PROCEEDINGS OF SCIENCE

Search for Strange Quark Matter from the International Space Station with the Mini-EUSO experiment

M. Casolino[a,*] **for the JEM-EUSO Collaboration**
(a complete list of authors can be found at the end of the proceedings)

[a] *Institution,*
Street number, City, Country

E-mail: casolino@roma2.infn.it

Mini-EUSO (Multiwavelength Imaging New Instrument for the Extreme Universe Space Observatory) is a telescope observing the Earth from the International Space Station since 2019. The instrument employs a Fresnel-lens optical system and a focal surface composed of 36 Multi-Anode Photomultiplier tubes, 64 channels each, for a total of 2304 channels with single photon counting sensitivity. Mini-EUSO observes the night-time Earth in the near UV range (predominantly between 290 - 430 nm) with a spatial resolution of about 6.3 km (full field of view equal to 44°) and a temporal resolution of 2.5 μs, observing our planet through a nadir-facing UV-transparent window located in the Russian Zvezda module. The detector can thus acquire triggered transient phenomena with a sampling rate of 2.5 μs and 320 μs, as well as perform continuous acquisition at 40.96 ms scale. Among the scientific objectives addressed by the mission is the observation of meteors (at the 40.96 ms time frame), the search for interstellar meteors and amongst them, the search for strange quark matter (SQM), appearing as anomalous (long track and fast-moving) meteor events. In this paper we discuss the observational capabilities for Mini-EUSO and the limits it will pose to SQM and other Macro-like particles.

PoS(ICRC2023)1410

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

ICRC2023
38th International Cosmic Ray Conference
The Astroparticle Physics Conference

---

[*] Speaker

https://pos.sissa.it/

1. Introduction

Mini-EUSO (Multiwavelength Imaging New Instrument for the Extreme Universe Space Observatory, known as *UV atmosphere* in the Russian Space Program) is a telescope operating in the near UV range, predominantly between 290 - 430 nm, with a square focal surface corresponding to a square field of view of 44°. Its spatial resolution at ground level is $\simeq 6.3 \times 6.3$ km^2, varying slightly with the altitude of the International Space Station (ISS) and the pointing direction of each pixel. Mini-EUSO was launched with the uncrewed Soyuz MS-14, on 2019-08-22. The first observations, from the nadir-facing UV-transparent window in the Russian Zvezda module, took place on 2019-10-07[1].

The Mini-EUSO detector was originally designed for the development of the study of Ultra High Energy Cosmic Rays (UHECRs) from space [2], as part of an ongoing effort by the JEM-EUSO (Joint Exploratory Missions for Extreme Universe Space Observatory) collaboration. So far, various instruments have been constructed and operated on the ground (EUSO-TA [3]), on stratospheric balloons (EUSO-Balloon [4, 5], EUSO-SPB1 [6] and EUSO-SPB2 [7]) and in space (TUS [8], in addition to the planned K-EUSO [9] and POEMMA [10, 11] missions).

The detector employs a BG3 filter (280 - 430 nm at 50% transmission) on its focal surface to perform observations where most of the fluorescence light from Extensive Air Showers (EAS) initiated by cosmic rays interacting in the atmosphere is emitted (300 - 430 nm range) [12][1], with a 48×48 pixel focal surface ($\simeq$ 6.3 km spatial resolution on the ground) and a sampling time of 2.5 μs. In the case of EAS, the light is emitted by the return to the ground state of nitrogen molecules (N_2) that are excited by the ionization of the charged particle component of the shower. In case of meteors and among them possible SQM (Strange Quark Matter) candidates, the ablation with the atmosphere makes them emit light detectable with Mini-EUSO continuous data readout at 40.96 ms.

