Publication Year	2019
Acceptance in OA	2021-01-07T10:18:12Z
Title	Gamma-ray binaries detected by AGILE
Authors	PIANO, Giovanni
Publisher's version (DOI)	10.1007/s12210-019-00794-9
Handle	http://hdl.handle.net/20.500.12386/29518
Journal	RENDICONTI LINCEI. SCIENZE FISICHE E NATURALI
Volume	30

Noname manuscript No.
(will be inserted by the editor)

Gamma-ray binaries detected by AGILE

G. Piano

Received: date / Accepted: date

Abstract The AGILE satellite is observing the γ-ray sky since its launch on April 23, 2007. Several important discoveries have been made in Galactic and extragalactic astrophysics starting from its observations above 50 MeV. In this work, I reviewed the most important findings in the study of γ-ray emitting Galactic binary systems: the first detection above 100 MeV of Cygnus X-1, the discovery of γ-ray transient emission from Cygnus X-3, the first observation of a colliding wind binary in γ rays. The AGILE continuous monitoring of the γ-ray sky is a fundamental ingredient to investigate the non-thermal emission from these sources, the disk-jet coupling, the limit of relativistic particle acceleration in the jet, the origin of the high-energy γ-ray radiation.

Keywords Gamma rays · Binary Systems

1 Introduction

The AGILE (Astrorivelatore Gamma a Immagini LEggero) satellite [15] is monitoring the γ-ray sky since April 2007. It had operated in a "pointing" mode data-taking, characterized by fixed attitude observations, until November 2009, when the satellite entered in "spinning" mode, covering a large fraction of the sky with a controlled rotation of the pointing axis. In this current observing mode, typical 2-day integration-time sensitivity (3σ) for sources in the Galactic plane and photon energy above 100 MeV is $\sim 10^{-6}$ photons cm^{-2} s^{-1}. In this work, I took into account the data collected by the *GRID* (Gamma-Ray Imaging Detector [1, 11]), the γ-ray silicon-tracker imager on board the AGILE satellite.

The AGILE observations have been crucial for better understanding the physical mechanisms regulating the most powerful Galactic and extragalactic particle-accelerator systems. Among them, a new class of Galactic γ-ray

INAF-IAPS, Via del Fosso del Cavaliere 100, I-00133, Roma, Italy E-mail: giovanni.piano@inaf.it

emitting astrophysical sources has been detected, showing strong transient emission above 50 MeV: the gamma-ray binaries. This class of high-energy emitting sources includes a large variety of heterogeneous binary systems [3]: microquasars, High Mass X-ray Binaries (HMXBs), colliding wind binaries, novae, millisecond pulsars.

In this paper I reviewed the most important AGILE findings in the field of γ-ray binaries, presenting the observations of the microquasars in the Cygnus region (Cygnus X-1, Cygnus X-3 and V404 Cygni), the colliding wind binary η-Carinae and the AGILE source AGL J2241+4454, possibly associated with MWC 656.

2 Microquasars in the Cygnus region

Observing towards the Cygnus region (Galactic coordinates $l \sim 75°$-$85°$) means looking through the Local Arm (Orion Spur), the Perseus Arm and the Outer Arm along the same line-of-sight. Thus, there is a huge superposition of Galactic objects (mainly distributed in the high-density arms) located at the same angular coordinates, but at different distances along the line-of-sight. In the γ-ray band (E > 50 MeV), AGILE and *Fermi*-LAT observed a strong diffuse emission underlying the radiation from several persistent (pulsars, SNRs, ...) and transient sources.

During the "pointing" mode, AGILE repeatedly pointed at the Cygnus region for a total of ~275 days, corresponding to a net exposure time of ~11 Ms. The current "spinning" data-taking configuration allows a constant monitoring of such a crowded region of the sky. Several episodes of transient γ-ray emission from three microquasars of the Cygnus region (Cygnus X-1, Cygnus X-3 and V404 Cygni) were detected by the AGILE-*GRID*.

