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AGILE Search for Gamma-Ray Counterparts of Gravitational Wave Events

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Abstract AGILE is a space mission of the Italian Space Agency dedicated to X–ray and gamma-ray astrophysics operating since 2007. Since the discovery of gravitational wave (GW) events by the LIGO-Virgo Collaboration (LVC) announced in February 2016, AGILE is playing a very important role in the search for possible X-ray and gamma-ray counterparts. The large fields of view of the gamma-ray and hard X-ray imagers (2.5 sr and 1 sr, respectively) and the current spinning mode allow AGILE to cover at any moment a very large fraction of the sky. We present here an overview of AGILE observations of

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GW events during the LVC observing periods O1 and O2 which span the time interval September 2015 - August 2017. In particular we focus on the main characteristics of AGILE observations of the events GW150914, GW170104 and GW170817. The latter event is of great relevance being associated with a "kilonova" counterpart: we establish important physical constraints on the possible γ-ray emission from a magnetar-like remnant in the first $\sim$ 1000 s following the GW event time. We also present further developments and preliminary results obtained in preparation of the O3 observing run (start in April 2019). AGILE is fully operative in the search for GW event counterparts, and continues to observe the sky in a unique way because of its combination of large field-of-view hard X-ray and gamma-ray detectors.

Keywords gamma rays: observations · gravitational waves · general relativity

1 Introduction

The era of gravitational wave detections of astronomical sources started in 2015 after the first source, GW150914, was detected by the LIGO interferometers [1]. Furthermore, a new era of multi-messenger astronomy started with the recent discovery of the first electromagnetic (e.m.) counterpart of the source GW170817/GRB 170817A with the contribution of the Virgo detector [2].

AGILE is a space mission of the Italian Space Agency dedicated to γ-ray and X–ray astrophysics, launched in a near equatorial orbit in 2007. It consists of an imaging γ–ray Silicon Tracker (ST; sensitive in the energy range 30 MeV − 30 GeV), a coded mask hard X–ray imager Super-AGILE (SA; 20 − 60 keV), a Mini-Calorimeter (MCAL; 0.4 − 100 MeV) and an anticoincidence (AC) system (see [3]). The combination of ST, MCAL and AC constitutes the AGILE Gamma-Ray Imaging Detector (GRID). The instrument is well suited for detecting γ–ray transients **in particular** GRB-like phenomena in time scales ranging from sub-milliseconds to tens-hundreds of seconds. Moreover, the standard AGILE maximum likelihood analysis is routinely executed in daily γ–ray sources monitoring, and can detect transients on time scales varying from $\sim$ hours to weeks.

The AGILE Team signed on November 2016 a Memorandum of Understanding with the LIGO-Virgo Collaboration (LVC) to participate to the e.m. counterpart searches during O2. We review here the main AGILE observations and the dedicated activities for the γ–ray counterparts search during O2, and additional results obtained more recently in preparation of the next observation run, O3. Some of these results have been also reported in [4].

2 A review of the AGILE search for e.m. counterparts of GW events

A summary of AGILE observations of the main GW LVC events detected during the period 2015-2017 is reported in Table 1. The table reports the time

Table 1 AGILE observations of LVC GW events.

GW ID	GCN #	LR Cov. % at T_0[1]	Δ t [T - T_0]	Comments
150914	—	0	+330	LR missed by 300 s; earliest ever γ-ray data on GW event; [5]
151226	—	30	0	—
170104	20375, 20395	36	0	partially exposed by GRID, fully exp. by MCAL; [9]
170608	21224, 21228	40	0	partially exposed by GRID, exposed by MCAL
170814	21477, 21482	0	+500	exposed after 500 s (1st with Virgo data)
170817	21525, 21526 21562, 21785	0	+930	exposed after 930 s; prompt OT not exposed; limits to magnetar-like emission; [2]

Notes: [1] Percentage of the 90% c.l. LVC LR covered by the prompt AGILE-GRID exposure.

difference Δt between the AGILE observations and the GW trigger time (T_0). The fraction of the LVC 90% c.l. localization region (LR) at time $T = T_0 + \Delta t$ overlapped by the AGILE-GRID Field of View (FoV) is also reported in the table, which shows that we had a partial coverage of the LR at event T_0 for three events.