2. Strange Quark Matter and other cold, penetrating matter

The existence of a different state of hadronic matter other than ordinary nuclear matter, called Strange Quark Matter (SQM), was proposed for the first time in the 1980s [15] . This kind of hadronic matter would be composed by a roughly equivalent number of u, d, and s quarks. Many models suggest that the presence of strange quarks in hadrons may lower the nucleon Fermi level with respect to a system with only ordinary quark flavours. If that is the case, SQM should be stable and may constitute the true ground state of hadronic matter. Instead of being separated in nucleons, quarks would therefore be lumped together, with densities typically comparable to the nuclear density. Furthermore, there are many other possible massive compact objects that could be present in our Galaxy (see Figure 1: among them, we quote Q-Balls [16], magnetic monopoles [17], lumps of fermionic exotic compact stars, primordial black holes [18]; Adler et al. 2001), mirror matter [19], Fermi balls [20], electroweak symmetric dark matter balls [21], antiquark nuggets (Gorham 2012), axion quark nuggets [22], six flavor quark matter, and non-strange quark matter [23]. We also mention elementary black holes [24] and - among them - Daemons [25]. Figure

---

[1] The maximum $X_{\max}$ of a 10^{19} eV$\leq E \leq 10^{20}$ eV cosmic ray shower occurs at 750 g/cm^2 $\leq X_{\max} \leq$ 800 g/cm^2, corresponding to an altitude between 2 and 2.5 km for a vertically incident event [13, 14].

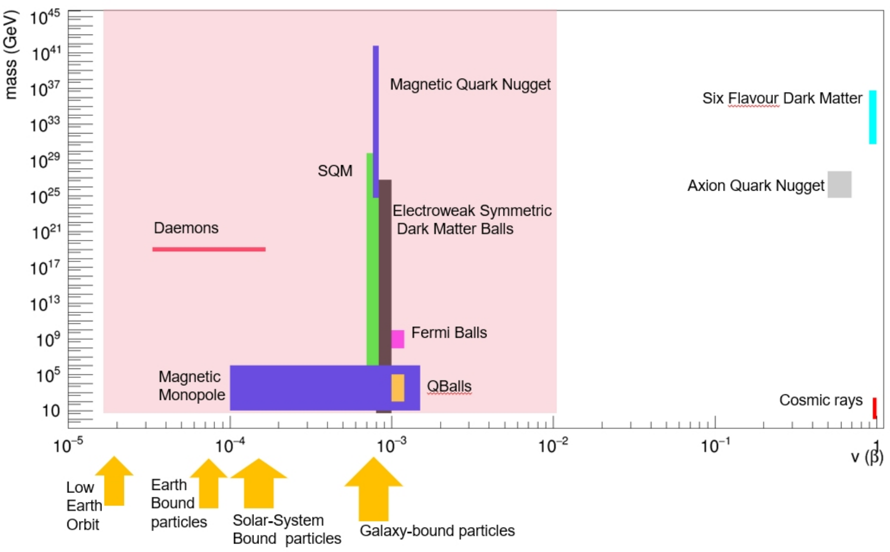

Figure 1: Plot of the velocity and mass range for various slow moving, massive particles. At the bottom right of the plot we have cosmic ray nuclei with $\beta \simeq 1$. Most of the particle types have $\beta \simeq 7 \cdot 10^{-4} - 8 \cdot 10^{-4}$ since they are considered to be bound in the Galaxy. However, many of these hypothesized particles can also have lower velocity since they could be bound in local interstellar space, in the vicinity of the Solar System, or even of our planet (e.g. Daemons). The masses range from the relatively light magnetic monopoles and Q-balls to the heavier Fermi and Dark Matter balls. SQM and Magnetic Quark Nuggets can reach the mass of a star, but only fragments are expected to reach the Earth. The mass-velocity range accessible by Mini-EUSO (for non-relativistic particles) is shown in pink.

1 shows the presumed mass and velocity range for the various candidates. We draw attention to the fact that the expected ranges for velocities, masses, and mass densities of these different candidates remain hypothetical and the literature does not offer precise values for any of these parameters. As discussed, our main target here are (very dense) particles that would be present in the Galaxy and move at typical orbital velocities, in an extended range between $3 \cdot 10^{-5}$ c and $3 \cdot 10^{-1}$ c. Many of these particles are also Dark Matter (DM) candidates: with the lack of evidence for supersymmetric neutralino-like particles from space-borne, underground-located, or accelerator (LHC) experiments, these hypotheses are being examined with increasing detail. These particles could account for a part or all the DM component in our Galaxy. Therefore, the discovery of these particles would have repercussions not only in astrophysics and nuclear physics, but also for the puzzle of the DM component in our Universe. For simplicity, in this idea we use the term SQM to refer to all the aforementioned types of quark-density particles. Each particle has a different origin, flux, and interaction signatures but they can be broadly characterized as slow-moving (galactic-bound, although unbound components are also examined) and massive (from less than picograms to tons) particles. The lower velocities of these objects are particularly interesting, since there are various scenarios in which these particles are bound in the Solar System on Strongly Elongated Earth Crossing Heliocentric Orbits (SEECHOs) or even in the gravitational field of the Earth (Near Earth Almost Circular Heliocentric Orbits - NEACHOs and Geocentric Earth Surface Crossing Orbits GESCOs) [25].

