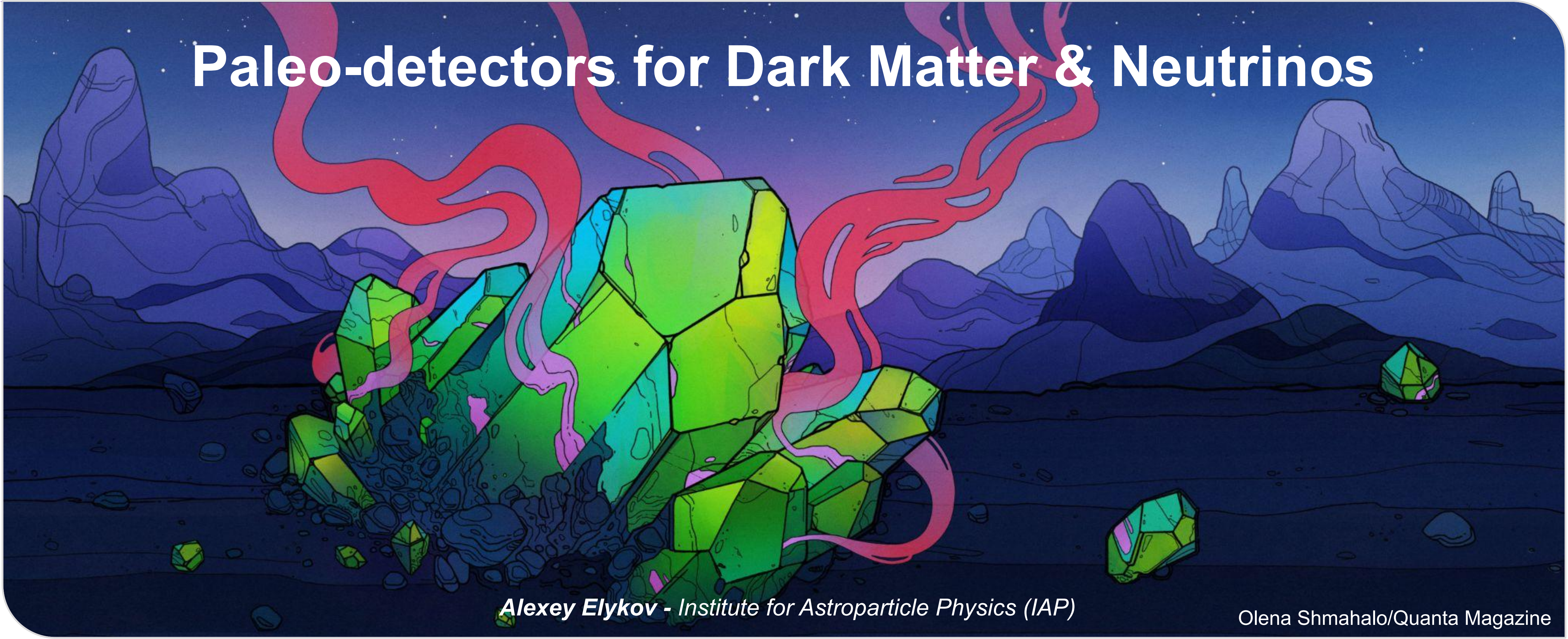
Karlsruhe Institute of Technology

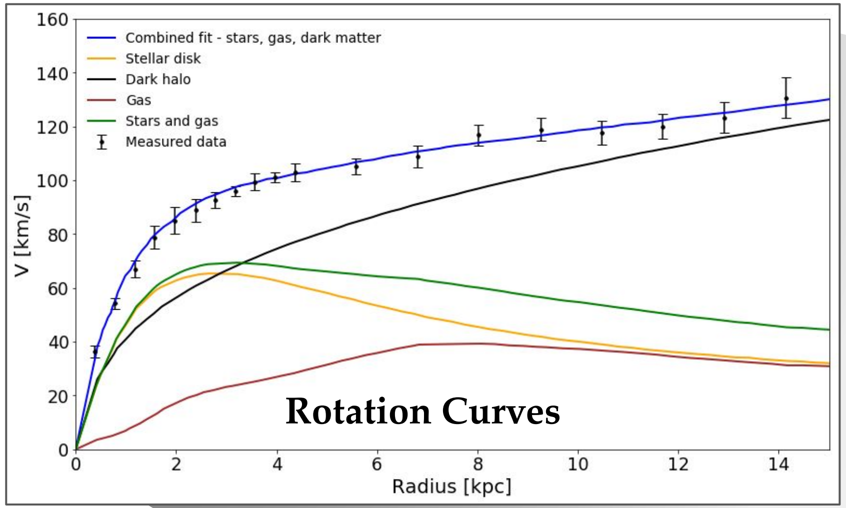
Paleo-detectors for Dark Matter & Neutrinos

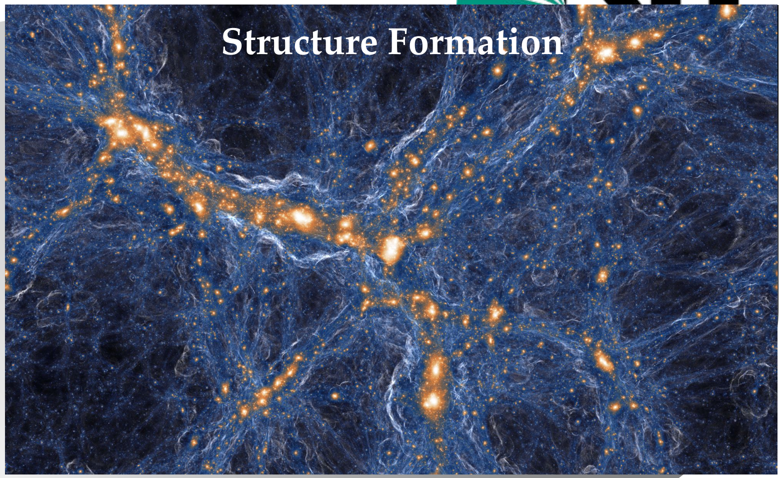


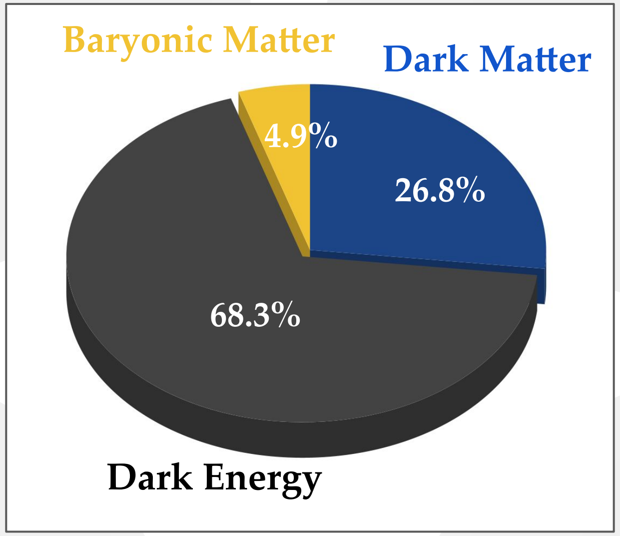
***Alexey Elykov** - Institute for Astroparticle Physics (IAP)*

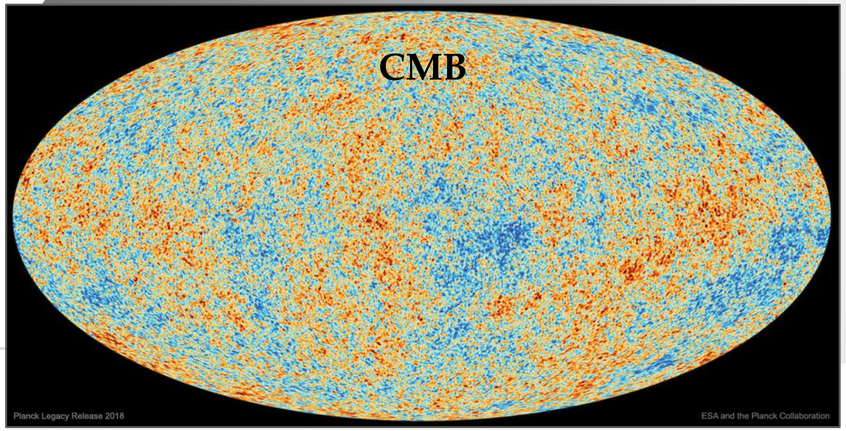
Olena Shmahalo/Quanta Magazine

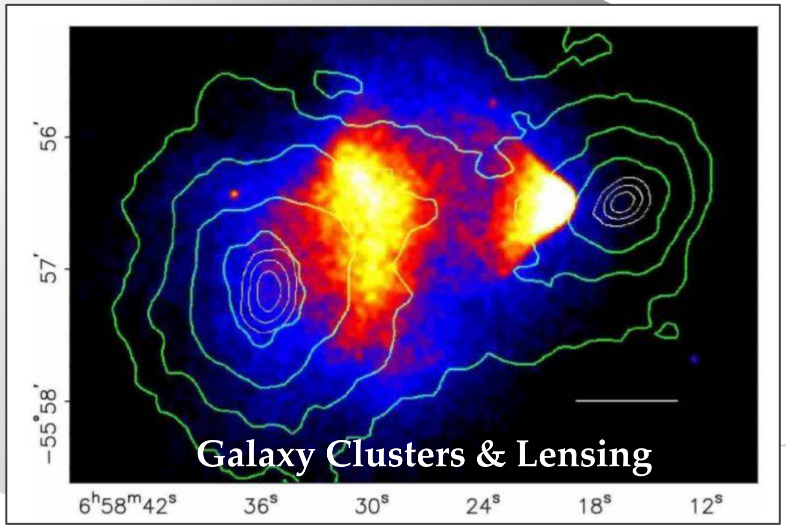
Dark Matter


Combined fit - stars, gas, dark matter
Stellar disk
Dark halo
Gas
Stars and gas
Measured data
V [km/s]
Radius [kpc]
0
20
40
60
80
100
120
140
160
2
4
6
8
10
12
14
Rotation Curves


Structure Formation


Baryonic Matter
Dark Matter
4.9%
26.8%
68.3%
Dark Energy


CMB
Planck Legacy Release 2018
ESA and the Planck Collaboration

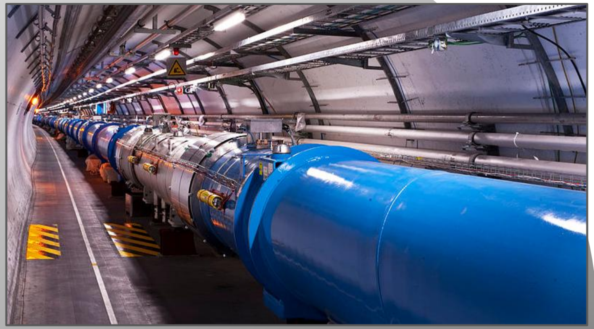

Galaxy Clusters & Lensing
56'
57'
−55°58'
6h58m42s
36s
30s
24s
18s
12s

Dark Matter

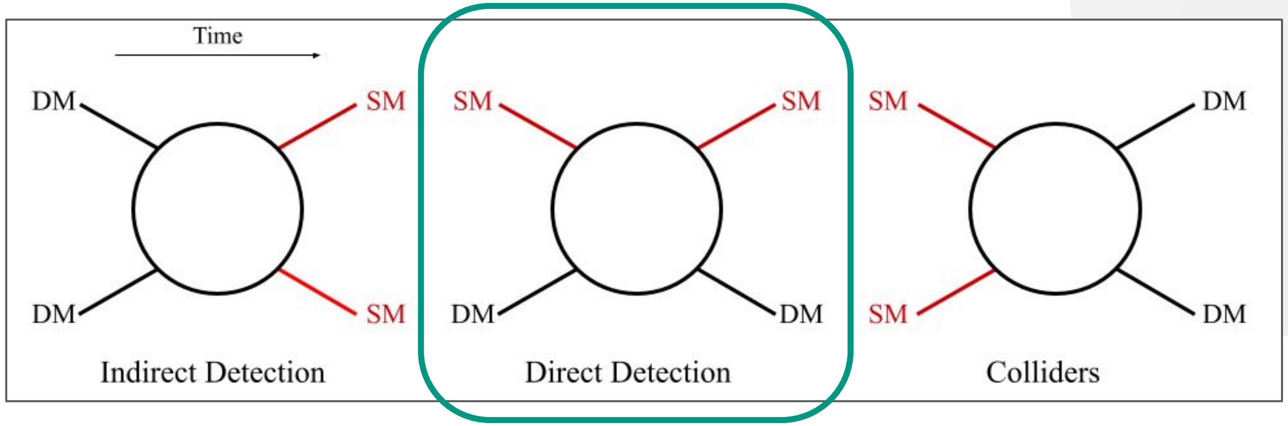
Dark Matter: ~ 85% of all matter in the Universe, unknown nature

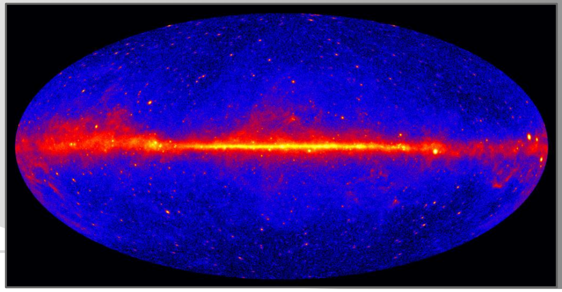
Dark Matter candidates:

- **W**eakly **I**nteracting **M**assive **P**articles (WIMPs), mass ≈ 10 GeV - few TeV
- SuperWIMPs, WIMPzillas, “fuzzy” Dark Matter, Axions, ALPs … etc…

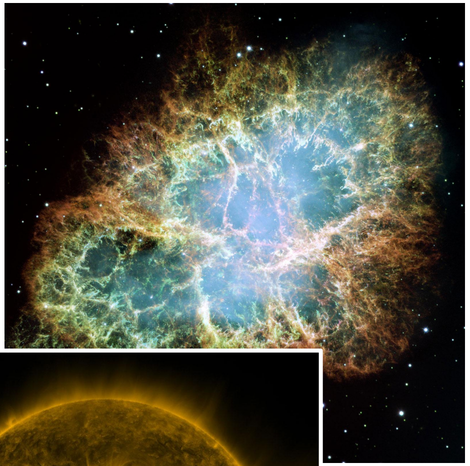


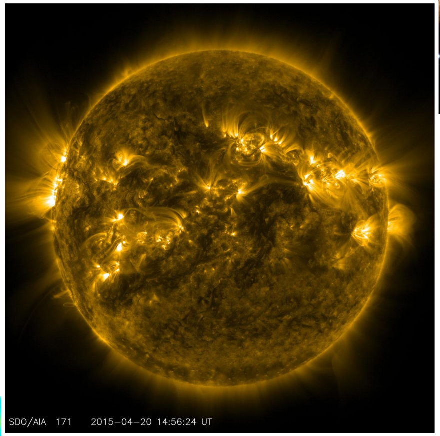
Paths for Dark Matter detection



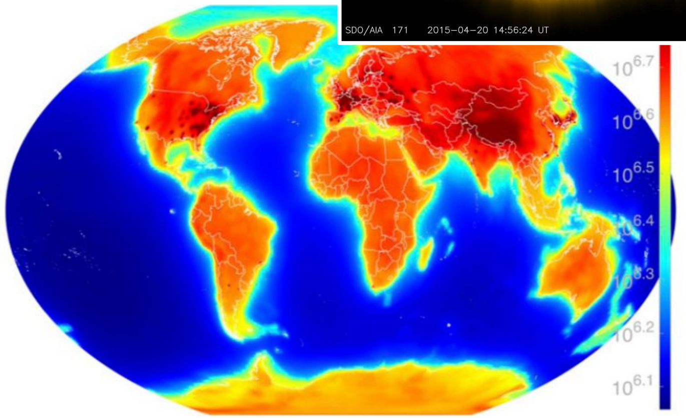


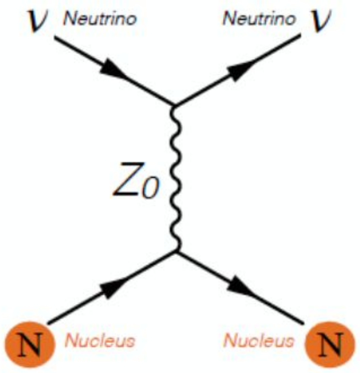
Neutrinos





- ❖ Properties are still largely unknown
- ❖ Can shed light on fundamental open questions
- ❖ Large range of energies
- ❖ **Astrophysical messengers (history & evolution)**
  - ➢ Sun
  - ➢ Supernovae
  - ➢ Cosmic-rays
  - ➢ Galactic & extragalactic
- ❖ Geoneutrinos

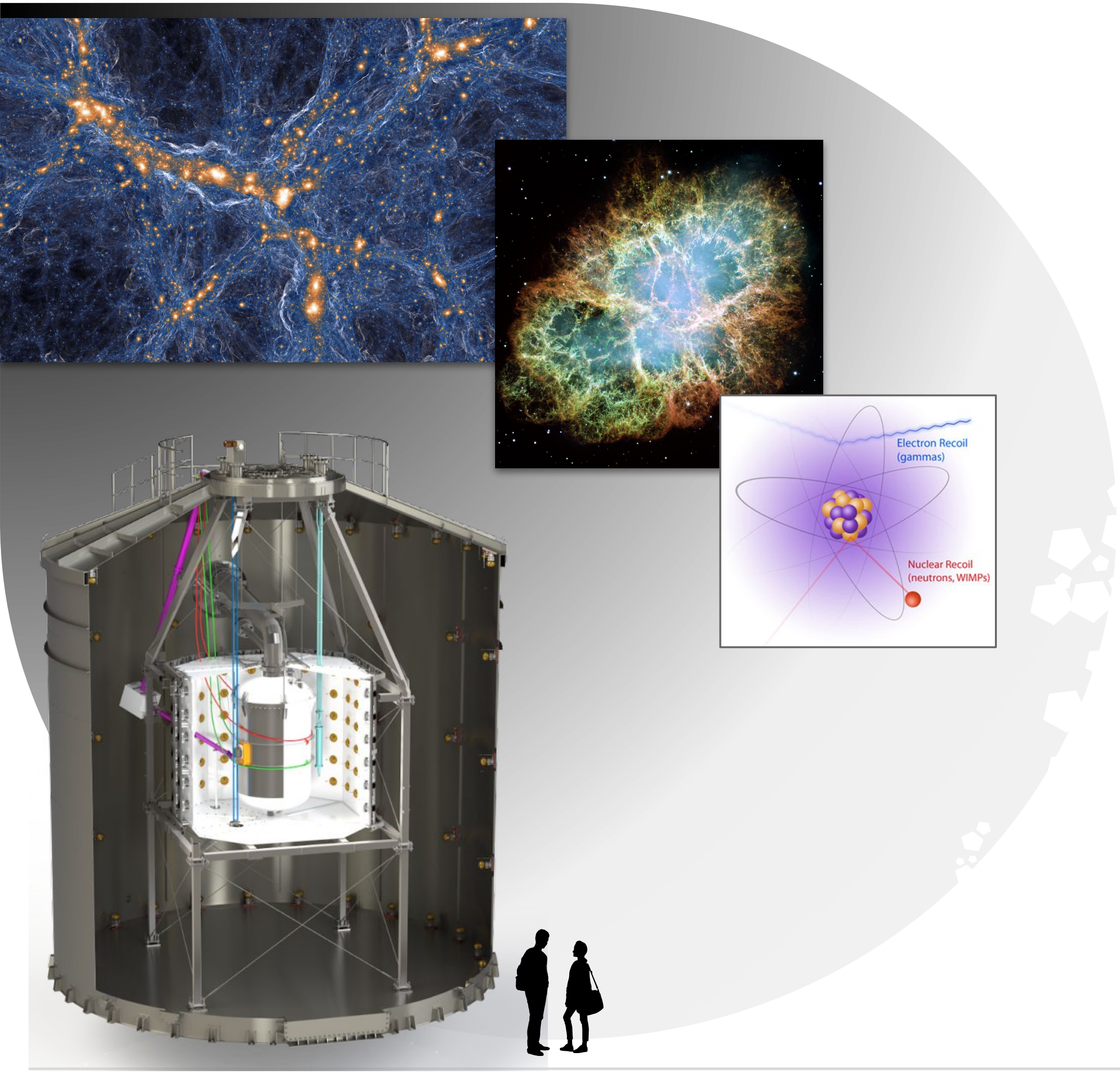




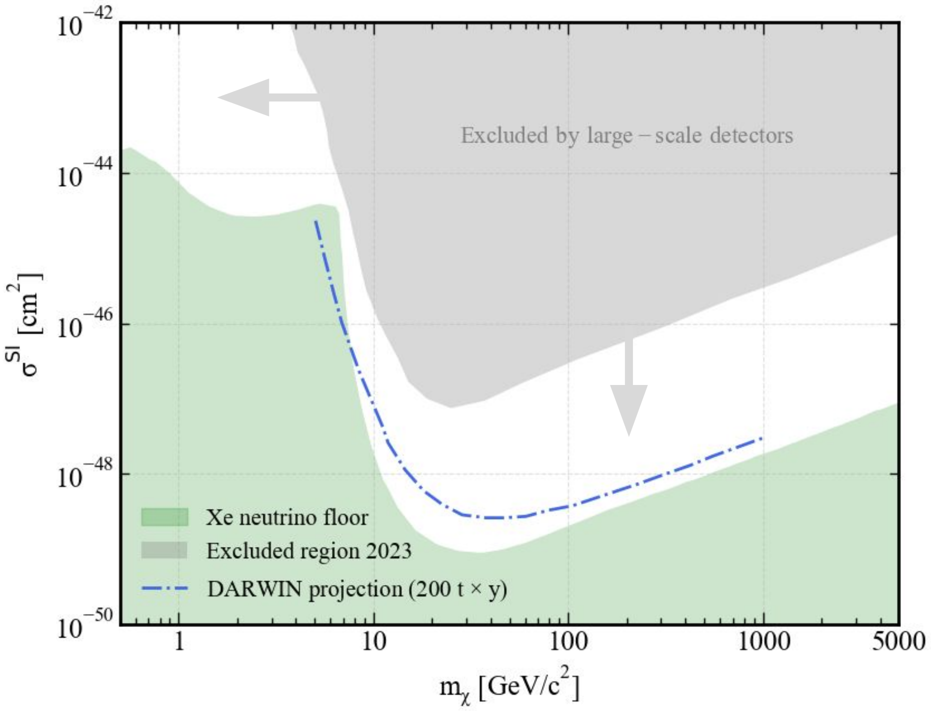
CEvNS

DOI: 10.1103/RevModPhys.92.045006

Dark Matter & Neutrinos - Detection



How interacting?

