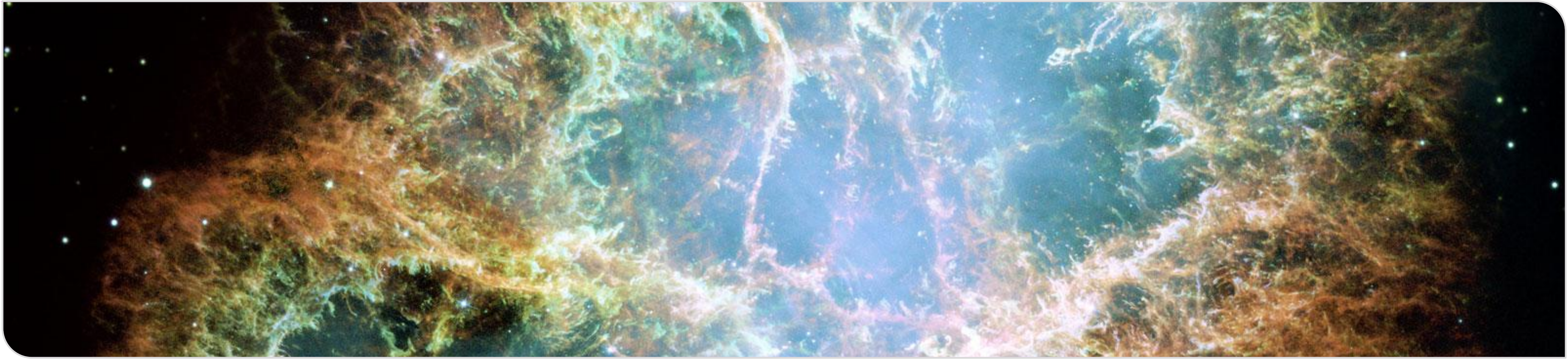
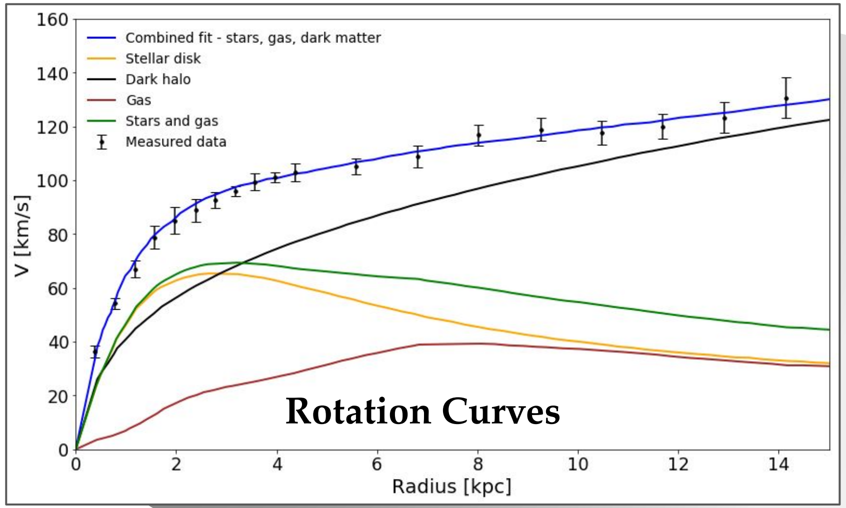
Karlsruhe Institute of Technology

Mineral Detection of Dark Matter and Neutrinos

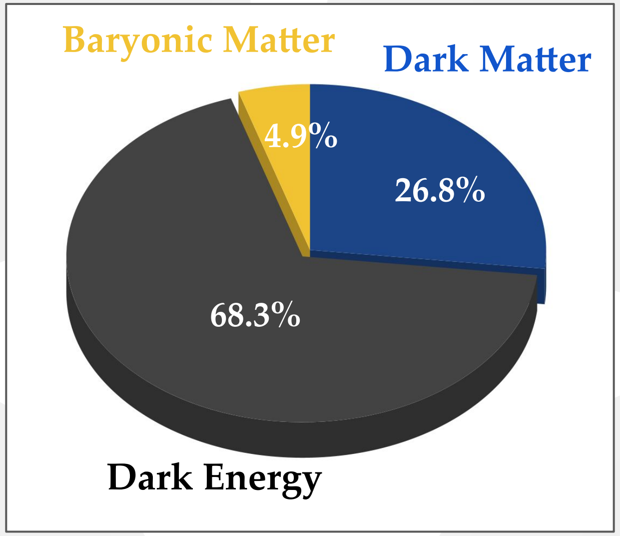
Alexey Elykov
Institute for Astroparticle Physics (IAP)



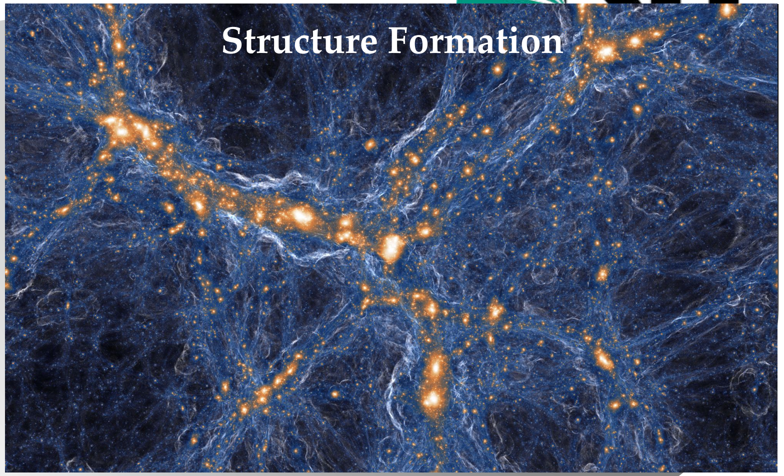
Dark Matter



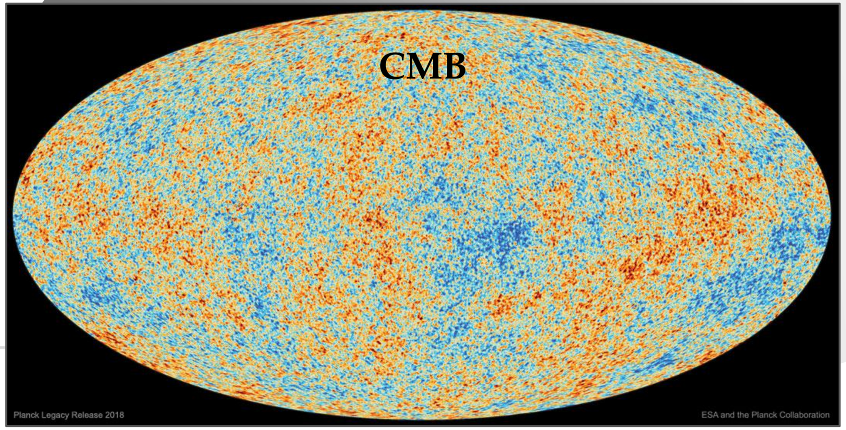
Combined fit - stars, gas, dark matter
Stellar disk
Dark halo
Gas
Stars and gas
Measured data
V [km/s]
Radius [kpc]
Rotation Curves



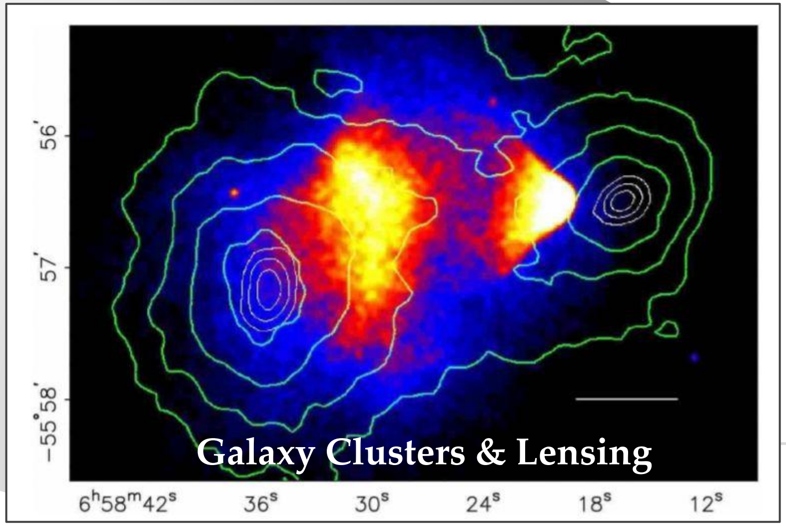
Baryonic Matter
Dark Matter
4.9%
26.8%
68.3%
Dark Energy



Structure Formation



CMB
Planck Legacy Release 2018
ESA and the Planck Collaboration



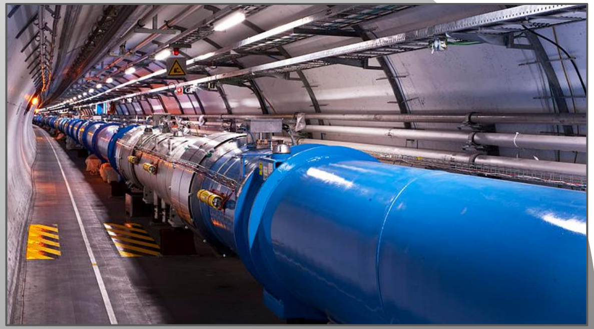
Galaxy Clusters & Lensing

Dark Matter

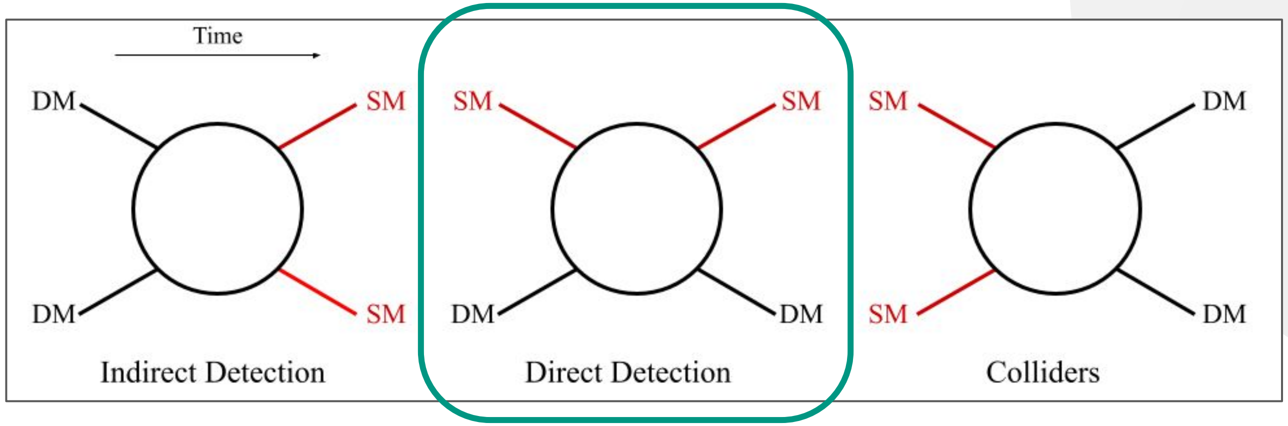
Dark Matter: ~ 85% of all matter in the Universe, unknown nature

