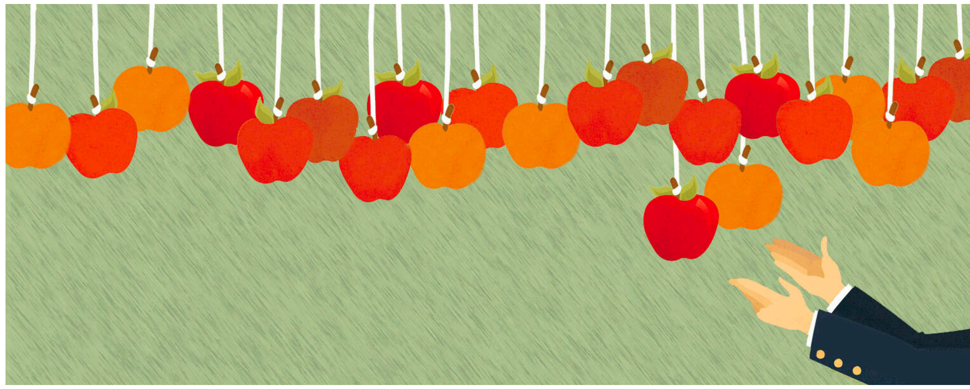
Imaging Atmospheric Neutrinos with Paleo-detectors

aka: low hanging fruit



Josh Spitz, University of Michigan
MDvDM 24, 1/10/2024

SPITZ GROμP

UNIVERSITY OF MICHIGAN

GORDON AND BETTY MOORE FOUNDATION

Editorial

Why am I attending this workshop?

- For the geologists and non-physicists in the room: the discovery of dark matter would be earth-shattering. This is not just a Nobel Prize winning discovery, this would be the most important physics Nobel in decades! Let's figure out what the Universe is made out of!

- The physics is there. The events are (er, could be) there. The technology is (getting) there. Very exciting.

Editorial

Why am I attending this workshop?

- Paleo-detectors provide exposure
  - A 100 g, 1 billion year old rock corresponds to an exposure of 100 kton*year.

Editorial

Why am I attending this workshop?

PHYSICAL REVIEW LETTERS **131,** 041002 (2023)

Editors' Suggestion   Featured in Physics

First Dark Matter Search Results from the LUX-ZEPLIN (LZ) Experiment

The LUX-ZEPLIN experiment is a dark matter detector centered on a dual-phase xenon time projection chamber operating at the Sanford Underground Research Facility in Lead, South Dakota, USA. This Letter reports results from LUX-ZEPLIN's first search for weakly interacting massive particles (WIMPs) with an exposure of 60 live days using a fiducial mass of 5.5 t. A profile-likelihood ratio analysis shows the data to be consistent with a background-only hypothesis, setting new limits on spin-independent WIMP-nucleon, spin-dependent WIMP-neutron, and spin-dependent WIMP-proton cross sections for WIMP masses above 9 GeV/c^2. The most stringent limit is set for spin-independent scattering at 36 GeV/c^2, rejecting cross sections above 9.2×10^{-48} cm^2 at the 90% confidence level.

($60M project)   (0.0009 kton*year)

Editorial

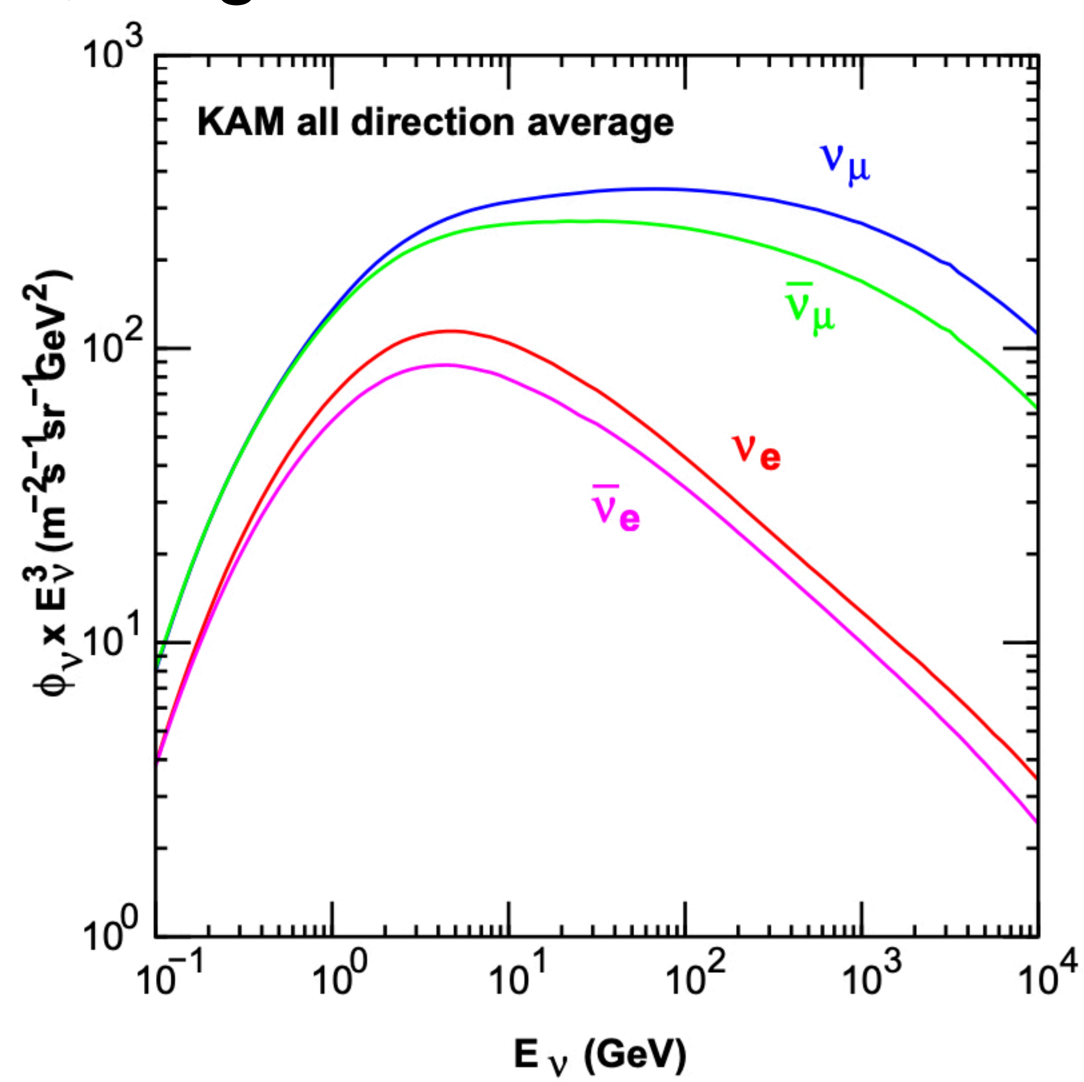
Why am I attending this workshop?

- Paleo-detectors provide exposure
  - A 100 g, 1 billion year old rock corresponds to an exposure of 100 kton*year.
- Paleo-detectors provide history
  - A way to look at the history of the Earth+Solar System over the past ~2 billion years.

Atmospheric neutrinos

- Atmospheric neutrinos (~GeV-scale) make big nuclear recoils.
- An intermediate step towards other paleo-detector goals, like DM and solar/supernova neutrinos.
  - We are talking about > 1 MeV recoils; long tracks!
    - 2-1000 um vs. nm-scale.
- But, also very cool science!

Paleo-detectors offer Earth+solar system 'history' in the context of atm. neutrinos. No real advantage in terms of exposure compared to 'live' detectors.



M. Honda, M. Sajjad Athar, T. Kajita, K. Kasahara, S. Midorikawa
PRD 92 023004 (2015)

The big questions

- What is the history of the cosmic ray rate at Earth?
    - Relevant in physics, astrophysics, biology, geology, …
    - Rare isotopes (^{10}Be) produced in cosmic ray interactions gets us back about 10 Myr.
    - Rare isotopes (^{40}K) in meteorites can get back to ~1 Gyr, but rate is highly dependent on sample's dynamic location/creation history, which is very hard to infer. Big uncertainties (>50%), contradictory results, etc.

