PROCEEDINGS OF SCIENCE

Searching for neutrinos from microquasar flares with ANTARES and KM3NeT

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Very high energy emissions are believed to happen through particle acceleration in the jet originating from microquasars. This hypothesis was corroborated by the recent detections from the HAWC collaboration of very high energy gamma-ray events in the vicinity of SS433 and V4641Sgr microquasars. Through hadronic processes, neutrinos are produced together with these gamma-rays. We present results from a search of a neutrino signal from 13 microquasars which, according to multiwavelength observations, exhibited events of fast bulk ejecta in the context of outbursts characterized by strong X-Ray flares and spectral state transitions. This search is focused on X-Ray flaring and transitioning periods determined from RXTE/ASM, MAXI/GSC and Swift/BAT public data monitoring. The analysis is performed using data from the ANTARES neutrino telescope, which was dismantled during 2022 after 16 years of steady data acquisition, as well as with its successor KM3NeT, in construction in the Mediterranean Sea, with data from the KM3NeT/ORCA detector in its 6 lines configuration. No significant excess was found and upper limits on the neutrino fluxes are computed in the total observed flaring times and in specific spectral states.

38th International Cosmic Ray Conference (ICRC2023)
26 July - 3 August, 2023
Nagoya, Japan

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PoS(ICRC2023)1505

1. Introduction

This study aims to search for a neutrino signal correlated with X-Ray flares from microquasars in the ANTARES and KM3NeT neutrino detectors. Microquasars are binary objects - with a compact object and a star - that exhibit phenomena of accretion/ejection in the form of an accretion disk/jet system. The matter is ejected with relativistic bulk speed, which could lead to the acceleration of particles to very high energy via shock formation. In the case of a significant hadronic contribution in the jet, a detectable neutrino flux could be emitted. The multiwavelength behaviour of these sources shows high levels of variability, with periods of intense flaring mostly detected in radio and X-Rays. This study focuses on the flaring periods, as these exhibit higher ejection rates, which lead to preferential conditions for neutrino production.

Sources are selected for this study that present the following behaviour: periods of clear X-Ray flaring with X-Ray spectra following the characteristic hysteresis cycle as shown in [1]. During this cycle a source typically exhibits an increase in luminosity followed by a transition from a hard X-Ray spectrum to a soft, thermal, spectrum. This cycle is the focus of the search due to its correlation with radio bright ejecta with relativistic bulk speeds, as seen in [2] for MAXI J1820+070.

2. Detectors

ANTARES and KM3NeT are undersea neutrino telescopes built with photo-multiplier tubes (PMT) aiming to detect Cherenkov light induced by secondary particles created in the interaction of neutrinos with sea water. These interactions generate in the detector two main event topologies: track-like from muons produced in the charged-current interaction of muon and anti-muon neutrinos and cascade-like from other kinds or interactions. The now-dismantled ANTARES telescope [3] was located 2500 meters deep near Toulon (France) and ran for 16 years before stopping data-taking in February 2022. It was composed of 12 vertical lines containing 885 PMTs and was optimised for the detection of high-energy neutrinos with energy ranging from a few hundreds GeV to a few PeV. KM3NeT [4] is its successor and is currently being built on two sites: ORCA, located near the ANTARES site and optimised for the detection of lower-energy neutrinos (GeV to TeV) and ARCA, located offshore of Sicily (Italy) and optimised for TeV to PeV neutrinos. The planned KM3NeT detector will be composed of 115 lines on the ORCA site and 230 lines on the ARCA site.

This analysis uses data from the ANTARES detector in most of its data taking duration, from January 2007 to February 2022 and data from the KM3NeT/ORCA detector in its 6-lines configuration (ORCA6), from January 2020 to November 2021. In both detectors, quality controls for the data taking condition are performed, resulting in a total live time of 4541 days for ANTARES and 555 days for KM3NeT/ORCA6.

