

# Galactic transient sources with the Cherenkov Telescope Array Observatory

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## ABSTRACT

A wide variety of Galactic sources show transient emission at soft and hard X-ray energies: low- and high-mass X-ray binaries containing compact objects, isolated neutron stars exhibiting extreme variability as magnetars as well as pulsar-wind nebulae. Although most of them can show emission up to MeV and/or GeV energies, many have not yet been detected in the TeV domain by Imaging Atmospheric Cherenkov Telescopes. In this paper, we explore the feasibility of detecting new Galactic transients with the Cherenkov Telescope Array Observatory (CTAO) and the prospects for studying them with Target of Opportunity observations. We show that CTAO will likely detect new sources in the TeV regime, such as the massive microquasars in the Cygnus region, low-mass X-ray binaries with low-viewing angle, flaring emission from the Crab pulsar-wind nebula or other novae explosions, among others. Since some of these sources could also exhibit emission at larger time-scales, we additionally test their detectability at longer exposures. We finally discuss the multiwavelength synergies with other instruments and large astronomical facilities.

**Key words:** binaries: general – stars: magnetars – novae, cataclysmic variables – pulsars: general – gamma-rays: general.

## 1 INTRODUCTION

Timing astronomy and variability studies have proven to be a powerful tool to study extreme astrophysical processes at very high energies (VHE,  $E > 100$  GeV). The improvement of the Imaging Atmospheric Cherenkov Technique (IACT) over the past decade has revealed new transient phenomena with variability time-scales from seconds to several weeks. The last generation of IACTs have discovered several classes of transient TeV sources such as gamma-ray bursts (GRBs, MAGIC Collaboration 2019; Abdalla et al. 2019), flaring blazars associated with high-energy (HE) neutrino sources (IceCube Collaboration 2018) or Galactic novae (H. E. S. S. Collaboration 2022; Acciari et al. 2022), among others, unveiling new types of VHE emitters with highly variable fluxes (Carosi & López-Oramas 2024).

The Cherenkov Telescope Array Observatory (CTAO) will be the next generation ground-based observatory for VHE astronomy. It will allow the detection of gamma rays in the 20 GeV–300 TeV domain, with two observatory sites, one in the Northern hemisphere (CTAO-N; Observatorio Roque de los Muchachos, La Palma, Spain) and another in the Southern one (CTAO-S; Paranal, Chile). It will provide an improved sensitivity with respect to the current generation of IACTs of about an order of magnitude (Cherenkov Telescope Array Consortium et al. 2019). Of special importance will be the sensitivity of CTAO to short-time-scale phenomena.<sup>1</sup>

CTAO will have  $10^4$ – $10^5$  better sensitivity than the LAT (Large Area Telescope) instrument onboard the *Fermi* satellite for the detection of short-duration transient events (Funk, Hinton & CTA Consortium 2013).

The low-energy threshold of  $\sim 20$  GeV of the largest telescopes of the array, the Large-Sized Telescopes (LSTs; CTA-LST Project et al. 2023) is key for the detection of new transient sources at the lower end of the VHE regime. This capability, together with the fast slewing response of the LSTs, which can be re-pointed in about 20 s, will allow a swift reaction to transient events. The Medium- and Small-Sized Telescopes (MSTs, SSTs) will also be key to understand the emission of this sources at higher energies. Finally, since the CTAO observatory will consist of two arrays located in two hemispheres, it will provide a better and more continuous coverage of many transient events accessible from both sites.

The core program of CTAO will consist of different Key Science Projects (KSPs) which were considered to address the science questions of CTAO (see Cherenkov Telescope Array Consortium et al. 2019, for more details). The Transients KSP is proposed to encompass the follow-up observations of several classes of targets such as GRBs, gravitational waves (GWs), HE neutrinos, core-collapse supernovae (CCSNe), and Galactic transients.

In this paper, we focus on Galactic sources hosting compact objects whose emission is not periodic and/or that display unexpected flaring events, outflows or jets as described in the Galactic transients section of the Transients KSP as defined in Cherenkov Telescope Array Consortium et al. (2019). Extragalactic transient events such as

<sup>1</sup>For CTAO performance, see: <https://www.CTAO.org/for-scientists/performance/>

GRBs, CCSNe or GWs will be addressed in separate publications. We discuss the capabilities of CTAO to detect new transient phenomena at VHE from sources of Galactic origin, ranging from microquasars, to pulsar-wind nebulae (PWNe) flares, to novae, transitional millisecond pulsars (tMSPs) or magnetars among others. Some of these sources could also exhibit persistent emission, hence we additionally test the detectability at longer exposures in some specific cases. Since the nature of the source classes of study and hence the physical processes are different, the simulated time-scales of the expected VHE emission also vary. We have used time-scales ranging from as low as 10 min to few hours for transient detection and up to 50–200 h to test persistent emission in certain sources of interest. For our simulations, we have used the software packages CTOOLS<sup>2</sup> (Knödlseider et al. 2016) and GAMMAPY<sup>3</sup> (Donath et al. 2023; Aguasca-Cabot et al. 2023) with the official CTAO observatory instrument response functions (IRFs).<sup>4</sup> For a full description of CTAO observatory IRFs and configurations, see Maier, Gueta & Zanin (2023).

The source classes of our interest are described in the following Sections 1.1–1.5. We present the sensitivity of CTAO to Galactic transient detection in Section 2 and population studies in Section 3. The simulations, analysis results, and discussion for each type of transient are collected in Section 4. Section 5 describes the synergies with multiwavelength and multimessenger astronomical facilities. The summary and final conclusions are listed in Section 6.

### 1.1 Microquasars

Microquasars are binary systems with a compact object (neutron star, NS or a black hole, BH) orbiting around and accreting material from a companion star. The matter lost from the star can lead to formation of an accretion disk around the compact object and a relativistic collimated jet (Mirabel & Rodríguez 1998).

At the moment more than 20 microquasars are known in the Galaxy (see i.e. Corral-Santana et al. 2016). Observations demonstrated correlations between the mass of the compact object, radio (5 GHz) and X-ray (2–10 keV) luminosities (e.g. Falcke, Körding & Markoff 2004), strengthening the link between active galactic nuclei (AGNs) and microquasars. In AGNs, jets are known to be places of efficient particle acceleration and produce broad-band non-thermal emission. The resulting radiation can extend from radio up to the VHE band. According to TeVCat<sup>5</sup> more than 65 AGNs have been already detected by current IACTs. If similar jet production and particle acceleration mechanisms operate in microquasars and AGNs, this might imply that microquasars should be sources of VHE  $\gamma$ -ray emission as well.

Up to now, only three microquasars have been detected in the HE ( $E > 100$  MeV) domain: Cygnus X-1 (Bulgarelli et al. 2010; Sabatini et al. 2010, 2013; Malyshev, Zdziarski & Chernyakova 2013; Zanin et al. 2016; Zdziarski et al. 2017), Cygnus X-3 (Tavani et al. 2009; Fermi LAT Collaboration 2009; Zdziarski et al. 2018), and SS 433 (Bordas et al. 2015; Sun et al. 2019; Rasul et al. 2019; Xing et al.

2019; Li et al. 2020), all of them hosting a massive companion star. In the case of low-mass microquasars, the only one that has displayed a strong hint of gamma-ray emission (at HEs) was the binary V404 Cyg during its 2015 outburst (Loh et al. 2016; Piano et al. 2017). Steady VHE emission was first detected from the interaction regions between the jet and the surrounding nebula for the time in SS 433 (Abeysekara et al. 2018a; H. E. S. S. Collaboration 2024). Other microquasars have been recently reported to be sources of persistent of TeV and PeV emission (for details, see i.e. Alfaro et al. 2024; LHAASO Collaboration 2024). Regarding flaring emission, the strongest hint reported was the  $4.1\sigma$  transient signal (post-trial) found at VHE in Cygnus X-1 (Albert et al. 2007). The expectations for the detection of both massive microquasars and low-mass X-ray binaries (LMXBs) with CTAO are presented in Sections 4.1 and 4.2.

The relevance for studying binary systems in the VHE regime has already been addressed by Paredes et al. (2013) and Chernyakova et al. (2019). In this paper, we do not focus on gamma-ray binaries displaying periodic orbital variability and likely powered by non-accreting pulsars, but only on systems powered by accretion and displaying jets, to better investigate the potential VHE emission of this specific class of binaries. We discuss high-mass microquasars (Section 4.1) separately to LMXBs (Section 4.2).

### 1.2 Transitional millisecond pulsars

tMSPs are a class of NS binaries that has emerged in the last decade with the discoveries of three confirmed systems: PSR J1023 + 0038 (Archibald et al. 2009; Patruno et al. 2014), XSS J1227–4853 (de Martino et al. 2010; Bassa et al. 2014), and IGR J1824–2452 in the globular cluster M28 (Papitto et al. 2013). Additionally, a handful of candidate tMSPs have been recently discovered in the X-ray and GeV ranges (see review by Papitto & de Martino 2022). tMSPs alternate between a radio-loud MSP state (RMSP, showing radio pulsations and no sign of an accretion disk) and a subluminescent LMXB state (forming an accretion disk and showing X-ray pulsations). These sources are the direct link between the LMXB and the radio MSP phases in which NSs are spun up to ms periods during the LMXB phase. Sudden transitions between the two states occur on a time-scale of a few days to weeks, and are accompanied by drastic changes across the electromagnetic spectrum. The transition from the RMSP to LMXB state is accompanied by brightening of optical, ultraviolet (UV, Patruno et al. 2014; Takata et al. 2014), X-ray, and gamma-ray (Stappers et al. 2014) emission with the disappearance of radio pulsations. The origin of these transitions is still debated and, for this, intense multiwavelength campaigns are ongoing to understand the phenomenology in both the RMSP and LMXB states. tMSPs were so far not detected in the VHE regime. The constraints to the VHE emission from tMSPs during the LMXB state are discussed in Section 4.3.

### 1.3 Pulsar wind nebulae

PWNe are bubbles or diffuse structures of relativistic plasma powered by a central highly magnetized rotating NS. They represent one of the largest Galactic populations at VHE. Recently, several PWNe have been suggested to be PeV particle (leptons) accelerators, with the detection of gamma-rays at  $E > 100$  TeV (Cao et al. 2021, 2024). The Crab nebula is the standard candle at VHE and both the nebula and the pulsar have been intensively studied. Pulsations have been measured up to TeV energies (Ansoldi et al. 2016) and the nebula spectrum has been detected up to 100 TeV by IACTs (MAGIC Collaboration 2020) and recently extended to PeV (Lhaaso Collaboration 2021).

<sup>2</sup>CTOOLS is a software specifically developed for the scientific analysis of gamma-ray data, see <http://CTAO.irap.omp.eu/ctools/index.html>

<sup>3</sup>GAMMAPY is an open-source PYTHON package developed for gamma-ray astronomy, see <https://gammapy.org/>

<sup>4</sup>The IRF version `prod3b-v2` is the one used throughout the manuscript, unless otherwise specified. The newest `prod5` version corresponding to the Alpha configuration, which corresponds to the first stage of CTAO observatory construction has also been tested in some science cases and are specified in the text.

<sup>5</sup><http://tevcat2.uchicago.edu/>

Unexpectedly, the Crab nebula displays rapid flaring emission over daily time-scales at HE as reported by AGILE (Astrorivelatore Gamma ad Imagini Leggero) and *Fermi*-LAT (Tavani et al. 2011; Abdo et al. 2011). The enhanced fluxes measured over different flaring episodes were a factor 3–6 times larger than the standard flux. These episodes of enhanced HE emission have been detected up to 10 GeV (as reported by Tavani et al. 2011) and can last up to few weeks. A detection of the synchrotron tail at higher energies or a additional inverse Compton component in the TeV domain could be expected. So far, no signs of variability have been reported at VHE (Mariotti 2010; Ong 2010; H. E. S. S. Collaboration 2014; van Scherpenberg et al. 2019). The characterization of the expected VHE emission to be putatively detected by CTAO is shown in Section 4.4.

#### 1.4 Novae

Novae are thermonuclear runaway explosions on the surface of a white dwarf star in binary systems involving a white dwarf accreting matter, often through an accretion disk, usually from a late-type star (Gallagher & Starrfield 1978). They are detected as transient events exhibiting huge and sudden increase of brightness. Though novae have been studied both observationally and theoretically for many decades, a comprehensive understanding of nova physics is still lacking (Iben 1982; Yaron et al. 2005; Bode & Evans 2008; Kato et al. 2014; Chomiuk, Metzger & Shen 2021). Particle acceleration in novae was predicted before the launch of the *Fermi* Gamma-ray space telescope (see Tatischeff & Hernanz 2007). Shortly after, GeV emission from the outburst of the symbiotic binary system V407 Cygni, comprised of a white dwarf and an evolved red giant companion, was first detected. Subsequently, classical novae with main-sequence donor stars were also detected (Abdo et al. 2010a; Ackermann et al. 2014).<sup>6</sup> More recently, VHE emission in novae has been predicted and searched for in a handful of sources (see e.g. Aliu et al. 2012; Ahnen et al. 2015), with the first detection at VHE gamma-rays occurring in 2021 in the recurrent nova RS Ophiuchi (RS Oph, Acciari et al. 2022; H. E. S. S. Collaboration 2022; Abe et al. 2025).

Since the first detection at HE gamma-rays from nova Cygni 2010, 19 novae<sup>7</sup> have been detected in this energy band (only RS Oph at VHE) with a rate of about one outburst detection per year. All novae so far detected at HE have been bright in the visible band ( $\leq 10$  mag), and the vast majority are nearby sources with distances within 5 kpc (Franckowiak et al. 2018). Non-thermal emission is expected to arise from leptonic and hadronic interactions by particles accelerated in radiative expanding shocks (Abdo et al. 2010a; Hernanz & Tatischeff 2012), which can originate from the interaction of the ejecta during the initial stage of the outburst and the circumbinary material, or with the fast wind produced by nuclear burning in later stages of the outburst (Abdo et al. 2010a; Ackermann et al. 2014; Martin et al. 2018). The VHE signal reported by Acciari et al. 2022; H. E. S. S. Collaboration 2022; Abe et al. 2025 is suggested to be of hadronic origin, due to protons accelerated in the nova shock.

Based on observations of novae in the nearby M31 Galaxy, as well as binary population synthesis models for the Milky Way, a rate of approximately 30 nova events per year is expected (see Section 4.5). However, a significant proportion of these will be obscured by intervening dust in the Galactic plane, preventing multiwavelength

follow-up observations. The number of nova events that will be detectable at HE and VHE gamma-rays will be further constrained by properties of the system, such as the shock velocity and the target material density. This dependence on the parameter space and prospects for detection of novae at VHE will be characterized for CTAO in Section 4.5.

#### 1.5 Magnetars

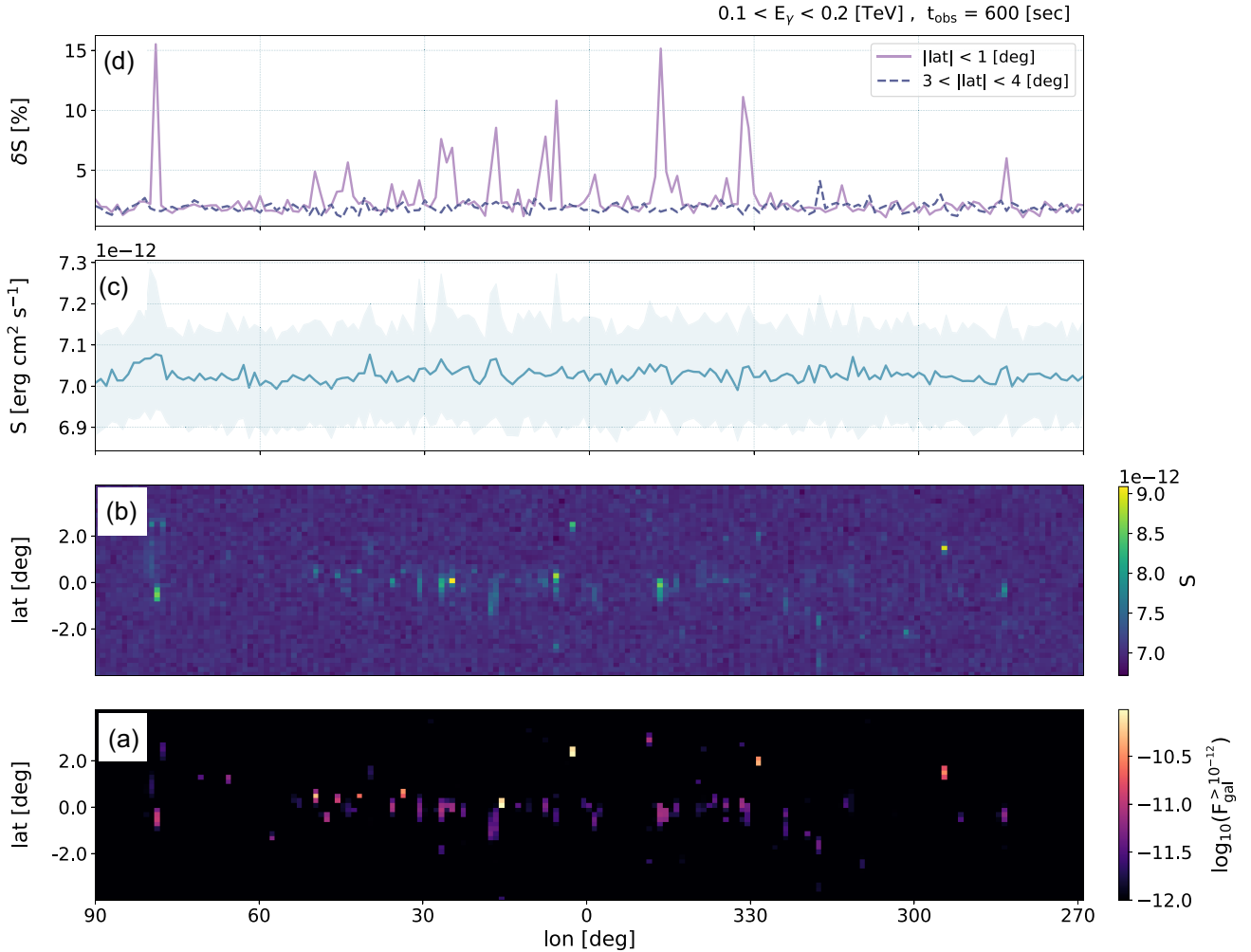
Magnetars are isolated NSs in which the main energy source is the magnetic field (e.g. Mereghetti, Pons & Melatos 2015; Kaspi & Beloborodov 2017, for reviews). They are observed as pulsed X-ray sources, with typical spin periods of a few seconds and strong spin-down rates (typically  $10^{-12}$ – $10^{-10}$  s  $s^{-1}$ ) (Harding, Contopoulos & Kazanas 1999), and/or through the detection of short bursts and flares in the hard X-ray/soft gamma-ray range. This led to their historical subdivision in the Anomalous X-ray Pulsars and Soft Gamma-ray Repeater classes (Mereghetti 2008), but it is now clear that these are just two different manifestations of the same underlying object: a strongly magnetized NS powered by magnetic energy, as proposed by Paczynski (1992) and Duncan & Thompson (1992).

About 30 magnetars are known so far. With the exception of two sources in the Magellanic Clouds, all of them lie in the Galactic plane. The majority of the magnetars are transient X-ray sources that have been discovered when they became active, with an increase of their X-ray luminosity (from a quiescent level of  $\sim 10^{33}$  up to  $\sim 10^{36-37}$  erg  $s^{-1}$ ), accompanied by the emission of luminous and rapid bursts. This means that the total Galactic population of magnetars is larger than the currently observed sample, and more sources of this class will be known at the time of CTAO observations. Furthermore, magnetar-like behaviour has recently been observed in some sources originally presumed to be of a different kind, such as rotation-powered (radio) pulsars (Gavriil et al. 2008; Göğüş et al. 2016), and even in the gamma-ray binary LS I + 61 303 (Torres et al. 2012; Weng et al. 2022).

For what concerns the persistent emission, magnetars have not been detected above few hundred keV (Abdo et al. 2010b; Aleksić et al. 2013). Their X-ray emission typically comprises a soft thermal component that dominates in the 1–10 keV range and a hard power-law component that is believed to originate from multiple resonant scattering in the magnetosphere. The upper limits (ULs) in the MeV range (Li et al. 2017) indicate a turn-off of this component implying that their detectability is below the CTAO capabilities, unless a different spectral component is present at higher energies. On the other hand, magnetar bursts and flares (in particular, the so-called Giant Flares) are potentially very interesting targets for CTAO, with the only disadvantage of their unpredictable time of occurrence. Giant flares are extremely energetic and bright events, reaching isotropic peak luminosities as high as a few  $10^{47}$  erg  $s^{-1}$  for a fraction of a second. However, they occur very rarely: only three have been seen from local magnetars in 40 yr. The high luminosity of their short ( $< 1$  s) initial peaks implies that they can be detected, with properties resembling those of short GRBs, up to distances of tens of Mpc by current hard X-ray instruments. Indeed, a few candidate extragalactic giant flares have been identified (Mazets et al. 2008; Frederiks et al. 2007; Svinkin et al. 2021; Roberts et al. 2021). Of particular interest regarding CTAO's perspective to detect giant flares is the case of the flare located in the Sculptor galaxy (NGC 253, at 3.5 Mpc) for which *Fermi*-LAT observation led to the detection of two HE photons with energies of 1.3 and 1.7 GeV, likely produced via synchrotron mechanism (Fermi-LAT Collaboration 2021). However, no emission from a magnetar has been yet detected at TeV energies (Abdalla

<sup>6</sup>Gomez-Gomar et al. (1998, and references therein) predicted gamma-ray emission from novae but of nuclear origin, in the keV–MeV domain.

