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

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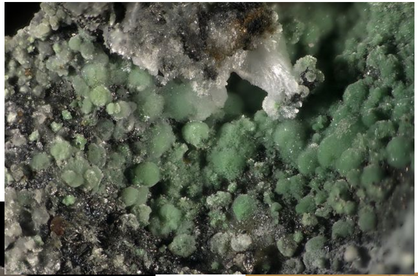
Yokohama
21/05/25

Paleo-Detectors: Minerals as Nature's Particle Recorders



Core Concept: Certain natural minerals act as natural solid-state nuclear track detectors.

Track Formation: Energetic particles (from nuclear recoils from cosmic messenger interactions, fission fragments) leave latent damage tracks (nm to µm scale) in the crystal lattice (amorphization, stress, color centers).

Geological Timescales: Tracks preserved for millions to billions of years, depending on mineral type and thermal history.

Mineral Detection: From Geochronology to Particle Physics

Established Applications in Geosciences:

Fission Track Dating: Using tracks from spontaneous fission of 238U, etc. (O(50) MeV recoils, O(10) μm tracks).

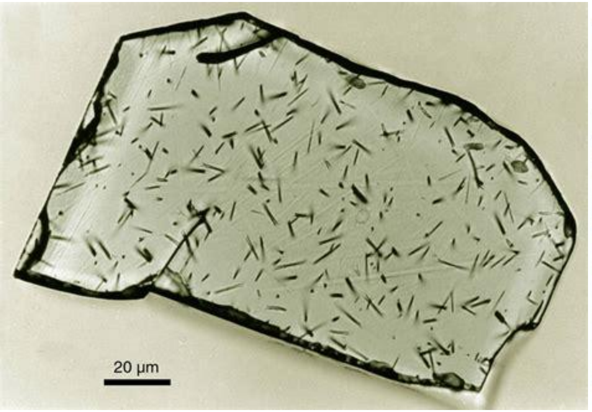
Alpha-Recoil Track (ART) Dating: Using tracks from O(100) keV recoils in decay chains (e.g., U/Th series).

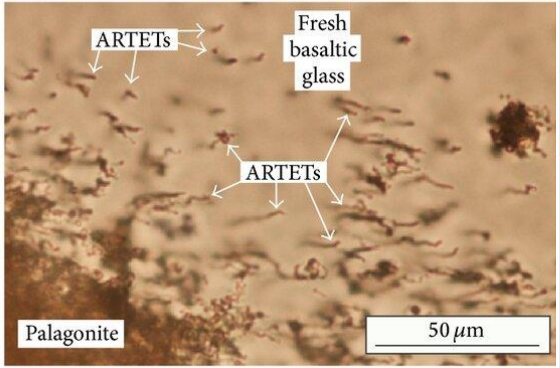
Emerging Applications in Particle Physics:

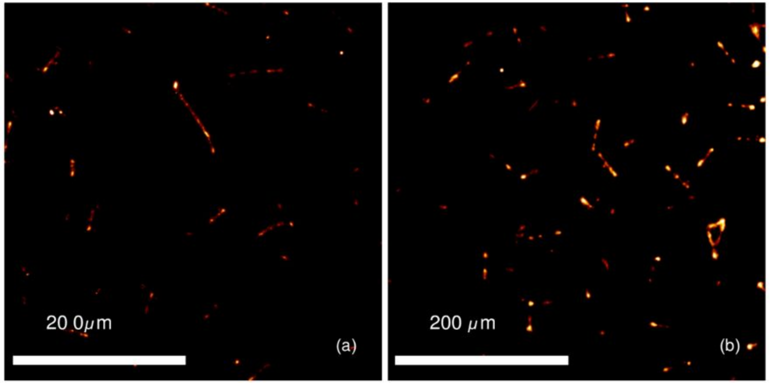
Dark Matter Searches: Seeking rare nuclear recoils from WIMP-nucleus interactions.

Neutrino Detection: Searching for coherent elastic neutrino-nucleus scattering (CEvNS) or other neutrino interactions.

Immense integrated exposure (mass × **time**) offered by natural samples.







PALEOECCENE collab.

Cosmic Ray Paleo-Astrophysics

Signal, Not Just Background:

CR-induced tracks can become the *signal* of interest, shifting from their role as background in DM/neutrino studies.

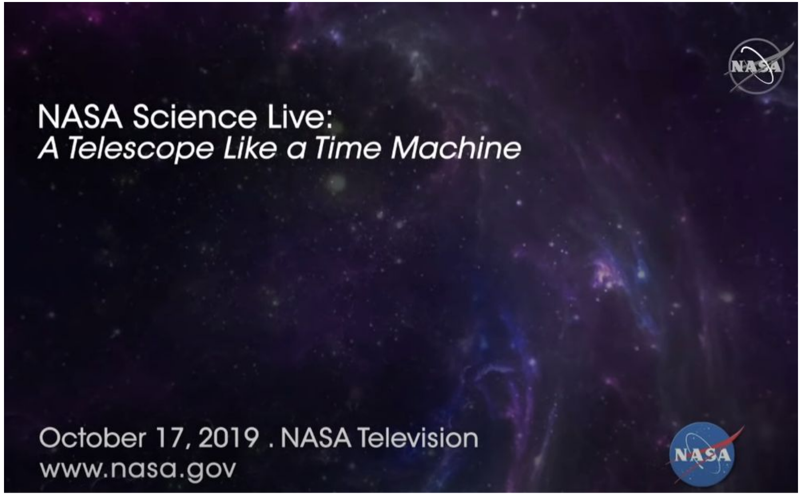
Telescopes as time machines | Dr. Michael Liu | TEDxHonolulu

4.305 visualizzazioni • 5 mar 2012

Smithsonian MAGAZINE

SCIENCE

If Telescopes Are Time Machines, the JWST Will Take Us the Furthest Back Yet



Historical memory of (some) paleo-detectors

Minerals with a history of exposure and shielding from the CR flux keep the record of the state of the universe at the time of exposure

Unique Historical Record: Direct observational window into Cosmic Ray flux over geological timescales (Myr-Gyr).

Probing High-Energy Events: Potential to find evidence of past nearby astrophysical events that modulated local CR flux.

Complementary Information: Different approach to cosmogenic isotopes (10Be, 14C) in meteorites or terrestrial archives.

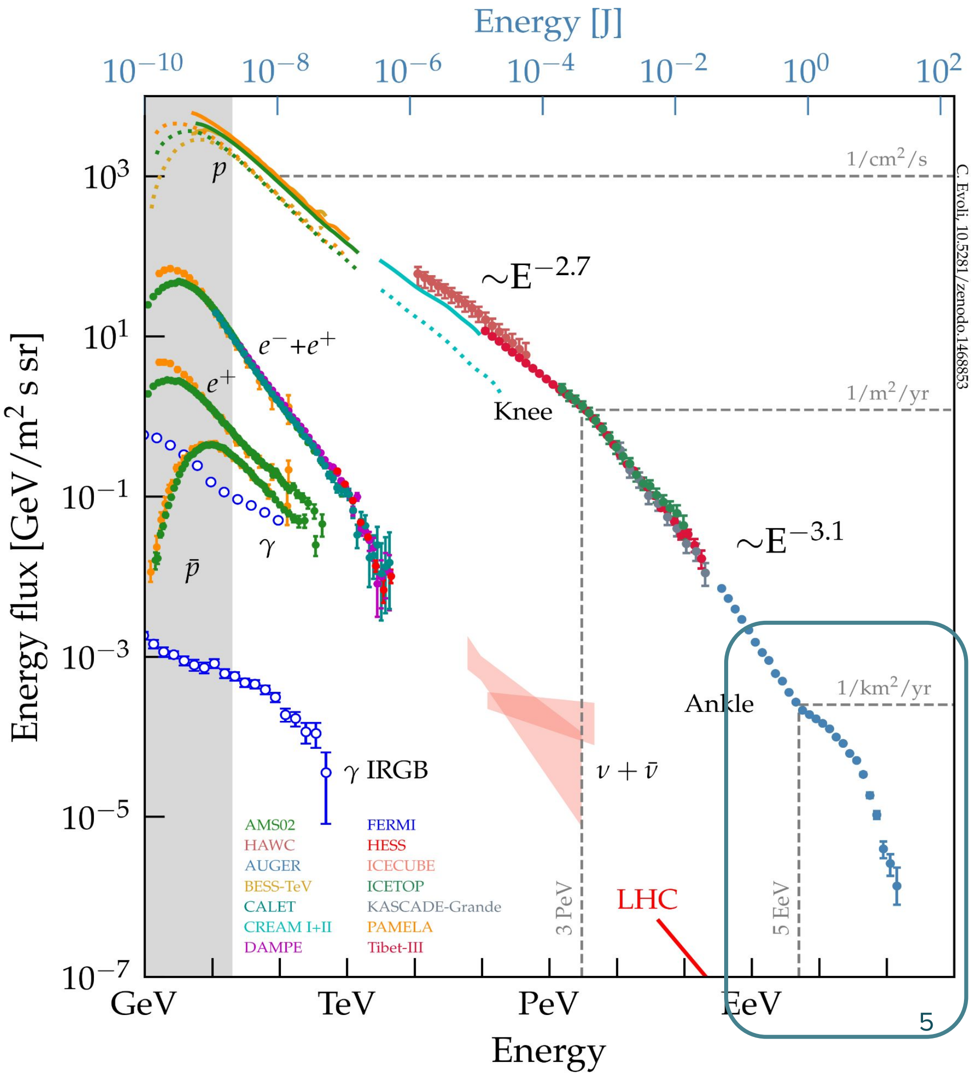
Understanding Cosmic Rays

Highly energetic particles with wide variation in flux
~87% protons, ~12% He nuclei, ~1% heavier nuclei
plus electrons, positrons, gamma rays.

