PROCEEDINGS OF SCIENCE

The Zirè experiment on board the NUSES space mission

Mateo Fernandez Alonso,[a,b,*] **Felicia C.T. Barbato,**[a,b] **Ivan De Mitri,**[a,b] **Adriano Di Giovanni**[a,b] **and Margherita Di Santo**[a,b] **for the NUSES collaboration**

[a] *Gran Sasso Science Institute,*
Viale Francesco Crispi 7, L'Aquila (AQ) 67100, Italy

[b] *Istituto Nazionale di Fisica Nucleare (INFN), Laboratori Nazionali del Gran Sasso,*
Assergi (AQ), I-67100, Italy

E-mail: mateo.fernandez@gssi.it, ivan.demitri@gssi.it

The Zirè experiment is part of the NUSES (NeUtrino and Seismic Electromagnetic Signals) space mission, proposed by the Gran Sasso Science Institute (GSSI) in collaboration with the Istituto Nazionale di Fisica Nucleare (INFN) and by Thales Alenia Space Italy (TAS-I), involving many Institutes and Universities from Europe and abroad. Zirè will perform measurements of electrons, protons and light nuclei from few up to hundreds of MeVs, for the study of low energy CRs, space weather phenomena and possible Magnetosphere-Litosphere-Ionosphere Coupling (MILC) signals. A further goal of the experiment is to test new tools for the detection of photons in the energy range 0.1 MeV - 50 MeV, allowing the investigation of transient phenomena and steady gamma sources. Zirè will also test an innovative feature for space-based particle detectors, exploiting a full Silicon Photo Multiplier (SiPM) technology for the readout system. In this work, a general overview of the design activities, together with the scientific goals and the development status of the Zirè payload will be presented.

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1. Introduction

The NUSES space mission project aims to exploit the conceptual heritage of past and on-going missions but also moving towards the exploration of advanced technologies for detectors operating on board satellites dedicated to the investigation of different scientific topics, playing the role of pathfinder for future experiments in Space [1]. This project has been proposed and led by the Gran Sasso Science Institute (GSSI) with the support of the Istituto Nazionale di Fisica Nucleare (INFN) and the industrial partnership with Thales Alenia Space Italy (TAS-I), involving many Institutes and Universities from Italy and abroad. It has also been approved by the Italian Space Agency (ASI).
The NUSES satellite will host two different instruments: TERZINA, devoted to the exploration of new observational approaches in the study of Ultra High Energy Cosmic Rays (UHECRs) and neutrino astronomy, and Zirè, which will detect low energy photons and Cosmic Rays (CRs) and investigate on possible correlations between natural activities occurring on Earth and unexpected phenomena in the surrounding magnetosphere and ionosphere such as particle bursts.
NUSES will fly on a Low Earth Orbit (LEO) at an altitude of 550 km at high inclination of 97.8°, traveling in a Sun-Synchronous and dusk-dawn mode along the day/night boundary line. The Zirè detector, together with a specific payload extension named Low Energy Module (LEM) designed for the detection of low energy electrons, will have several observational windows for different scientific purposes, while the Terzina telescope will be installed on top of the NUSES platform pointing at the dark side of the Earth's limb and exploring the Cherenkov light detection technique in space [2]. A schematic view of the NUSES satellite design is shown in Fig.1, where the position and pointing direction of the instruments is highlighted.
This work will focus on the Zirè experiment, by describing the scientific framework in which this instrument will start its exploration and the studies about its design.

