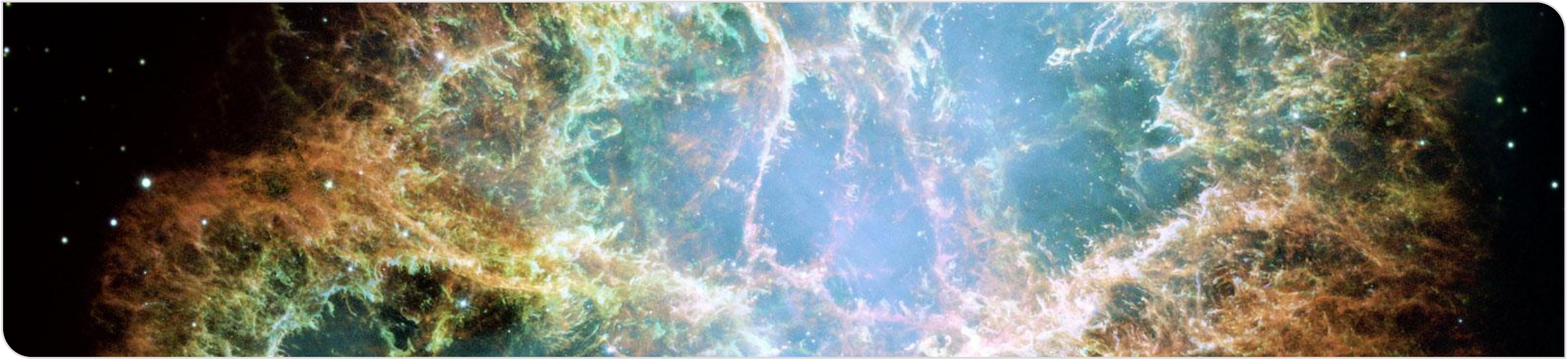
Karlsruhe Institute of Technology

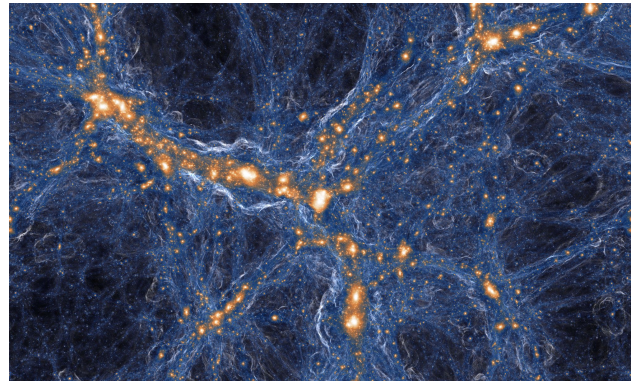
# Dark Matter & Neutrinos under the Microscope

***Alexey Elykov***

*Institute for Astroparticle Physics (IAP)*



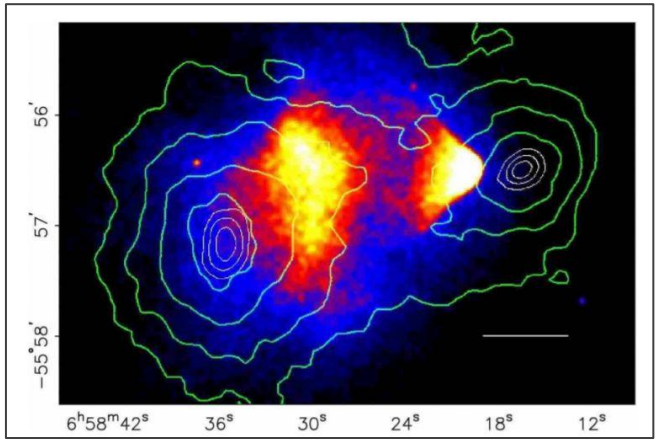
# Dark Matter



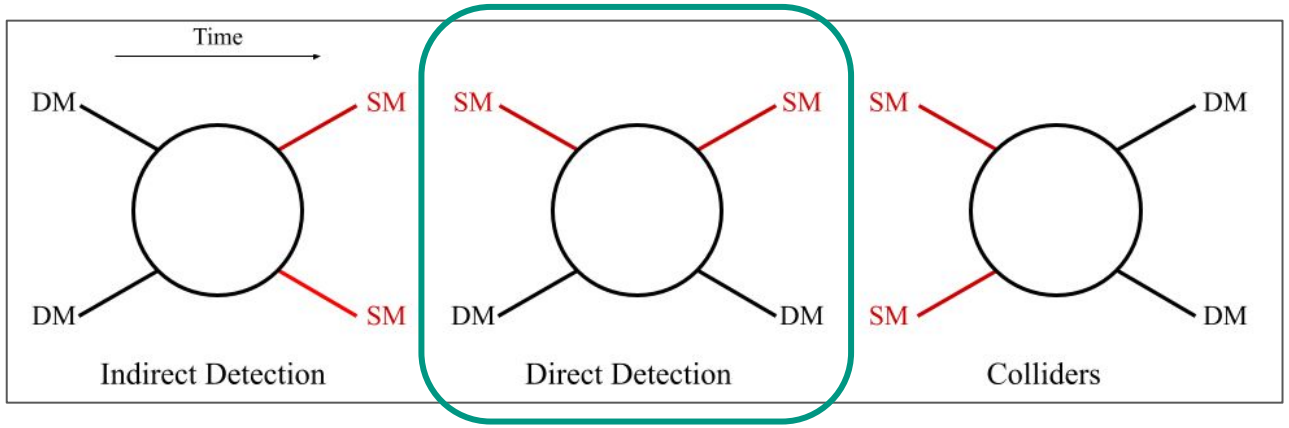
**Dark Matter**: ~ 85% of all matter in the Universe, unknown nature

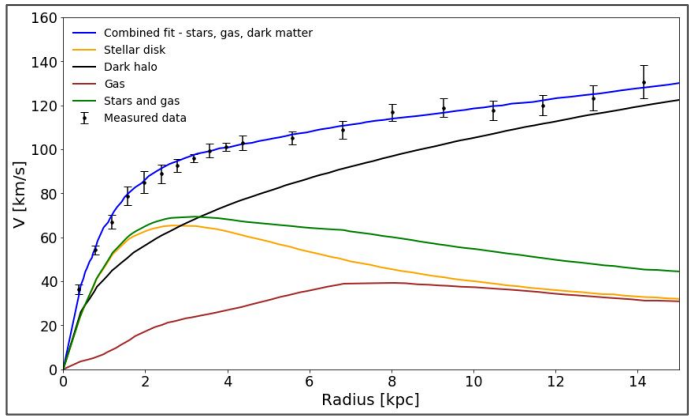
**Dark Matter candidates:**

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



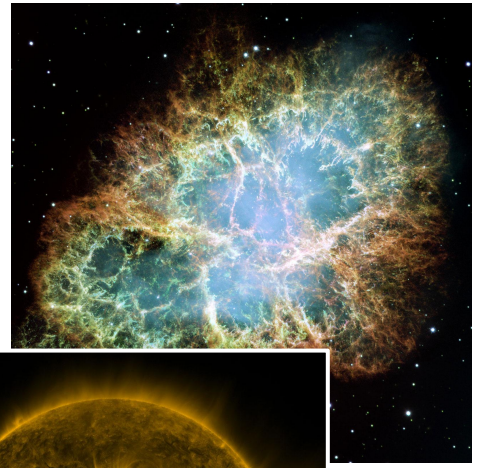

**Paths for Dark Matter detection**

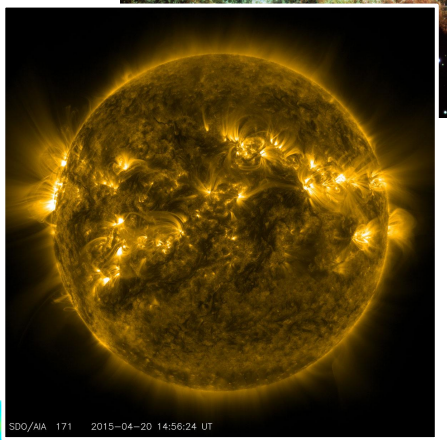


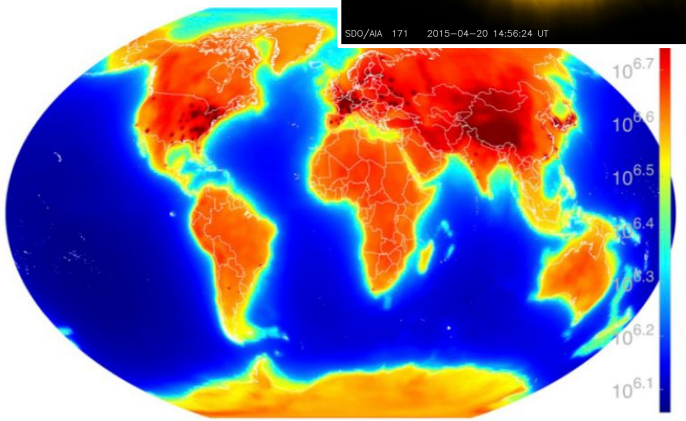



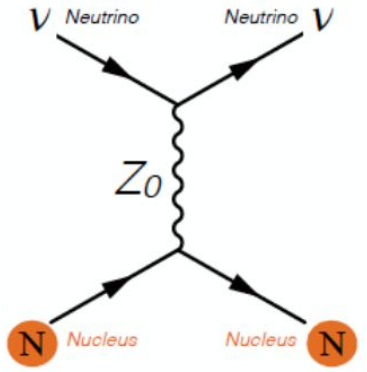
# Neutrinos

- 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

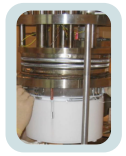
# Dark Matter & Neutrinos - Detection

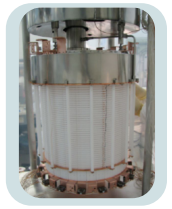
XENON dark matter direct detection experiments
at Laboratori Nazionali del Gran Sasso (LNGS)