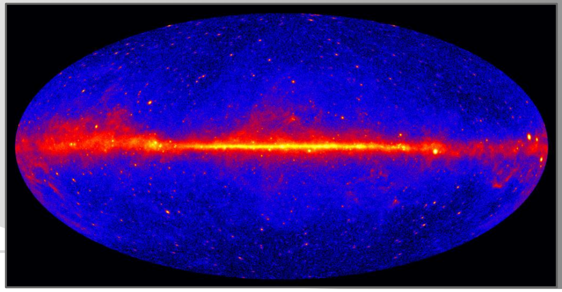
Dark Matter candidates:

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

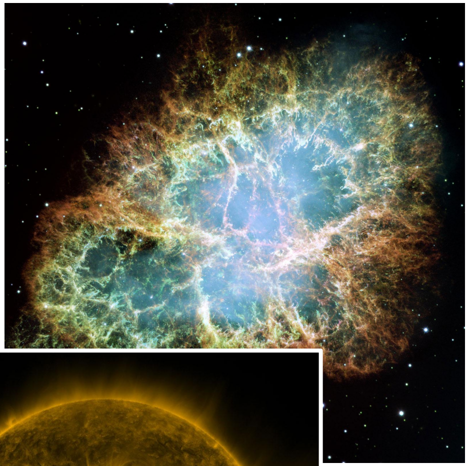


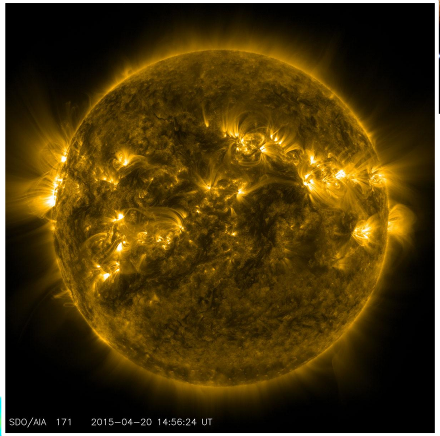
Paths for Dark Matter detection



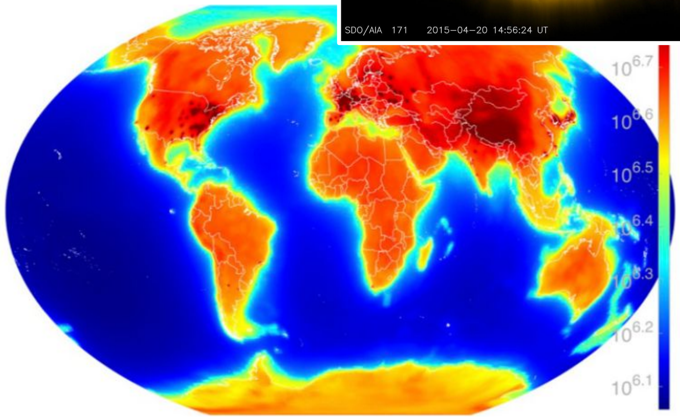


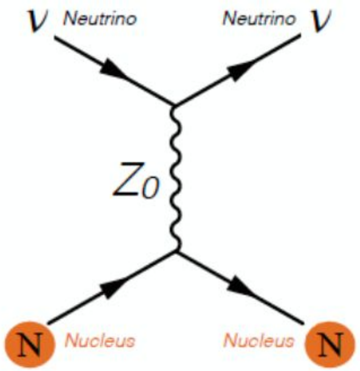
Neutrinos





- 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

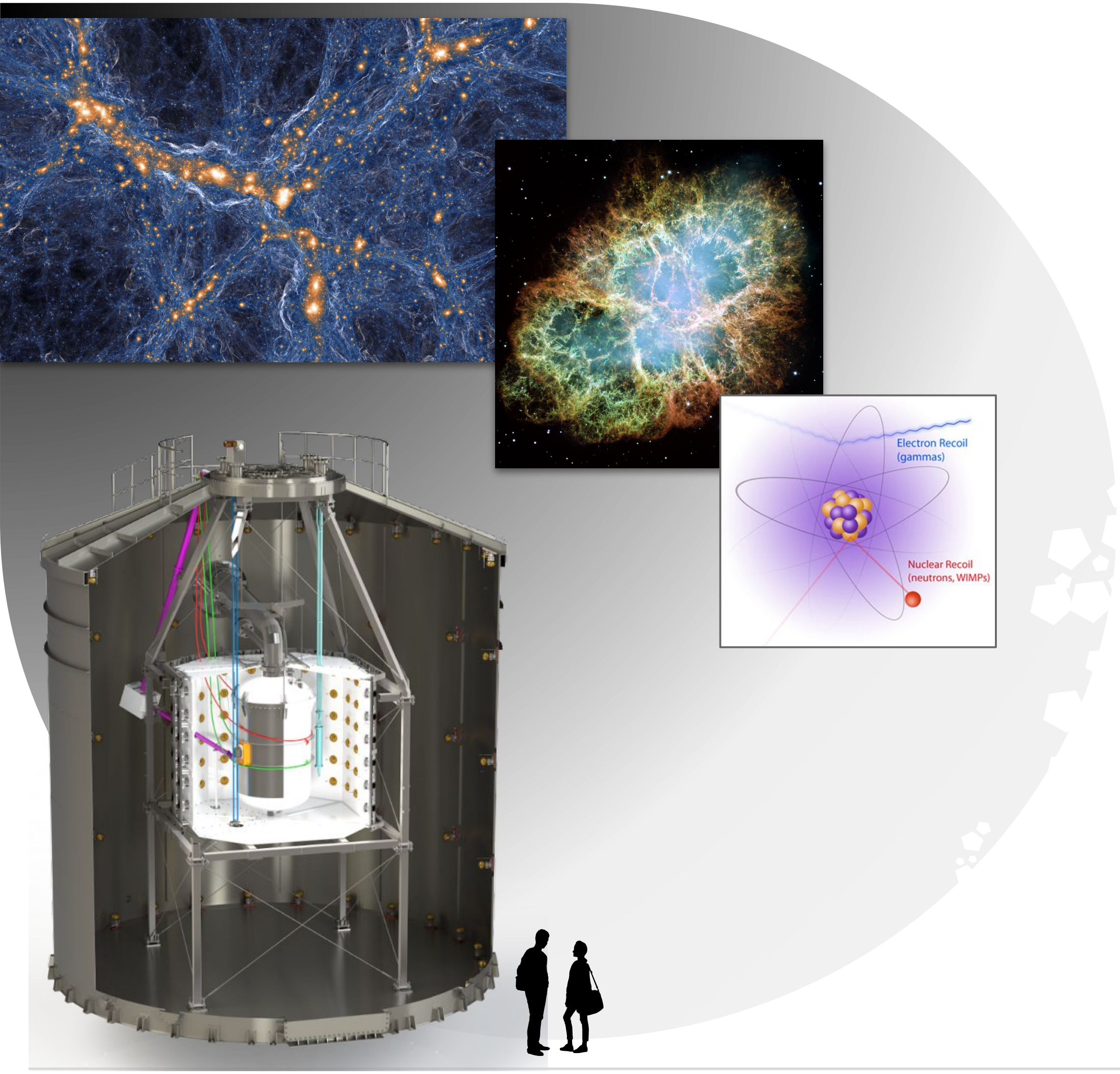


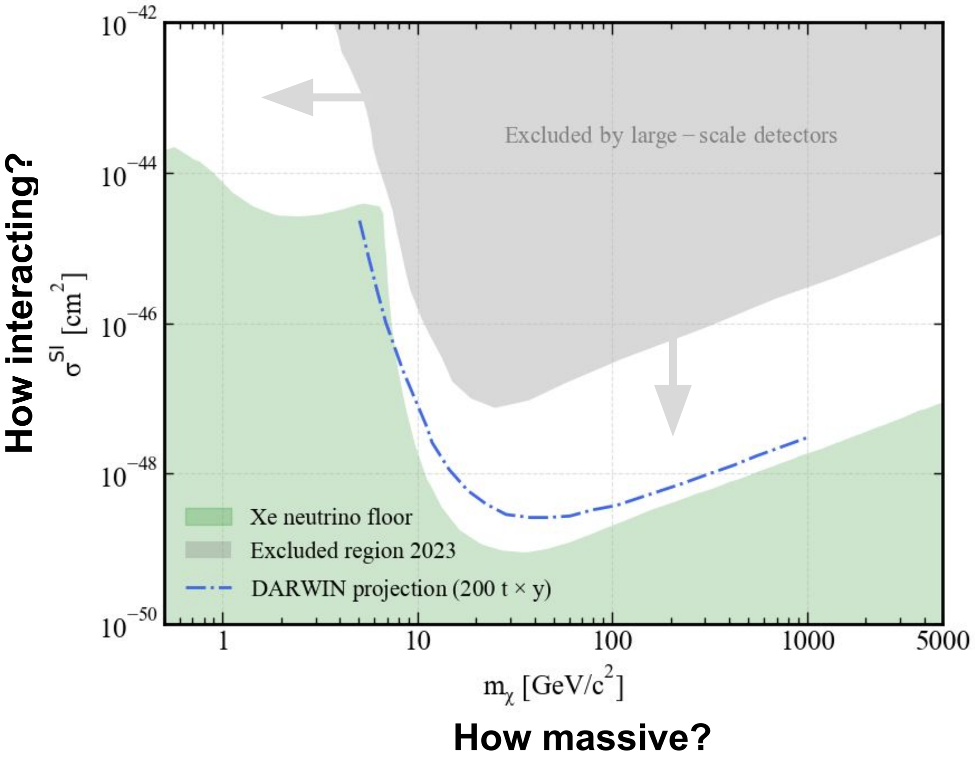


CEvNS

DOI: 10.1103/RevModPhys.92.045006

Dark Matter & Neutrinos - Detection

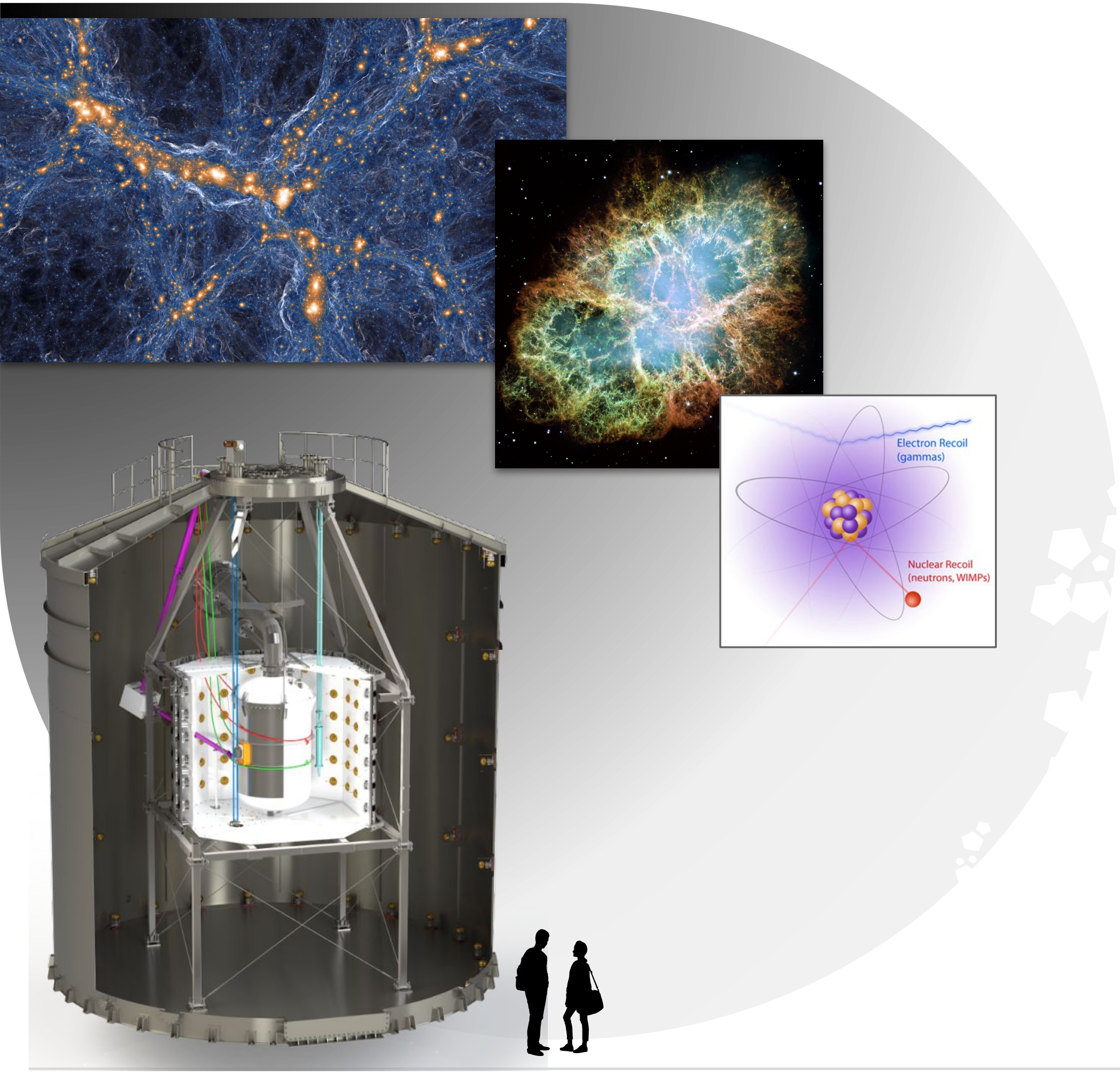


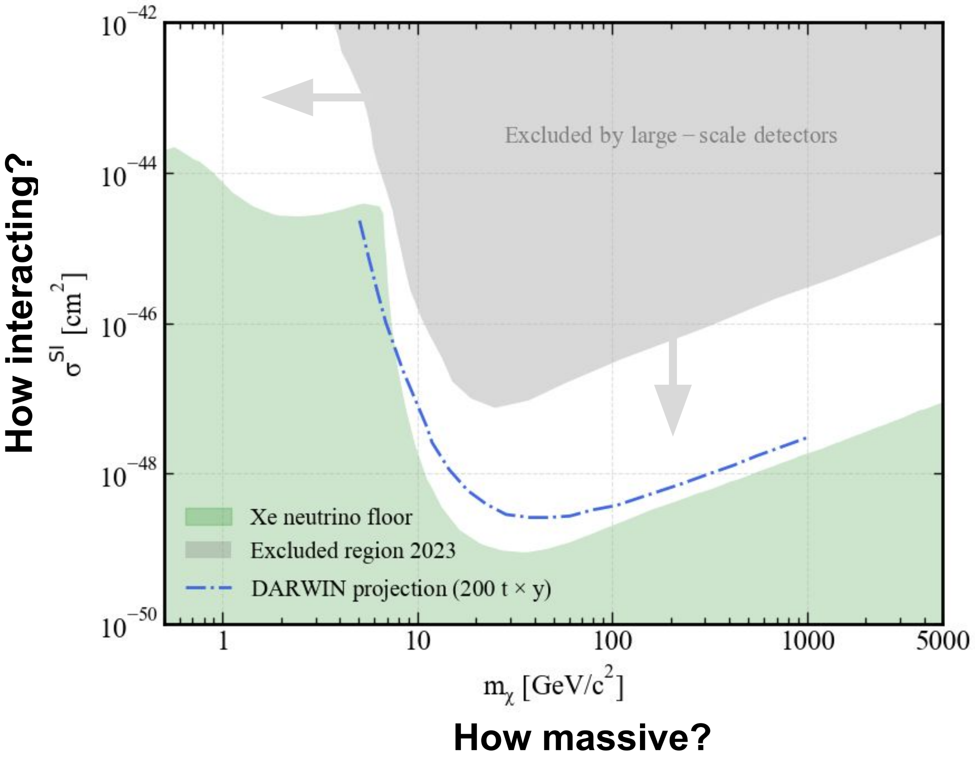