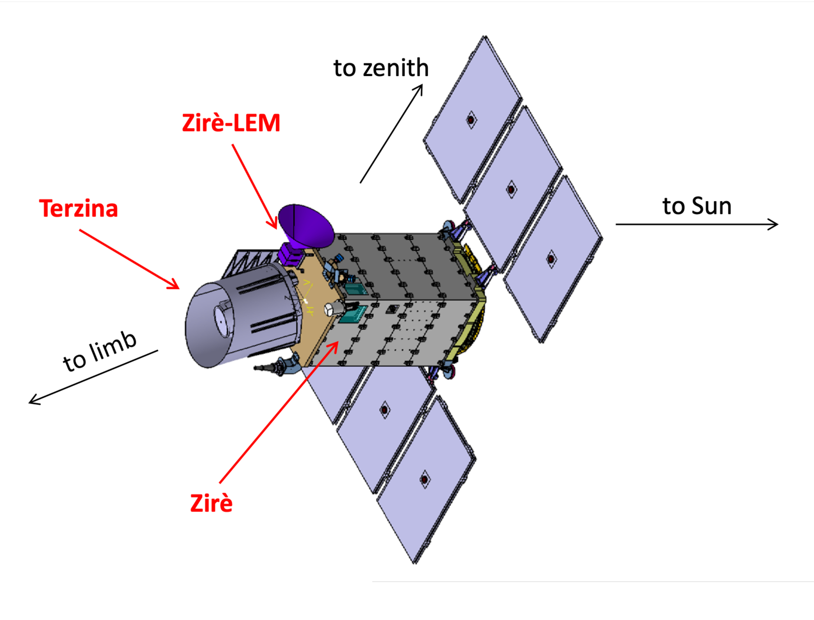

Figure 1: General scheme of the NUSES satellite design. The conical structure close to the LEM is just showing its Field Of View (FOV).

2. The Zirè experiment

The main purpose of the Zirè experiment is to detect Cosmic Rays with energies from few up to hundreds of MeVs, not only for the study of their spectral features, but also looking for possible hints of anomalies in their counting rates which can be eventually linked to natural events occurring on Earth such as earthquakes, volcanic eruptions or associated with strong Gamma Ray Bursts (GRBs).
Several experiments, both on ground and orbiting in Space at Low Earth Orbit altitudes, have already observed unexpected phenomena in the ionosphere such as electromagnetic and plasma density perturbations or an anomalous rise of low-energy electron and proton counting rates trapped in the Van Allen Belts (VABs). These observations could be theoretically well described by the *Magnetospheric-Ionospheric-Lithospheric Coupling* (MILC) model [3]. The study of low energy Galactic Cosmic Rays could also allow the monitoring of an high intensity solar particle emission, since their energy spectrum is strongly affected by the solar activity, especially for particles with rigidity lower than 10 GV. Solar activity is characterized by a periodicity of about 11 years and consists also on transient phenomena such as solar flares and Coronal Mass Ejections (CME). These events cause the emission of Solar Energy Particles (SEPs) with energies from a few tens of keV to a few GeV which are accelerated and transported by the heliosphere, reaching the Earth and being responsible of space weather phenomena such as geomagnetic storms.
The Zirè payload will also be devoted to the detection of photons with energies from 0.1 MeV up to few tens of MeVs allowing the study of transient (Gamma Ray Bursts, elettromagnetic follow-up of GW events, SN emission lines,...) and steady γ sources. Given the instruments onboard Zirè, possible correlations of large intensity GRBs with local effects on charge particles might also be studied [4].

2.1 The Zirè design

A sectional view of the CAD design for the Zirè module is shown in Fig. 2. It basically consists in a small calorimeter for spectral measurements of Cosmic Ray electrons, protons and light nuclei, which starting from the left in Fig. 2, is composed by:

- three X-Y modules of Fiber TracKer (FTK) with 9.6×9.6 cm^2 of cross section and 2.5 cm of spacing. Each module consists of two planes and the fibers of each plane will be orthogonal to those of the next. The fibers have a double-layer structure consisting of a polystyrene core (inner side) with a fluorescent agent (n=1.59), an inner cladding of Polymethylmethacrylate (PMMA) (n=1.49) and an outer cladding of fluorinated polymer (n=1.42).The total thickness of each module is about 2×0.8 mm to reduce the multiple Coulomb scattering and to keep the charged particle energy loss as low as possible [5];

- a tower of 32 Plastic Scintillator (PS) layers (PST), each one composed by three PS X-Y bars. The first six layers of the PST, namely the ones below the FTK, are of 12 cm $\times$ 12 cm $\times$ 1 cm, while the other 26 layers have dimensions of 12 cm $\times$ 12 cm $\times$ 0.5 cm;

- a calorimeter (CALOg) made by a 4×4×2 matrix of Lutetium-yttrium oxyorthosilicate (LYSO) boxes with size 2.5 cm $\times$ 2.5 cm $\times$ 3.0 cm;