SQM with an exactly equal number of u, d, and s quarks is electrically neutral. However, the neutrality condition may be expected to be only approximate, e.g. because strange quarks are heavier and thus slightly disfavoured with respect to the others [15] allowing strangelets to have a small residual electrical charge. In the case of a small excess of one quark species, a slightly charged particle would therefore have a very high mass and a low electric charge. A very large mass to-charge ratio would thus result, compared to ordinary nuclear matter (apparent $A \gg Z$ with equivalent nucleon number A and electric charge Z). The mass of a strangelet could range from the minimum stable mass, which strongly depends on the model employed for the calculations, up to values typical of a compact star, $A \simeq 10^{57}$ [26]. Several papers [27] have studied the conditions required to have stability for these objects: using the MIT bag model approximation, heavier objects appear more stable. More detailed models that take into account shell structure in the nuclear matter [28] predict stability regions for strangelets with completely filled quark shells, allowing also for lighter particles to be stable or metastable. SQM could be produced in the Big Bang (Chodos et al. 1974), be part of baryonic dark matter (Atreya et al. 2014), be present in the core of neutron stars, or exist as "strange quark stars", either 'pure' (Alcock et al. 1986; Haensel et al. 1986) or constituted of hadrons and quark (Drago et al. 2016; Drago Pagliara 2016; [29]). Other sources of SQM are the production and acceleration in the ergosphere of black holes via the Penrose process [30]. Lumps of SQM could be ejected as a consequence of collisions between these stars in binary systems [31]. Subsequent collisions among the produced fragments can inject fragments of SQM of various sizes in the Galaxy, which then reach the Earth where they could be detected with cosmic-ray detectors such as Mini-EUSO. Depending on their mass and nature, they can be stopped in the atmosphere ($m < 4 \cdot 10^{-14}$ g), ionize the atmosphere, or even cross the whole planet ($m > 10^{-9}$ g) [32]. Indeed, over the years, different balloon- and space-borne experiments have tried to detect strangelets using mass spectrometers on Earth or Moon dust, analyzing mica tracks, both with passive and active methods: PAMELA magnetic spectrometer [33]; Pi of the SKY, searching for fast meteors [34]; DIMS experiment using two cameras for a stereoscopic view of meteors and determination of their trajectory [35]; Mini-EUSO, the subject of this paper, looking for fast meteor-like events from the ISS.

figvelocity

3. Search for SQM with Mini-EUSO

Meteors are relatively slow ($v \leq 72$ km/s) and long-lasting (a few seconds) events which illuminate in sequence several light sensitive pixels of the Mini-EUSO focal surface (See Figure 2). Mini-EUSO will contribute to meteor hazard estimation by covering a projected surface on the ground of about 320 x 320 km^2 including inter-pixel dead areas (at 100 km altitude, where meteors burn, the field of view is about 240 x 240 km^2); it could be considered a precursor for the optimization of future instruments for detecting meteors from space. The maximum observable magnitude is between 4 and 5 depending on background conditions,[37]. The time dependence of the light intensity is determined for each event. The frequency-intensity distribution of the observation of meteors allows to study from space the population of near-Earth objects from space with a large field of view and the advantage of not being covered by clouds. From the two-dimensional projection of the trajectory it is also possible to reconstruct their original heliocentric orbit.

