Digging for astroparticles:

techniques and challenges for paleo-detectors

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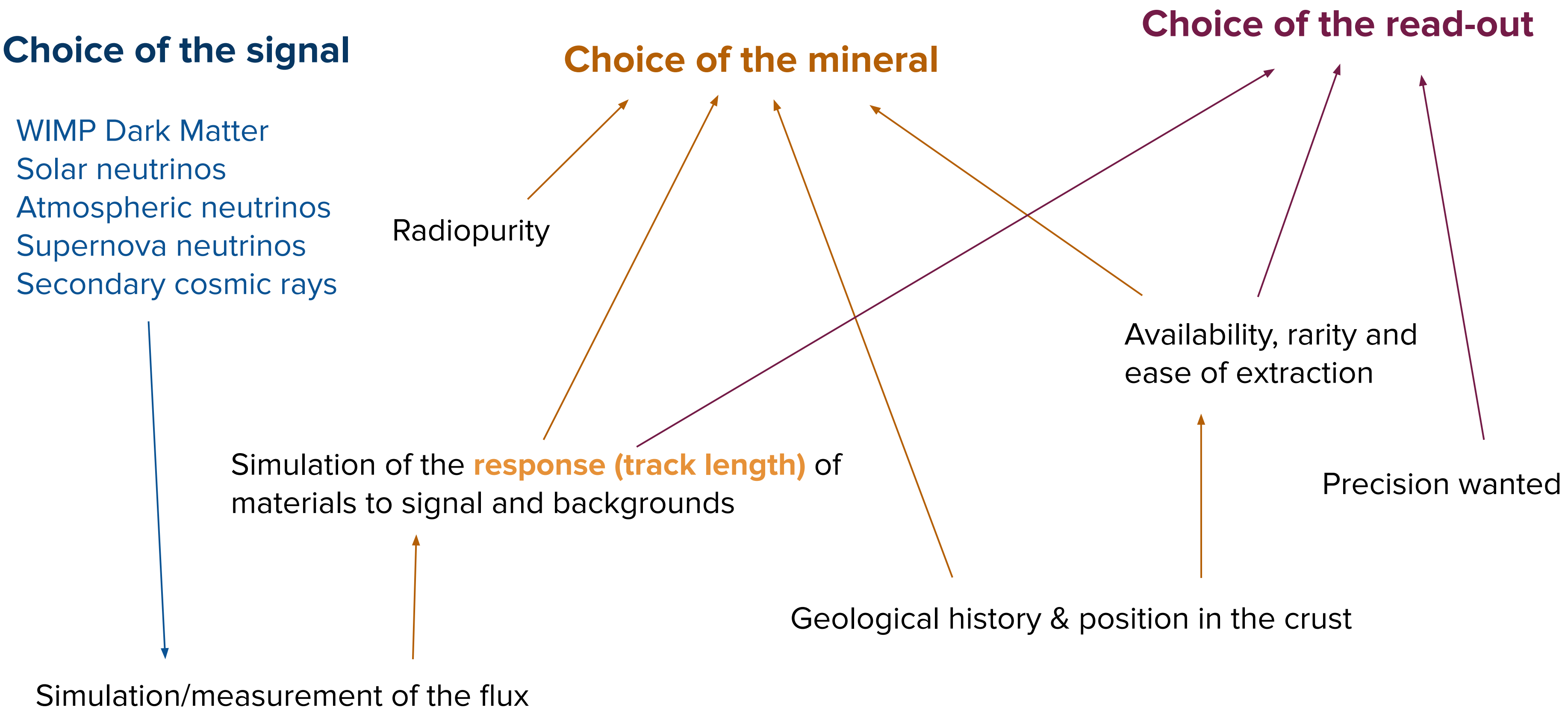
22/11/22, Astroparticle symposium
Institut Pascal

The recipe for paleo-detectors



Choice of the signal

WIMP Dark Matter
Solar neutrinos
Atmospheric neutrinos
Supernova neutrinos
Secondary cosmic rays

Choice of the mineral

Choice of the read-out

Radiopurity

Availability, rarity and ease of extraction

Simulation of the **response (track length)** of materials to signal and backgrounds

Precision wanted

Geological history & position in the crust

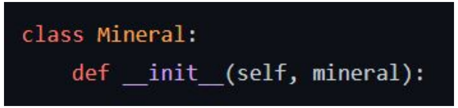
Simulation/measurement of the flux

Simulations: the paleopy package

https://github.com/tedwards2412/paleopy

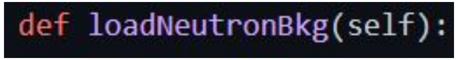
Thomas Edwards
Bradley Kavanaugh

paleopy computes the **track length spectrum** for different sources and backgrounds in selected materials



```
class Mineral:
    def __init__(self, mineral):
```

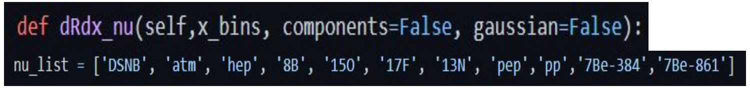
It defines the characteristics of the mineral: number of different nuclei, mass/charge of the components, molar mass
Currently supported: nchwaningite, halite, epsomite, nickelbischofite, olivine, sinjarite + morenosite, obisidian (in progress)



```
def loadNeutronBkg(self):
```

Computes backgrounds for the selected mineral: neutrons, fission products

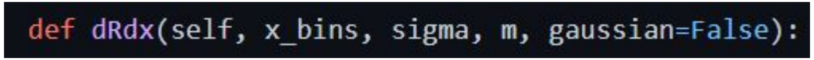
→ From SOURCES4A, SRIM



```
def dRdx_nu(self,x_bins, components=False, gaussian=False):
nu_list = ['DSNB', 'atm', 'hep', '8B', '15O', '17F', '13N', 'pep','pp','7Be-384','7Be-861']
```

Computes track lengths for neutrinos of different sources:
can be used for other particles

