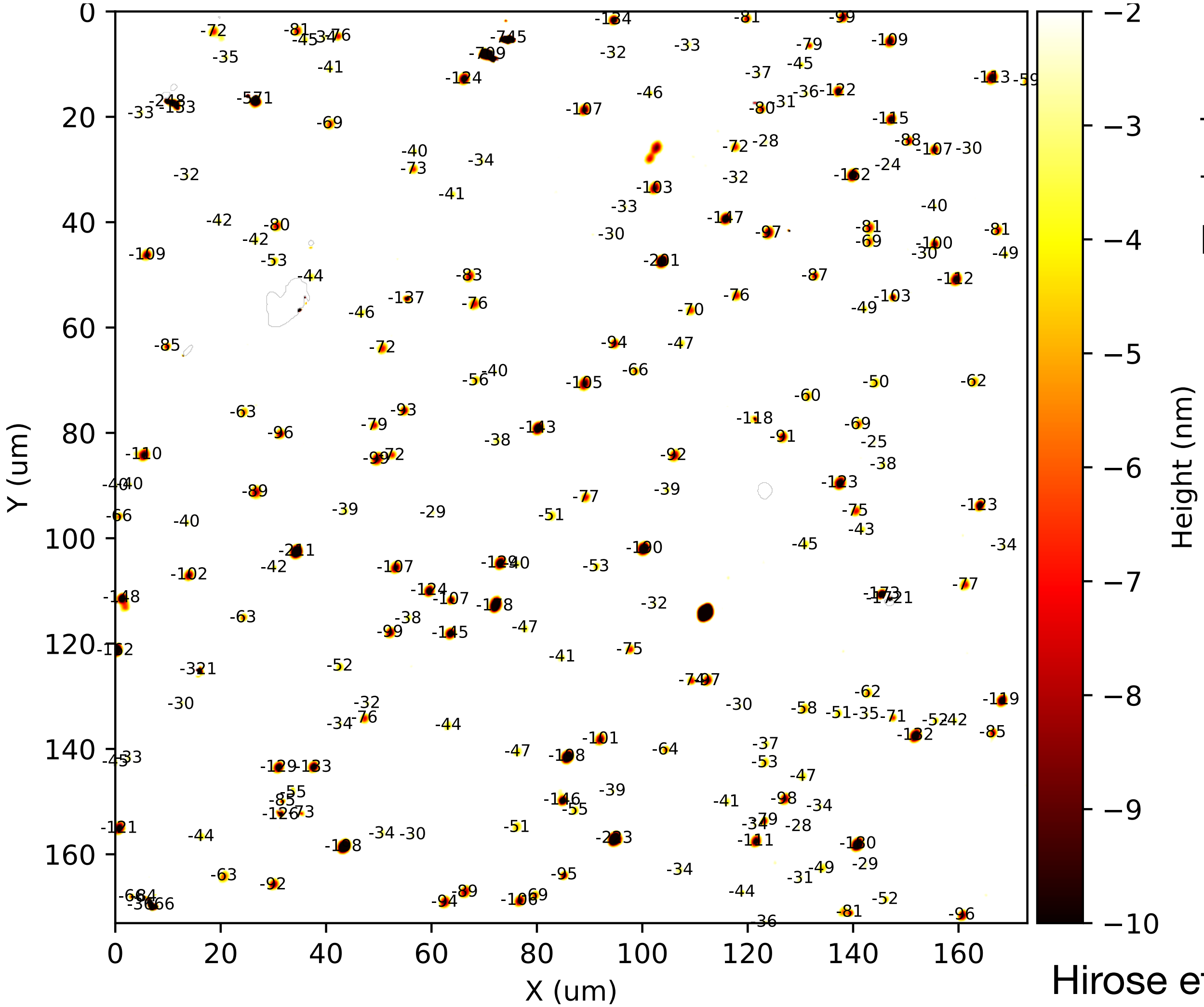
Discussion

Analysis and Simulation Tools for Mineral Detection

MDvDM'24

Pit measurement using an optical profiler



173umx173um with 1000x1000 px

The numbers are the heights in Å of the deepest pixels in clusters passing a 20 Å, 16 pixels

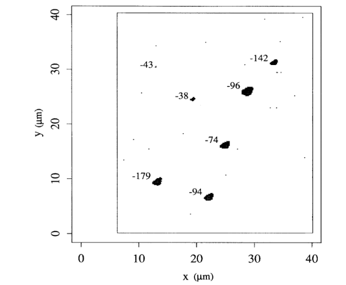


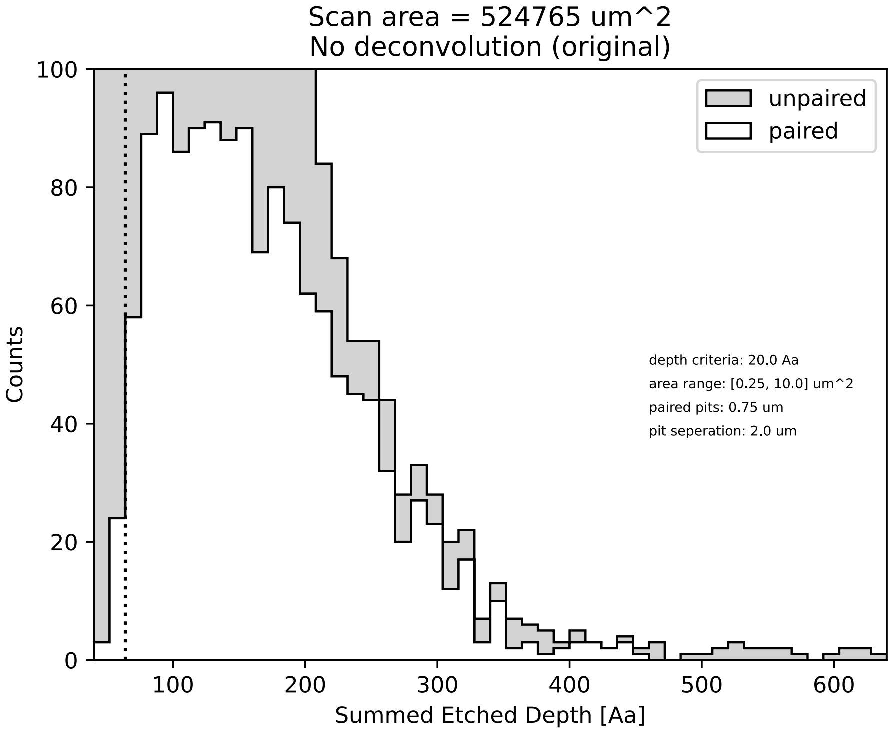
FIG. 2. A processed AFM image. The numbers are the heights in Å of the deepest pixels in clusters passing a 20 Å, 3 pixel cut.

40umx40um with 256x256 px
Snowden-Ifft et al. 1995

Hirose et al. in prep

DMICA has tentatively processed mica of 524,765 um^2, 6.5x Snowden-Ifft et al.

DMICA: 524,765 um^2 scan
(1.5 min. / 6.5e-6 ton yr = 0.45 yr / 1 ton yr)



Hirose et al. in prep

Snowden-Ifft et al. 1995: 80,720 um^2 scan

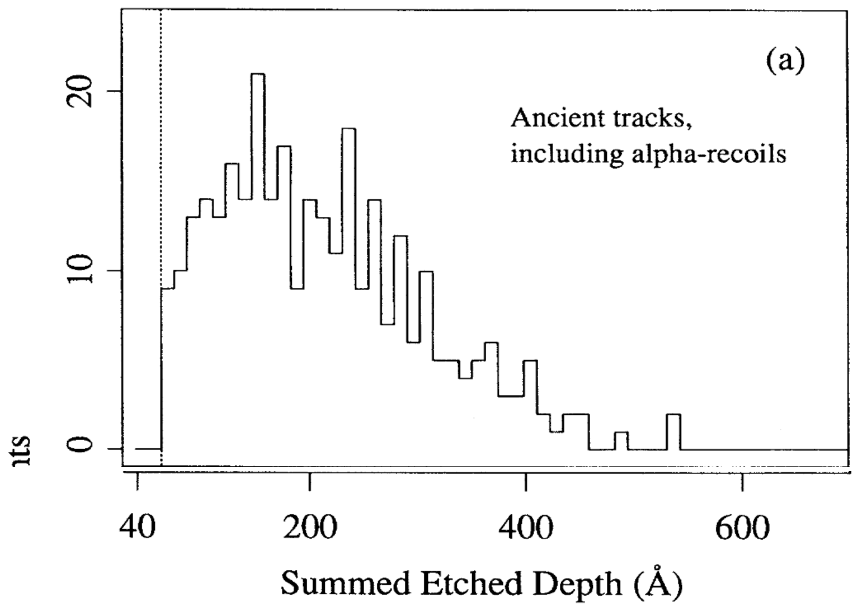
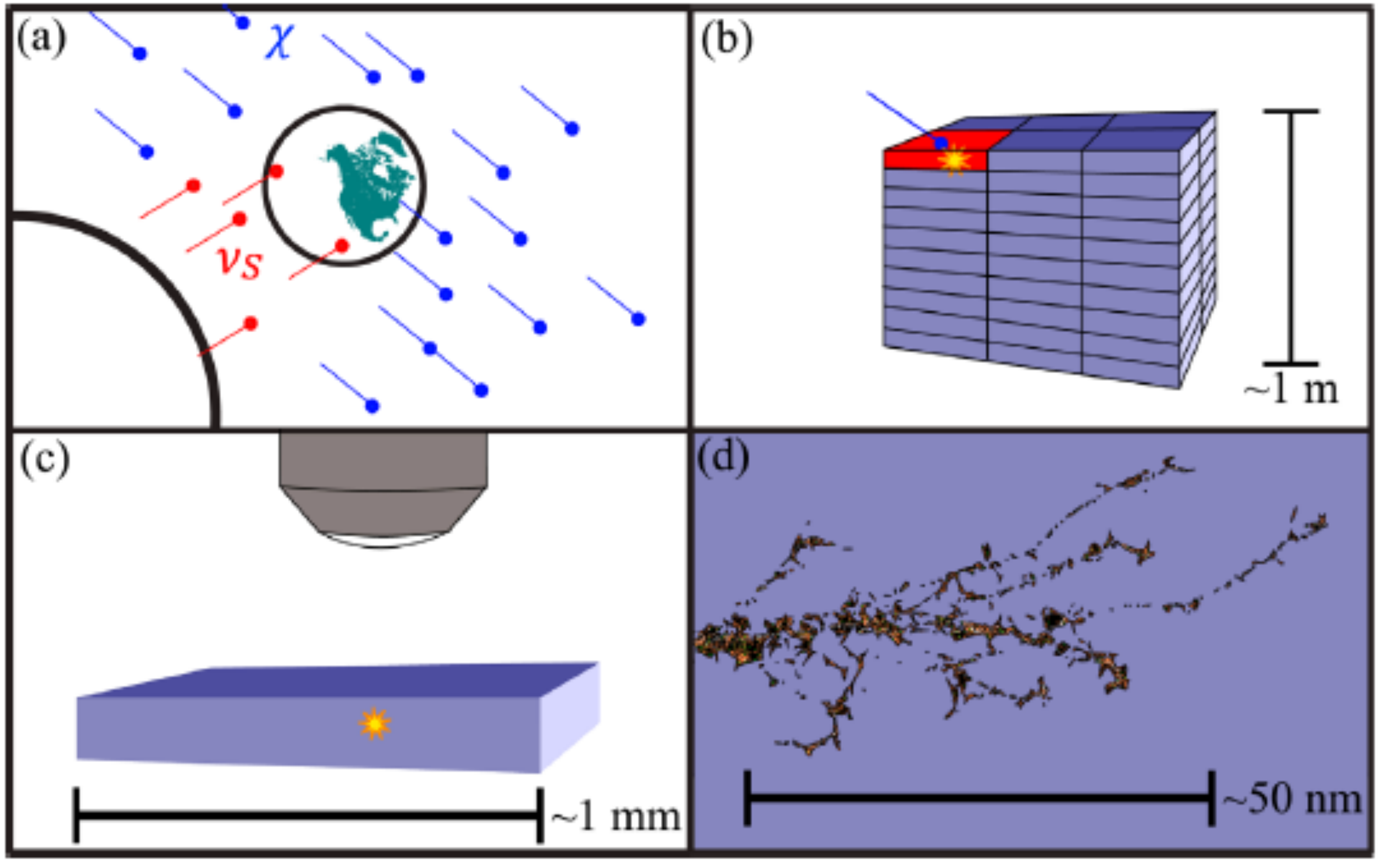


