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Carosi, A.; López-Oramas, A.; Longo, F.; CTA Collaboration

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The Cherenkov Telescope Array transient and multi-messenger program

Alessandro Carosi, Alicia López-Oramas and Francesco Longo on behalf of the CTA Collaboration
(a complete list of authors can be found at the end of the proceedings)

*DPNC – University of Geneva 24 quai Ernest Ansermet, CH1211 Genève 4, Switzerland

bInstituto de Astrofísica de Canarias and Universidad de La Laguna, La Laguna, Spain

University of Trieste and INFN, Trieste, Italy

E-mail: alessandro.carosi@unige.ch

The Cherenkov Telescope Array (CTA) is a next generation ground-based very-high-energy gamma-ray observatory that will allow for observations in the >10 GeV range with unprecedented photon statistics and sensitivity. This will enable the investigation of the yet-marginally explored physics of short-time-scale transient events. CTA will thus become an invaluable instrument for the study of the physics of the most extreme and violent objects and their interactions with the surrounding environment. The CTA Transient program includes follow-up observations of a wide range of multi-wavelength and multi-messenger alerts, ranging from compact galactic binary systems to extragalactic events such as gamma-ray bursts (GRBs), core-collapse supernovae and bright AGN flares. In recent years, the first firm detection of GRBs by current Cherenkov telescope collaborations, the proven connection between gravitational waves and short GRBs, as well as the possible neutrino-blazar association with TXS 0506+056 have shown the importance of coordinated follow-up observations triggered by these different cosmic signals in the framework of the birth of multi-messenger astrophysics. In the next years, CTA will play a major role in these types of observations by taking advantage of its fast slewing (especially for the CTA Large Size Telescopes), large effective area and good sensitivity, opening new opportunities for time-domain astrophysics in an energy range not affected by selective absorption processes typical of other wavelengths. In this contribution we highlight the common approach adopted by the CTA Transients physics working group to perform the study of transient sources in the very-high-energy regime.

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1. Introduction

In recent years, the field of very-high-energy (VHE, E>100 GeV) transient astronomy has begun evolving toward the observations of new sources in the context of a multi-messenger approach. The comprehension of the connection between time-domain and multi-messenger astrophysics is rapidly becoming of primary importance since VHE photons are produced in extreme, violent environments potentially associated with cosmic accelerators and therefore to the production of high-energy cosmic-rays and neutrinos. Furthermore, VHE radiation might be expected from stellar collapses and compact object mergers which power supernovae, gamma-ray bursts (GRBs) and gravitational wave (GW) emission. Transients are an integral part of the CTA Key Science Projects (KSP) [1]. A dedicated Science Working Group (Transient and multi wavelength SWG) is in place to prepare first observations (react to fast target of opportunities-ToO, define the observation program, prepare the scientific analysis, etc.) and set up the needed multi wavelength/multi-messenger connections and synergies with external facilities. The main scientific goals of the group, include the release of dedicated consortium publications focused on key topics such as GRBs, gravitational waves, neutrino ToOs, galactic transients and core-collapse supernovae. The group is also involved in other activities such as evaluating the detection prospects of serendipitous VHE transients identified via the CTA real-time analysis and the VHE transient survey, by exploring the divergent pointing capability in association with the CTA extragalactic survey KSP.

In this contribution, we will report on the general Transients KSP and each of the main sub-projects (namely consortium publications) under development within the Transients SWG, their current status and planned activities.

2. The Transients KSP

The Transients KSP is an important part of the CTA science core program and one of its main goals is to prepare the response of CTA to a wide range of multi-wavelength and multi-messenger alerts, including GRBs, GWs and high-energy neutrinos. The sensitivity achievable to emission on short timescales and the fast response to external alerts will allow CTA to probe ultra-fast variability over early phases of transient events in unprecedented detail compared to current generation imaging atmospheric Cherenkov telescopes (IACTs) and space-based instrumentation (see Fig.1 left panel).

This would allow us to shed some light on some fundamental topics such as:

- The investigation of the physical mechanisms that drive jets and winds around neutron stars and black holes
- The study of and potential discrimination between the different emission scenarios and physical processes capable of producing the observed HE and VHE radiation from GRBs
- The origin of the ultra-high energy cosmic rays (UHECRs) and high-energy neutrinos
- The study of the physical mechanisms at the origin of GWs and their electromagnetic counterparts
Figure 1: *Left:* Sensitivities of CTA and *Fermi*-LAT in their overlapping energy range as a function of observation time. Differential flux sensitivities at three energies are compared. For CTA, the proposed *alpha configuration* with 4 large sized telescopes (LST) and 9 medium sized telescopes (MST) in the north array is reported. From https://www.cta-observatory.org/science/cta-performance. *Right:* Summary of the observation proposed in the Key Science Project proposal in [1].

Starting from these key science topics, and also using the extensive experience of current IACTs, the transient KSP is poised to optimize the CTA response to transient alerts by providing a list of detailed use cases covering a wide range of observational steps: from the receiving of the alerts to the reaction of the arrays; from data taking to the rapid feedback to the astronomical community on the VHE properties of the observed transients. A preliminary list of the proposed observations within the CTA transient KSP is reported in Fig.(1) although the outlined numbers are currently going under a major revision according to the latest, state-of-the-art knowledge derived from current IACTs follow-ups.

