

Nuclear recoil detection with color centers in bulk lithium fluoride

based on arXiv:2503.20732 for the
PAssive Low Energy Optical Color CEnter Nuclear rEcoil
(PALEOCENE) collaboration

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 **SMASH**
machine learning for science and humanities postdoctoral program

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Physics > Instrumentation and Detectors

*[Submitted on 28 Aug 2025]***Mineral Detection of Neutrinos and Dark Matter 2025 Proceedings**

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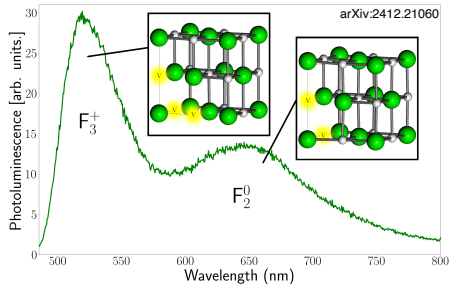
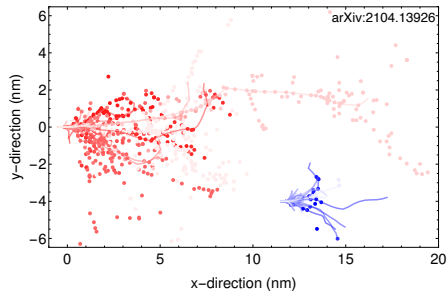
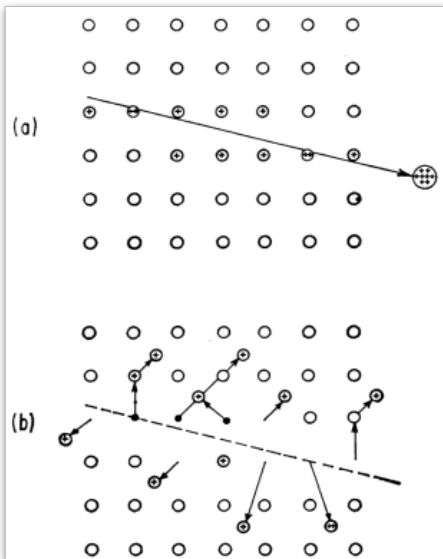
MD ν DM community

- Groups across Europe, North America and Japan
- Astroparticle theorists, experimentalists, geologists, and materials scientists

Also check out the whitepaper!
arXiv:2301.07118, 2405.01626

- History of mineral detectors
- Review of scientific potential for particle physics, reactor neutrinos and geoscience

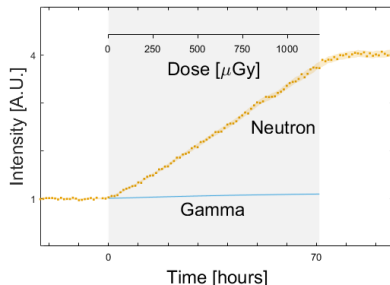
Damage induced by nuclear recoils in mineral detectors



Mineral detectors alternative to conventional experiments

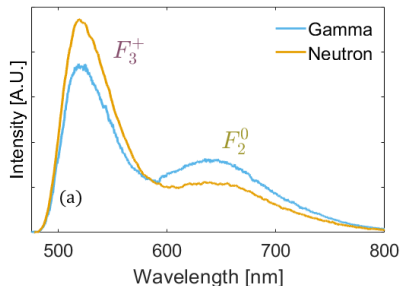
Irradiation of LiF samples

- Gammas from ^{60}Co for response to ionizing radiation
- Fast neutrons from AmBe for background calibration
- Thermal neutrons moderated by high-density polyethylene

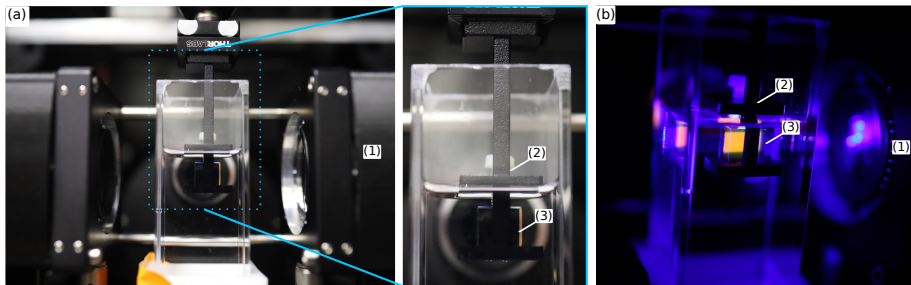
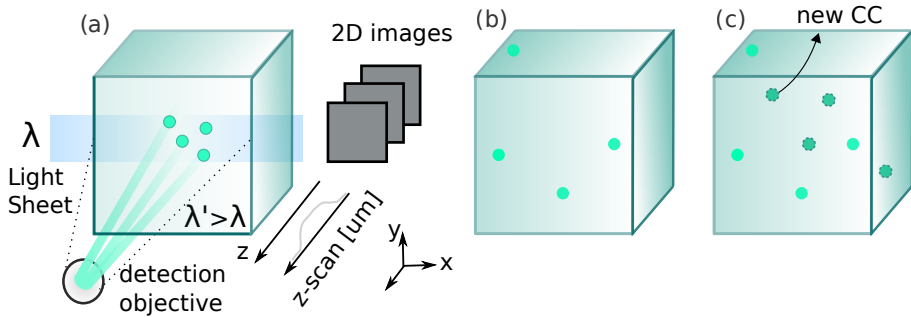