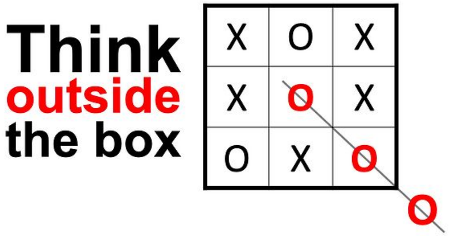
Dark Matter still eludes detection &

we are still puzzled by the nature of neutrinos!

Dark Matter & Neutrinos - Detection





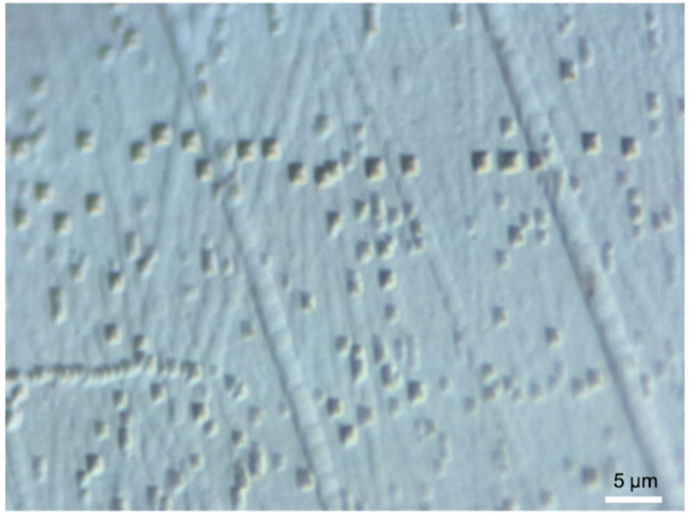


Solid State Nuclear Track Detectors (SSNTDs)

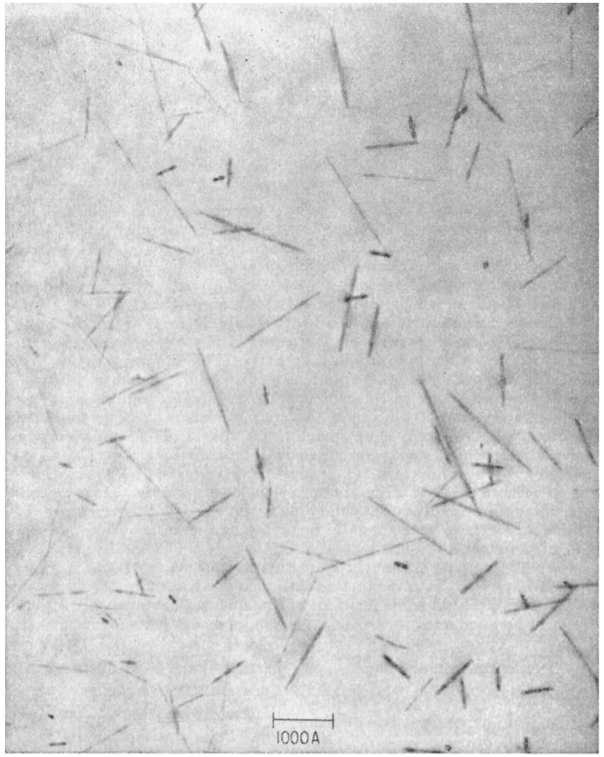
Karlsruhe Institute of Technology

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

- Ionizing radiation produces damage tracks
- Chemical etching
- Readout with microscopy



Etch pits in Olivine - courtesy of U. Glasmacher



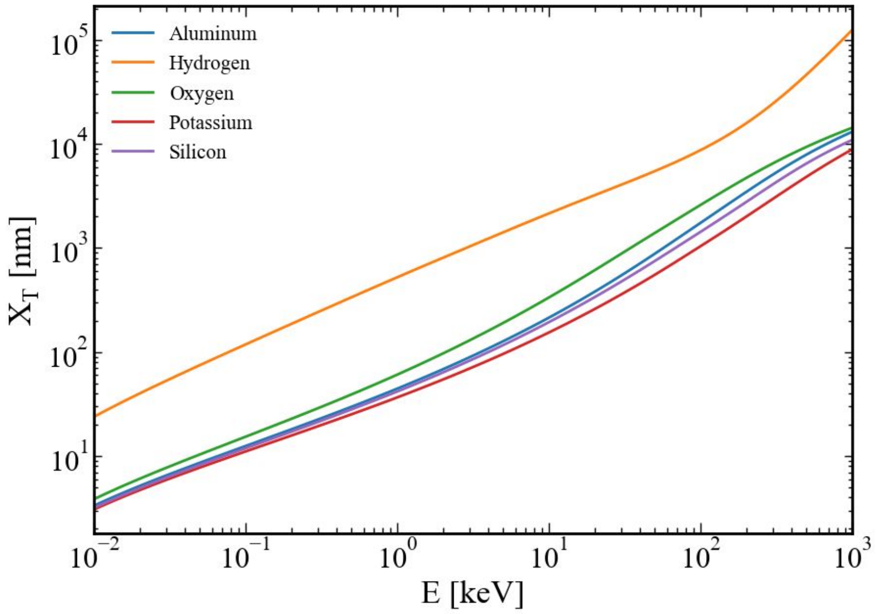
***1963** : Fission tracks in synthetic mica as viewed by TEM (DOI: 10.1029/JZ068i016p04847)*

