PROCEEDINGS OF SCIENCE

Searching for massive, non-relativistic particles in space with the SQM-ISS detector

Marco Casolino,[a] **Francesca Liberatori,**[b] **Laura Marcelli,**[a] **Etienne Parizot,**[c,d] **Zbigniew Plebaniak**[a,*] **and Enzo Reali**[a,b] **for the SQM-ISS group**

[a] *Istituto Nazionale di Fisica Nucleare - Sezione di Roma Tor Vergata, Via della Ricerca Scientifica 1 – 00133, Roma, Italy*
[b] *Università di Roma Tor Vergata - Dipartimento di Fisica, Via della Ricerca Scientifica 1 – 00133, Roma, Italy*
[c] *Université de Paris, CNRS, AstroParticule et Cosmologie, F-75013 Paris, France*
[d] *Institut Universitaire de France (IUF), France*

E-mail: zbigniew.plebaniak@roma2.infn.it

SQM-ISS is a detector that will look for massive particles among cosmic rays from the International Space Station. Some of these candidates include strange quark matter, Q-balls, lumps of fermionic exotic compact stars, primordial black holes, mirror matter, Fermi balls and others. These compact and dense objects are expected to be much heavier than normal nuclei, to travel at speeds typical of objects on their way to the centre of a galaxy, and to be able to penetrate deeply. Some of these particles might account for all or part of the non-baryonic dark matter inferred by cosmology without requiring new fundamental physics. The SQM-ISS detector is made up of a layer of scintillator and piezoelectric elements that provide information on both charge state and mass. Experimental tests have validated its ability to discriminate between particle types based on charge and velocity measurements (v > 220 km/s), with timing data further supporting velocity determination. The experiment was already chosen by ESA through the Open Space Innovation Platform. The integration of advanced data acquisition and real-time processing systems further enhances operational reliability, ensuring accurate measurements in the challenging space environment. This effort not only advances detector technology, but also opens the way for exploring fundamental questions about the composition and evolution of the universe. The experimental results are expected to provide crucial insights into the dynamics of non-standard cosmic ray components, potentially revising our understanding of high-energy astrophysics and the search for new states of matter beyond the Standard Model. In this work I will describe the detector, its observational capabilities and its potential for advancing our understanding of exotic cosmic particles.

39th International Cosmic Ray Conference (ICRC2025)
15–24 July 2025
Geneva, Switzerland

ICRC 2025
The Astroparticle Physics Conference
Geneva July 15-24, 2025

*Speaker

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1. Introduction

We are used to saying that almost all of the observable hadronic matter around us is made up of just two types of quarks: up (u) and down (d). However, since the time when Zwicky showed in the first half of the twentieth century that the high velocity dispersion in the Coma cluster suggested a much higher mass density than what could be explained by visible matter [1], humanity has been searching for candidates for the so-called dark matter. So far, many theories have been developed to try to explain the missing component in the composition of the Universe. One of these theories is the existence of a different state of hadronic matter, called Strange Quark Matter (SQM), which was first proposed by Witten in the 1980s [2]. Because quarks are fermions, adding a third flavour (the strange quark) increases the number of available quantum states and lowers the Fermi energy compared to a two-flavour quark system, potentially stabilising SQM. Large droplets of strange quark matter are referred to as strangelets. Larger strangelets are energetically favoured as a result of the decreasing influence of surface and Coulomb energies relative to volume energy. As the system size increases, the average energy per baryon decreases, potentially leading to the absolute stability of strange quark matter beyond a critical baryon number. The stability of such matter depends sensitively on the parameters of the MIT bag model, particularly the bag constant, which governs the energy balance; the reduction in surface and Coulomb contributions further improves stability in larger systems [3]. For this reason, SQM is expected to exhibit a preference for clustering into larger SQM lumps with high baryon numbers, typically above a few dozen. The concept of stable strange quark matter is therefore fully accommodated within the Standard Model framework. In addition, many other hypothetical massive objects may be present in our galaxy, including Q-balls [4], magnetic monopoles [5], primordial black holes [6], Fermi balls [7], electroweak symmetric dark matter balls [8] or axion quark nuggets [9]. Figure 1 shows the presumed masses and velocities of various objects, many of which are considered candidates for dark matter particles. It should be emphasised that most of them are hypothetical, and their exact properties are difficult to estimate. We are interested in heavy particles moving at velocities around 220 km/s, as this is the typical speed of dark matter particles in the galactic halo according to the standard halo model.