Microquasars [7] – the stellar-scale version of a quasar – are X-ray binaries powered by accretion of matter from a stellar companion onto a compact object (a black hole or a neutron star). In these systems a significant fraction of the accretion energy is channeled to launch relativistic jets, characterized by non-thermal emission.

2.1 Cygnus X-1

Cygnus X-1 is the archetypal black hole binary system of our Galaxy. It is located at a distance of 1.9 kpc, and is composed of a black hole of 4.8-14.8 $M_\odot$ and a O9.7 Iab supergiant star companion. The orbital period is 5.6 days. It is one of the brightest persistent sources in the X-ray sky. Typical X-ray spectral states of Cygnus X-1 have been classified as "low/hard" and "soft/high". The system usually spends ~90% of its time in the low/hard state, whose Spectral Energy Distribution (SED) is characterized by a prominent peak around 100 keV and a high-energy cutoff ~150 keV. The soft/high spectrum is described by a strong black-body component (kT ~ 0.5 keV) and a power-law tail with index $\Gamma \sim 2 - 3$.

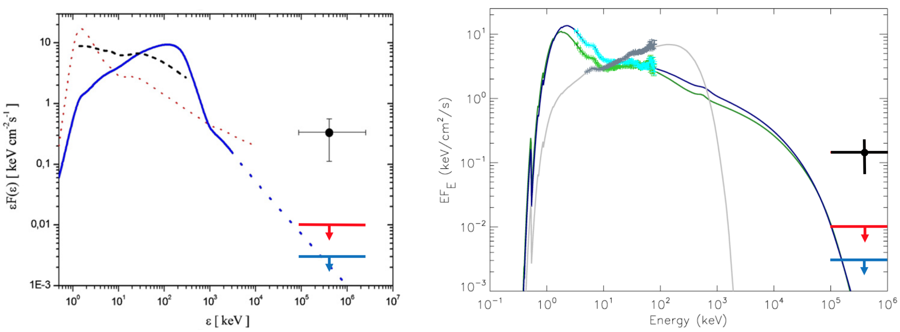

Fig. 1 *Left panel:* AGILE broad-band spectrum of Cygnus X-1 (black point) for the October 15-16 2009 flaring episode, with the corresponding typical X-ray SEDs for the soft/high (dotted red line), intermediate (dashed black line) and low/hard (blue solid line) states [12]. *Right panel:* AGILE broad-band spectrum of Cygnus X-1 (black point) for the June 30 – July 02 2010 flaring episode, with the corresponding X-ray spectra before and after the hard-to-soft spectral transition [13]. In both panels, red and blue points are AGILE 2-sigma upper limits related to long-time observations during soft and hard spectral states, respectively.

AGILE detected two strong γ-ray flares, the first one (October 15-16 2009) during a hard state [12], and the second one (June 30 – July 02 2010) during a hard-to-soft spectral transition [13]. The γ-ray flare detected by AGILE cannot by accounted for by the standard Comptonization models – related to the physics of the disk-corona – that perfectly fit the X-ray spectra of the system (see Fig. 1). A new component is required in order to account for the high-energy γ-ray flares, possibly related to the physics of the relativistic jets.

Besides the flaring-episode detections, the AGILE spectral upper limits from long-term observations gave important constraints to the standard Componization models both for the high/soft and low/hard states [13].

2.2 Cygnus X-3

Cygnus X-3 was discovered, as an X-ray source, in 1966 [5]. It is located at a distance of 7-10 kpc and it is composed of a Wolf-Rayet (WR) star ($M > 7M_{\odot}$) with a strong helium wind and a compact object, whose nature is still uncertain. The orbital period, as inferred from infrared, X-ray and γ-ray observations, is 4.8 hours. Owing to its very tight orbit (orbital distance $d \approx 3 \times 10^{11}$ cm), the compact object is totally enshrouded in the wind of the companion star.

