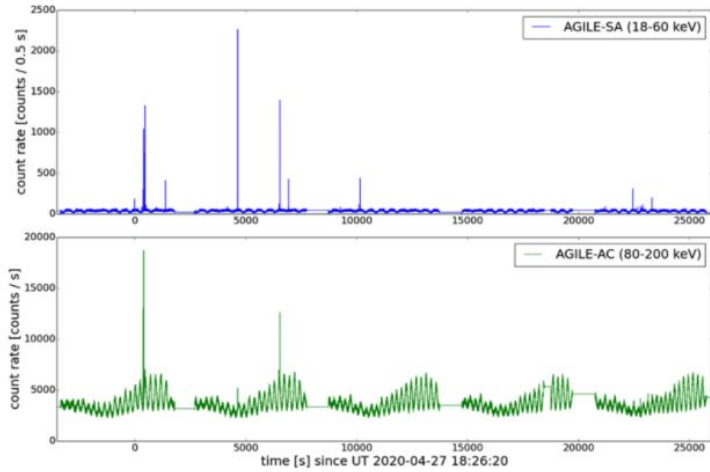






CTA 102 activity as seen by SPOT6 in Nov-Dec 2016

1) The magnetar is active in X-rays April 27, 2020:



AGILE observations of the SGR 1935+2154 "burst forest"

ATel #13682: A. Ursi (INAF/IAPS), C. Pittori (SSDC and INAF/OAR), P. Tempesta (TeleSpazio), F. Verrecchia (SSDC and INAF/OAR), M. Tavani (INAF/IAPS, and Univ. Roma Tor Vergata), M. Cardillo, C. Casentini, G. Piano (INAF/IAPS), A. Bulgarelli, V. Fioretti, N. Parmiggiani (INAF/IASF-Bo), F. Lucarelli (SSDC and INAF/OAR), I. Donnarumma (ASI), S. Vercellone (INAF/OA-Brera), F. Gianotti, M. Trifoglio (INAF/IASF-Bo), A. Giuliani, S. Mereghetti, P. Caraveo, F. Perotti (INAF/IASF-MI), A. Chen (Wits University), A. Argan, E. Costa, E. Del Monte, Y. Evangelista, M. Feroci, F. Lazzarotto, I. Lapshov, L. Pacciani, P. Soffitta, V. Vittorini (INAF/IAPS), G. Di Cocco, F. Fuschino, M. Galli, C. Labanti (INAF/IASF-Bo), M. Marisaldi (INAF/OAS-Bologna, and Bergen University), A. Pellizzoni, M. Pilia, A. Trois (INAF/OA-Cagliari), G. Barbiellini, E. Vallazza (INFN Trieste), F. Longo (Univ. Trieste and INFN Trieste), A. Morselli, P. Picozza (INFN and Univ. Roma Tor Vergata), M. Prest (Univ. dell'Insubria), P. Lipari, D. Zanello (INFN and Univ. Roma Sapienza), P. W. Cattaneo, A. Rappoldi (INFN Pavia), A. Ferrari (Univ. Torino and CIFS), F. Paoletti (East Windsor RSD Hightstown and INAF/IAPS), A. Antonelli (INAF/OAR), P. Giommi, L. Salotti, G. Valentini, and F. D'Amico (ASI)

on 28 Apr 2020; 21:40 UT

2) The day after: **radio burst** reported by CHIME/FRB at T0 = 2020-04-27 14:34:33 UTC

3) AGILE ATEL: for the first time a coincidence with a X-rays signal!!!!

AGILE detection of a hard X-ray burst in temporal coincidence with a radio burst from SGR 1935+2154

ATel #13686: M. Tavani (INAF/IAPS, and Univ. Roma Tor Vergata), A. Ursi (INAF/IAPS), F. Verrecchia (SSDC and INAF/OAR), C. Casentini (INAF/IAPS), C. Pittori (SSDC and INAF/OAR), M. Pilia (INAF/OA-Cagliari), M. Cardillo, G. Piano (INAF/IAPS), A. Bulgarelli, V. Fioretti, N. Parmiggiani (INAF/IASF-Bo), F. Lucarelli (SSDC and INAF/OAR), I. Donnarumma (ASI), S. Vercellone (INAF/OA-Brera), F. Gianotti, M. Trifoglio (INAF/IASF-Bo), A. Giuliani, S. Mereghetti, P. Caraveo, F. Perotti (INAF/IASF-MI), A. Chen (Wits University), A. Argan, E. Costa, E. Del Monte, Y. Evangelista, M. Feroci, F. Lazzarotto, I. Lapshov, L. Pacciani, P. Soffitta, V. Vittorini (INAF/IAPS), G. Di Cocco, F. Fuschino, M. Galli, C. Labanti (INAF/IASF-Bo), M. Marisaldi (INAF/OAS-Bologna, and Bergen University), A. Pellizzoni, A. Trois (INAF/OA-Cagliari), G. Barbiellini, E. Vallazza (INFN Trieste), F. Longo (Univ. Trieste and INFN Trieste), A. Morselli, P. Picozza (INFN and Univ. Roma Tor Vergata), M. Prest (Univ. dell'Insubria), P. Lipari, D. Zanello (INFN and Univ. Roma Sapienza), P. W. Cattaneo, A. Rappoldi (INFN Pavia), A. Ferrari (Univ. Torino and CIFS), F. Paoletti (East Windsor RSD Hightstown and INAF/IAPS), A. Antonelli (INAF/OAR), P. Giommi, L. Salotti, G. Valentini, and F. D'Amico (ASI)

on 29 Apr 2020; 11:05 UT

