PROCEEDINGS OF SCIENCE

Probing Ancient Cosmic Ray Flux with Paleo-Detectors and the Launch of the PRIμS Project

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Paleo-detectors offer a unique opportunity to probe the long-term history of cosmic ray flux, potentially revealing evidence of nearby supernovae and other high-energy astrophysical events. This technique relies on the persistent damage tracks left in natural minerals by nuclear recoils induced by cosmic ray secondaries, providing an integrated record of particle flux over geological timescales. In this contribution, we present our recently published work demonstrating that evaporites formed during the Messinian Salinity Crisis (6 Myr ago) could provide an ideal natural archive for secondary cosmic ray interactions. By modeling the density of nuclear recoil tracks preserved in these minerals and taking into account the deposition and shielding rate in the geological event, we show that percent-level variations in the primary cosmic ray flux could be detected, extending the reach of paleo-detectors beyond dark matter and neutrino searches to cosmic ray paleo-astrophysics. We also introduce PRIµS, an INFN-funded experimental effort that is the natural extension of our phenomenological work. Using high-throughput optical microscopy and plasma etching techniques, PRIµS aims to analyze a variety of samples, with a focus on halite and other evaporites, with the goal of validating theoretical models and refining background estimates for future paleo-detector applications.

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1. Introduction: Mineral Detection and Paleo-detectors

The study of cosmic rays (CRs) provides a direct probe of the most energetic phenomena in the universe. While the origins of lower-energy CRs are associated with galactic sources like supernovae, the highest-energy particles are believed to originate from extragalactic objects such as Active Galactic Nuclei or Gamma-Ray Bursts [2, 3]. Our current understanding is based on a snapshot in time from detectors built over the last century. A major unanswered question in astrophysics is how this flux has varied over geological timescales as our solar system journeyed through the Galaxy and the local universe. Answering this requires a completely new kind of detector—one with an exposure time measured in millions of years.

This contribution introduces the emerging field of "paleo-detectors," which repurposes common, ancient minerals as natural particle detectors [1, 7]. The underlying principle is that when an energetic particle induces a nuclear recoil within a mineral's crystal lattice, it leaves a trail of permanent damage. This "latent track," often nanometers in diameter and microns in length, is preserved over geological timescales, provided the mineral has remained in a thermally stable environment [8]. By developing techniques to read out these ancient tracks, we can effectively use the Earth itself as a vast, long-exposure observatory.

1.1 The Paleo-Detector Technique

The formation of tracks in minerals has been studied for decades, primarily for geochronology, where tracks from the spontaneous fission of ^{238}U impurities are used to date rocks [1]. The paleo-detector concept extends this to search for much rarer interactions from external particle fluxes. The interaction of a particle with a nucleus in the crystal can damage the lattice, resulting in amorphization or the creation of point defects like color centers [1].

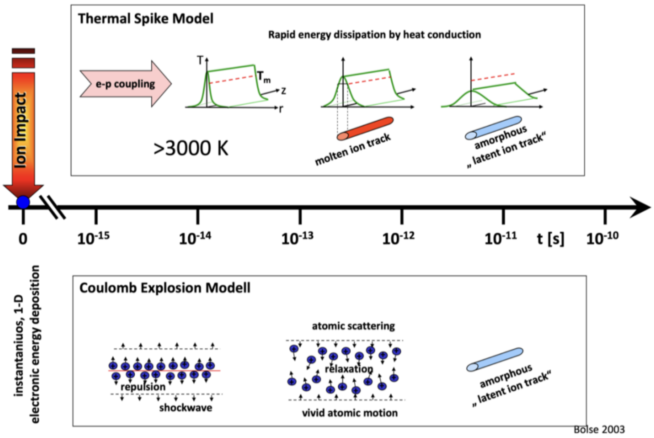

Figure 1: Two different models for the formation of latent fission tracks in condensed matter. From [1].

The great promise of paleo-detectors lies in their immense integrated exposure (mass × time), which could potentially surpass human-built experiments by many orders of magnitude. This has spurred a vibrant, interdisciplinary research effort aimed at two of the most significant goals in fundamental physics:

- **Dark Matter Searches:** A leading hypothesis posits that dark matter consists of Weakly Interacting Massive Particles (WIMPs). These particles, forming a halo around galaxies, would stream through the Earth, occasionally scattering off a nucleus in a mineral. Such a rare event would produce a single recoil track. By searching for a statistically significant excess of tracks with a specific length spectrum in ancient, deeply-buried minerals (to shield from CRs), it may be possible to detect WIMPs or set new limits on their interaction cross-section [1].