The AGILE spinning operation mode allows the instrument to scan a LR with a sequence of exposure maps (typically with 100 s integrations) preceding and following a GW event (for GW150914 see Fig. 1). All integrations are independent and consecutive, and if combined into a total integration of about 7 minutes, we can obtain a coverage of up to $\sim 80\%$ of the sky (depending on the Earth occultation). The analysis of the first GW event GW150914 was carried out after its public announcement on February 11, 2016, and later used as template to plan the on-ground dedicated automatic pipelines.

GW150914 (binary BHs system): trigger time is $T_0 = $ 09:50:45 UTC, 2015 September, 14. We carried out an archival search analysis after the event announcement. We find that the GW event 90% c.l. LR was not exposed by the GRID near T_0 because of the satellite attitude rotation. However, it was possible to obtain a good spatial coverage of the LR with the GRID at +330 s (with respect to T_0) with an integration of 100 s ([5]). We determined a $2\,\sigma$ γ-ray upper limit (UL) of 1.9×10^{-8} erg cm^{-2} s^{-1} in the 50 MeV – 10 GeV energy band and compared this UL with the GRID and Fermi/LAT light curves of the short GRB 090510 rescaled at z = 0.1 (Fig. 1). The UL was the earliest available measurement in the γ-ray band for a GW event, **although, unlike binary NS or NS-BH systems, no e.m. emission is expected for BH mergers**. An extrapolation of the GRID sensitivity at T_0 shows that AGILE might be able to detect prompt γ-ray emission similar to that of GRB 090510. In any case the AGILE early data near +300 s are very constraining.

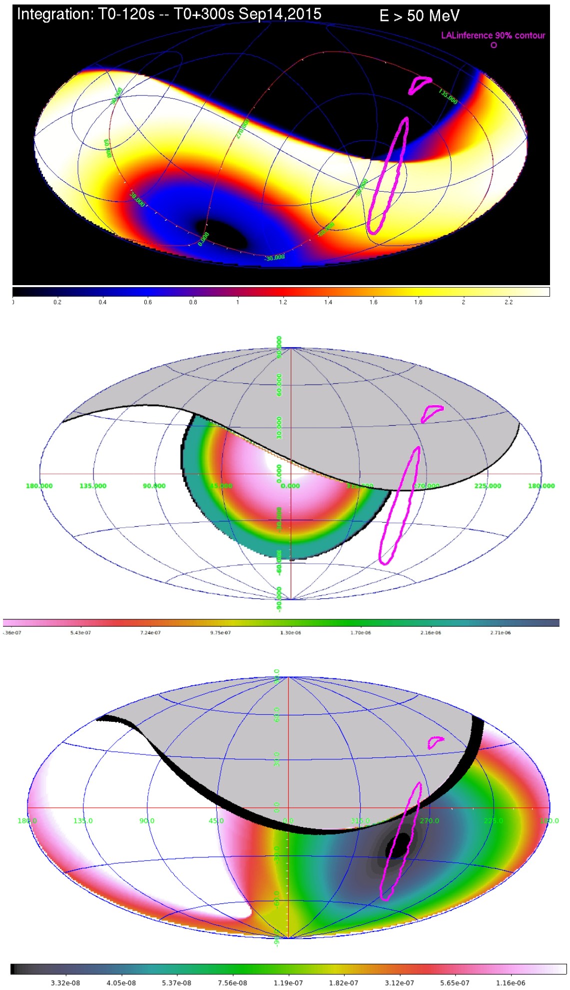

Fig. 1 The AGILE-GRID observations of the first announced GW event, GW150914. Maps are in Galactic coordinates; the 90% confidence level localization region (LR) of GW150914 is marked in magenta color; the sky region occulted by the Earth is shown in gray color. *Top panel:* Aitoff exposure map in the 50 MeV − 10 GeV energy band for a 7-minute integration from -120 s to +300 s (with respect to T_0). *Middle panel:* Aitoff map of GRID upper limits (ULs) obtained with a 4 s integration near the GW150914 T_0. The AGILE GRID just missed exposing the GW event LR in this case. *Bottom panel:* Aitoff map of the GRID ULs map obtained for the first available coverage of a substantial fraction of the GW event LR, which occurred at +330 s after T_0.