→ From Corsika, Geant & other software



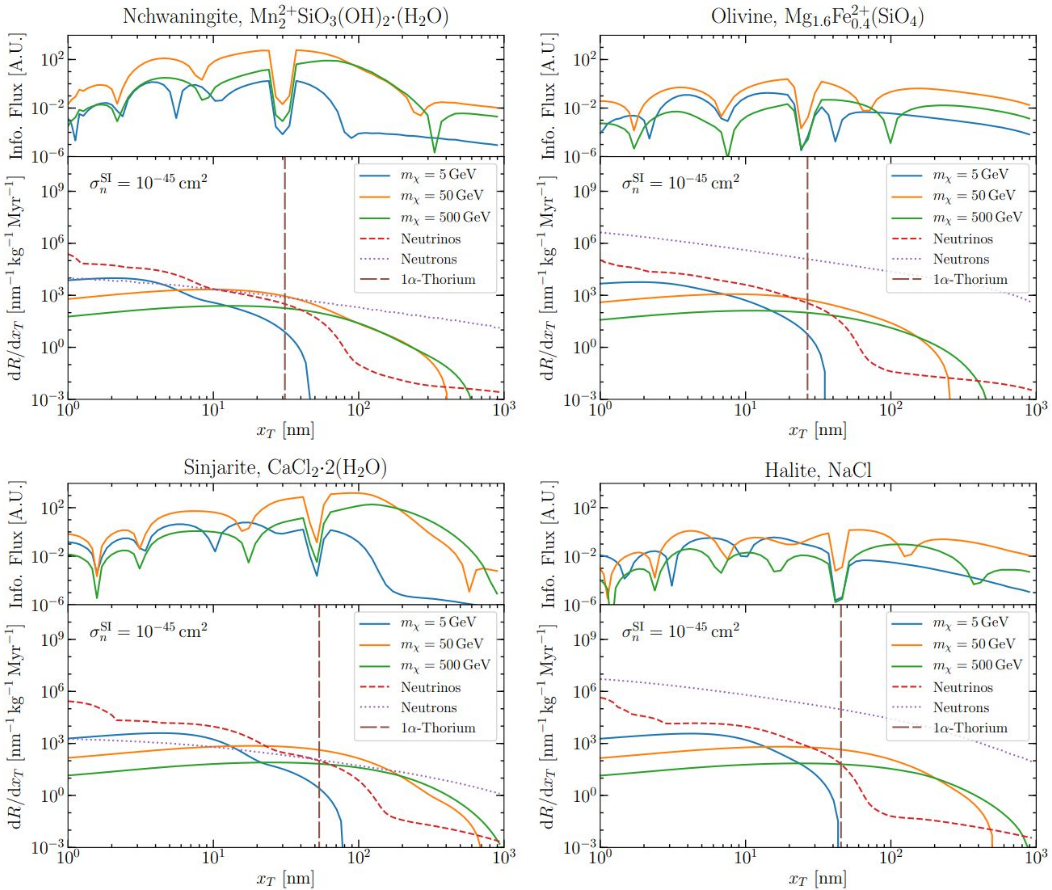
```
def dRdx(self, x_bins, sigma, m, gaussian=False):
```