- Related: What is the history of our solar system?
    - The solar system revolves around the center of the galaxy once very 250 million years.
    - Did the Earth encounter a transient event?
        - Nearby supernova, neutron star merger, etc.
    - Stellar density and supernova rate at solar system location as a function of time.
        - The solar system moves in and out of galactic spiral arms as we orbit. Since higher cosmic ray rates likely come with higher star/supernova density, can we see this?

PHYSICAL REVIEW LETTERS **125,** 231802 (2020)

Featured in Physics

Measuring Changes in the Atmospheric Neutrino Rate over Gigayear Timescales

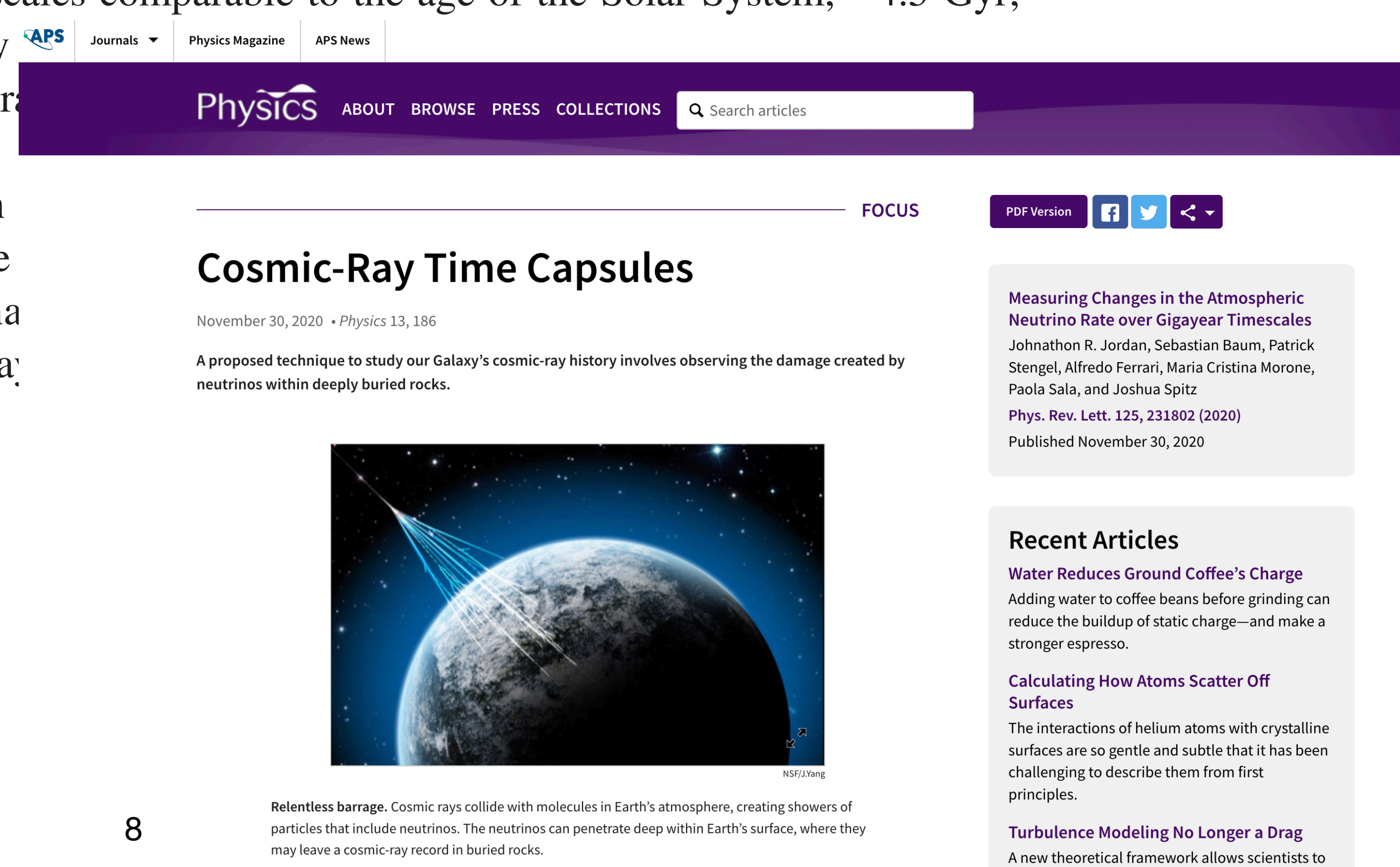
Johnathon R. Jordan,[1,*] Sebastian Baum,[2,3,†] Patrick Stengel,[3,‡] Alfredo Ferrari,[4]
Maria Cristina Morone,[5,6] Paola Sala,[7] and Joshua Spitz[1,§]

[1]*University of Michigan, 450 Church Street, Ann Arbor, Michigan 48109, USA*
[2]*Stanford Institute for Theoretical Physics, Department of Physics, Stanford University, Stanford, California 94305, USA*
[3]*The Oskar Klein Centre for Cosmoparticle Physics, Department of Physics, Stockholm University, Alba Nova, 10691 Stockholm, Sweden*
[4]*CERN, 1211 Geneva 23, Switzerland*
[5]*Physics Department, University of Roma Tor Vergata, 00133 Rome, Italy*
[6]*INFN Roma Tor Vergata, 00133 Rome, Italy*
[7]*INFN Milano, via Celoria 16, 20133 Milano, Italy*

(Received 24 April 2020; revised 10 August 2020; accepted 28 October 2020; published 30 November 2020)

Measuring the cosmic ray flux over timescales comparable to the age of the Solar System, ~4.5 Gyr, could provide a new window on the history
present a technique to indirectly measure the r
atmospheric neutrinos in "paleo-detectors,"
recoils. Minerals commonly found on Earth
cosmic ray history on timescales of the same
differently aged samples dated with reasona
measuring historical *changes* in the cosmic ra
geophysics.

DOI: 10.1103/PhysRevLett.125.231802


APS | Journals | Physics Magazine | APS News

Physics ABOUT BROWSE PRESS COLLECTIONS Search articles

FOCUS

PDF Version

Cosmic-Ray Time Capsules

November 30, 2020 • *Physics* 13, 186

A proposed technique to study our Galaxy's cosmic-ray history involves observing the damage created by neutrinos within deeply buried rocks.

NSF/J.Yang

Relentless barrage. Cosmic rays collide with molecules in Earth's atmosphere, creating showers of particles that include neutrinos. The neutrinos can penetrate deep within Earth's surface, where they may leave a cosmic-ray record in buried rocks.

Measuring Changes in the Atmospheric Neutrino Rate over Gigayear Timescales
Johnathon R. Jordan, Sebastian Baum, Patrick Stengel, Alfredo Ferrari, Maria Cristina Morone, Paola Sala, and Joshua Spitz
Phys. Rev. Lett. 125, 231802 (2020)
Published November 30, 2020