2.1 AGILE preparation for LIGO O2 run: on-board reconfiguration

In preparation of the LIGO O2 run, an on-board reconfiguration of the AGILE instrument was carried out in August 2016. The activity mainly included an improved MCAL burst detection with a lower threshold to allow trigger-

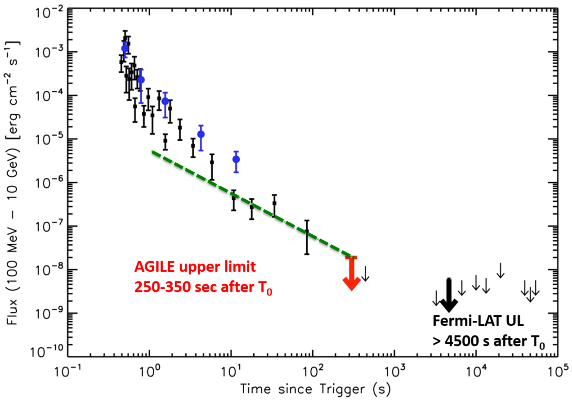

Fig. 2 The AGILE-GRID $2\,\sigma$ UL in the 50 MeV – 10 GeV band (red arrow) compared with the GRB 090510 AGILE-GRID (blue) and Fermi/LAT (black) light curves rescaled at the GW redshift 0.1, with an extrapolation curve at earlier time (green dotted).

ing from the "sub-threshold" events (STE; assumed to be similar to the GRB 090510 precursor event). Moreover, an AGILE-GW LVC notice/Circular reaction pipeline was developed to improve the performance of MCAL and GRID data processing in reaction to the publication of an LVC notice or circular, and to alert members of the newly formed AGILE-GW flare advocate group, active continuously for all the run on daily shifts.

3 AGILE observations during the O2 LVC run

We report below the results of the observations of the main GW events detected during O2.

GW170104 (binary BHs system): the event occurred at $T_0 = 10{:}11{:}58.59$ UTC, 2017 January 4. AGILE analysis started soon after the LVC circular publication ([6]) and two GCNs on MCAL and GRID data analysis were published ([7], [8]) reporting that at T_0 the 90% c.l. LR was partially covered by AGILE (Fig. 3).

We report the main analyses of AGILE detectors data in [9]. In particular, MCAL photon-by-photon data were acquired over a time window of 12.6 s including T_0 due to an on-board trigger. However, after a refined filtering of data, the original trigger was found to be spurious, while a candidate event was detected on the 32 ms time binning in full energy band at -0.5 s. This possible "precursor" event has a pre-trial significance of $4.4\,\sigma$. After considering its "false-alarm" rate ($\mathrm{FAR}_{E2} = 1 \times 10^{-4}$ Hz), the post-trial significance resulted to be between 2.4 and $2.7\,\sigma$. **This sub-threshold candidate event was published to alert the scientific community in case of detection of a time-coincident event from other high-energy instruments, even**

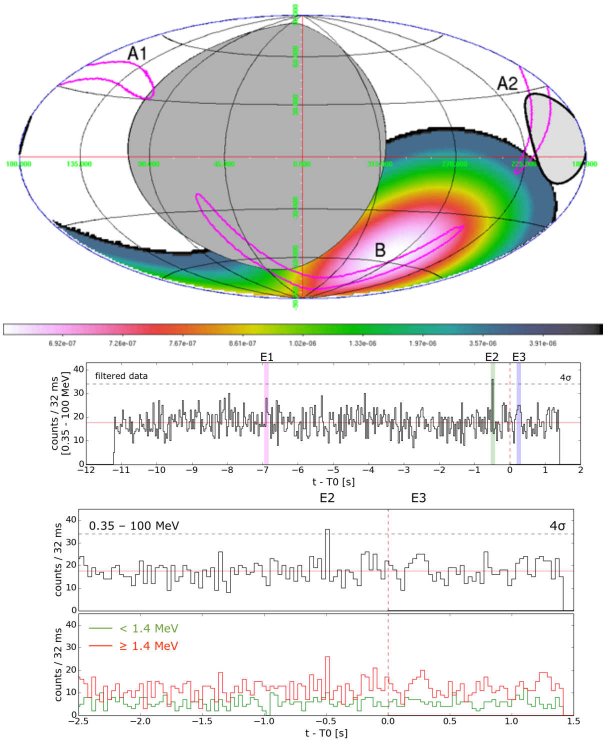

Fig. 3 *Top panel:* The GRID $3\,\sigma$ UL map (in 50 MeV – 10 GeV) on 4 s integration around GW170104 T_0 showing a partial spatial coverage of the event LR. Map is in Galactic coordinates; the GW170104 90% c.l. LR is marked in magenta color; the sky region occulted by the Earth is shown in gray color while the Sun unaccessible region is in light gray. *Middle panel:* MCAL 12.6 s photon-by-photon data, including T_0 (middle panel), showing three flagged times of which E2 is a candidate precursor event. *Bottom panel:* a smaller time interval around E2 in two energy bands is also shown.

if e.m. emission is unfavoured.

