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Mercedes Paniccia (AMS), Merlin R. Kole (POLAR-2), Martina D'Arco, Teresa Montaruli, Caterina Trimarelli (Terzina)

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The next future of space projects on cosmic ray physics

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In this article, we describe three pioneering space-based experiments, involving the Département de Physique Nucléaire et Corpusculaire of the Faculté de Science de l'Université de Genève. They aim at improving our understanding of high-energy astrophysical phenomena, such as gamma-ray bursts (GRBs) and cosmic rays below the knee at a few PeVs (the knee of protons is the steepening of the cosmic ray spectrum from a power law ${dN}/{dE} \propto E^{-2.7}$ to $E^{-3.1}$ at about 3×10^{15} eV = 3 PeV for protons) and in the region beyond 100 PeV to beyond the ankle (the hardening of the spectrum at about 5×10^{19} eV) of Ultra High Energy Cosmic Rays (UHECRs).

After a short introduction on cosmic rays, the AMS experiment, in operation for 13 years, and its results are presented. Then, two next future missions are described: POLAR-2, which builds upon the legacy of its predecessor POLAR and aims at unravelling the polarization signatures of GRBs with unprecedented precision. Additionally, we foresee in 2026 the launch by ASI of the NUSES satellite mission, with on board a payload focusing on the detection of Cherenkov light emitted by EAS induced by UHECRs and neutrinos in the Earth's atmosphere.

1. Intro to Galactic cosmic rays in the GeV to multi-TeV energy range

In the energy range from 0.5 GeV to multi-TeV, cosmic rays are predominantly protons, with helium nuclei accounting for ~10 %, electrons, and nuclei heavier than helium only about a few %. Positrons and antiprotons are very rare as they are mostly secondary products of interactions of heavier cosmic rays with the interstellar medium. Their abundance relative to protons amounts to only about 1/1000 and 1/10'000 respectively. So far, there is no confirmed observation of anti-nuclei: anti-helium nuclei abundance relative to helium nuclei is less than $1/10^9$. Cosmic protons, electrons, and most nuclei, such as oxygen, silicon, and iron, are primaries originating from cosmic sources. Some nuclei, such as lithium, beryllium, boron, fluorine, scandium, titanium, and vanadium, are overwhelmingly produced in spallation reactions of heavier primary cosmic-ray nuclei with the interstellar medium during their journey through the galaxy. Most cosmic nuclei are a mixture of two or more isotopes having different origins, as He nuclei which are composed of the primary ^{4}He and the secondary ^{3}He. Secondary species and radioactive isotopes in secondary cosmic rays, which have a lifetime of the same order of magnitude as the cosmic-ray propagation time scale in the galaxy, are of particular importance in modelling galactic cosmic rays. Cosmic rays are accelerated diffusing through expanding shocks and propagate in the interstellar medium scattering on the irregularities of the galactic magnetic field. Both these mechanisms depend on the particle's momentum, or magnetic rigidity R = momentum/charge. Cosmic-ray propagation is described in terms of a rigidity-dependent diffusion coefficient which embeds the properties of the galactic magnetic field turbulence. Simultaneous measurements of the individual rigidity spectra of secondary species and their primary progenitors, as B/C, B/O, F/Si, or Sc/Fe, are the key experimental tools to probe cosmic-ray propagation as their ratio directly maps the rigidity dependence of the diffusion coefficient. Comparing the spectra of unstable secondaries, as ^{10}Be, to those of stable secondaries, as ^{9}Be, allows us to determine the grammage (the distance times the density) through which cosmic rays propagate in the volume of the galaxy (or equivalently their escape time from the Galaxy), and to derive the normalization of the diffusion coefficient. Current models assume that all primary nuclei have identical featureless power-law rigidity spectra, and that the diffusion coefficient follows a featureless power law in rigidity, and it is independent of the particle's charge, leading to identical featureless power-law spectra for all secondary nuclei. The AMS-02's observations are challenging this paradigm.

2. AMS-02 and its upgrade

The Alpha Magnetic Spectrometer, AMS-02, is a state-of-the-art high-energy particle detector installed on the International Space Station (ISS) in May 2011 to perform precision measurements of cosmic-ray particles, anti-particles, nuclei, and anti-nuclei of energies ranging from 0.5 GeV to multi-TeV. The AMS-02 experiment addresses outstanding questions in fundamental physics, the matter-antimatter asymmetry, the nature of dark matter, and the existence of exotic forms of matter, and in cosmic-ray physics, the origin, the acceleration, and propagation mechanisms of galactic cosmic rays. Thanks to its large acceptance and long-duration mission, spanning over more than an entire 11-year solar cycle, AMS-02 is also delivering time-resolved particles and nuclei fluxes of great interest to solar physics, space weather, and space radiation studies.