3. Gamma-ray Bursts

GRBs have always been considered a primary targets for all modern IACT telescopes. The detection of VHE gamma-ray from a number of events including GRB 180720B [2], GRB 190114C [3] and GRB 190829A [4] represents a long-awaited result and a remarkable step forward in our understanding of GRB physics. For long time, the search for VHE signals associated with GRBs posed a major challenge for IACTs from both the technical and the scientific point of view (see e.g. [5] [6]). The possibility of detecting a VHE gamma-ray signal from a GRB is indeed crucial for clarifying the poorly-known physics of these objects during the different phases of their emission, in particular during the early afterglow phase when the co-existence of forward and reverse shocks in the emitted outflow could yield a large variety of different emitting scenarios. The CTA array will routinely perform follow-up observations of GRB triggers. The estimation of the detection prospects for such observations are necessarily still preliminary and are dependent on the final array layout and performance. However, even starting with simplified assumptions about the GRB emission, the CTA Consortium already reported the possibility of detecting ~hundreds (or more) of photons from moderate to bright GRB allowing for a significant improvement in the photon statistics and for the possibility to have good-quality time-resolved spectra [7]. In order to achieve a step forward in the determination of CTA’s prospects for GRB follow-ups, the Transient SWG is currently working on a new publication where the potential detection rate is estimated using a theoretical-based approach.
Figure 2: (Left:) Scheme of the GRB consortium publication work. Synthetic spectra and light curves are obtained by a population synthesis code and used to feed the CTA analysis pipeline. (Right:) Workflow for the GW consortium publication. After the simulation of BNS merger, a phenomenological (short) GRB is associated to it. The optimal pointing strategy is then obtained by a dedicated algorithm in order to cover efficiently the sky area of the GW source. Each pointing is then analyzed by means of the CTA analysis pipeline.

Such an approach is based on the *PO*ulation *S*ynthesis *T*heory *I*ntegrated code for *V*ery high *e*nery *E*mission (POSyTIVE) population model for GRBs [8]. The resulting population is built by considering few intrinsic properties and assumptions:

- $E_{\text{peak}}$ redshift distribution
- $E_{\text{peak}}$-$E_{\text{iso}}$ correlation (Amati relation) [9]
- Bulk Lorentz factor distribution obtained by measured the time of the afterglow onset (providing the bulk Lorentz factor of the event’s coasting phase)

The population obtained (for both long and short GRBs) is calibrated against a wide data set of multi-wavelength observations. In order to derive the final expected spectrum, both the prompt and the afterglow emission are simulated according to standard leptonic synchrotron and synchrotron self-Compton models [10]. The GRB spectra obtained are then used to simulate the detailed CTA response through the use of dedicated analysis pipelines based on gammapy\(^1\) and ctools\(^2\).

4. Gravitational Waves

The link between GWs and short GRBs (sGRBs) has been discussed widely in literature in the past and was proven definitively after the observation of the coincidence between GRB 170817A and the gravitational signal GW 170817 [11]. Although all of the GRBs detected so far by current IACTs were long GRB, sGRBs are also expected to emit VHE radiation. Nevertheless, only a hint of emission in this energy band are reported so far for sGRBs by the MAGIC telescopes [12]. However, this result, as well as the significant programs put in place by the major IACT collaborations [see e.g., 13, 14] for follow-up campaigns of GW triggers confirms the scientific potential of these observations. Thanks to its unprecedented sensitivity and the increased number of GW events expected in the near future, CTA will be able to increase the number of VHE counterpart detections

\(^{\text{1}}\)https://gammapy.org/
\(^{\text{2}}\)http://cta.irap.omp.eu/ctools/
providing a deeper insight into their physical processes. The detection of the potential electromagnetic counterpart is, however, challenging due to the relatively large location uncertainties provided by GW interferometers. Within the transient SWG, a detailed study to establish the number of possible successful CTA detections of VHE counterparts of GWs is under development [15].

In contrast to the GRB case, a purely phenomenological approach is used: a short GRB is associated to a set of simulated binary neutron star (BNS) mergers extracted from the public database GWcosmos [16] providing the GW skymap, distance and orientation. The corresponding VHE emission is derived from the empirical correlations between the X-ray and TeV luminosities as observed in the VHE GRB sample (as in GRB 190114C). The optimal pointing strategy is then obtained by a dedicated algorithm in order to cover efficiently the sky area of the GW source. Each pointing is subsequently analyzed by means of a dedicated analysis pipeline in order to provide the final outcome on a possible detection. The CTA GW follow-up program is currently being defined and implemented. The results of these studies will be the subject of a dedicated consortium publication expected by the end of 2021.

5. Neutrino Follow-up

The IceCube detection of the high-energy neutrino event (IC-170922A) associated with the flaring gamma-ray blazar TXS 0506+056 represents the best evidence so far seen for an astrophysical neutrino point source [17]. The extensive multi-wavelength follow-up campaign that also involved many of the currently operating IACTs, stands as an important test case for the optimization of the CTA Neutrino Target of Opportunity (NToO) program. The aim of this program is to develop a strategy for CTA follow-up of neutrino alerts to maximize the chance of detecting a VHE counterpart. Neutrino point source simulations are based on FIRESONG [18], which takes into account the cosmological evolution of different source classes and the recent results from IceCube (i.e., the measured diffuse flux of astrophysical neutrinos). These are then the input for simulating the expected VHE gamma-ray emission. Neutrinos might indeed be accompanied by VHE gamma rays produced according to typical pp and p\text{\pbar} models. CTA, with its fast reaction time and lower energy threshold, will enable sensitive searches for such VHE counterparts for well-localized, likely astrophysical neutrino events up to much higher redshifts than those accessible to current IACTs (Fig. 3). Preliminary results [19, 20] show that, for flaring blazars, CTA will be able to detect a VHE counterpart for about one third of the cases after \(\sim 10\) mins of observations, with lower detection probabilities for steady neutrino sources. For more details, see the dedicated contribution at this conference [21].

