Digging for astroparticles:
natural minerals as paleo-detectors to study the history of the Galaxy

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Multi-messenger astrophysics

The last 2-3 decades have made it clear how helpful can **astroparticles** be for astronomy

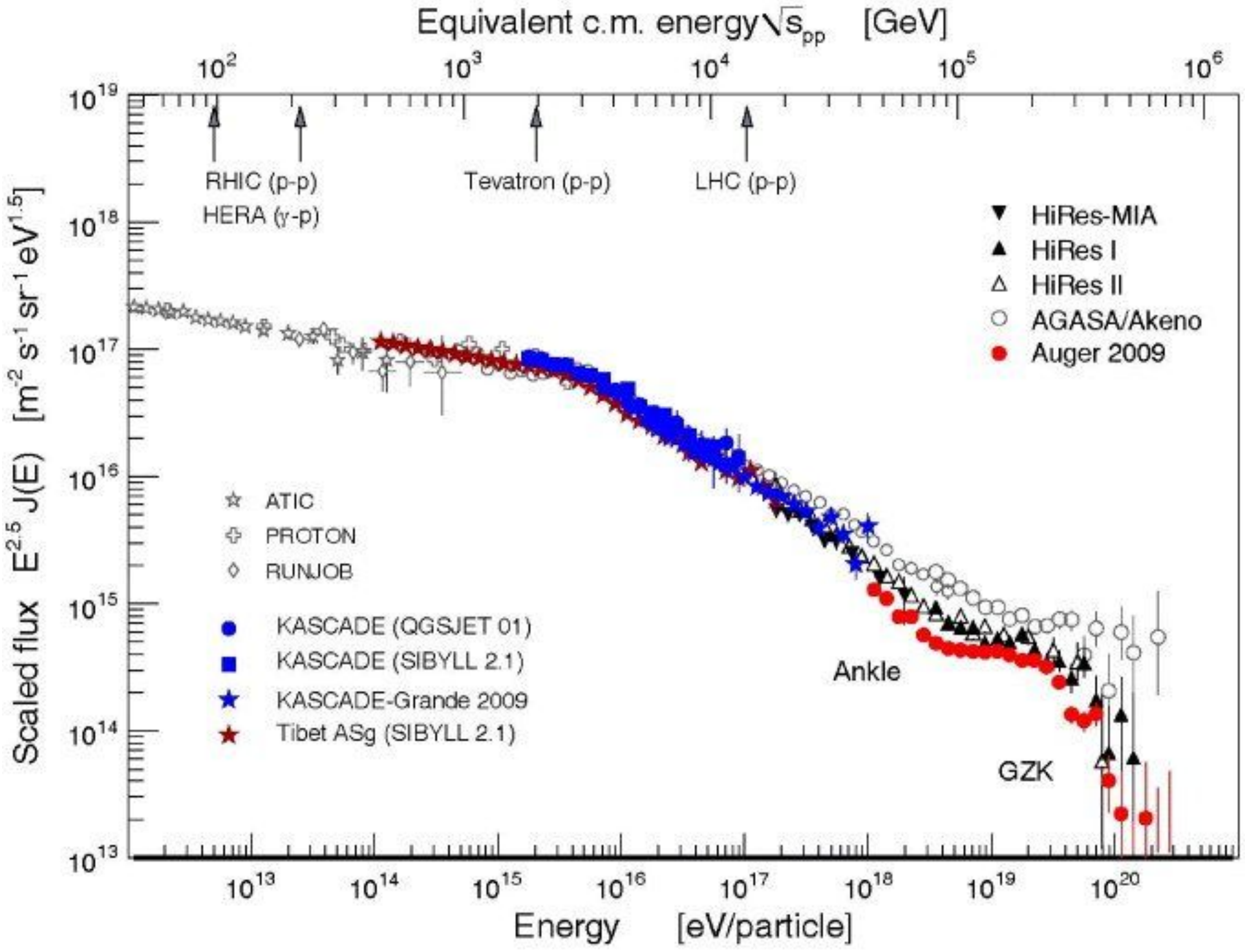
- Particles have the advantage of probing specific processes or, as neutrinos, interact less with matter and thus bring information from the interior of their sources.
- This comes at a cost: observing astroparticles is more difficult than observing light for a number of reasons.

- **Solar neutrinos** gave us unique insights on the fusion reactions in the Sun
- Neutrinos from **SN 1987a** helped us understanding supernovae
- The existence of **HE neutrinos** proved non-thermal emission extragalactic sources and now we have a signal from M77
- the distribution of arrival direction of **Ultra-high energy cosmic rays (E>8 EeV)** proved that they're not (currently) accelerated in our Galaxy

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?), AGN or starburst galaxies

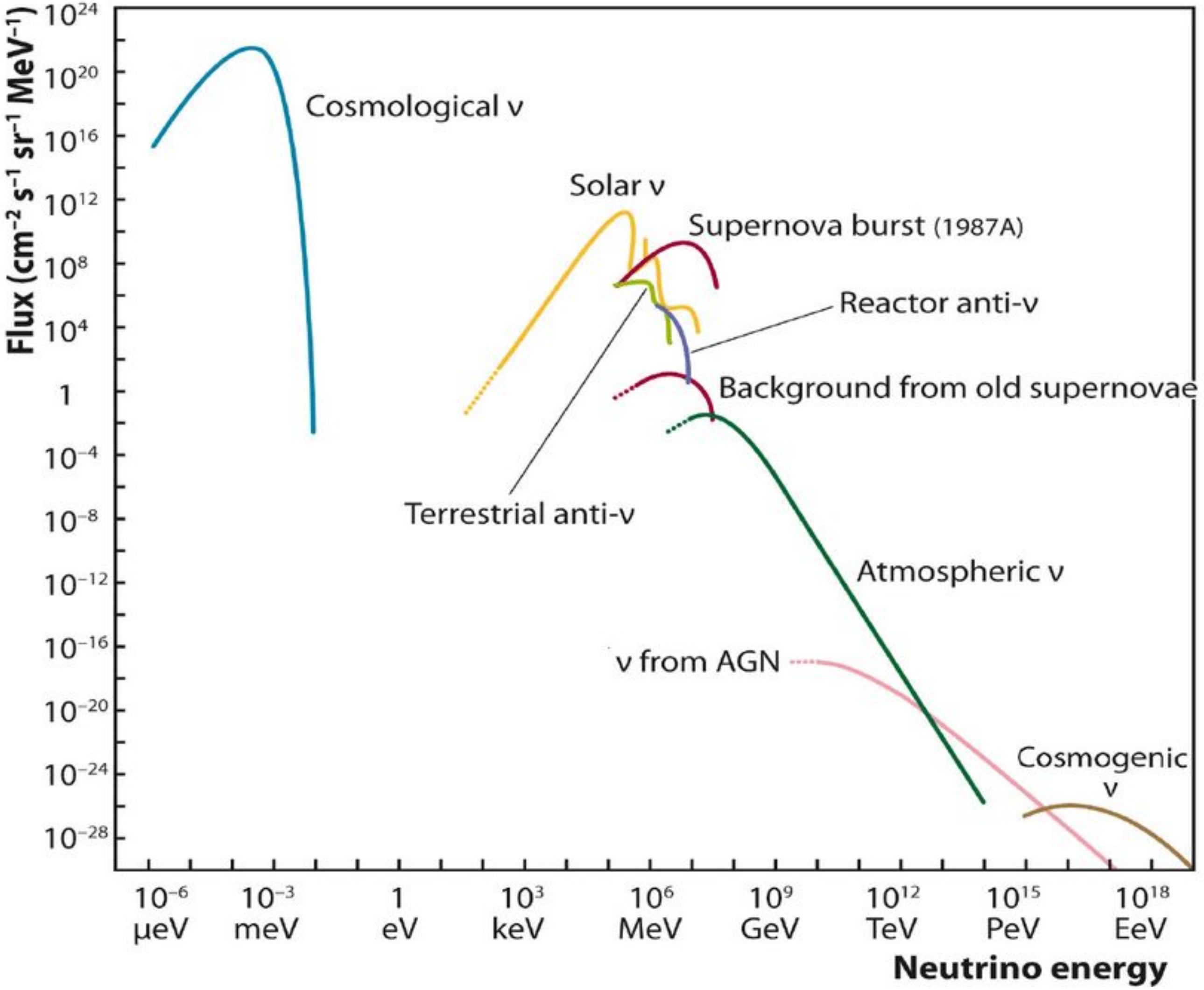


Neutrinos

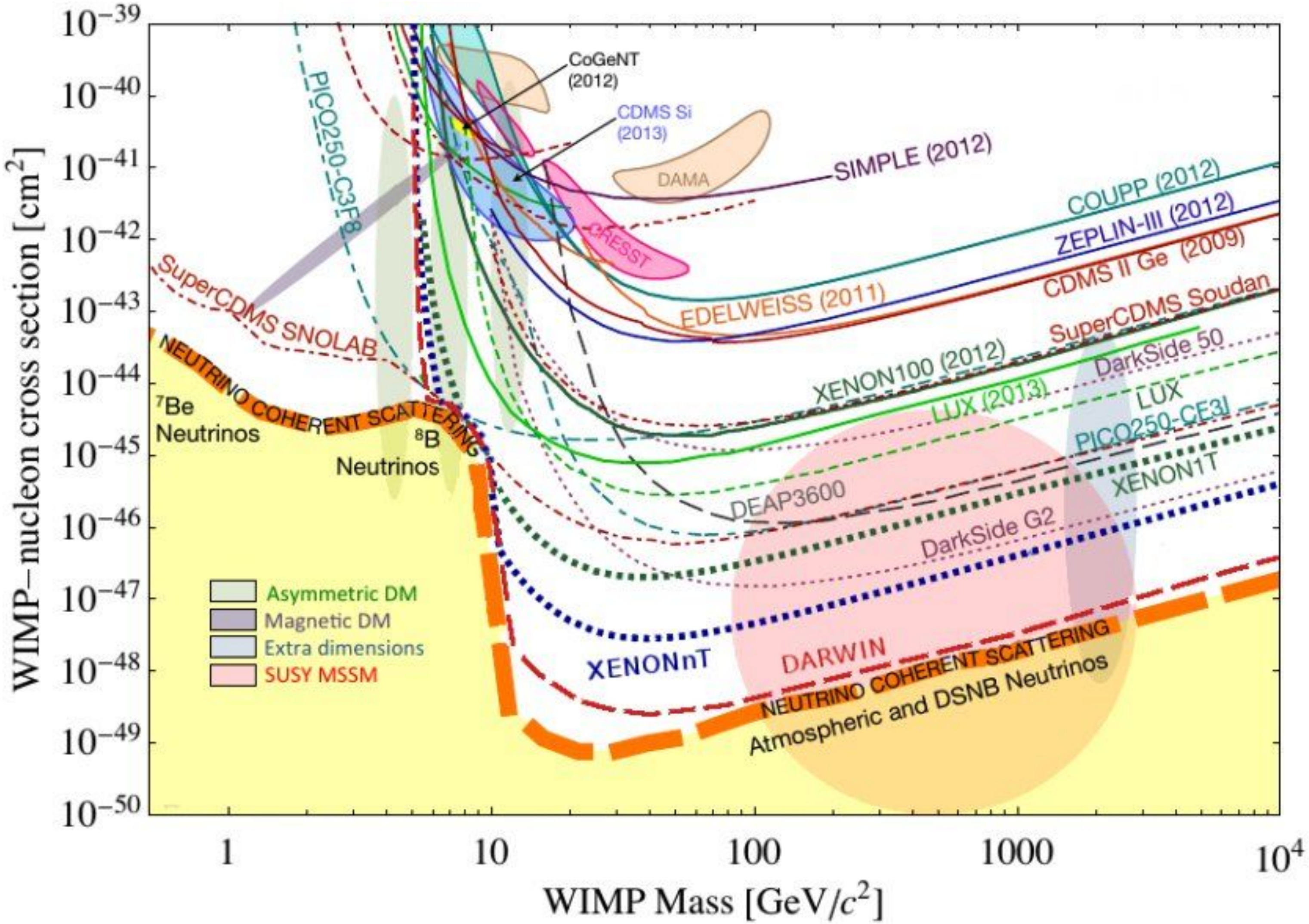
Poorly interacting particles with near-zero masses

Difficult to reveal: their interaction is very unlikely

- need for large volumes
- at low energy main background is radioactivity
- Atmospheric neutrino background is practically ineliminable
- at the highest energies almost background-free but huge volumes (>km^3) needed



Dark matter


WIMP–nucleon cross section [cm^2]
WIMP Mass [GeV/c^2]
10^{-39}
10^{-40}
10^{-41}
10^{-42}
10^{-43}
10^{-44}
10^{-45}
10^{-46}
10^{-47}
10^{-48}
10^{-49}
10^{-50}
1
10
100
1000
10^4
CoGeNT (2012)
CDMS Si (2013)
DAMA
SIMPLE (2012)
CRESST
PICO250-C3F8
COUPP (2012)
ZEPLIN-III (2012)
CDMS II Ge (2009)
EDELWEISS (2011)
SuperCDMS Soudan
SuperCDMS SNOLAB
DarkSide 50
XENON100 (2012)
LUX (2013)
LUX
PICO250-CF3I
DEAP3600
XENON1T
DarkSide G2
XENONnT
DARWIN
^{7}Be Neutrinos
^{8}B Neutrinos
NEUTRINO COHERENT SCATTERING
NEUTRINO COHERENT SCATTERING
Atmospheric and DSNB Neutrinos
Asymmetric DM
Magnetic DM
Extra dimensions
SUSY MSSM

Why digging?

