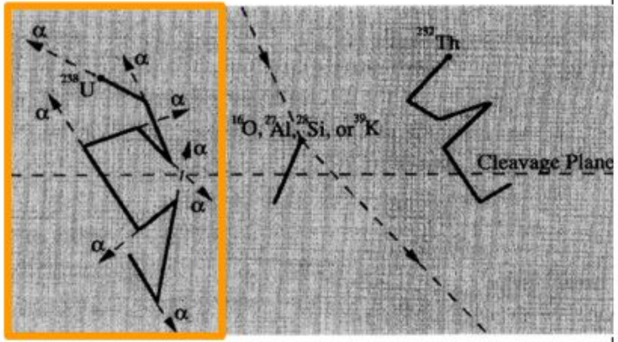
1 kg sample

1 Gyr old

10^{-10} g/g ^{238}U

10^{14} clusters

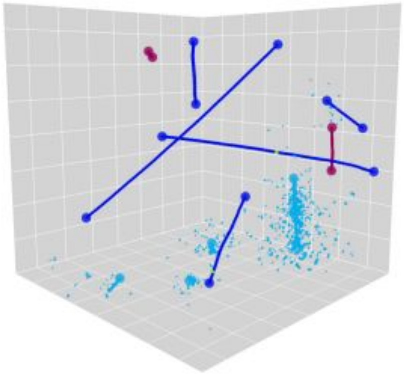


science goal

Only $1/10^6$ voxels contain part of track

Use LArTPC sparse convolution methods

Can SPIM efficiently reject clustered **α**'s ?



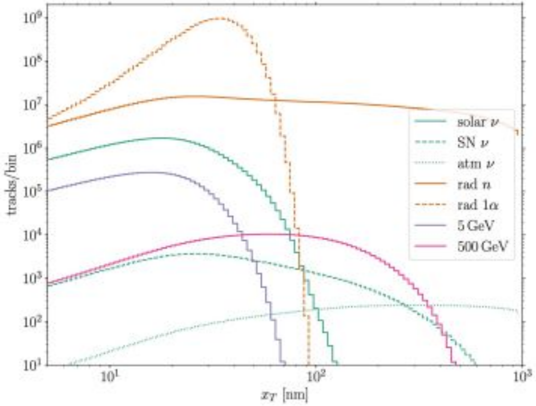
experiment

Muscovite

10nm resolution

Gaussian track length smearing

Only isolated **α**'s

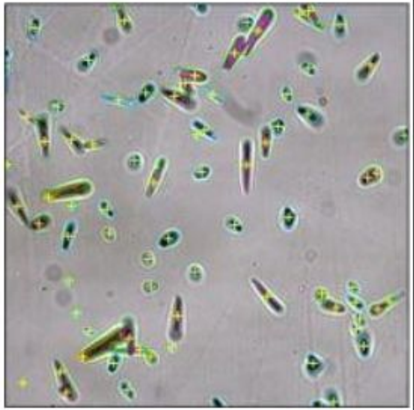


theory

Current methods use CNNs for fission tracks

Overlapping fission tracks for 10^{-3} g/g ^{238}U

α decay 10^6 faster than SF but less damage



gaps/risks

Measure the Haystack, Patrick Stengel, Jozef Stefan Institute

Action Items for the Haystack

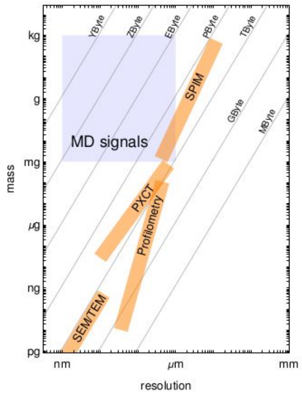
Simulation

- Are we reading out tracks via soft/hard x-rays or color centers with SPIM?
- Could inform simulated damage features with real data from e.g. Au tracks in Quartz and/or color centers in LiF
- Can simulate both with TRIM and distribute in ‘background free’ volume
- Setting up TRIM to run in a cluster environment with UM group for alpha backgrounds in proton decay search
- Use as ‘first order’ simulation of mineral detector volume to start data analysis within first two weeks of February