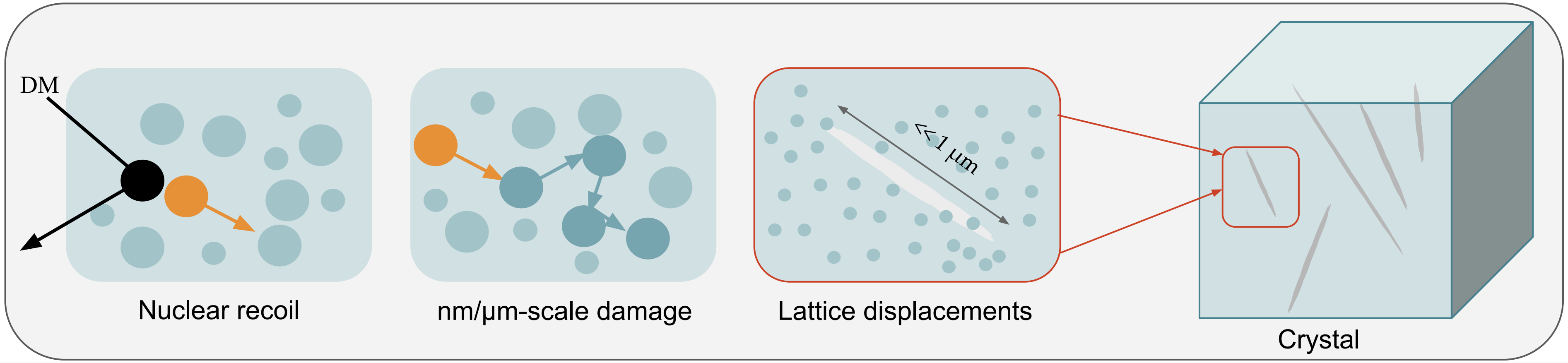
Track & Damage Features Formation

- **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





Mineral-Detectors in the Past

People tried this in the past!

VOLUME 56, NUMBER 12 PHYSICAL REVIEW LETTERS 24 MARCH 1986

Search for Supermassive Magnetic Monopoles Using Mica Crystals

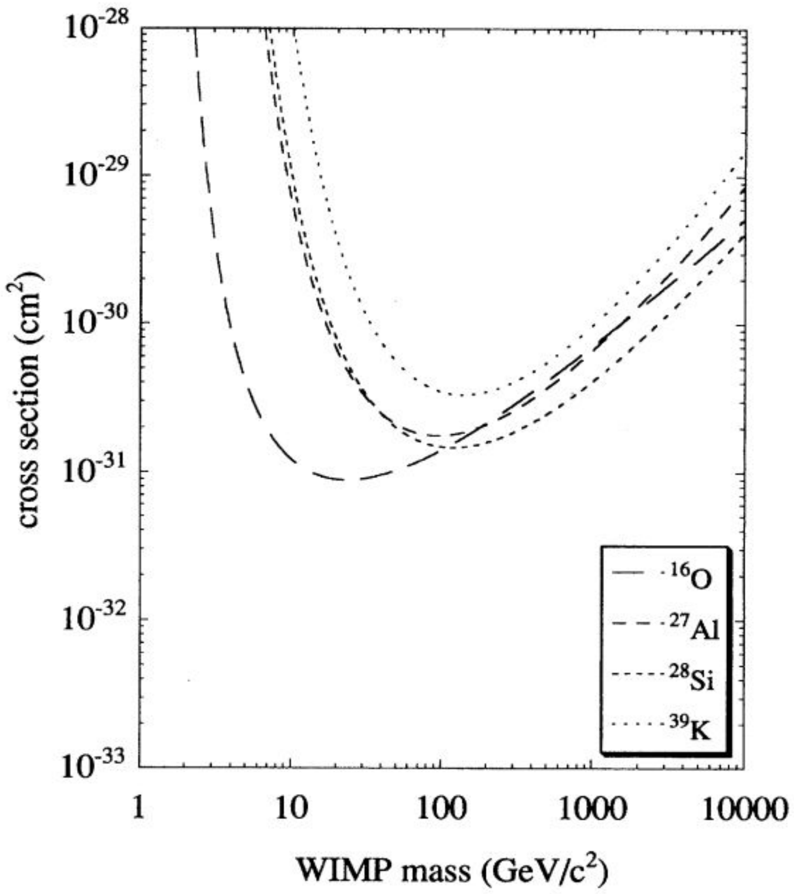
P. B. Price and M. H. Salamon
Department of Physics, University of California, Berkeley, California 94720
(Received 18 November 1985)

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)*

Mineral-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

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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**

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nature

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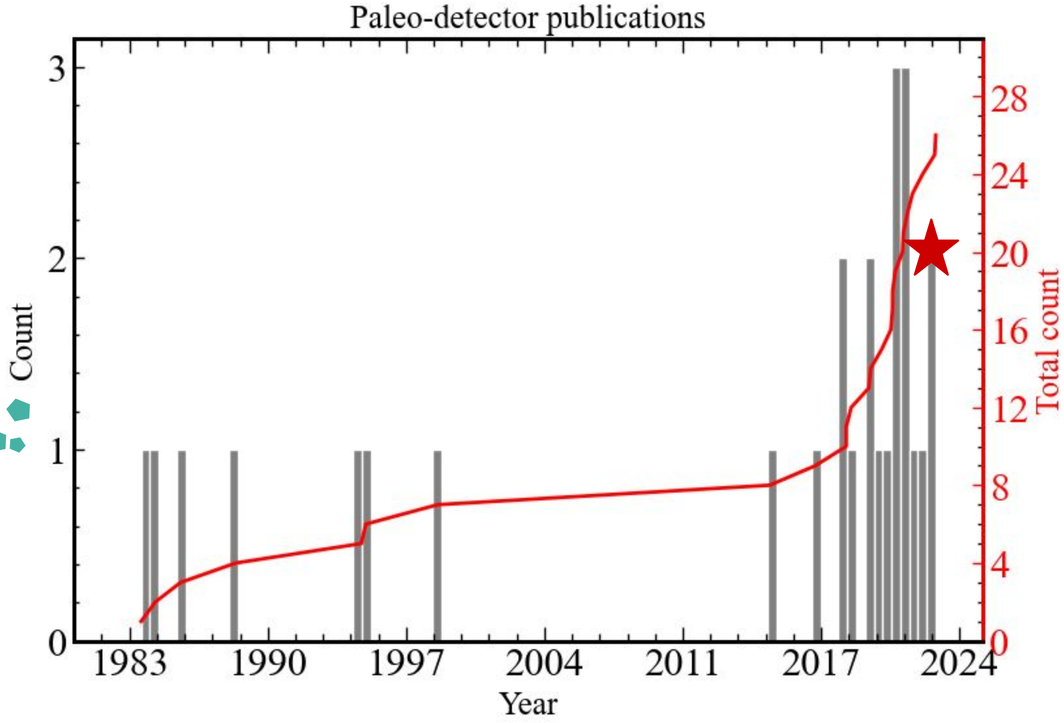
Anil Ananthaswamy

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



Mineral-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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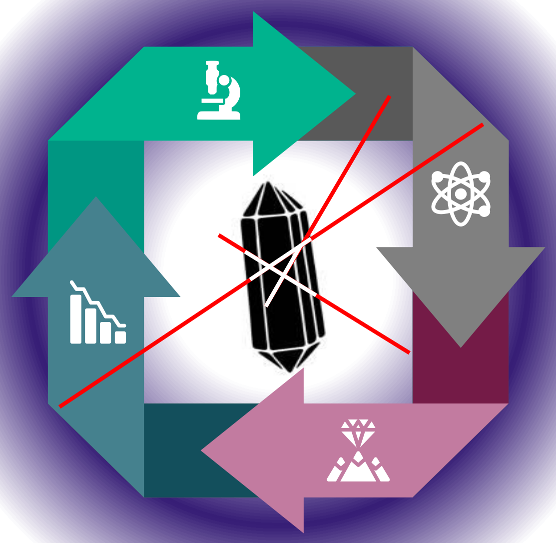
Astrophysics > Cosmology and Nongalactic Astrophysics