Recent Articles

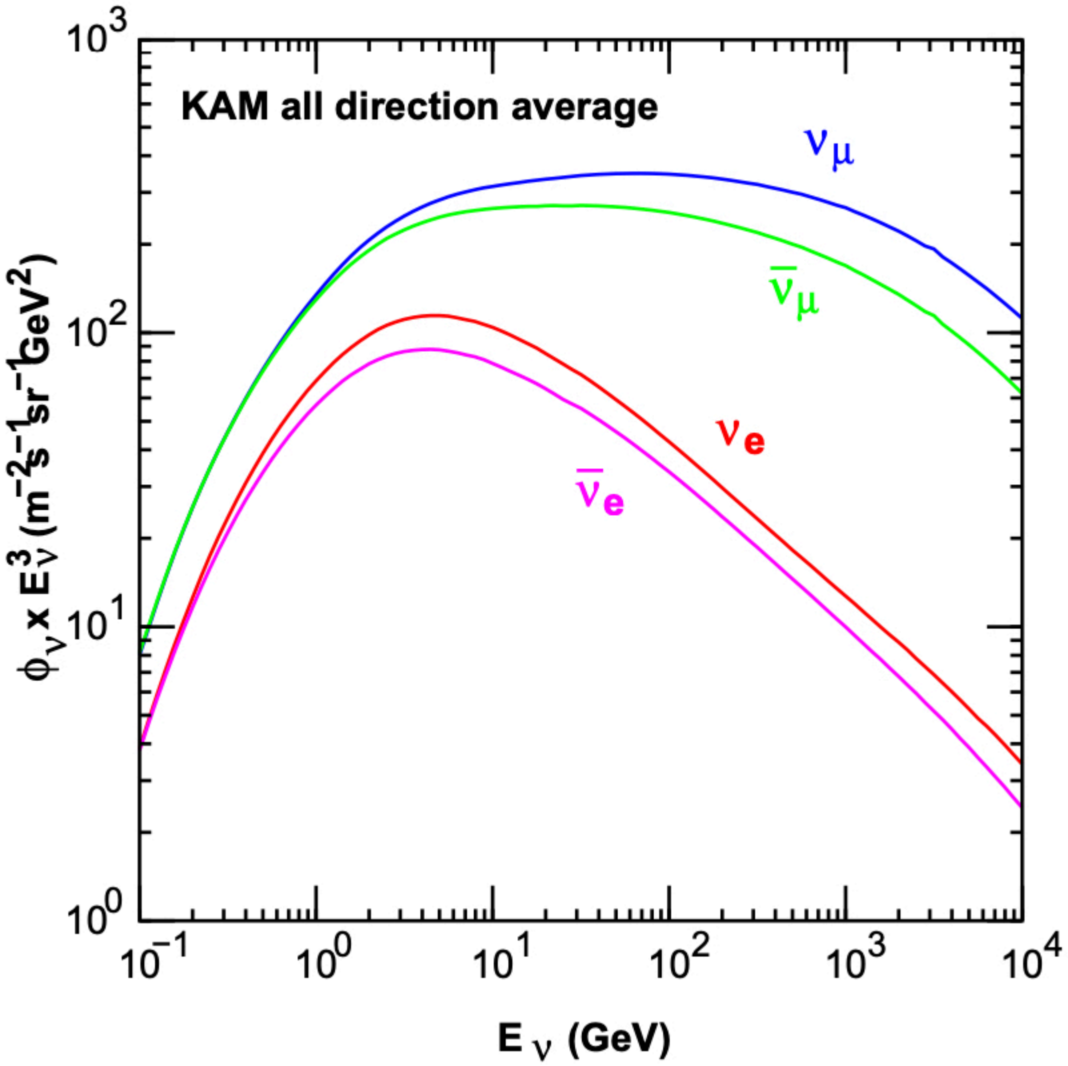
Water Reduces Ground Coffee's Charge
Adding water to coffee beans before grinding can reduce the buildup of static charge—and make a stronger espresso.

Calculating How Atoms Scatter Off Surfaces
The interactions of helium atoms with crystalline surfaces are so gentle and subtle that it has been challenging to describe them from first principles.

Turbulence Modeling No Longer a Drag
A new theoretical framework allows scientists to

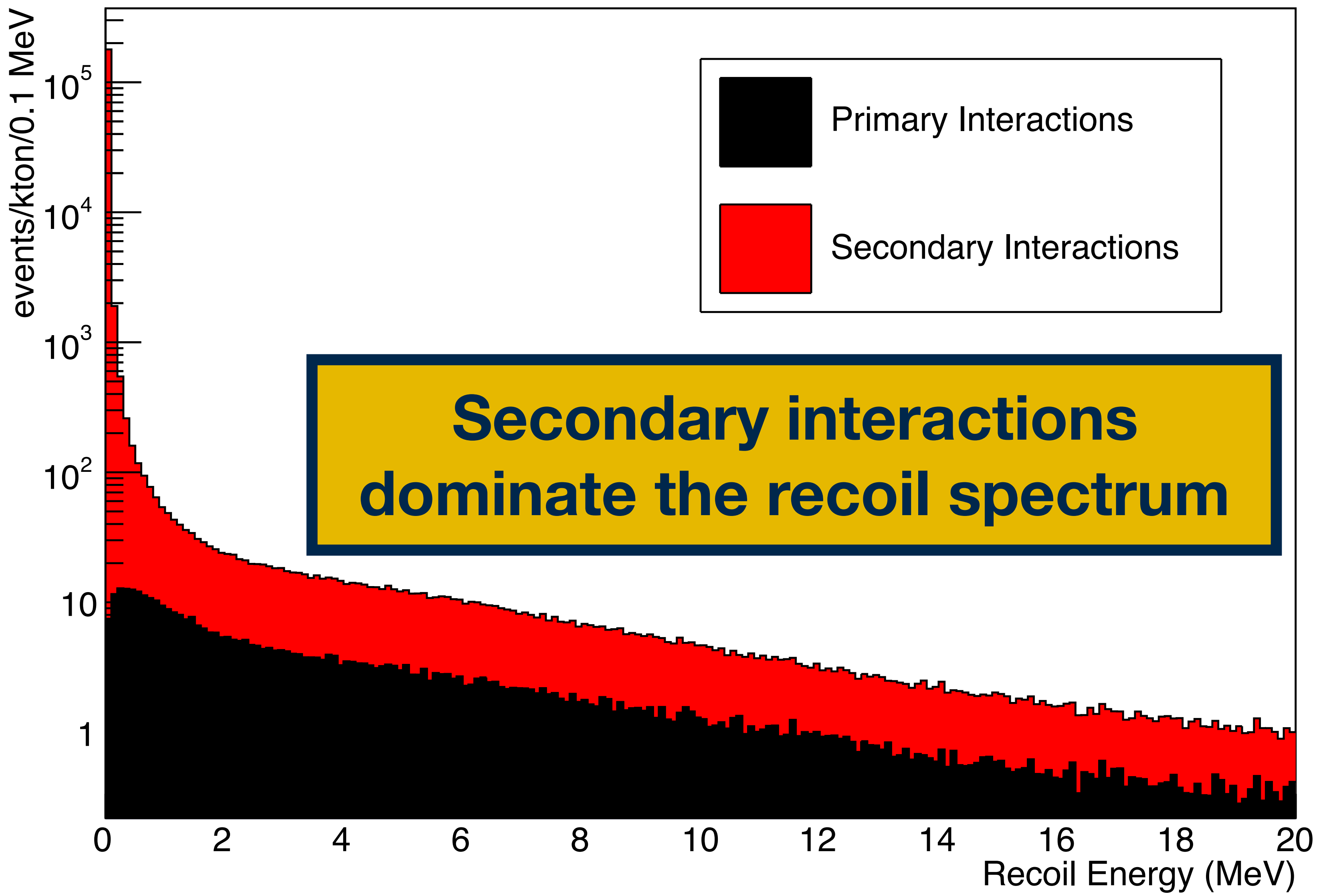
Atmospheric neutrinos

- Atmospheric neutrino rate is an excellent proxy for cosmic ray rate.
- Looking for neutrino interactions is better than looking for actual cosmic interactions in paleo-detectors, since the neutrino interaction rate is not sensitive to (dynamic, hard to infer over time) overburden.