If SQM contains equal numbers of s, u, and d quarks, it would be electrically neutral. However, there are models suggesting that SQM may carry a net electric charge depending on the initial conditions under which it was formed. For ordinary strange quark matter (non-CFL) with large baryon numbers $A \gg 150$, the electric charge Z scales as $Z \approx 8A^{1/3}$, due to charge screening in a surface layer, as described in [10]. In contrast, for color-flavour locked (CFL) strangelets, the charge scales as $Z \approx 0.3A^{2/3}$ for all A, resulting from surface suppression of strange quarks, as shown in [11]. Compared to normal nuclear matter (composed of up and down quarks), which typically has a charge-to-baryon ratio $Z/A \approx 0.5$ (e.g., in protons or nuclei like iron), strangelets exhibit significantly lower Z/A ratios. Typical baryon number values for stable strangelets vary depending on the model, ranging from a few dozen to 10^6. However, the upper limit for strange stars before collapsing into a black hole is around 10^{57} [12]. SQM could be produced in the Big Bang [13], be part of baryonic dark matter [14] or be present in the core of neutron stars or exist as strange quark stars [15, 16]. Lumps of SQM may be released as a result of collisions between strange stars in binary systems [17].

Despite many attempts, strange quark matter (SQM) particles have not been detected so far.

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The PAMELA experiment searched for strange quark matter by identifying anomalous high-rigidity particles with unusual mass-to-charge ratios that could indicate the presence of stable or metastable strangelets. The Van de Graaff accelerator at Yale was used to search for stable strange quark matter in lunar soil samples by scanning for unusual nuclei in the mass range A = 42–70 and with charges Z = 5, 6, 8, 9, and 11. The experiment set very low upper limits on the possible presence of strangelets. If SQM exists in the form of particles traveling through space, we will need new detection methods in order to observe them.

