A cosmic-ray harvest in the dried-out Mediterranean basin

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Federico Maria Mariani

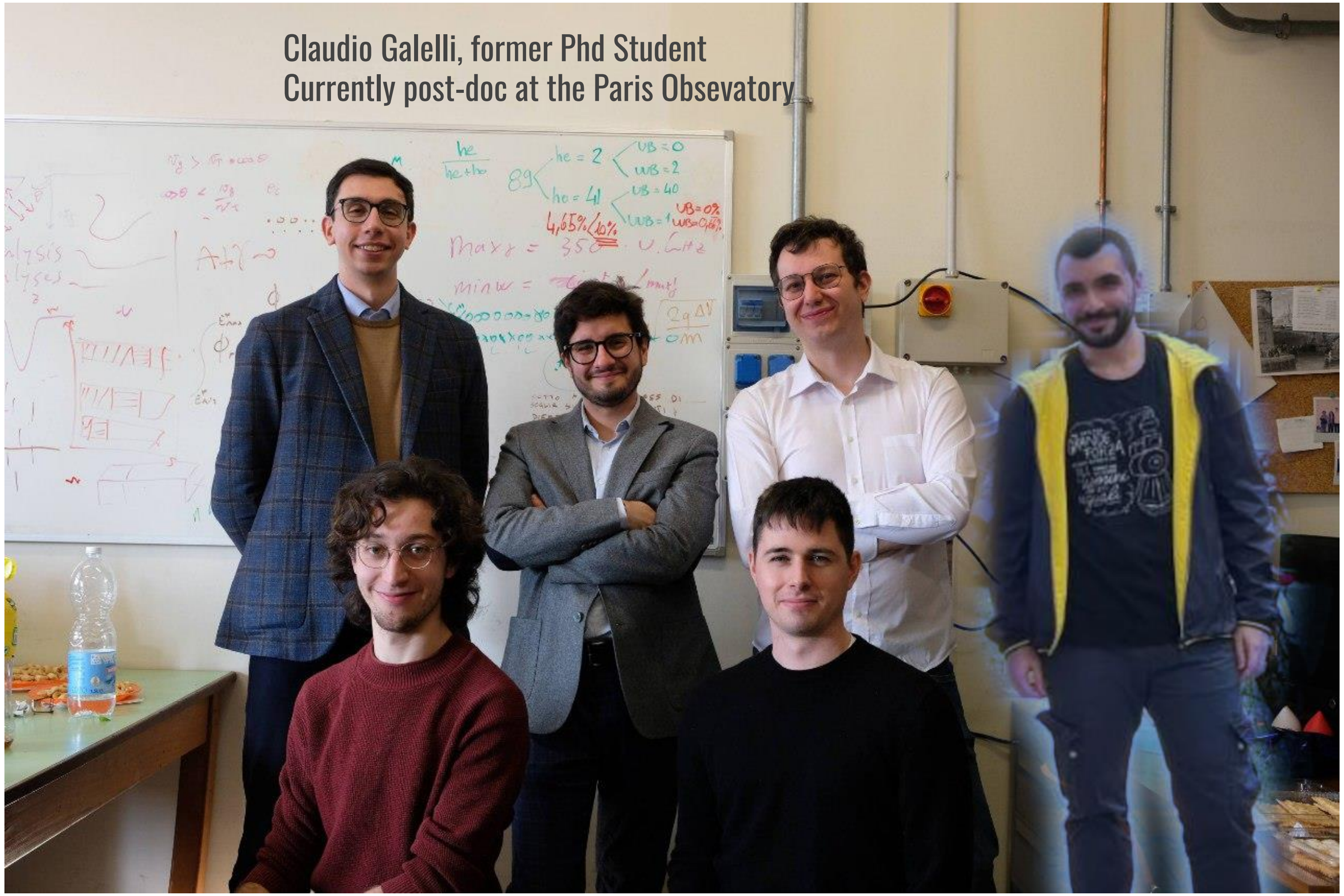
The Milan group

We mainly work on UHECR within the Pierre Auger Observatory collaboration, having fun with Paleo detectors!

Claudio Galelli, former Phd Student
Currently post-doc at the Paris Obsevatory

Federico Mariani, PhD student

Alessandro Veutro, former Master student currently PhD student in Rome on km3net



Paolo Magnani, Master student

Lorenzo Apollonio, PhD student

Cosmic rays

Mineral Detection of ~~Neutrinos and Dark Matter~~

Jan 8 – 11, 2024

US/Eastern timezone

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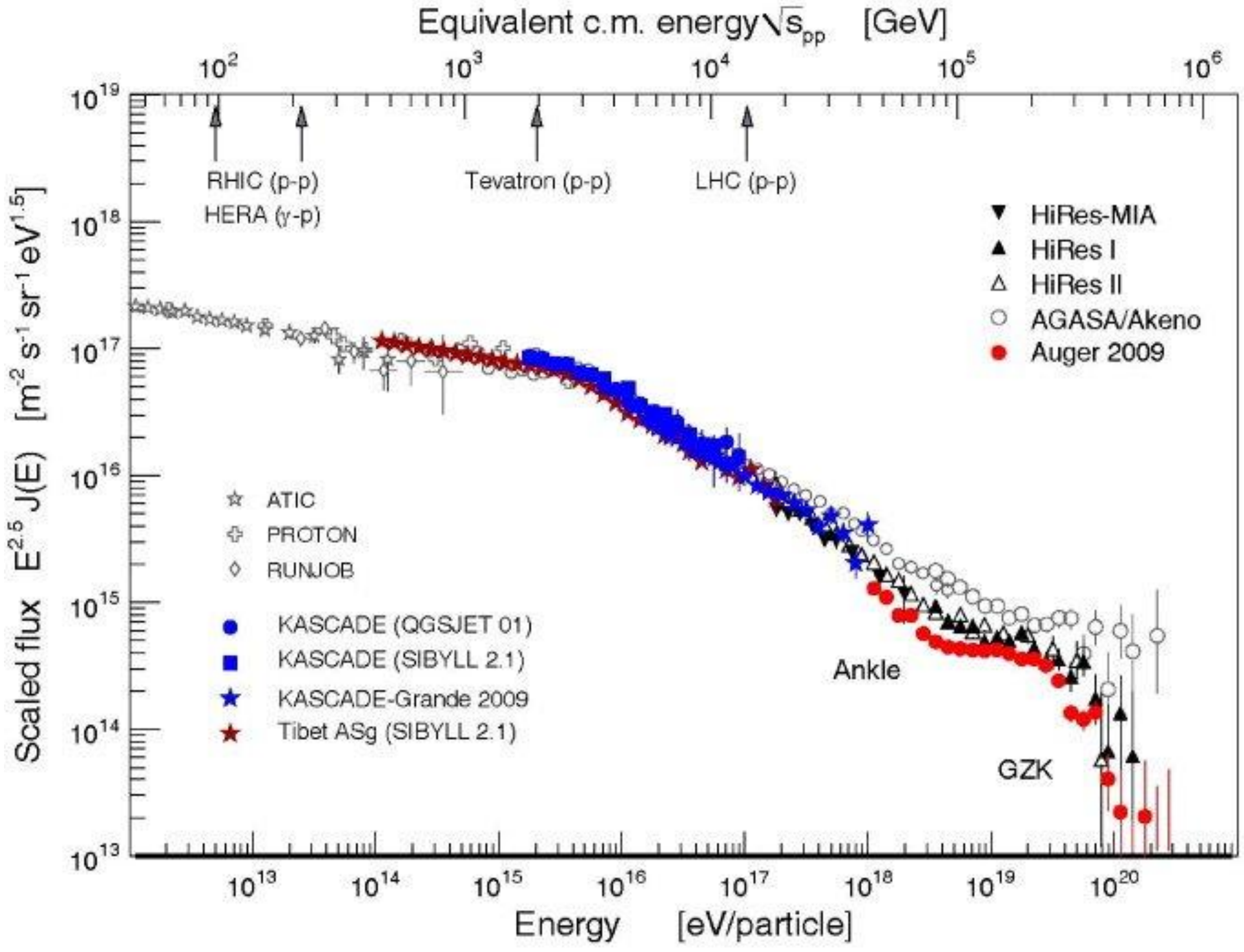
Cosmic rays

Ranging from few GeV to hundreds of EeV (1 EeV= 10^{18} eV)

- Most energetic particles known
- They produce extensive air showers of secondary particles when they interact with the atmosphere: in these showers are muons, neutrons and neutrinos
- primary cosmic rays mostly charged particles and are deflected by galactic (and extragalactic) magnetic fields, and thus delayed wrt to neutral particles
- cosmic rays in the TeV-PeV region associated to supernova remnants, higher energy may be accelerated by compact objects (magnetars?)
- Evidence for extragalactic origin above few EeV (AGN or starburst galaxies?).



Why digging?

Why should we use paleo detectors
when we have much more refined detectors?

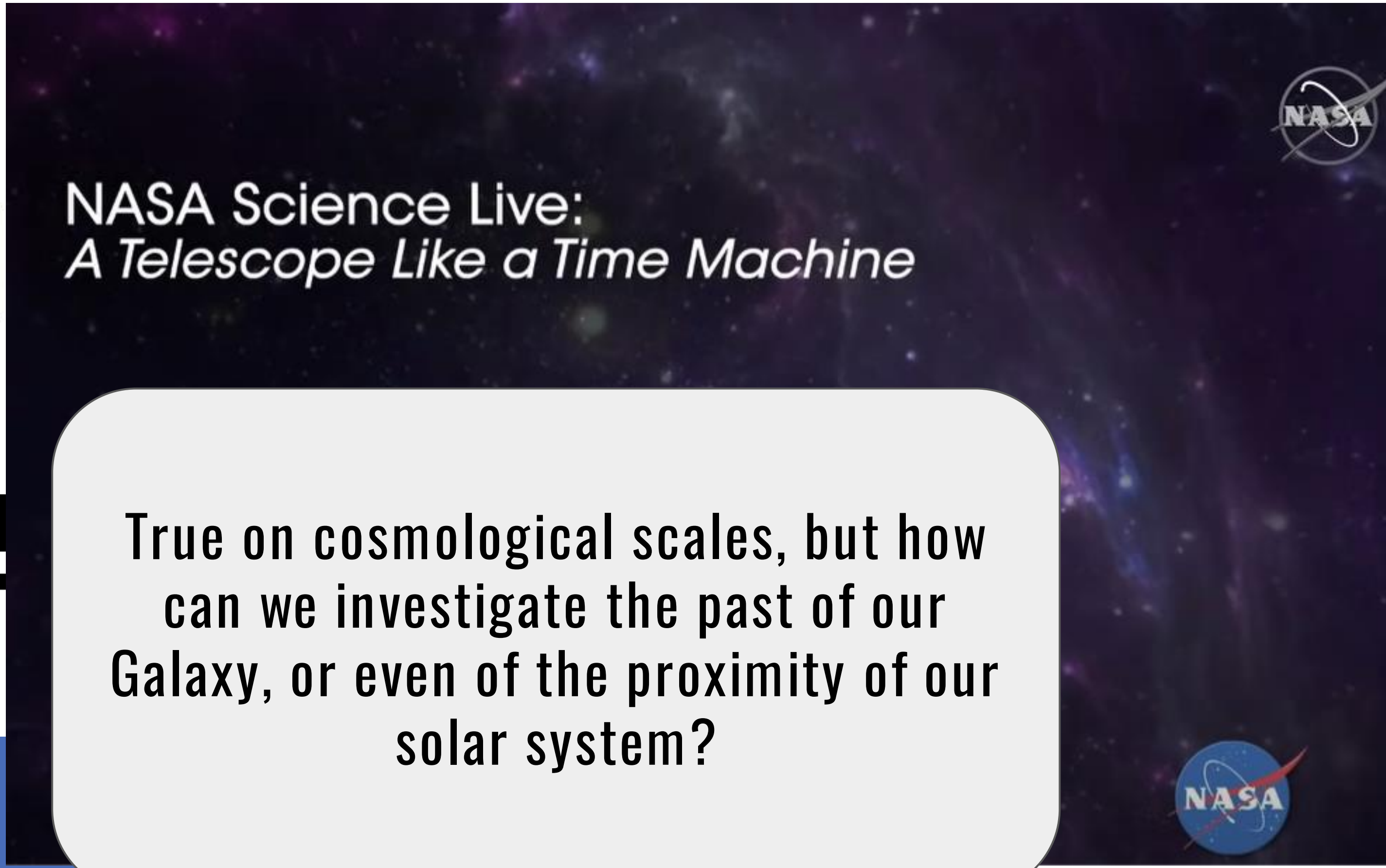
They can reach a very large exposure, even with a small sample