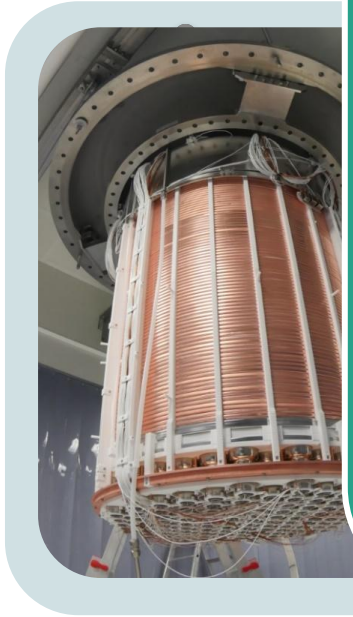
Growing **bigger** & more **sensitive**

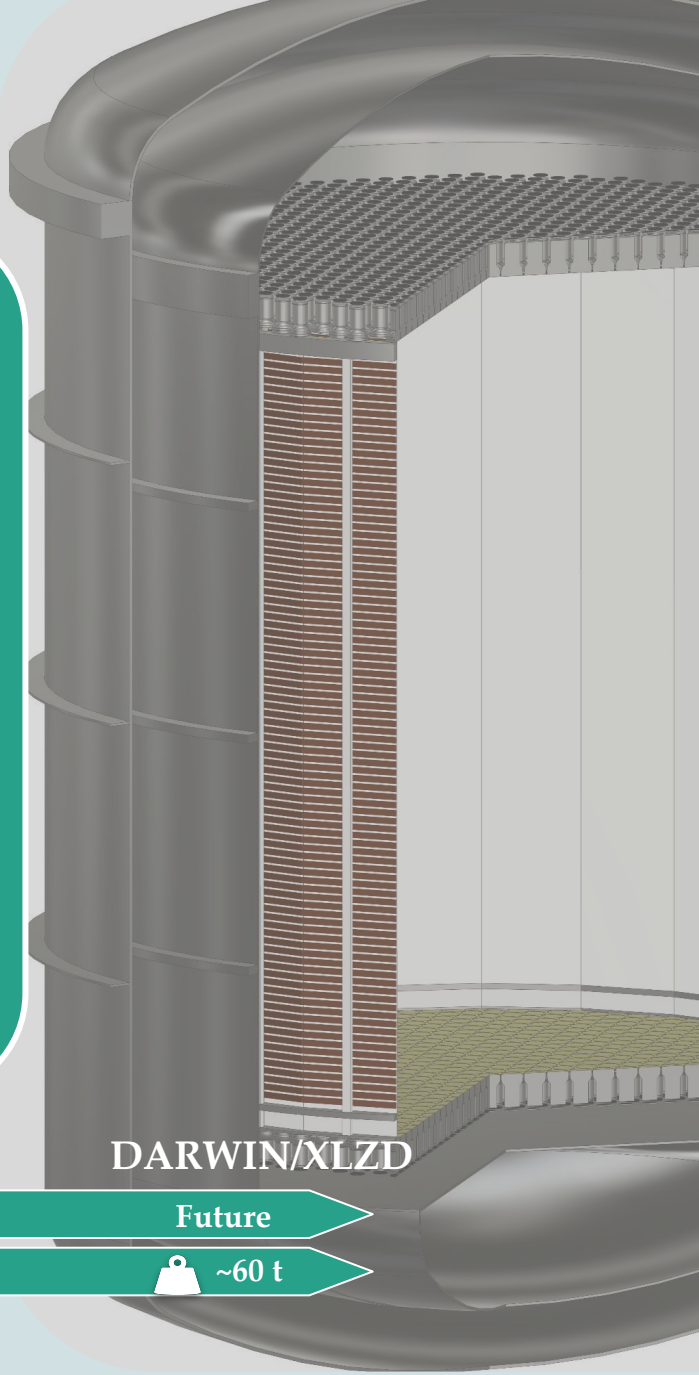
XENON

DARWIN





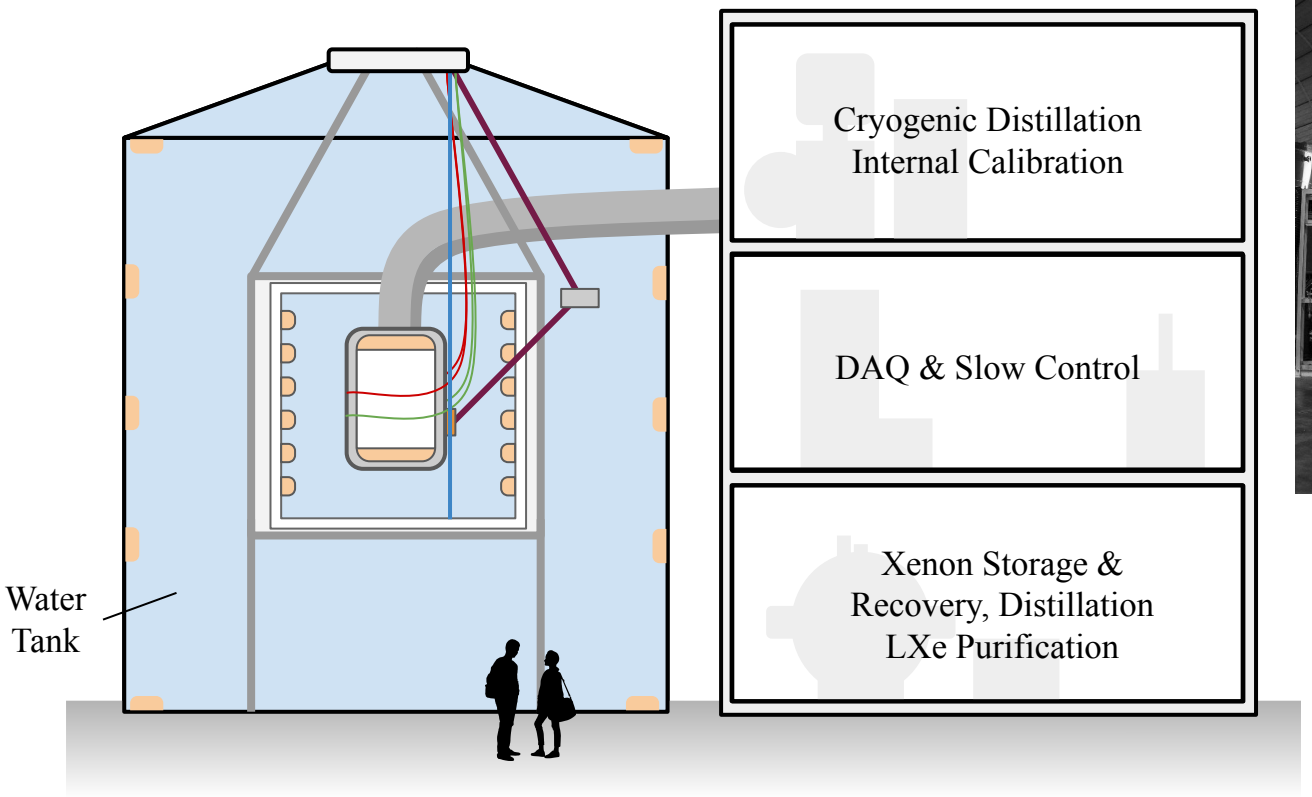




| XENON10 | XENON100 | XENON1T | XENONnT | DARWIN/XLZD |
|---|---|---|---|---|
| 2005 - 2007 | 2008 - 2016 | 2016 - 2019 | 2020 - Now | Future |
| 15 kg | 161 kg | 3.2 t | 8.5 t | ~60 t |

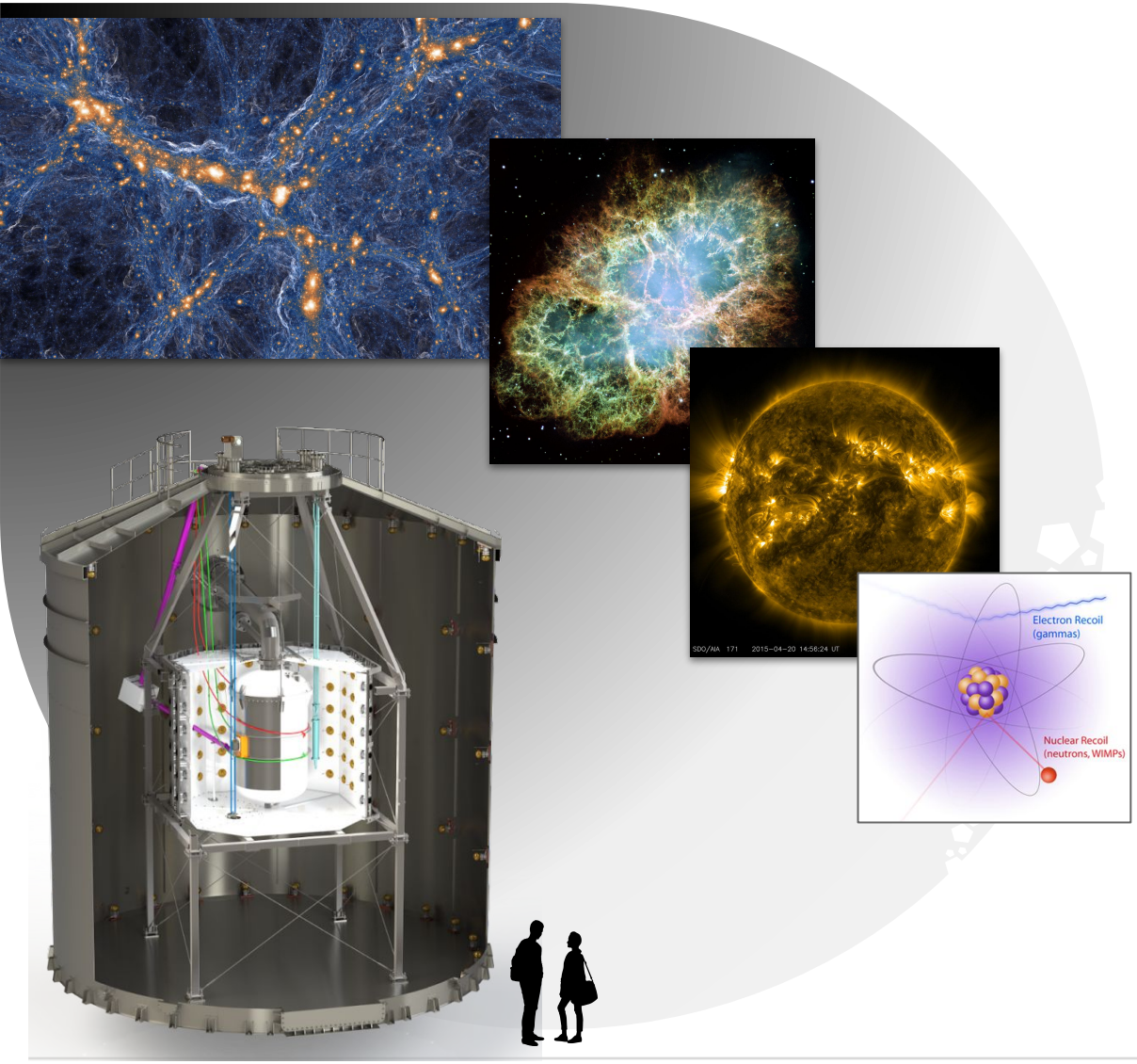
# Dark Matter & Neutrinos - Detection

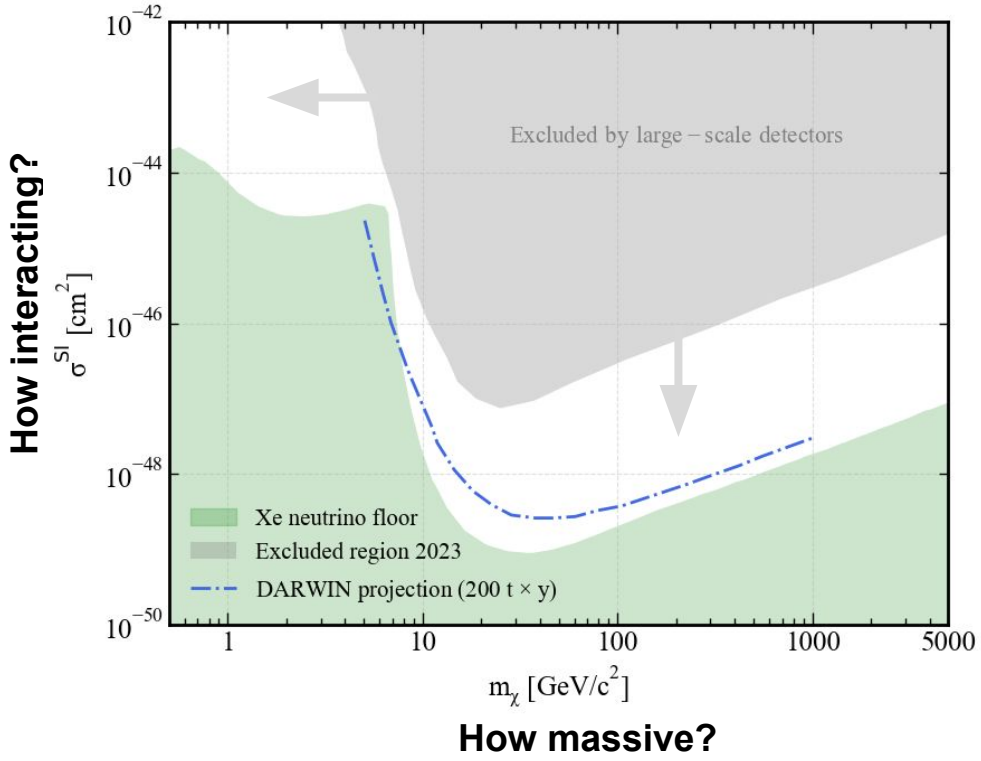
Located at Laboratori Nazionali del Gran Sasso, Italy
~1500 m rock overburden (3600 m.w.e.)