Computes track length for DM of mass m

→ From WIMPy_NREFT

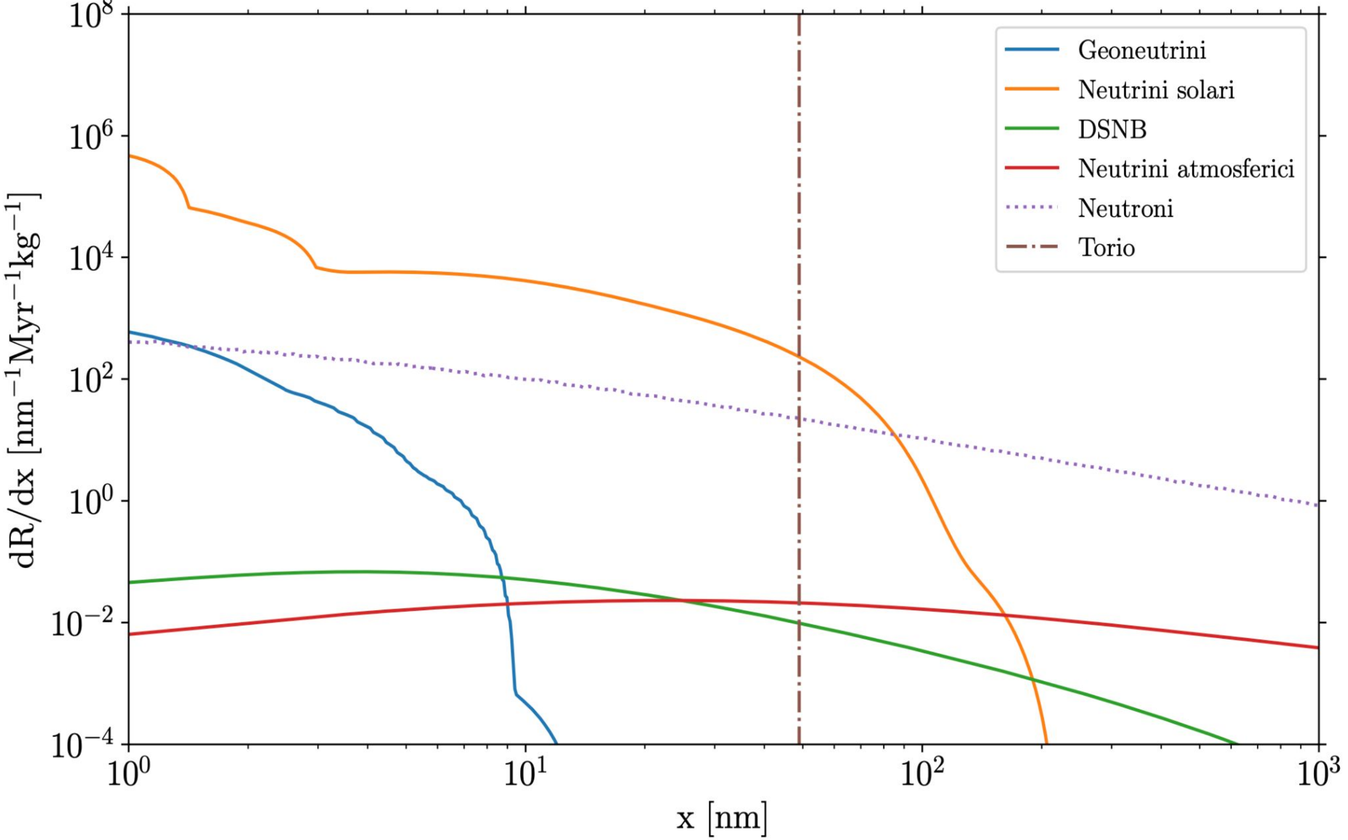
Simulations: the paleopy package

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

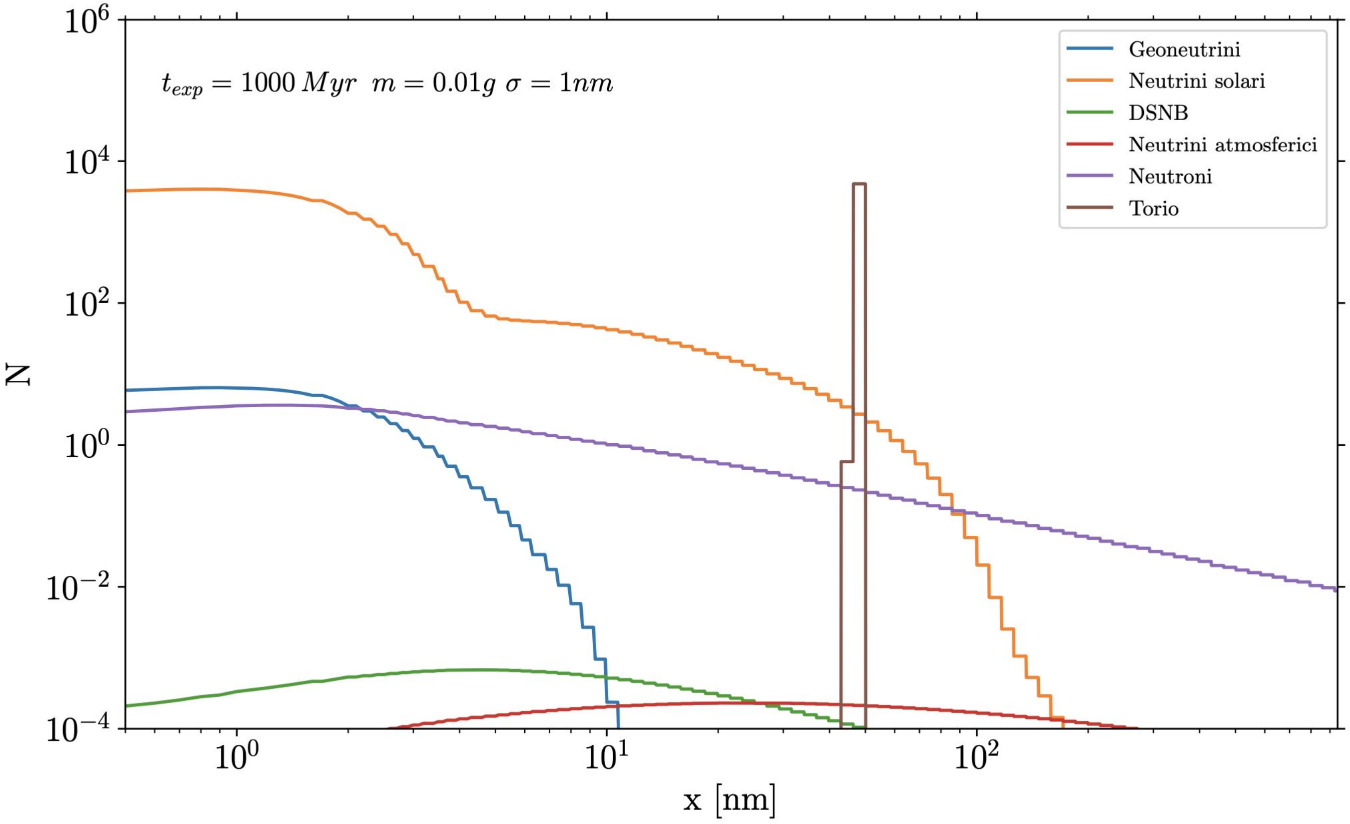


Simulations: the paleopy package

Epsomite ($MgSO_4 7(H_2O)$)



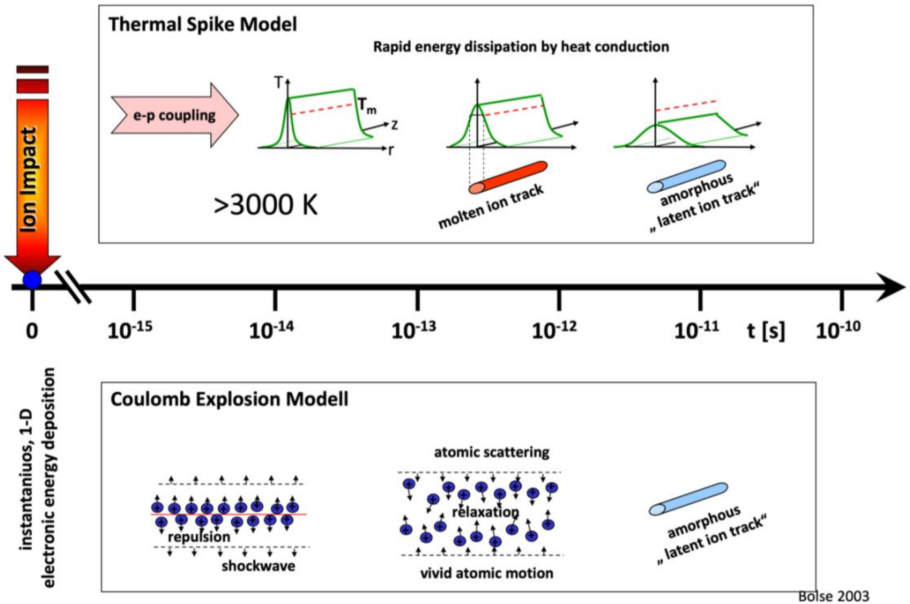
Simulations: the paleopy package



Choosing the Mineral

Generalities

The mechanism of track formation is not yet fully understood



Bolse 2003

A wishlist for the perfect paleo-detector candidate:

- **Insulators or poor semiconductors**
- **Low radioactive isotope content** to lower fission fragments contribution
- (Possibly) high H content to mitigate neutron background
- Easy to datate
- Easy to retrieve
- Abundant in different parts of the globe
- Forming often in Earth’s history

Choosing the Mineral

Backgrounds: fission products and neutrons

Neutrons

From (ɑ,N) reactions and spontaneous fission

Neutrons interact preferentially with hydrogen losing most of their energy
Hydrogen is too light to form tracks

More hydrogen = good

Fission fragments

Spontaneous fission from ^{238}U gives rise to two daughter nuclei that recoil back-to-back

Long - O(μm) double tracks

The more radiopure the better!