Natural minerals can be (under certain conditions) particle detectors (see next talk by Claudio for details).

Why should we use them 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

Small detectors with a (very) long history

Minerals can be extracted from the Earth's crust with ages up to the order of Gyr

Xenon 1T
~1000 kg
~10 years data taking
Under ~ 1500 m of rock

-> Exposure= 10^4 kg yr

Morenosite crystals
~100 g
~1 Gyr
Under >2000 m of rock

-> Exposure= 10^7 kg yr

The first proposals

Mica was one of the first targets (comes naturally in thin foils).

-> limits for DM comparable to those available at the time

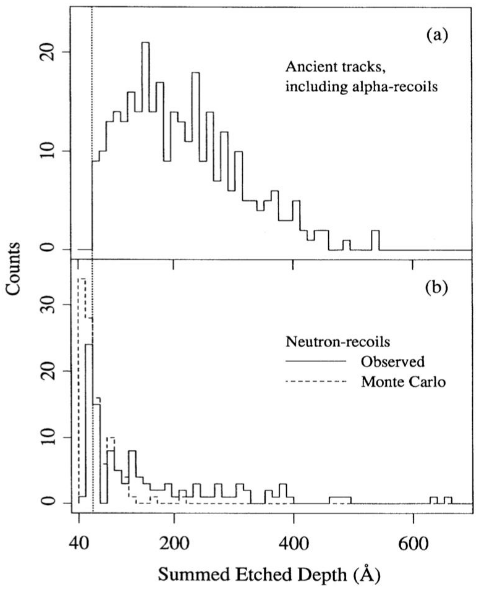
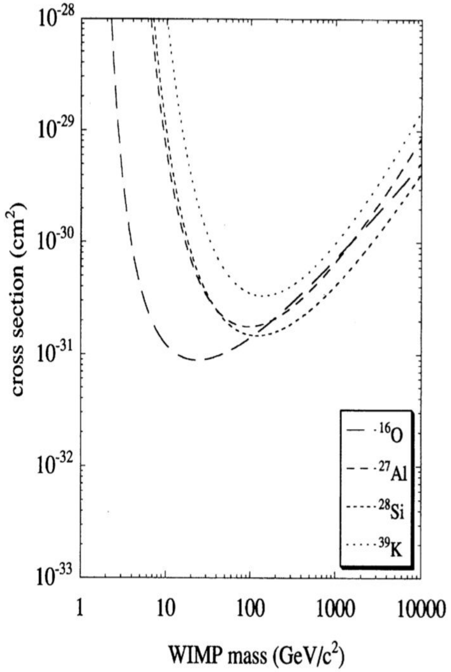
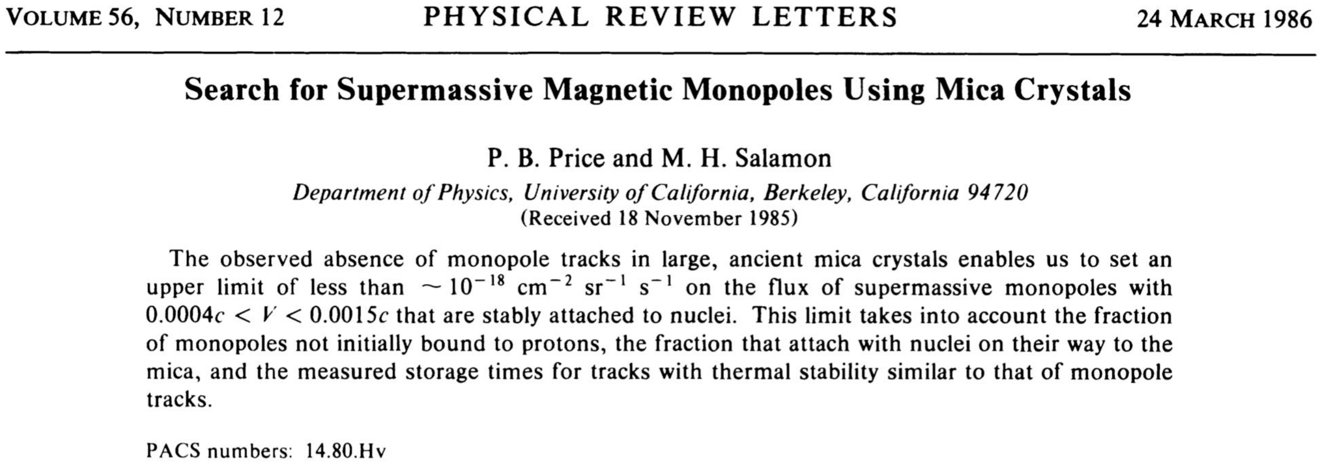


FIG. 3. (a) The summed etched depths of tracks recorded in a 80 720 μm^2 scan of 0.5 Gyr old muscovite mica. No events appear between our cutoff of 40 and 64 Å (shown with a dashed vertical line). (b) The solid line shows the summed depths of etched neutron-recoil tracks. The dashed line shows the results of a MC program of these data. In both the real and MC data a large fraction of the events appear in the 40–64 Å gap.





VOLUME 56, NUMBER 12 PHYSICAL REVIEW LETTERS 24 MARCH 1986

Search for Supermassive Magnetic Monopoles Using Mica Crystals

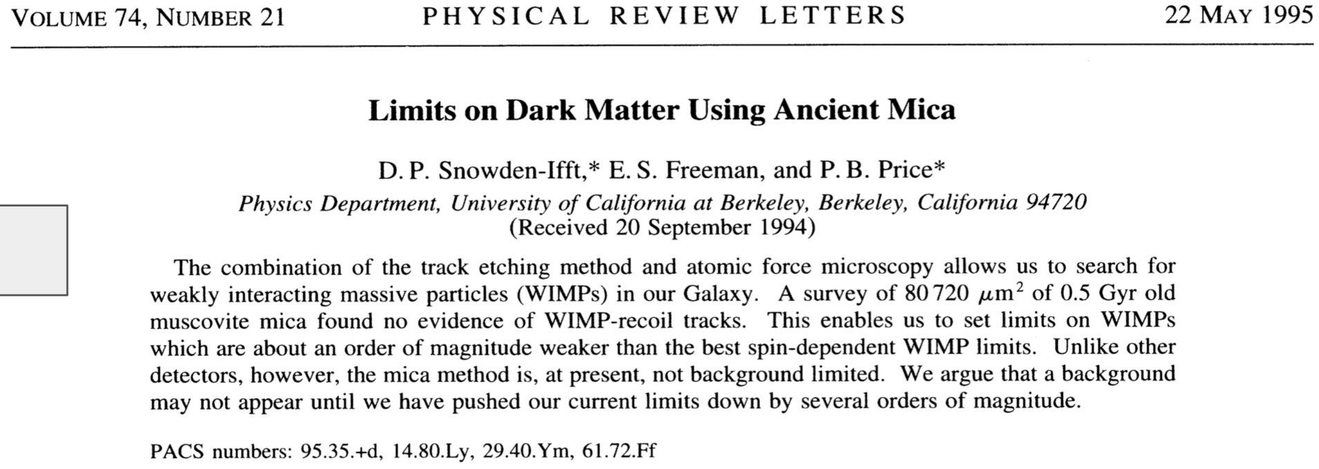
P. B. Price and M. H. Salamon

Department of Physics, University of California, Berkeley, California 94720

(Received 18 November 1985)

The observed absence of monopole tracks in large, ancient mica crystals enables us to set an upper limit of less than $\sim 10^{-18}$ cm^{-2} sr^{-1} s^{-1} on the flux of supermassive monopoles with $0.0004c < V < 0.0015c$ that are stably attached to nuclei. This limit takes into account the fraction of monopoles not initially bound to protons, the fraction that attach with nuclei on their way to the mica, and the measured storage times for tracks with thermal stability similar to that of monopole tracks.

PACS numbers: 14.80.Hv



VOLUME 74, NUMBER 21 PHYSICAL REVIEW LETTERS 22 MAY 1995

Limits on Dark Matter Using Ancient Mica

D. P. Snowden-Ifft,* E. S. Freeman, and P. B. Price*

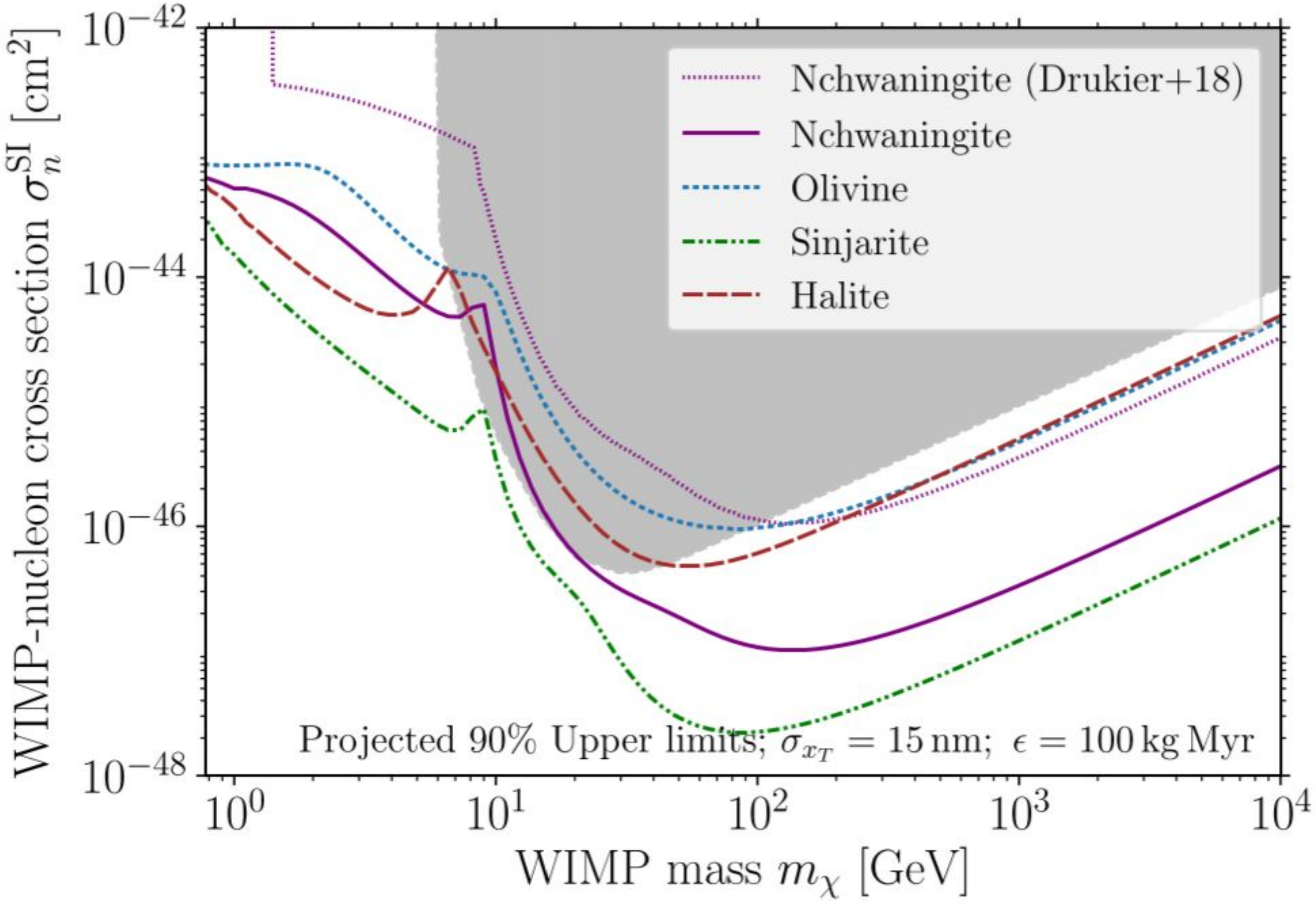
Physics Department, University of California at Berkeley, Berkeley, California 94720

(Received 20 September 1994)

The combination of the track etching method and atomic force microscopy allows us to search for weakly interacting massive particles (WIMPs) in our Galaxy. A survey of 80 720 μm^2 of 0.5 Gyr old muscovite mica found no evidence of WIMP-recoil tracks. This enables us to set limits on WIMPs which are about an order of magnitude weaker than the best spin-dependent WIMP limits. Unlike other detectors, however, the mica method is, at present, not background limited. We argue that a background may not appear until we have pushed our current limits down by several orders of magnitude.

PACS numbers: 95.35.+d, 14.80.Ly, 29.40.Ym, 61.72.Ff

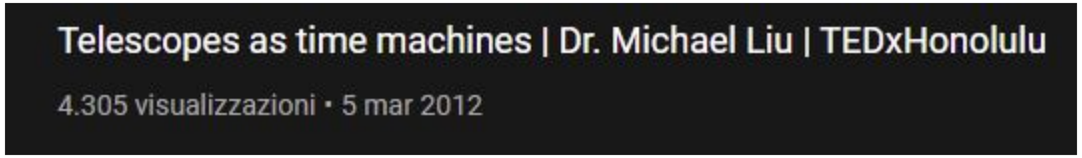
2018 revival: paleo-detectors for dark matter detection



Projected paleo-detector 90% Upper Limits on WIMP-like DM. Assumes σ = 15 nm; = 100 kg Myr (high exposure case)

T. D. P. Edwards, B. J. Kavanagh, C. Weniger, S. Baum, A. K. Drukier, K. Freese, M. Gorski and P. Stengel, "Digging for dark matter: Spectral analysis and discovery potential of paleo-detectors," *Phys. Rev. D,* vol. 99, no. 4, p. 043541, 2019 arXiv:1811.10549

How do we investigate the past of the universe?