<sup>7</sup>According to <https://asd.gsfc.nasa.gov/Koji.Mukai/novae/latnovae.html> (as of 2024 February).



**Figure 1.** Differential flux sensitivity,  $S$ , of the Southern CTAO array within 100–200 GeV for 10 min observation intervals, considering different putative source locations along the Galactic plane. Panel (a) shows a simulation of  $F_{\text{gal}}^{>10^{-12}}$ , the Galactic emission (Galactic diffuse emission and a simulated population of Galactic sources) above a threshold of  $10^{-12} \text{ erg cm}^{-2} \text{ s}^{-1}$ , which is derived for different Galactic longitudes (lon) and latitudes (lat). Panel (b) shows the corresponding CTAO sensitivity. In panel (c), we present the median of  $S$  for different longitudes within the range,  $-4 < \text{lat} < +4$  deg, where the shaded uncertainty region represents the  $1\sigma$  variance of  $S$ . Finally, panel (d) shows the relative  $1\sigma$  variance,  $\delta S$ , (compared to the median) derived for two ranges in latitude, as indicated. The variance away from the Galactic plane ( $3 < |\text{lat}| < 4$  deg) represents the intrinsic statistical uncertainty of the sensitivity calculation. The variance in the inner Galactic region ( $|\text{lat}| < 1$  deg) includes the intrinsic uncertainty, as well as the additional effect of the Galactic foregrounds, which are concentrated in this region.

et al. 2021; López-Oramas et al. 2021). For further discussion, see Section 4.6.

## 2 SENSITIVITY OF CTAO TO TRANSIENT DETECTION IN THE GALACTIC PLANE

CTAO will have unprecedented sensitivity over a broad energy range and will devote a large amount of time to sources in the Galactic plane, both with a dedicated Galactic Plane Survey (GPS, for details on the pointing strategy and expected results, see CTA Consortium 2024) and with pointed observations on specific targets. These are ideal capabilities for the discovery of new Galactic transients at TeV energies.

It is then important to characterize the sensitivity of CTAO in the Galactic plane. The differential sensitivity of CTAO for detecting a new source is defined as the minimal flux of a source, multiplied by the mean energy squared within the given energy interval, such

that the source is detectable at the  $5\sigma$  significance level. It is defined within a given energy range, and for a given observation interval or exposure. We assume a test point source power-law spectral model,

$$F(E) = P_f \left( \frac{E}{E_0} \right)^{-\gamma} \quad (1)$$

where we set the pivot energy,  $E_0 = 1$  TeV, and the spectral index,  $\gamma = 2.5$ , using typical values for Galactic VHE sources. The prefactor,  $P_f$  is varied as part of the sensitivity calculation, in order to find the minimal flux value for a  $5\sigma$  detection. In order to be compatible with previous analyses (e.g. Fioretti et al. 2019), we also require that the source emits at least 10 gamma-ray photons. In addition, we validate that this number of events is larger than 5 per cent of the corresponding contribution from backgrounds (cosmic rays; electrons) and foregrounds (other coincident gamma-ray sources).

We explore the performance of CTAO in the Galactic plane region for various short observation intervals. For illustration, the sensitivity of the Southern array is shown in Fig. 1, considering different putative source locations. In this example, we estimated the performance for short observation intervals of 10 min within the energy range 100–200 GeV, exploring the detection potential of new sources in the low-energy range of CTAO. We use a publicly available Galactic sky model, based on observations of known gamma-ray sources and interstellar emission from cosmic-ray interactions in the Milky Way (CTA Consortium 2024).<sup>8</sup> We simulate our putative transients on top of the emission derived from this sky model, such that the latter constitutes an additional background to the search.

As may be inferred from Fig. 1, upward fluctuations of the sensitivity (requiring brighter transient emission for detection), are correlated with the steady emission from Galactic sources. In the selected energy range, the flux of the simulated Galactic foreground is mostly below the level of a few  $10^{-11}$  erg cm<sup>-2</sup> s<sup>-1</sup>. This is of the same order as the nominal sensitivity of the observatory in the absence of foregrounds. Correspondingly, the overall degradation in sensitivity to transients is not expected to be significant.

In order to verify this, we calculated  $\delta S$ , the relative variation of the sensitivity (compared to the median value) for different Galactic longitudes. The steady foreground sources are concentrated in the inner Galactic region. We therefore derived  $\delta S$  for two regions in latitude, in order to enhance or suppress their effect. Away from the Galactic plane, we find  $\delta S \sim 2$ –3 per cent which amounts to the intrinsic statistical uncertainty of the sensitivity calculation. In the more crowded inner region, the variation is of the order of 5–15 per cent. This represents a mild increase in the flux threshold for a new transient source to be discovered, though only when coinciding with strong Galactic emitters.

We show the median sensitivity for various combinations of energy ranges and observation intervals in Fig. 2. Here, we consider an area of 4 deg<sup>2</sup> next to the Galactic centre, where the steady emission is relatively strong. The observed variation in sensitivity is mild, of the order of 1–10 per cent.

As a test, the presence of possible source variability is assessed in Section 4.1.1. Other topics such as the study of Galactic Centre sources and interstellar emission through observations of the Galactic Centre region and GPS and the prospects for the CTAO and its scientific results are covered in other KSPs (see Cherenkov Telescope Array Consortium et al. 2019; CTA Consortium 2024).

We conclude that the performance of CTAO in the Galactic plane is consistent with the corresponding nominal extragalactic sensitivity. (That is, the sensitivity in the absence of significant emission from other gamma-ray sources.)

### 3 DETECTABILITY OF TRANSIENTS OF UNKNOWN ORIGIN

Apart from the transient sources of clearly identifiable type, others of unknown nature could also be serendipitously observed e.g. during a scan of the GPS. The detailed study of serendipity and corresponding observational strategies for CTAO will be addressed in a dedicated separate publication. However, to assess capabilities of CTAO for the detection of Galactic transient sources of unknown origin, a population of generic sources can be used. A full study of such populations requires considering various models of sources,

population sizes, and observational setups, and therefore will be presented separately. Here, we illustrate the methodology with a specific, simplified example. We simulate the populations of 100 generic transients. We consider the relatively short observation time of 1 h (compatible with the strategy defined in CTA Consortium 2024) during which it would be possible to detect the source and make a decision about further observations.

We simulated the variability of each source using the following lightcurve model:

$$F(t) = \frac{2F_0}{\exp(\frac{t_0-t}{T_r}) + \exp(\frac{t-t_0}{T_d})}$$

where  $T_r$  and  $T_d$  stand for time rise and time decrease and  $t_0$  is the time at which  $F = F_0$ ; we normalize the lightcurve to  $F = 1$  at its maximum. Such a lightcurve describes the flux of a transient during its growth, at peak and when it falls, allowing the simulation of observations at each of these stages. We assume  $T_r$ ,  $T_d$ , and  $t_0$  to be in ranges 1 – 86400 s, 86400 – 604800 s, and  $T_d - T_r$  respectively.

We used the model of Yusifov & Küçük (2004) for the radial distribution of sources. For simplicity, we did not take into account the visibility constraints, assuming that all sources are visible to either array at the time of observation.

For each population, the parameters defining the spectrum and the lightcurve of each source are assigned randomly for each of them, assuming a log-uniform distribution for the prefactor and a uniform one for other parameters. The pivot energy for all sources is 1 TeV.

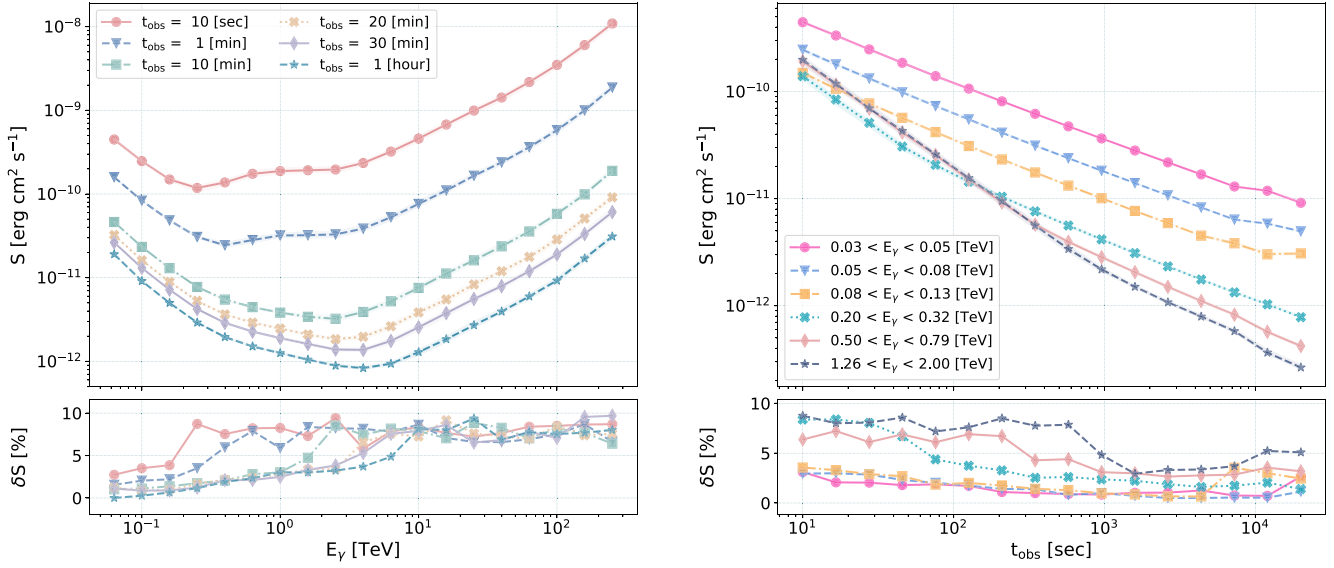
Four simulated populations are summarized in Table 1. They include different spectral shapes and parameters. For the log-parabola model we assume the range of curvature [–0.25, 0.25]. Note that populations 1 and 4 are two different populations sharing only the spatial distribution of the sources. For each population, we employed the 0.5 h IRFs for both CTAO-N and CTAO-S, and also tested the Alpha configuration in the case of population 4. Both IRF sets contain three zenith angle observation options at 20°, 40°, and 60°; and they also account for the azimuth dependence coming from the geomagnetic field pointing direction: North, South or an average over the azimuth direction.

For each source, we simulate the photon events list for 1 hr both for the CTAO-N and CTAO-S sites with a 5.0° Region of Interest (ROI) centred at a source, without any other sources within it, accounting only for the IRF background as seen in Figs 1 and 2. The energy ranges used for both configurations at each site are collected in Table 2.

The energy dispersion effect has been also taken into account (according to the IRFs). We then performed an unbinned maximum-likelihood fitting. The test statistic (TS) equal or higher than 25 is used as criterion for a source detection. The TS for different values of prefactor and spectral index are shown in Figs 4 and 5, respectively.

The results for all populations and observation configurations are presented in Figs 3–6. Since the simulated lightcurves have different time-scales and to have an idea at which lightcurve stage the observation takes place and how it affects the detectability of a source, we present in Fig. 6 the TS versus the value of lightcurve averaged over the observation time for each source in the simulated populations. We found that in the case of having a power-law spectra and fluxes in the range of  $10^{-14}$ – $10^{-09}$  photons cm<sup>-2</sup> s<sup>-1</sup> TeV<sup>-1</sup>, 73 – 83 per cent of sources for 20° and 40° zenith angles and 65 – 74 per cent of sources for 60° zenith angle will be detected, while for the population with fluxes  $< 10^{-13}$  photons cm<sup>-2</sup> s<sup>-1</sup> TeV<sup>-1</sup>, CTAO will not detect any source during 1 h of observation.

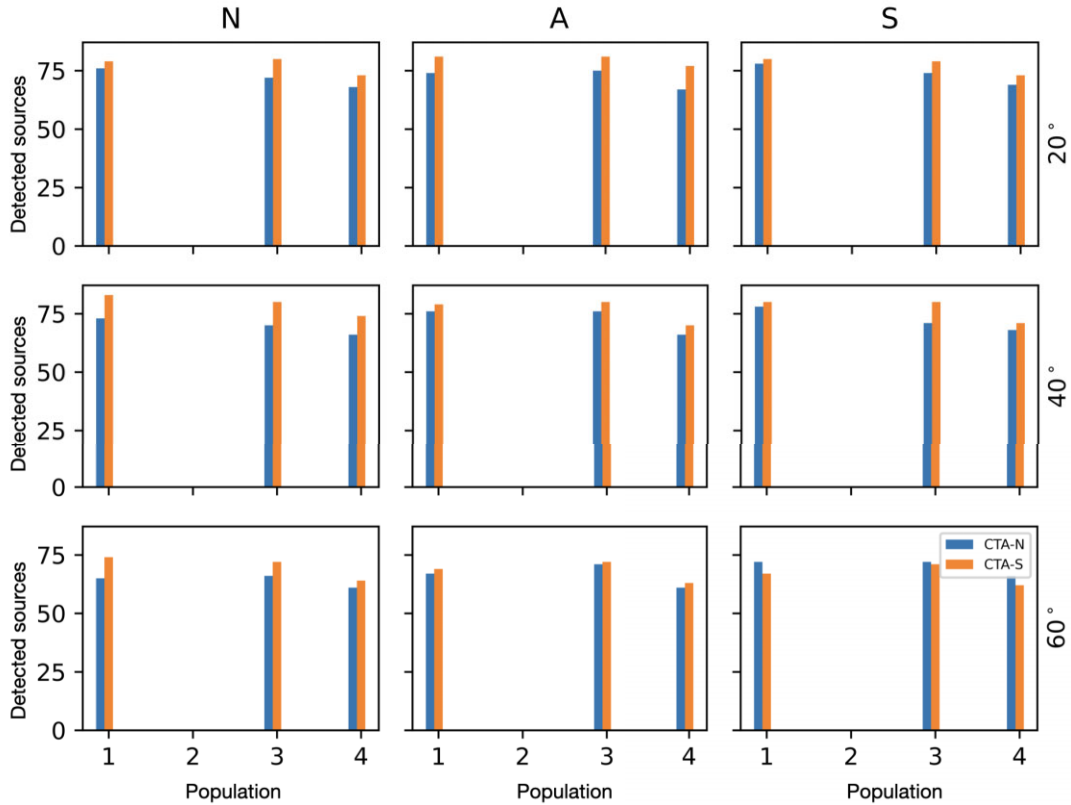
<sup>8</sup>Galactic sky model available at <https://zenodo.org/records/10008527>



**Figure 2.** The differential flux sensitivity,  $S$ , of the Southern CTAO array for different energy ranges,  $0.03 < E_\gamma < 200$  TeV, and observation intervals,  $10 < t_{\text{obs}} < 2 \times 10^4$  s. The sensitivity is derived as the median value for various putative source positions, considering an area of  $4 \text{ deg}^2$  close to the Galactic centre. The bottom panels show the relative  $1\sigma$  variance of the sensitivity,  $\delta S$ , compared to the median. The variance accounts for both the intrinsic statistical uncertainty of the sensitivity calculation, and the degradation of performance due to the presence of steady sources.

In most cases, CTAO-S performs marginally better than CTAO-N, with the larger difference for the North magnetic field configuration. Adding a curvature to the spectrum does not affect the detection rate in a statistically significant way. Using the Alpha configuration

(which corresponds to a first construction phase) slightly decreases the detectability, which is expected due to the reduced number of telescopes and the lack of LSTs in the CTAO-S Alpha configuration (Maier et al. 2023).



**Figure 3.** Number of detected sources in populations 1–4 for CTAO-N (blue, left bars) and CTAO-S (orange, right bars), including the Alpha configuration in population 4. From left to right: different configurations of the geomagnetic field (North, average, and South). From top to bottom: different zenith angles ( $20^\circ$ ,  $40^\circ$ , and  $60^\circ$ ).

**Table 1.** Simulated populations. We consider sources with different spectral shapes and parameters.

Population	Spectrum	Prefactor (photons cm <sup>-2</sup> s <sup>-1</sup> TeV <sup>-1</sup> )	Spectral index
1	Power-law	10 <sup>-14</sup> –10 <sup>-09</sup>	[−3.50, −1.50]
2	Power-law	10 <sup>-18</sup> –10 <sup>-13</sup>	[−3.50, −1.50]
3	Log-parabola	10 <sup>-14</sup> –10 <sup>-09</sup>	[−3.50, −1.50]
4	Power-law (Alpha)	10 <sup>-14</sup> –10 <sup>-09</sup>	[−3.50, −1.50]

**Table 2.** Energies (TeV) assumed in the simulations depending on the array location, configuration, and zenith angle. Different energy ranges were assumed depending on the geomagnetic field (average, North, South) for CTAO-N Alpha configuration, as produced in the dedicated IRFs (Observatory & Consortium 2021).

Site	20°	40°	60°
CTAO-N	0.03–200	0.04–200	0.11–200
CTAO-S	0.03–200	0.04–200	0.11–200
CTAO-N (Alpha)	0.03–200	0.04–200	0.06–200 (A)
			0.12–200 (N)
			0.08–200 (S)
CTAO-S (Alpha)	0.04–200	0.06–200	0.18–200

In the case of ROIs not centred in a source, we present in Fig. 7 the dependence of the detection probability on the source distance (in degrees) from the ROI centre, with a clear decrease in detectability for the offsets > 3°.

Finally, to roughly estimate how source visibility affects the presented observation probabilities, we compute, as an example, the number of detected sources for 1-h long observations starting at 2:00 UTC on three different nights taking into account the visibility constraints at each observatory site. For sources with zenith angle ranges of [0°, 33°], [33°, 54°], and [54°, 66°], we employed the IRFs corresponding to zenith angles of 20°, 40°, and 60°, respectively (observations were not considered for zenith angles exceeding than 66°). Each source was evaluated using the IRF appropriate for its azimuth. The results are presented in Table 3. We see that while the detection probabilities without these constraints are high, there is a significant reduction in detection probabilities when visibility constraints are taken into account.

## 4 SOURCE DETECTION WITH CTAO

Galactic transients that exhibit MeV–GeV emission are specially interesting to be studied with CTAO, since it is already known that non-thermal mechanisms leading to gamma-ray production are at work. We aim at understanding whether these sources of interest can also emit VHE radiation, which can be produced by the same HE mechanisms and be detected as a spectral extension, or be created by an additional component at TeV energies.