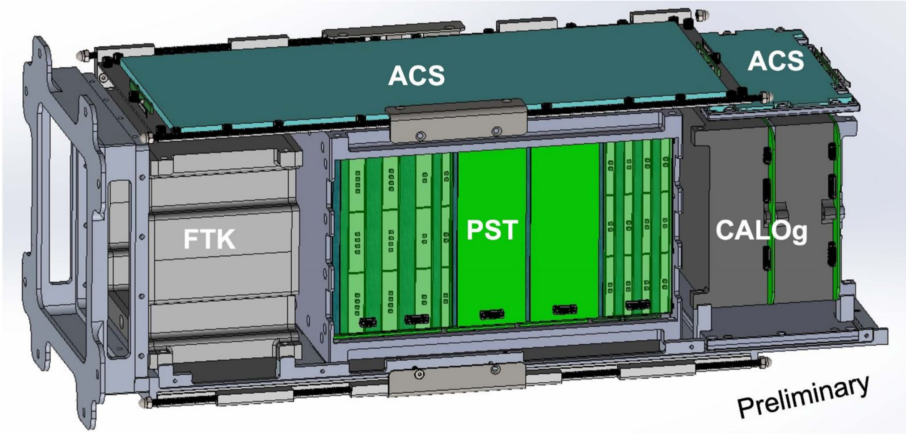

Figure 2: Preliminary mechanical design of the Zirè detector. Charged particles will reach the detector from the left through a dedicated thin window, crossing the FTK, PST and then the CALOg (see text). Low energy gamma-ray measurements will be done using two additional windows placed close to the CALOg (right and top side in the image, corresponding to horizontal (H) and zenith (V) direction respectively). The LEM sub-detector is not shown in this figure.

- 9 PS layers with 0.5 cm of thickness working as AntiCoincidence System (ACS) surrounding the instrument from all the directions except for the one where the FTK is located.

The line of sight of FTK, PST and CALOg will always be pointing towards the celestial horizon, with three entrance windows: one on the FTK side and the other two on the CALOg (one towards the horizon and the other towards zenith, H and V respectively). The ACS surrounds the detector on its five sides, except the FTK entrance window, thus acting, with the FTK, as anticoincidence for gamma-ray events. The FTK, PST and CALOg subdetectors will also provide different triggers such as the MIP, the High Energy (HE) and Low Energy (LE) triggers for protons, electrons and γ-rays by remotely setting the needed requirements from ground about the number of layers with signals and the energy thresholds. The readout of each subdetector will be performed with Silicon Photo Multipliers (SiPMs), replacing the PhotoMultiplier Tubes (PMTs) mostly adopted for experiments in Space. The innovative use of SiPMs both for Zirè and Terzina experiments onboard the NUSES satellite, is one of the features of this space mission. Indeed, a full SiPM-based technology turns out to be the best choice not only for the reduced size and the low power consumption of such sensors, but also for their excellent detection capability.

Preliminary Monte Carlo (MC) simulations of incoming electron and proton events have been performed by using the Geant4 toolkit [6]. Two examples of simulated events for an incoming proton and an electron crossing the Zirè detector are shown in Fig. 3. The produced MC data set allowed a first study of the detector performances, such as the shower containment and the effective acceptance. A preliminary estimate of the effective acceptance for both protons and electrons is shown in Fig. 4, obtained by selecting those events satisfying a trigger activation requirement consisting on an energy deposit greater than 0.1 MeV and 0.3 MeV in the FTK and in the first PST layer (PS0) respectively, together with the full containment request. Further MC simulations have been carried out to generate 100k events of electrons, protons and helium nuclei with continuous energy spectrum from 2 MeV up to 500 MeV. From the analysis of these simulated data, the particle