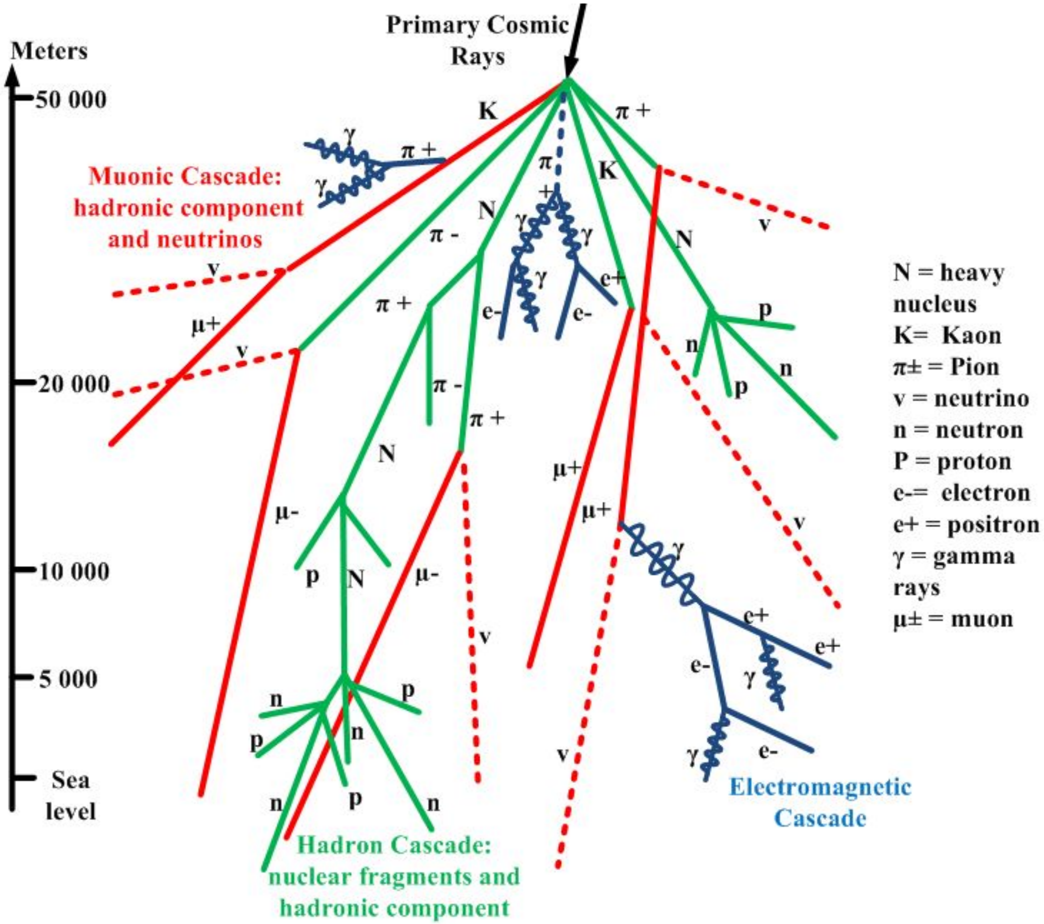
Ultra High Energy CRs (UHECRs) are the most energetic particles in the universe. Composition ranges from mostly protons at the EeV (1e18 eV) to mostly Iron at 100 EeV.

Detection is direct in space missions for low energy CRs

VHE and UHE CRs are detected indirectly through showers of secondary particles with arrays of detectors on earth.



From Air Shower to Mineral Track



Atmospheric Interactions

Extensive Air Showers - EAS:

Primaries collide with atmospheric nuclei (N, O).

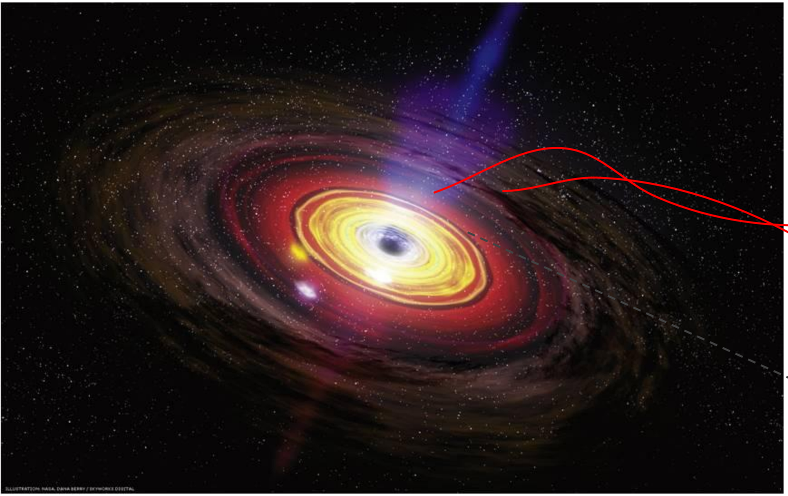
Produce a cascade of secondary particles: pions, kaons, muons, neutrinos, electrons, photons, neutrons, protons.

Key Secondary CRs for Paleo-Detectors:

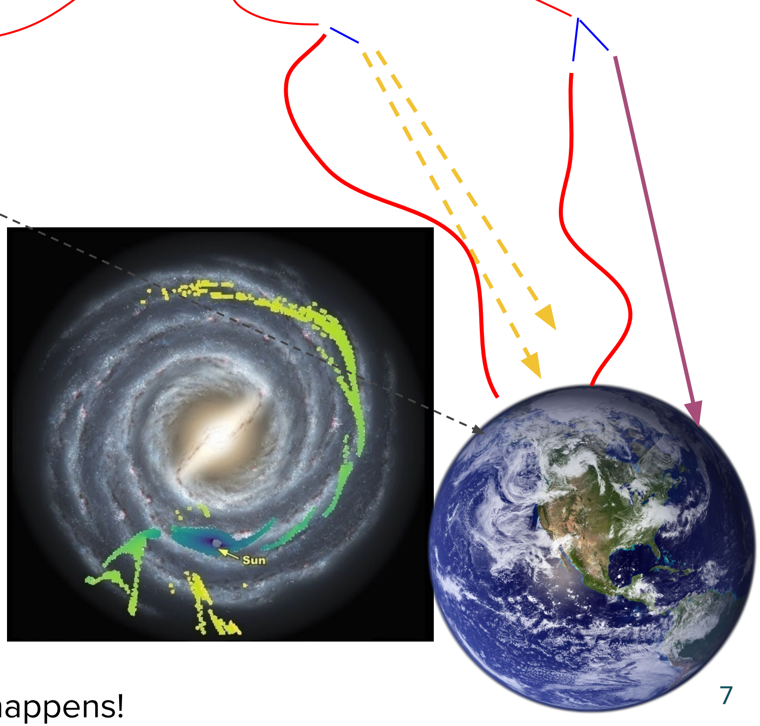
Muons (μ): Highly penetrating component of EAS. Can reach significant depths underground.

Neutrons (n): Also produced in EAS and by muon interactions in rock/soil.

Hadrons (protons, pions at shallow depths).



Cosmic ray propagation and origin



Galactic CR origin probably **supernovae and supernova remnants.**

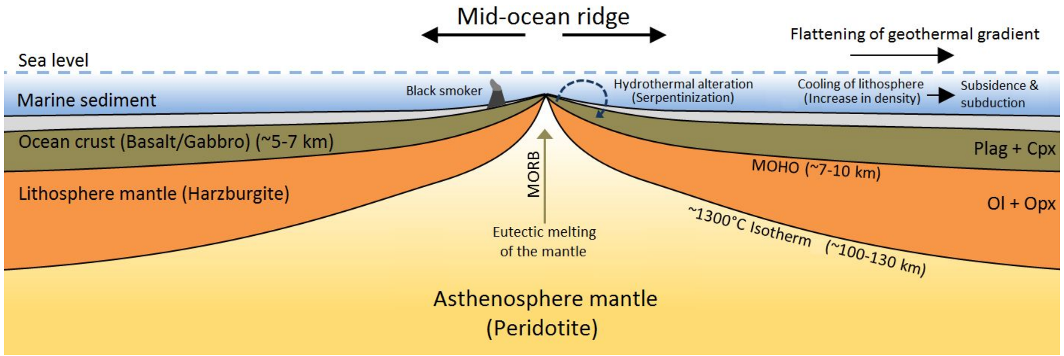
UHECR sources are unknown: **Active Galactic Nuclei**, gamma-ray burst populations, **Starburst** superwinds are the main candidates

Problem: CRs are **deflected and delayed** by Gal and EGal magnetic fields

Origins and time of emission are blurred - only the lightest and most energetic (most ***rigid***) carry sufficient information.

Paleo-detectors with well-chosen samples could **catch the emission** as it happens!

Geological opportunity: the Mid-Atlantic ridge



The continuous production of crust in the oceanic rift can be dated with paleomagnetism - could be exploited as a series of samples exposed for different integrated times.