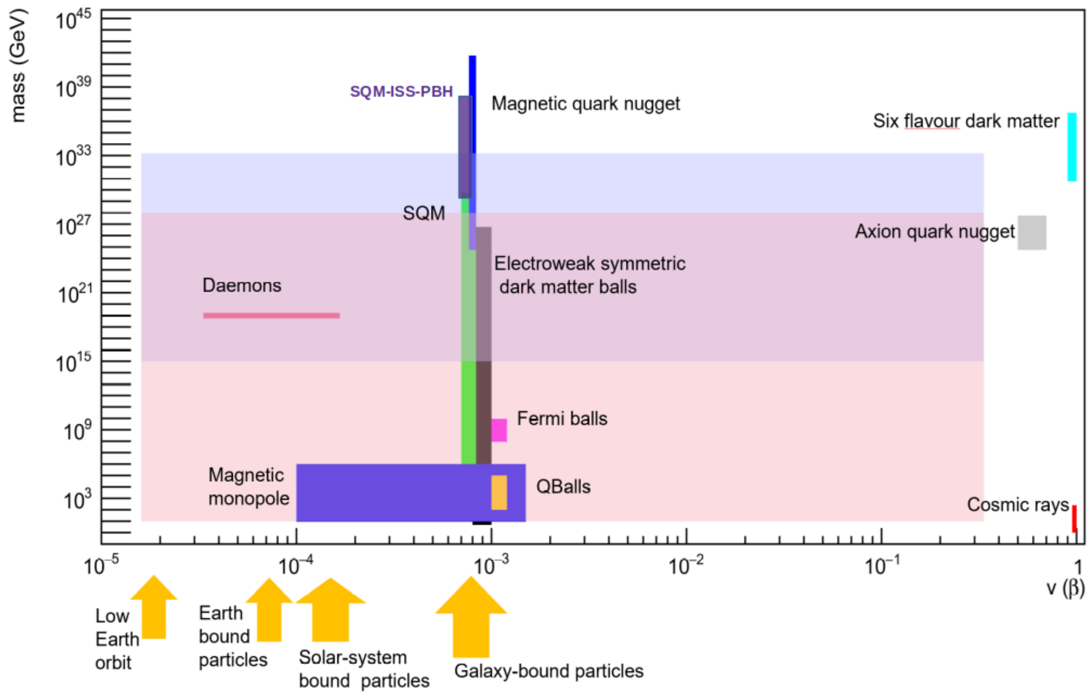

Figure 1: The figure displays the β-mass phase space for hypothetical, slowly moving massive particles- ranging from light magnetic monopoles and Q-balls, through heavier Fermi balls and fragments of strange-quark matter (SQM) or magnetic quark nuggets, and extending up to the region where primordial black holes (PBHs) are expected to be measured by the piezoelectric detector. Most candidates move at velocities of about 7-8 $\times 10^{-4}$ c, characteristic of objects gravitationally bound to the Galaxy, although slower ones could be trapped in the Solar System or even near Earth. For reference, cosmic-ray nuclei ($\beta \approx 1$, $m \lesssim 200$ GeV) are marked in the lower right. The pink band indicates the sensitivity of the scintillator/SiPM detectors, while the blue band corresponds to the piezoelectric detectors in case of SQM measurements; together they probe velocities from 3×10^{-5} to 3×10^{-1} c. Such broad coverage in mass and speed maximises the chance of detecting exceptionally dense, exotic objects.

2. The SQM-ISS experiment

The SQM-ISS detector is a space-station-based instrument dedicated to the direct detection of the passage of slow heavy particles in a very wide mass and charge state. The instrument is a part of the project "SQM-ISS, Search for Strange Quark Matter and nuclearites on board the

International Space Station". The idea was submitted to the ESA program called “Reserve Pools of Science Activities for ISS: a SciSpacE Announcement of Opportunity”, as part of the 2022 call, and evaluated as “excellent”. The detector will work in dual-mode. It will be composed of a stack of scintillators ($10 \times 10 \times 0.5$ cm each, read by silicon photomultipliers to detect the passage of charged particles) and a stack of copper plates (read by piezoelectric sensors to detect vibrations caused by the passage of SQM or PBHs). Each scintillator tile will be divided into 5 stripes, each read out by two SiPMs placed at the ends. The four layers, including the piezoelectric detectors, will have a total thickness of 7 cm. The whole system is housed in $15{\times}15{\times}14 cm^3$ metal container with a weight of 10 kg. The geometric factor of a four-fold coincidence of the scintillator planes is $\sim$ 100 cm^2 sr, while a three-fold coincidence of the scintillators or the metal plates results in a geometrical factor of $\sim$ 130 cm^2 sr. For a two-fold coincidence, the geometrical factor increases to $\sim$ 200 cm^2 sr, but signals from such configurations are affected by a higher background.

As mentioned earlier, SQM particles are expected to carry an electric charge, although it would be smaller (for a given particle mass) than that of standard atoms. However, SQM should leave a measurable trace when passing through a scintillator. Due to their large masses, SQM particles are also expected to deposit a phononic signal while passing through metal plates, proportional to their momentum. Since SQM particles are expected to travel with a galactic orbital velocity of about 250 km/s, the layered structure of the detector, together with a dedicated Time-of-Flight system, will allow the separation of SQM signals from the background noise caused by relativistic particles present in low Earth orbit.

The trigger threshold for the scintillating channel is set at $\approx$ 16 MIP (minimum ionising particle), which corresponds to the energy deposit of a relativistic ion with charge $Z{\approx}4$. This level is high enough to suppress the ubiquitous background of single protons and helium nuclei, whose signals are only 1-4 MIP. Consequently, any event that passes the threshold is very likely to be a genuinely heavy, highly charged particle rather than a random coincidence of light cosmic ray ions. The limit condition on $Z > 4$ translates into a minimum measurable mass of SQM on the order of 10^{-25} g, assuming the model-dependent relationship cited previously between Z and A.

The vibrations generated in copper plates by passing SQM particles will be read by piezoelectric detectors (160.01-V6V-1, produced by DSPM Industria). The sensitivity of these accelerometers is approximately 100 mV$/g \pm 20\%$, which based on laboratory tests allows the detection of SQM with masses greater than 10^{-9} g. Considering the described detector geometry, the expected number of detections of particles with a mass of 10^{-8} g, recorded simultaneously by both read-out channels, is on the order of several hundred over the three-year mission duration. The detector geometry can be further optimized to increase the geometric factor.

