

Paleo-Detectors & Friends:

Mineral Detectors for Neutrinos and Dark Matter

Sebastian Baum

Stanford
University



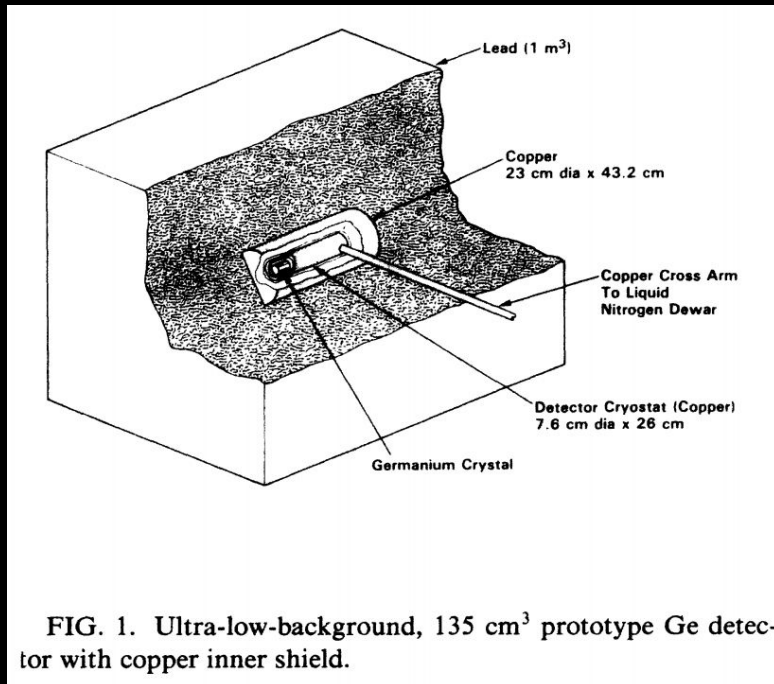
TTK Institute for
Theoretical
Particle Physics
and Cosmology

RWTHAACHEN
UNIVERSITY

Requirement List for Dark Matter (/neutrino) Detectors

- Low recoil energy threshold ($\sim \text{keV?}$)
- Low backgrounds
- Large exposure (= target mass \times integration time)

1987: 750 g of Ge



[Ahlen+ '87, Avignone+ '86]

2021: 8 tonnes of Xe



[XENON collaboration]

Mineral Detectors for Neutrinos and Dark Matter

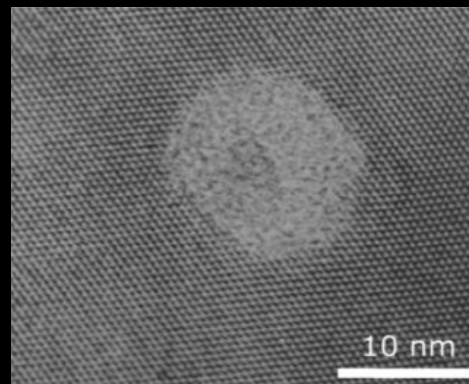


Fossil Tracks in
Madagascar Phlogopite;
optical microscopy after
chemical etching.



[Price&Walker '63]

High-resolution TEM



[Toulemonde+ '06]

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
 Yoshitaka Itow,³¹ Takashi Kamiyama,³² Takenori Kato,³¹ Bradley J. Kavanagh,³³
 Yoji Kawamura,²⁴ Shingo Kazama,³⁴ Christopher J. Kenney,⁴ Ben Kilminster,⁵
 Yui Kouketsu,⁶ Yukiko Kozaka,³⁵ Noah A. Kurinsky,^{4,36} Matthew Leybourne,⁹
 Thalles Lucas,⁹ William F. McDonough,^{37,38,39} Mason C. Marshall,^{15,40}
 Jose Maria Mateos,⁴¹ Anubhav Mathur,¹⁶ Katsuyoshi Michibayashi,⁶
 Charlotte Mkhonto,⁹ Kohta Murase,⁴² Tatsuhiro Naka,²⁸ Kenji Oguni,²⁴
 Surjeet Rajendran,¹⁶ Hitoshi Sakane,⁴³ Paola Sala,¹¹ Kate Scholberg,⁴⁴
 Ingrida Semenec,⁹ Takuya Shiraishi,²⁸ Joshua Spitz,⁴⁵ Kai Sun,⁴⁶ Katsuhiko Suzuki,⁴⁷
 Erwin H. Tanin,¹⁶ Aaron Vincent,⁹ Nikita Vladimirov,⁴⁸ Ronald L. Walsworth,^{14,15,40}
 and Hiroko Watanabe³⁷

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MDvDM community

- Astroparticle theorists, experimentalists, geologists, and materials scientists
- Groups across North America, Europe, and Japan
- First meeting in Oct '22 at IFPU, Trieste

Check out our whitepaper!

- History of mineral detectors
- Review of scientific potential for (cosmo)particle physics, reactor neutrinos, and geoscience
- Summary of ongoing and planned experimental efforts

Mineral Detection of Neutrinos and Dark Matter. A Whitepaper

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Katherine G. Gribble,¹⁴ M. H. Good,¹⁵

MDvDM'24 in Washington, DC
Jan 8-11, 2024
<https://indico.phys.vt.edu/event/62/>

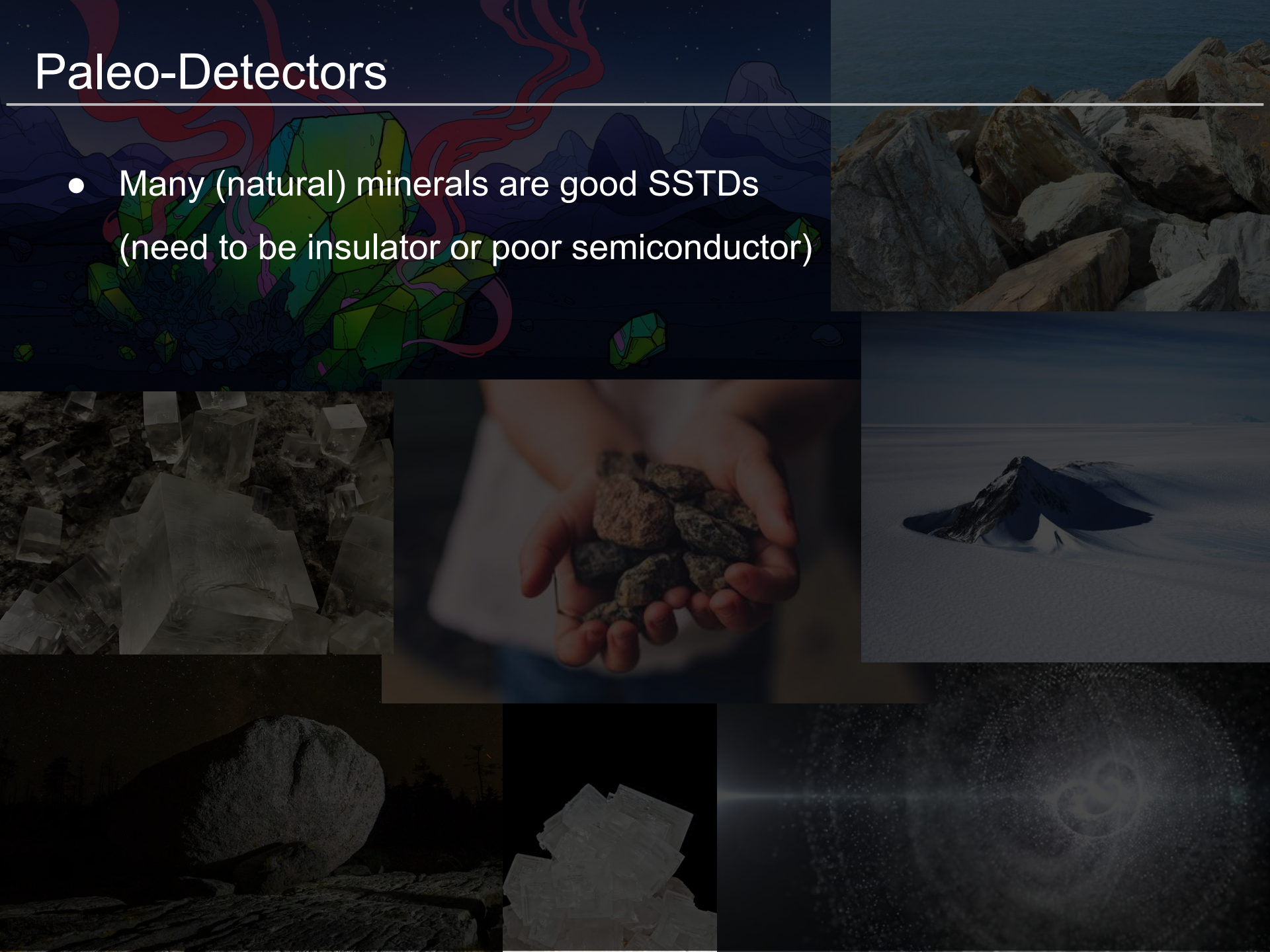
MDvDM

- Astroparticle physics, neutrino and dark matter experiments and materials
- Groups across North America, Europe, and Japan
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- Review of scientific potential for (cosmo)particle physics, reactor neutrinos, and geoscience
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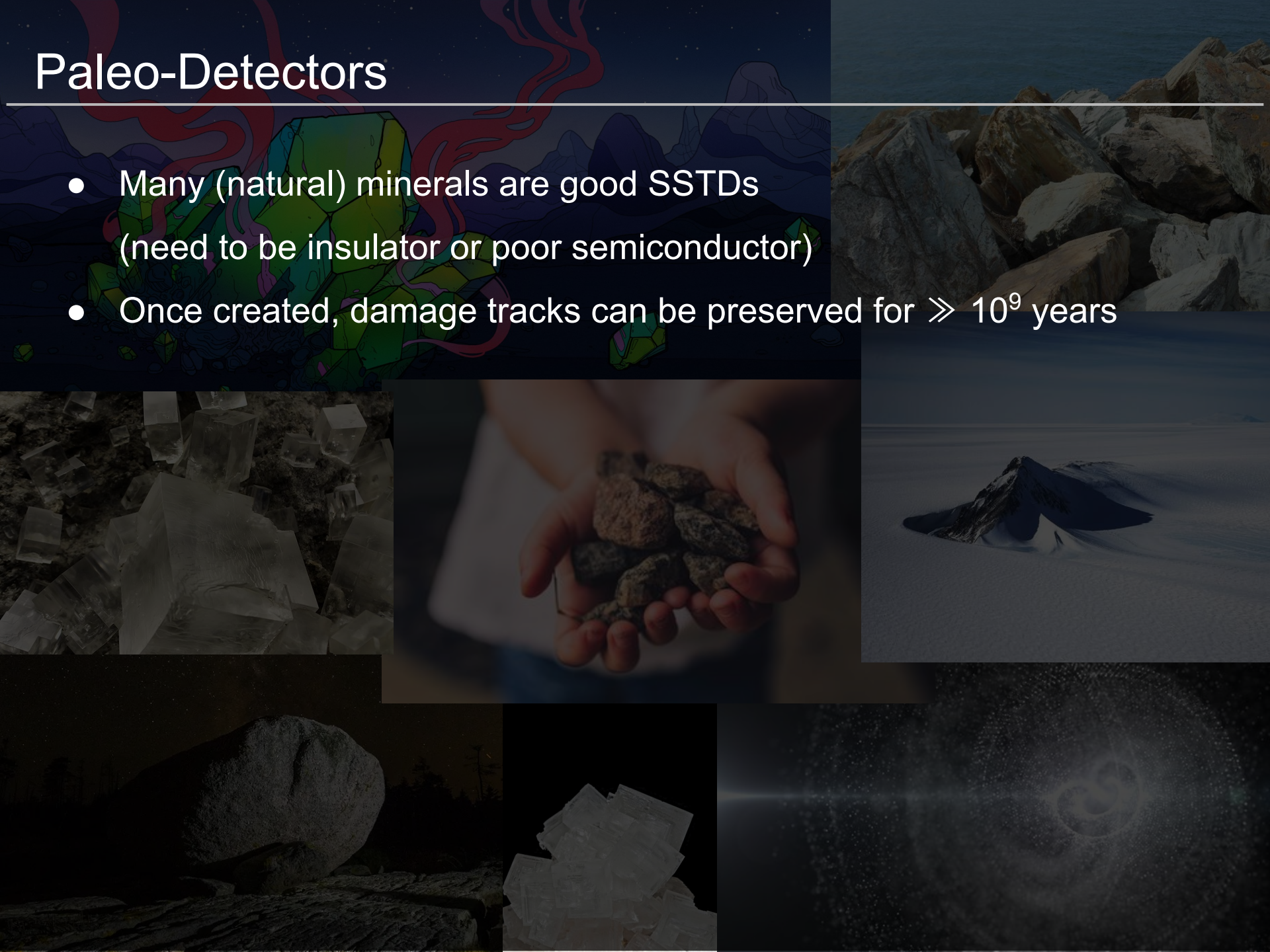
Paleo-Detectors

- Many (natural) minerals are good SSTDs (need to be insulator or poor semiconductor)