[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

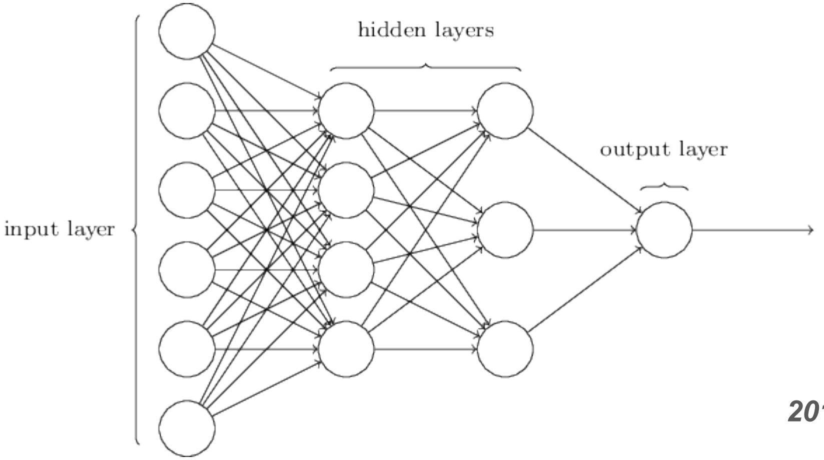
Mineral-Detectors Now

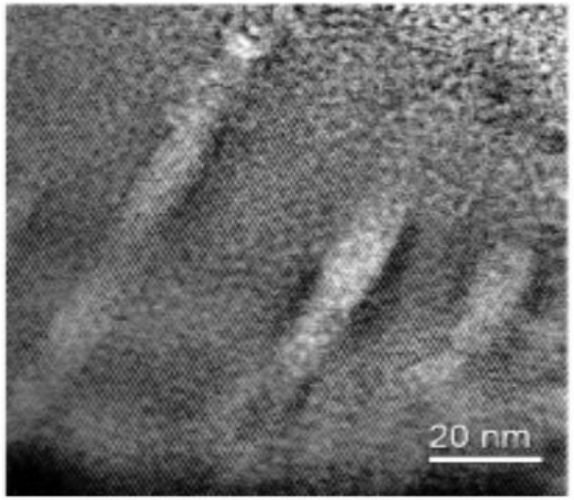


… and more …

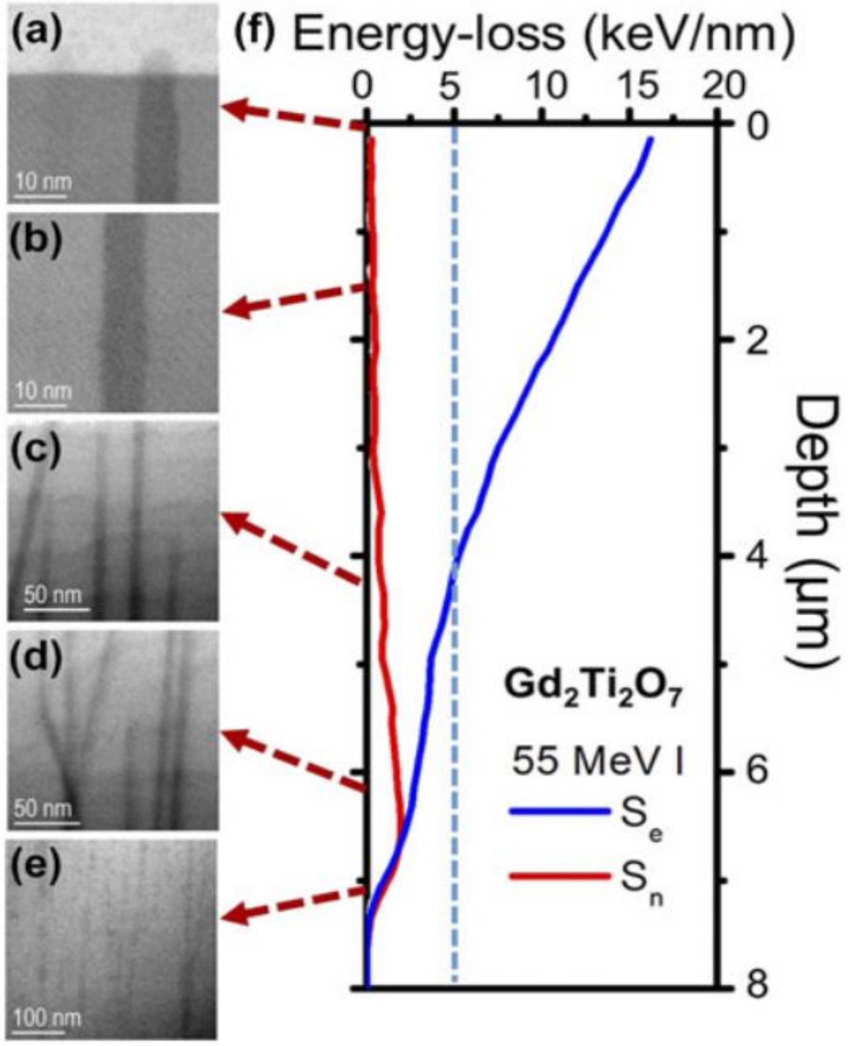
Mineral-Detectors - Why Now?

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





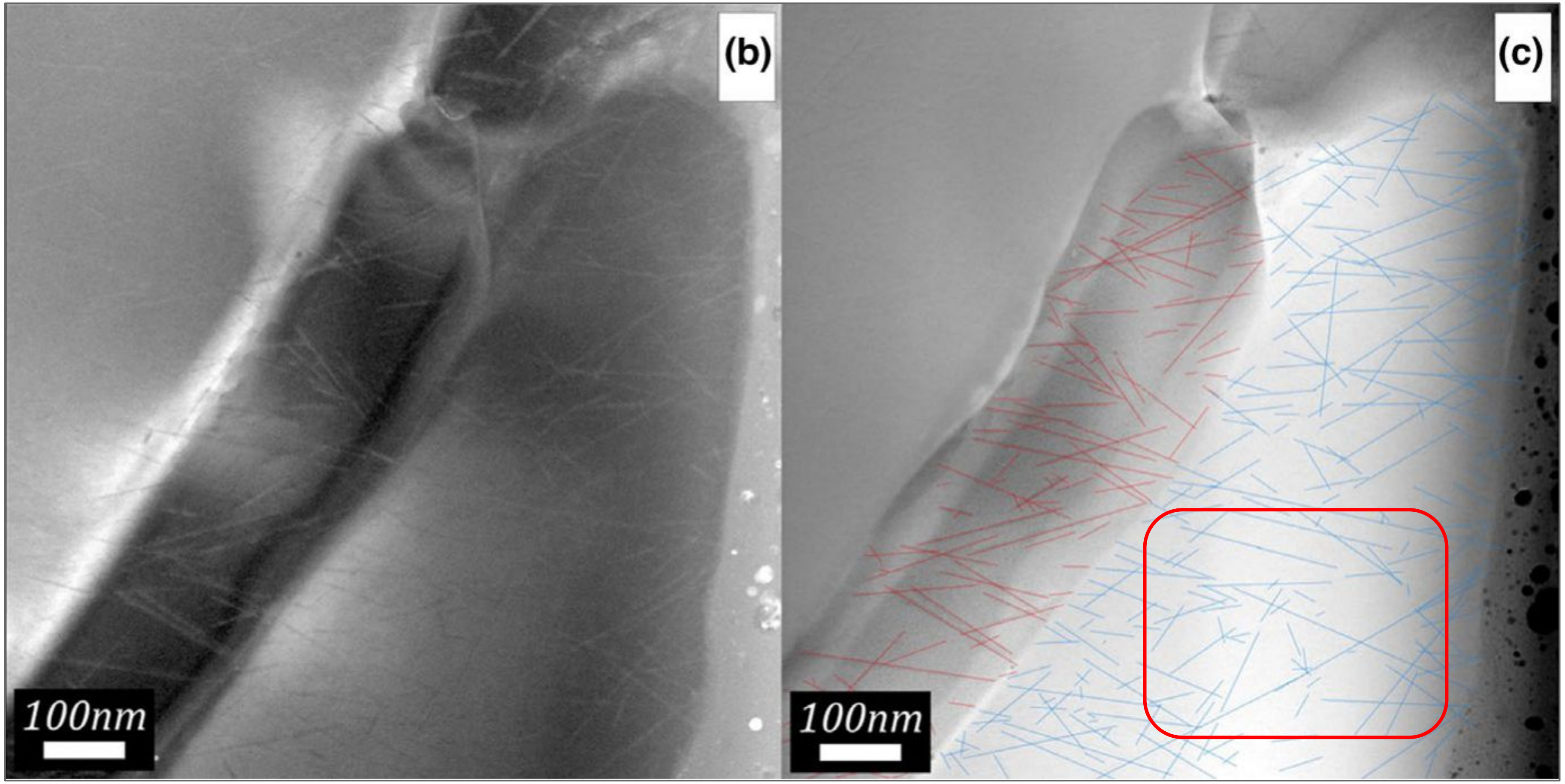
2011 *: TEM imaged tracks in apatite from 2.2 GeV Au ions (DOI: 10.1103/PhysRevB.83.064116)*



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

Mineral-Detectors - Why Now?

Apollo 16 - Lunar sample

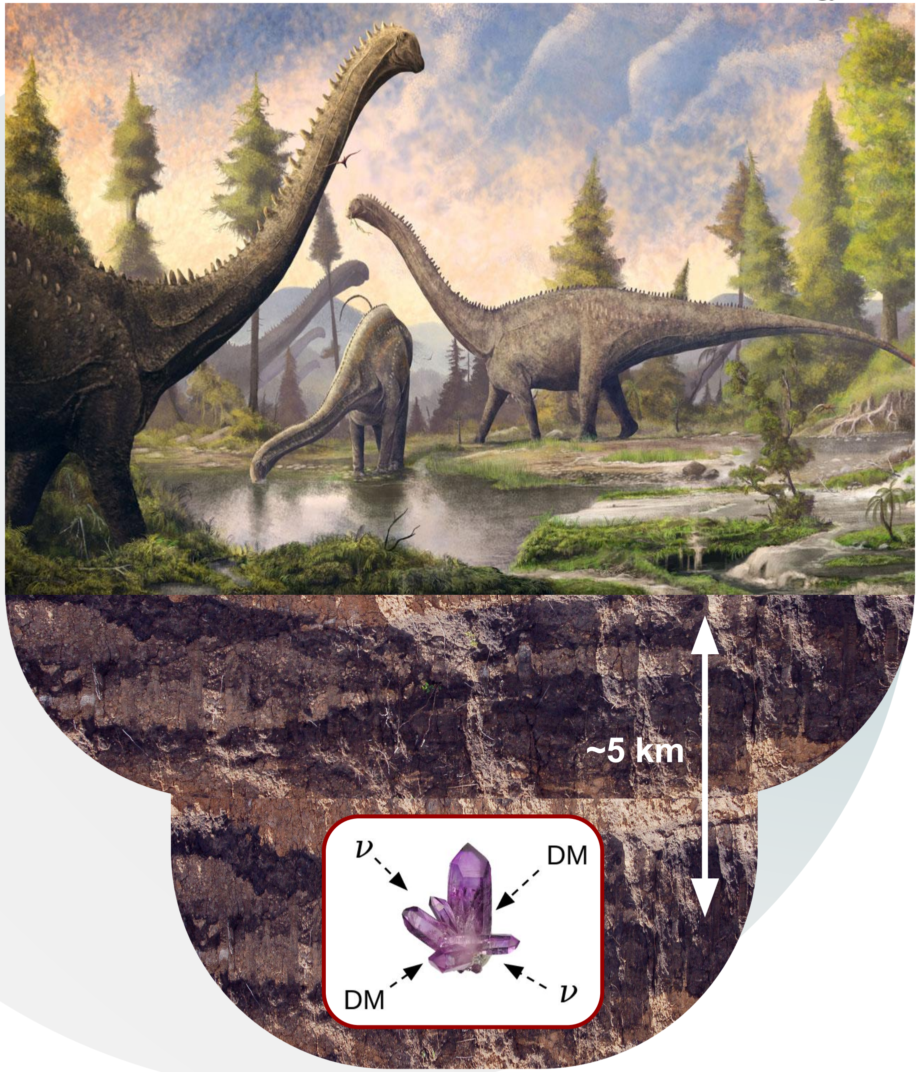


2021 *: STEM images from a lunar sample. Solar energetic particle induced tracks are present in olivine and plagioclase. (b) STEM images. c) Tracks are highlighted in red and blue for the olivine and plagioclase grains, respectively. (DOI: 10.1111/maps.13732)*