3. Detection of Primordial Black Holes with SQM-ISS

The SQM-ISS detector, designed to be installed aboard the International Space Station (ISS), offers a novel approach to detecting massive, slow-moving, and highly penetrating particles in space. Among its most compelling capabilities is its potential to identify Primordial Black Holes (PBHs)-hypothetical compact objects that may have formed in the early Universe and could constitute a component of dark matter. PBHs were first proposed by Zel’dovich and Novikov [6] and later by Hawking (1971) [18]. Unlike astrophysical black holes, which originate from stellar collapse,

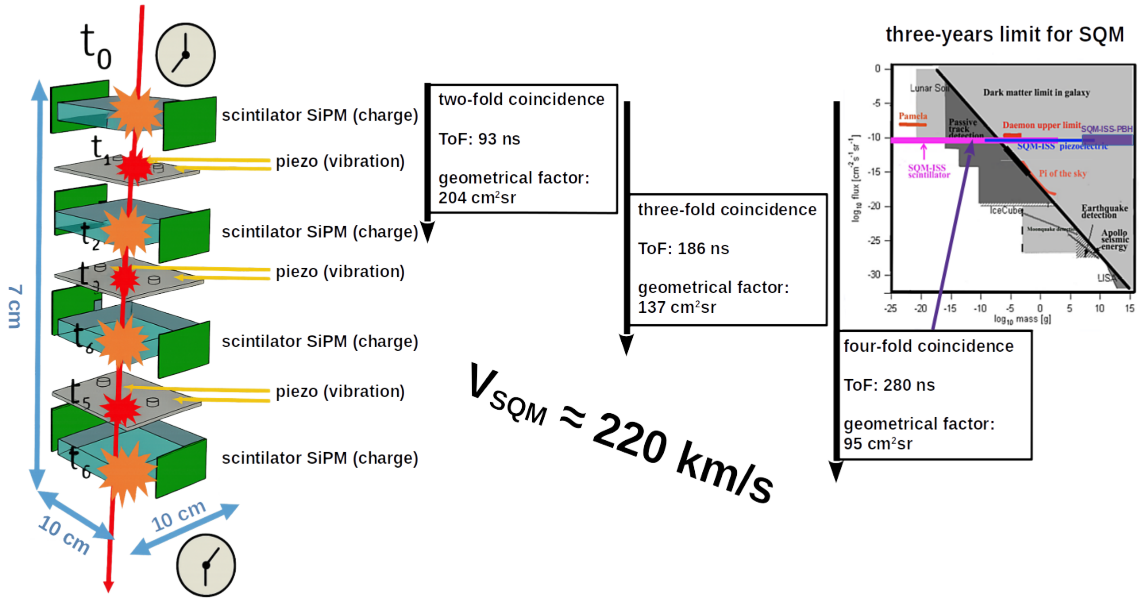

Figure 2: Schematic of the SQM-ISS detector and its performance parameters. The setup consists of repeating layers of scintillators (read out by SiPMs) and metal plates (read by piezoelectric sensors), allowing simultaneous detection of ionisation and phononic signals from traversing particles. The expected ToF (Time of Flight) for a hypothetical SQM particle with galactic velocity ($v_{\mathrm{SQM}} \approx 220$ km/s) is shown for two-, three-, and four-fold scintillator coincidences, along with the corresponding geometrical acceptance factors. The right panel shows the upper flux limit set by SQM-ISS after three years of data-taking in the absence of a detection, assuming a four-fold coincidence configuration. The limit is compared with those from other experiments and astrophysical constraints.

PBHs may have formed from the gravitational collapse of large density fluctuations shortly after the Big Bang, especially during the inflationary epoch [19]. Alternative formation mechanisms include cosmic strings, domain walls, or phase transitions [20], which could naturally generate peaks in the PBH mass distribution [21]. PBHs are particularly interesting as dark matter candidates because they are non-baryonic, can span a wide mass range-from below 10^{12} kg to stellar scales-and, according to Hawking radiation theory, would only survive to the present day if their mass exceeds 10^{11} g. However, recent developments in string theory propose the fuzzball paradigm, where black holes have no singularity or well-defined event horizon, potentially avoiding Hawking evaporation [22]. Under this model, long-lived PBHs could still exist today, even at low masses. The SQM-ISS instrument is uniquely suited to explore this parameter space. These features make SQM-ISS sensitive to both exotic candidates such as Strange Quark Matter and primordial black holes.

A PBH passing through the detector with a velocity on the order of 220-250 km/s - compatible with galactic orbital speeds-is expected to produce a mechanical signal detected by the piezoelectric sensors.

Unlike typical cosmic rays or light charged particles, a PBH would traverse multiple layers of the detector without significant energy loss, yet deposit enough momentum to induce measurable mechanical vibrations. These correlated signals across multiple layers offer a distinctive signature.

SQM-ISS can detect PBHs through two primary mechanisms:

1. Direct atomic interaction, which requires the Schwarzschild radius of the PBH to be comparable to the atomic spacing within the detector material-only feasible for extremely small but dense objects.