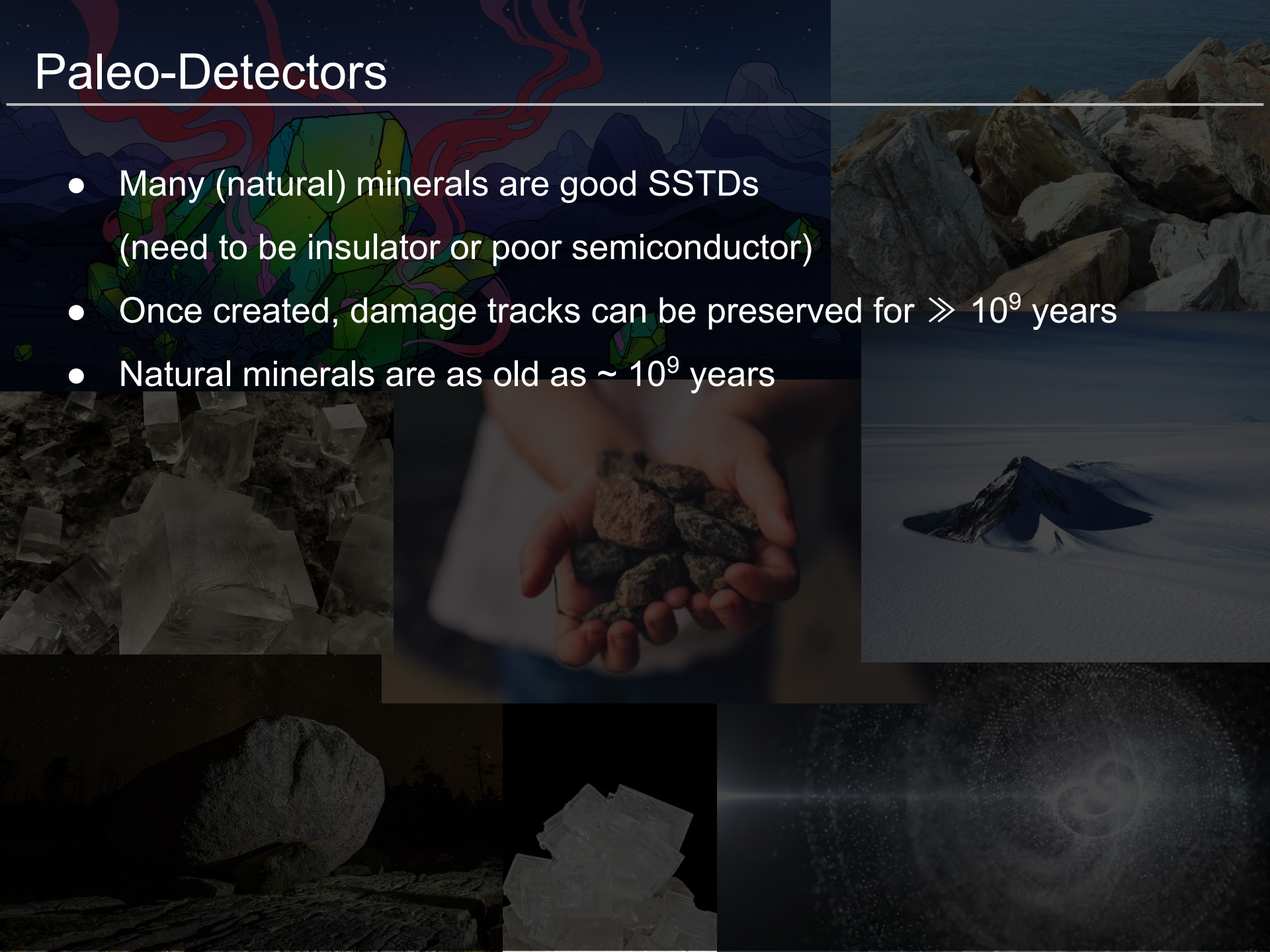
Paleo-Detectors

- Many (natural) minerals are good SSTDs (need to be insulator or poor semiconductor)
- Once created, damage tracks can be preserved for $\gg 10^9$ years



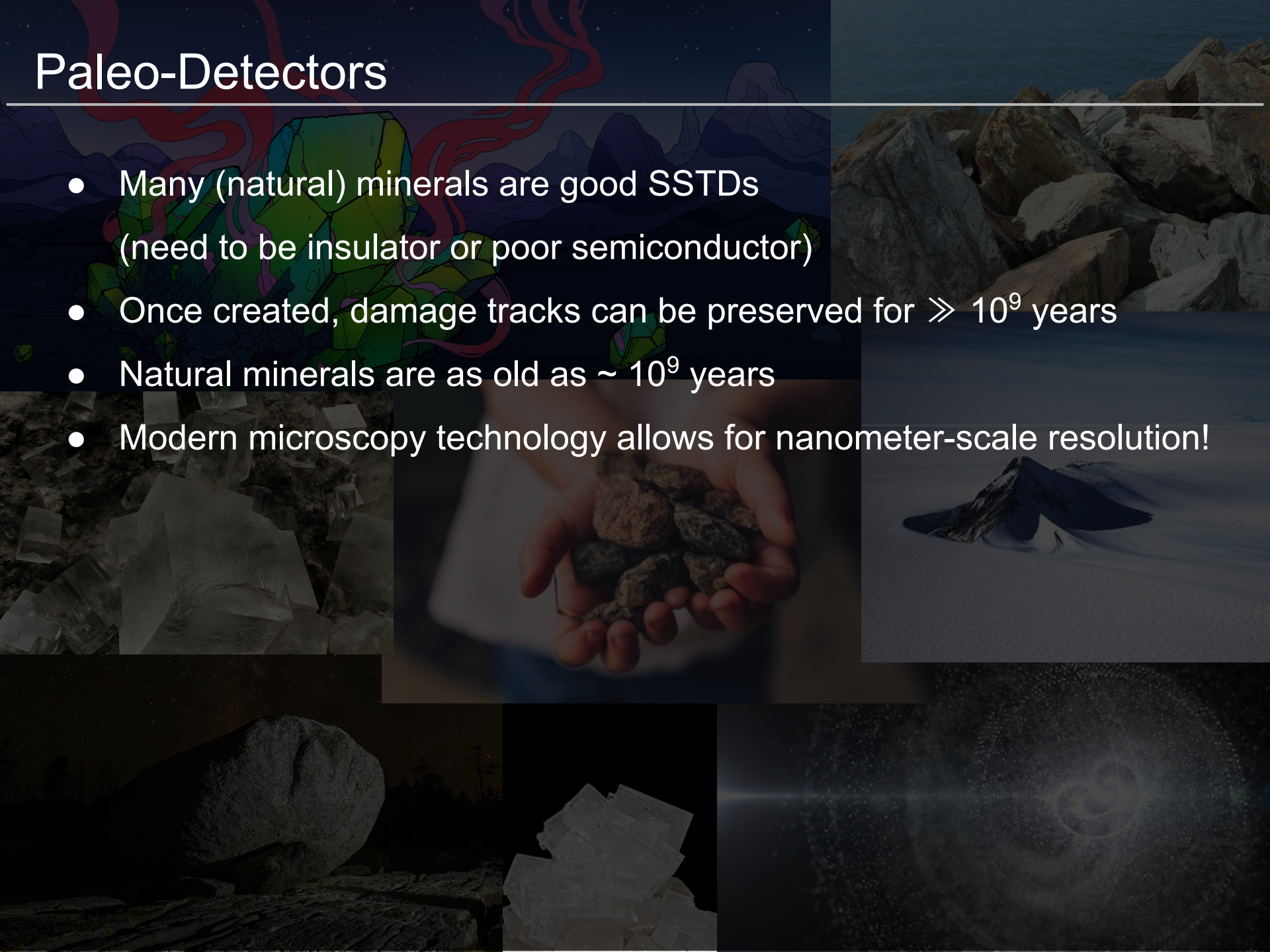
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Exposure through time

$$100 \text{ g} \times 1 \text{ Gyr} = 10 \text{ kilotonne} \times 10 \text{ yr}$$

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\lesssim keV recoil thresholds

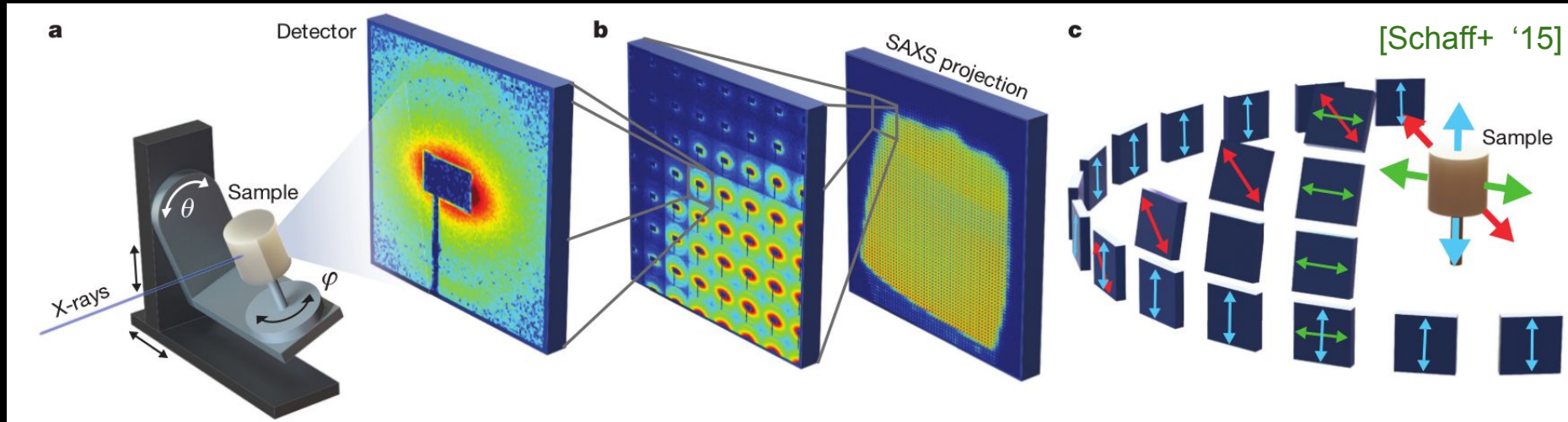
Readout methods: an incomplete list

Throughput

- Optical microscopy
 - Chemical etch + optical (phase contrast) imaging
 - Fluorescence microscopy of color centers (superresolution)
- X-ray microscopy
 - Soft X-ray scattering (table top)
 - Hard X-ray microscopy (synchrotron/FEL) (ptychography!)
- Scanning Probe Microscopy
 - Atomic Force Microscopy
- Focused Beam Microscopy
 - Scanning Electron Microscopy
 - Focused Ion Beam Microscopy (Dual-beam FIB+SEM, He⁺-BM)
 - (Scanning) Transmission Electron Microscopy

Spatial Resolution

Read-out example: X-ray Ptychography



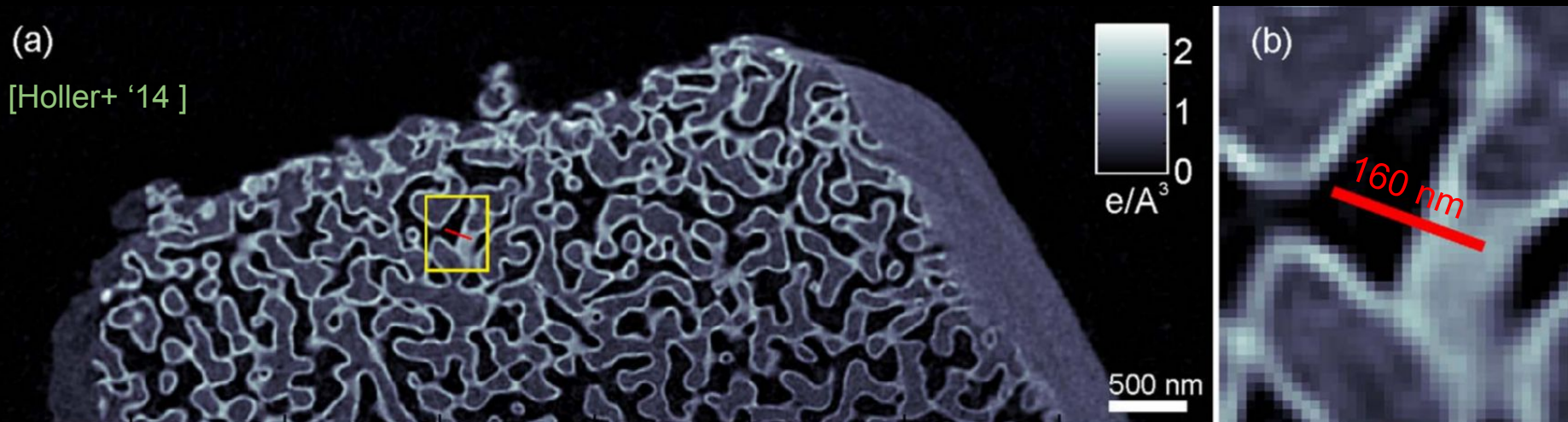
Single "pixel" of sample

Combine "pixels" into 2D picture

Reconstruct 3D image from 2D pictures

Read-out example: X-ray Ptychography

- 16 nm isotropic 3D resolution demonstrated!
- Requires synchrotron light source