Telescopes as time machines | Dr. Michael Liu | TEDxHonolulu

4.305 visualizzazioni • 5 mar 2012


Night Sky Network

Astronomy Clubs bringing the wonders of the universe to the public

Telescopes as Tim

How long has the light from differen
been traveling to reach

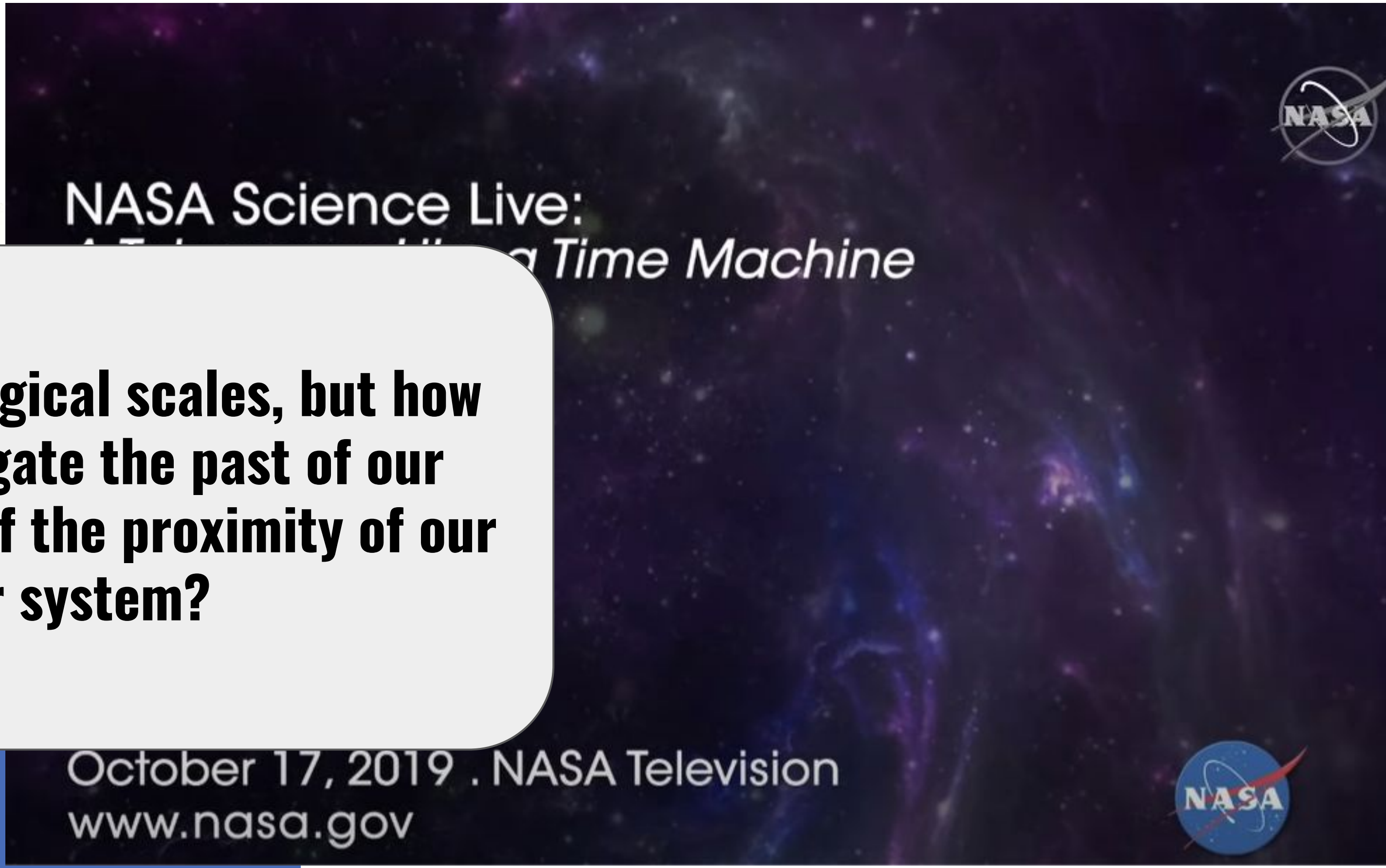

Smithsonian MAGAZINE

SCIENCE

If Telescopes Are Time Machin
Us the Furthest Back Yet


WHY DO WE NEED TELESCOPES?

TELESCOPES AS TIME MACHINES


NASA Science Live:
A T… …a Time Machine

October 17, 2019 . NASA Television
www.nasa.gov

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

Traces of recent and close supernovae events

- ^{60}Fe deposit on oceanic crust
- Identified as trace of very close (100-200 pc) supernove 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.

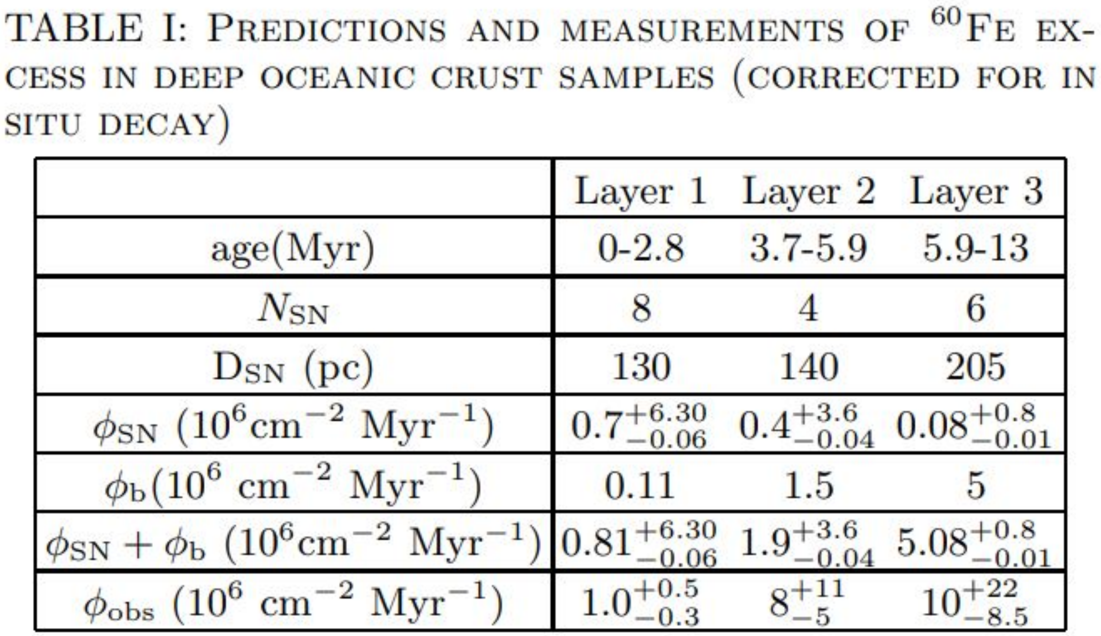
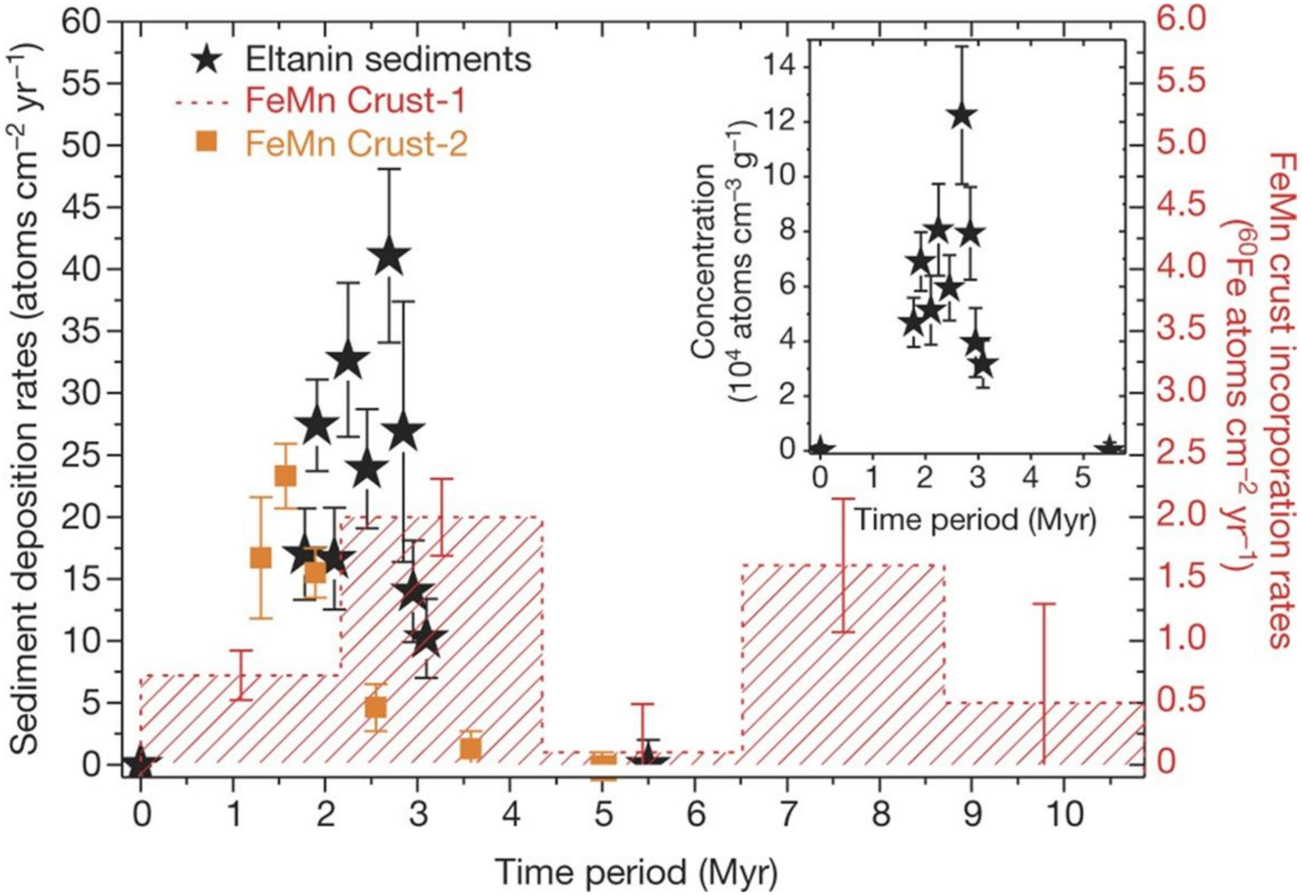


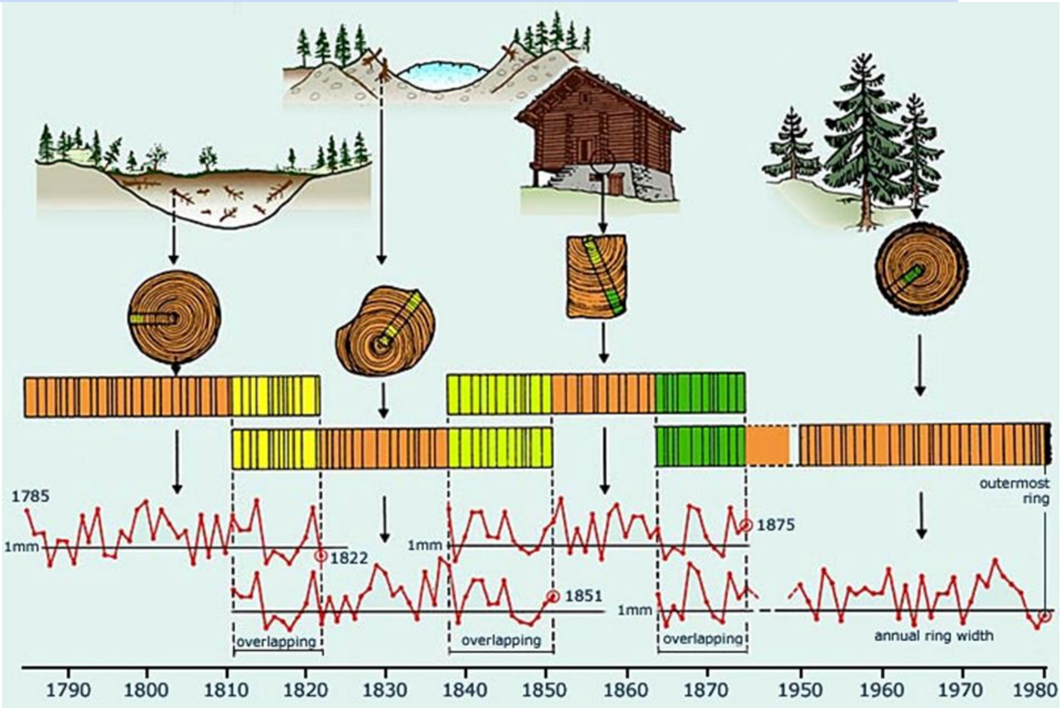
TABLE I: PREDICTIONS AND MEASUREMENTS OF ^{60}FE EXCESS IN DEEP OCEANIC CRUST SAMPLES (CORRECTED FOR IN SITU DECAY)