M. Honda, M. Sajjad Athar, T. Kajita, K. Kasahara, S. Midorikawa
PRD 92 023004 (2015)

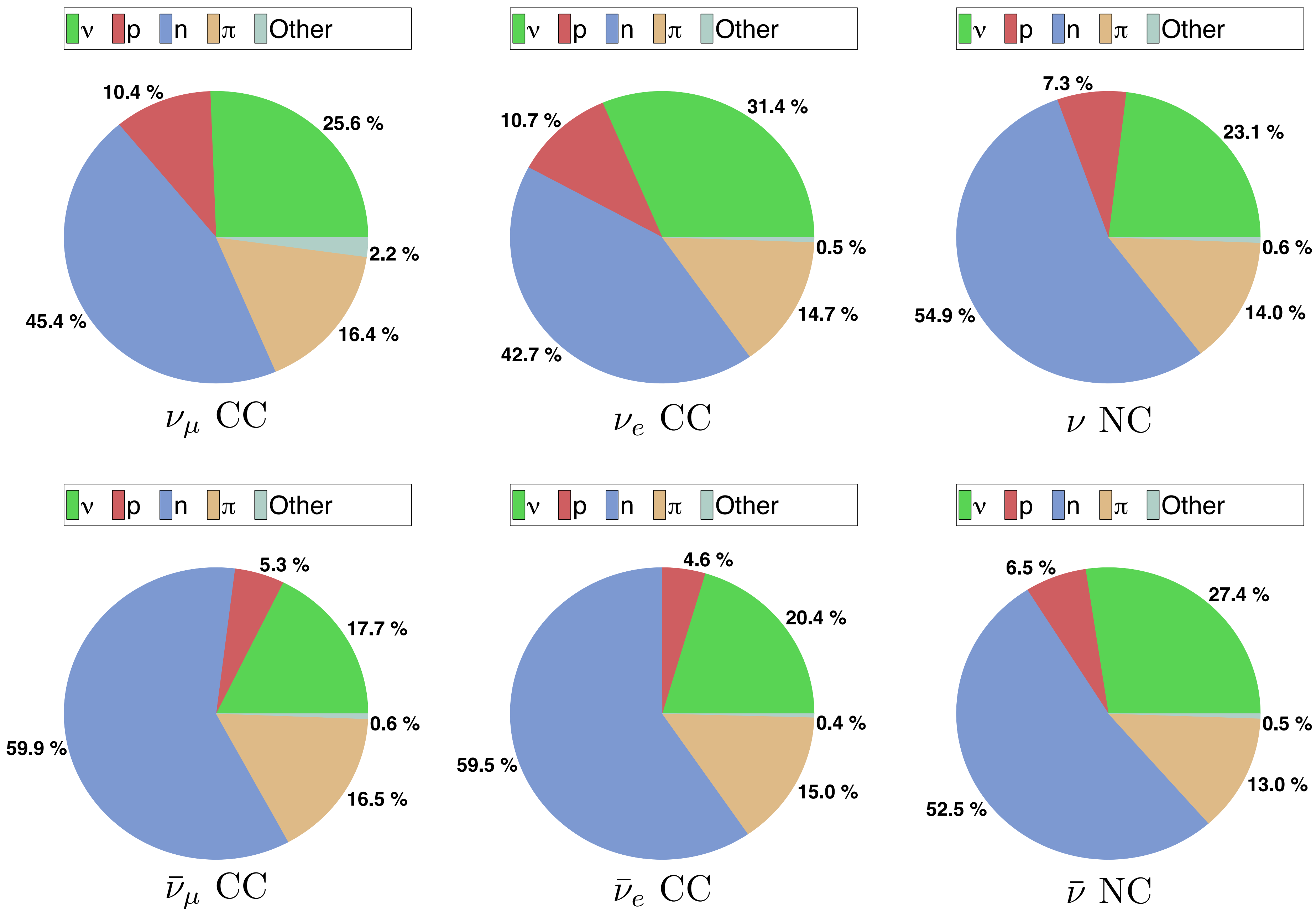
Atmospheric neutrinos



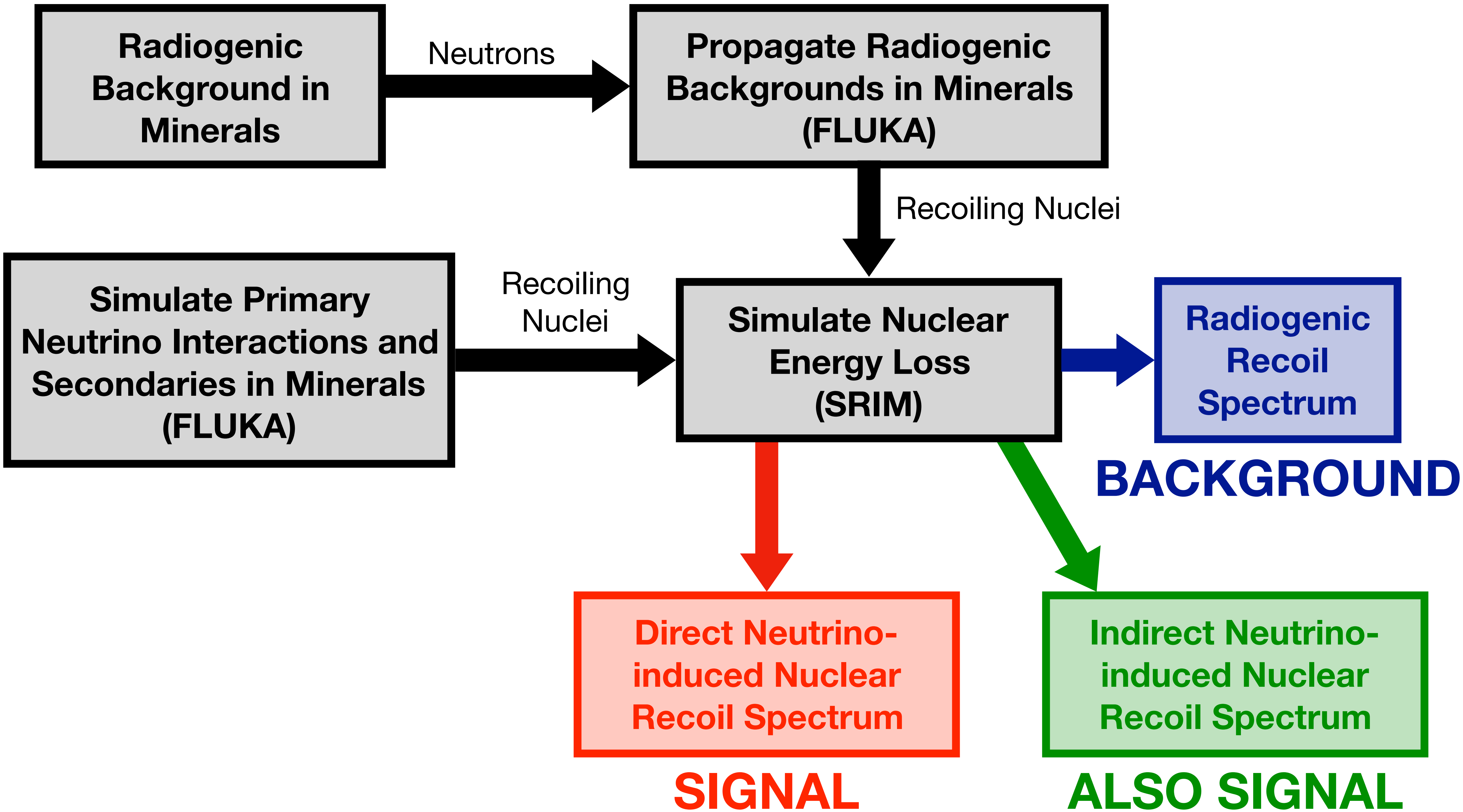
primary interaction and secondary propagation/ interaction simulated with FLUKA