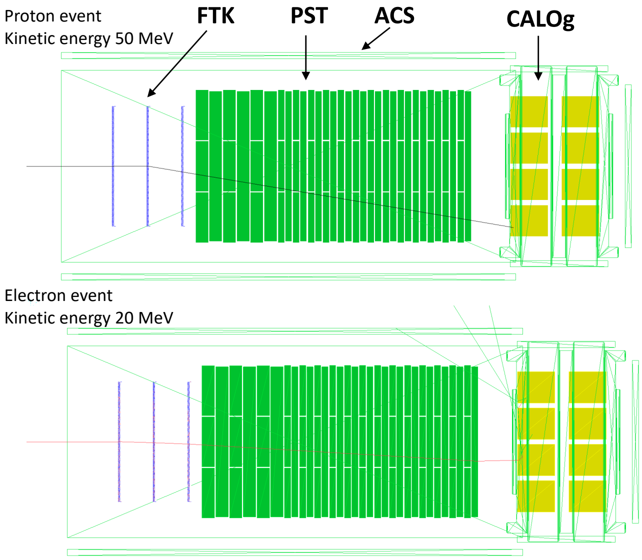

Figure 3: Display of two simulated events, one for an incoming proton with 50 MeV of kinetic energy (Top view) and the other one for an electron with energy of 20 MeV (Bottom view) crossing the Zirè detector, where the FTK is represented in blue, the PST in green, the CALOg in yellow and the ACS layers are depicted only by their green edges for visualization reasons.

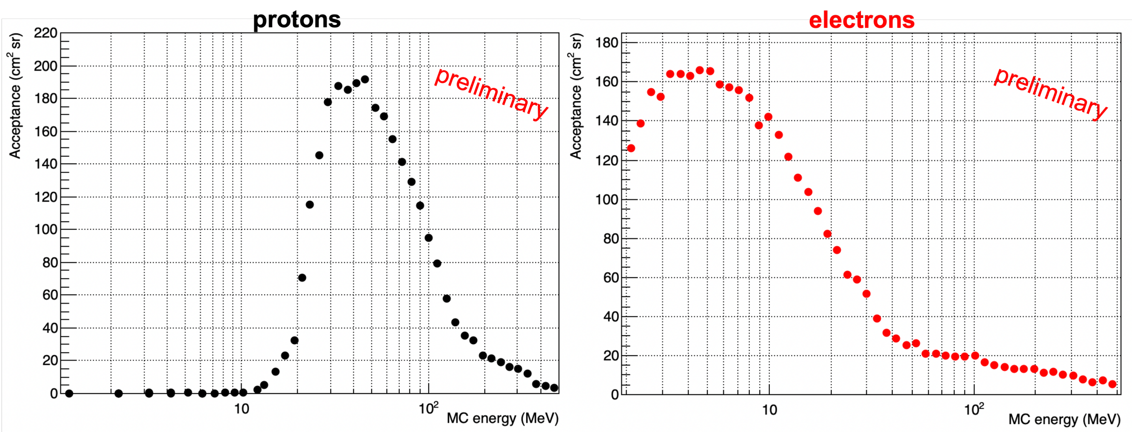

Figure 4: Preliminary effective acceptance for protons (Left) and electrons (Right) obtained by selecting all those events satisfying a trigger and a full containment requirement.

identification capability for the Zirè module can be observed looking at the plot of the energy deposit inside the FTK+PS0 as a function of the inverse of the total energy deposition inside the whole detector, as shown in Fig. 5 where the sample separation is clearly observable.

The CALOg sub-detector will be also independently used for the study of low energy gamma rays in the energy range between 0.1 MeV-50 MeV. Two windows in the structure surrounding the CALOg have been specifically included in the design for this purpose (see Fig. 2), one pointing

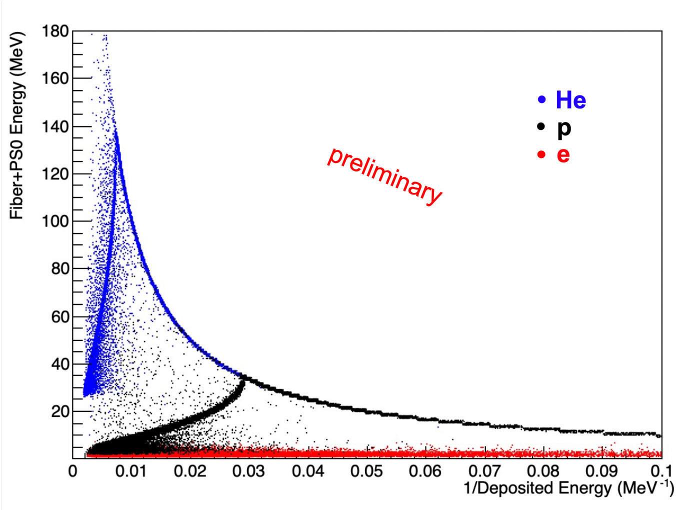

Figure 5: (Left) Total energy deposition inside the Fiber tracker and the first layer of the PST (PS0) as a function of the inverse of the energy deposited inside the full instrument for contained electron (in red), proton (in black) and helium (in blue) simulated events.