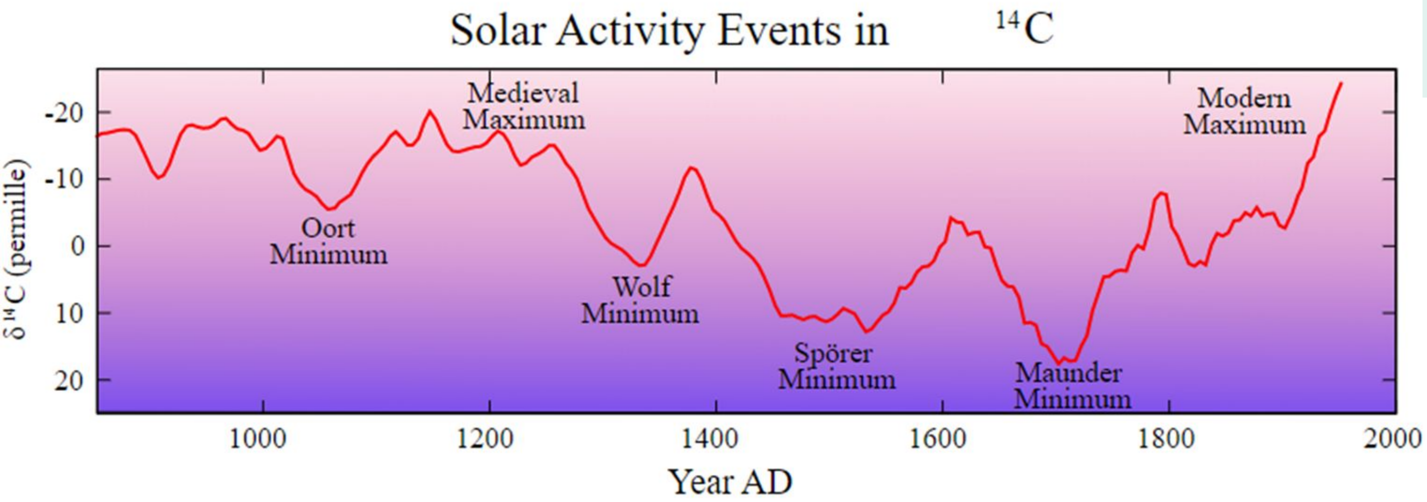
	Layer 1	Layer 2	Layer 3
age(Myr)	0-2.8	3.7-5.9	5.9-13
N_{SN}	8	4	6
D_{SN} (pc)	130	140	205
ϕ_{SN} (10^6cm^{-2} Myr^{-1})	$0.7^{+6.30}_{-0.06}$	$0.4^{+3.6}_{-0.04}$	$0.08^{+0.8}_{-0.01}$
ϕ_b(10^6 cm^{-2} Myr^{-1})	0.11	1.5	5
$\phi_{SN} + \phi_b$ (10^6cm^{-2} Myr^{-1})	$0.81^{+6.30}_{-0.06}$	$1.9^{+3.6}_{-0.04}$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



^{14}C evolution in atmosphere

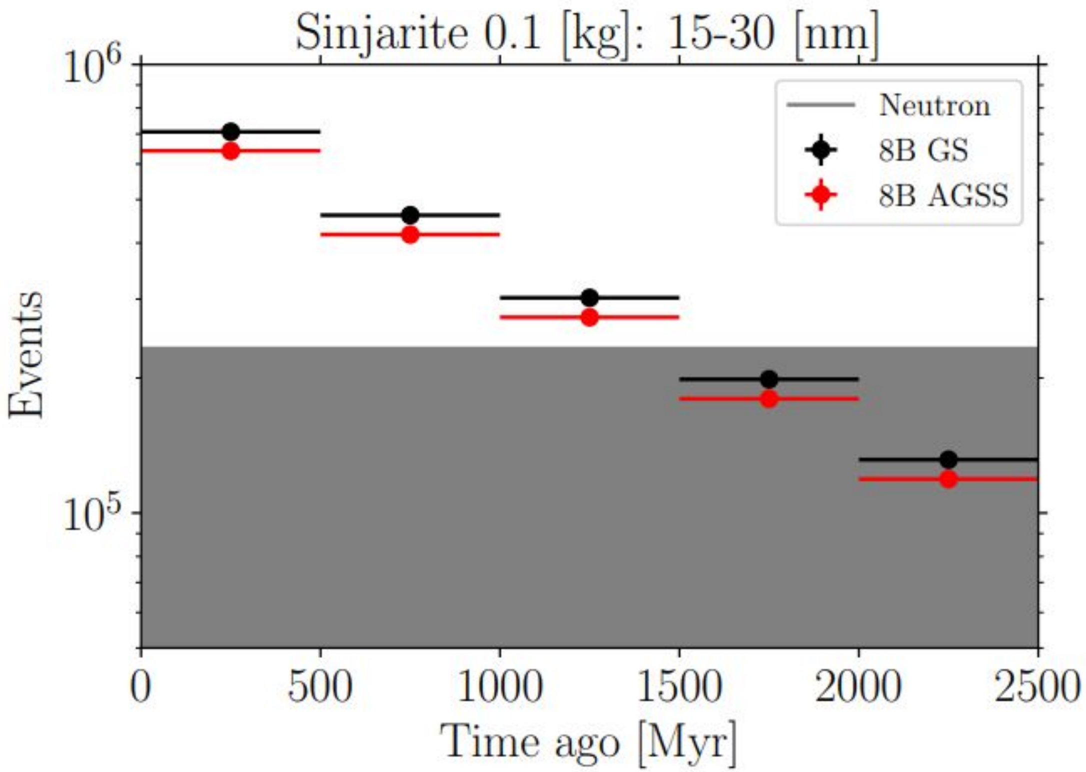
- ^{14}C is produced by cosmic rays in atmosphere
- production is dominated by low energy cosmic rays that are strongly affected by solar activity
- the rate of ^{14}C is of huge interest for calibrating the dating technique
- one of the most powerful method to track ^{14}C abundance is to use dendrochronology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

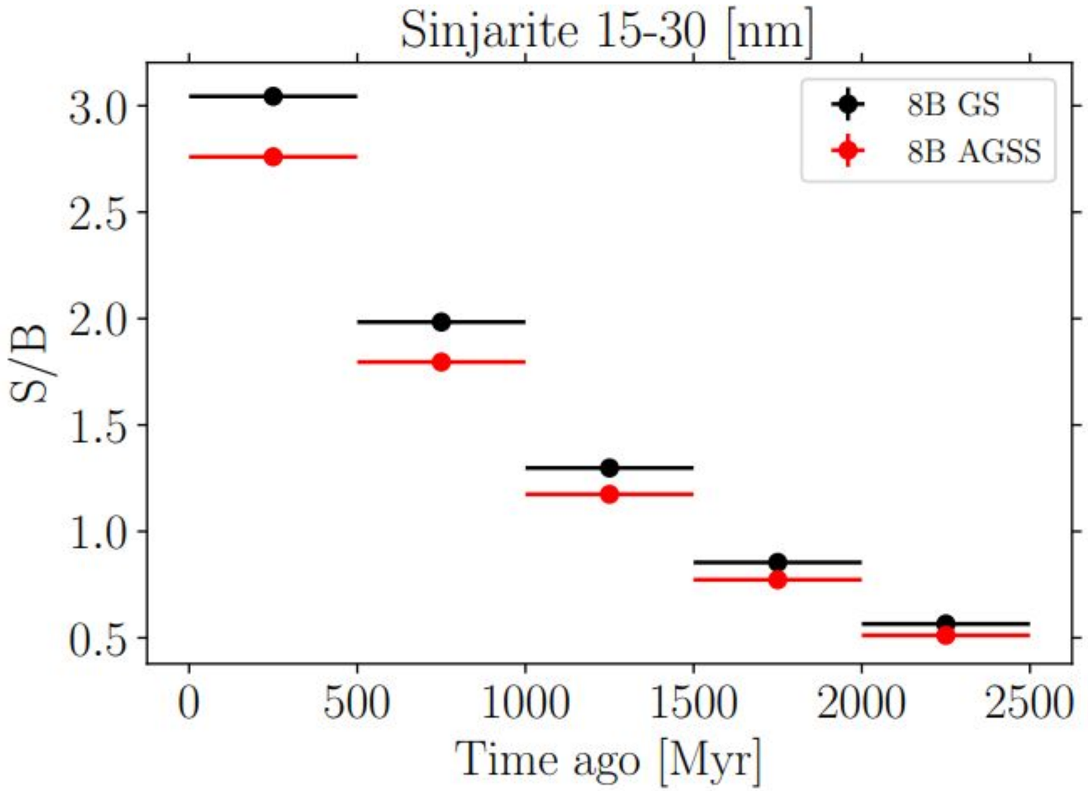




Paleo-detectors for solar neutrinos

- Paleo-detectors have been suggested also to study the flux of solar neutrinos to understand the sun metallicity
- Focus on ^{8}B neutrinos which are the most sensible to metallicity
- Collect samples at different ages might give you an idea of how the metallicity of the sun evolved

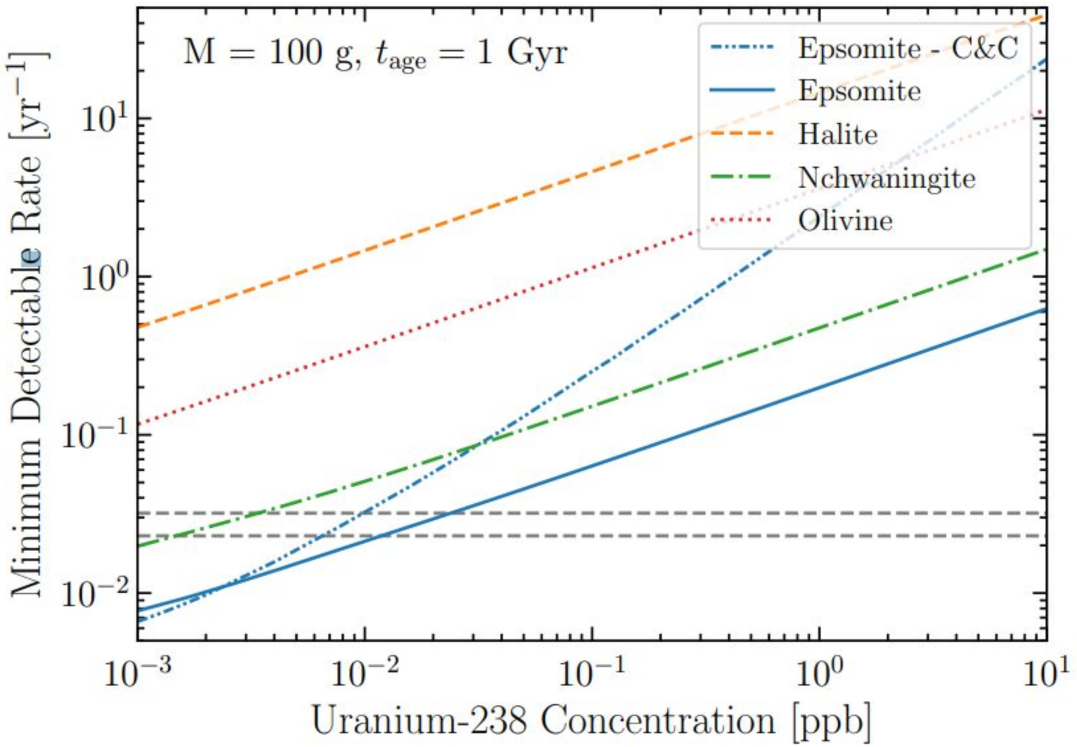


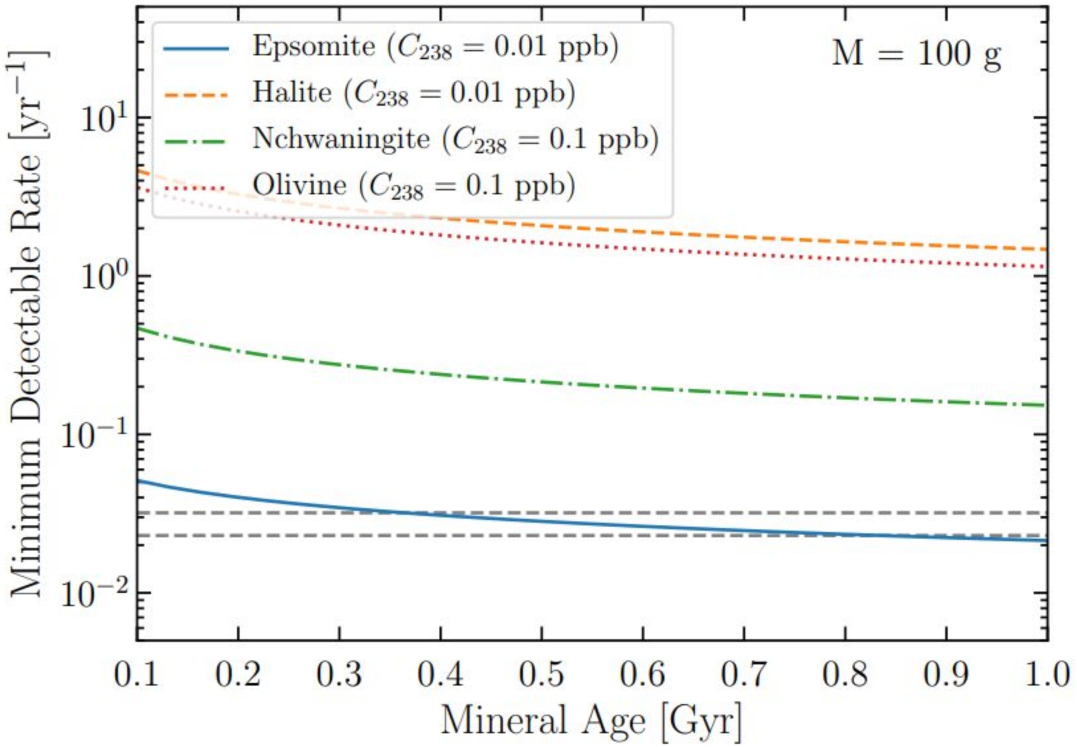


N. Tapia-Arellano and S. Horiuchi, "Measuring solar neutrinos over gigayear timescales with paleo detectors," *Physical Review D*, p. 123016, 2021