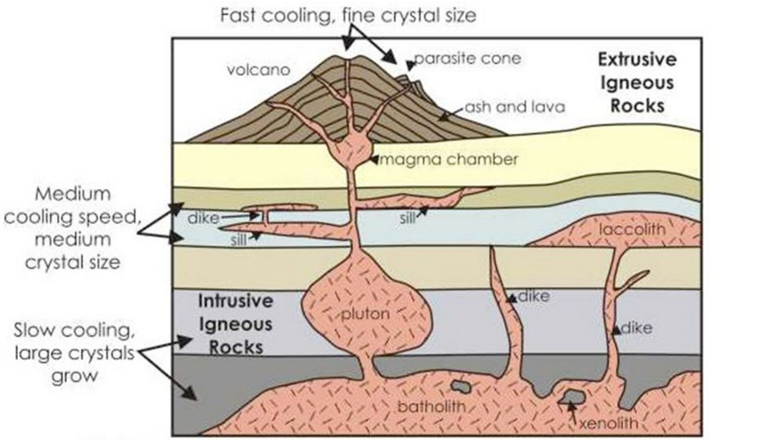
The Mid-Atlantic rift has **different overburdens** of water, from ~4 km to full exposure (Iceland), which can be used to “select” high energy secondary particles, mostly produced by **UHE primaries**

Geological opportunity: Xenoliths

Xenoliths are intrusions into magmatic flows originating **from the mantle** and **easily be dated** with the associated eruptions.

The association of the cycle of exposure and overburden with eruptions could preserve “differential” **information on the variability of the CR flux** in successive epochs.

Caveat: varying and **complicated composition**

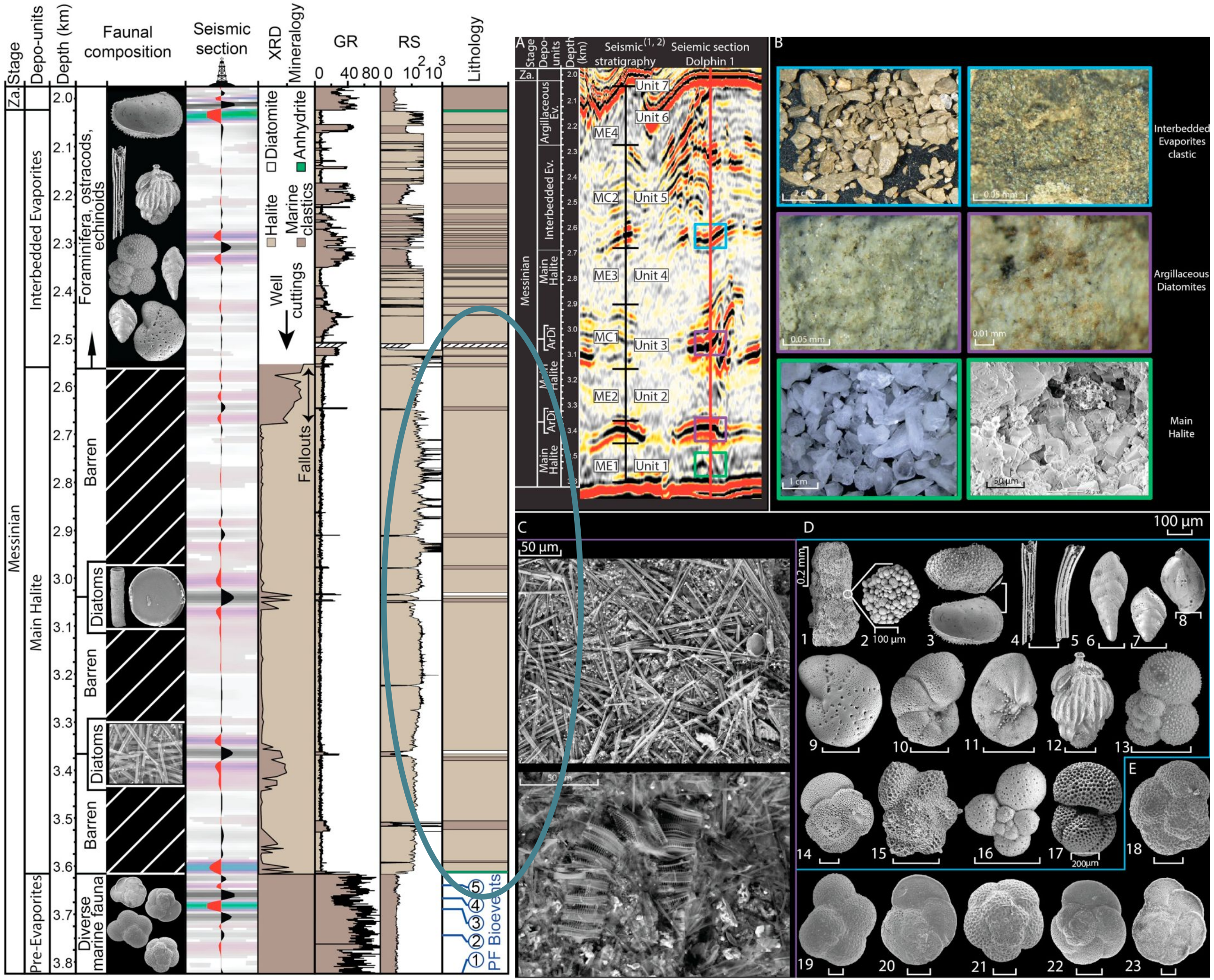


University of Canterbury, (unknown), taken 09/04/06 from http://outreach.canterbury.ac.nz/resources/geology/glossary/igneous.

Geological opportunity: the Messinian Salinity Crisis

Timing: Late Miocene, 5.97 - 5.33 Ma. Restricted Atlantic-Mediterranean gateways led to partial/near-complete **desiccation of the Mediterranean**

Consequences: Dramatic sea-level drop, formation of vast salt flats and brine pools in deep basins.



MSC:“main Halite”

Well studied and sampled in geological surveys especially in the eastern mediterranean basin

Geological samples show broad range of depths with uninterrupted halite deposit - a fantastic possible source of material in the age and depth target.

“Chronology with a pinch of salt: Integrated stratigraphy of Messinian evaporites in the deep Eastern Mediterranean reveals long-lasting halite deposition during Atlantic connectivity”
Meilijson et al., Earth-science reviews, 2019

MSC Evaporites: Ideal Targets for Ancient Cosmic Rays

- **Evaporite Formation:** Massive deposits of minerals like halite (NaCl, rock salt) and gypsum formed.
  - Focus on "Main Halite" units in basins like the Levant Basin.
- **Well-Defined differential CR Exposure Window (~500 kyr):**
  - Minerals formed and were **exposed to cosmic rays** at/near the surface or under shallow, highly saline water, **then overburdened** by other evaporites.
- **Rapid Shielding (The "Switch-Off"):**
  - Zanclean Flood (~5.33 Ma) catastrophically refilled the Mediterranean.
  - **Buried evaporites under kilometers** of water and subsequently sediment.
  - This provided immense and rapid shielding, "freezing" the CR record from that exposure period.
- **Potentially Low Intrinsic Radioactivity:** Halite is expected to be relatively pure (low U, Th).

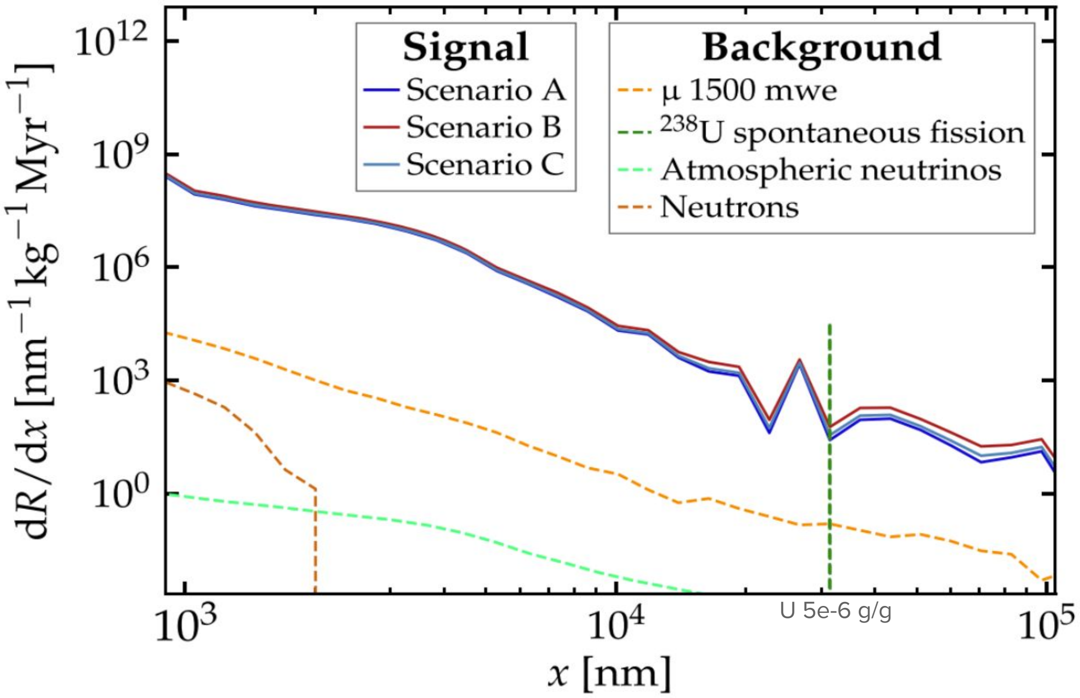
Modeling the Signal: Strategy & Key CR Components

- **Goal:** Predict the density and characteristics of nuclear recoil tracks from secondary CRs in MSC halite.
- **Primary Focus on Muons:**
    - **Most penetrating** charged component of secondary CRs.
    - Dominant source of nuclear recoils at depths relevant to surface/shallow sub-surface exposure.
- **Other Subdominant CR Components:**
    - Neutrons (cosmogenic and muon-induced): Can also cause recoils.
    - Contribution from atmospheric neutrinos (vastly subdominant for these track energies/lengths).
- **Depth:** Modeling CR flux **attenuation** through any shallow brine or **initial sediment** during exposure.