Imaging color centers in cm^3 samples

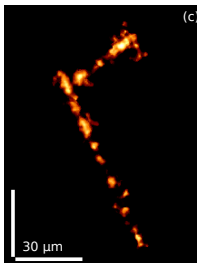
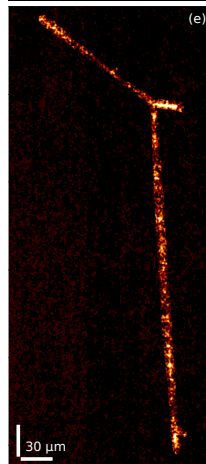
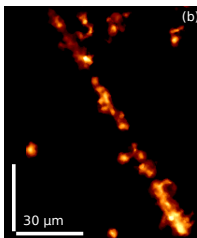
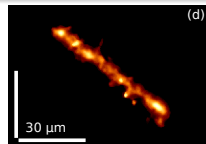
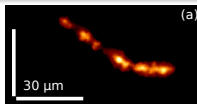
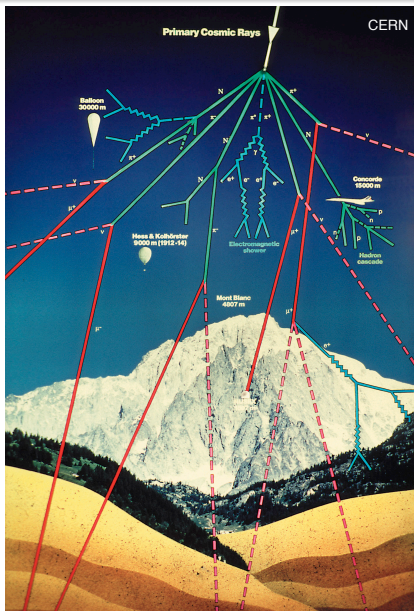
- Bulk fluorescence measurements at VT showed LiF $\sim 50\times$ more responsive to fast neutrons
- Localize color centers to $\sim \mu\text{m}^3$ voxels using SPIM at UZH



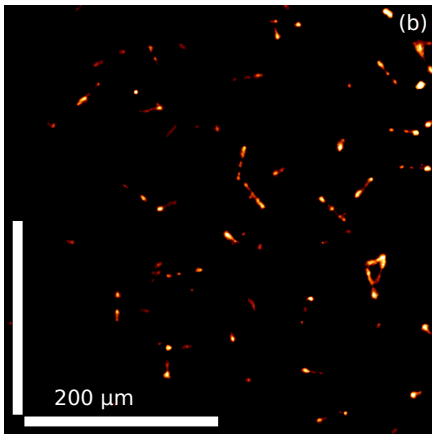
Selective plane illumination microscopy for color centers



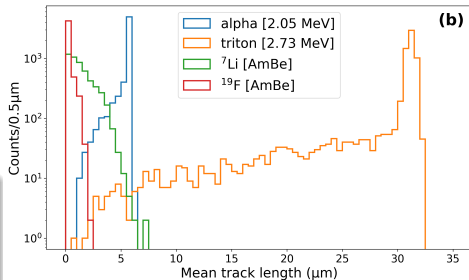
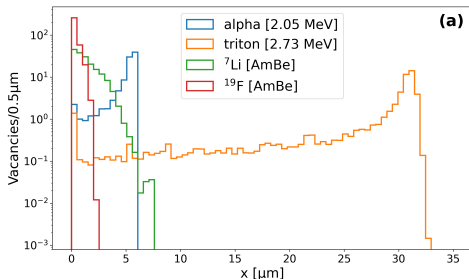
Spallation from cosmic ray muons interacting in samples



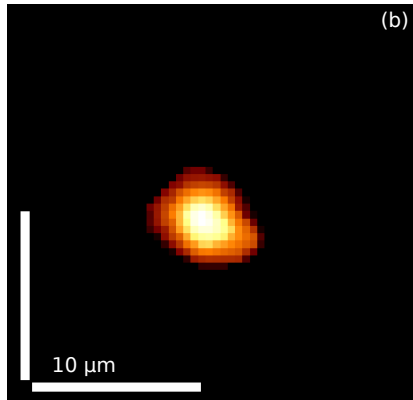
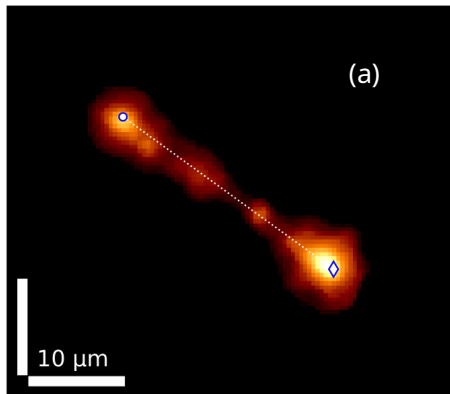
Compare SPIM data to TRIM simulations of nuclear recoils