3. Search periods determination

The flaring periods of the candidate sources are determined using publicly available X-Ray lightcurve data from the following telescopes: RXTE/ASM (2-10 keV), MAXI/GSC (2-20 keV) and Swift/BAT (15-150 keV).

An estimation of the baseline rates and standard deviations for each source and telescope is performed with a Gaussian fit of the daily averaged rates of the lightcurves. Data points are retained that verify $F - \Delta F > \mu_{\mathrm{BL}} + 8\,\sigma_{\mathrm{BL}}$, with F the flux and ΔF its corresponding error, μ_{BL} and σ_{BL} the mean and standard deviation of the Gaussian fitted baseline. To account for possible instrumental effects, data points verifying this criterion are removed if they are not accompanied by another selected point in a ± 5-days time window. The resulting high-significance data points are used as seeds to search for flaring time windows: starting from each point, the flaring period is defined by the time window in which the flux verifies $F - \Delta F > \mu_{\mathrm{BL}} + 2\,\sigma_{\mathrm{BL}}$ in at least 1 point in a 5-day sliding time window starting from each high-significance data point. A neutrino search is performed if a flaring period is found in any telescope. The lightcurves for GX339-4 with the corresponding flaring periods are shown in Figure 1. From the initial source list, 3 microquasars exhibit flaring in X-Ray during the KM3NeT/ORCA6 period: GX339-4, AqlX-1 and 4U1630-472, with observation livetimes of respectively 250, 143 and 83 days.

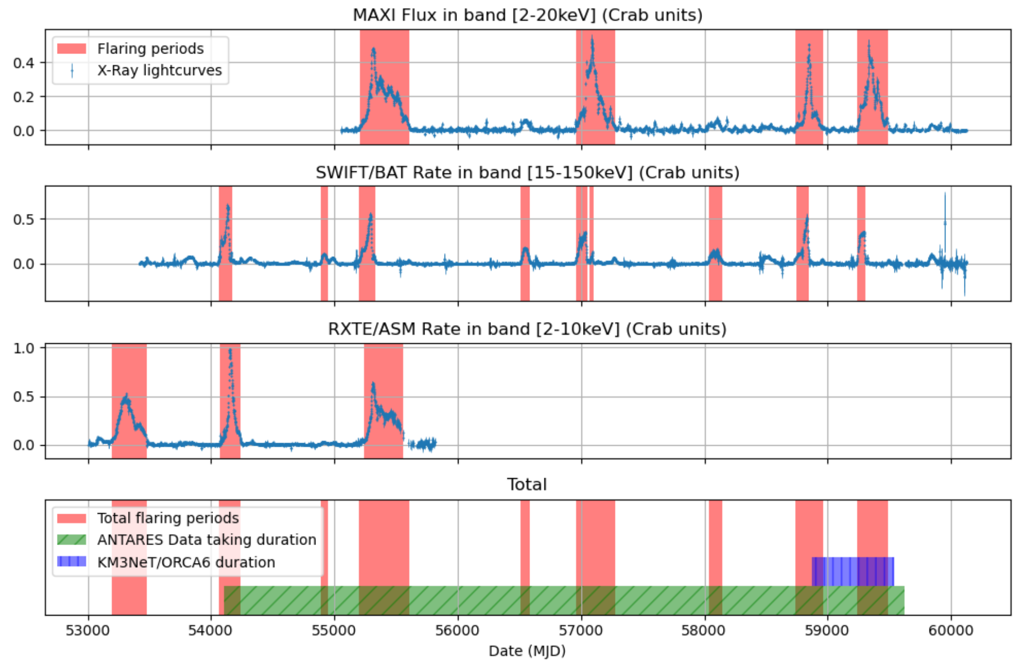

Figure 1: X-Ray lightcurves from GX339-4, recorded by MAXI/GSC, Swift/BAT and RXTE/ASM. Flaring periods are highlighted in red. The ANTARES data-taking duration is represented as a green line and the KM3NeT/ORCA6 data-taking duration is represented as a blue line. The total flaring periods are a stacking of the flaring periods in each telescope and define the neutrino signal search window.