12 countries
27 institutions
170+ scientists

# Dark Matter & Neutrinos - Detection

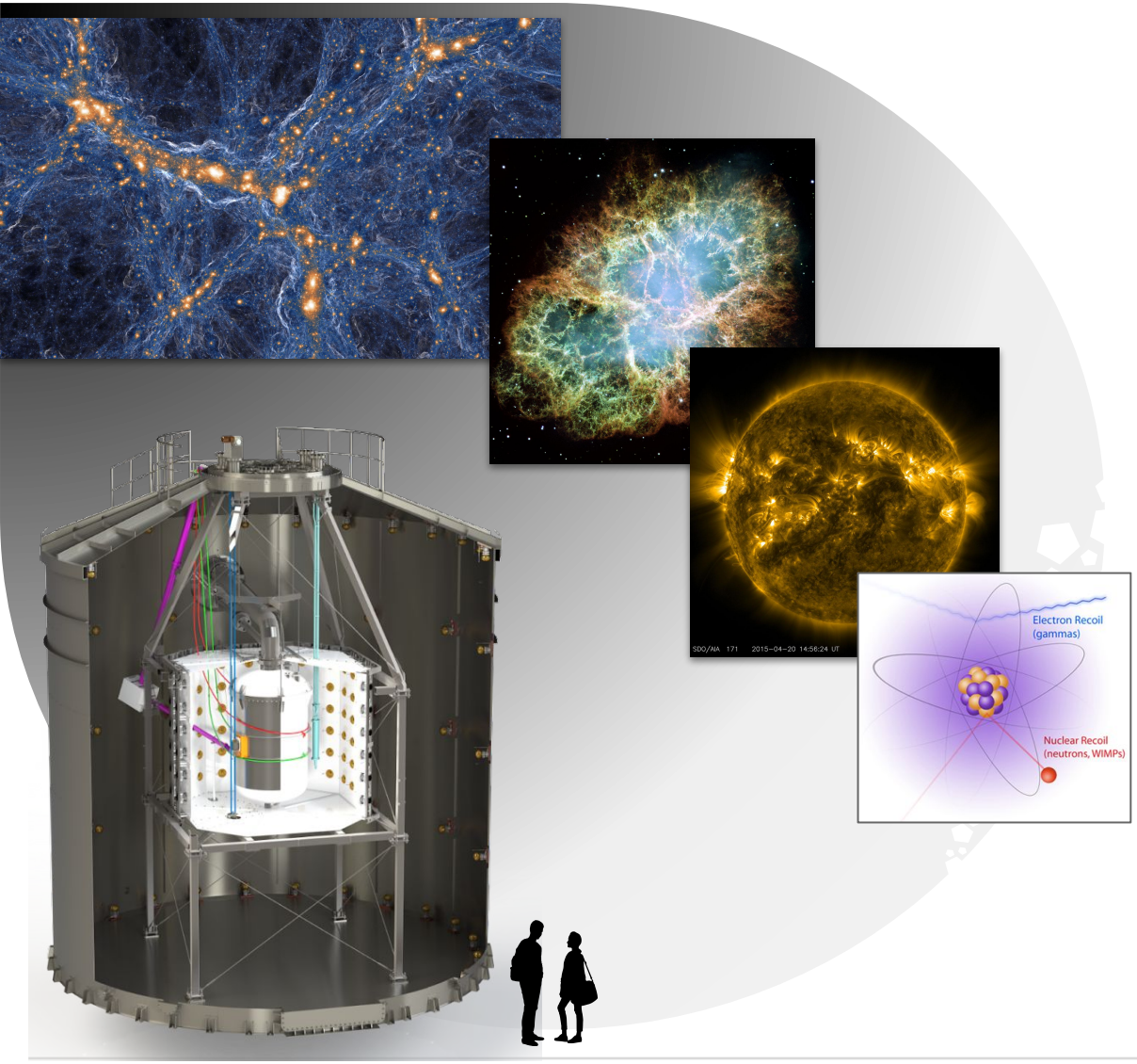


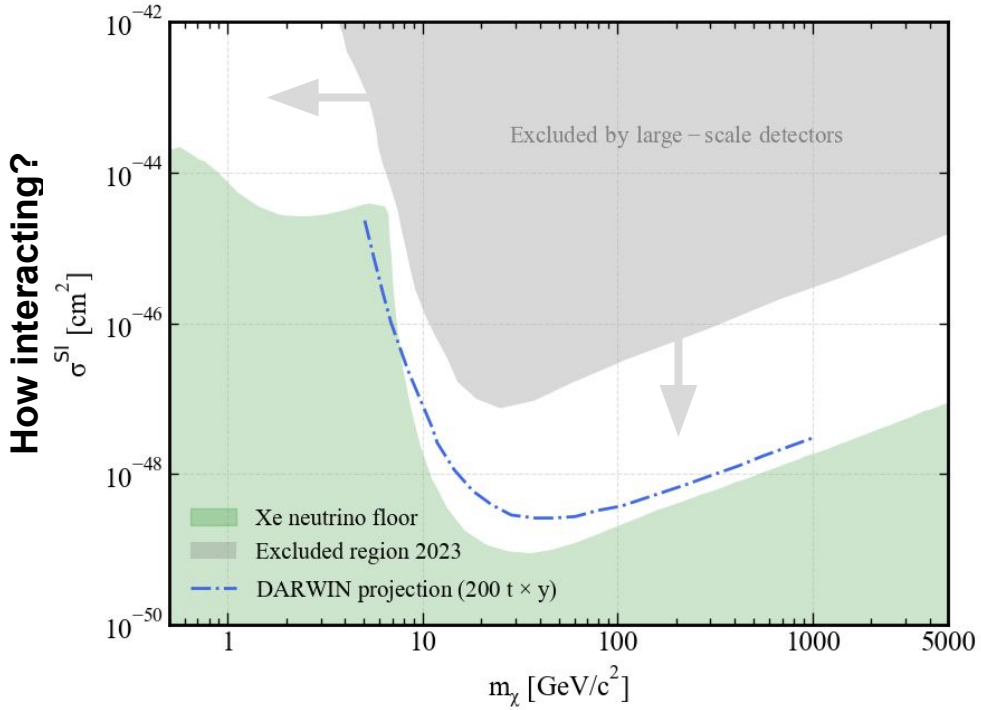



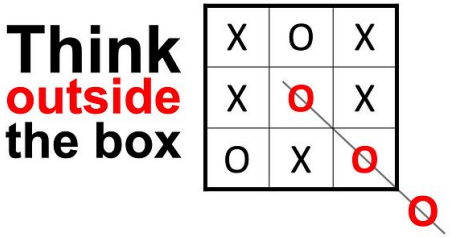

**Dark Matter still eludes detection &**

**we are still puzzled by the nature of neutrinos!**

# Dark Matter & Neutrinos - Detection



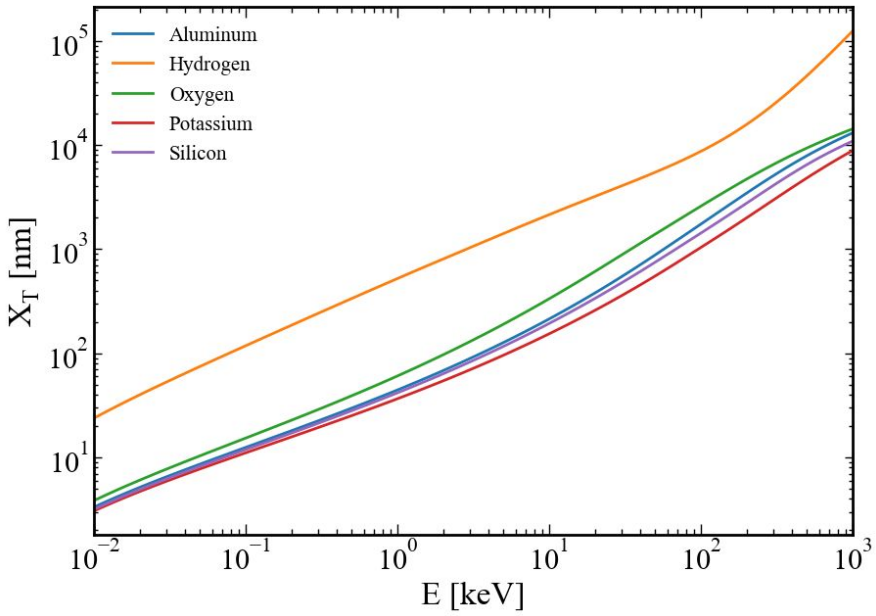



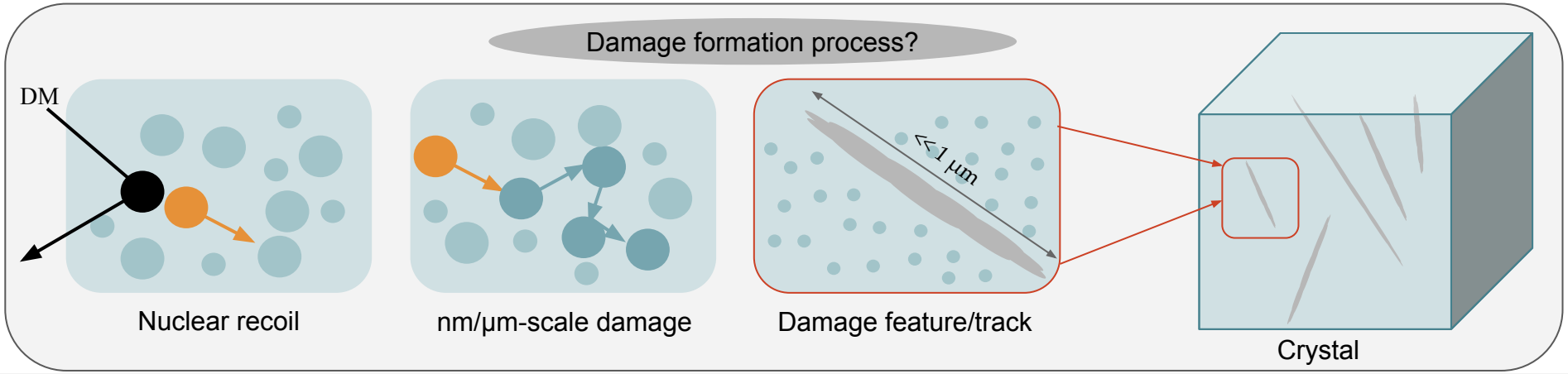



# Track & Damage Features Formation

- **Energy loss in solid materials due to :**
  - Electronic stopping (off electron clouds)
  - Nuclear stopping (off nuclei)
  - Nuclear recoils down to 0.1 - 1 keV