AMS-02 combines five detectors, a Transition Radiation Detector (TRD), a Time Of Flight (TOF), a nine-layer (L1 to L9) Silicon Tracker, of which 7 inserted in a permanent magnet, a Ring Imaging Cerenkov (RICH), and an electromagnetic calorimeter (ECAL). They provide redundant measurements of the particle's charge along its trajectory inside the apparatus, and independent measurements of the particle's rigidity, velocity, and energy. The silicon tracker measures the rigidity and charge sign from the track's bending inside the magnetic field. The two TOF layers and the RICH determine the particle's velocity at percent and permille accuracy respectively. Combined with the rigidity measurement, these provide isotope identification in the kinetic energy per nucleon range from 0.5 GeV/n to 12 GeV/n. The ECAL measures the energy of electrons and positrons with percent accuracy. Identification of leptons against hadrons with a rejection power of $1/10^5$ is achieved combining the ECAL 3D shower reconstruction with the TRD response. The redundancy of the AMS-02 detector also allows the measurement of nuclei fragmentation cross sections and to determine the isotopic composition of light fragments. So far, AMS-02 has collected more than 230 billion cosmic ray events and has provided unprecedented-precision measurements of specie-resolved energy spectra of electrons and positrons, rigidity spectra of protons, antiprotons, nuclei from helium to silicon, sulfur,

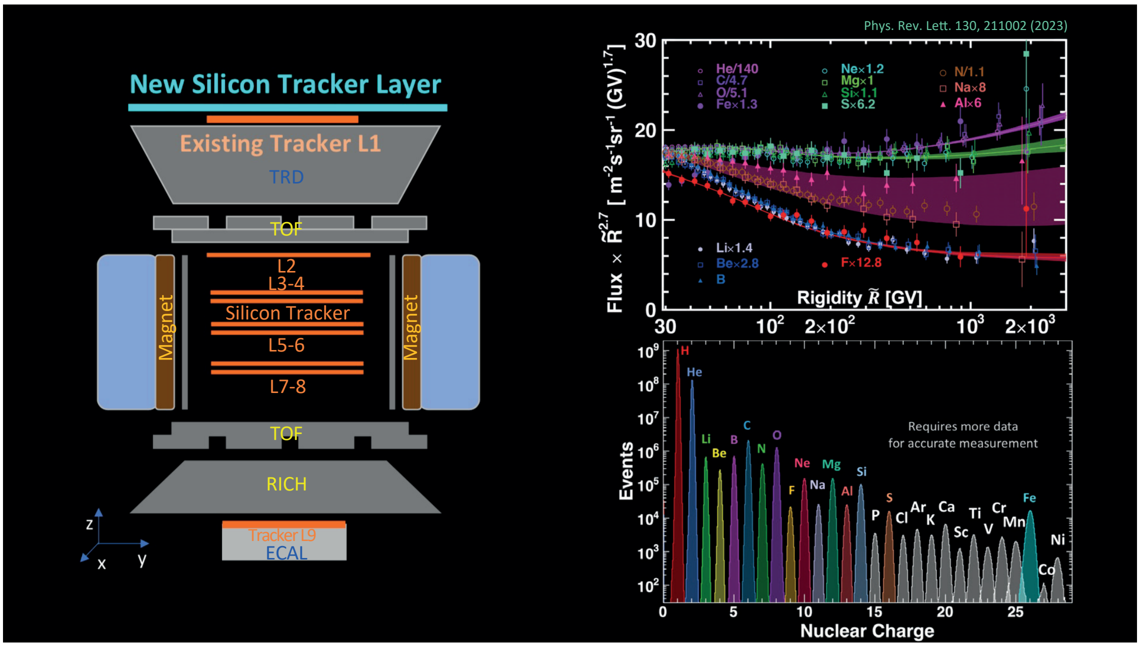

Figure 1: Left: Schematic view of the AMS-02 apparatus with its five detectors, the nine-layers of Silicon Tracker (L1 to L9) and the permanent magnet, the Transition Radiation Detector (TRD), the Time Of Flight (TOF), the Ring Imaging Cerenkov (RICH), and the electromagnetic calorimeter (ECAL). Also shown is the upgraded AMS-02 with the addition of a new Silicon Tracker layer at the top of the apparatus. Right: current AMS-02 results on cosmic nuclei rigidity spectra (top) and collected statistics for all cosmic-ray nuclei up to nickel (bottom).