- 3D imaging of CCs in bulk
- Low ionizing CC tracks
- Could scan $\sim \text{cm}^3$ in hours



Color center tracks from irradiation of LiF with neutrons



- Predict track length $30 - 35\mu\text{m}$
- Sparse CCs along track $\sim 4\mu\text{m}^{-1}$
- Bragg peaks brighter at the ends

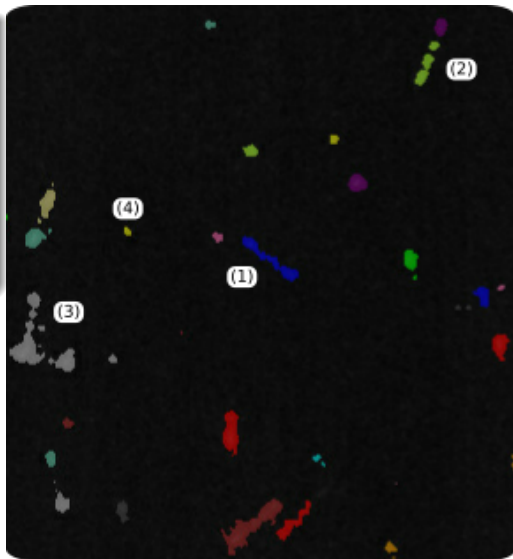
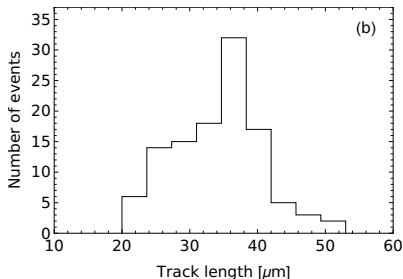
Elastic scattering of n off (Li,F)

- Calibrate LiF response with fast neutrons from AmBe
- Detect cosmogenic neutrons

Classification of ${}^6\text{Li}$ fission events and CR background

Data analysis pipeline

- Raw data selection and pre-processing for ML
- Voxel segmentation using random forest in Ilastik
- Extract feature properties
- Post-processing and analysis



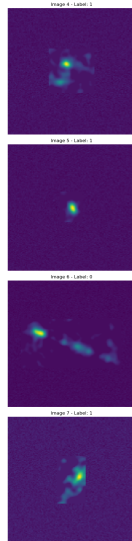
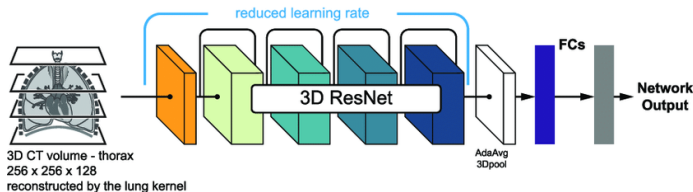
Trying out deep learning techniques for track classification



Training the CNN model

slide from Xianyi Zhang and Jason Brodsky

- Model is trained upon the 1-channel 3D Resnet
- All samples are 16x128x128 volumes, all light intensity are baseline subtracted
- Trainings were done on LLNL HPC, each 200-epoch training cycle takes 8 hours with a single GPU.

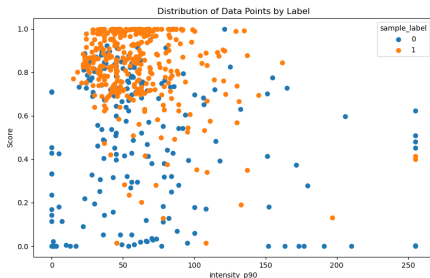


Preliminary analysis of classified sample properties

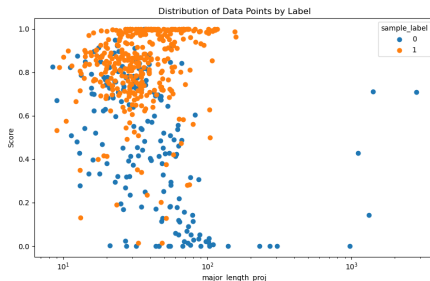
- Quantify properties based on scores
 - Use scikit image to calculate sample volume, length, shape
 - Calculate median brightness

slide from Xianyi Zhang and Jason Brodsky

Preliminary light intensity distribution by score



Preliminary length distribution by score



- Currently, segmented data are labeled based on its data types
 - 0: features in non-irradiated crystals, including cosmogenic tracks and optical features
 - 1: features in fast neutron irradiated crystals, predominantly neutron-nucleus recoils
 - 2: features in thermal neutron irradiated crystals, predominantly n-Li capture tracks

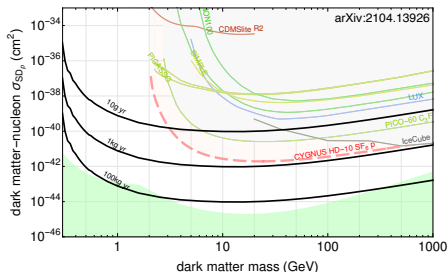
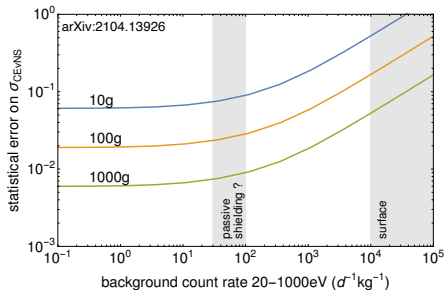
Mineral detectors could probe rare and/or previous events