Data Analysis

- Need data format for given read-out method, ‘toy’ sample of SPIM data?
- What features should we focus on?
- Start with pixel/voxel position and brightness, potentially add ‘higher-level’ features (e.g. wavelength, number of CCs)
- Need to determine what size chunks of data are reasonable to look at in one shot
- Will eventually need some kind of trigger to discard empty (i.e. only noise) pixels
- Try clustering algorithms, semantic segmentation, point proposal network etc.
- Aim to have analysis framework by March

Show that we can find very sparse things in a large volume and characterize them with high-resolution methods



science goal

We can scan large volumes mm^3-cm^3 optically in LiF

We need to transfer coordinates to the FIB machine and cut the ROI out of the sample

-> TEM -> ptychography

experiment

What kind of track?

alpha/triton from n+6Li
fast neutron recoil
cosmic ray
heavy ion, can we do low enough fluence (<1E6 cm^-2)?

theory

What are the gaps/risks?

Coordinate system can not be established and transferred at required accuracy

FIB or other sample prep/shipping interferes with signals

gaps/risks

resolution vs volume I, Patrick Huber, VT

Characterizing the effect of irradiation on the photoluminescence (PL) from color centers: • Change in intensity, shape, and location of PL emission from color centers, • Directly image tracts of color center emitters from irradiation. science goal	**Spectroscopy of color center emissions:** • 0.5m spectrometer with LN cooled CCD camera • Extensive experience with low intensity emitter sources such as upconversion, • Wavelengths, WL, from 400 to 1050 nm available, Confocal microscopy of color center emission tracts. experiment
In ionic crystals color centers, anion vacancies, can trap electrons: • Acts like a square well → distinct energy levels, • Individual color centers can be seen in visible light by fluorescence spectroscopy (NV in diamond, SiC), • Observed in a wide class of materials. theory	**Challenges for PL measurements**: • Contamination from rare earths, • Inconsistent sample composition from suppliers, • Modern color center emission theory needed Challenges for confocal measurement, • Limited selection of excitation WLs available, • Bleaching of color centers, • Limited scanning area. gaps/risks

Optical Characterization of color centers, Brenden Magill, Virginia Tech

Quad Chart

Science Goal

- measure the length and density of a certain kind of line defect present in natural minerals

~1-3 nm width, up to 1 mm in length

- Have certainty in ascribing these tracks to the passage of a DM particle in a mineral

Experiment

- Need mineral samples with the right shape/size
- Perform X-ray lightsource experiments to visualize tracks

Synthetic first: Implant pristine silicon, mica, diamond, olivine, halite

-range of ion energies: 30-200 keV, 1 MeV or more?

-range of track lengths: 15-500 nm tracks

-range of angles, 6-45 degrees to normal

Theory

Leverage multi-modal data collection (XRD, imaging, spectroscopy, optical, TEM/SEM) & data fusion with AI:

- Filter on track morphology to steer where is best to look for a likely candidate of a DM particle track

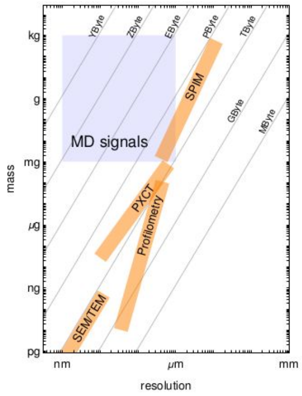
Gaps/Risks

•Establish procedures and/or metrics for discerning Dark Matter particle tracks from other types of tracks (fast neutrons, neutrinos, radiogenic/cosmogenic sources)