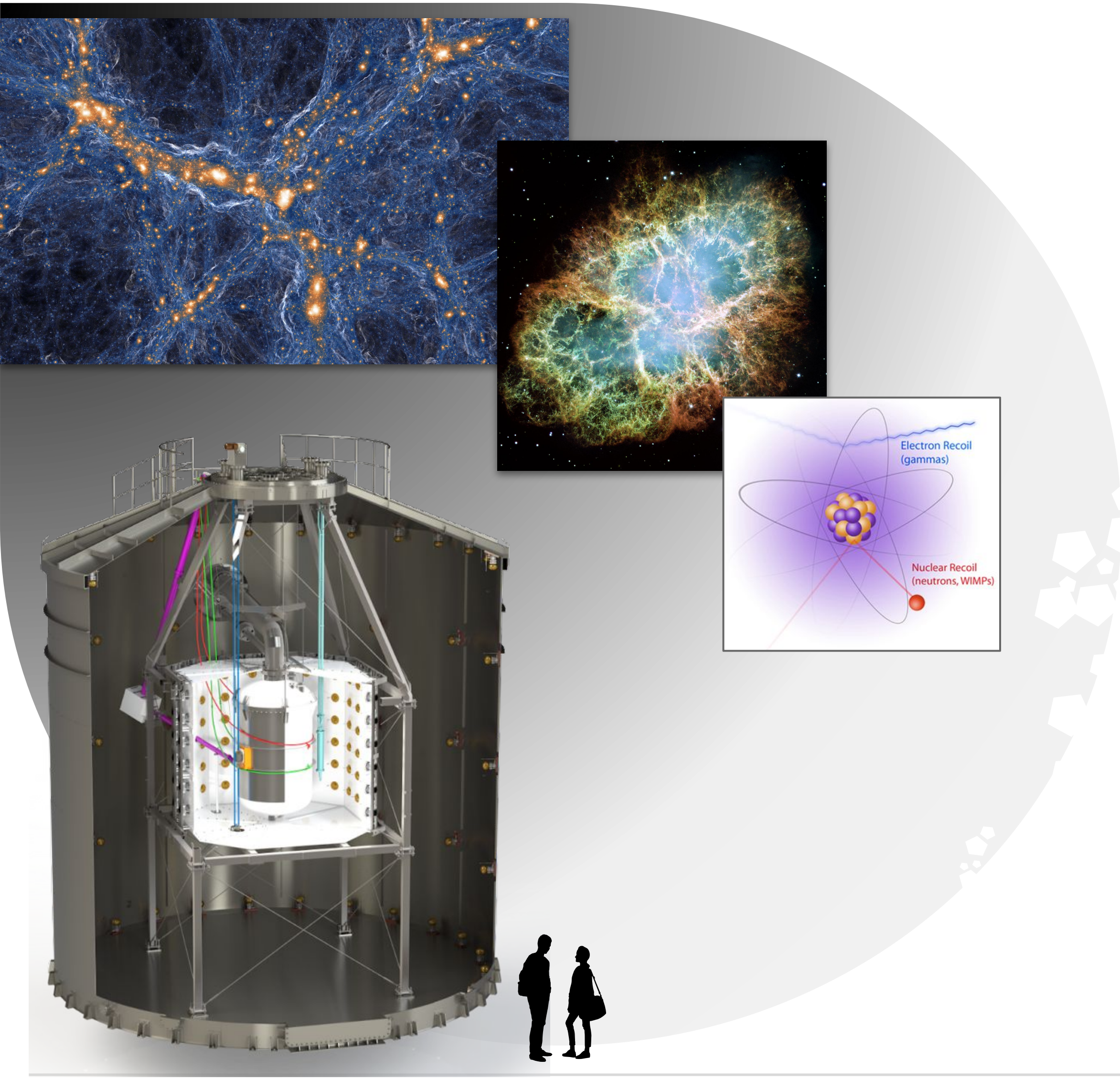


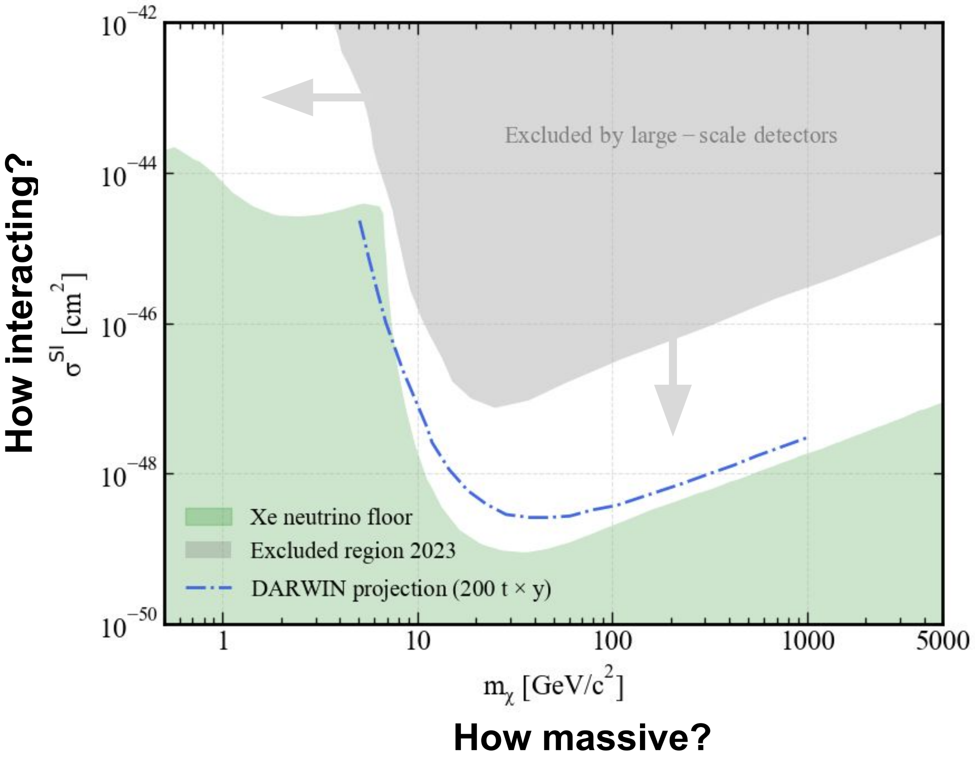
How massive?

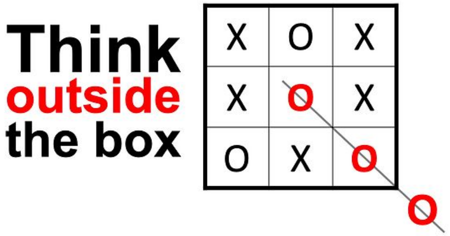
Dark Matter still eludes detection &

we are still puzzled by the nature of neutrinos!

Dark Matter & Neutrinos - Detection







Can ROCKS help us uncover the history of our Galaxy & composition of our Universe?

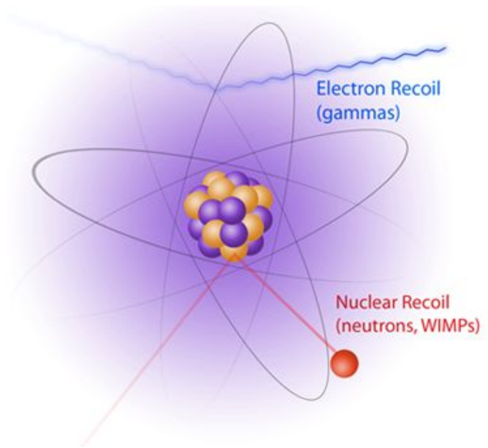
Olivine

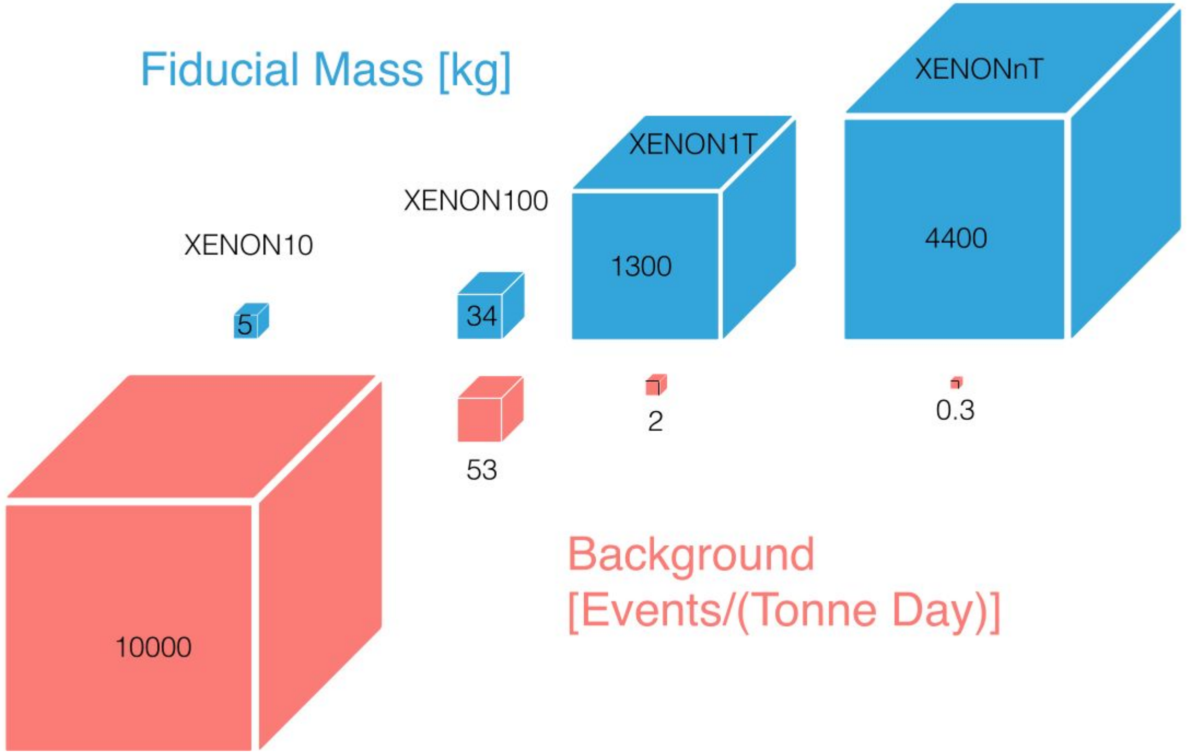
Halite

Raw Muscovite Mica

How to Build a Direct Detection Experiment?

- Low recoil energy threshold (≤ keV)
- Low backgrounds
- Large exposure (target mass × integration time)
- Feasible to construct & operate



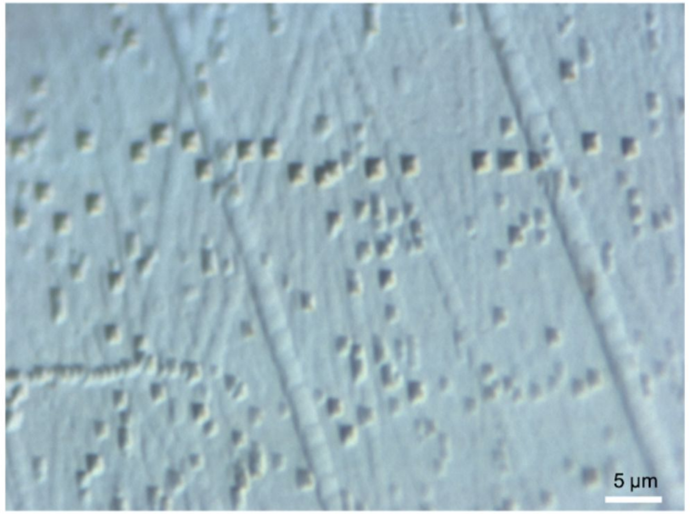


Solid State Nuclear Track Detectors (SSNTDs)

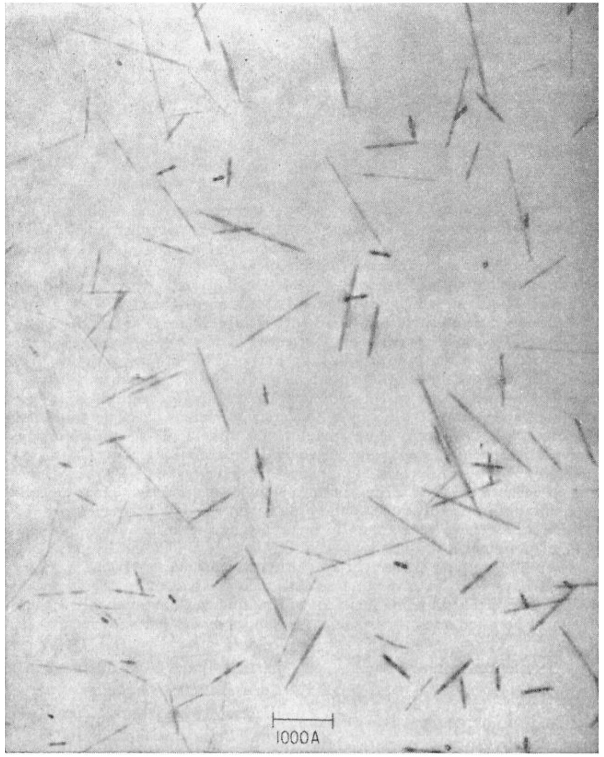
Karlsruhe Institute of Technology

- **SSNTDs - natural & synthetic crystals**
  - Geology & geophysics
  - Radiation damage
  - Cosmochemistry
  - Material science
  - Astrophysics

- Ionizing radiation produces **damage tracks**
- Chemical etching
- Imaging with microscopy



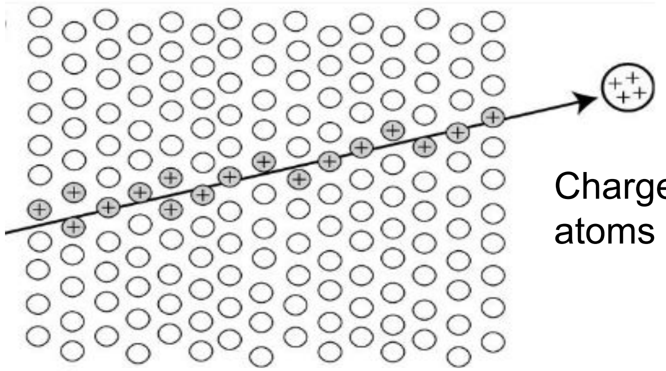
Etch pits in Olivine - courtesy of U. Glasmacher



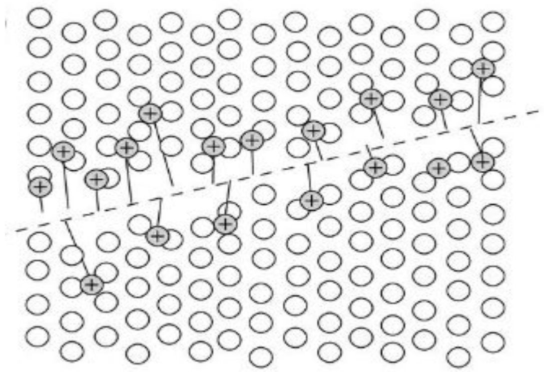
1963 *: Fission tracks in synthetic mica as viewed by TEM (DOI: 10.1029/JZ068i016p04847)*

Track & Damage Features Formation

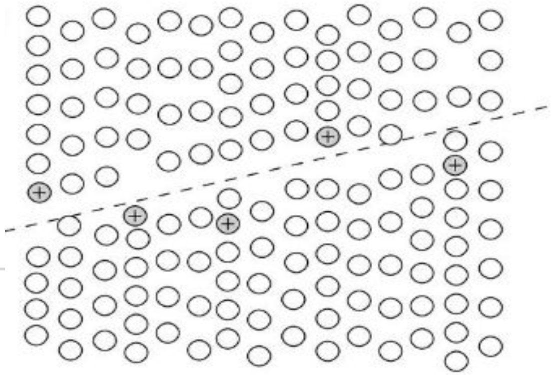
Ion explosion spike - Fleischer et al. (1975)



Charged particle ionizes lattice atoms along its trajectory.



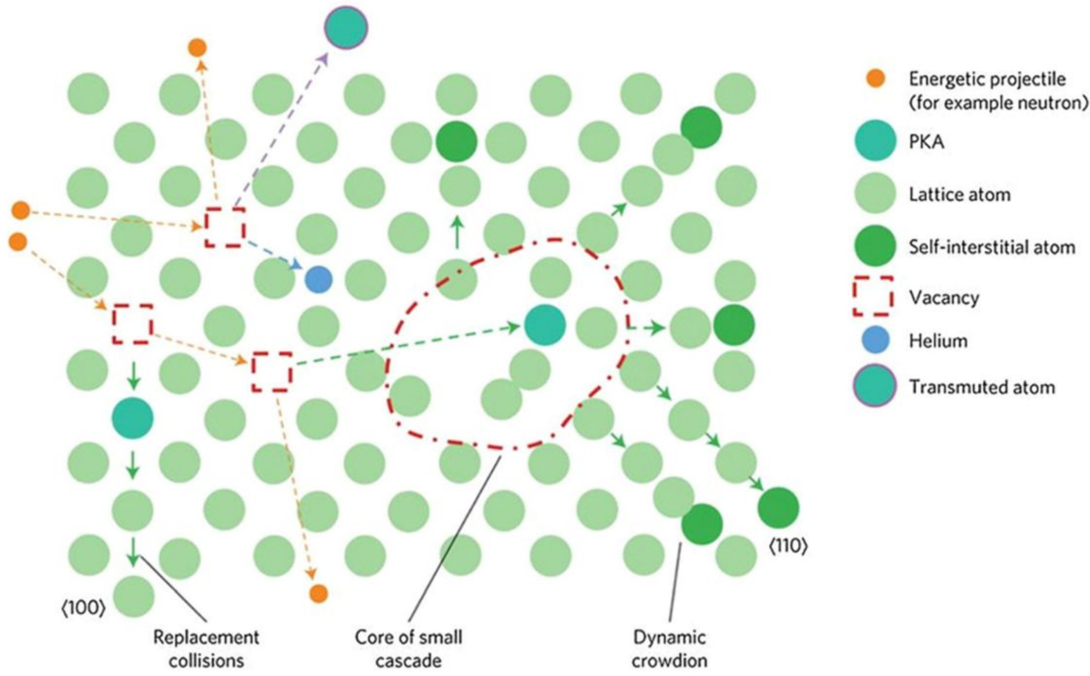
Electrostatic repulsion causes displacement of atoms along path



“Track” formation along the path of the particle

Neutron induced damage

- ❖ Effects are the result of atomic displacement
- ❖ Primary knock-on atom (PKA) - causes further displacements

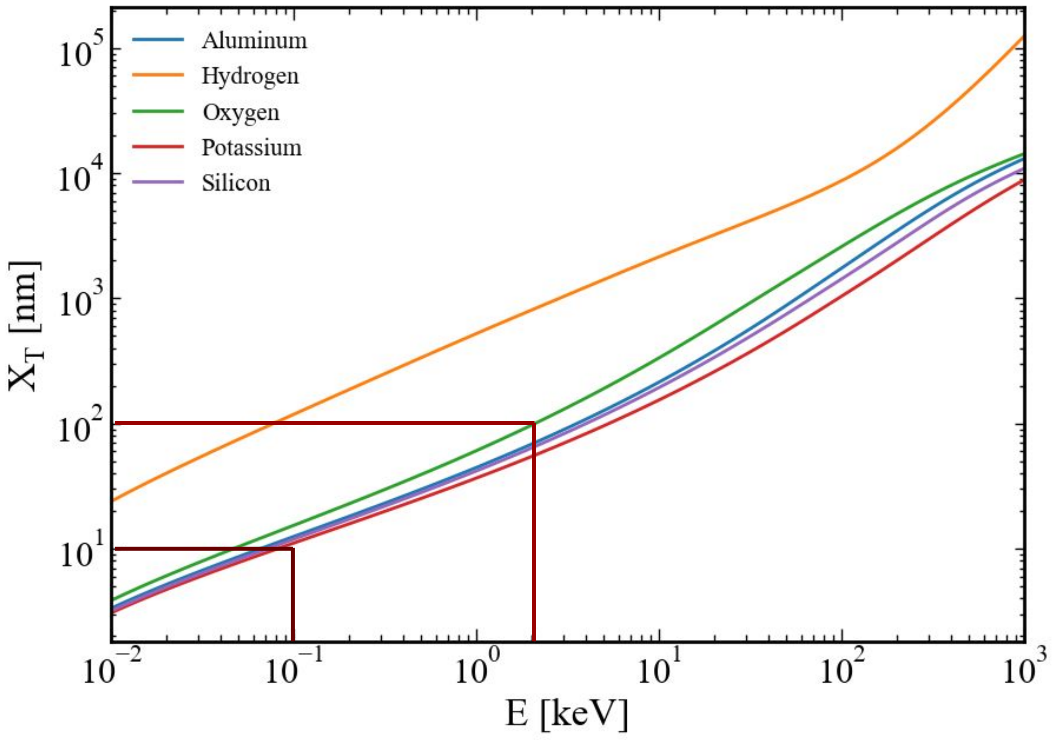


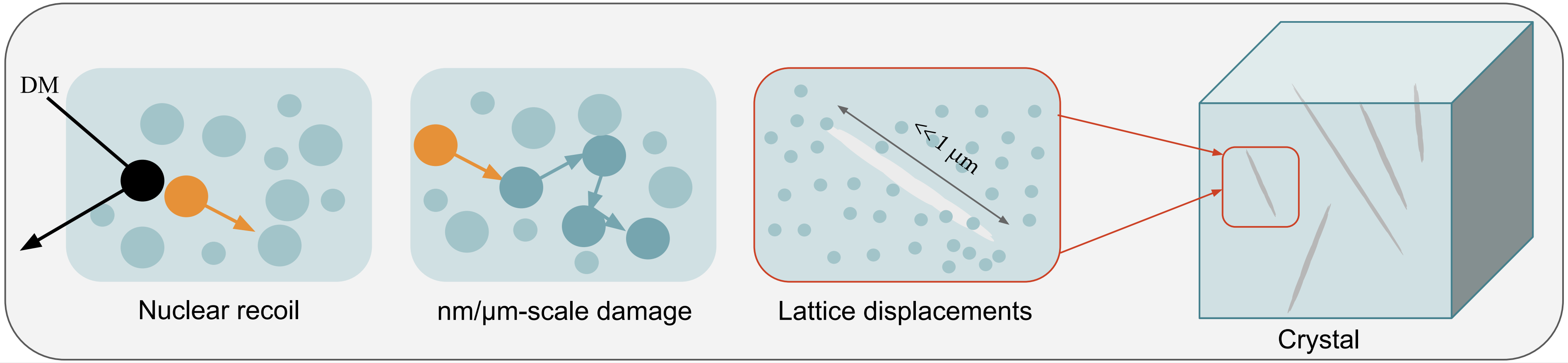
Track & Damage Features Formation

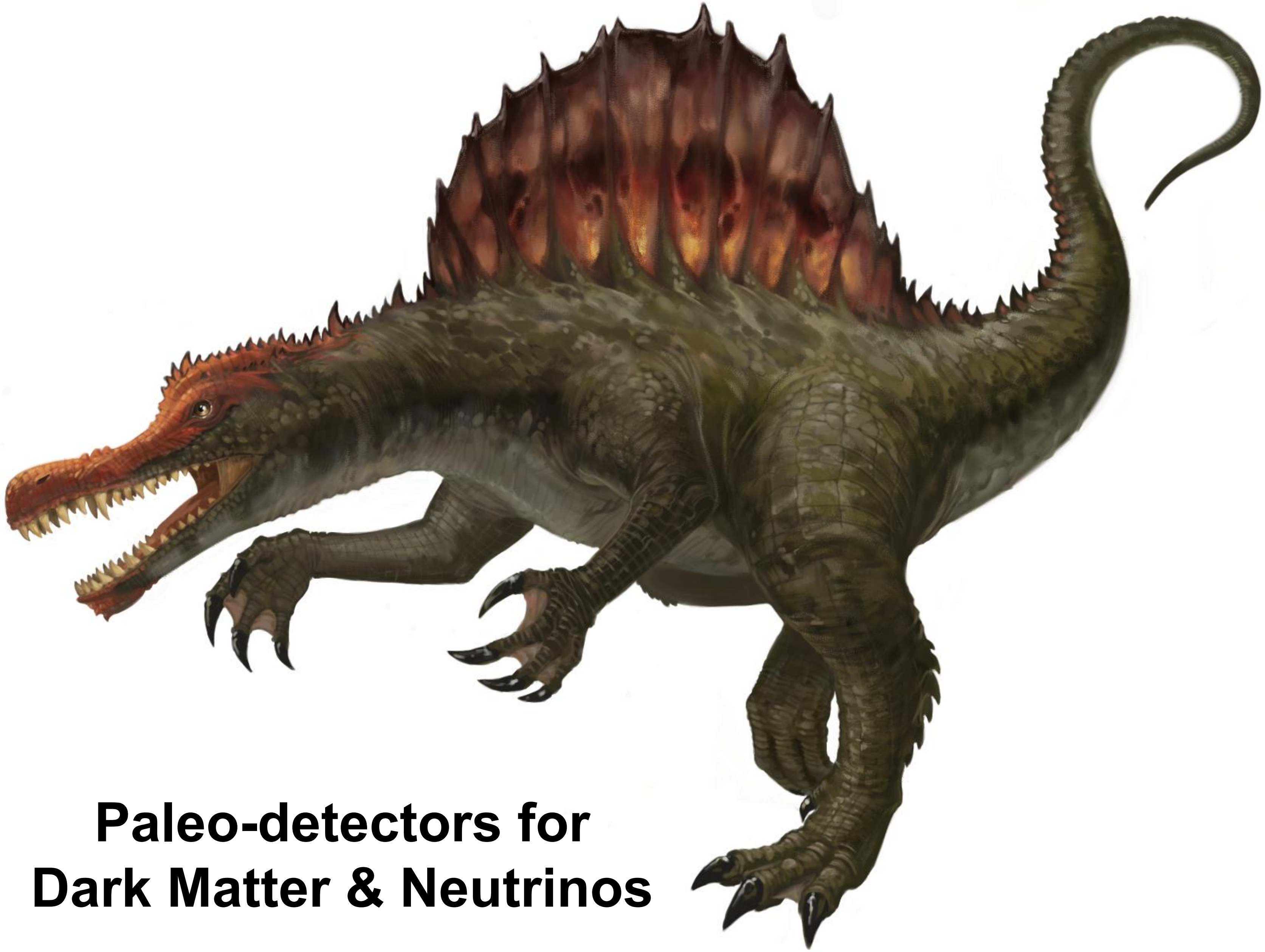
- **Energy loss in solid materials due to :**
  - Electronic stopping (off electron clouds)
  - Nuclear stopping (off nuclei)