FIG. 3. (a) The summed etched depths of tracks recorded in a 80 720 μm^2 scan of 0.5 Gyr old muscovite mica. No events appear between our cutoff of 40 and 64 Å (shown with a dashed vertical line). (b) The solid line shows the summed depths of etched neutron-recoil tracks. The dashed line shows the results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

General detector requirements

- Low background diamonds
  - No pre-existing features that resemble WIMP tracks
- Imaging with high resolution
- Fast and efficient scanning to keep up with event rate
  - Goal: complete stages 1-3 in < 3 days



Stage 3 alternative method: super-resolution spectroscopy of NV centers

- Image damage track by looking at strain shift on single NVs in its vicinity
  - Employ pattern recognition/machine learning techniques to determine initial recoil detections
  - Optimize density of NVs (typically $1/(30\ \text{nm})^3$) based on damage track size
- Requires optical microscopy below the diffraction limit
  - Super-resolution NV imaging techniques have been previously developed in our group
- Advantage: setup could be deployed locally near DM detector

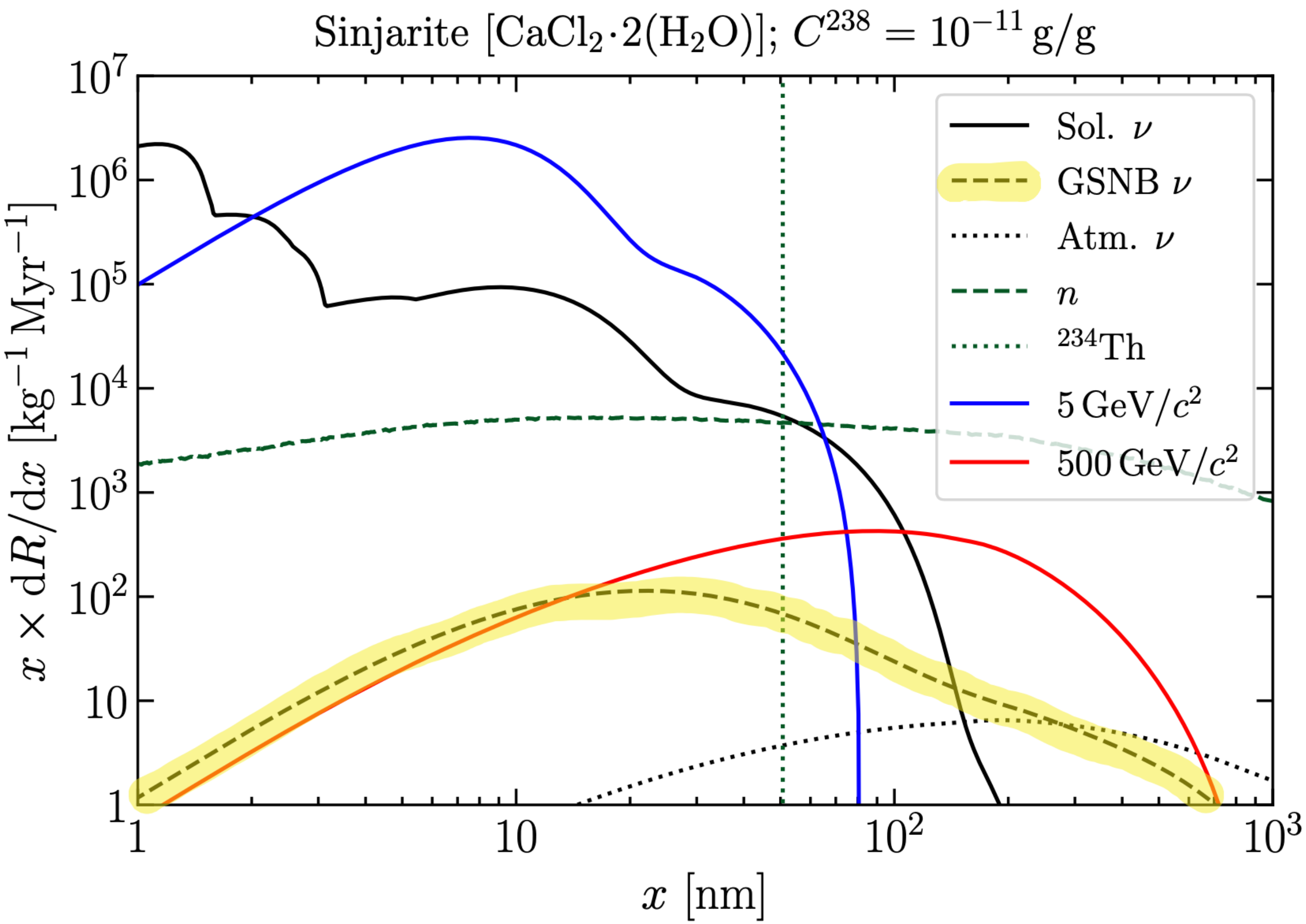
Michigan group goals

- 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?

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.

What about mineral detection for ***prompt*** Galactic supernova ***burst*** detection?



For 10 kpc SN, get few-10s of fresh ns-μs tracks per ton in ~10s of seconds

2023 Mineral Detection white paper

Can we find them promptly?

What would it take to go after these?

- **ton scale** or more of target
- **~nm track resolution**
- ability to scan/monitor/interrogate entire target on short timescale
  (minutes best!... at least hours... days maybe OK)
  → **ton/hour**
- freshly annealed/blank target (integrated paleo SN signal is bg!)
- low ambient and cosmogenic background
  (probably, underground location)
- external prompt trigger (SNEWS) could be possible

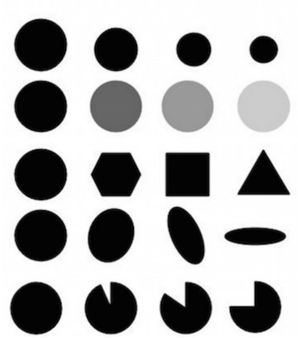
How to do this? Is this completely crazy?

- I don't know ... seems to need 10^6-10^9 scale up of some of the ideas from this workshop...
- Multi-modal/hybrid approach? i.e., zoom in on ROI to scan small volume (emulsion detector style)