and iron, and helium isotopes. The AMS experiment is run by an international collaboration of 44 research institutes and universities from 14 countries in Europe, Asia, and the Americas. The experiment is led by the US Department of Energy and sponsored by NASA. The University of Geneva is a founding member of the AMS Collaboration through the AMS group at the Department of Nuclear and Particle Physics. The Geneva group has played an important role in the construction and commissioning of the silicon tracker, and currently, its activities are focused on data analysis. In the last years, it has given primary contributions to the measurements of the spectra of nuclei heavier than oxygen and is now leading the measurement of the isotopic composition of beryllium and lithium nuclei. The nuclei measurements have led to the first observation of two classes of spectral shapes for both primary, He-C-O-Fe and Ne-Mg-Si-S, and secondary nuclei, Li-Be-B and F, and to the detailed characterization of the spectra of mixed primary and secondary nuclei, N, Na, and Al. In addition, all the nuclei spectra measured so far by AMS-02 are not compatible with the assumption of featureless power laws as all hardens above 200 GV, as previously observed for protons and helium from other experiments. The AMS-02 measurements of light secondary-to-primary ratios, B/C, Be/C, Li/C, B/O, Be/O, and Li/O have shown for the first time that the hardenings of the spectra of nuclei up to oxygen are due to a hardening of the diffusion coefficient. Moreover, AMS-02 has observed that the medium-mass secondary-to-primary ratio, F/Si, is different from light secondary-to-primary ratios questioning the assumption of an universal diffusion coefficient. The origin of this difference is not yet understood. It may arise from the properties of the galactic interstellar medium at different distances. Heavy cosmic nuclei probe smaller galactic volumes because of the dependence of their fragmentation cross-sections with the mass.

Precision measurements of secondary nuclei heavier than fluorine, namely titanium, scandium and vanadium, and their ratios to their main progenitor, iron, will bring crucial information to solve the fluorine puzzle. AMS-02 has the needed sensitivity to perform such measurements. However, due to the natural low abundance of heavy species, to obtain individual spectral measurements of such nuclei with precision comparable to that of lighter nuclei, the collection of more events is required. AMS-02 is operating smoothly and it will continue acquiring data for the entire ISS lifetime, until at least 2030 as in the currently approved NASA financial budget. The AMS-02 detector had originally been designed with a super-conducting magnet, lately replaced by the permanent magnet to match the lifetime of the spectrometer to the ISS's lifetime at the cost of reducing the geometrical acceptance by a factor of 3. To restore the originally planned acceptance, AMS-02 will be upgraded by installing an additional silicon tracker layer, L0, at the top of the apparatus. The upgrade will also allow us to improve the current AMS-02 measurements of electrons, positrons, and antiprotons at high energy. L0 is currently under construction in China. The launch of the ISS and its installation are scheduled for early 2026.

3. POLAR-2

Gamma-ray bursts (GRBs) are, and will during the coming years, remain one of the prime targets of multi-messenger astrophysics. On the 17th of August 2017, the first Gravitational Wave (GW) signal from a binary neutron star merger event was observed jointly by 2 gamma-ray detectors as well as a range of X-ray, optical and radio telescopes. The observed event was a GRB, an extra-galactic phenomenon previously only observed through photons.

Despite gamma rays being the messengers through which the very first GRB was discovered, one of its parameters, its polarization, remains largely unmeasured. Studies using the 3 other parameters, their arrival time, direction, and energy, have each led to novel insights into GRBs. The momentum, or arrival direction, of the photons, has been used to prove the extra-galactic nature of GRBs. The arrival time has allowed us to divide them into short and long GRBs and associate these with different progenitors. Finally, their energy has provided us with a wealth of insights, one of which being that the emission is not purely thermal but rather originates from some, yet unknown process inside of relativistic jets. Although 1000's GRBs have been detected over the last 50 years, the origin of the gamma-ray emission remains a

