



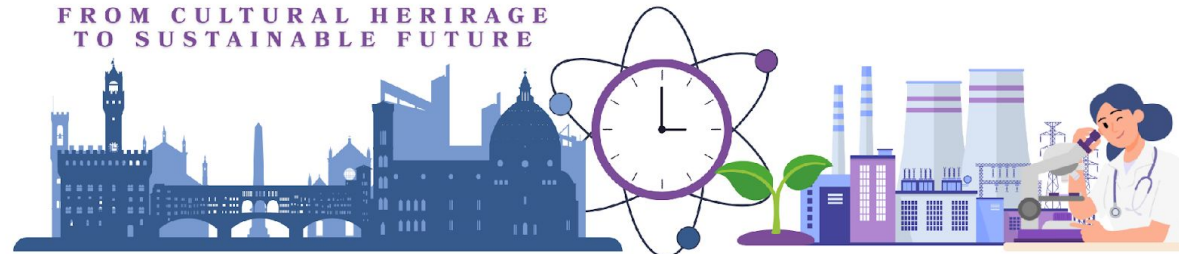
# PROBING MUON ISOTOPE PRODUCTION AND PAST ASTROPARTICLE FLUXES USING NUCLEAR RECOIL TRACKS IN PALEO-DETECTORS

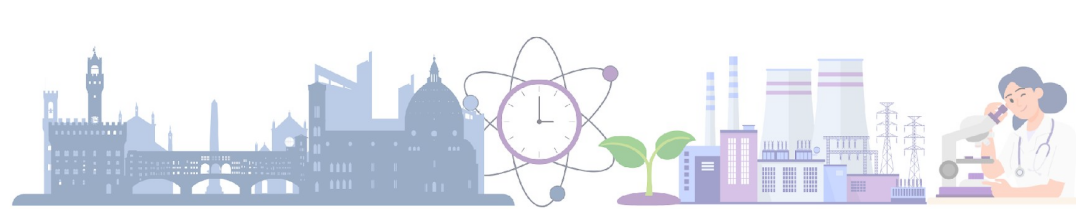
Claudio Galelli [claudio.galelli@mi.infn.it](mailto:claudio.galelli@mi.infn.it)



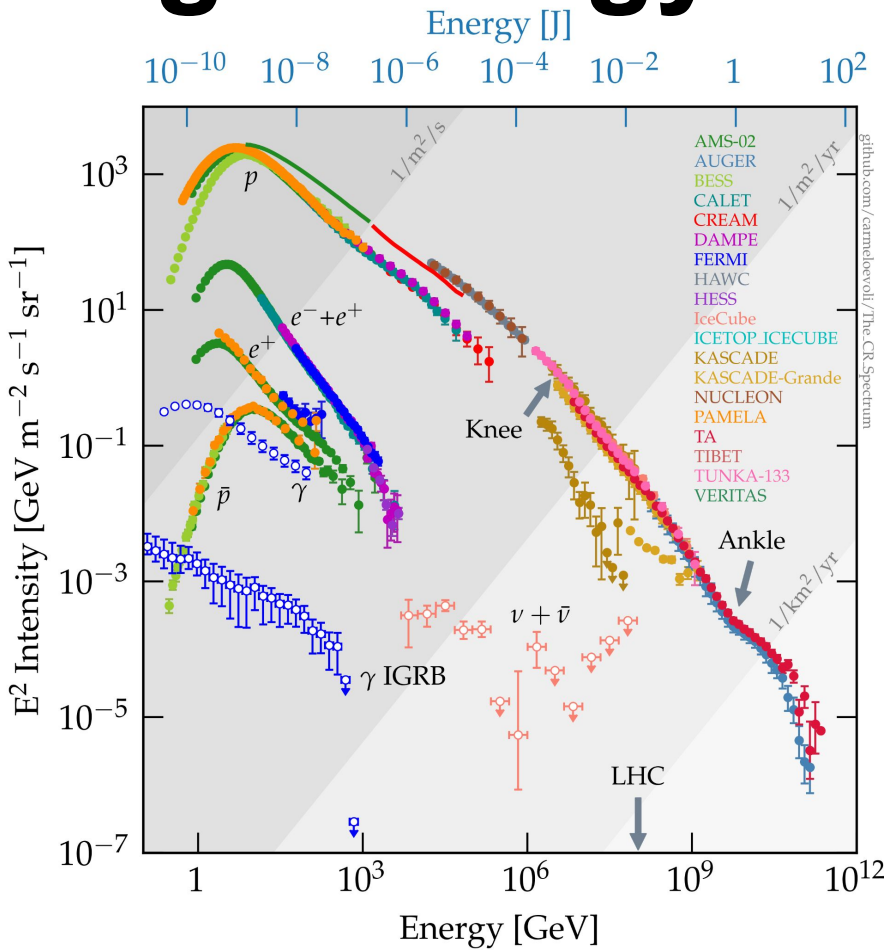
## PRIMUS

**ISOTOPIC TIME MACHINE**  
FROM CULTURAL HERITAGE  
TO SUSTAINABLE FUTURE



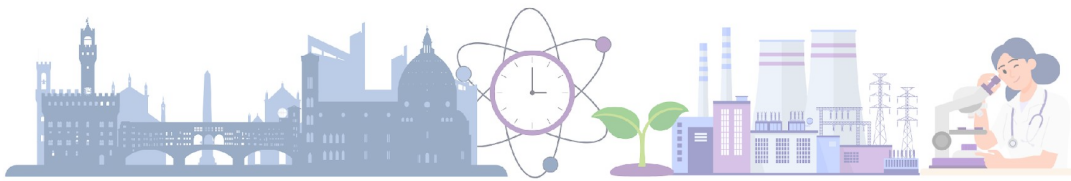


# Cosmic rays: a window into the high-energy universe



**The Primary Messengers:** Cosmic rays span an **enormous range of energies**, fluxes and species, carrying direct information about dynamic astrophysical sources and the **most extreme events in the universe**





# The shower of secondaries

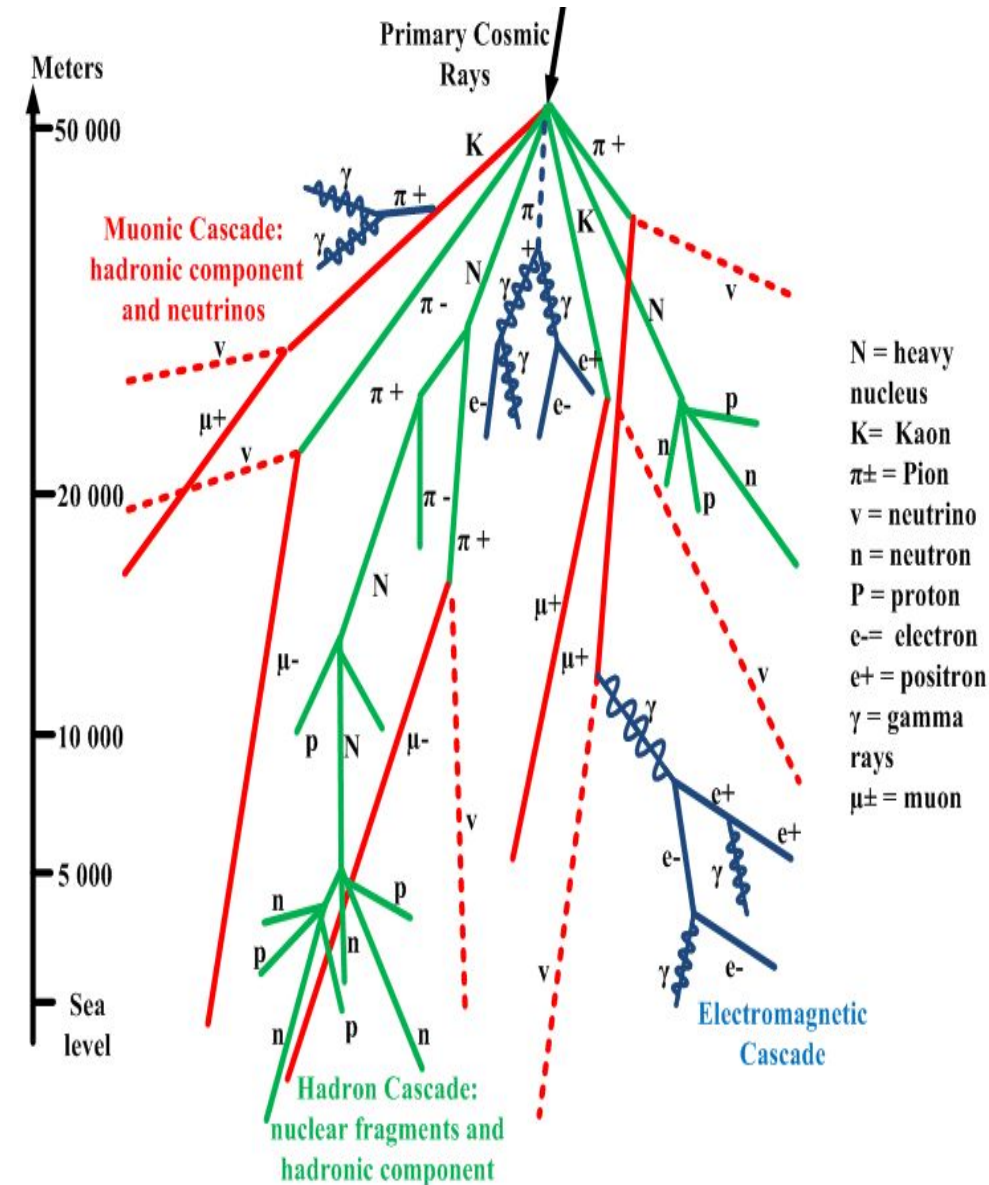
## Atmospheric Interactions Extensive Air Showers - EAS:

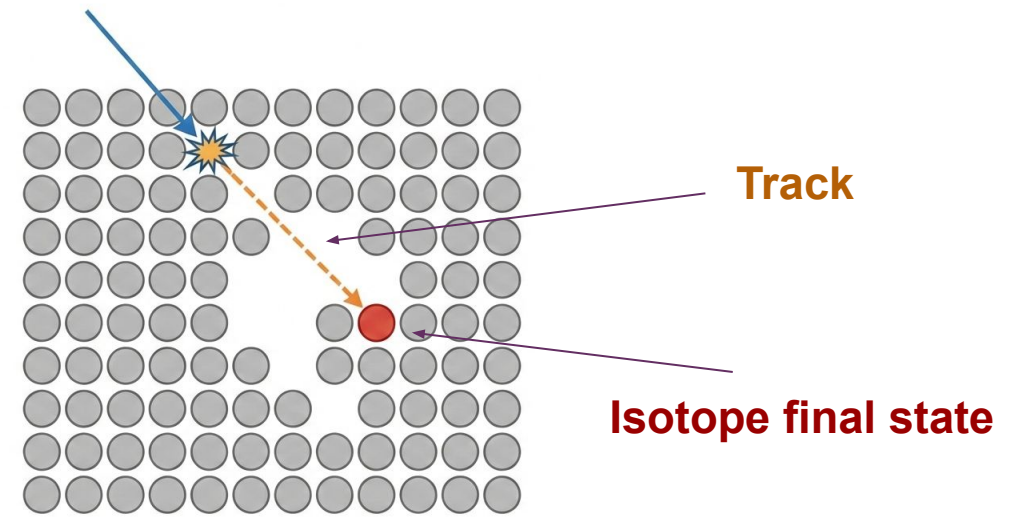
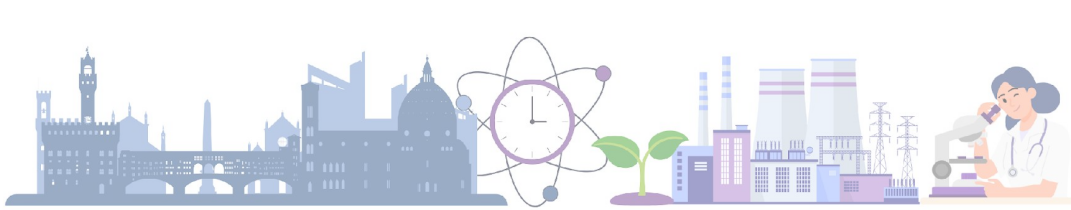
Primaries collide with atmospheric nuclei (N, O).  
 Produce a cascade of secondary particles: pions, kaons, muons, neutrinos, electrons, photons, neutrons, protons.  
 Secondaries reach earth and **interact in the crust**

### Key Secondary CRs:

**Muons ( $\mu$ ):** Highly penetrating component of EAS. Can reach significant depths underground.

**Neutrons (n):** Produced in EAS and by muon interactions in rock/soil.  
 Hadrons (protons, pions at shallow depths).





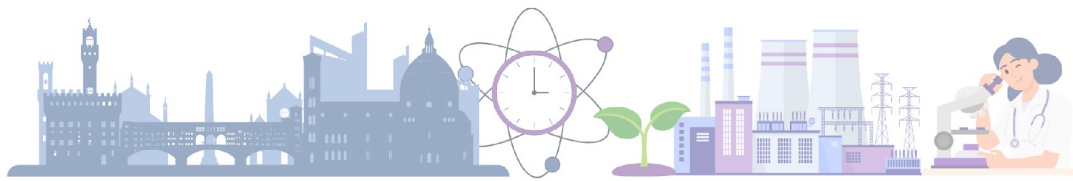
# Digging for cosmic rays: Paleo-detectors

The geochemical standard: counting the **accumulation of specific cosmogenic isotopes** left by interactions of secondaries an **inventory** of past events

➡ **"how many" interactions occurred**, for surface exposure dating and erosion studies

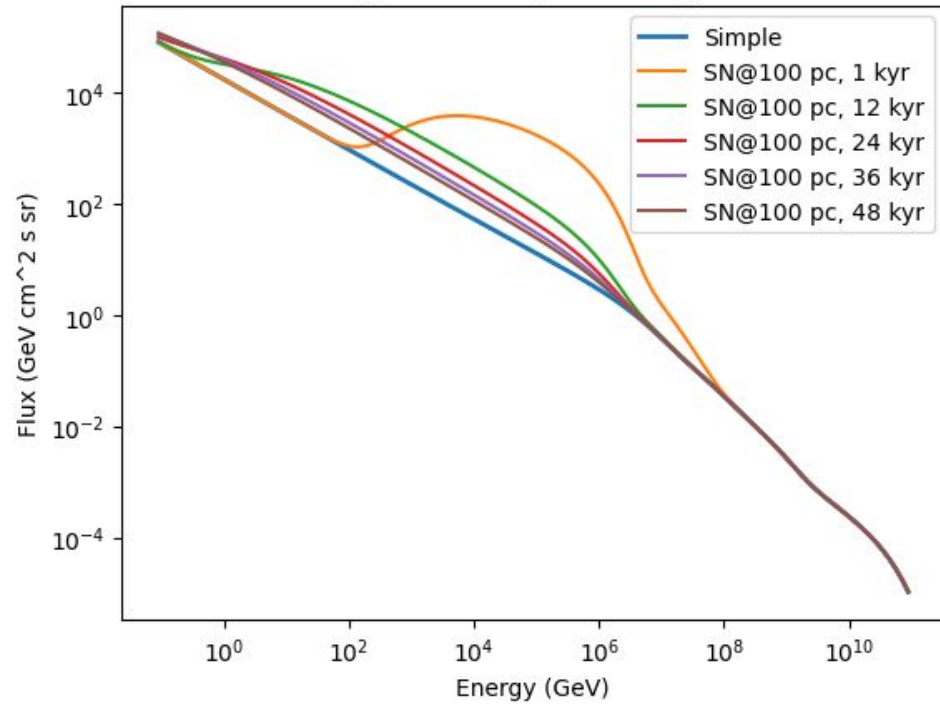
**Paleo-detectors - look at the momentum transfer:** we want to treat the mineral lattice as a **solid-state detector** that captures the kick energy from the interaction. Instead of counting final atoms, we detect the **nuclear recoil track**: the “scar” left in the crystal as the nucleus recoils.

The technique has been proposed also for **rare event detection**: DM, neutrinos



# Modeling track production: Cosmic ray spectra

Primary Cosmic Ray Flux comparison



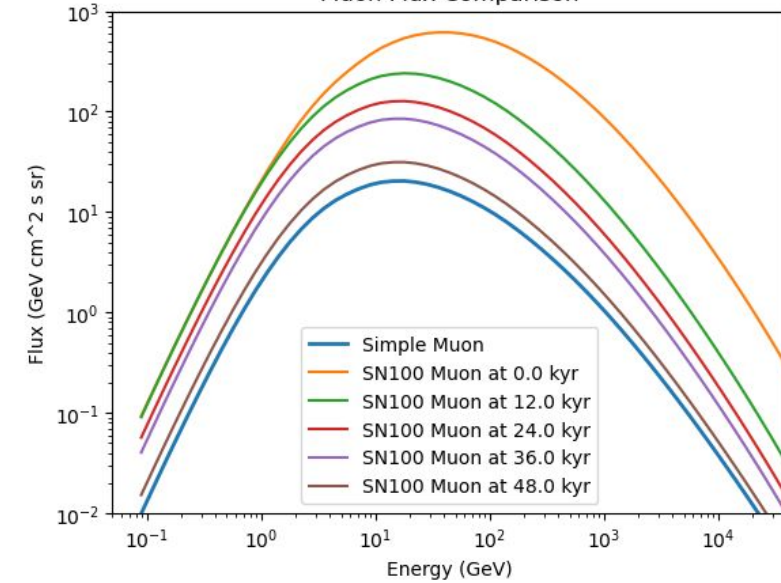
**Primary Variations:** We simulate possible historical variations in the primary cosmic-ray spectrum, such as the enhanced flux from a nearby supernova.