•Know mineral provenance and map mineral thermal history

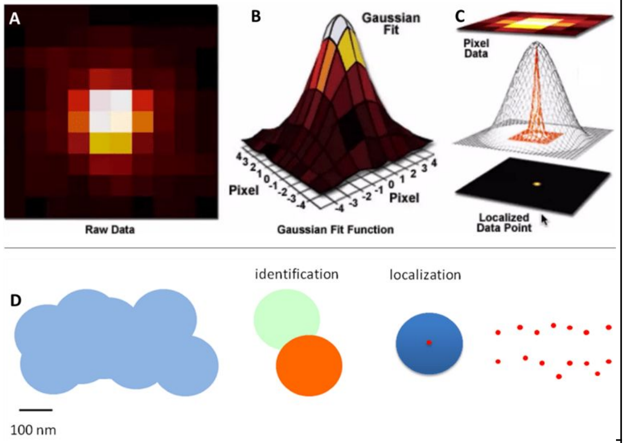
•NEED larger volume scans, 10s of mm^3

Show that we can find sparse things in a large volume and still obtain sufficient resolution

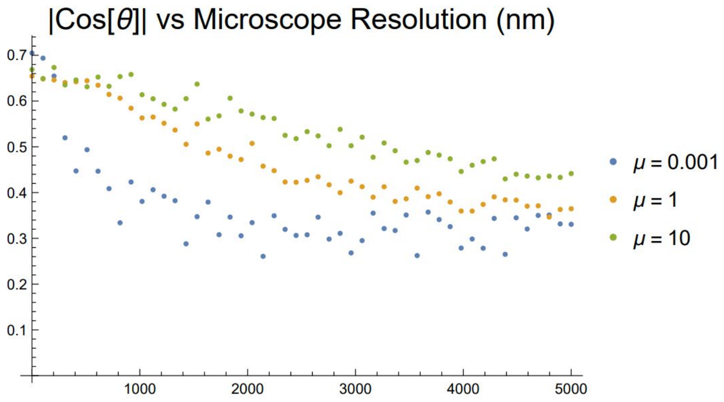


science goal

Super resolution microscopy: N photons provide √N more resolution



experiment



theory

What are the gaps/risks?

Can we get enough light from LiF (bleaching?)
Data processing
Better (=brighter) materials?
How much resolution is “sufficient”?

gaps/risks

resolution vs volume II, Patrick Huber, VT

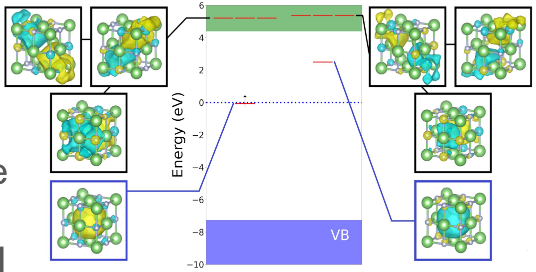
Our group is focused on first-principles method development and calculations of color center (CC) defect electronic structure and formation.

We have recently completed a thorough analysis of color centers in LiF, and in the future plan to compute the properties in other MDDM materials of interest.

Absorption spectra available for many defects; need photoluminescence (emission) spectra to compare with theory

Any other measurements of defect structure or electronic properties (strain dependence, spin resonance, dephasing times, etc) are a plus and would help identify CCs

- While some models and calculations of CCs exist, a full treatment of all MDDM materials is lacking
- Formation energy calculations are insufficient – need molecular dynamics and NEB to compute energy barriers for finding nuclear recoil energy loss



Existing methods for computing the electronic structure of defects suffer from significant errors when handling strongly localized & correlated states, which is a particular problem for alkali halides. Our group is working on developing new methods for treating localized defect states for which the degree of correlation is not known a priori.