possibly larger than we could ever build artificially

They can measure the fluxes of astroparticles in the past

One of the very few chances of studying any astrophysical emission in the past

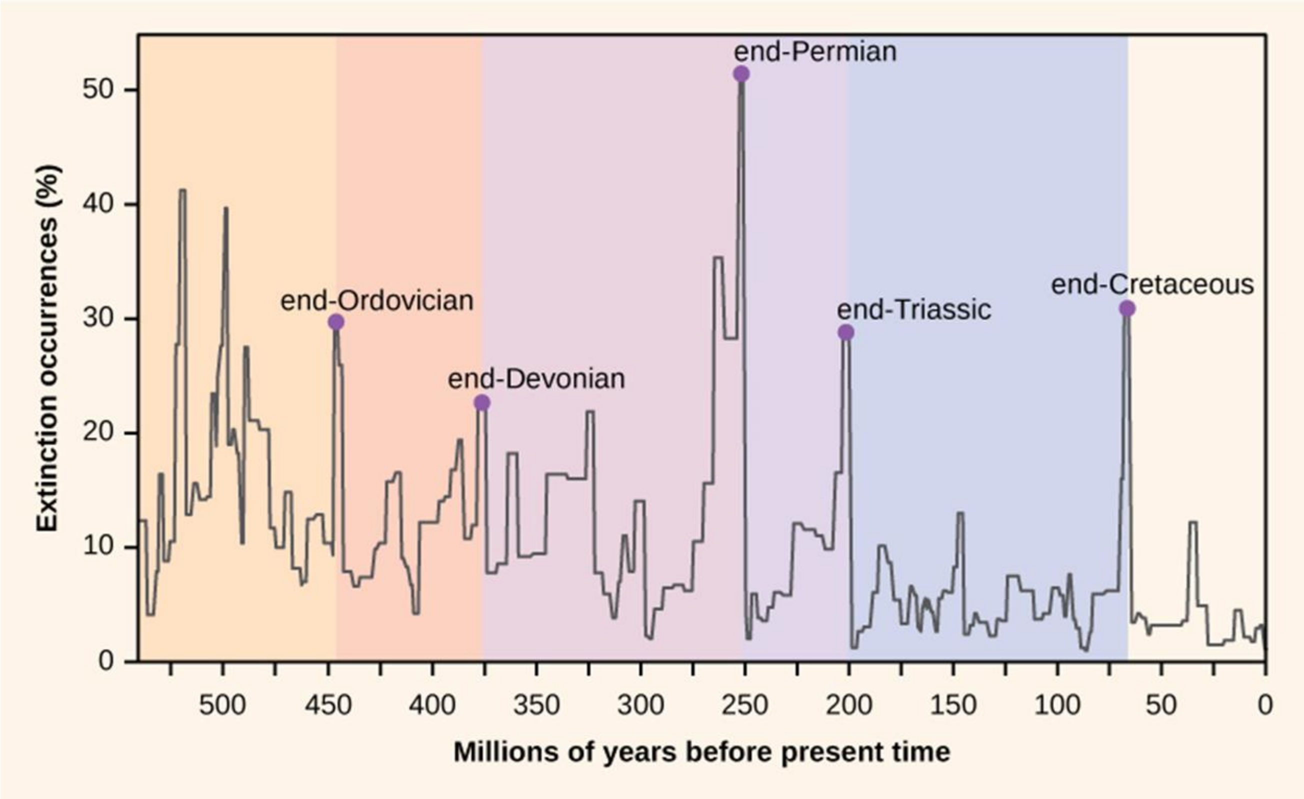
How do we investigate the past of the universe?



True on cosmological scales, but how can we investigate the past of our Galaxy, or even of the proximity of our solar system?

Mass extinctions: caused by nearby astrophysical events?

- It was suggested in various occasion that a nearby catastrophic astrophysical event might be the cause of some of the various mass extinctions that happened on Earth
- gamma emission from SN or GRB could have depleted the ozone layer, causing harmful UV radiation to kill surface-living species (or making them evolve quicker)
- some extinctions show however that also deep-sea and deep-underground creatures were affected. It was suggested that it might be the effect of elevated muon (and/or neutron?) fluxes induced by a burst of primaries
- such a flux might easily have left tracks in paleo-detectors



Mass extinctions: caused by nearby astrophysical events?

- The possible 62Myr periodicity in mass extinctions might be correlated to the motion of the solar system in the Galaxy?

D. R. Gies and J. W. Helsel 2005 *ApJ* **626** 844**DOI** 10.1086/430250

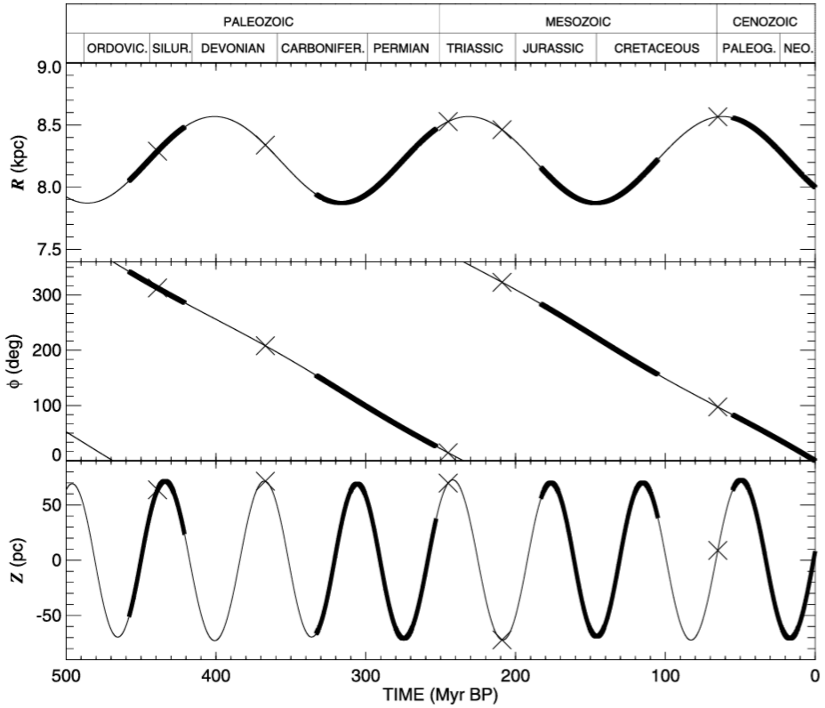
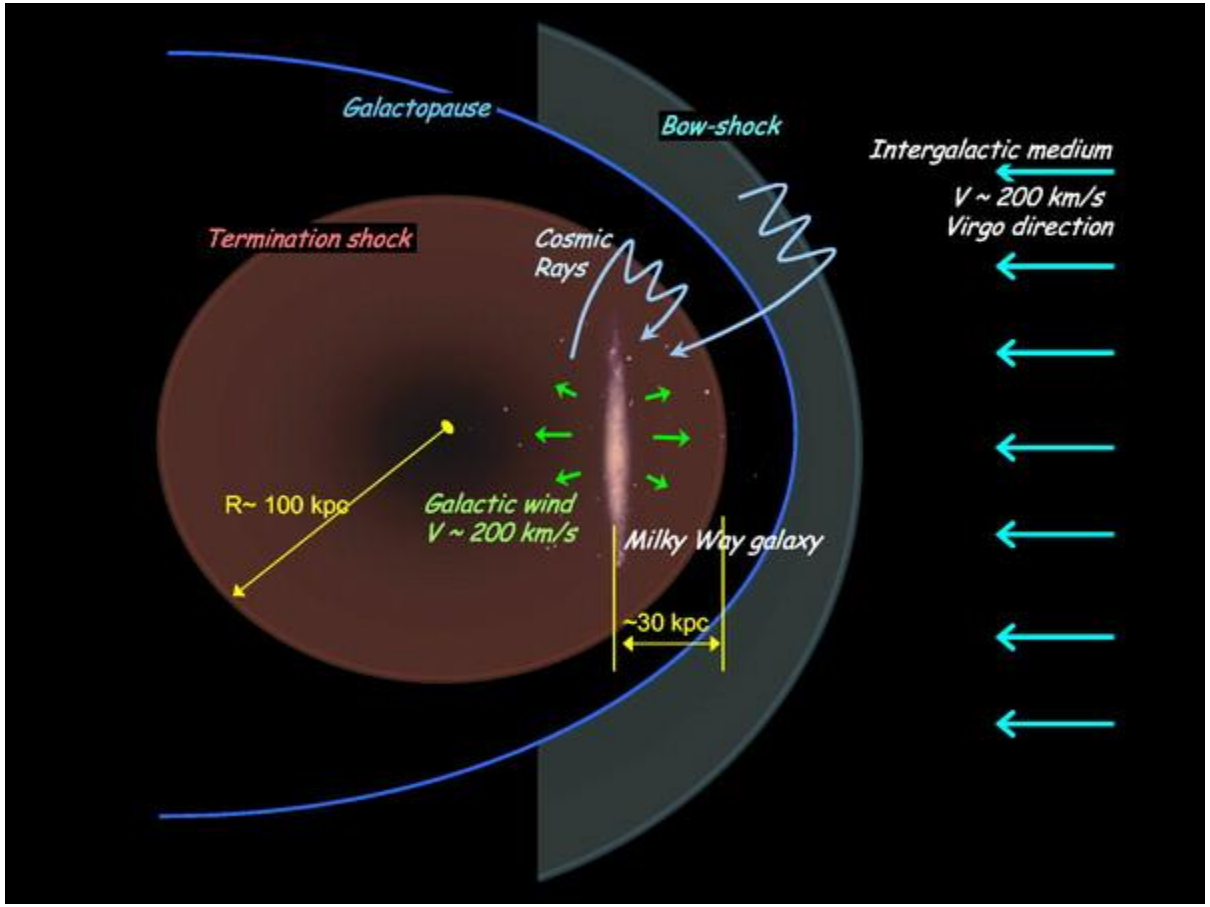


Fig. 1.—Sun's position in the Galaxy over the last 500 Myr expressed in cylindrical coordinates; R is the distance from Galactic center (*top*), ϕ is the azimuthal position in the disk relative to $\phi = 0°$ at present (*middle*), and Z is the distance from the plane (*bottom*). Thick line portions mark icehouse epochs on Earth (Frakes et al. 1992), and crosses indicate times of large mass extinctions on Earth. The names of the geological eras and periods over this time span are noted at the top of the figure.