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



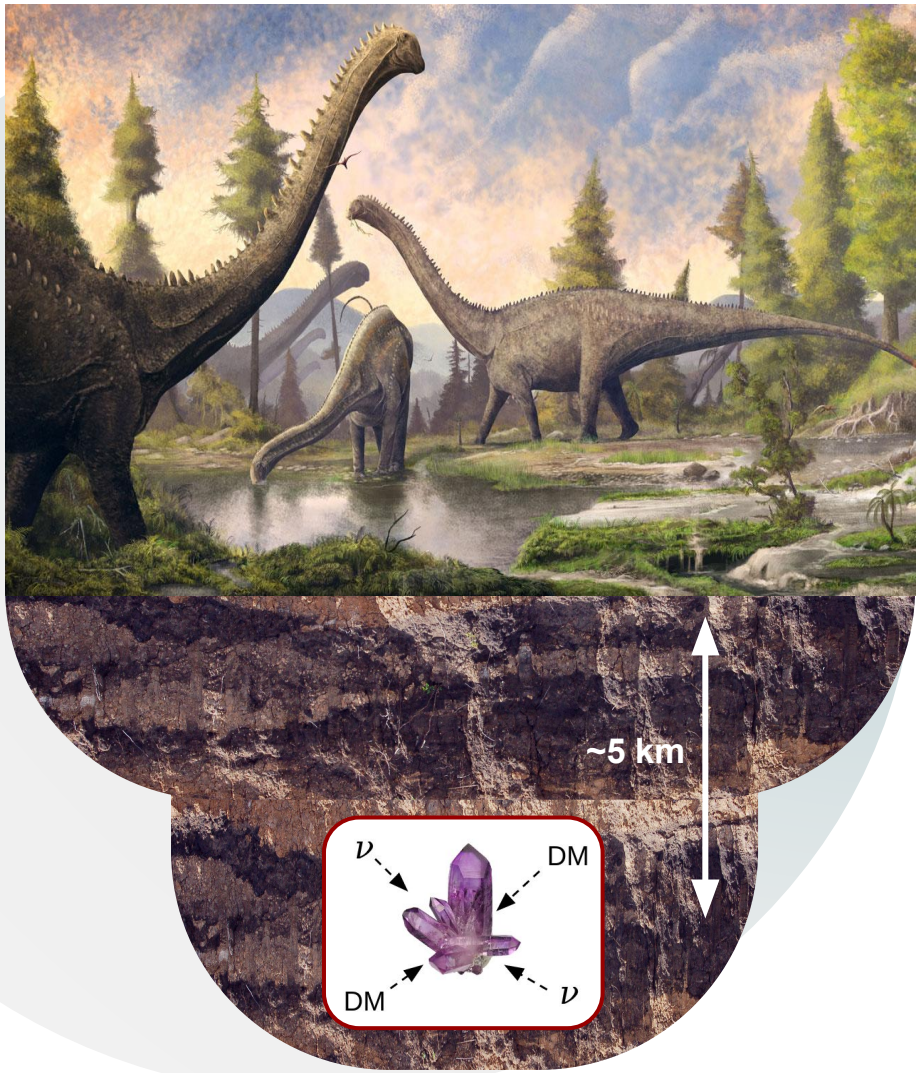



# Ancient Natural Crystals - Paleo-Detectors

**Ancient minerals - look into the past**

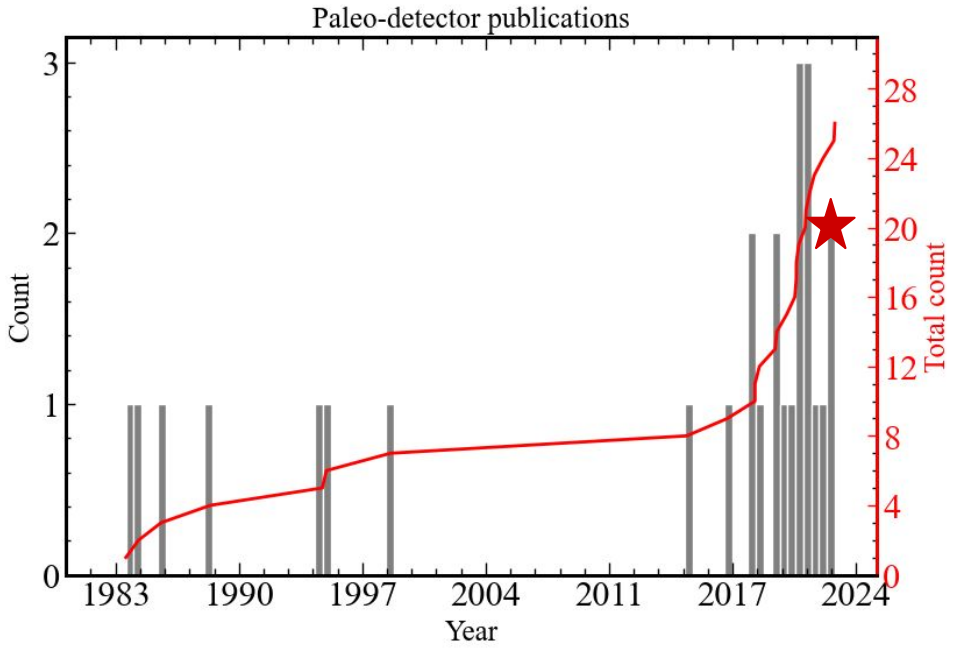
- Natural minerals - good SSNTDs
- **Tracks** - nuclear recoils induced by Dark Matter & Neutrinos
- Preserve tracks for Myr/Gyr
- Accessible, relatively cheap

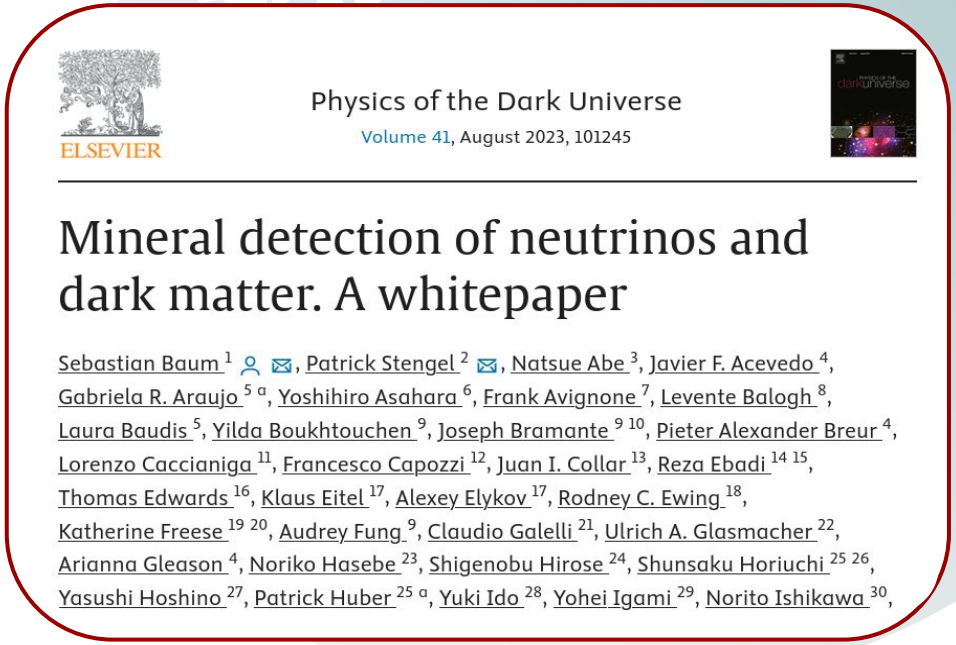
- **Small samples** but **Myr/Gyr exposure**
- **Neutrinos** - guaranteed signal/background



# Paleo-Detectors Now

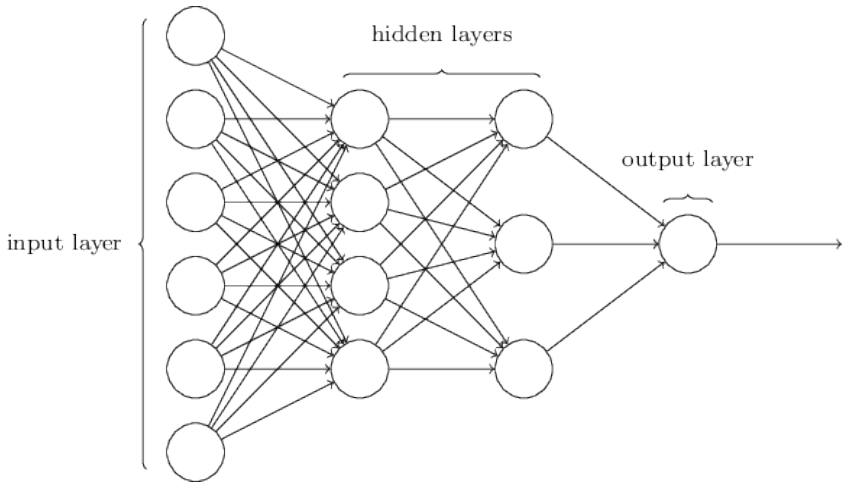
- **Worldwide interest - novel emerging research field**
- **Growing amount of publications in last ~ 5 yr**
- **White paper in "*Physics of the Dark Universe*" (editor's invitation)**
  - ➢ 67 authors, 46 institutions, 113 pages

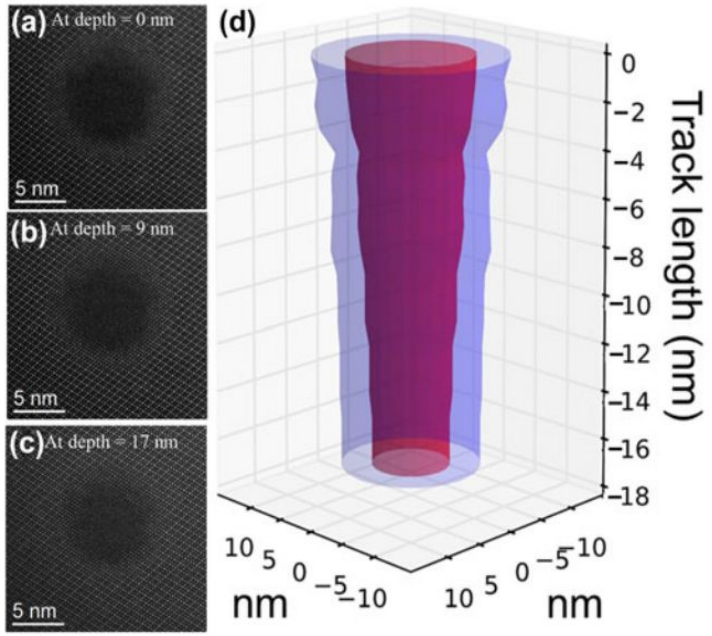


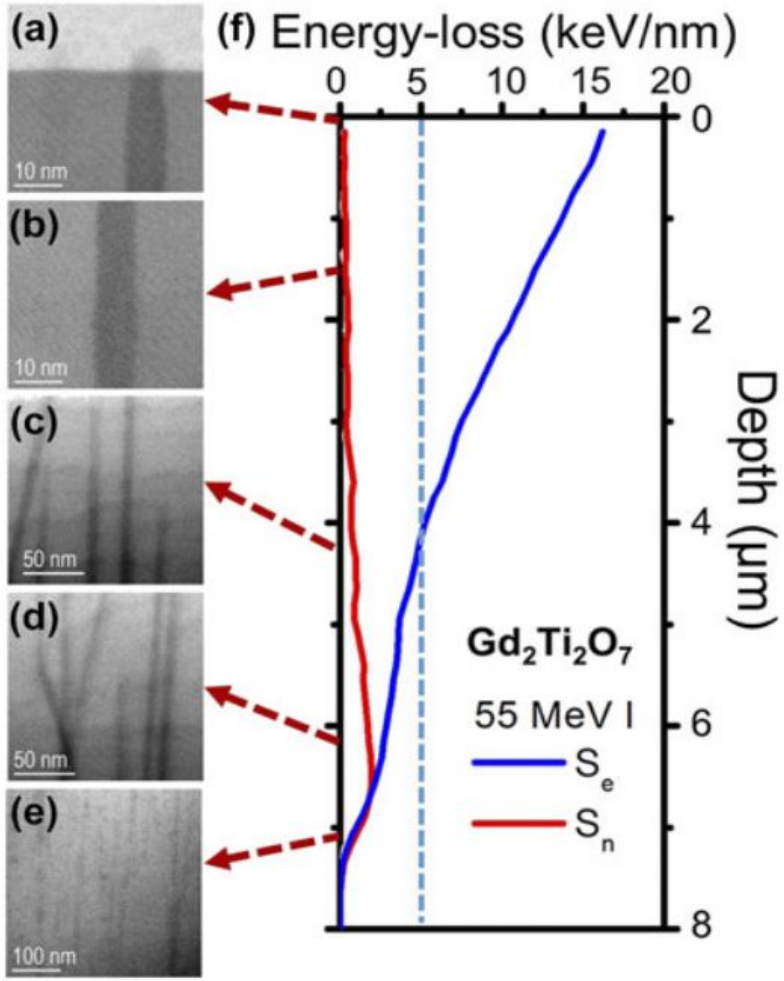
# Paleo-Detectors - Why Now?