First principles calculations of color center properties,Vsevolod, Virginia Tech

Science Goal: 1. Characterize the near-field signature of tracks using SPM, including AFM, NSOM, EFM, etc. 2. Use non-linear optical spectroscopies for track characterization (SHG, transient pump-probe scattering experiments) 3. Rationalize high-throughput far-field techniques science goal	What is known/needed experimentally 1. Samples that have been calibrated using other techniques. 2. Samples with different levels of known signals so we can try to build statistical models of the sample population as we expect we will not be able to do so on an individual track basis 3. High track density samples experiment
What is known/needed theoretically 1. If there are any types of materials that we are considering that might be more amenable to this type of analysis. 2. Any new AI/ML algorithms or methods that are used to help identify possible signals, especially if we think there will be a lot of backgrounds to try and overcome theory	What are the gaps/risks? 1. Defects/tracks lifetime, low track density 2. Are all tracks luminescent? 3. Sample preparation/existence gaps/risks

Near-field/local characterization of tracks, Chris Kelso and Greg Wurtz, UNF

Your science goal **Characterization of microstructures in different minerals using advanced techniques and correlate them to theory predicted microstructures by dark matters/neutrinos** science goal	What is known/needed experimentally *** Minerals selection: Quartz and olivine (natural and synthesized)** *** High energy ion accelerators: 15MeV gold, 9MeV Oxygen and other ions** *** SEM/FIB, XRM and TEMs** experiment
What is known/needed theoretically *** Ion matter interactions** *** TEM imaging theories** theory	What are the gaps/risks? *** Differences in sampling volume and spatial resolutions between XRM and TEM based techniques** *** e-beam damage effect** gaps/risks

Kai Sun, Department of Materials Science and Engineering, University of Michigan

Name of the problem, presenter name, affiliation

Quad Chart 1: UM Spitz Group Paleo Work

Science Goal	**Experiment**
To study the formation and morphology of nuclear recoil damage tracks in chosen target minerals. Inducing tracks of a given length range, width, and density in synthetic or annealed samples will help us understand our resolution and detection limitations with various microscopes we have access to. We can then estimate the feasibility of readout technology for dark matter tracks and other signals.	Ion/neutron irradiation of quartz, olivine, and other target minerals with predetermined flux/fluence, beam current/density, ion (& net charge), and irradiation time to meet the conditions mapped in theoretical models or natural ancient mineral samples. STEM imaging.
Theory	**Gaps/Risks:**
Need to understand the approximate background and target signal in our natural ancient samples by using geographic, radioactive, depth, elemental, thermal, and any other relevant information accessible to us. We also need a general understanding of the impact of ion species and/or net charge on the inflicted damage in the samples, so we can attempt to mimic a similar spectrum of natural tracks that we expect to see.	Gaps: (Pending experiment) effects of ion irradiation (track spectrum) between single crystal, lab-grown, pure minerals and natural minerals (that will have randomly oriented grains, contaminates, etc); annealing conditions for natural minerals

Ion Irradiation and Microscopy Experiments, Emilie LaVoie-Ingram/Joshua Spitz/Kai Sun/Igor Jovanovic, University of Michigan

Quad Chart 1 Action Items: UM Spitz Group Paleo Work

Task 1: Oxygen and (if possible) Silicon irradiation of synthetic and annealed natural quartz. Study of track morphology of lighter element recoils/tracks in synthetic and natural quartz samples. Also tests the compatibility of quartz under TEM x-ray imaging. Initial data analysis comparing track spectra between synthetic v. natural quartz.
Owner: Kai Sun, Emilie LaVoie-Ingram
Due Date: January 2025 - February 2025

Task 2: Resolution test with ion-milled/ion-irradiated samples (synthetic, or annealed natural). Create a controlled sample group with well-understood defect parameters (size of tracks - both diameter and length, density, position..) These will be used to test resolution on various imaging techniques - especially x-rays. Can use samples in SLAC collaboration or in-house testing at U-M. Likely Au or heavy element. (need to touch base with Arianna, decide on sample parameters and beam/proposal timeline!!!)
Owner: Emilie LaVoie-Ingram, Kai Sun, Igor Jovanovic (if neutron irradiation), Arianna (SLAC)
Due Date: February 2025 - March 2025

Task 3: Oxygen and (if possible) Silicon irradiation of synthetic and annealed natural olivine. We have Au irradiated synthetic olivine, but looking to replicate experiment in task 1 for another mineral. Contingent upon chemical analysis of natural olivine coming back positive (indeed is olivine, unaltered, minimal contaminants and in proper crystal structure).
Owner: Emilie LaVoie-Ingram, Kai Sun
Due Date: February 2025 - March 2025