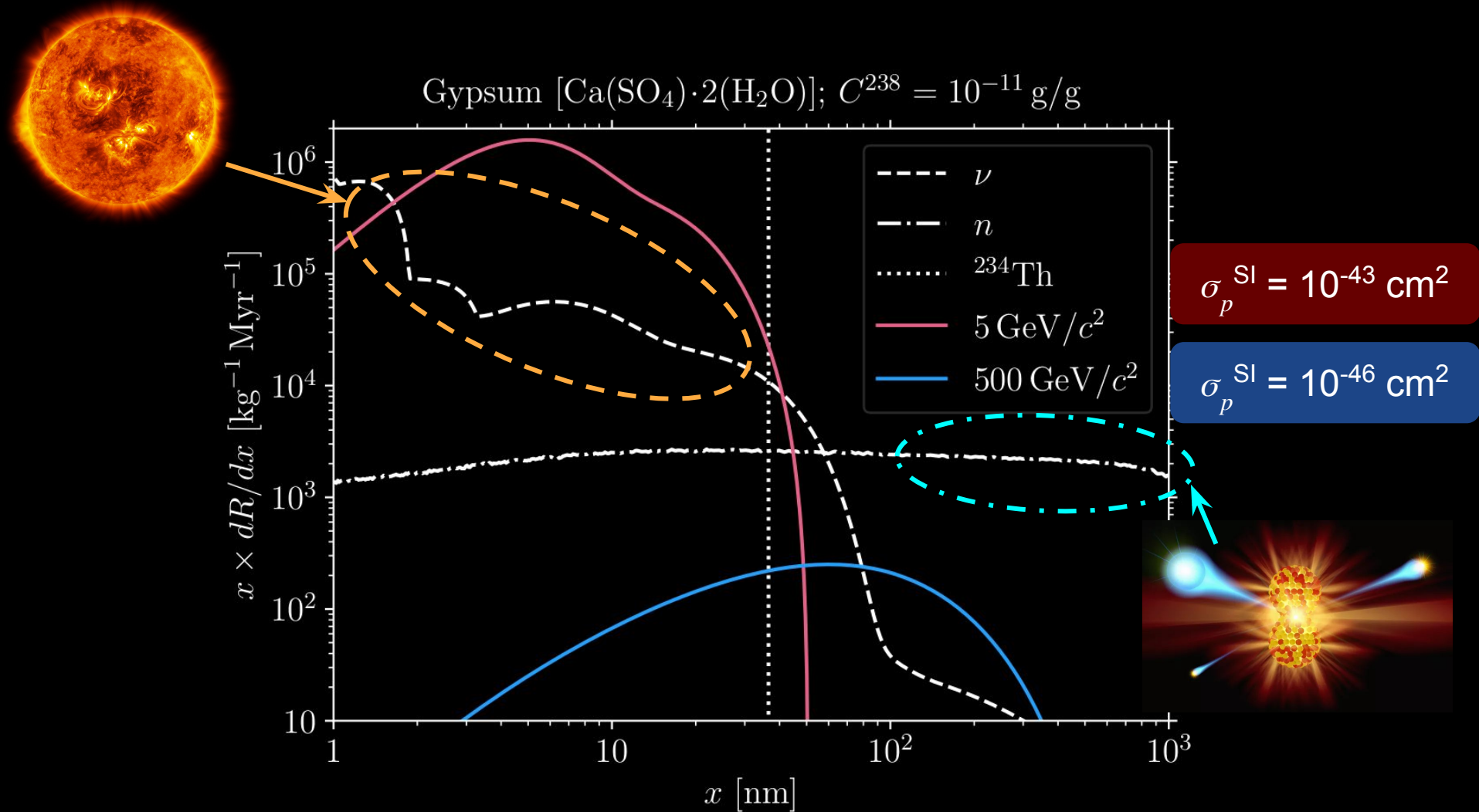


Backgrounds, Backgrounds, Backgrounds

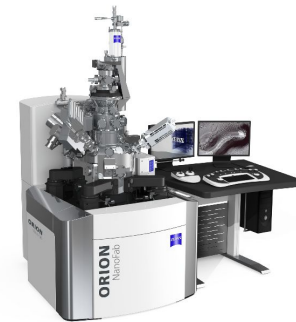
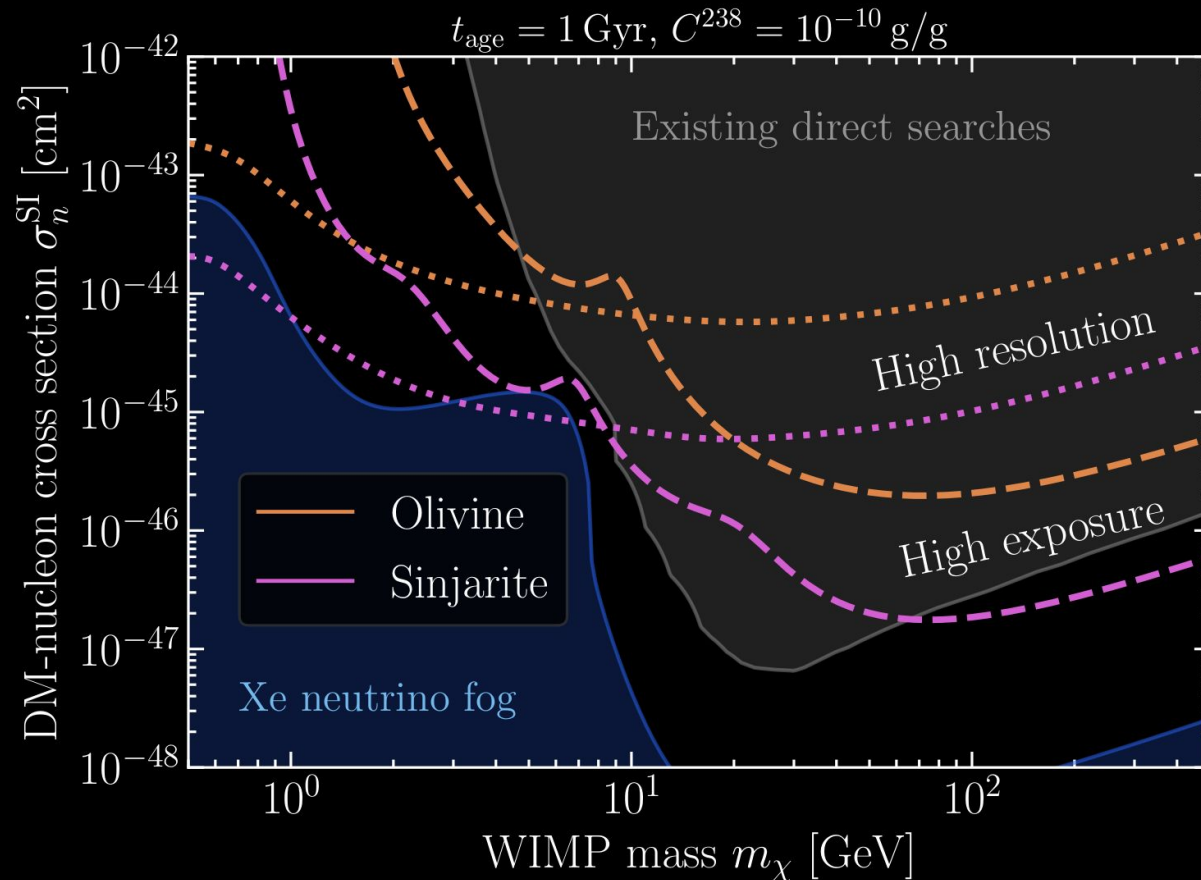
- Natural Defects → no confusion with signal
- Cosmogenic → use target samples from deep underground
- Radioactivity → get radiopure samples (containing hydrogen)
- Neutrinos → background or signal?



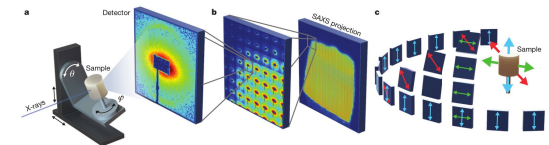
Use track length spectrum to pick up DM signal



Dark Matter Sensitivity Projections

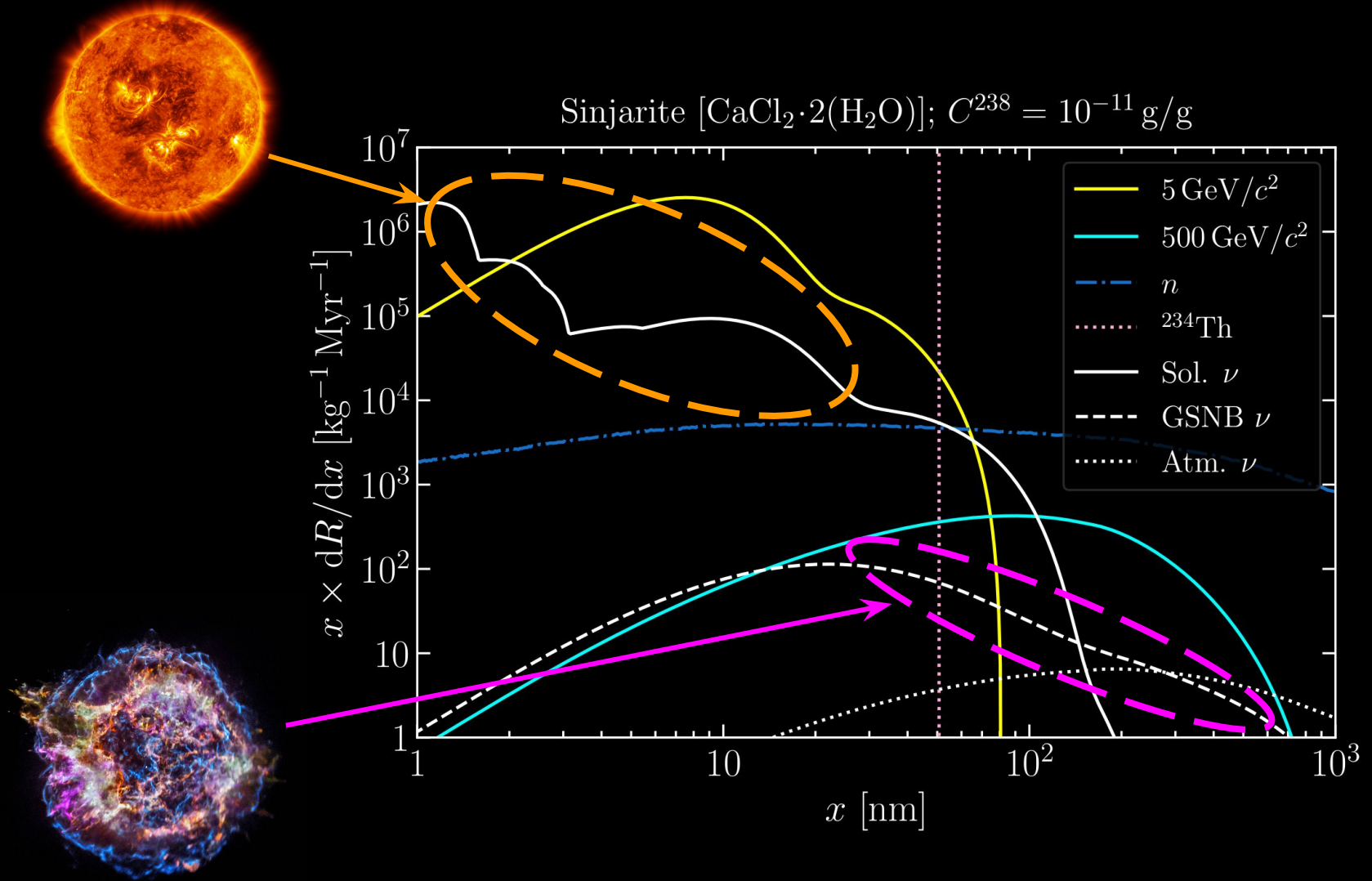


- 1 nm spatial resolution
- (10 mg) x (1 Gyr)

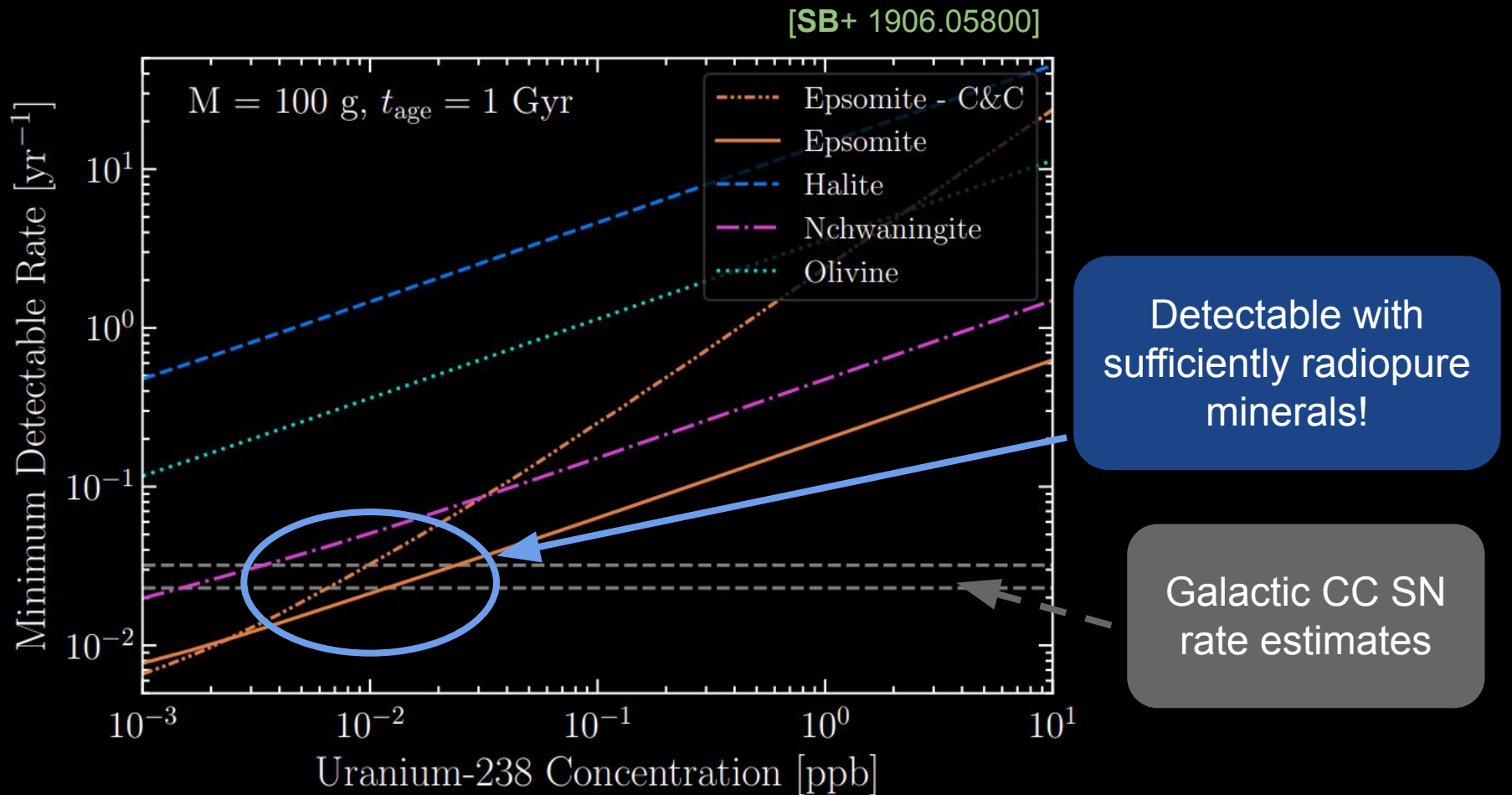


- 15 nm spatial resolution
- (100 g) x (1 Gyr)

What about those neutrinos?