**Propagation in the atmosphere:** The atmospheric cascade models translate these primary cosmic-ray variations into secondary muon and neutron fluxes at sea level.

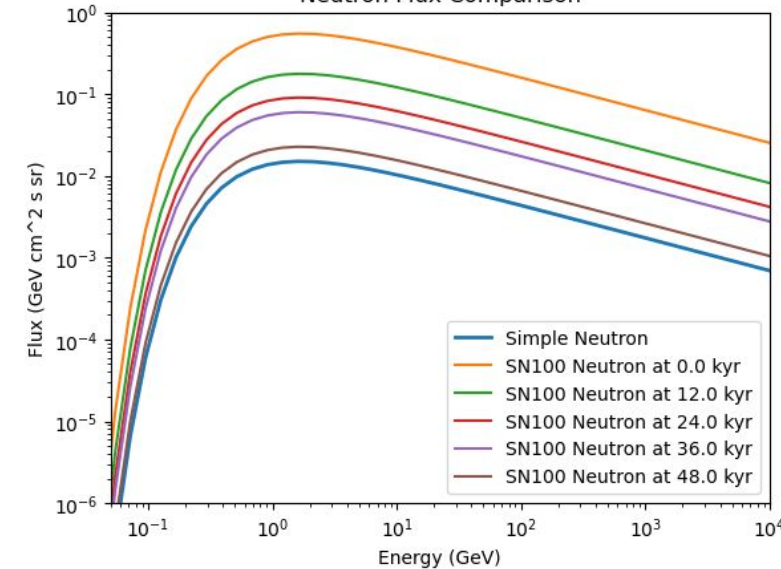
<https://github.com/mceq-project/MCEq>

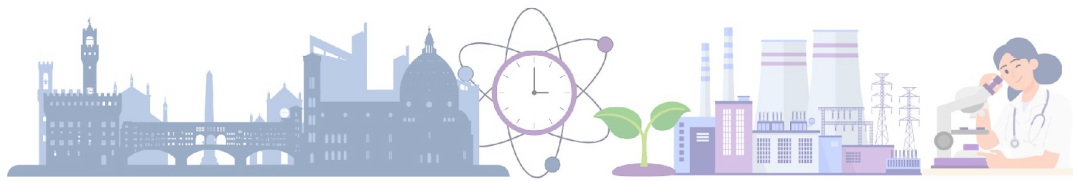
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Muon Flux Comparison



Neutron Flux Comparison



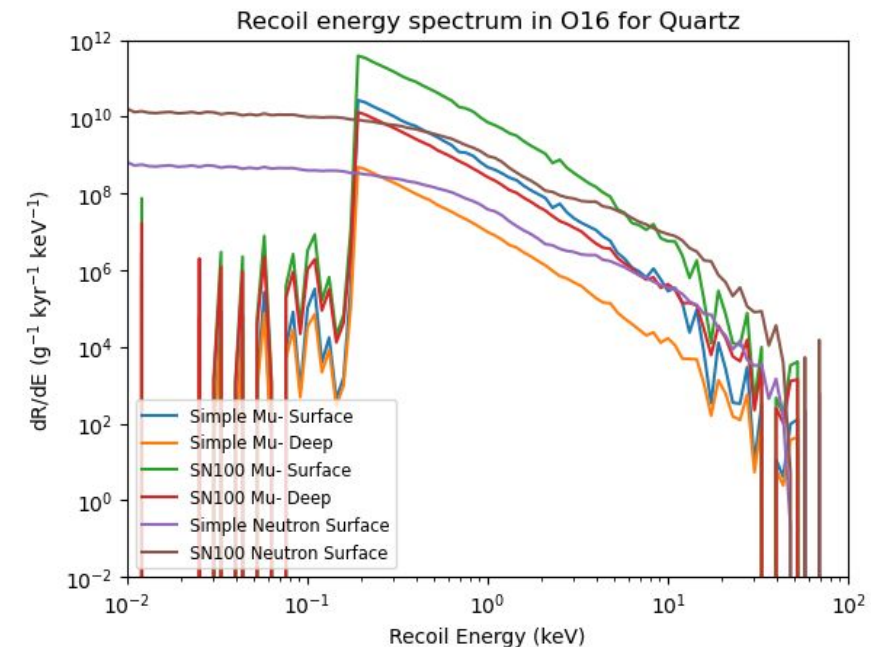
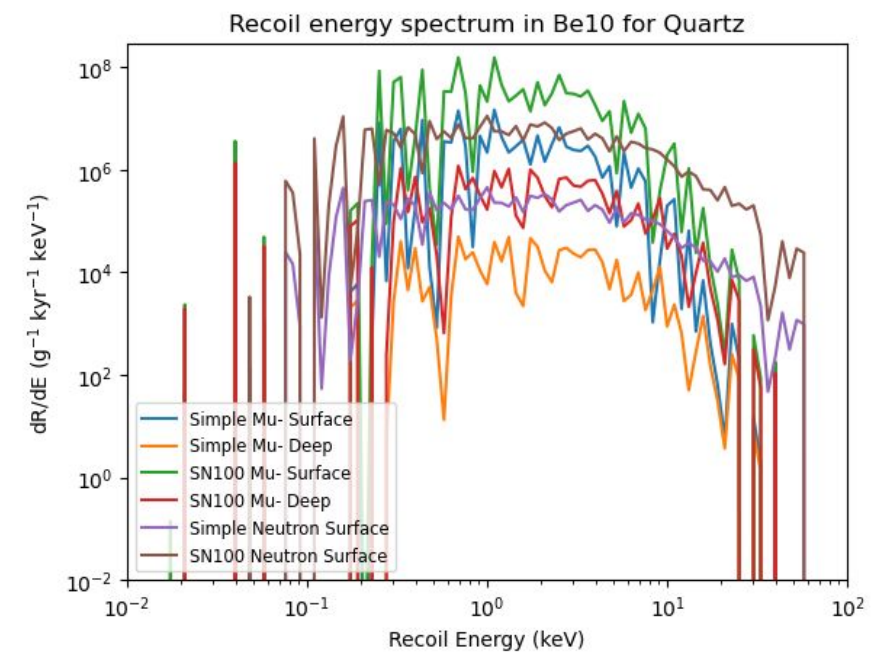


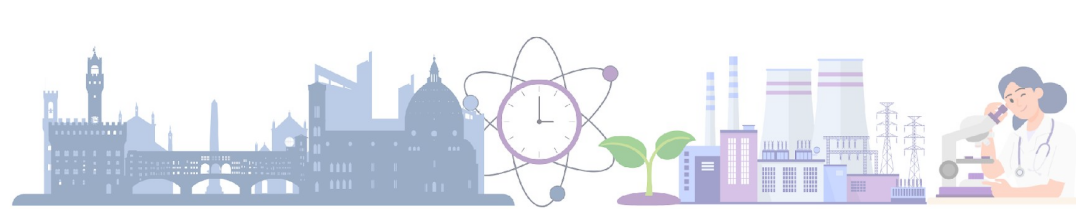
# Modeling track production: Particle interactions

**Recoil rate:** interactions simulated with **Geant4** - recoil spectrum is a convolution of **interaction rate**, **depth probability**, **original spectrum**.

**Surface Muons + Neutrons:** At the surface, neutrons provide a significant component of the recoil spectrum. Recoils from neutrons have a low-energy part not present for muons, which does not leave significant tracks.