Reconstructing Nuclear Recoil Damage Tracks

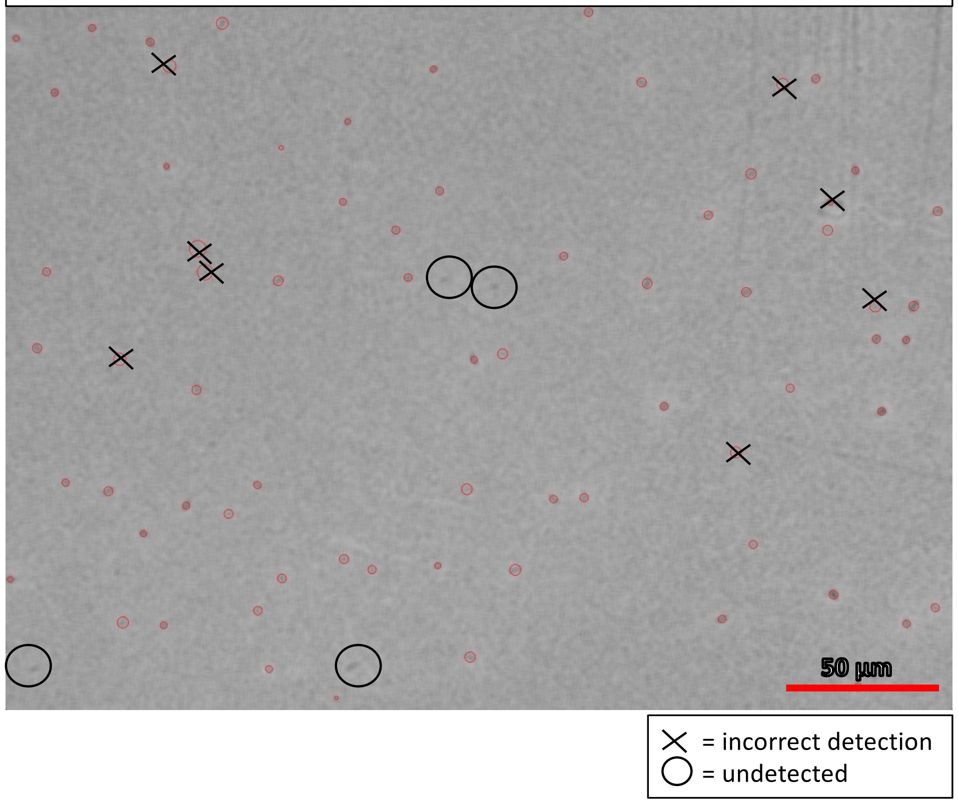
Automatic Track Detection Code

- Python code to automatically detect track-like shapes ('blobs') in greyscale images (OpenCV library)
- Significantly cuts down time finding & measuring tracks
- Shape detection can be filtered by
  - Pixel area
  - Color (contrast)
  - Circularity
  - Inertia Ratio
  - Convexity



- Successful for images with little noise
  - Sometimes encounter incorrect detection or undetected tracks in noisy images

Code output: detected tracks circled in a laser image of halite



Reconstructing Nuclear Recoil Damage Tracks

Automatic Track Detection Code

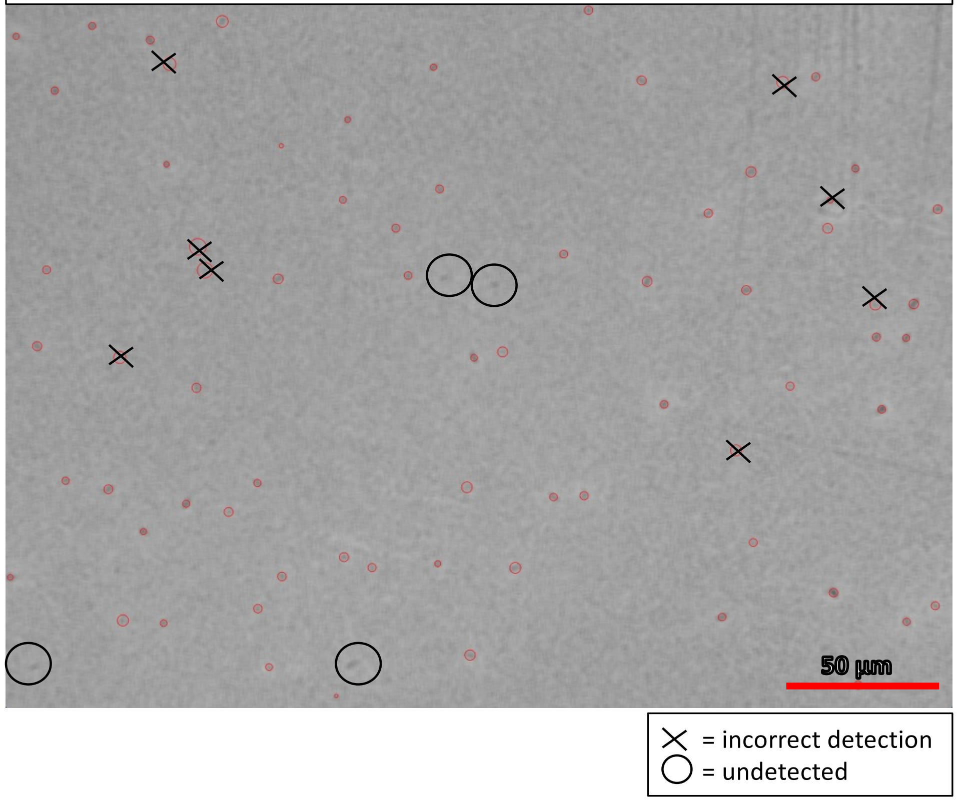
Code input:

1. Greyscale laser image (no scale bar or labels!)
2. Height information per pixel in .csv format
3. User-given magnification (50 or 150)

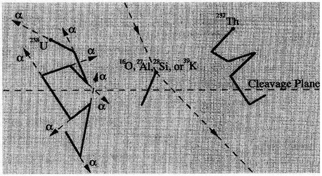
Code output:

1. Statistical profile.csv
    1. Number of tracks detected
    2. Dimensions (diameter and depth) & aspect ratio
    3. Various roughness calculations
    4. Imaging parameters
2. 'Blob map' (circled tracks and corresponding number to .csv output)
3. Histogram of track diameters and depth

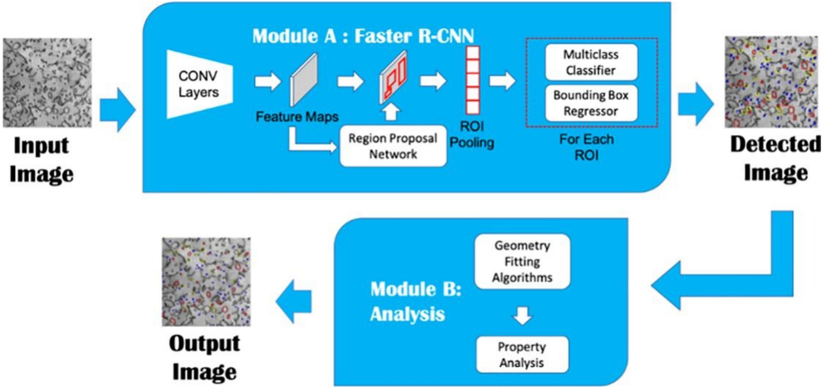
Code output: detected tracks circled in a laser image of halite



Recognition of sparse tracks is a data analysis challenge

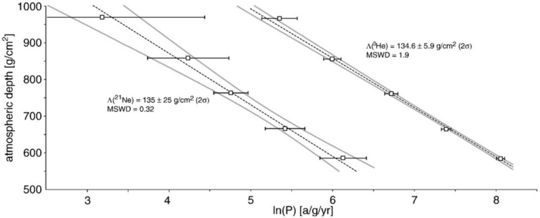


- 15 nm resolution of 100 g sample $\Rightarrow 10^{19}$ mostly empty voxels
- 1 Gyr old with $C^{238} = 0.01$ ppb $\Rightarrow 10^{13}$ voxels for α-recoil tracks



Our plans

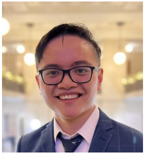
1. Systematic investigation of scanning methodologies - the key to unlocking larger target masses with more precision:
   1.1 Using previously listed local/national facilities.
   1.2 Machine-learning enhanced analysis pipelines.
2. One scientist's background is another's signal:
   2.1 Expose samples to cosmic-rays/artificial sources. ART analysis.
   2.2 Assess the backgrounds to physics signals, while at the same time expanding their use as geochronological tools.



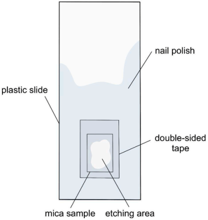
left: ARTs under the SEM, right: cosmogenic ^{3}He and ^{21}Ne in artificial quartz targets (`http://dx.doi.org/10.1016/j.epsl.2009.05.007`)

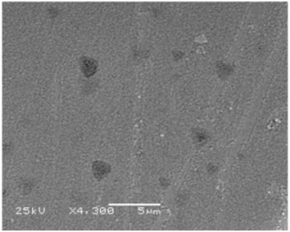
MSci project 2022-23

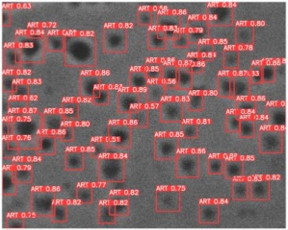
1. Perform some preliminary experiments with mica etching and microscopy. We are confident that we can see alpha recoil track signatures.
2. Initial attempts at machine-learning approaches to the analysis of microscope images.