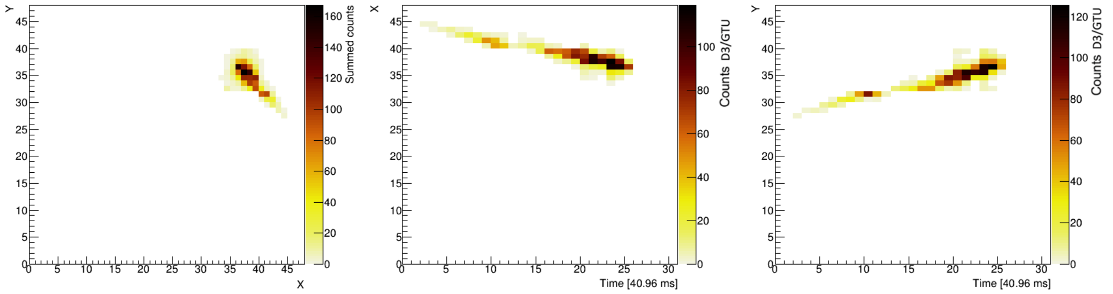

Figure 2: Top: A meteor track as it develops in the field of view of Mini-EUSO. The X and Y axis represent the PDM pixels. Bottom: the meteor track projected on the PDM (xy - Left), and on the x-t and y-t profiles (centre and right, respectively). Colour denotes counts/GTU (2.5 μs).

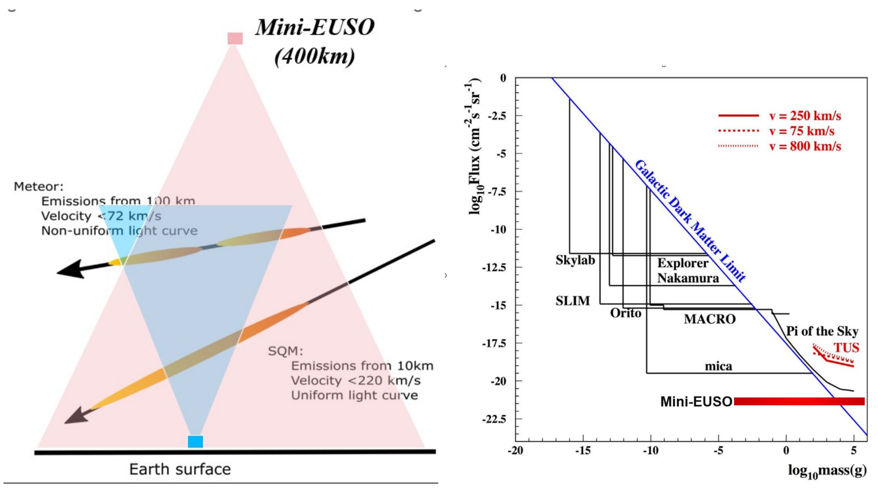

Figure 3: Left: Method of search of SQM by Mini-EUSO. Meteors burn in the atmosphere at $\simeq 100 km$ whereas SQM would have a longer track higher velocity and lower burning altitude. Right: Preliminary limits on nuclearite sensitivity of Mini-EUSO compared with previous experiments. Adapted from [36], limits are from references therein.

Mini-EUSO has so far recorded more than 24,000 meteor events in the first 44 sessions (more than 80 sessions have been acquired at the time of writing), among them the calculation for velocity, magnitude, and trajectory has been performed to look for anomalous events with velocity incompatible with events in the Solar System

If SQM nuggets - also called nuclearites - are present in our Galaxy they could encounter the Earth and interact with its atmosphere. The high density of these nuclearites would produce a long and constant signal in the atmosphere [32], with a track range incompatible with that of usual chondritic or metallic meteors. Furthermore, their interstellar origin would result in higher speed than that of solar system meteors. These features should permit a clear identification of this class of events [34]. As mentioned, Mini-EUSO is able to observe meteors down to magnitude 4 and 5, corresponding to a SQM nugget size of 10^{24} GeV/c or higher [37]. In Figure 3 is shown an estimation of the upper limit that could be reached with Mini-EUSO assuming three years of observations, with 3-4 sessions of 12 hours per month.

4. Conclusions

Mini-EUSO can observe meteors with a magnitude of M ≤ 6, depending on the background conditions. Taking advantage of its large field of view and high detection rate Mini-EUSO has been recording more than 24,000 meteor events in 44 sessions. Among them, the search for interstellar meteors and SQM is progressing, with good perspectives for a more stringent upper limit on these particles.

5. Acknowledgements

This work was supported by the Italian Space Agency through the agreement n. 2020-26-Hh.0, by the French space agency CNES, and by the National Science Centre in Poland grants 2017/27/B/ST9/02162 and 2020/37/B/ST9/01821. This research has been supported by the Interdisciplinary Scientific and Educational School of Moscow University “Fundamental and Applied Space Research” and by Russian State Space Corporation Roscosmos. The article has been prepared based on research materials collected in the space experiment “UV atmosphere”. We thank the Altea-Lidal collaboration for providing the orbital data of the ISS.