Simulating Muon-Induced Tracks in Halite

1. **Geant4:** interaction and recoil rate
2. **SRIM:** stopping power
3. **Paleopy:** spectrum

https://github.com/tedwards2412/paleopy Thomas Edwards Bradley Kavanaugh

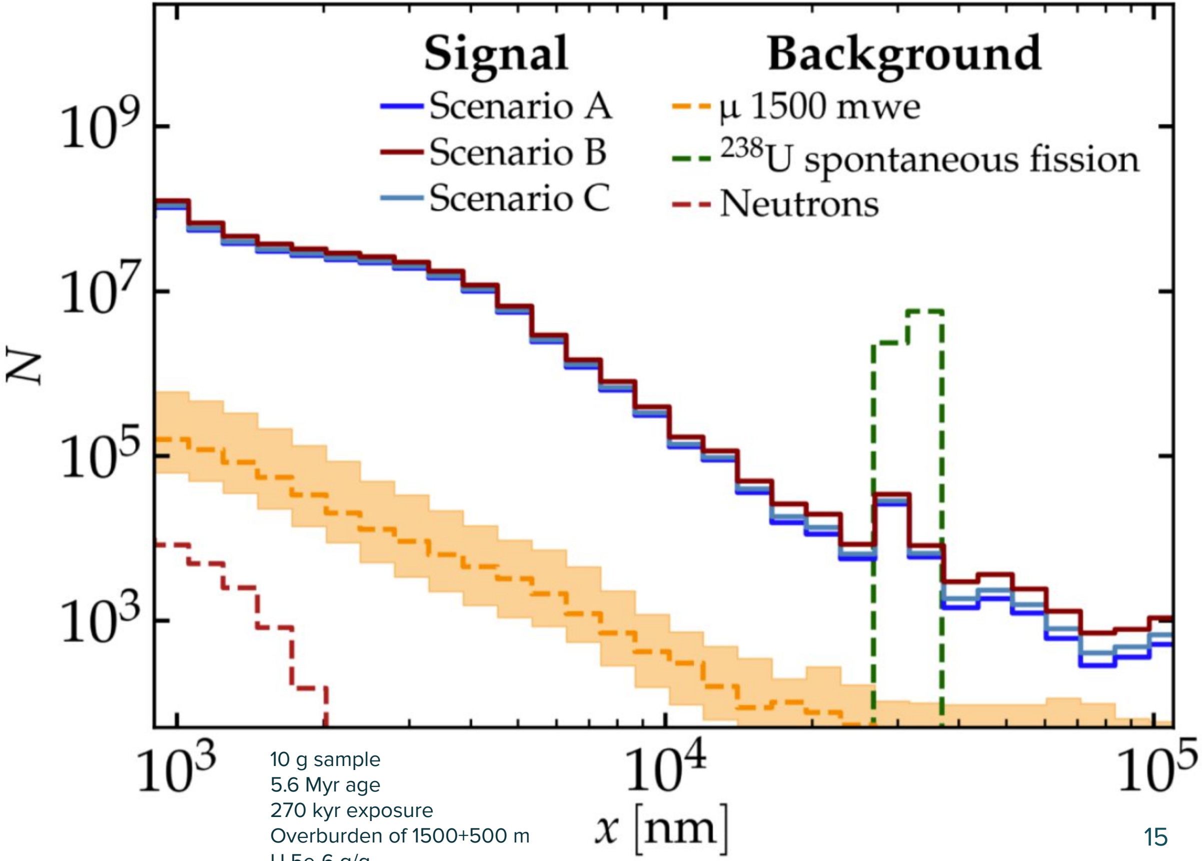


1. **Muon Flux & Spectrum:** Estimate muon flux and energy spectrum at the sample's (paleo-)depth.
2. **Interaction Mechanisms in Halite:**
   a. Muon-induced spallation (**direct nucleon knockout by muons**).
   b. Negative muon capture by Na or Cl nuclei, followed by nuclear de-excitation and particle emission (neutrons, protons).
   c. Neutrons produced by these primary muon interactions also induce recoils.
3. **Nuclear Recoils:** Calculate energy spectra and types of recoiling nuclei (Na, Cl).
4. **Track Formation Simulation :**
   a. Model the range (length) and morphology of damage tracks from these recoils.
   b. Expected track lengths: broad range extending into the tens of microns for typical muon-induced recoils in halite.

Key Findings: Halite as a Sensitive CR Probe

Halite Confirmed as a Good Target:

- Track abundance should be enough for spectrum studies if large sample
- Geological history (MSC exposure + Zanclean shielding) is **highly favorable** and effective at removing contributions from more recent CRs: even **strong modulations after the event do not impact** the signal.
- Expected low intrinsic radioactivity minimizes internal backgrounds
- Astrophysical scenarios **modulating the CR spectrum by %-level** spread the expected spectrum divergence.



10 g sample
5.6 Myr age
270 kyr exposure
Overburden of 1500+500 m
U 5e-6 g/g

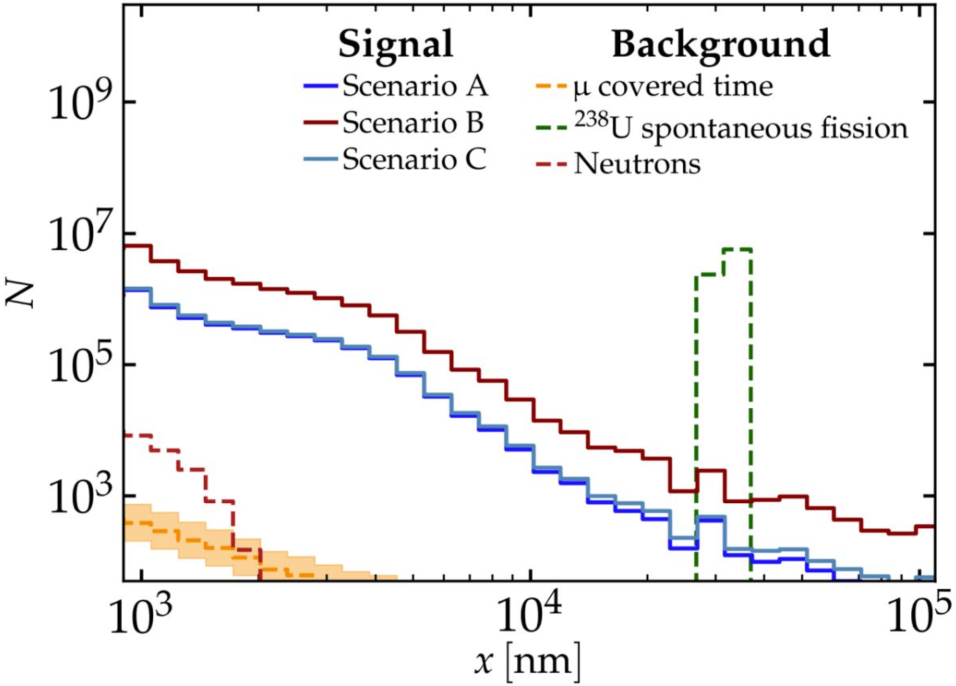
A more realistic scenario: continuous deposit

Evaporite production is a continuous process: the overburden of new halite has to be considered

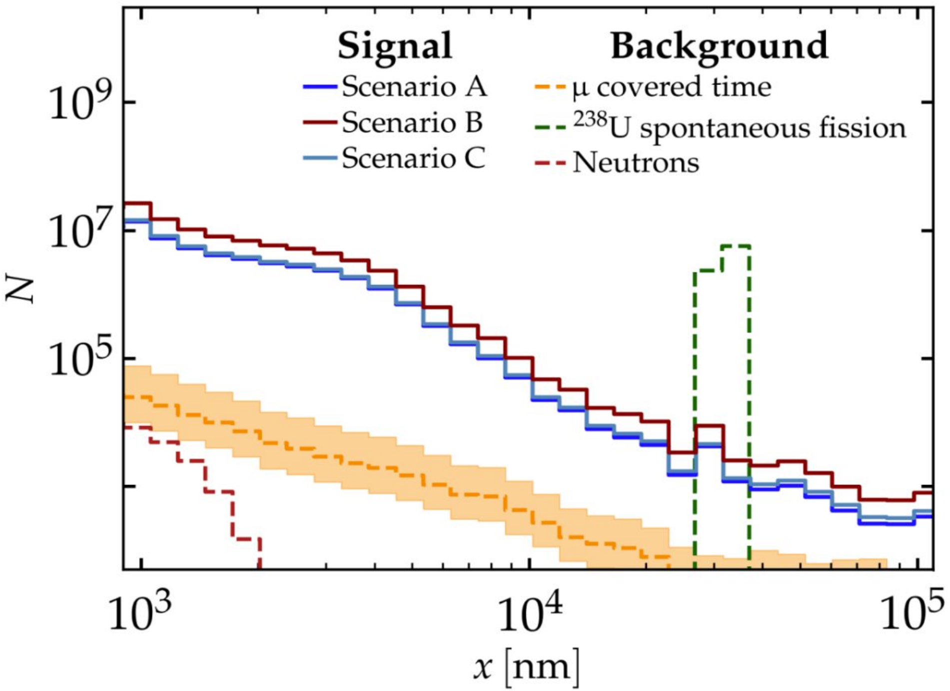
Bad: less tracks, hard to find the window of exposure