Atmospheric neutrinos

Particles Responsible for > 1 MeV nuclear recoils

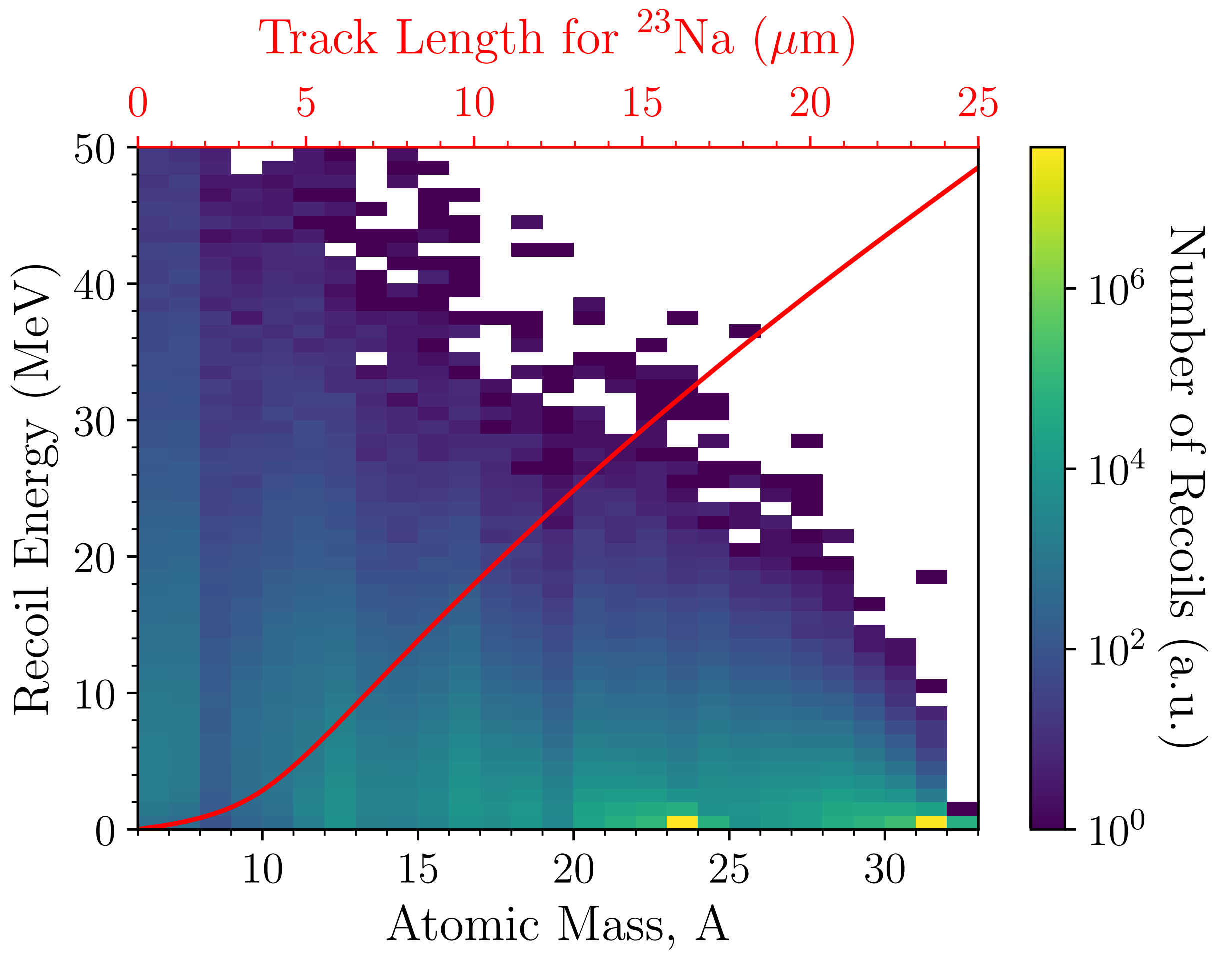


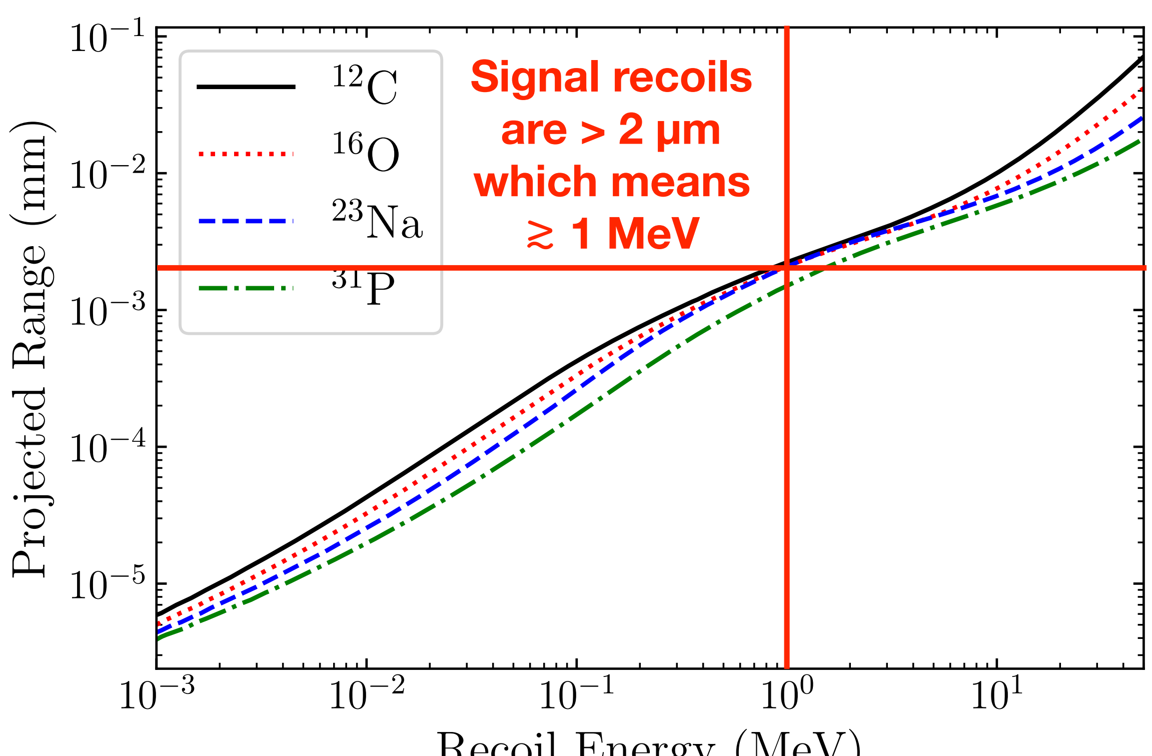
Secondaries mainly come from neutrons



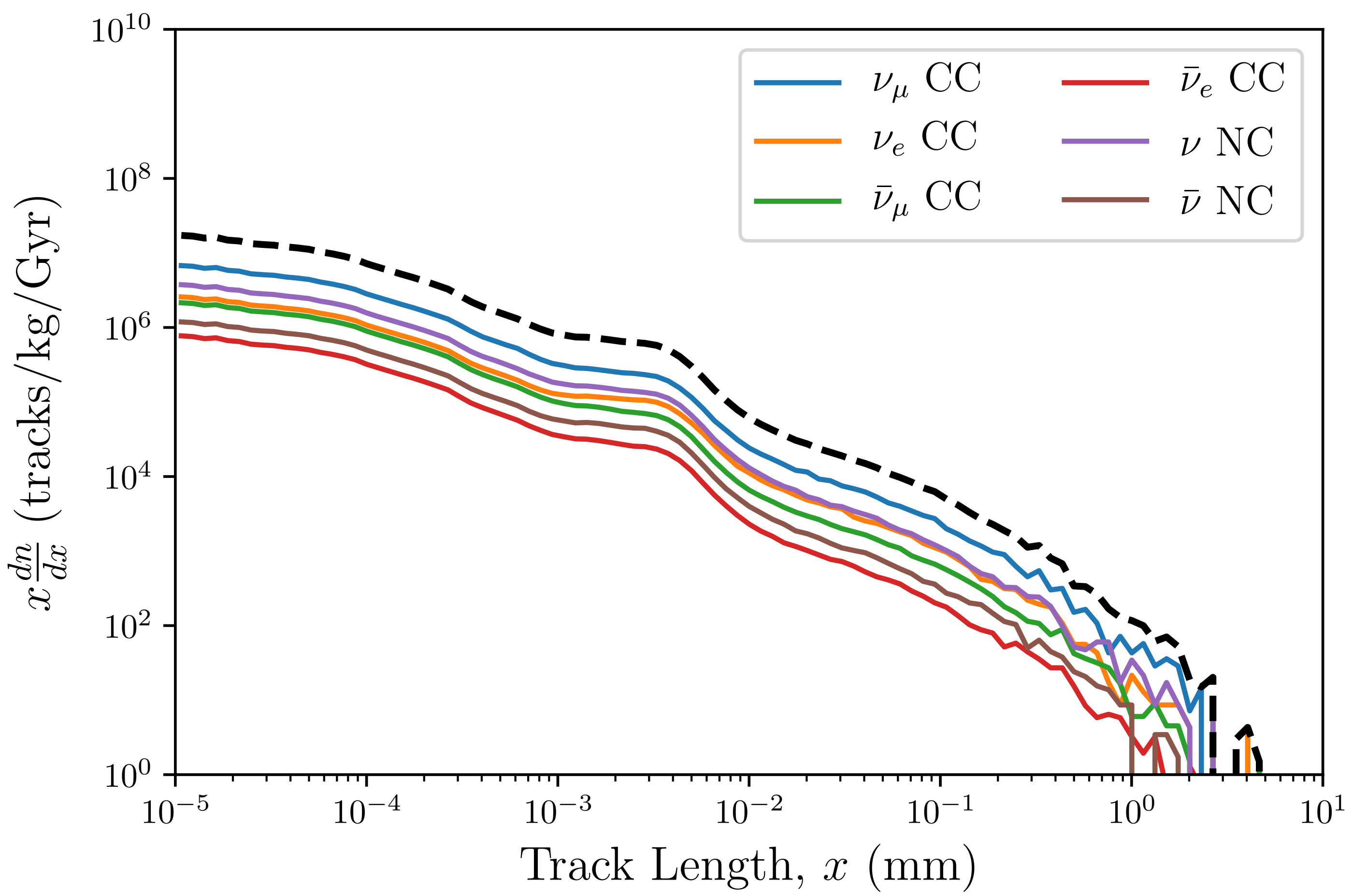
-Radiogenics leading to neutrons simulated with SOURCES
-Spontanteous fission simulated with FREYA