Additionally, for sources MAXIJ1820+070 and GX339-4 the search is also performed in 3 subdivisions of the flaring periods, each corresponding to a given X-Ray spectral state: the Hard State, Hard to Soft state transitions, and Soft State. This is motivated by the fact that these sources exhibit different multi-wavelength properties in each state, and neutrino fluxed are expected to also differ.

For MAXIJ1820+070, periods are taken from [5], rounded to the floor/ceiling Modified Julian Day (MJD) for the beginning/end of the period to account to ensure a flat Right Ascension background distribution. They are as follow, given in MJD: Hard State from 58189 to 58304, State Transition from 58304 to 58311 and Soft State from 58311 to 58380.

GX339-4 exhibits regular flares with multiple state transitions. The spectral states where divided using X-Ray hardness ratios from RXTE/ASM and MAXI/GSC, with total livetimes of 248, 30 and 634 days for the Hard States, State transitions, and Soft States respectively.

4. Analysis methods

4.1 ANTARES

The signal search in ANTARES data is a standard unbinned likelihood analysis. The likelihood PDF is built using spatial, time and energy distributions obtained from simulations, taking into account event rate fluctuations over the detector life time [6]. Pseudo-experiments are performed to obtain the distribution of test statistic (TS) used to compute flux sensitivities for each source. The TS is defined as the ratio of the signal plus background likelihood, for which the number of signal events is fitted, over the background-only likelihood.

The search is performed in the time windows obtained in the previous section. They are defined as a box-shaped PDF term in the likelihood. In the case of discontinuous flaring periods the analysis is performed only once, effectively stacking the multiple flares on a single search. The analysis takes into account track-like and cascade-like event topologies. The events are selected on the quality of their reconstruction to reduce the background coming from atmospheric muons and to improve the angular resolution. Cuts on these quality parameters are then chosen by maximizing the probability of a 5σ discovery assuming an incoming neutrino spectrum of $\phi(\mathrm{E}) = 10^{-7}\ \mathrm{E}^{-2}\ \mathrm{GeV}^{-1}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$

4.2 KM3NeT

The analysis is a binned ON/OFF region search, similar to the one used in [7] and [8]. It is a counting experiment in which the rate of events in an OFF (control) region is used to estimate the number of background events in an ON (signal) region, which is the search region. These ON/OFF regions are defined as follows: the ON region is a circle with a radius to be optimised (Region of Interest, RoI), centered to the coordinates of the source, and the OFF region is a band in equatorial coordinates, +/- 10° around the source, minus the RoI defining the ON region. Here the OFF events are recorded at the same time as the ON events, to obtain a reasonable estimate of background event rate in the search region. The expected N_{ON} coming from background is then: Exp.Bkg $= \mathrm{N}_{\mathrm{OFF}} \times \Omega_{\mathrm{ON}}/\Omega_{\mathrm{OFF}}$ with Ω the solid angles of the corresponding regions. In this search only events reconstructed as upgoing or horizontal are taken into account, with events selected with a reconstructed zenith angle θ such as $\cos(\theta) > -0.1$. This allows to significantly reduce the number of background events coming from atmospheric muons, with the remaining background being misreconstructed muons and atmospheric neutrinos. Moreover, the analysis only uses events reconstructed as a muon track-like, typically associated with muons. Tracks originating from neutrinos are separated from tracks originating from misreconstructed muons using a boosted decision tree (BDT) classifier, based on gradient boosting [9]. The training is done using simulated events, with all-flavor ν events as signal and atmospheric muons as background. The final selection criteria are determined by minimizing the upper limit expected from the background and a neutrino signal modelled by $\phi(\mathrm{E}) \propto \mathrm{E}^{-2}$ [10]. The two free parameters for this minimization are the classification score and the radius of the ON region (RoI). The optimization is performed using data from the OFF region defined above to estimate the background level.