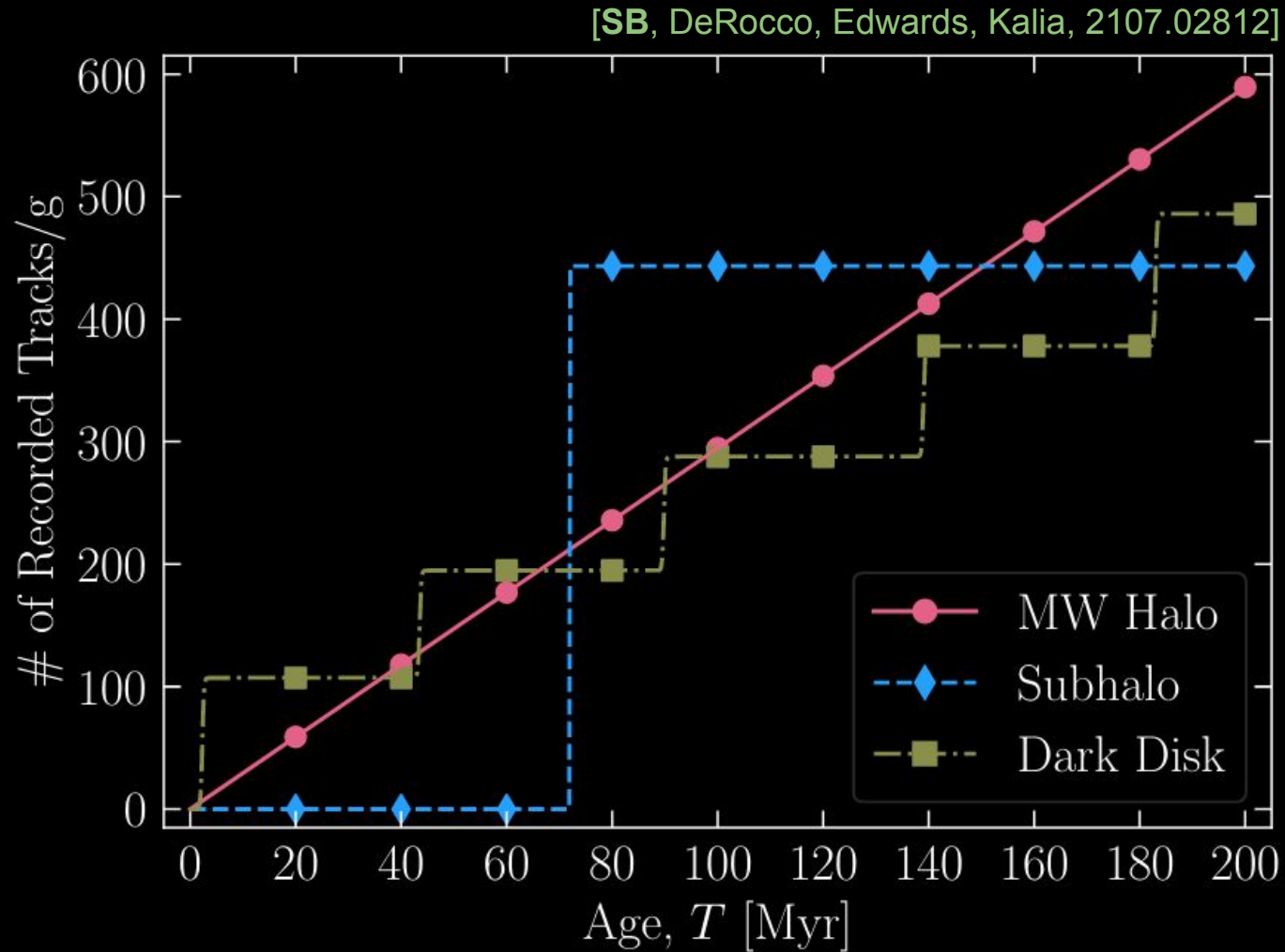
Measuring the Galactic Supernova Rate?



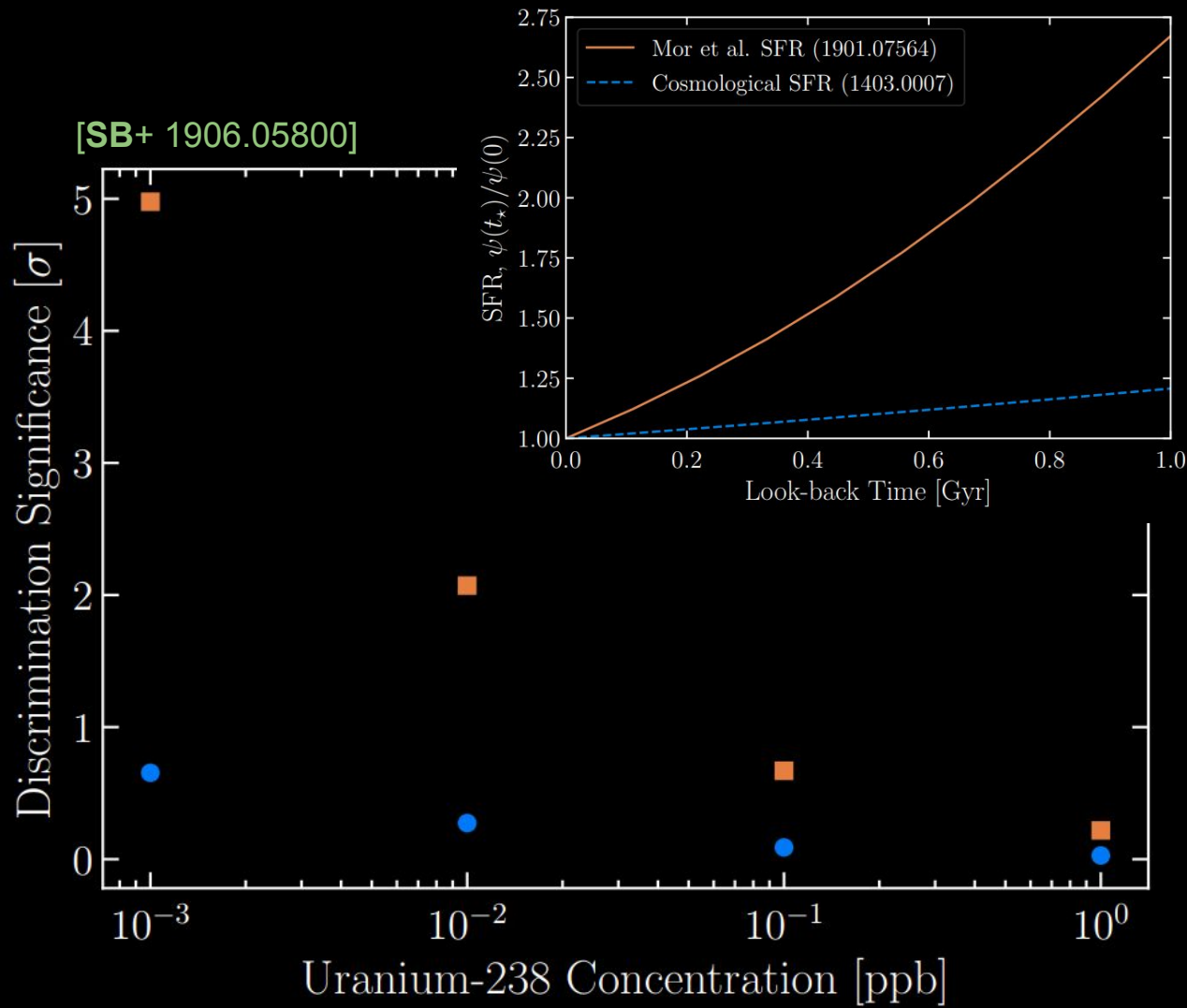
- Halite -- NaCl
- Epsomite -- $\text{MgSO}_4 \cdot 7(\text{H}_2\text{O})$

- Olivine -- $\text{Mg}_{1.6}\text{Fe}_{0.4}(\text{SiO}_4)$
- Nchwaningite -- $\text{Mn}_2\text{SiO}_3(\text{OH})_2 \cdot (\text{H}_2\text{O})$

Beyond the rate: Time-varying Signals



Learning about the Time-Dependence of the SN rate?



Epsomite -- $\text{MgSO}_4 \cdot 7(\text{H}_2\text{O})$

Ongoing and planned feasibility studies

- SLAC
 - Irradiate samples (mica, silicon, ...) with ~10 keV - 1 MeV ions
 - Image with electron beam tomography, chemical/sputter-etch + AFM, coherent X-ray imaging @ LCLS-II, ...
- JAMSTEC
 - Irradiate samples (gypsum, mica, olivine...) with ~10 keV - 200 MeV ions
 - Image with SEM, TEM, chemical etch+AFM, chemical etch+optical, ...
- Toho & Nagoya Universities
 - Irradiate samples with 100 MeV - 10 GeV ions, fission tracks
 - Image with optical (superresolution) microscopy (w/ & w/o chemical etch)
- Karlsruhe Institute for Technology & Heidelberg University
 - Irradiate samples with keV - MeV ions
 - Image with AFM, FIB-SEM, TEM, He⁺-BM, ...

Ongoing and planned feasibility studies (cont'd)

- Queen's University
 - Irradiate samples (olivine & galena) with 1-10 MeV ions
 - Image with HRTEM/...
- PALEOCCENE
 - Irradiate samples (CaF_2) with MeV neutrons
 - Image with fluorescence microscopy
- Maryland University +
 - Low-energy ion implantation in diamond samples with color centers, active instrumentation for charge/phonon readout + optical fluorescence NV-strain microscopy + X-ray diffraction microscopy
 - SEM-CL scanning of Australian Gyr-old quartz for composite DM

100 Myr old mineral
samples from the right
geological environments

Imaged with modern
nanometer-resolution
microscopy

Rocks could teach us about the history of our
Galaxy, what makes up our Universe, and more!

What was the Milky Way's star
formation rate 500 million
years ago?

What is Dark Matter?

STAY TUNED!

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Some other Dark Matter applications

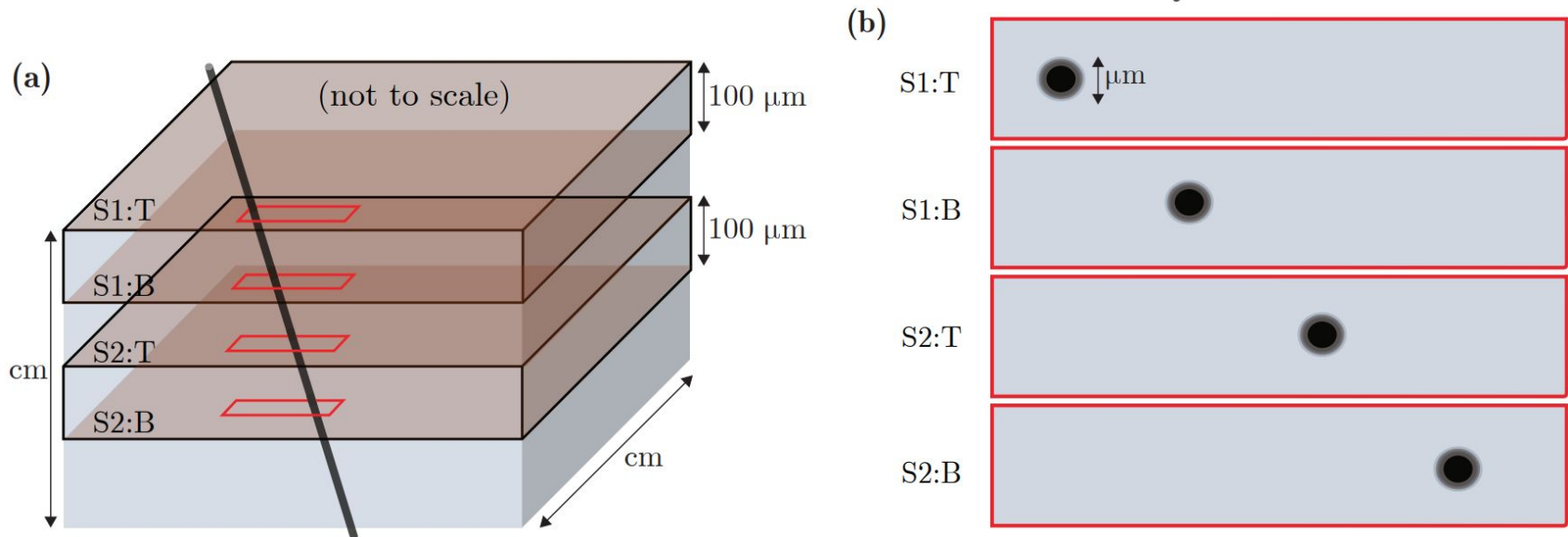
Paleo-detectors for composite DM detection

$$\text{DM flux on Earth: } \Phi_{\text{DM}} \sim 1 \text{ m}^{-2} \text{ yr}^{-1} \left(\frac{10^{19} \text{ GeV}}{m_{\text{DM}}} \right) \sim 10^4 \text{ cm}^{-2} \text{ Gyr}^{-1} \left(\frac{10^{19} \text{ GeV}}{m_{\text{DM}}} \right)$$

[Ebadi+ 2105.03998; Acevedo, Bramante, Goodman 2105.06473]