6. Galactic Transients

Several sources in our Galaxy exhibit transient emission via different processes, such as outflows interacting with the surrounding interstellar medium, strong winds or accretion/ejection from/onto a compact object. Some of these events are energetic enough to accelerate particles via non-thermal mechanisms and produce high-energy gamma-ray emission in the MeV range. But the main question that arises is whether these MeV emitters can also be sources of VHE gamma rays. For the moment, searches for VHE emission from different types of gamma-ray emitters have not
revealed any signal with current IACTs. CTA, with its unprecedented sensitivity to short-timescale transient events, will perform first-time detections of the VHE component of many MeV-emitters and will likely achieve serendipitous discoveries of yet unknown sources. CTA observations of these flaring objects will be triggered by external facilities such as X-ray or high-energy monitoring satellites. Serendipitous detections might also happen while performing, i.e., surveys such as that of the Galactic Plane. For the detection of Galactic transients, the real-time analysis will play a key role in the follow-up and observation strategies of these externally triggered events. Among the different types of Galactic transients, we have tested the capabilities of CTA to detect transient emission from two types of MeV-emitters: flares from pulsar wind nebulae (PWNe) and microquasars. A more detailed analysis of these and others Galactic transient sources, is reported in [22].

Flares from the Crab Nebula: PWNe are bubbles of relativistic plasma which are powered by the magnetically-driven winds of a central highly-magnetized rotating neutron star (pulsar). The Crab Nebula PWN is the brightest persistent VHE source in the TeV gamma-ray sky, and is referred to as the standard candle. AGILE, however, discovered flaring activity from this source [23], which was subsequently confirmed by Fermi-LAT [24]. We prove that CTA-N will be able to detect VHE flaring emission from the Crab Nebula down to 10% of flare intensity measured by AGILE, thanks to its wide energy range and its improved sensitivity with respect to the current generation of IACTs.

Microquasars: Microquasars are binaries composed of a compact object (which can be a black hole or a neutron star) and a companion star. Matter is accreted onto the compact object, creating an accretion disk and (eventually) generating collimated jets of plasma. We have tested whether some MeV emitters, such as the microquasars in the Cygnus region, can also be detected at VHE by CTA. We have tested whether the two massive microquasars Cyg X-1 and Cyg X-3, which are known MeV sources [25, 26] could also be detected with CTA-N, even if no evidence for VHE emission has been claimed by current IACTs [27, 28]. Only marginal evidence for a VHE signal was observed by the MAGIC telescopes during an 80-minute long observation in 2006 [29], coincident with a hard X-ray flare. We highlight the capability of the CTA-N array to detect transient emission from both of the microquasars, emphasizing the detection of transient emission from Cyg X-1 in
only 30 minutes.

CTA will provide crucial insights which will help to refine emission models for microquasars and jet formation, and will reveal the mechanisms at work in flaring PWNe at VHE. Its unique sensitivity to short-time events and its large energy coverage will allow CTA to discover the VHE components of many Galactic MeV emitters and to reveal serendipitous detections of unknown sources.

7. Core-Collapse Supernovae

A core-collapse supernova (CCSNe) represents the catastrophic explosion of a massive star at the end of its life. The energy is mainly released in the form of kinetic energy of a non-relativistic expanding outflow. In the resulting fast-moving shock wave, particles are accelerated via the first-order Fermi mechanism. The accelerated particles, interacting with the surrounding interstellar matter, might lead to the production of a gamma-ray signal up to the VHE band that can be potentially detected by CTA. A wide range of different types of CCSNe exists (IIP, IIL, Iib, IIn, etc.) which could each have a different signature in the VHE regime. A dedicated work on the prospects for the CTA detection of such a signal has recently started within the Transients working group. A set of known CCSne will be used as a template to model the expected VHE emission in the CTA energy range. Such emission is then input to dedicated CTA analysis pipelines to study the CTA prospects for such observations during the first days/months (and possibly years) after the explosion.

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Full Authors List: CTA Collaboration