Mikhail V. Medvedev and Adrian L. Melott 2007 *ApJ* **664** 879**DOI** 10.1086/518757
Atri and Melott Geophys. Res. Lett., 38, L19203, doi:10.1029/2011GL049027

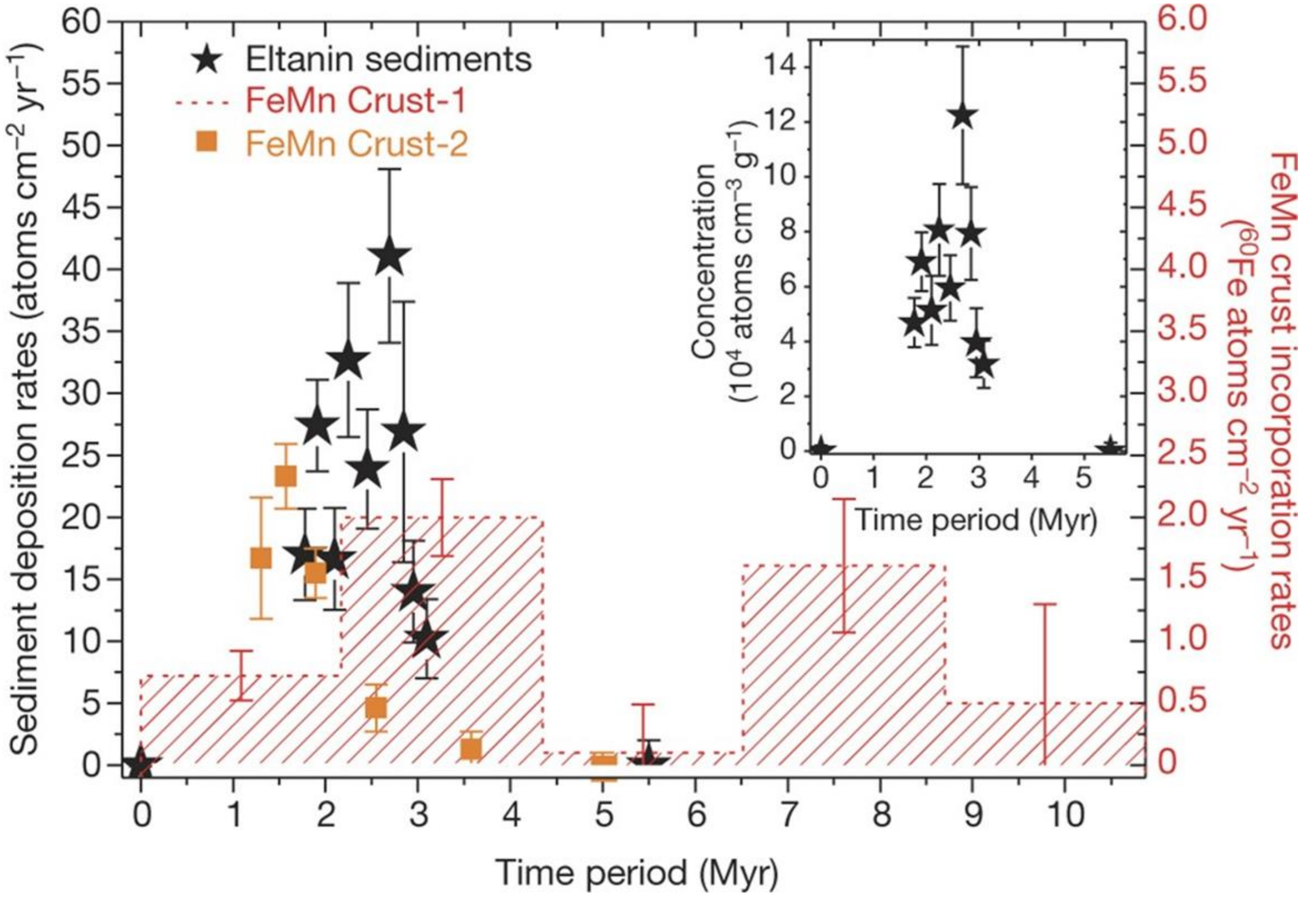
Traces of recent and close supernovae events

- ^{60}Fe deposit on oceanic crust
- Identified as trace of close (100-200 pc) supernovae in the recent (few Myr) past

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.

TABLE I: PREDICTIONS AND MEASUREMENTS OF ^{60}FE EXCESS IN DEEP OCEANIC CRUST SAMPLES (CORRECTED FOR IN SITU DECAY)

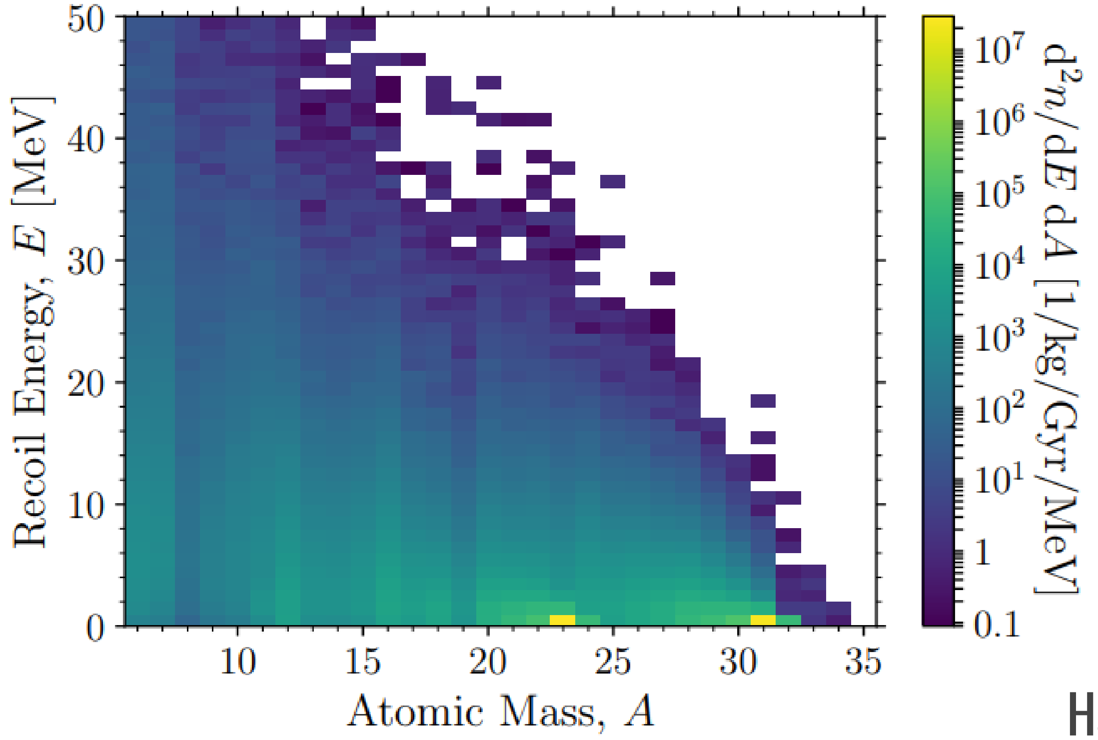
	Layer 1	Layer 2	Layer 3
age(Myr)	0-2.8	3.7-5.9	5.9-13
$N_{\rm SN}$	8	4	6
$D_{\rm SN}$ (pc)	130	140	205
$\phi_{\rm SN}$ (10^6cm^{-2} Myr^{-1})	$0.7^{+6.30}_{-0.06}$	$0.4^{+3.6}_{-0.04}$	$0.08^{+0.8}_{-0.01}$
$\phi_{\rm b}$(10^6 cm^{-2} Myr^{-1})	0.11	1.5	5
$\phi_{\rm SN} + \phi_{\rm b}$ (10^6cm^{-2} Myr^{-1})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

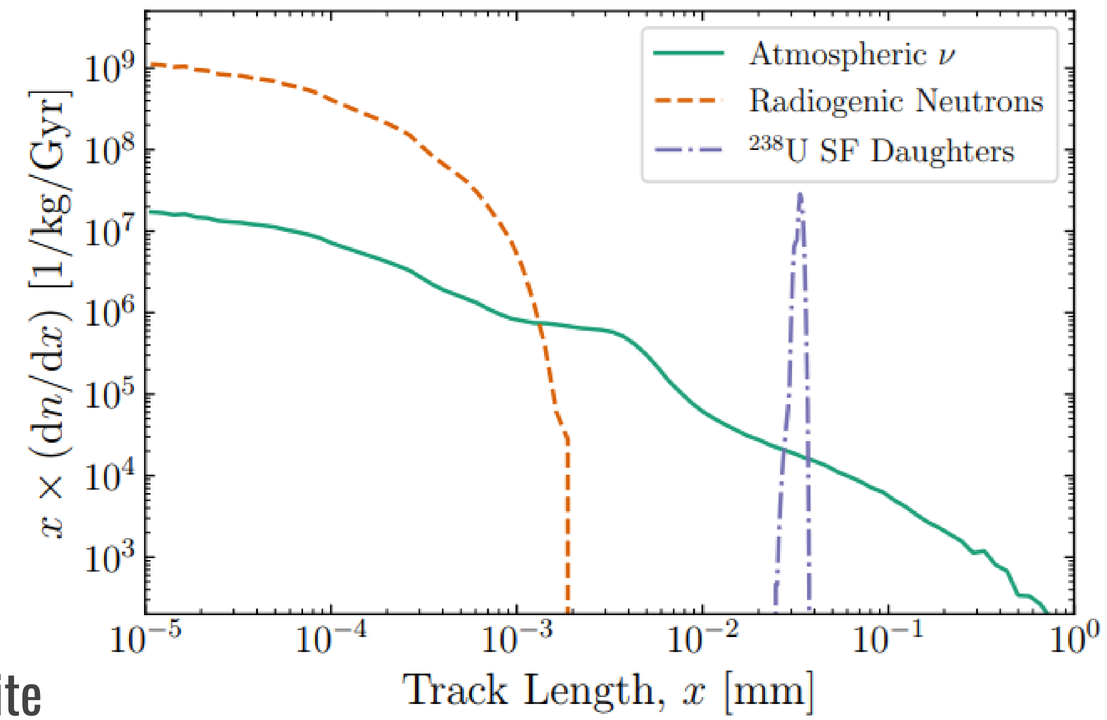


Paleo-detectors for cosmic rays

- Cosmic rays are always measured through the secondary particles they generate, amongst them there are the atmospheric neutrinos:

J. R. Jordan, S. Baum, P. Stengel, A. Ferrari, M. C. Morone, P. Sala and J. Spitz, «Measuring Changes in the Atmospheric Neutrino Rate over Gigayear Timescales,» *Phys. Rev. Lett.*, vol. 125, n. 23, p. 231802, 2020



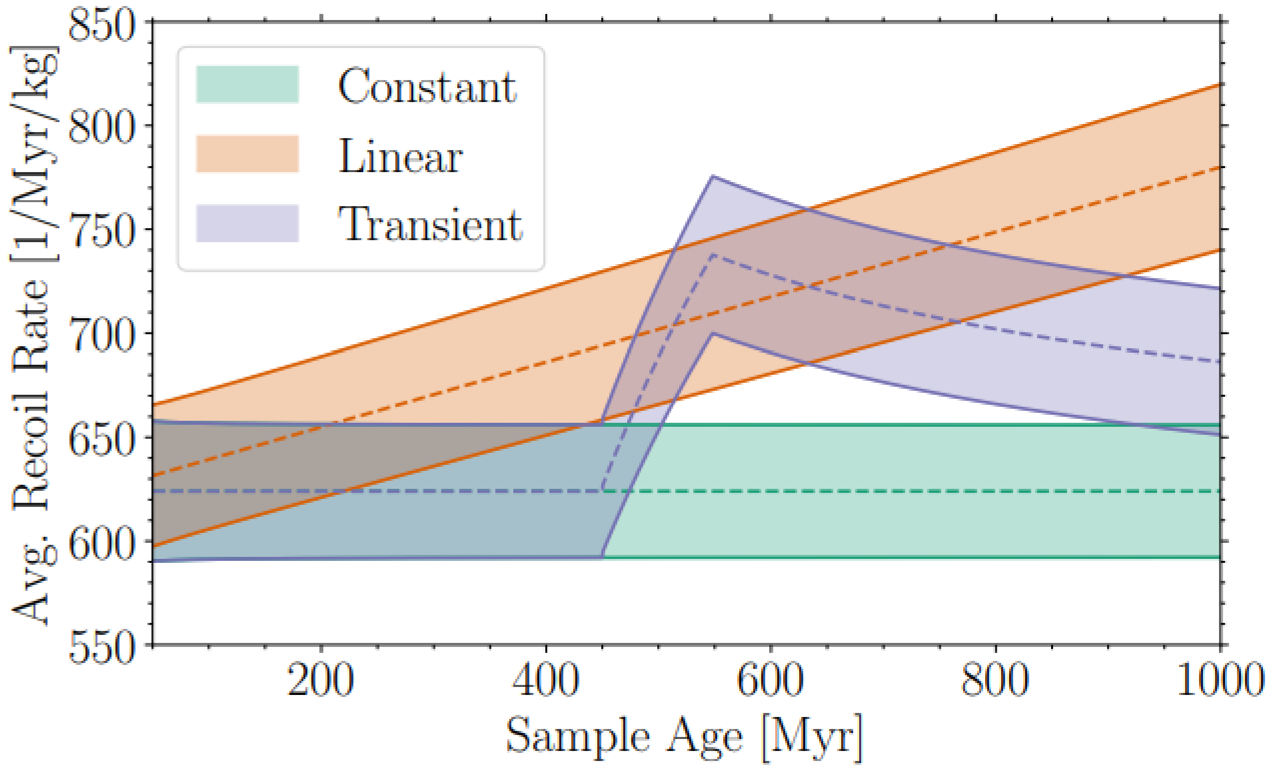


Halite

Paleo-detectors for cosmic rays

- Atmospheric neutrinos might be able to trace an evolution of the flux of cosmic rays and search for long transients (100 Myr)
- For shorter transients a different approach might be better (see after)
- The ability of measuring CR transients depends on where the transients are located: cosmic rays are charged particles and are thus delayed by magnetic fields
- Depending on their rigidity, they might even be trapped inside the Galactic Magnetic Field (GMF)
- Exception: if sufficiently close and/or energetic neutrons can arrive to Earth.
  decay length ~9 kpc * (E [EeV])

J. R. Jordan, S. Baum, P. Stengel, A. Ferrari, M. C. Morone, P. Sala and J. Spitz, «Measuring Changes in the Atmospheric Neutrino Rate over Gigayear Timescales,» *Phys. Rev. Lett.*, vol. 125, n. 23, p. 231802, 2020



The exposure problem

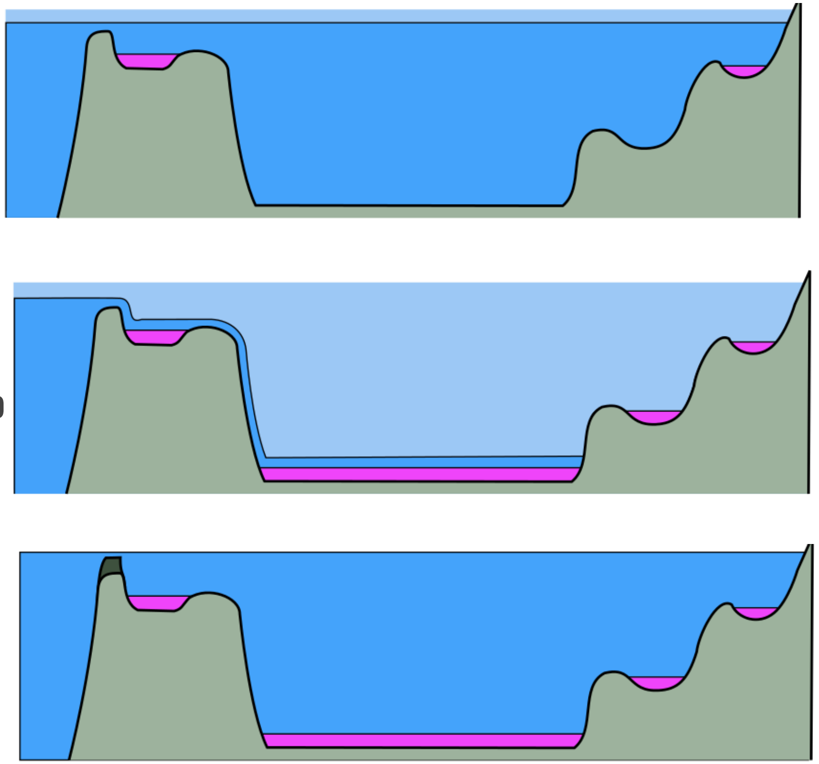
- A part from atmospheric neutrinos, also the other components of EAS can produce nuclear recoils (much easier!) -> the problem is to know the exposure time of the mineral to the air
- We will focus on muons as they are the most penetrating component of EAS, a part from neutrinos (we're going to consider also neutrons in the near future) and are less affected by small overburdens
- We need to know the geological history of the sample

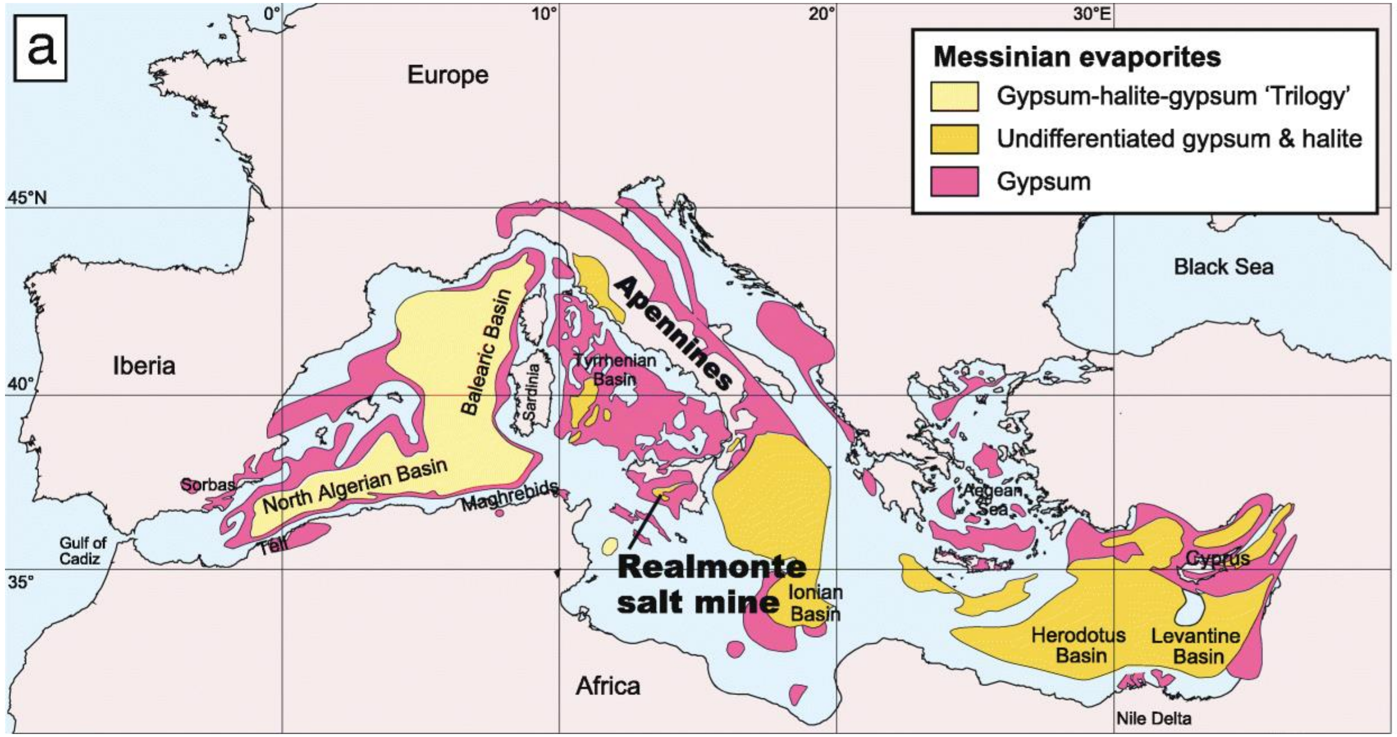
An option: the messinian salinity crisis.