Ultra-Heavy Dark Matter Search with Electron Microscopy of Geological Quartz

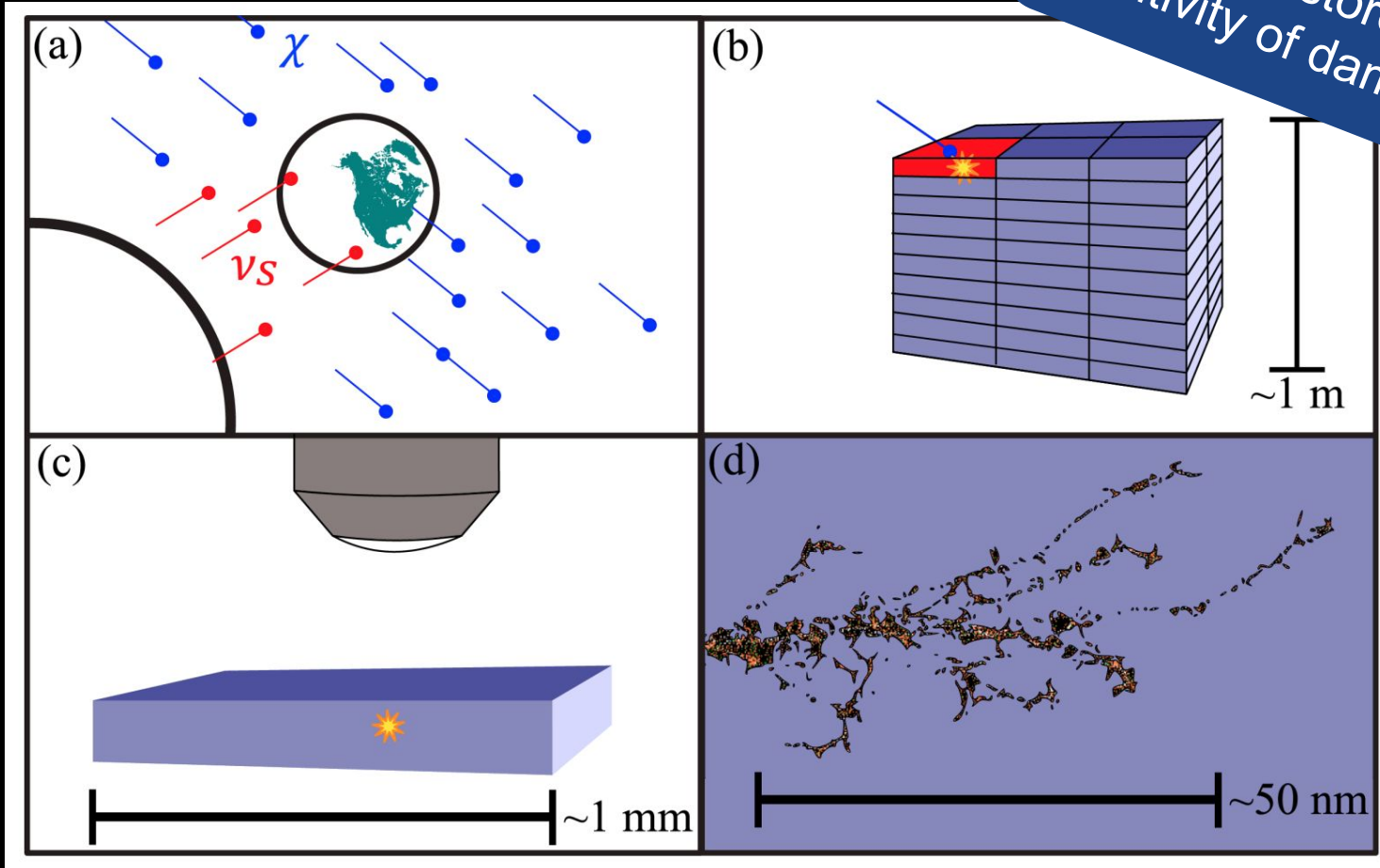
Reza Ebadi ^{†,1,2,*} Anubhav Mathur ^{3,†} Erwin H. Tanin ^{3,†} Nicholas D. Tailby,⁴
 Mason C. Marshall ^{2,5,6} Aakash Ravi ² Raisa Trubko,^{7,8,9} Roger R. Fu,⁹
 David F. Phillips ^{6,‡} Surjeet Rajendran ^{3,§} and Ronald L. Walsworth ^{1,2,5,¶}



Mineral Detectors for as directional DM detectors?

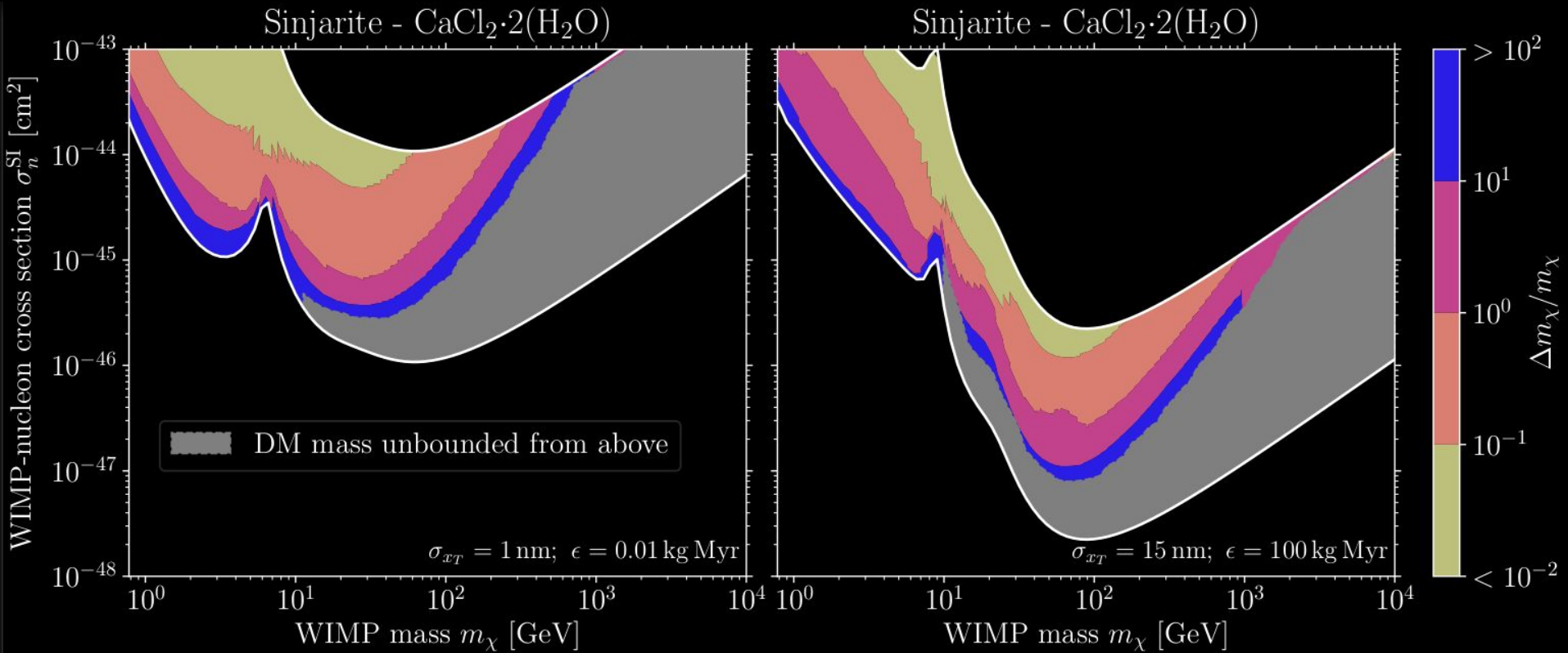
[Rajendran+ 1705.09760, Marshall+ 2009.01028,
Ebadi+ 2203.06037]

Time-tag restores directional
sensitivity of damage track!



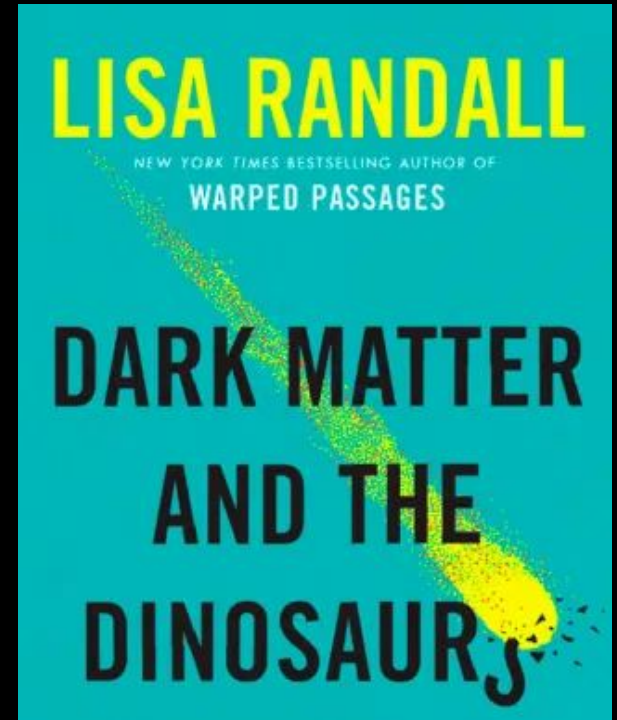
Measuring the Dark Matter mass

[Edwards, SB+ 1811.10549]

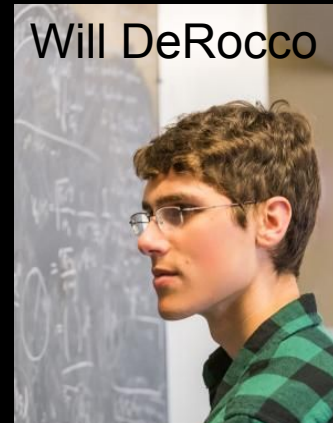


Time-Dependent Dark Matter Signals?

[Springel+ (Aquarius) '08]

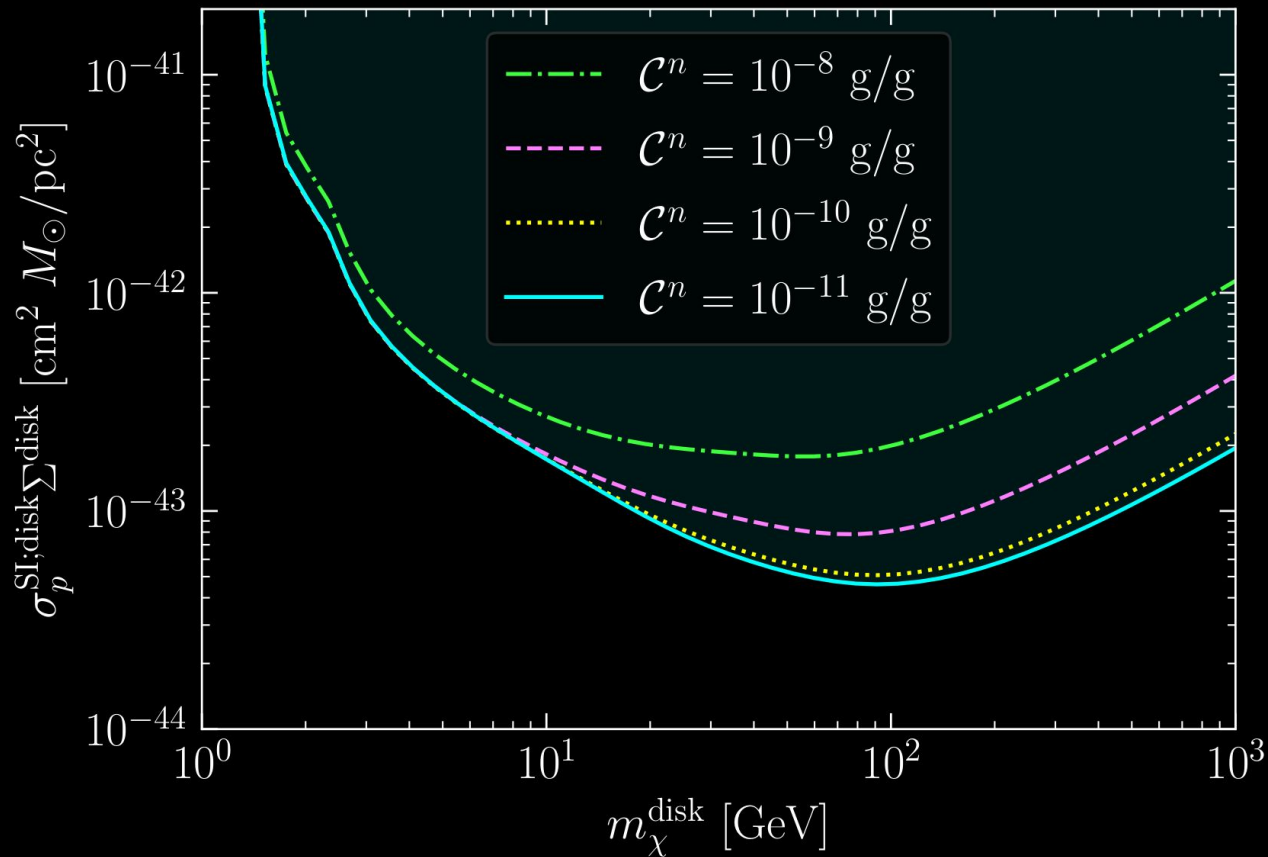


Will DeRocco



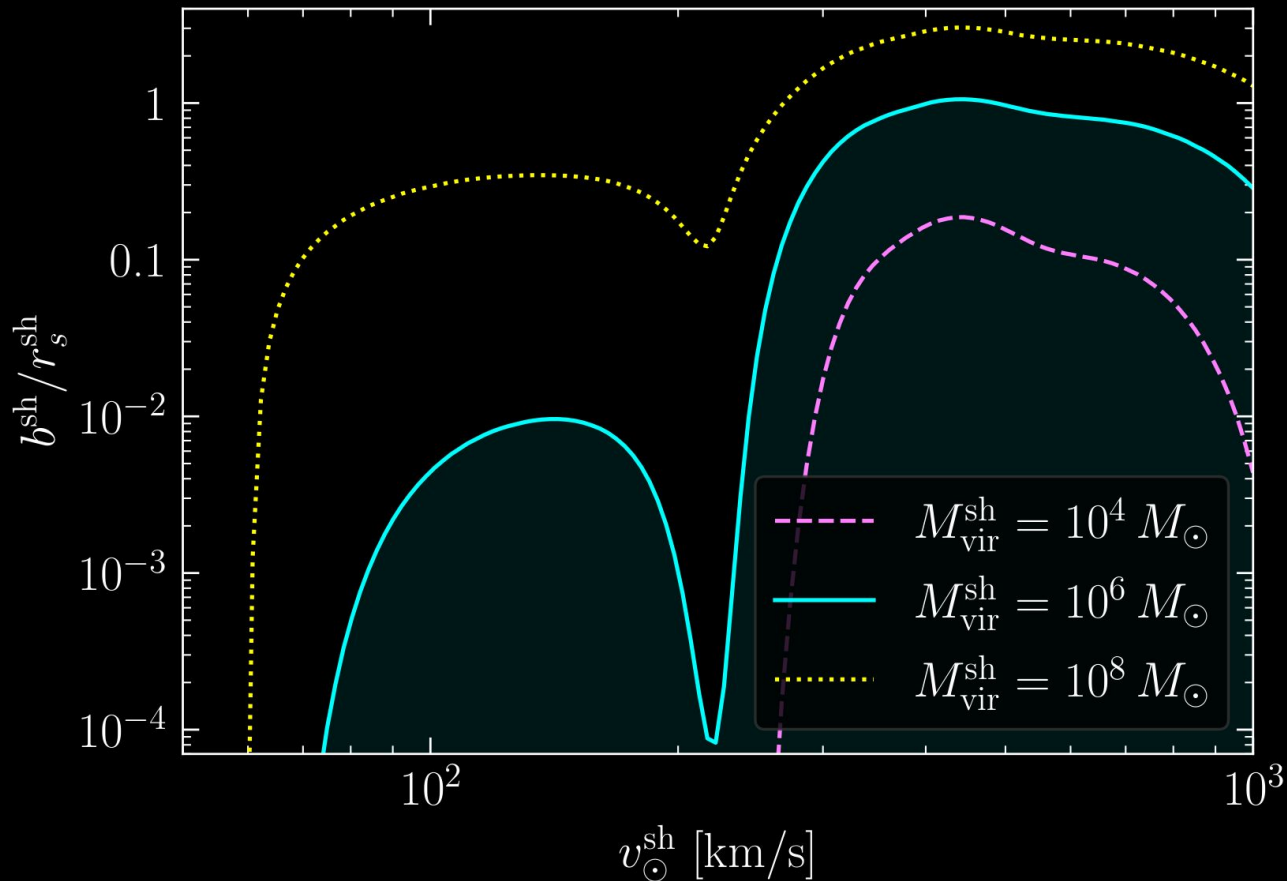
Saarik Kalia

Could we see a dark disk?