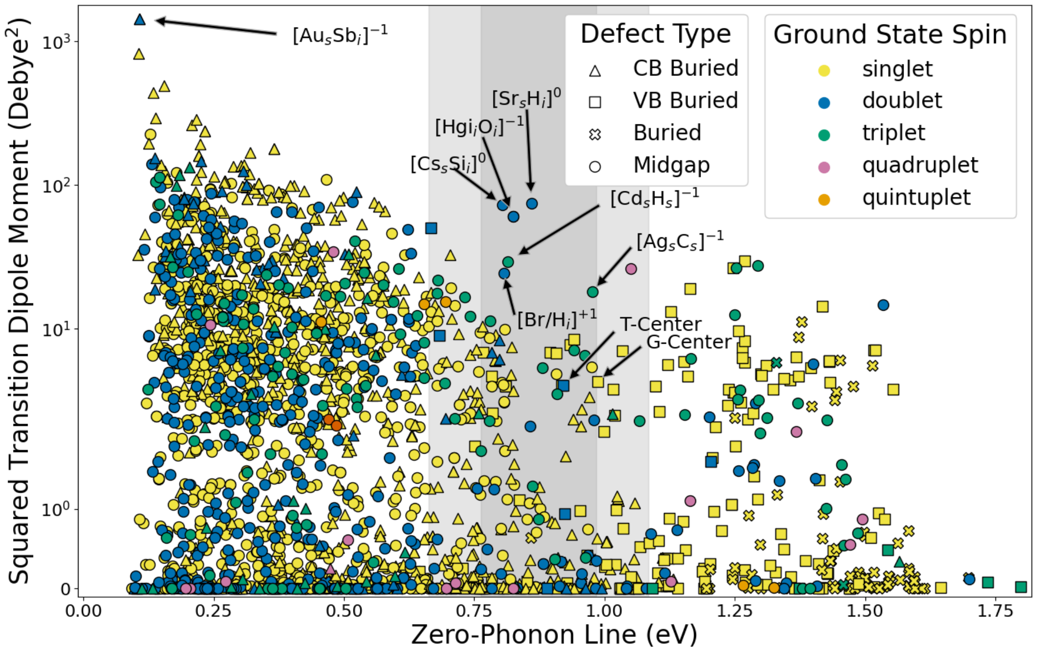
Tiemothy Wuisan







Database of Quantum Defects



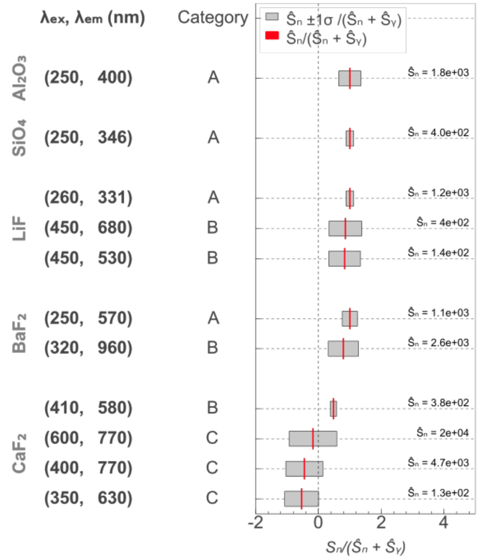
~50,000 Multi-element defects →

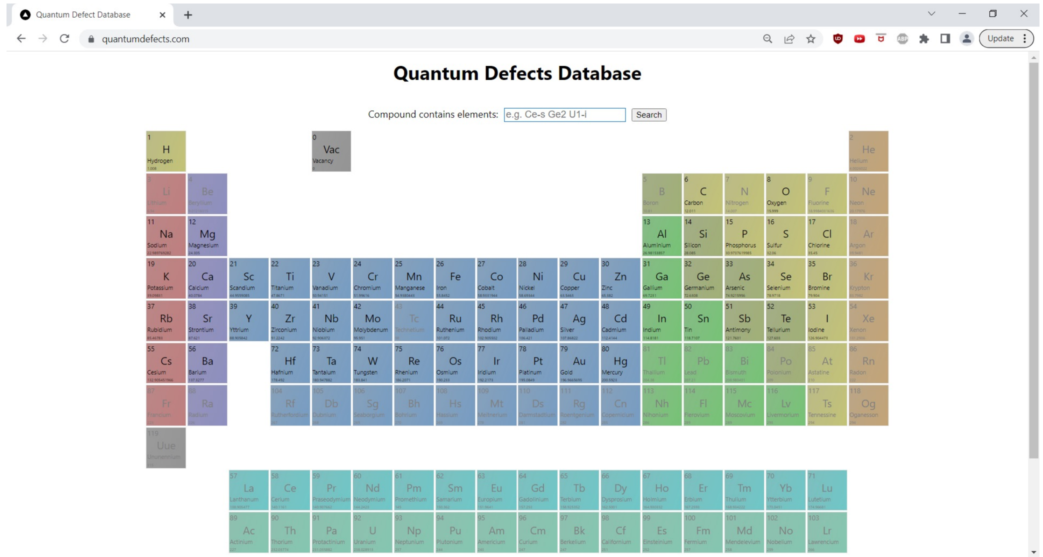
- Opportunities to explore elemental interactions & chemistry
- Many new candidates for spin-photon interface (spin qubit) and bright single-photon sources!

quantumdefects.com

Database of Quantum Defects

arXiv:1902.10668 →





Phys. Rev. Applied **16**, 064060x

material	A [u]	m_A [%]	density [g cm^{-3}]	melting point [K]	TDE [eV]	$E_{1/2}$ [eV]	CEvNS events	selection efficiency [%]	usable events
LiF	19.0	73.2	2.64	1120	27	80	5600	75	4200
BaF_2	137.3	78.3	4.88	1625	35	105	48800	20	9600
NaI	126.9	85.0	3.67	935	24	65	46900	32	15100
CsI	132.9	~100	4.51	900	23	55	55700	37	20600
$CaWO_4$	183.8	63.9	6.06	1895	41	110	55400	8	4600
$Bi_{12}GeO_{20}$	209.0	86.4	9.22	1175	28	85	83500	17	14000

quantumdefects.com

Paleo-Detectors at KIT

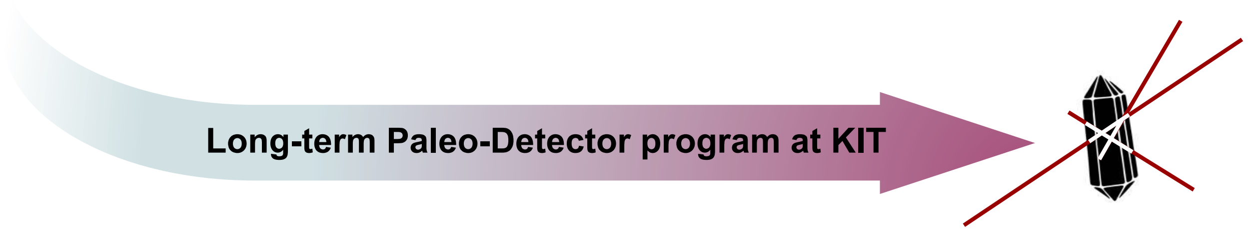
1. **Mineral Selection & Preparation**
   - ➢ Range of minerals - sensitivity predictions, input from geology, microscopy
   - ➢ Muscovite (blank), Biotite (irradiated with Xe ions) - as a starting point

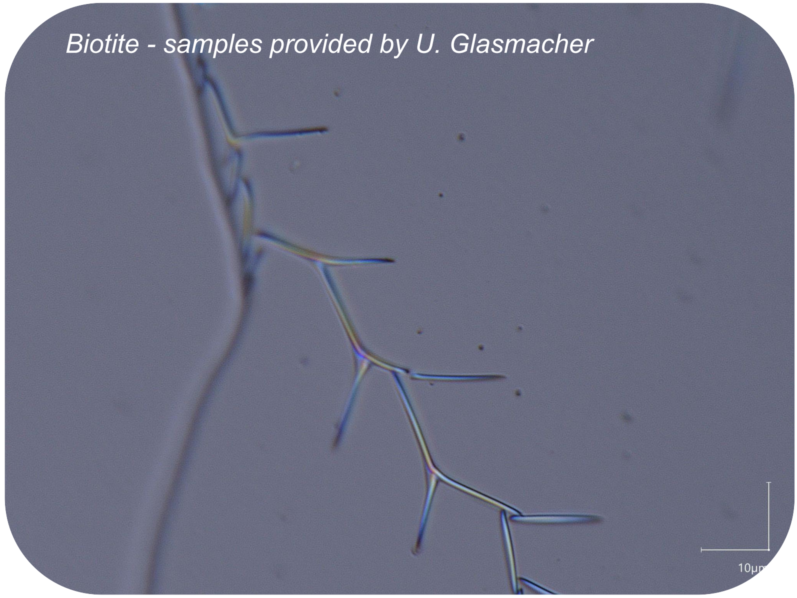
2. **Calibration - Track Production**
   - ➢ Local lab - anneal samples
   - ➢ ^{252}Cf (n ~2.2 MeV), ^{241}AmBe (n 2-10 MeV) - nm & µm-scale damage features

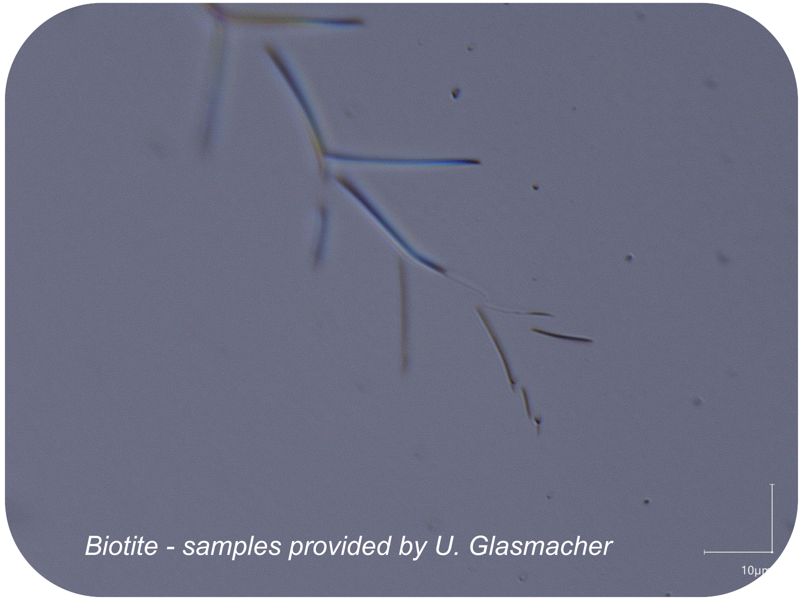
3. **Mineral & Track Imaging**

   Use & compare several microscopy techniques with nm- & µm-scale resolution

4. **Analysis & Characterization**
   - ➢ Identify & classify observed tracks using ML algorithms
   - ➢ Correlate morphology of tracks with deposited energy