Low energy nuclear recoils in LiF

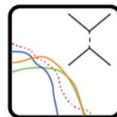
- CE ν NS measurement at nuclear reactor to probe neutrino interactions
- Dark matter scattering detection with sensitivity to low mass dark matter

Foundation for natural minerals

- Record nuclear recoils over geological timescales
- Need geological history of rock
- Radiopure samples from depth
- Could probe stellar evolution and substructure of Milky Way



NSF GCR Mineral Detection of Dark Matter



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Xianyi Zhang



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Laura Baudis,
Nikita Vladimirov,
Christian Wittweg

Fission fragments can be seen by TEM/optical microscopes

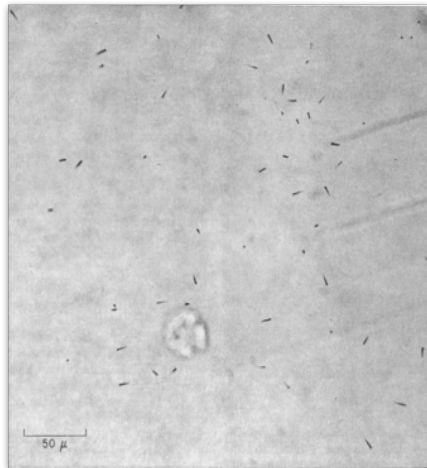
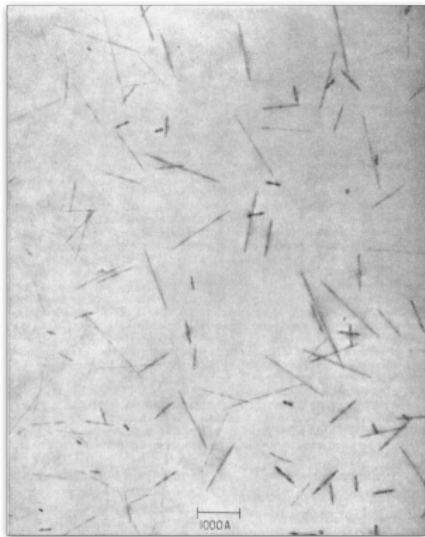


Figure: Price+Walker '63

Mineral detectors used to constrain WIMPs before

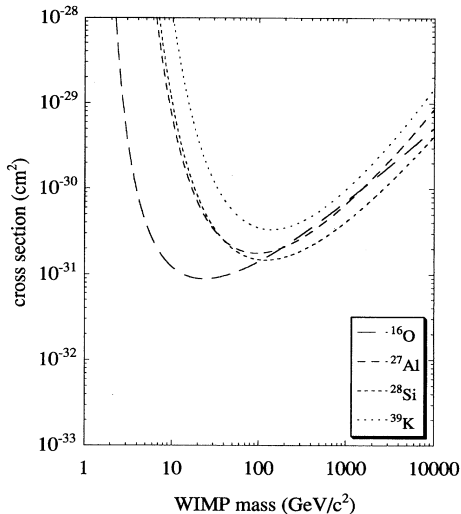
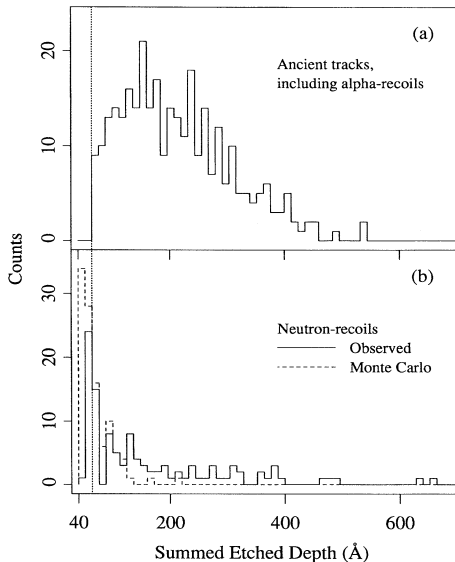


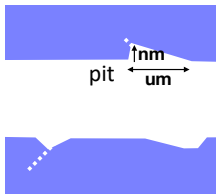
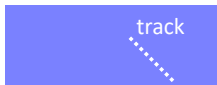
Figure: Snowden-Ifft et al. (1995)

New techniques allow for much larger readout capacity

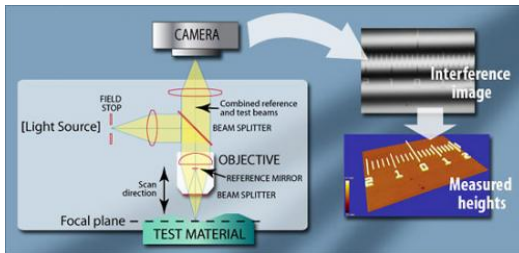
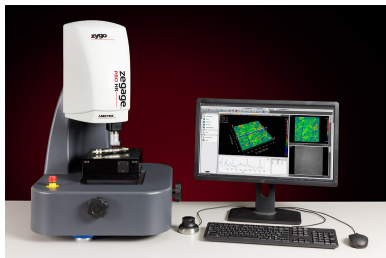
Cleave