- Gypsum $[\text{Ca}(\text{SO}_4) \cdot 2(\text{H}_2\text{O})]$
- “High-Resolution” scenario
- 5 samples with ages $T^n = \{20, 40, \dots, 100\} \text{ Myr}$

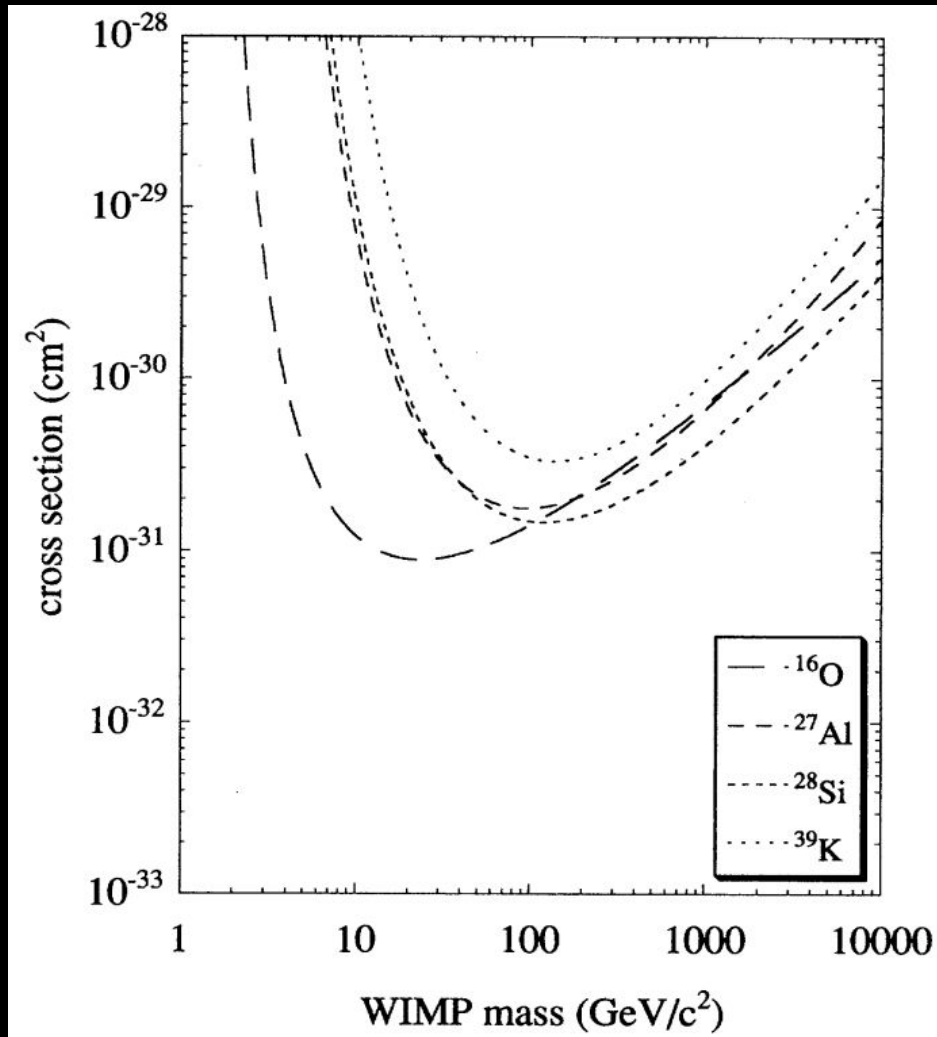
What if we went through a subhalo?



- Gypsum [$\text{Ca}(\text{SO}_4) \cdot 2(\text{H}_2\text{O})$]
- “High-Exposure” scenario
- 5 samples with ages $T^n = \{200, 400, \dots, 1000\}$ Myr

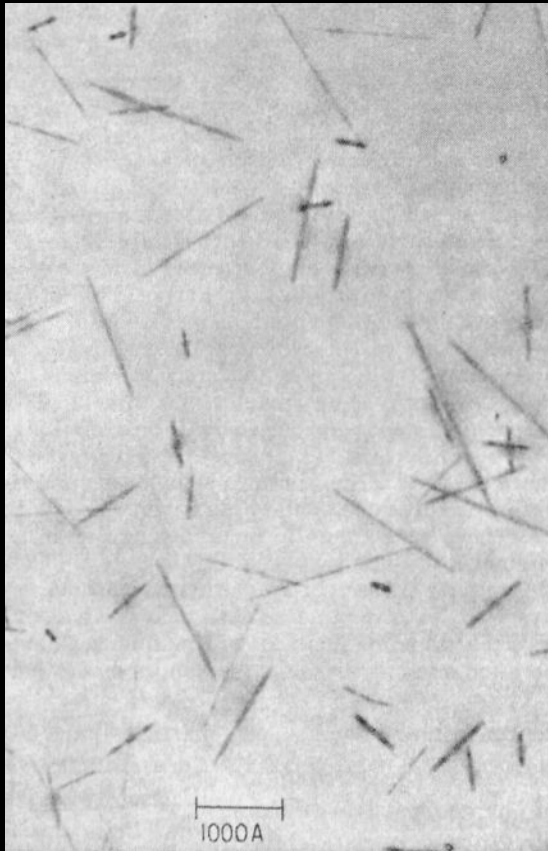
Limits on Dark Matter Using Ancient Mica

D. P. Snowden-Ifft,* E. S. Freeman, and P. B. Price*



What has changed?

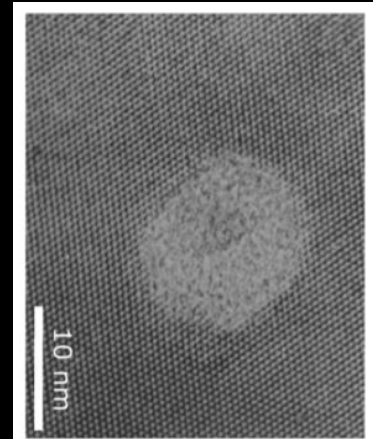
Fission fragment tracks
in synthetic Mica, TEM



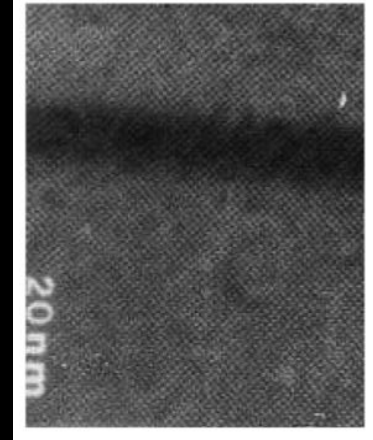
[Price&Walker '63]

High-resolution TEM
pictures of ion tracks

Pb on Mica



Xe on $\text{Y}_3\text{Fe}_5\text{O}_{12}$



[Toulemonde+ '06]



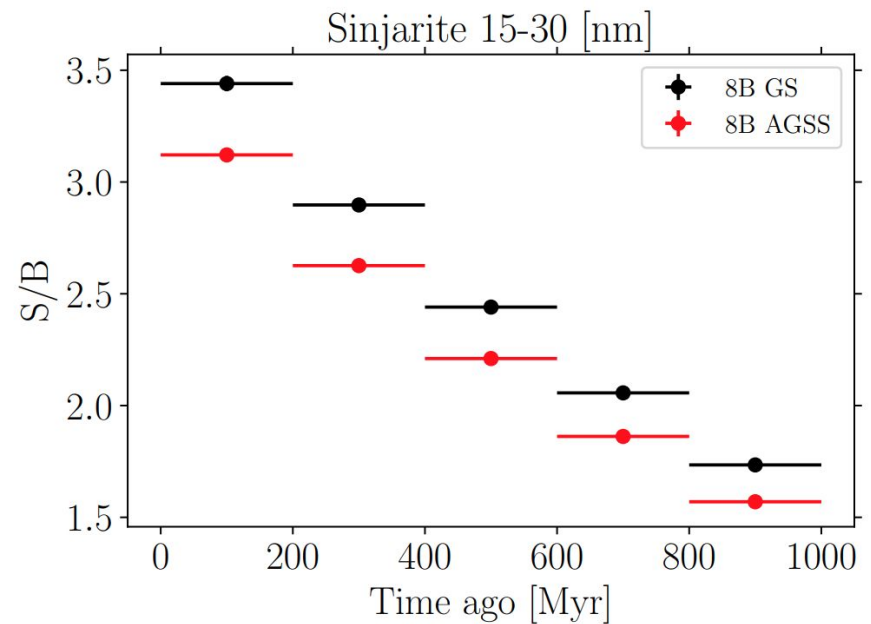
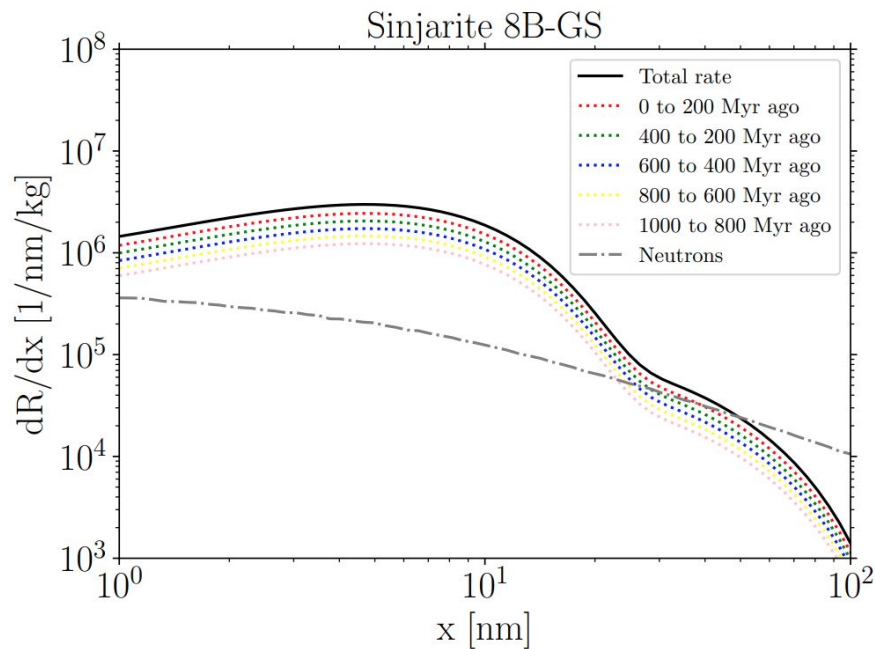
Some other Neutrino applications

What about a little less energetic neutrinos?

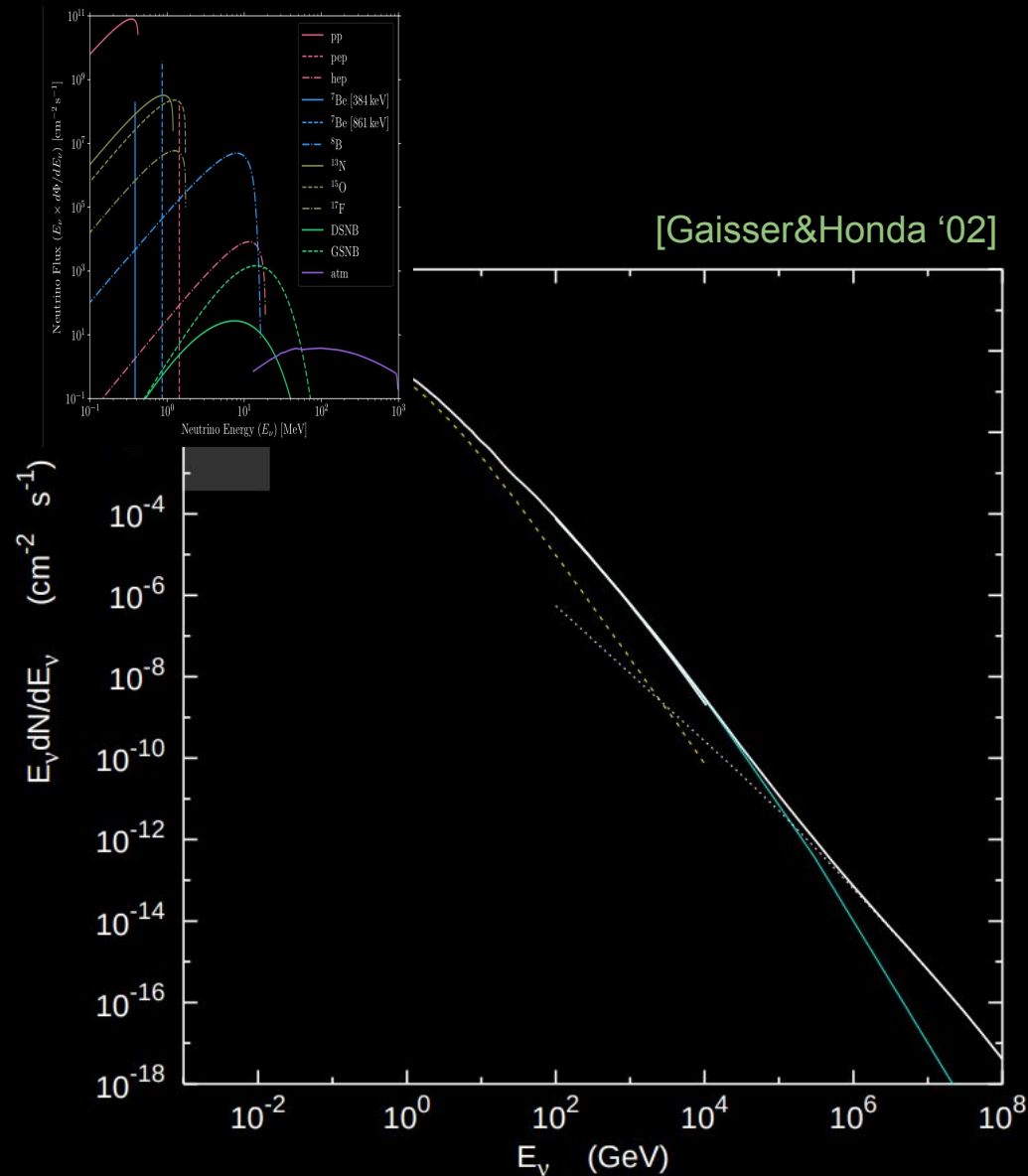
[2102.01755]