References

[1] S. Bacholle et al., *Mini-EUSO Mission to Study Earth UV Emissions on board the ISS*, *Astrophys. J. Suppl.* **253** (2021) 36 [`2010.01937`].

[2] M. Casolino, P. Klimov and L. Piotrowski, *Observation of ultra high energy cosmic rays from space: Status and perspectives*, *Progress of Theoretical and Experimental Physics* **2017** (2017) [`https://academic.oup.com/ptep/article-pdf/2017/12/12A107/23166273/ptx169.pdf`].

[3] G. Abdellaoui, S. Abe, J.H. Adams, A. Ahriche, D. Allard, L. Allen et al., *EUSO-TA - First results from a ground-based EUSO telescope*, *Astroparticle Physics* **102** (2018) 98.

[4] J.H. Adams, S. Ahmad, D. Allard, A. Anzalone, S. Bacholle, P. Barrillon et al., *A review of the euso-balloon pathfinder for the jem-euso program*, *Space Science Reviews* **218** (2022) 3.

[5] G. Abdellaoui, S. Abe, J.H. Adams, A. Ahriche, D. Allard, L. Allen et al., *Ultra-violet imaging of the night-time earth by EUSO-Balloon towards space-based ultra-high energy cosmic ray observations*, *Astroparticle Physics* **111** (2019) 54.

[6] L. Wiencke, A. Olinto and JEM-EUSO Collaboration, *EUSO-SPB1 Mission and Science*, *International Cosmic Ray Conference* **301** (2017) 1097.

[7] J. Eser, A.V. Olinto and L. Wiencke, *Science and mission status of EUSO-SPB2*, *PoS* **ICRC2021** (2021) 404.

[8] P.A. Klimov, M.I. Panasyuk, B.A. Khrenov, G.K. Garipov, N.N. Kalmykov, V.L. Petrov et al., *The tus detector of extreme energy cosmic rays on board the lomonosov satellite*, *Space Science Reviews* **212** (2017) 1687.

[9] P. Klimov, M. Battisti, A. Belov, M. Bertaina, M. Bianciotto, S. Blin-Bondil et al., *Status of the k-euso orbital detector of ultra-high energy cosmic rays*, *Universe* **8** (2022) .

[10] A. Olinto, J.H. Adams, R. Aloisio, L.A. Anchordoqui, D.R. Bergman, M.E. Bertaina et al., *POEMMA: Probe of Extreme Multi-Messenger Astrophysics*, in , vol. 51, p. 99, Sept., 2019 [`1907.06217`].

[11] A. Olinto, J. Krizmanic, J. Adams, R. Aloisio, L. Anchordoqui, A. Anzalone et al., *The POEMMA (probe of extreme multi-messenger astrophysics) observatory*, *Journal of Cosmology and Astroparticle Physics* **2021** (2021) 007.

[12] M. Ave, M. Bohacova, B. Buonomo, N. Busca, L. Cazon, S. Chemerisov et al., *Measurement of the pressure dependence of air fluorescence emission induced by electrons*, *Astroparticle Physics* **28** (2007) 41.

[13] R.U. Abbasi, M. Abe, T. Abu-Zayyad, M. Allen, R. Azuma, E. Barcikowski et al., *Depth of ultra high energy cosmic ray induced air shower maxima measured by the telescope array black rock and long ridge FADC fluorescence detectors and surface array in hybrid mode*, *The Astrophysical Journal* **858** (2018) 76.

[14] P.K.F. Grieder, *Cosmic rays at earth: Researcher's reference, manual and data book*, Elsevier (2001).

[15] E. Witten, *Cosmic separation of phases*, **30** (1984) 272.

[16] A. Kusenko, V. Kuzmin, M. Shaposhnikov and P.G. Tinyakov, *Experimental signatures of supersymmetric dark-matter Q-balls*, *Phys. Rev. Lett.* **80** (1998) 3185.

[17] P.B. Price, S.-l. Guo, S.P. Ahlen and R.L. Fleischer, *Search for grand-unified-theory magnetic monopoles at a flux level below the parker limit*, *Phys. Rev. Lett.* **52** (1984) 1265.