$$x_T(E_R) = \int_0^{E_R} \left| \frac{dE}{dx_T} \right|^{-1} dE$$

  - Nuclear recoils down to 0.1 - 1 keV



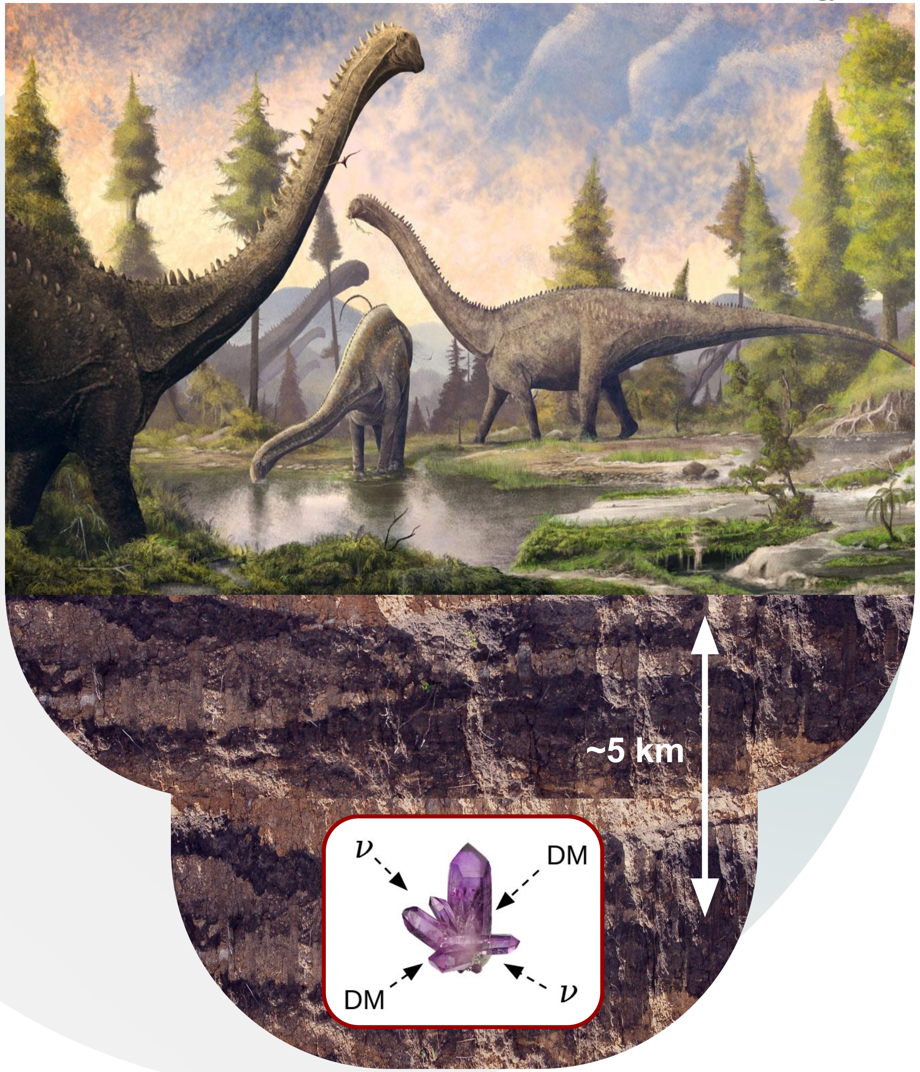




Paleo-detectors for Dark Matter & Neutrinos

Ancient Natural Crystals - Paleo-detectors

- Natural minerals - good SSNTDs
  - Need to be insulators or poor semiconductors
- **Tracks** - nuclear recoils induced by Dark Matter & Neutrinos
- Once created, tracks are preserved for Myr/Gyr
- Accessible, relatively cheap
- **Small samples** but **Myr/Gyr exposure**
  - 100 g x 1 Gyr = 10 kilotonne x 10 yr
- Neutrinos - guaranteed signal/background



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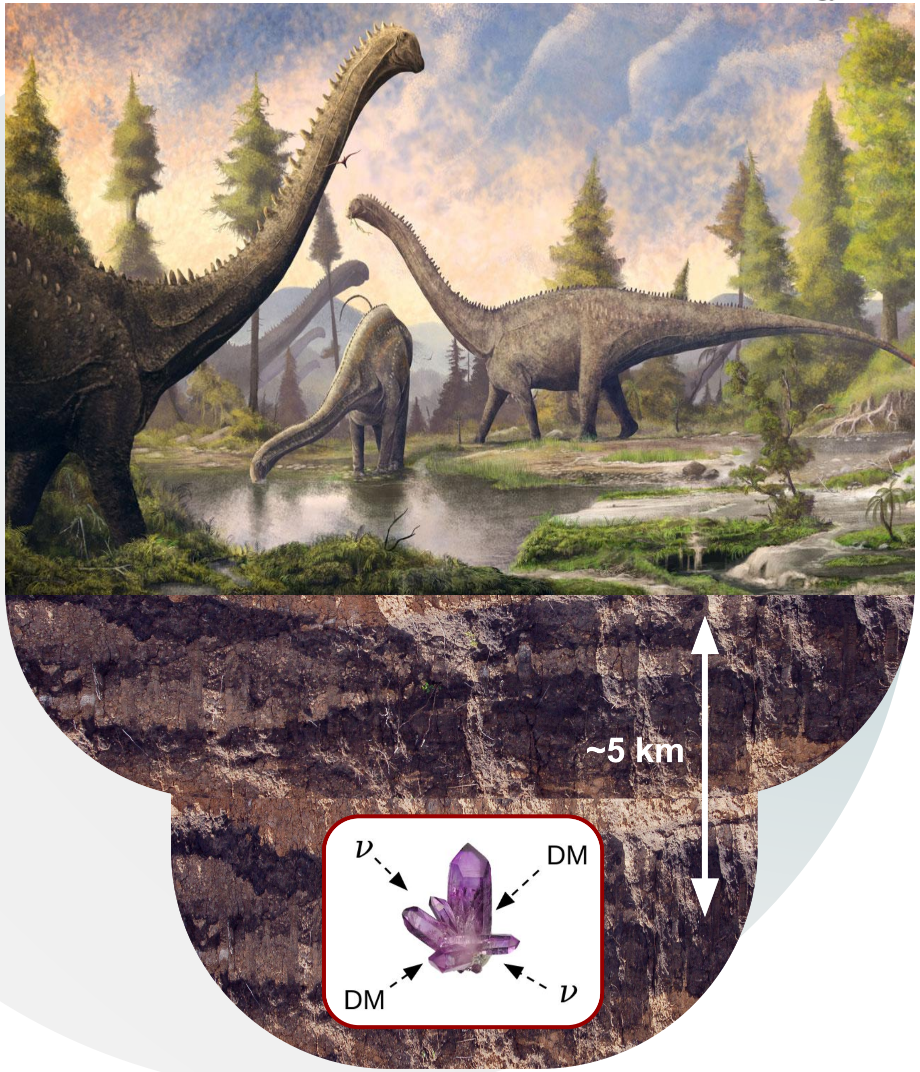


Paleo-detectors in the Past

Karlsruhe Institute of Technology

People tried this in the past!

VOLUME 56, NUMBER 12 PHYSICAL REVIEW LETTERS 24 MARCH 1986

Search for Supermassive Magnetic Monopoles Using Mica Crystals

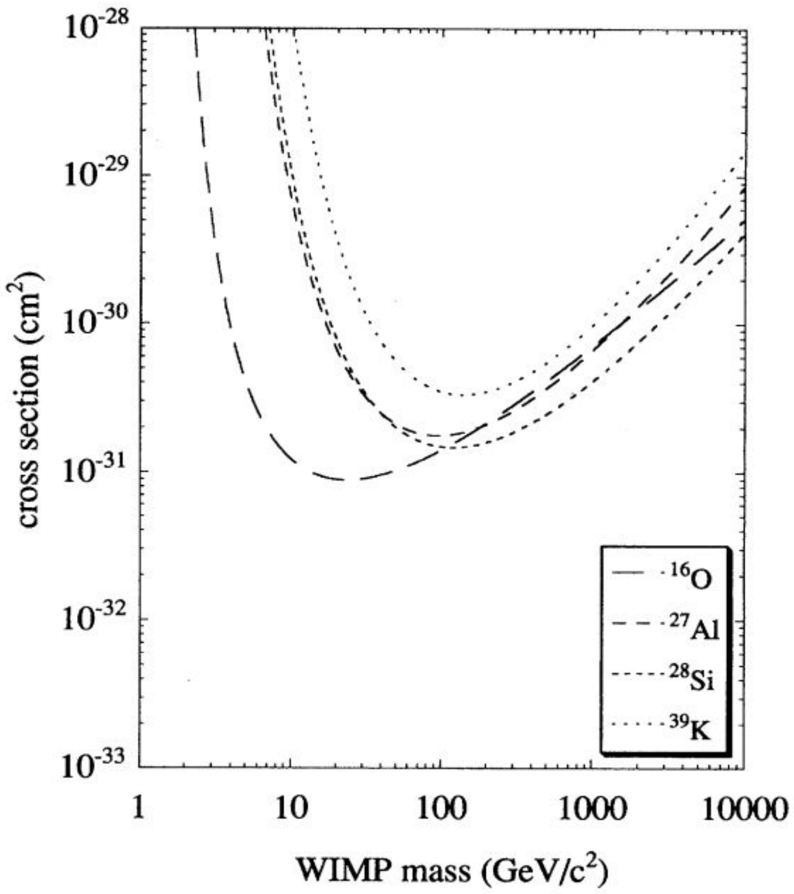
P. B. Price and M. H. Salamon
Department of Physics, University of California, Berkeley, California 94720
(Received 18 November 1985)

Nuclear tracks from Cold Dark Matter interactions in mineral crystals: a computational study

J.I. Collar *, F.T. Avignone III
Department of Physics and Astronomy, University of South Carolina, Columbia, SC 29208, USA
Received 26 July 1994; revised form received 8 November 1994

Limits on Dark Matter Using Ancient Mica

D. P. Snowden-Ifft,* E. S. Freeman, and P. B. Price*
Physics Department, University of California at Berkeley, Berkeley, California 94720
(Received 20 September 1994)



***1995** : Limits on Dark Matter Using Ancient Mica*
(DOI: 10.1103/PhysRevLett.74.4133)

Paleo-detectors Now

Digging for dark matter: Spectral analysis and discovery potential of paleo-detectors

Thomas D. P. Edwards, Bradley J. Kavanagh, Christoph Weniger, Sebastian Baum, Andrzej K. Drukier, Katherine Freese, Maciej Górski, and Patrick Stengel
Phys. Rev. D **99**, 043541 – Published 27 February 2019

Measuring Changes in the Atmospheric Neutrino Rate over Gigayear Timescales

Johnathon R. Jordan, Sebastian Baum, Patrick Stengel, Alfredo Ferrari, Maria Cristina Morone, Paola Sala, and Joshua Spitz
Phys. Rev. Lett. **125**, 231802 – Published 30 November 2020

Paleodetectors for Galactic supernova neutrinos

Sebastian Baum, Thomas D. P. Edwards, Bradley J. Kavanagh, Patrick Stengel, Andrzej Katherine Freese, Maciej Górski, and Christoph Weniger
Phys. Rev. D **101**, 103017 – Published 13 May 2020

Rocks, water, and noble liquids: Unfolding the flavor conte neutrinos

Sebastian Baum, Francesco Capozzi, and Shunsaku Horiuchi
Phys. Rev. D **106**, 123008 – Published 9 December 2022

nature

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Hunt for dark matter turns to ancient minerals

Kilometres beneath Earth's surface, some minerals could bear the scars of collisions with dark matter.

Anil Ananthaswamy

- ❖ **Worldwide interest - novel emerging research field**

Paleo-detectors Now

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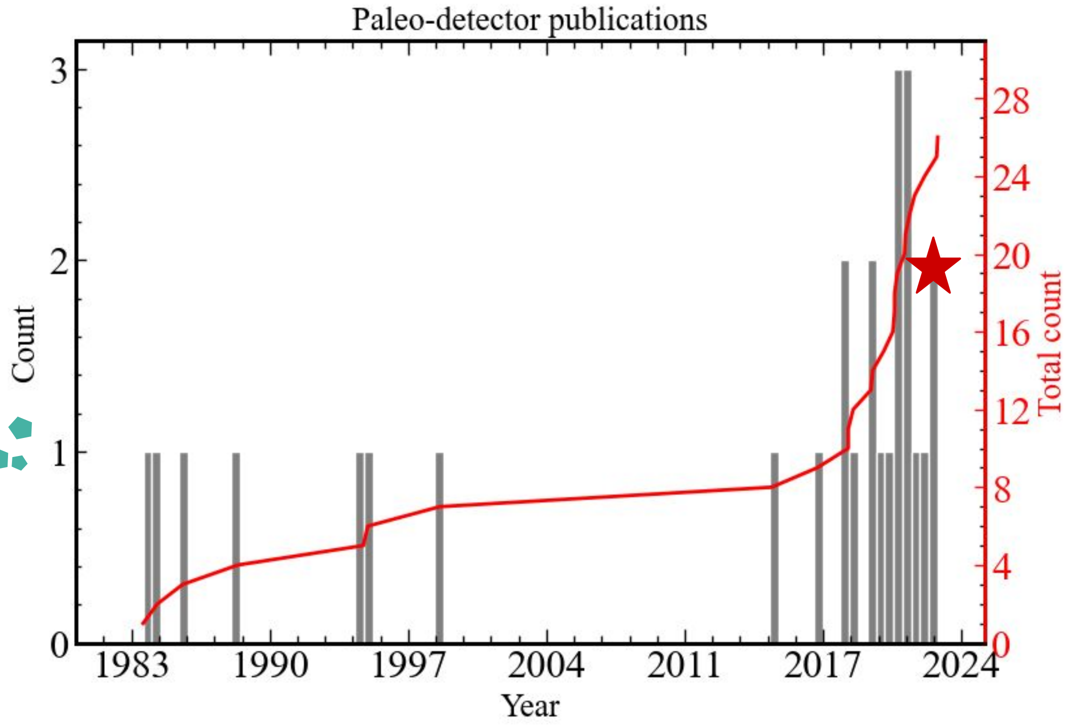
Anil Ananthaswamy

- ❖ **Worldwide interest - novel emerging research field**
- ❖ **Growing amount of publications in last ~ 5 yr**



Paleo-detectors Now

Karlsruhe Institute of Technology

- ❖ **Worldwide interest - novel emerging research field**
- ❖ **White paper in "*Physics of the Dark Universe*" (editor's invitation)**
  - ➢ 67 authors, 46 institutions, 113 pages

- ❖ **MDvDM Jan. 2024** - Virginia Tech, USA

ELSEVIER

Physics of the Dark Universe

Volume 41, August 2023, 101245

Mineral detection of neutrinos and dark matter. A whitepaper

Sebastian Baum [1], Patrick Stengel [2], Natsue Abe [3], Javier F. Acevedo [4], Gabriela R. Araujo [5 a], Yoshihiro Asahara [6], Frank Avignone [7], Levente Balogh [8], Laura Baudis [5], Yilda Boukhtouchen [9], Joseph Bramante [9 10], Pieter Alexander Breur [4], Lorenzo Caccianiga [11], Francesco Capozzi [12], Juan I. Collar [13], Reza Ebadi [14 15], Thomas Edwards [16], Klaus Eitel [17], Alexey Elykov [17], Rodney C. Ewing [18], Katherine Freese [19 20], Audrey Fung [9], Claudio Galelli [21], Ulrich A. Glasmacher [22], Arianna Gleason [4], Noriko Hasebe [23], Shigenobu Hirose [24], Shunsaku Horiuchi [25 26], Yasushi Hoshino [27], Patrick Huber [25 a], Yuki Ido [28], Yohei Igami [29], Norito Ishikawa [30],

arXiv > astro-ph > arXiv:2405.01626

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Help | Adv

Astrophysics > Cosmology and Nongalactic Astrophysics

[Submitted on 2 May 2024]

Mineral Detection of Neutrinos and Dark Matter 2024. Proceedings

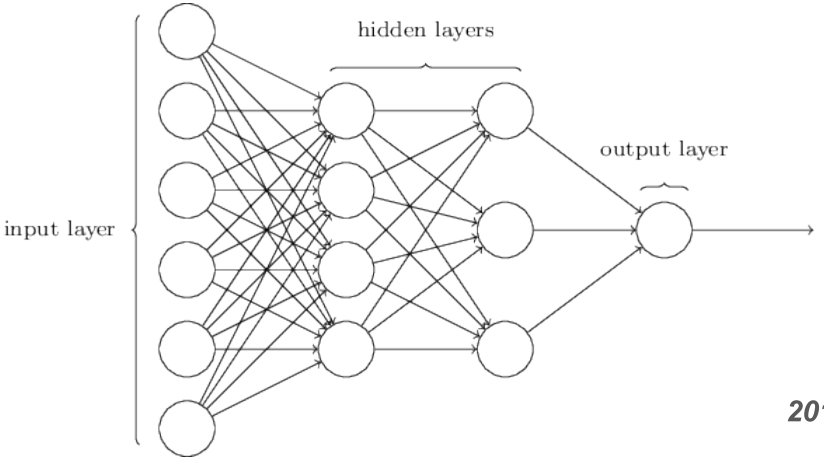
Sebastian Baum, Patrick Huber, Patrick Stengel, Natsue Abe, Daniel G. Ang, Lorenzo Apollonio, Gabriela R. Araujo, Levente Balogh, Pranshu Bhaumik Yilda Boukhtouchen, Joseph Bramante, Lorenzo Caccianiga, Andrew Calabrese-Day, Qing Chang, Juan I. Collar, Reza Ebadi, Alexey Elykov, Katherine Freese, Audrey Fung, Claudio Galelli, Arianna E. Gleason, Mariano Guerrero Perez, Janina Hakenmüller, Takeshi Hanyu, Noriko Hasebe, Shigenobu Hirose, Shunsaku Horiuchi, Yasushi Hoshino, Yuki Ido, Vsevolod Ivanov, Takashi Kamiyama, Takenori Kato, Yoji Kawamura, Chris Kelso, Giti A. Khodaparast, Emilie M. LaVoie-Ingram, Matthew Leybourne, Xingxin Liu, Thalles Lucas, Brenden A. Magill Federico M. Mariani, Sharlotte Mkhonto, Hans Pieter Mumm, Kohta Murase, Tatsuhiro Naka, Kenji Oguni, Kathryn Ream, Kate Scholberg, Maximilian Shen, Joshua Spitz, Katsuhiko Suzuki, Alexander Takla, Jiashen Tang, Natalia Tapia-Arellano, Pieter Vermeesch, Aaron C. Vincent, Nikita Vladimirov, Ronald Walsworth, David Waters, Greg Wurtz, Seiko Yamasaki, Xianyi Zhang

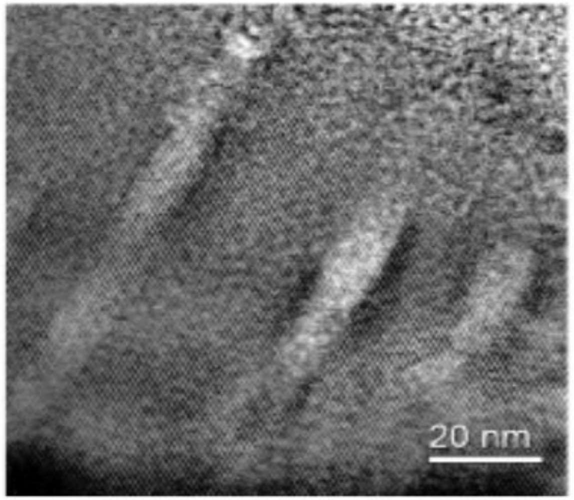
Paleo-detectors Now

… and more …

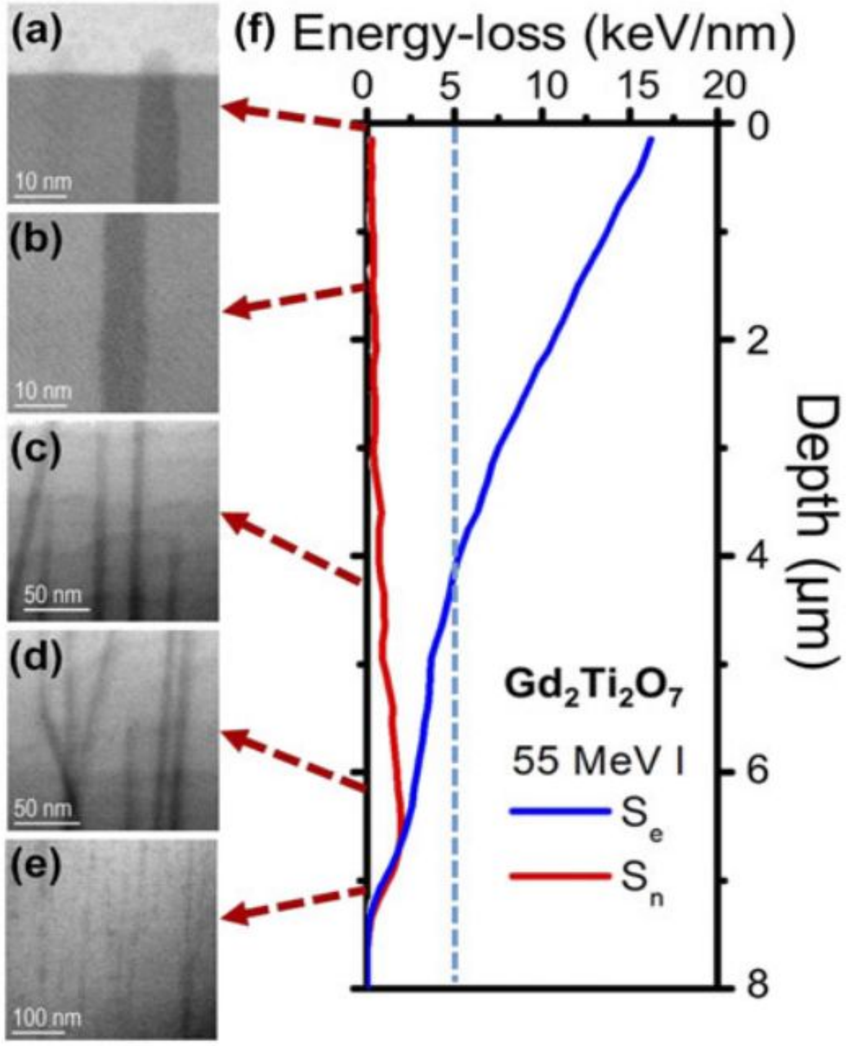
Paleo-detectors - Why Now?