Etch with HF



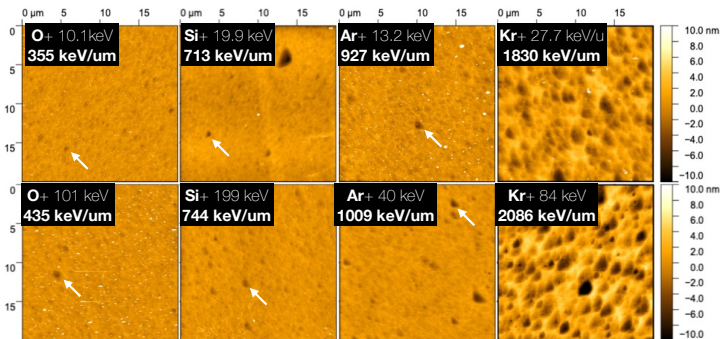
melts over
a thickness of 10 nm



Increase throughput from AFM to optical profilometry



Irradiation dose is 80 ions per field of view (20umx20um).

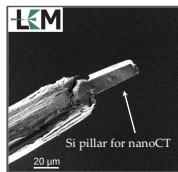
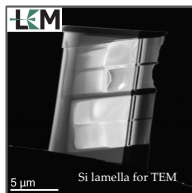
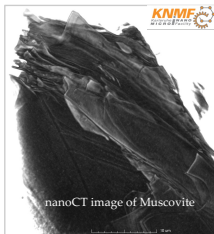


proxy	DM scattering		alpha recoils
pit formation efficiency	several to 10 %		~ 100%

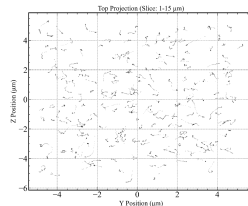
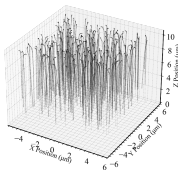
Karlsruhe Institute of Technology

Contact: alexey.elykov@kit.edu

Sample preparation & imaging



3.183MeV He in LIF Ion Trajectories



Track simulation & analysis

- **Collaborative project** - KIT institutes (astroparticle, microscopy) & **Uni. Heidelberg** (geology)
- **Experimental studies** of natural & artificial samples (irradiated & blank), accompanied by simulations
- **Establish** the techniques for **imaging** & **analysis** of **particle-induced tracks** in minerals

Atmospheric Neutrino and Dark Matter Detection at the University of Michigan

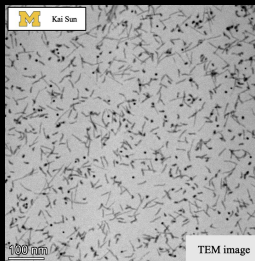
PI: Josh Spitz, spitz@umich.edu

RA: Emilie LaVoie-Ingram, emlavoie@umich.edu

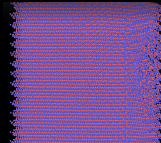
- Ion irradiation of various minerals to study morphology of nuclear recoil damage tracks
- TEM imaging for high resolution measurements
 - Currently testing x-rays for high throughput, high resolution track imaging at U-M and SLAC
- Automatic track detection algorithm
- LAMMPS molecular dynamics simulations to study track formation
- GEANT4 simulations to study cosmogenic neutron background in ancient minerals as a function of rock overburden

GORDON AND BETTY
MOORE
FOUNDATION

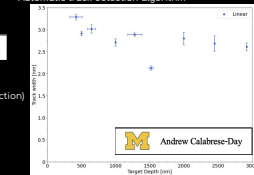
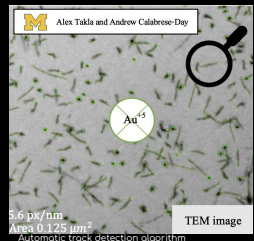
SPITZ
GROUP



Gold ion tracks in olivine



LAMMPS simulation of gold ion penetrating quartz



Track width v. depth data for gold irradiated olivine

EURECApd project

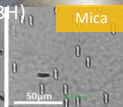
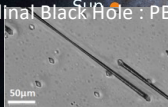


Toho U., Nagoya U., Kyoto U. Kanagawa U. JAMSTEC



Ultra Heavy Dark Matter

- composite dark matter
e.g., Q-ball, quark, nugget, nuclearite •
- Magnetic Monopole
- (Primordial Black Hole : PBH)



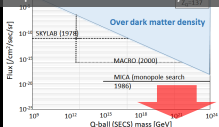
Mica

Ultra Heavy Element

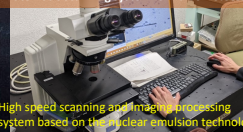
- meteorite analysis
- Transuranium element
- r-process in Neutron star merger (NSM)
- Accelerator mechanism
- Solar flare



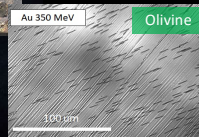
The deepest search for ultra heavy dark matter



Automatic scanning system for Paleo Detector



High speed scanning and imaging processing system based on the nuclear emulsion technology