Paleo-detectors for supernova neutrinos

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

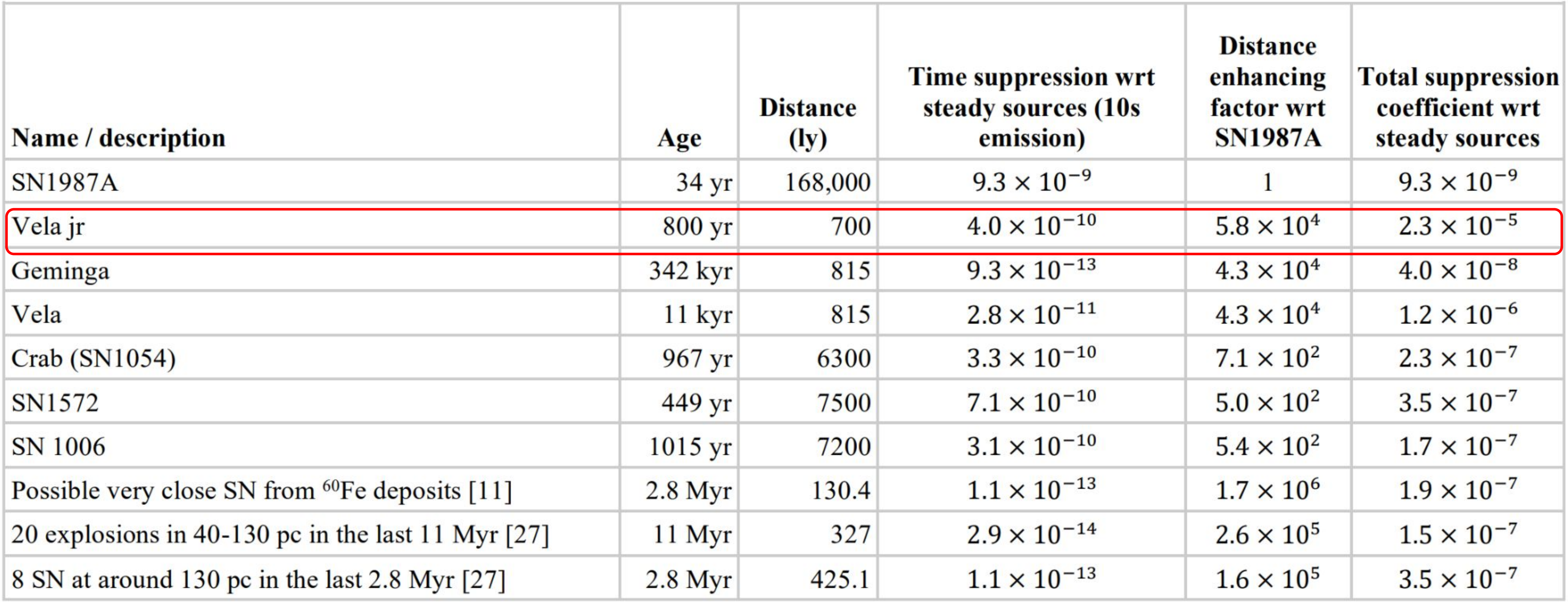




S. Baum, T. D. P. Edwards, B. J. Kavanagh, P. Stengel, A. K. Drukier, K. Freese, M. Gorski and C. Weniger, «Paleodetectors for Galactic supernova neutrinos,» *Phys. Rev. D*, vol. 101, n. 10, p. 19, 2020

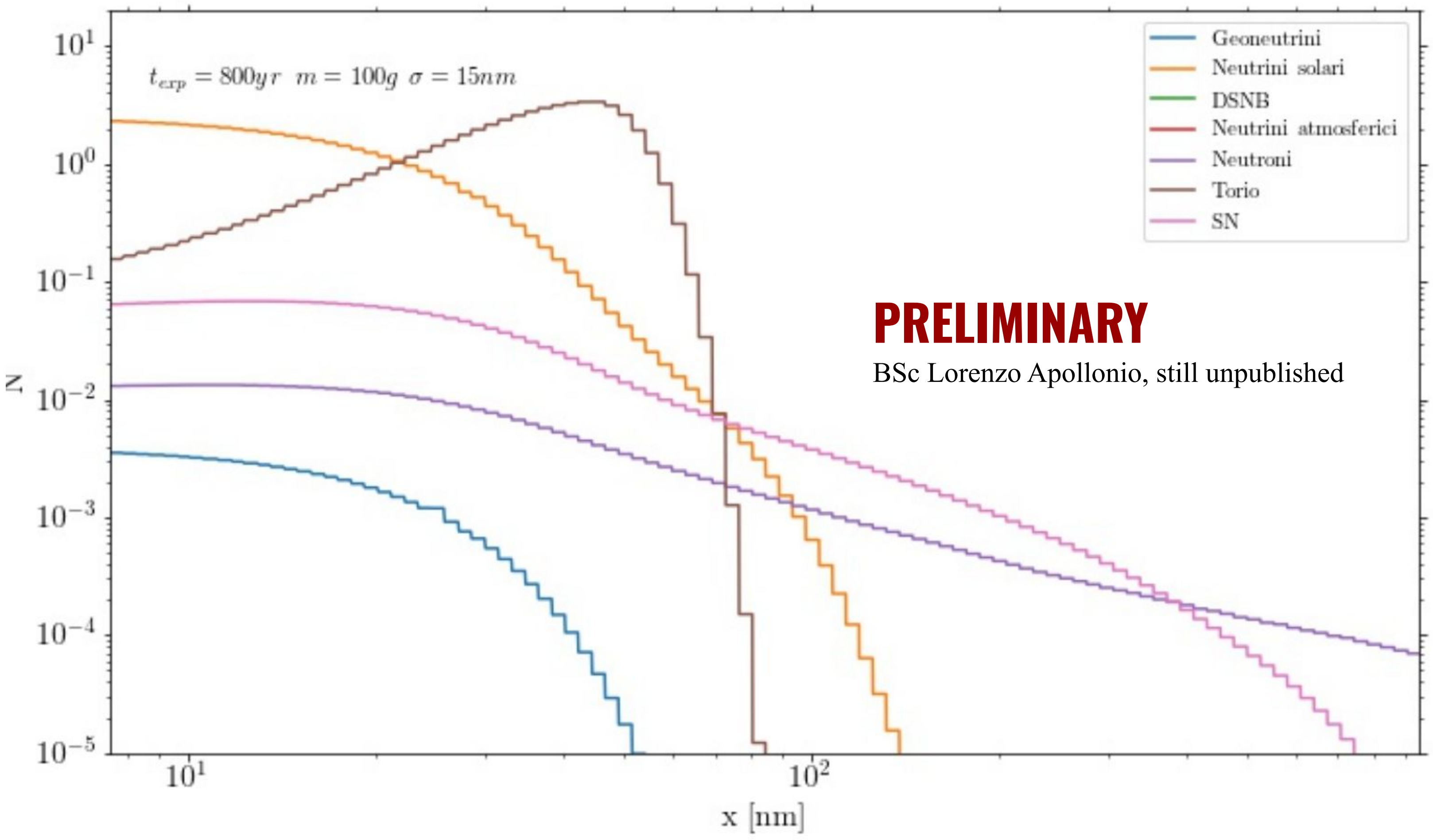
Paleo-detectors for supernova neutrinos

- 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

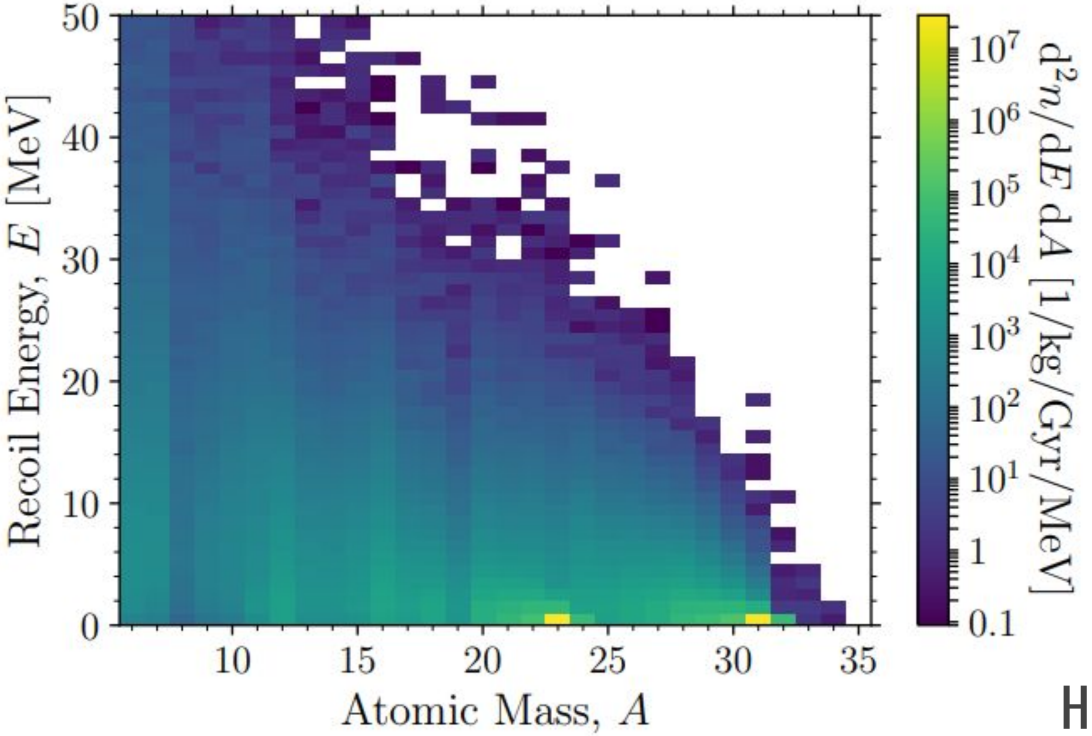
BSc Lorenzo Apollonio, still unpublished

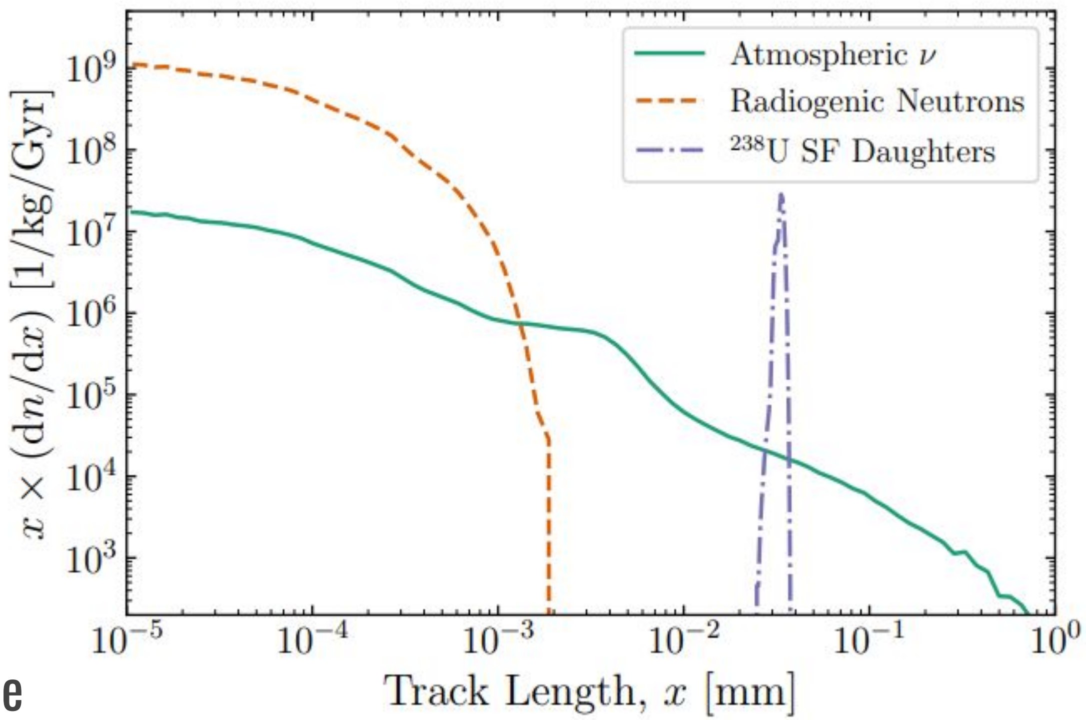
→ Desperate need to scan large volumes!