From recoil energy to track length



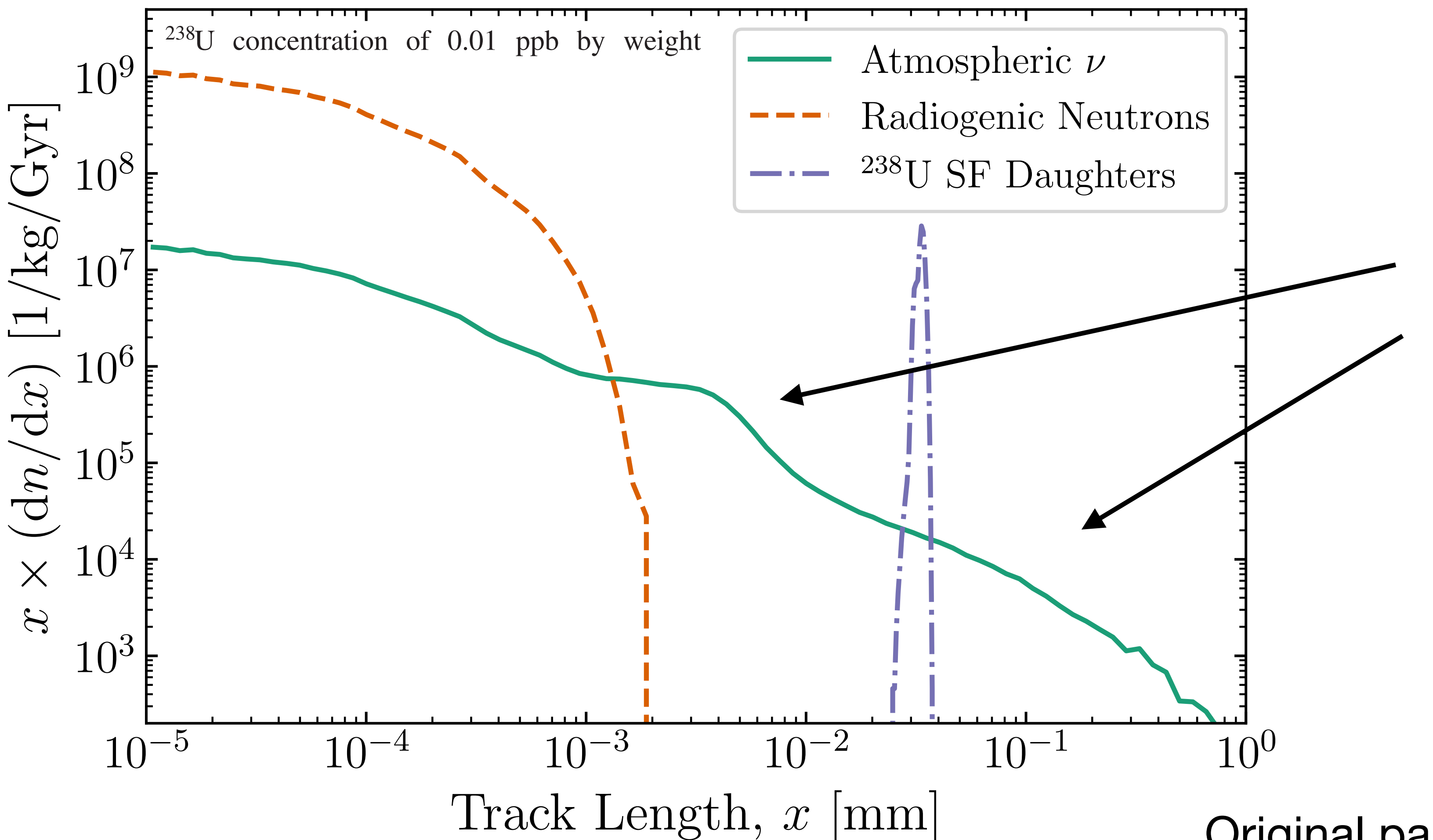


SRIM-based



Original paper featured Halite (NaCl).
Our focus is now on Olivine.