Au 350 MeV

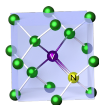
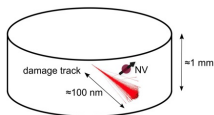
Olivine



Mineral detection at the University of Maryland: Directional detection of neutrinos and dark matter with quantum diamond sensors

gtc.umd.edu

Lead personnel: Prof. Ronald Walsworth, Dr. Daniel Ang (dga@umd.edu)



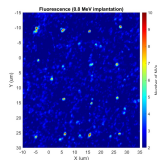
Nitrogen-vacancy center

- WIMP dark matter particles and neutrinos can induce nuclear recoils that leave 10-100 nm damage tracks in diamond
- Goal:** locate and characterize damage track with nitrogen-vacancy (NV) quantum sensors embedded in the diamond to deduce energy and direction of initial particle
- Directionality allows distinguishing WIMPs from the solar neutrino background
- Requires state-of-the-art quantum diamond microscopy techniques at the micro- and nanoscales
- See [Ebadi et al., AVS Quantum Sci. 4 \(4\): 044701 \(2022\)](#)



Current research activities

- Experiments creating and detecting artificial ion-induced damage tracks (at Sandia National Lab)
- Developing light-sheet quantum diamond microscope (LS-QDM) for high-speed, high-resolution diamond scanning
- Developing NV super-resolution imaging techniques to resolve and characterize individual damage tracks at the nanoscale



Single ion impact damage sites



LS-QDM @ UMD

Direct detection experiments for low energy nuclear recoils

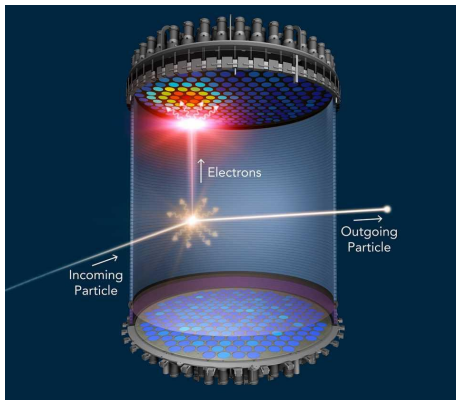
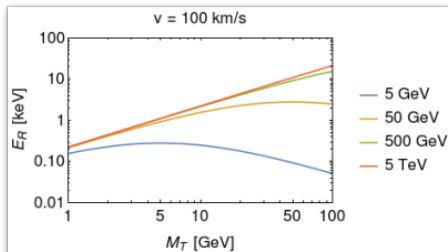


Figure: LUX-ZEPLIN (LZ) Collaboration
/ SLAC National Accelerator Laboratory



Scattering kinematics $\Rightarrow$ event rate

- Interactions with quarks, gluons
 $\Rightarrow$ with nucleons $\Rightarrow$ with nuclei
- Convolute with dark matter flux inferred from stellar observations
- Sensitivity depends on nuclear recoil energy threshold