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



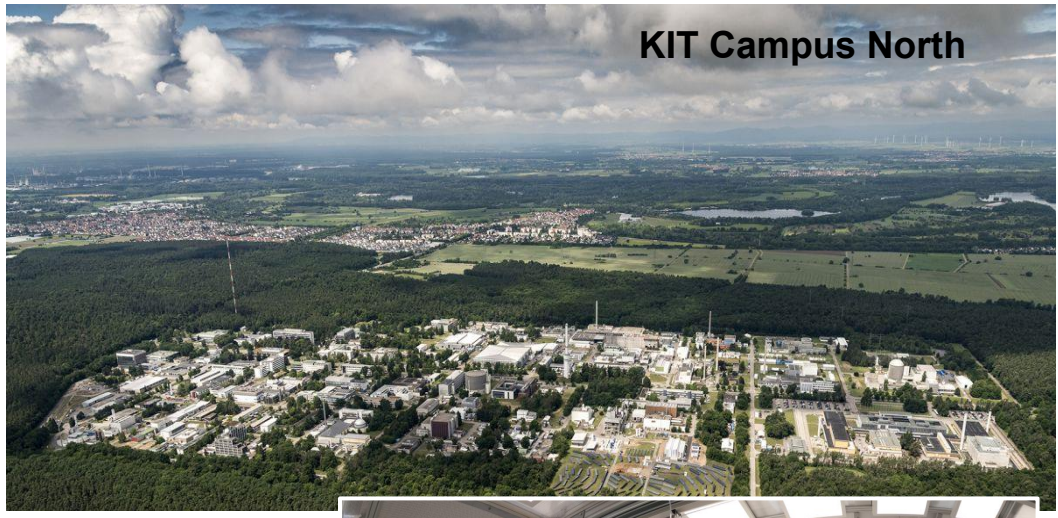




***2017:*** *STEM-HAADF images and reconstruction of an ion track. (DOI: 10.1557/jmr.2016.418)*




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

# Why at KIT?


KIT Campus North

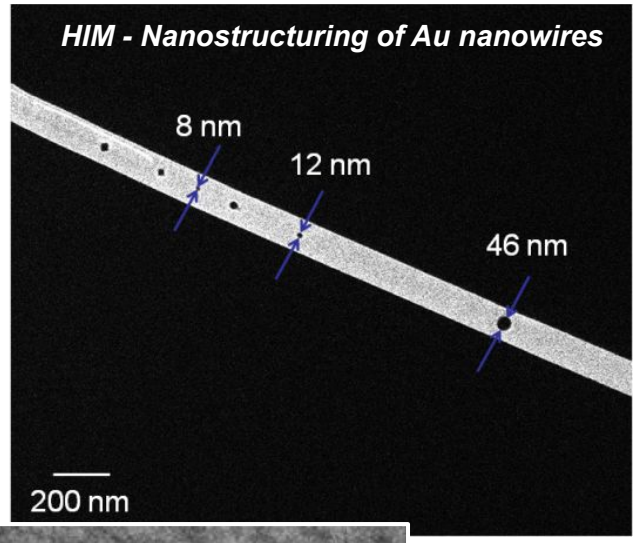
**Karlsruhe Institute of Technology (KIT)**

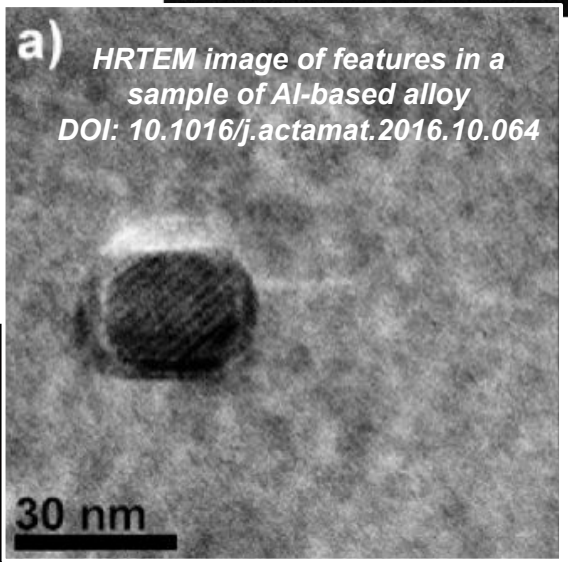
- **KIT is one of the major scientific research institutes in Europe**
  - ~9,500 scientific & other workers
  - ~24,000 students on various levels
- **Multiple Research Topics**
  - **Among others**: Energy, materials, information, geology …

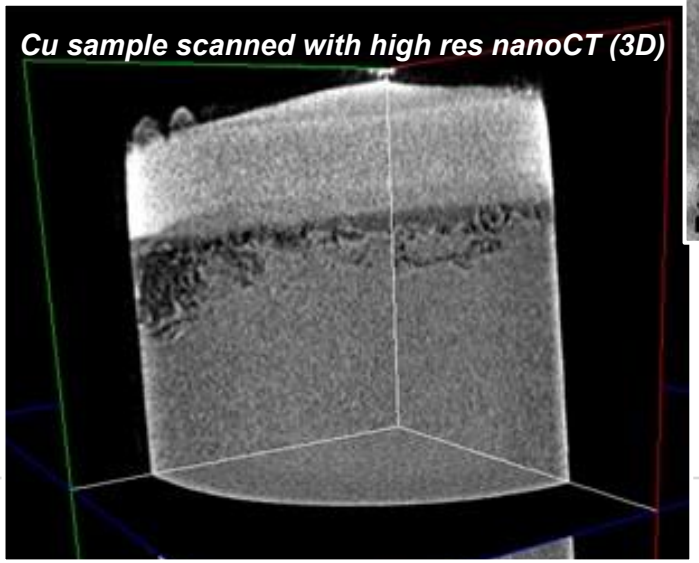
- **Particle & Astroparticle Physics**
  - Theoretical & experimental collider physics
  - Theoretical astroparticle physics
  - Pierre Auger Observatory, IceCube
  - XENONnT, KATRIN
  - Expertise in electronics, simulations, hardware R&D, data analysis & more …

# Why at KIT? - Microscopy

- **Unique combination of different microscopy facilities & expertise**
  - Cutting edge nm-scale & µm-scale microscopy
  - **Helium Ion Microscopy - HIM**
    - Resolution: ≤ 0.35 nm
    - FoV: 900 µm - 100 nm
  - **Transmission Electron Microscopy (TEM)**
    - Resolution: << 1 nm
  - **nanoCT (3D)**
    - X-ray energy: 5.4 keV
    - FoV: 16 µm (HRES), 65 µm (LRES)
    - Resolution: 50 - 100 nm
    - Non-destructive

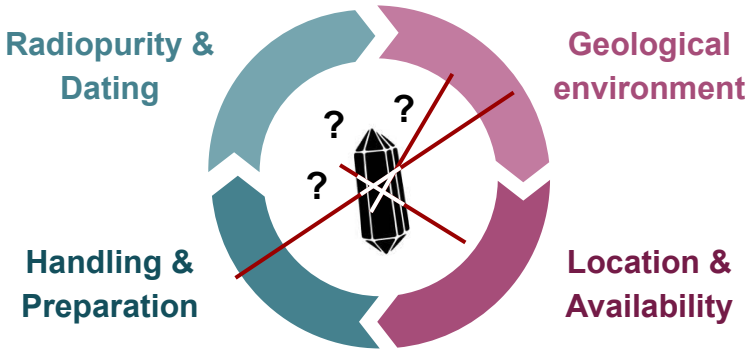


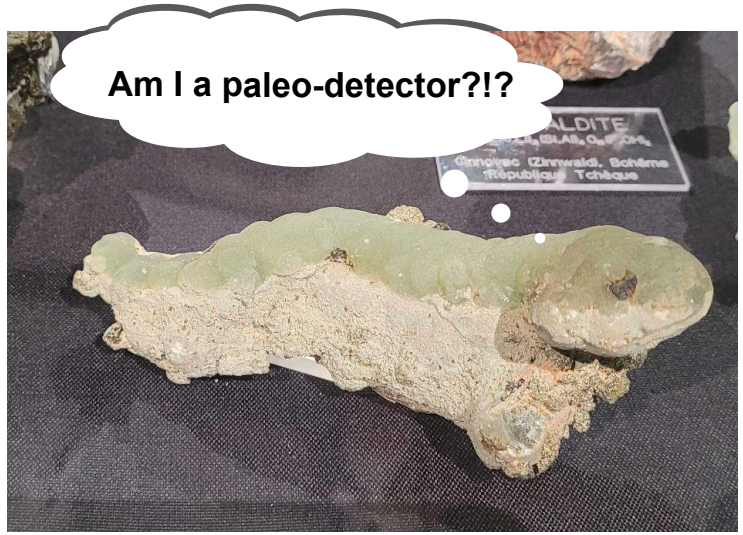




**Many other microscopy facilities …**

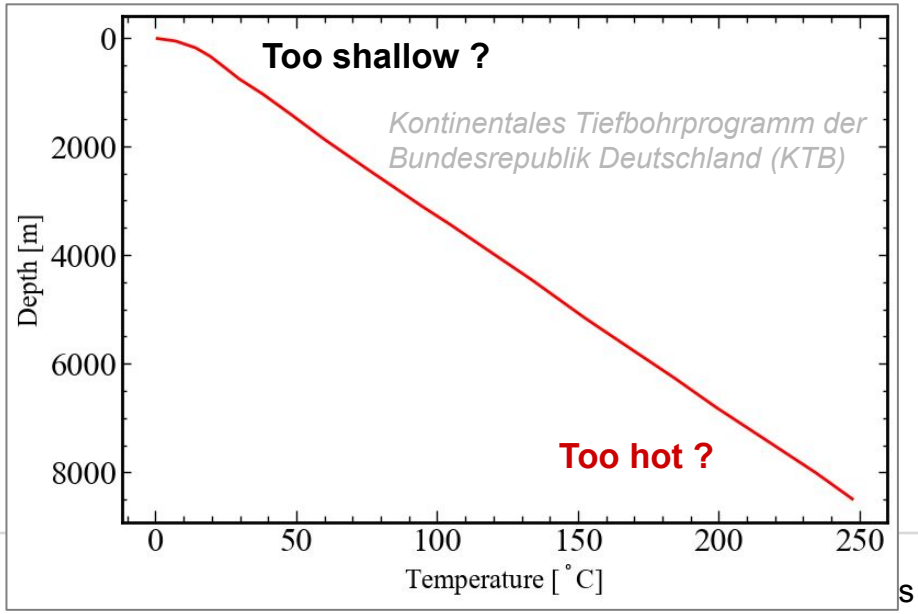
# Why at KIT? - Geology




- **KIT Institute of Applied Geosciences**
  - ➢ Expertise in geochemistry
  - ➢ LA-ICP-MS analysis
- **Cooperation with geologists from Heidelberg University**