### 4.1 High-mass microquasars

The microquasars of the Cygnus region, Cyg X-3, Cyg X-1, and the system SS 433 are the only microquasars that have been detected in the HE regime, hence they can be considered as potential targets for the CTAO observatory. After the discovery of persistent gamma-ray emission from SS 433 above 20 TeV by High Altitude Water Cherenkov (HAWC, Abeysekara et al. 2018a), the latest LHAASO

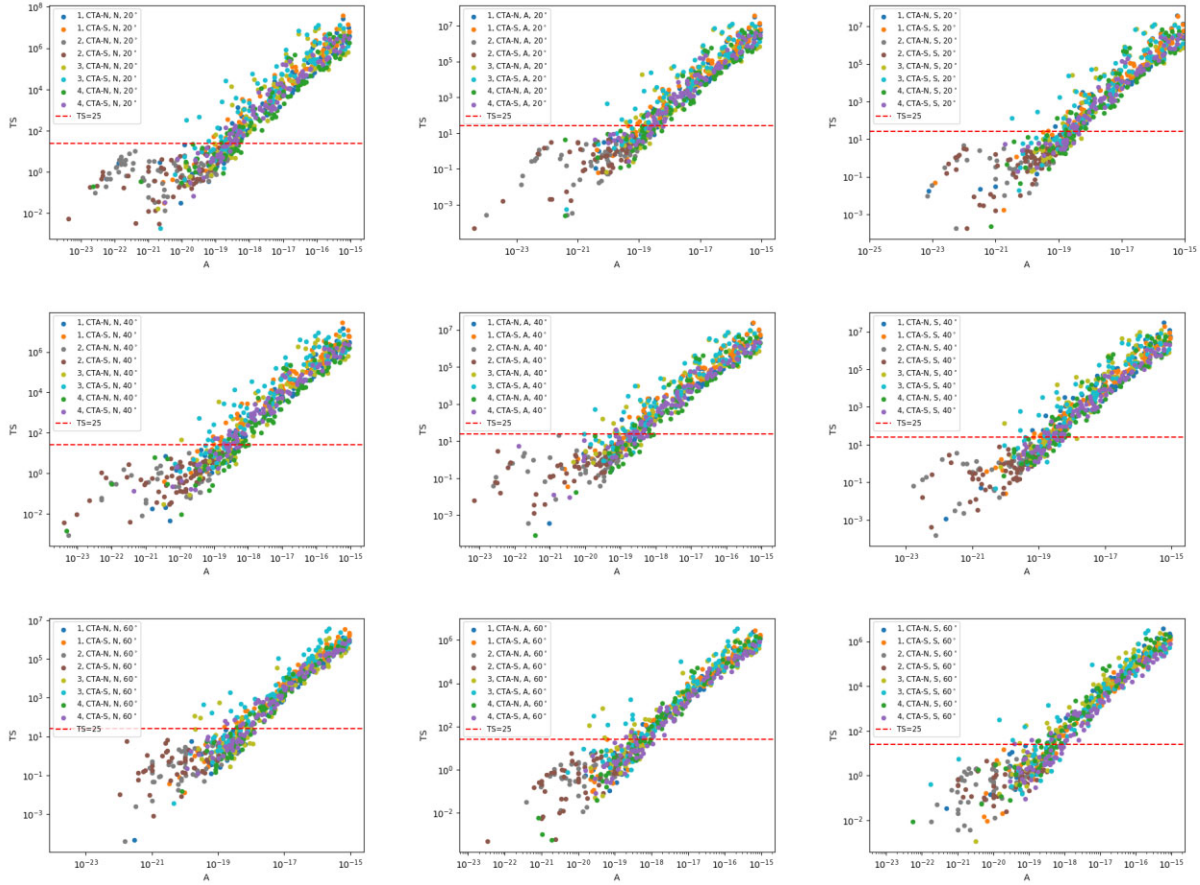
detections (LHAASO Collaboration 2024), and specially the first detection by an IACT (H. E. S. S. Collaboration 2024), the CTAO observations of these microquasars will be crucial to shed light on the physical mechanism responsible for the VHE emission in this type of binary systems, by investigating the limits of extreme particle acceleration in the jet.

The importance of observing this subclass of binary systems with CTAO has been previously discussed in Paredes et al. (2013). In particular, a detailed study on a possible detection of a TeV flare from Cyg X-1 was presented in that paper, showing conclusions similar to our findings (see Section 4.1.3). In this section, we show simulations on the first microquasar detected in the VHE regime, SS 433, and estimate the detectability both of transient and persistent emission from Cyg X-3 and Cyg X-1. Even if the detection of persistent emission is not the scope of this paper, we perform this additional exercise to complement the expectations to detect microquasars with CTAO. For the case of the microquasars in the Cygnus region, we carried out several CTAO observation simulations by using the latest `prod5-v0.1` IRFs to check if these two systems could already be detected in the first years of operation of CTAO. Almost all the simulations have been carried out in the lowest range of energies for the CTAO observatory, where the bulk of the emission from these binary systems is expected. For each set of observations, besides the emission from the microquasars, we simulated the main field sources of the Cygnus region: 2HWC J2006 + 341 (Araya & HAWC Collaboration 2019), VER J2016+371, VER J2019 + 368 (Aliu et al. 2014b), Gamma Cygni SNR (Ackermann et al. 2017; Abeysekara et al. 2018b), TeV J2032 + 4130 (emission model as detected by MAGIC before the periastron passage of 2017 November, Abeysekara et al. 2018c). This approach also applies to the case of the LMXB V404 Cyg located in the same region (see Section 4.2.1).

#### 4.1.1 SS 433

SS 433 is a binary system containing a supergiant star that is overflowing its Roche lobe with matter accreting onto a compact object, either a BH or an NS (see e.g. Margon 1984; Fabrika 2004). Two jets of ionized matter, with a bulk velocity of approximately one quarter of the speed of light in vacuum, extend from the binary, perpendicular to the line of sight, and terminate inside the supernova remnant W50 (e.g. Fabrika 2004). The lobes of W50 in which the jets terminate about 40 pc from the central source, are accelerating charged particles, as it follows from radio and X-ray observations, consistent with electron synchrotron emission (Geldzahler, Pauls & Salter 1980; Brinkmann et al. 2007).

At TeV energies SS 433 was detected by both the HAWC Observatory (1017 d of measurements, Abeysekara et al. 2018a) and H.E.S.S. (200 h of observations, H. E. S. S. Collaboration 2024). These observations demonstrate presence of two regions of gamma-ray emission of leptonic nature at the positions of the eastern and western jets. The reported H.E.S.S. fluxes at 1 TeV [(2.30 ± 0.58) × 10<sup>-13</sup> TeV<sup>-1</sup> cm<sup>-2</sup> s<sup>-1</sup> and (2.83 ± 0.70) × 10<sup>-13</sup> TeV<sup>-1</sup> cm<sup>-2</sup> s<sup>-1</sup> for the eastern and western jets, correspondingly] are inline with HAWC data. Quality of the H.E.S.S. data also allow to study the energy dependence of the source morphology, demonstrating that while the gamma-ray emission above 10 TeV appears only at the base of the jets, the lower energy gamma-rays have their peak surface brightness at locations further along each jet, reflecting an energy-dependent particle energy loss time-scale.



**Figure 4.** TS for different values of prefactor in the simulated populations. From left to right: different configurations of the geomagnetic field (North, average, and South). From top to bottom: different zenith angles ( $20^\circ$ ,  $40^\circ$ , and  $60^\circ$ ). The dashed line marks  $TS = 25$ .

Analysis of the *Fermi*-LAT data led to the discovery of the significant HE gamma-ray emission from the region around SS 433 (see Bordas et al. 2015; Sun et al. 2019; Rasul et al. 2019; King et al. 2019; Li et al. 2020). However, the analysis is model dependent and can lead to very different conclusions on the position and extension of the source. In Rasul et al. (2019), authors report evidence at  $3\sigma$  level for the modulation of the  $\gamma$ -ray emission with the precession period of the jet of 162 d. This result suggests that at least some of the gamma-ray emission originates close to the base of the jet. Li et al. (2020) detected HE emission in the vicinity of SS 433 which shows periodic variation compatible with the precessional period of the jets.

While we do not expect to detect variability in the VHE emission coming from the lobes, microquasars are known to have flaring emission on various time-scales coming from its central source. To test the possibility of CTAO to detect a central source and its putative variability, we simulate the local region of SS 433 with the diffuse background and the nearby MGRO 1906 + 06 source, where SS 433 consists of both the aforementioned lobes and a central point source.

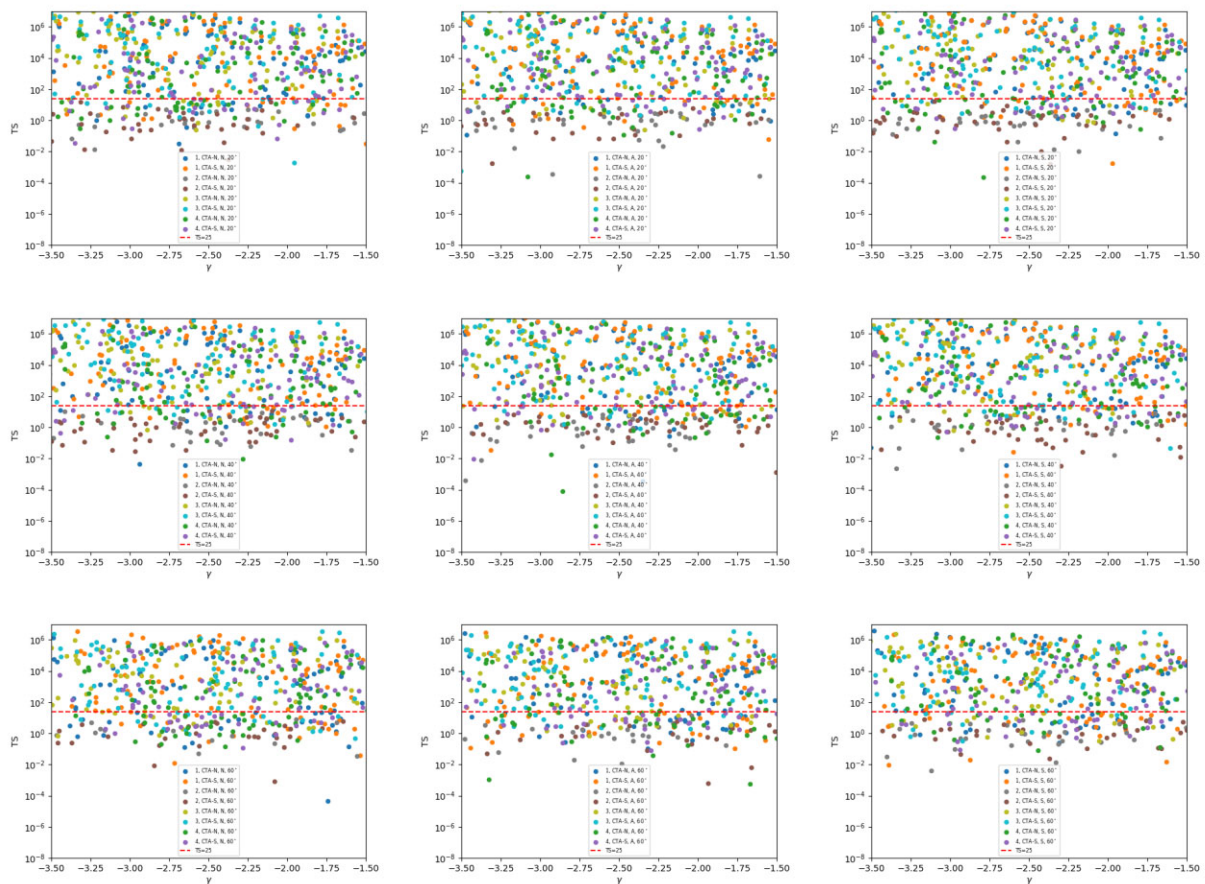
Following the H.E.S.S. observations, we have modelled the eastern and western lobes as a combination of three hotspots with Gaussian profiles (with the parameters summarized in table S4 of H. E. S. S. Collaboration 2024). Spectral models of the lobes were organized so that different hotspots appear in different energy bands. To represent the spectral model of each hotspot in agreement with H. E. S. S. Collaboration (2024), we assumed that they follow a powerlaw distribution with a superexponential cut-off at both HE and low

energies, to allow hotspots to arise at different energies:

$$F(E) = \phi_0 \left( \frac{E}{1\text{TeV}} \right)^{-\Gamma_1} \left( 1 + \left( \frac{E}{E_{B2}} \right)^{\left( \frac{\Gamma_3 - \Gamma_2}{\beta_2} \right) - \beta_2} \right) \times \left( \frac{E}{1\text{TeV}} \right)^{-\Gamma_2} \left( \frac{E}{E_{B1}} \right)^{\left( \frac{\Gamma_2 - \Gamma_1}{\beta_1} \right) - \beta_1}$$

The parameters chosen to represent the H.E.S.S. spectrum are given in Table 4. No low-energy cut-off was assumed for the e1 and w1 sources. The spectral model of the central source was obtained directly from the H.E.S.S. ULs, and was modelled using a simple power-law model with a flux falling below the H.E.S.S. UL value. As it is seen in Fig. 8, 20 h of CTAO observations is enough to clearly measure the energy-dependent source structure as well as to detect the central source at the assumed flux level. The dependence of the central source relative flux errors on the exposure time is shown in Fig. 9.

To study the CTAO possibility to detect possible variability of about 15 per cent with the precession and orbital periods at the level proposed by Rasul et al. (2019), we have simulated a 500 h observation of the source uniformly distributed along the precessional period, assuming  $F(\varphi) = (0.99 + 0.14 \sin(2\pi(\varphi + 0.84))) \times F$  and 500 h observation of the source uniformly distributed along the orbital period, assuming  $F(\varphi) = (1.07 + 0.18 \sin(2\pi(\varphi + 0.81))) \times F$ . The expected variability is shown in Fig. 10.



**Figure 5.** TS for different values of spectral index in the simulated populations. From left to right: different configurations of the geomagnetic field (North, average, and South). From top to bottom: different zenith angles ( $20^\circ$ ,  $40^\circ$ , and  $60^\circ$ ).

To systematically study the CTAO sensitivity to detect different level of variability for various levels of the source flux we run batches of 5000 simulations for low exposure times of 30 and 60 min, and batches of 1000 simulations for higher exposure times of 300, 600, and 6000 min using the North and South site IRFs

The flux was calculated after every simulation and the total data was compiled into histograms for each exposure time to determine the error range of the detections. As SS 433 could be viewed from both the North and South hemispheres, the results of error measurements from both sites were compared to determine which can produce more sensitive detections. Fig. 11 shows the comparison of this flux error ratio depending on the integrated source flux above 1 TeV and exposure for both Northern (left) and Southern arrays. In this figure, one can see also simulations for the values exceeding the H.E.S.S. UL on the central source ( $\sim 10^{-13}$  photons  $\text{cm}^{-2} \text{s}^{-1}$ ). This was done to test the effectiveness of CTAO on dim transient sources to determine what level of variability can be observed with short exposures.

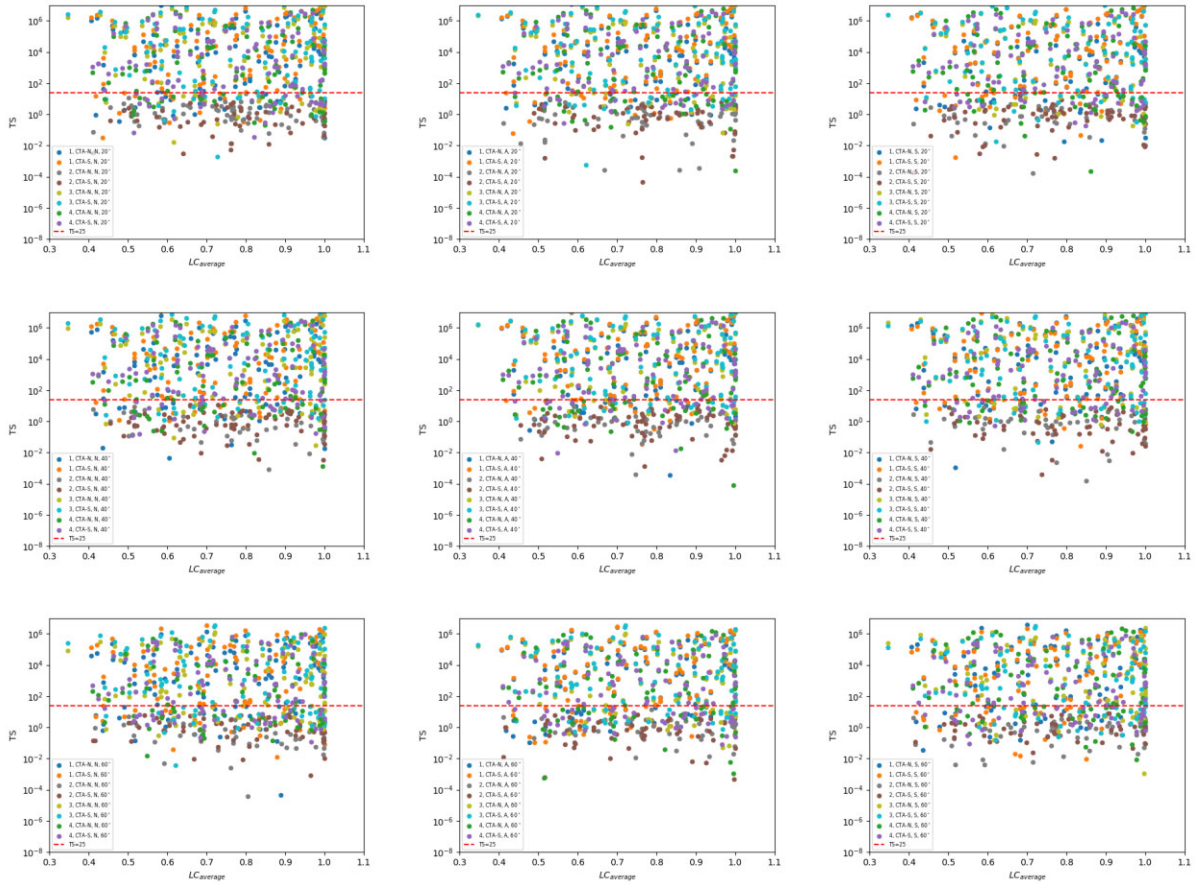
Based on the simulations run at different fluxes, sources with a photon flux  $< 1 \times 10^{-13}$  photons  $\text{cm}^{-2} \text{s}^{-1}$  will require exposure times of more than 10 h in order to detect flux variability at about 50 percent level. However, for sources with a flux  $\geq 1 \times 10^{-13}$  photons  $\text{cm}^{-2} \text{s}^{-1}$ , CTAO may be able to detect variability as low as  $\sim 10$  per cent observing from 5 to 10 h. At a photon flux  $\geq 3 \times 10^{-12}$  photons  $\text{cm}^{-2} \text{s}^{-1}$ , the  $1\sigma$  ratio gets as low as  $\sim 5$  per cent with exposure times of an hour long, meaning that even

low variability may be detectable from relatively bright sources with short observations.

To be sure that our results are applicable to the sources located in crowded regions we compared our results assuming that the source with the flux of  $\sim 10^{-13}$  photons  $\text{cm}^{-2} \text{s}^{-1}$  was located either in the uncrowded region, like SS 433, or in the region with multiple nearby TeV sources, like LS 5039. It was found that the observed flux of the central source and its error agreed in these two cases within few percents and thus our results are valid for sources located in both crowded and uncrowded regions.

#### 4.1.2 Cyg X-3

Cyg X-3 is an HMXB (high-mass X-ray binary) located at a distance of  $\sim 9$  kpc (Reid & Miller-Jones 2023). The companion star is a Wolf-Rayet (WR) with a strong wind mainly composed of helium. The nature of the compact object is still unknown, although a BH scenario is favoured (Zdziarski, Mikolajewska & Belczynski 2013; Antokhin et al. 2022). The orbital period is very short,  $\sim 4.8$  h, indicating that the compact object is very close to the WR star, totally enshrouded in its stellar wind (orbital distance  $\sim 3 \times 10^{11}$  cm). Recent observations with the Imaging X-ray Polarimetry Explorer (IXPE) show a high X-ray polarization degree from the system, during different spectral states, indicating the presence of collimated optically thick outflows, which hide the central engine (Veledina et al. 2024a, b). The binary system is known to produce giant radio flares (flux  $> 10$  Jy), produced



**Figure 6.** TS for different values of the lightcurve averaged over the observation time in the simulated populations. From left to right: different configurations of the geomagnetic field (North, average, and South). From top to bottom: different zenith angles ( $20^\circ$ ,  $40^\circ$ , and  $60^\circ$ ). The dashed line marks  $TS = 25$ .

by synchrotron processes from a relativistic jet oriented very close to the line of sight. Transient gamma-ray activity above 100 MeV was reported for the first time in 2009 by AGILE (Tavani et al. 2009) and *Fermi*-LAT (Fermi LAT Collaboration 2009), and reported in several studies over the years, since its discovery (see Prokhorov & Moraghan 2023 for a recent study on the transient activities observed by *Fermi*-LAT). The flaring activity (typical duration: 1–2 d) was observed in coincidence with a repetitive pattern of multifrequency emission (Piano et al. 2012): the gamma-ray flares have been detected (i) during soft X-ray spectral states (around minima of the hard X-ray lightcurve), (ii) in the proximity of spectral transitions, and (iii) a few days before giant radio flares. In particular, transient gamma-ray emission was found when the system is moving into or out of the quenched state, a spectral state – characterized by a very low (or undetectable) flux at radio and hard X-ray frequencies – that is known to occur a few days before major radio flares.