- The mediterranean sea evaporates quicker than rivers can compensate
- In normal conditions, it receives constantly water from the Atlantic ocean
- Roughly 6 Myr the precursor of the Gibraltar strait closed up due to tectonic movements
- A large part of the mediterranean sea evaporated in the following few tens/hundreds of kyrs

Messinian salinity crisis

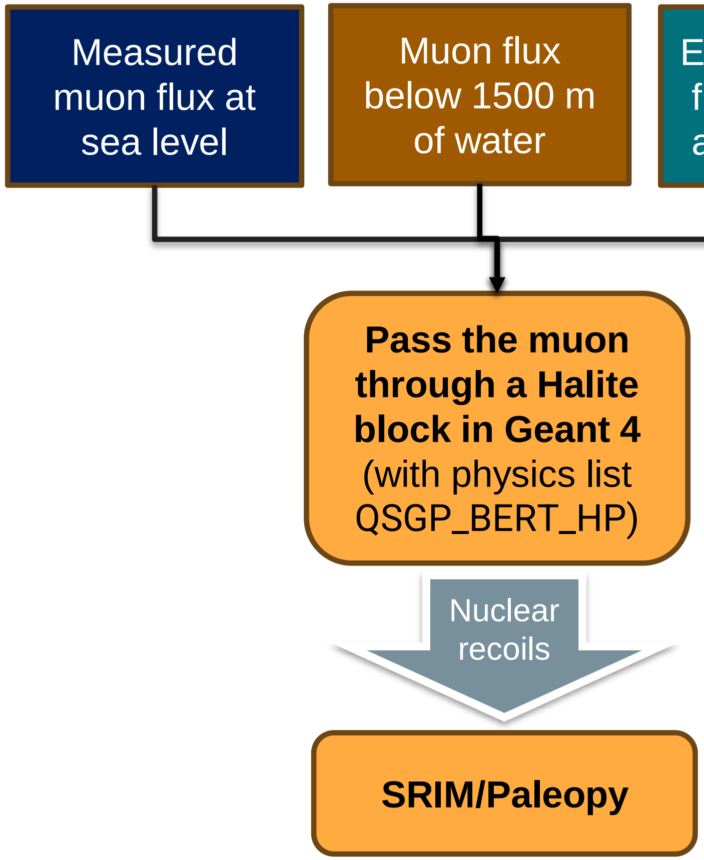
- A huge amount of evaporites was produced, mostly halite [NaCl] and gypsum [$CaSO_4\ 2(H_2O)$]
- These minerals have been exposed directly to cosmic rays for ~300 kyr
- The Gibraltar strait opened again, and the mediterranean basin was quickly flooded («Zanclean flood») again

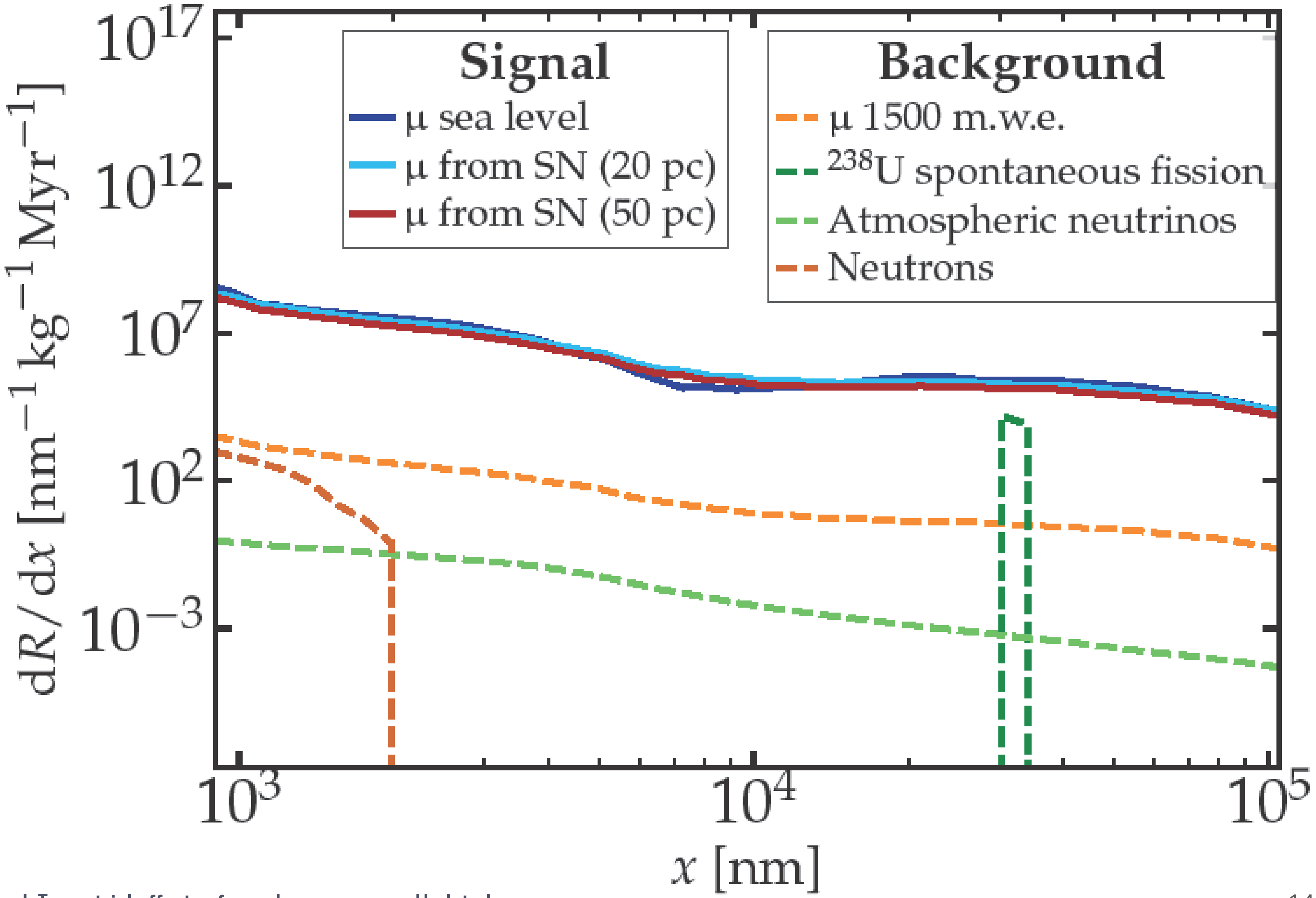




Isaji, Y., Yoshimura, T., Kuroda, J. *et al.* Biomarker records and mineral compositions of the Messinian halite and K–Mg salts from Sicily. *Prog Earth Planet Sci* **6**, 60 (2019). https://doi.org/10.1186/s40645-019-0306-x

Simulating the tracks

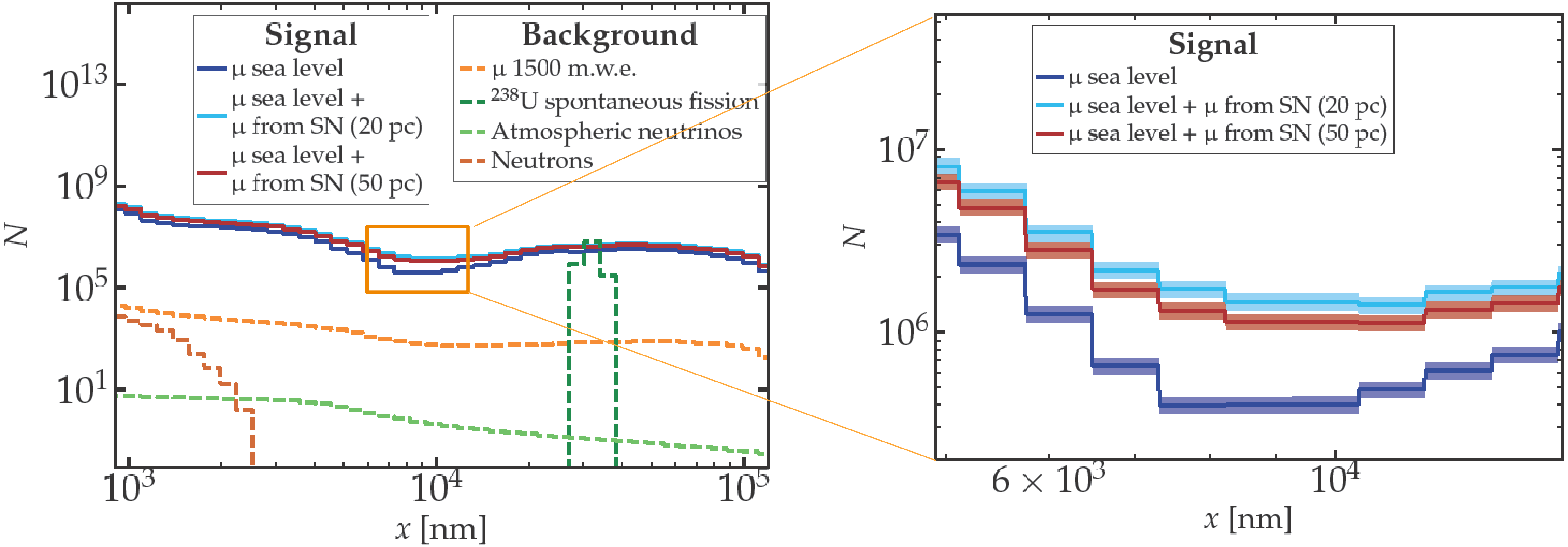




[1] B. C. Thomas and A. M. Yelland, Terrestrial effects of nearby supernovae: Updated modeling, The Astrophysical Journal 950, 41 (2023).

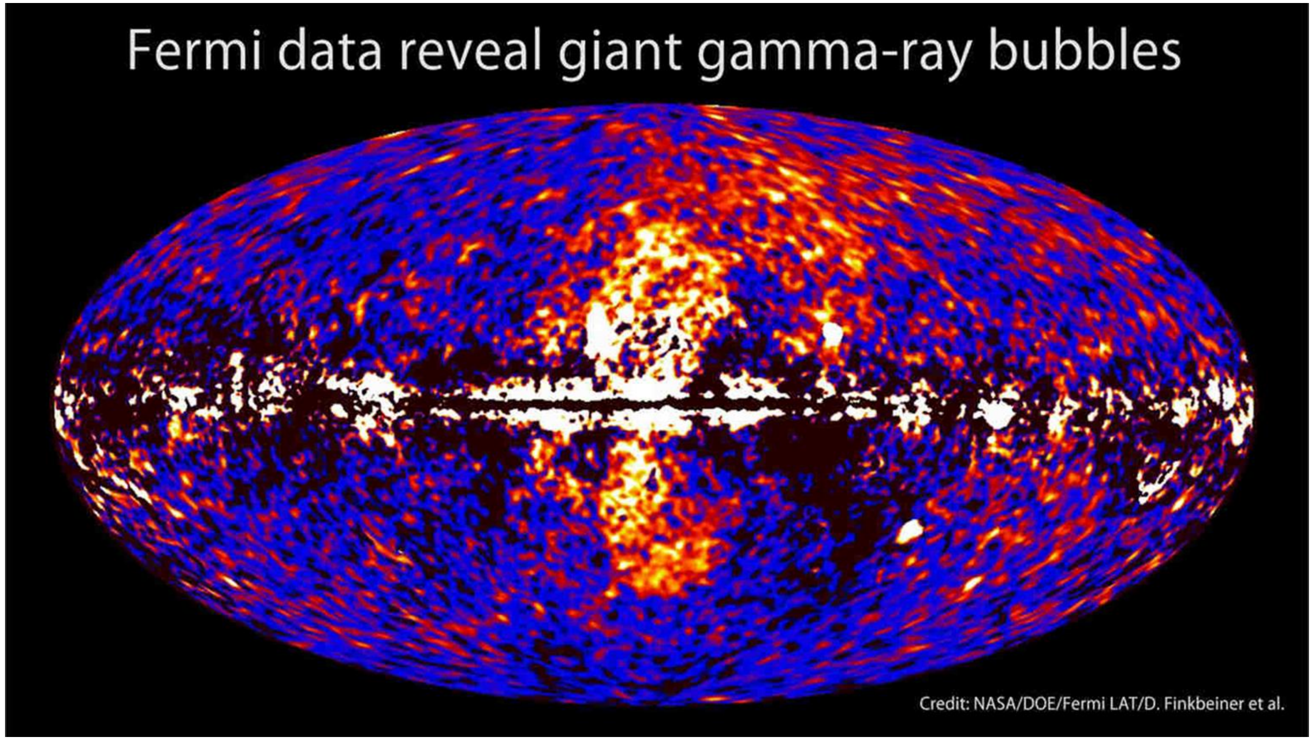
Simulating the tracks

- Integrate on a 10g mass the signal for 270 kyr, the background for 5.6 Myr (background underwater muons for 5.3 Myr)



A tantalizing coincidence: Fermi Bubbles (and their age)

- The observation of bubble-like structure perpendicular to the galactic plane in gamma showed that our Galaxy might have been active in the recent past
- Is it possible that this activity was associated to high energy cosmic ray emission?
- Some studies date these structures at 5-6 Myr
- Problem: cosmic ray delay and shielding due to galactic magnetic fields in reaching Earth



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.