1: Centre for Space Research, North-West University, Potchefstroom, 2520, South Africa
2: Institute for Cosmic Ray Research, University of Tokyo, 5-1-5, Kashiwa-no-ha, Kashiwa, Chiba 277-8582, Japan
3: Pontificia Universidad Católica de Chile, Av. Libertador Bernardo O’Higgins 340, Santiago, Chile
4: AIM, CEA, CNRS, Université Paris-Saclay, Université Paris Diderot, Sorbonne Paris Cité, CEA Paris-Saclay, IRFU/DAp, Bat 709, Orme des Merisiers, 91191 Gif-sur-Yvette, France
5: Centre for Advanced Instrumentation, Dept. of Physics, Durham University, South Road, 13
Durham DH1 3LE, United Kingdom
6: Port d’Informació Científica, Edifici D, Carrer de l’Albareda, 08193 Bellaterra (Cerdanyola del Vallès), Spain
7: School of Physics and Astronomy, Monash University, Melbourne, Victoria 3800, Australia
8: Laboratoire Leprince-Ringuet, École Polytechnique (UMR 7638, CNRS/IN2P3, Institut Polytechnique de Paris), 91128 Palaiseau, France
9: Department of Physics, Columbia University, 538 West 120th Street, New York, NY 10027, USA
10: University of Oslo, Department of Physics, Sem Sælundsvei 24 - PO Box 1048 Blindern, N-0316 Oslo, Norway
11: EMFTEL department and IPARCOS, Universidad Complutense de Madrid, 28040 Madrid, Spain
12: Instituto de Astrofísica de Andalucía-CSIC, Glorieta de la Astronomía s/n, 18008, Granada, Spain
13: Institute of Space Sciences (ICE-CSIC), and Institut d’Estudis Espacials de Catalunya (IEEC), and Institució Catalana de Recerca i Estudis Avançats (ICREA), Campus UAB, Carrer de Can Magrans, s/n 08193 Cerdanyola del Vallès, Spain
14: Instituto de Física Teórica UAM/CSIC and Departamento de Física Teórica, Universidad Autónoma de Madrid, c/ Nicolás Cabrera 13-15, Campus de Cantoblanco UAM, 28049 Madrid, Spain
15: Dublin Institute for Advanced Studies, 31 Fitzwilliam Place, Dublin 2, Ireland
16: Universidad Nacional Autónoma de México, Delegación Coyoacán, 04510 Ciudad de México, Mexico
17: University of Geneva - Département de physique nucléaire et corpusculaire, 24 rue du Général-Dufour, 1211 Genève 4, Switzerland
18: INFN Dipartimento di Scienze Fisiche e Chimiche - Università degli Studi dell’Aquila and Gran Sasso Science Institute, Via Vetoio 1, Viale Crispi 7, 67100 L’Aquila, Italy
19: Instituto de Astronomia, Geofísico, e Ciências Atmosféricas - Universidade de São Paulo, Cidade Universitária, R. do Matão, 1226, CEP 05508-090, São Paulo, SP, Brazil
20: LUTH, GEPI and LERMA, Observatoire de Paris, CNRS, PSL University, 5 place Jules Janssen, 92190, Meudon, France
21: INAF - Osservatorio di Astrofisica e Scienza dello spazio di Bologna, Via Piero Gobetti 93/3, 40129 Bologna, Italy
22: INAF - Osservatorio Astrofisico di Arcetri, Largo E. Fermi, 5 - 50125 Firenze, Italy
23: INFN Sezione di Perugia and Università degli Studi di Perugia, Via A. Pascoli, 06123 Perugia, Italy
24: INFN Sezione di Napoli, Via Cintia, ed. G, 80126 Napoli, Italy
25: INFN Sezione di Roma Tor Vergata, Via della Ricerca Scientifica 1, 00133 Rome, Italy
26: Argonne National Laboratory, 9700 S. Cass Avenue, Argonne, IL 60439, USA
27: Aix-Marseille Université, CNRS/IN2P3, CPPM, 163 Avenue de Luminy, 13288 Marseille cedex 09, France
28: INAF - Osservatorio Astronomico di Roma, Via di Frascati 33, 00040, Monteporzio Catone, Italy
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29 : INAF - Osservatorio Astrofisico di Catania, Via S. Sofia, 78, 95123 Catania, Italy
30 : Grupo de Electronica, Universidad Complutense de Madrid, Av. Complutense s/n, 28040 Madrid, Spain
31 : National Astronomical Research Institute of Thailand, 191 Huay Kaew Rd., Suthep, Muang, Chiang Mai, 50200, Thailand
32 : Instituto de Astrofisica de Canarias and Departamento de Astrofisica, Universidad de La Laguna, La Laguna, Tenerife, Spain
33 : FZU - Institute of Physics of the Czech Academy of Sciences, Na Slovance 1999/2, 182 21 Praha 8, Czech Republic
34 : Astronomical Institute of the Czech Academy of Sciences, Bocni II 1401 - 14100 Prague, Czech Republic
35 : CCTVal, Universidad Técnica Federico Santa María, Avenida España 1680, Valparaíso, Chile
36 : ETH Zurich, Institute for Particle Physics, Schafmattstr. 20, CH-8093 Zurich, Switzerland
37 : The University of Manitoba, Dept of Physics and Astronomy, Winnipeg, Manitoba R3T 2N2, Canada
38 : Department of Astronomy, University of Geneva, Chemin d’Ecogia 16, CH-1290 Versoix, Switzerland
39 : Laboratoire Univers et Particules de Montpellier, Université de Montpellier, CNRS/IN2P3, CC 72, Place Eugène Bataillon, F-34095 Montpellier Cedex 5, France
40 : Centro Brasileiro de Pesquisas Físicas, Rua Xavier Sigaud 150, RJ 22290-180, Rio de Janeiro, Brazil
41 : Institut de Fisica d’Altes Energies (IFAE), The Barcelona Institute of Science and Technology, Campus UAB, 08193 Bellaterra (Barcelona), Spain
42 : University of Groningen, KVI - Center for Advanced Radiation Technology, Zernikelaan 25, 9747 AA Groningen, The Netherlands
43 : School of Physics, University of New South Wales, Sydney NSW 2052, Australia
44 : INAF - Osservatorio Astrofisico di Torino, Strada Osservatorio 20, 10025 Pino Torinese (TO), Italy
45 : Univ. Savoie Mont Blanc, CNRS, Laboratoire d’Annecy de Physique des Particules - IN2P3, 74000 Annecy, France
46 : Department of Physics, TU Dortmund University, Otto-Hahn-Str. 4, 44221 Dortmund, Germany
47 : University of Zagreb, Faculty of electrical engineering and computing, Unska 3, 10000 Zagreb, Croatia
48 : University of Namibia, Department of Physics, 340 Mandume Ndemufayo Ave., Pioneerspark, Windhoek, Namibia
49 : Nicolaus Copernicus Astronomical Center, Polish Academy of Sciences, ul. Bartycka 18, 00-716 Warsaw, Poland
50 : Universität Hamburg, Institut für Experimentalphysik, Luruper Chaussee 149, 22761 Hamburg, Germany
51 : Graduate School of Science, University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo 113-0033, Japan
52: Deutsches Elektronen-Synchrotron, Platanenallee 6, 15738 Zeuthen, Germany
53: Max-Planck-Institut für Kernphysik, Saupfercheckweg 1, 69117 Heidelberg, Germany
54: RIKEN, Institute of Physical and Chemical Research, 2-1 Hirosawa, Wako, Saitama, 351-0198, Japan
55: INFN Sezione di Padova and Università degli Studi di Padova, Via Marzolo 8, 35131 Padova, Italy
56: Escuela Politécnica Superior de Jaén, Universidad de Jaén, Campus Las Lagunillas s/n, Edif. A3, 23071 Jaén, Spain
57: Department of Physics and Electrical Engineering, Linnaeus University, 351 95 Växjö, Sweden
58: University of the Witwatersrand, 1 Jan Smuts Avenue, Braamfontein, 2000 Johannesburg, South Africa
59: Institut für Theoretische Physik, Lehrstuhl IV: Plasma-Astroteilchenphysik, Ruhr-Universität Bochum, Universitätsstraße 150, 44801 Bochum, Germany
60: Faculty of Physics and Applied Computer Science, University of Lódź, ul. Pomorska 149-153, 90-236 Lódź, Poland
61: INAF - Istituto di Astrofisica Spaziale e Fisica Cosmica di Milano, Via A. Corti 12, 20133 Milano, Italy
62: INFN and Università degli Studi di Siena, Dipartimento di Scienze Fisiche, della Terra e dell’Ambiente (DSFTA), Sezione di Fisica, Via Roma 56, 53100 Siena, Italy