- **Renewed interest worldwide**
  - Unprecedented advances in nm-scale microscopy & manipulation
  - Computational advances - simulations, data processing
  - Machine learning





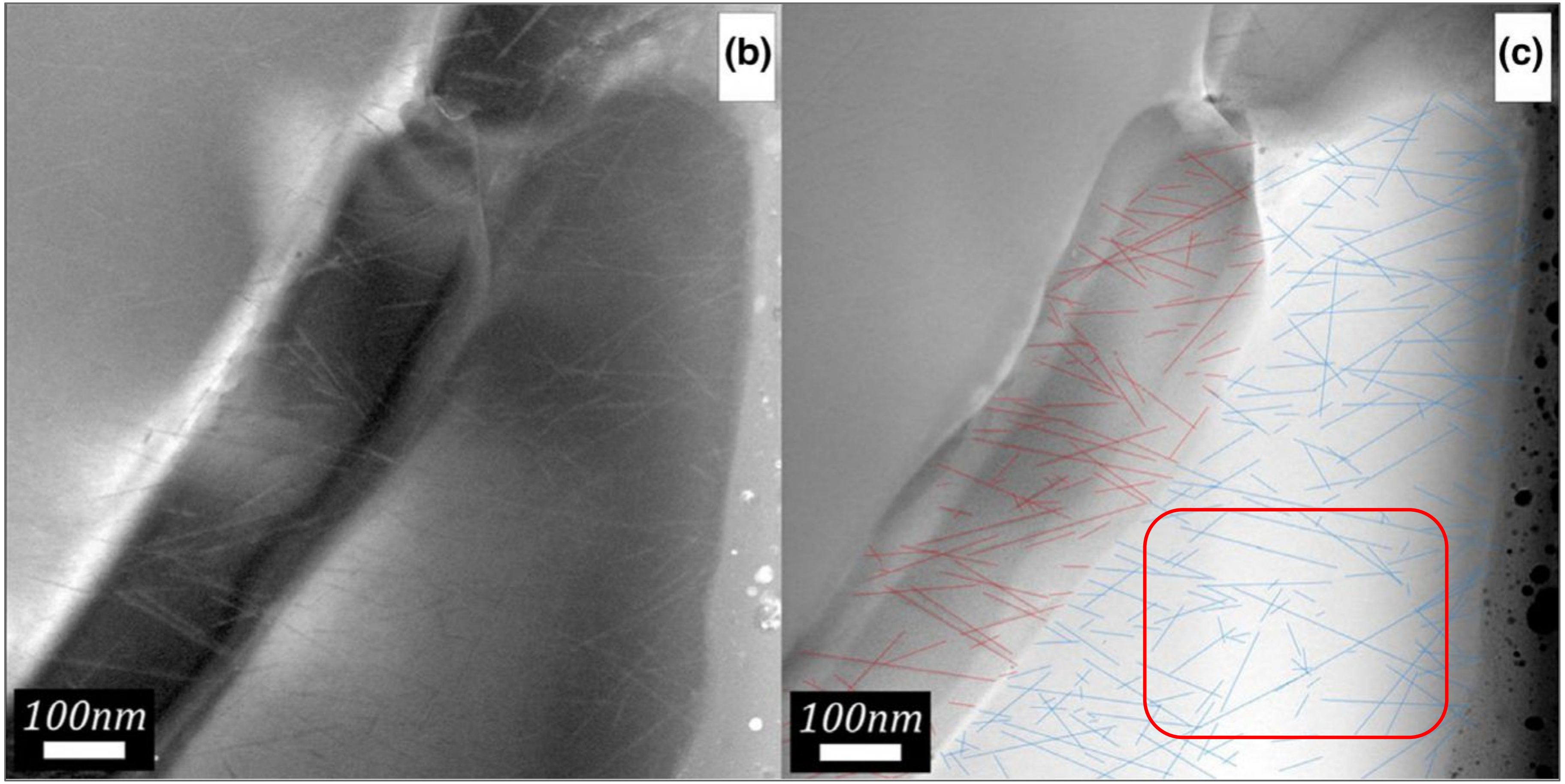
2011 *: TEM imaged tracks in apatite from 2.2 GeV Au ions (DOI: 10.1103/PhysRevB.83.064116)*



2016 : *Ion track morphology at different depths in the material. (DOI: 10.1557/jmr.2016.418)*

Paleo-detectors - Why Now?

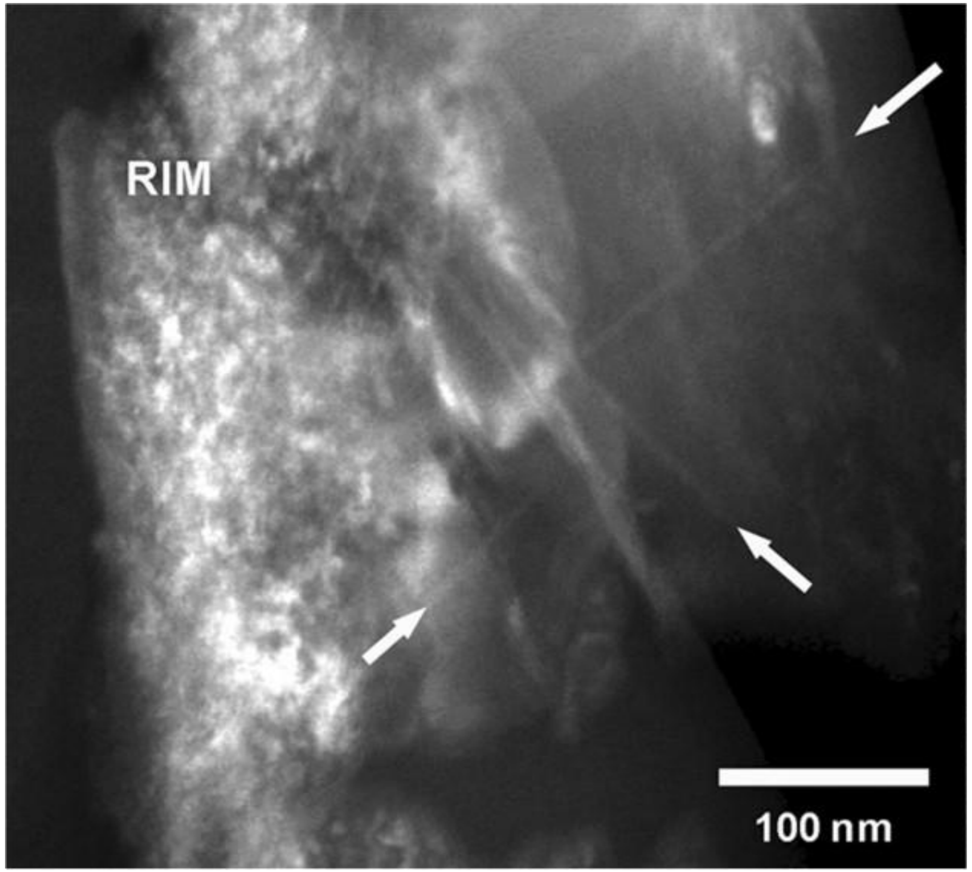
Apollo 16 - Lunar sample



2021 *: STEM images from a lunar sample. Solar energetic particle induced tracks are present in olivine and plagioclase. (b) STEM images. c) Tracks are highlighted in red and blue for the olivine and plagioclase grains, respectively. (DOI: 10.1111/maps.13732)*

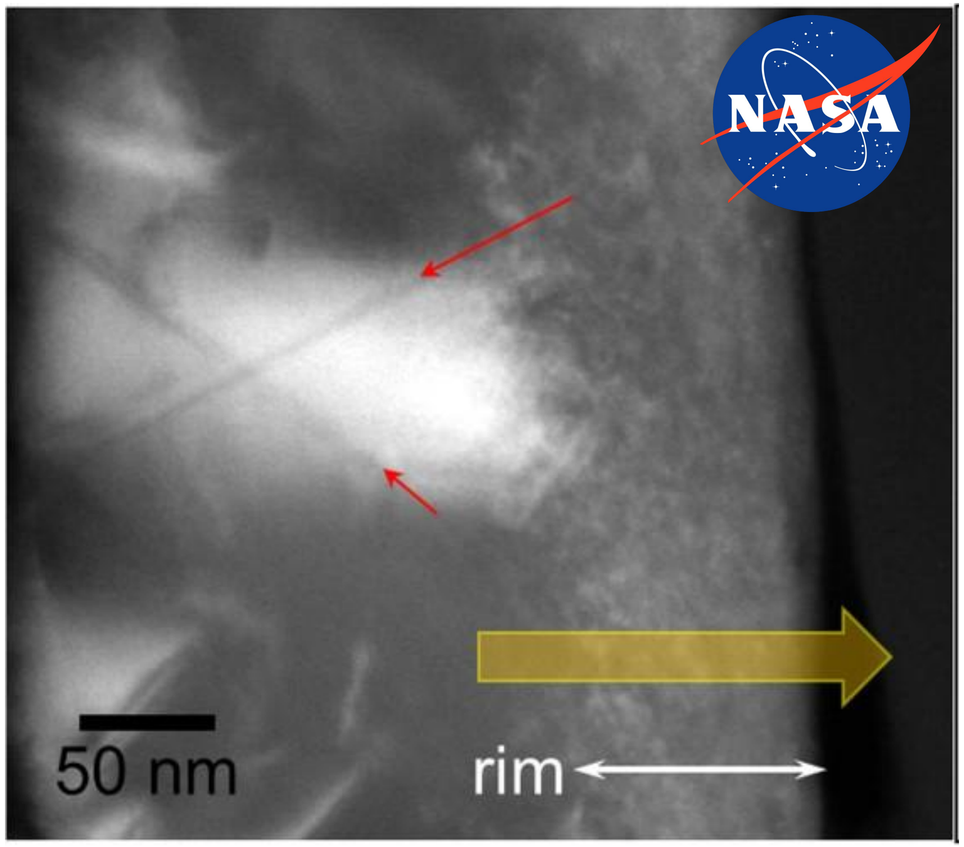
Paleo-detectors - Why Now?

Asteroid 25143 Itokawa



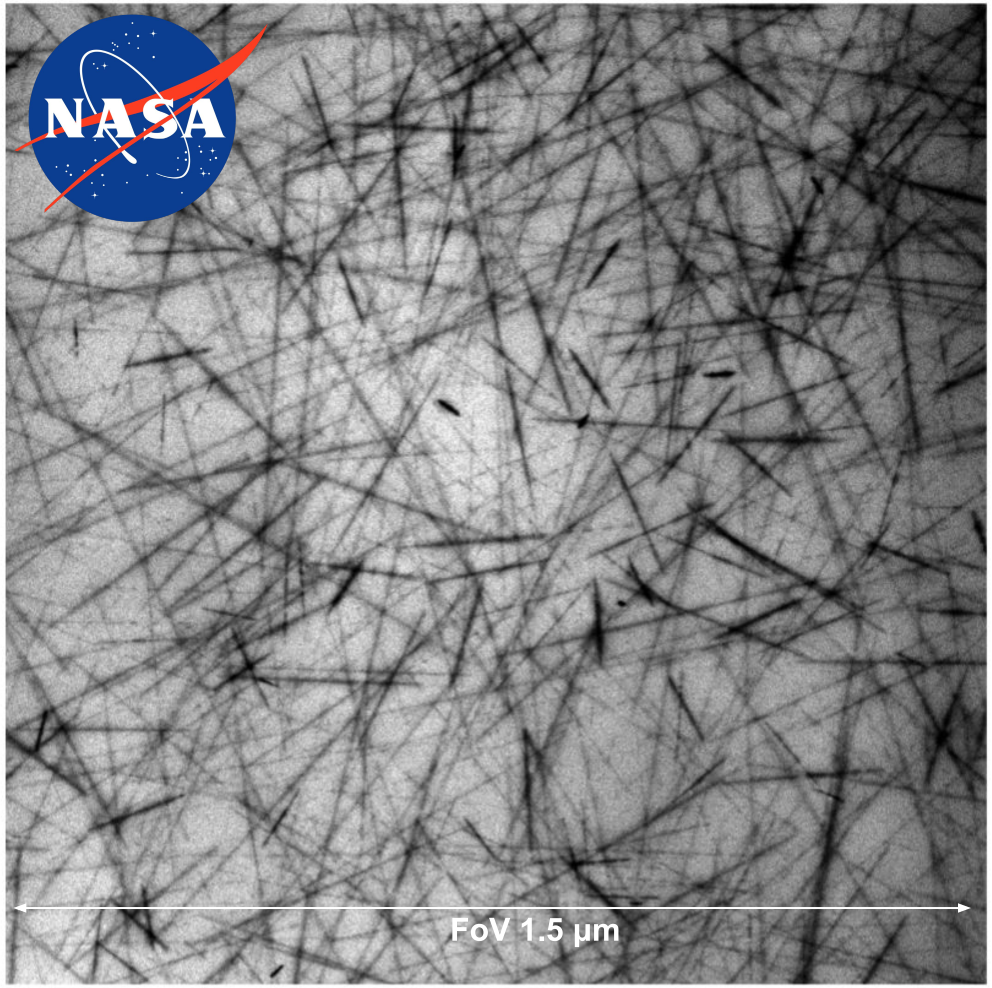
2014 : *Dark-field STEM image of solar flare induced tracks in an asteroid particle. (DOI: 10.1186/1880-5981-66-71)*

Lunar sample

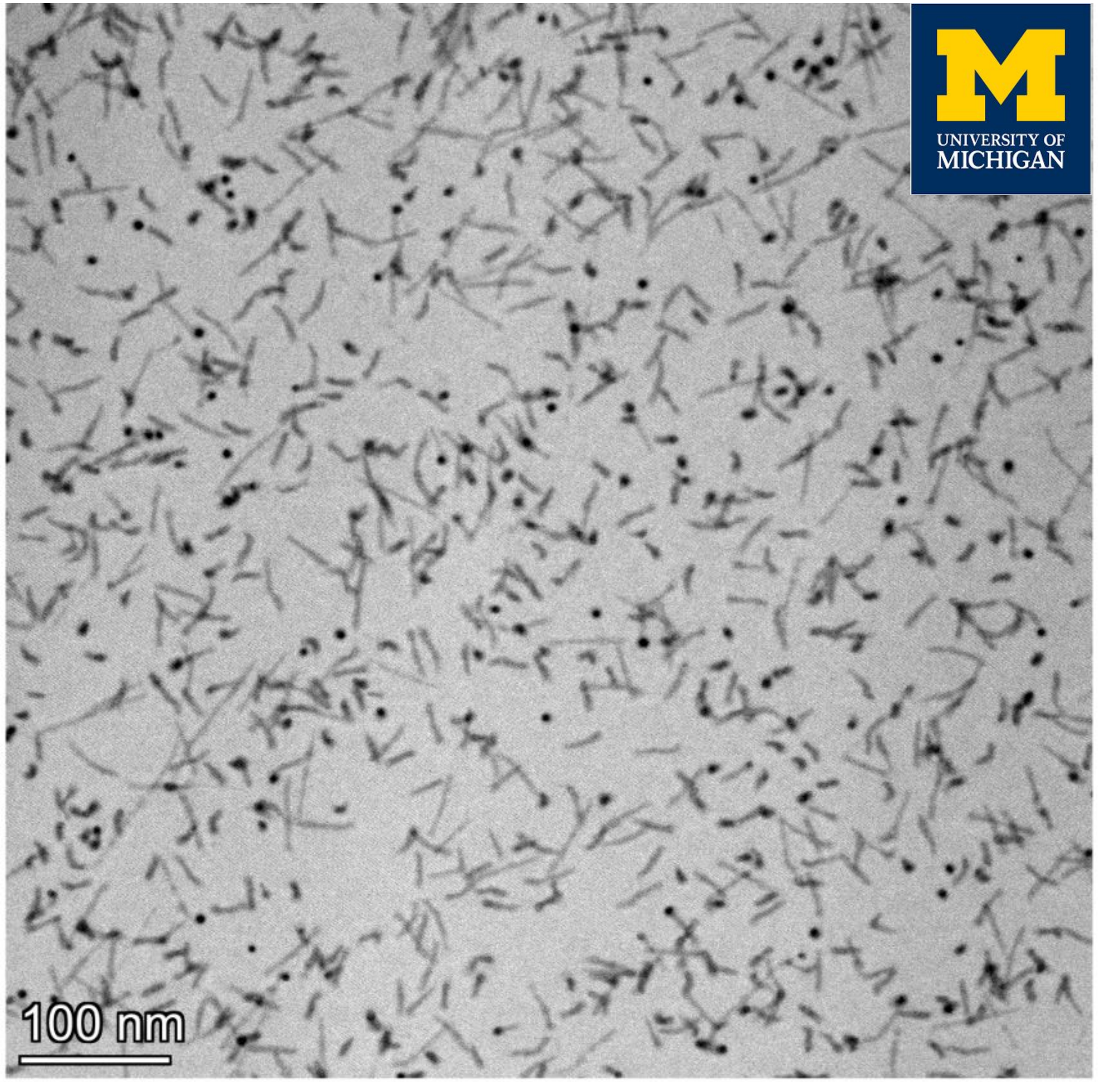


2014 : *Dark-field STEM image of the disordered rim in a lunar olivine grain. (DOI: 10.1186/1880-5981-66-71)*

Paleo-detectors - Why Now?

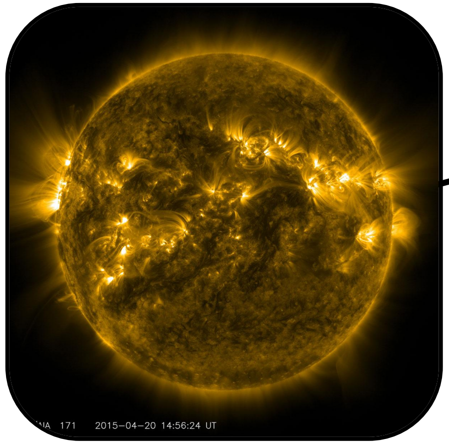


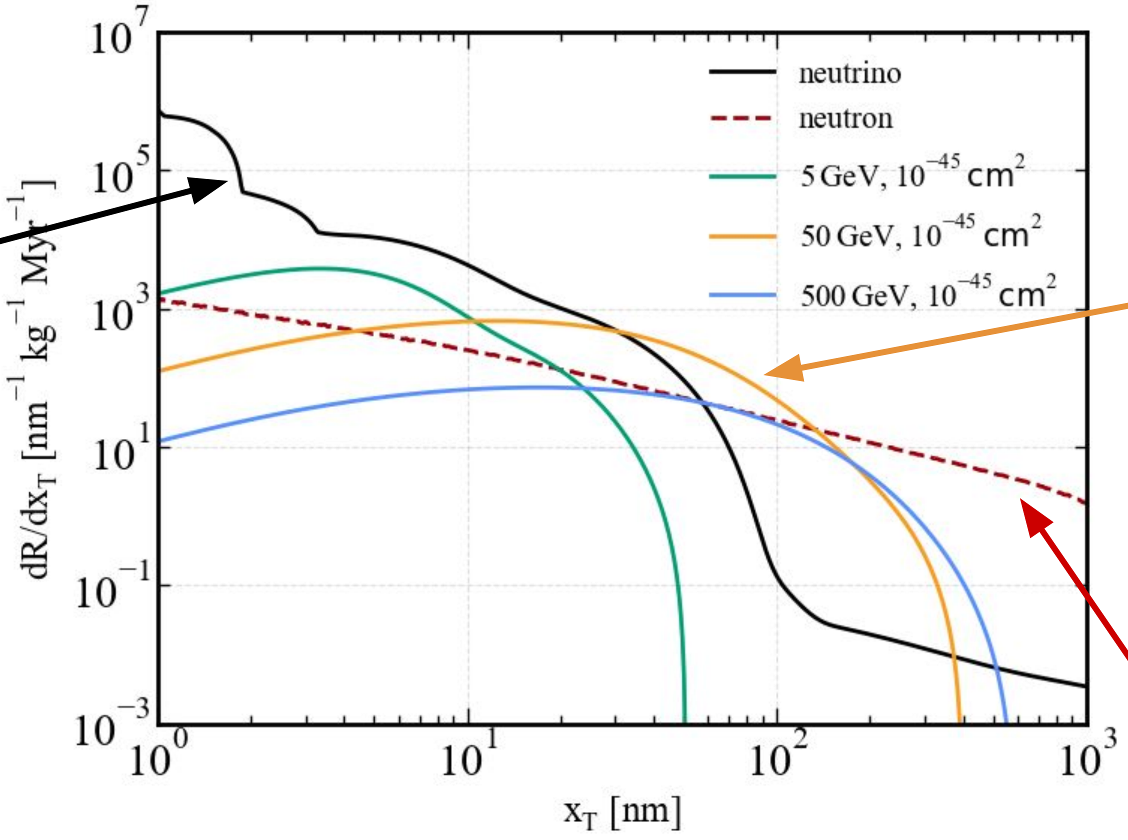
A brightfield TEM image from a thin section of an olivine grain from lunar soil 71501.