Dark matter density in the galaxy

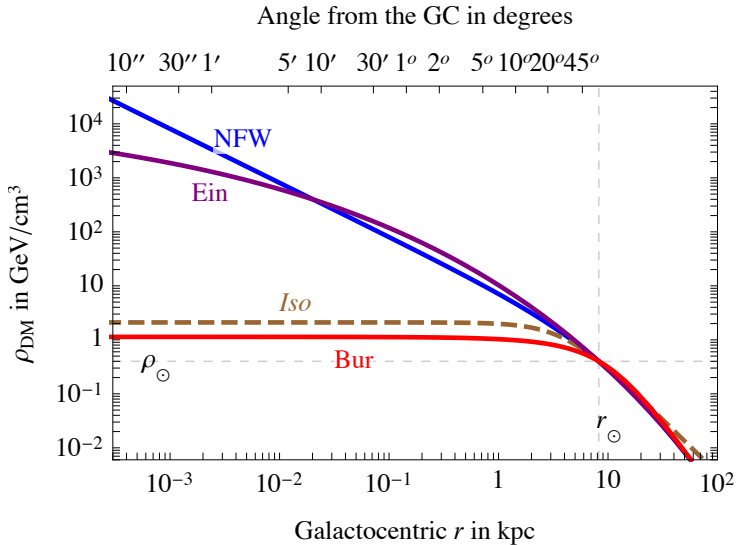


Figure: 2406.01705

WIMP velocity distribution and induced recoil spectra

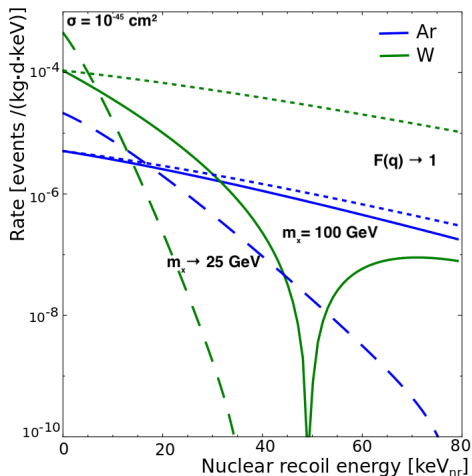
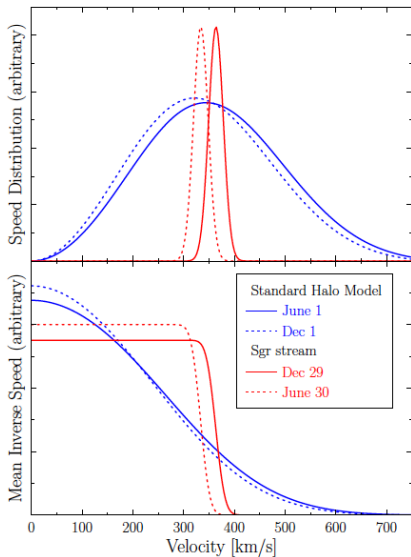
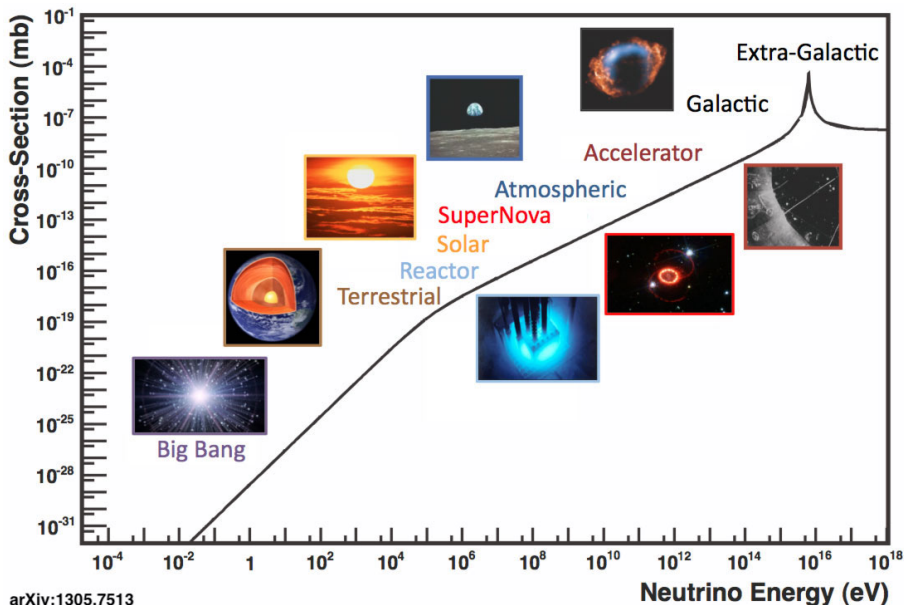


Figure: (left) 1209.3339 (right) 1509.08767

Neutrinos come from a variety of sources



arXiv:1305.7513

Reactor ν 's produced in β decays of fission fragments

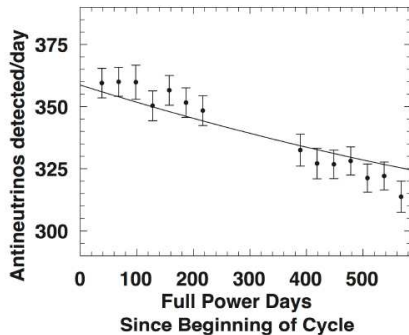
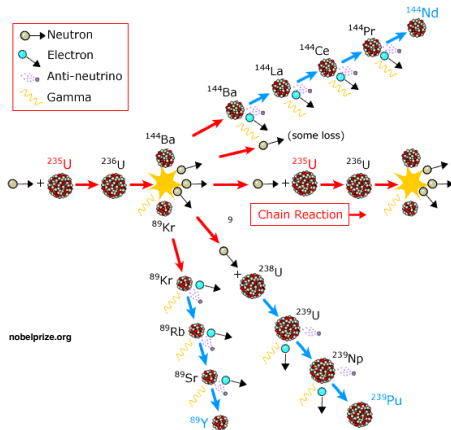


Figure: Processes yielding reactor ν 's and time dependence over the course of reactor fuel cycle for ^{239}Pu (1605.02047)

Nuclear non-proliferation safeguards

- Measure soft nuclear recoils
- Passive and robust detectors operable at room temperature

Solar ν 's produced in fusion chains from H to He

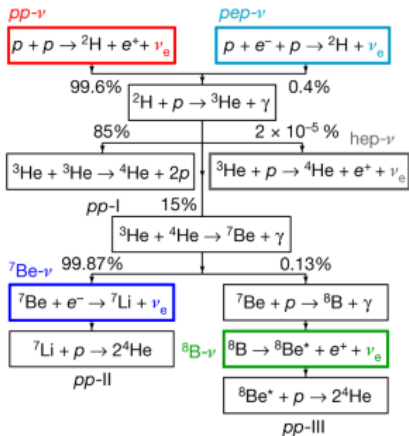
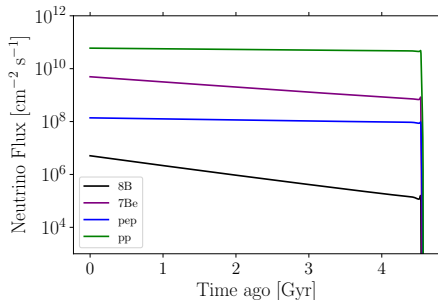
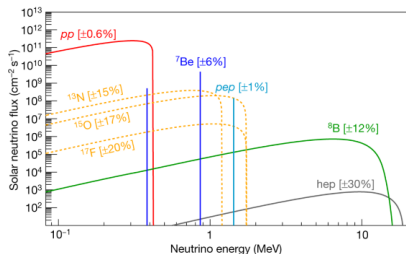