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



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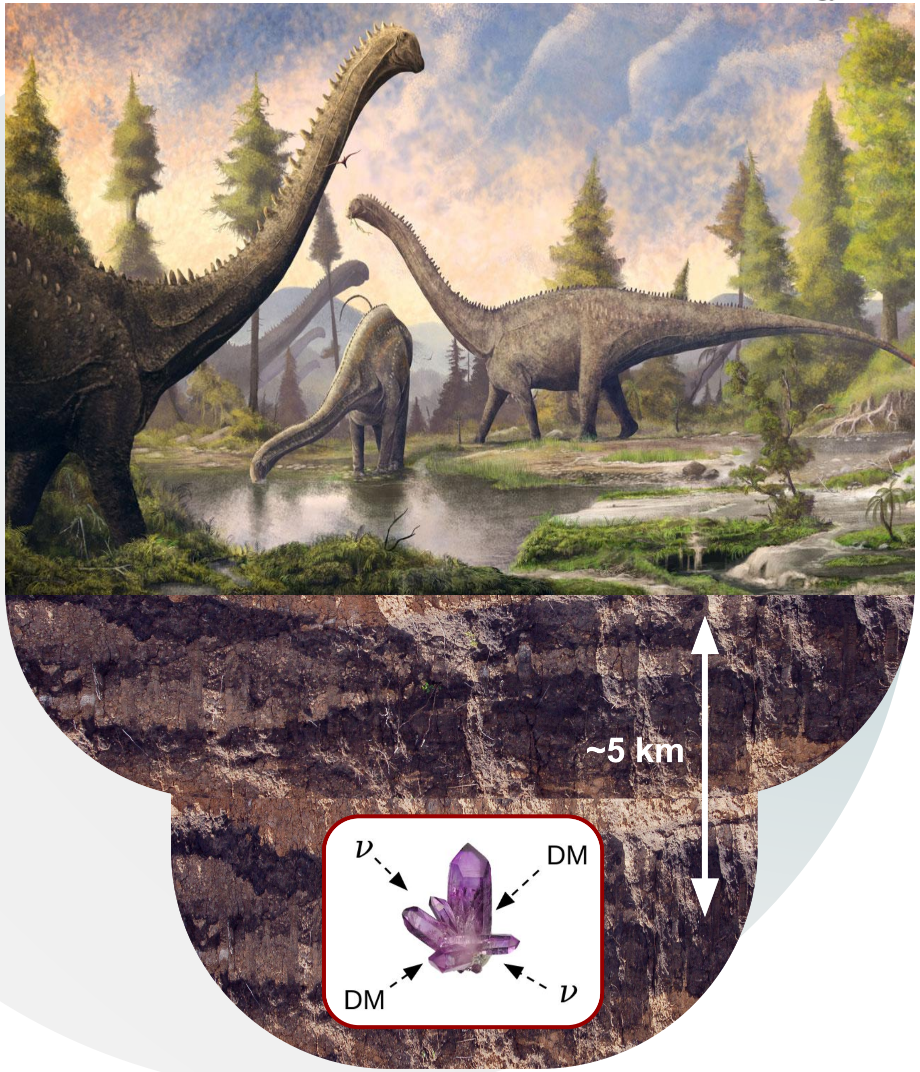
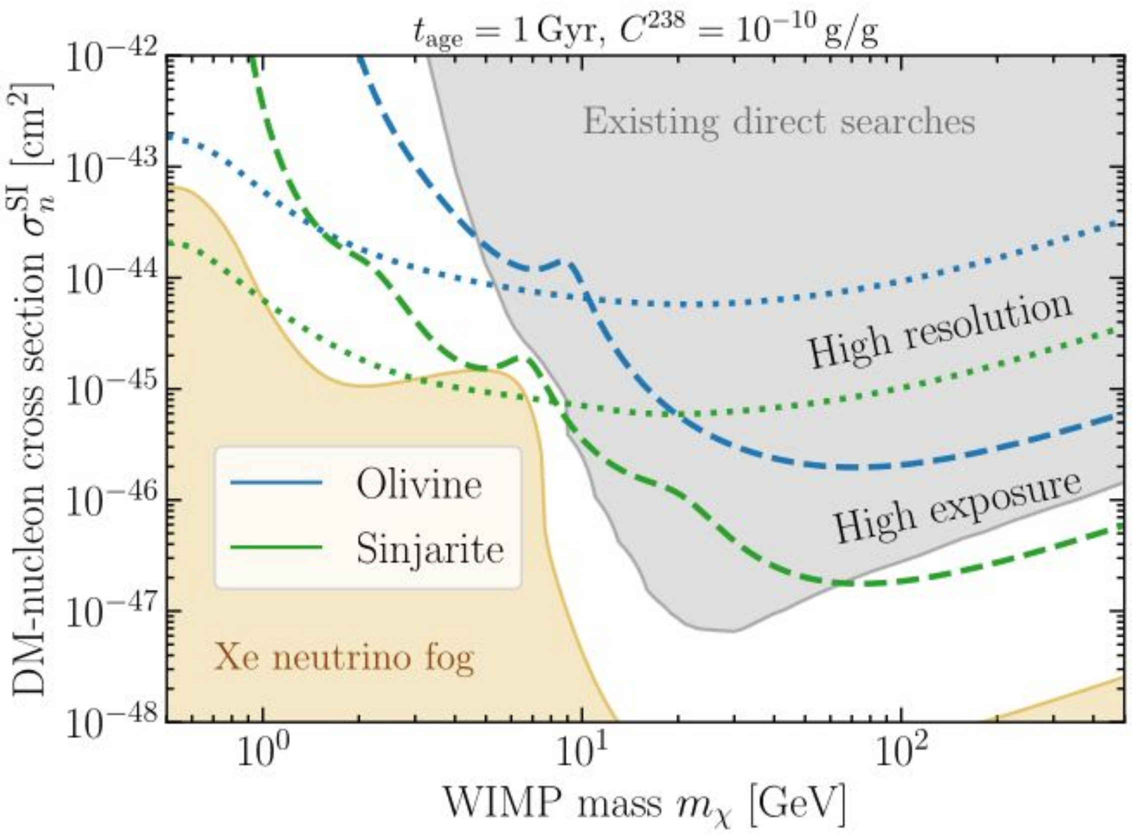


Excellent Dark Matter Discovery Reach

- 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

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

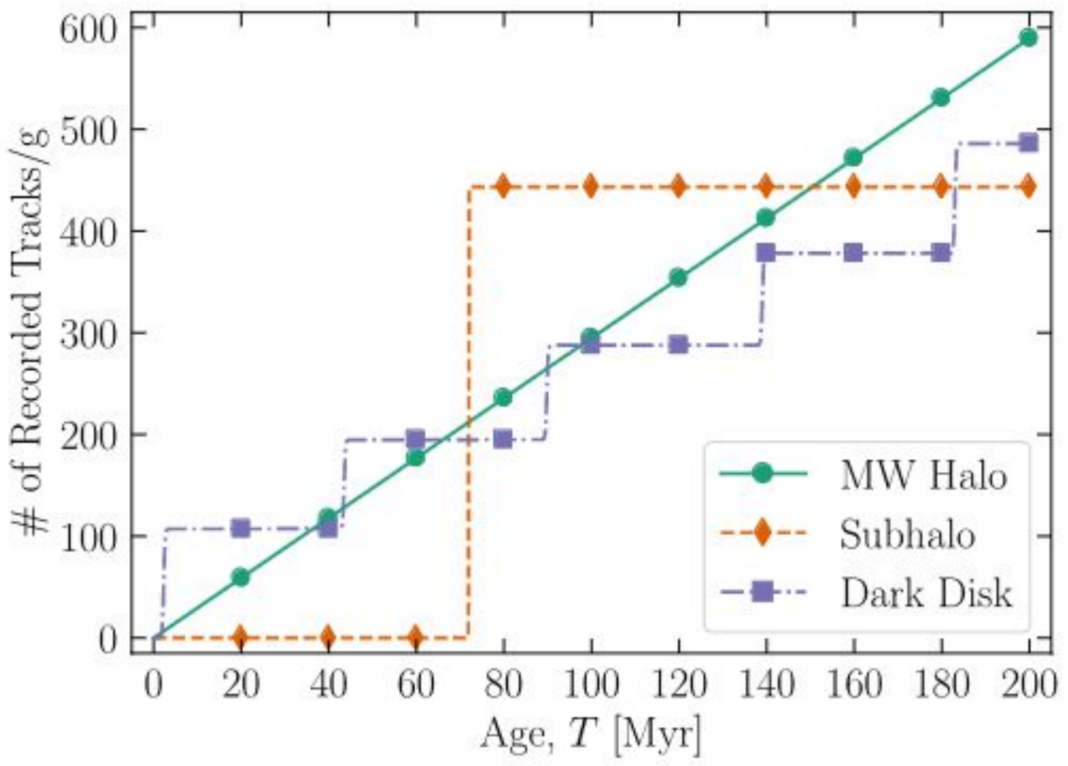


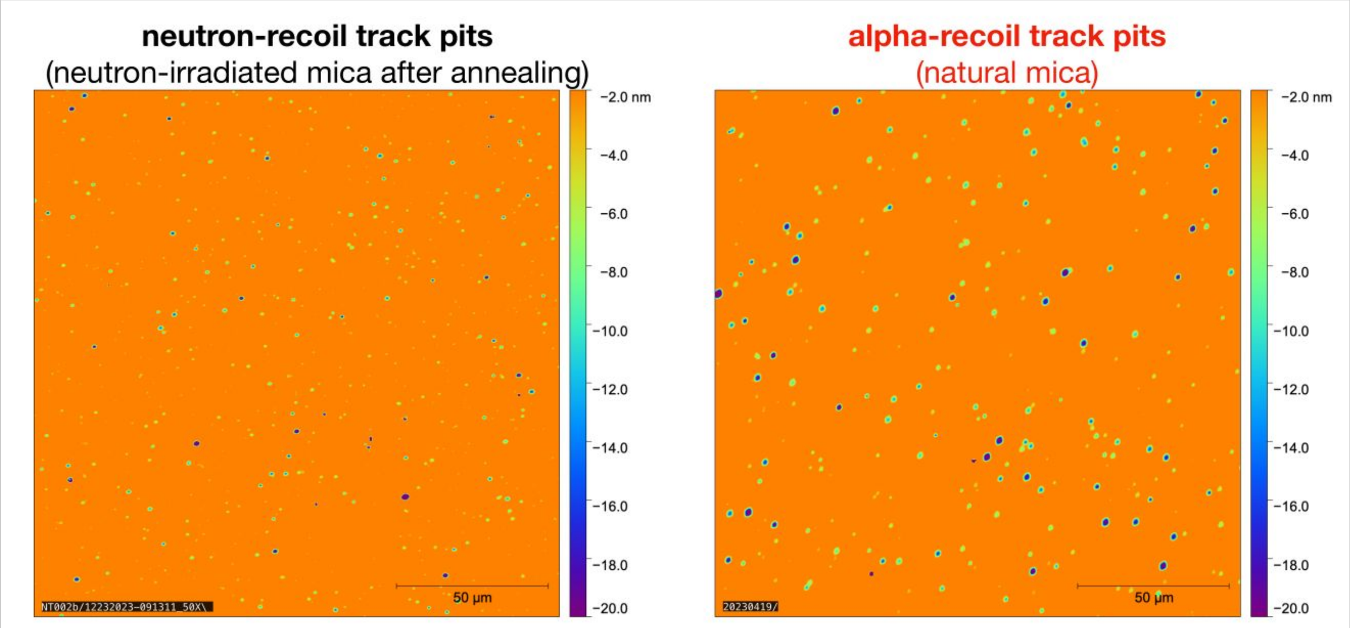
Illustration of the time-dependence of the number of damage tracks which would be recorded in a gram-sized paleo-detector of age T for three different DM signals.