Good: could be massively more sensitive to modulation

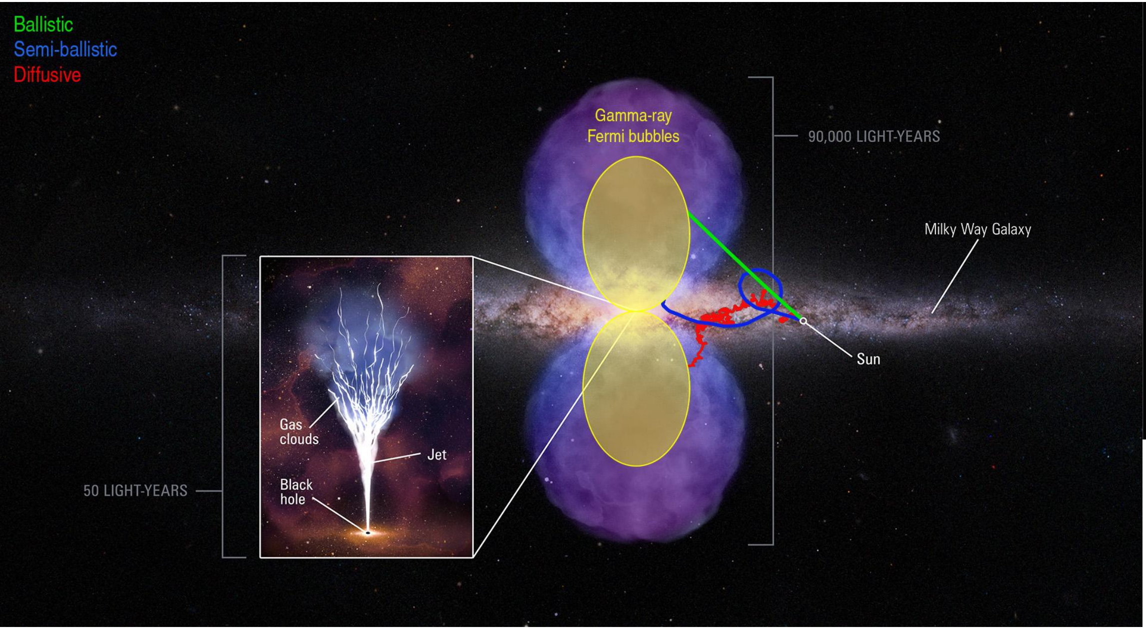
30 m/kyr deposition

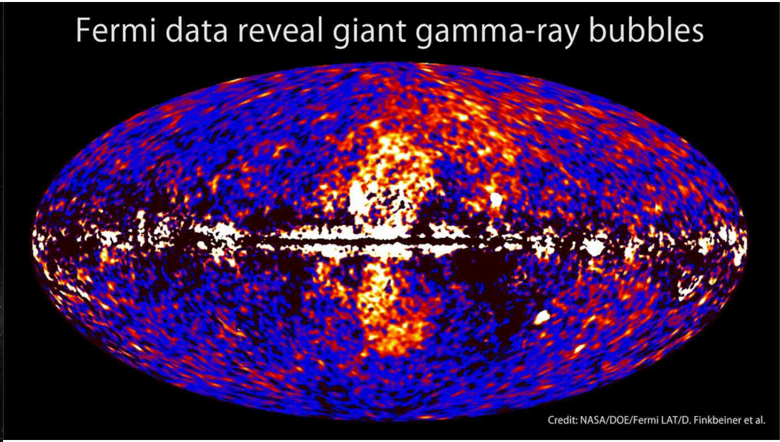


2.5 m/kyr deposition



Astrophysical scenarios: the Fermi Bubbles





M. Su and D. P. Finkbeiner, "EVIDENCE FOR GAMMA-RAY JETS IN THE MILKY WAY," Astrophys. Journal, vol. 753, no. 61, 2012.
R. Zhang and F. Guo, «Simulating the Fermi Bubbles as Forward Shocks Driven by AGN Jets,» Astrophys. Journal, vol. 894, n. 117, 2020.
M. Su, T. Slatyer and D. Finkbeiner, «GIANT GAMMA-RAY BUBBLES FROM FERMI-LAT: ACTIVE GALACTIC NUCLEUS ACTIVITY OR BIPOLAR GALACTIC WIND?,» Astrophys. Journal., vol. 724, p. 1044, 2010.

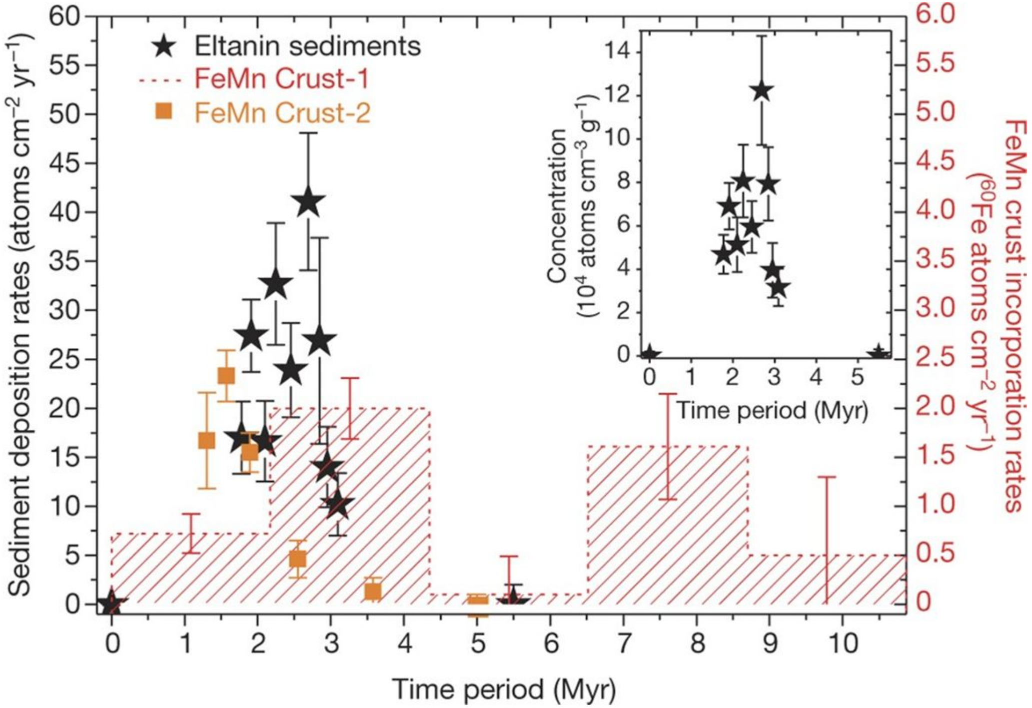
The Event: The observation of **bubble-like structures** perpendicular to the galactic plane in VHE ad HE gamma, and X radiation shows that our Galaxy, and in particular SGrA* might have been active in the cosmologically recent past.
Timing: Could be remnants of an emission **5-6 Ma**
Theories: Explanations mostly point to leptonic emission, but some favor lepto-hadronic scenarios - a Milky Way AGN?

Astrophysical scenarios: close-by supernovae

The Event: Sediments containing Iron isotopes in high concentration in the deep sea crust.
Timing: Successive layers **2-6-13 Ma**
Theories: Explanations exist pointing to **multiple SN explosions** in or **close to the local bubble**

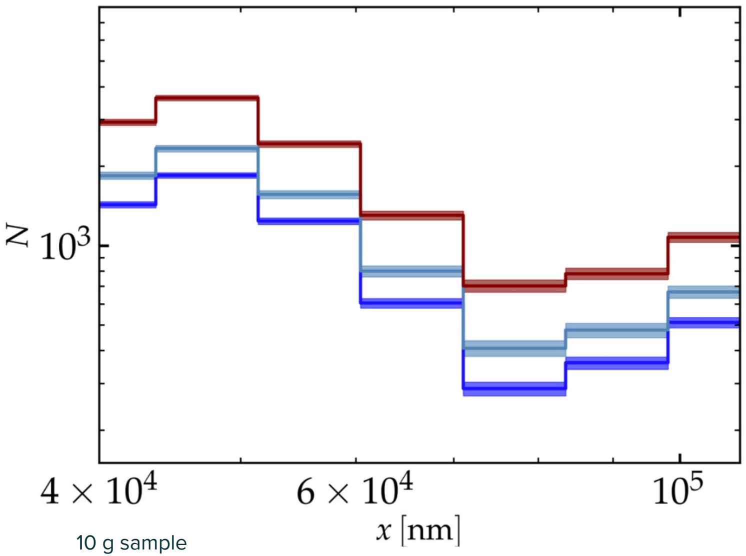
TABLE I: Predictions and measurements of ^{60}Fe excess in deep oceanic crust samples (corrected for in situ decay)