Paleo-detectors for cosmic rays

- When considering cosmic rays, the energy range raise: interactions become inelastic and we need to use more advanced softwares like FLUKA, GEANT, CORSIKA
- 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



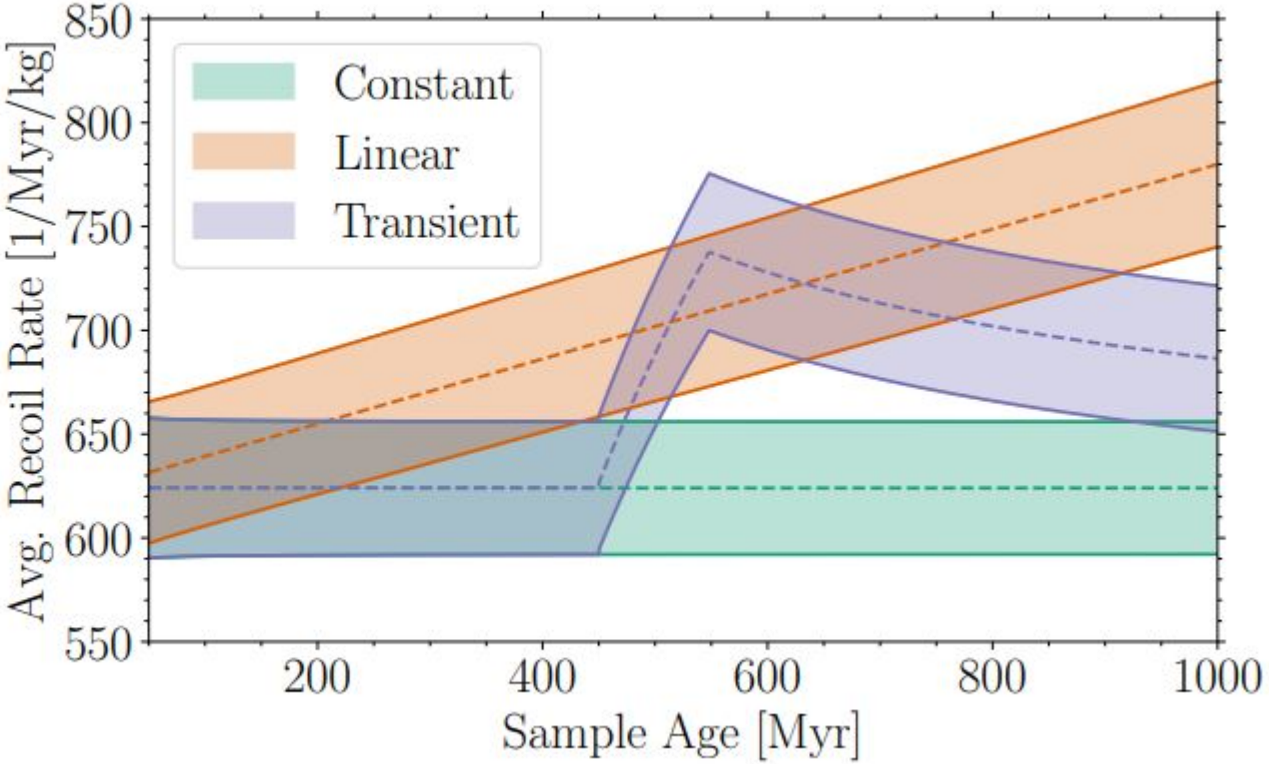


Halite

Paleo-detectors for cosmic rays

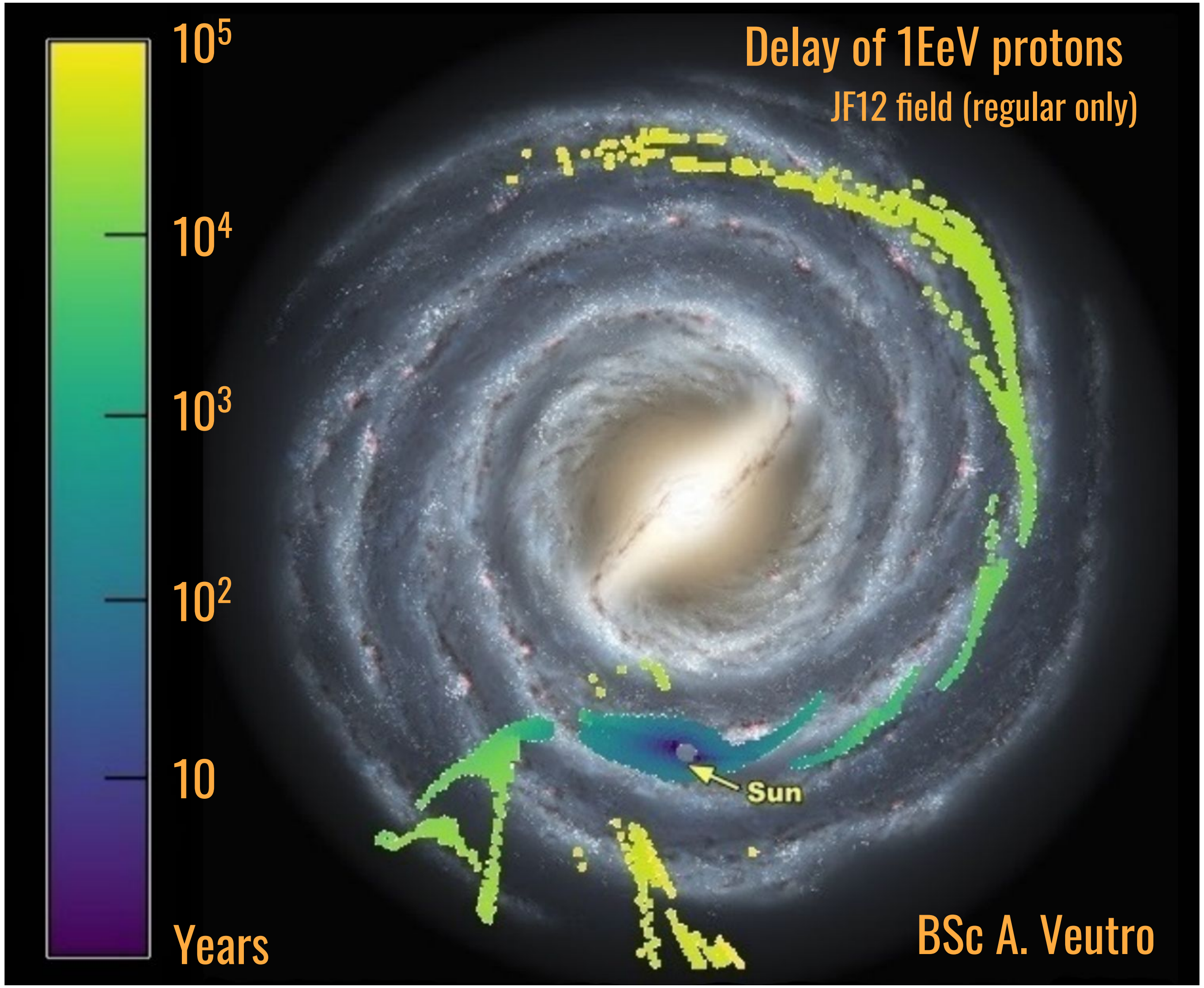
- Atmospheric neutrinos might be able to trace an evolution of the flux of cosmic rays and search for long transients (100 Myr)
- For shorter transients a different approach might be better (see after)
- The ability of measuring **CR transients** depends on where the transients are located: cosmic rays 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



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 (10-100 PV?) likely a transition from ballistic to diffuse propagation occur



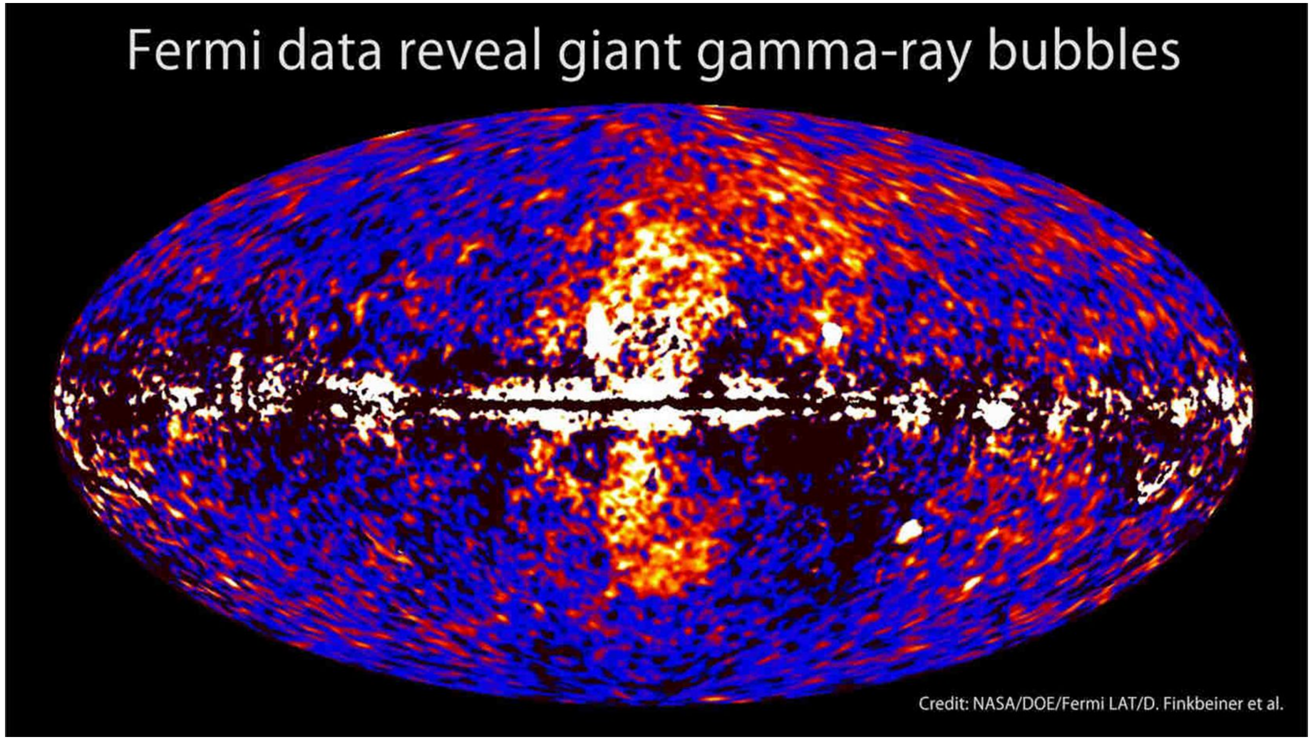
Messinian salinity crisis

- A part from atmospheric neutrinos, also the other components of EAS can produce nuclear recoils -> the problem is to know the **exposure** time of the mineral to the air, even a **small overburden** might change the flux dramatically.
- Evaporites (such as Halite) produced in that event were exposed for a known period (~500 kyr) and then very briefly (possibly just **few years**) covered by a ~km of water

MSC RECREATION BY AARON MICALLEF, DANIEL GARCIA-CASTELLANOS, ANGELO CAMERLENGHI / UNIVERSITY OF MALTA / MEDSALT

A possible case study: 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 ->** nicely fits the period where the Mediterranean was **mostly evaporated (5.9 Myr)**

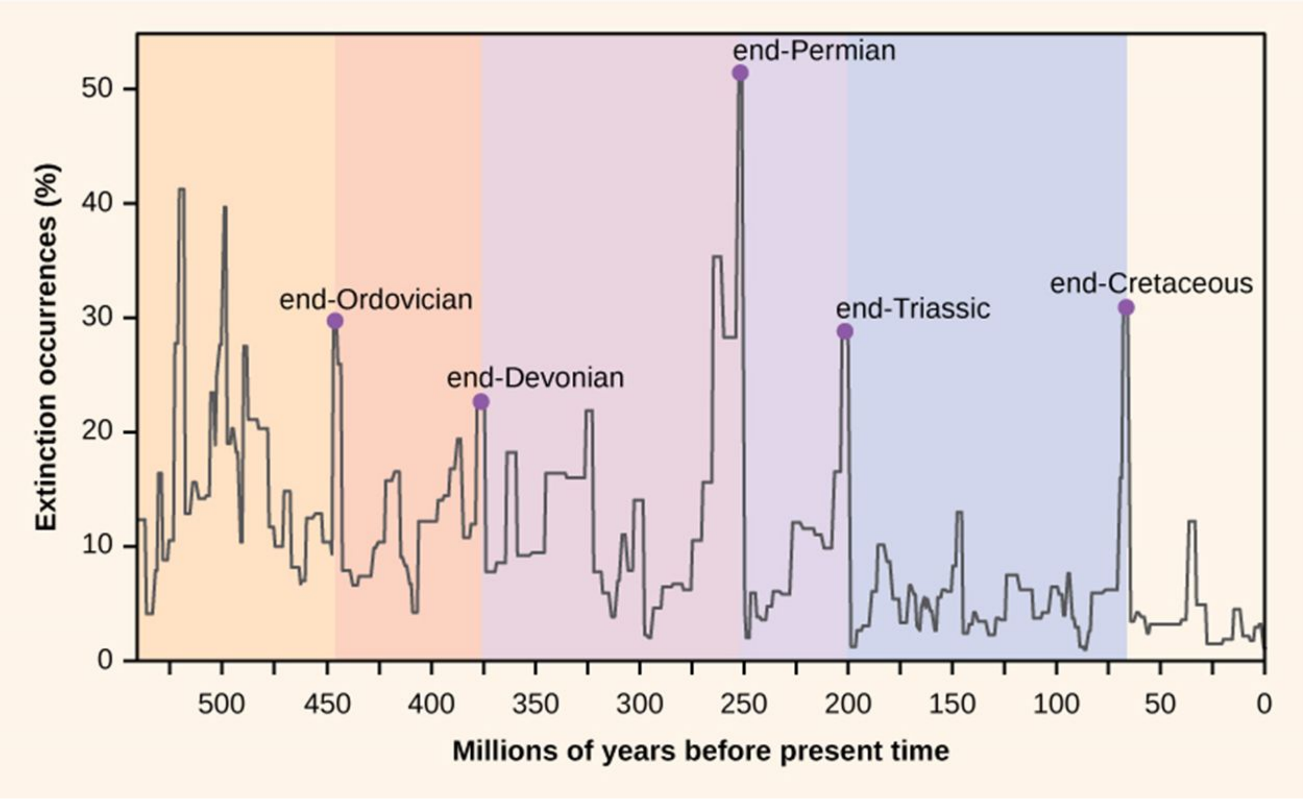


Credit: NASA/DOE/Fermi LAT/D. Finkbeiner et al.