63: Center for Astrophysics | Harvard & Smithsonian, 60 Garden St, Cambridge, MA 02180, USA
64: INFN Sezione di Torino, Via P. Giuria 1, 10125 Torino, Italy
65: Finnish Centre for Astronomy with ESO, University of Turku, Finland, FI-20014 University of Turku, Finland
66: Pidstryhach Institute for Applied Problems in Mechanics and Mathematics NASU, 3B Naukova Street, Lviv, 79060, Ukraine
67: Bhabha Atomic Research Centre, Trombay, Mumbai 400085, India
68: Center for Astrophysics and Cosmology, University of Nova Gorica, Vipavska 11c, 5270 Ajdovščina, Slovenia
69: Institut für Astronomie und Astrophysik, Universität Tübingen, Sand 1, 72076 Tübingen, Germany
70: Research School of Astronomy and Astrophysics, Australian National University, Canberra ACT 0200, Australia
71: Department of Physics and Astronomy, University of California, Los Angeles, CA 90095, USA
72: INFN Sezione di Bari and Politecnico di Bari, via Orabona 4, 70124 Bari, Italy
73: Laboratoire de Physique des 2 infinis, Irene Joliot-Curie,IN2P3/CNRS, Université Paris-Saclay, Université de Paris, 15 rue Georges Clemenceau, 91406 Orsay, Cedex, France
74: INFN Sezione di Pisa, Largo Pontecorvo 3, 56217 Pisa, Italy
75: IRFU/DEDP, CEA, Université Paris-Saclay, Bat 141, 91191 Gif-sur-Yvette, France
76: INAF - Osservatorio Astronomico di Padova, Vicolo dell’Osservatorio 5, 35122 Padova, Italy
77 : INAF - Osservatorio Astronomico di Palermo "G.S. Vaiana", Piazza del Parlamento 1, 90134 Palermo, Italy
78 : School of Physics, University of Sydney, Sydney NSW 2006, Australia
79 : Sorbonne Université, Université Paris Diderot, Sorbonne Paris Cité, CNRS/IN2P3, Laboratoire de Physique Nucléaire et de Hautes Energies, LPNHE, 4 Place Jussieu, F-75005 Paris, France
80 : Instituto de Física de São Carlos, Universidade de São Paulo, Av. Trabalhador Sãocarlense, 400 - CEP 13566-590, São Carlos, SP, Brazil
81 : Departament de Física Quàntica i Astrofísica, Institut de Ciències del Cosmos, Universitat de Barcelona, IEEC-UB, Martí i Franquès, 1, 08028, Barcelona, Spain
82 : Department of Physics, Washington University, St. Louis, MO 63130, USA
83 : Saha Institute of Nuclear Physics, Bidhannagar, Kolkata-700 064, India
84 : INAF - Osservatorio Astronomico di Capodimonte, Via Salita Moiariello 16, 80131 Napoli, Italy
85 : Université de Paris, CNRS, Astroparticule et Cosmologie, 10, rue Alice Domon et Léonie Duquet, 75013 Paris Cedex 13, France
86 : Astronomy Department of Faculty of Physics, Sofia University, 5 James Bourchier Str., 1164 Sofia, Bulgaria
87 : Institut de Recherche en Astrophysique et Planétologie, CNRS-INSU, Université Paul Sabatier, 9 avenue Colonel Roche, BP 44346, 31028 Toulouse Cedex 4, France
88 : School of Physics and Astronomy, University of Minnesota, 116 Church Street S.E. Minneapolis, Minnesota 55455-0112, USA
89 : IRFU, CEA, Université Paris-Saclay, Bât 141, 91191 Gif-sur-Yvette, France
90 : INAF - Istituto di Radioastronomia, Via Gobetti 101, 40129 Bologna, Italy
91 : INAF - Istituto di Astrofisica Spaziale e Fisica Cosmica di Palermo, Via U. La Malfa 153, 90146 Palermo, Italy
92 : Astronomical Observatory, Department of Physics, University of Warsaw, Aleje Ujazdowskie 4, 00478 Warsaw, Poland
93 : Armagh Observatory and Planetarium, College Hill, Armagh BT61 9DG, United Kingdom
94 : INFN Sezione di Catania, Via S. Sofia 64, 95123 Catania, Italy
95 : INAF - Osservatorio Astronomico di Brera, Via Brera 28, 20121 Milano, Italy
96 : Kavli Institute for Particle Astrophysics and Cosmology, Department of Physics and SLAC National Accelerator Laboratory, Stanford University, 2575 Sand Hill Road, Menlo Park, CA 94025, USA
97 : Universidade Cruzeiro do Sul, Núcleo de Astrofísica Teórica (NAT/UCS), Rua Galvão Bueno 8687, Bloco B, sala 16, Libertade 01506-000 - São Paulo, Brazil
98 : Universidad de Valparaíso, Blanco 951, Valparaíso, Chile
99 : INAF - Istituto di Astrofisica e Planetologia Spaziali (IAPS), Via del Fosso del Cavaliere 100, 00133 Roma, Italy
100 : Lund Observatory, Lund University, Box 43, SE-22100 Lund, Sweden
101 : The Henryk Niewodniczański Institute of Nuclear Physics, Polish Academy of Sciences, ul. Radzikowskiego 152, 31-342 Cracow, Poland
102 : Escola de Engenharia de Lorena, Universidade de São Paulo, Área I - Estrada Municipal do Campinho, s/n°, CEP 12602-810, Pte. Nova, Lorena, Brazil
103 : INFN Sezione di Trieste and Università degli Studi di Udine, Via delle Scienze 208, 33100 Udine, Italy
104 : Palacky University Olomouc, Faculty of Science, RCPTM, 17. listopadu 1192/12, 771 46 Olomouc, Czech Republic
105 : Max-Planck-Institut für Physik, Föhringer Ring 6, 80805 München, Germany
106 : CENBG, Univ. Bordeaux, CNRS-IN2P3, UMR 5797, 19 Chemin du Solarium, CS 10120, F-33175 Gradignan Cedex, France
107 : Dublin City University, Glasnevin, Dublin 9, Ireland
108 : Dipartimento di Fisica - Università degli Studi di Torino, Via Pietro Giuria 1 - 10125 Torino, Italy
109 : Tata Institute of Fundamental Research, Homi Bhabha Road, Colaba, Mumbai 400005, India
110 : Università degli Studi di Napoli "Federico II" - Dipartimento di Fisica "E. Pancini", Complesso universitario di Monte Sant’Angelo, Via Cintia - 80126 Napoli, Italy
111 : Oskar Klein Centre, Department of Physics, University of Stockholm, Albanova, SE-10691, Sweden
112 : Yale University, Department of Physics and Astronomy, 260 Whitney Avenue, New Haven, CT 06520-8101, USA
113 : CIEMAT, Avda. Complutense 40, 28040 Madrid, Spain
114 : University of Oxford, Department of Physics, Denys Wilkinson Building, Keble Road, Oxford OX1 3RH, United Kingdom
115 : School of Physics & Astronomy, University of Southampton, University Road, Southamp- ton SO17 1BJ, United Kingdom
116 : Department of Physics and Technology, University of Bergen, Museplass 1, 5007 Bergen, Norway
117 : Western Sydney University, Locked Bag 1797, Penrith, NSW 2751, Australia
118 : School of Physical Sciences, University of Adelaide, Adelaide SA 5005, Australia
119 : INFN Sezione di Roma La Sapienza, P.le Aldo Moro, 2 - 00185 Roma, Italy
120 : INFN Sezione di Bari, via Orabona 4, 70126 Bari, Italy
121 : University of Rijeka, Department of Physics, Radmile Matejcić 2, 51000 Rijeka, Croatia
122 : Institute for Theoretical Physics and Astrophysics, Universität Würzburg, Campus Habl- land Nord, Emil-Fischer-Str. 31, 97074 Würzburg, Germany
123 : Universidade Federal Do Paraná - Setor Palotina, Departamento de Engenharias e Exatas, Rua Pioneiro, 2153, Jardim Dallas, CEP: 85950-000 Palotina, Paraná, Brazil
124 : Dept. of Physics and Astronomy, University of Leicester, Leicester, LE1 7RH, United Kingdom
125 : Univ. Grenoble Alpes, CNRS, IPAG, 414 rue de la Piscine, Domaine Universitaire, 38041 Grenoble Cedex 9, France
126 : National Centre for nuclear research (Narodowe Centrum Badań Jądrowych), Ul. Andrzeja Soltana7, 05-400 Otwock, Świerk, Poland
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Alessandro Carosi