	Layer 1	Layer 2	Layer 3
age(Myr)	0-2.8	3.7-5.9	5.9-13
N_{SN}	8	4	6
D_{SN} (pc)	130	140	205
ϕ_{SN} (10^6cm^{-2} Myr^{-1})	$0.7^{+6.30}_{-0.06}$	$0.4^{+3.6}_{-0.04}$	$0.08^{+0.8}_{-0.01}$
ϕ_b(10^6 cm^{-2} Myr^{-1})	0.11	1.5	5
$\phi_{SN} + \phi_b$ (10^6cm^{-2} Myr^{-1})	$0.81^{+6.30}_{-0.06}$	$1.9^{+3.6}_{-0.04}$	$5.08^{+0.8}_{-0.01}$
ϕ_{obs} (10^6 cm^{-2} Myr^{-1})	$1.0^{+0.5}_{-0.3}$	8^{+11}_{-5}	$10^{+22}_{-8.5}$



K. Knie, G. Korschinek, T. Faestermann, E. A. Dorfi, G. Rugel and A. Wallner, «60Fe Anomaly in a Deep-Sea Manganese Crust and Implications for a Nearby Supernova Source,» *Phyis. Rev. Lett.*, vol. 93, n. 17, p. 171103, 2004.

Astrophysical scenarios: close-by supernovae



10 g sample
5.6 Myr age
270 kyr exposure
Overburden of 1500 m

3-scenario test:

A. CR flux is **as today** From Gaisser, Engel, Resconi
B. CR flux is enhanced by a simultaneous **SN at 20 pc**
C. CR flux is enhanced by a simultaneous **SN at 100 pc**

Assumed SN 2.5e51 erg with 10% conversion rate B. C. Thomas and A. M. Yelland, Astrophys. J. 950, 41

Good separation: The associated track count is predicted from the simulations to vary up to a **factor 3** in some length bins.

Down to counting: the maximum counting error to still separate scenarios is 15%/7% for scenario B/C in the base hypothesis.

Detecting CR Flux Variations: Model suggests that **percent-level integrated variations** in the primary CR flux during MSC exposure period could be detectable: this sensitivity opens the door to observing **similar astrophysical imprints**.

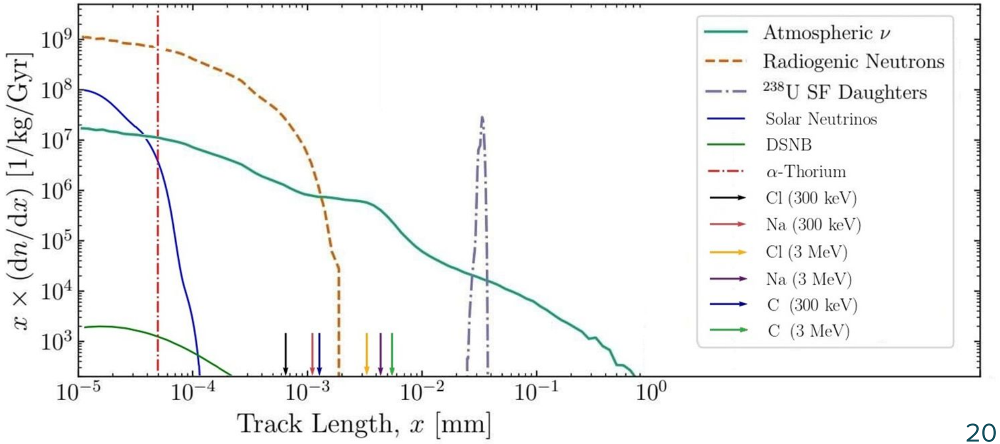
Tackling backgrounds

Internal Radioactivity (within the mineral):

- **Spontaneous Fission:** Tracks from 238U. Typically well localized in the µm scale when compared to the broad range expected muon-induced tracks. Expected very low in pure halite. Density of 5e-6 g/g assumed in simulations.
- **(α,n) Reactions & Alpha Recoils:** Alpha particles from U/Th decay chains can cause (α,n) reactions, producing neutrons that cause recoils. The alpha particles themselves also cause short recoil tracks. Expected low in pure halite.

External Sources (during MSC exposure):

- **Atmospheric Neutrinos:** Can produce nuclear recoils. Generally much lower rate compared to muon-induced ones.
- **Cosmogenic Neutrons (at surface/shallow depth):** Can produce recoil tracks similar to muon-induced ones. Flux needs modeling.



PHYSICAL REVIEW D **110,** L121301 (2024)

Letter | Featured in Physics

Sedimentary rocks from Mediterranean drought in the Messinian age as a probe of the past cosmic ray flux

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We propose the use of natural minerals as detectors to study the past flux of cosmic rays. This novel application of the *paleo-detector* technique requires a specific approach as it needs samples that have been exposed to secondary cosmic rays for a well defined period of time. We suggest here the use of the evaporites formed during the desiccation of the Mediterranean sea ~6 Myr ago. These minerals have been created and exposed to the air or under a shallow water basin for ~500 kyr before being quickly submerged again by a km-scale overburden of water. We show that, by looking at the damages left in the minerals by muons in cosmic ray showers, we could detect differences in the primary cosmic ray flux during that period, as the ones expected from nearby supernova explosions, below the percent-level. We show also that little to no background from radioactive contamination and other astroparticles is expected for this kind of analysis.

DOI: 10.1103/PhysRevD.110.L121301

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SYNOPSIS

Seeking Supernovae in Seafloor Sediments

December 17, 2024 • *Physics* 17, s136

Minerals exposed during an ancient Mediterranean Sea desiccation should reveal damage caused by muons, providing evidence of enhanced cosmic-ray fluxes.

https://physics.aps.org/articles/v17/s136

SCIENZA / Fisica e Matematica

Nel Mediterraneo i minerali custodi della storia dell'universo

Conservano tracce dei raggi cosmici che hanno colpito la Terra

https://www.ansa.it/canale_scienza/notizie/fisica_matematica/2024/12/18/nel-mediterraneo-i-minerali-custodi-della-storia-delluniverso-_d72754a9-a185-4d9d-b073-2bca03b6bef3.html

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FISICA Physics

Possibili indizi sulla storia dell'Universo dai minerali del Mediterraneo

L. CACCIANIGA, C. GALELLI 28-02-2025 LEGGI IN PDF CONDIVIDI SU

https://www.primapagina.sif.it/article/1974/possibili-indizi-sulla-storia-dell-universo-dai-minerali

Challenges & Future Directions

Challenges:

- Obtaining pristine **MSC halite samples** with well-documented provenance.
- Verifying sample purity and homogeneity (absence of U/Th-rich inclusions).
- Precisely constraining track annealing rates in halite over geological timescales.
- Further **refining simulation** models for CR interactions and track formation.

Future Outlook:

- **Experimental search for CR muon-induced tracks** in actual MSC samples.
- If successful, attempt to reconstruct CR flux variations during the MSC.
- Explore **other** evaporite deposits or different events/**minerals** for CR paleo-detection.

PRIμS:

Paleo-astroparticles Reconstructed with the Interactions of MUons in Stone

- The **natural experimental extension** of the phenomenological work (MSC paper). Time to look for the tracks!
- **Funding:** An INFN CSN5-funded experimental effort - 150 k€ over 2 years for laboratory and IT equipment.
- Based in the **Milano INFN group** with a small but appreciated contribution from **LPC - Clermont Ferrand**

- **Primary Goals:**
  - **Validate Theoretical Models:** Experimentally verify models of track formation by secondary CRs (especially muons) in minerals.
  - **Refine Background Estimates:** Characterize and quantify backgrounds for mineral detection studies in relevant samples.
  - **Analyze Various Samples:** Focus on halite and other evaporites, but explore other minerals.
  - Develop and **optimize readout and analysis** techniques, also useful for other INFN research lines.