5. Results

In the ANTARES analysis, the likelihood fit yielded no signal event for each source and time period. Upper limits are given as the 90% confidence level sensitivities derived from pseudo-experiments. The upper limits on the fluence for the flaring periods are shown as a function of the source galactic longitude Figure 2 and as a function of the search livetimes Figure 3. For the different spectral states of MAXIJ1820+070 and GX339-4, the upper limits on the fluence and flux normalisation are given in Figure 4. Due to the smaller observation time windows, the flux is less constrained during the state transition periods, but it should be highlighted that these periods are the most favourable for neutrino emission in the case of luminous ejecta with high bulk Lorentz factor [11].

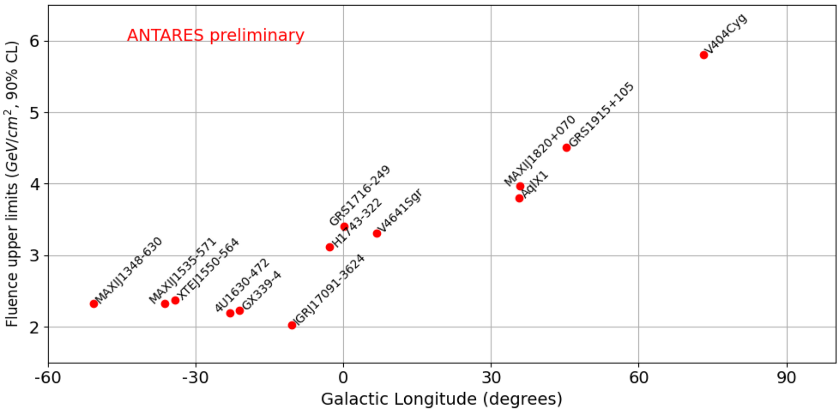

Figure 2: Neutrino fluence upper limits with ANTARES against the galactic longitudes of the studied sources.

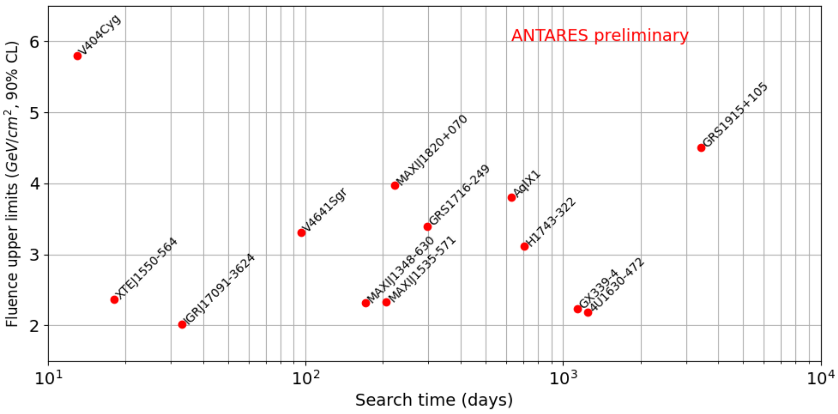

Figure 3: Neutrino fluence upper limits with ANTARES against the search time. This duration corresponds to the flaring time of each source under good data-taking conditions.

The fluence is defined as :

$$\mathcal{F} = \Delta T \int_{E_{5\%}}^{E_{95\%}} E \frac{\mathrm{d}N}{\mathrm{d}E} \mathrm{d}E \tag{1}$$