[18] Y.B. Zel'dovich and I.D. Novikov, *The Hypothesis of Cores Retarded during Expansion and the Hot Cosmological Model*, **10** (1967) 602.

[19] R. Foot and S. Gninenko, *Can the mirror world explain the ortho-positronium lifetime puzzle?*, *Physics Letters B* **480** (2000) 171.

[20] A.L. Macpherson and J.L. Pinfold, *Fermi ball detection*, 1994.

[21] E. Pontón, Y. Bai and B. Jain, *Electroweak symmetric dark matter balls*, *Journal of High Energy Physics* **2019** (2019) 11.

[22] K. Lawson and A. Zhitnitsky, *The 21 cm absorption line and the axion quark nugget dark matter model*, *Physics of the Dark Universe* **24** (2019) 100295.

[23] B. Holdom, J. Ren and C. Zhang, *Quark matter may not be strange*, *Phys. Rev. Lett.* **120** (2018) 222001.

[24] J.D. Barrow, E.J. Copeland and A.R. Liddle, *The cosmology of black hole relics*, *Phys. Rev. D* **46** (1992) 645.

[25] R. BERNABEI, P. BELLI, F. CAPPELLA, R. CERULLI, A. D'ANGELO, F. EMILIANI et al., *Search for daemons with nemesis*, *Modern Physics Letters A* **27** (2012) 1250031 [`https://doi.org/10.1142/S0217732312500319`].

[26] J. Madsen, *Strangelet propagation and cosmic ray flux*, *Phys. Rev. D* **71** (2005) 014026.

[27] E. Farhi and R.L. Jaffe, *Strange matter*, *Phys. Rev. D* **30** (1984) 2379.

[28] E.P. Gilson and R.L. Jaffe, *Stability of very small strangelets*, **71** (1993) 332 [`hep-ph/9302270`].

[29] A. Drago, A. Lavagno and G. Pagliara, *Can very compact and very massive neutron stars both exist?*, *Phys. Rev. D* **89** (2014) 043014.

[30] M. Bianchi, M. Casolino and G. Rizzo, *Accelerating strangelets via penrose process in non-bps fuzz-balls*, *Nuclear Physics B* **954** (2020) 115010.

[31] A. Drago and G. Pagliara, *Merger of two neutron stars: Predictions from the two-families scenario*, *The Astrophysical Journal Letters* **852** (2018) L32.

[32] A. De Rujula and S. Glashow, *Nuclearites: A Novel Form of Cosmic Radiation*, *Nature* **312** (1984) 734.

[33] O. Adriani, G.C. Barbarino, G.A. Bazilevskaya, R. Bellotti, M. Boezio, E.A. Bogomolov et al., *New Upper Limit on Strange Quark Matter Abundance in Cosmic Rays with the PAMELA Space Experiment*, *Physical Review Letters* **115** (2015) 111101.

[34] L.W. Piotrowski, K. Małek, L. Mankiewicz, M. Sokołowski, G. Wrochna, A. Zadrożny et al., *Limits on the flux of nuclearites and other heavy compact objects from the pi of the sky project*, *Phys. Rev. Lett.* **125** (2020) 091101.

[35] S. Abe et al., *DIMS Experiment for Dark Matter and Interstellar Meteoroid Study*, *PoS* **ICRC2021** (2021) 554.

[36] D. Barghini, M. Bertaina, A. Cellino, F. Fenu, S. Ferrarese, A. Golzio et al., *Uv telescope tus on board lomonosov satellite: Selected results of the mission*, *Advances in Space Research* **70** (2022) 2734.

[37] J.H. Adams, S. Ahmad, J.-N. Albert, D. Allard, L. Anchordoqui, V. Andreev et al., *JEM-EUSO: Meteor and nuclearite observations*, *Experimental Astronomy* **40** (2015) 253.