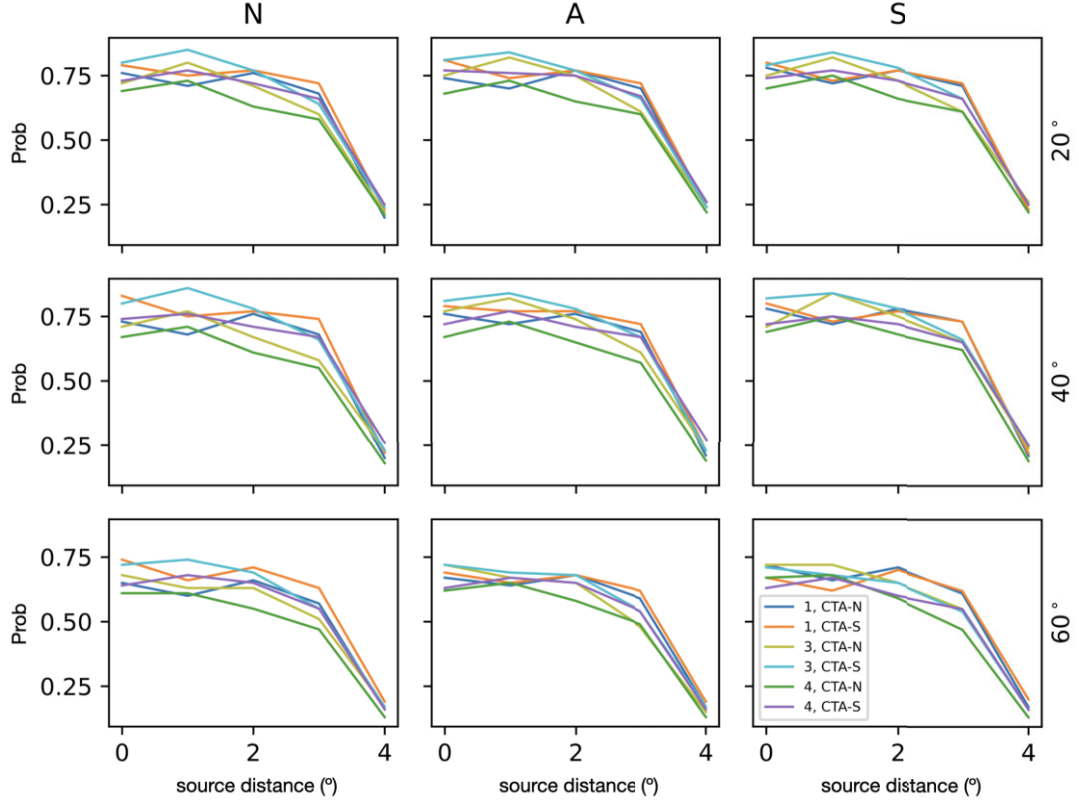
The quenching activity of Cyg X-3 turns out to be a key condition for the observed activity above 100 MeV. According to theoretical models, a simple leptonic scenario – based on inverse Compton (IC) scattering between electrons/positrons accelerated in the jet and seed photons from the WR companion – can account for the flaring gamma-ray fluxes and the 4.8 h modulation detected by *Fermi*-LAT during the transient activity (Dubus, Cerutti & Henri 2010; Prokhorov & Moraghan 2023). A simple phenomenological picture, based on dominant leptonic processes in the jet, can account for the non-thermal emission pattern: around the quenching, the jet

would consist of plasmoids, ejected with high Lorentz factor. This transient jet would be responsible for the HE flare (for IC processes), produced in the proximity of the binary system ( $10^{10} - 10^{12}$  cm), and it would subsequently produce the major radio flares (synchrotron processes), by moving out from the central engine (distances  $> 10^{14}$  cm). MAGIC repeatedly observed Cyg X-3, both during hard and soft spectral states, but never detected any significant VHE activity from the microquasar (Aleksić et al. 2010).

*Cyg X-3: transient emission.* We carried out simulations by assuming two different theoretical models based on IC processes in the jet (Piano et al. 2012; Zdziarski et al. 2018), in order to test the possibility of a CTAO detection of transient VHE gamma rays from Cyg X-3.

We performed a binned analysis in the energy range 100 GeV–1 TeV with CTOOLS, by simulating observations with the Alpha configuration of the Northern array of the CTAO observatory (IRF: `North_z20`), taking into account the energy dispersion. A multi-source input model with the main background TeV sources (see Section 4.1) and the CTAO instrumental background (CTAO`IRF-Background`) has been considered.

In the first case, we adopted a simple power-law spectrum (see equation 1) inferred from the leptonic model A from Piano et al. (2012), where prefactor  $P_f = 1.34 \times 10^{-21}$  photons  $\text{cm}^{-2} \text{s}^{-1} \text{MeV}^{-1}$ , index  $\gamma = 4.5$  and pivot energy  $E_0 = 1$  TeV. The leptonic model is based on IC scatterings between accelerated electrons in the jet and soft seed photons from the accretion disk (X-rays) and from



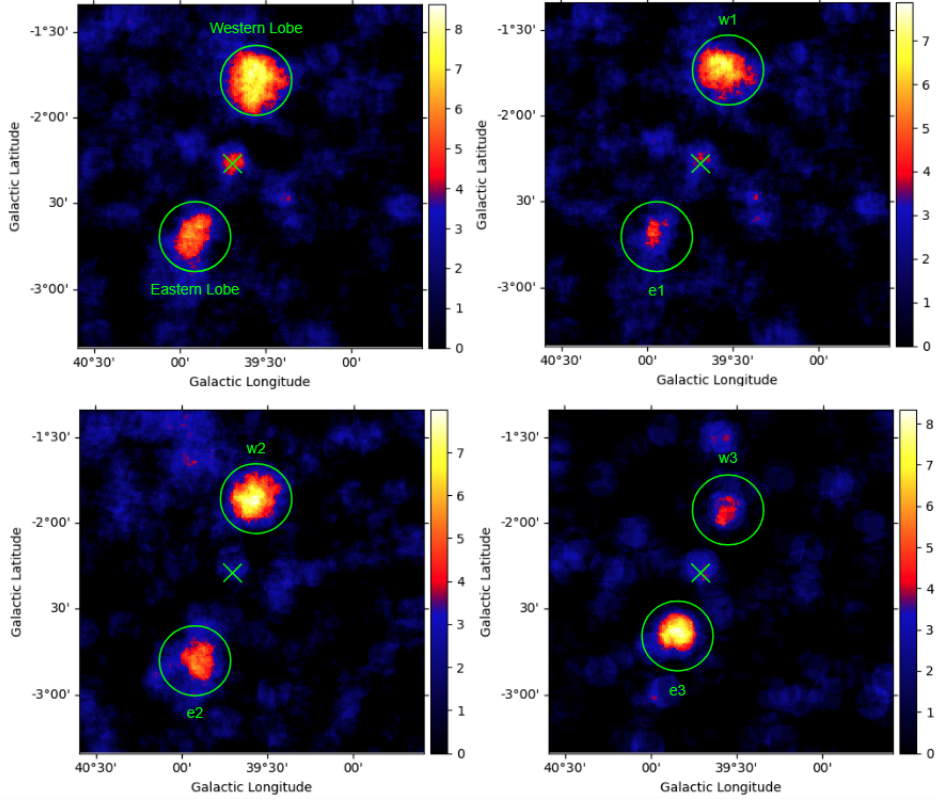
**Figure 7.** Dependence of the CTAO detection probability (vertical axis) on the source distance (horizontal, in degrees) from the ROI centre. From left to right: different configurations of the geomagnetic field (North, average, and South). From top to bottom: different zenith angles (20°, 40°, and 60°).

**Table 3.** Number of detected sources in populations 1, 3, and 4 including the visibility constraints for observations taking place from 2:00 to 3:00 UTC.

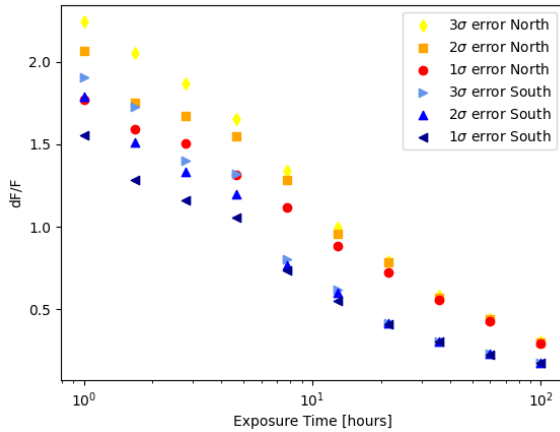
Population	IRF zenith angle	2025-05-22						2025-08-22						2025-11-22						
		CTAO-N			CTAO-S			CTAO-N			CTAO-S			CTAO-N			CTAO-S			
		N	A	S	N	A	S	N	A	S	N	A	S	N	A	S	N	A	S	
1	20°	0	3	1	0	0	0	0	3	0	11	24	2	0	0	0	0	0	0	0
	40°	0	17	10	0	14	13	0	13	0	15	4	7	0	1	0	0	0	0	0
	60°	0	4	11	0	13	1	0	6	0	3	1	2	0	1	0	0	0	0	0
3	20°	0	4	1	0	0	0	1	0	0	9	25	1	0	0	0	0	0	0	0
	40°	0	15	8	0	14	16	0	11	0	11	4	11	1	1	0	0	0	0	0
	60°	0	2	12	0	14	0	1	7	0	3	1	4	0	1	0	0	1	0	0
4	20°	0	2	1	0	1	0	1	2	0	13	23	2	0	0	0	0	0	0	0
	40°	0	17	12	0	12	12	0	9	0	13	2	6	0	0	0	0	0	0	0
	60°	0	2	12	0	12	0	0	5	0	1	2	2	0	0	1	0	1	0	0

**Table 4.** Spectral model parameters.

Source	$\phi_0$ [ $\text{TeV}^{-1}\text{cm}^{-2}\text{s}^{-1}$ ]	$\Gamma_1$	$\Gamma_2$	$\Gamma_3$	$E_{B1}$ [TeV]	$E_{B2}$ [TeV]	$\beta_1$	$\beta_2$
Central source	$2.00 \times 10^{-14}$	2.00						
East 1	$2.40 \times 10^{-13}$		2.18	10.0		2.00		1.00
East 2	$1.00 \times 10^{-14}$	-2.10	1.00	2.80	2.50	7.00	0.10	0.01
East 3	$1.00 \times 10^{-16}$	-2.10	1.04	4.00	10.0	100	0.50	0.01
West 1	$3.00 \times 10^{-13}$		2.40	10.0		2.00		1.00
West 2	$1.20 \times 10^{-14}$	-2.12	1.15	2.80	2.50	7.00	0.10	0.10
West 3	$1.00 \times 10^{-16}$	-2.10	1.15	4.00	10.0	100	0.50	0.01

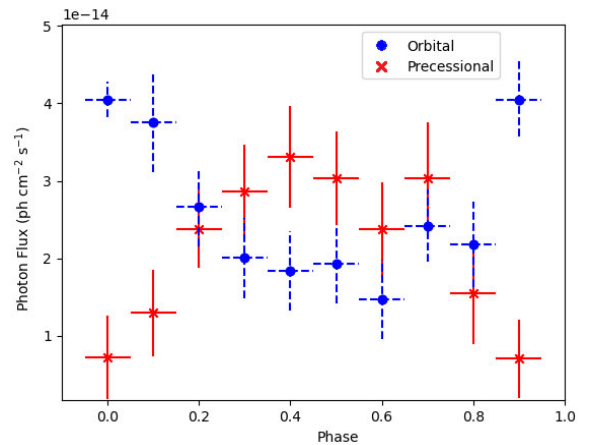


**Figure 8.** SS433 Simulations, taken with 20 total hours of exposure time spread across two precessional periods. Top right: 0.8–2.5 TeV. Bottom left: 2.5–10 TeV. Bottom right: >10 TeV. Top left: total model from 0.8–100 TeV. The position of the central source is marked with a cross.



**Figure 9.** Comparison of the relative flux errors for the SS 433 central source at different exposure times for the Northern and Southern arrays.

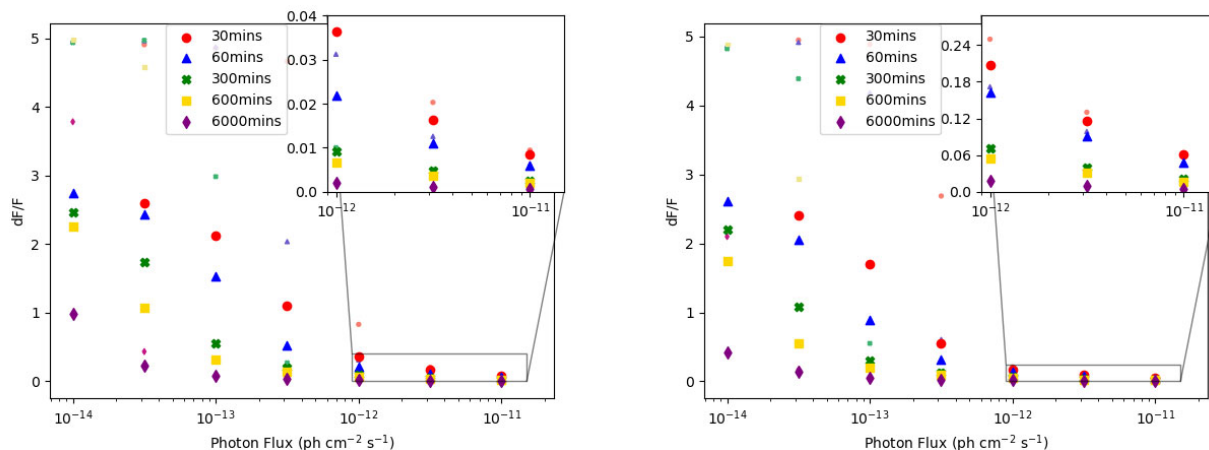
the companion star (UV). We simulated 5 and 50 h observations, and we investigated the resulting simulated data, by performing a binned analysis. The resulting spectra are shown in Fig. 12, together with the X-ray ‘hypersoft’ spectrum (Koljonen et al. 2010), the AGILE flaring spectrum (Piano et al. 2012), and the MAGIC flux ULs observed during the soft states (Aleksić et al. 2010). All the spectra (not simultaneous observations) are referred to the same spectral state of Cyg X-3 when the transient gamma-ray activity is detected at MeV–GeV energies (quenched state). We show the reference theoretical model and the input simulated power law, together with the CTAO simulated spectra. By assuming this input spectrum we found no



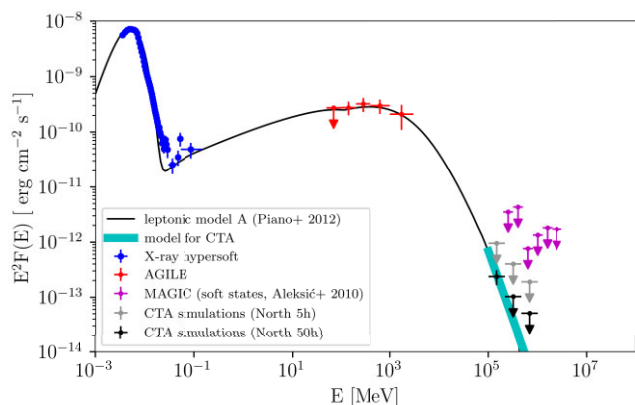
**Figure 10.** 500-h observations of SS433 as observed with the Southern array folded with the precessional and orbital periods.

detection with CTAO-N with 5-h observation and a weak hint of signal ( $\sim 3\sigma$ ) for 50 h of observation time.

In the second case, we assumed a different theoretical model, developed by Zdziarski et al. (2018) in order to fit the flaring spectrum from Cyg X-3 as detected by *Fermi*-LAT (cumulative spectrum of 49 1-d flares detected between 2008 August and 2017 August). The theoretical model presented in their paper is similar to the one presented in Piano et al. (2012), but in Zdziarski et al. (2018), the electrons in the jet scatter blackbody soft photons from the companion star only. The orbital and geometrical parameters are similar. Also in this case,



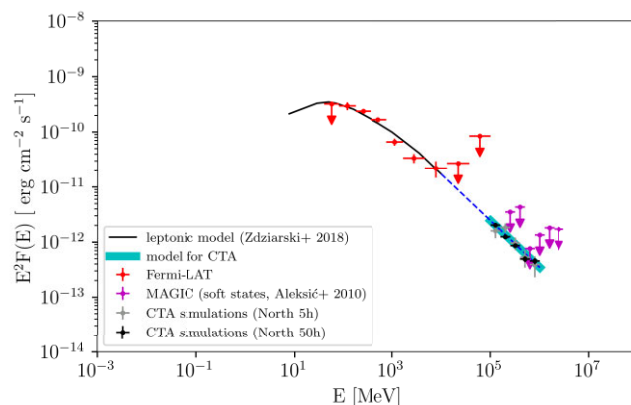
**Figure 11.** Dependence of the  $1\sigma$  and  $3\sigma$  relative flux error ratio on the photon flux for the Northern (left) and Southern (right) arrays. Different exposure times are given by different colours and shapes as indicated in the legend.  $3\sigma$  relative flux errors are shown with smaller and fainter symbols.



**Figure 12.** Multifrequency SED of Cyg X-3. Solid curve: leptonic model A (Piano et al. 2012). Cyan thick solid curve: CTAO input model for the simulation. ‘Hypersoft’ X-ray spectrum (Koljonen et al. 2010), *RXTE*-PCA, and *RXTE*-HEXTE data ( $\sim 3$  to  $\sim 150$  keV, blue points). HE gamma-ray cumulative flaring spectrum (Piano et al. 2012), *AGILE* (50 MeV–3 GeV, red points). VHE gamma-ray flux ULs (95 per cent C.L.) from Aleksić et al. (2010), *MAGIC* (199 GeV–3.16 TeV, magenta points). CTAO flux ULs for a simulated observation of 5 h (grey points). CTAO spectrum for a simulated observation of 50 h (black points).

the model is focused on the HE emission from the microquasar ( $E \leq 100$  GeV). Thus, we assumed a simple power-law extension of the model up to TeV energies (assuming: prefactor  $P_f = 2.15 \times 10^{-19}$  photons  $\text{cm}^{-2} \text{s}^{-1} \text{MeV}^{-1}$ , index  $\gamma = 2.85$ , and pivot energy  $E_0 = 1$  TeV). Similarly, we simulated 5 and 50 h observations. The results of these simulations are shown in Fig. 13. In this case, by assuming a harder and brighter input spectrum, we found clear detections with CTAO-N:  $\sim 10\sigma$  with 5-h observation, and  $\sim 30\sigma$  with-50 h observation.

Thus, by assuming two simple power-law input spectra adapted from theoretical leptonic models – both created ad hoc in order to account for the flaring activity observed by *AGILE* and *Fermi*-LAT – a possible detection with CTAO North is plausible even with a few hours observations. It is important to note that these extrapolation do not take into account  $\gamma\gamma$  absorption for pair production in the companion star’s photon field, which could be not negligible between 100 GeV and 1 TeV (Zdziarski et al. 2012). Nevertheless, we cannot

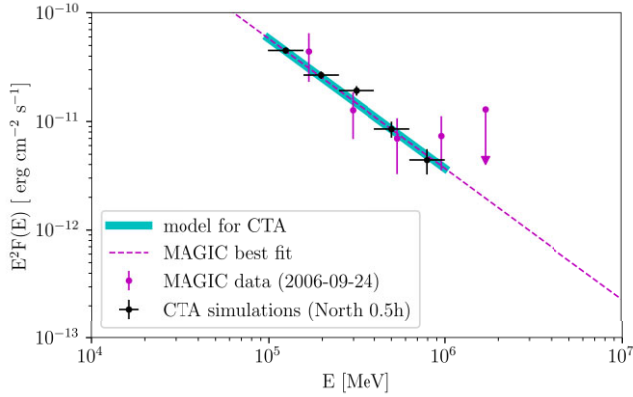


**Figure 13.** Gamma-ray SED of Cyg X-3. Solid curve: leptonic model (Zdziarski et al. 2018). Power-law extension of the model up to TeV energies. Cyan solid thick curve: CTAO input model for the simulation. HE gamma-ray cumulative flaring spectrum (Zdziarski et al. 2018), *Fermi*-LAT (50 MeV–100 GeV, red points). VHE gamma-ray flux ULs (95 per cent C.L.) from Aleksić et al. (2010), and *MAGIC* (199 GeV–3.16 TeV, magenta points). CTAO spectrum for a simulated observation of 5 h (grey points). CTAO spectrum for a simulated observation of 50 h (black points).

rule out to detect the 4.8 h orbital modulation, in the case of a prolonged TeV flare. A CTAO detection of transient VHE gamma-ray activity would represent an unprecedented result for this elusive system, never observed at TeV energies. Nevertheless, a CTAO non-detection would give new strong constraints on theoretical models about microquasars. The lack of a transient VHE signal from Cyg X-3, correlated with non-thermal flaring activity, could indicate that: (i) the TeV signal, eventually produced in the jet, is absorbed for pair production by the companion star’s UV photons; and (ii) the acceleration efficiency in the jet is intrinsically low, the maximum energies of the jet particles are not sufficient to generate TeV photons.

