Atmospheric Neutrino and Dark Matter Detection with Paleo-Detectors at the University of Michigan

MDvDM - Yokohama, Japan
May 20-23, 2025

Emilie LaVoie-Ingram, Joshua Spitz

Big Paleo Picture

Research motivations — What are we interested in detecting? What are the leading questions across science that could be answered with this research?

Obtain a rock sample — Where can we find controlled natural samples under the constraints we need?

Characterize rock sample — What should our standard workflow be for characterizing and preparing a sample?

Find, image, & measure tracks — Is there nm-scale readout available on the mass-scales we want to scan?

Additional step worth some thought -> data processing

Background subtraction — Can we accurately account for and/or simulate backgrounds in our targets?

Results — New physics? Anomalous signals? New technological advancements?

Characterizing a Natural Rock Sample

Natural Sample Workflow & Characterization

Fidelity of our data comes down to how well we understand our rock… and that can be *very* difficult!

Obtain a natural sample

Chemical Analysis

Bulk Composition

EDS

- What nuclei are producing recoil tracks

Accurate recoil spectrum

Trace Elements

ICP-MS

- Low % of elements that EDS cannot detect
- U/Th or rare isotope concentration

Thermal History & Formation

Imaging

SEM + Petrology

- Analysis of specific grains - diffusion of elements through boundaries
- Geologists can pinpoint evidence of thermal process, or way that a rock formed

Literature Review

Literature Review

"Geologist-vetted"

- Well-studied regions with abundance of published literature ('geologist-vetted')
- Rock formations that are relatively cool & still
- U/Th or rare-isotope dating methods on host rock

Accurate age & radiogenic background modeling of sample

Depth (& Transit) History

Record-keeping

Logs

- Transfer between facilities/personnel
- How long on surface
- Airplane travel
- Dates of extraction
- Storage facilities

Accurate cosmogenic background modeling of sample

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Imaging & Measuring Tracks

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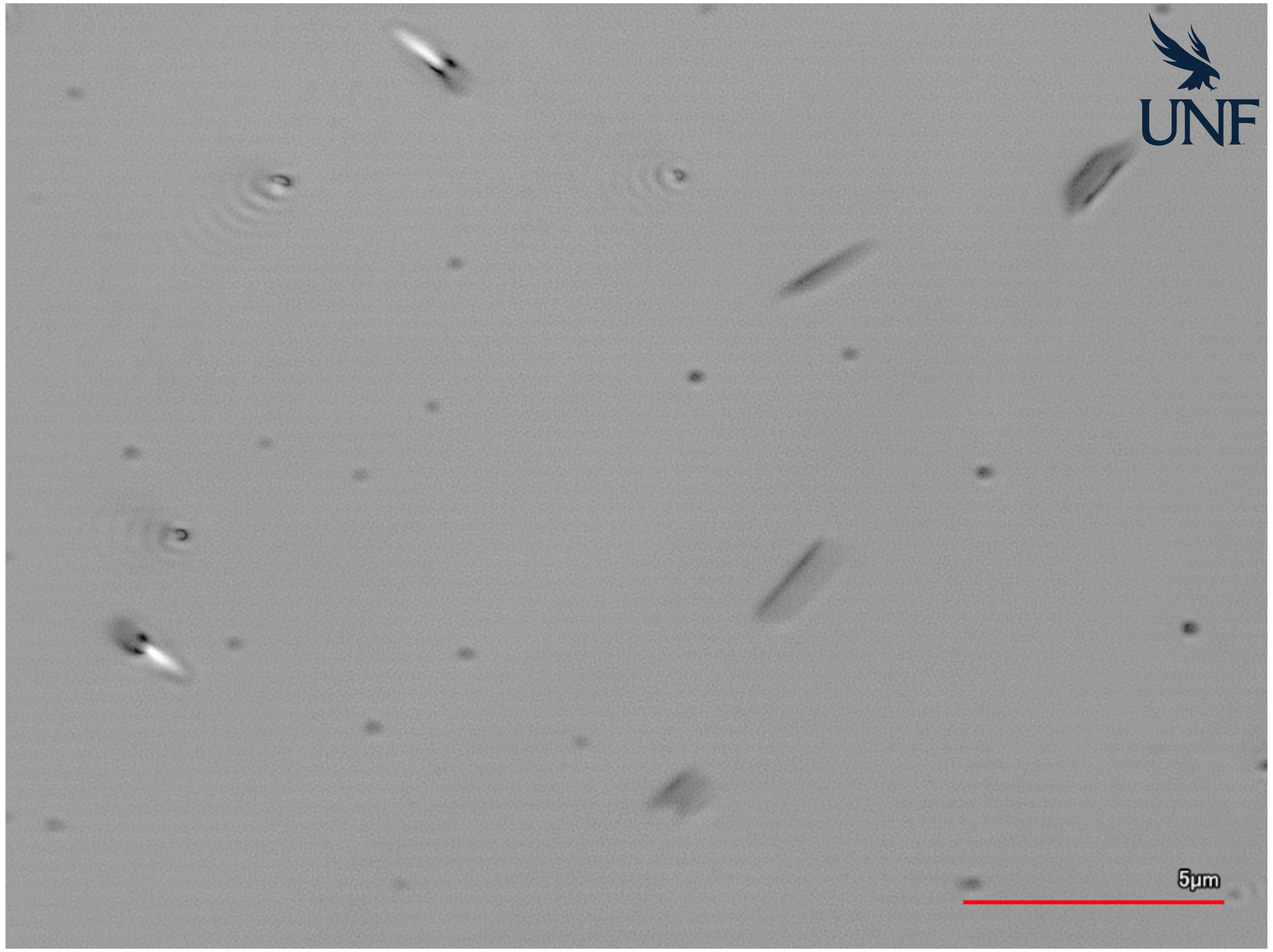
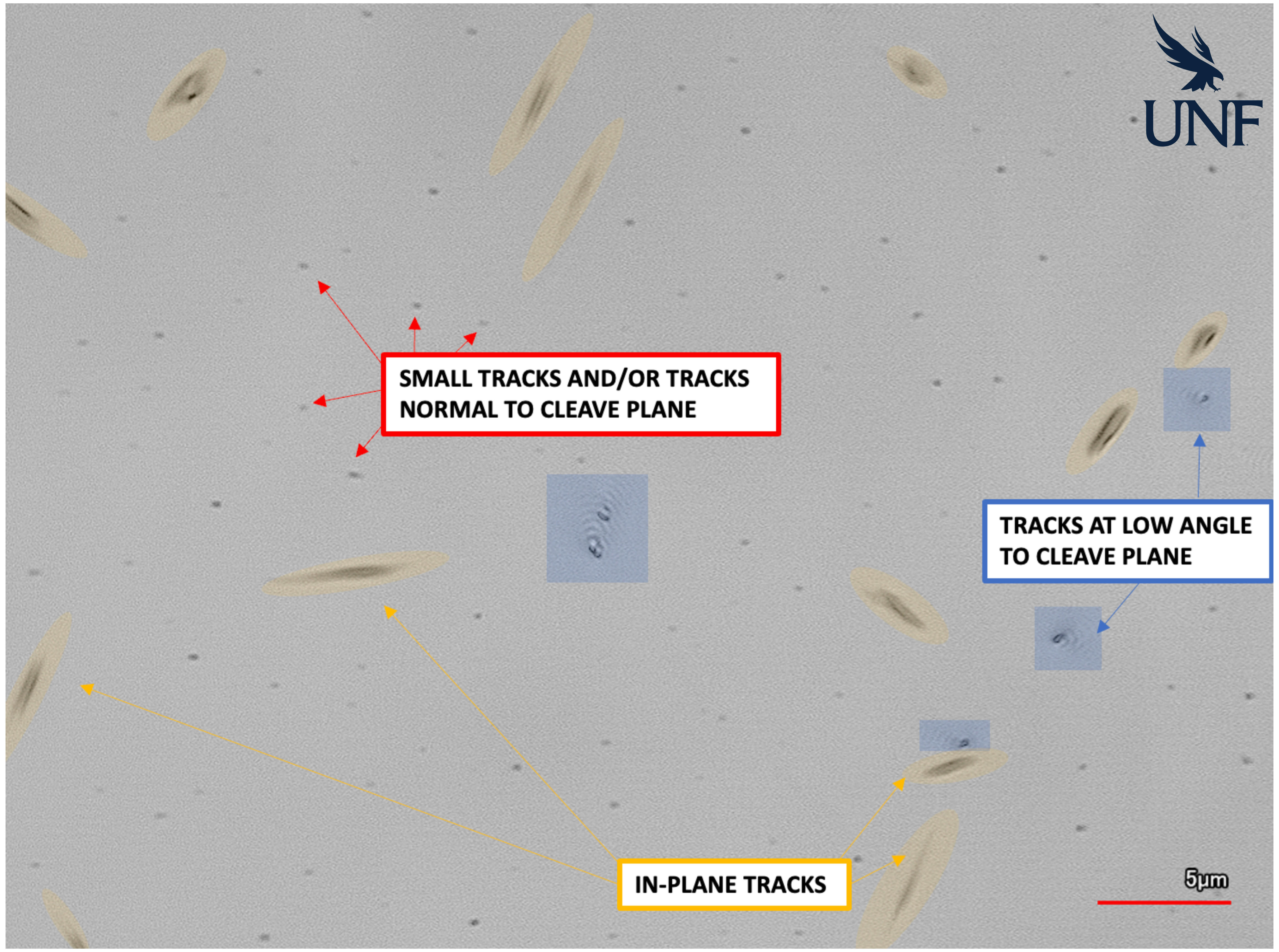
Nuclear Recoil Tracks in Halite

Plasma Etched - Imaged w/ Laser Confocal Microscopy





Previous work of Emilie LaVoie-Ingram at the University of North Florida
Master's Thesis under Chris Kelso, Ph.D.

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Halite Tracks: Experimental Workflow

Cleave & Etch Method

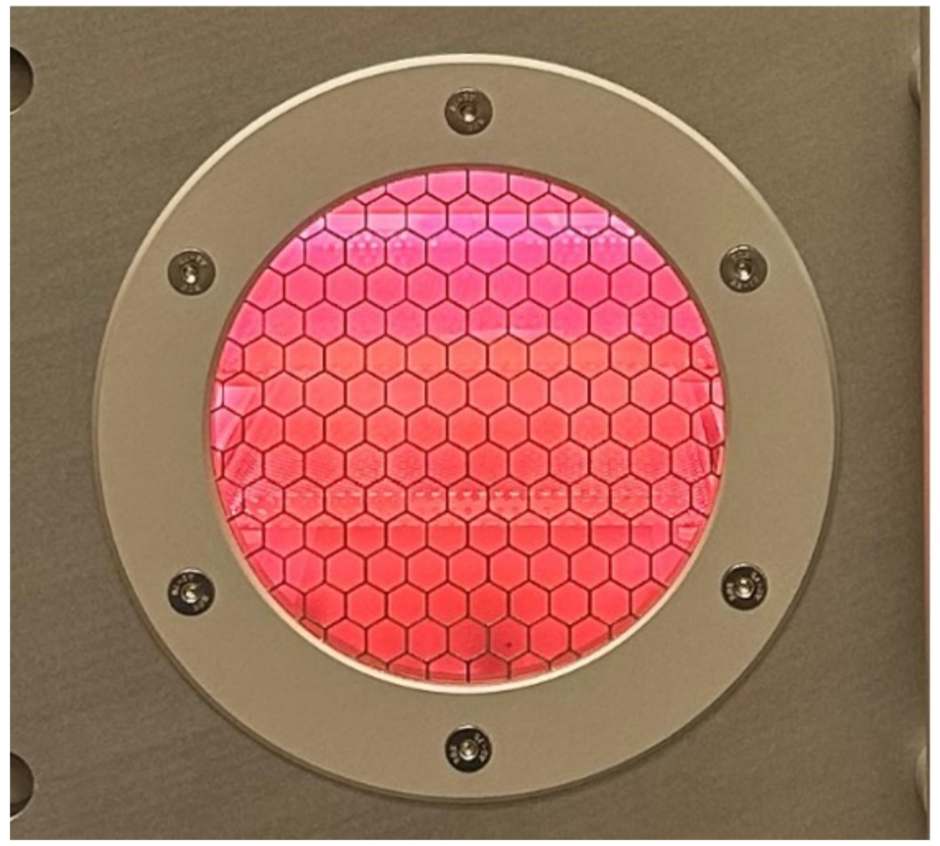
Cleave
(Smash, cut, peel!)

Plasma or Chemical Etch
(Enlarge the tracks)

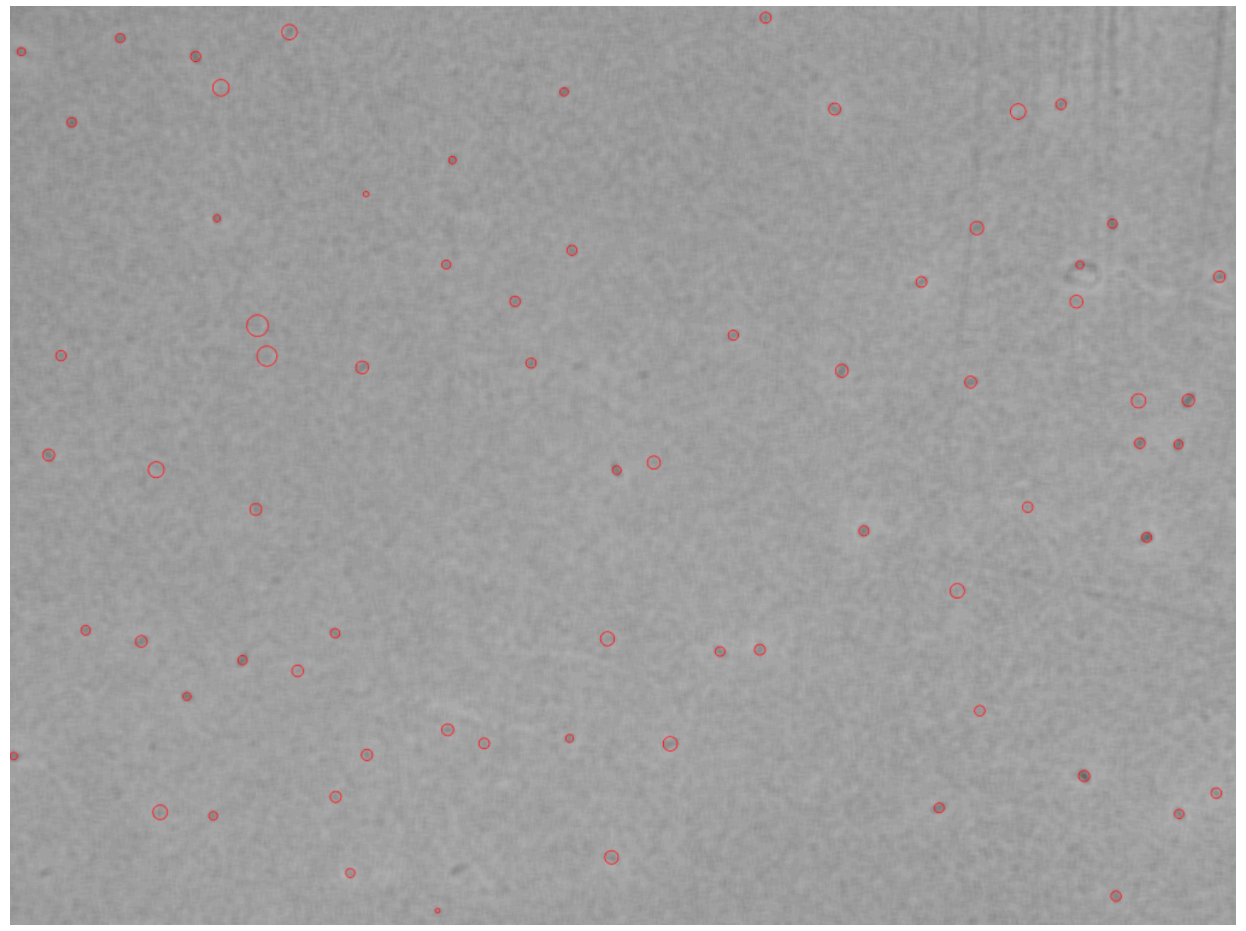
Imaging
Laser Confocal Microscopy or
Atomic Force Microscopy)

Background Subtraction
(Estimate backgrounds &
compare to experiment)

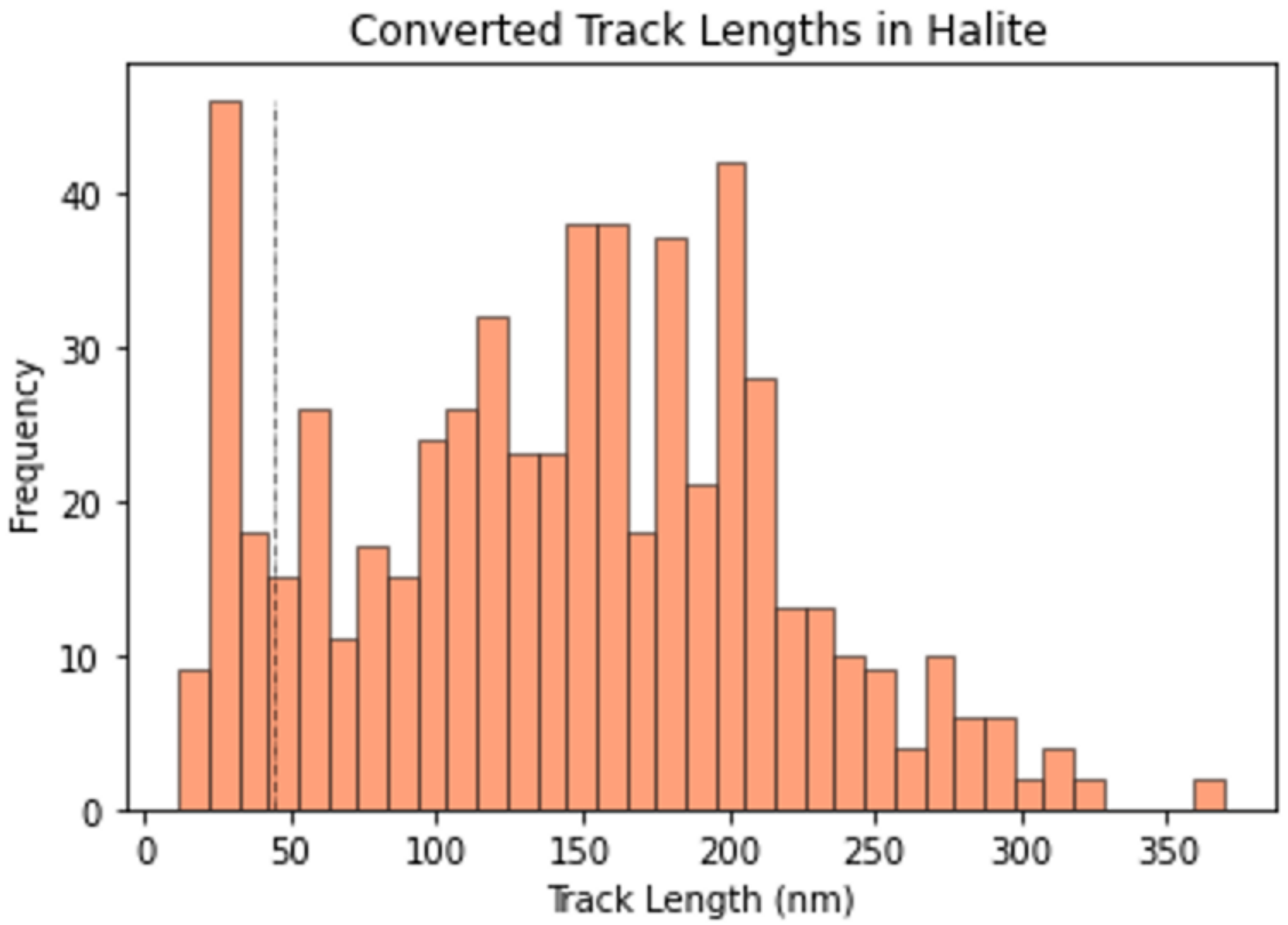
Chris Kelso, UNF, will elaborate more about this step in his talk!