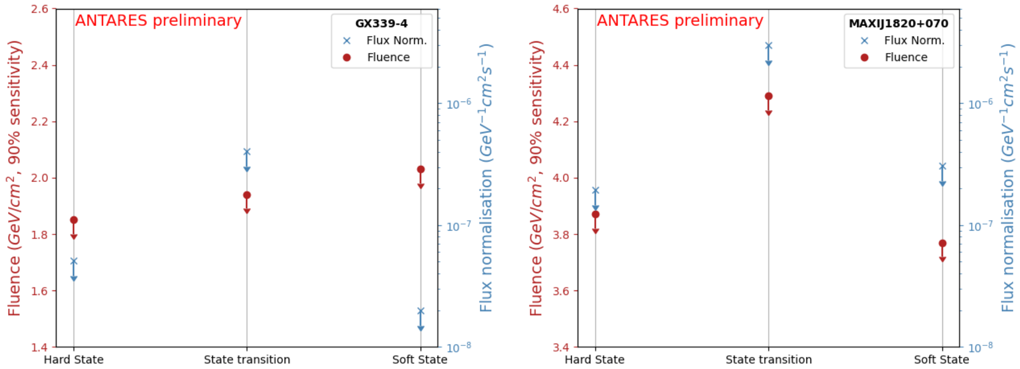

Figure 4: Upper limits with ANTARES on neutrino fluence (in GeVcm^{-2}) and flux normalisations (in GeV^{-1}cm^{-2}s^{-1}), assuming an incoming neutrino flux with an energy spectrum $\phi(\mathrm{E}) \propto \mathrm{E}^{-2}$. Limits are given in 3 X-Ray spectral states: Hard State, State Transition, and Soft State for GX339-4 (left) and MAXIJ1820+070 (right).

with ΔT the observation livetime and with $E_{5\%}$ and $E_{95\%}$ the 5th and 95th energy percentiles of the signal events energy distribution, assuming a power law spectral distribution: $\frac{\mathrm{d}N}{\mathrm{d}E} \propto E^{-2}$. The energy ranges are as follows: for the KM3NeT/ORCA6 detector, $E_{5\%}$ = 100 GeV and $E_{95\%}$ = 9 TeV while for the ANTARES detector, $E_{5\%}$ = 3 TeV and $E_{95\%}$ = 3 PeV.

For the KM3NeT/ORCA6 analysis, the results can be found in Table 1. No significant excess was found, with the lowest p-value being 32% for 4U1630-472 assuming the background follows Poisson statistics. Upper limits are computed using Rolke confidence intervals [12], with a 90% confidence level. In this computation the background is assumed to follow Poisson statistics and the detection efficiency is modeled as a Gaussian with a relative standard deviation of 30% to conservatively take into account systematic effects. The flux and fluence upper limits are computed assuming the incoming neutrino flux has an energy spectrum $\phi(\mathrm{E}) \propto \mathrm{E}^{-2}$ and are evaluated using simulations. For the 3 sources that could be observed in a flaring state with KM3NeT/ORCA6 and ANTARES, upper limits on the flux as a function of energy can be found in Figure 5. The KM3NeT/ORCA6 upper limit is less constraining due to the smaller detector and the shorter observation times, but provides complementary coverage in a lower energy range with respect to ANTARES.

6. Conclusion

This contribution presents a search for a neutrino signal correlated with X-Ray flares from 13 microquasars with ANTARES with its full life time, and with KM3NeT/ORCA in its 6 lines configuration. No significant signal was observed in either case and upper limits on the neutrino fluxes were derived.

In a recent analysis from the Icecube neutrino detector [13] that included a similar search that the one presented here, the microquasar V404 Cyg yielded a signal with a pre-trial p-value of 1.4% , while taking into account trial correction led to results fully compatible with background expectations. The complete KM3NeT detector will be able to further study galactic objects as

Source		4U1630-472		GX339-4		Aql X-1	
N_{ON}	Time (MJD) Dist. from source	**2**	59495.887, 59526.473 1.77°, 1.80°	**1**	58956.383 1.35°	**1**	59128.48 1.52°
N_{OFF}		474		648		291	
Exp.Bkg		1.15		1.35		0.60	
p-value		0.32		0.74		0.45	
Φ_0^{UL} (GeV^{-1}cm^{-2}s^{-1})		6.7×10^{-6}		2.2×10^{-6}		8.8×10^{-6}	
$\mathcal{F}^{UL}$ (GeVcm^{-2})		3.3×10^2		1.9×10^2		2.5×10^2	