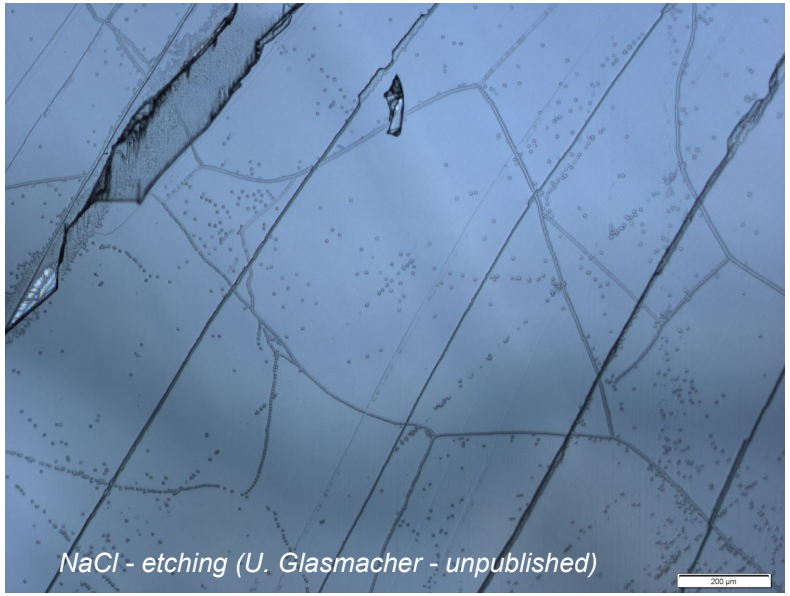
**Want to tie the different aspects together…**



# 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*"



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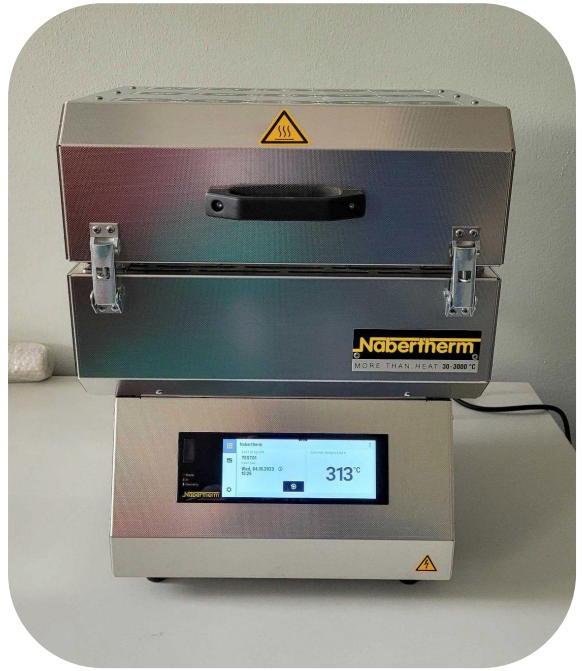
**From 2023 - onward:**

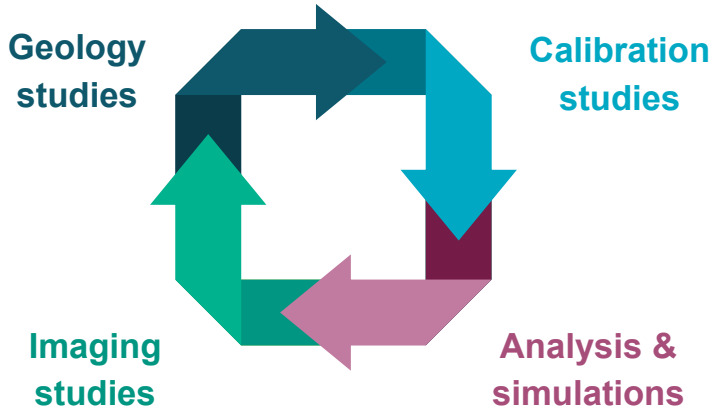
- Strong support by KIT IAP for a long-term Paleo-Detectors project
- KCETA - Seed funding for preliminary studies
- Establishing small-scale lab for paleo-detector studies
- **Experimental feasibility studies**

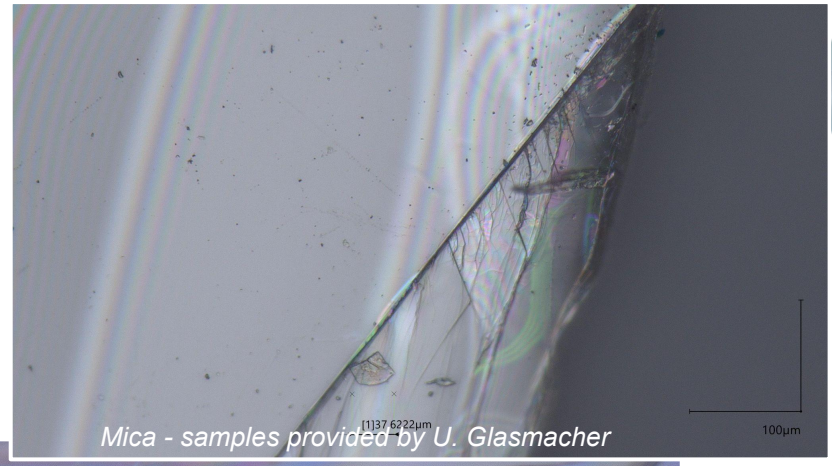


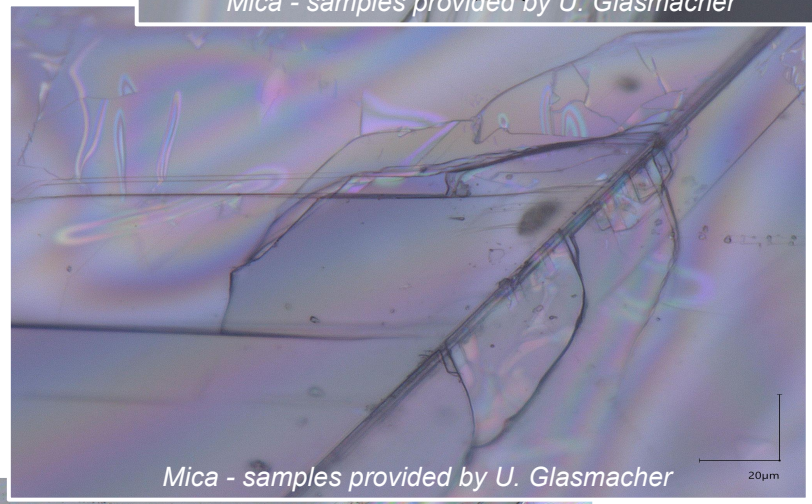
# Paleo-Detectors at KIT

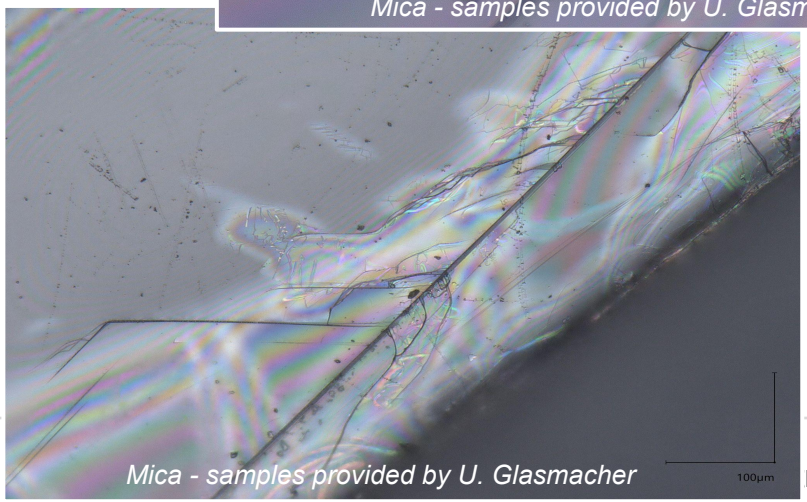
- **GOAL I:** Establish technology for track imaging & analysis in selected minerals
- **GOAL II:** Establish a realistic list of paleo-detector candidate minerals
- **GOAL III:** Deepen cooperation with microscopy & geology experts

- Cooperating with microscopy experts from KIT & geologists from Heidelberg



# Paleo-Detectors at KIT

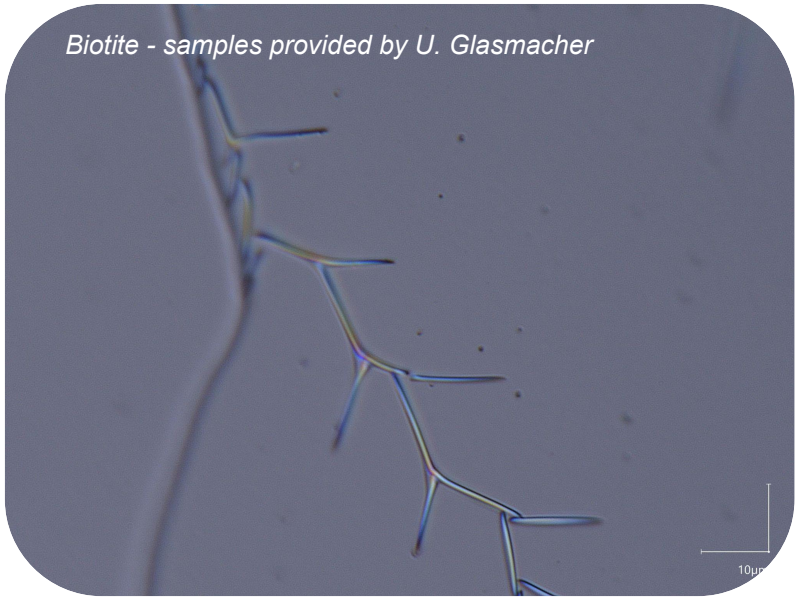
1. **Mineral Selection & Preparation**
   - ➢ Range of minerals - sensitivity predictions, input from geology, microscopy
   - ➢ Muscovite (blank), Biotite (irradiated with Xe ions) - as a starting point

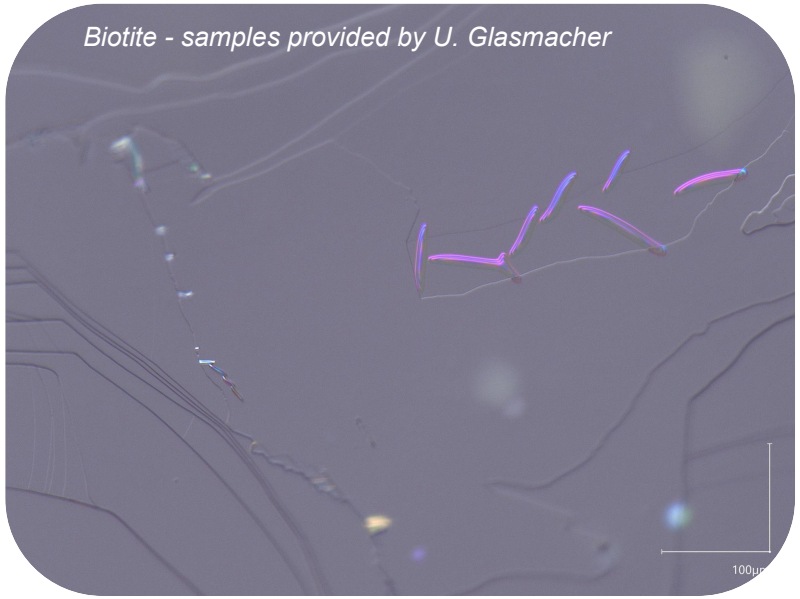
2. **Calibration - Track Production**
   - ➢ Local lab - anneal samples
   - ➢ $^{252}$Cf (n ~2.2 MeV), $^{241}$AmBe (n 2-10 MeV) - nm & µm-scale damage features