Conclusions (for astrophysicists and biologists)

- The measurement of tracks due to secondary cosmic rays can shed a light on the (relatively recent) history of the neighborhood of our solar system and, perhaps, of our Galaxy.
- Wrt other astroparticles, cosmic rays have the advantage of being shieldable: if one can find a mineral with the right geological history, we can investigate specific periods of time.
- An example is the Messinian salinity crisis: evaporites produced in that event were exposed for a specific period of time
- The number of transient events happened in the past near our planet could be related to different events in the biosphere.

Conclusions (for people interested only in MDvDM)

- CR-induced tracks should be more common and longer than the ones induced by neutrinos and dark matter
It should be an even lower-hanging fruit than atmospheric neutrinos
- Searching for this kind of tracks can greatly benefit the experimental path to MDvDM:

- We can show that *we can indeed see astroparticle tracks in natural minerals*
- We can show that our track length simulations are correct at least in this regeme (or correct them if they are not)
- We can show that we have control on one of the backgrounds for neutrino and DM measurements
- We can use for MDvDM samples that are not necessarily completely shielded from CR if we can model the background well enough.

Even having just a couple of these tasks completed could increase the concreteness of the MDvDM proposals and enhance funding opportunities

Next steps

Theoretical part:

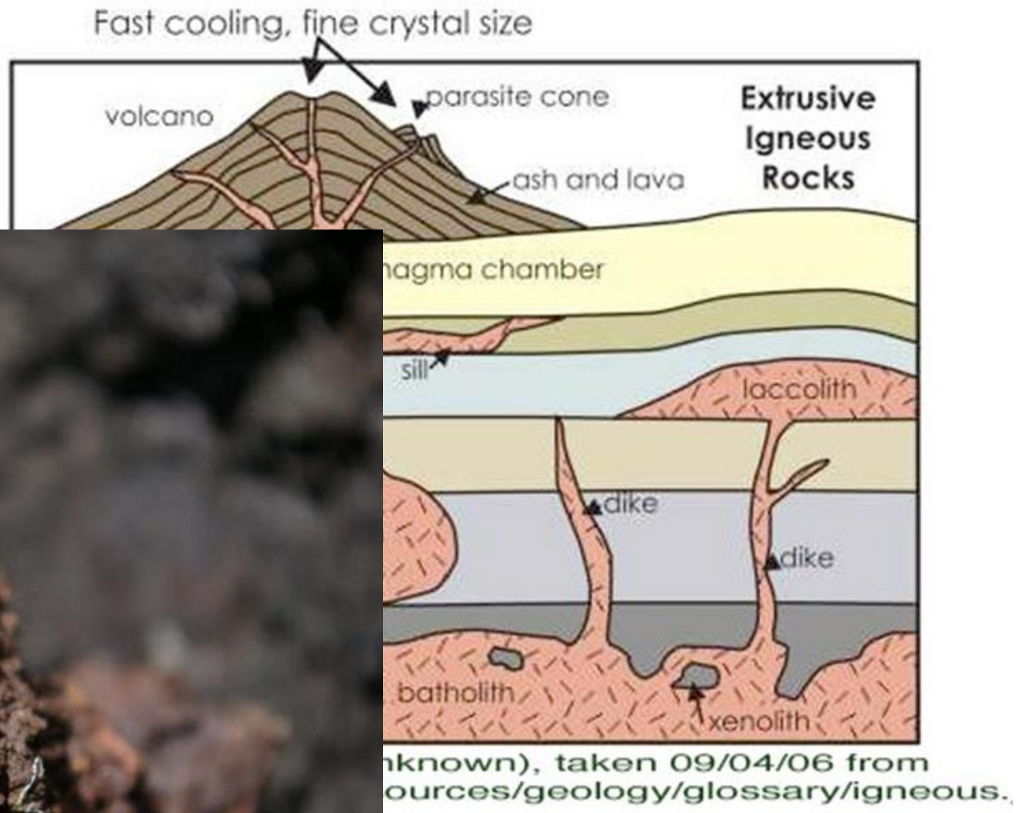
- Simulate the cosmic ray neutrons for the Messinian scenario
- Consider other seabed minerals that can be exposed rather than Halite
- Search for other opportunities apart from the Messinian (e.g. other sea evaporations, minerals produced or exposed in volcanic eruptions...)
- Coordinate with information from cosmogenic nuclides

Experimental part:

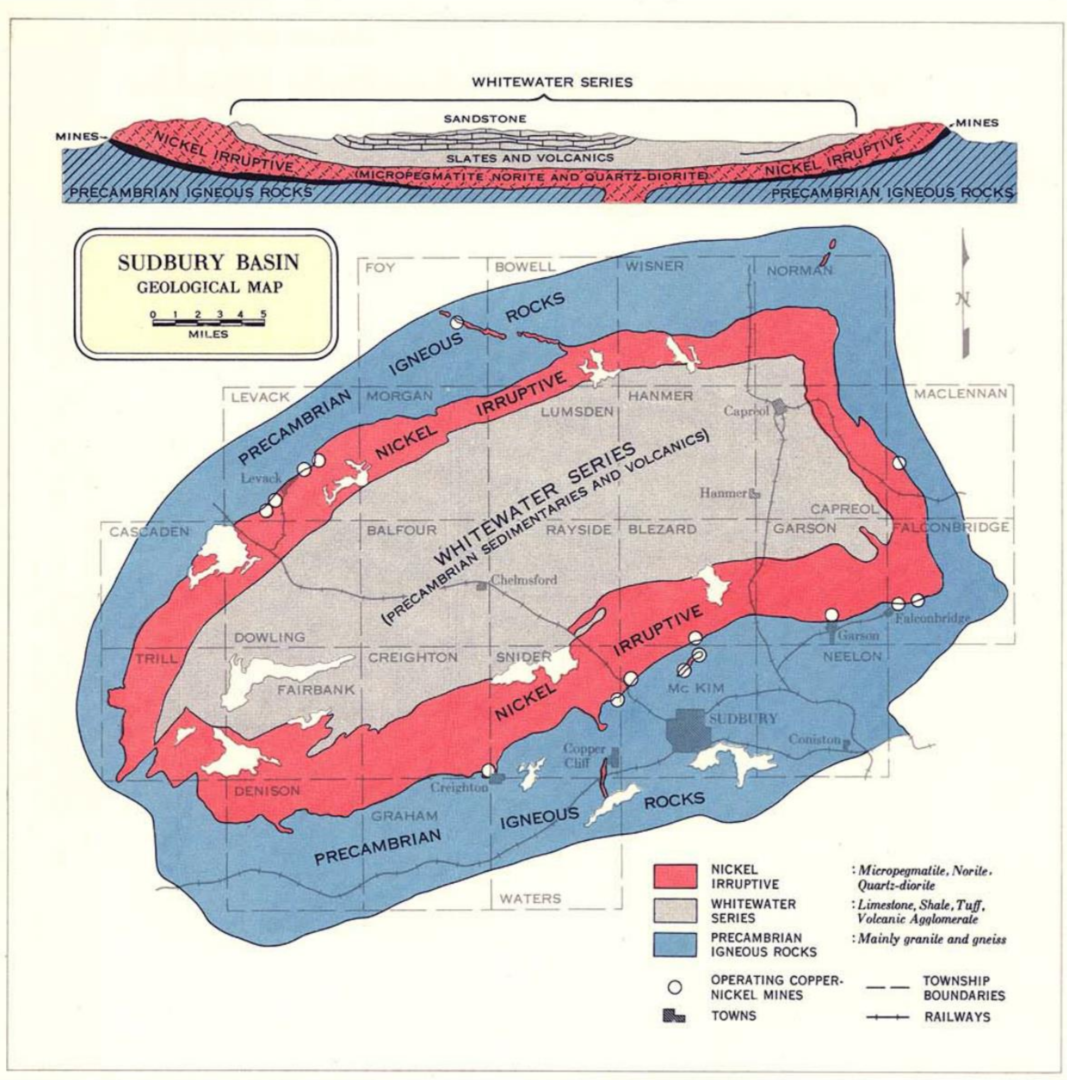
- Identify cosmic ray tracks in Halite samples currently exposed to cosmic rays
- Study annealing effects in Halite
- Verify that the measurements fit the predictions (or correct models accordingly)
- Find suitable messinan Halite sample and recover them (possibly from multiple sites)
- Measure tracks and obtain the flux of cosmic rays 5.5 Myr ago!
- Repeat with suitable samples from other periods

Backup Slides

Xenoliths


Fast cooling, fine crystal size
volcano
parasite cone
Extrusive
Igneous
Rocks
ash and lava
agma chamber
sill
laccolith
dike
dike
batholith
xenolith
known), taken 09/04/06 from
ources/geology/glossary/igneous.