Table 1: KM3NeT/ORCA6 search results. N_{ON} and N_{OFF} are respectively the number of events in the ON and OFF regions after selection. The times and distances from the source are given for events in the ON region. Exp.Bkg. is the expected number of background events in the search region. The p-value is computed assuming a Poisson-distributed background. Φ_0^{UL} and $\mathcal{F}^{UL}$ are respectively the upper limits of the flux normalisation and the fluence, assuming an incoming neutrino flux with an energy spectrum $\phi(E) \propto \Phi_0 E^{-2}$. Upper limits are given with a 90% confidence level.

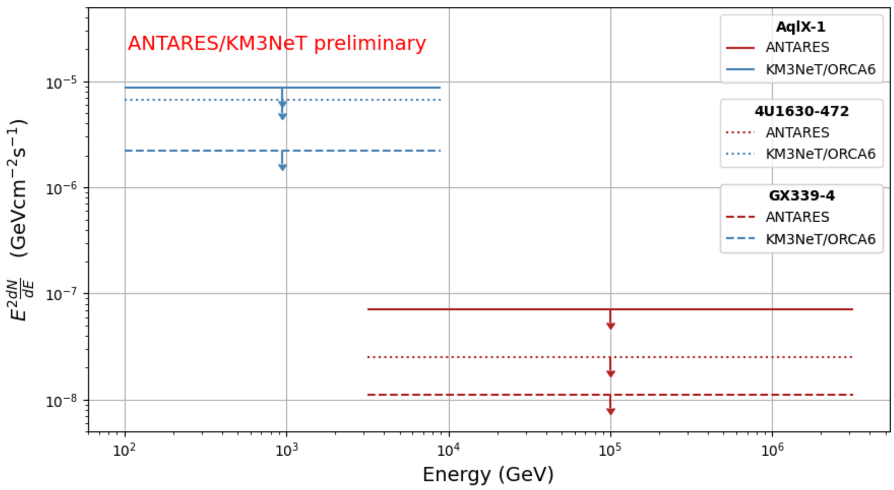

Figure 5: Neutrino flux upper limits for AqlX-1 (solid), 4U1630-472 (dotted) and GX339-4 (dashed) in KM3NeT/ORCA (blue) and ANTARES (red) energy ranges. Limits are given as $E^2\frac{dN}{dE}$, (in GeVcm^{-2}s^{-1}), assuming an incoming neutrino flux with an energy spectrum $\phi(E) \propto E^{-2}$.

potential neutrino sources thanks to its location in the northern hemisphere allowing a good view of the galactic center.

The KM3NeT detector, which is under construction, is already showing performances competing with ANTARES with 18 lines in ORCA and 21 in ARCA as of summer 2023. Plus, the KM3NeT/ORCA detector is demonstrating capabilities for neutrino astronomy with its lower energy range, with already 6 out of the 115 planned lines.

References

[1] R.P. Fender, T.M. Belloni and E. Gallo, *Towards a unified model for black hole x-ray binary jets*, *Monthly Notices of the Royal Astronomical Society* **355** (2004) 1105.

[2] J.S. Bright, R.P. Fender et al., *An extremely powerful long-lived superluminal ejection from the black hole MAXI j1820+070*, *Nature Astronomy* **4** (2020) 697.

[3] ANTARES collaboration, *ANTARES: the first undersea neutrino telescope*, *Nucl. Instrum. Meth. A* **656** (2011) 11 [1104.1607].

[4] KM3NeT collaboration, *Letter of intent for KM3NeT 2.0*, *J. Phys. G* **43** (2016) 084001 [1601.07459].