Minerals born in the **Mantle**

Evaporites from seawater

Choosing the Mineral

Geological history

The **history** of the mineral is as or more important than its composition

Dark matter and neutrino searches need very high overburdens to shield the minerals from secondary CRs (=muons)

Studies on the **evolution of the cosmic ray flux** need a source of samples with different ages but similar history

Searches for **transients** need samples of slightly different ages - born before and after the event

Studies on the **CR flux in a fixed moment** in the past need a sample that was exposed for a time and then shielded

These conditions often overwrite the preference on the mineral

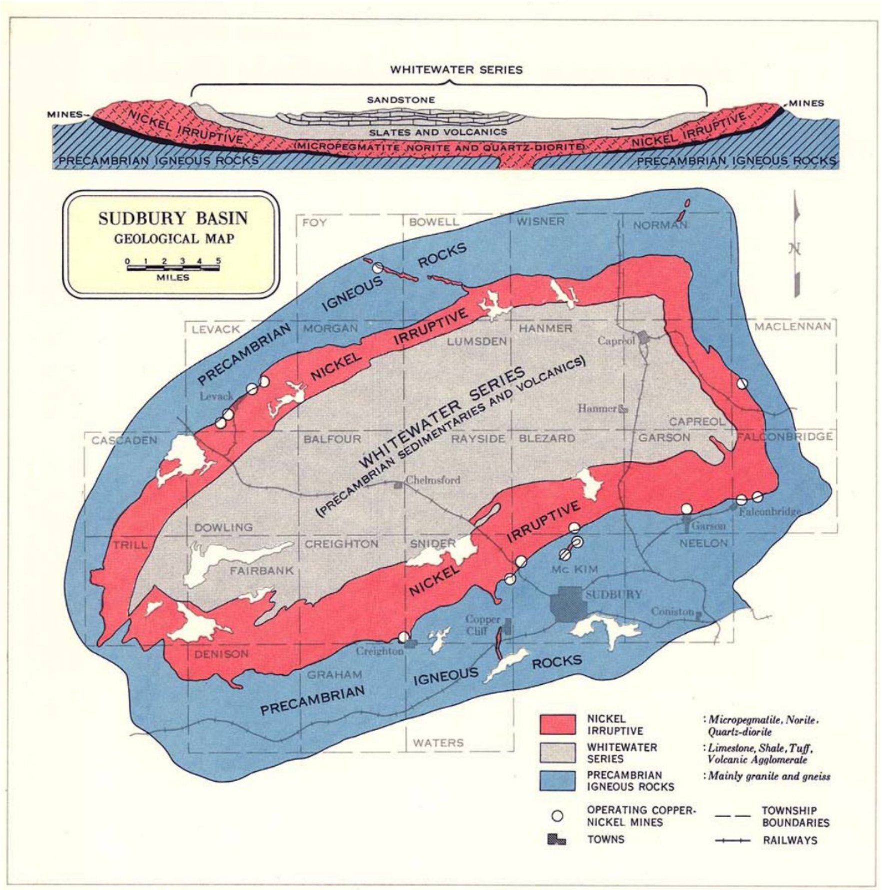
Geological history: examples of interest

The Sudbury region

Sudbury is a good candidate for paleo-detector extraction for searches that need high overburden, as it is recognised as the result of an asteroid impact that happened 1.85 Gyr ago: **well dated.**

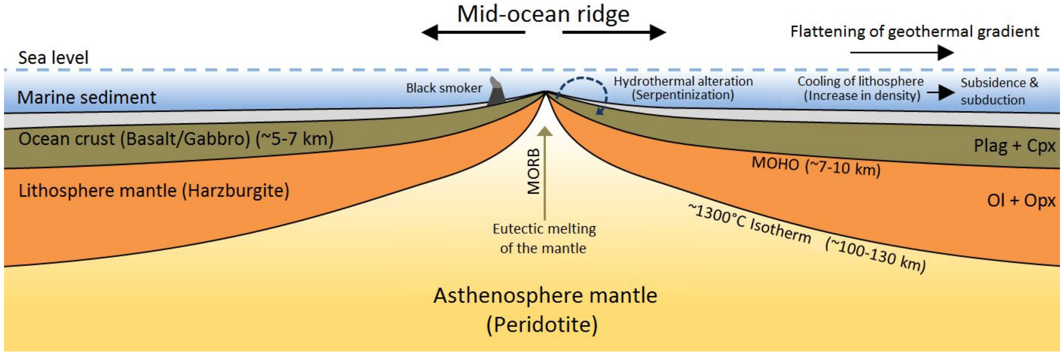
It has many access points to **deep strata** in Nickel mines: excavation is possible

SNOLAB at 2km of depth is the deepest science facility in the world: it could provide on-site analysis possibilities, without the need of exposing the samples to present-day CR fluxes



Geological history: examples of interest

The Mid-Atlantic rift



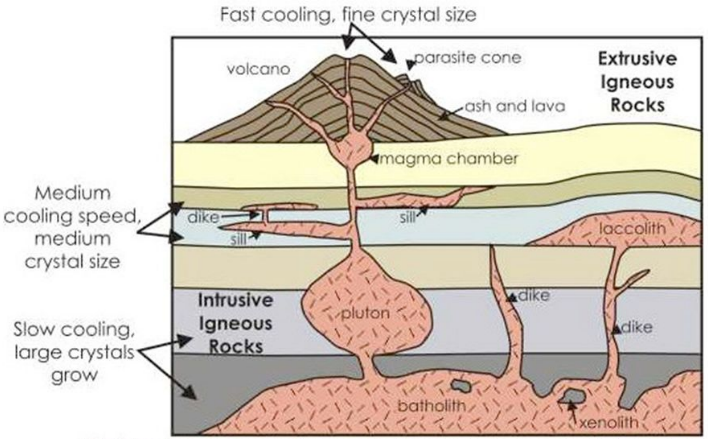
The continuous production of crust in the oceanic rift, which can be dated with paleomagnetism could be exploited to have a continuous series of samples exposed for different integrated times.