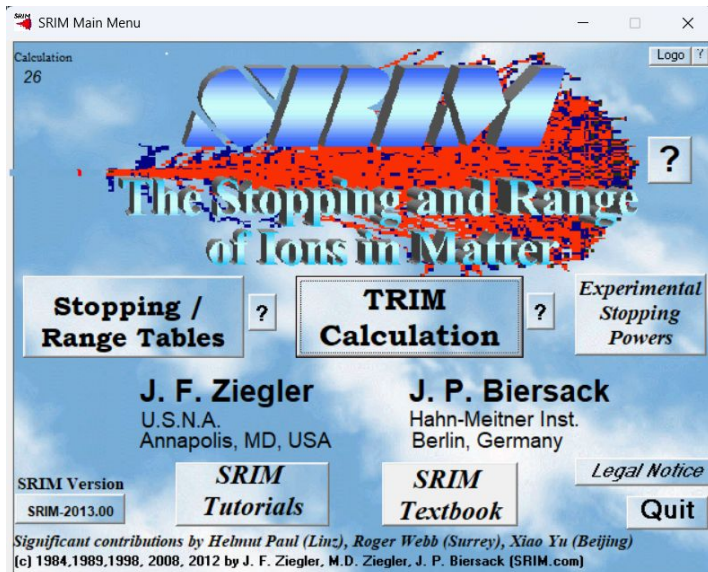
**Deep Muons:** Deep underground, the neutron component is heavily suppressed. Muons become the dominant ionizing particle



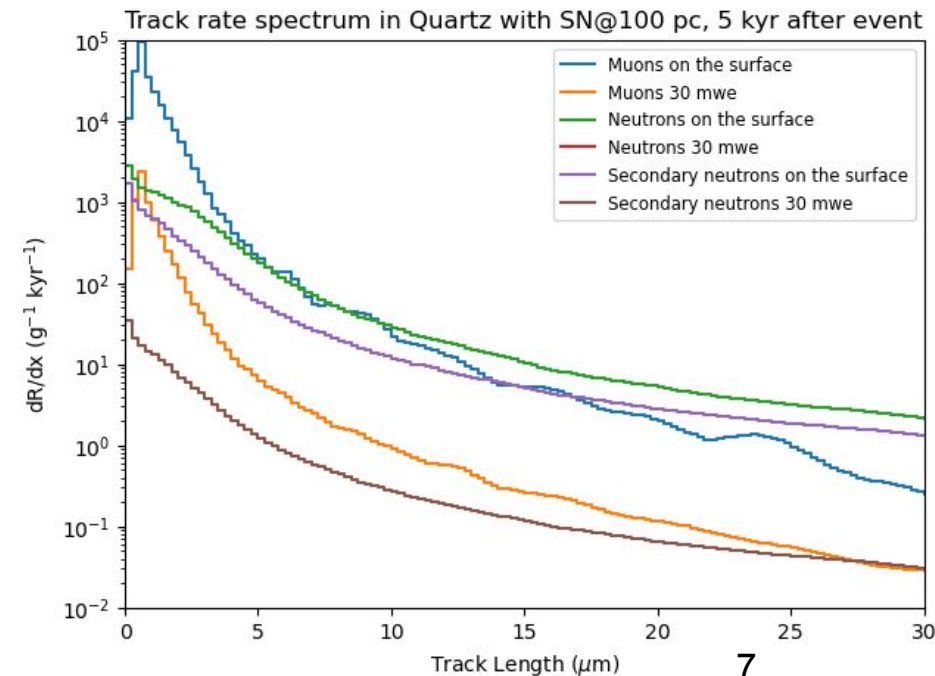
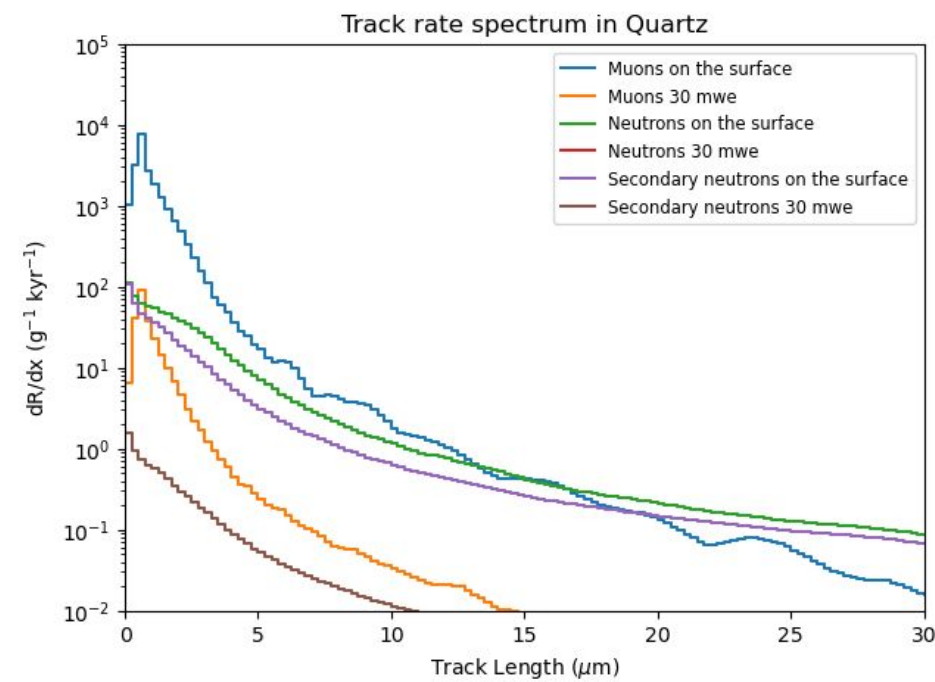


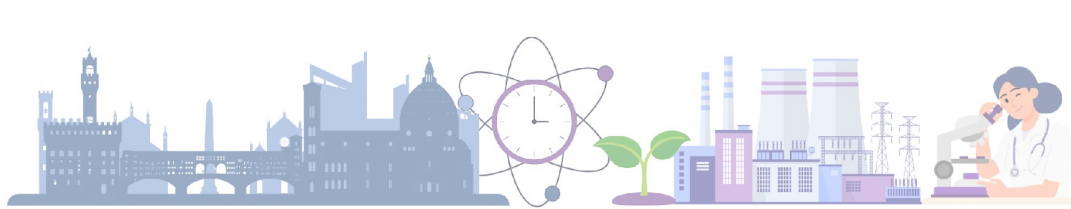
# Modeling track production: Recoil to track length

**Energy to Geometry:** We use SRIM to calculate the projected range of each recoiling nuclide in the material as a function of its kinetic energy.

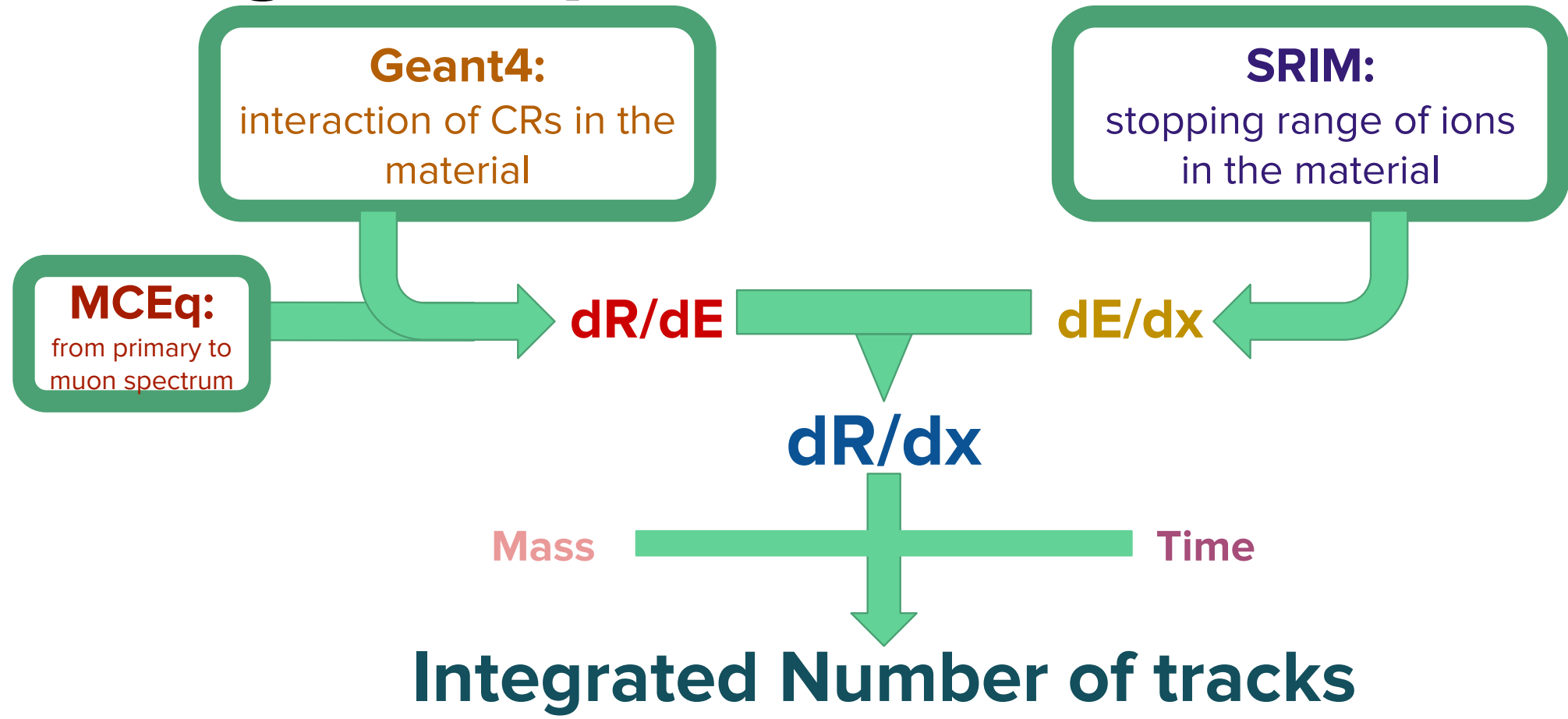


**Track Fingerprints:** The resulting track length distribution is directly correlated with the recoil energy spectrum and the species of the produced isotopes. Lighter nuclear fragments generally produce longer tracks.