Measuring solar neutrinos over Gigayear timescales with Paleo Detectors

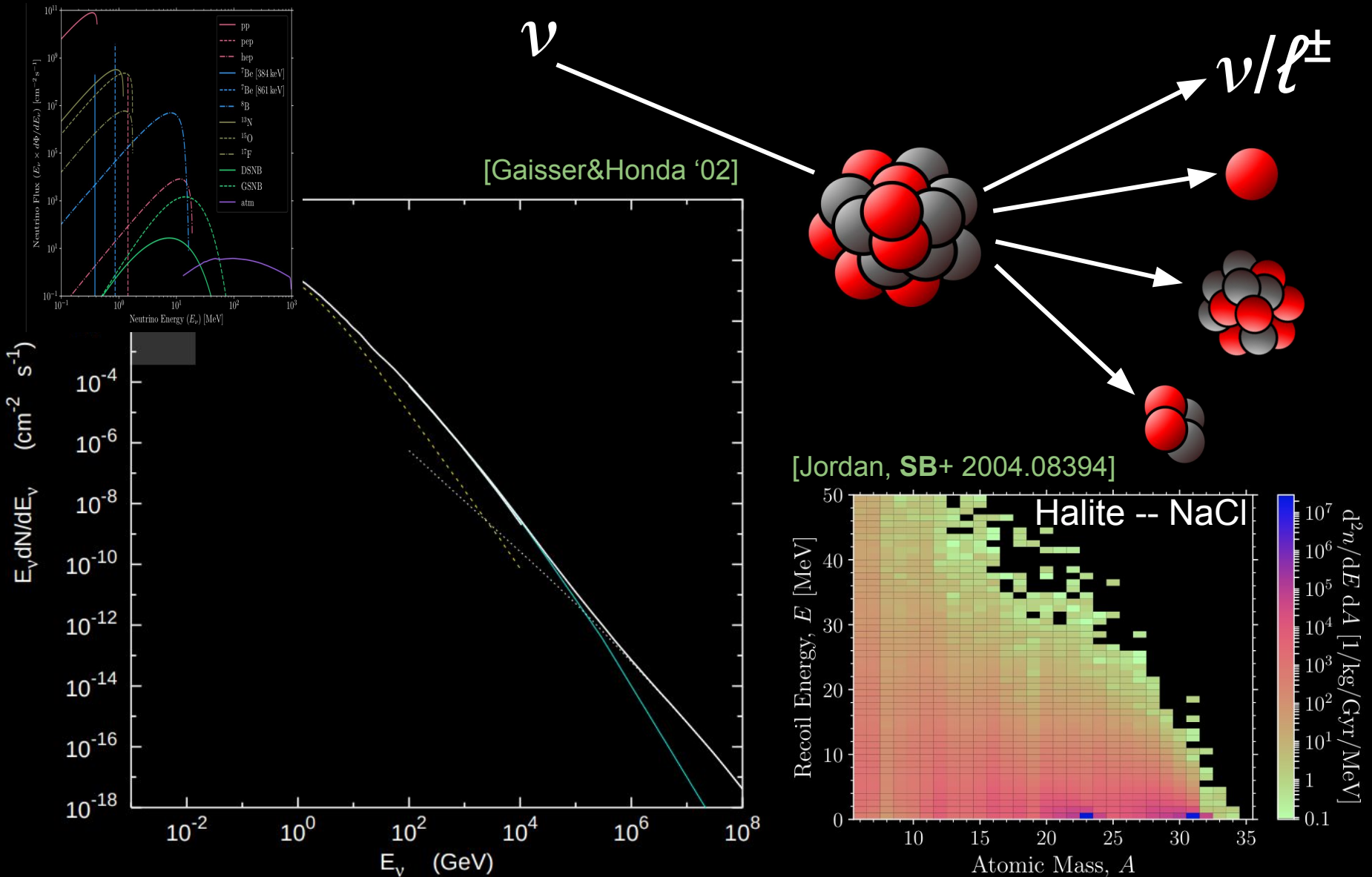
Natalia Tapia-Arellano^{1,*} and Shunsaku Horiuchi^{1,†}



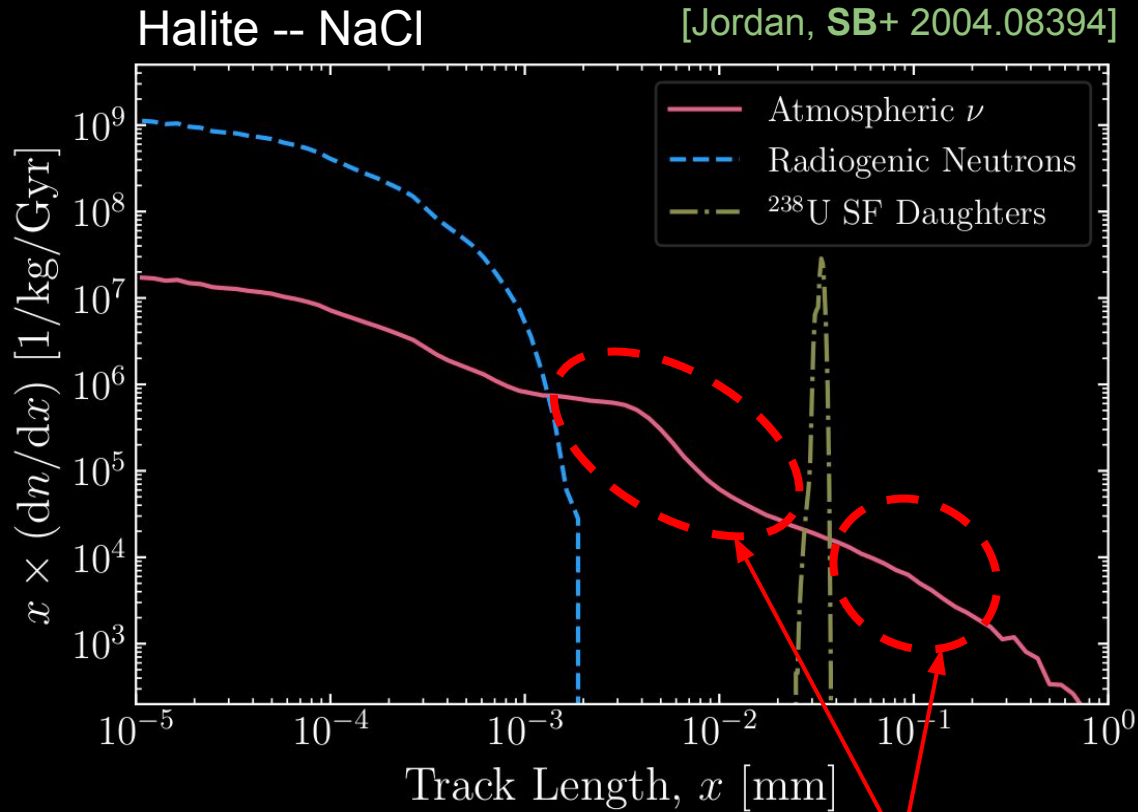
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What About a Little More Energetic Neutrinos?



Cosmic Rays & Atmospheric Neutrinos



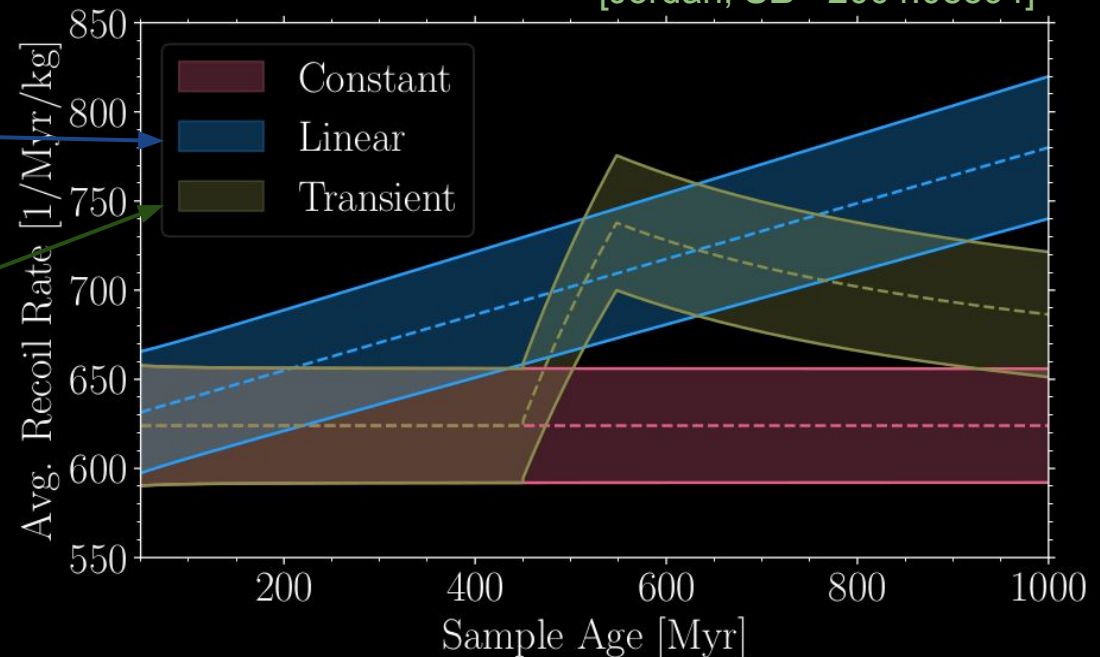
Cosmic Rays & Atmospheric Neutrinos

Could we learn about the rate of cosmic rays hitting Earth going back one billion years?

[Jordan, SB+ 2004.08394]

50% drop over 1 Gyr

100% enhancement for 100 Myr

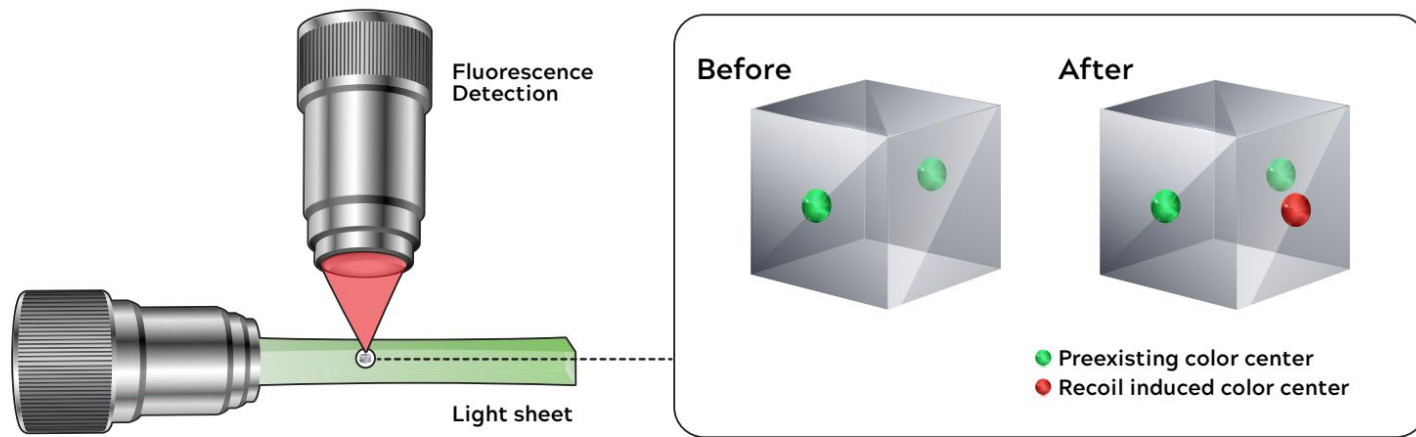


What about man-made neutrinos?