High-energy γ-ray activity from Cygnus X-3 was firmly discovered in late 2009: the AGILE team found evidence of strong γ-ray transient emission above 100 MeV coincided with special X-ray/radio spectral states [16], and the *Fermi*-LAT collaboration announced the detection of γ-ray orbital modulation [4]. By analyzing the AGILE data, a repetitive pattern of multiwavelength emission was found (see Fig. 2.2): the γ-ray flares usually occur during

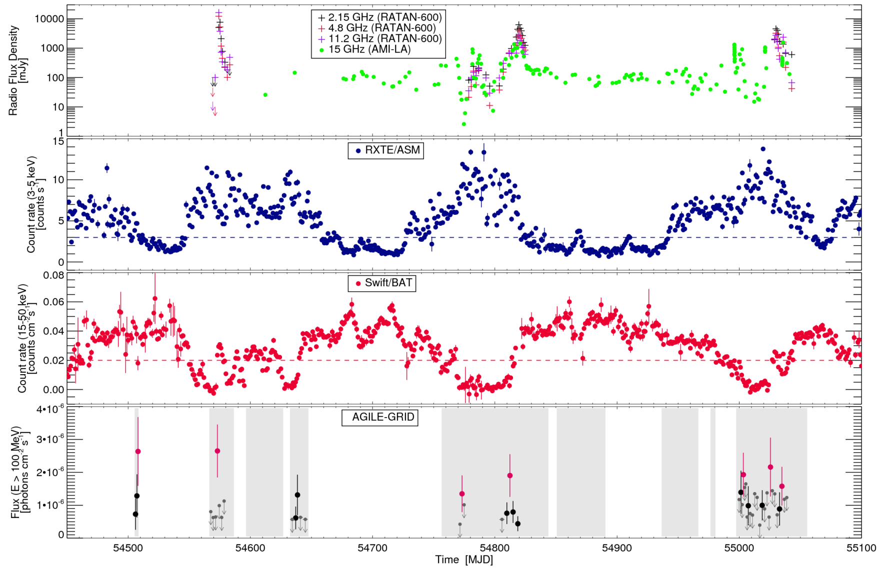

Fig. 2 Multi-frequency light curve of Cygnus X-3 from 2007 December 12 to 2009 September 26 (MJD: 54450-55100). From top to bottom: radio flux density [RATAN-600 (2.15, 4.8, 11.2 GHz) and AMI-LA (15 GHz)], soft X-ray count rate [*RXTE*/ASM (3-5 keV)], hard X-ray count rate [*Swift*/BAT (15-50 keV)], and gamma-ray photon fluxes [AGILE-*GRID* (above 100 MeV)]. In the bottom panel, gray regions represent the AGILE pointing at the Cygnus region; *magenta* points are the main events of γ-ray activity with $\sqrt{TS} \geqslant 3$, *black* points are the γ-ray detections with $2 \leqslant \sqrt{TS} < 3$, and *dark-gray* arrows are the 2σ upper limits related to $\sqrt{TS} < 2$. The dashed lines in the panels of the *RXTE*/ASM and *Swift*/BAT count rate represent the transition level of 3 counts s^{-1} and 0.02 counts cm^{-2} s^{-1} respectively [9].

soft X-ray spectral states, a few days before strong radio outbursts [9]. In particular, the γ-ray transient emission is revealed when the system is moving into or out of the quenched state of Cygnus X-3, a characteristic radio/X-ray spectral state that in general precedes major radio flares. Thus, from a phenomenological point of view, the quenched state represents a key condition for the γ-ray activity above 100 MeV. The flaring γ-ray emission requires a new component in the multiwavelength SED, possibly related to the physics of the relativistic jets: both a leptonic (inverse Compton – IC – processes between electrons/positrons in the jet and soft photons from the star and the accretion disk) and a hadronic (γ rays from the decay of π^0 mesons produced in inelastic collisions between hadrons of the jet and nuclei of the WR wind) emission models can account for the γ-ray radiation detected by AGILE. Nevertheless, a leptonic scenario is favored: it can explain in a more natural way the observed γ-ray modulation (anisotropic IC scattering), requires a lower jet kinetic power ($L^e_{kin} \leq 10^{37}$ erg s^{-1}, $L^p_{kin} \approx 10^{38}$ erg s^{-1}), and suggests a spectral link with the X-ray hypersoft spectrum (the characteristic spectrum for the quenched state).