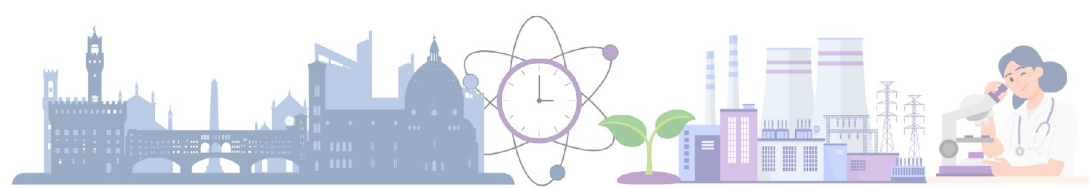




# Modeling track production



<https://github.com/cgalelli/PrimusCode>



**Nel Mediterraneo i minerali custodi della storia dell'universo**



# Choosing the right geology 1: Halite and The messinian salinity crisis

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

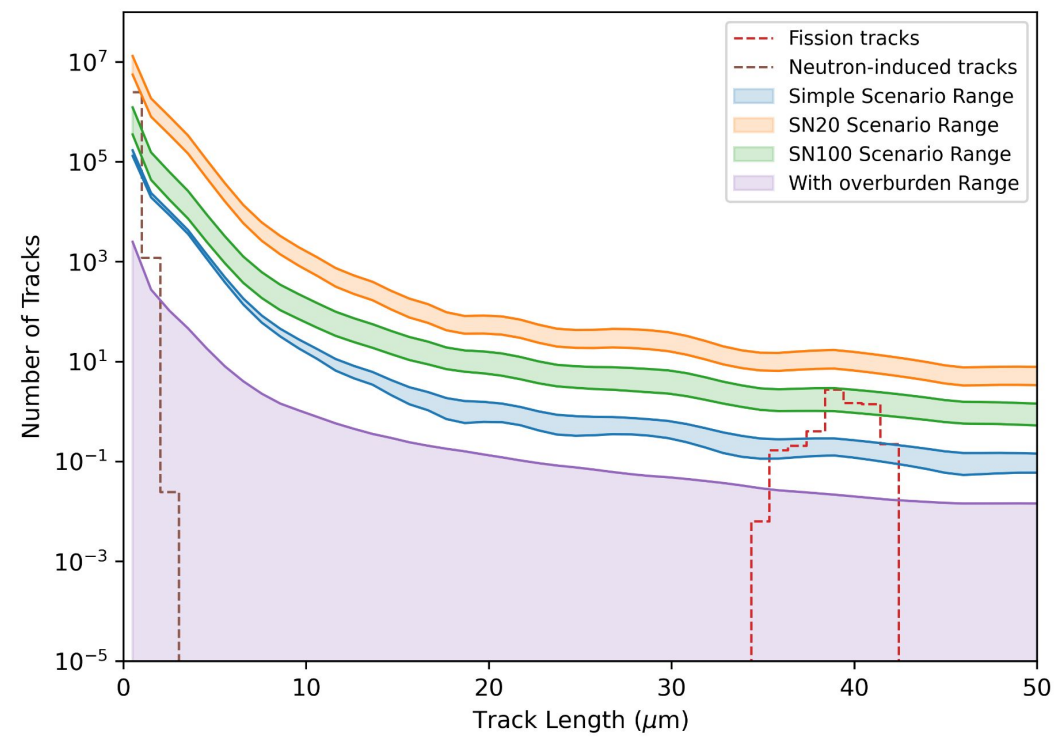
**Consequences: Evaporite Formation-** Massive deposits of halite.

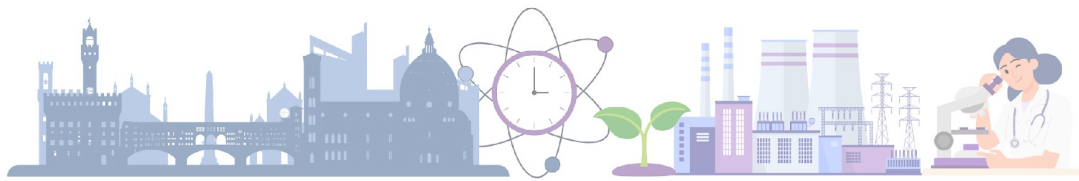
**Well-Defined CR Exposure Window (~500 kyr):** Minerals formed and were **exposed to cosmic rays** at/near the surface or under shallow, highly saline water, **then overburdened**, until the final Zanclean flood  
 Evaporites continually deposited during the MSC - deposition rate **models vary from 2.5 to 30 m/kyr.**

Quicker deposition scenario:  
**less** tracks, **more** sensitivity to variation.

Bands **well separated** - overburden tracks from 1e-2 of normal scenario to **completely suppressed.**

<https://journals.aps.org/prd/abstract/10.1103/PhysRevD.110.L121301>





# Choosing the right geology 2: Olivine Xenoliths as a chronosequence

Target paleo-detector: **olivine-rich xenoliths** (mantle inclusions in volcanic material) from a sequence of eruptions in Auvergne, France



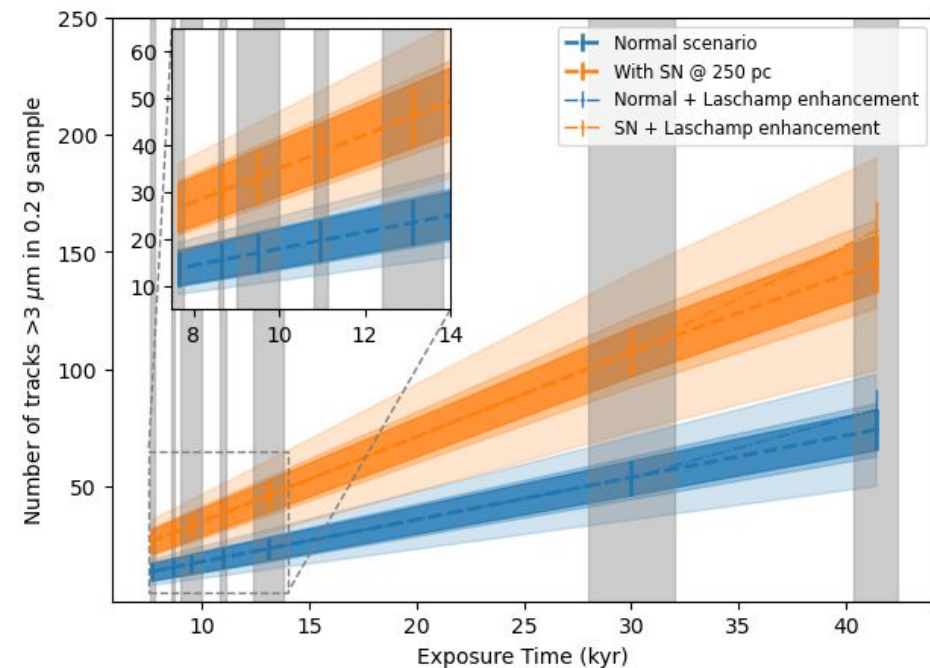
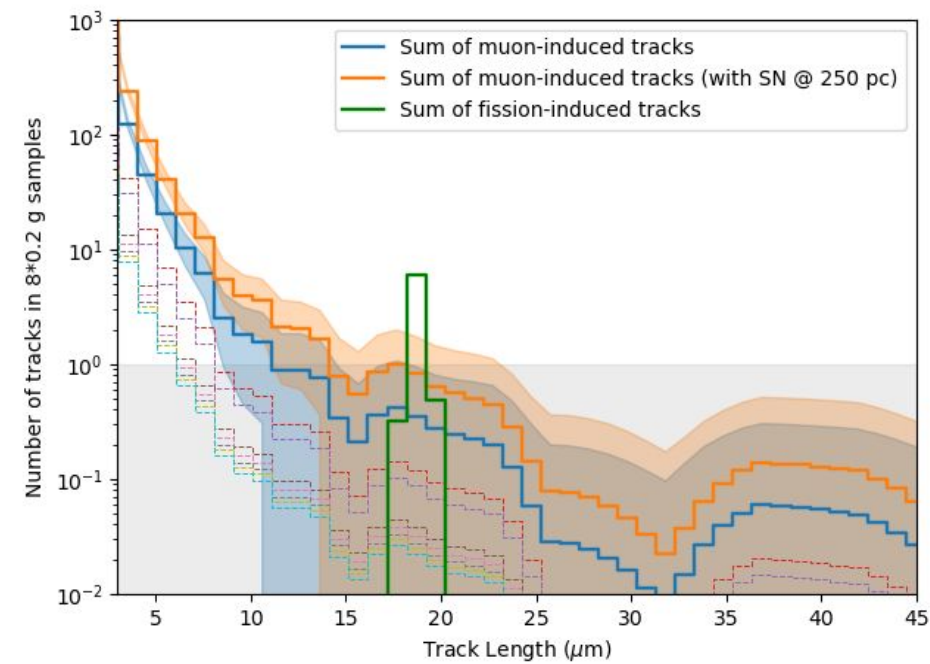
**A natural Furnace:** Host basaltic magma exceeds 1000°C, completely **annealing any pre-existing tracks** and "resetting the clock" of the xenolith precisely at the time of eruption.