GW170814 (binary BHs system): the event occurred at $T_0 = $ 10:30:43 UTC, 2017 August 14, the first event including an important contribution to the localization by the Virgo detector. AGILE analysis started immediately after the LVC circular notification, and two GCNs on MCAL and GRID data analysis were published a few hours later ([10], [11], [12]). The event LR was much smaller than previous ones because of Virgo detector data, but it was occulted by the Earth at the T_0 (see Fig. 4). The earliest complete coverage of the event LR was been obtained with a 100 s exposure centered at +550 s, producing a $3\,\sigma$ γ-ray UL of $3.4 \times 10^{-8}\,\mathrm{erg\,cm^{-2}\,s^{-1}}$ in the 50 MeV – 10 GeV energy band.

GW170817 (binary NSs system): the GW trigger time was $T_0 =$ 12:41:06 UTC, 2017 August 17, and the detection of GRB 170817A by Fermi/GBM and INTEGRAL/SPI-ACS followed after 1.7 s ([2], [13], [14], [15]). AG-

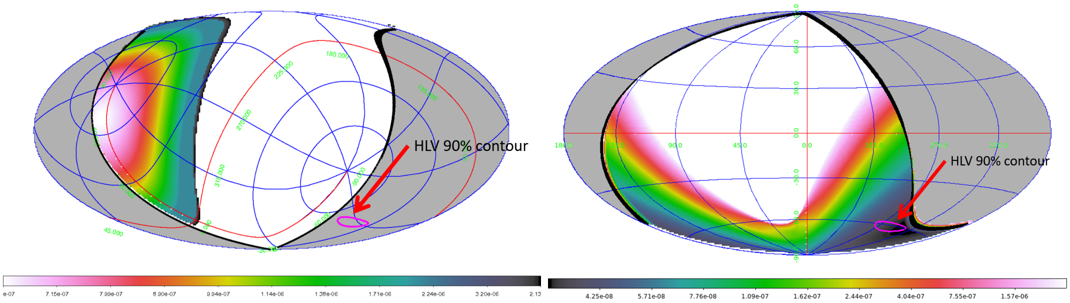

Fig. 4 *Left panel:* the GRID 3 σ UL map (in 50 MeV – 10 GeV) on 4 s integration around the GW170814 T_0 showing Earth occultation of the event LR. *Right panel:* the 100 s best exposure of the LR at +550 s after T_0, with a complete coverage. Maps are in Galactic coordinates; the 90% c.l. LR of GW170814 is marked in magenta color; the sky region occulted by the Earth is shown in gray color.

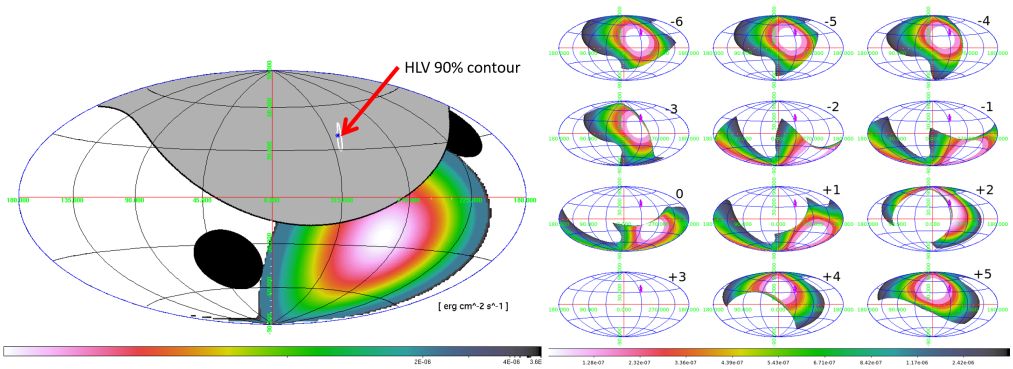

Fig. 5 *Left panel:* the GRID 2 σ UL map (in 30 MeV – 10 GeV) on 4 s integration around the GW170817 T_0, showing the LR occulted by the Earth. Maps are in Galactic coordinates; the 90% c.l. LR of GW170817 is marked in white color; the sky region occulted by the Earth is shown in gray color while the Sun unaccessible region is in black.*Right panel:* the 150 s exposure UL map scan preceding and following T_0 evaluated at the optical transient position. Maps are in Galactic coordinates; the GW170817 90% c.l. LR is marked in magenta color.