2.3 V404 Cygni

V404 Cygni is a Low Mass X-ray Binary (LMXB) located at a distance of (2.39 $\pm$ 0.14) kpc. It is composed of a K3 III ($0.7^{+0.3}_{-0.2}$ $M_\odot$) and a $9^{+0.2}_{-0.6}$ $M_\odot$ black hole with an orbital period of 6.4714$\pm$0.0001 days. After a quiescence period of $\sim$26 years, the system entered in an active phase on June 15, 2015 that lasted $\sim$2 weeks and was observed across all wavelengths (from radio to γ rays). AGILE (50-400 MeV) and *Fermi*-LAT (60-400 MeV) detected a bright γ-ray flare on June 24-26, 2015 (see Fig. 3) [10], coincident with a bright outburst detected in radio (RATAN: 2.4-21.7 GHz), hard X-ray (*Swift*/BAT: 15-50 keV) and soft γ rays (INTEGRAL: continuum 100-200 keV and 511 keV annihilation line). The observations strongly support a microquasar scenario for V404 Cygni with a dominant leptonic component. In particular, the simultaneous e^+e^- annihilation line emission suggests a strong presence of antimatter (positrons) in the jet.

3 Eta Carinae

η-Carinae is a Colliding Wind Binary (CWB) system located at a distance of 2.3 kpc, and is composed of a $\sim$100 $M_\odot$ luminous blue variable star and a O companion star. The orbit has a period of 5.53 years and is highly eccentric ($e > 0.9$). It represents the first CWB ever observed in γ rays [17]: AGILE monitored the periastron passage (2007 July - 2008 October) and detected γ-ray activity from the source (average flux $F_\gamma = (37 \pm 5) \times 10^{-8}$ photons cm^{-2} s^{-1}), with a time evolution consistent with the X-ray light curve. According to the theoretical models, the γ-ray emission is produced by relativistic particles accelerated by shocks produced by the interaction of the dense and high velocity gaseous winds of the stars ($\dot{M}_1 \simeq 2\times10^{-4} M_\odot$ yr^{-1}, $\dot{M}_2 \simeq 2\times10^{-5} M_\odot$ yr^{-1}, $v_1 \simeq 600$ km/s, $v_2 \simeq 3000$ km/s).

4 AGL J2241+4454

AGILE detected transient γ-ray activity from a previously unidentified source, AGL J2241+4454, in July 2010 [6]. This detection triggered an important discovery: the first Be binary system hosting a black hole, MWC 656, was discovered by analyzing optical data from the source [2]. After the first serendipitous detection, we carried out a blind search in the AGILE data, looking for other transient γ-ray signals from AGL J2241+4454. We found 10 2-day flaring events from the source between 2007 and 2013 (both in pointing and spinning data-taking periods). In order to test the possible association with the binary system, we folded the data with the 60.37 day orbital period, but no periodicity was observed [8]. Thus, the association with MWC 656 remains uncertain.