- **Neutrino Physics:** Neutrinos from various astrophysical and geological sources interact with matter via Coherent Elastic Neutrino-Nucleus Scattering (CEνNS), producing low-energy nuclear recoils. Paleo-detectors could provide a time-integrated measurement of these fluxes. For example, the PALEOCCENE collaboration is investigating the use of color centers in minerals like lithium fluoride to detect such events, with the potential to study the solar neutrino flux over gigayear timescales or neutrinos from past supernovae [8].

1.2 Paleo-detectors for Cosmic Rays

In the searches for dark matter and neutrinos, secondary particles from CR showers—primarily high-energy muons and their spallation products like neutrons—are the most significant and irreducible background. The CR-induced tracks are expected to be far more numerous than the sought-after rare signals, requiring these experiments to use samples from deep underground sites (e.g., >5 km depth) to shield against the cosmic ray flux [1].

Our work inverts this paradigm. We propose to use the most abundant source of tracks not as a background, but as the *signal* itself. By selecting minerals with a known and well-defined period of exposure at or near the Earth's surface, the dense record of CR-induced tracks becomes a direct probe of the cosmic ray flux at that point in Earth's history. This approach creates a new scientific goal: CR paleo-astrophysics, with the potential to find evidence of ancient astrophysical events through their impact on the local CR environment. The PRIμS project is the first experimental program dedicated to this goal.

2. The Messinian Salinity Crisis

To use paleo-detectors for CR history, a sample must satisfy stringent criteria: it needs a known age, low internal radioactivity, and, most importantly, a well-defined "exposure window." This means a known period of exposure to surface-level CRs, followed by a rapid and permanent shielding event that effectively "turns off" the detector and preserves the recorded tracks from that specific epoch. Our recent phenomenological work has identified an ideal target that meets these criteria: evaporite minerals formed during the Messinian Salinity Crisis (MSC) [2].

The MSC was a profound geological event, occurring between 5.97 and 5.33 million years ago, when tectonic restriction of the Atlantic gateways caused the Mediterranean Sea to partially or nearly completely desiccate [5]. During this 640 kyr period, vast deposits of evaporite minerals, primarily halite (NaCl, rock salt) and gypsum, formed in the deep basins. These newly formed minerals were exposed to the full secondary CR flux at the surface or under shallow, highly saline water.

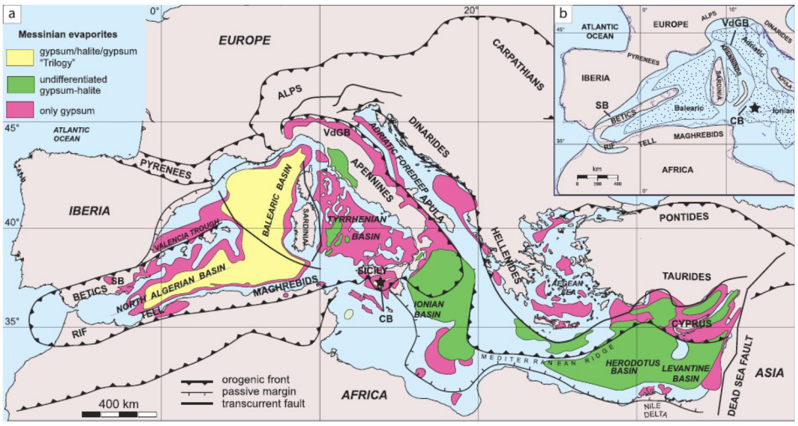

Figure 2: a) Map of the Messinian evaporites in the Mediterranean. The term "trilogy" indicates the threefold deeper succession of Western Mediterranean that, based on seismic, includes a halite unit sandwiched between two gypsum units. B) Paleocenaographic map of the Western Mediterranean basins during the Messinian salinity crisis, showing the main evaporite depocentres (dotted areas). Emerged areas are in gray. Dotted line is the modern coastline. From [5]

The crisis ended catastrophically with the Zanclean Flood (5.33 Ma), which refilled the Mediterranean basin in what was, geologically speaking, an instant. This event buried the Messinian evaporites under kilometers of water and subsequent marine sediment. This rapid burial provided an immense and permanent shield, perfectly preserving the record of CR interactions from the 500 kyr exposure window of the late Miocene.

Halite is a particularly suitable detector medium. It can be found in layers of exceptional purity, leading to very low intrinsic radioactivity from elements like Uranium and Thorium. This minimizes the main internal background source: tracks from spontaneous fission [2].