Sudbury



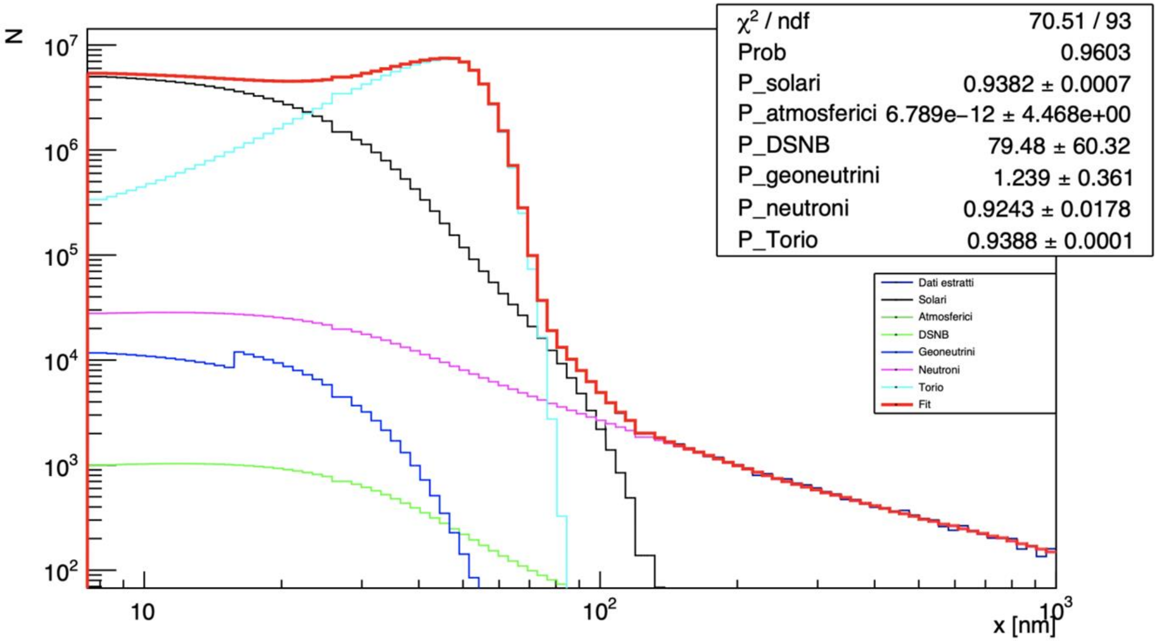
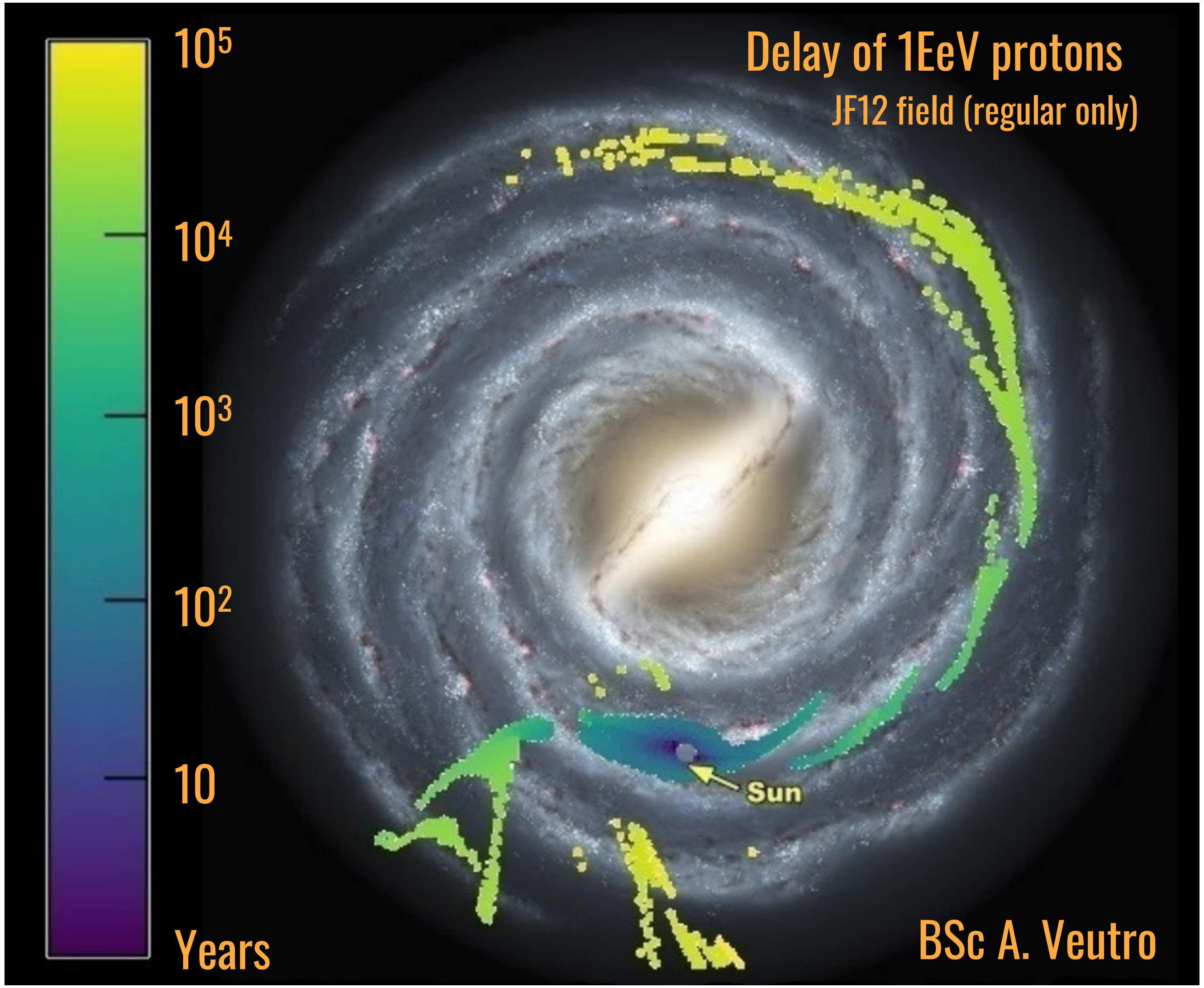


Figura 5.8: Fit della simulazione di tracce in un campione di Morenosite nel caso ad alta esposizione

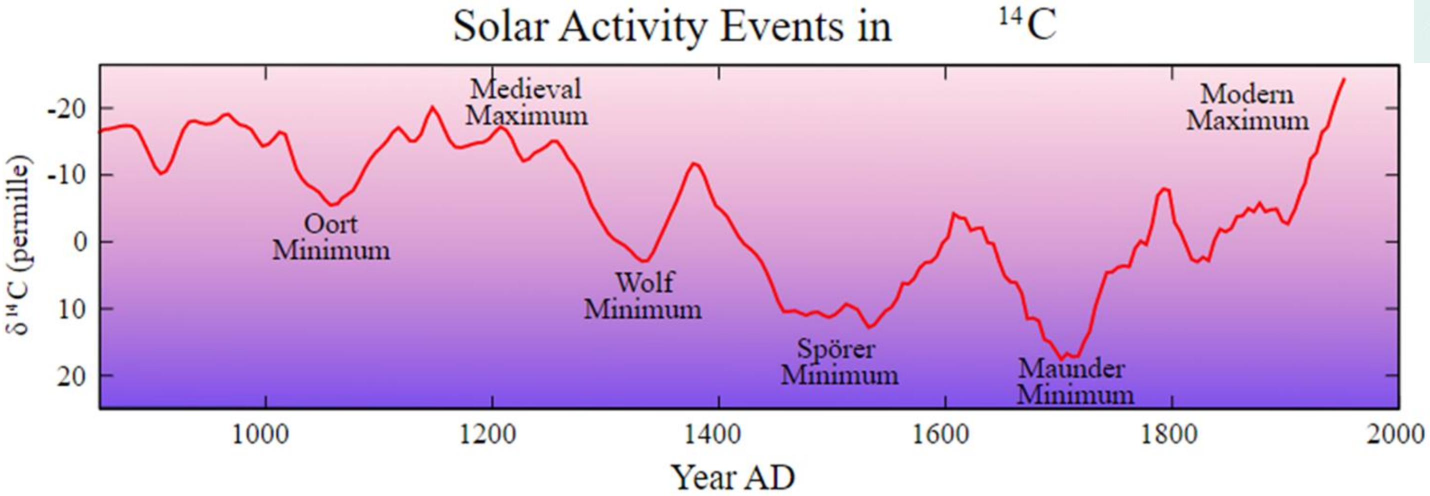
Cosmic ray delay in Galactic Magnetic Field

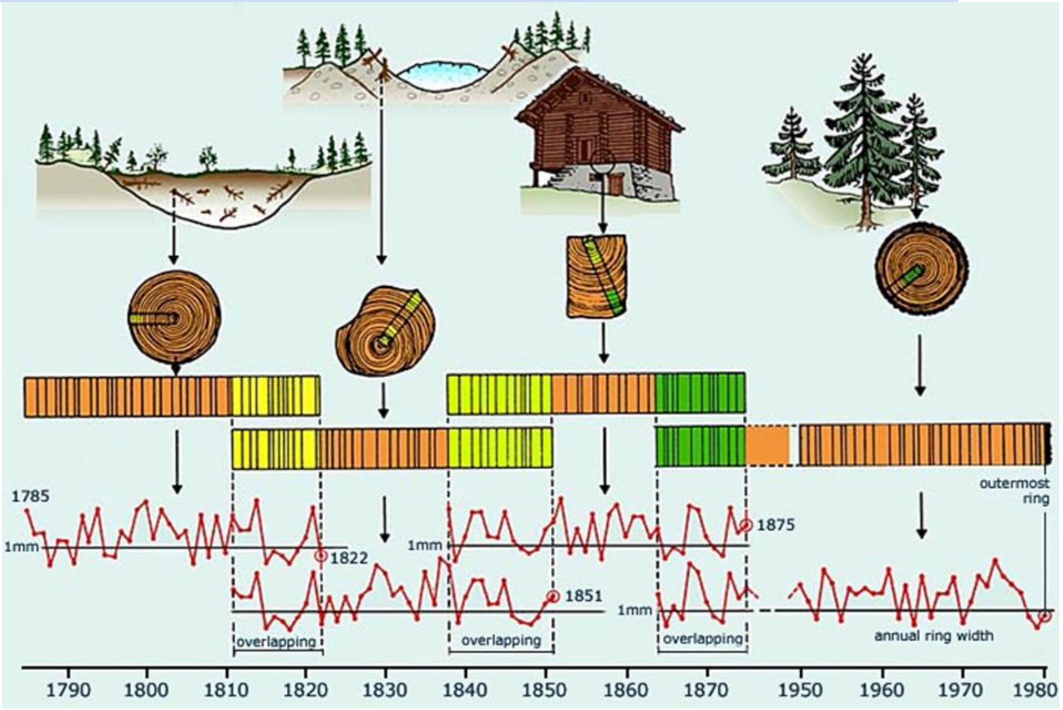
- Measuring the GMF (and even more extragalactic magnetic fields) is a difficult task, obtained through measurements of starlight polarization, Faraday rotation measure (RM) and synchrotron emission.
- Different models exist, which can disagree strongly on the direction of the deflection, but usually agree at least on the order of magnitude of its absolute value
- Delay is rarely considered -> need for dedicated simulations
- Below a certain rigidity likely a transition from ballistic to diffuse propagation occur