Glow of argon plasma, used in the etching of halite and mica crystals at UNF



Automatic track detection/measurement



U-M Experimental Workflow

Multi-modal approach to imaging tracks

Large-scale, low-resolution scan

Tens of nanometers to microns in spatial resolution

Identify areas of high defect density

Gram-scale sample sizes

+

Sparse, high-resolution scans

Sub-nanometers in spatial resolution

Clear imaging of track structure

Nano- to picogram-scale sample sizes

Extrapolate to entire sample

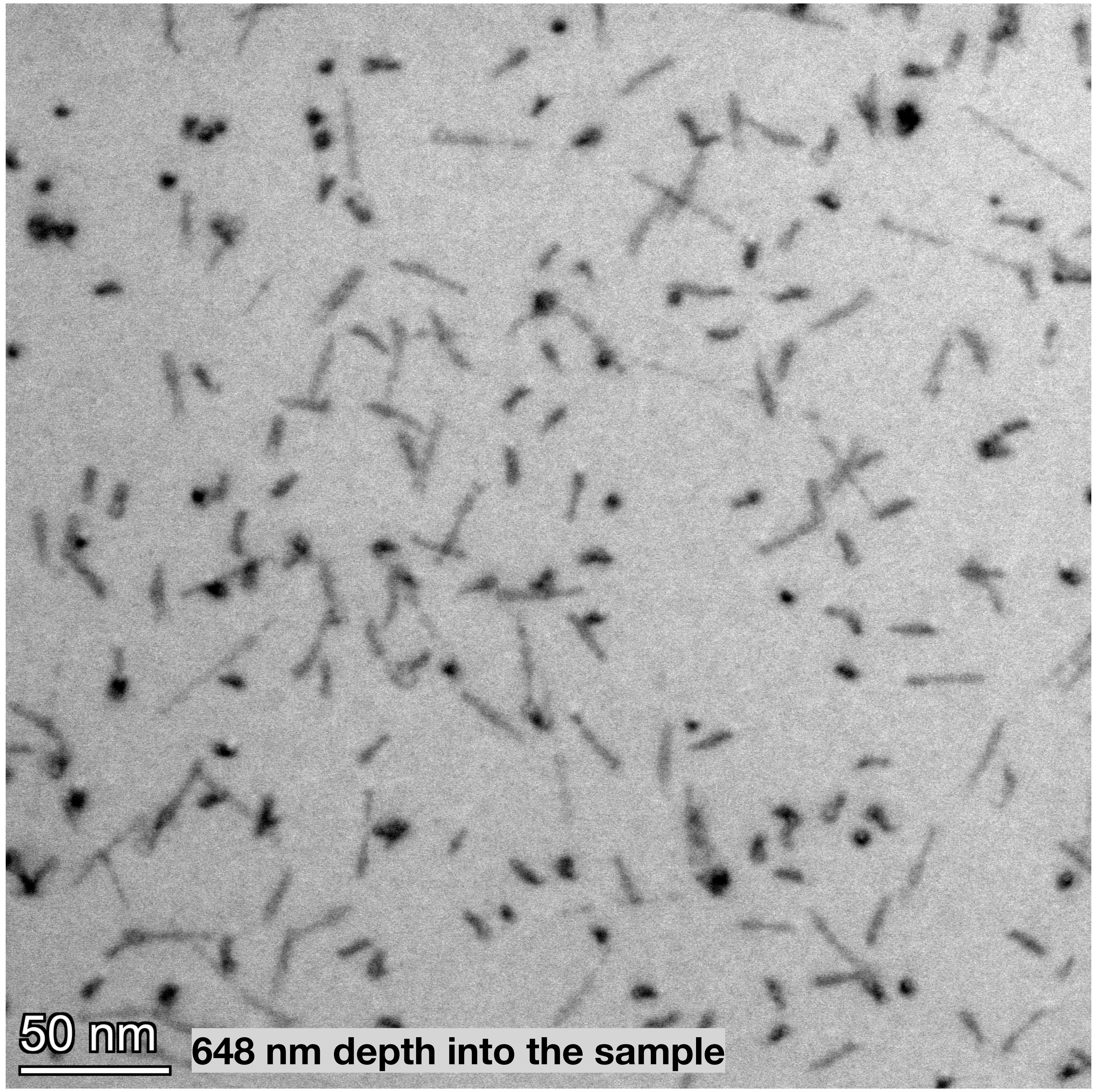
Automatic defect detection and screening (ML implications?)

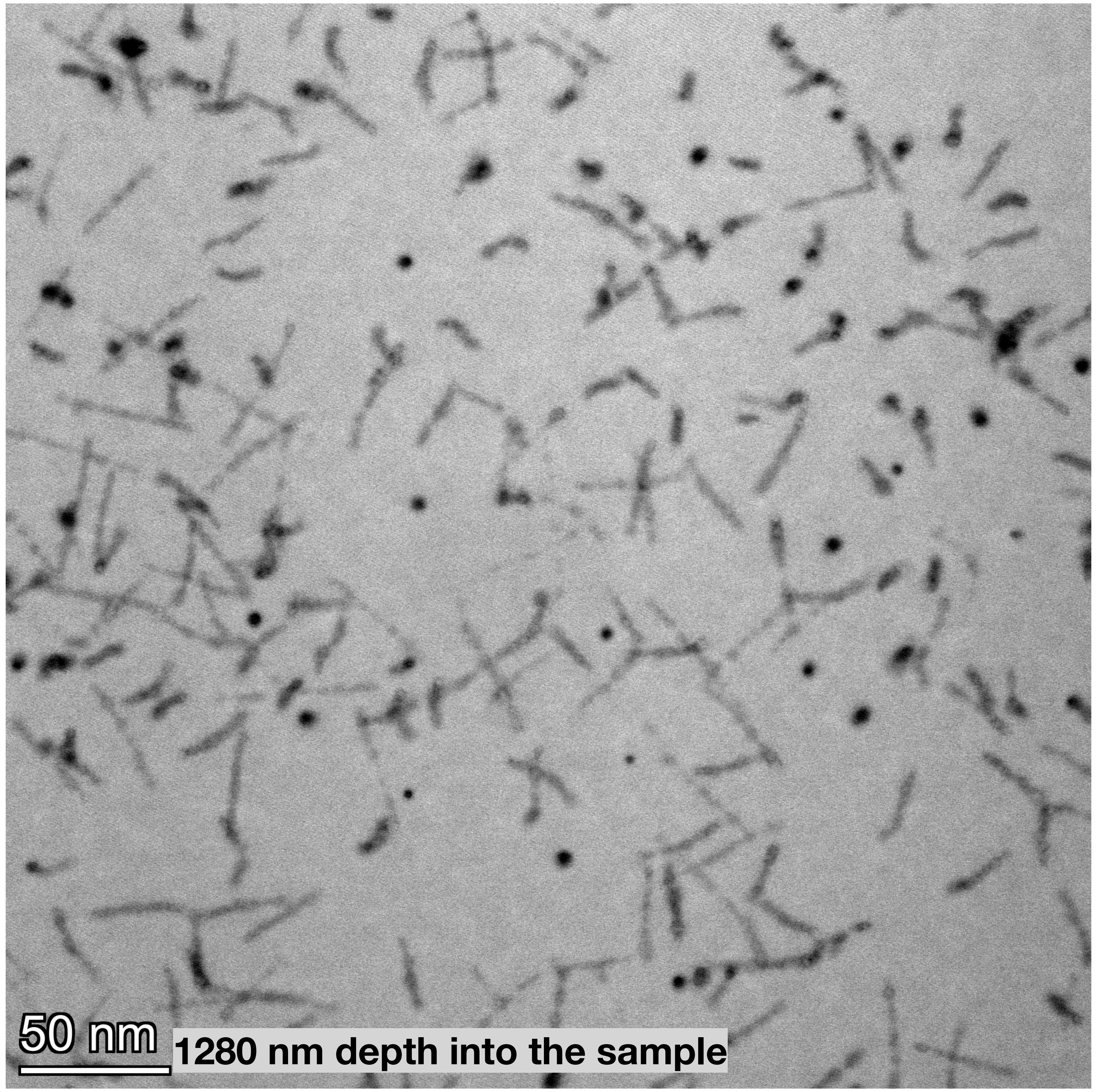
Standardized sample characterization & preparation

Accurate background estimates

Ion Tracks in Olivine $(Mg, Fe)_2 SiO_4$

15 MeV Au^{+5} imaged with TEM





Ion tracks going into the page

Credit:
Kai Sun, Ph.D.

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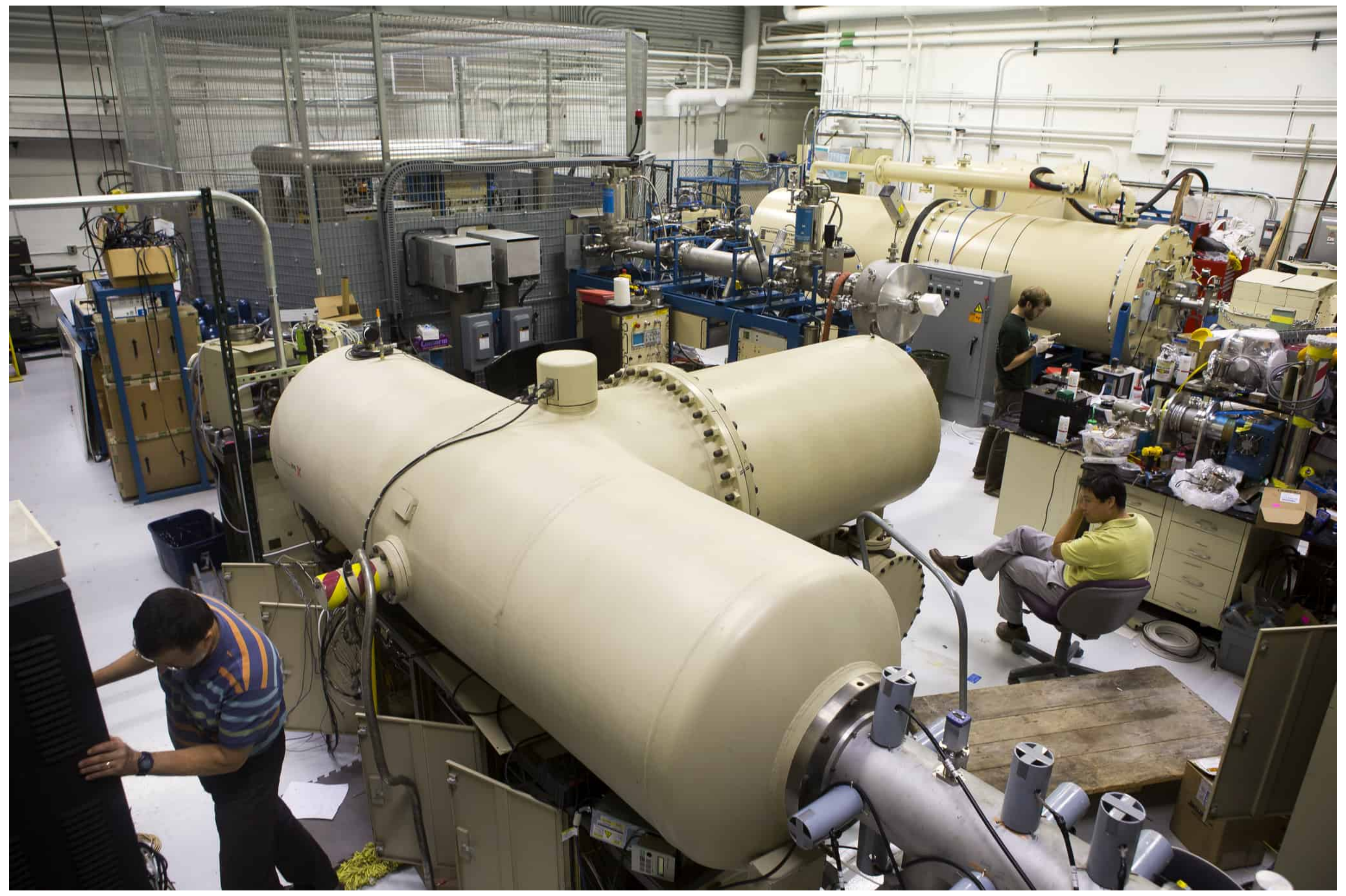
https://mibl.engin.umich.edu/

https://mibl.engin.umich.edu/mibl/capabilities/

Michigan Ion Beam Laboratory

Let's collaborate!

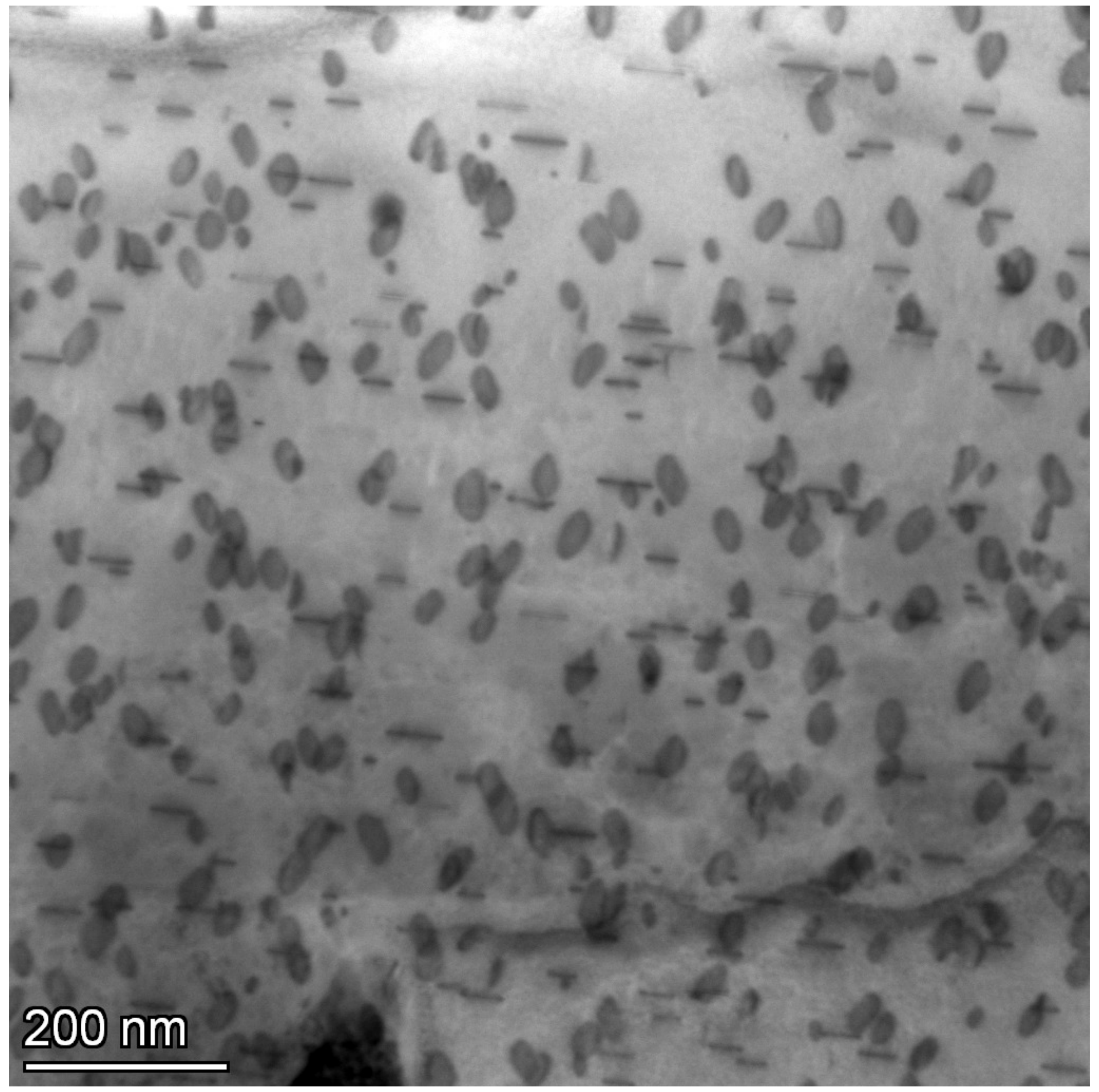


- **Wolverine: 3 MV Tandem particle accelerator**
  - Peabody brand PS120 external Cs sputter source capable of delivering more than 500 nA of Fe++ ions. The maximum energy achieved for Fe+++ is 9 MeV and a range of ions in stainless steels of about 2 um
  - Torvis ion source (NEC) capable of delivering up to 100 uA at the low energy end and with currents of about 25-30 uA on targets (40 uA total)
  - Alphatross ion source (NEC) for production of He currents at or above 50 nA levels on targets for surface analysis
- **Maize: 1.7 MV Tandem particle accelerator**
  - Ions from gases and sputtered materials
  - < 2.9 MeV for protons , < 4.50 MeV for He
  - < 2 uA for protons, < 1000 nA for He
- **Blue: 400 kV Implanter**
  - 30-400 keV (higher for multiple ion states)
  - Virtually anything from the periodic table of elements
  - Current - in excess of 10's of uA depending on ion type

<u>Upcoming Experiments:</u>

- 100 keV Au irradiation of quartz
- 9 MeV O irradiation in olivine
- 9 MeV O irradiation in quartz
- ~1-100 keV range C in diamond (UMD collaboration) →

Molecular Dynamics validation study!