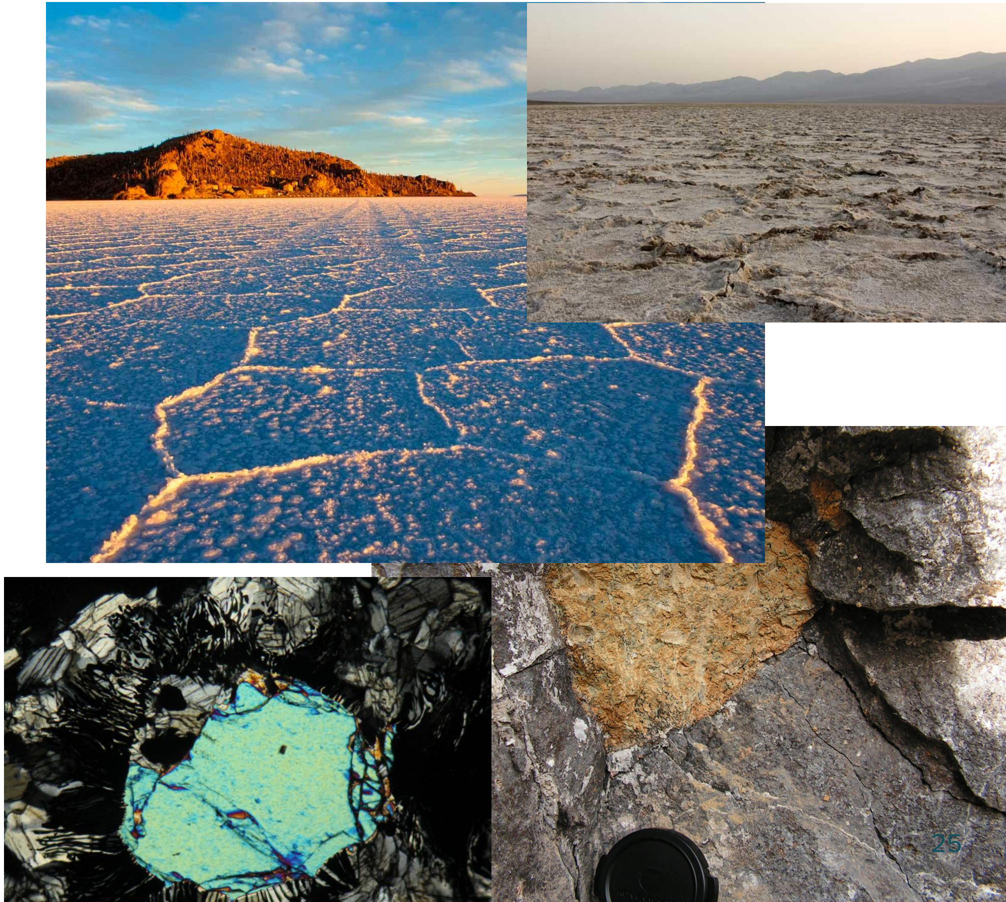
PRIμS: Finding the Right "Stones"

Primary Focus: Halite and other evaporites from the Messinian Salinity Crisis. Offer well-defined exposure histories and expected intrinsic radiopurity.

Other Potential Samples: Other similar sources of halite, different minerals with good selection score (**Xenoliths**)

Key Selection Criteria:

- **Known Geological History:** Age, formation conditions, burial history (shielding).
- **Defined Exposure Time:** Period at/near the surface.
- **Low Intrinsic Radioactivity:** Minimize internal backgrounds (U, Th content).
- **Good Track Retention:** Stability against track fading (annealing) over geological time.
- **Availability and Suitability for Analysis** (etching).



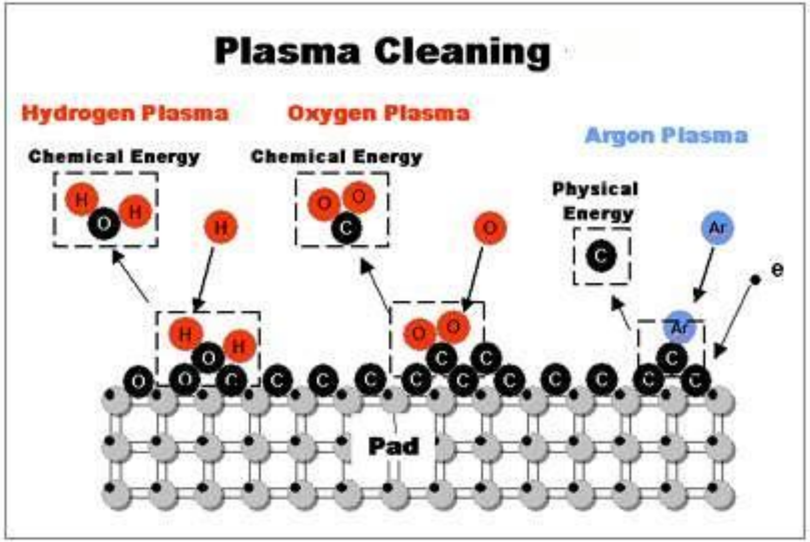
PRIμS Readout: Core Techniques

Plasma Etching:

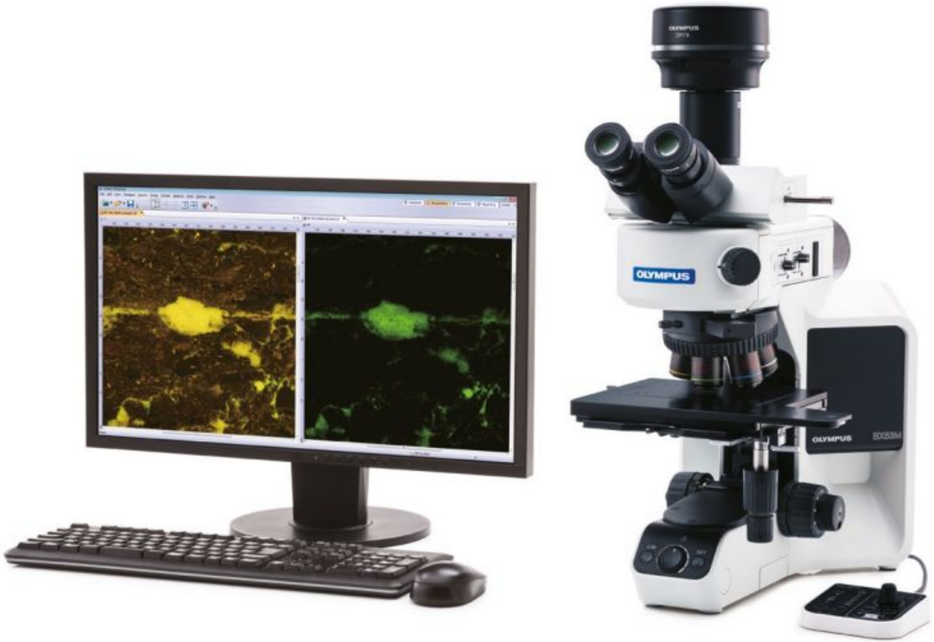
- Chosen for controlled etching of certain minerals.
- Can offer advantages over wet chemical etching: efficiency, time, eco-friendliness, safety.
- Aim to **thoroughly test plasma etching protocols** for halite and other target minerals.

High-Throughput Optical Microscopy:

- **Essential for scanning** statistically significant sample areas (cm^2 or more).
- Automated stage, autofocus, and image acquisition.
- Aim to identify and **count etched tracks efficiently**.



PRIμS Readout: Automated Optical Microscopy



New Capability: PRIμS has purchased and is awaiting delivery of an **automated microscopy station** by Evident.

Key Features for High-Throughput Analysis:

- **Large Area Scanning:** Designed to scan samples up to ~50 cm2 automatically.
- **High Magnification and wide range:** Capable of imaging from 5x to 100x objectives
- **Multi-Plane Focusing (Z-stacking):** Can automatically acquire images at ~10 (or more) **different focus planes**. Crucial for capturing tracks that may not all be on a single focal plane.
- **Speed:** Aiming for scanning O(10-100 cm2) with multiple focus planes **within a day** at maximum mag.
- **Impact:** Enables systematic scanning of large mineral surfaces, crucial for detecting rare tracks and building robust statistics.
- Cost: 35.5k€ (40k$/5.8kkJPY)

From Images to Data: Challenges of Automated Track ID

The Data Deluge: High-throughput microscopy can generate several GB to TB of image data.

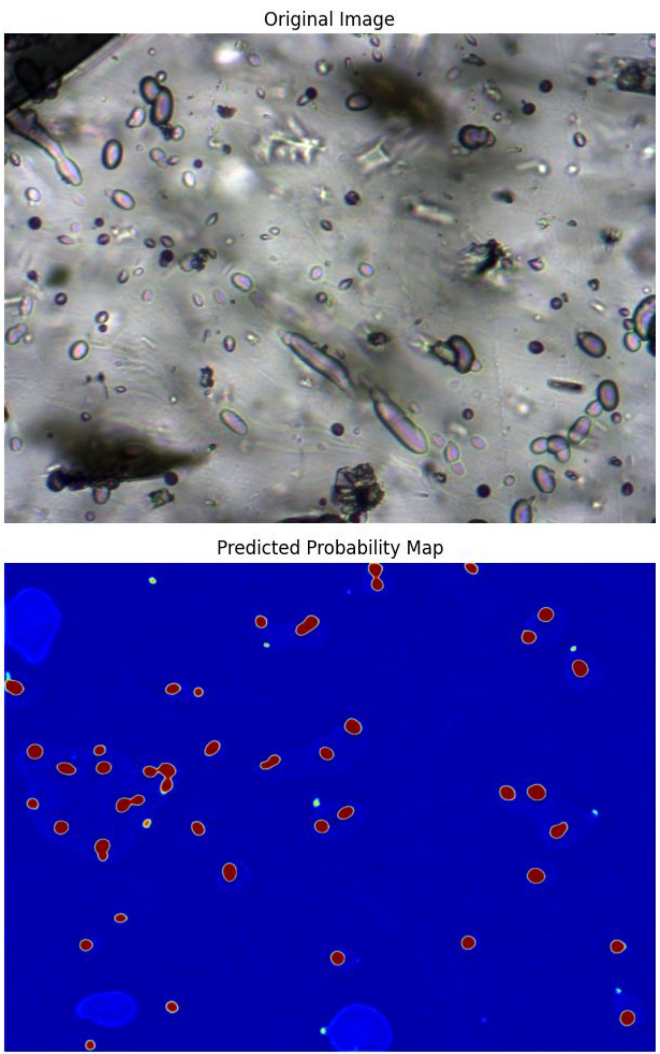
Manual Analysis is Impractical: Visually inspecting every image and counting/measuring tracks by hand is too slow and prone to bias and error.