127 : Enrico Fermi Institute, University of Chicago, 5640 South Ellis Avenue, Chicago, IL 60637, USA
128 : Institut für Physik & Astronomie, Universität Potsdam, Karl-Liebknecht-Strasse 24/25, 14476 Potsdam, Germany
129 : Department of Physics and Astronomy, Iowa State University, Zaffarano Hall, Ames, IA 50011-3160, USA
130 : School of Physics, Aristotle University, Thessaloniki, 54124 Thessaloniki, Greece
131 : King’s College London, Strand, London, WC2R 2LS, United Kingdom
132 : Escola de Artes, Ciências e Humanidades, Universidade de São Paulo, Rua Arlindo Bettio, CEP 03828-000, 1000 São Paulo, Brazil
133 : Dept. of Astronomy & Astrophysics, Pennsylvania State University, University Park, PA 16802, USA
134 : National Technical University of Athens, Department of Physics, Zografos 9, 15780 Athens, Greece
135 : University of Wisconsin, Madison, 500 Lincoln Drive, Madison, WI, 53706, USA
136 : Astronomical Observatory of Taras Shevchenko National University of Kyiv, 3 Observatorna Street, Kyiv, 04053, Ukraine
137 : Department of Physics, Purdue University, West Lafayette, IN 47907, USA
138 : Unitat de Física de les Radiacions, Departament de Física, and CERES-IEEC, Universitat Autònoma de Barcelona, Edifici C3, Campus UAB, 08193 Bellaterra, Spain
139 : Institute for Space-Earth Environmental Research, Nagoya University, Chikusa-ku, Nagoya 464-8601, Japan
140 : Department of Physical Science, Hiroshima University, Higashi-Hiroshima, Hiroshima 739-8526, Japan
141 : Department of Physics, Nagoya University, Chikusa-ku, Nagoya, 464-8602, Japan
142 : Friedrich-Alexander-Universität Erlangen-Nürnberg, Erlangen Centre for Astroparticle Physics (ECAP), Erwin-Rommel-Str. 1, 91058 Erlangen, Germany
143 : Santa Cruz Institute for Particle Physics and Department of Physics, University of California, Santa Cruz, 1156 High Street, Santa Cruz, CA 95064, USA
144 : IRFU/ DIS, CEA, Université de Paris-Saclay, Bat 123, 91191 Gif-sur-Yvette, France
145 : INFN Sezione di Trieste and Università degli Studi di Trieste, Via Valerio 2 I, 34127 Trieste, Italy
146 : School of Physics & Center for Relativistic Astrophysics, Georgia Institute of Technology, 837 State Street, Atlanta, Georgia, 30332-0430, USA
147 : Alikhanyan National Science Laboratory, Yerevan Physics Institute, 2 Alikhanyan Brothers St., 0036, Yerevan, Armenia
148 : INAF - Telescopio Nazionale Galileo, Roche de los Muchachos Astronomical Observatory, 38787 Garafia, TF, Italy
149 : INFN Sezione di Bari and Università degli Studi di Bari, via Orabona 4, 70124 Bari, Italy
150 : University of Split - FESB, R. Boskovica 32, 21 000 Split, Croatia
151 : Universidad Andres Bello, República 252, Santiago, Chile
152 : Academic Computer Centre CYFRONET AGH, ul. Nawojki 11, 30-950 Cracow, Poland
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Alessandro Carosi