ILE data analysis started soon after the LVC circular publication, and two GCNs on MCAL and GRID analysis results were published later. Later on, two more GCNs on GRID data analysis exposing the position of the optical transient (OT) were published ([16], [17], [18], [19]). The event LR was occulted by the Earth at T_0 (see Fig. 5), and the earliest exposure was obtained +930 s after T_0. **If the event would have been exposed, according to the prompt spectral emission detected by GBM, it would be marginally detectable by MCAL but well compatible with the SA hard X–ray imager band and sensitivity, which however had useful data starting**

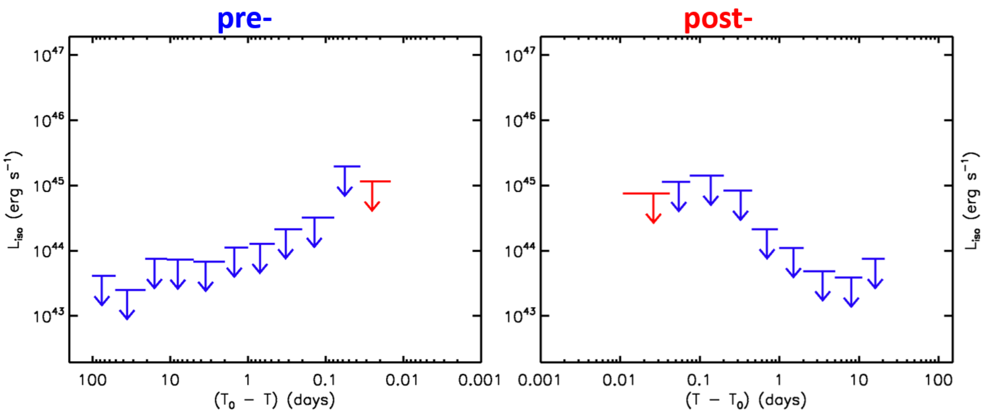

Fig. 6 The GRID $2\,\sigma$ UL scan (in 30 MeV – 10 GeV) preceding (left panel) and following (right panel) GW170817 T_0, for integration times around T_0 ranging from 150 s to 50 days (red and blue arrows).

at +0.53 d after T_0. No prompt emission was detected in the γ-ray energy band by other missions. Furthermore, several time windows before and after T_0 were explored **in the GRID data** to search for possible precursor and/or delayed emissions. GRID data analysis was executed on three

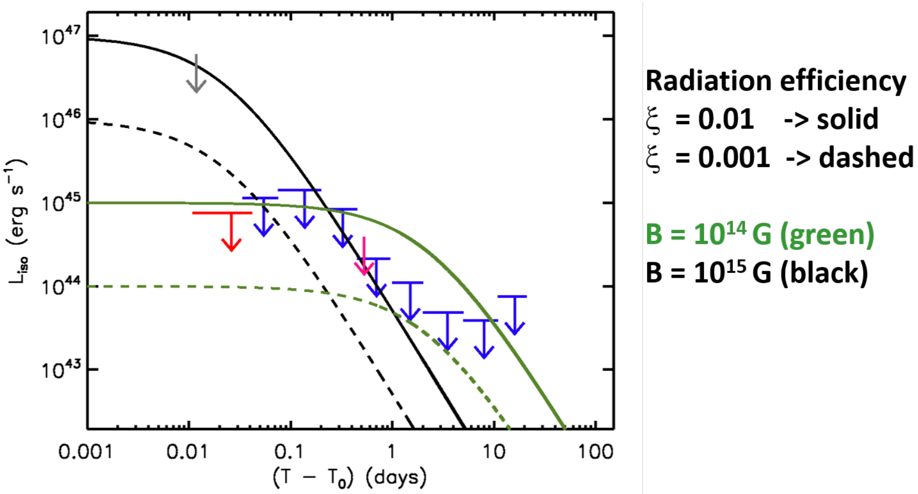

Fig. 7 The isotropic luminosity limits (in erg s^{-1}) derived from flux ULs following GW170817 T_0, for the OT distance of 40 Mpc. The AGILE-GRID ULs in 30 MeV – 10 GeV (red and blue arrows), and the SA and MCAL ones (magenta and gray) in the 20 – 60 keV and 400 keV – 100 MeV energy bands, respectively. We also show the high-energy luminosity curve relative to the magnetar-like remnant model described in [20].