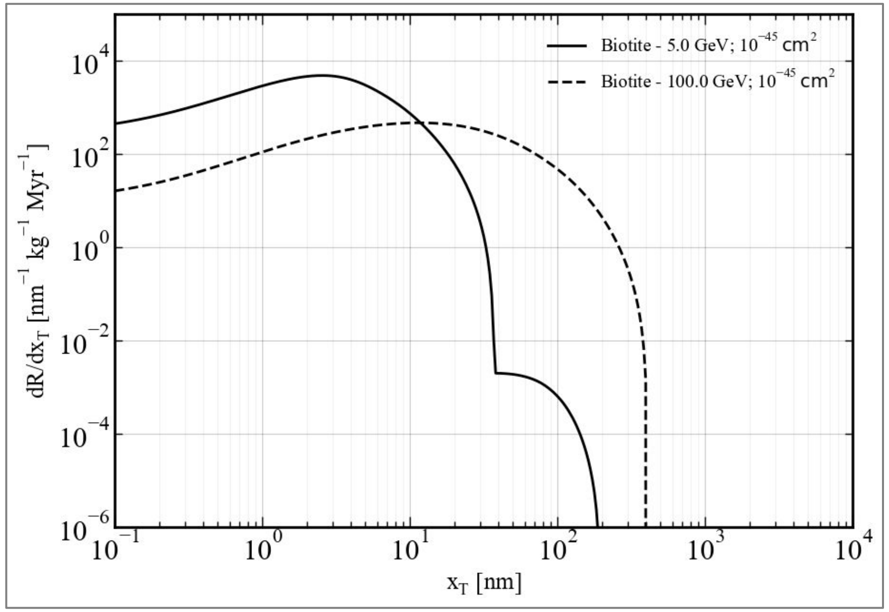

Biotite - samples provided by U. Glasmacher

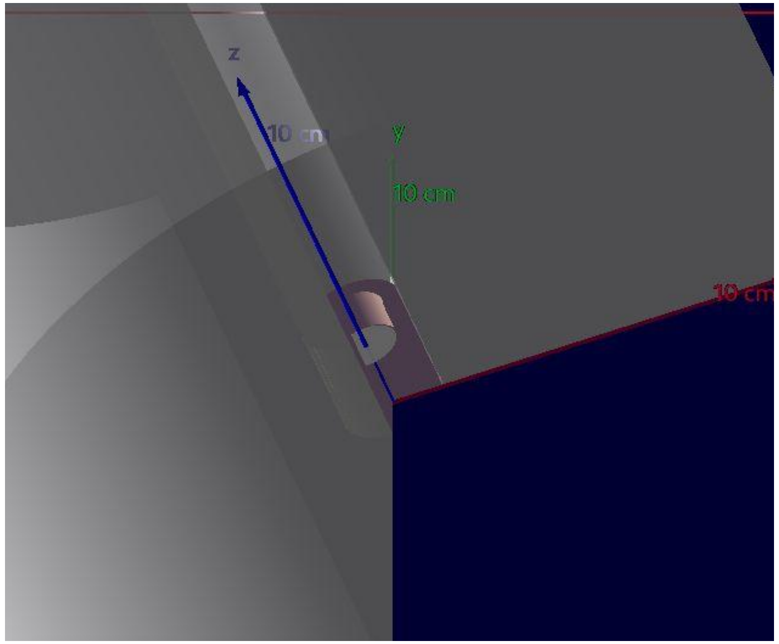

Biotite - samples provided by U. Glasmacher

Software & Simulations

- **paleoKIT**
  - Python-based
  - Imaging & physics analysis tools
  - **Ongoing**: SRIM sims of selected minerals
  - **TODO**: Sensitivity of select minerals

- **paleoSIM**
  - GEANT4 simulations
  - **Ongoing**: neutron irradiation studies using ^{252}Cf, $^{241}AmBe$
  - **TODO**: Ion & n-induced track studies

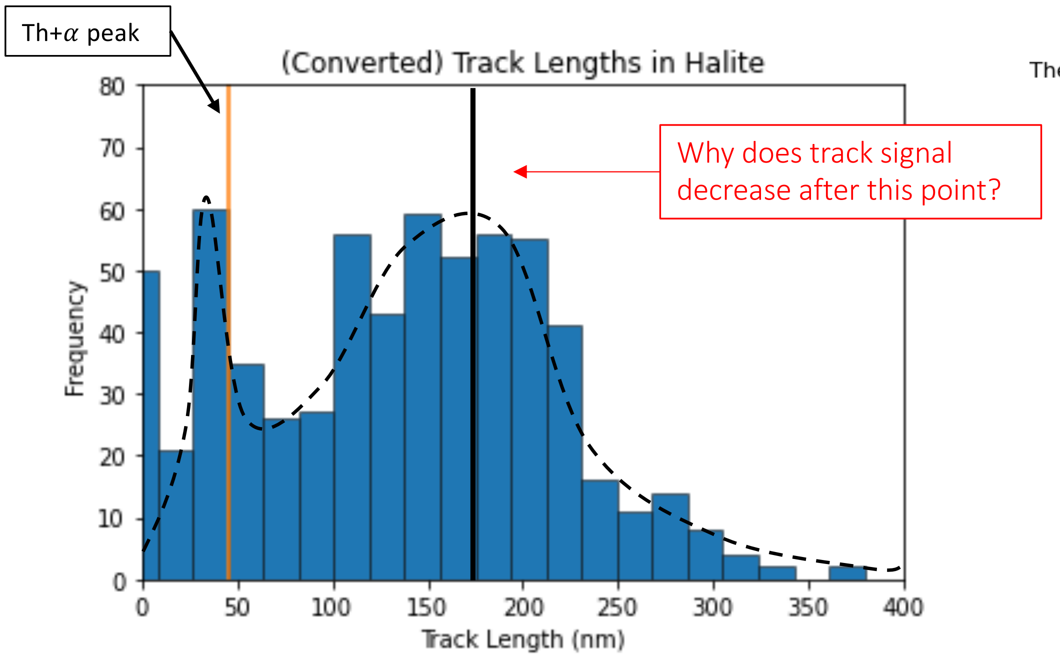


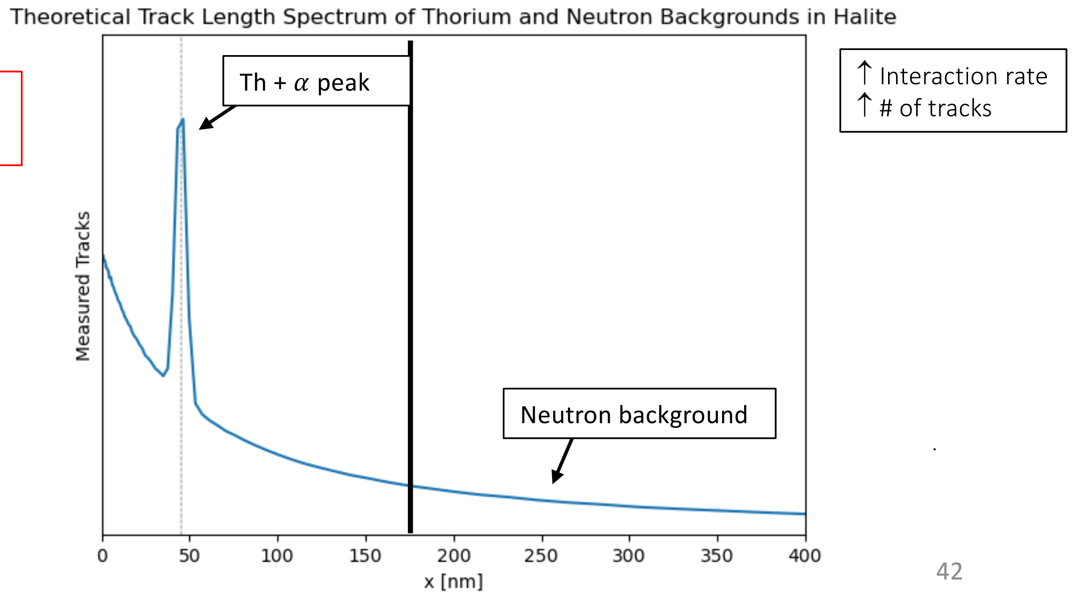


Halite Track Detector

Analysis of Experimental Data

- Both plots: peak at Th-α peak track length
- Experimental data - track signal is suppressed at a certain point, but this is not reflected in theoretical data





Halite Track Detector

Mathematical Model

$$\frac{1}{1+\ e^{-cx}} \quad \times \quad \left[\ A\ \ e^{-\frac{1}{2}\left(\frac{x\ -x_0}{\sigma}\right)^2} \quad + \quad [\ B\ \times\ neutron\ background\ ]\ \right]$$

c = slope of Sigmoid (efficiency function)

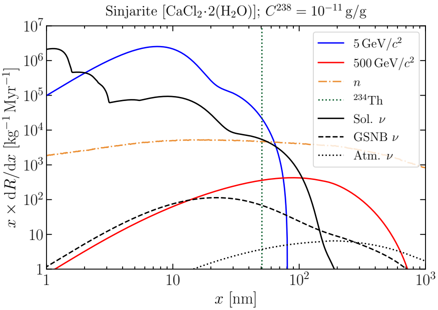
A = Amplitude of thorium background

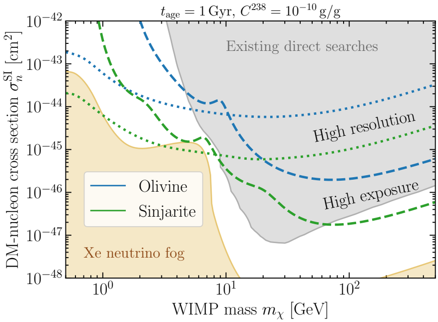
σ = width of gaussian (range of track lengths included in background)