153: University of Liverpool, Oliver Lodge Laboratory, Liverpool L69 7ZE, United Kingdom
154: Department of Physics, Yamagata University, Yamagata, Yamagata 990-8560, Japan
155: Astronomy Department, Adler Planetarium and Astronomy Museum, Chicago, IL 60605, USA
156: Faculty of Management Information, Yamanashi-Gakuin University, Kofu, Yamanashi 400-8575, Japan
157: Department of Physics, Tokai University, 4-1-1, Kita-Kaname, Hiratsuka, Kanagawa 259-1292, Japan
158: Centre for Astrophysics Research, Science & Technology Research Institute, University of Hertfordshire, College Lane, Hertfordshire AL10 9AB, United Kingdom
159: Cherenkov Telescope Array Observatory, Saupfercheckweg 1, 69117 Heidelberg, Germany
160: Tohoku University, Astronomical Institute, Aobaku, Sendai 980-8578, Japan
161: Department of Physics, Rikkyo University, 3-34-1 Nishi-Ikebukuro, Toshima-ku, Tokyo, Japan
162: Department of Physics and Astronomy and the Bartol Research Institute, University of Delaware, Newark, DE 19716, USA
163: Institut für Astro- und Teilchenphysik, Leopold-Franzens-Universität, Technikerstr. 25/8, 6020 Innsbruck, Austria
164: Department of Physics and Astronomy, University of Utah, Salt Lake City, UT 84112-0830, USA
165: IMAPP, Radboud University Nijmegen, P.O. Box 9010, 6500 GL Nijmegen, The Netherlands
166: Josip Juraj Strossmayer University of Osijek, Trg Ljudevitija Gaja 6, 31000 Osijek, Croatia
167: Department of Earth and Space Science, Graduate School of Science, Osaka University, Toyonaka 560-0043, Japan
168: Yukawa Institute for Theoretical Physics, Kyoto University, Kyoto 606-8502, Japan
169: Astronomical Observatory, Jagiellonian University, ul. Orla 171, 30-244 Cracow, Poland
170: Landessternwarte, Zentrum für Astronomie der Universität Heidelberg, Königstuhl 12, 69117 Heidelberg, Germany
171: University of Alabama, Tuscaloosa, Department of Physics and Astronomy, Gallalee Hall, Box 870324 Tuscaloosa, AL 35487-0324, USA
172: Department of Physics, University of Bath, Claverton Down, Bath BA2 7AY, United Kingdom
173: University of Iowa, Department of Physics and Astronomy, Van Allen Hall, Iowa City, IA 52242, USA
174: Anton Pannekoek Institute/GRAPPA, University of Amsterdam, Science Park 904 1098 XH Amsterdam, The Netherlands
175: Faculty of Computer Science, Electronics and Telecommunications, AGH University of Science and Technology, Kraków, al. Mickiewicza 30, 30-059 Cracow, Poland
176: Faculty of Science, Ibaraki University, Mito, Ibaraki, 310-8512, Japan
177: Faculty of Science and Engineering, Waseda University, Shinjuku, Tokyo 169-8555, Japan
178 : Institute of Astronomy, Faculty of Physics, Astronomy and Informatics, Nicolaus Copernicus University in Toruń, ul. Grudziądzka 5, 87-100 Toruń, Poland
179 : Graduate School of Science and Engineering, Saitama University, 255 Simo-Ohkubo, Sakura-ku, Saitama city, Saitama 338-8570, Japan
180 : Division of Physics and Astronomy, Graduate School of Science, Kyoto University, Sakyo-ku, Kyoto, 606-8502, Japan
181 : Centre for Quantum Technologies, National University Singapore, Block S15, 3 Science Drive 2, Singapore 117543, Singapore
182 : Institute of Particle and Nuclear Studies, KEK (High Energy Accelerator Research Organization), 1-1 Oho, Tsukuba, 305-0801, Japan
183 : Department of Physics and Astronomy, University of Sheffield, Hounsfield Road, Sheffield S3 7RH, United Kingdom
184 : Centro de Ciências Naturais e Humanas, Universidade Federal do ABC, Av. dos Estados, 5001, CEP: 09.210-580, Santo André - SP, Brazil
185 : Dipartimento di Fisica e Astronomia, Sezione Astrofisica, Università di Catania, Via S. Sofia 78, I-95123 Catania, Italy
186 : Department of Physics, Humboldt University Berlin, Newtonstr. 15, 12489 Berlin, Germany
187 : Texas Tech University, 2500 Broadway, Lubbock, Texas 79409-1035, USA
188 : University of Zielona Góra, ul. Licealna 9, 65-417 Zielona Góra, Poland
189 : Institute for Nuclear Research and Nuclear Energy, Bulgarian Academy of Sciences, 72 boul. Tsarigradsko chaussee, 1784 Sofia, Bulgaria
190 : University of Białystok, Faculty of Physics, ul. K. Ciołkowskiego 1L, 15-254 Białystok, Poland
191 : Faculty of Physics, National and Kapodestrian University of Athens, Panepistimiopolis, 15771 Ilisia, Athens, Greece
192 : Universidad de Chile, Av. Libertador Bernardo O’Higgins 1058, Santiago, Chile
193 : Hiroshima Astrophysical Science Center, Hiroshima University, Higashi-Hiroshima, Hiroshima 739-8526, Japan
194 : Department of Applied Physics, University of Miyazaki, 1-1 Gakuen Kibana-dai Nishi, Miyazaki, 889-2192, Japan
195 : School of Allied Health Sciences, Kitasato University, Sagamihara, Kanagawa 228-8555, Japan
196 : Departamento de Astronomía, Universidad de Concepción, Barrio Universitario S/N, Concepción, Chile
197 : Charles University, Institute of Particle & Nuclear Physics, V Holešovičkách 2, 180 00 Prague 8, Czech Republic
198 : Astronomical Observatory of Ivan Franko National University of Lviv, 8 Kyryla i Mephodia Street, Lviv, 79005, Ukraine
199 : Kobayashi-Maskawa Institute (KMI) for the Origin of Particles and the Universe, Nagoya University, Chikusa-ku, Nagoya 464-8602, Japan
200 : Graduate School of Technology, Industrial and Social Sciences, Tokushima University, Tokushima 770-8506, Japan
201 : Space Research Centre, Polish Academy of Sciences, ul. Bartycka 18A, 00-716 Warsaw, Poland