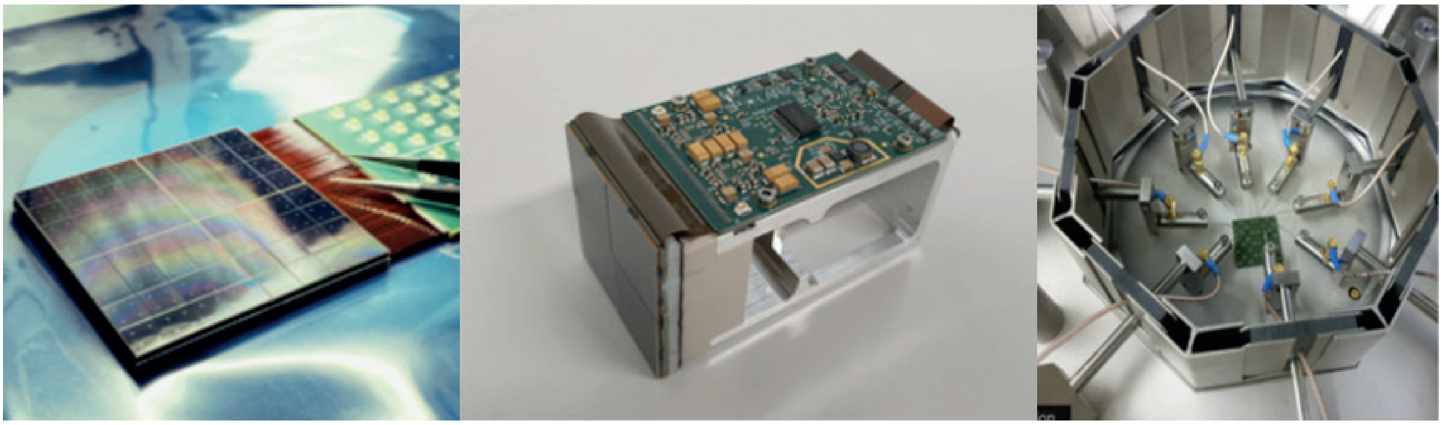

Figure 2: The SiPM array used to read out 64 scintillators from POLAR-2 on the right. The middle figure shows the SiPM connected to the POLAR-2 front-end electronics. On the right, the probe station which tests the SiPMs is shown.

mystery and traditional studies appear to be unable to solve this. The most promising mesurement to break the current stalemate on game-ray burst modeling is determining their polarisation. Such measurements are highly challenging; however, they are theorized to answer questions regarding the origin of the gamma rays, the geometry of the emission region and the potential presence of magnetic fields. Due to the large wealth held by the polarization, a range of attempts has been made over the last 20 years to measure it. The most successful of which were performed by the POLAR collaboration.

The POLAR mission, a Chinese, Swiss and Polish mission, detected 55 GRBs after being launched as part of the Tiangong-2 space lab in 2016. It performed polarization measurements in the energy range of 50—500 keV of 14 of these as well as of the Crab pulsar. Although the measurement results of POLAR are the most constraining GRB polarization measurements to date, they are only able to constrain the polarization degree to be below ~ 40 %. Therefore, the results remain consistent with most of the existing theoretical predictions. This, along with the hint of an evolution of the polarization with time observed in 2 of the GRBs indicates the need for a significantly more sensitive detector. For this purpose, the POLAR-2 detector was initiated in 2017, followed by an approval for launch towards the China Space Station (CSS), through a United Nations Office for Outer Space Affairs call in 2019. The project is currently foreseen to be launched in 2027 towards the CSS. A prototype of the detector successfully underwent space qualification measurements in 2022, and its scientific performance was tested extensively during 2023 with dedicated polarized beams. The production of the flight model was started in 2024 by an international collaboration consisting of teams from Switzerland, Poland, Germany, and China.

Compared to its predecessor, the POLAR-2 detector will be a factor of 4 larger, thereby employing a total of 6400 plastic scintillator bars. These scintillators are read out in groups of 64, using segmented SiPM arrays connected to their frontend, the electronics holding the Silicon Photomultipliers (SiPMs) developed for POLAR-2 are shown in Figure 2. As the GRB photons enter the detector they can undergo Compton scattering in the detector array, followed by photo-absorption in a second scintillator. Their azimuthal scattering angle can be constrained using the relative position of the two scintillators in which the photon interacted. As the photons will scatter preferentially perpendicular to their initial polarization, this measurement allows us to determine the polarization of the incoming photon flux.