the Atlantic rift has different overburden of water, from ~4 km to practically none (iceland), which can be used to “select” high energy secondary particles, mostly produced by high energy primaries

Geological history: examples of interest

Xenoliths and flux evolution

Xenoliths are intrusions into magmatic flows, taken mostly from the mantle and can easily be dated together with their associated eruptions.
Could be good candidates for studying the evolution of cosmic ray fluxes over successive eruptions



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

Main compositions include spinel (Mg+Al), dunite, peridotite (Olivine)

Geological history: examples of interest

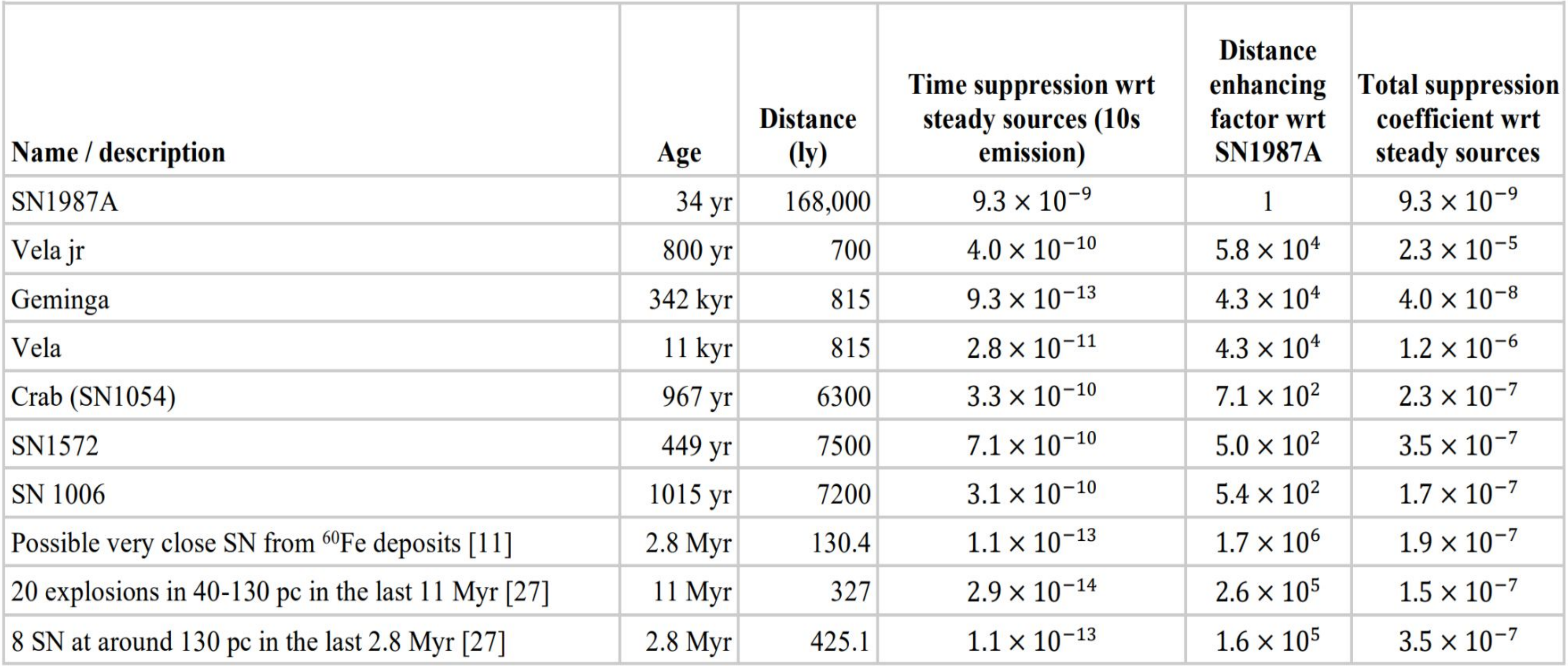
The Messinian Salinity Crisis and cosmic ray flux in the past

Main problem in paleo-detectors for cosmic rays 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

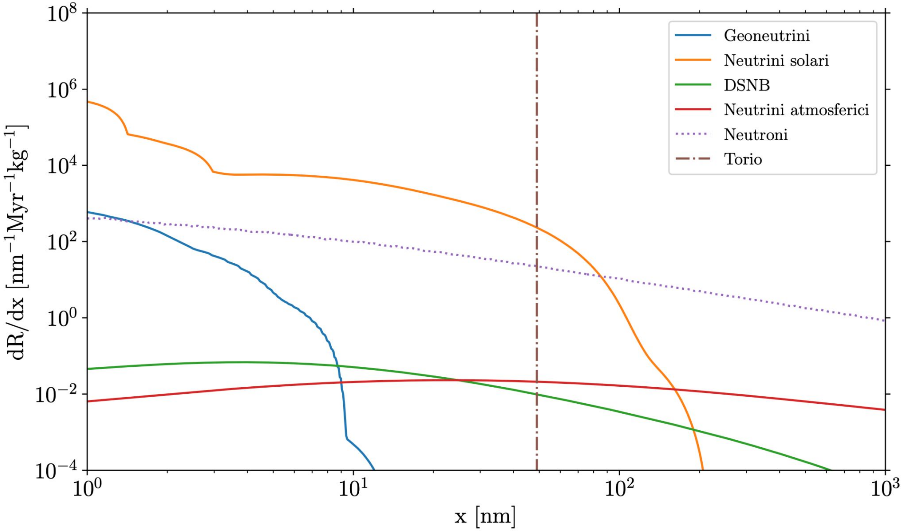
Case study 1: neutrinos from galactic supernovae