DOI: 10.1103/PhysRevD.104.123015

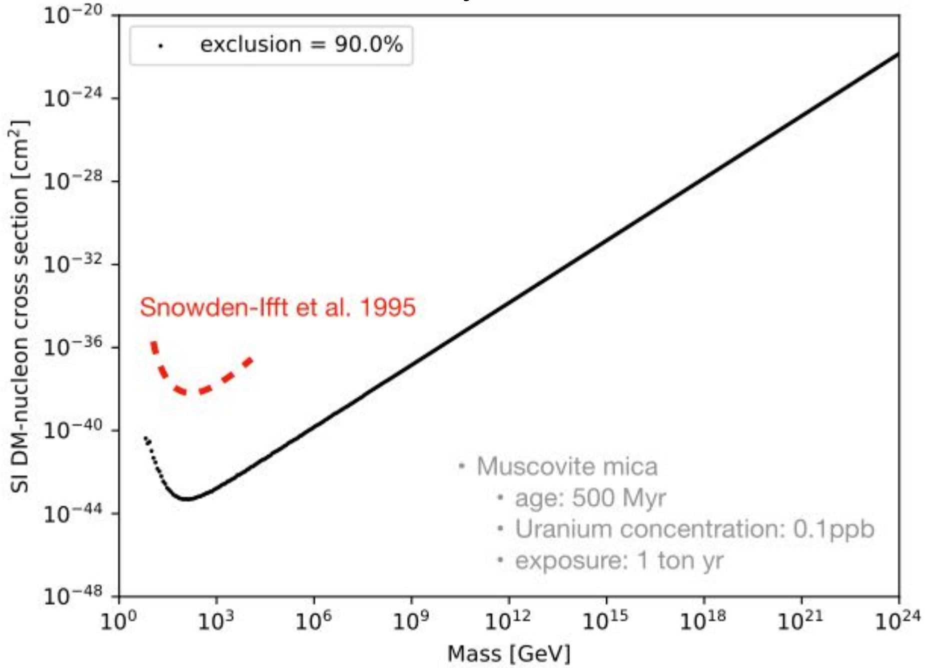
Mineral-Detectors around the World

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
  - DMICA aims to scan ~1 ton-year exposure



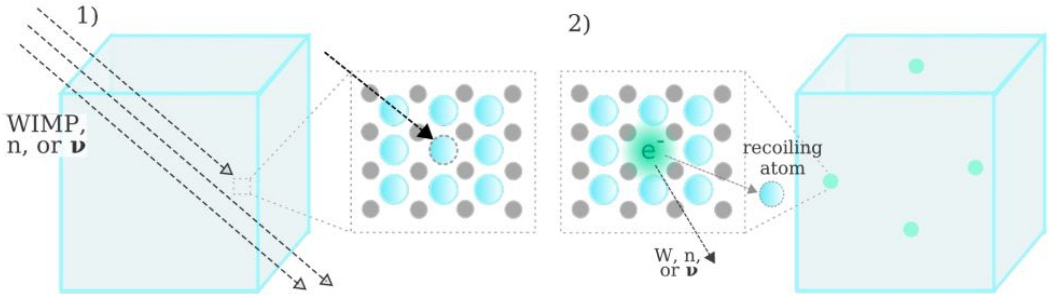
Sensitivity forecast

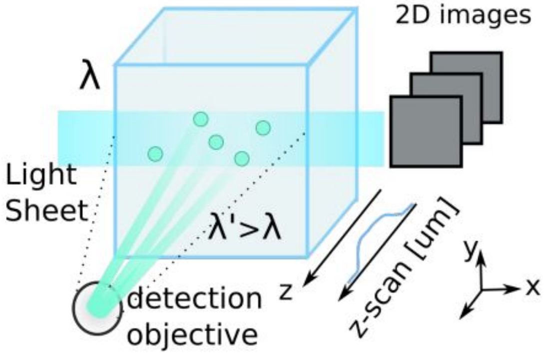


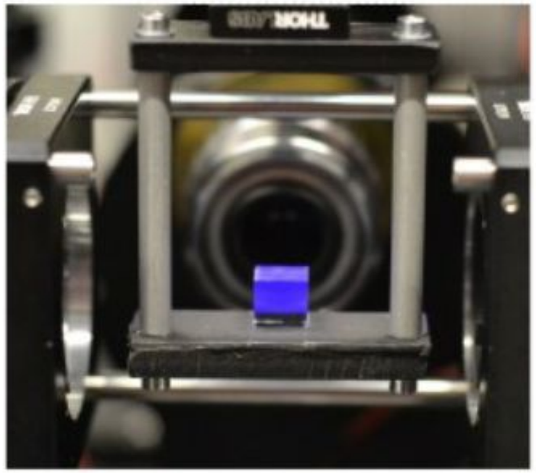
Shigenobu Hirose et al.

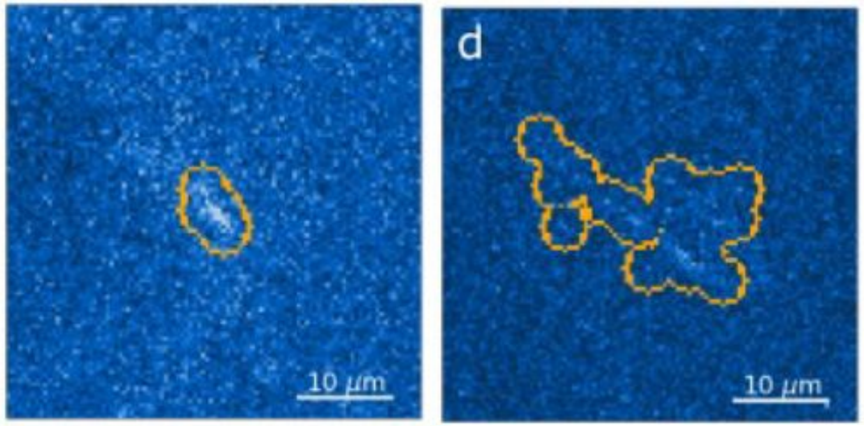
Mineral-Detectors around the World

- **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…









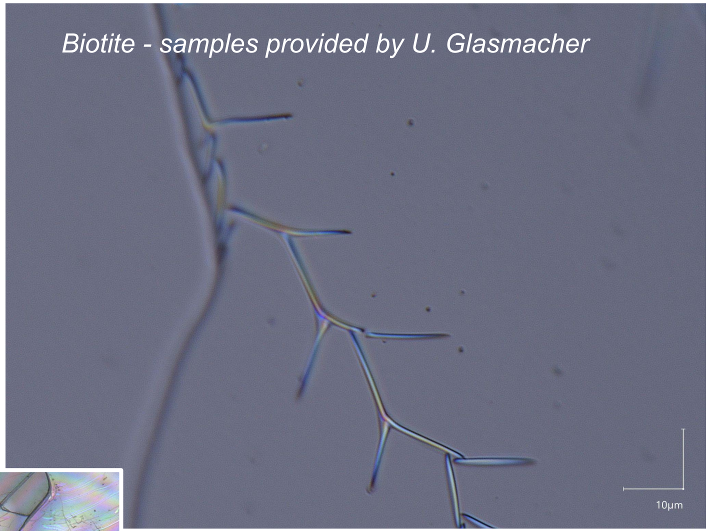
Gabriela R. Araujo et al.

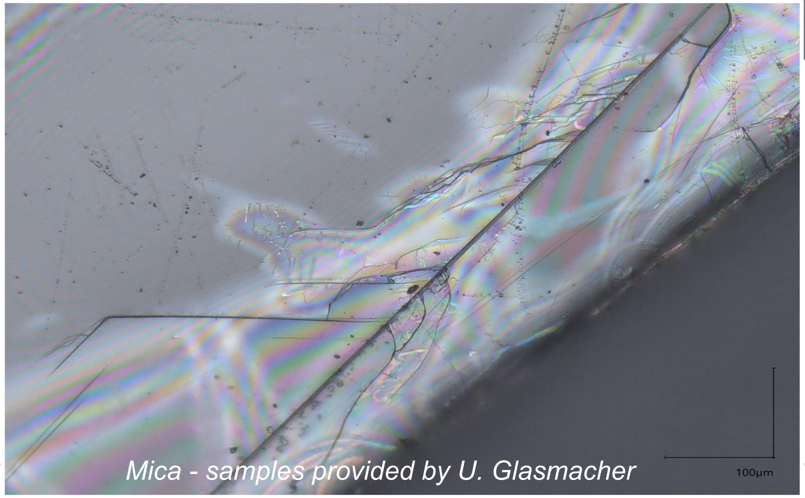
Mineral-Detectors at KIT

- ❖ Established connections with geologists - U. Glasmacher
- ❖ KCETA - seed funding for preliminary studies & lab setup
- ❖ Unique combination of different microscopy facilities & expertise