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.

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**



Conclusions

At this point, we have plenty of interesting theoretical results, but it's time to try and move forward:

- Each work so far focused on a **single generic scenario**, i.e. practically all are *backgrounds* for the others

  -> we need to develop a **comprehensive simulation framework** to model all emissions from different candidate sources and understand which are the best characteristics that we require for the samples

- There are numbers of astrophysical objects of which we can estimate **age**, **position** and **distance**, can we make assumptions on their astroparticle emission and build a **model of the expected fluxes at a given time in the past**?

It's still **unclear** if we can indeed obtain the right balance of all the necessary conditions to actually see the traces and make it really useful for astrophysics -> **see Claudio's talk**

If we can, however, this would be one of the few ways of studying directly the evolution of our Galaxy and of the proximity of the Solar System, so I think it's worth trying!

Backup Slides

Xenoliths

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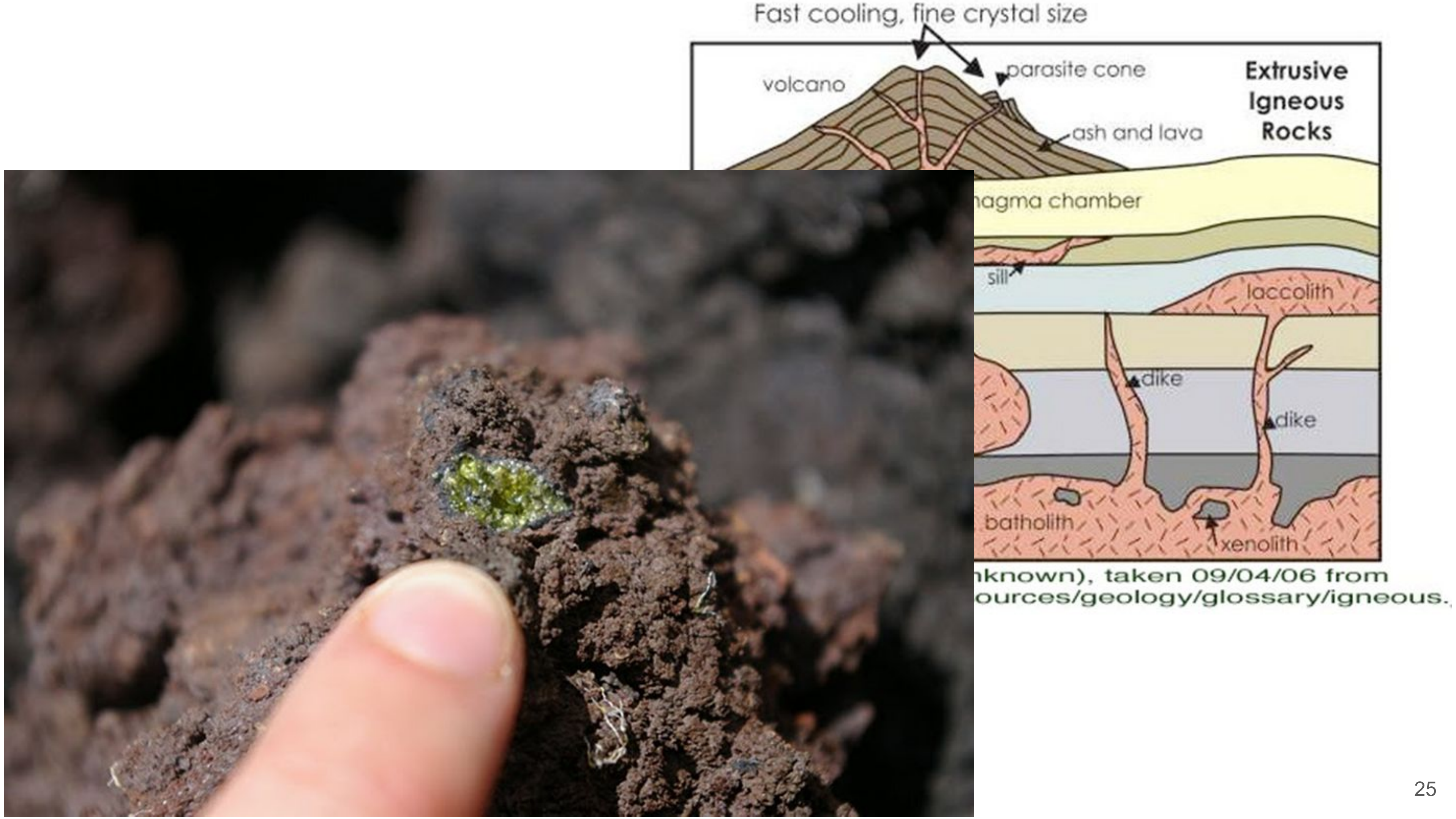
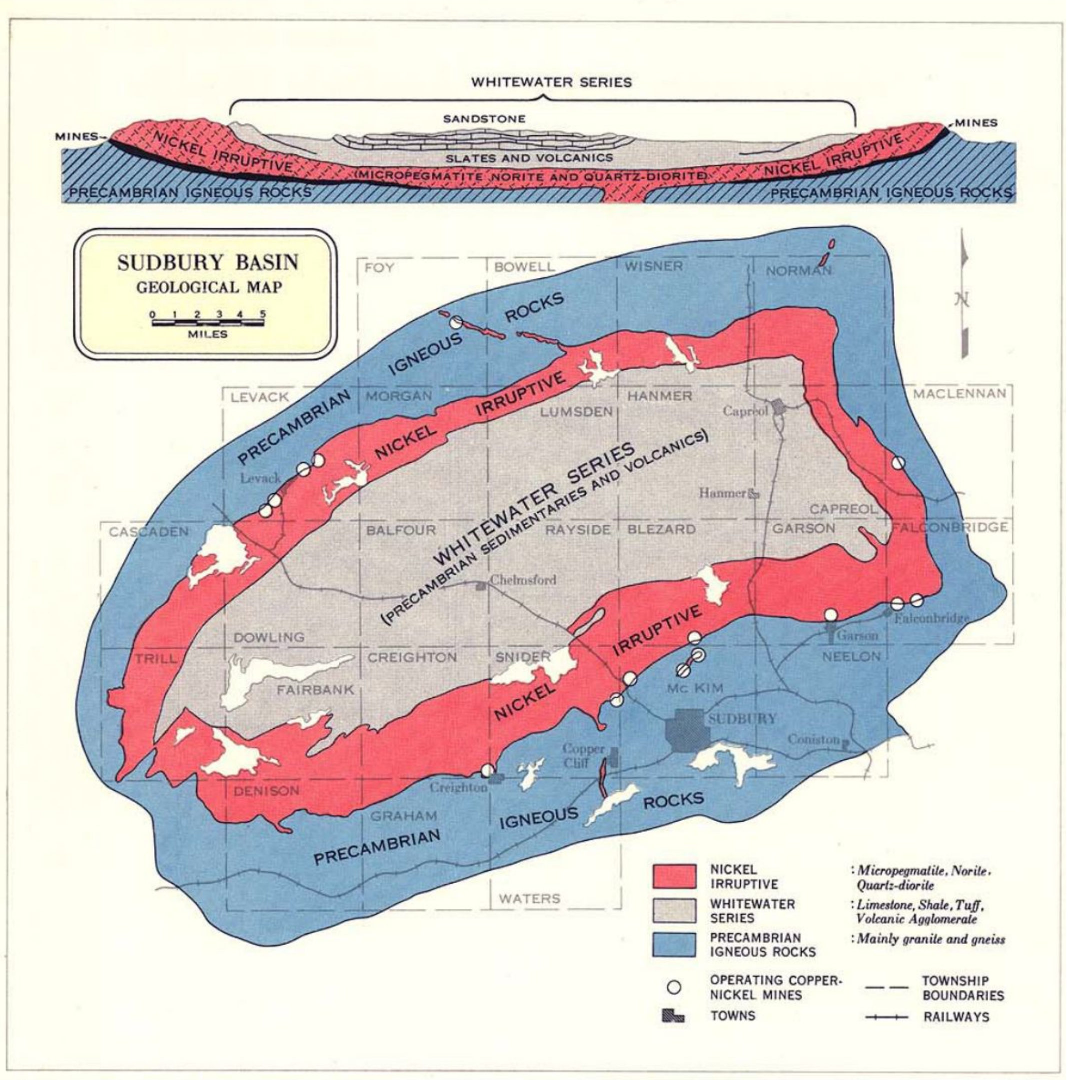


nknown), taken 09/04/06 from
ources/geology/glossary/igneous.

Sudbury



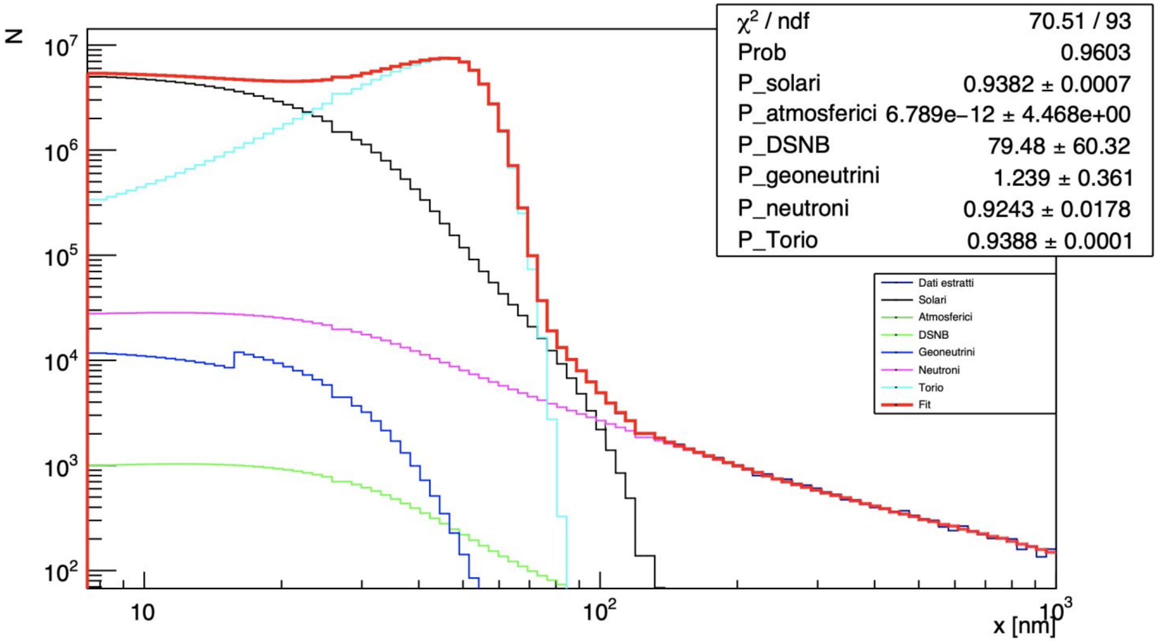
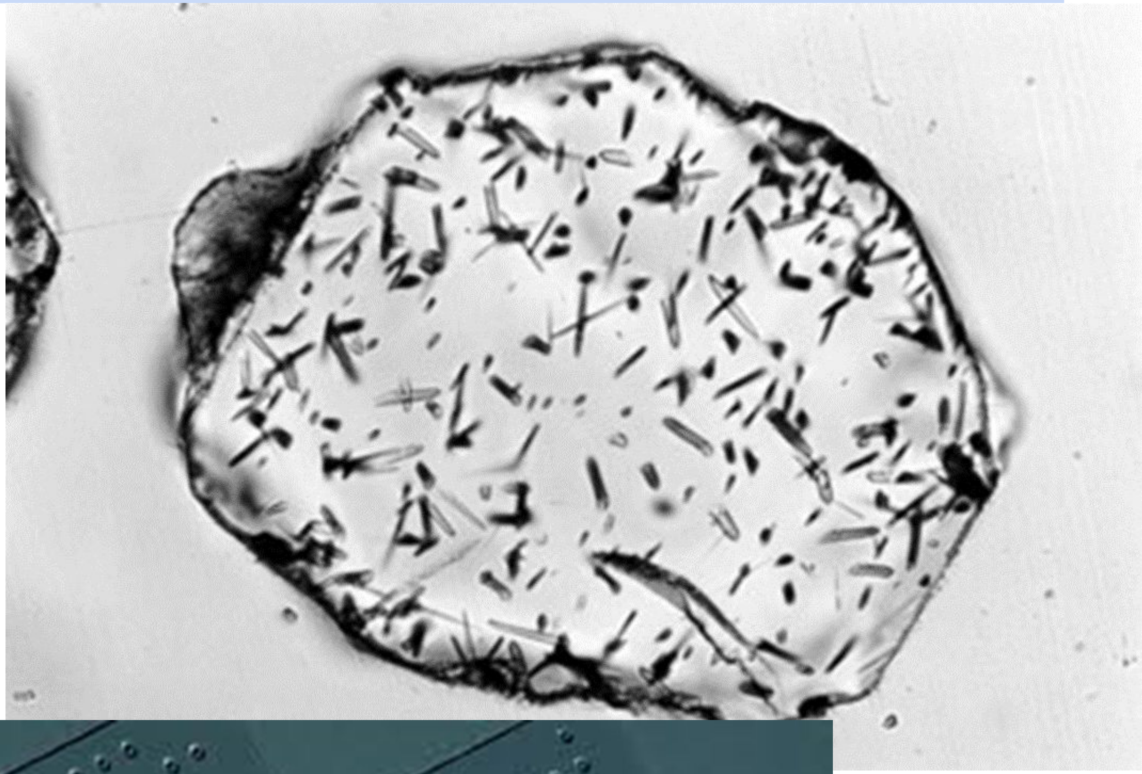
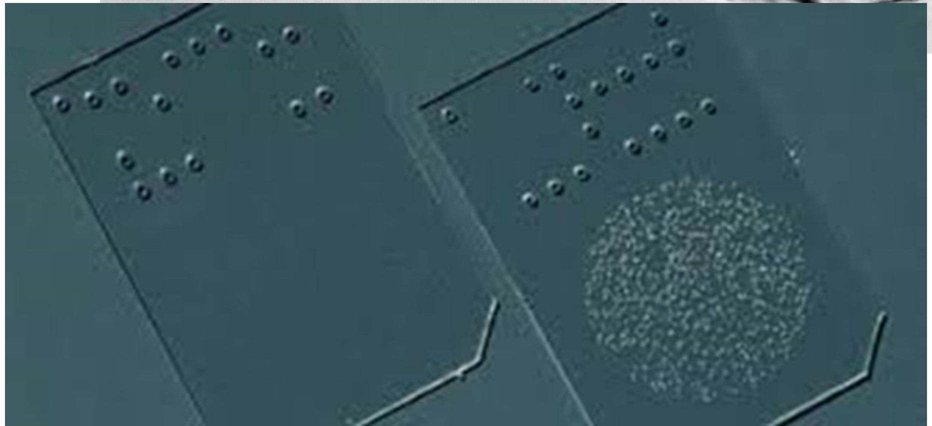