x_0 = characteristic ~ 45 nm track length of Th-α peak

B = amplitude of neutron background

Analyze track length spectra to pick out WIMP signal





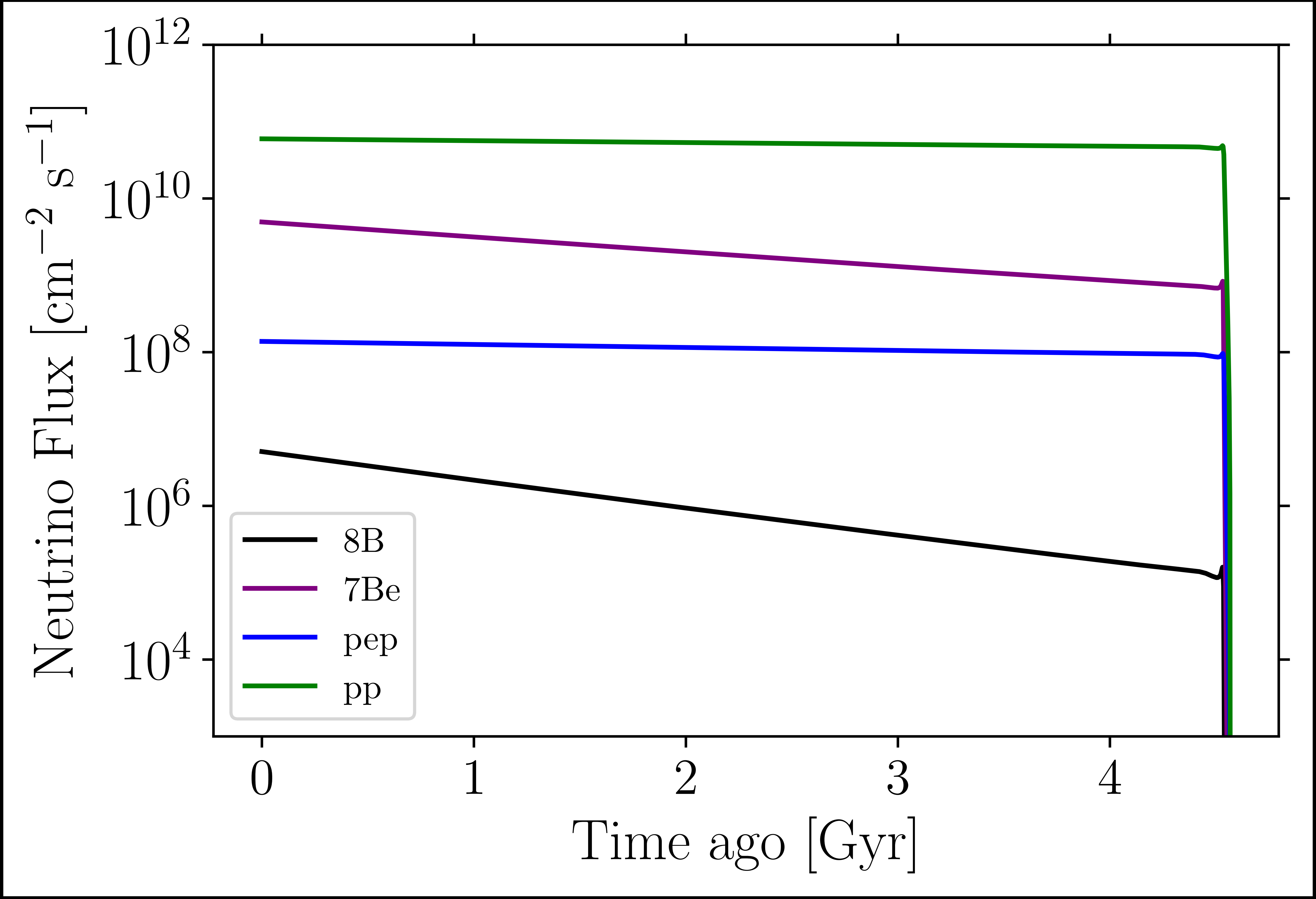
Small signal on top of background

- Use adversarial NNs to reconstruct 1α-recoil peak
- BDTs, DNNs, etc. for signal and background classification

ML techniques are critical

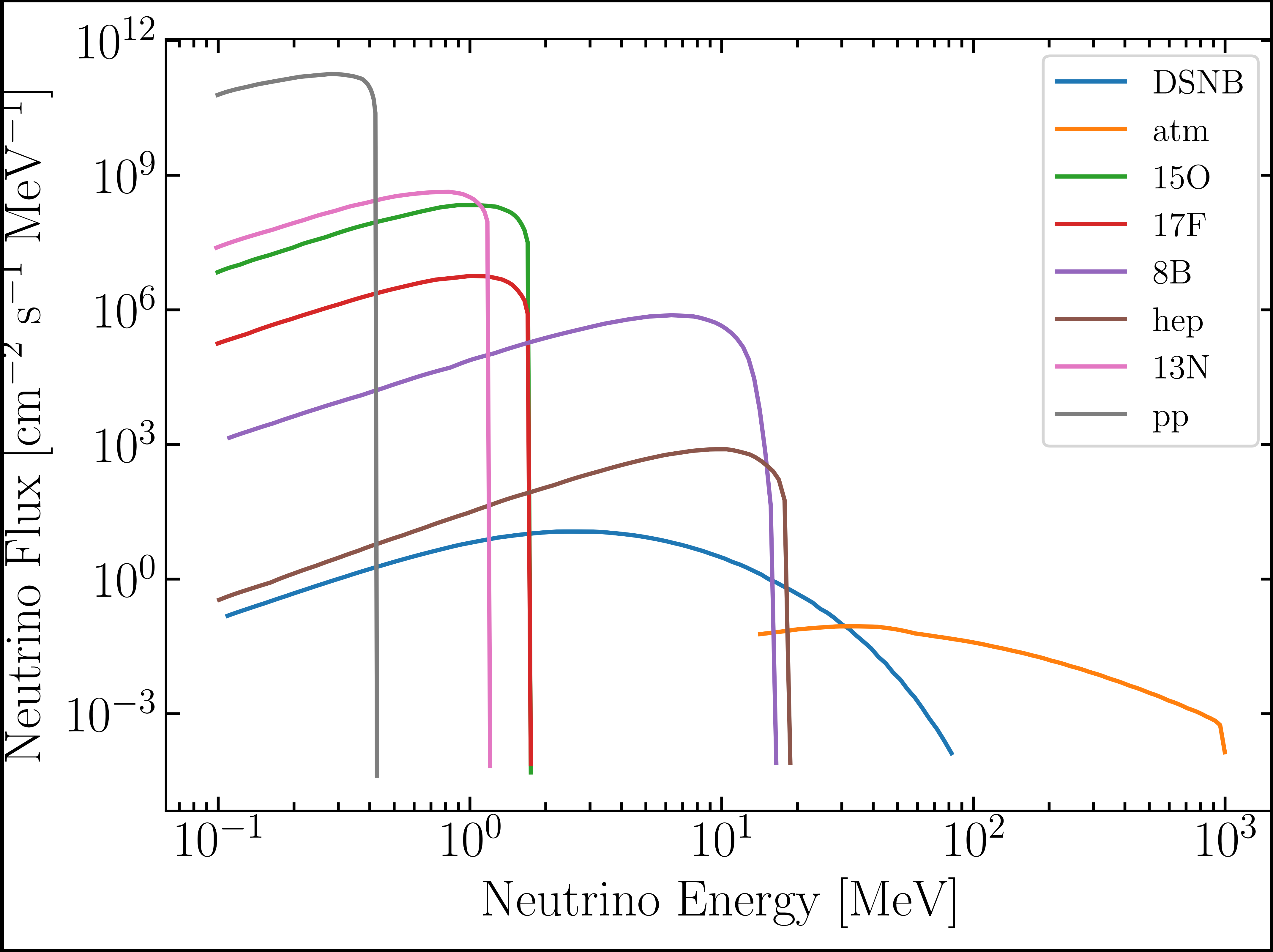
- Establish the feasibility of a mineral detector experiment
- Demonstrate potential sensitivity to WIMP signals