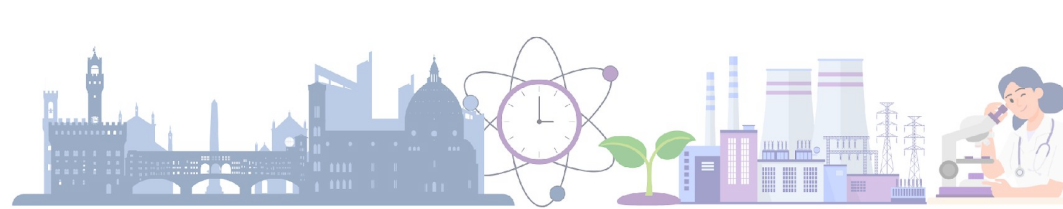
**The Chronosequence:** Successive eruptions source similar mantle material, providing a series of **well-dated, overlapping exposures**.

**Time-Resolved Flux:** If the cosmic-ray flux is constant, track density scales flatly with age. **Deviations from expected linearity** allow us to probe past variations in the astrophysical environment.

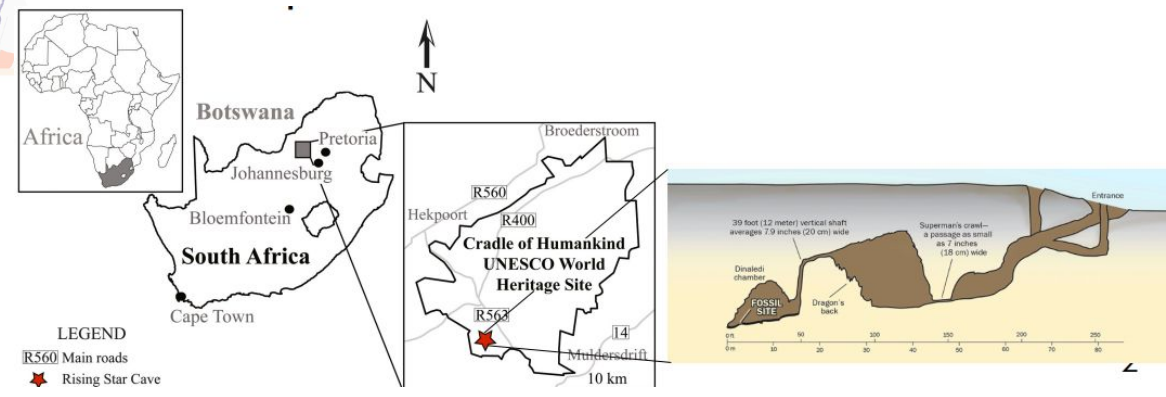
<https://arxiv.org/abs/2510.23126> (accepted for publication on JCAP)

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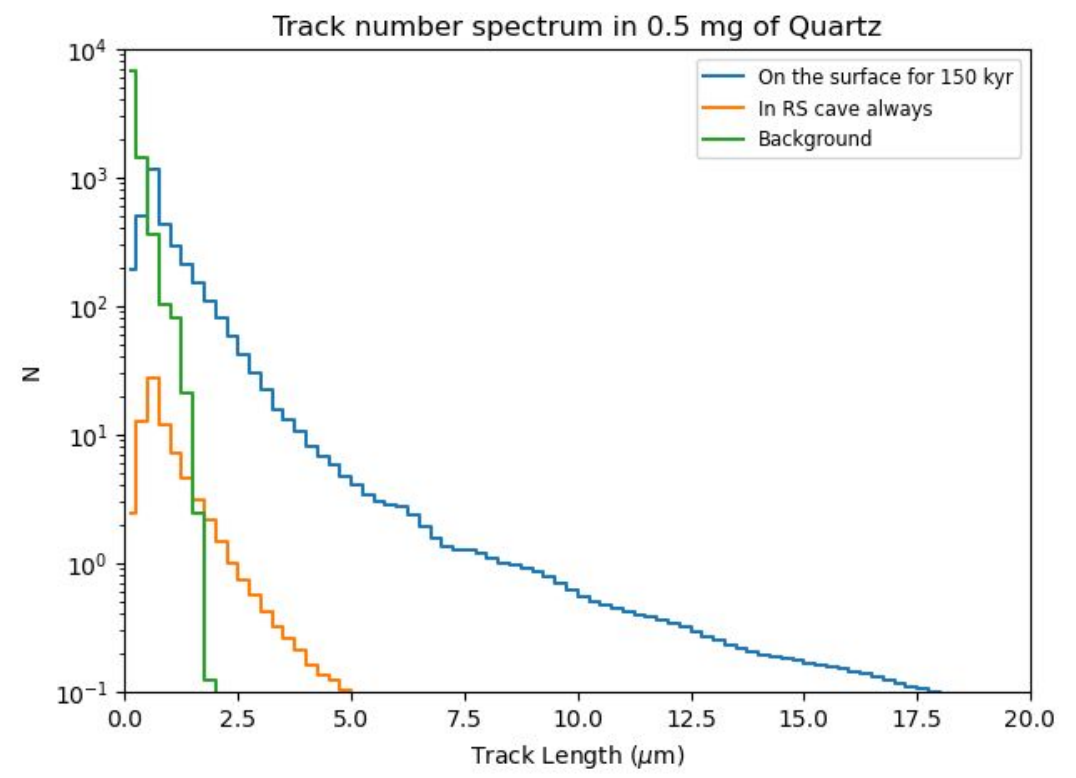
# As applied physics: ideas from the cradle of humankind

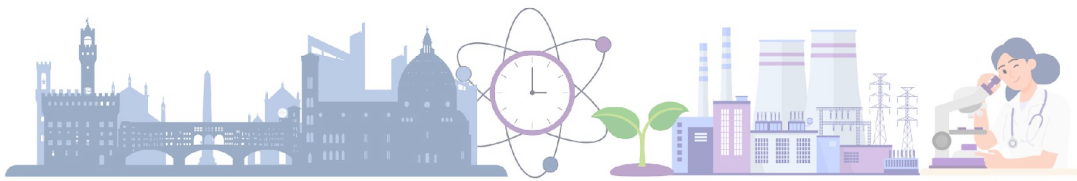


Paleo-detectors can also be used as a **control technique** for dating of minerals and **overburden studies**.

An example: coupled with  $^{10}\text{Be}/^{26}\text{Al}$  studies from **MuSTAR** at the Cradle of Humankind, SA, to understand the history of peculiar hominid fossils

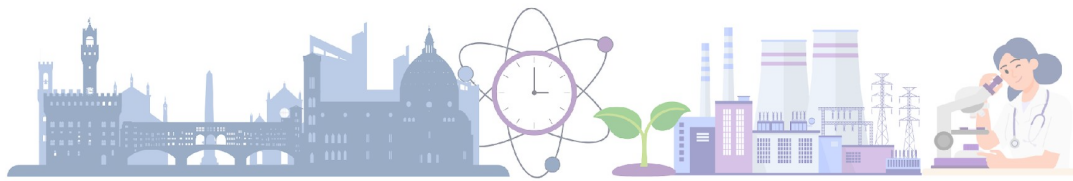
-> **See talk by Sara Rabaglia tomorrow**





# PRImuS: from models to action

- The **natural experimental extension** of the phenomenological work. 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** - collaboration with **LPC - Clermont Ferrand, KIT - Karlsruhe, UMich - Ann Arbor**
- **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 olivine, but explore other minerals.
  - Develop and **optimize readout and analysis** techniques, **understanding instrumental and preparation effects** on tracks.