Figura 5.8: Fit della simulazione di tracce in un campione di Morenosite nel caso ad alta esposizione

Tracks from nuclear recoils

- So-called “solid state nuclear track dectors”
- The length of the track depends on the energy of the recoil
- Already used in natural minerals for dating in particular with fission fragments from uranium e.g. in obsidian, apatite, zircon
- Specifically crafted plastic materials used to be inexpensive particle detector via this method, e.g. for dosimeters
- Tracks can be etched with chemicals to make them larger but (mostly) keeping proportionality with the original size





Suggested reference: S.-L. Guo, B.-L. Chen and S. A. Durrani, «Solid-state nuclear track detectors,» in *Handbook of radioactivity analysis*, Academic Press, 2020, pp. 307-407.

Paleo-detectors

- Early ideas suggested in the 70s, first attempts made with mica in the 80s and 90s to look for exotic physics (e.g. monopoles) and dark matter
- Recently (2018) the idea was renewed in a series of papers
- The original idea: a small (e.g. 100g) crystal exposed for Gyr timescale have a larger exposure than current large detectors (Ton-size) that work for a decade
- Electrons cannot give recoils energetic enough, so the background is limited to cosmic rays, internal radioactivity and neutrons induced from (α, n) reactions

-> best candidate for this purpose are very old minerals digged from large depth (>2000m) with low uranium concentration and hydrogen to help remove the neutron background

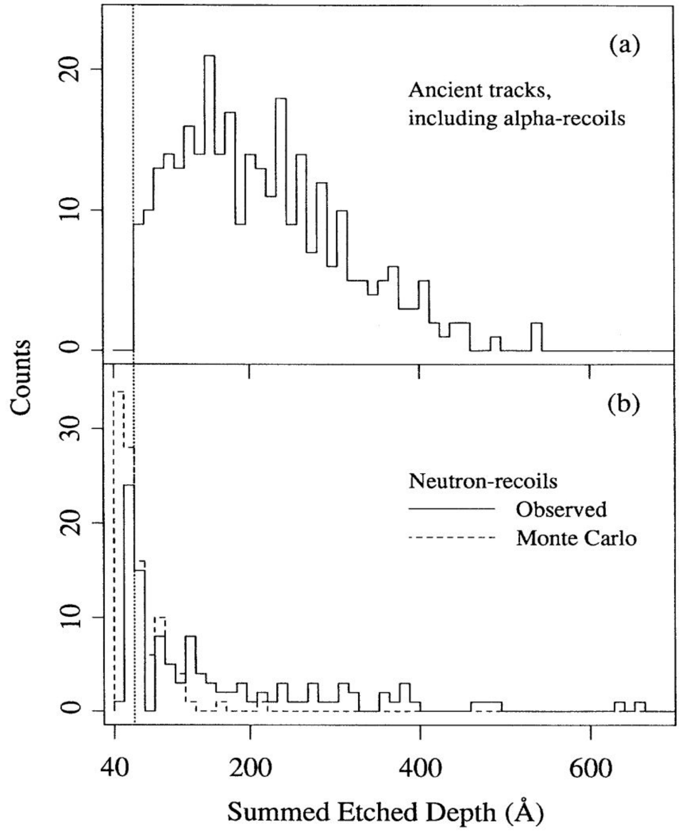


FIG. 3. (a) The summed etched depths of tracks recorded in a 80 720 μm^2 scan of 0.5 Gyr old muscovite mica. No events appear between our cutoff of 40 and 64 Å (shown with a dashed vertical line). (b) The solid line shows the summed depths of etched neutron-recoil tracks. The dashed line shows the results of a MC program of these data. In both the real and MC data a large fraction of the events appear in the 40–64 Å gap.

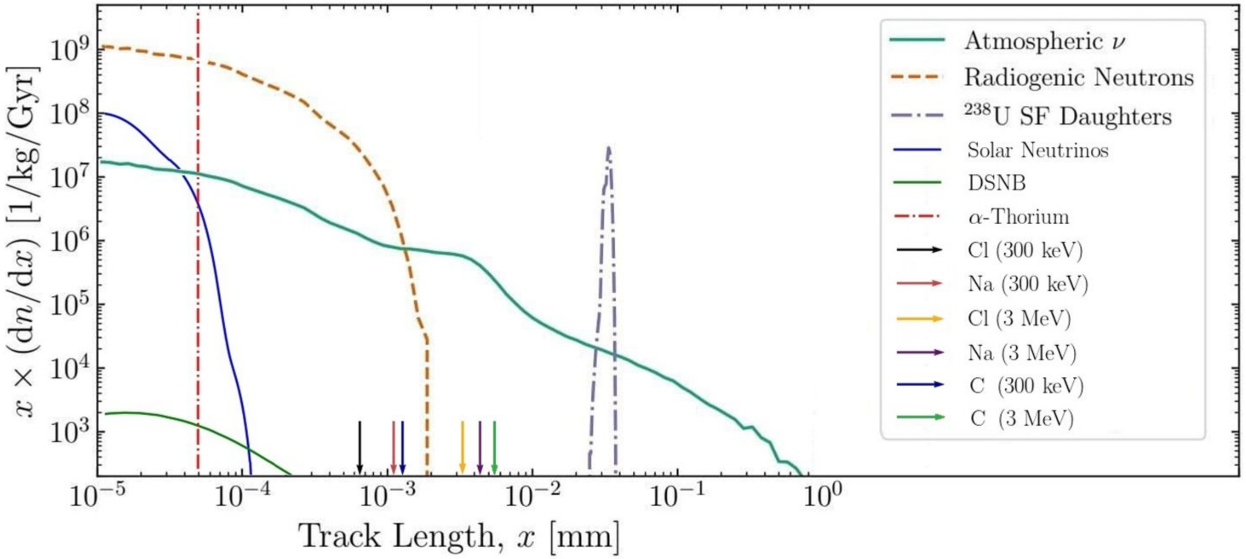
D. Snowden-Ifft, E. Freeman and P. Price, «Limits on dark matter using ancient mica,» *Phys Rev Lett.*, vol. 74, n. 21, pp. 4133-4136, 1995

Track detection techniques

- So far I presented you theoretical results
- They predict the formation of tracks from few nm (solar neutrinos) to hundreds of μm (cosmic rays)
- The former are much more common (1/kg/yr) than the latter (1/kg/Myr or less)

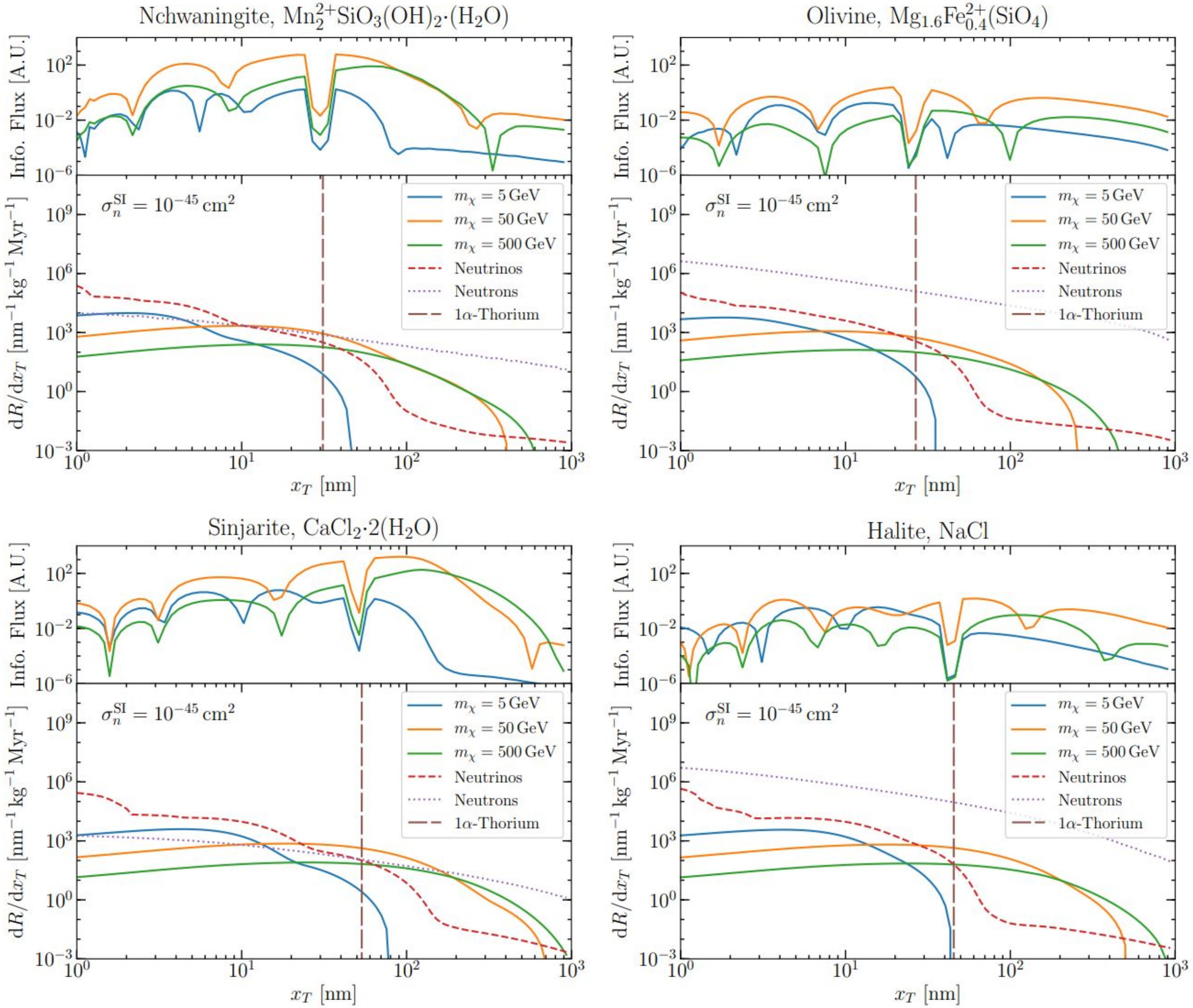
The detection of these tracks can be done with different methods:

- **Optical microscopes**: suitable only for tracks longer than o(μm), can be automated to fastly scan large surfaces. E.g. microscopes used to scan nuclear emulsion can reach 200 cm^2/h possibly up to 5000 cm^2/h in the near future (still need to slice the sample)
- Various types of **electron microscopes** (SEM, AFM, HIB…) can reach a resolution of the nm, but only few mm^2 (possibly cm^2) can be scanned, and samples often need preparation



- **X-ray tomography and dark-field diffraction.** Has the advantage of scanning the whole sample in one time, with little to no preparation needed. Unclear if these tracks can have the right contrast for these methods. Probably can reach resolution of 10-100 nm

Paleo-detectors



T. D. P. Edwards, B. J. Kavanagh, C. Weniger, S. Baum, A. K. Drukier, K. Freese, M. Gorski and P. Stengel, "Digging for dark matter: Spectral analysis and discovery potential of paleo-detectors," *Phys. Rev. D,* vol. 99, no. 4, p. 043541, 2019