Solution: Automated Image Analysis:

- Develop and apply image processing algorithms.
- **Machine Learning:** Train models to automatically identify, segment, and characterize tracks.

ML for Tracks: The U-Net Architecture

- **Semantic Segmentation:** The task of classifying each pixel in an image (e.g., "track" or "background").
- **U-Net Architecture:**
  - A Convolutional Neural Network (CNN) specifically designed for biomedical image segmentation, but widely applicable.
  - **Encoder Path:** Captures context (downsampling, feature extraction).
  - **Decoder Path:** Enables precise localization (upsampling, combines features from encoder via skip connections).
- **Why U-Net for Tracks?**
  - **Effective at segmenting objects** of varying sizes and shapes.
  - Skip connections help preserve fine details, important for track morphology and size.
- **Input:** Microscope images of mineral surfaces.
- **Output:** A **"mask"** where pixels belonging to tracks are highlighted.

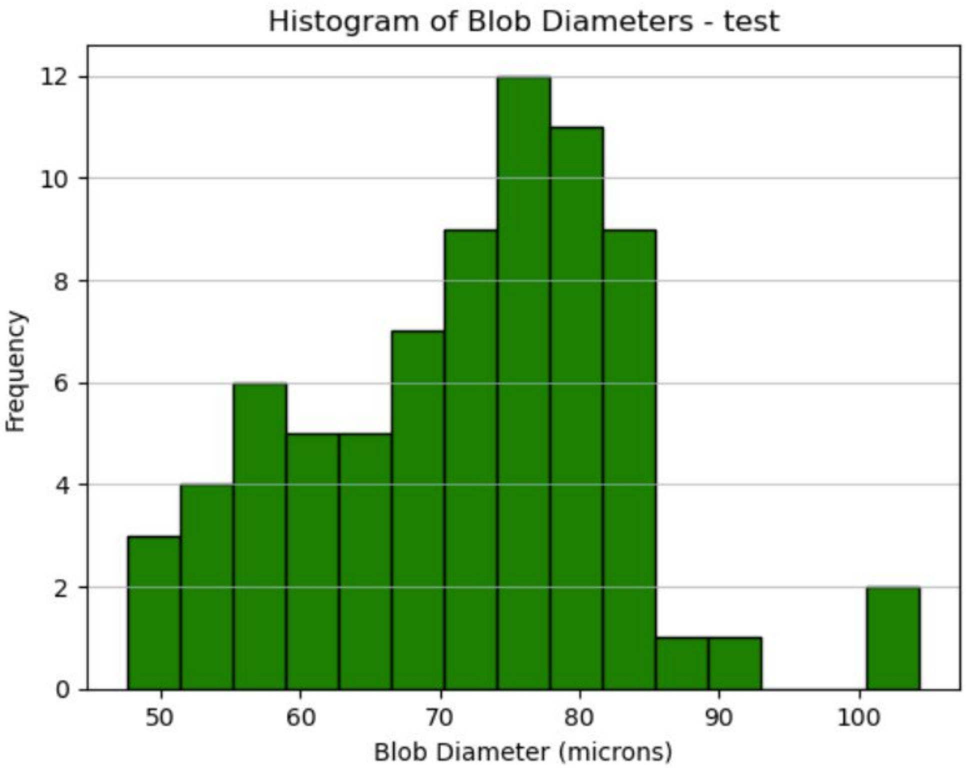


Development & Current Testing

- **Model Overview:**
  - Implemented in Python using **PyTorch**.
  - Includes: Data loading/preprocessing (image normalization, augmentation), U-Net model definition, training loop, evaluation metrics.
- **Current Development & Testing:**
  - The U-Net model is currently being developed and tested on images of **fission tracks in obsidian**.
  - Obsidian provides a good testbed: fission tracks are relatively well-defined and abundant in irradiated samples.
  - This allows for initial model training, hyperparameter tuning, and validation of the analysis pipeline.
- **Goal:** Adapt and retrain this model for the specific characteristics of CR-induced tracks in halite and other PRIµS target minerals.
- **Challenges:** Acquiring **sufficient labeled training data** for new mineral/track types, ensuring **model generalization**.

https://github.com/cgalelli

PRIμS Data Analysis: Extracting Physics



Once tracks are segmented by the ML model:

- **Quantify Track Density** on the resulting mask
- **Measure Track Length Distributions:** Provide information on the energy of the recoiling nuclei.
- **Characterize Track Morphology:** Shape, width, etc.
- **Comparison with Simulations:** Compare experimental track densities and length distributions with predictions from models (like those in MSC paper). This comparison is key to interpreting the results and searching for **deviations from expected CR flux.**

OpenCV

PRIμS: What We Aim to Achieve (1/2)

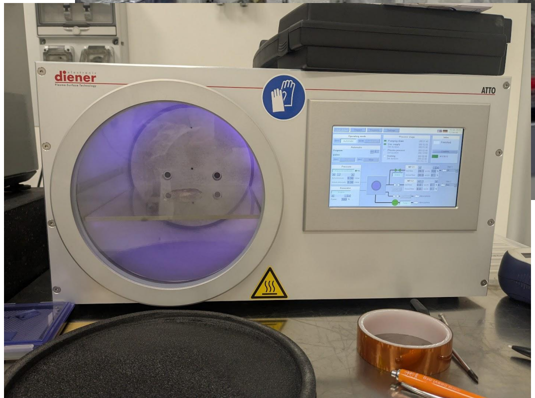
- **Experimental Validation of Models:**
  - Provide **systematic experimental validation** of theoretical models for track formation by secondary cosmic ray muons in natural minerals (especially halite).
- **Comprehensive Background Characterization:**
  - Improve understanding and **quantification of all relevant backgrounds** (radiogenic, cosmogenic) in target minerals.
  - This is crucial not only for CR studies but for ***all* mineral detection applications** (DM, neutrinos), as muon tracks and CR-induced neutrons are a key background.

PRIμS: What We Aim to Achieve (2/2)

- **Advancement of Paleo-Detector Techniques:**
  - Develop and **optimize high-throughput readout** (etching, automated microscopy).
  - Advance automated analysis techniques (ML/AI for track recognition).
- **Probing Past Cosmic Ray Flux:**
  - Potential for ***direct detection and measurement* of CR muon-induced tracks** in ancient, well-shielded geological samples.
  - Lay the experimental **groundwork for larger-scale efforts** to reconstruct the history of CR flux.
  - Possibility to find evidence for, or place new **constraints on, variations in CR flux** due to past nearby astrophysical events (e.g., supernovae).

PRIμS: Current Status (May 2025)

- **Project Officially Launched:** INFN-funded project is underway.
- **Key Infrastructure and calibration:**
  - **Automated Microscopy Station:** An Evident (Olympus) automated station has been purchased and is awaiting delivery. This will be a cornerstone for high-throughput scanning.
  - **Plasma cleaning is in testing** before purchasing a dedicated machine - thanks to the ATLAS INFN group
  - A sample of mine **halite has been sent for irradiation** to induce fission for calibration - thanks to the Luna INFN group
- **Software Development:**
  - **Automated Track Identification Software:** The U-Net based neural network is actively being developed and tested.
  - Initial tests are focused on detecting fission tracks in obsidian samples to refine algorithms and the analysis pipeline.
- **Preparatory Work:**
  - Literature review and refinement of target sample criteria.
  - Initial **contacts for sample sourcing**.



PRIµS: The Path Forward - Immediate Next Steps

- **Setup & Calibration of Readout Systems:**
  - Installation and **commissioning** of the new automated microscopy station.
  - Establish and calibrate **plasma etching facilities**/protocols for target minerals.
- **More modeling**
  - Refine models for halite, MSC and different origins
  - Start modeling other thargets (**Xenoliths**)
- **Refinement of Analysis Tools:**
  - Continue development and **training of ML models** (U-Net) using calibration data and simulated tracks.
  - Build the end-to-end data analysis pipeline.
- **Calibration Experiments:**
  - Study the **irradiated reference mineral** samples to calibrate track formation efficiency and etching response. This is crucial for interpreting data from natural samples.
- **Final Sample Acquisition & Preparation:**
  - Secure and prepare batches of Messinian halite and/or other priority samples.
  - Detailed mineralogical and geochemical characterization (elemental/structural properties, U/Th levels...)

Soon: Talk at ICRC25 on MSC paper and PRIµS

Summary and outlook

- **Paleo-detectors for CRs:** a new promising avenue to probe CR flux history over geological timescales.
- **MSC Paper:** Established MSC evaporites as excellent targets, with modeling showing sensitivity to %-level CR flux variations ~6 Myr ago, potentially probing nearby supernovae or other astrophysical events.
- **PRIμS Project Launched-** experimental program to:
    - Validate the theoretical framework for CR track formation.
    - Develop and refine readout and analysis techniques (automated microscopy, AI/ML).
    - Perform direct measurements of CR muon-induced tracks in ancient minerals.
- **Long-Term Vision:**
    - Extend searches to different minerals and geological epochs and events.
    - Build a more continuous record of CR flux over Earth's history.
    - Potentially identify specific ancient astrophysical events (supernovae, GRBs) through their CR signatures in paleo-detectors
    - Contribute to understanding Galactic structure evolution and its impact on the local CR environment.
- **A New Window:** Paleo-detectors could revolutionize our understanding of the high-energy universe on Myr-Gyr timescales.

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