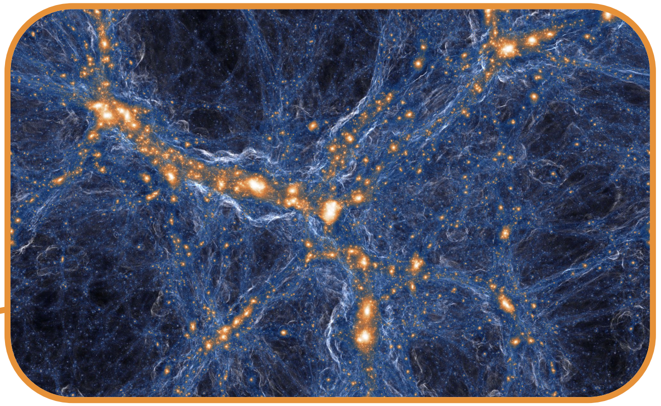


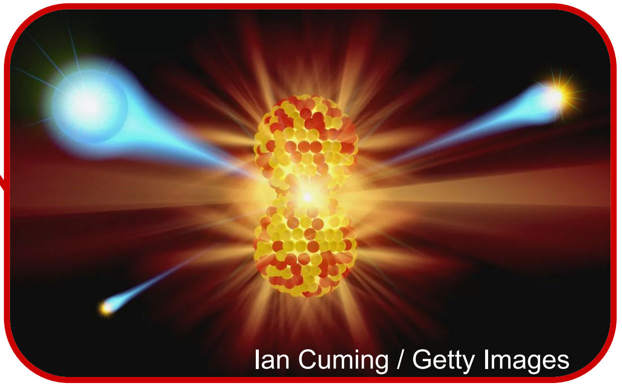
***2024 :** ~10 MeV Au ions in Olivine (MgFeSiO4) sample, imaged with TEM, aimed at mimicking MeV-scale neutrino-induced nuclear recoils*
(presented on 12.07.2024)

Dark Matter & Neutrino Induced Track Spectra





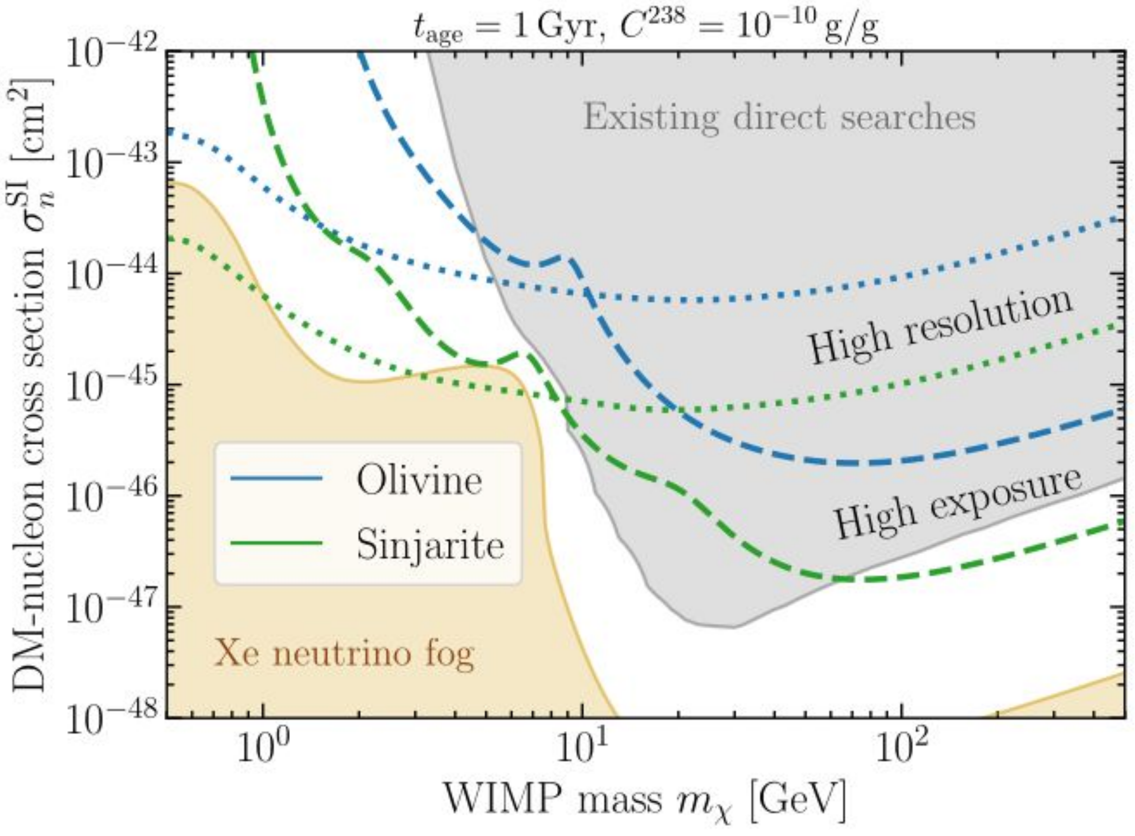




- No exact timing information
- Very large time scales ~ Myr-Gyr

Dark Matter Discovery Reach

- ❖ Nuclear recoil energy thresholds down to 0.1 - 1 keV
- ❖ Mineral, readout method & resolution dependent
- ❖ Leverage high-exposure or/and high-resolution
  - ➢ Probe large range of Dark Matter candidates
- ❖ Competitive & complementary to large-scale detectors



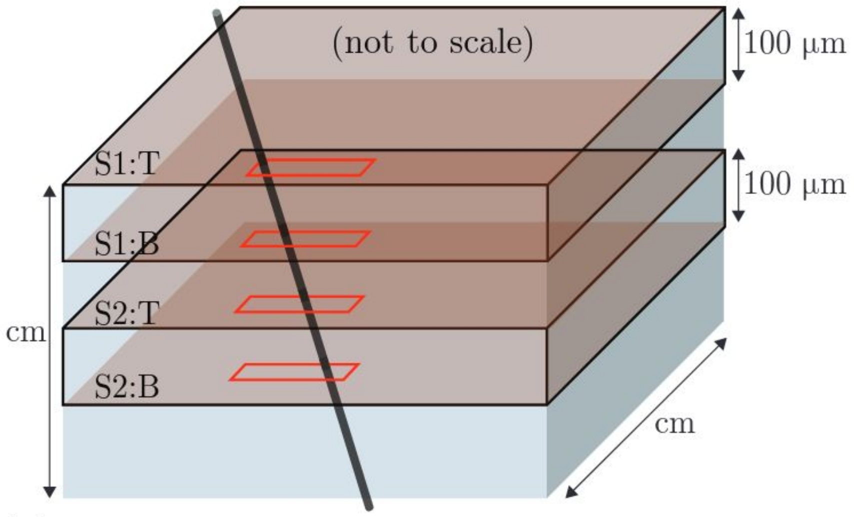
Two scenarios : High resolution (σ_x = 1 nm, M_sample = 10 mg, dotted lines), High exposure (σ_x = 15 nm, M_sample = 100 g, dashed lines). The projections were produced using https://github.com/sbaum90/paleoSens.git

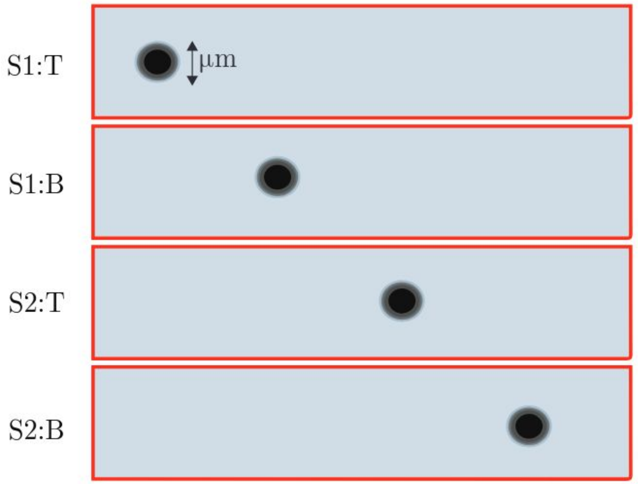
DOI: 10.1016/j.dark.2023.101245

Ultra-heavy Dark Matter

Ultra-Heavy Dark Matter searches in geological Quartz

- ❖ Self-interacting dark matter into ultra heavy composite states with low number density
- ❖ Use geological Quartz - Myr exposure compensates for low number density
- ❖ Use electron microscopy to image slices of Quartz





DOI: 10.1103/PhysRevD.104.015041

Dark Matter Flux Variation

Karlsruhe Institute of Technology

- ❖ Unique ability to study **time varying signals** over Myr to Gyr
  - ➢ Complementary to modern large-scale detectors
  - ➢ Dark Matter halo substructure e.g. sub-halos, “Dark Disk”

- ❖ **Smooth DM halo**
- ❖ **DM disk** - Earth would pass every ~45 Myr
- ❖ **DM subhalo** - Earth encountered during the past Gyr

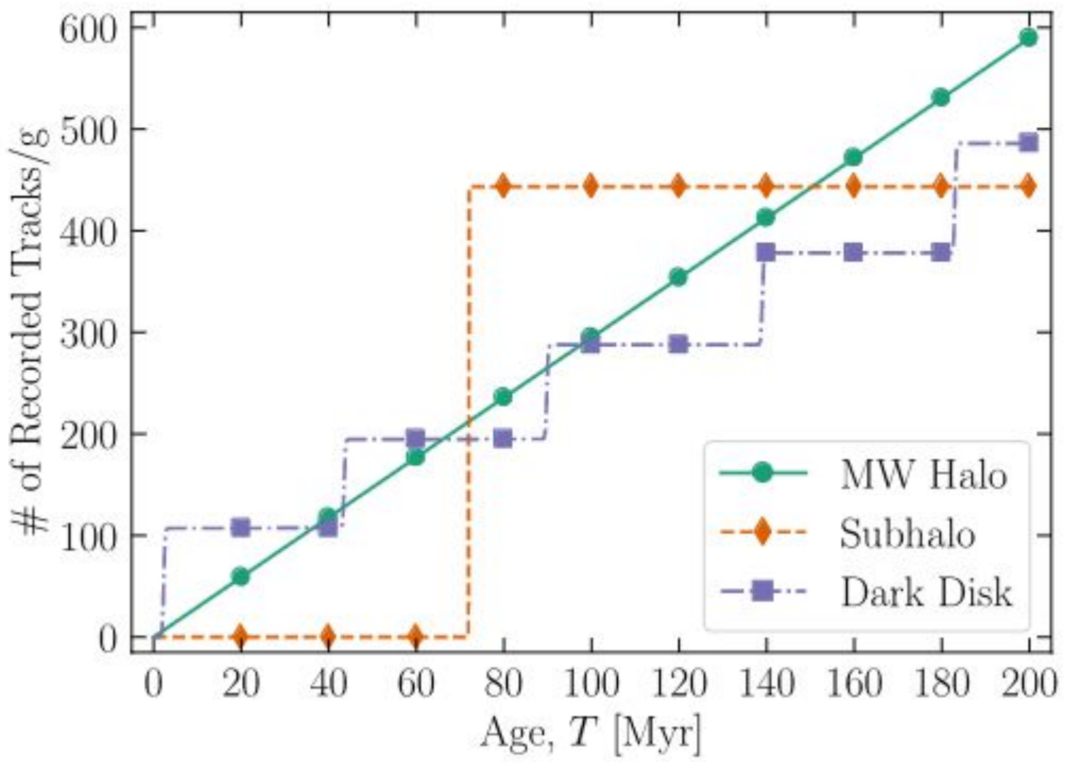
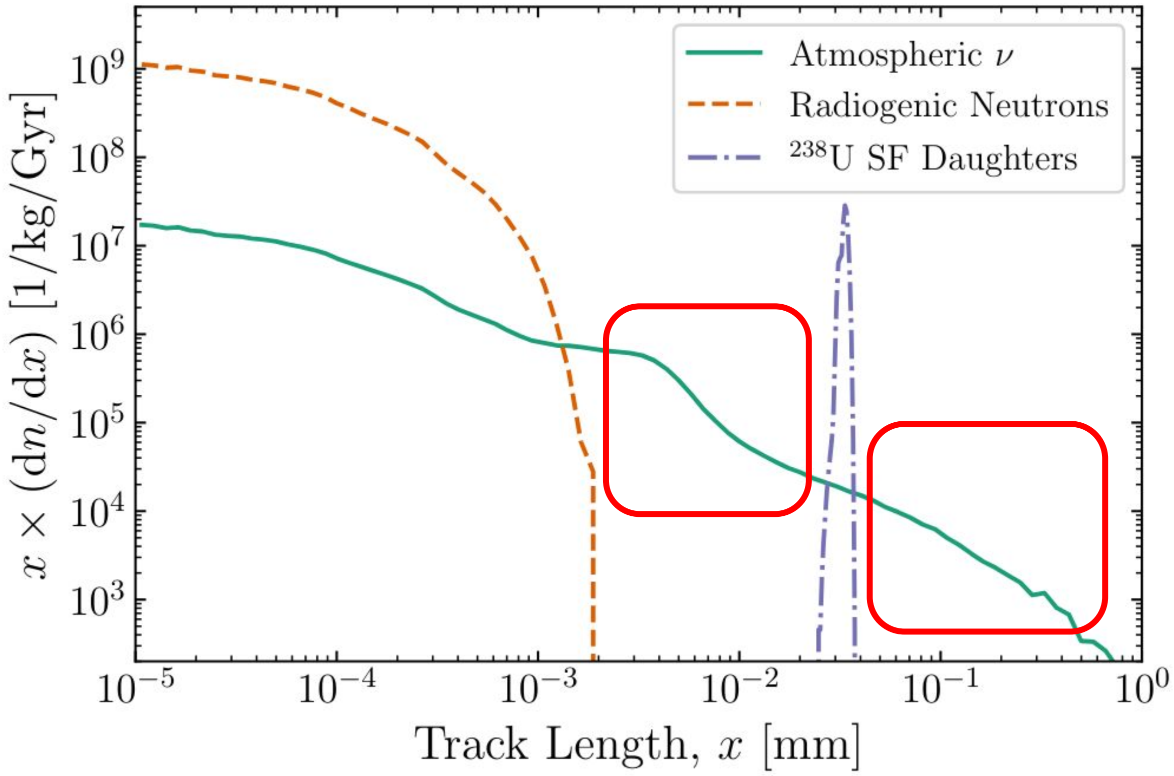
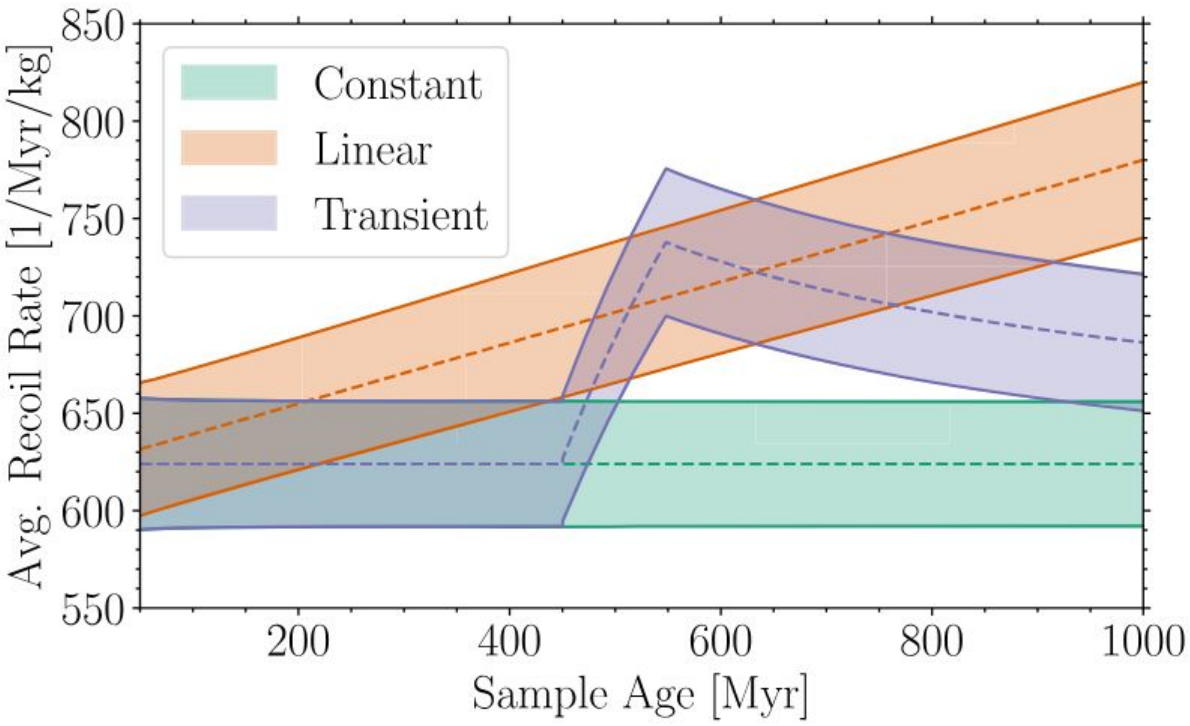


Illustration of the time-dependence of the number of damage tracks which would be recorded in a gram-sized paleo-detector of age T for three different DM signals.

DOI: 10.1103/PhysRevD.104.123015

Cosmic Rays & Atmospheric Neutrinos





- ❖ Potentially background free regions
- ❖ Track with lengths on ~ µm-scale

- ❖ Explore variation of atmospheric ν over Myrs

DOI: 10.1103/PhysRevLett.125.231802

Some Challenges & Open Questions

How to Image Minute Tracks?

Karlsruhe Institute of Technology

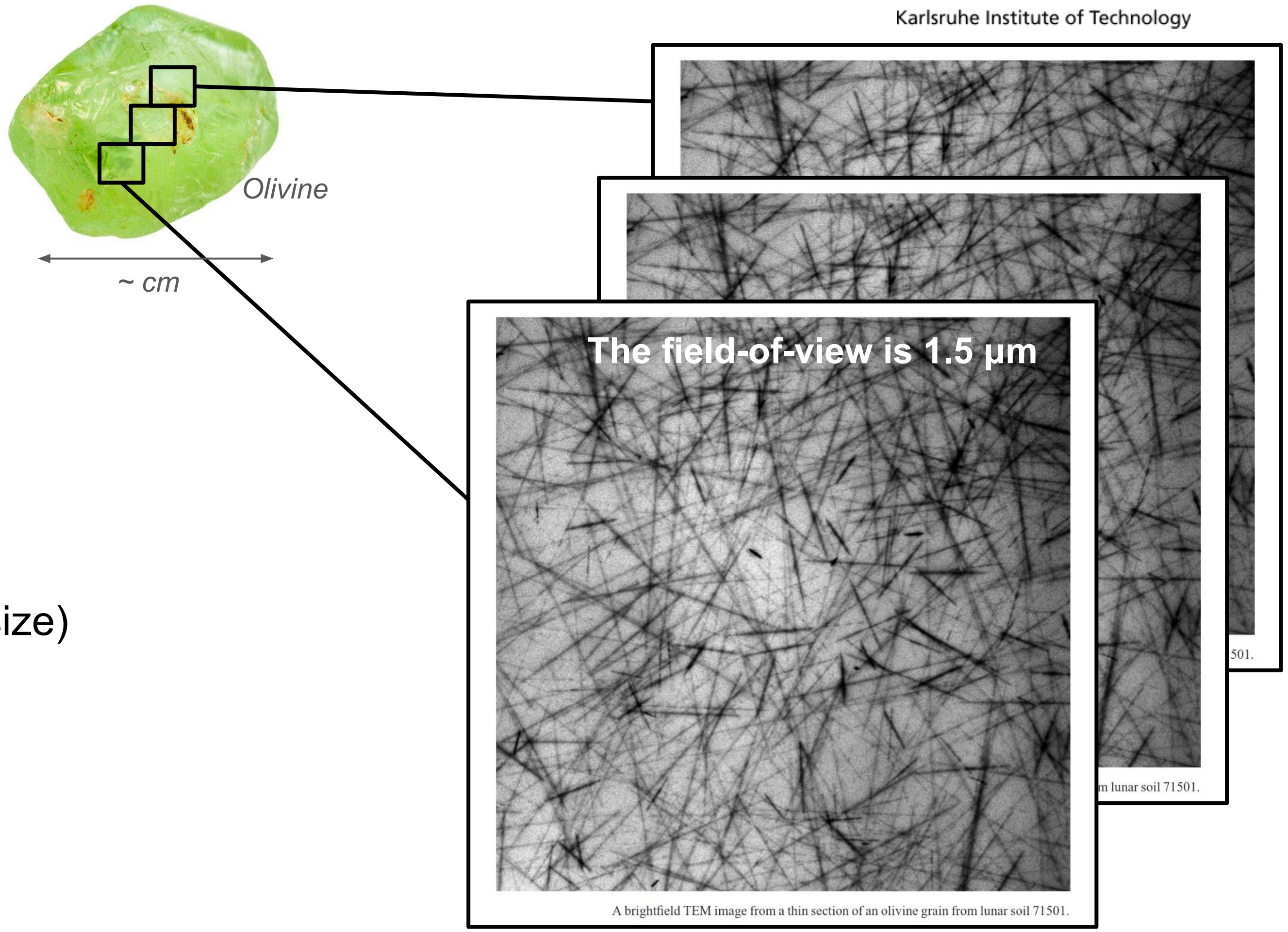
Data Throughput

- **Optical microscopy**
  - Chemical etch + optical (phase contrast) imaging
  - Fluorescence microscopy of color centers
- **X-ray microscopy**
  - Soft X-ray scattering
  - Hard X-ray microscopy (synchrotron/FEL) (ptychography)
- **Scanning Probe Microscopy**
  - Atomic Force Microscopy
- **Focused Beam Microscopy**
  - Scanning Electron Microscopy
  - Focused Ion Beam Microscopy (FIB+SEM, HIM …)
  - Scanning/Transmission Electron Microscopy

Spatial Resolution

How to Image Minute Tracks?

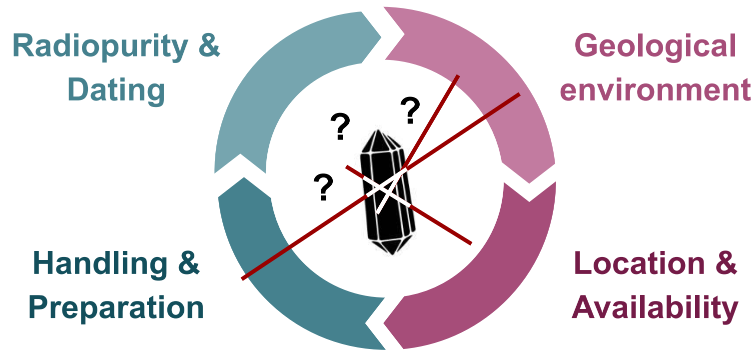
- ❖ **Numerous potential imaging methods:**
  - ➢ X-rays, SEM/FIB, TEM, HIM, AFM
  - ➢ color centers, else…
- ❖ **Resolution:** nm & µm-scale
- ❖ **Imaging in 3D:**
  - ➢ Need to cut sample to small lamellae (nm- µm-size)
  - ➢ 3D might not have enough resolution
- ❖ **Electron/ion energy** - destructive to sample/tracks
- ❖ How to read out data & analyze?