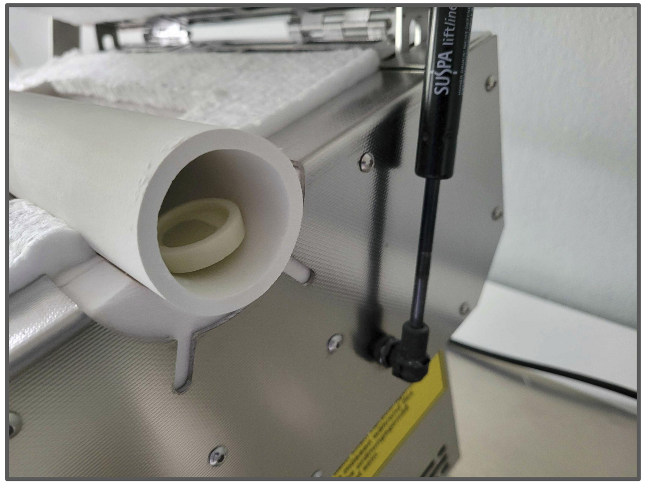
➢ **Transmission Electron Microscopy (TEM)**
- Resolution: << 1 nm

➢ **nanoCT (3D)**
- X-ray energy: 5.4 keV
- FoV: 16 µm (HRES), 65 µm (LRES)
- Resolution: 50 - 100 nm
- Non-destructive



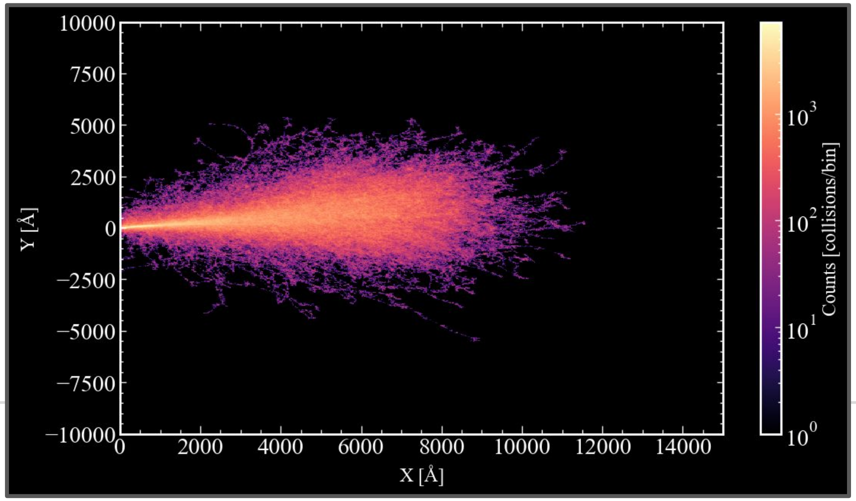


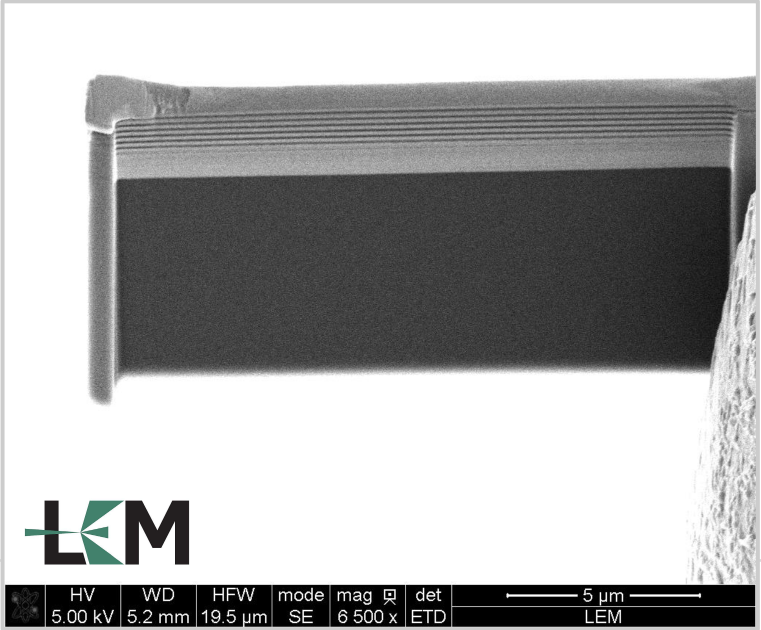
Mineral-Detectors at KIT

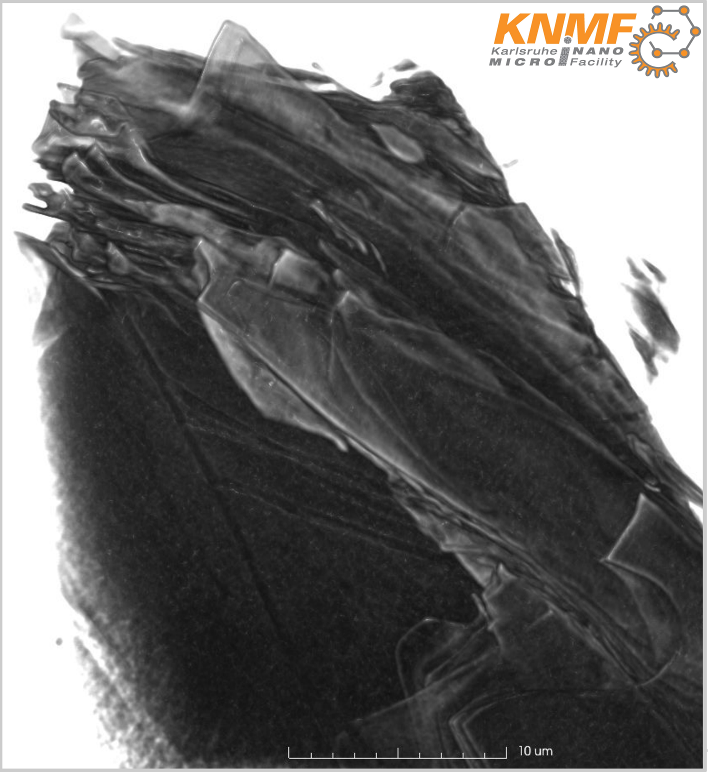


Main Goals of the Pilot Project

- ❖ Establish technology for track imaging & analysis in selected minerals
- ❖ Establish a realistic list of paleo-detector candidate minerals
- ❖ Deepen cooperation with microscopy & geology experts





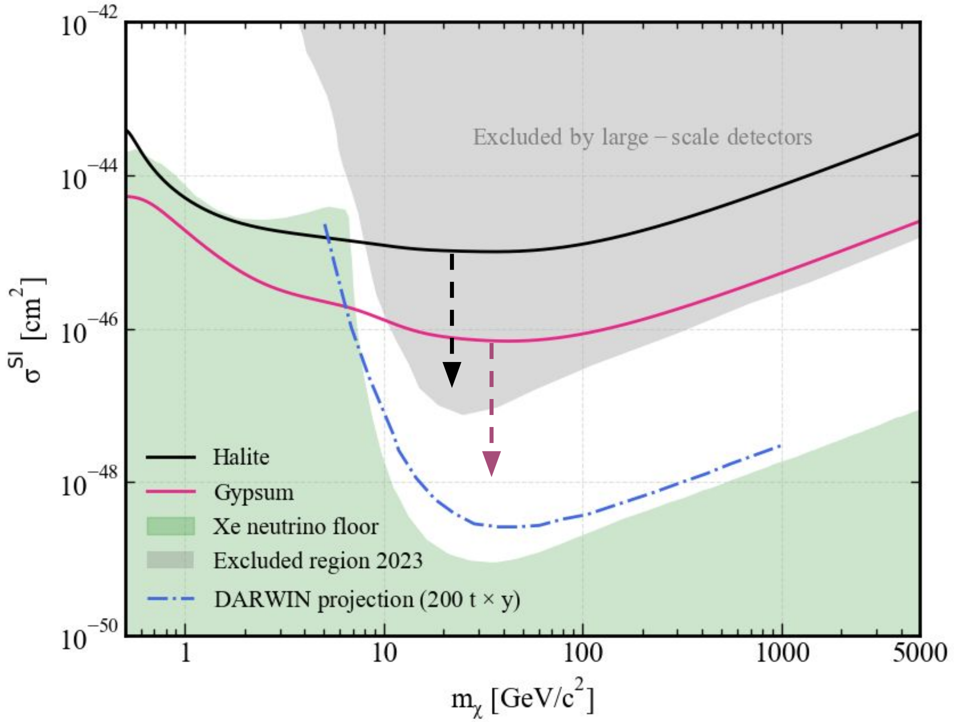


Challenging Project

- ❖ **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

Mineral-Detectors - Summary

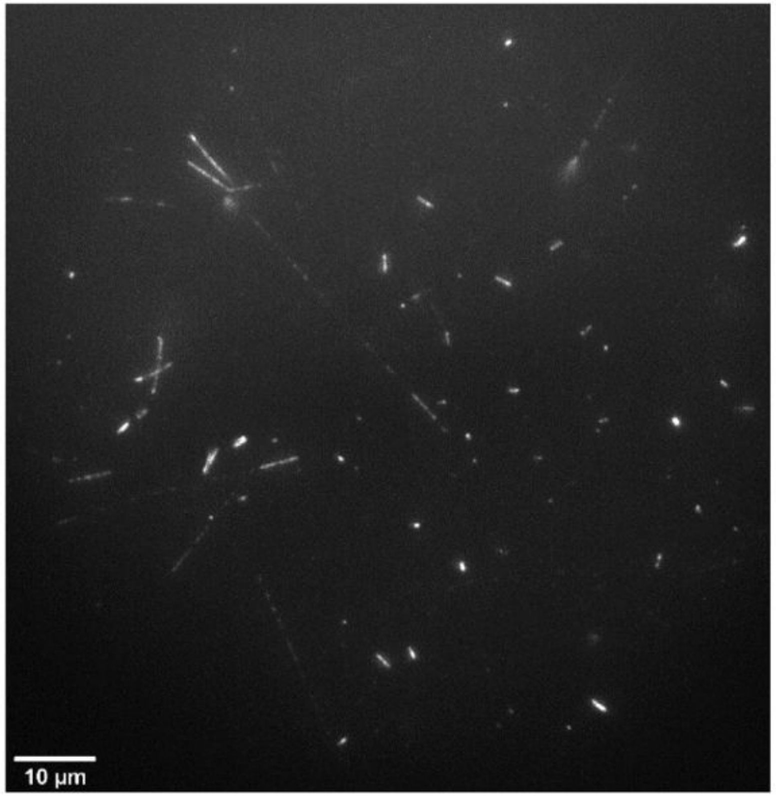
Karlsruhe Institute of Technology

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
- ❖ 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!**



DOI: 10.1016/j.radmeas.2018.06.022

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

alexey.elykov@kit.edu, pstengel@fe.infn.it