#### 4.1.3 Cyg X-1

Cyg X-1 is an HMXB, composed of a BH ( $M_X = 21.2 \pm 2.2 M_\odot$ ) and a O9.7Iab supergiant companion star ( $M_{\text{opt}} = 40.6^{+7.7}_{-7.1} M_\odot$ , Miller-Jones et al. 2021). The system is located at a distance of

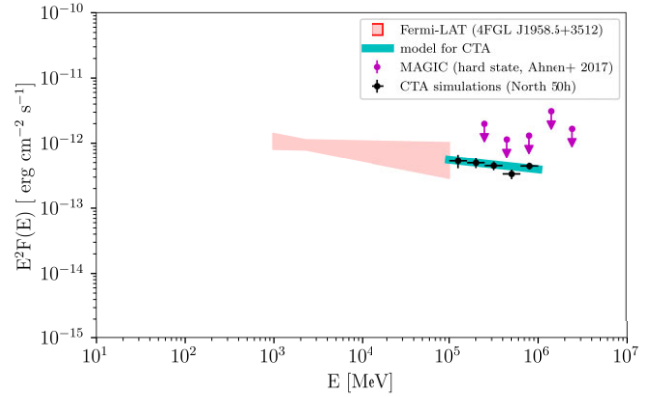


**Figure 14.** VHE gamma-ray SED of Cyg X-1, related to the 2006-September flaring activity VHE gamma-ray spectrum from Albert et al. (2007), MAGIC (150 GeV–1.9 TeV, magenta points), accounting for 78.9 min of observation. Dashed line: MAGIC best fit. Solid curve: CTAO input model for the simulation. CTAO spectrum for a simulated observation of 30 min (black points).

$2.22^{+0.82}_{-0.17}$  kpc (Miller-Jones et al. 2021), and the orbital period is 5.6 d. The X-ray spectra can be accurately modelled by hybrid Comptonization models (Coppi 1999). The soft state of Cyg X-1 is characterized by a strong disk blackbody component peaking at  $kT \sim 1$  keV and a power-law tail extending up to  $\sim 10$  MeV, related to Comptonization processes in the corona. In the hard state, the accretion disk is truncated and the emission from the corona is dominant. In this state, the coronal plasma is composed by a hot quasi-thermal population of electrons ( $kT \sim 100$  keV) with a sharp cut-off at  $\sim 200$  keV. At sub-MeV energies, the microquasar exhibits a non-thermal power-law tail with a strong linear polarization (Laurent et al. 2011; Jourdain et al. 2012). This emission could be ascribed either to synchrotron processes in the jet, by assuming a very efficient particle acceleration and strong jet magnetic fields (Zdziarski et al. 2014), or to the corona itself (Romero, Vieyro & Chaty 2014). Recent studies investigate the physical origin of this power-law tail at sub-MeV energies, detected during both soft and hard spectral states (Cangemi et al. 2021). Above 100 MeV, deep observations with *Fermi*-LAT found evidences of persistent emission from Cyg X-1 only during hard X-ray spectral states (Zanin et al. 2016; Zdziarski et al. 2017). Transient HE emission was observed by AGILE (Bulgarelli et al. 2010; Sabatini et al. 2010, 2013) on 1–2 d time-scales, in coincidence with both hard and soft X-ray spectral states. At TeV energies, a hint of detection ( $\sim 4\sigma$ ) was observed by MAGIC on 2006 September 24 (Albert et al. 2007), during a hard X-ray flare of Cyg X-1. A  $\sim 4\sigma$  persistent TeV signal was recently reported by LHAASO (LHAASO Collaboration 2024).

For Cyg X-1, we investigated the possibility that CTAO will detect both transient and persistent emission from the microquasar.

*Cyg X-1: transient emission.* In this case, we carried out a simulated short-term observation of Cyg X-1, during a possible VHE gamma-ray flare. We simulated a 30-min observation with the same setup reported in Section 4.1.2: a multisource simulation with photon energies between 100 GeV and 1 TeV. We assumed, as input spectrum for the simulation, the same power-law observed by MAGIC in 2006 September 24 (Albert et al. 2007; prefactor  $P_f = 2.3 \times 10^{-18}$  photons  $\text{cm}^{-2} \text{s}^{-1} \text{MeV}^{-1}$ , index  $\gamma = 3.2$ , and pivot energy  $E_0 = 1$  TeV). We obtained an overall detection of the source at a significance level of  $\sim 38\sigma$ . The resulting spectrum is shown in Fig. 14, together with the observed flaring spectrum

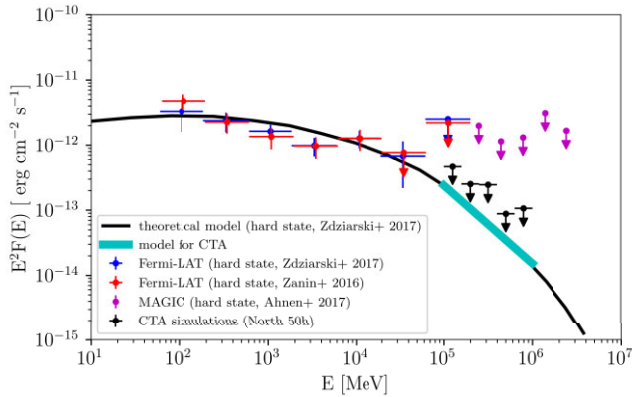


**Figure 15.** Gamma-ray SED of Cyg X-1, for a possible steady emission up to VHE The *Fermi*-LAT 4FGL Catalogue HE steady spectrum (Abdollahi et al. 2020), and *Fermi*-LAT (1–100 GeV, red shade butterfly region). Solid curve: CTAO input model for the simulation. MAGIC (160 GeV–3.5 TeV, magenta points) VHE ULs (95 per cent C.L.) from Ahnen et al. (2017b). CTAO spectrum for a simulated observation of 50 h (black points).

observed by MAGIC. Our results confirm that CTAO will be able to detect a flare similar to the one reported by MAGIC in 2006 in a few minute observation, with unprecedented spectral accuracy. A fainter TeV flare – weaker than the one reported by MAGIC – would require a longer CTAO observation (a few hours) to be significantly detected. This possibility will be properly assessed in a potential ToO observation, on the basis of the triggering flare flux in other wavelengths.

*Cyg X-1: persistent emission.* Cyg X-1 exhibits persistent HE emission during the hard state, as observed by *Fermi*-LAT (Zanin et al. 2016; Zdziarski et al. 2017). Thus, we investigated the possibility of a CTAO detection of VHE persistent emission above 100 GeV. Again, we assumed the same setup as reported in Section 4.1.2. We analysed three different scenarios. In the first one, we assumed as input spectral model for CTAO, a simple extension of the power-law spectral shape reported in the *Fermi*-LAT 4FGL Catalogue, without any cut-off around 100 GeV (Abdollahi et al. 2020). In the second scenario, we assumed a spectral shape based on a purely leptonic theoretical model, in which gamma-ray emission is produced due to IC scatterings in the persistent jet during the hard state (Zdziarski et al. 2017). According to this model, a sharp cut-off – due to the Klein–Nishina effects – is predicted at  $\sim 100$  GeV. In the third scenario, we assumed a spectral shape based on the lepto-hadronic theoretical model presented in Kantzas et al. (2021). In that paper, the authors modelled the GeV persistent spectrum as detected by *Fermi*-LAT during the hard state, by assuming that both electrons and protons are accelerated in the jet. A comprehensive model, based on a superposition of leptonic (IC scatterings) and hadronic processes (gamma rays from the decay of neutral mesons, produced in  $p\gamma$  interactions) can properly fit the multiwavelength spectrum up to the HE emission from Cyg X-1.

For the first hypothesis (4FGL-like spectrum), we assumed a simple power-law (assuming: prefactor  $P_f = 3.2 \times 10^{-14}$  photons  $\text{cm}^{-2} \text{s}^{-1} \text{MeV}^{-1}$ , index  $\gamma = 2.15$ , and pivot energy  $E_0 = 4.15$  GeV). A multisource simulation with photon energies between 100 GeV and 1 TeV has been carried out. With this spectrum, we obtained a detection with a significance of  $\sim 17\sigma$  for a 50-h simulated observation. The resulting simulated spectrum is shown in Fig. 15, together with the *Fermi*-LAT 4FGL spectrum (Abdollahi et al. 2020), and the MAGIC flux ULs during the hard state (Ahnen et al. 2017b).

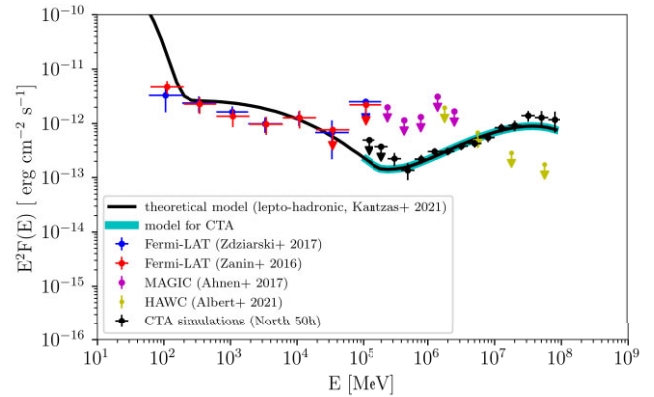


**Figure 16.** Gamma-ray SED of Cyg X-1, for a possible steady emission up to VHE. Black solid curve: theoretical model from Zdziarski et al. (2017), based on IC processes in the jet during the hard state. HE steady spectrum during the hard state (Zdziarski et al. 2017), *Fermi*-LAT (60 MeV–200 GeV, blue points), HE steady spectrum during the hard state (Zanin et al. 2016), and *Fermi*-LAT (60 MeV–200 GeV, red points). MAGIC (160 GeV–3.5 TeV, magenta points) VHE flux ULs (95 per cent C.L.) from Ahnen et al. (2017b). Cyan solid thick curve: input model used for the simulation. Simulated spectrum for a CTA observation of 50 h (black points).

For the second hypothesis (spectrum inferred from Zdziarski et al. 2017), we assumed a simple power law (with prefactor  $P_f = 9.5 \times 10^{-21}$  photons  $\text{cm}^{-2} \text{s}^{-1} \text{MeV}^{-1}$ , index  $\gamma = 3.2$ , and pivot energy  $E_0 = 1$  TeV). A multisource simulation with photon energies between 100 GeV and 1 TeV has been carried out. In this case, we did not detect any significant emission with CTAO with a simulated observation of 50 h (significance  $\sim 2\sigma$ ). The resulting differential spectral ULs are shown in Fig. 16, together with the theoretical model from Zdziarski et al. (2017), the HE gamma-ray spectra as detected by *Fermi*-LAT (Zanin et al. 2016; Zdziarski et al. 2017), and the MAGIC ULs related to the hard state (Ahnen et al. 2017b).

For the third hypothesis (spectrum inferred from Kantzas et al. 2021), we used as input the theoretical model itself, by simulating photon energies between 100 GeV and 100 TeV. We carried out the usual multisource binned analysis, and we found a clear detection with a significance of  $\sim 36\sigma$  for a 50-h simulated observation. The resulting simulated spectrum is shown in Fig. 17, together with the theoretical model from Kantzas et al. (2021), the HE gamma-ray spectra as detected by *Fermi*-LAT (Zanin et al. 2016; Zdziarski et al. 2017), the MAGIC flux ULs during the hard state (Ahnen et al. 2017b), and the HAWC flux ULs between 0.1 and 100.0 TeV (Albert et al. 2021). In particular, we note that above 10 TeV, the HAWC ULs for a prolonged stacked observation (1523 d) are below our theoretical model. This spectral behaviour could weaken the chance of a CTAO sharp detection at the highest energies.

Thus, according to our simulations, CTAO will be able to detect a possible persistent VHE gamma-ray emission from the jet of Cyg X-1, if the spectrum is not characterized by a sharp cut-off around 100 GeV. According to purely leptonic models, a sharp cut-off is expected below 1 TeV. On the contrary, hadronic processes could be responsible for a bright emission above 1 TeV, which could be detected by the CTAO Observatory.



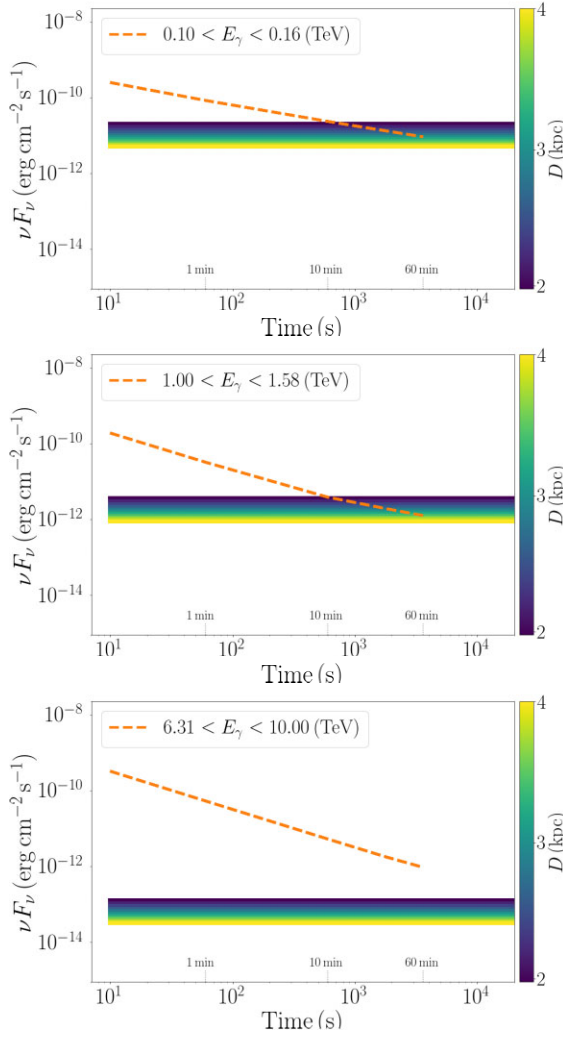
**Figure 17.** Gamma-ray SED of Cyg X-1, for a possible steady emission up to VHE. *Fermi*-LAT, MAGIC and CTAO points as reported in Fig. 16 are represented again. HAWC observations (Albert et al. 2021, yellow ULs). Solid curve: theoretical model from Kantzas et al. (2021), based on lepto-hadronic processes in the jet during the hard state. Cyan thick solid curve: input model used for the simulation. Simulated spectrum for a CTAO observation of 50 h (black points).

#### 4.2 Low-mass X-ray binaries

LMXBs harbour a low-mass companion star and a BH (or an accreting NS), object tightly connected to jet launching that are responsible for the non-thermal multiwavelength emission (see review in Chaty 2022). Up to now, no LMXB has been detected at HE (apart from tMSPs) and only strong hints of emission at HE have been reported in V404 Cyg. No LMXB has neither been detected at VHE by any IACT (see e.g. Aleksić et al. 2011; Ahnen et al. 2017a; H. E. S. S. Collaboration 2018). The most recent X-ray outburst of a BH LMXB which was followed up by the IACTs MAGIC, H.E.S.S., and VERITAS was that of MAXI J1820+070, without detecting any VHE emission (Abe et al. 2022). We examine here if CTAO will be able to detect such a similar exceptionally bright outburst but for a hypothetical source located within a maximal distance of 4 kpc from Earth. Based on the theoretical lepto-hadronic model of Kantzas et al. (2022), used since the modelled LMXB can be considered a canonical source, we perform a number of simulations where we rescale the predicted VHE emission for a number of different jet inclination angles between  $5^\circ$  and  $65^\circ$ . We perform each simulation for a number of different hypothetical sources at different distances within 2 and 4 kpc.

In Fig. 18, we show the predicted VHE flux for a BH-LMXB with inclination angle of  $30^\circ$  assuming that the emission persists in three different energy bins between 0.1 and 10 TeV, for at least 2 weeks, and compare it to the CTAO sensitivity curves (see Fig. 1).

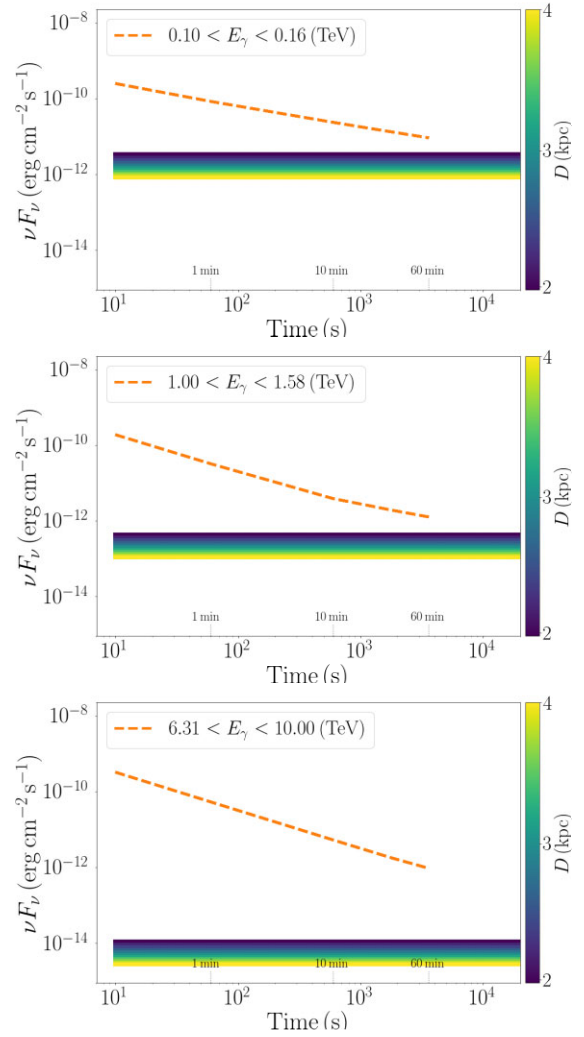
We overall see that CTAO will be able to detect an outburst similar to MAXI J1820+070 in the sub-TeV regime within a few tens of minutes if the LMXB is located closer than  $\sim 4$  kpc at energies  $< 1.6$  TeV. The inclination angle of the LMXB we assume here is relatively small compared to the average value between  $40^\circ$  and  $70^\circ$  (see e.g. Tetarenko et al. 2016), but LMXBs with an inclination angle greater than  $\sim 30^\circ$  fail to be detected within the first hour of observations (Fig. 19). Sources with an inclination angle less than  $\sim 20^\circ$  could be observed within a few minutes, such as the case of MAXI J1836–194 or V4641 Sgr, both microblazar candidates (Russell et al. 2014; Gallo, Plotkin & Jonker 2014).



**Figure 18.** Predicted VHE emission of a hypothetical BH-LMXB for three different energy bins, as shown in the legends. The BH-LMXB follows the recent outburst of MAXI J1820+070, but with an inclination angle of  $30^\circ$  instead, and its distance given by the colour map (lighter colours correspond to more distant sources). We assume an emission lasting at least two weeks. The CTAO sensitivity for each energy bin is represented as a dashed line.

#### 4.2.1 The case of V404 Cyg

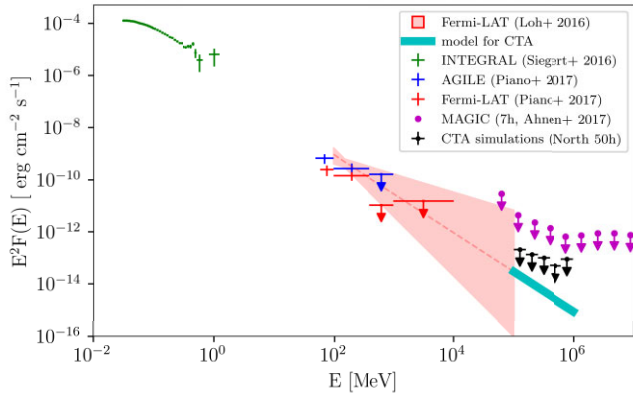
The system V404 Cyg is an LMXB located at a distance of  $2.39 \pm 0.14$  kpc, inferred through parallax measurements (Miller-Jones et al. 2009). The system is composed of a  $9_{-0.6}^{+0.2} M_\odot$  BH and a  $0.7_{-0.2}^{+0.3} M_\odot$  K3 III companion star with an orbital period of  $6.4714 \pm 0.0001$  d (Casares, Charles & Naylor 1992). LMXBs are known to undergo long periods of quiescence (years) and rapid outburst states (weeks). After a  $\sim 26$  yr-long quiescent phase, V404 Cyg entered in a bright active phase in the second half of 2015 June. The outburst, lasting  $\sim 2$  weeks, was observed in all the bands of the electromagnetic spectrum, from radio to GeV energies. AGILE-GRID and *Fermi*-LAT observed a strong hint of emission in gamma rays ( $\approx 4\sigma$ ), coincident with the brightest peak of luminosity observed in radio, hard X-ray, and soft gamma-ray bands (Loh et al. 2016; Piano et al. 2017). The gamma-ray event was observed between June 24 and 26 and it is simultaneous with rapid transitions between the optically thin and the optically thick phases of the radio emission in the jet, and coincident



**Figure 19.** Same as Fig. 18, but for an inclination angle of  $40^\circ$ .

with a bright peak of the 511 keV emission line detected by the INTERNATIONAL GAMMA-RAY ASTROPHYSICS LABORATORY (INTEGRAL, Siegert et al. 2016). As for other microquasars, the HE emission could be related to either leptonic (IC scattering on soft photons) or hadronic processes (decay of  $\pi^0$  mesons produced in proton-proton collisions) in the jet. Nevertheless, in this case the companion is an old spectral type, cold, and small star, and it does not provide a sufficiently high density of seed photons and hadronic material in the stellar wind. Thus, the HE emission is possibly related to interactions between the particles accelerated in the jet and the radiation (and the magnetic field) of the jet itself. MAGIC repetitively pointed at V404 Cyg between June 18 and 27, for more than 10 h, but the observations did not show any significant emission at TeV energies (Ahnen et al. 2017a).