While the increase in the detector dimensions provides an increase in the effective area of a factor of 4 compared to POLAR, further improvements to its design allow for additional improvements in its sensitivity. Particularly the switch from PMTs as used in POLAR, to SiPMs results in a significant increase in sensitivity at lower energies.

Thanks to all the design improvements, POLAR-2 is approximately an order of magnitude more sensitive compared to POLAR. The instrument will be able to perform constraining polarization measurements for GRBs with fluences as low as 10^{-6} erg/cm^{-2} (10^{-13} J/cm^{-2}) which typically occur several times per week. As a result, POLAR-2 will produce approximately 50 measurements per year with a precision equal to or better than the most precise measurements available to date.

Although dedicated to gamma-ray polarimetry, the POLAR-2 detector will also play a leading role in providing transient alerts to the multi-messenger community. This is thanks to its large effective area, which exceeds 2000 cm^2. This large effective area, combined with continuous observations of half the sky and almost continuous communication to ground will allow POLAR-2 to send alerts within one minute from the onset of about 1 GRB every 2 days. Current predictions indicate that POLAR-2 will perform approximately 2 joint detections per year with gravitational wave detectors. As the instrument furthermore has access to a GPU onboard the CSS, studies are currently ongoing on how to optimize GRB spectral and location information within such alerts. As a result, POLAR-2 will, for many GRBs, provide the first detailed alert to the ground to instruments such as CTA, optical and radio telescopes.

4. The Terzina telescope on board the NUSES satellite

The NUSES (Neutrinos and Seismic Electromagnetic Signals) satellite mission is an upcoming project aimed at exploring new scientific and technological pathways for future astroparticle physics space-based detectors. The mission is scheduled to be launched in 2026 and will operate at a Low Earth Orbit (LEO) with an altitude at the Beginning of Life (BoL) of 535 km, along with a high inclination of 97.8° (LTAN = 18:00) in a sun-synchronous orbit along the day-