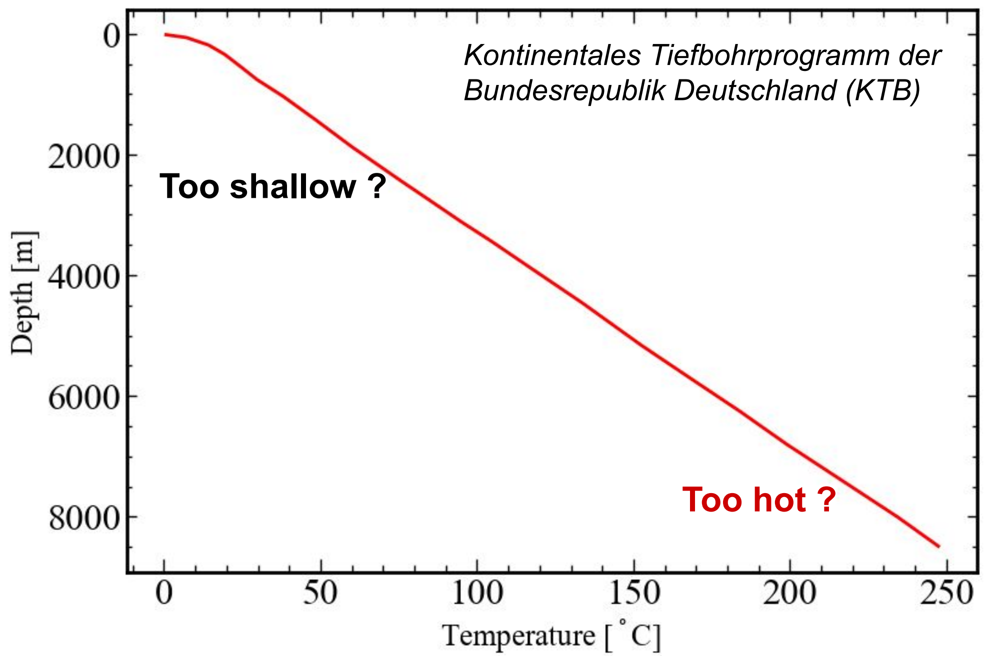


A transmission electron microscope image from a thin (100 nm) section of an olivine grain from lunar soil 71501. (DOI : 10.1111/maps.13516)

Where to Find Minerals?

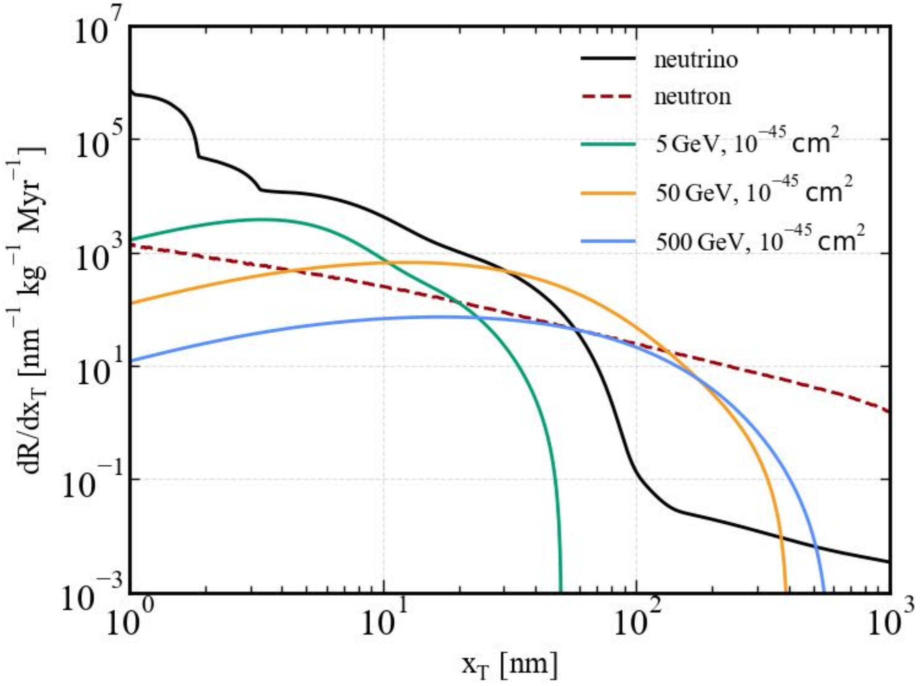
- ❖ **Boreholes, mines** - where?
  - ➢ **Deep** enough to protect from cosmogenic backgrounds
  - ➢ **Not too deep** - temperature will anneal crystals
- ❖ **Accessible** with reasonable effort
- ❖ **Geologically stable** over Myr/Gyr
- ❖ Low radioactivity environment (U, Th)





Backgrounds & Solutions

- ❖ **Natural crystal defects**
  - ➢ Complicating readout but should be distinguishable
- ❖ **Cosmogenic**
  - ➢ muons, fast neutrons
- ❖ **Radioactive decays** (^{238}U, α-decay)
- ❖ **Neutrons** - SF, (α, n)



Differential rate of tracks for different sources of nuclear recoils within Gypsum. Used : https://github.com/sbaum90/paleoSpec

Backgrounds & Solutions

- **Natural crystal defects**
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    - Use minerals from deep underground
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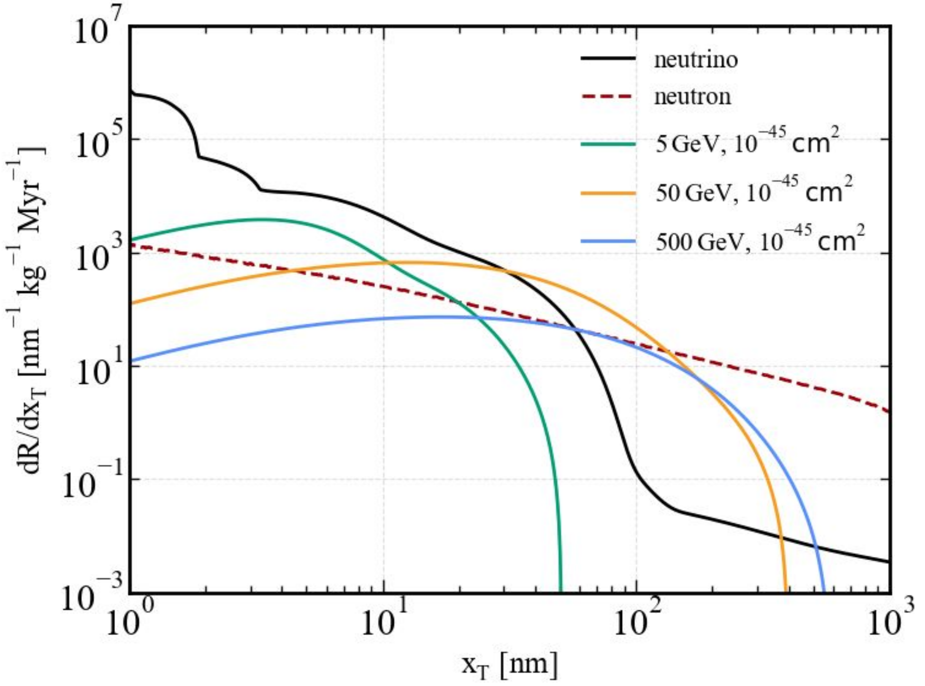
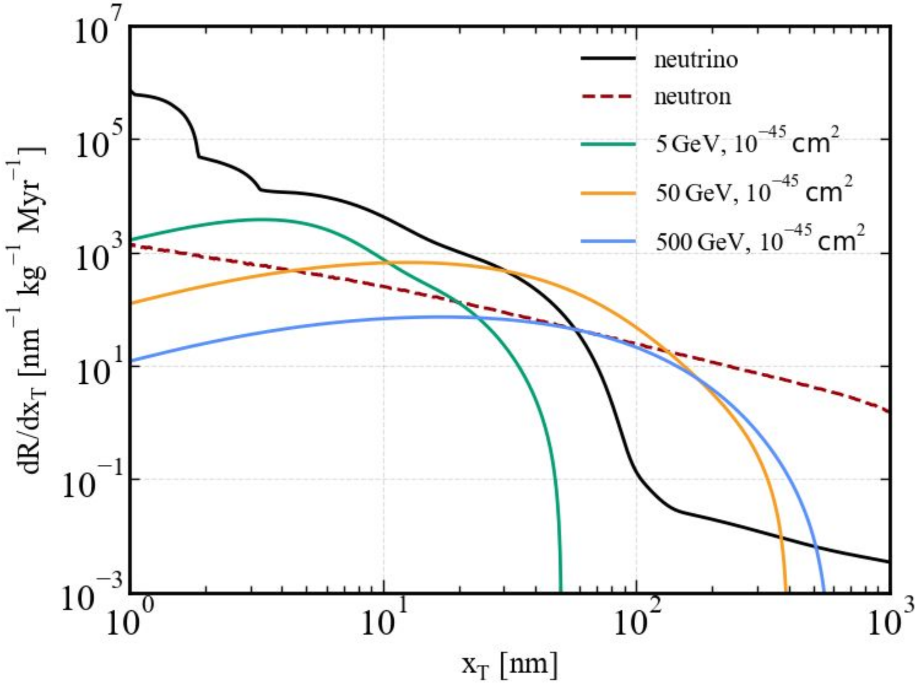


Differential rate of tracks for different sources of nuclear recoils within Gypsum. Used : https://github.com/sbaum90/paleoSpec

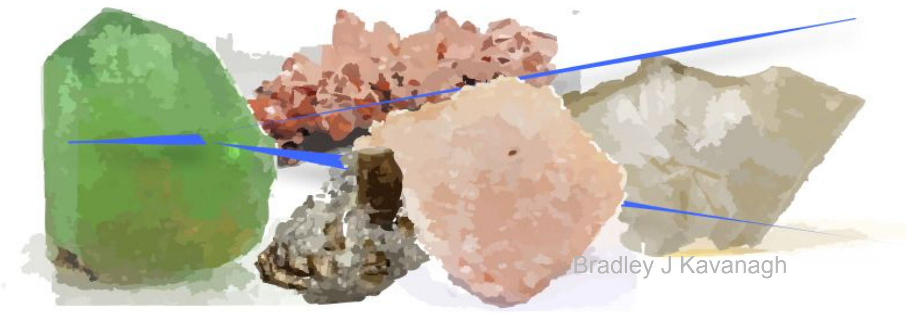
Backgrounds & Solutions

- Natural crystal defects
  - Complicating readout but should be distinguishable
- Cosmogenic
  - muons, fast neutrons
    - Use minerals from deep underground
- **Radioactive decays** (^{238}U, α-decay)
  - Select radiopure minerals
  - “Cluster” track morphology
- **Neutrons** - SF, (α, n)
  - Select radiopure minerals



Differential rate of tracks for different sources of nuclear recoils within Gypsum. Used : https://github.com/sbaum90/paleoSpec

Some Feasibility Studies
Ongoing & Planned



Paleo-detectors around the World

Atomic Force Microscopy (AFM)

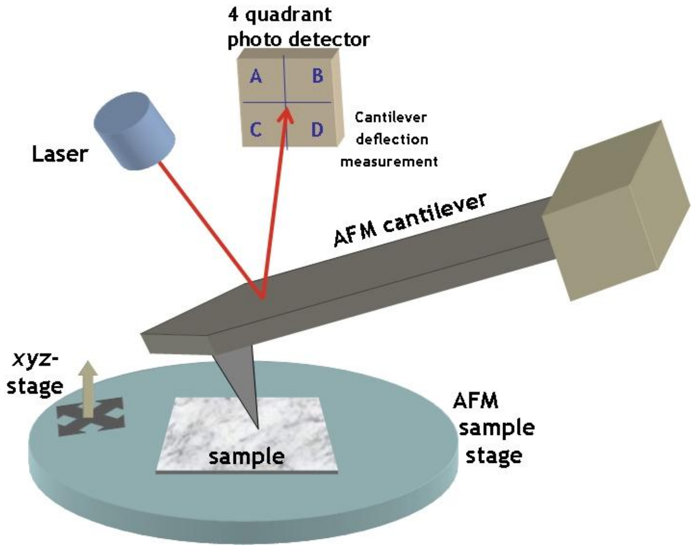
- ❖ Chemically etch surface - scan - sputter (~nm) - chemically etch - scan …

Data Acquisition

- ❖ Scan **10 mg** sample with **~1 nm** resolution
- ❖ Data throughput can reach petabyte/day
- ❖ Custom FPGA/GPU-based data acquisition & processing
- ❖ Triggering on areas/information of interest

Currently - Preliminary Studies

- ❖ Silicon & mica samples to be scanned with AFM, x-ray, electron microscopy

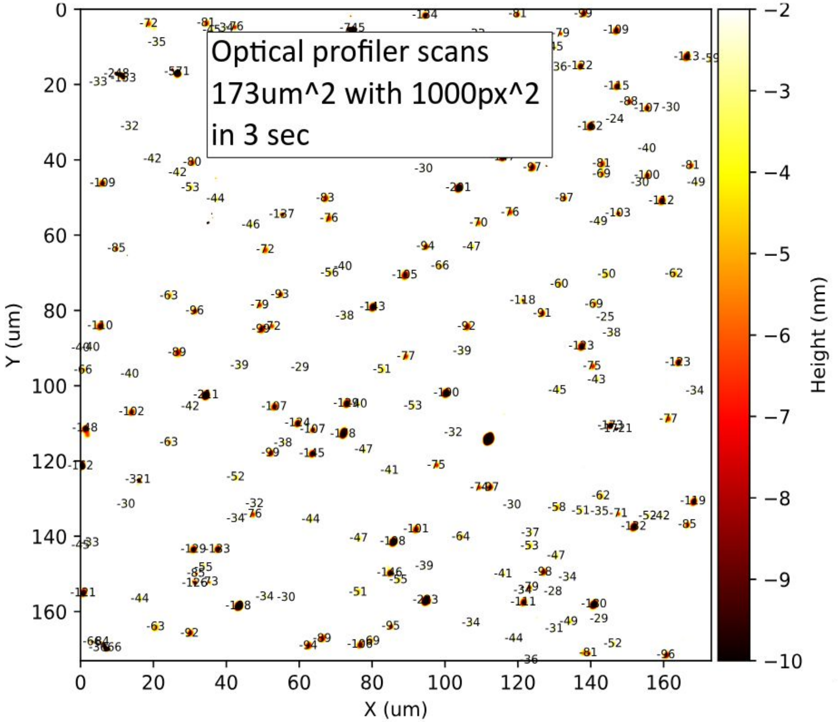


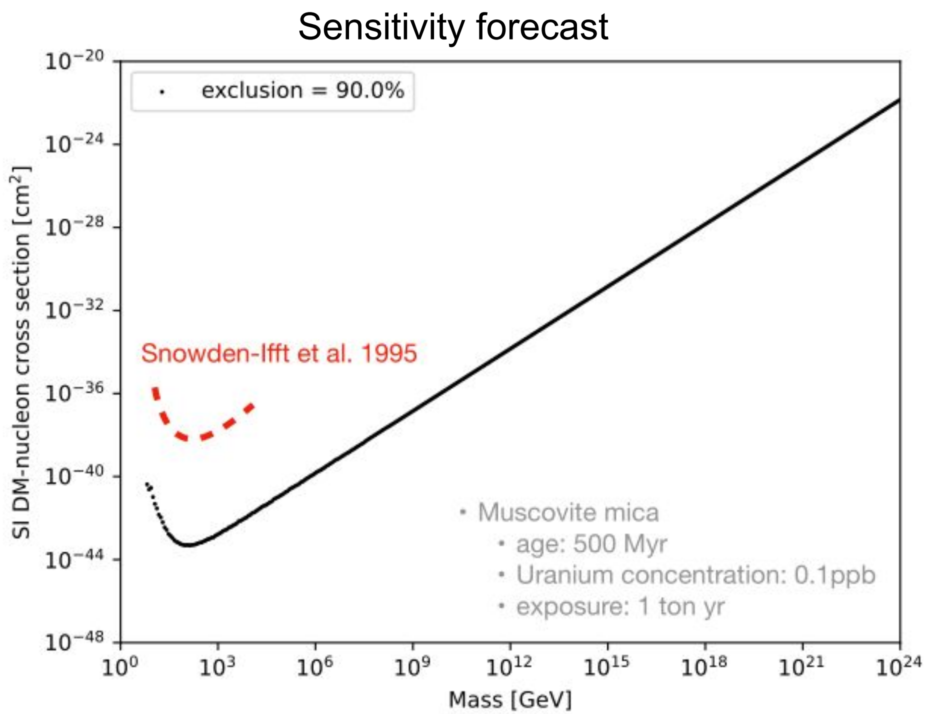
DOI: 10.1016/j.dark.2023.101245

Paleo-detectors around the World

DMICA: exploring **D**ark Matter in natural muscovite **MICA**

- ❖ Employ methodology established by Snowden et al. (1995)
  - ➢ Chemical etching
  - ➢ Pit depth measurement optical profiler instead of AFM
  - ➢ Processed a mica of 524,765 μm² - **aims to scan ~1 t × y exposure**

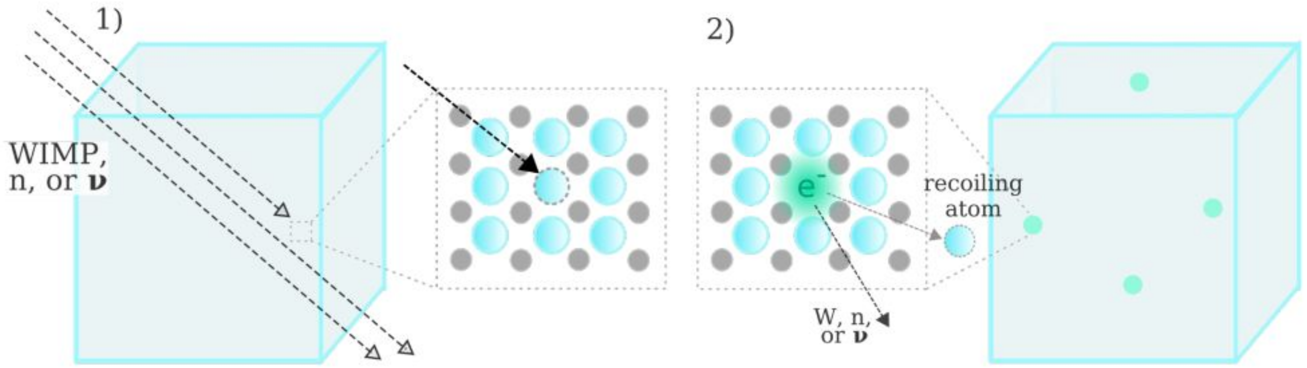


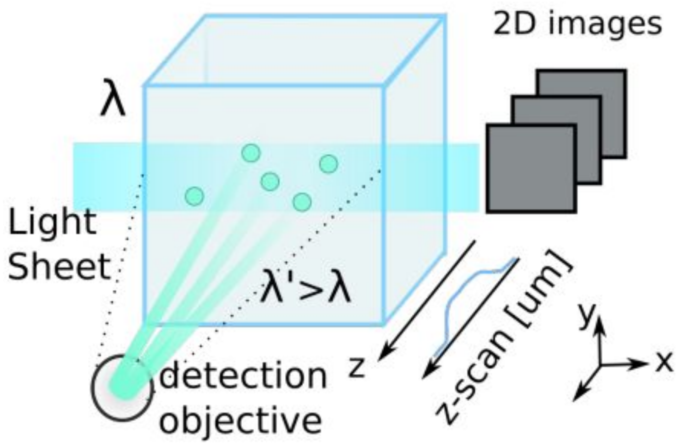


Shigenobu Hirose et al. IDM 2024

Paleo-detectors around the World

- **Passive low energy nuclear recoil detection with color centers - PALEOCCENE**
  - Large-scale light-sheet microscopy with mesoSPIM (mesospim.org)
  - Non-destructive, resolution < 10 μm
  - Suitable crystals - CaF_2, LiF, etc…





Gabriela R. Araujo et al.

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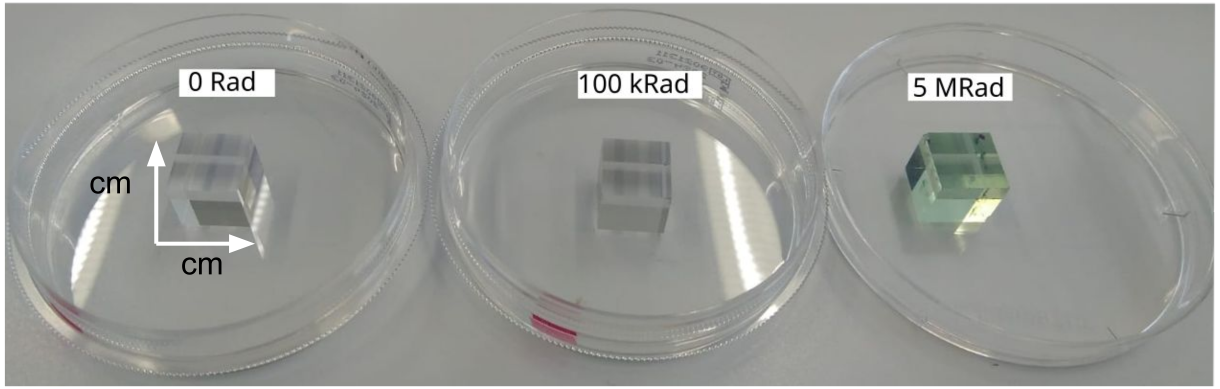

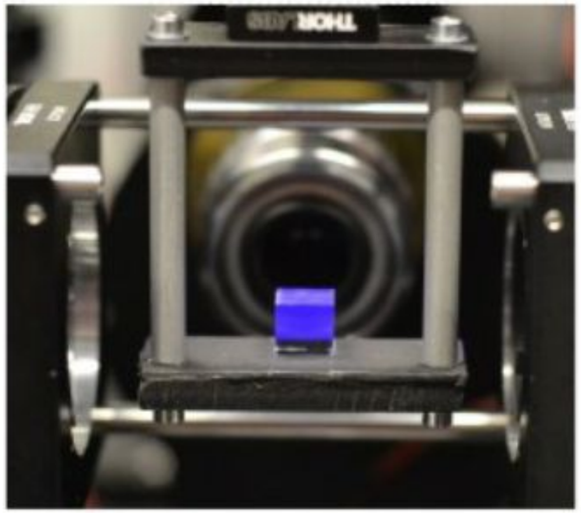

Gabriela R. Araujo et al.