Time evolution of neutrinos

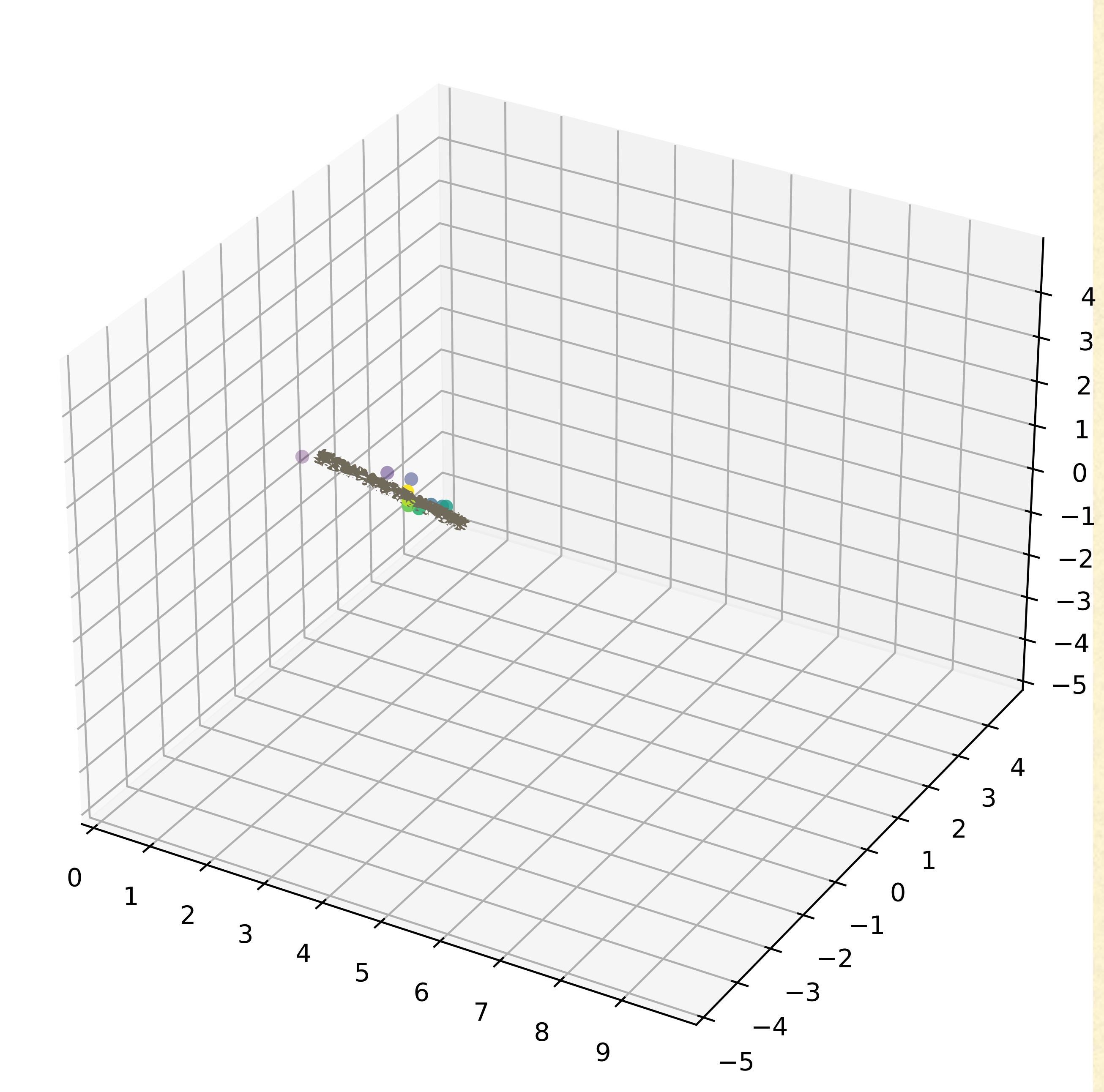


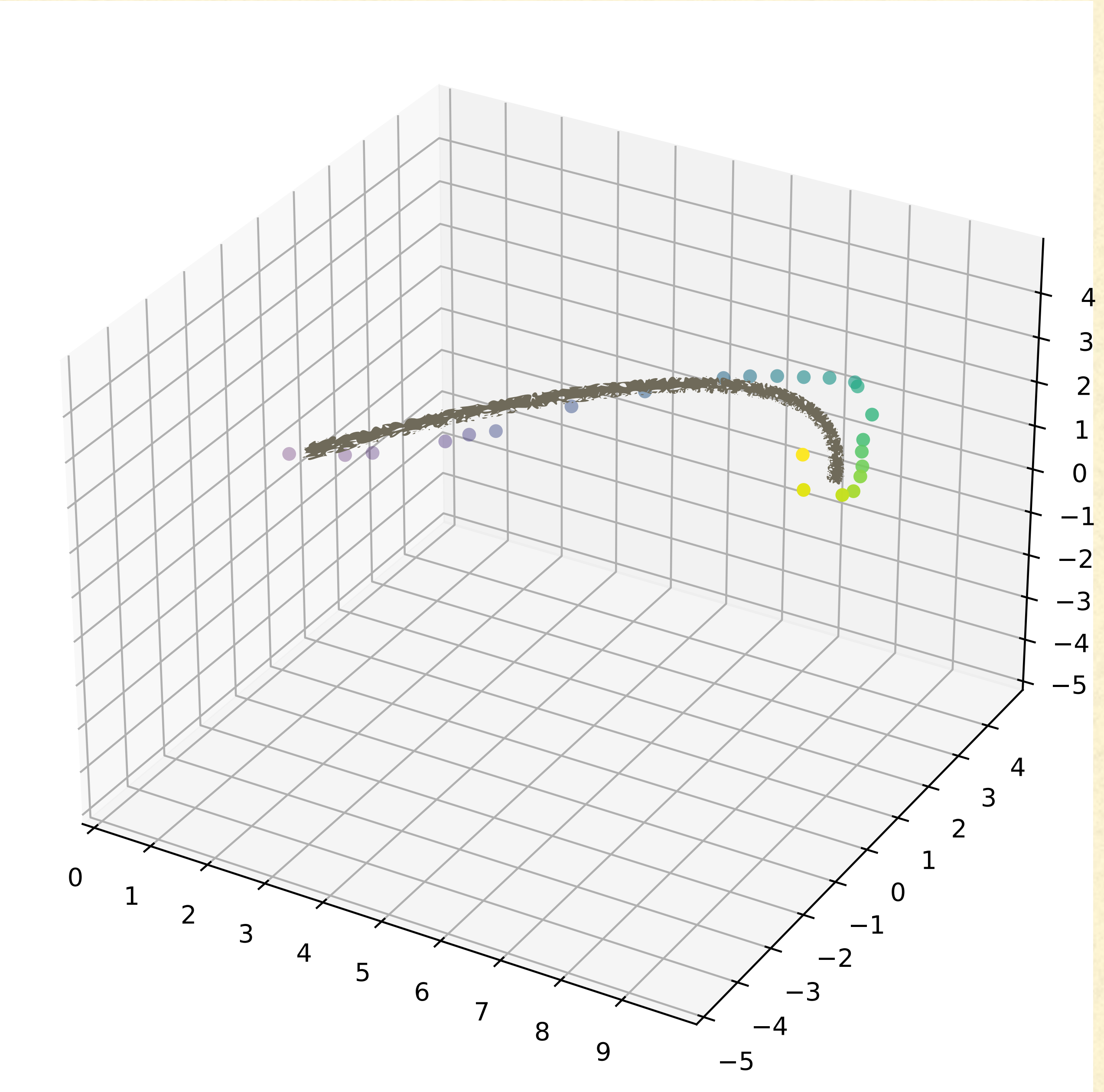
MESA: Modules for Experiments in Stellar Astrophysics