Task X: (ongoing, throughout collaboration) ion irradiation of minerals upon request from other institutions. Collaborating institution will give Kai irradiation parameters and sample (or we'll use one of our samples)
Owner: Kai Sun, collaborating institution
Due Date: ongoing

(MAYBE) Task 4: Test feasibility of diamond as a DM detector. Would require obtaining synthetic and natural samples, and irradiating under conditions within the energy range we intend to probe for WIMP (or other model) dark matter. Can use TEM or (maybe) x-rays to image - would need to determine whether tracks actually form and preserve in diamond. Or any defects, for that matter. There is still a LOT of question around whether we can use diamond. This is connected to target mineral quad chart, task X (- obtaining diamond samples).
Owner: Emilie LaVoie-Ingram (obtaining sample, data analysis), Kai Sun (irradiation, imaging)
Due Date: Spring 2025

Quad Chart 2: UM Spitz Group Paleo Work

Science Goal	**Experiment**
Imaged induced and natural damage tracks with high resolution x-ray tomography. Goal is to reconstruct 3D images of samples with enough resolution to automatically detect tracks with minimal error in length. Likely inapplicable to DM searches at U-M, but can potentially collaborate with other x-ray source teams.	Awaiting ZEISS Xradia 810 Ultra X-ray microscope with ~15 nm spatial voxel resolution. Imaging experiments will include using irradiated samples with well-known track spectrum, and comparing the tracks resolvable in microscope images.
Theory	**Gaps/Risks:**
Necessary to understand x-ray transparency in sample, contrast threshold to resolve tracks, various optics parameters as they relate to material properties (ex: high contrast samples will result in better resolution and signal-to-noise ratio)	Risks: not being able to resolve width of tracks with current limit of voxel resolution. Average width will be a few nm, so we expect at the very best to identify a ~20% change in intensity along a ~15 nm voxel containing a ~3 nm wide track. However, the length is >> voxel res., so this will help.

Imaging with X-ray Tomography, Emilie LaVoie-Ingram/Joshua Spitz/Kai Sun/Igor Jovanovic, University of Michigan

Quad Chart 2 Action Items: UM Spitz Group Paleo Work

Task 1: Train on x-ray microscope, understand beam parameters and what we can adjust. Use well understood sample to align and image - test resolution. This task is essentially getting familiar with the microscope and prerequisite imaging before we look for tracks.
Owner: Emilie LaVoie-Ingram, Kai Sun
Due Date: (whenever machine arrives) anticipating Feb 2025

Task 2: Collaboration with SLAC (joint item with quad chart 1, task 2). Test resolution of TXM beam line at SLAC. Use samples prepared in Task 2 Quad Chart 1 to test feasibility of x-ray beam line at SLAC. Proof of concept study - question is whether we can actually *see* tracks with x-rays. Start with large defects, work our way down. This is a large action item as is considers proposal creation, sample preparation (fully at UM), beam time, and data analysis
Owner: Emilie LaVoie-Ingram, Kai Sun, Arianna (SLAC), etc
Due Date: February 2025 - March 2025 proposal, anticipated April beam time, May 2025 data analysis

Task 3: Test whether we can resolve Au ion tracks in olivine or quartz with XRM. This can be with synthetic or natural crystals. But beforehand we need to know what tracks are present and approximately what size/density. This can be done with initial TEM studies. Using the same minerals under the same ion beam conditions. Ongoing during task: look for mega tracks (heavy DM)?
Owner: Emilie LaVoie-Ingram, Kai Sun
Due Date: March 2025-April 2025