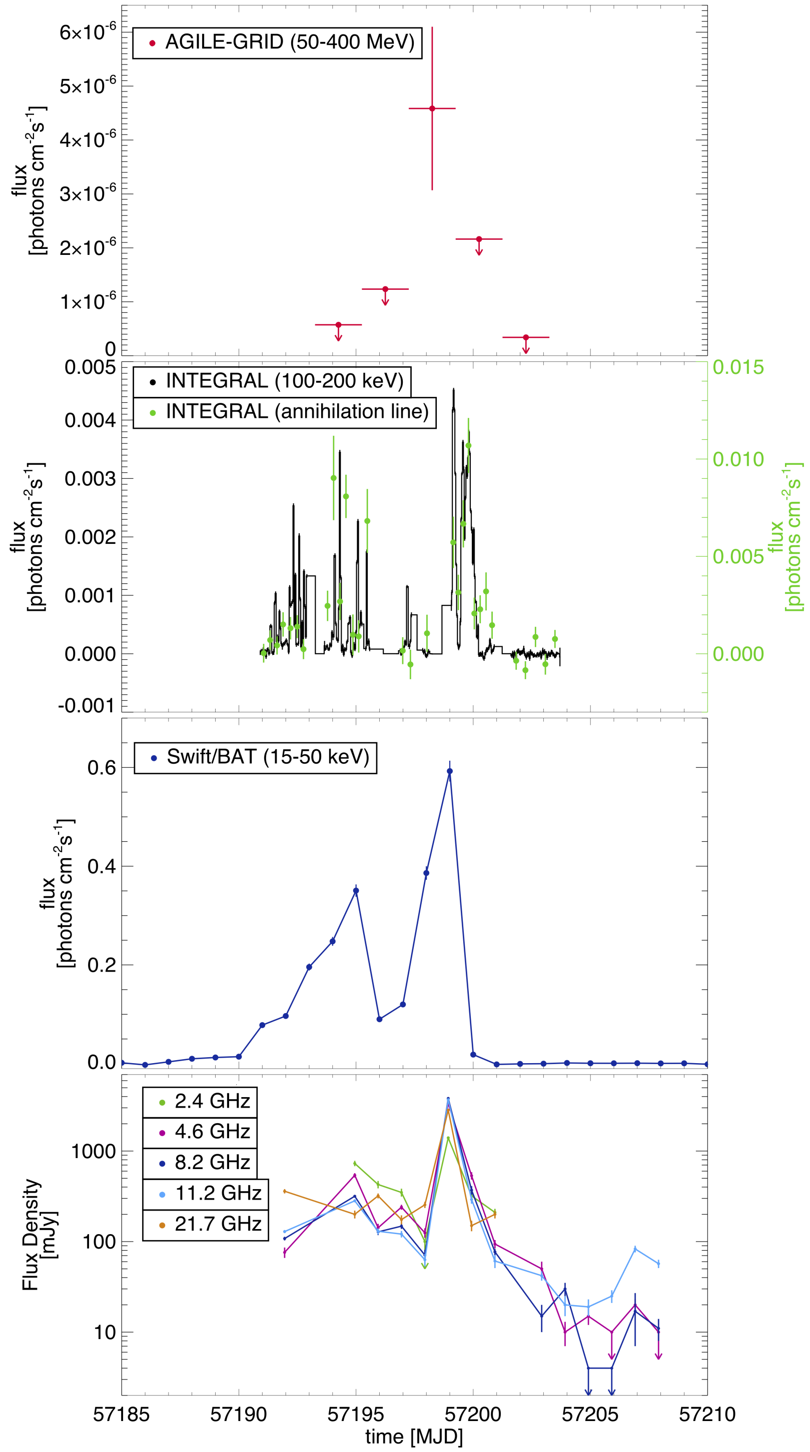

Fig. 3 Multiwavelength light-curve throughout the June 2015 outburst of V404 Cygni. From top to bottom: AGILE-*GRID* 50–400 MeV, 48 hours integration; INTEGRAL/SPI continuum (100-200 keV, black histogram) and annihilation line (green points); *Swift*/BAT 15–50 keV, 1-day bin; RATAN-600 radio flux density (2.4, 4.6, 8.2, 11.2 and 21.7 GHz) [10].

5 Conclusions and future perspectives

The AGILE observations shed new light in the understanding of γ-ray binaries, giving important constraints to the theoretical models that describes the physics of this heterogeneous class of astrophysical sources. AGILE's continuous monitoring of the γ-ray sky represent a fundamental ingredient to study the transient activity from these systems in a multiwavelegth and multimessenger context.