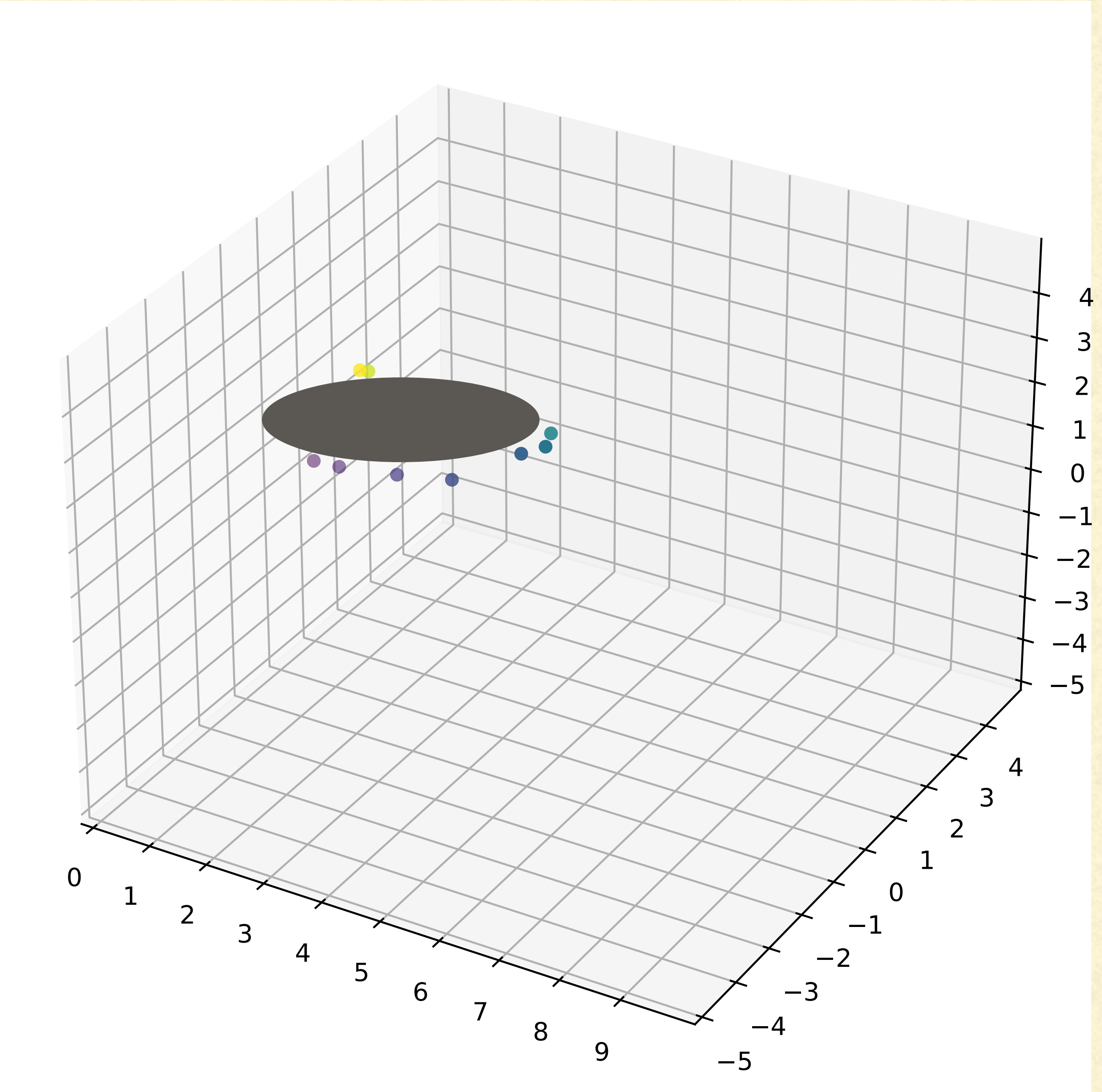
Energy Spectrum



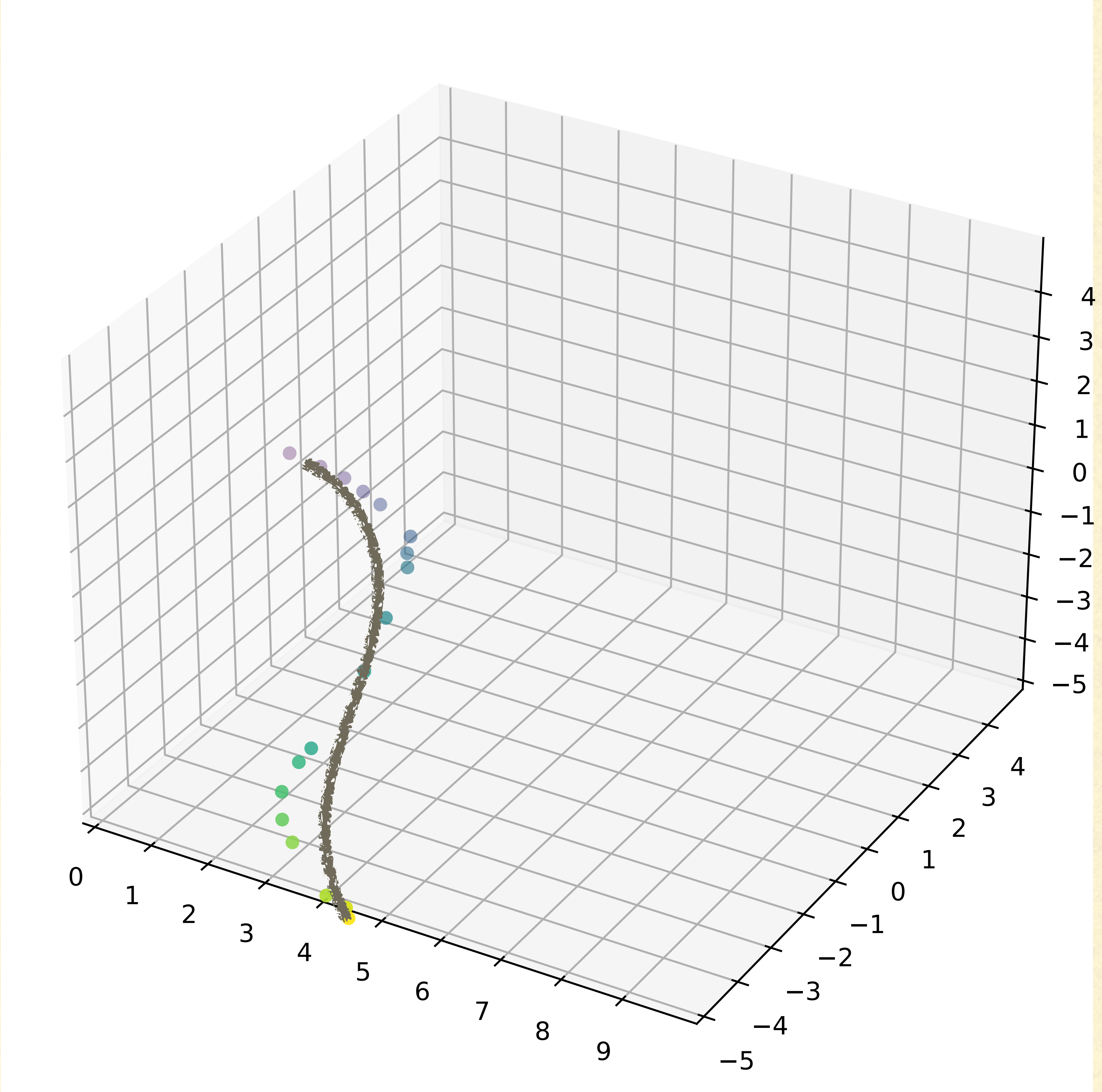
DEFINING TRACK LENGTH

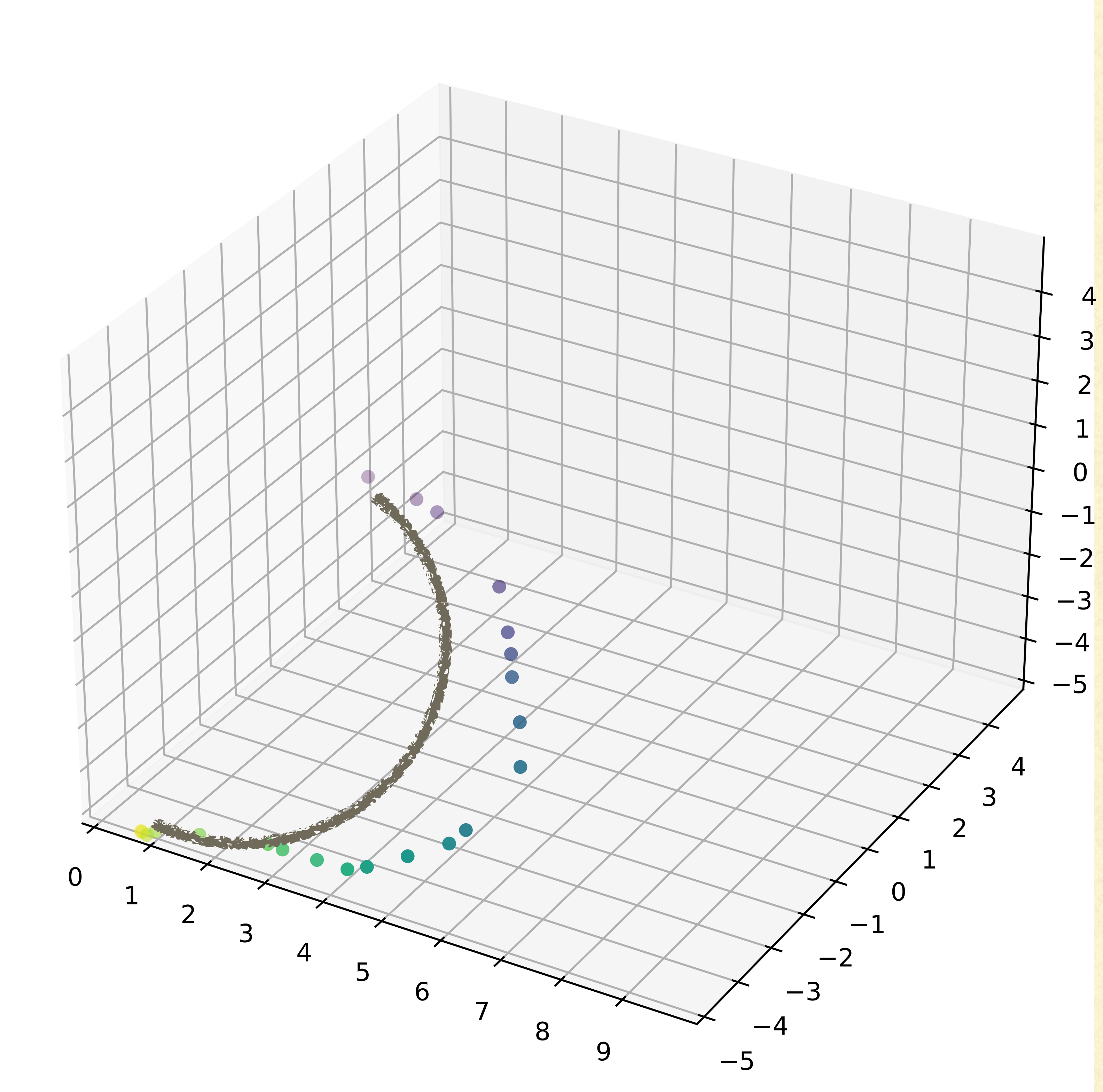




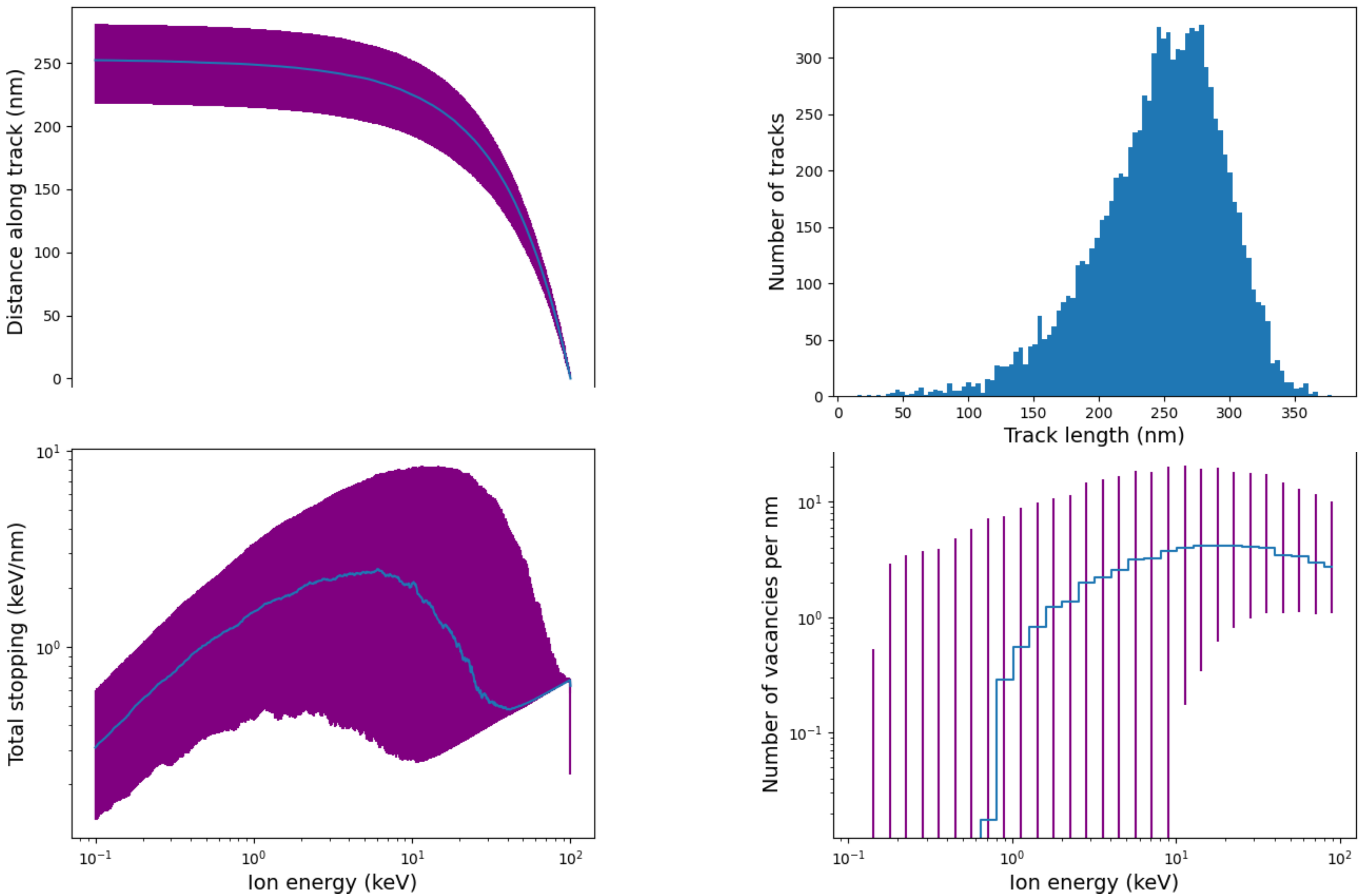


BEZIER CURVE FITTING





TRIM 100 keV Oxygen recoils in Olivine



TRIM 1 MeV alphas in LiF