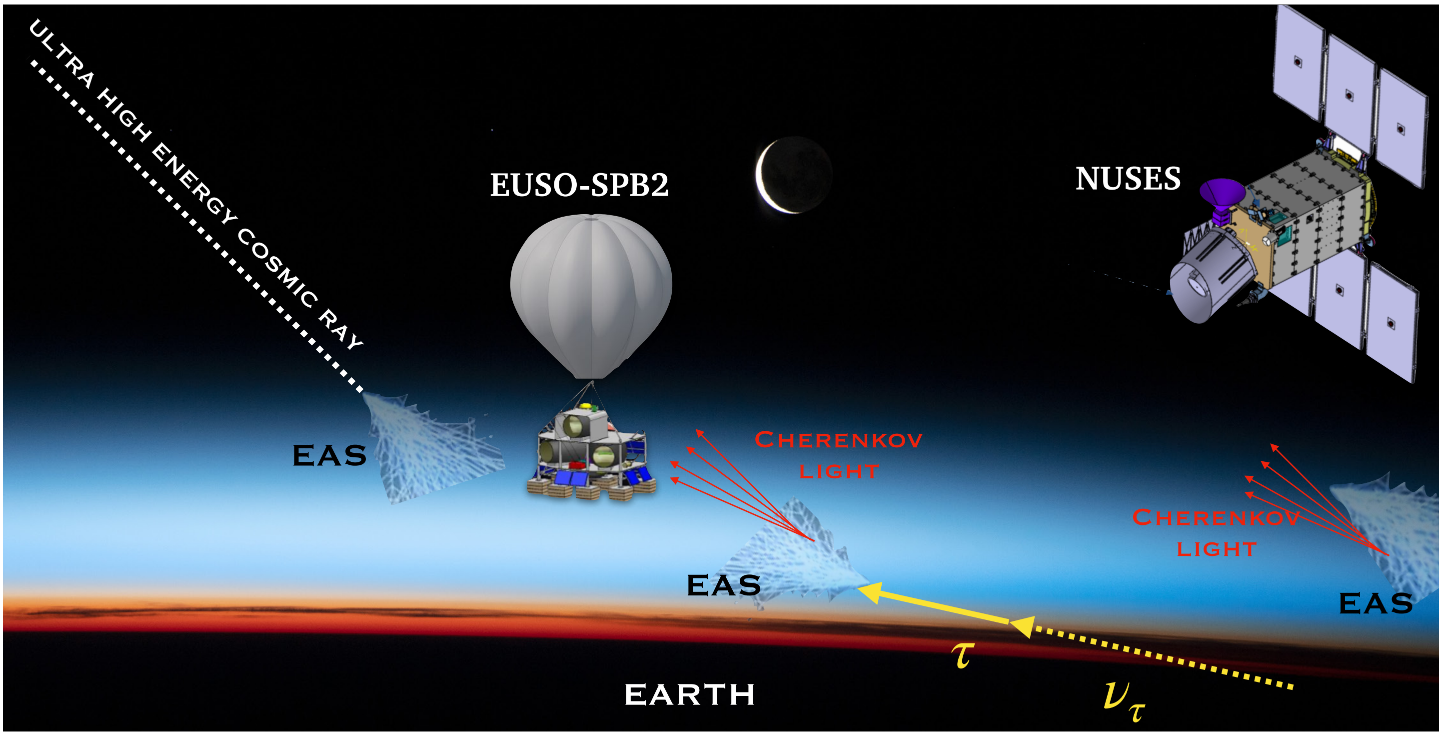

Figure 3: The principle of detection of Cherenkov light emitted by downing extensive air showers induced by ultra-high energy cosmic rays and upgoing ones induced by earth-skimming neutrinos from balloon-born experiments, such as EUSO-SPB2 [1], and space missions as NUSES.

night boundary. The NUSES mission is expected to last for three years.

The satellite will host two innovative scientific payloads: Ziré and Terzina. Ziré is a scintillation and silicon photo-sensing matrix that aims to study Gamma-Ray Bursts (GRBs) and detect cosmic rays (CRs) in the energy range of a few to hundreds of MeVs. It will also search for possible correlations of earthquakes with electrons in the van Allen belts. The second payload, Terzina, is a new optical telescope concept designed to detect Cherenkov light in space and neutrinos. It serves as a pathfinder to future space missions like POEMMA dedicated to UHECR detection and UHE earth-skimming neutrinos. POEMMA and Terzina use SiPMs for the detection of the Cherenkov light induced by extensive air showers (EAS) in the Earth's atmosphere. This needs to be dark to detect the flash of light which lasts typically 10 ns up to several tens of nanoseconds.

In the following, we will focus on Terzina. However, it is worth mentioning the technology developments targeted by NUSES as this microsatellite will be a pathfinder and a precursor of a fleet of flying elements. The Thales company in Italy (TAS-I) will prove the concept of the New Italian Micro BUS (NIMBUS), which is a new ballistic platform concept for LEO microsatellites. This foresees a modular approach relying on standard trays. Additionally, at UNIGE, we are cooperating with the Fondazione Bruno Kessler on the development of robust photosensors for space applications. These are based on the NUV-MT, which uses metal trenches to reduce crosstalk between sensor microcells to a few per cent level of accuracy.

Terzina's science scope is to detect the Cherenkov light emitted by extensive air showers (EAS) induced by ultra-high-energy cosmic rays (UHECRs) and Earth-skimming neutrinos. At extremely high energies, tau neutrinos and muon neutrinos passing through the Earth can produce tau and muon leptons, which can emerge by decaying or interacting in the atmosphere. These interactions result in Earth skimming events, which create EAS moving in the atmosphere from bottom to top, unlike the downgoing EAS