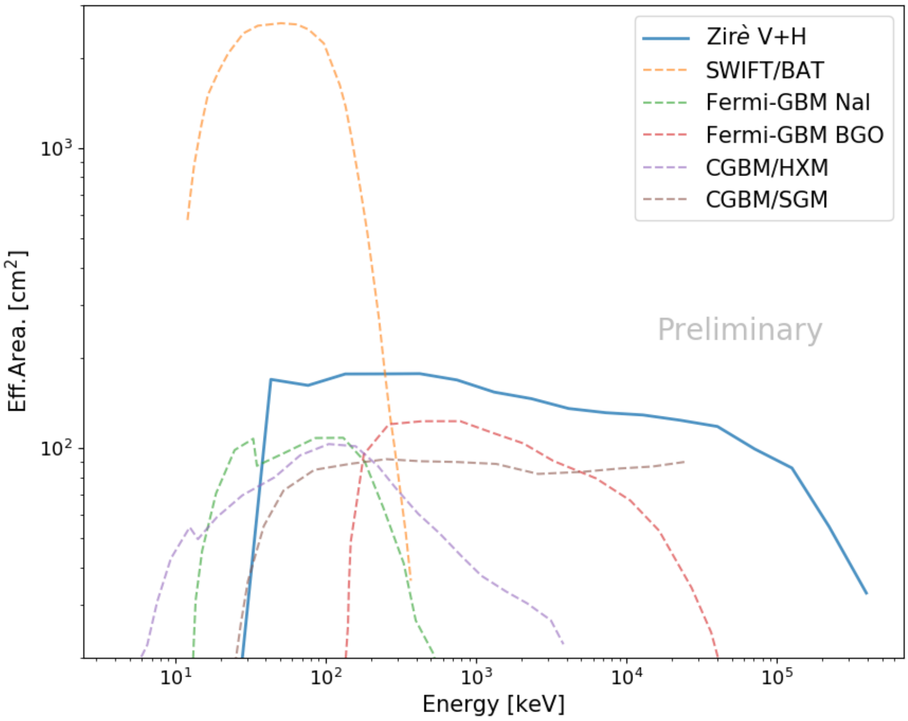

Figure 6: Preliminary estimate of the Zirè (V+H) effective area for gamma detection, along with the analogous curves from Fermi-GBM (NaI/BGO) [7], CALET-GBM (HXM/SGM) [8] and SWIFT/BAT [9].

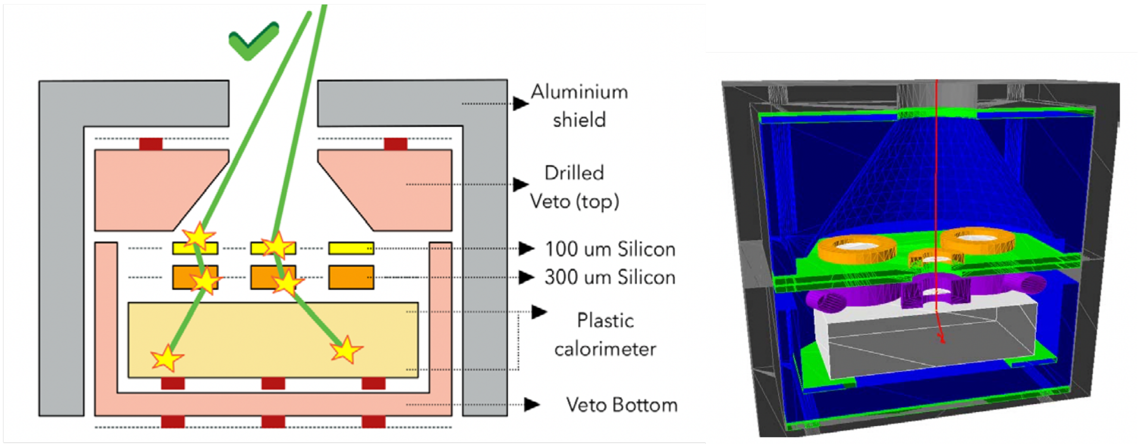

Figure 7: Geometry and detection concept of LEM instrument (Left) and GEANT4 geometry used for preliminary MC simulations (Right).