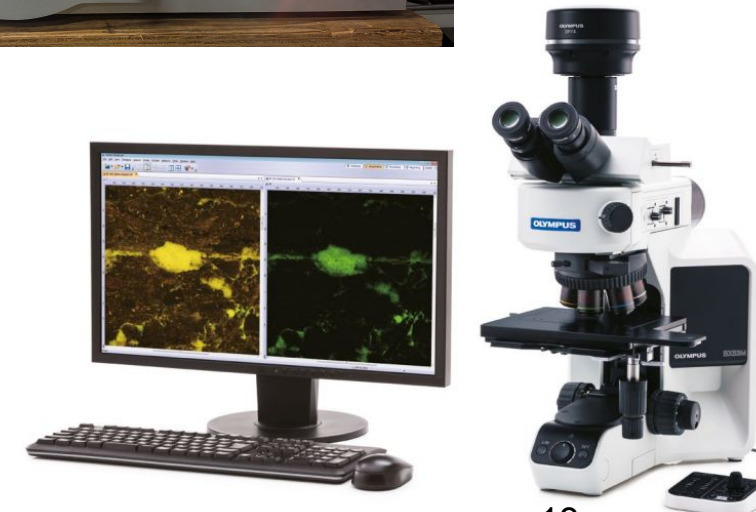
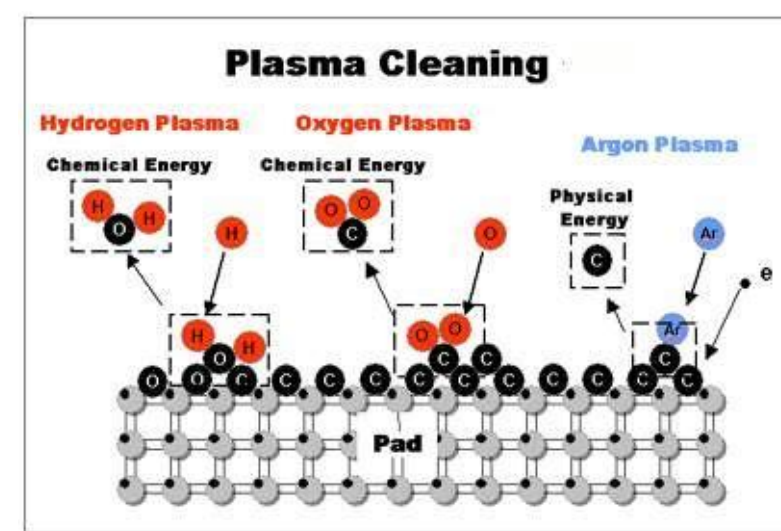
# PRImuS in the laboratory

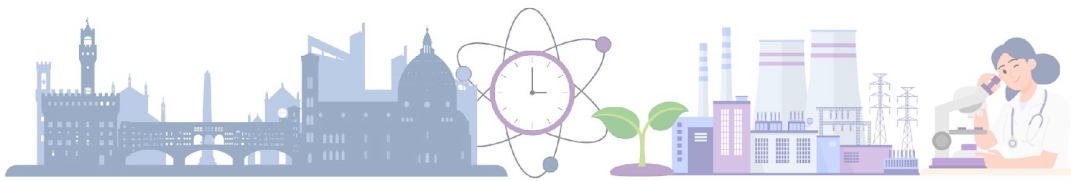
## Plasma Etching:

- 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 targets.

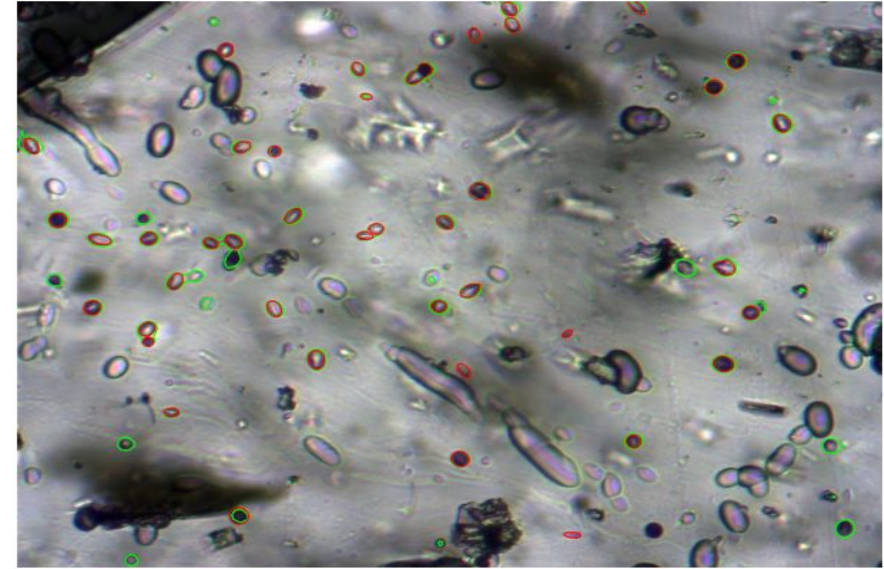
## High-Throughput Optical Microscopy:

- Optimal for **size of signal**
- **Essential for scanning** significant sample areas (cm<sup>2</sup> or more).
- Automated stage, autofocus, and image acquisition.
- Aim to identify and **count etched tracks efficiently**.



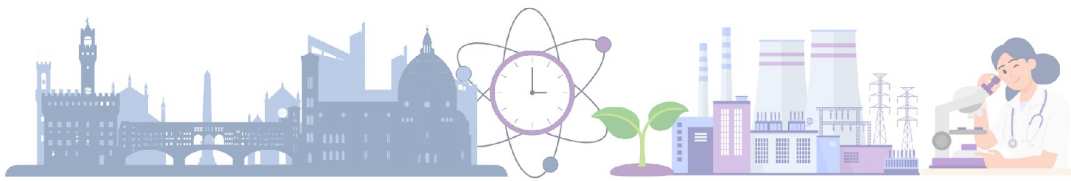


Overlay (Prediction Contours)



# PRImuS: track detection

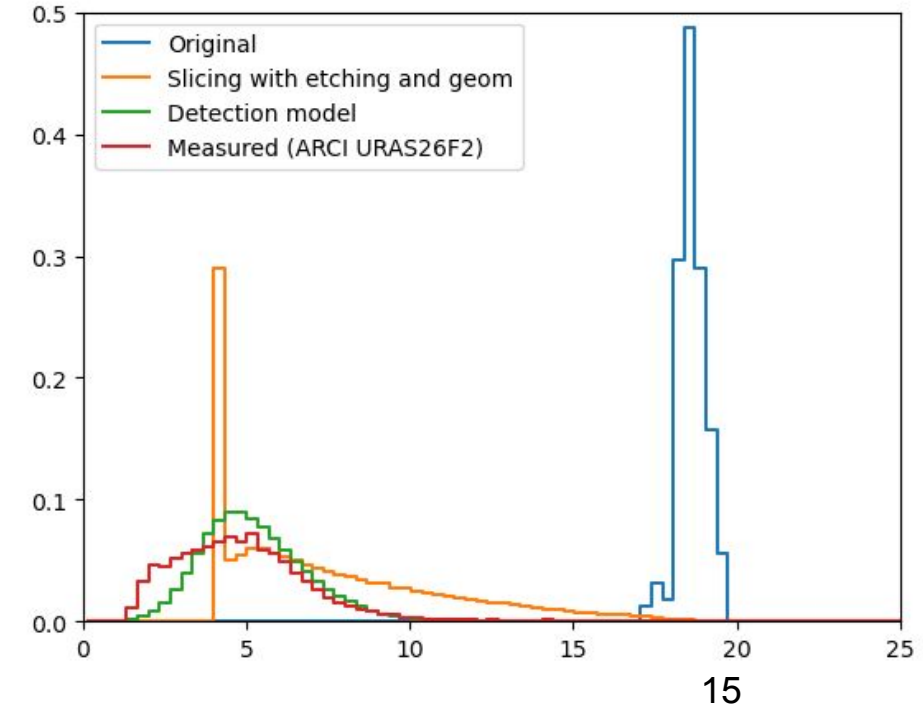
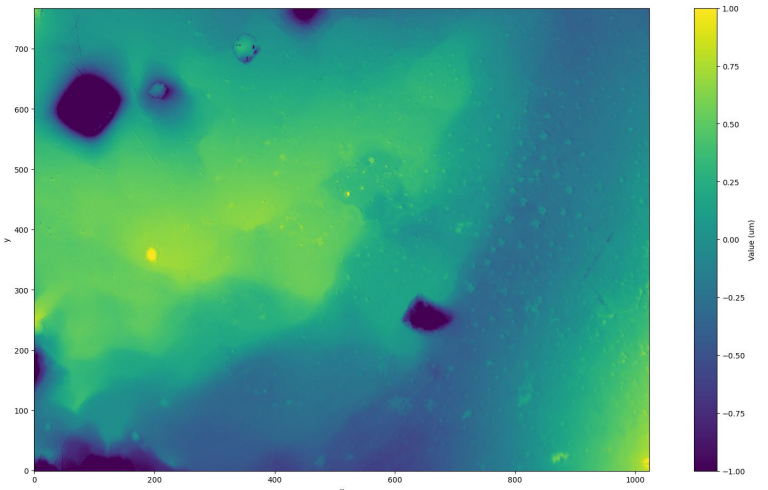
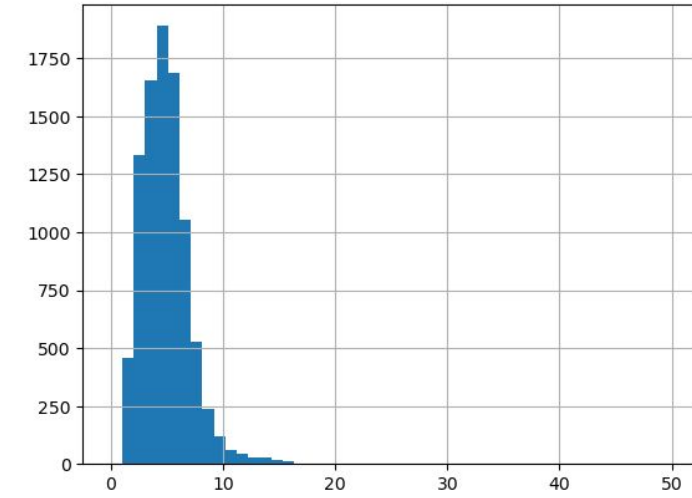
- **Chosen architecture: U-Net - optimal for segmentation**
  - Implemented in Python using **PyTorch**.
  - Includes: Data loading/preprocessing (image normalization, augmentation), model definition, training loop, evaluation metrics.
- **Current Development & Testing:**
  - The U-Net model is currently being developed and tested on images of **fission tracks in obsidian** - 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 PRImuS target minerals.
- **Challenges:** Acquiring **sufficient labeled training data** for new mineral/track types, ensuring **model generalization**.