Credit: Kai Sun, Ph.D.

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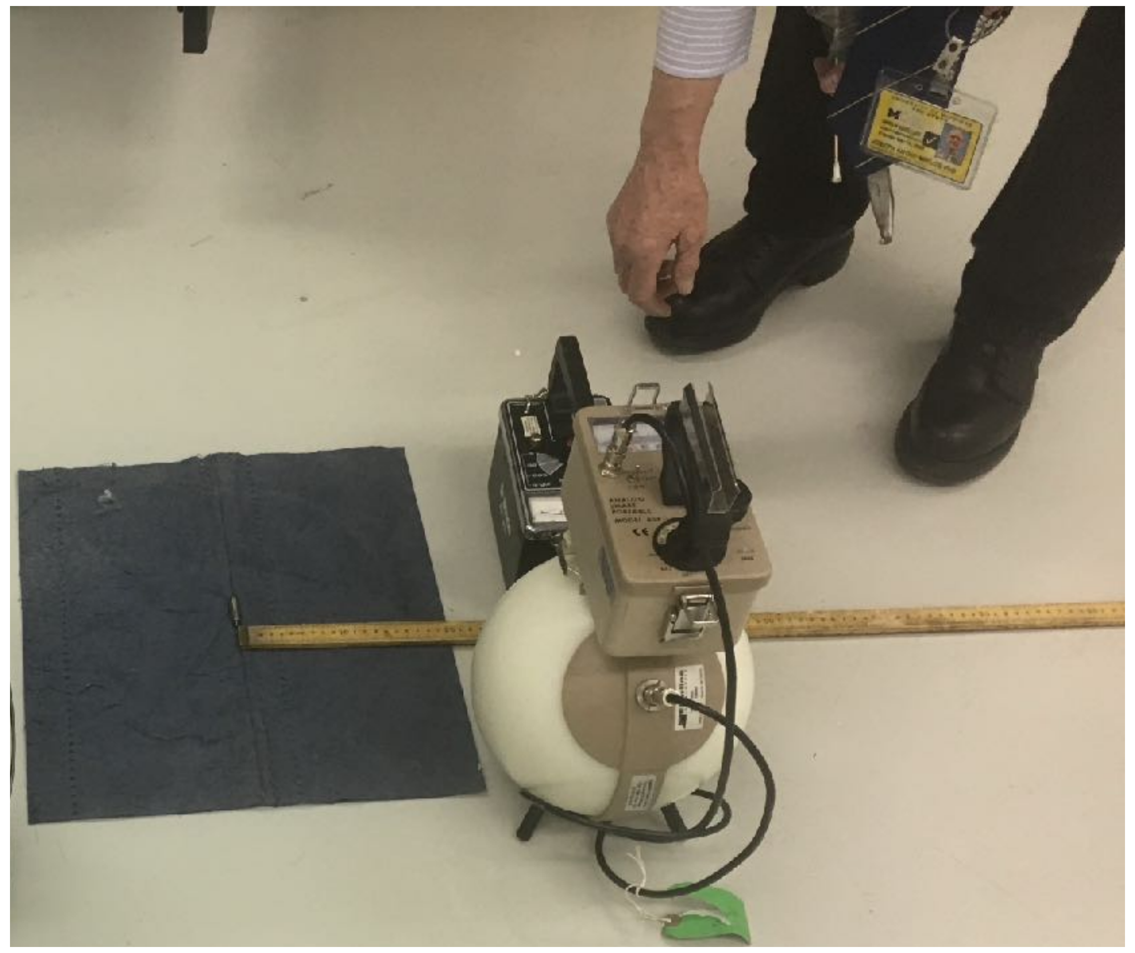
Available Neutron Sources - Preview to Igor Jovanovic's Talk!

Radioisotopes

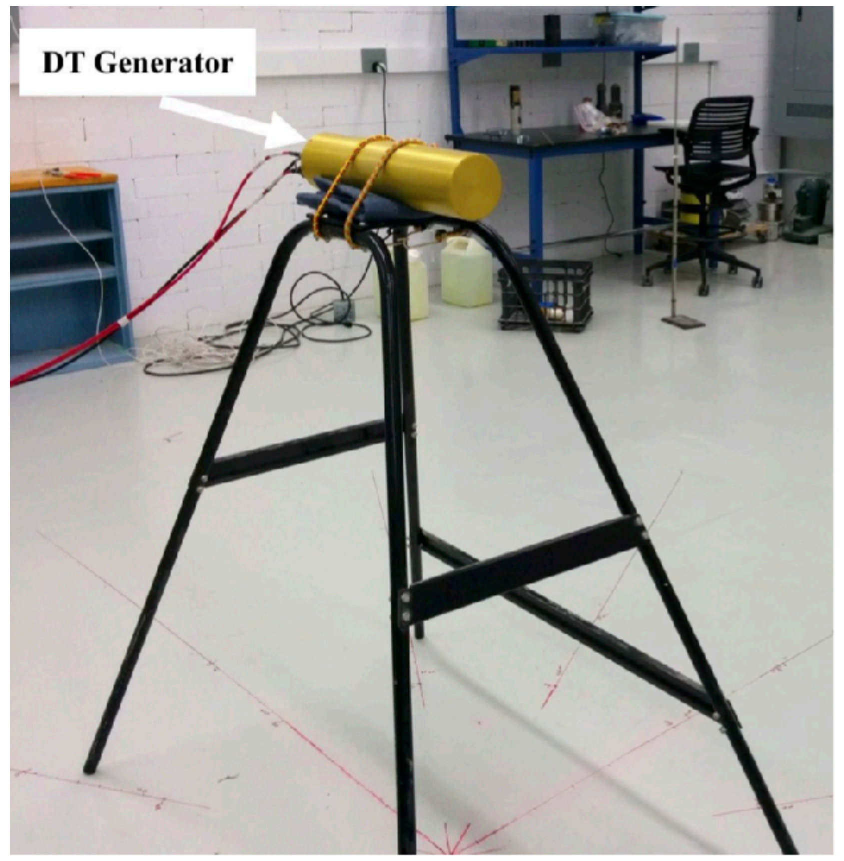
spontaneous fission
(alpha, n)



Neutron generators

DD

DT

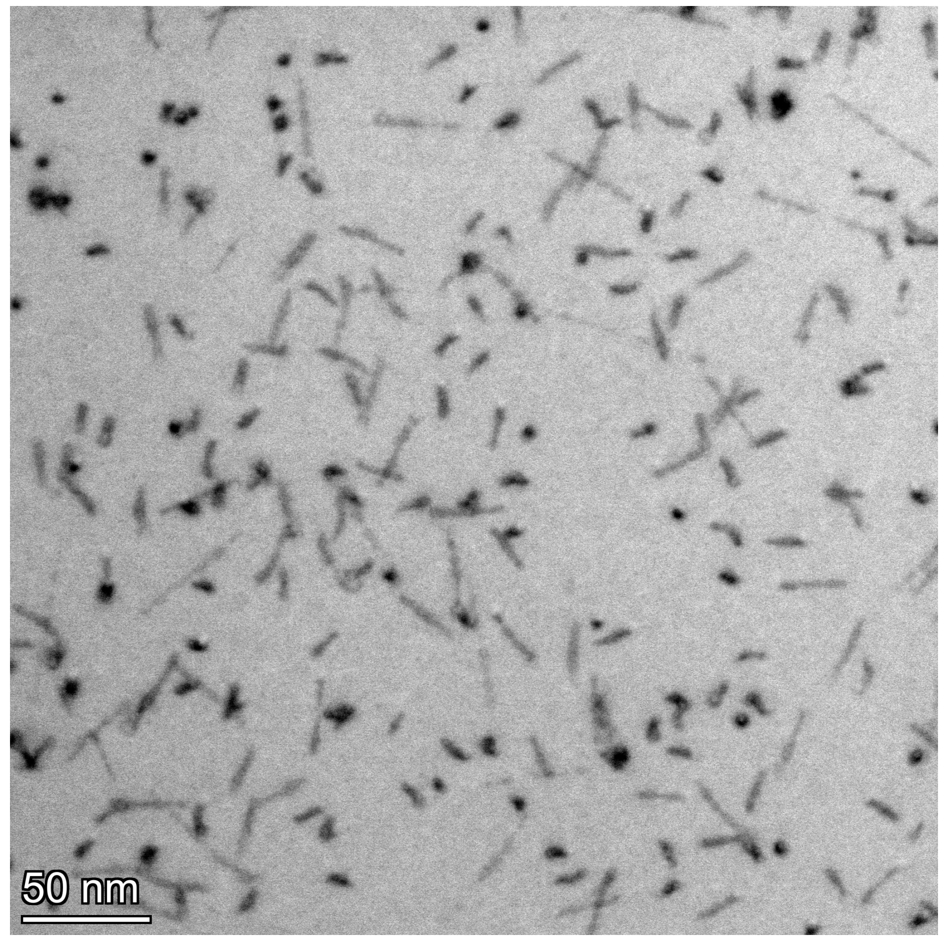


Nuclear reactors

Igor Jovanovic, Ph.D.

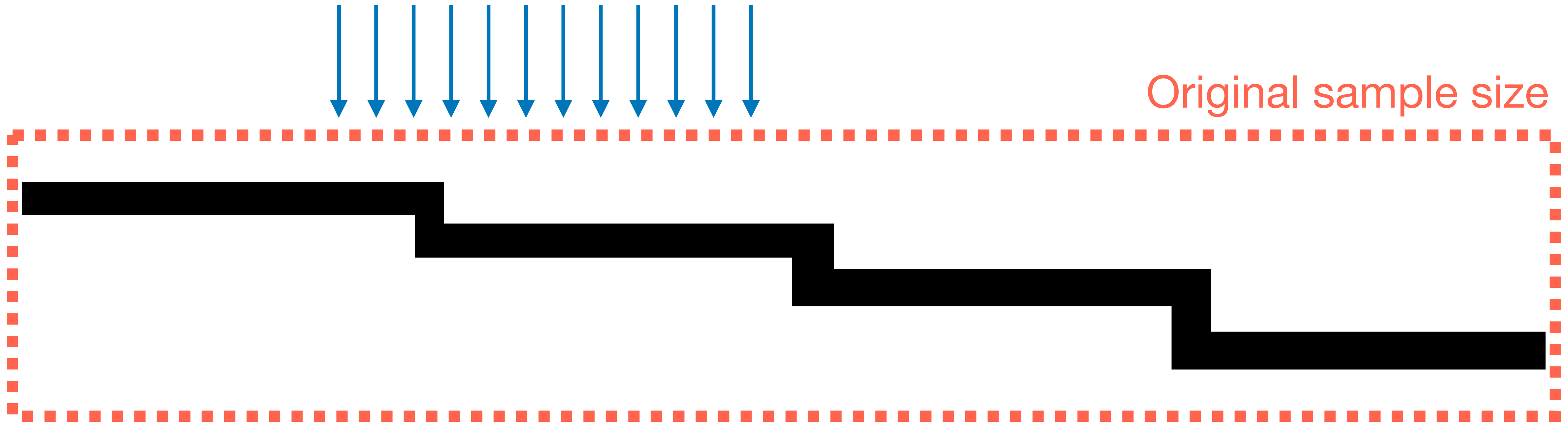
Transmission Electron Microscopy

- TEM is an atomic-scale imaging technique, **but does not have the throughput we need**
- Typical TEM image is on the order of picograms (prepared with focused ion beam (FIB) - Ga or Xe ions)
- Likely will take a multi-modal approach, and continue to use TEM for high-resolution, scarce sampling of minerals
- Currently using ion irradiation + TEM to characterize track width (diameter) as a function of ion trajectory (depth into sample)



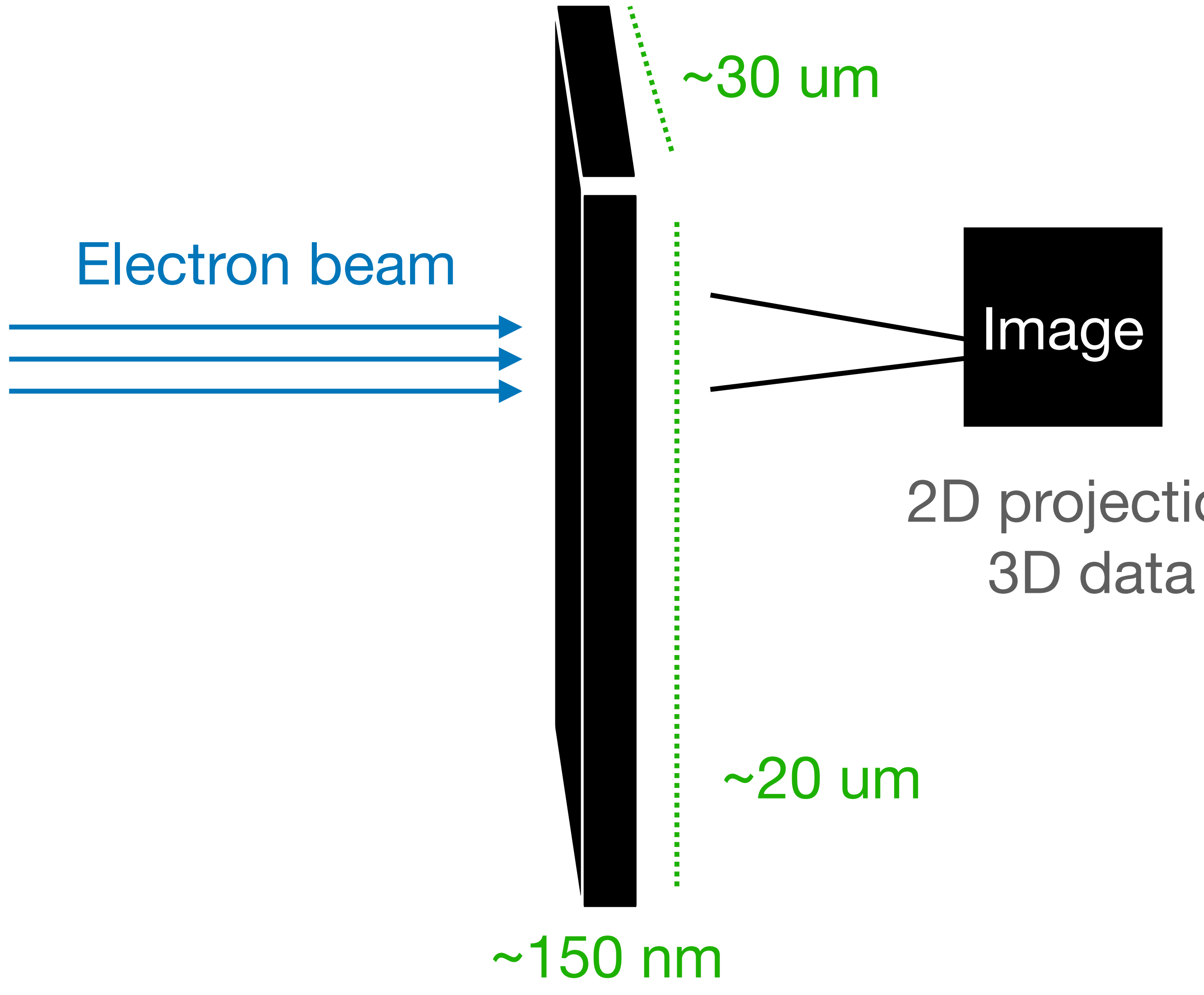
Example: this image volume is 8.632e-14 grams (0.08632 picograms!)