^{14}C evolution in atmosphere

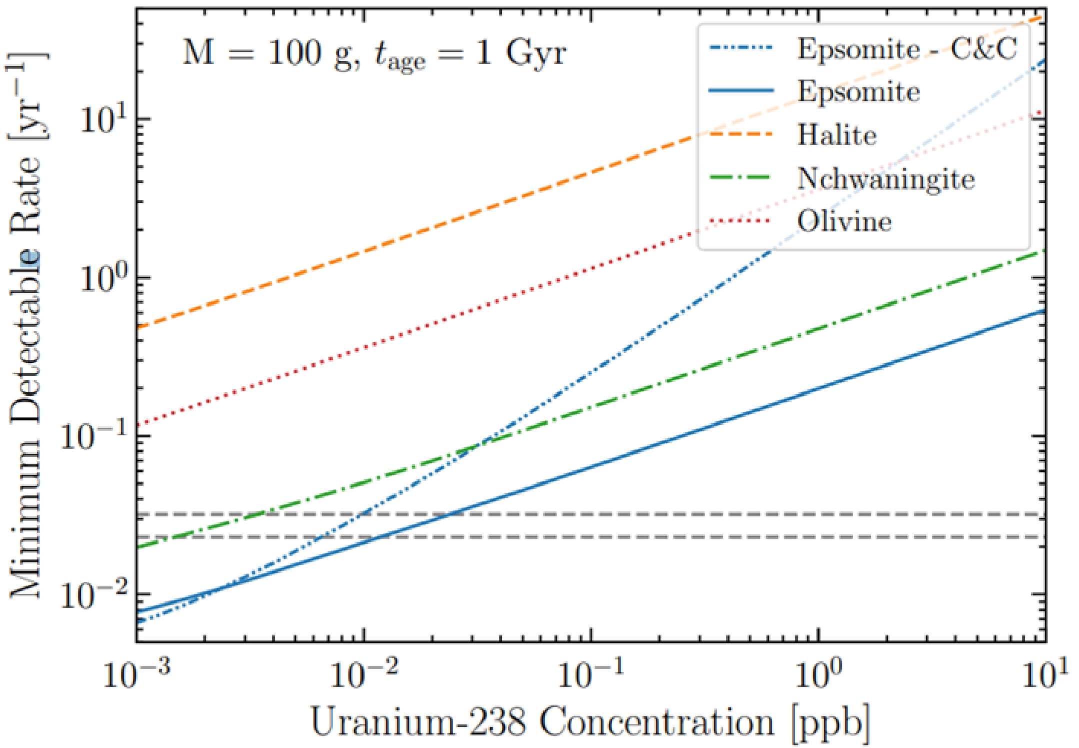
- ^{14}C is produced by cosmic rays in atmosphere
- production is dominated by low energy cosmic rays that are strongly affected by solar activity
- the rate of ^{14}C is of huge interest for calibrating the dating technique
- one of the most powerful method to track ^{14}C abundance (with a o(yr) precision!) is to use dendrochronology (limited to few kyr)

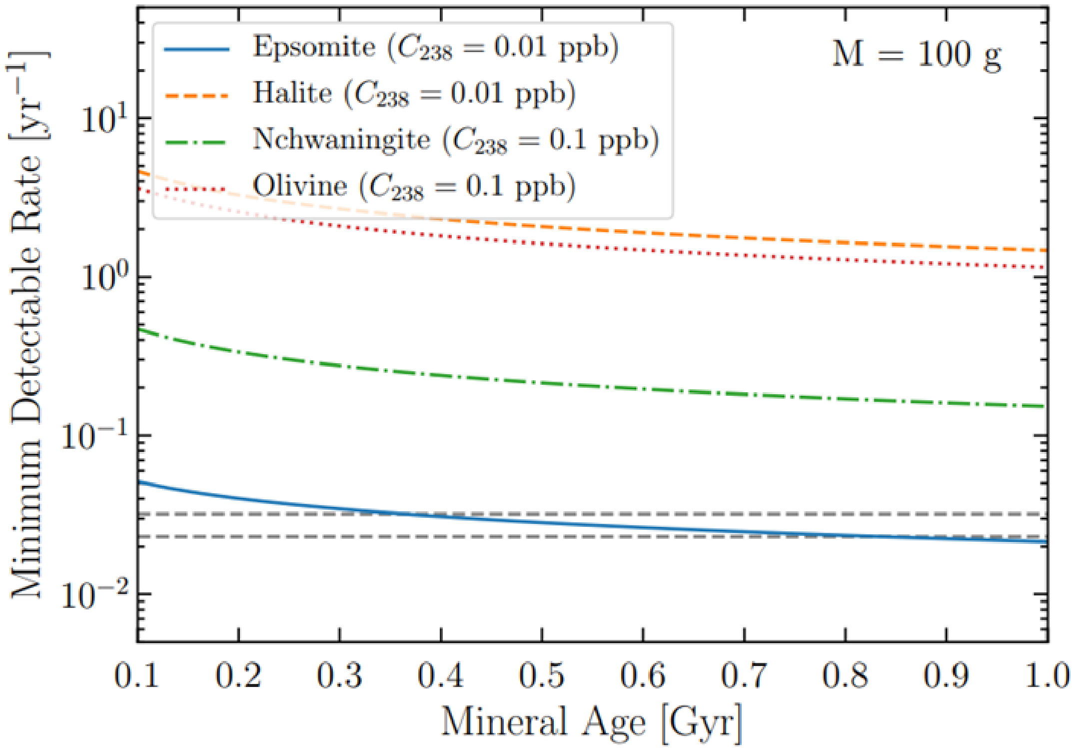




Paleo-detectors for supernova neutrinos

- Supernova neutrinos have a high flux but for a very short (10s) time
- It has been proposed that paleo-detectors might be able to measure the rate of SN in our Galaxy





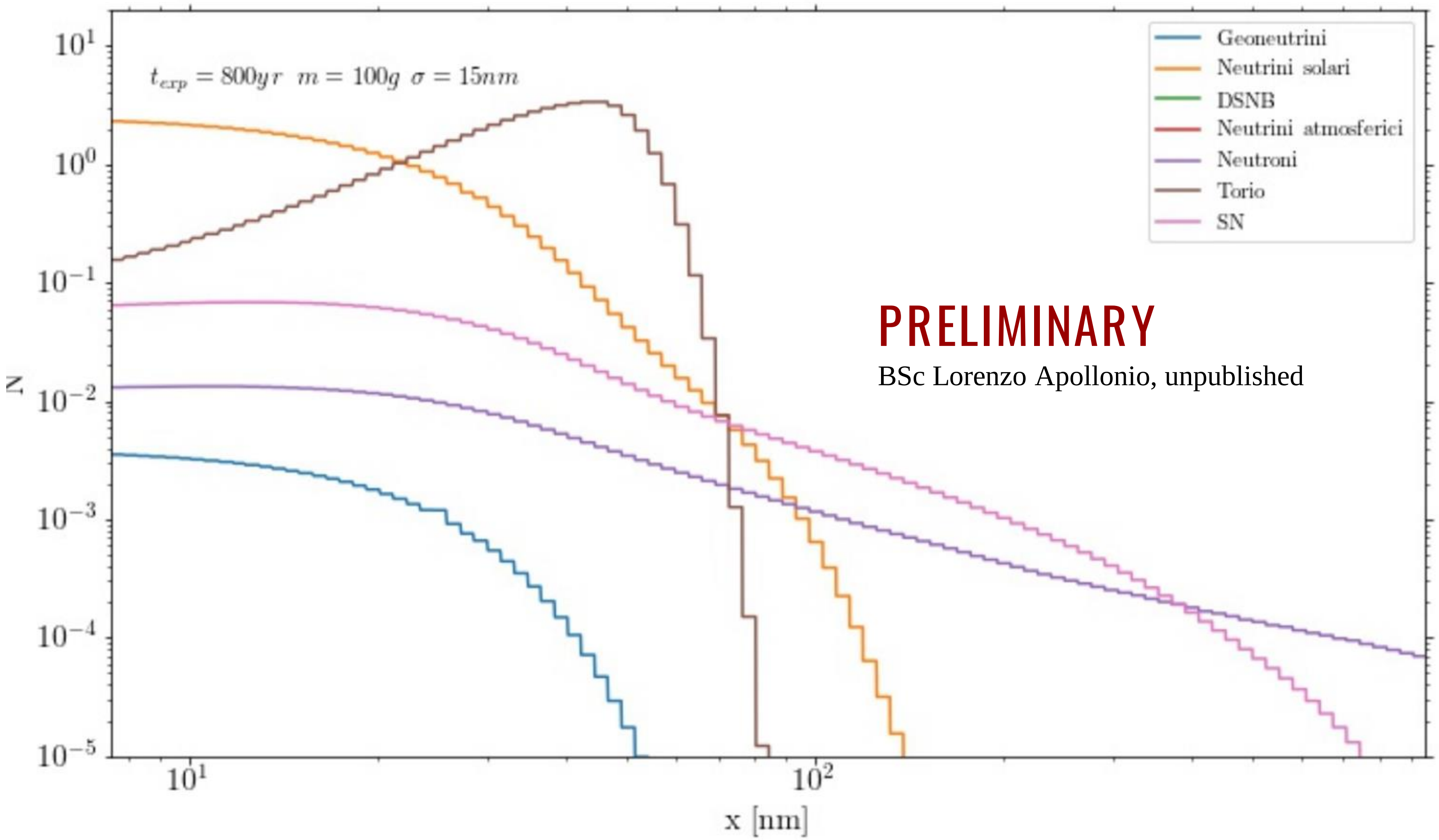
S. Baum, T. D. P. Edwards, B. J. Kavanagh, P. Stengel, A. K. Drukier, K. Freese, M. Gorski and C. Weniger, «Paleodetectors for Galactic supernova neutrinos,» *Phys. Rev. D*, vol. 101, n. 10, p. 19, 2020

Paleo-detectors for supernova neutrinos

- what about a single sn event? Need to be close and recent to have any chance of having a decent S/N

Name / description	Age	Distance (ly)	Time suppression wrt steady sources (10s emission)	Distance enhancing factor wrt SN1987A	Total suppression coefficient wrt steady sources
SN1987A	34 yr	168,000	9.3×10^{-9}	1	9.3×10^{-9}
Vela jr	800 yr	700	4.0×10^{-10}	5.8×10^{4}	2.3×10^{-5}
Geminga	342 kyr	815	9.3×10^{-13}	4.3×10^{4}	4.0×10^{-8}
Vela	11 kyr	815	2.8×10^{-11}	4.3×10^{4}	1.2×10^{-6}
Crab (SN1054)	967 yr	6300	3.3×10^{-10}	7.1×10^{2}	2.3×10^{-7}
SN1572	449 yr	7500	7.1×10^{-10}	5.0×10^{2}	3.5×10^{-7}
SN 1006	1015 yr	7200	3.1×10^{-10}	5.4×10^{2}	1.7×10^{-7}
Possible very close SN from ^{60}Fe deposits [11]	2.8 Myr	130.4	1.1×10^{-13}	1.7×10^{6}	1.9×10^{-7}
20 explosions in 40-130 pc in the last 11 Myr [27]	11 Myr	327	2.9×10^{-14}	2.6×10^{5}	1.5×10^{-7}
8 SN at around 130 pc in the last 2.8 Myr [27]	2.8 Myr	425.1	1.1×10^{-13}	1.6×10^{5}	3.5×10^{-7}

Paleo-detectors for supernova neutrinos



PRELIMINARY

BSc Lorenzo Apollonio, unpublished

Desperate need to scan large volumes!