3. **Mineral & Track Imaging**

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

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



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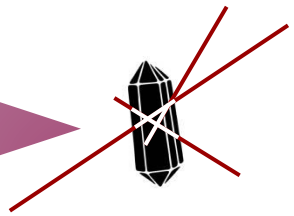
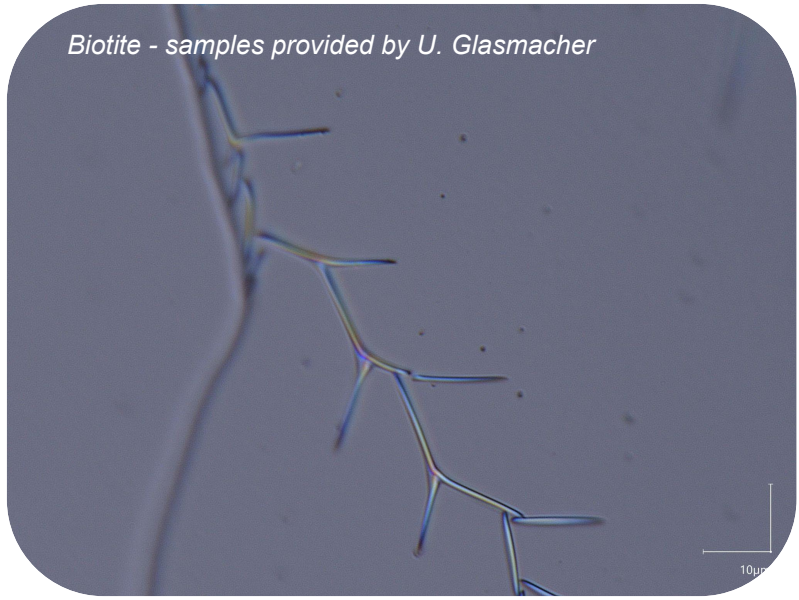
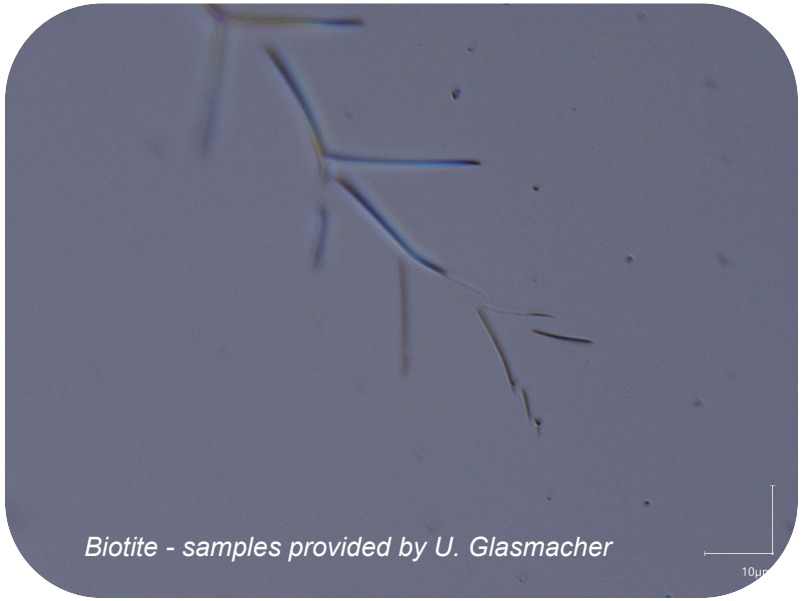
**Long-term Paleo-Detector program at KIT**

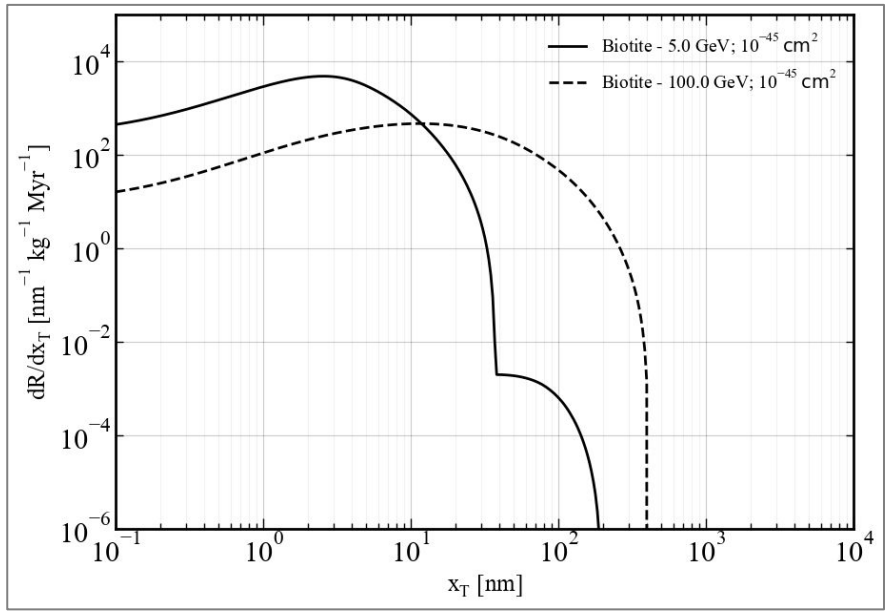




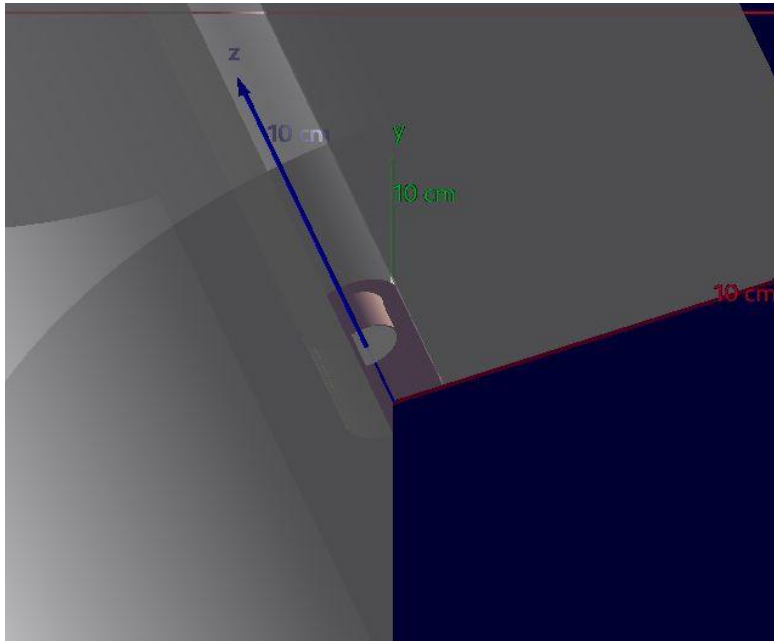



# Software & Simulations

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

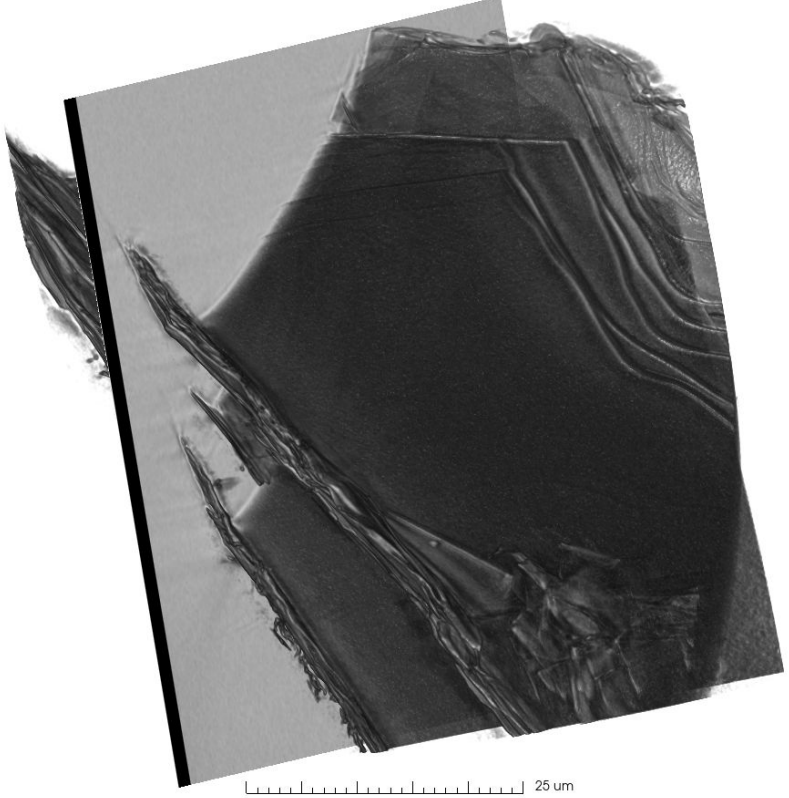


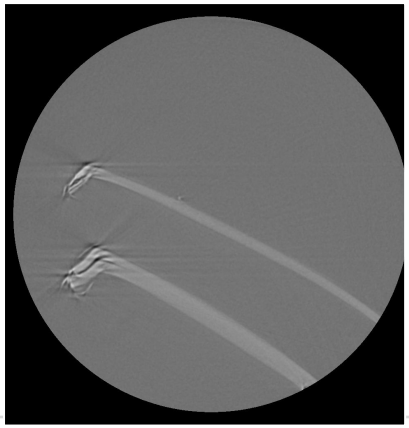

- **paleoSIM**
  - GEANT4 simulations
  - **Ongoing**: neutron irradiation studies using $^{252}$Cf, $^{241}$AmBe
  - **TODO**: Ion & n-induced track studies

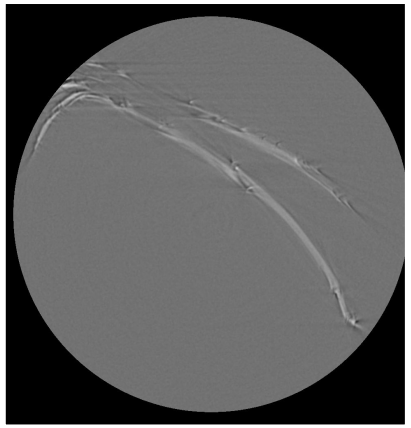


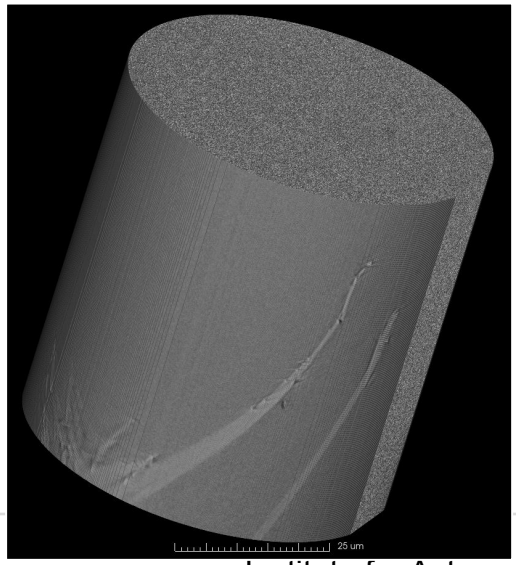
# Mineral Imaging - nanoCT

- **First calibration studies**
  - ➢ Devise best practices for preparing samples
- 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?