We performed a detailed phenomenological study to quantify the expected signal in these samples [2]. Our simulation pipeline involved:

- Modeling the primary CR flux and its interaction with the Earth's atmosphere to generate Extensive Air Showers (EAS).
- Propagating the secondary particles, with a focus on the highly penetrating muon component, through the atmosphere and any overburden to the halite sample surface.
- Using Geant4 [9] to simulate the muon interactions within a large volume of halite, recording the energy and species of every resulting nuclear recoil.
- Converting the recoil energy spectra into a track length distribution using the SRIM code [10] and the Paleopy package [11].

Our results show that track densities on the order of $10^4 - 10^6$ tracks/cm^2 are expected, a density that is readily measurable. We modeled three primary signal scenarios: (A) the CR flux as it is today; (B) the current flux plus an enhancement from a nearby supernova at 20 pc; and (C) the same for a supernova at 100 pc. The simulations (Fig. 3) show a clear, measurable difference in the expected track length spectrum between these scenarios. We find that this method is sensitive to percent-level variations in the primary CR flux during the exposure window. This sensitivity is sufficient to probe for local flux enhancements predicted from astrophysical events, like the supernovae explosions potentially responsible for the ^{60}Fe deposits found in deep-sea crusts from a similar epoch.

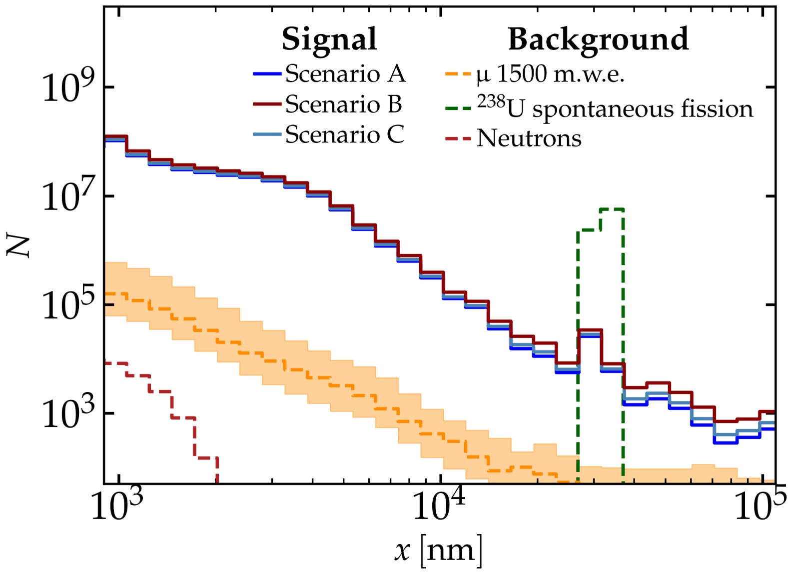

Figure 3: Expected total number of tracks in a 10 g sample of halite which was created 5.6 Myr ago, exposed for 270 kyr to muons and then covered by a 1.5 km overburden of water. The backgrounds are integrated for the whole age of the sample with the exception of the underwater μ, which is integrated for the period when the sample is sea-covered, i.e. 5330 kyr.

3. The PRIμS Experiment

The promising results of our phenomenological study have led to the launch of the PRIμS (Paleo-astroparticles Reconstructed with the Interactions of MUons in Stone) project [3]. Funded by INFN, PRIμS is an experimental program designed to move from theoretical modeling to a direct, first-of-its-kind measurement of the ancient cosmic ray flux. The project strategy is built on several key pillars:

3.1 Experimental Goals and Techniques

The primary objective of PRIμS is to experimentally detect and characterize CR-induced recoil tracks in ancient minerals. To achieve this, a multi-stage approach is required.

First, interesting samples of MSC halite and other candidate minerals (like xenoliths from volcanic regions) must be obtained and characterized. This involves geochemical analysis (e.g., ICP-MS) to measure trace element concentrations, particularly U and Th, to constrain internal backgrounds.

Second, the samples must be prepared for microscopy. This involves cleaving or polishing to create a pristine surface. We will then employ etching techniques to enlarge the nanometer-scale latent tracks to a size visible with optical methods. While chemical etching has been traditionally used, PRIμS will focus on developing and optimizing protocols for **plasma etching**. This technique can offer better control, efficiency, and safety compared to wet chemical etching with hazardous acids.