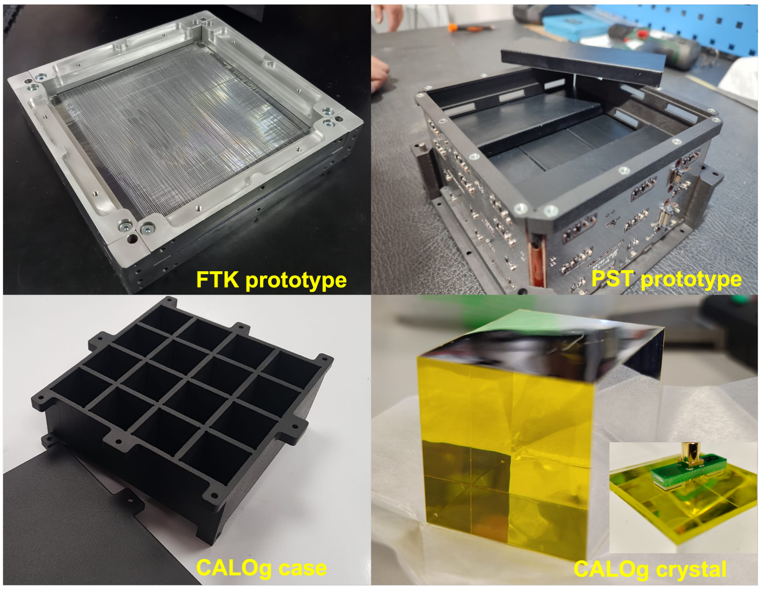

Figure 8: Pictures of the FTK, PST and CALOg sub-detectors already assembled for the Zirèttino prototype (see text). In this case also GAGG crystals will be tested.

towards the zenith (Zirè V) and another towards the horizon (Zirè H). Fig. 6 shows a preliminary estimation of the effective area summing the contributions of the two observing windows. The features in the curve and its general trend toward higher energies can be explained from the LYSO absorption properties and the applied selection cuts.

A specific Zirè payload extension named Low Energy Module (LEM) will be designed for the detection of low energy electrons (namely, with energies lower than 7 MeV) and protons (in the 3 MeV- 50 MeV range) which could provide a larger sensitivity for MILC studies. Hence, the LEM module will be a particle spectrometer for time resolved measurements of differential flux distribution of low-energy charged particles. It will be installed on an ACS layer of Zirè and will consist of 5 independent silicon detectors, a plastic calorimeter, 2 veto systems on top and at the bottom of the instrument, everything surrounded by an aluminum mask with a scintillating collimator for the direction reconstruction of the incoming particle. The design of the LEM and its detection concept is shown in Fig. 7, together with the GEANT4 geometry used for preliminary MC simulations [10].

A small prototype of the Zirè detector, called Zirèttino, has been built-up in order to test/calibrate the different subdetectors and acquisition chain by using cosmic rays in the lab and with beam-test activities at CERN. A collection of few pictures for the sub-detectors of the Zirèttino detector is shown in Fig. 8.

3. Conclusions and Outlook

The Zirè detector flying onboard the NUSES satellite will contribute not only to the investigation of different scientific topics involving low energy Galactic Cosmic Rays and gamma rays in the keV-MeV regime, but it will also play a crucial role in the development and testing of advanced technologies such as the SiPM-based one to be used for detectors in space. Many activities are currently on-going for the optimization of the instrument design in order to ensure the best performances for its scientific goals and a test of a dedicated prototype is about to be carried out.

Acknowledgements

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Full Authors List: NUSES Collaboration