Task 4: (Contingent upon if we can resolve Au tracks) Test whether we can see tracks from lighter elements, like O or Si with XRM. This can be with synthetic or natural crystals. But beforehand we need to know what tracks are present and approximately what size/density. This can be done with initial TEM studies. Using the same minerals under the same ion beam conditions. Essentially a resolution study - if we see tracks, what are the smallest tracks we can see? Ongoing during task: look for mega tracks (heavy DM)?
Owner: Emilie LaVoie-Ingram, Kai Sun
Due Date: March 2025-April 2025

Task X:
Owner:
Due Date:

Quad Chart 3: UM Spitz Group Paleo Work

Science Goal	**Experiment**
To study and refine the ideal target mineral for paleo-detection of WIMP dark matter. Heavily relies on elemental composition (related to resulting dimensions of damage track in WIMP spectrum). Very important factor is possibility of finding the ideal mineral at the age, depth, and radioactive background constraints required.	(In progress) collect a variety of applicable minerals at a variety of constraint combinations (i.e., different depths, geographic regions, ages) and compare data between them. Can determine signal to noise or feasibility of an accurate background determination (e.g., are there things we cannot know? Is error in age too large?)
Theory	**Gaps/Risks:**
Composition/bonding/structure of crystal, reactivity to surrounding environment, fragility/hardness, performance under electron/x-ray microscopy, ability to mine, oldest and deepest available crystals, time at surface (cosmogenic background), annealing conditions, contamination, overall track length spectrum	Risk: Inability to find minerals with proper constraints Gaps: lack of experimental data to get an idea of which minerals will be better suited lack of research (although currently ongoing at U-M) into feasibility of both old (> few Myr) and ultra-deep (2-5 km) minerals

Mineral Target Optimization, Emilie LaVoie-Ingram/Joshua Spitz/Kai Sun/Igor Jovanovic, University of Michigan

Quad Chart 3 Action Items: UM Spitz Group Paleo Work

Task 1: Chemical and phase analysis of natural samples on hand at U-M. These include olivine, quartz, and a variety of what is expected to be carbonates. Bulk chemical analyses and bulk phases proportions will be collected for each sample set. This is needed to properly map background spectrum for each sample set. Also hoping to get more information about U-Th concentration in each mineral sample set. XRD and XRF are in plan for now.
Owner: Emilie LaVoie-Ingram
Due Date: analyze by mid-February 2025 (dependent on whether we need to contract out a lab or if we can do it internally)

Task 2: Refine background spectrum to natural minerals with chemical composition, depth, and approximate age information. This will be a large task that will rely on the contribute of geologists, especially when it comes to dating samples and getting an approx. depth v. time plot for the mineral. This will help us not only study the samples we already have but give us a good idea of what depth/age/chemical compositions of natural samples will be adequate for DM detection. Will upload into sample inventory and make accessible to whole group!
Owner: Emilie LaVoie-Ingram, U-M/external geologists, etc.
Due Date: mid-February to Mid-March 2025

Task 3: TEM (and/or x-ray) imaging of natural tracks present in natural samples on hand at U-M. Get an idea of the track spectrum (up to about ~200 nm depending on imaging thickness) present in samples. Approximate density and track length within region can be reconstructed. Compare against initial background spectrum predictions.
Owner: Emilie LaVoie-Ingram, Kai Sun
Due Date: mid-February to Mid-March 2025 (can image while we regine backgrounds)

Task 4: Ion irradiation of annealed natural samples and imaging with TEM and/or x-rays. We can then compare the track length spectrum, track diameter/morphology, and density difference between pristine minerals and natural minerals that have been irradiated under the same conditions. Will reveal crucial information about how tracks form in natural samples and if there are additional resolution limits or limitations on sensitivity.
Owner: Emilie LaVoie-Ingram, Kai Sun, (opt) Igor Jovanovic, (opt) Arianna (SLAC)
Due Date: mid-March to mid-May 2025 (extended date due to increased travel/conferences)

Task 5: Data analysis - thoughtful comparisons between pristine and natural sample track morphology/resolution studies. What is working, what isn't working? What else can we refine/try? What have we learned? Large window for reflection on what additional experiments we could do, or what other minerals to pursue
Owner: Emilie LaVoie-Ingram, Josh Spitz, Kai Sun, Igor Jovanovic, (opt) NSF GCR MDDM group members in general, U-M/external geologists/geoscientists
Due Date: on-going, but will likely start in April/May 2025