Ion beam (on whole sample)



TEM samples prepared at different depths into the sample (or different *portions of ion trajectory*)

Typical TEM sample dimensions

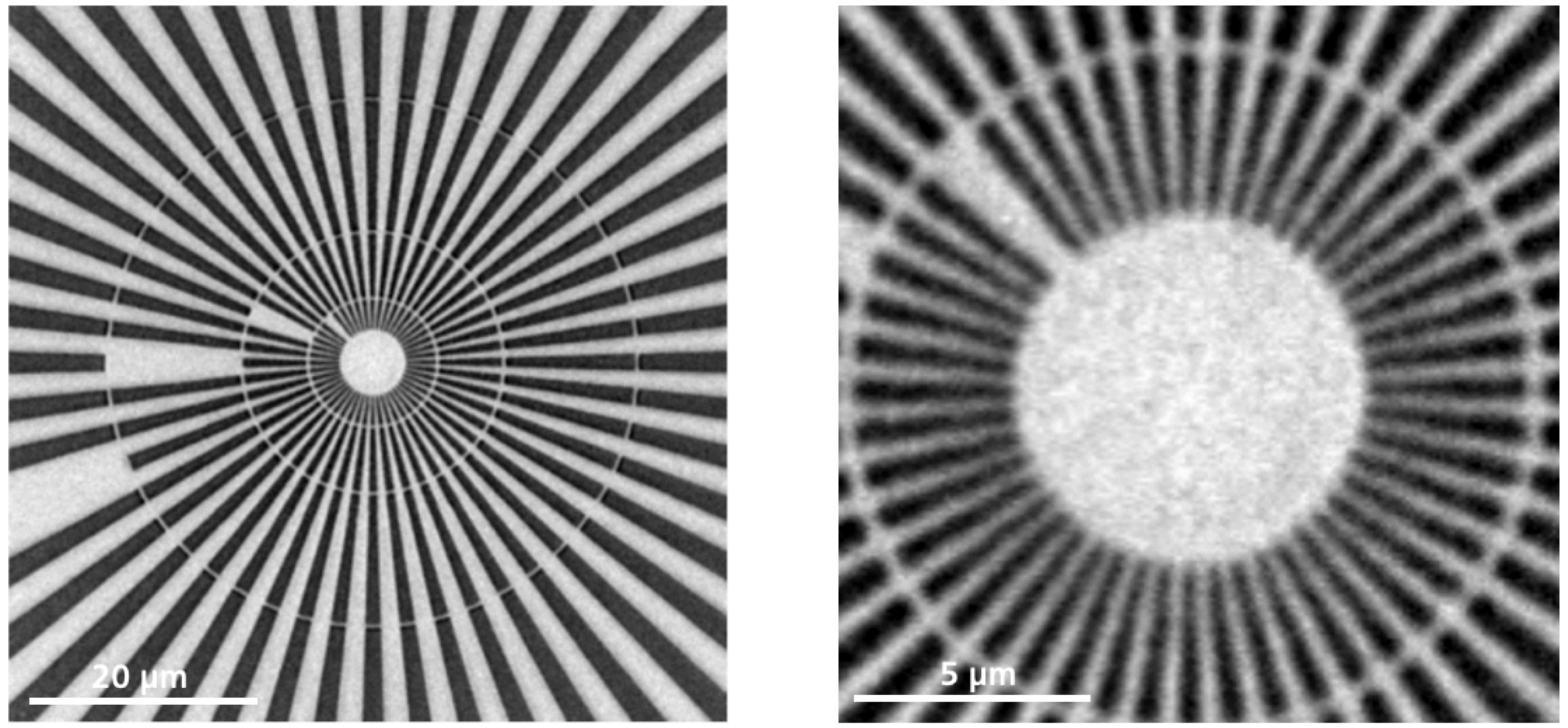


2D projection, 3D data

Transmission X-ray Microscopy & Tomography

Bulk readout, lower resolution

- X-rays offer higher throughput, but lower resolution
    - March 2025 NSF GCR MDDM group @ SLAC - watch Chris Kelso's talk for details!!
- New ZEISS machine expected to arrive at U-M this month - estimating ~15 nm voxel resolution w/ phase + absorption contrast
    - Note: ~5x smaller than typical track diameter
- mm-sized samples (hopefully) + tomography
    - Atmospheric neutrino searches in track lengths of 20 um - 1 mm!
- Also applying for beam time at synchrotron sources (APS/PSI)
    - Coherent, phase + absorption contrast imaging with x-rays
- Big question: **can we see track with x-rays?**



Resolution target: 50 nm lines and spaces, left: overview, right: detail view of center.

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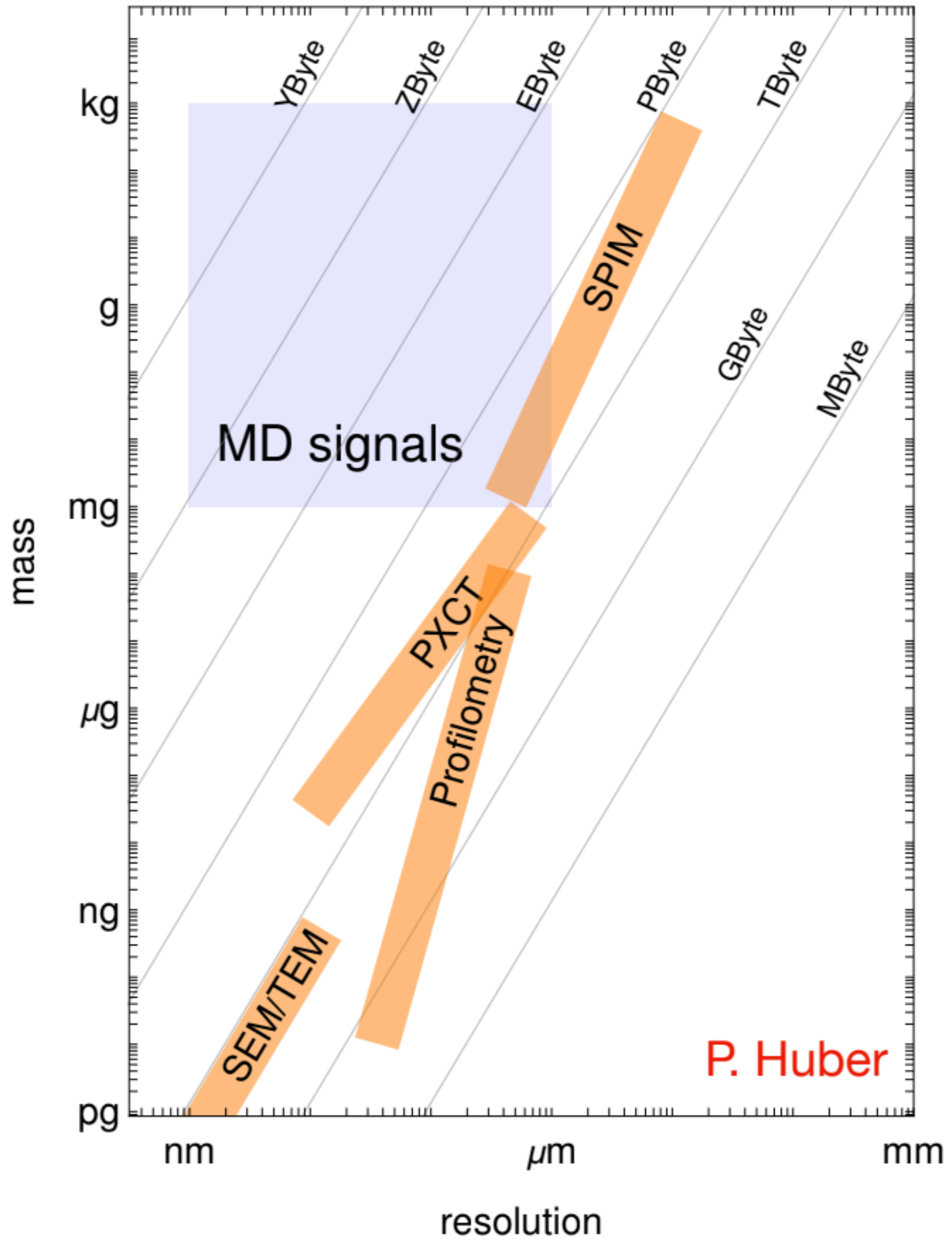
Additional Techniques? Data Processing?

- There has been lots of discussion about the available and applicable readout methods for DM and neutrino detection with minerals
- We need nanometer-scale resolution, but gram-scale readout (shaded purple on plot)
- Small angle x-ray scattering? (Diffraction-based)
- Ptychography? (< TEM throughput)
- **<u>Data processing with 3D readout at gram-scale:</u>** Potentially talking about ~10^17 voxels per sample (~0.1 g) — machine learning implications? Computing power? Automatic track detection + measurement algorithms?



Background Subtraction

Cosmogenic Background Simulation Workflow

Leading Questions: How many cosmogenic neutron-induced (muon spallation) tracks are in our natural minerals? What if the mineral changed depth over time, or has been on the surface for long geological times?

Calculate muon energy spectrum at the surface (CRY)

Propagate muons through overburden of given depth and material (muon survival matrices - PROPOSAL/MUTE)

Neutron energy spectrum from muon spallation at given depth & mineral volume (GEANT4)

Skip if calculating neutrons produced at the surface

Return kinetic energy spectrum per element in target mineral (GEANT4)

Calculate corresponding stopping power per target mineral (SRIM)

Convert recoil spectrum to track length spectrum using flux and mass density

(Halite example)

```
# dR/dEr [1/keV/kg/Myr]
# Er [keV]    ,  Na23   ,  Cl35 ,   Cl37
1.012E-03   5.482E+09   3.030E+10   1.068E+09
1.035E-03   5.279E+09   3.040E+10   1.031E+09
1.059E-03   5.384E+09   3.023E+10   9.427E+08
1.084E-03   5.261E+09   3.032E+10   1.024E+09
1.109E-03   5.337E+09   2.982E+10   9.480E+08
1.135E-03   5.310E+09   2.906E+10   9.132E+08
1.162E-03   5.268E+09   2.840E+10   9.827E+08
1.189E-03   5.407E+09   2.787E+10   9.245E+08
1.216E-03   5.360E+09   2.694E+10   8.542E+08
1.245E-03   5.332E+09   2.631E+10   7.977E+08
1.274E-03   5.302E+09   2.567E+10   8.700E+08
1.303E-03   5.331E+09   2.523E+10   8.042E+08
1.334E-03   5.392E+09   2.491E+10   7.885E+08
1.365E-03   5.310E+09   2.415E+10   7.756E+08
```

Integrate over all elements in target mineral & map background signal!

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Cosmogenic Background Simulation Workflow

Validating our model with literature comparison

Current location: https://github.com/NSF-GCR-MDDM/paleo-bg-sim/tree/main

PHYSICAL REVIEW D **73,** 053004 (2006)

Muon-induced background study for underground laboratories

D.-M. Mei and A. Hime

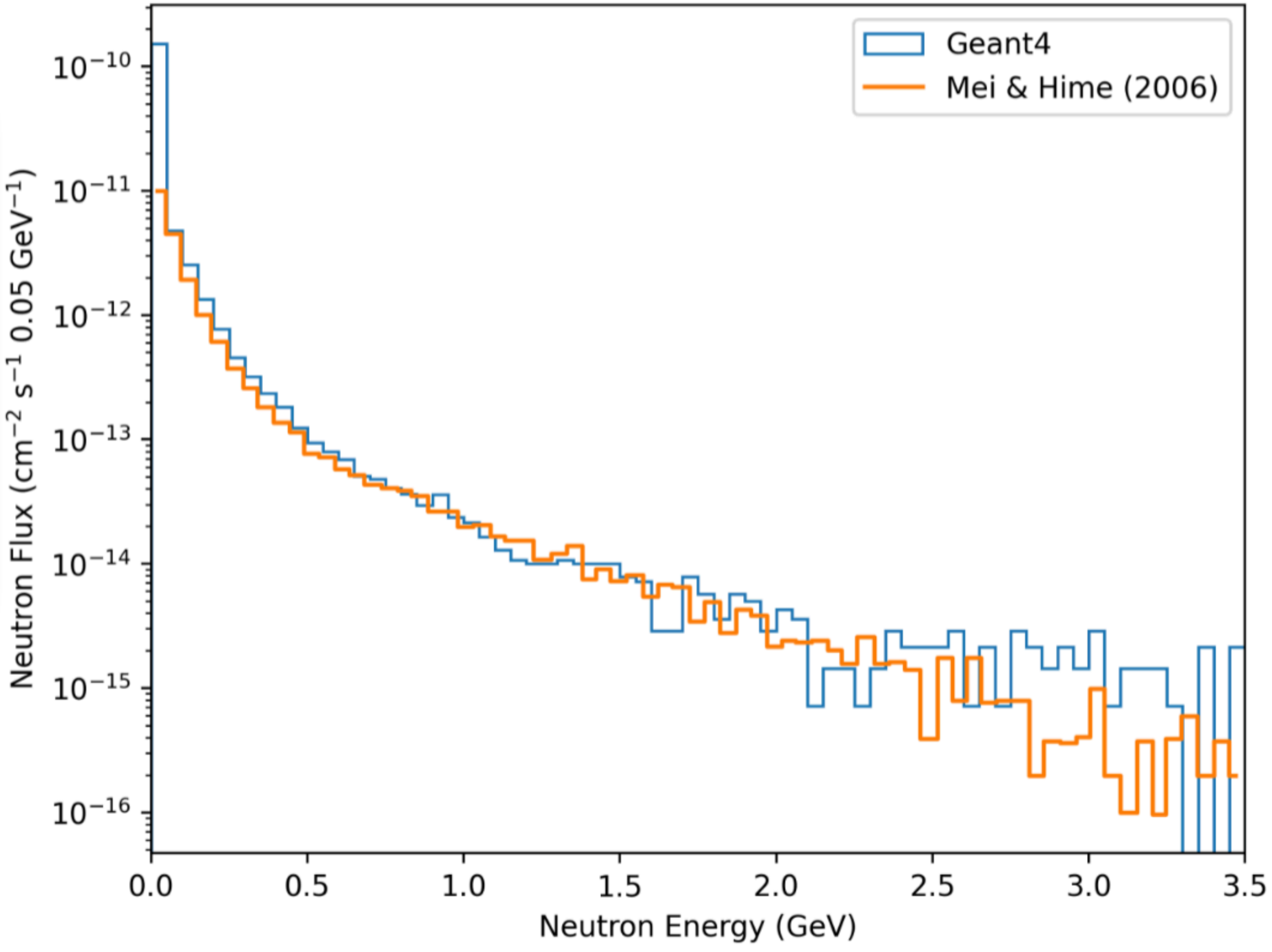
Physics Division, MS H803, Los Alamos National Laboratory, Los Alamos, New Mexico 87545, USA

(Received 5 December 2005; published 6 March 2006)

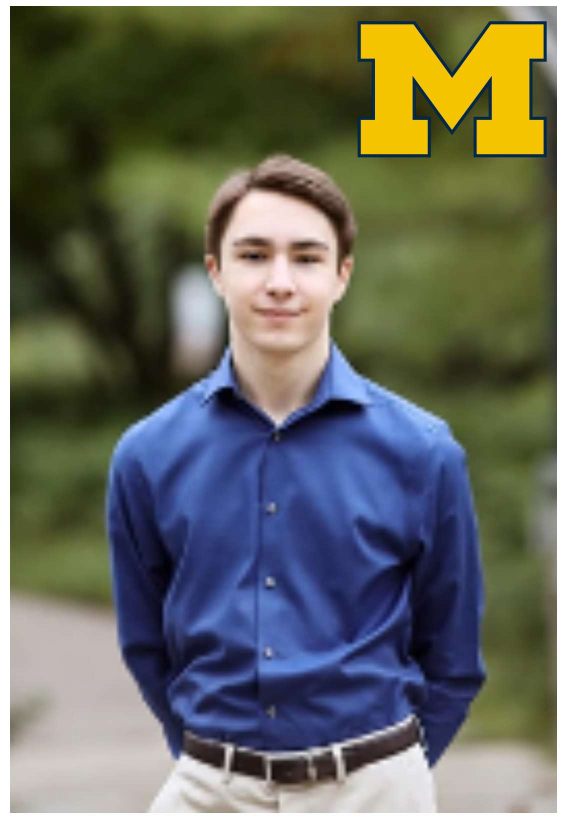
We provide a comprehensive study of the cosmic-ray muon flux and induced activity as a function of overburden along with a convenient parametrization of the salient fluxes and differential distributions for a suite of underground laboratories ranging in depth from ~1 to 8 km.w.e.. Particular attention is given to the muon-induced fast neutron activity for the underground sites and we develop a depth-sensitivity relation to characterize the effect of such background in experiments searching for WIMP dark matter and neutrinoless double-beta decay.