2. Gravitational interaction, the more sensitive and promising mode. A PBH, even without physically contacting the detector atoms, could generate a measurable gravitational acceleration of the metallic layers as it passes through, recorded by the piezoelectric sensors.

Through accurate velocity reconstruction and multi-layer signal analysis, SQM-ISS will constrain the flux of compact, non-relativistic objects in Earth's orbit. These measurements complement other detection methods such as gravitational microlensing and gravitational wave observations, which are typically sensitive only to much more massive PBHs.

The calculation of the ability of a PBH to interact directly with atomic nuclei is analogous to the mechanism proposed for Strange Quark Matter (SQM) particles. In the case of SQM, detection relies on elastic collisions between the traversing massive object and the atoms of a metallic layer, producing measurable lattice vibrations detected by piezoelectric sensors - even in the absence of significant ionisation. A similar principle can be extended to PBHs, replacing the nuclear scale with the Schwarzschild radius R_s, which depends only on the PBH mass M:

$$R_s = \frac{2GM}{c^2} \tag{1}$$

If $R_s \ll d_a$, where d_a is the atomic spacing of the detector material, the PBH will pass through the detector with negligible direct interaction with the atomic nuclei. However, if the Schwarzschild radius is comparable to or larger than the atomic scale, the PBH may begin to interact directly with nuclei-either through absorption or gravitational disruption along its path. We take the atomic spacing of copper as a reference value:

$$d_a = 2.55 \times 10^{-10}\,\mathrm{m} \tag{2}$$

$$r_a = \frac{1}{2} d_a = 1.27 \times 10^{-10}\,\mathrm{m} \tag{3}$$

By equating this to the Schwarzschild radius, we can estimate the minimum PBH mass required for direct interaction:

$$r_a = \frac{2GM_{\min}}{c^2} \tag{4}$$

$$M_{\min} = \frac{c^2 r_a}{2G} \approx 8.55 \times 10^{16}\,\mathrm{kg} \tag{5}$$

Therefore, under this mechanism, only PBHs with masses greater than $M_{\min}$ will have Schwarzschild radii large enough to interact effectively with the atomic lattice. In the intermediate regime, where $R_s \lesssim d_a$, partial interactions may still occur depending on the lattice orientation and the PBH trajectory.

In addition to potential direct interactions with matter, a primordial black hole (PBH) traversing the SQM-ISS detector may also produce a measurable signal via its gravitational attraction [23].

Even in the absence of ionisation or nuclear collisions, the PBH can induce an acceleration in the metallic layers, which can be detected through the piezoelectric sensors.

To model this effect, the sensor plane is approximated as a thin circular disk of mass M and radius R, lying in the $z = 0$ plane. A PBH of mass m, moving along the z-axis at galactic velocity ($v \sim 220$ km/s), generates a gravitational force on the disk, resulting in a vertical acceleration. A numerical simulation computes the resulting time-dependent acceleration profile as the PBH approaches and crosses the plane.

The gravitational acceleration imparted to the disk reaches a maximum when the PBH is near the surface. If this acceleration exceeds the sensitivity threshold of the piezoelectric sensor, a detectable signal is produced. Given the sensor's sensitivity (100 mV/g) and a conservative minimum signal threshold of 5 mV, the smallest detectable acceleration is:

$$a_{\min} \approx 0.05\ g \approx 0.49\ \mathrm{m/s^2}$$

Simulations show that a PBH of mass $m \simeq 10^6$ kg induces a peak acceleration near this threshold, identifying it as the minimum detectable mass under purely gravitational interaction.

This result suggests that the dominant detection mechanism for low-mass PBHs is the gravitational force they exert on the detector structure, rather than direct nuclear interactions. Accordingly, future designs should optimize the mechanical coupling of the metal planes to maximize displacement sensitivity along the z-axis.

4. Summary

In this work we present an overview of the **SQM-ISS**, the instrument specifically designed to search for strange-quark matter and other exotic, slowly moving particles in space. The payload combines a dual read-out system consisting of plastic scintillators (for ionisation charge) and piezoelectric plates (for mechanical energy deposition), combined with a nanosecond - resolution time-of-flight system, enabling the unambiguous identification of deeply penetrating sub-relativistic objects such as SQM nuggets and primordial black holes. Detecting even a single SQM candidate would change our understanding of the dark-matter content of the Universe. The project has now entered its implementation phase: key engineering-model components have already been designed. The launch, followed by installation in the *Columbus* module of the International Space Station is planned for 2028.

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