Task X: (ongoing task throughout years of grant) Discussion with geologists and mines: what minerals exists under the conditions we need, and what is accessible? Continuous search/discussion for mineral targets. Geologists and mines will be the primary points of contact. Planning of field work and/or shipment of samples within continent or across the world necessary. Could also include planning a deep sea drilling expedition or collaborating with geologists/mines/drilling companies across the world.
Owner: Emilie LaVoie-Ingram (primary lead of contact)
Due Date: ongoing, 2025-2027/30

Quad Chart 4: UM Jovanovic Group Paleo Work

<u>Science Goal</u> Provide high-fidelity, quantifiable, and repeatable neutron irradiations at various energies (thermal – 14 MeV) in various materials to help identify unique signatures of nuclear recoils at energy scales relevant to the GCR program.	**<u>Experiment</u>** • Low-room-return irradiation with 2.5 MeV and 14 MeV monoenergetic neutrons, Cf-252, and PuBe neutrons in NSL • Thermal and fast neutron ride-along irradiations at OSU-NRL 
<u>Theory</u> Detailed validated simulations of irradiation conditions based on existing models of the Michigan Neutron Science Laboratory (NSL) and Ohio State University Nuclear Reactor Laboratory (OSU-NRL) sources and environment.	**<u>Gaps/Risks:</u>** <u>Risk:</u> Access to OSU-NRL may be limited, and the gamma environment may be challenging to control <u>Gaps:</u> Incomplete understanding of required environmental conditions, storage, and transport.

Jay
Thomas

Grow minerals with prescribed U concentrations ranging from 0 to 1000 ppm (by weight) U

Piston-cylinder experiments

Irradiate to produce tracks

Use different uranium sources (UO2, U nitrate, coffinite ($U(SiO_4)_{1-x}(OH)_{4x}$) should produce zircons with different U concentrations

Develop:

1. AI/ML development community centered around public dataset
2. A public data portal for:
   a. education/training
   b. Outreach
   c. Advance research

science goal

What to try:

- Dataset with the right format
  - Data (and metadata) curation
  - Tools to access and stream data fast
- Concise documentation for dummies
- Clear scientific challenge metrics
- Organize events “Data Olympics”
  - Open dataset X months in advance
  - New dataset unblinded at the event

experiment

What is known/to-expect:

- A common place to point out to new members for a concise scientific challenges to make immediate impact
- Contributions (often very welcomed) from researchers within and outside our community
- Increase scientific value for your dataset and credit scope

theory

Gaps/Risks

- Dataset owners might not want to contribute
- Data curation may take significant effort
  - But we should be doing this anyway
  - No need to be curated for all possible research but start with specific research challenge to be listed initially.

gaps/risks

Name of the problem, presenter name, affiliation

Develop: 1. Fast algorithms for detecting the region of interest in large images 2. If necessary, a model for noise removal 3. Quality algorithms for identifying the signal (i.e. tracks) type and kinematics 4. Develop above for various type of minerals and target signals science goal	Key points: • No good simulation models • Can "easily" produce lots of data (it depends, but LiF data is already available) Experimentation: • Develop self-supervision techniques • Develop a human-in-loop optimization • As simulation gets developed, integrate into the optimization methods experiment
Not much is known: • There are models that work for 2D/3D image data albeit most prevalent applications are for photographs or 3D scene of the real world • Kazu has to learn about data and physics behind image features to say anything more useful. theory	Gaps/Risks • Self-supervision techniques might not work in a straightforward manner. We may have to utilize utilizing physics model knowledge • High-risk/return: applications developed in this project likely useful in other science areas that use the same imaging methods • Reach out to ML colleagues at SLAC who work on LCLS/CryoEM/etc. … gaps/risks

Name of the problem, presenter name, affiliation