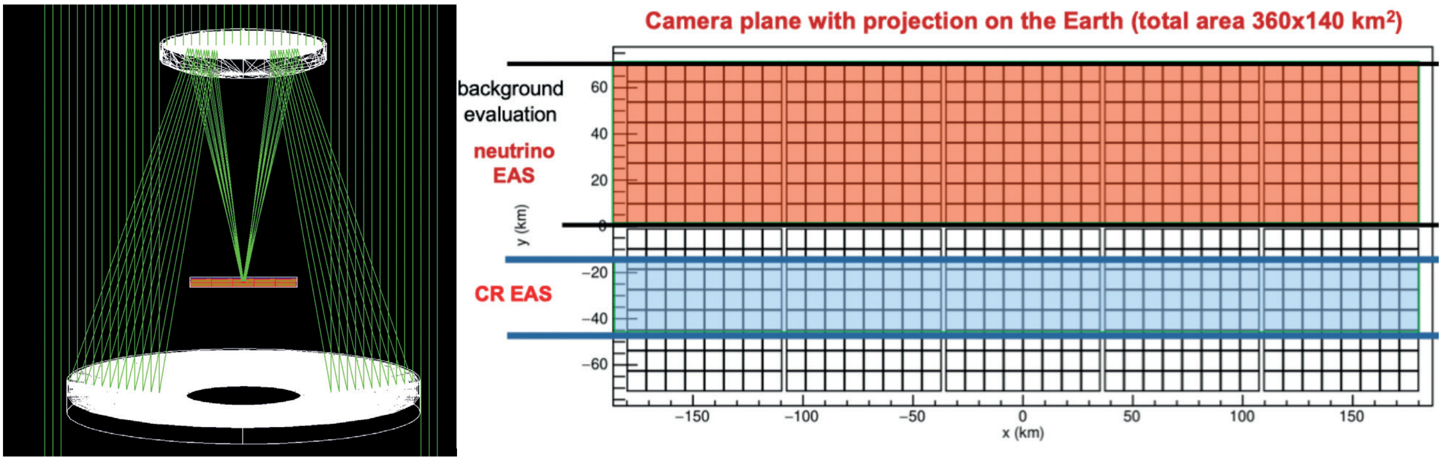

Figure 4: Left side: the optical system of Terzina. Right side: the focal plane with two row of 5 SiPM arrays of 8 × 8 pixels. The upper arrays will be sensitive to the Earth and UHE neutrinos and the lower to the UHECRs produced in the Earth's atmosphere.

produced by UHECRs in the layer of the atmosphere above the limb. The Cherenkov emission from these EAS can be detected by space-based instruments with high exposures. As Terzina is sensitive to particle interactions at distances of few 1000 km, the effective detection area is huge compared to the mirror area of the order of 0.1 m^2 of the telescope.

The telescope will be inclined at an angle of 67.5° with respect to the nadir, with the optical axis pointing towards the dark side of the Earth's limb. The expected duty cycle of the telescope is around 40% due to the passage of the Moon across the orbit and residual sunlight in the detector, with the addition of a random background from lights of cities and thunderstorms and reflections of light on other satellites.

The Terzina detector is made up of a near-UV-optical telescope with Schmidt-Cassegrain optics and a Focal Plane Assembly (FPA) shown in Fig. 4 on the right. The optical system uses a dual-mirror configuration (see Fig. 4 on the left) consisting of a primary mirror, which is placed about 40 mm away from the FPA and has a radius of about 394 mm, and a secondary mirror with a radius of about 144 mm. The two mirrors are positioned about 280 mm apart and the equivalent focal length is 735 mm.

The FPA is designed to detect photons from both below and above the Earth's limb. It has a rectangular shape with a 2:5 aspect ratio and is composed of 10 SiPM (Silicon Photomultiplier) arrays. Each array contains 8 × 8 pixels of 3 × 3 mm^2 each, arranged in 2 rows of 5 arrays each, for a total of 640 pixels overall.

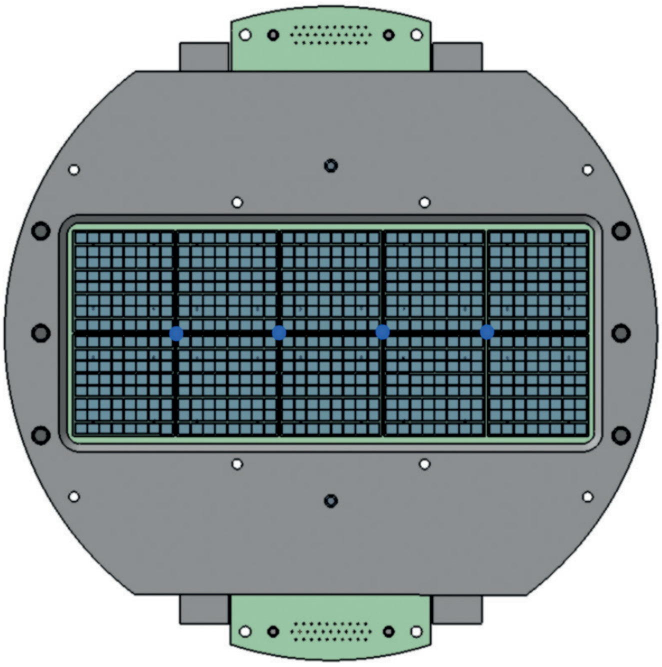

Figure 5: The TERZINA SiPM photosensing plane (FPA) composed of 10 8 × 8 tiles of 3 × 3 mm^2 produced by FbK.