[5] M. Shidatsu, S. Nakahira, K.L. Murata, R. Adachi, N. Kawai, Y. Ueda et al., *X-ray and optical monitoring of state transitions in MAXI j1820+070*, *The Astrophysical Journal* **874** (2019) 183.

[6] ANTARES collaboration, *Search for Flaring Neutrino Sources with the ANTARES Neutrino Telescopes*, *PoS* **ICRC2023** (these proceedings) 1480.

[7] KM3NeT collaboration, *Refined neutrino follow-up of GRB 221009A with ARCA and ORCA detectors*, *PoS* **ICRC2023** (these proceedings) 1503.

[8] KM3NeT collaboration, *Follow-up of multimessenger alerts with KM3NeT ARCA and ORCA*, *PoS* **ICRC2023** (these proceedings) 1521.

[9] T. Chen and C. Guestrin, *Xgboost: A scalable tree boosting system*, *CoRR* **abs/1603.02754** (2016) [1603.02754].

[10] G.C. Hill and K. Rawlins, *Unbiased cut selection for optimal upper limits in neutrino detectors: the model rejection potential technique*, *Astroparticle Physics* **19** (2003) 393.

[11] C. Distefano, D. Guetta, E. Waxman and A. Levinson, *Neutrino flux predictions for known galactic microquasars*, *The Astrophysical Journal* **575** (2002) 378.

[12] W.A. Rolke, A.M. López and J. Conrad, *Limits and confidence intervals in the presence of nuisance parameters*, *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* **551** (2005) 493.

[13] R. Abbasi et al., *Search for High-energy Neutrino Emission from Galactic X-Ray Binaries with IceCube*, *Astrophysical Journal, Letters* **930** (2022) L24 [2202.11722].

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Acknowledgements

The authors acknowledge the financial support of the funding agencies: Agence Nationale de la Recherche (contract ANR-15-CE31-0020), Centre National de la Recherche Scientifique (CNRS), Commission Européenne (FEDER fund and Marie Curie Program), LabEx UnivEarthS (ANR-10-LABX-0023 and ANR-18-IDEX-0001), Paris Île-de-France Region, France; Shota Rustaveli National Science Foundation of Georgia (SRNSFG, FR-22-13708), Georgia; The General Secretariat of Research and Innovation (GSRI), Greece Istituto Nazionale di Fisica Nucleare (INFN), Ministero dell'Università e della Ricerca (MIUR), PRIN 2017 program (Grant NAT-NET 2017W4HA7S) Italy; Ministry of Higher Education, Scientific Research and Innovation, Morocco, and the Arab Fund for Economic and Social Development, Kuwait; Nederlandse organisatie voor Wetenschappelijk Onderzoek (NWO), the Netherlands; The National Science Centre, Poland (2021/41/N/ST2/01177); The grant "AstroCeNT: Particle Astrophysics Science and Technology Centre", carried out within the International Research Agendas programme of the Foundation for Polish Science financed by the European Union under the European Regional Development Fund; National Authority for Scientific Research (ANCS), Romania; Grants PID2021-124591NB-C41, -C42, -C43 funded by MCIN/AEI/ 10.13039/501100011033 and, as appropriate, by "ERDF A way of making Europe", by the "European Union" or by the "European Union NextGenerationEU/PRTR", Programa de Planes Complementarios I+D+I (refs. ASFAE/2022/023, ASFAE/2022/014), Programa Prometeo (PROMETEO/2020/019) and GenT (refs. CIDEGENT/2018/034, /2019/043, /2020/049. /2021/23) of the Generalitat Valenciana, Junta de Andalucía (ref. SOMM17/6104/UGR, P18-FR-5057), EU: MSC program (ref. 101025085), Programa María Zambrano (Spanish Ministry of Universities, funded by the European Union, NextGenerationEU), Spain; The European Union's Horizon 2020 Research and Innovation Programme (ChETEC-INFRA - Project no. 101008324).

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