Figure: Today's flux at Borexino (Nature, 2018) and time dependence of GS metallicity model, 2102.01755



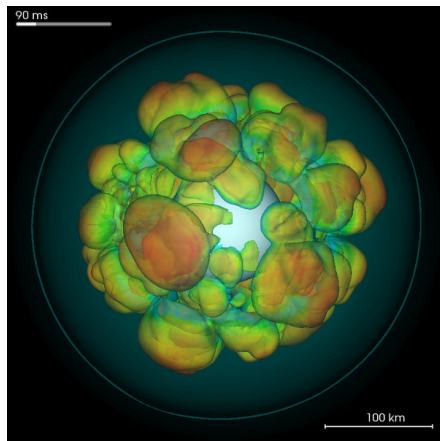
Galactic contribution to ν flux over geological timescales

Figure: Supernova simulation after CC

Only ~ 2 SN 1987A events/century

- Measure galactic CC SN rate
- Traces star formation history

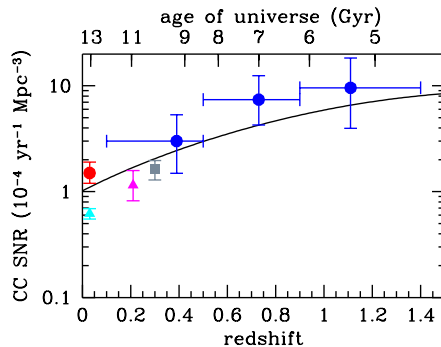
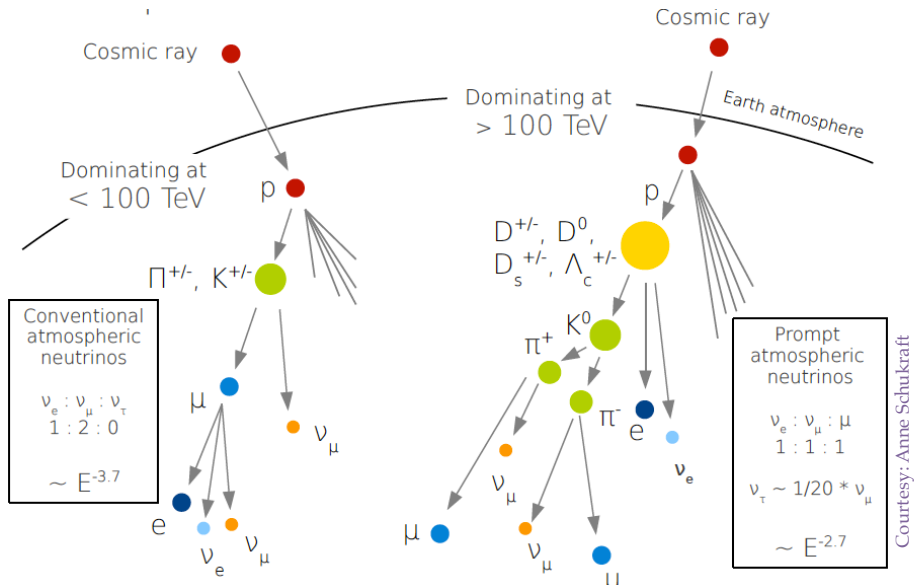


Figure: Cosmic CC SNR, 1403.0007

Atmospheric ν 's originating from CR interactions



Nuclear recoil spectrum depends on neutrino energy

$$\frac{dR}{dE_R} = \frac{1}{m_T} \int dE_\nu \frac{d\sigma}{dE_R} \frac{d\phi}{dE_\nu}$$

- **Quasi-elastic** for $E_\nu \gtrsim 100$ MeV
- **Resonant π production** at $E_\nu \sim \text{GeV}$
- **Deep inelastic** for $E_\nu \gtrsim 10$ GeV

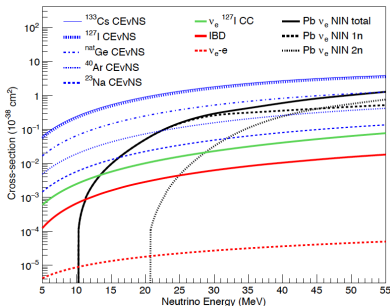


Figure: COHERENT, 1803.09183

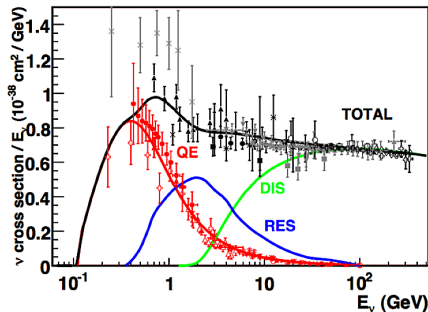


Figure: Inclusive CC $\sigma_\nu N$, 1305.7513