Future missions as e-ASTROGAM [14] would be crucial in the study of this important class of sources, analyzing with unprecedented sensitivity a new window of the non-thermal spectrum. In particular, observations in the 10-100 MeV band would be compelling in order to better understand the physics of disk-jet coupling, to disentangle between leptonic and hadronic emission model, and to explore new physics in these intriguing Galactic sources (see Fig. 4).

The Cherenkov Telescope Array (CTA)[1] will be fundamental in exploring the limit of extreme particle acceleration that is responsible of the high-energy γ-ray radiation from these binary systems.

Acknowledgements Research partially supported by the ASI grant no. I/028/12/5 and the INAF PRIN SKA-CTA: "Towards the SKA and CTA: discovery, localization and physics of transients".

References

1. Barbiellini, G., Fedel, G., Liello, F., et al., *The AGILE silicon tracker: testbeam results of the prototype silicon detector*, Nuclear Instruments and Methods in Physics Research A, 490, 146 (2002)
2. Casares, J., Negueruela, I., Ribó, M., et al., *A Be-type star with a black-hole companion*, Nature, 505, 378 (2014)
3. Dubus, G., *Gamma-ray binaries and related systems*, The Astronomy and Astrophysics Review, 21, 64 (2013)
4. Fermi LAT Collaboration, Abdo, A. A., et al., *Modulated High-Energy Gamma-Ray Emission from the Microquasar Cygnus X-3*, Science, 326, 1512 (2009)
5. Giacconi, R., Gorenstein, P., Gursky, H., & Waters, J. R., *An X-Ray Survey of the Cygnus Region*, The Astrophysical Journal Letters, 148, L119 (1967)
6. Lucarelli, F., Verrecchia, F., Striani, E., et al., *AGILE detection of the new unidentified gamma-ray source AGL J2241+4454*, The Astronomer's Telegram, 2761 (2010)
7. Mirabel, I. F., *Gamma-Ray Binaries Revealed*, Science, 335, 175 (2012)
8. Munar-Adrover, P., Sabatini, S., Piano, G., et al., *The Gamma-Ray Source AGL J2241+4454 as the Possible Counterpart of MWC 656*, ApJ, 829, 101 (2016)
9. Piano, G., Tavani, M., Vittorini, V., et al., *The AGILE monitoring of Cygnus X-3: transient gamma-ray emission and spectral constraints*, A&A, 545, A110 (2012)
10. Piano, G., Munar-Adrover, P., Verrecchia, F., et al., *High-energy Gamma-Ray Activity from V404 Cygni Detected by AGILE during the 2015 June Outburst*, ApJ, 839, 84 (2017)
11. Prest, M., Barbiellini, G., Bordignon, G., et al., *The AGILE silicon tracker: an innovative γ-ray instrument for space*, Nuclear Instruments and Methods in Physics Research A, 501, 280 (2003)