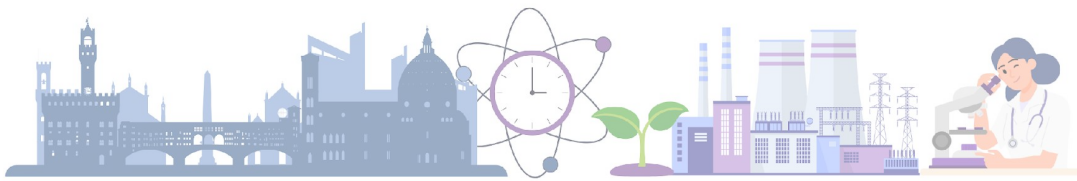


# PRImuS: density estimation

Once tracks are segmented by the ML model: OptimusPrimus

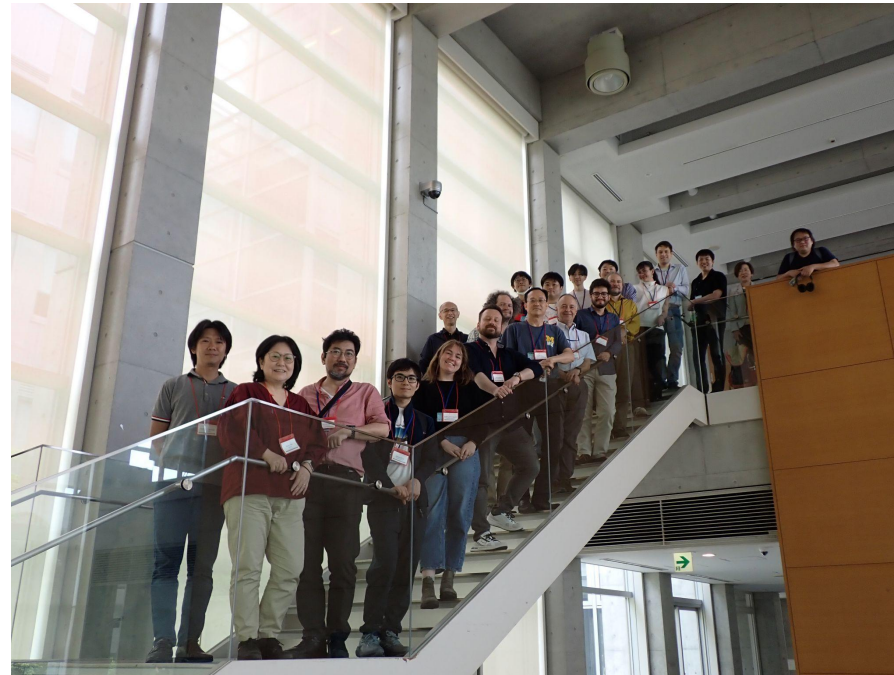
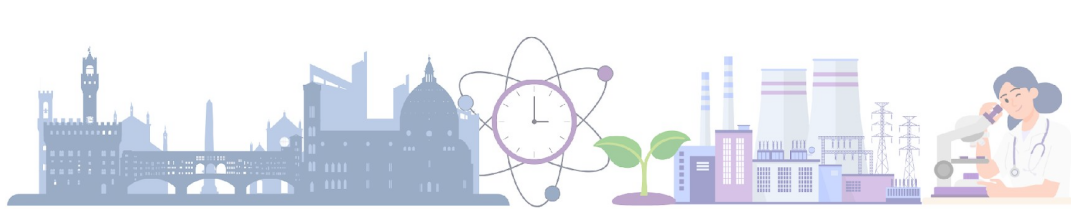
- **Quantify Track Density** on the resulting mask
- **Measure Track Length Distributions** using 2D methods
- **Convolve the model with instrumental effects:** cutting, geometry, etching and **compare**
- **Calibrate the instrumentals** with high-accuracy methods in Z





# Outlook

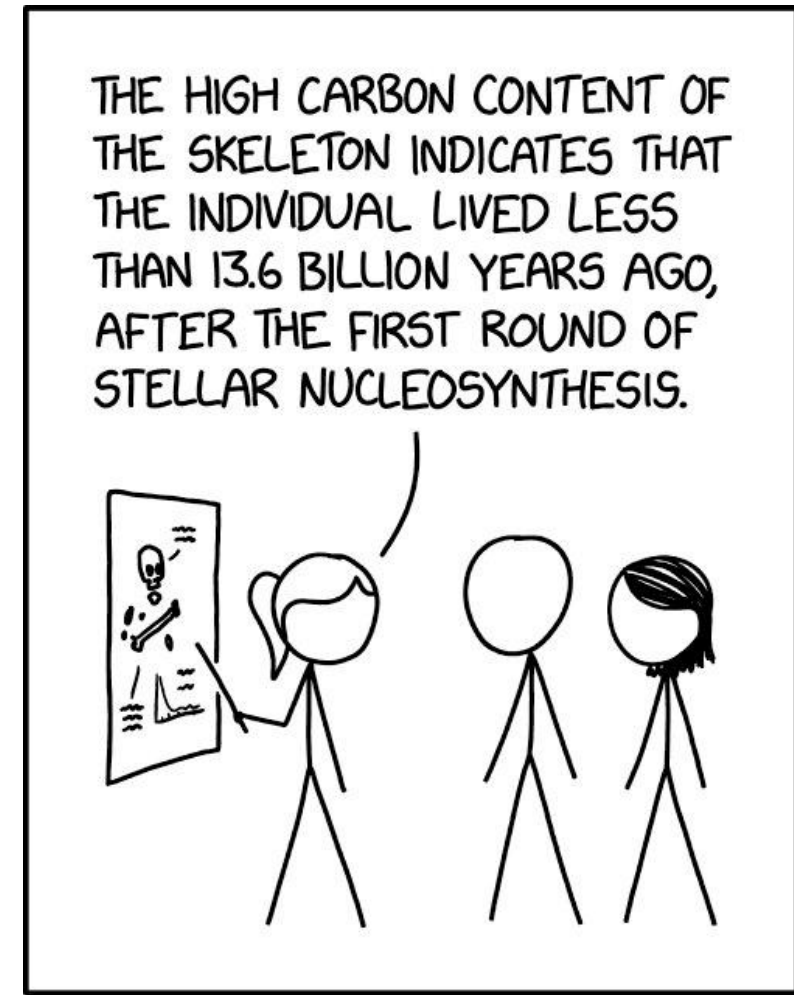
- We have established a **robust simulation chain** from primary astrophysical flux variations to physical track-lengths in natural crystals
- We are moving from modeling to calibration: **transitioning to experimental validation**, using an automated chain - microscopy + ML image recognition to **proof the method for big loads of data**
- Commencing the **analysis of olivine xenoliths** from the Chaîne des Puys to study the astrophysical history of the last ~50,000 years
- **PRImuS aims to complement traditional AMS 'inventories'** with 'kinetic tracks,' providing a new, high-resolution window into the high-energy paleo-universe



May 2025 MDvDM meeting in Yokohama, Japan



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COSMOLOGIST CARBON DATING