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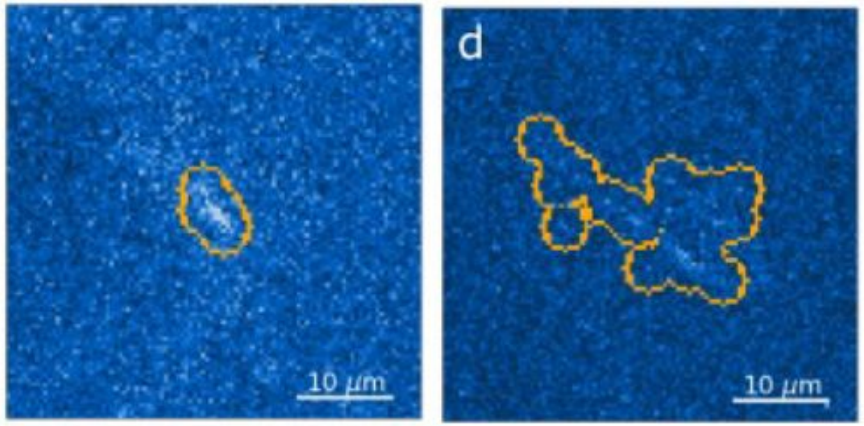
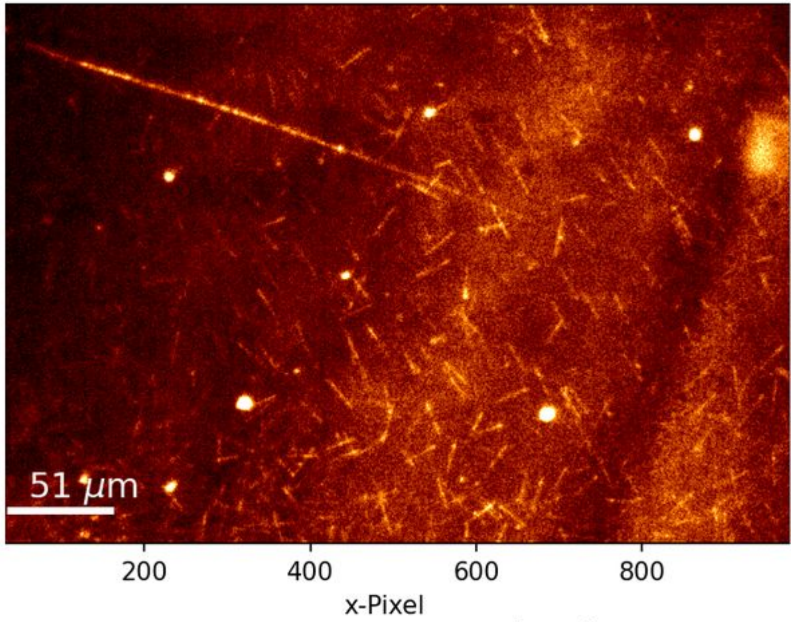
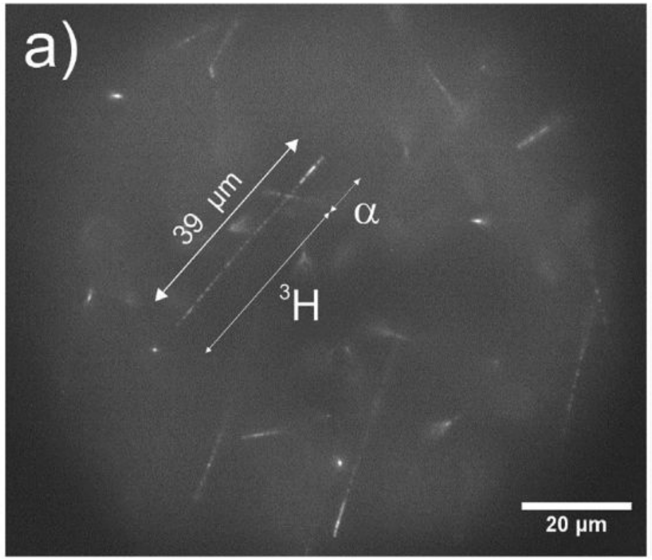
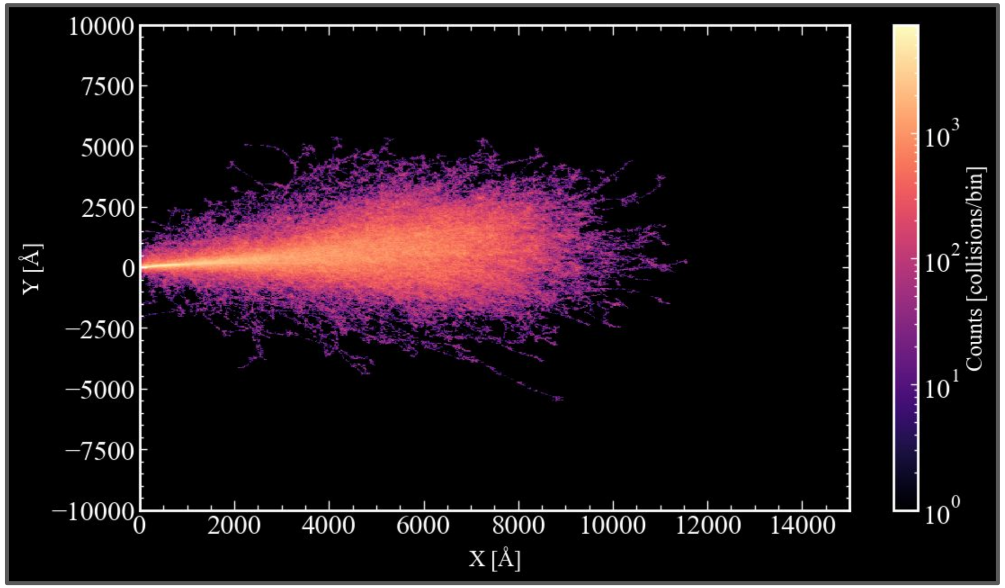






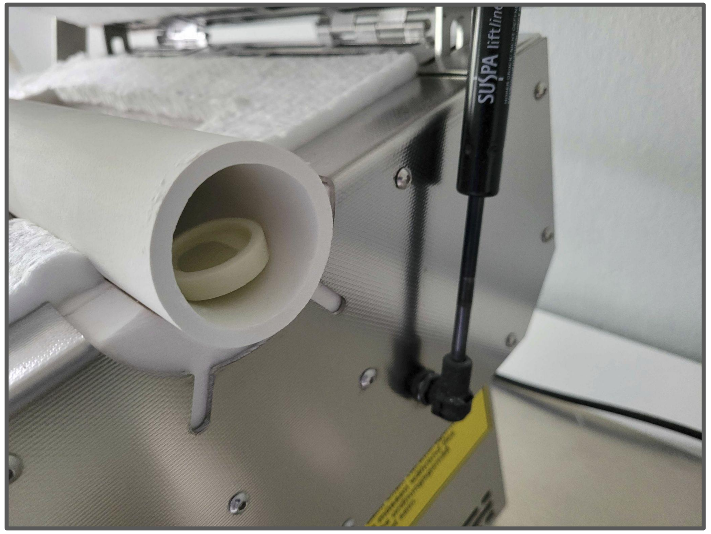
Gabriela R. Araujo et al.

Paleo-detectors at KIT



- ❖ **KIT - Unique combination of different facilities & expertise**
  - ➢ Cutting edge nm-scale & µm-scale microscopy
  - ➢ Dark Matter & Neutrino physics
  - ➢ Numerical simulations, data acquisition & analysis
  - ➢ ML - identification of minute structures in images

- ❖ **Previous work: HEiKA 2019 - 2020, K. Eitel & U. Glasmacher**
  - ➢ "*Searching for Dark Matter particle signatures with salt minerals as Palaeo-Detectors*"



- ❖ **Current work**
  - ➢ Multiple mineral samples - irradiated & "blank"
  - ➢ Ongoing studies together with U. Heidelberg, KIT microscopy, UZH
  - ➢ Combine microscopy techniques to image tracks

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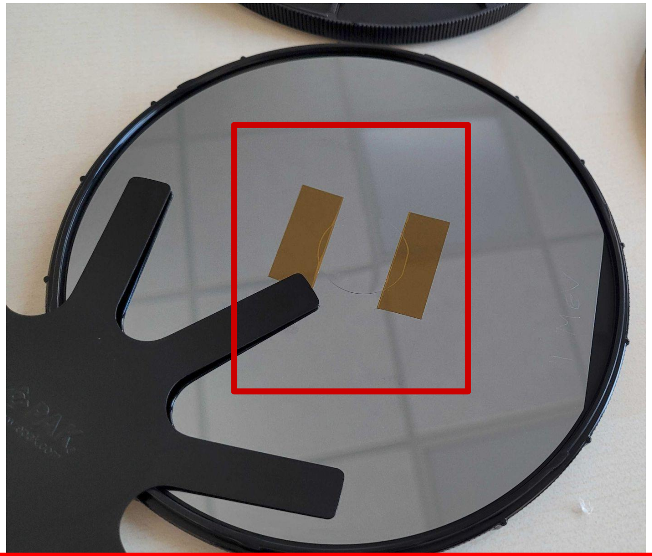

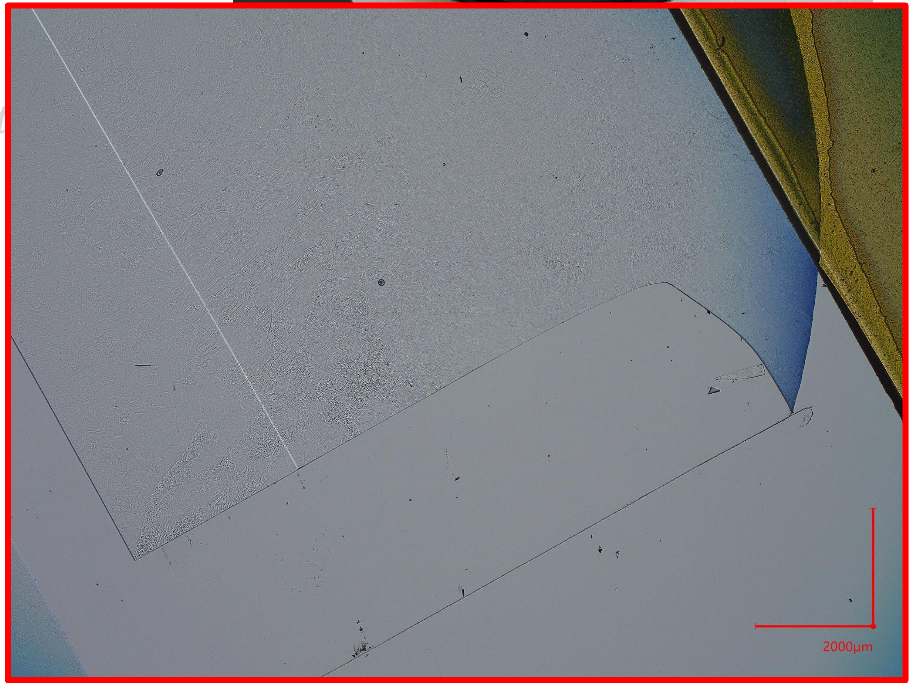

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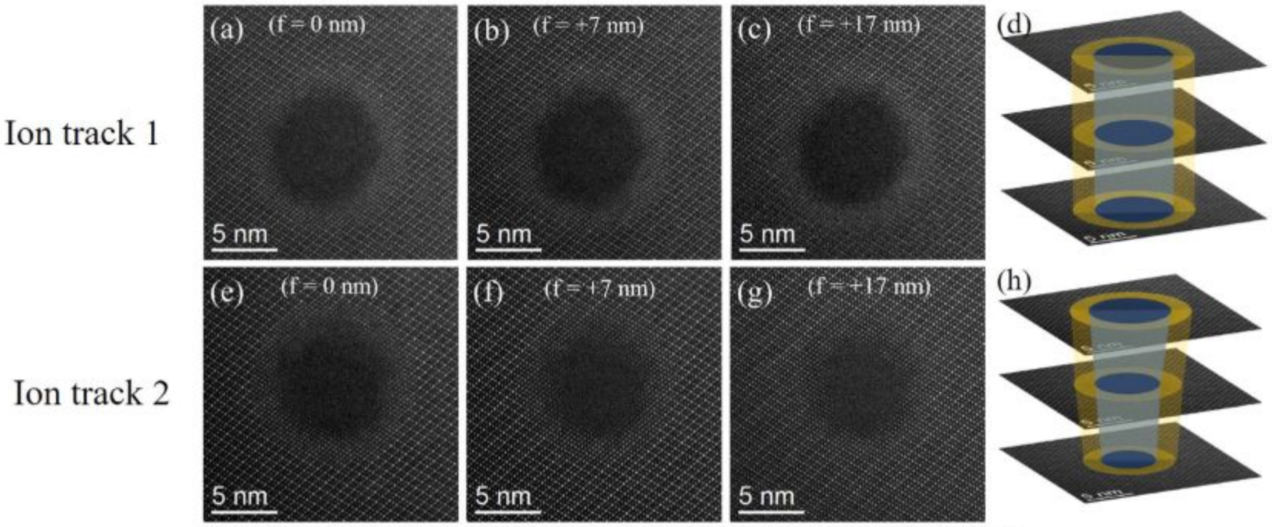
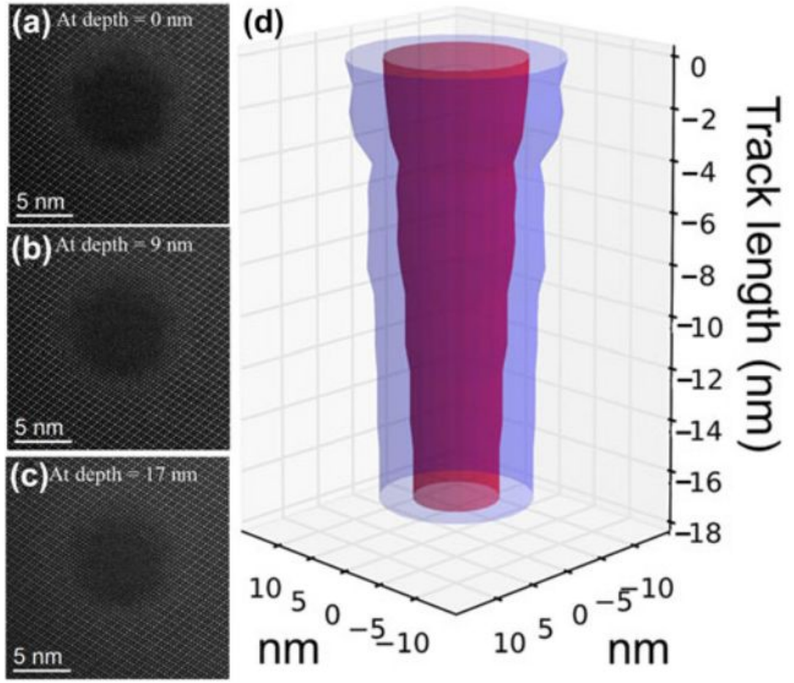
  - Ongoing studies together with U. Heidelberg, KIT microscopy, UZH
  - Combine microscopy techniques to image tracks

Mineral & Track Imaging - TEM (example)

- Resolution << 1 nm
- No 3D information
  - Will require mechanical/ion beam, cutting & creation of ~100 nm thick lamellae
- Destructive effects of electrons on nm-sized tracks?
- Easy to probe ion tracks - what about low-energy recoils?



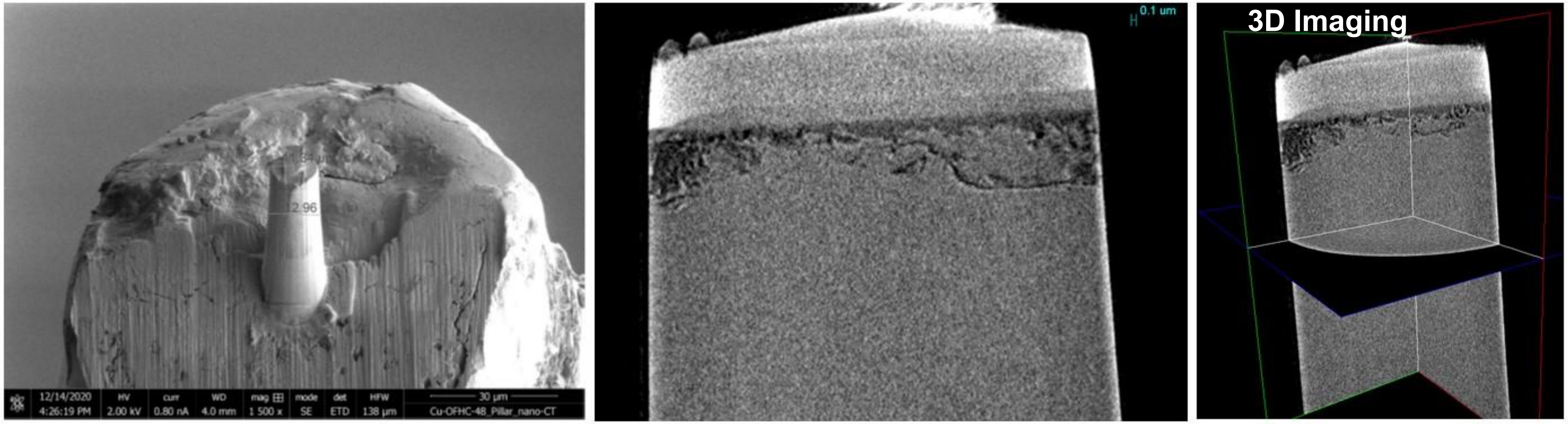
***2016:** The variation in ion track size and morphology of three different ion tracks produced by 2.3 GeV 208 Pb ions. dE/dx is dominated by electronic loss. (DOI: 10.1038/srep27196)*



***2017:** STEM-HAADF images and reconstruction of an ion track. (DOI: 10.1557/jmr.2016.418)*

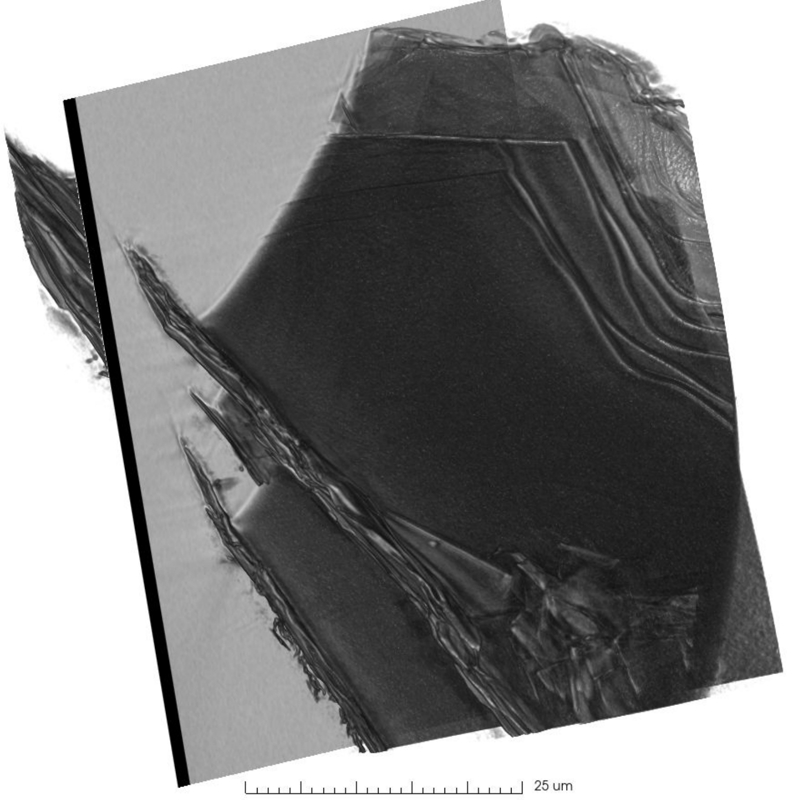
Mineral & Track Imaging - nanoCT (example)

- X-ray energy: 5.4 keV, FoV: 16 or 65 µm
- Non-destructive
- Characterization of 3D samples - resolution down to 50 nm
- Thickness less than twice the X-ray absorption length
- Might not resolve nm-scale tracks, but can resolve substructure & µm-sized tracks?



Cu sample scanned in absorption contrast with high resolution (resolution = 50 nm).
(a) Pillar sample prepared by FIB (Image: Julia Rau), (b) 2D view, (c) 3D view. (https://www.knmf.kit.edu/nanoCT.php)

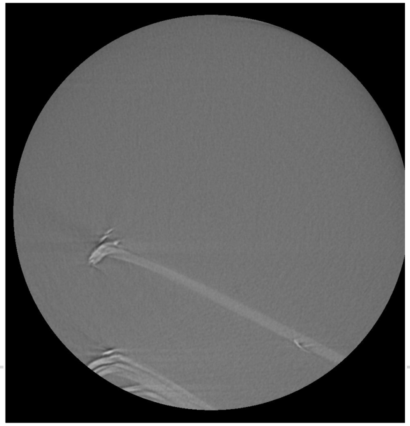
Mineral & Track Imaging - nanoCT

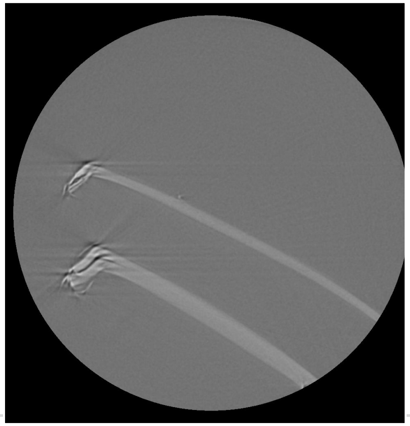


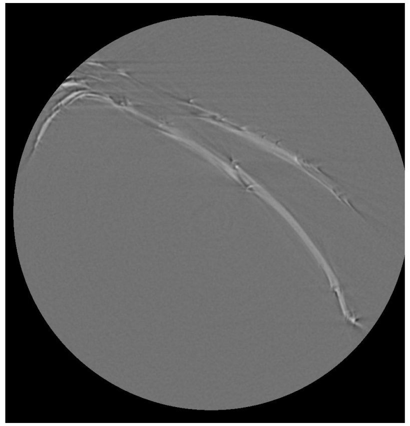
First calibration studies

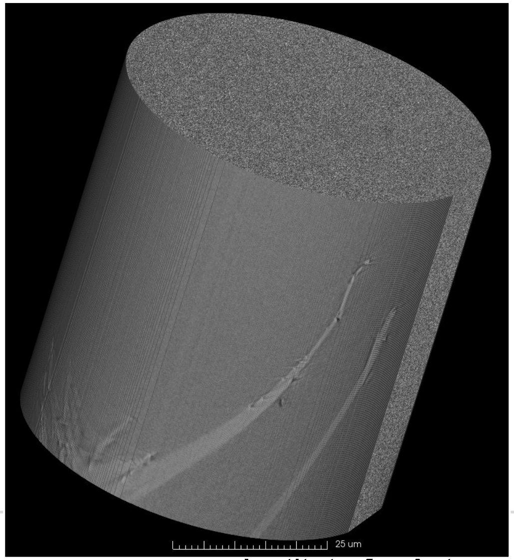
- ➢ Devise best practices for sample preparation

- ❖ Full 3D profile of the imaged sample
- ❖ 64 nm resolution per pixel for O(10)um samples
  - ➢ Image inner structure prior to high res imaging - natural damage, cracks
  - ➢ Can resolve substructure & µm-sized tracks/damage features?