Full Authors list: The JEM-EUSO Collaboration

S. Abe[fq], J.H. Adams Jr.[pd], D. Allard[cb], P. Alldredge[pd], L. Anchordoqui[pe], A. Anzalone[eh,ed], E. Arnone[ek,el], M. Bagheri[ph], B. Baret[cb], D. Barghini[el,ek], M. Battisti[ek,el,cb], R. Bellotti[ea,eb], A.A. Belov[kb], M. Bertaina[ek,el], P.F. Bertone[pf], M. Bianciotto[ek,el], P.L. Biermann[db], F. Bisconti[ei], C. Blaksley[ft], S. Blin-Bondil[cb], K. Bolmgren[na], S. Briz[pb], J. Burton[pd], F. Cafagna[ea.eb], G. Cambié[ei,ej], D. Campana[ef], F. Capel[de], R. Caruso[ec,ed], M. Casolino[ft,ei,ej], C. Cassardo[ek,el], A. Castellina[ek,em], K. Černý[bb], M.J. Christl[pf], R. Colalillo[ef,eg], L. Conti[en,ei], G. Cotto[ek,el], H.J. Crawford[pa], R. Cremonini[el], A. Creusot[cb], A. de Castro Gónzalez[pb], C. de la Taille[ca], R. Diesing[pb], P. Dinaucourt[ca], A. Di Nola[eg], A. Ebersoldt[db], T. Ebisuzaki[ft], J. Eser[pb], F. Fenu[eo], S. Ferrarese[ek,el], G. Filippatos[pc], W.W. Finch[pc], F. Flaminio[eg], C. Fornaro[en,ei], D. Fuhne[pc], C. Fuglesang[na], M. Fukushima[fe], S. Gadamsetty[ph], D. Gardiol[ek,em], G.K. Garipov[kb], E. Gazda[ph], A. Golzio[ek,el], F. Guarino[ef,eg], C. Guépin[pb], A. Haungs[db], T. Heibges[pc], F. Isgrò[ef,eg], E.G. Judd[pa], F. Kajino[ff], I. Kaneko[ft], M. Kleifges[db], P.A. Klimov[kb], I. Kreykenbohm[da], J.F. Krizmanic[pj], V. Kungel[pc], E. Kuznetsov[pd], F. López Martínez[pb], D. Mandát[bc], M. Manfrin[ek,el], A. Marcelli[ej], L. Marcelli[ei], W. Marszał[ia], J.N. Matthews[pg], A. Menshikov[db], M. Mese[ef,eg], S.S. Meyer[pb], J. Mimouni[ad], H. Miyamoto[ek,el], Y. Mizumoto[fi], A. Monaco[ea,eb], S. Nagataki[ft], J. M. Nachtman[pi], D. Naumov[ka], A. Neronov[cb], T. Nonaka[fe], T. Ogawa[ft], S. Ogio[ft], H. Ohmori[ft], A.V. Olinto[pb], Y. Onel[pi], G. Osteria[ef], A.N. Otte[ph], A. Pagliaro[eh,ed], B. Panico[ef,eg], E. Parizot[cb,cd], I.H. Park[gb], T. Paul[pe], M. Pech[bc], F. Perfetto[ef], P. Picozza[ei,ej], L.W. Piotrowski[ib], Z. Plebaniak[ei,ej], J. Posligua[pi], M. Potts[ph], R. Prevete[ef,eg], G. Prévôt[cb], M. Przybylak[ia], E. Reali[ei,ej], P. Reardon[pd], M.H. Reno[pi], M. Ricci[ee], O.F. Romero Matamala[ph], G. Romoli[ei,ej], H. Sagawa[fe], N. Sakaki[ft], A. Santangelo[dd], O.A. Saprykin[kc], F. Sarazin[pc], M. Sato[fo], H. Schieler[db], P. Schovánek[bc], V. Scotti[ef,eg], S. Selmane[cb] S.A. Sharakin[kb], K. Shinozaki[ia], S. Stepanoff[ph], J.F. Soriano[pe], J. Szabelski[ia], N. Tajima[ft], T. Tajima[ft,pn], Y. Takahashi[fo], M. Takeda[fe], Y. Takizawa[ft], C. Tenzer[dd], S.B. Thomas[pg], L.G. Tkachev[ka], T. Tomida[fh], S. Toscano[ob], M. Traïche[aa], D. Trofimov[cb,kb], K. Tsuno[ft], P. Vallania[ek,em], L. Valore[ef,eg], T. M. Venters[pj], C. Vigorito[ek,el], M. Vrabel[ia], S. Wada[ft], J. Watts Jr.[pd], A. Weindl[db], L. Wiencke[pc], J. Wilms[da], D. Winn[pm], H. Wistrand[pc], I.V. Yashin[kb], R. Young[pf], M.Yu. Zotov[kb].