DOI: 10.1103/PhysRevD.73.053004 PACS numbers: 12.15.−y, 23.40.−s, 26.65.+t, 95.35.+d

Experimentally collected muon flux & energy spectrum at various underground sites, different overburden composition and geometry.
**used FLUKA to generate neutrons



Sam Hedges



Andrew Calabrese-Day

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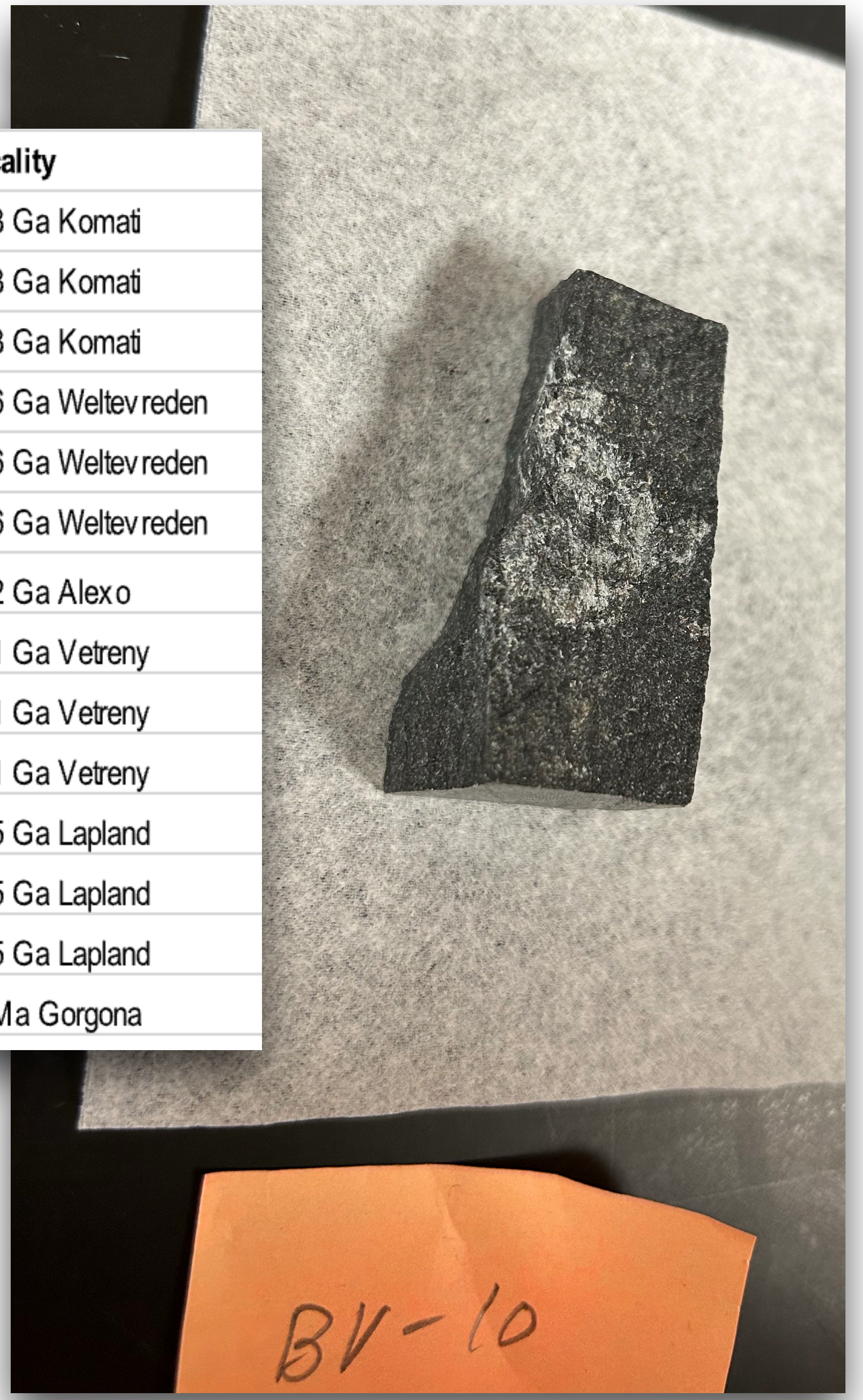
Note - there are more of these in the 200-300 Myr range that we can get!

Atmospheric Neutrino Detection with South African Komatiite Olivine

- Mainly forsterite (Mg_2SiO_4), from ancient lava flows, ejected and quickly buried
- The burial rate and depth transient is **unknown** after eruption
- However, **everything else -** the rock's composition, radioactive concentration, location, and age **- *is very well-constrained,*** with an abundance of literature published!

Sample#	Locality
BV-10	3.48 Ga Komati
BV-15	3.48 Ga Komati
BV-16	3.48 Ga Komati
501-8	3.26 Ga Weltevreden
501-9	3.26 Ga Weltevreden
564-1	3.26 Ga Weltevreden
ALX-26	2.72 Ga Alexo
121001	2.41 Ga Vetreny
12105	2.41 Ga Vetreny
12117	2.41 Ga Vetreny
KD-06	2.05 Ga Lapland
KD-09	2.05 Ga Lapland
KD-10	2.05 Ga Lapland
GOR 1901	89 Ma Gorgona



Could we reconstruct an average depth history based on the amount of cosmogenic neutron tracks we detect + simulation estimates with best known history?

Lithophile and siderophile element systematics of Earth's mantle at the Archean–Proterozoic boundary: Evidence from 2.4 Ga komatiites

Ultra-depleted 2.05 Ga komatiites of Finnish Lapland: Products of grainy late accretion or core-mantle interaction?

Pt–Re–Os and Sm–Nd isotope and HSE and REE systematics of the 2.7 Ga Belingwe and Abitibi komatiites

Insights into early Earth from Barberton komatiites: Evidence from lithophile isotope and trace element systematics

Insights into early Earth from the Pt–Re–Os isotope and highly siderophile element abundance systematics of Barberton komatiites

Igor S. Puchtel[a,*], Richard J. Walker[a], Mathieu Touboul[a], Euan G. Nisbet[b], Gary R. Byerly[c]

We have several > 20 gram samples from the same host rock, of a variety of ages — **a great sample set for atmospheric neutrino searches!**

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Atmospheric Neutrino Detection

Collection of geological samples from the same host rock,
with variety of ages spanning between tens of Myr, to several Gyr

“Background free” regions allow for easier readout of atmospheric neutrino tracks

Longer track lengths (tens of microns —> mm) make detector less sensitive to radiogenic and cosmogenic backgrounds

However, longer tracks require larger sample scans (high throughput, high resolution imaging techniques)

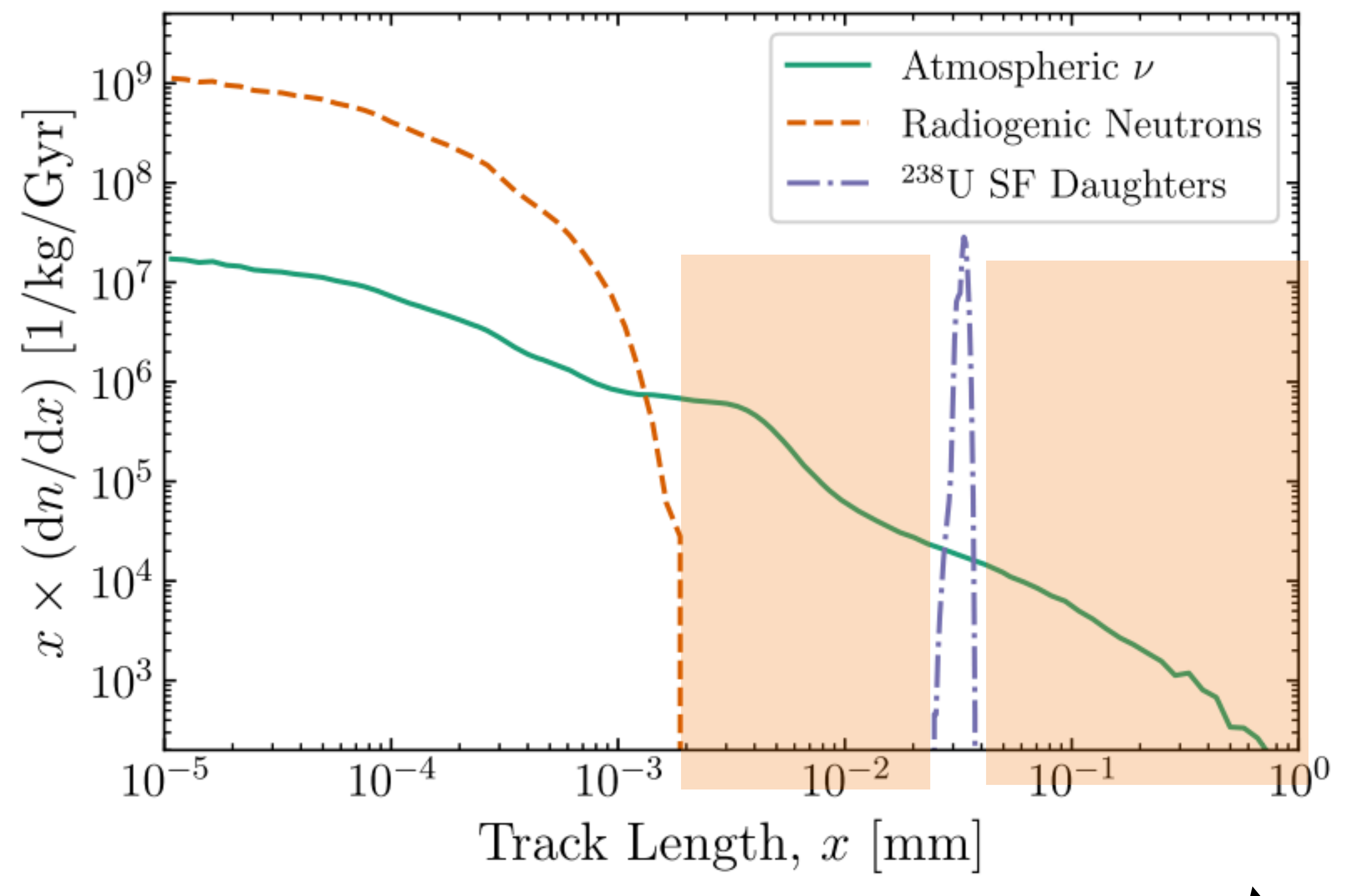
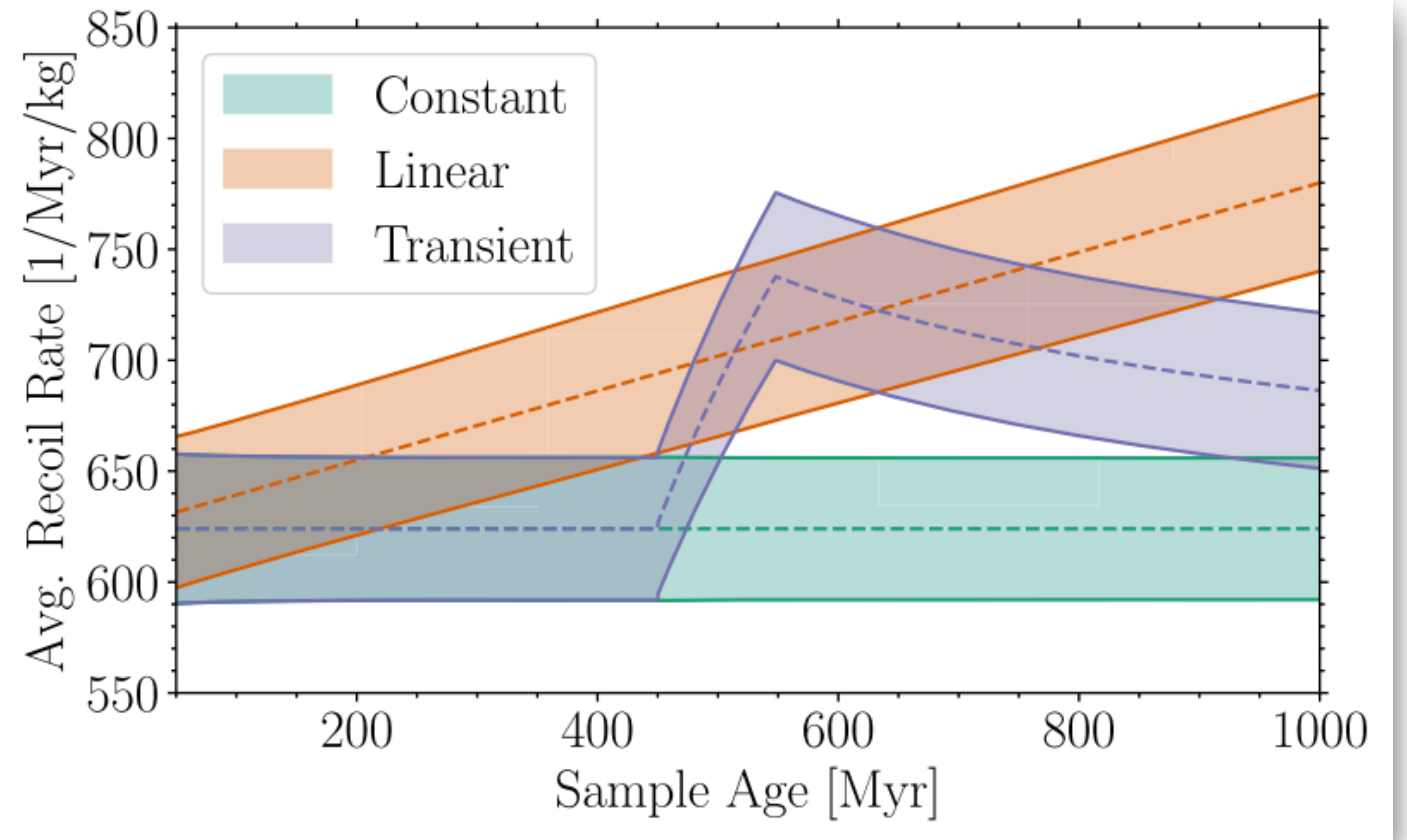


FIG. 1. Differential distribution of the number of recoils per unit target mass and unit time (n) with respect to the recoil track length (x) for a halite paleo-detector (modeled as ^{23}Na and ^{31}P; see text). In addition to the signal induced by interactions of atmospheric neutrinos (solid green), we also show the spectrum of background tracks induced by interactions of radiogenic neutrons (dashed orange) and the track length spectrum from spontaneous fission daughters (purple dash-dotted) assuming a ^{238}U concentration of 0.01 ppb by weight, consistent with previous work on paleo-detectors [15]. See the text for a discussion of these backgrounds. Note that there are two virtually background-free track length regions: 2 μm $\leq x \leq$ 20 μm and 50 μm $\leq x \leq$ 1 mm. Only recoils with $A > 4$ are included; lighter nuclei are not expected to give rise to visible tracks.

DOI: 10.1103/PhysRevLett.125.231802



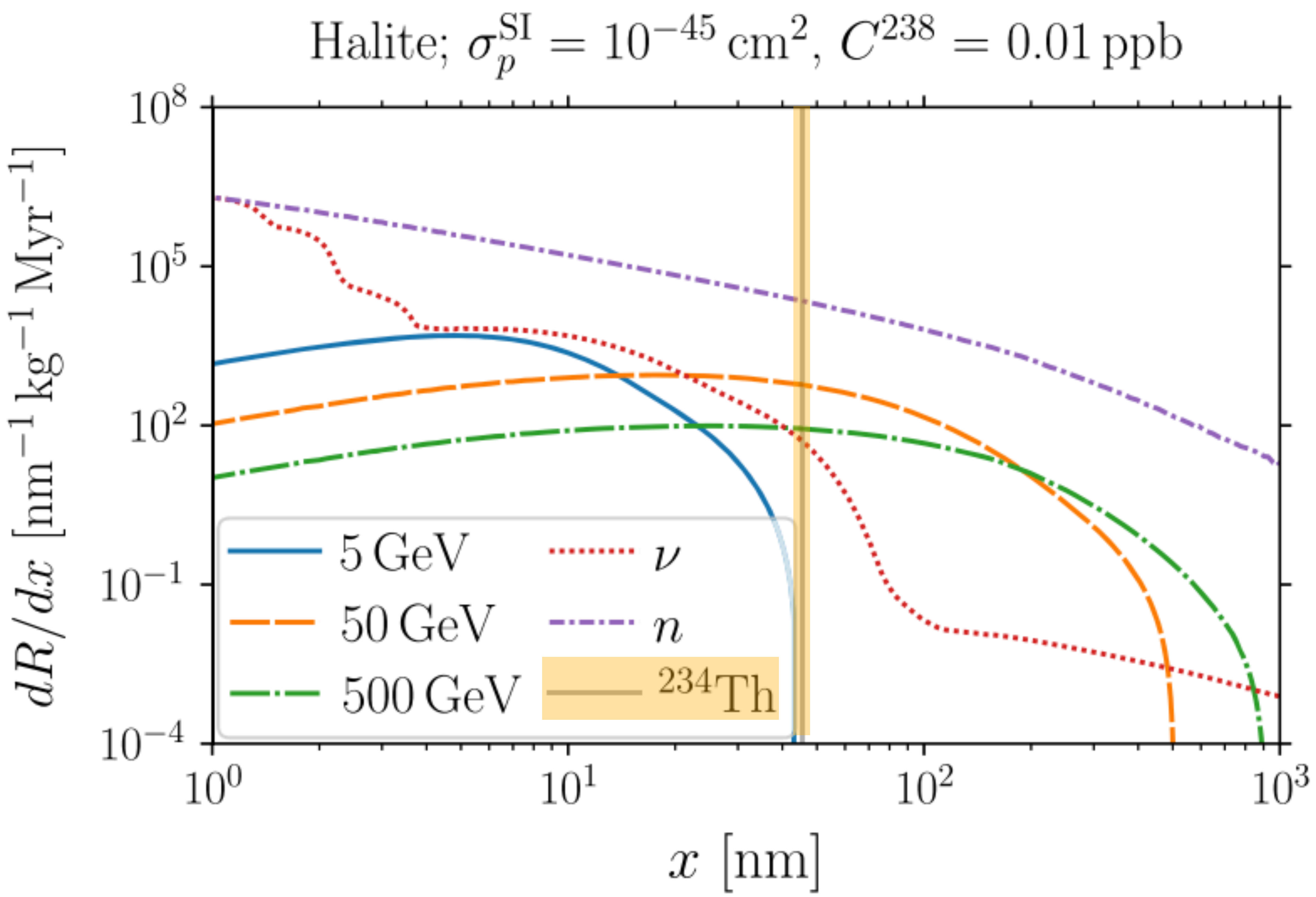
Changes in the atmospheric neutrino rate (thus cosmic ray rate) over history of Earth? Changes in composition/density of the atmosphere?

Note — this plot doesn’t take into account cosmic ray backgrounds, but *maybe* negligible at these track lengths!