[1] https://www.cta-observatory.org

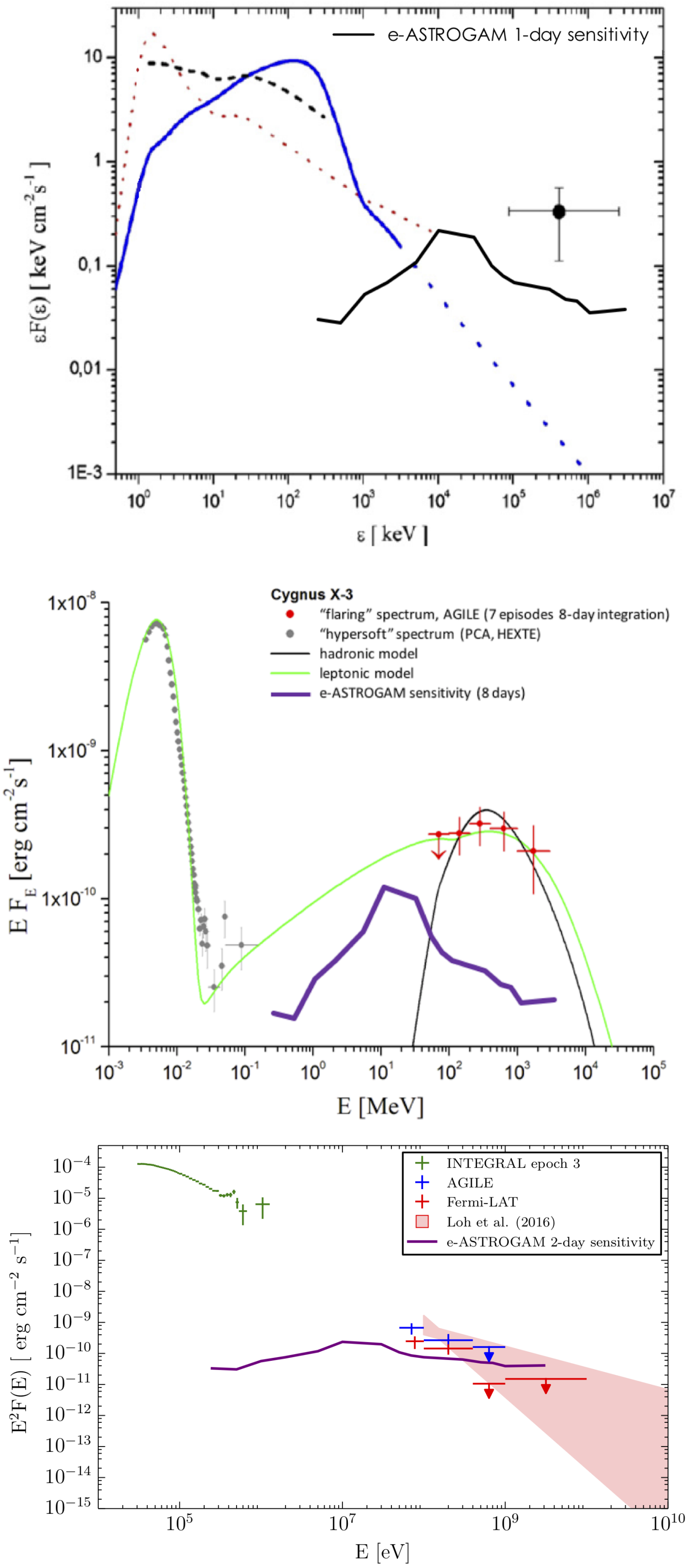

Fig. 4 *Upper panel:* Cygnus X-1 flaring spectrum (October 15-16 2009 [12]) with the corresponding e-ASTROGRAM sensitivity. *Central panel:* Cygnus X-3 flaring spectrum [9], leptonic (green) and hadronic (black) emission models, with the corresponding e-ASTROGAM sensitivity. *Bottom panel:* V404 Cygni flaring spectrum [10] with the corresponding e-ASTROGAM sensitivity.

12. Sabatini, S., Tavani, M., Striani, E., et al., *Episodic Transient Gamma-ray Emission from the Microquasar Cygnus X-1*, The Astrophysical Journal Letters, 712, L10 (2010)
13. Sabatini, S., Tavani, M., Coppi, P., et al., *Gamma-Ray Observations of Cygnus X-1 above 100 MeV in the Hard and Soft States*, ApJ, 766, 83 (2013)
14. Tatischeff, V., De Angelis, A., Tavani, M., et al., , Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series, 10699, 106992J (2018)
15. Tavani, M., Barbiellini, G., Argan, A., et al., *Gamma-ray Astrophysics with The AGILE Mission*, ApJ, 502, 995 (2009)
16. Tavani, M., Bulgarelli, A., Piano, G., et al., *Extreme particle acceleration in the microquasar CygnusX-3*, Nature, 462, 620 (2009)
17. Tavani, M., Sabatini, S., Pian, E., et al., *Detection of Gamma-Ray Emission from the Eta-Carinae Region*, ApJL, 698, L142 (2009)