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}

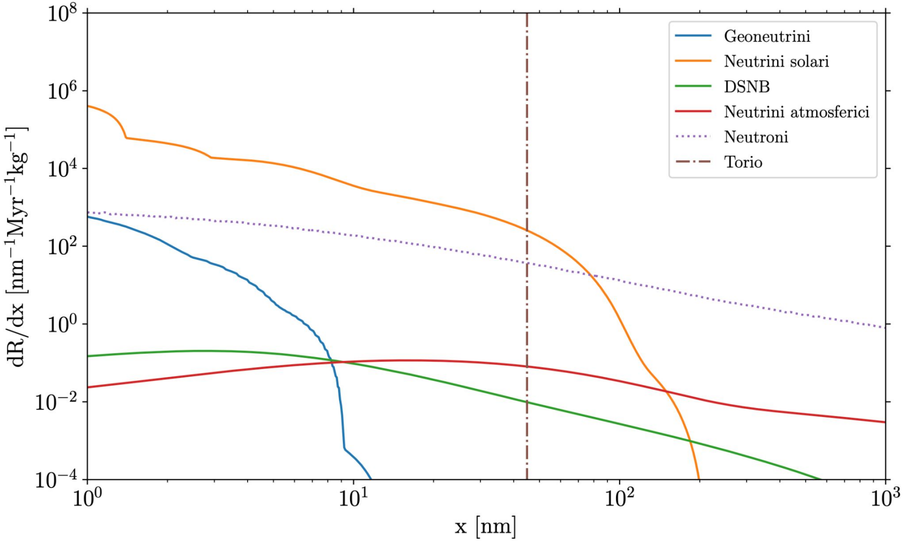
Case study 1: neutrinos from galactic supernovae

Epsomite ($MgSO_47(H_2O)$)



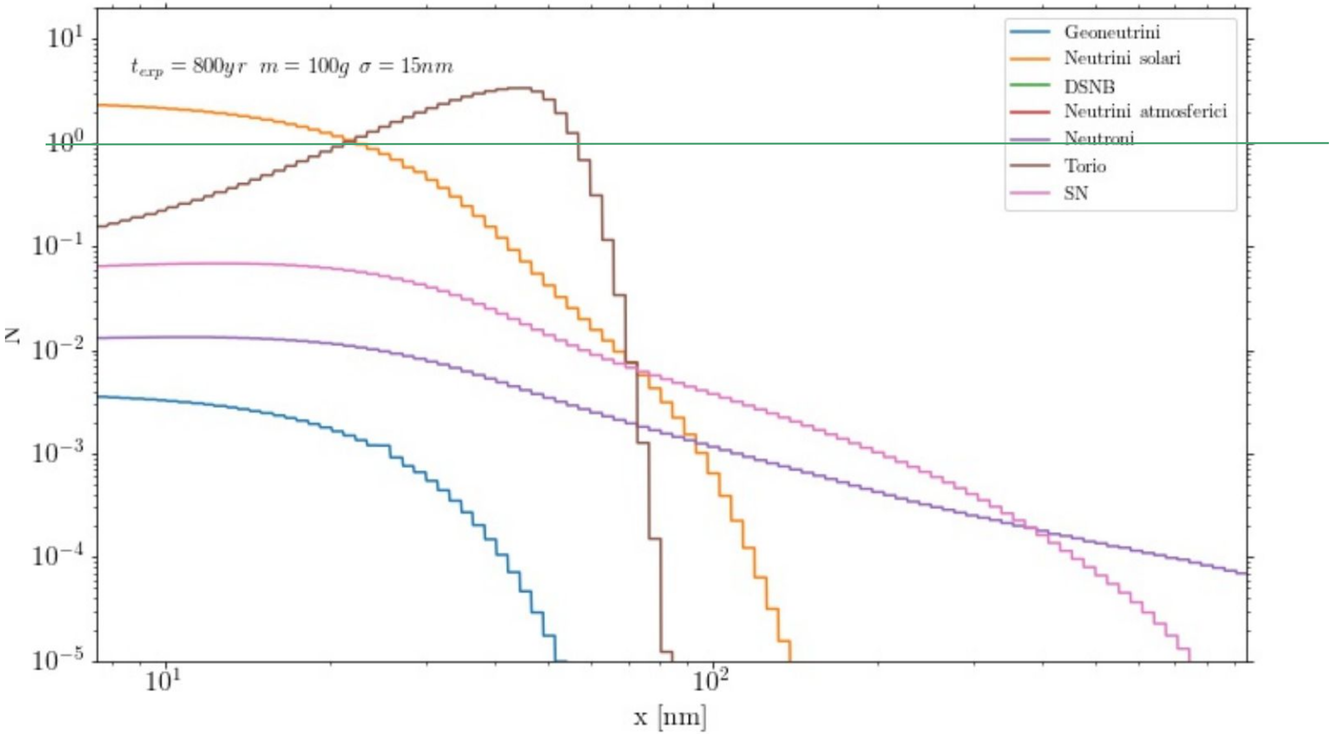
Hard to obtain with high enough overburdens: mostly found in carsic sediments and dried salt basins

Morenosite ($NiSO_47(H_2O)$)



Found in Sudbury’s Nickel mines

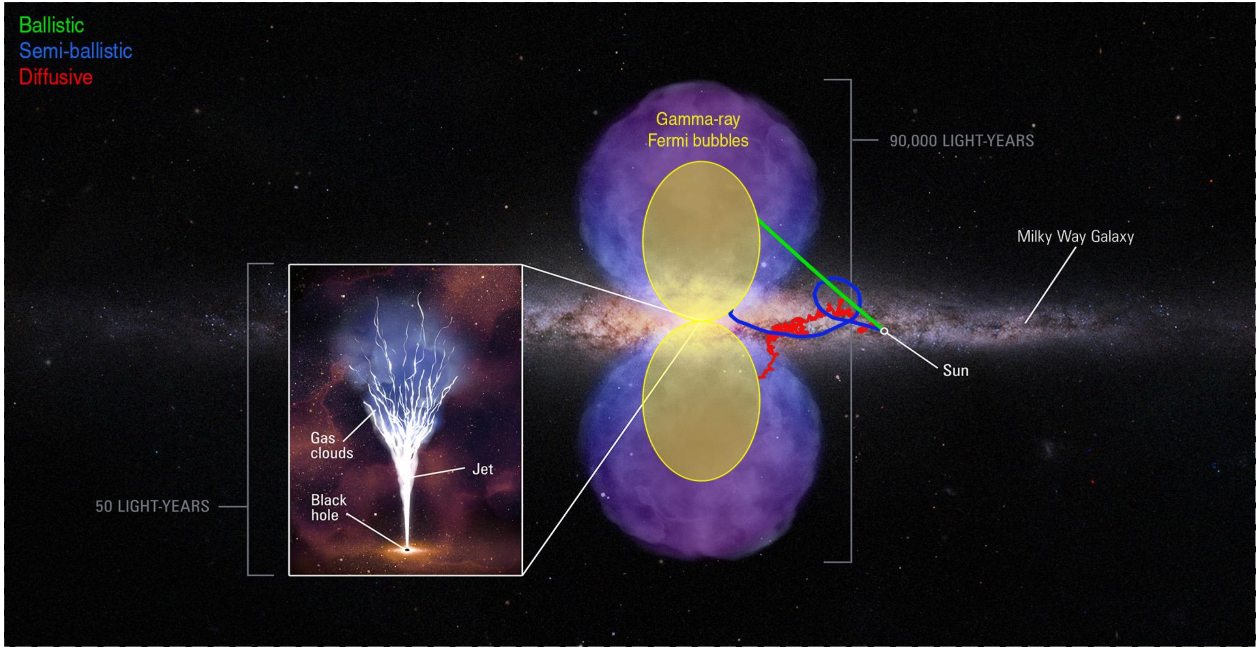
Case study 1: neutrinos from galactic supernovae