Radiogenic Background Estimates

Combination of sample characterization + literature review

- Radiogenic backgrounds include tracks from:
  - Spontaneous fission
  - Alpha-recoils
  - Fast neutrons
- **Example**: can extract U/Th concentration from Inductively Coupled Plasma Mass Spectrometry (ICP-MS)
  - extremely sensitive technique to measure ppb - ppt trace levels
  - ICP: atomizes/ionizes sample
  - MS: separates and quantifies ions
- Well-constrained age & characteristic peak of Th-234 alpha-induced tracks in samples can help constrain background



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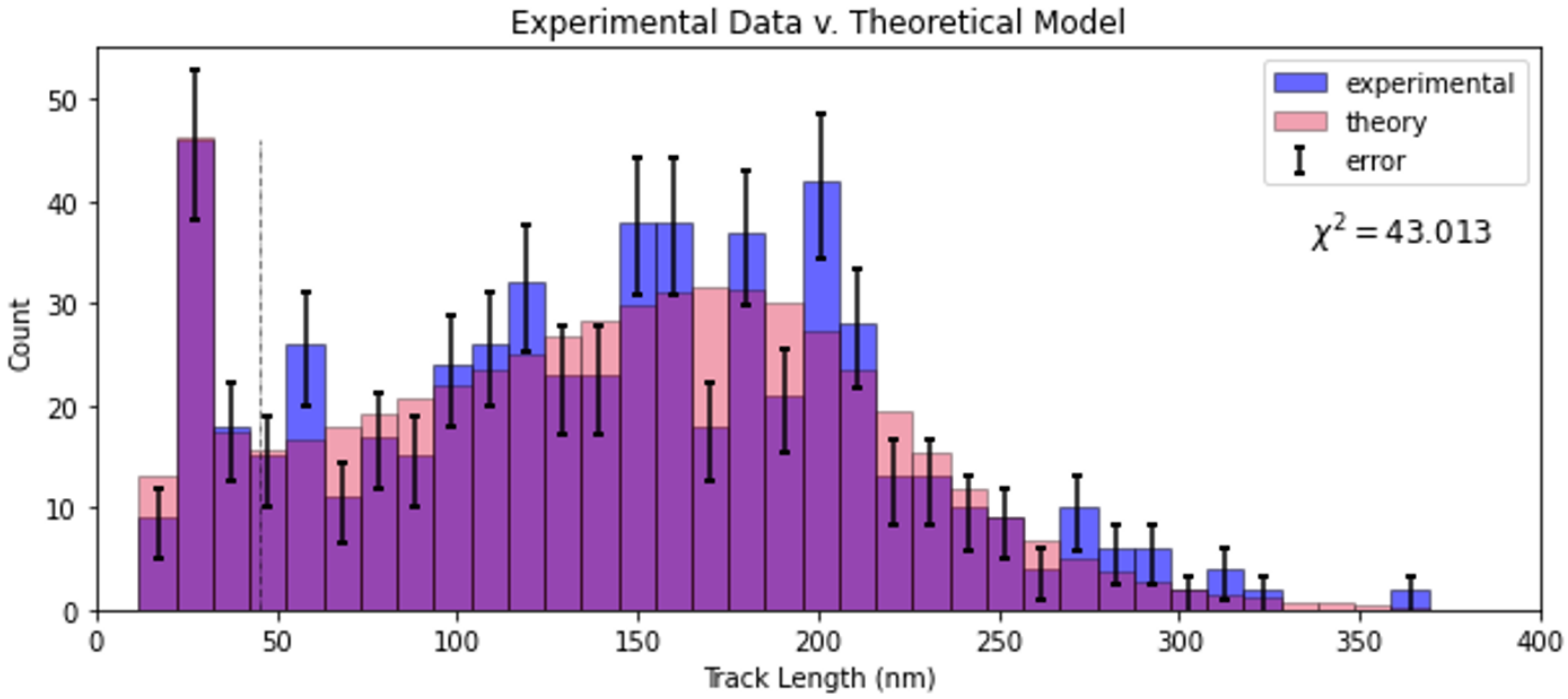
Track Length Spectrum - Comparison with Experimental Data

Example: Halite Thesis Work at UNF

- Experimental data output: histogram of track counts v. length bins
- Integrate over theoretical track length spectrum to compare
- **Note:** spectrum on right doesn't take cosmogenic neutrons into account !!



Credit:
Emilie LaVoie-Ingram, Chris Kelso
University of North Florida

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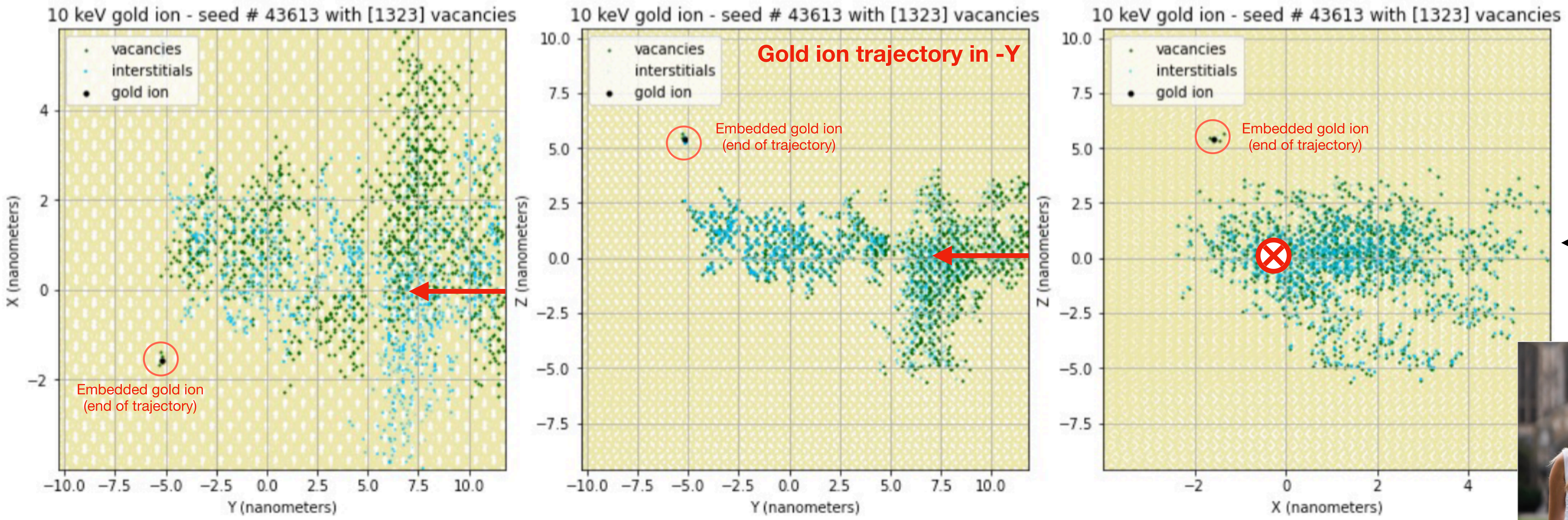
Additional Simulation Work

Simulating Track Formation with Molecular Dynamics (LAMMPS)

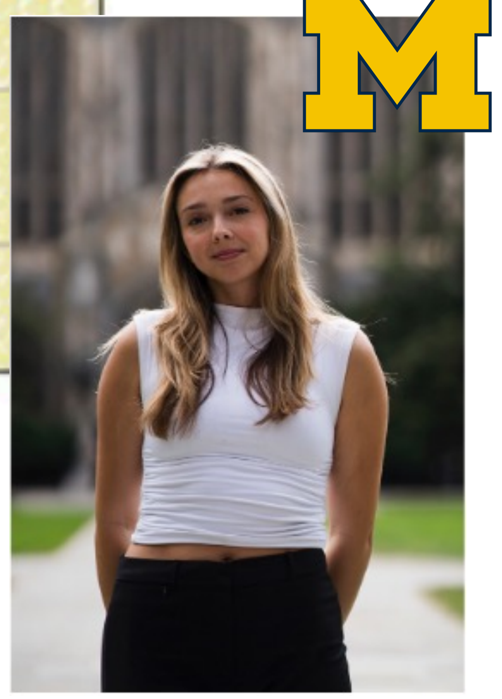
- Simulating formation of tracks/vacancies - can then compare with experiment

Define Lattice & Ion/PKA → Define Potentials → Relax Lattice & Initiate Temp. → Recoil → Relaxation/ Recombination → Result: # Vacancies

10 keV Au ion shot into crystalline SiO2

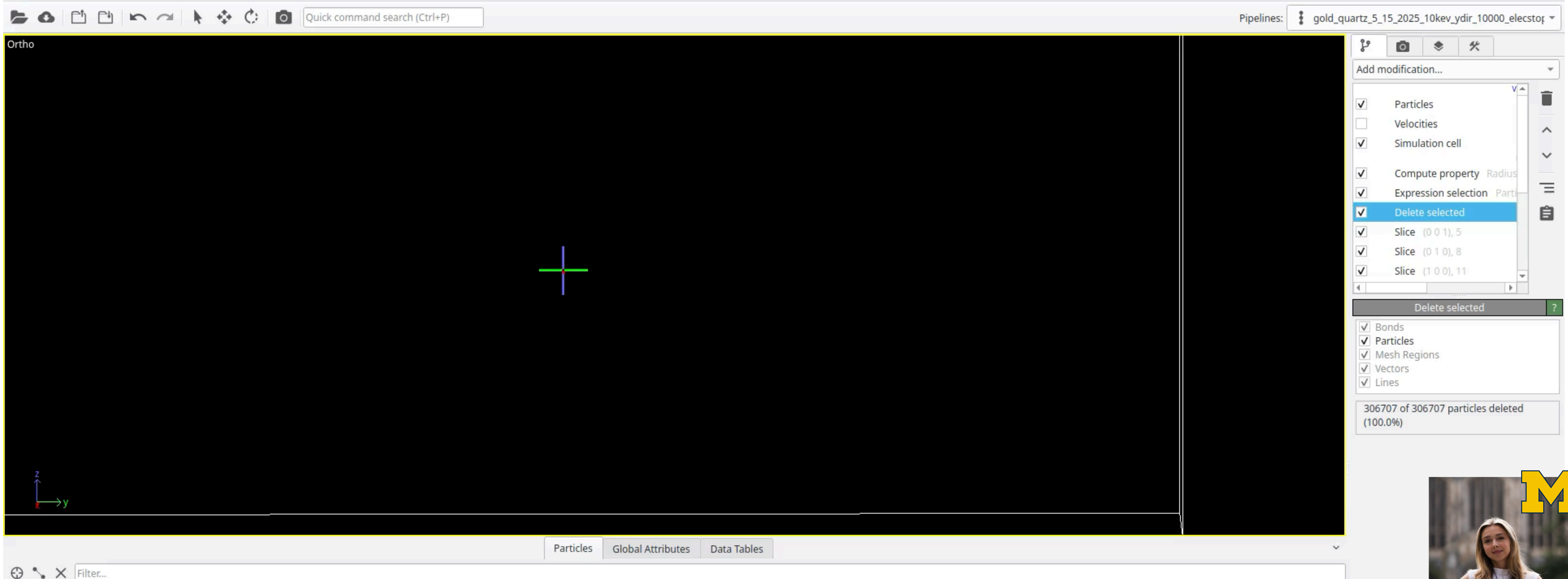


Simulation credit:
Katie Ream

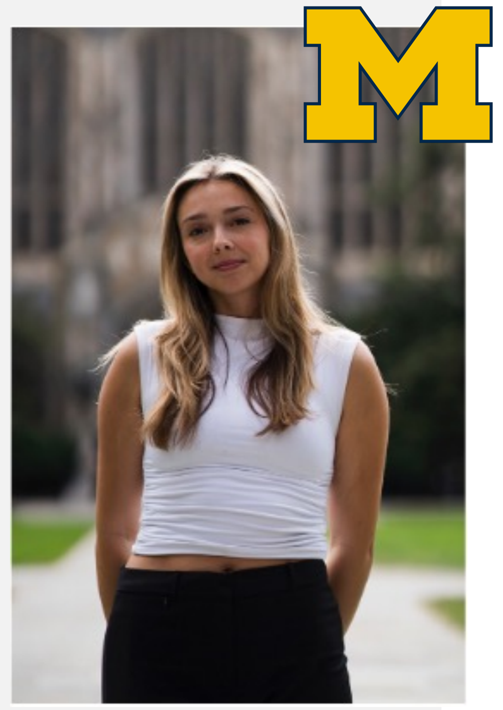


Simulating Track Formation with Molecular Dynamics (LAMMPS)

10 keV Au ion (enlarged for visualization) shot into crystalline SiO2



Simulation credit:
Katie Ream



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SimpleScreenRecorder

Summary & Discussion Points

- Currently in R&D stage, and open to trying new techniques and perspectives
- Fidelity of data is highly dependent on how well we understand and characterize our natural sample
- We're aiming for a multi-modal approach, using x-rays for bulk scanning at low-resolution, and TEM (+ more?) for sparse high-resolution scans
    - Atmospheric neutrinos dependent on bulk readout like x-rays **
- Simulations can help us characterize backgrounds, and investigate defect formation in various targets

U-M Paleo-Detector Team

Josh Spitz, Ph.D. | Kai Sun, Ph.D. | Igor Jovanovic, Ph.D. | Valentin Fondement, Ph.D. | Ethan Todd | Cassie Little | Emilie LaVoie-Ingram | Katie Ream | Andrew Calabrese-Day | Audrey Wu | Pranav Parvathaneni

NSF GCR MDDM Collaborators:

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Syracuse University: Jay Thomas

Jožef Stefan Institute: Patrick Stengel

University of North Florida: Chris Kelso, Greg Wurtz

SLAC National Accelerator Laboratory: Arianna Gleason, Sulgiye Park, Kazu Terao

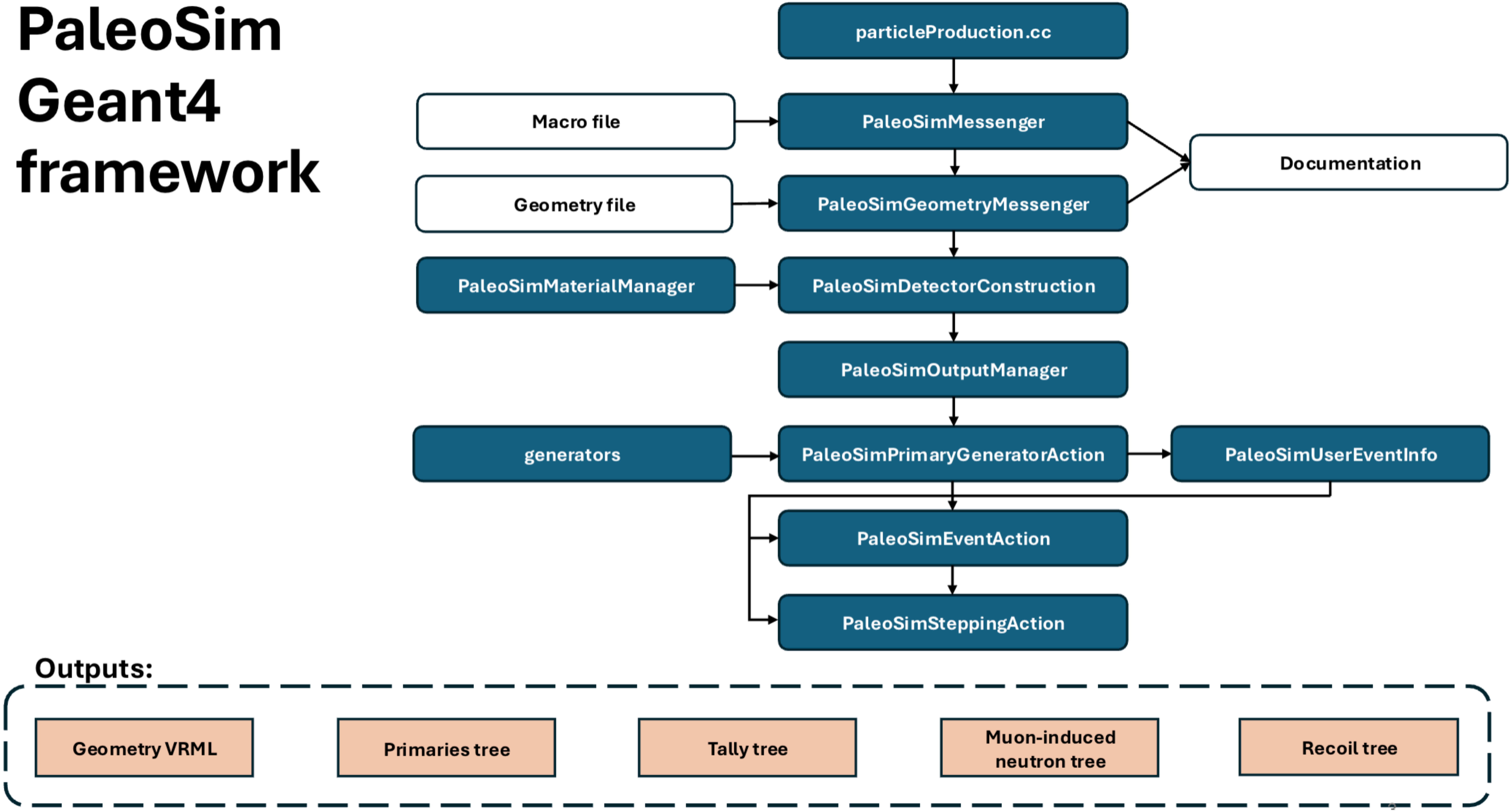
Virginia Tech: Robert Bodnar, Judah DiStefano, Samuel Hedges, Patrick Huber, Vsevolod Ivanov, Giti Khodaparast, Brenden Magill, Maverick Morrison, Thomas O'Donnell, Abigael Parks, Arjun Uppal, Keegan Walkup

Texas, The University of Texas at Austin: Katherine Freese, Dionysius Theodosopoulos