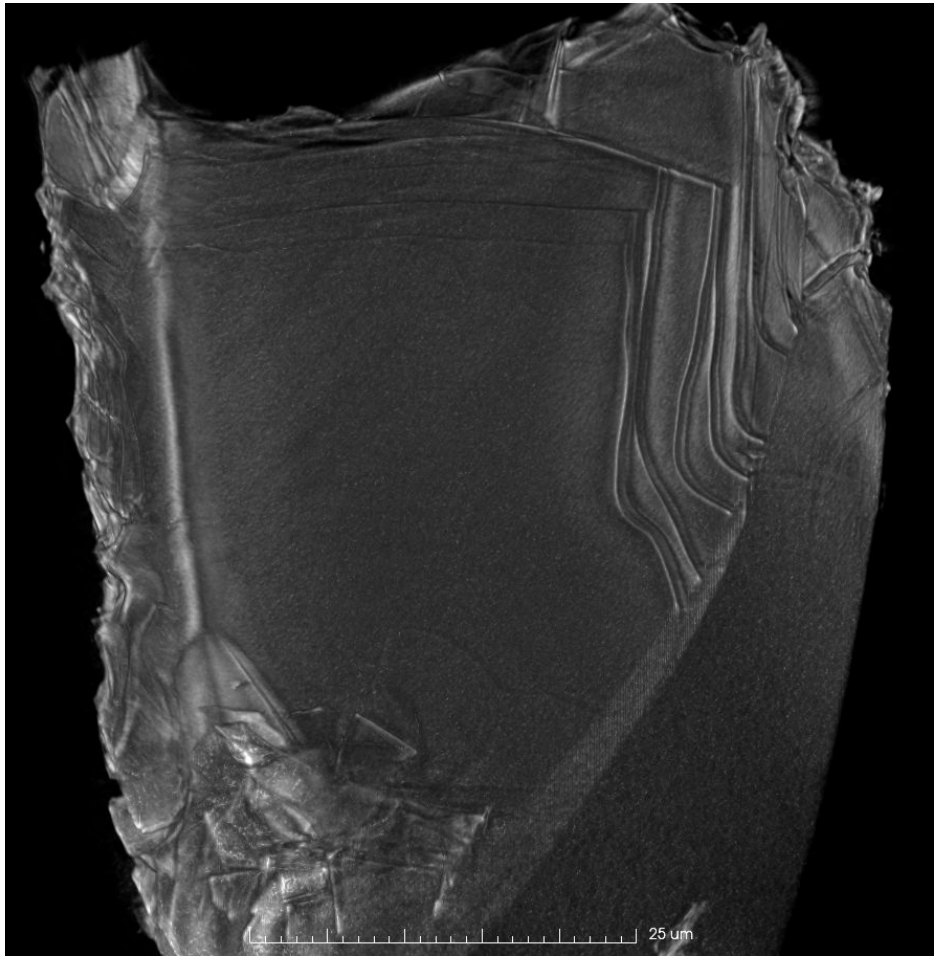


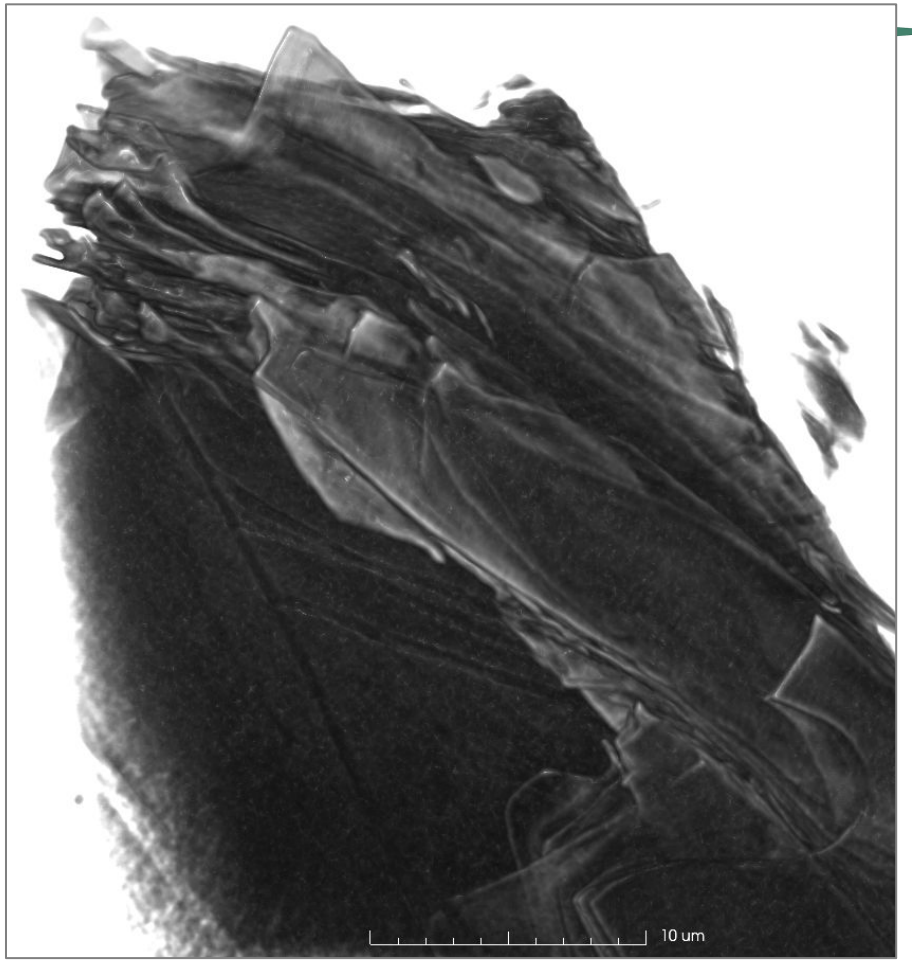







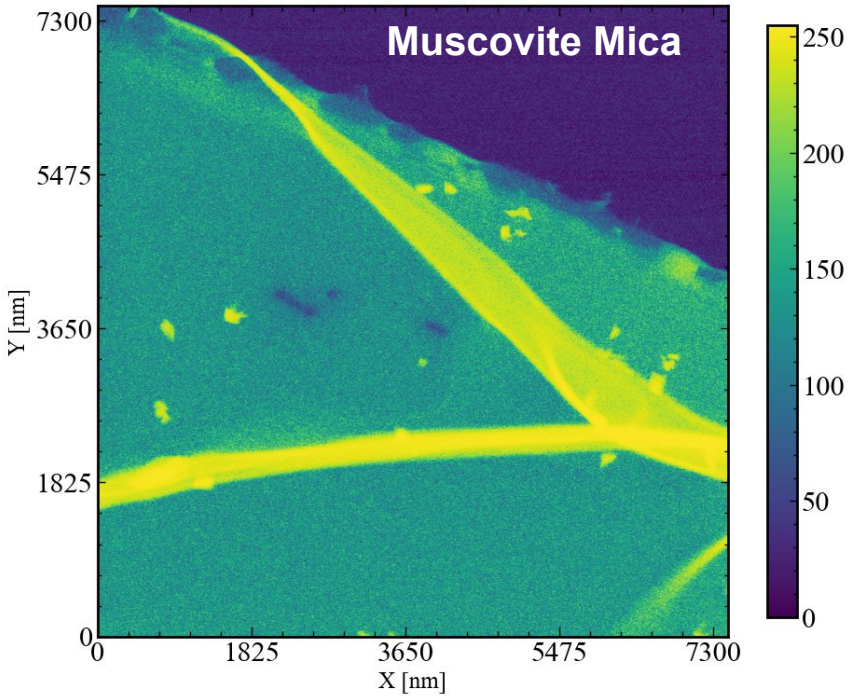
# Mineral Imaging - nanoCT

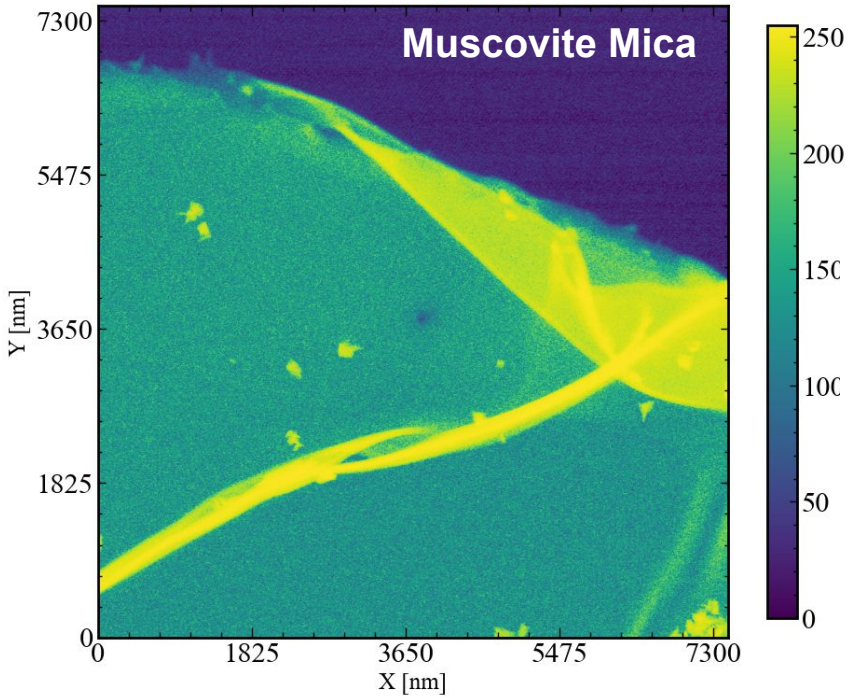


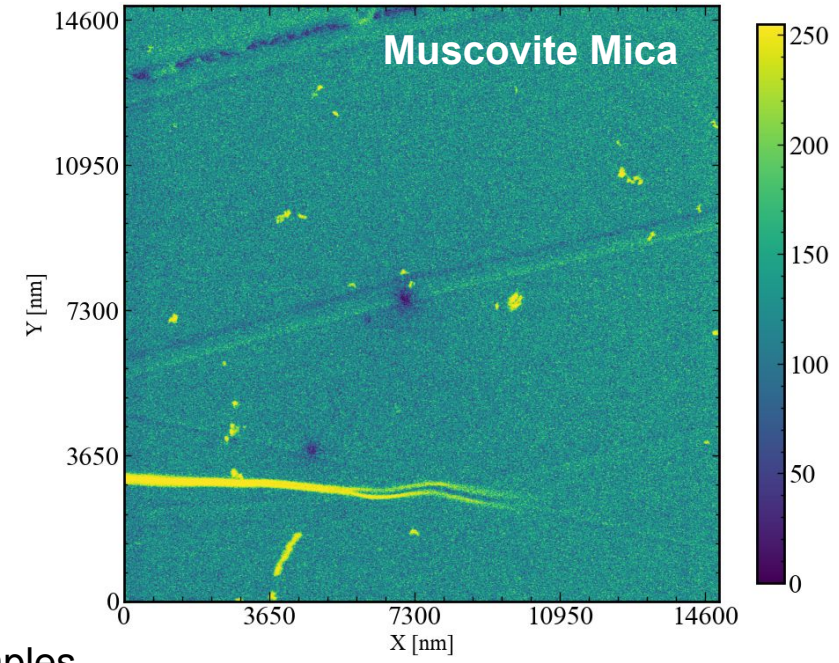




- Imaging < 1 μm features in crudely prepared Muscovite samples - can definitely improve
- Preliminary results are interesting & promising

# Mineral Imaging - TEM



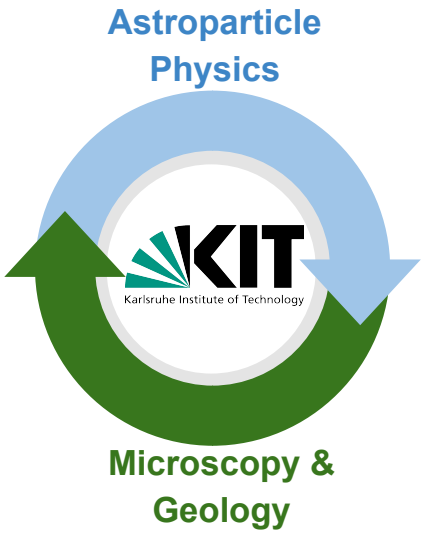




- **First calibration studies**
  - ~3 nm per pixel
  - Imaging non conductive samples
  - Sample preparation - mechanical cutting, FIB to create ~200 nm thick lamellae
- Prevent destructive effects from electrons
- After tests with “blank” Muscovite samples will move to Biotite & irradiated Muscovite samples

# Summary & Outlook

- **KIT - Unique combination of different facilities & expertise**
  - ➢ Perfect place for a mineral-based detector project

- Preliminary studies ongoing
  - ➢ Software development for analysis & calibration studies
  - ➢ Imaging studies with microscopy experts
  - ➢ Want to identify & test realistic mineral candidates
  - ➢ Only just crossed the starting line, but great potential!




- **Establishing a long-term Paleo-Detector program at KIT - contact us!**

*Hope to see you in the next MDvDM meeting & show you some results.*


*alexey.elykov@kit.edu, klaus.eitel@kit.edu*