time scales with two different methods ([20]), with increasing integration times from 150 s to 50 days. We did not detect significant emission [20] **however we could exclude delayed γ-ray emission from a simple magnetar remnant model from a NS-NS coalescence event.** This exposure scan allowed **in fact** to obtain an interesting set of $2\,\sigma$ flux ULs in the 30 MeV $-$ 10 GeV (see Fig. 6). We show in Fig.7 the γ-ray flux ULs converted into isotropic luminosity limits assuming the OT distance of 40 Mpc. These limits are shown together with the predictions of a magnetar model, (i.e., a rapidly rotating NS remnant with a high poloidal magnetic field B_p). We assume the γ-ray emission to be proportional to the magnetar spin-down luminosity with conversion to radiation efficiency ξ. AGILE γ-ray ULs are particularly constraining in the first thousand of seconds after T_0 for $B_p = 10^{15}$G and $\xi = 10^{-2}$.

4 Recent developments in preparation of the O3 run

We continue to improve the performance of the MCAL burst trigger algorithm. We developed a new automatic detection MCAL pipeline using various binning time scales from 8 to 128 ms. This procedure has been integrated with the GRB and TGF pipelines, together with the one dedicated to even weaker events, the so-called STEs. Examples of detection of a short GRB, GRB 170816A, and of an STE are shown in Fig.8.

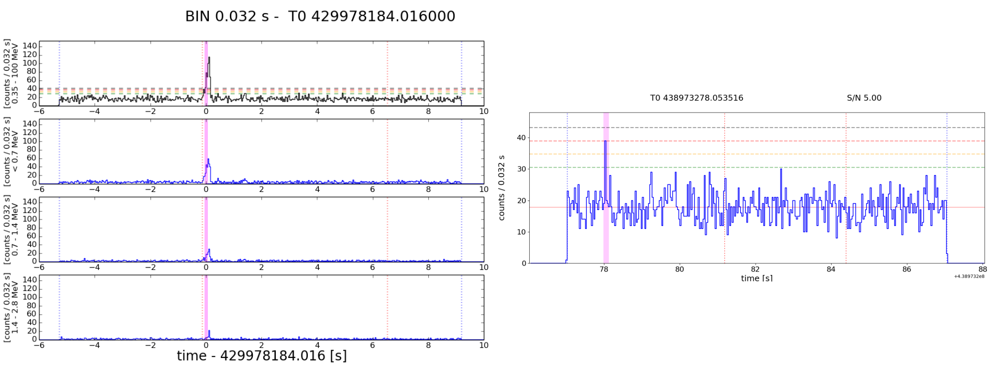

Fig. 8 *Left panel:* an example of automatic GRB detection, the short GRB 170816A (in 32 ms bin, at $33\,\sigma$) light curve. *Right panel:* an example of "sub-threshold" (STE) event (in 32 ms bin, at $5\,\sigma$).

Analysis of the next LIGO-Virgo O3 observation run needs an optimal instrument configuration, a continuous time coverage which requires a full telemetry daily acquisition (about 14 contacts/day), and a further improved on-ground sensitivity to weak STE events. The new automatic pipeline on MCAL data before O3 is undergoing an extensive testing phase on the automatic detection of either standard GRBs (short and long) or STE events, and its validation is currently almost completed. The events detected since the updated configuration activation have been compared with the public IPN sample in [21].

5 Summary

AGILE interestingly observed all the GW events detected by the LIGO and Virgo detectors in the O1 and O2 runs. Considering the two confirmed 2015 events and all the confirmed O2 ones, we had partial coverage at T_0 for 50% of the events. The results for GW170817/GRB 170817A and those obtained on MCAL data for GW170104, have shown the importance of enhanced on ground activities, such as an automatic MCAL detection pipeline to issue AGILE alerts to LVC and the scientific community. Also important will be the continuous on-board TM acquisition of the hard X–ray SA data, which could *detect and localize* X–ray counterparts similar to GRB 170817A.

AGILE is going to play a crucial role in O3 in the search for e.m. counterparts of GW events. Its unique detection and imaging capabilities in the hard X-ray/MeV/GeV ranges are assets well suited for future searches. Moreover a further dedicated effort is ongoing to improve on-board and ground detection, processing and automatic alerting procedures. AGILE is well equipped to participate in the unveiling of the exciting phenomena of the New Astronomy of gravitational wave sources.

6 Compliance with Ethical Standards

Conflict of Interest: The authors declare that they have no conflict of interest.

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