R. Aloisio[1,2], C. Altomare[3], F. C. T. Barbato[1,2], R. Battiston[4,5], M. Bertaina[6,7], E. Bissaldi[3,8], D. Boncioli[2,9], L. Burmistrov[10], I. Cagnoli[1,2], M. Casolino[11,12], A. Cummings[13], N. D'Ambrosio[2], I. De Mitri[1,2], G. De Robertis[3], C. De Santis[11], A. Di Giovanni[1,2], A. Di Salvo[7], M. Di Santo[1,2], L. Di Venere[3], J. Eser[14], M. Fernandez Alonso[1,2], G. Fontanella[1,2], P. Fusco[3,8], S. Garbolino[7], F. Gargano[3], R. A. Giampaolo[1,7], M. Giliberti[3,8], F. Guarino[15,16], M. Heller[10], R. Iuppa[4,5], J. F. Krizmanic[17,18], A. Lega[4,5], F. Licciulli[3], F. Loparco[3,8], L. Lorusso[3,8], M. Mariotti[19,20], M. N. Mazziotta[3], M. Mese[15,16], H. Miyamoto[1,7], T. Montaruli[10], A. Nagai[10], R. Nicolaidis[4,5], F. Nozzoli[4,5], A. V. Olinto[14], D. Orlandi[2], G. Osteria[15], P. A. Palmieri[6,7], B. Panico[15,16], G. Panzarini[3,8], A. Parenti[1,2], L. Perrone[21,22], P. Picozza[12,11], R. Pillera[3,8], R. Rando[19,20], M. Rinaldi[11], A. Rivetti[7], V. Rizi[2,9], F. Salamida[2,9], E. Santero Mormile[6], V. Scherini[21,22], V. Scotti[15,16], D. Serini[3], I. Siddique[1,2], L. Silveri[1,2], A. Smirnov[1,2], R. Sparvoli[11], S. Tedesco[7,23], C. Trimarelli[10], L. Wu[1,2,†], P. Zuccon[4,5], S. C. Zugravel[7,23].

[1]Gran Sasso Science Institute (GSSI), Via Iacobucci 2, I-67100 L'Aquila, Italy
[2]Istituto Nazionale di Fisica Nucleare (INFN) - Laboratori Nazionali del Gran Sasso, I-67100 Assergi, L'Aquila, Italy
[3]Istituto Nazionale di Fisica Nucleare, Sezione di Bari, via Orabona 4, I-70126 Bari, Italy
[4]Dipartimento di Fisica, Università di Trento, via Sommarive 14 I-38123 Trento, Italy
[5]Istituto Nazionale di Fisica Nucleare (INFN) - TIFPA, via Sommarive 14 I-38123 Trento, Italy
[6]Dipartimento di Fisica, Università di Torino, Via P. Giuria, 1 I-10125 Torino, Italy
[7]Istituto Nazionale di Fisica Nucleare (INFN) - Sezione di Torino, I-10125 Torino, Italy
[8]Dipartimento di Fisica M. Merlin, dell'Università e del Politecnico di Bari, via Amendola 173, I-70126 Bari, Italy
[9]Dipartimento di Scienze Fisiche e Chimiche, Università degli Studi di L'Aquila, I-67100 L'Aquila, Italy
[10]Département de Physique Nuclèaire et Corpusculaire, Université de Genève, 1205 Genève, Switzerland
[11]INFN Roma Tor Vergata, Dipartimento di Fisica, Universitá di Roma Tor Vergata, Roma, Italy
[12]RIKEN, 2-1 Hirosawa, Wako, Saitama, Japan
[13]Departments of Physics and Astronomy & Astrophysics, Institute for Gravitation and the Cosmos, Pennsylvania State University, University Park, PA 16802, USA
[14]Department of Astrophysics & Astronomy, The University of Chicago, Chicago, IL 60637, USA
[15]Istituto Nazionale di Fisica Nucleare, Sezione di Napoli, via Cintia, I-80126 Napoli, Italy
[16]Dipartimento di Fisica E. Pancini dell'Università di Napoli Federico II, via Cintia, I-80126 Napoli, Italy
[17]CRESST/NASA Goddard Space Flight Center, Greenbelt, MD 20771, USA
[18]University of Maryland, Baltimore County, Baltimore, MD 21250, USA
[19]Università di Padova, I-35122 Padova, Italy
[20]Istituto Nazionale di Fisica Nucleare (INFN) - Sezione di Padova, I-35131 Padova, Italy
[21]Dipartimento di Matematica e Fisica "E. De Giorgi", Università del Salento, Via per Arnesano, I-73100 Lecce, Italy
[22]Istituto Nazionale di Fisica Nucleare - INFN - Sezione di Lecce, Via per Arnesano, I-73100 Lecce, Italy
[23]Department of Electrical, Electronics and Communications Engineering, Politecnico di Torino, Corso Duca degli Abruzzi 24, I-10129 Torino, Italy
[†]Now at Institute of Deep Space Sciences, Deep Space Exploration Laboratory, Hefei 230026, China