*V404 Cyg: transient emission.* We carried out a 50-h CTAO simulated observation for V404 Cyg with the same setup described in Section 4.1.2: 100 GeV–1 TeV simulated photons with a multisource approach. The CTAO input spectral model for V404 Cyg is a simple extension of the power-law spectrum observed by *Fermi*-LAT during the 2015-June flaring activity and reported by Loh et al. (2016) (assuming: prefactor =  $8 \times 10^{-22}$  photons  $\text{cm}^{-2} \text{s}^{-1} \text{MeV}^{-1}$ , index  $\gamma = 3.5$ , and pivot energy  $E_0 = 1$  TeV). The resulting spectrum from



**Figure 20.** Multifrequency SED of V404 Cyg, related to the 2015-June flaring activity. Hard X-ray spectrum (Siebert et al. 2016), INTEGRAL data (30 keV–2 MeV, green points), HE flaring spectrum (Piano et al. 2017), and AGILE (50 MeV–1 GeV, blue points), HE flaring spectrum (Piano et al. 2017), and *Fermi*-LAT (60 MeV–10 GeV, red points) Shaded region: HE flaring spectrum, (Loh et al. 2016), and *Fermi*-LAT (100 MeV–100 GeV), MAGIC (50 GeV–10 TeV, magenta points) VHE flux ULs (95 per cent C.L.) from Ahnen et al. (2017a). Cyan solid thick curve: input model used for the simulation. Simulated spectrum for a CTAO observation of 50 h (black points).

our simulation is shown in Fig. 20, together with the non-thermal HE spectra observed during the 2015-June flare. Thus, even if we assume the same spectral trend as observed by the HE gamma-ray detectors, we expect no detection with CTAO in a 50-h observation. This is in agreement with the simulations on LMXBs described in Section 4.2.

### 4.3 Transitional millisecond pulsars

Out of the three confirmed tMSPs, only PSR J1023 + 0038 is currently in the LMXB state, whereas XSS J1227–4853 and IGR J18245–2452 are currently in the RMSP state. As previously mentioned, other candidates were found through X-ray peculiar variability and association with *Fermi*-LAT sources (see review by Papitto & de Martino 2022). Particularly interesting are the two confirmed tMSPs PSR J1023 + 0038 and XSS J1227–485 that when in LMXB state they were found by *Fermi*-LAT with a luminosity of about  $10^{34}$  erg  $s^{-1}$  in the energy range 0.1–10 GeV, which is up to 10 times brighter than the levels observed during the RMSP state (Papitto & Torres 2015; Torres et al. 2017). This fact makes them particularly interesting for a possible detection with CTAO. In this section, we estimate the chances of detecting these two tMSPs with CTAO given also their relatively close distance of about 1.5 kpc.

#### 4.3.1 PSR J1023 + 0038

This tMSP was initially detected as a variable source in the radio band (Bond et al. 2002) and showing clear characteristics of an accretion disk around the compact object in the optical band. Later, Thorstensen & Armstrong (2005) suggested PSR J1023 + 0038 as an NS-LMXB. The observations did not reveal an accretion disk but the existence of a strong irradiation on the optical star from an unseen companion. The compact object was identified as a 1.69 ms radio pulsar in a 4.75 h orbit around a  $0.2 M_{\odot}$  companion star (Archibald et al. 2009). In 2013 June, the source came back to an LMXB state, where it has remained until now, and the radio pulsar

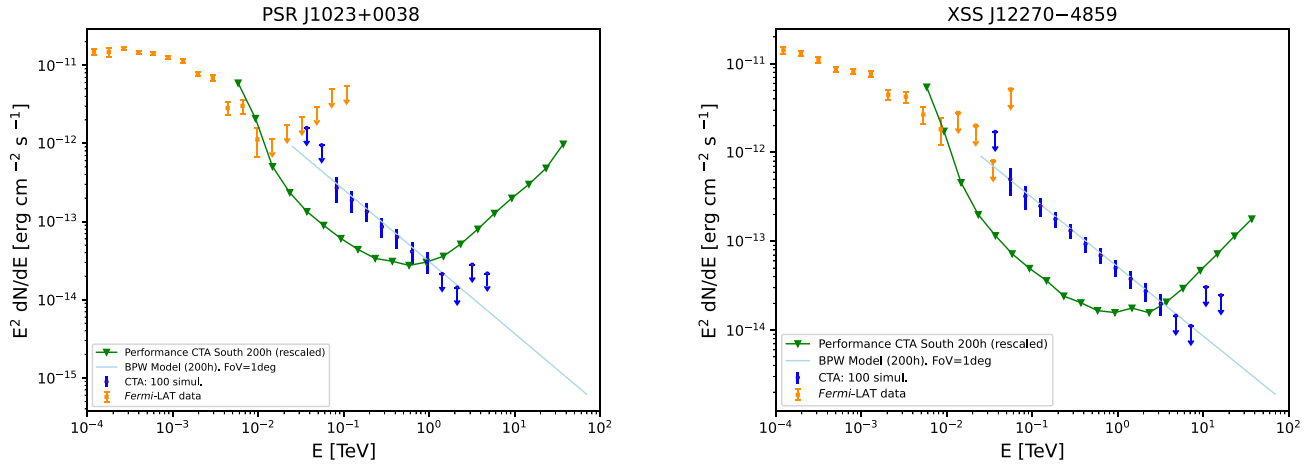
signal switched off. During the LMXB state, PSR J1023 + 0038 shows a peculiar behaviour in X-rays: it exhibits frequent modes switching between three different X-ray levels, dubbed high, low, and flaring (Bogdanov et al. 2015). The HE gamma-ray emission detected by *Fermi*-LAT has been reported to brighten by a factor of 5 after the transition. The average *Fermi*-LAT spectrum is described by a power law with index 1.8 and a cut-off at an energy of 2.3 GeV according to Takata et al. (2014) and by a power law with index 2 and an energy cut-off at 3.7 GeV, the significance of the cut-off is  $4.3\sigma$  level according to Torres et al. (2017). Neither pulsations nor steady emission were found in the VHE regime (Aliu et al. 2016). To test the capability of CTAO to detect emission from this source, we first studied the HE gamma-ray emission from *Fermi*-LAT during the LMXB state (2013–2021), in order to obtain the spectral parameters of the source. For the *Fermi*-LAT analysis, all photons in the energy range 0.1–300 GeV included in a circular region of  $10^{\circ}$  centred on the source were considered. The binned likelihood analysis was performed using 20 energy bins. The two spectral models that have been considered for the CTAO simulations are a log-parabola and a broken power law. We considered only these two models, because the simulation with the power law with an exponential cut-off model did not return any detectable spectral bin in the VHE range (the cut-off is at very low energies, a few GeV). On the other hand a simple power-law extending in the energy range from GeV up to 1 TeV appears physically difficult to achieve. This is compatible by the low significance of the results by Takata et al. (2014) and Torres et al. (2017).

The spectral input parameters inferred from the analysis of the *Fermi*-LAT data in the accretion phase are for the broken power law: prefactor  $P_f = (0.06 \pm 0.01) \times 10^{-10}$  photons  $cm^{-2} s^{-1} MeV^{-1}$ ,  $\alpha_1 = -2.12 \pm 0.03$ ,  $\alpha_2 = -2.91 \pm 0.06$ , and energy break =  $(1.15 \pm 0.09)$  GeV; while for the log-parabola: prefactor  $P_f = (0.34 \pm 0.007) \times 10^{-10}$  photons  $cm^{-2} s^{-1} MeV^{-1}$ ,  $\alpha = 2.23 \pm 0.02$ ,  $\beta = 0.16 \pm 0.02$ , and energy break = 0.524 GeV.

Batches of 100 simulations were run using both CTAO-N and CTAO-S IRFs for 50, 100, and 200 h of observations; we binned the simulated data into initial 20 logarithmic energy bins considering an energy range of 0.03–100 TeV. The resulting spectrum of PSR J1023 + 0038 is shown in Fig. 21 and, for simplicity, only the results with the highest statistic are reported (200 h observations). The full analysis results for the broken power-law model are reported in Table 5. The parameters obtained from the unbinned analysis are:  $P_f = 7.31 \times 10^{-12}$  photons  $cm^{-2} s^{-1} MeV^{-1}$ ,  $\alpha_1 = -2.12$ ,  $\alpha_2 = -2.91$ , and energy break = 1.15 GeV. We find that long integration times are needed to detect this tMSP, with at least 100 h for CTAO-N and 50 h for CTAO-S. We tried to also fit the simulation obtained with a log-parabola model but the fit did not converge, despite several attempts changing various parameters (prefactor, ROI, etc.). This is likely caused by the very low statistics of the simulated spectrum.

#### 4.3.2 XSS J1227–48538

XSS J1227–48538 was initially detected as a hard X-ray source and was tentatively identified as a cataclysmic variable, similarly to PSR J1023 + 0038, based on the double-peaked emission lines (typical of an accretion disk) in the optical spectrum (Masetti et al. 2006). While the low X-ray luminosity was not in contrast with a cataclysmic variable interpretation, the peculiar X-ray variability with mode switching and the unexpected association with a *Fermi*-LAT source prone to identify XSS J1227–48538 as an unusual LMXB (de Martino et al. 2010). The system transitioned to a radio pulsar state between 2012 November 14 and December 21, characterized by the disappearance of the emission lines in the optical spectrum and



**Figure 21.** CTAO-S simulations for the tMSP PSR J1023 + 0038 (on the left) and XSS J1227–48538 (on the right) considering the broken power-law model. We consider 200 h of observations. The CTAO performance curve (thick green with inverted triangles) is rescaled for 200 h. The *Fermi*-LAT spectrum during the accretion phase is reported (squared orange symbols).

**Table 5.** Broken power-law model significance’s results for North and South IRFs, considering 50, 100, and 200 h of observations of the tMSP PSR J1023 + 0038.

	Hours	TS	$\sigma$
North	50	18.50	4.30
	100	39.86	6.31
	200	77.15	8.78
South	50	29.36	5.42
	100	55.47	7.45
	200	114.77	10.71

the softening observed in the radio, optical, X-ray, and gamma-ray bands (Bassa et al. 2014; Torres et al. 2017). Just after the transition, observations with the Giant Metrewave Radio Telescope allowed to detect a radio pulsar with a 1.69 ms spin period in a binary system with an orbital period of 6.9 h (Roy et al. 2015). Before the transition to the radio state, the gamma-ray emission was a factor of 2 larger (Torres et al. 2017). The *Fermi*-LAT analysis performed for the period in which the source was in the subluminal disk state (2008–2012) provides results consistent with those reported by Xing & Wang (2015) and Torres et al. (2017): XSS J1227–48538 is best described by a power law with a cut-off at  $E_{\text{cut}} = 5.3$  GeV (at  $3.4\sigma$ ) and a spectral index of  $\gamma = 2$ . The *Fermi*-LAT analysis procedure performed on this source is similar to that described before for the other tMSP.

Similarly to PSR J1023 + 0038, the two spectral models considered for the CTAO simulations are the log-parabola and the broken power law. As input models for the CTAO simulations we considered the output from the *Fermi*-LAT study. For the broken power law:  $P_f = (2.71 \pm 0.71) \times 10^{-12}$  photons  $\text{cm}^{-2} \text{s}^{-1} \text{MeV}^{-1}$ ,  $\text{Index}_1 = -2.23 \pm 0.04$ ,  $\text{Index}_2 = -2.77 \pm 0.10$ , and energy break =  $(1.32 \pm 1.44)$  GeV. For the log-parabola:  $P_f = (3.26 \pm 0.91) \times 10^{-11}$  photons  $\text{cm}^{-2} \text{s}^{-1} \text{MeV}^{-1}$ ,  $\alpha = 2.28 \pm 0.05$ ,  $\beta = 0.09 \pm 0.02$ , and energy break =  $(4.45 \pm 5.42)$  GeV. We performed batches of 100 simulations using only the CTAO-S site IRFs and 50, 100, and 200 h of observations. The simulated data were binned into 20 logarithmic energy bins in an energy range of 0.03–100 TeV.

The resulting spectrum of XSS J1227–48538 is shown in Fig. 21 and, for simplicity, we reported only the results with the highest statistics. The complete results of the analysis for the broken power

**Table 6.** Broken power-law model significance’s results for South IRFs, considering 50, 100, and 200 h of observations of the tMSP XSS J1227–48538.

	Hours	TS	$\sigma$
South	50	66.26	8.14
	100	128.04	11.31
	200	253.99	15.94

law are reported in Table 6 and the parameters of the unbinned analysis are:  $P_f = 3.15 \times 10^{-12}$  photons  $\text{cm}^{-2} \text{s}^{-1} \text{MeV}^{-1}$ ,  $\alpha_1 = -2.23$ ,  $\alpha_2 = -2.78$ , and energy break = 1.33 GeV. The source could be detected with CTAO-S at  $8.14\sigma$  with 50 h of observation.

As for PSR J1023 + 0038, we interpret the non convergence of the log-parabola model as caused by the fact that the flux inferred from the fit falls marginally below the CTAO sensitivity curve for 200 h.

Our simulations prove that the detection of the spectral component seen by *Fermi*-LAT from of close-by tMSPs when in a disk state could be possible with long exposures, provided that the emission has no cut-off at few GeVs. While this will likely not allow to catch fully a transition if lasting less than several days, here we demonstrate that once a transition has occurred CTAO could be able to detect such type of sources, identifying tMSPs as VHE emitters for the first time. While during the rotation-powered state MSP binaries will not be at the reach of CTAO, the known tMSPs have demonstrated an increase of their HE flux by a factor of 3–10 when transitioning from the radio to the disk states (see Torres et al. 2017). The possibility to lookback in the CTAO Galactic plane and other higher latitude pointings, where many MSP binaries are located, will be crucial for assessing any possibly related VHE flux increase or for complementing the X-rays and lower energy coverage in case only ULs are obtained. Also, if there are additional components (not considered here, such as magnetic reconnection of pulsar wind) it could be possible to detect changes in the VHE flux along transitions.

#### 4.4 Flares in PWN: the Crab Nebula

The Crab Nebula is the best-studied PWN in the VHE regime. It is located at a distance of  $\approx 2.2$  kpc with  $\approx 3.8$  pc of size (Trimble 1973; Davidson & Fesen 1985). Since 2009, several rapid and bright

flares have been detected from the nebula at HE with space-borne gamma-ray instruments (Tavani et al. 2011; Abdo et al. 2011; Buehler et al. 2012; Mayer et al. 2013; Striani et al. 2013; Arakawa et al. 2020). The observed flares presented variability time-scales of hours. During these flaring periods, the nebula showed rapid variations of flux and large releases of energy (Tavani et al. 2011; Abdo et al. 2011). Several multiwavelength campaigns involving *Chandra* X-Ray Observatory, Keck Observatory, and Very Large Array (VLA, Weisskopf et al. 2013) and TeV searches by IACTs (Mariotti 2010; Ong 2010; H. E. S. S. Collaboration 2014; Aliu et al. 2014a; van Scherpenberg et al. 2019) were carried out to follow these flares. However, none of them reported a correlation of the flares with morphological and/or spectral variations in the nebula.

CTAO will cover a fundamental energy range to understand the origin of these flares: on the one hand, the low-energy threshold will allow the sampling of the *Fermi*-LAT spectral shape at few tens of GeV of synchrotron nature, providing important clues on the acceleration and emission processes; on the other hand, the excellent sensitivity in the TeV regime will serve to explore the IC component that might arise at a detectable level from the electron population behind the MeV flares, off-scattering soft photon fields.

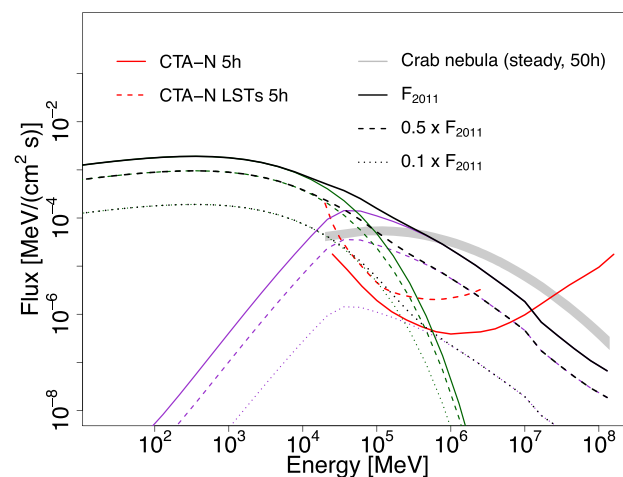
To evaluate the capability of CTAO to detect Crab flares, we performed simulations of the SEDs both in flaring and steady (non-flaring) states of the nebula. We simulated flares of different spectral characteristics starting from a parent particle population, varying the physical properties of the environment. In particular, we simulated three types of flares: a very bright flare with a similar flux (at hundreds of MeV) to the one observed by *Fermi*-LAT in 2011 April (Buehler et al. 2012; Striani et al. 2013), which is the flare with the largest flux to date, and two dimmer flares corresponding to the first one rescaled by a factor of 0.5 and 0.1. Thus, the corresponding flux enhancement at the simulated flares' peaks (above 100 MeV of energy) ranges from 3 to 30 times the average flux of the nebula, as observed in tens of flares detected since 2007 (Huang, Yuan & Fan 2021). Since no spectral variability has been reported at HE, we assume the same spectral model for these dimmer flares.

The simulations of the nebula in flaring and steady states are performed for the CTAO-N with the methods and tools presented in previous works (Mestre et al. 2020, 2021). Mestre et al. (2021) pointed to the crucial role of the LSTs, best sensitive at the sub-TeV energy regime, in the prospects for the Crab flares' detection (even in the early stages of CTAO-N operations). The latter, however, cast doubts on CTAO-S prospects due to the lack of LSTs in the Alpha configuration. The electron population was simulated with a fixed index ( $\Gamma_e$ ) of 2.5, to guarantee the detection in the TeV regime (e.g. from 1.25 to 50 TeV) of the brightest model of flare in less than 10 h at 95 per cent confidence level (see fig. 6 of Mestre et al. 2021). The different flare models are computed for a magnetic field ( $B$ ) in the acceleration region ranging from 100  $\mu\text{G}$  to 1 mG and compared (see section 2 of Mestre et al. 2021) to the steady nebula SED in both tens of GeV (e.g. from 20 to 200 GeV) and TeV regimes. We obtained the simulations of the Crab nebula SED in steady state from Mestre et al. (2020). To compare the flaring and steady nebula simulations, we computed the mean total expected excess (e.g. counts from the source after background subtraction), both in flaring and steady state, in 21 bins of energy from 12 GeV to 200 TeV with observation times ranging from a few minutes to 500 h. We compared the excess distributions using the Pearson's chi-squared test, corresponding the null hypothesis ( $H_0$ ) to the steady state. Then, we consider the flare implies a detectable flux level if  $H_0$  is rejected at  $3\sigma$  significance (see Table 7; values in parentheses correspond to  $5\sigma$  confidence).

**Table 7.** In the second, third, and fourth columns, the observation time (in hours) necessary to detect different models of flares from 1.25 to 50 TeV with CTAO-N at  $3\sigma$  ( $5\sigma$ ) significance.

Model B [ $\mu\text{G}$ ]	Model SED		
	$F_{2011}$	$0.5 \times F_{2011}$	$0.1 \times F_{2011}$
1000	22 (46)	351* (> 500)	> 500*
500	0.8 (1.6)	14* (31)	> 500*
100	0.03 (0.05)	0.13 (0.24)	68* (133)

*Notes.* The first column indicates the magnetic field chosen for the acceleration region. The observation times in the second column are computed for flare models fitted to the *Fermi*-LAT SED (at the moment of maximum flux level) of the 2011 April flare. For the third and fourth columns, the LAT SED (dubbed  $F_{2011}$ ) was rescaled prior to the fit by a factor of 0.5 and 0.1, respectively. The models with an asterisk imply an energy in electrons above 1 TeV larger than  $5 \times 10^{43}$  erg. We assume Crab is in flaring state during the entire observation time.



**Figure 22.** The synchrotron (green lines), IC (purple lines), and total (black lines) emission from the Crab Nebula for different flare models. The solid lines correspond to the model fitted to the *Fermi*-LAT 2011 April flare data at energies above 80 MeV for a particle index of 2.5. The dashed and dotted lines correspond to the same model rescaled by a factor of 0.5 and 0.1, respectively. All the models are computed for a magnetic field of 500  $\mu\text{G}$ . The red solid and dashed lines correspond to the sensitivities of the CTAO-N and, if considering only its four LSTs for 5 h of integration time, respectively. The Crab Nebula steady spectrum simulations for 50 h of observation time with CTAO-N are noted with the grey shaded area ( $3\sigma$  region).