Huge volume needed for detection! - even in the best case scenario

Case study 2: MSC and the Fermi bubbles

Phase 1: Simulate UHECR emission from the Fermi Bubbles, propagate and check which emitted particles can affect evaporites from the MSC before they are shielded by the flood

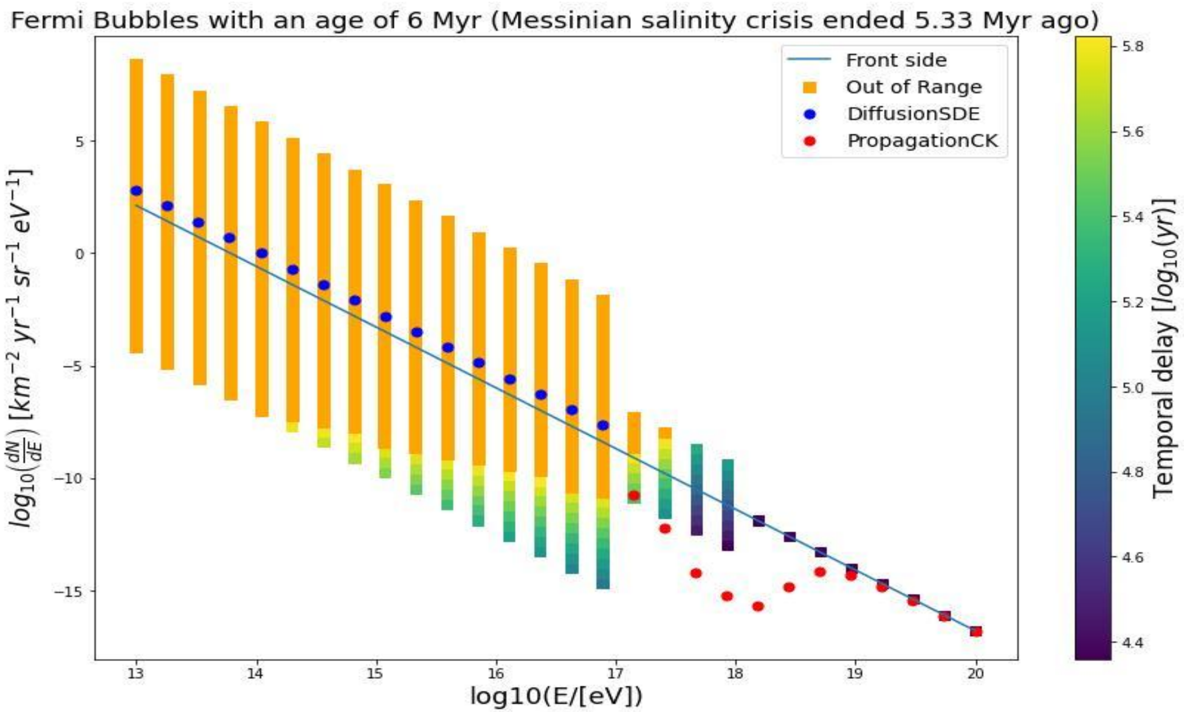


Toy model for FB emission:
-2.7 power law spectrum normalized to the excess flux observed in the direction of CenA, rescaled with distance

↓

Propagation in GMF (JF12) using CRPropa (Diffusion+ballistic)