Thanks to the Schmidt-Cassegrain optics, the upper row of 5 SiPM arrays is dedicated to observing events coming from below the Earth's limb. It will provide a clear characterization of the background and might observe a few neutrino-induced EAS. Even one would be of such high energy that would be sent as a trigger to all electromagnetic and other neutrino telescope detectors. The lower row of 5 SiPM arrays will observe UHECRs above the limb.

A simulation pipeline has been constructed at the UNIGE to evaluate the performance of the telescope. Using the Extensive Air Shower Cherenkov Simulation (EASCherSim) computational framework, the Cherenkov emission observed from a space-based telescope during an above-the-limb EAS has been estimated. The Cherenkov emission can be observed from a small layer of the atmosphere with an angular size of less than 1°, at an altitude above the limb ranging from 20 km up to 50 km, given the observation geometry from the Terzina altitude and atmospheric characteristics. The Cherenkov spectrum shifts more to the red wavelength than for Cherenkov light observed from the ground and is affected by a dip due to ozone absorption. We have implemented in the Geant4 toolkit the design of the Terzina telescope geometry mechanically and optically implemented by the Italian company Officina Stellare (see the CAD model of the telescope in Fig. 6). The result is a dedicated Monte Carlo simulation of photon propagation to the telescope which will allow to exactly predict the performance of the telescope.

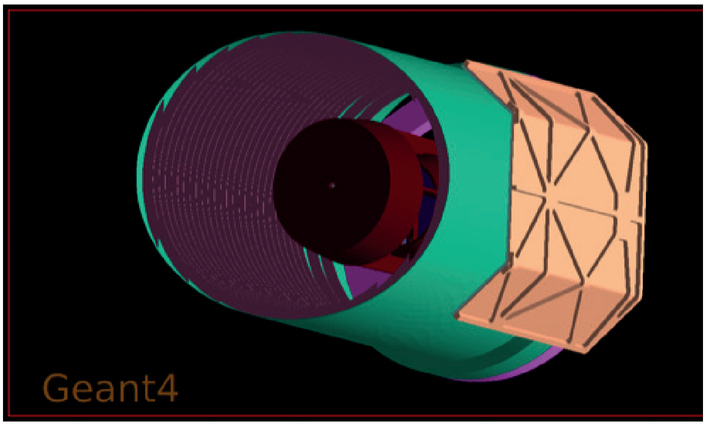

Figure 6: The Terzina CAD model

The background of Terzina is expected to consist of electrons (trapped) and protons (trapped and solar). It will also include the Night Glow Background and city lights, as well as atmospheric factors such as auroras, lightning, and clouds.

We anticipate that cosmic ray electrons and protons will be the primary sources of background as the ionizing radiation from protons and heavier nuclei can cause damage to the silicon of SiPMs. Additionally, neutrons can induce dislocations within the crystal structure. These sources of damage increase the Dark Count Rate (DCR). The extent of the damage depends on the cosmic ray radiation spectra obtained with the SPENVIS NASA code for the Terzina's orbit. We utilize the full simulation of the telescope to estimate the radiation dose accumulated during the 3-year mission by the SiPMs. We compare the simulation to the results of tests of electron and proton radiation exposure tests. The sensors were exposed to a proton beam of about to MeV at the IFJ PAN Institute and electrons from strontium ^{90}Sr/^{90}Y decay which has a two-decay mode extending to 2 MeV.

As SiPM performance degrades under the action of (mostly ionizing) radiation, their robustness for space application will depend on their radiation hardness, the strategy to recuperate their performance through annealing and the radiation quantity to which they will be exposed. An annealing strategy was defined as compatible with the maximum dissipation allowed for the photo-sensing plane of the camera of 5 W, where the recovery at each cycle is about 40 % at moderate achievable temperatures of about 60°C after 60 hours of heating. The main effect of the damage in the sensors will be due to solar protons and 1/3 trapped protons in the van Halen belts. If the damage accumulates over time the power consumption due to the dark count rate it generates will become out of specification.

In conclusion, the Terzina telescope is an innovative optical telescope designed to detect high-energy neutrinos and cosmic rays. The mission holds the promise of advancing our understanding of astrophysical phenomena and paving the way for future breakthroughs in space-based astroparticle physics research.

[1] Eser, J., Olinto, A. and Wiencke. L., for the EUSO Collaboration, Overview and First Results of EUSO-SPB2, in Proc. of Int. Cosmic Ray Conference 2023, PoS ICRC2023