[aa] Centre for Development of Advanced Technologies (CDTA), Algiers, Algeria
[ad] Lab. of Math. and Sub-Atomic Phys. (LPMPS), Univ. Constantine I, Constantine, Algeria
[bb] Joint Laboratory of Optics, Faculty of Science, Palacký University, Olomouc, Czech Republic
[bc] Institute of Physics of the Czech Academy of Sciences, Prague, Czech Republic
[ca] Omega, Ecole Polytechnique, CNRS/IN2P3, Palaiseau, France
[cb] Université de Paris, CNRS, AstroParticule et Cosmologie, F-75013 Paris, France
[cd] Institut universitaire de France (IUF)
[da] ECAP, University of Erlangen-Nuremberg, Germany
[db] Karlsruhe Institute of Technology (KIT), Germany
[dd] Institute for Astronomy and Astrophysics, Kepler Center, University of Tübingen, Germany
[de] Max Planck Institute for Physics, Munich, Germany
[ea] Istituto Nazionale di Fisica Nucleare - Sezione di Bari, Italy
[eb] Universita' degli Studi di Bari Aldo Moro and INFN - Sezione di Bari, Italy
[ec] Dipartimento di Fisica e Astronomia "Ettore Majorana", Universita' di Catania, Italy
[ed] Istituto Nazionale di Fisica Nucleare - Sezione di Catania, Italy

[ee] Istituto Nazionale di Fisica Nucleare - Laboratori Nazionali di Frascati, Italy
[ef] Istituto Nazionale di Fisica Nucleare - Sezione di Napoli, Italy
[eg] Universita' di Napoli Federico II - Dipartimento di Fisica "Ettore Pancini", Italy
[eh] INAF - Istituto di Astrofisica Spaziale e Fisica Cosmica di Palermo, Italy
[ei] Istituto Nazionale di Fisica Nucleare - Sezione di Roma Tor Vergata, Italy
[ej] Universita' di Roma Tor Vergata - Dipartimento di Fisica, Roma, Italy
[ek] Istituto Nazionale di Fisica Nucleare - Sezione di Torino, Italy
[el] Dipartimento di Fisica, Universita' di Torino, Italy
[em] Osservatorio Astrofisico di Torino, Istituto Nazionale di Astrofisica, Italy
[en] Uninettuno University, Rome, Italy
[eo] Agenzia Spaziale Italiana, Via del Politecnico, 00133, Roma, Italy
[fe] Institute for Cosmic Ray Research, University of Tokyo, Kashiwa, Japan
[ff] Konan University, Kobe, Japan
[fh] Shinshu University, Nagano, Japan
[fi] National Astronomical Observatory, Mitaka, Japan
[fo] Hokkaido University, Sapporo, Japan
[fq] Nihon University Chiyoda, Tokyo, Japan
[ft] RIKEN, Wako, Japan
[gb] Sungkyunkwan University, Seoul, Republic of Korea
[ia] National Centre for Nuclear Research, Otwock, Poland
[ib] Faculty of Physics, University of Warsaw, Poland
[ka] Joint Institute for Nuclear Research, Dubna, Russia
[kb] Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Russia
[kc] Space Regatta Consortium, Korolev, Russia
[na] KTH Royal Institute of Technology, Stockholm, Sweden
[ob] ISDC Data Centre for Astrophysics, Versoix, Switzerland
[pa] Space Science Laboratory, University of California, Berkeley, CA, USA
[pb] University of Chicago, IL, USA
[pc] Colorado School of Mines, Golden, CO, USA
[pd] University of Alabama in Huntsville, Huntsville, AL; USA
[pe] Lehman College, City University of New York (CUNY), NY, USA
[pf] NASA Marshall Space Flight Center, Huntsville, AL, USA
[pg] University of Utah, Salt Lake City, UT, USA
[ph] Georgia Institute of Technology, USA
[pi] University of Iowa, Iowa City, IA, USA
[pj] NASA Goddard Space Flight Center, Greenbelt, MD, USA
[pm] Fairfield University, Fairfield, CT, USA
[pn] Department of Physics and Astronomy, University of California, Irvine