Case study 2: MSC and the Fermi bubbles



Simulated **observed spectrum** and the **GMF induced delay** at earth

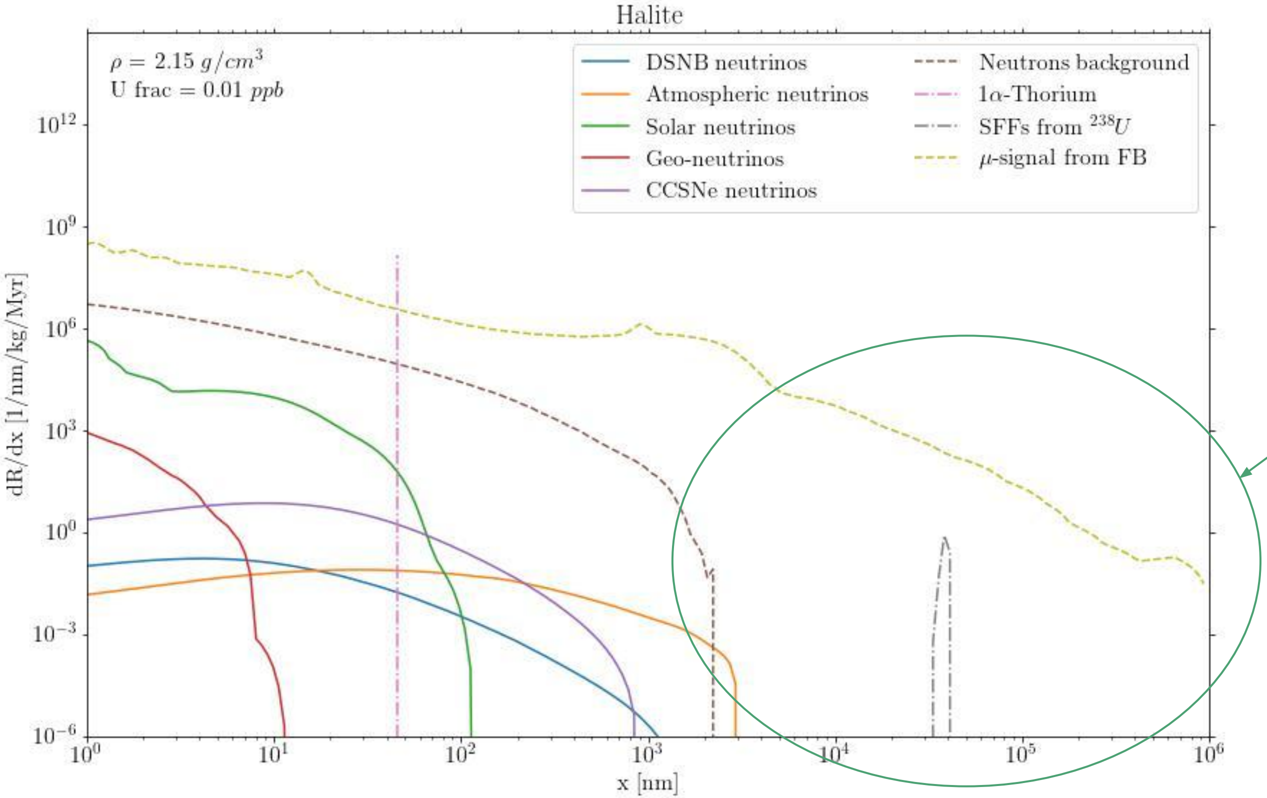
orange means out of temporal bounds

Phase 2: Simulate using Corsika the expected muon flux associated with the “observed” FB spectrum

Phase 3: Compute the nuclear recoil spectrum from muons hitting nuclei in a Halite target using Geant4

Case study 2: MSC and the Fermi bubbles

Phase 5: compute the track length spectra in Halite



Promising region for detection:

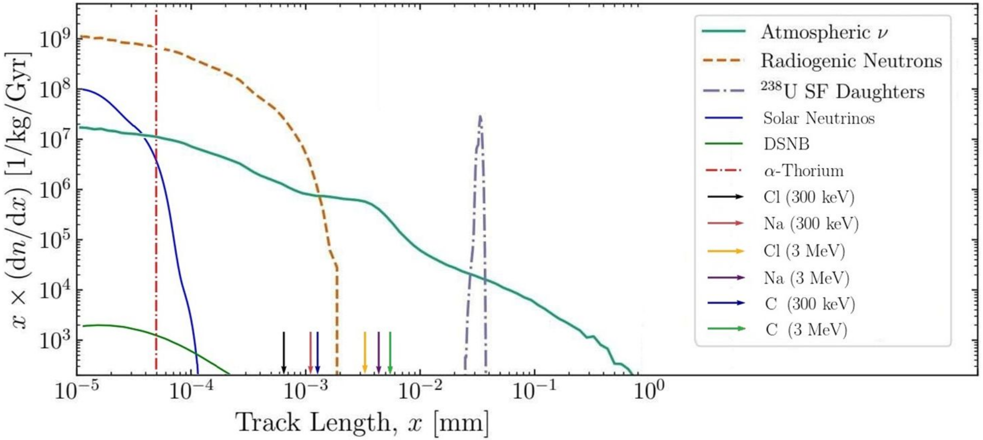
- low to no background
- mature for readout due to fission tracks

Readout techniques

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

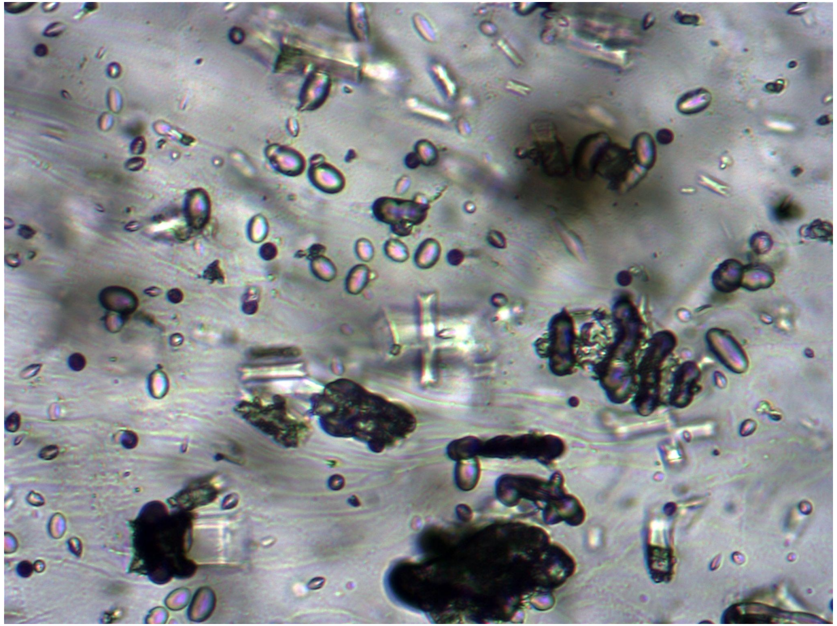


- **X-ray tomography and dark-field diffraction.** Has the advantage of scanning the whole sample in one time, with little to no preparation needed. Unclear if these tracks can have the right contrast for these methods. Probably can reach resolution of 10-100 nm

Readout techniques

Learning from nuclear physics: etching for µm-size tracks

For the MSC+FB analysis we are learning how to look for tracks in the µm range using optical microscopy



Infrastructure for etching and samples (obsidian) provided by the natural radioactivity group

Double objective:

- get comfortable with the readout and preparation of samples (easy-ish)
- Check the background calculation by simulating obsidian in paleopy (hard)

The (near) future: move to Halite and automate the process for efficient search in large volumes

The paleo-detectors community

The field of paleo-detectors is flourishing after the revival of the idea:

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
N. Tapia-Arellano and S. Horiuchi, *Measuring solar neutrinos over gigayear timescales with paleo detectors*, Phys. Rev. D, p. 123016, 2021
S. Baum, T. D. P. Edwards, B. J. Kavanagh, P. Stengel, A. K. Drukier, K. Freese, M. Gorski and C. Weniger, *Paleo-detectors for Galactic supernova neutrinos*, Phys. Rev. D, vol.101, n.10, p. 19, 2020
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

~6 other groups we know of which are actively working on experimental studies
Spread across North America, Europe and Japan.

Short Snowmass2021 LoI: Paleo Detectors Sebastian Baum et al.

Whitepaper currently in preparation:
80 pages from science case to details about the experimental techniques. To be published shortly!