Signal and background

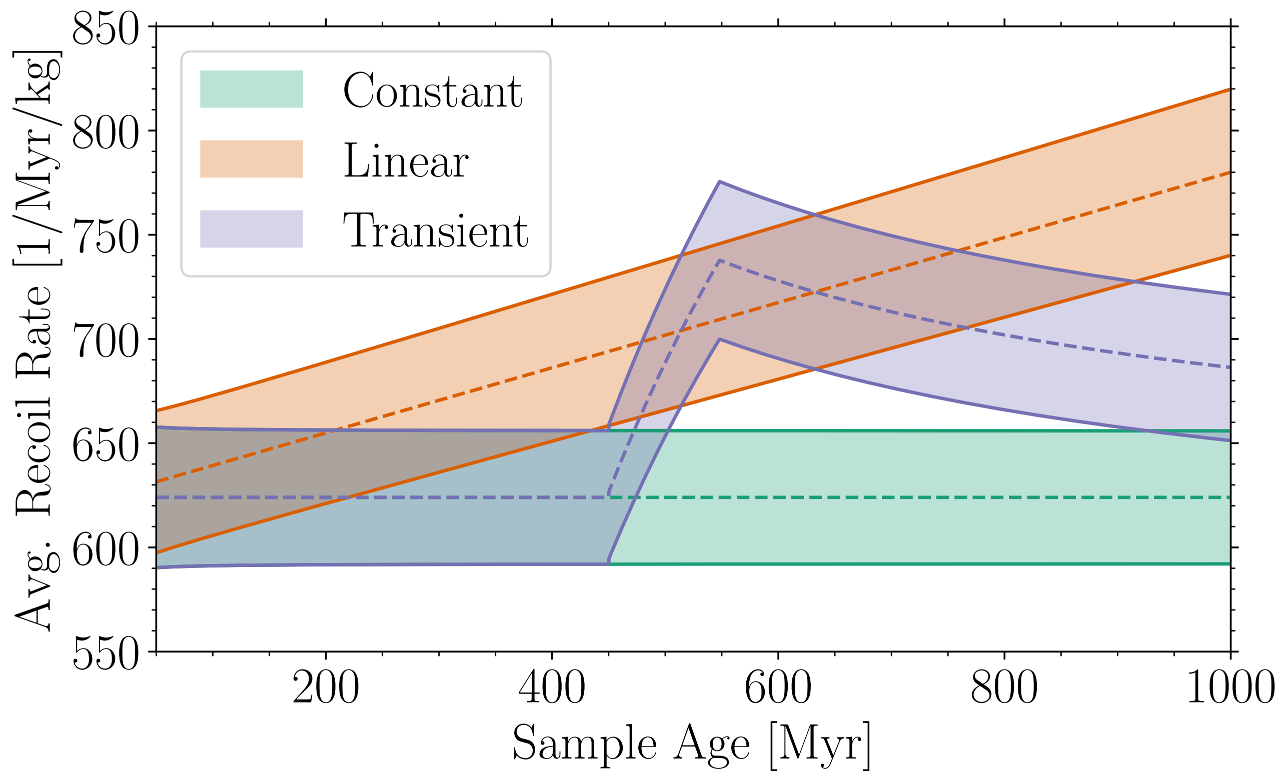


Original paper featured Halite (NaCl).
Our focus is now on Olivine.

- For a 100 g, 1Gyr sample (NaCl):
  - 60,000 total tracks [2-20 um, 50-1000 um]
    - About 75% of >1 um tracks are from secondary nuclear recoils (from neutrino products).

Sensitivity to rate change

- Obtain a few samples of rocks with different ages.
- Count atmospheric neutrino induced recoils.
  - Already systematics limited with a 0.5 g, 1 Gyr sample (300 events)!



$$\Delta_t = 5\% \text{ and } \Delta_M = 1\%$$

Dating precision

Mass/efficiency precision

- Example ‘Linear’ change -> linearly decreasing by 50% over 1 Gyr
- Example ‘Transient’ change -> 100% flux increase for 100 Myr

Michigan paleo-detector group

Note: Looking to hire a grad student and postdoc ASAP!

Josh Spitz

Kai Sun

Cassie Little

Katie Ream

Andrew Calabrese-Day

Imaging strategy

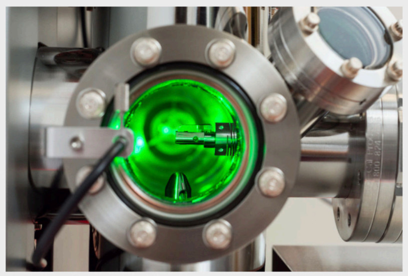
- The tracks **are there** and there are **a lot** of them (60k per 100 g, 1 Gyr).
  - Cleave and etch can be used to find these tracks. But, a dream is to be able to find dense vacancy locations with X-rays!
    - Put rock in machine, scan, use software to find tracks.
- In theory, the resolution of these devices is capable of finding tracks, at least in the longitudinal direction. But, are tracks ‘visible’ without etching? The vacancies are there, but is ‘contrast’ high enough to see these thin tracks?
- Current strategy: find ROI with nano/micro-CT, confirm with TEM.

MICHIGAN ENGINEERING
MICHIGAN CENTER FOR MATERIALS CHARACTERIZATION

Search

Home | People | Use & Service | Instruments | Training Videos | News & Events | Education & Outreach

MICHIGAN CENTER FOR MATERIALS CHARACTERIZATION > TECHNIQUES AND INSTRUMENTS



Techniques and Instruments

Specimen Preparation

- Equipment

Scanning Electron Microscopy (SEM)

- TESCAN MIRA3 FEG SEM
- TESCAN RISE

Scanning Electron and Focused Ion Beam Instruments (SEM/FIB)

- Thermo Fisher Nova 200 Nanolab SEM/FIB
- Thermo Fisher Helios 650 Nanolab SEM/FIB
- Thermo Fisher Helios G4 PFIB UXe

Transmission Electron Microscopy

- Thermo Fisher Spectra 300 Probe-Corrected S/TEM
- Thermo Fisher Talos F200X G2 S/TEM
- Thermo Fisher Tecnai G2 F30 TWIN Electron Microscope
- JEOL 3100R05 Double Cs Corrected TEM/STEM

Atom Probe Tomography

- Cameca LEAP 5000HR

3D X-ray Microscopy

- Zeiss Xradia Versa 520 3D X-ray Microscope with DCT module

Atomic Force Microscopy

- Veeco Dimension Icon AFM

X-ray PhotoElectron Spectroscopy

- Kratos Axis Ultra XPS

QUICK LINKS

- Become a User
- Instrument Scheduling
- Other Facilities
- Contact Staff

Search

Search

SOCIAL

Also: Zeiss micro-CT with 16 nm voxel resolution coming soon!