Lawrence Livermore National Laboratory: Xianyi Zhang

Back up

PaleoSim Geant4 framework



Current location: https://github.com/NSF-GCR-MDDM/paleo-bg-sim/tree/main

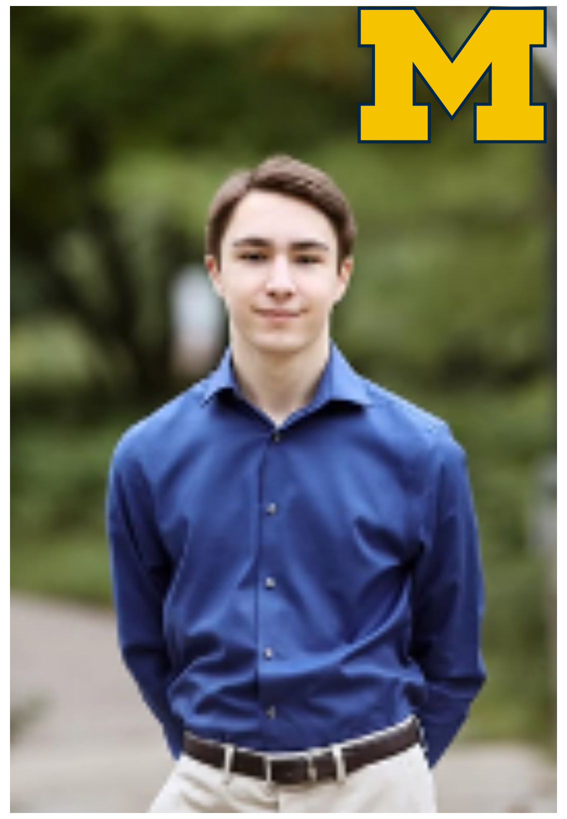
Comparison of muon-induced neutrons

- Mei & Hime simulated 6m x 6m x 6m air cavity surrounded by 20m x 20m x 20m rock volume, track neutrons entering cavity
  - Use FLUKA, apply a correction to their data to increase its flux ~35% to match experimental data
- GEANT4 with current physics lists predicts larger neutron flux by a factor of ~3, particularly at low energies
  - Currently code double counts neutrons that enter

Source	Total flux	Flux > 1 MeV	Flux > 10 MeV	Flux > 100 MeV
Geant4	0.164	0.052	0.019	0.007
Mei & Hime (2006)	0.054	0.020	0.018	0.005

All fluxes in units of 10^{-9} n/cm^2/sec

Sam Hedges

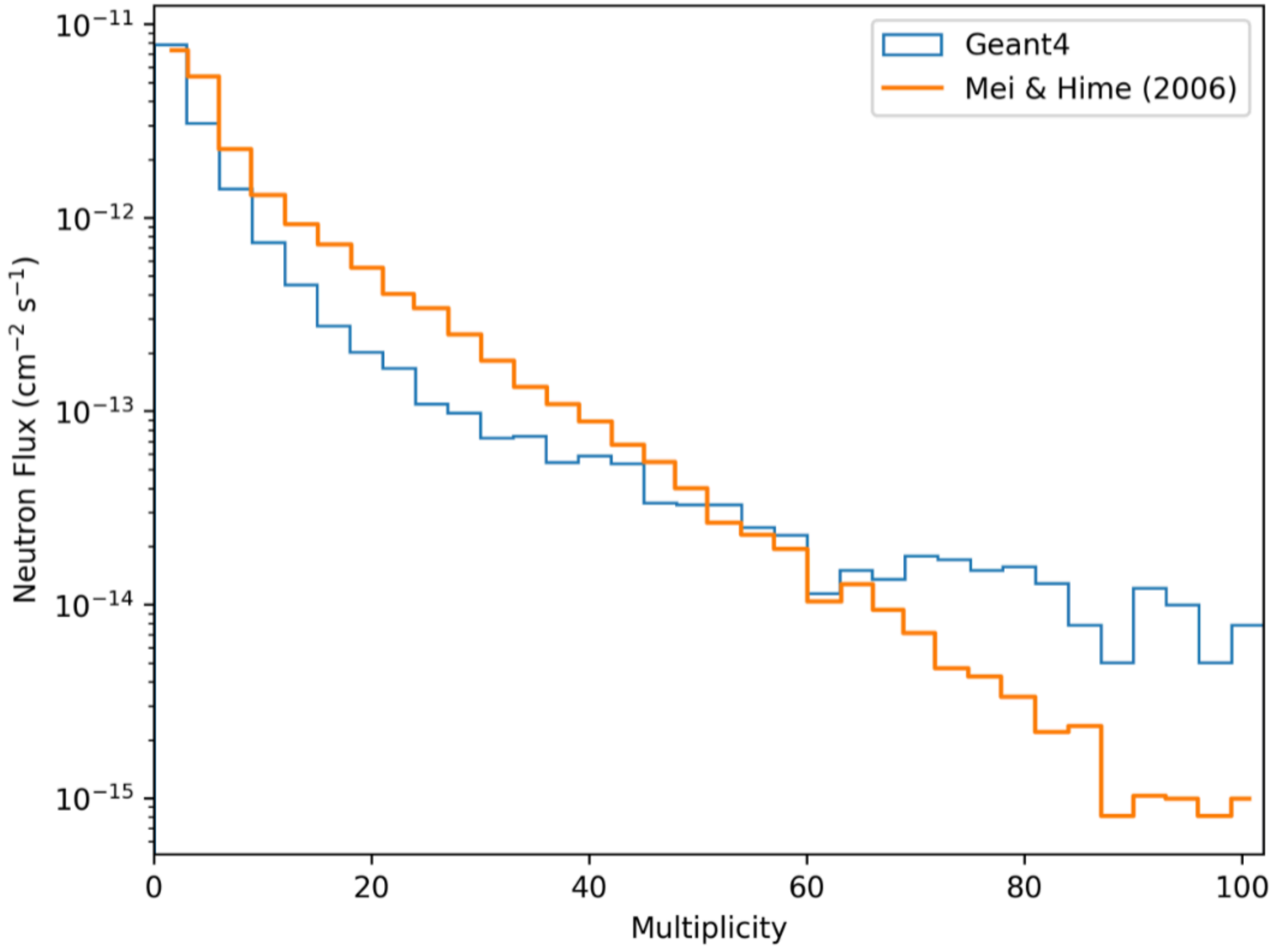


Andrew Calabrese-Day

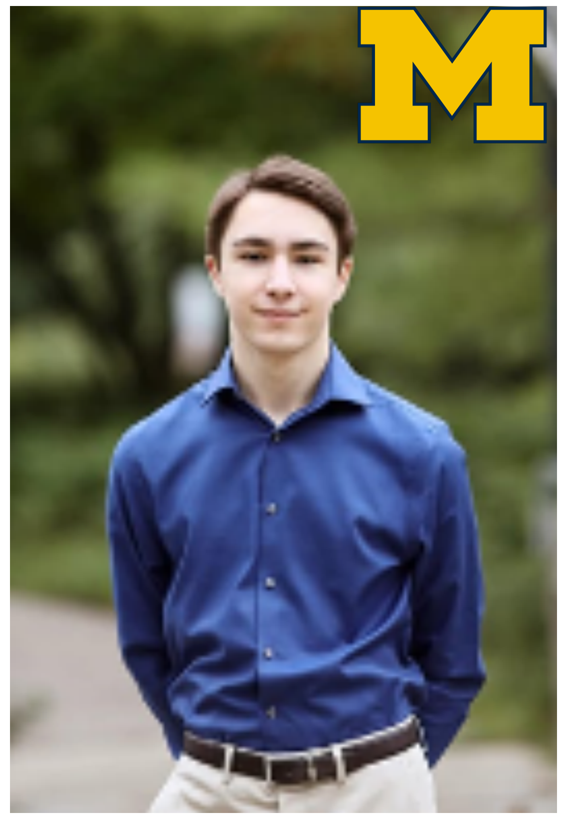
4

Muon-induced neutron multiplicity

- Plot multiplicity of neutrons entering the air cavity
- Geant4 sim predicts more large-multiplicity events
  - Need to look into energy-dependence of this distribution



Sam Hedges



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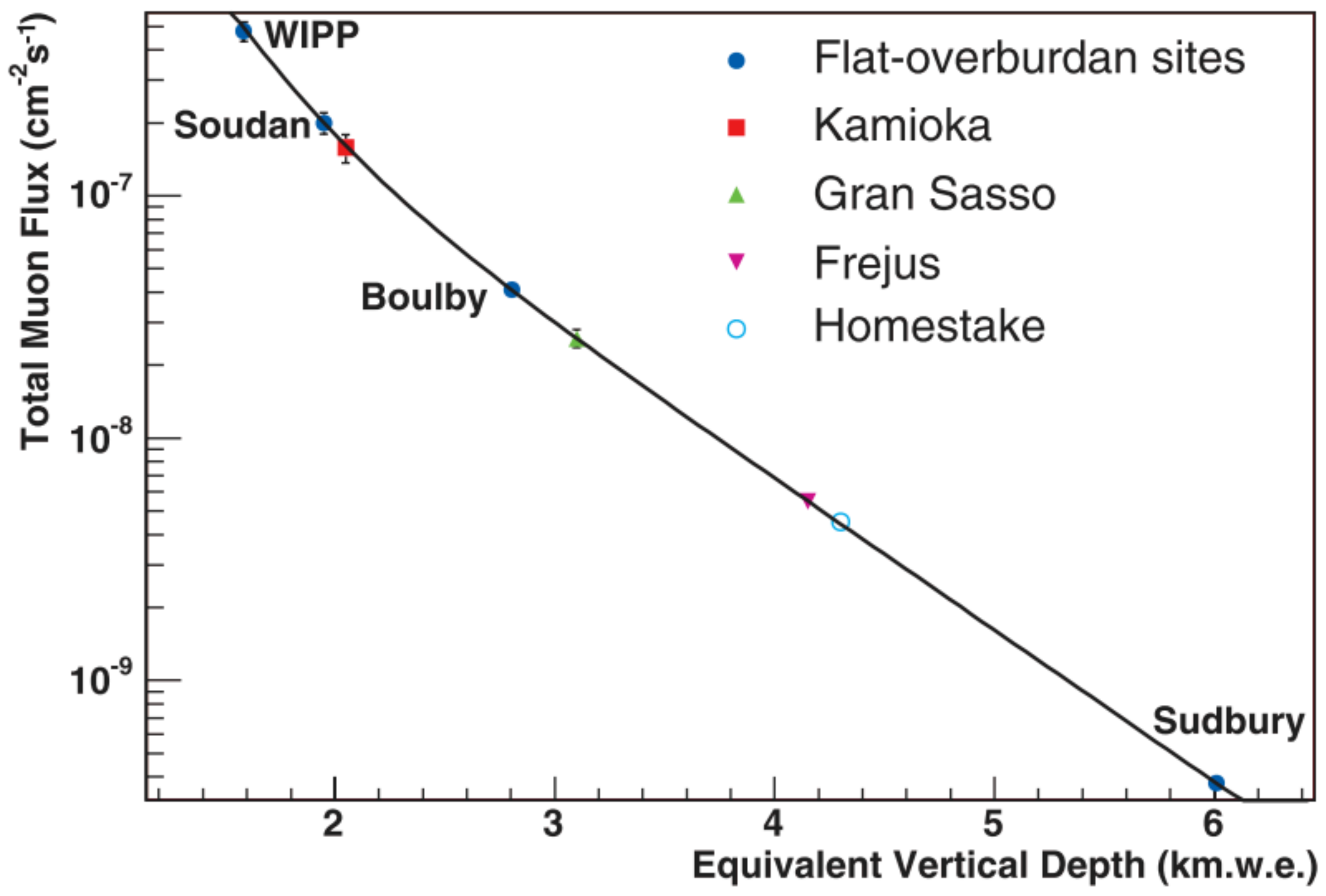


FIG. 3 (color). The total muon flux measured for the various underground sites summarized in Table I as a function of the equivalent vertical depth relative to a flat overburden. The smooth curve is our global fit function to those data taken from sites with flat overburden [Eq. (4)].

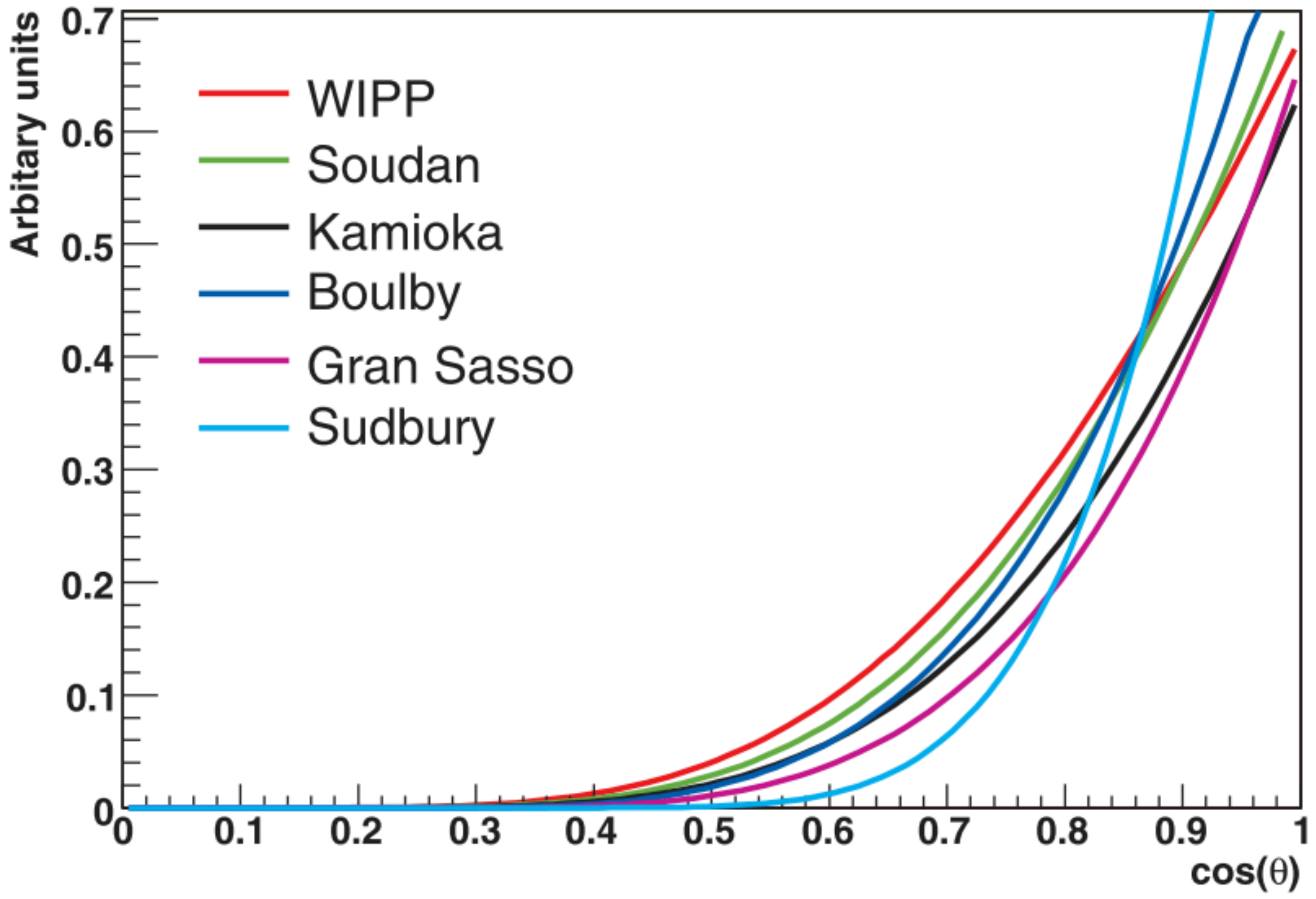


FIG. 7 (color). The muon angular distribution local to the various underground sites based on Eq. (3). All curves have been normalized to the total muon intensity for comparison purposes.

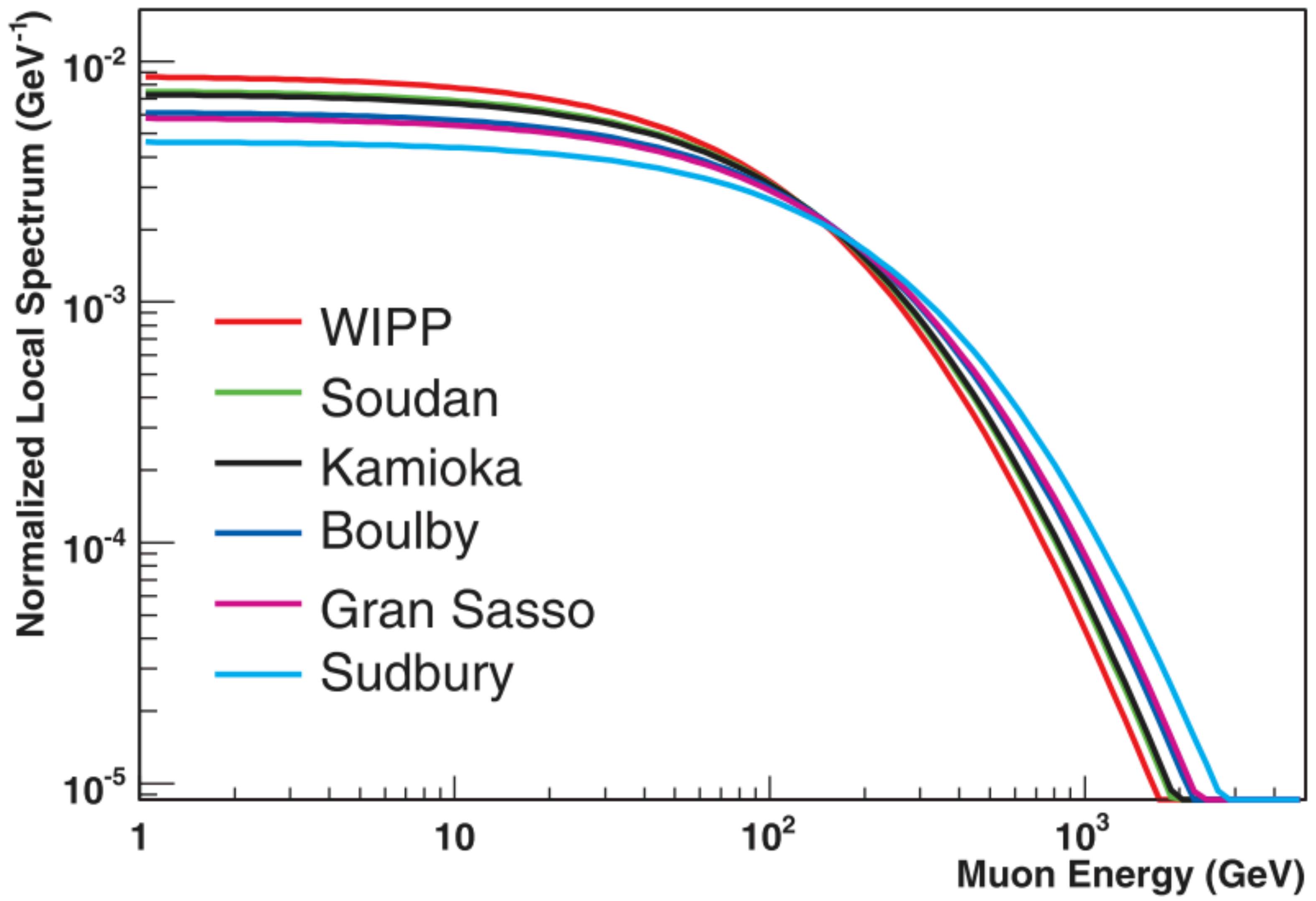


FIG. 6 (color). The muon energy spectrum local to the various underground sites calculated using Eq. (8). The areas under the curves are normalized to the vertical muon intensity for comparison purposes.