The simulations performed show that the different models of flare are best detected in the GeV regime and in particular in less than an hour at energies below 200 GeV, see Fig. 22. In the TeV regime, flares dimmer than 2011 April flare by a factor 0.5 (at hundreds of MeV) would be detected in less than 10 h for  $B < 500 \mu\text{G}$  (see Table 7). As a reference, the gamma-ray flares from the Crab detected with *Fermi*-LAT showed varied duration scales from a few days to weeks and complex substructures, with subflares of a few hours or day-long duration (Huang et al. 2021). Some of the models considered imply an energy in TeV electrons larger than  $\tau_{\text{syn}} \times L_{\gamma} \approx 5 \times 10^{43}$  erg, being  $\tau_{\text{syn}}$  the synchrotron cooling time, and  $L_{\gamma} \sim 2 \times 10^{35}$  erg  $\text{s}^{-1}$ , the luminosity of the nebula in gamma rays (Rudak & Dyks 1998). However, note that the energy in electrons available in the nebula is not limited to the one computed above if particle re-acceleration takes place, which would introduce additional boosts in the electron

population energy reservoir. The simulations performed, together with previous results reported (see Mestre et al. 2021), provide excellent prospects for detecting flares from the Crab Nebula with CTAO, especially for the LST subarray, featuring the best sensitivity at energies of a few tens of GeV.

#### 4.5 Novae

The only nova that has been detected at TeV energies so far is the symbiotic system RS Oph (Acciari et al. 2022; H. E. S. S. Collaboration 2022; Abe et al. 2025) which shows recurrent outburst every 15–20 yr and harbours a white dwarf accreting from a late-type giant companion star. However, it could be argued that the detection is due to selection effects based on the fact that RS Oph is relatively nearby (see below). By number, novae that involve a small, low-mass donor such as a main-sequence star (these are usually the classical novae, see Chomiuk et al. 2021) are by far the most common type of system. The majority of novae have been observed in outburst only once in a human life time-scale, and so far only a handful of novae are known to erupt with a recurrence time of  $\sim$  tens of years. It has been predicted from binary population synthesis studies (Kemp et al. 2021, 2022) that most commonly, novae with evolved donors are more likely to contribute to the total current Galactic nova rate, even though by number these systems make up a smaller fraction of nova binaries.

As pointed out recently by De et al. (2021), a large number of novae in optical bands might be being missed due to a number of sources residing behind and in the Galactic bulge. Taking obscuration by dust into account, De et al. (2021) estimated a current Galactic nova rate of  $43.7 \pm_{8.7}^{19.5} \text{ yr}^{-1}$ . This is notably much larger than the actual Galactic nova detection rate of  $\lesssim 10 \text{ yr}^{-1}$ .

Kemp et al. (2022) estimated the Galactic nova rate to be  $33 \text{ yr}^{-1}$ . That study showed that the most common type of nova in our Galaxy today is expected to originate from a binary system involving a giant-like donor (see fig. 11 in the aforementioned paper as a guide). As mentioned previously, currently the only system to have clearly been detected at VHE (and detected also at HE) is the symbiotic recurrent nova RS Oph. Though some groups have investigated detailed modelling of shock generation in nova systems (Metzger et al. 2016; Hachisu & Kato 2022), which is believed to be mainly hadronic in nature, it is still not clear how many Galactic novae would be detectable by CTAO at and beyond the  $\sim$ TeV energy range. The majority of novae thus far detected at GeV energies with no clear evidence for a TeV component have been classical novae (not symbiotic systems like RS Oph, see e.g. Zheng et al. 2022). None the less, we anticipate several more novae could be observed with CTAO (see Chomiuk et al. 2021), particularly if these novae are detected at other wavelengths early on enabling rapid triggering and follow-up. However, assuming we can expect of the order of  $\sim 30$  Galactic novae per year, even with adequate triggering, it is unlikely that all of these outbursts will be detectable by CTAO. If CTAO-N would have been operational since 2008 August to 2023 April, it would have been able to perform observations of seven novae detected in HE gamma-ray by *Fermi*-LAT, in the five nights after their detection in optical. Assuming a similar rate of novae detected at HE gamma-ray in the future, it means that CTAO-N would observe  $\sim 0.5$  novae per year triggered by their HE gamma-ray emission.

CTAO observations will be important to put constraints on the maximum energies attainable in nova explosions and the physical mechanisms involved in the production of VHE gamma-rays. We estimated the capability of CTAO to detect nova outbursts based on

both theoretical modelling and empirical results. First, simple theoretical considerations based on the RS Oph detection are adopted to assess the gamma-ray emission at different outburst stages, following the approach in Acciari et al. (2022) and H. E. S. S. Collaboration (2022). Second, a parametric study based on phenomenological parameters involved in the emission of gamma rays in nova outbursts is performed to estimate the parameter space we could constrain with CTAO observations. Finally, we considered dedicated numerical simulations of RS Oph to assess the expected detectability with CTAO.

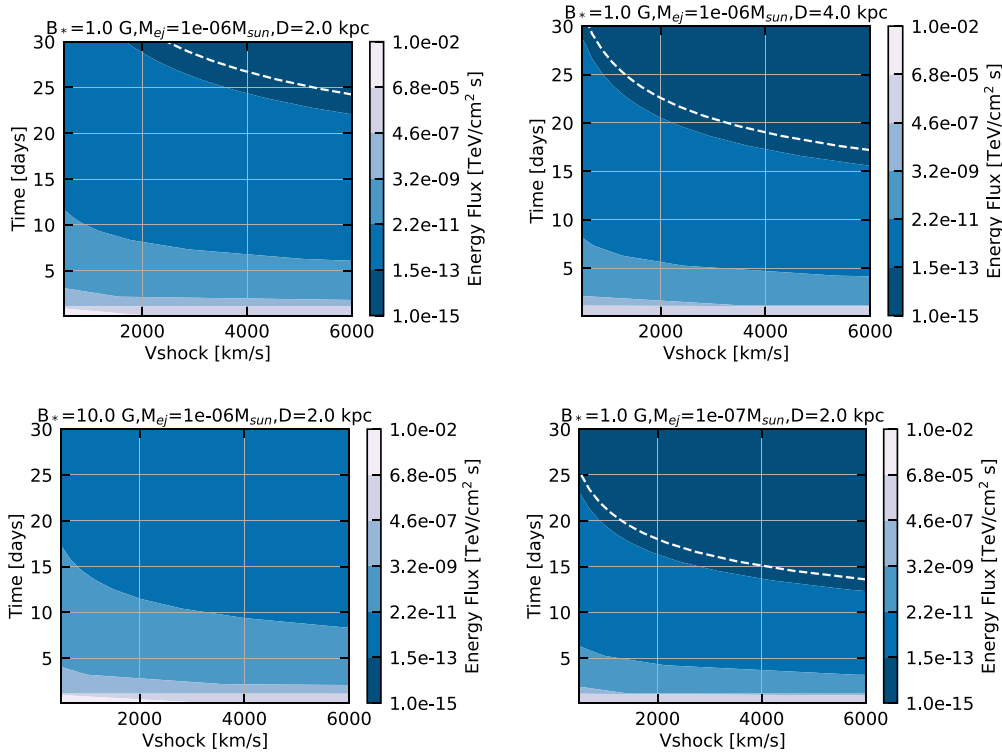
##### 4.5.1 Modelling approach

We explored the capability of CTAO to constrain the physical parameters of nova phenomena of different types, building up from basic arguments. The expected gamma-ray emission is obtained for different properties of a shock expanding with velocity  $v_{\text{sh}}(t)$ , generated by ejected material of total mass  $M_{\text{ej}}(t)$  slamming into the companion star’s wind and producing gamma rays through hadronic interactions. To accelerate protons to HEs via diffusive shock acceleration (DSA), the magnetic field has to be amplified in the shock. The maximum energy particles attain at a shock is limited ultimately by the Hillas (1984) condition. However, a more constraining limit is determined by either the time taken before radiative cooling dominates over acceleration, or by the necessary escape of the particles upstream of the shock, in order to excite magnetic field fluctuations to a sufficient level ahead of the shock (Bell 2004). The maximum energy  $E_{\text{max}}$  in the particle spectrum, defined as as power-law function with an exponential cut-off, can be then described as:

$$E_{\text{max}} = 10 \left( \frac{v_{\text{sh}}}{5000 \text{ km s}^{-1}} \right) \left( \frac{R_{\text{sh}}}{1 \text{ au}} \right)^{-1} \left( \frac{B_*}{1 \text{ G}} \right) \text{ TeV}, \quad (2)$$

with  $R_{\text{sh}}$  the position of the shock with respect to the white dwarf, and  $B_*$  the companion surface magnetic field (typically  $\sim 1 \text{ G}$  for a red giant).  $R_{\text{sh}}$  can be expressed in terms of shock velocity, for which we assumed free expansion during the first few days, followed by radiative expansion when entering the Sedov–Taylor phase (Bode & Kahn 1985). The particle flux per unit of time and energy is computed using the condition that a fixed fraction (50 per cent) of the kinetic energy of the protons ( $E_{\text{kin}} = \frac{1}{2} M_{\text{ej}} v_{\text{sh}}^2$ ) is transferred to non-thermal particles (Acciari et al. 2022; H. E. S. S. Collaboration 2022). Once the particle spectrum is defined as function of these three parameters ( $v_{\text{sh}}$ ,  $B_*$ , and  $M_{\text{ej}}$ ) at different evolutionary stages of the shock expansion, we derive the gamma-ray emission originated by proton–proton interaction assuming a density of the ejecta which can be approximated following equation (4) in Acciari et al. (2022). The particle spectrum and density was used to compute the non-thermal emission, using the *Naima* spectral model class (Zabalza 2015) included in *GAMMAPY*.

In Fig. 23, we show the expected gamma-ray flux at different times from the nova explosion, considering several physical parameters in the shock. The upper panels show the expected emission for a explosion similar to RS Oph, with  $B_*$  and  $M_{\text{ej}}$  equal to  $1 \text{ G}$  and  $10^{-6} M_{\odot}$ , respectively, located at a distance of 2 kpc (left) and of 4 kpc (right). The effect of increasing the star surface magnetic field (10 G) and decreasing the ejecta mass ( $10^{-7} M_{\odot}$ ) is shown in the bottom panels, for a fixed distance of 2 kpc. For reference, the isoflux line at  $10^{-13} \text{ TeV cm}^{-2} \text{ s}^{-1}$  is marked when possible with a white line. The region below such line should be easily accessible to CTAO.



**Figure 23.** Expected energy flux in gamma rays with time after nova explosion as a function of shock velocity, integrated above 10 GeV. Top left: for an RS Oph-like system at 2 kpc. Top right: for the same physical properties yet at a larger distance of 4 kpc. Bottom left: with increased magnetic field strength. Bottom right: with decreased mass-loss rate. In all plots, the white dashed line indicates the CTAO isoflux line at  $10^{-13} \text{ TeV cm}^{-2} \text{ s}^{-1}$ . Below this line, the region should be easily accessible to CTAO.

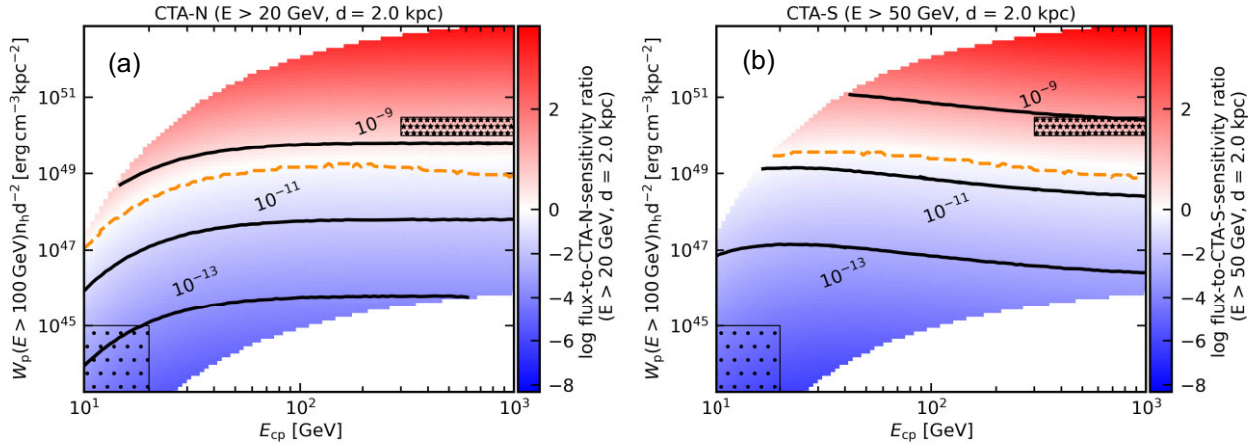
#### 4.5.2 Parametric space study

We utilized a phenomenological approach to study the parameter space of gamma-ray emission from novae. The emission was assumed to be produced by hadronic processes from  $\pi^0$  decay (Kafexhiu et al. 2014), as indicated by the gamma-ray emission of RS Oph (see Section 4.5.3). The  $\pi^0$  decay radiative model was parametrized using the target proton density ( $n_h$ ) and the relativistic proton energy distribution. For the latter, we considered a particle distribution function parametrized as a power-law model with an exponential cut-off. We described the parameter space under study as a 3D space, where we set the parameter space domain in the range of plausible values based on observed novae at gamma rays. A 2D grid was defined with different values for the prefactor ( $A$ ) and the cut-off energy ( $E_{cp}$ ) of the proton energy distribution. The former in the range between  $A = [10^{28}, 10^{32}]$  protons  $\text{eV}^{-1}$  at a pivot energy of 100 GeV and the latter between  $E_{cp} = [10, 1000]$  GeV. Two slices for the target proton density were used for the third axis,  $n_h = 10^8$  and  $10^{11} \text{ cm}^{-3}$ , which correspond to typical shock density values in novae (Metzger et al. 2016). The distance to the gamma-ray emitter was fixed to  $d = 2 \text{ kpc}$ . The SED for each model was obtained using the software package *Naïma* (Zabalza 2015).

The emission detectability was assessed for both arrays of CTAO using the official IRFs from `prod5-v0.1` in the Alpha configuration (20deg-AverageAz for 5 h observation time). The results of the simulations for CTAO-N and CTAO-S are shown in panels (a) and (b) of Fig. 24, respectively. The total proton energy above 100 GeV ( $W_p$ ) multiplied by  $\frac{n_h}{q^2}$ , hereafter ‘effective proton energy reservoir’, was used as a function of  $E_{cp}$  to display the ratio between the integral

source flux and the CTAO sensitivity. This ratio was computed to obtain a qualitative estimation of the detectability of CTAO for each model in the parameter space. The higher the integral flux-to-CTAO-sensitivity ratio, the more feasible the detection. Moreover, the region where we would detect each model with CTAO in at least one energy bin is lower delimited in Fig. 24 by a dashed orange line to have a more precise boundary of the detection region. Therefore, the region between the dashed orange line and the white region (integral flux-to-CTAO-sensitivity close to 0) delimits the border of the parameter space where CTAO will likely begin to detect the gamma-ray emission of the models. Qualitatively, RS Oph would be located approximately in the top-right corner of Fig. 24, while V959 Mon (the first classical nova discovered by *Fermi*-LAT; Ackermann et al. 2014) would be in the lower left region of the plots.

The integral gamma-ray emission and the integral flux-to-CTAO-sensitivity ratio in Fig. 24 increases as the effective proton energy reservoir and  $E_{cp}$  increase. Both top regions of plots (a) and (b) in Fig. 24 have positive values of integral flux-to-CTAO-sensitivity ratio (about 30 per cent of the total combinations), while the bottom region do not (about 70 per cent of the total combinations). When comparing the results between CTAO-N and CTAO-S, the former extends the parameter space region with positive integral flux-to-CTAO-sensitivity towards models with  $E_{cp} < 250 \text{ GeV}$ . On the other hand, the latter presents a wider detection region towards  $E_{cp} > 250 \text{ GeV}$  than CTAO-N. CTAO-N overperforms CTAO-S with about 10 per cent more detections. The better performance of CTAO-N at low energies is expected because the parameter space under study was restricted to produce most of the gamma-ray emission below 1 TeV



**Figure 24.** Logarithmic integral flux-to-CTAO-sensitivity ratio for CTAO-N (panel a), integrated above 20 GeV and CTAO-S (panel b), integrated above 50 GeV for different values in the defined parameter space (see the text) of  $n_h$ , cut-off energy ( $E_{cp}$ ) and prefactor ( $A$ ) of the proton energy distribution function at a fixed distance of  $d = 2.0$  kpc. The sensitivity was computed for a total observation time of 5 h. The orange dashed line indicates the domain in the parameter space with detection in at least one energy bin for different values of  $n_h$ ,  $E_{cp}$ , and  $A$ . Solid black lines are curves at constant integrated flux ( $10^{-13}$ ,  $10^{-11}$ , and  $10^{-9}$   $\text{cm}^{-2}\text{s}^{-1}$ ) above 20 and 50 GeV for CTAO-N and CTAO-S panels, respectively. The regions where V959 Mon and RS Oph would be approximately located in the parameter space are marked with black dots and stars, respectively.

and it is also connected with the presence of four LSTs in the CTAO-N Alpha configuration, as it is observed from current novae detected at gamma rays. Therefore, the lack of LSTs, which dominates the CTAO sensitivity at these energies (Cherenkov Telescope Array Consortium et al. 2019), in the Southern array (Alpha configuration) will reduce the parameter space of detectability with CTAO-S.

Thus, CTAO is expected to give strong constraints only to a subspace of the whole parameter space under study. For about 30 per cent of the area of the parameter space covered in Fig. 24 could be likely detected with CTAO, in particular, where the relativistic protons have a high value of prefactor and cut-off energy. Assuming that the target proton number density is the number density of the main ejection of matter in the outburst, the results suggest that for denser ejecta, the detection region with CTAO will cover a wide range of parameter values of the relativistic proton energy distribution. CTAO-N should outperform CTAO-S for novae with  $E_{cp} < 250$  GeV, while for  $E_{cp} > 250$  GeV, CTAO-S should perform better than CTAO-N at HEs.

#### 4.5.3 RS Oph

RS Oph is a symbiotic nova formed by a high-mass white dwarf ( $1.2 - 1.4 M_{\odot}$ ) and a red giant star (M0 III, Anupama & Mikolajewska 1999), which transfers material to the compact object. In the literature, its distance has been estimated ranging from 1 to 5 kpc (Barry et al. 2008, see also the discussion about the distance estimation in section C.1 of the supplementary material of Acciari et al. 2022), being the most recent value of about  $2.68 \pm 0.16$  kpc from *Gaia* DR3 catalogue (Gaia Collaboration 2020) RS Oph undergoes recurrent nova outbursts with a periodicity of about 15 yr. Its last eruption occurred in 2021 August. Covered widely at different wavelengths, the 2021 outburst was detected at VHE gamma-rays, adding a new object class to the list of VHE emitters. The HE and VHE gamma-ray emission was consistent mainly with a hadronic origin (dominated by  $\pi^0$  decay), likely originated by the interaction of the ejected material with the dense wind of the red giant (Acciari et al. 2022; H. E. S. S. Collaboration 2022). The gamma-ray spectrum

showed hints of hardening with time produced by the migration of gamma rays to higher energies (Acciari et al. 2022). The HE lightcurve presented a power-law decay after reaching the maximum emission phase. The index of the temporal decay at HE with *Fermi*-LAT and the one obtained at VHE by the H.E.S.S. Collaboration were compatible within errors with values  $1.35 \pm 0.07$  and  $1.43 \pm 0.18$ , respectively (Cheung et al. 2022; H. E. S. S. Collaboration 2022). It is expected that RS Oph will undergo another outburst when CTAO will be in operation. Hence, we carried out numerical simulations of RS Oph to estimate its detectability with CTAO along the temporal evolution of the outburst.