Michigan Ion Beam Lab

1.7 MV and 3 MV tandem particle accelerators w/ multiple species (H, He, D, O, Ar, Ni, Mg, Si, Fe, etc.)

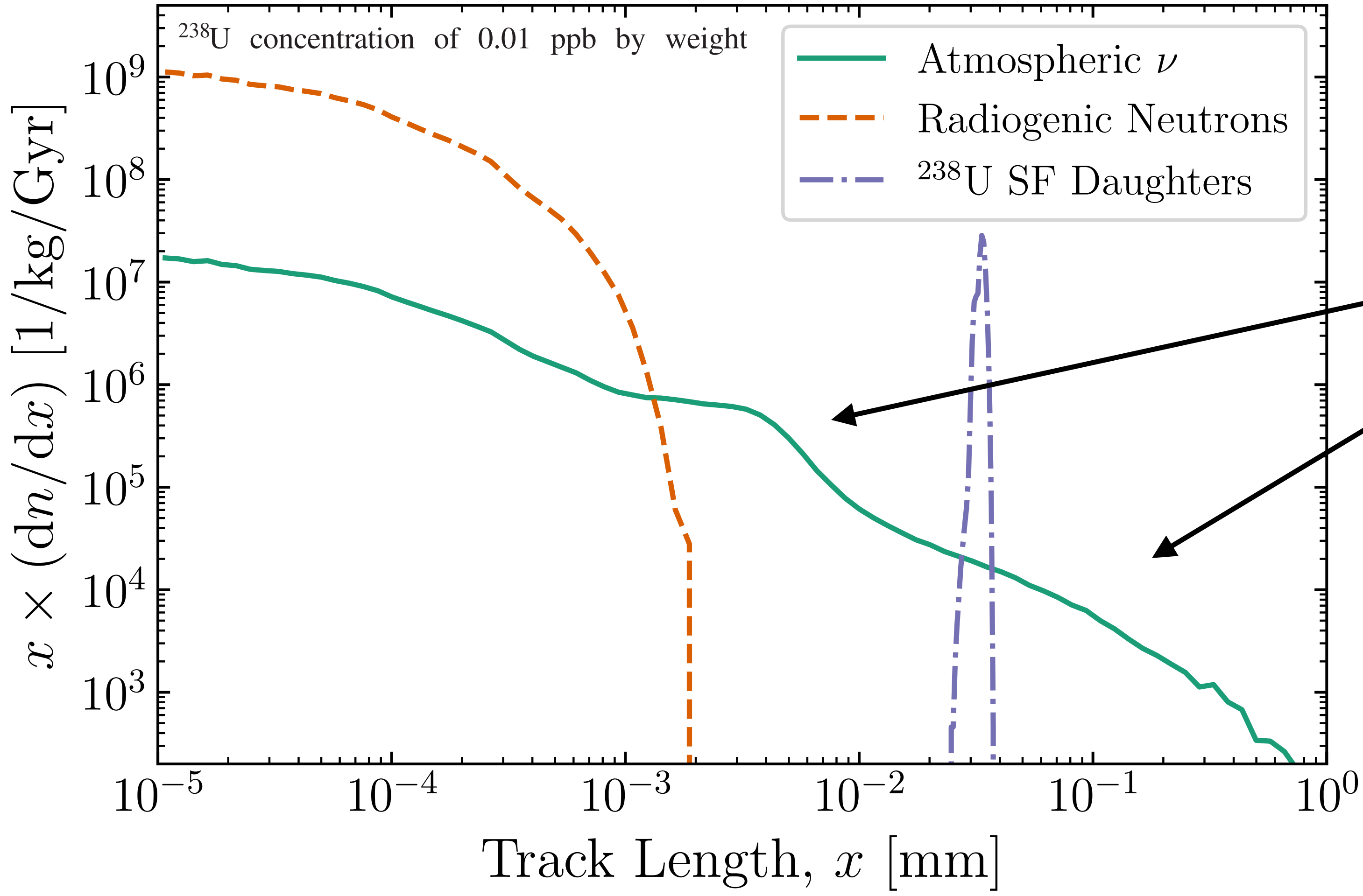
Michigan group goals

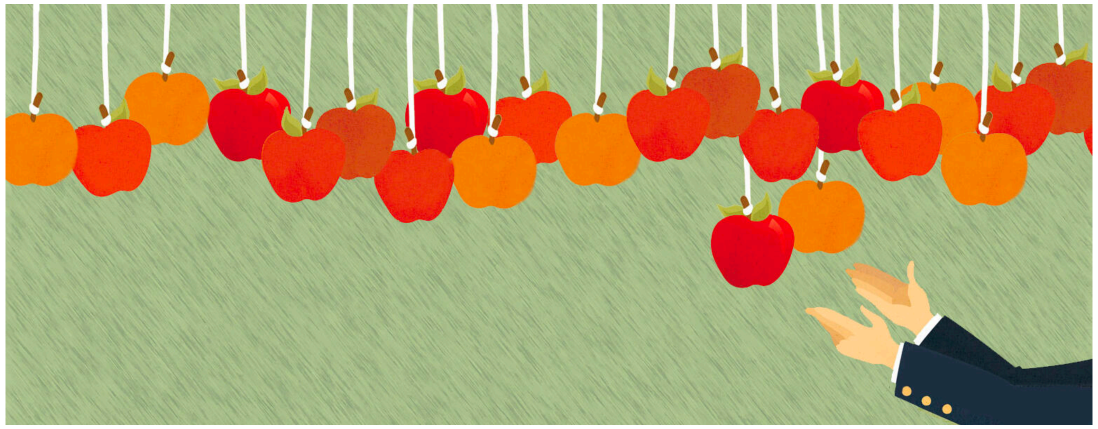
- What are the properties of characteristic atmospheric-neutrino-induced primary and secondary nuclear-recoil damage tracks in olivine, in terms of longitudinal and transverse width and energy deposition (stopping power)?
- Can the recoiling nucleus be reliably identified using the energy deposition properties of the track?
- Are typical mineral fractures and other imperfections in the minerals an issue for imaging?
- What is the optimal mineral imaging strategy in consideration of track resolution (including length and direction), detection thresholds and efficiency, backgrounds, and throughput (or, mass scanned per unit time)?
- Can multiple nuclei from a single vertex, as expected for some neutrino events, be efficiently imaged?
- What is the optimal data handling, pattern recognition, and overall computing strategy for analyzing tracks?
- What is the rate of track fading/annealing when a sample is exposed to high temperatures?
- Are there (currently unexpected) edge events in which a background fast-neutron induced nuclear recoil track can mimic a signal neutrino-induced event or interfere with pattern recognition?
- Is olivine optimal for these studies? Or, should another mineral be considered?
- What is the detailed plan, including logistics, personnel, instrumentation, industrial collaboration, etc., for extracting comparable minerals from boreholes at different locations, and then analyzing them in the lab?

Michigan group progress

- We are just getting started (9/2023).
- See Kai's talk!
  - TLDR;
    - We have started taking some pictures of Olivine with micro-CT (0.7 um resolution) and TEM.
    - Olivine composition analysis with SEM+EDS.
    - Preparing to implant ions.
    - Awaiting "16 nm voxel" CT machine.

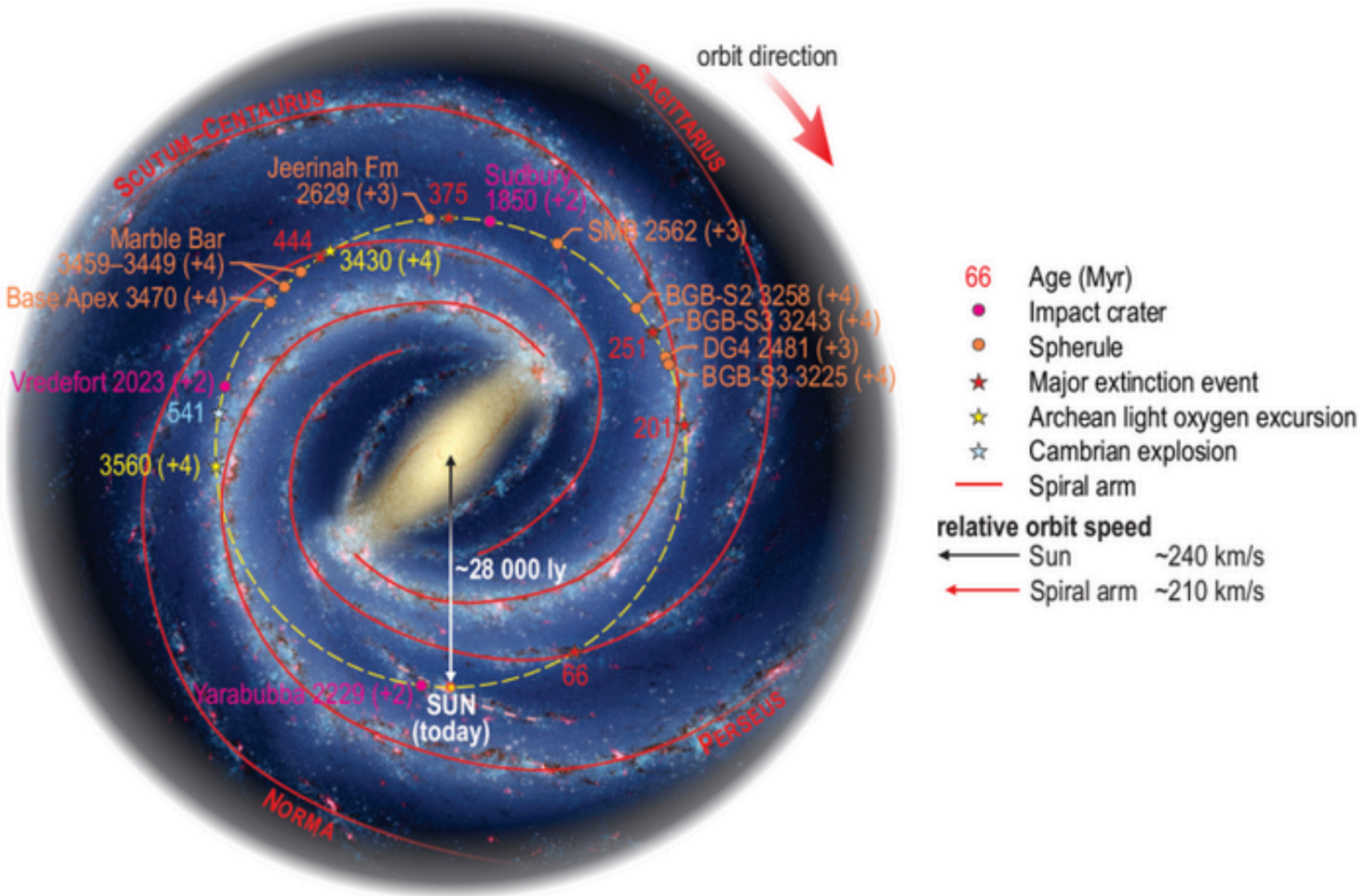
Atmospheric neutrinos; Let's measure these!





Signal windows

Backup



Credi

Spiral Galaxy from Kirkland et al.

« Movement of the solar system through the Milky Way's galactic spiral arms helped form Earth's first continents