202 : Instituto de Física - Universidade de São Paulo, Rua do Matão Travessa R Nr.187 CEP 05508-090 Cidade Universitária, São Paulo, Brazil

203 : International Institute of Physics at the Federal University of Rio Grande do Norte, Campus Universitário, Lagoa Nova CEP 59078-970 Rio Grande do Norte, Brazil

204 : University College Dublin, Belfield, Dublin 4, Ireland

205 : Centre for Astro-Particle Physics (CAPP) and Department of Physics, University of Johannesburg, PO Box 524, Auckland Park 2006, South Africa

206 : Departamento de Física, Facultad de Ciencias Básicas, Universidad Metropolitana de Ciencias de la Educación, Santiago, Chile

207 : Núcleo de Formação de Professores - Universidade Federal de São Carlos, Rodovia Washington Luis, km 235 CEP 13565-905 - SP-310 São Carlos - São Paulo, Brazil

208 : Physik-Institut, Universität Zürich, Winterthurerstrasse 190, 8057 Zürich, Switzerland

209 : Department of Physical Sciences, Aoyama Gakuin University, Fuchinobe, Sagamihara, Kanagawa, 252-5258, Japan

210 : University of the Free State, Nelson Mandela Avenue, Bloemfontein, 9300, South Africa

211 : Faculty of Electronics and Information, Warsaw University of Technology, ul. Nowowiejska 15/19, 00-665 Warsaw, Poland

212 : Rudjer Boskovic Institute, Bijenicka 54, 10 000 Zagreb, Croatia

213 : Department of Physics, Konan University, Kobe, Hyogo, 658-8501, Japan

214 : Kumamoto University, 2-39-1 Kurokami, Kumamoto, 860-8555, Japan

215 : University School for Advanced Studies IUSS Pavia, Palazzo del Broletto, Piazza della Vittoria 15, 27100 Pavia, Italy

216 : Aalto University, Otakaari 1, 00076 Aalto, Finland

217 : Agenzia Spaziale Italiana (ASI), 00133 Roma, Italy

218 : Observatoire de la Cote d’Azur, Boulevard de l’Observatoire CS34229, 06304 Nice Cedex 4, France