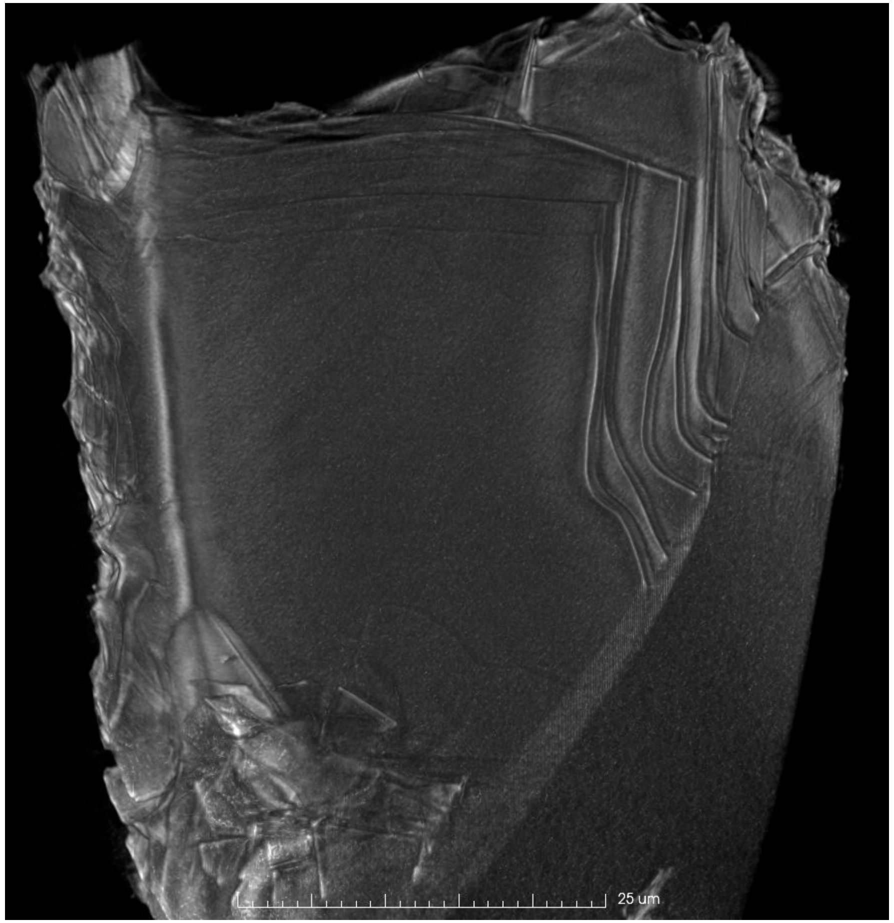


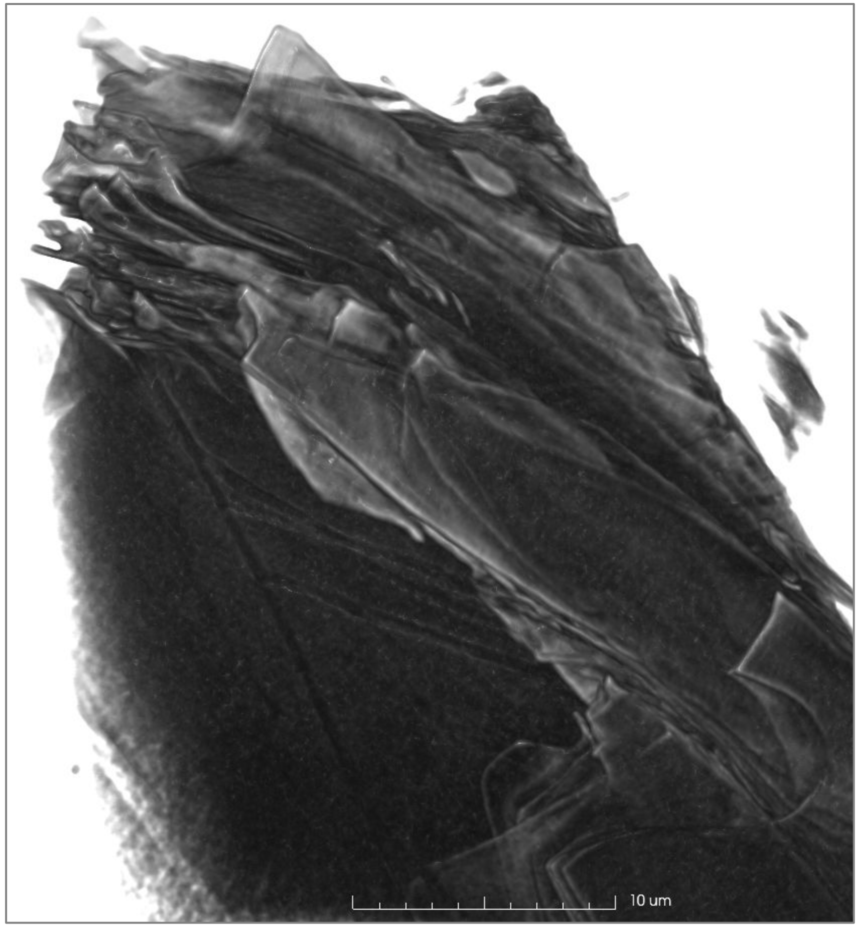






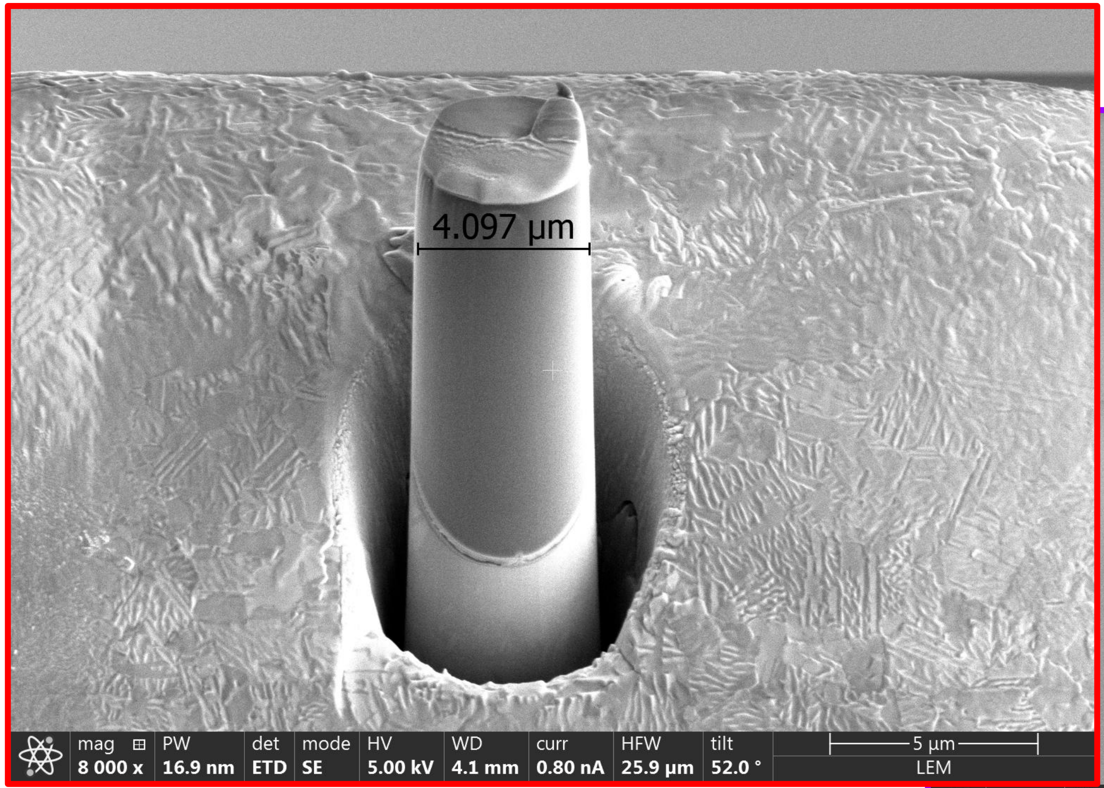
Mineral & Track Imaging - nanoCT

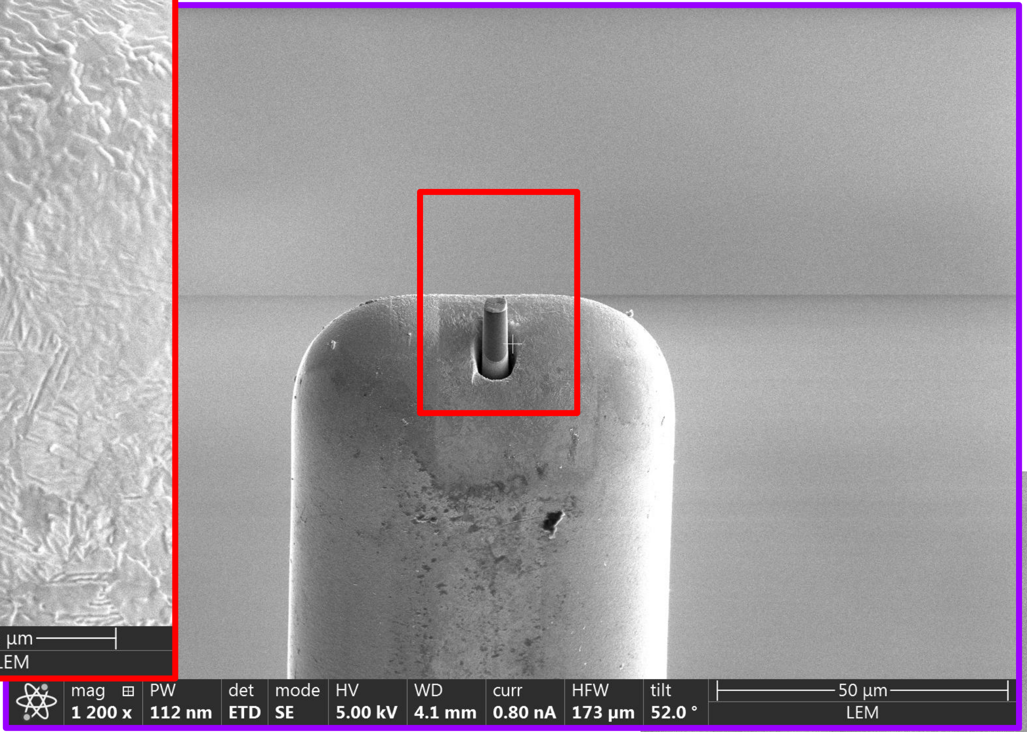


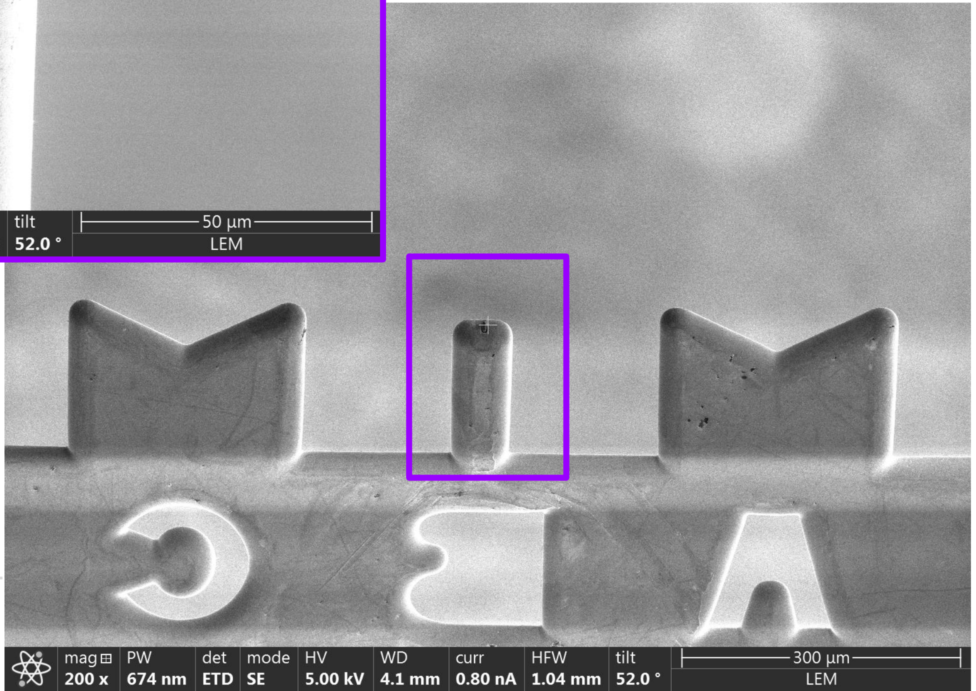


- ❖ Imaging < 1 µm features in crudely prepared Muscovite samples - can definitely improve
- ❖ Preliminary results are interesting & promising

Imaging - Electron Microscopy/FIB

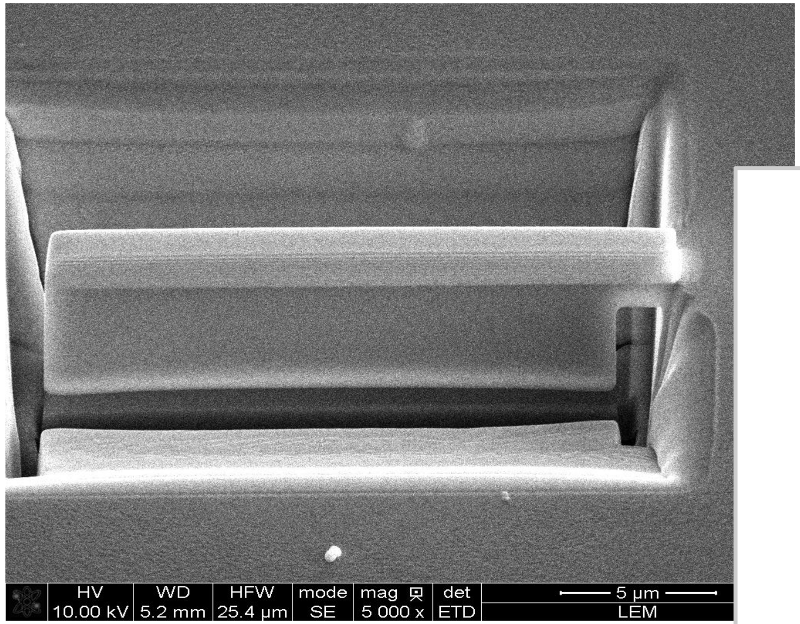


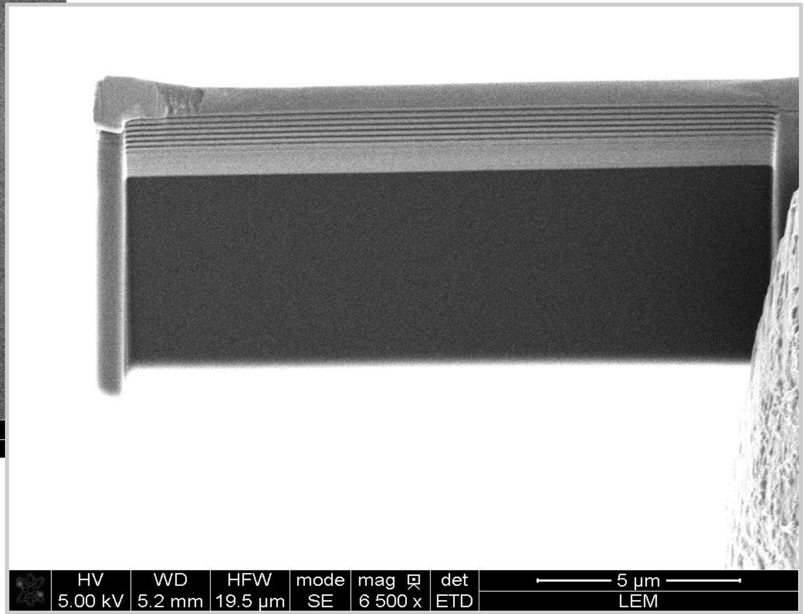


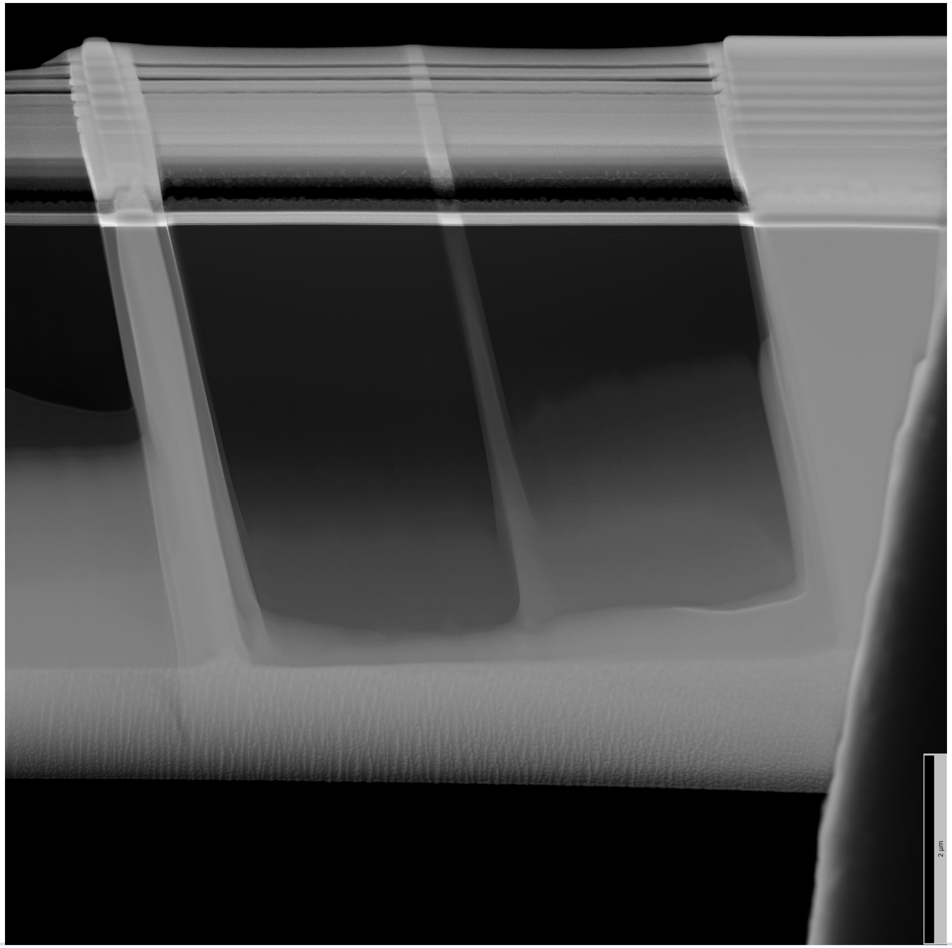


❖ Sub-sample cutting/preparation for nanoCT imaging

Mineral & Track Imaging - TEM







First calibration studies

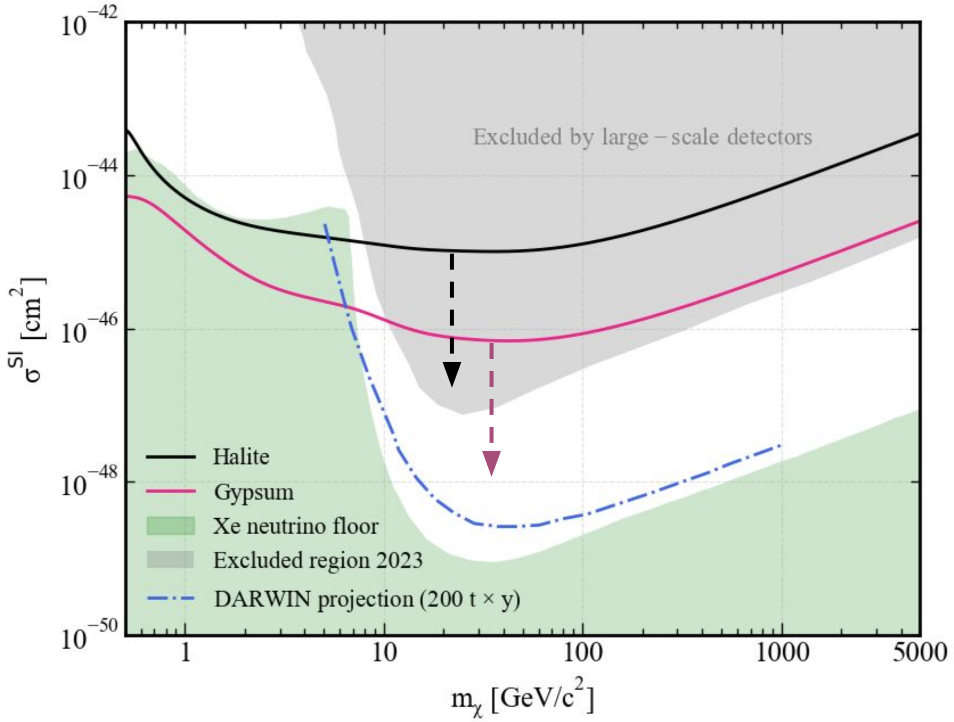
- Cutting out a lamella from a sample crystal & thinning to ~80 nm
- Image with TEM
- ~3 nm per pixel
- Challenging to image non conductive samples

Summary - Challenging Project

- **Suitable minerals** - not only theoretically
  - Sensitivity, attainable, chemistry, backgrounds, etc…
- **Geology** - tracks survival over Myr-Gyr?
- **Readout** & imaging techniques (< 10 nm resolution)
- **Data acquisition** & processing (~ mg samples)
- **Data analysis** - ML techniques

… It is worth it!

Mineral-detectors may compete with large-scale experiments



Projected WIMP Dark Matter discovery reach. The grey region is excluded by modern experiments while the green region is the so-called neutrino floor (neutrino expectation) for xenon-based detectors. Used : https://github.com/sbaum90/paleoSens

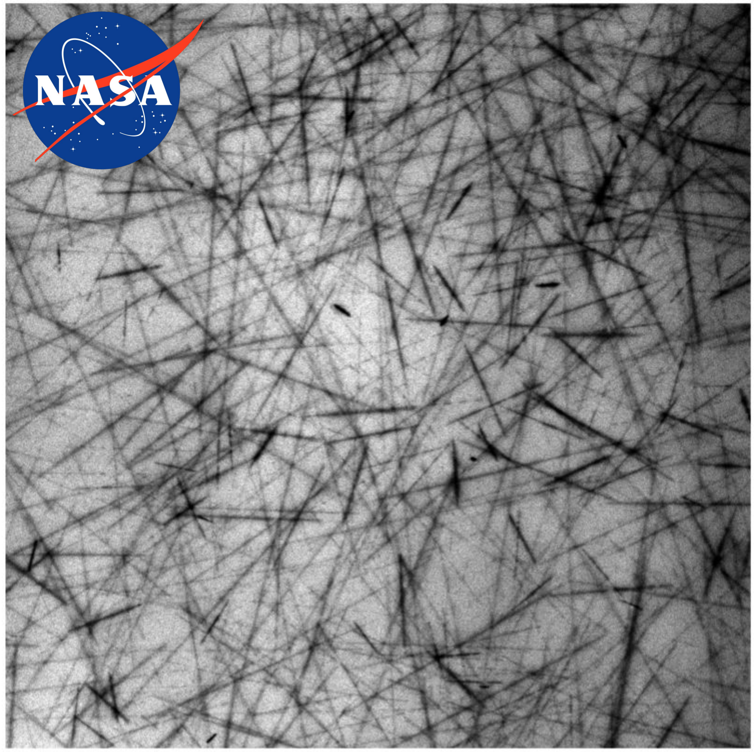
Summary - Paleo-detectors

Breakthrough potential for Dark Matter & Neutrino physics

- ❖ **Paleo-detectors** - ancient minerals store information about nuclear recoils
  - ➢ Myr/Gyr exposure - probe of DM, ν, cosmic rays
- ❖ Applications for "**mundane**" neutron/neutrino detection & more!
- ❖ Nuclear recoils down to 0.1 - 1 keV

Growing community & interest around the world

- ❖ **Interdisciplinary:** microscopy, geology, physics, ML & more
- ❖ **If you're interested in mineral-based detectors - contact us!**



A brightfield TEM image from a thin section of an olivine grain from lunar soil 71501.

The experiment was already conducted by nature,
we just need to read out the data!

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