Third, the etched samples will be scanned using a **high-throughput automated optical microscopy station**. The PRIμS project has acquired a new system by Evident (Olympus) capable of scanning large areas (up to 50 cm^2) with high magnification (up to 100x) and automated Z-stacking (multi-plane focusing). This capability is crucial for scanning the large sample areas required to obtain statistically significant track counts and for fully characterizing 3D track morphology.

3.2 The Data Analysis and Software Pipeline

The high-throughput microscopy readout creates a formidable data challenge, potentially generating terabytes of high-resolution images. Manually identifying and measuring millions of faint, micron-sized tracks in this data is unfeasible and would be prone to human bias.

To overcome this bottleneck, the development of a fully automated analysis pipeline is the cornerstone of PRIμS. This is where the machine learning model we are currently building plays a critical role.

- **Semantic Segmentation with U-Net:** The core of our software is a **U-Net**, a deep convolutional neural network architecture. We are training this network to perform semantic segmentation: it takes a raw microscopy image as input and outputs a pixel-wise probability map that identifies which pixels belong to a "track" versus the "background" mineral lattice. We chose the U-Net architecture due to its proven success in biomedical imaging, where its encoder-decoder structure with skip connections allows for precise localization of features—exactly what is needed to delineate faint track boundaries.

- **Post-processing and Data Extraction:** This segmentation is the crucial first step in data reduction. The output binary mask is then fed into a post-processing stage. Using standard computer vision algorithms (e.g., `cv2.connectedComponentsWithStats`), we can automatically extract high-level physical parameters for each and every identified track, including its precise location (centroid), area (which relates to the recoil energy), and shape descriptors.

- **Physics Output:** The final output of this software pipeline is not just the masks on images, but a structured data catalog of all detected tracks and their properties. This automated catalog is what allows for the final physics analysis: building track density maps, generating track size spectra, and comparing these distributions to our simulation models to ultimately reconstruct the ancient CR flux.

Finally, to ensure the accuracy of our final results, the entire analysis chain must be calibrated. We will perform irradiation experiments at accelerator facilities, exposing mineral samples to beams of known particles (e.g., muons, neutrons) at known energies. By analyzing these irradiated samples with our microscopy and ML pipeline, we can calibrate the relationship between a particle interaction and the measured properties of the track it creates.

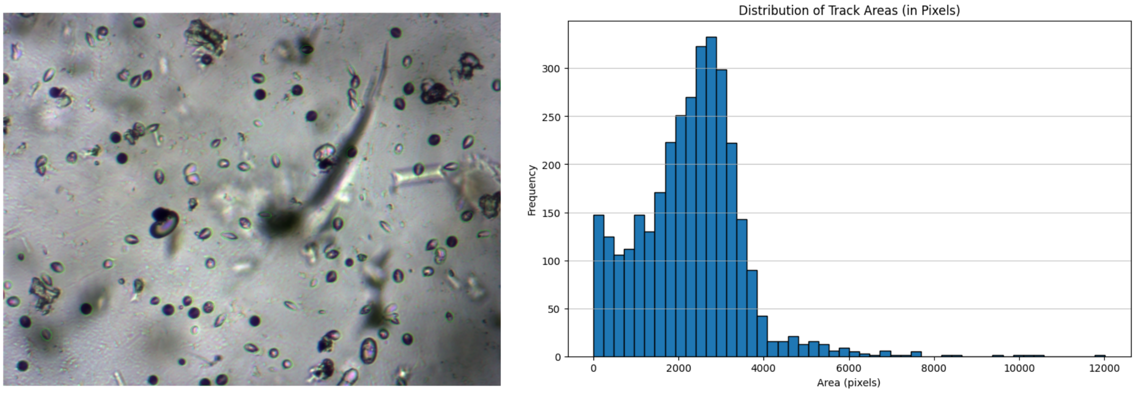

Figure 4: Test results of the analysis pipeline applied to enlargements on chemically treated irradiated obsidian containing induced fission tracks. Left: detected track mask (in green) for an image overlaid on the original image. Right: histogram of pixel size for all the tracks detected over 60 test images.

4. Conclusion

The history of the cosmic ray flux is a largely unexplored domain. Paleo-detectors offer a novel method to access this history by using Earth's own minerals as natural particle recorders. Our work has identified evaporites from the Messinian Salinity Crisis as ideal targets for a first measurement, with simulations confirming their sensitivity to astrophysically interesting variations in the CR flux. The newly launched PRImuS project will develop the necessary experimental and analytical techniques—with an automated, `U-Net`-based image analysis pipeline at its core—to make these pioneering measurements a reality, opening a new window onto the history of the high-energy universe and providing crucial background characterization for the broader field of mineral-based rare event searches.

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