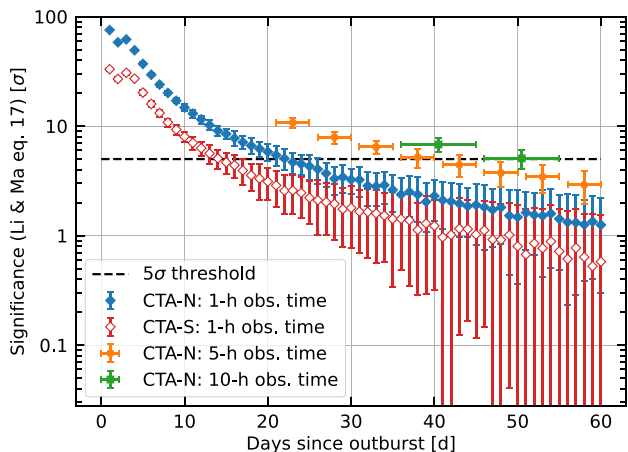
#### 4.5.4 RS Oph: CTAO simulations

We performed the numerical simulations of RS Oph with CTAO using the official IRFs from `prod5-v0.1` for the CTAO northern and southern arrays. In particular, the closest IRFs set to the culmination of RS Oph in the CTAO-N and CTAO-S site were used (North-40deg-SouthAz and South-20deg-NorthAz) for 0.5 h observation time. A total of 59 daily observations of 1 h each were simulated starting one day after the beginning of the nova outburst (batches of 100 simulations per day). We simulated this source based on the gamma-ray spectral and temporal profile reported by the MAGIC and H.E.S.S. Collaborations, respectively. The best daily-fit spectral log-parabola models from Acciari et al. (2022) were considered to model the gamma-ray emission. Spectral variations were only contemplated for the simulations of the first four days, when spectral information in Acciari et al. (2022) was available during the outburst. The spectral parameter values utilized in the different log-parabola models are shown in Table 8. After the fourth day, the spectral profile was fixed to the one from the last day with spectral information (fourth day), and the simulated gamma-ray emission was scaled to follow the power-law temporal decay reported by H.E.S.S. We set the index value of the power-law decay to  $\gamma = 1.4$ .

The statistical detection significance as a function of time is shown in Fig. 25. The results confirm that RS Oph would be clearly detected

**Table 8.** Daily parameter values of the log-parabola spectral models used to simulate RS Oph. Adapted from Acciari et al. (2022).

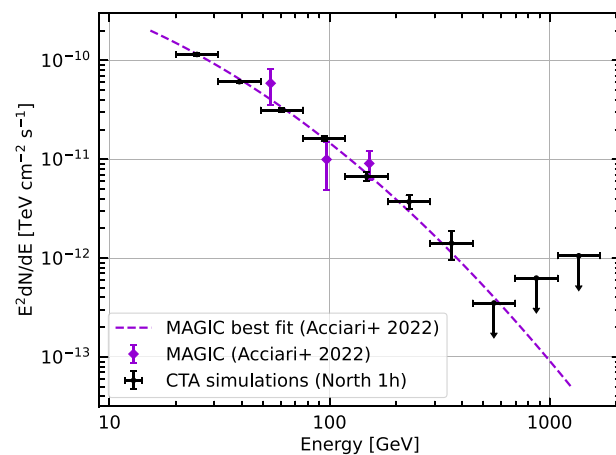
Model day	Prefactor at 130 GeV [ $10^{-10} \text{ TeV}^{-1} \text{ cm}^{-2} \text{ s}^{-1}$ ]	$\alpha$	$\beta$
Day 1	5.40	3.86	0.194
Day 2	4.54	3.73	0.175
Day 3	5.37	3.64	0.173
Day 4 – 59	5.00	3.44	0.147



**Figure 25.** Daily statistical detection significance (equation 17 of Li & Ma 1983) from 1-h simulated observation with CTAO-N and CTAO-S (blue filled diamonds and red empty diamonds, respectively) as a function of the number of days since the outburst of RS Oph. The 5-d (i.e. 5-h observation time, filled orange circles) and 10-d (i.e. 10-h observation time, filled green squares) combined significance for CTAO-N are computed when the daily and 5-d statistical detection significance reach a  $5\sigma$  detection (dashed black line), respectively. Error bars correspond to the standard deviation of the statistical detection significance distribution for the 100 simulations per day.

with CTAO-N and CTAO-S for the first days, reaching a detection significance of about  $60\sigma$  and  $30\sigma$  in an hour with CTAO-N and CTAO-S, respectively. RS Oph is not only detectable with CTAO during the first days after the outburst, but CTAO would also daily detect RS Oph up to 20 and 15 d after the outburst with the northern and southern arrays, respectively. If we consider the combined data of 5 and 10 adjacent days with CTAO-N, the detection would be possible even up to 36 – 40 and 46 – 55 d, respectively. The  $5\sigma$  detection would be limited down to 23 – 27 and 38 – 47 d with CTAO-S. The resulting SED for the first simulated observation (day 1 after the outburst) is shown in Fig. 26 together with the observed spectrum obtained with MAGIC for the same observation time. The results suggest that CTAO will be able to probe the gamma-ray emission for several weeks after the outburst with a precise spectral coverage at least during the first days. Using 1-h observation, CTAO would be able to characterize the curvature of the VHE gamma-ray emission of RS Oph. For example, for the simulated observation of day 1, a log-parabola spectral model is preferred over a power-law model at  $3.7\sigma$ .

Consequently, if one assumes that the next RS Oph outburst follows the same behaviour as the 2021 eruption, a plausible assumption based on the similarities observed at radio, optical and X-ray for the first weeks between 2006 and 2021 outbursts (Munari et al. 2022; Acciari et al. 2022; Page et al. 2022), CTAO observations



**Figure 26.** VHE  $\gamma$ -ray SED of RS Oph after 1 d since the outburst. The best-fitting model from Acciari et al. (2022) using MAGIC and *Fermi*-LAT for the first night of observation is used (purple dashed line) to simulate the source with CTAO. The CTAO-N flux points for a 1-h observation time are shown (black points). Also, the MAGIC flux points (computed using 1-h observation time of data after cuts) from Acciari et al. (2022) are displayed (purple diamonds).

can provide detailed coverage of the gamma-ray emission during the future RS Oph outburst. Also, we could probe the maximum energy of the accelerated particles and the nova physical conditions across different outburst stages.

#### 4.5.5 Other novae

To date, RS Oph is the only recurrent nova system from which gamma-ray emission at TeV energies has been detected during outburst. Nevertheless, several other recurrent novae, in particular symbiotic binary systems with high mass-transfer rates and dense winds, are also promising potential gamma-ray emitters. T Coronae Borealis in particular is a nearby symbiotic binary system, located closer to Earth than RS Oph, from which two prior outbursts have been observed in optical wavelengths (Schaefer 2023). Models predict that the next outburst will occur in  $2024.4 \pm 0.3$  yr (Schaefer et al. 2023) and, if a shock evolution comparable to RS Oph can be assumed, particle acceleration and detectable VHE gamma-ray emission is highly expected. Other novae that are expected to plausibly occur over the lifetime of CTAO are the recurrent novae V394 Coronae Australis, CI Aquilae or V3890 Sgr and possible superflares arising from V2487 Oph (Schaefer 2019; Schaefer, Pagnotta & Zoppelt 2022).

Recurrent novae – those from which more than a single outburst has been observed – tend to be associated with symbiotic binary systems due to their high mass-transfer rate. This also renders them good candidates for particle acceleration to VHEs. Although MeV to GeV emission has been detected from classical novae by *Fermi*-LAT, the extension of their SEDs into the energy range detectable by IACTs is not expected a priori. Only continued observations of a range of novae during outburst with different physical properties will provide further insights into particle acceleration occurring in these systems.

#### 4.6 Magnetars: discussion

On 2020 April 15, the *Fermi*-GBM (Gamma-ray Burst Monitor) and the *Fermi*-LAT instruments detected MeV and GeV gamma-ray emission from a giant flare event of a magnetar located in the NGC 253 galaxy (Roberts et al. 2021; Fermi-LAT Collaboration 2021). The first time detection of GeV emission from a giant magnetar flare is particularly interesting, with the detection of two photons with energies 1.3 and 1.7 GeV. According to Fermi-LAT Collaboration (2021), these two GeV photons are produced via synchrotron emission considering the presence of a strong magnetic field which is generated in the shocks. It is proposed that these GeV photons are produced in the dissipation associated with the collision of the giant flare outflow and the external shell generated from swept-up material. This indicates that non-thermal processes accelerating particles at HEs are at work. IC scattering can also occur in these events, and giant magnetar flares have been proposed as potential GeV–TeV emitters. TeV emission on millisecond time-scales could be produced during giant flare events, which might be luminous enough to be detectable by IACTs (Lyubarsky 2014; Murase, Kashiyama & Mészáros 2016), including CTAO. This TeV emission could be produced via synchrotron maser mechanism, triggered by strong magnetic disturbances from the magnetosphere and propagating outwards, until they dissipate by interacting with the ambient nebula. In the case of dissipation of disturbances within the magnetar wind, a non-thermal tail can plausibly arise, potentially leading to the production of VHE gamma-ray emission (Metzger, Fang & Margalit 2020).

Magnetars are also relevant for their possible connection with other transient sources, such as, e.g. GRBs, super luminous supernovae, and fast radio bursts (FRB).

The association of a burst from the Galactic magnetar SGR 1935+2153 with an extremely bright FRB-like radio pulse on 2020 April 28 led to the first unequivocal association between FRBs and magnetars (CHIME/FRB Collaboration 2020; Bochenek et al. 2020; Mereghetti et al. 2020; Tavani et al. 2021). The radio flare showed a double-peak structure, pattern also detected at X rays. The X-ray burst was of intermediate energetics, significantly too faint to be classified as a giant flare. However, even if the X-ray emission was not particularly energetic, this burst showed a harder spectra with respect to the typical bursts from SGR 1935+2154 and other magnetars.

Comparing the peak emission of the 2020 April 28 burst (Mereghetti et al. 2020), which reached a value of 50 photons  $\text{cm}^{-2}\text{s}^{-1}$  (in the 15–50 keV band) to other energetic transient events, such as GRB 190114C (MAGIC Collaboration 2019), we see that the X-ray energetics are compatible with those of the second X-ray peak. Current IACTs such as H.E.S.S. (Abdalla et al. 2021) and MAGIC (López-Oramas et al. 2021) have led campaigns to search for a VHE component in SGR 1935+2154. Abdalla et al. (2021) observed the source 2 h prior the CHIME and STARE2 flare and then simultaneously to different X-ray flares. No VHE emission was detected and an UL at  $E > 600$  GeV of  $2.4 \times 10^{-12}$  erg  $\text{cm}^{-2} \text{s}^{-1}$  was established. Similarly, the MAGIC multiwavelength monitoring campaign (López-Oramas et al. 2021) did not find any significant signal, even though some X-ray flares were present during the monitoring campaign. On October 8, The Canadian Hydrogen Intensity Mapping Experiment (CHIME) detected three more millisecond events (Good & CHIME/FRB Collaboration 2020) from SGR 1935+2154 (with no X-ray counterpart reported), which were confirmed by FAST on October 9 (Zhu et al. 2020). The radio fluence of these event was lower than that of 2020 April. During

simultaneous observations by *Swift* and MAGIC on October 9, a forest of bursts was detected in the hard X-ray range, but no TeV emission was revealed (López-Oramas et al. 2021). The H.E.S.S. and MAGIC observations set constraints to the persistent emission in SGR1935 + 2154 and to the bursting emission. However, depending on the emission region in the magnetar and the interaction with the surrounding nebula (existing in the case of SGR 1935+2154), future detection of VHE bursts is still plausible.

The new radio facilities that will operate at the time of CTAO will provide the detection of up to hundreds of FRB per day. Many of these will have good localizations and will be inside the CTAO field of view, making it possible to search for prompt and/or delayed VHE emission. Although no magnetar outburst has been yet detected at TeV, the existence of MeV and GeV emission maintains the expectations of a possible TeV component, making magnetars good source candidates for CTAO. The CTAO Observatory should aim at observing magnetar flares as soon as possible, triggering on external alerts. Automatic re-pointing of the telescopes can take place whenever certain observational criteria (such as i.e. flare type, brightness, multiwavelength counterparts, or distance) are fulfilled. The high sensitivity of CTAO at short time-scales while provide new insights onto the physics of magnetars at VHE.

## 5 SYNERGIES WITH LARGE ASTRONOMICAL FACILITIES

Simultaneous coordinated observations with telescopes and facilities at different wavelengths are crucial for understanding the processes and mechanisms at work in the sources of our interest (see Cherenkov Telescope Array Consortium et al. 2019 for a detailed review). Coordination, response to real-time alerts and target-of-opportunity (ToOs) are key in time-domain astrophysics when observing transient events. In the case of Galactic transients, external alerts can trigger ToO observations by CTAO of new Galactic events or renewed activity of known sources. The trigger criteria is dependent on the type of source observed, with different time urgency and duration varying in terms of the evolution of the specific phenomena. Regarding the observational strategy, a first description on the triggering criteria, expected trigger rate and target priority is already provided in Cherenkov Telescope Array Consortium et al. (2019). Updated strategies for multiwavelength follow-up and needs are already being collected and discussed in a dedicated operations requirement document,<sup>9</sup> where different studies for the planning and optimization of the CTAO follow-up programme are being conducted.

For a prompt reaction and fast reposition, CTAO will need to manage external and internal scientific alerts, for which a transient handler subsystem is under development (Egberts et al. 2022). The LST-1 transient handler is already operational and has allowed the follow-up of different transient alerts (Carosi et al. 2021). Furthermore, a real-time analysis will be performed by CTAO via the Science Alert Generation system with the goal of issuing science alerts of transient phenomena to the community with a latency of about 20 s (Bulgarelli et al. 2024), increasing the synergies of CTAO with the astronomical community.

The radio band is of general interest for providing information of the non-thermal processes, and radio facilities are key for locating acceleration sites and shocks and to provide feedback on fast events such as magnetar flares or stellar flares. For that purpose, CTAO

<sup>9</sup>In preparation

will need an external trigger from a radio observatory sensitive to (millisecond) bursts and capable of issuing prompt alerts. Current generation of telescopes such as CHIME, with a large field of view and collecting area, have proven their efficiency for detecting these alerts (CHIME/FRB Collaboration 2020). An example of clear synergies are those with the MeerTRAP project to follow-up fast radio signals (Rajwade et al. 2020; Bezuidenhout et al. 2022).

In the optical and infrared domain prompt reaction would be facilitated by coordinating with external observatories within time zones close to those of CTAO sites. In the case of CTAO-N, it should be pursuing synergies mainly with La Palma, Tenerife (and CAHA) telescopes in Spain, while in the CTAO-S, the most appropriate choice would be the different ESO telescopes and other large facilities in Chile, such as the Rubin Observatory Legacy Survey of Space and Time, which will be key for time-domain astronomy (see Hambleton et al. 2023). The availability of imaging and spectroscopic instrumentation in both hemispheres does largely fulfill the observational needs required for coordinated campaigns. Specific ToO proposals could be eventually placed by the CTAO community. In parallel, small optical telescopes either on-site or operated by nearby CTAO institutions could also play a key role in this effort if the targets are bright enough as in the case of novae or gamma-ray binaries. This could serve to mitigate the often high-time pressure on large telescopes. Additionally, support optical telescopes would ensure a fast follow-up on transients and would provide sufficient coverage in the case of bright sources.

Space missions will allow to study the X-ray domain with improved capabilities. The Space Variable Objects Monitor [4–150 keV range] has been recently launched and although its core science is focused in GRB detection, it has the capabilities for detecting i.e. thermonuclear explosions and outbursts of Galactic origin due to the sensitivity of the ECLAIRS (50 mCrab per orbit) telescope (Wei et al. 2016). Synergies with future instruments such as the Advanced Telescope for High-ENergy Astrophysics [0.2–12 keV] (Barcons et al. 2017), scheduled for launch in mid 2030s contemporaneous to the CTAO era, are also expected.

The HE band ( $E > 100$  MeV) is currently explored by the *Fermi*-LAT satellite (Atwood et al. 2009). Triggers from *Fermi*-LAT have been important for the detection of Galactic transients such as novae in the VHE domain. Simultaneous MeV–GeV information is also important to disentangle between hadronic and leptonic processes. If *Fermi* lifetime extends through (at least partially) CTAO lifetime, it will provide the needed coverage and alerts to certain observations/triggers. Just recently, the AGILE satellite, that also operated in this energy range, ceased its operations and re-entered the atmosphere (Tavani, Addis & Argan 2024). For the moment, there is no obvious successor to *Fermi* or AGILE in the same energy domain, although some missions could take over. A successor will be crucial to fully exploit the full potential of gamma-ray astronomy. The High Energy cosmic-Radiation Detection facility (HERD) is expected to be operational from 2026 on board of the Chinese Space Station, detecting gamma-rays above 0.5 GeV and with potential for transient detection (Cagnoli, Kyrtatzis & Serini 2024).

Finally, in a multimessenger context, CTAO will be able to search for the electromagnetic counterpart of GWs and neutrinos in the Milky Way. The Laser Interferometer Space Antenna mission will be the first GW observatory on space (scheduled launch on 2030) and will be key to study white dwarf mergers (Lamberts et al. 2019; Georgousi et al. 2023). Neutrino alerts from the next generation of detectors such as IceCube-Gen2 will also be crucial in the case of a Galactic CCSN (Aartsen et al. 2021).

## 6 SUMMARY AND CONCLUSIONS

We have studied the capabilities of the forthcoming CTAO to detect transient and variable emission from Galactic sources of different nature. We additionally tested longer exposure times in specific cases of high interest for the observatory. CTAO will be able to discover new transients with not significant degradation in the sensitivity, with a maximum of 15 per cent in the crowded inner regions of the Galaxy when overlapping with strong emitters. Similarly, in order to detect variability from dim systems, our simulations have shown that sources with a photon flux  $< 1 \times 10^{-13}$  photons  $\text{cm}^{-2} \text{s}^{-1}$  will require  $> 10$  h of observations to detect this variability. For sources with fluxes above this threshold, only 5–10 h are required. In the case of strong sources ( $\geq 3 \times 10^{-12}$  photons  $\text{cm}^{-2} \text{s}^{-1}$ ), short exposures 0.5–1.0 h are required, implying that low variations in the flux can be detectable from bright sources. For the case of generic transient sources with the fluxes  $< 10^{-13}$  photons  $\text{cm}^{-2} \text{s}^{-1} \text{TeV}^{-1}$  CTAO will not detect any source in about one hour observation time, while for those with fluxes  $< 10^{-9}$  photons  $\text{cm}^{-2} \text{s}^{-1} \text{TeV}^{-1}$  in an uncrowded region, CTAO would be able to detect  $\geq 65$  per cent of sources within just 1 h of observation for both arrays for the different zenith angles and configurations of the geomagnetic field used in this study if all sources are visible. Any visibility constraints will significantly lower this number.

The unique sensitivity at short time-scales together with the fast slewing capabilities of the LSTs and the aforementioned capacities of CTAO will allow the detection and discovery of a variety of sources of different nature, according to our simulations:

(i) CTAO will detect VHE from microquasars and from the interaction between their jets and the surrounding environment. Our simulations show that CTAO will likely detect both transient and persistent emission from the massive microquasars Cyg X-1 and Cyg X-3. CTAO will also significantly detect SS 433 including possible flux variability. In the case of LMXBs, CTAO will detect outbursts within few tens of minutes from a nearby source ( $< 4$  kpc) with relatively small inclination angle ( $< 30^\circ$ ). Longer exposure times are required for LMXBs with larger angles.

(ii) We tested the case of tMSPs, concluding that CTAO will need long integration times ( $> 50$  h) to be able to detect the possible emission of tMSPs when they are in the LMXB state. These systems could be detected during a transition from RSMP to LMXB if an additional VHE component is present, which could provide crucial information on particle interaction.

(iii) Flaring emission from the Crab Nebula will be best detected by CTAO (or LST subarray) at low energies ( $E < 200$  GeV) in less than 1 h. In the TeV regime, integration times of  $< 10$  h will be needed, specially for the detection of dimmer flares.

(iv) In the case of novae, CTAO will be able to detect close-by novae. As an example of the only VHE novae known to date, our simulations reveal that CTAO will detect the symbiotic recurrent nova RS Oph with high significance in only 30 min, allowing for a detailed measurement, and therefore detailed modelling, of its SED from energies as low as 20 GeV. Combined with multiwavelength observations, the temporal and spectral analyses of CTAO observation would improve our understanding of the acceleration processes in novae.

Regarding sources of different nature from the aforementioned, we could expect CTAO to detect emission from magnetars during a giant flare and even likely during intermediate flares associated with an FRB. Other possible transient events are flares from Supergiant Fast X-ray Transients (SFXTs), for which a detection would definitely

identify SFXTs as VHE emitters. Other variable VHE candidates are runaway stars and young stellar objects. Serendipitous discoveries are also possible while performing, e.g., surveys. Simultaneous multiwavelength and multimessenger observations will be crucial to maximize the scientific output of the CTAO observatory.

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## DATA AVAILABILITY

The official CTAO observatory IRFs (Maier et al. 2023) used in this manuscript are available in: `prod3b-v2`, <https://zenodo.org/record/5163273> and `prod5-v0.1`, <https://zenodo.org/record/5499840>. The CTOOLS (`asc1:1601.005`) DOI is: [10.5281/zenodo.4727876](https://zenodo.org/doi/10.5281/zenodo.4727876). The GAMMAPY DOI is [10.5281/zenodo.4701488](https://zenodo.org/doi/10.5281/zenodo.4701488). The simulations of the GPS used in Section 2 were retrieved from <https://zenodo.org/doi/10.5281/zenodo.8402519>.

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