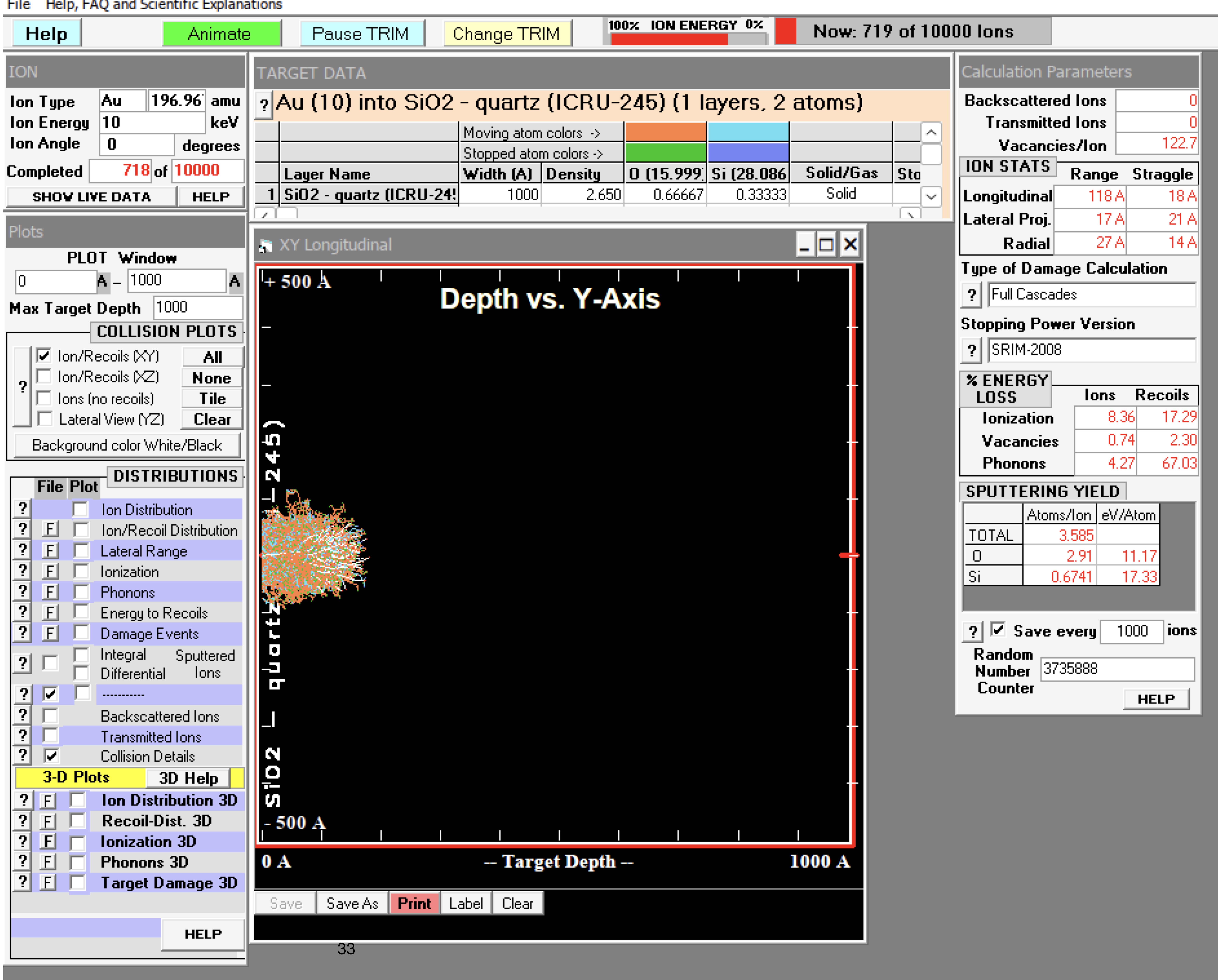
Simulation Workflow with LAMMPS (MD)

- **Define units & atom style** → Units = metal, atom_style = charge (we want to include coulomb interactions)
- **Define boundary conditions and import lattice file** → Periodic boundary conditions in directions perpendicular to ion, shrink-wrapped in ion direction. Lattice file - cubic cell of quartz, effective charges of Si and O included.
- **Define potentials (Tersoff, ZBL)** → Tersoff - two- and three-body potential validated for crystalline, α-quartz (SiO2)
  ZBL - close range repulsive potential (the potential driving the track-formation)
- **Energy minimization (lattice relaxation to local minimum)** → Energy minimization allows the atoms to perturb and relax into a local minimum energy arrangement in lattice - this process is based strictly on the potentials we define in the simulation. This overall reduces strain in the lattice, which will increase the displacement energy of atoms (important for vacancy production)
- **Thermal equilibration (lattice relaxation to local minimum)** → Allow lattice to relax once you initiate it at room temperature - same resort to local energy minimum but in this case it is based on the velocity of atoms (making sure there are no atoms with insanely high velocities that would cause instability)
- **Add fixed & thermal layer in lattice** → Fixed layers around the very outer boundaries of cell, and thermal layer to absorb energy before phonons reach the periodic boundary conditions (removes the ‘boomerang’ effect)
- **Create ion with energy & direction** → We’ve experimented with 1 - 20 keV Au, normal to the surface of quartz
- **Run simulation - variable stepping** → ~0.1 femtoseconds during irradiation, increase to more crude steps during lattice relaxation after ion comes to a stop (recombination of vacancies/interstitials)
- **Data output & analysis** → Isolating vacancies and interstitials, comparing to SRIM, approximating track length and radius

TRIM to predict vacancy production for given material and ion

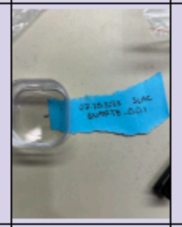
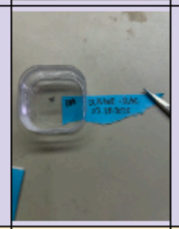
Note, possibly inaccuracies in nuclear-dominate stopping power regime

But gives us a ballpark until we perform low-E ion irradiation experiments



NSF GCR MDDM Rock Database

INVENTORY TABLE

nde	Image	unique_sampl	INST_YEAR_MINERAL_SOURCE_DEPTH_SAMP#	type_code	owner	owner_institution	current_institution	current_room	last_procedure
95		c0095	UM_2025_APATITE_DURANGO_SURF_SAMP_0.0.2	SAMP	Emilie LaVoie-Ingram	University of Michigan	University of Michigan	Randall 2208	saw, soaked in acetone to dissolve resin
96		c0096	UM_2025_APATITE_DURANGO_SURF_SAMP_0.0.3	SAMP	Emilie LaVoie-Ingram	University of Michigan	University of Michigan	Randall 2208	Etched with 5M HNO3 for 20 sec at room temperature
97		c0097	UM_2025_MICA_MC2_SLAC_0.0.1	SAMP	Kai Sun	University of Michigan	University of North Flori...	in transport	transmission x-ray microscopy
98		c0098	UM_2025_QUARTZ_MC2_SLAC_0.0.1	SAMP	Kai Sun	University of Michigan	SLAC	SSRL 6-2c	transmission x-ray microscopy
99		c0099	UM_2025_QUARTZ_MC2_SLAC_0.0.2	SAMP	Kai Sun	University of Michigan	University of North Flori...	in transport	irradiation
100		c0100	UM_2025_OLIVINE_MC2_SLAC_0.0.1	SAMP	Kai Sun	University of Michigan	SLAC	SSRL 6-2c	transmission x-ray microscopy
101		c0101	UMD_2025_DIAMOND_HOST_0.0.1	HOST	Daniel Ang	University of Maryland	University of Michigan	MC2	focused ion beam cutting - TEM prep
102	N/A - TEM	c0102	UMD_2025_DIAMOND_SAMP_0.0.1	SAMP	Daniel Ang	University of Maryland	University of Michigan	MC2	transmission x-ray microscopy

Inventory of all samples

Detailed record-keeping of where the sample has been, and what has been done to it

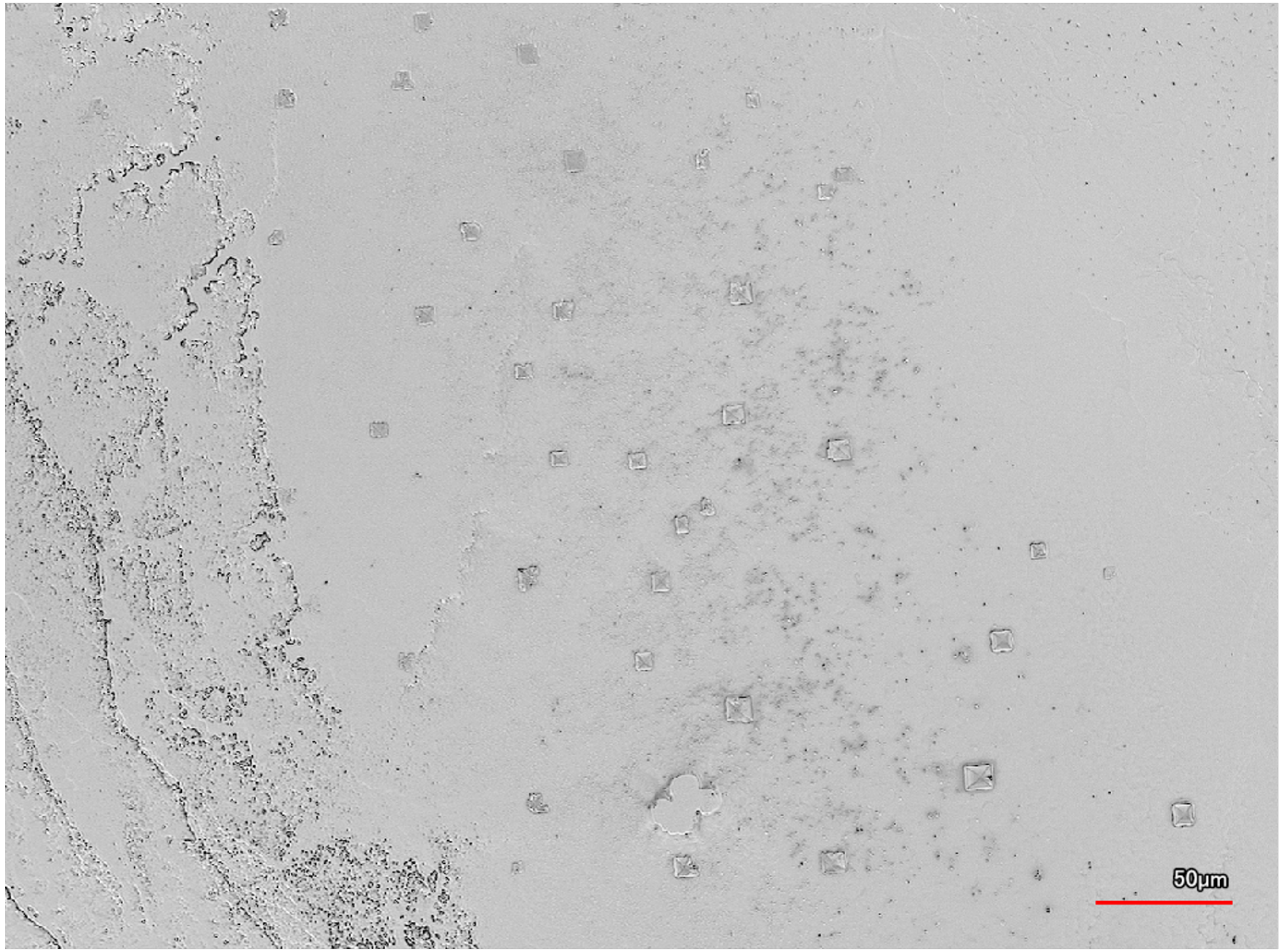
Submission/Request Forms for samples

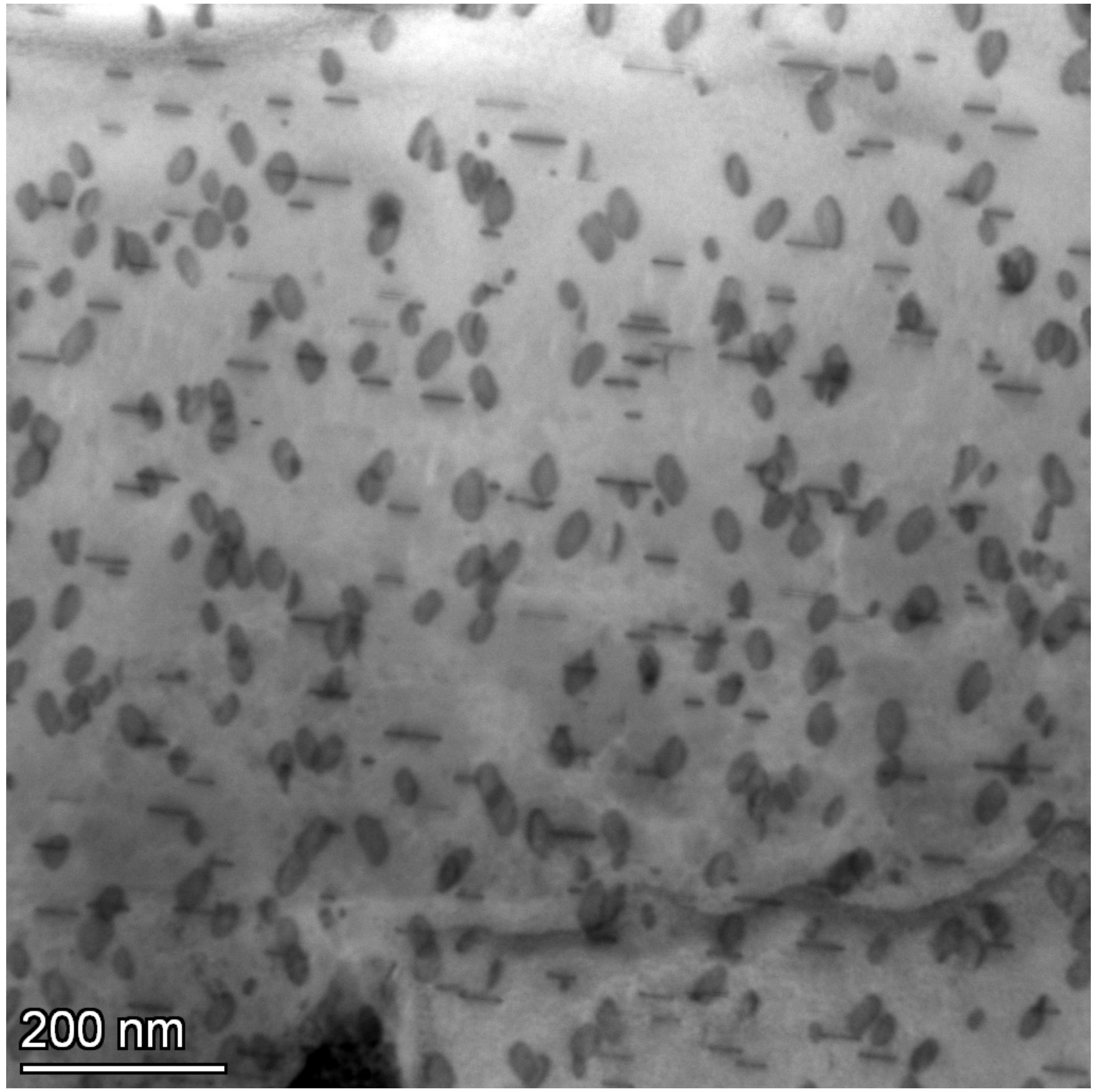
Standardized shipping and transit protocols

Directories and links to sample data

Will eventually transition to web-based UI format!

https://docs.google.com/spreadsheets/d/1CrIWUvxvVzWBqSrm8_fI5V51sA_mmfjtOznu3ppPeSE/edit?usp=sharing


50μm


200 nm

Mineral	Readout Technique	Spatial Resolution	Throughput

U-M Paleo-Detector Team

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