[Cogswell, Goel, Huber 2104.13926; Alfonso+ 2203.05525]

Passive low-energy nuclear recoil detection with color centers

Bernadette K. Cogswell,^{1,*} Apurva Goel,^{2,†} and Patrick Huber^{1,‡}



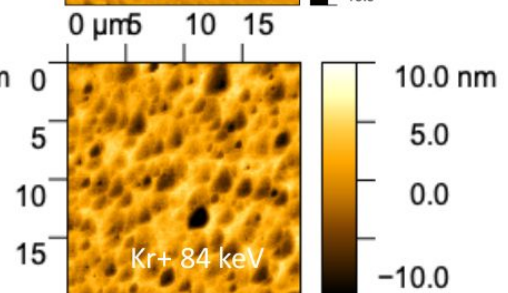
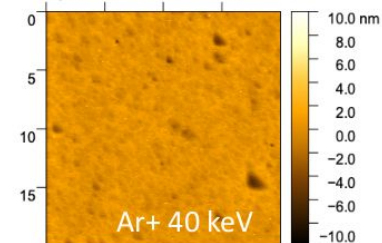
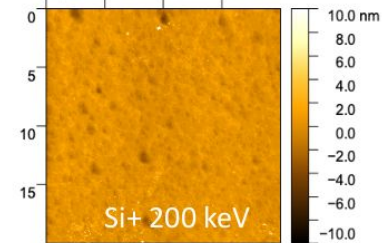
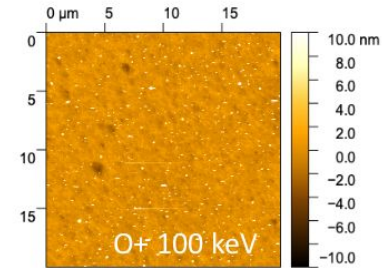
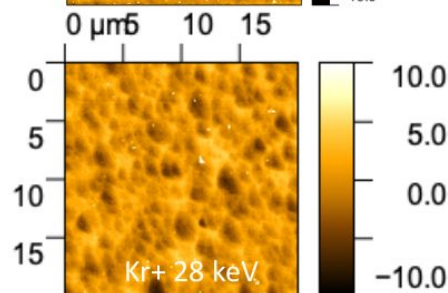
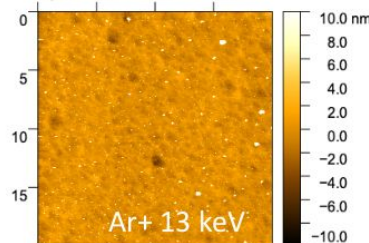
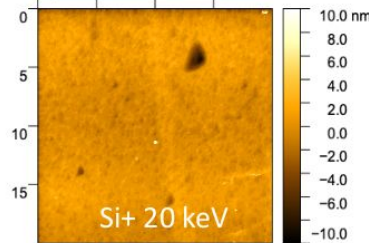
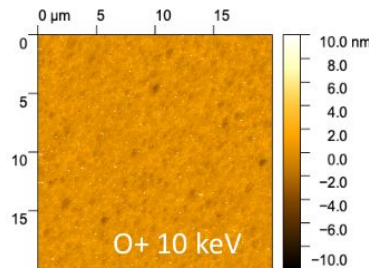
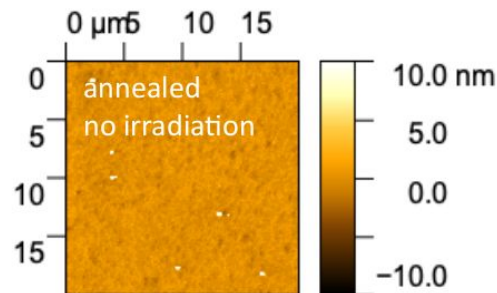
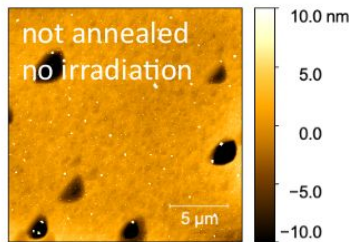
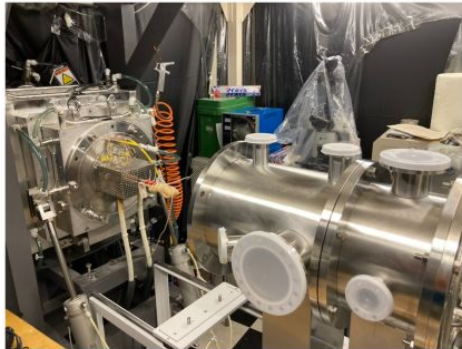
Search for defects from O(100) eV nuclear recoils caused by CEvNS by reactor neutrinos in man-made crystals

→ monitor nuclear reactors?

Feasibility studies

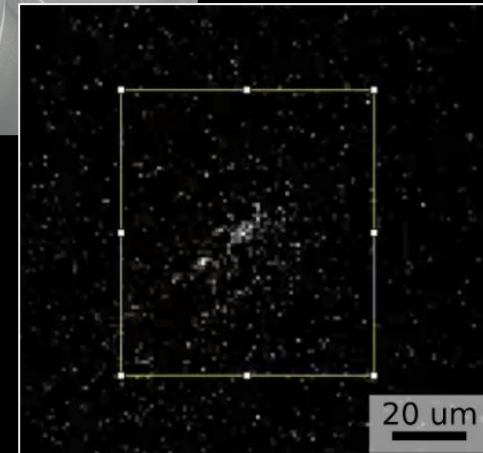
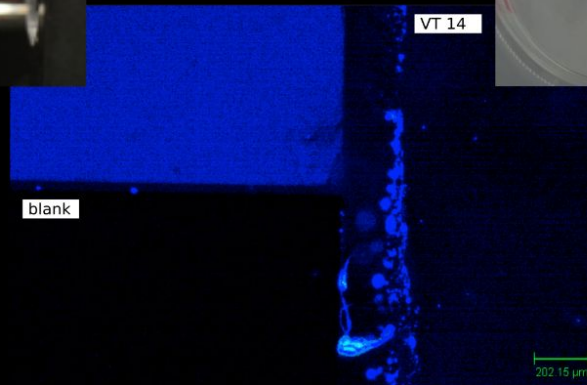
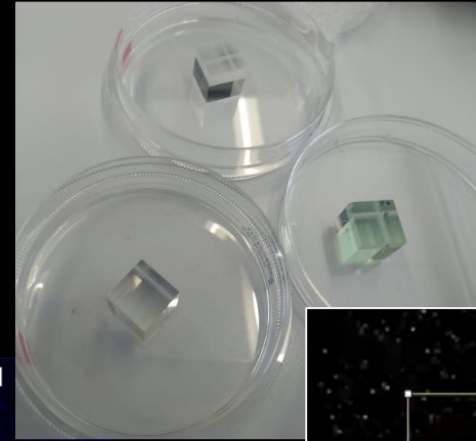
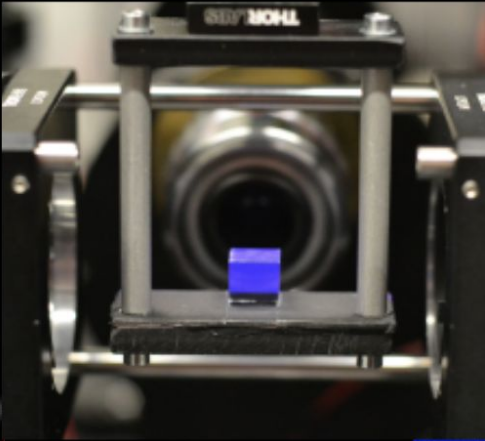
Feasibility studies by Shigenobu Hirose @ JAMSTEC

Ion beam experiments at Kanagawa U.



Feasibility studies: Gabriela Araujo+ @ U Zurich

- Fluorescence (light sheet) microscopy

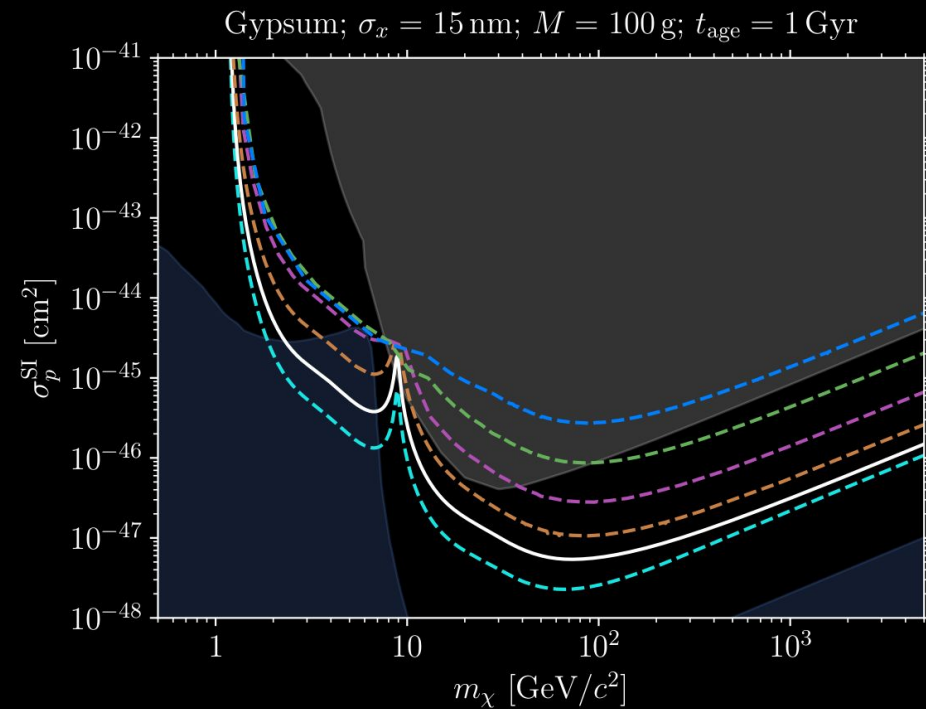
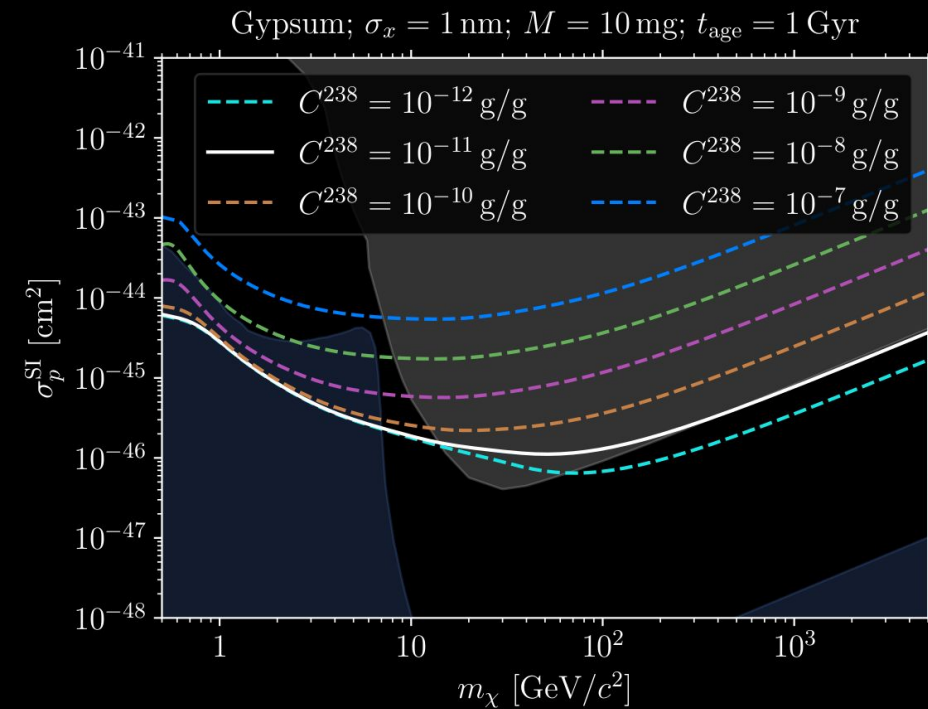


Backup

DM sensitivity for different radiopurities

“High Resolution”

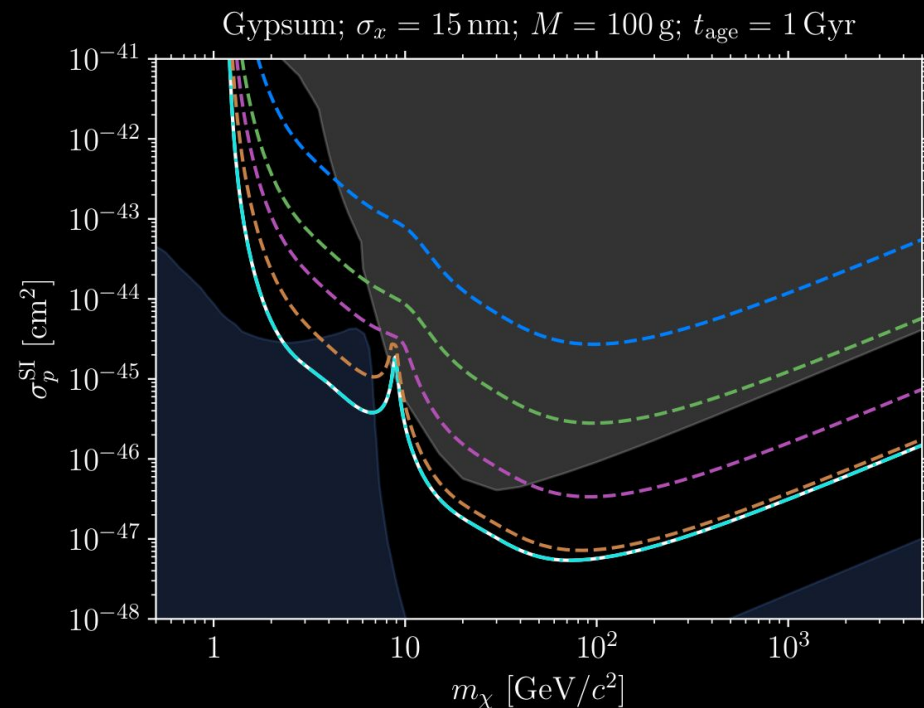
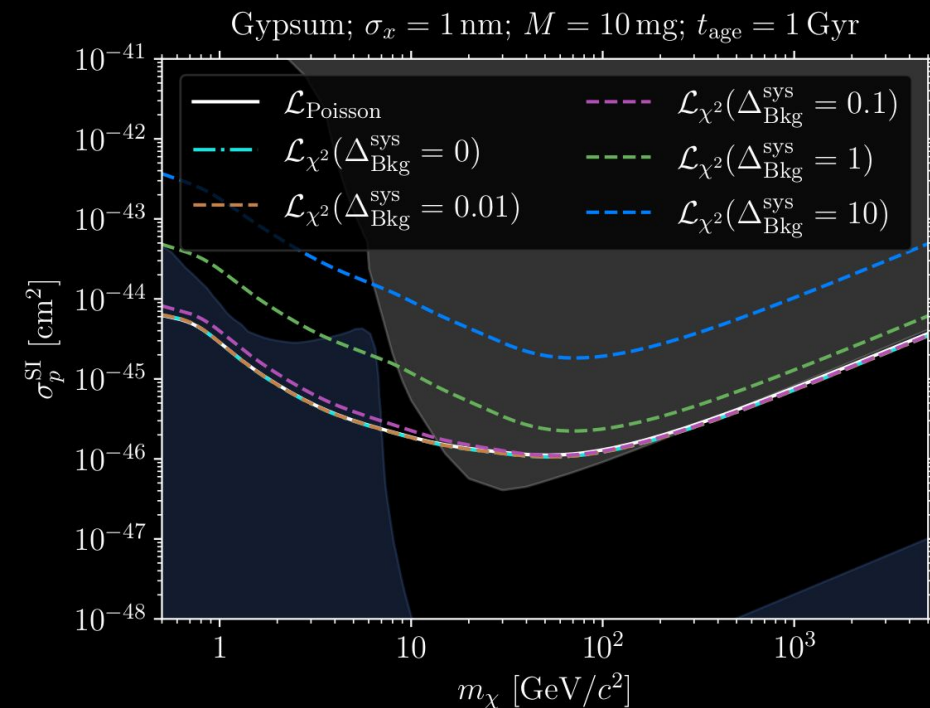
“High Exposure”



Robustness Against Errors in Background Shape

“High Resolution”

“High Exposure”



Sensitivity Projections: SD Proton-Only

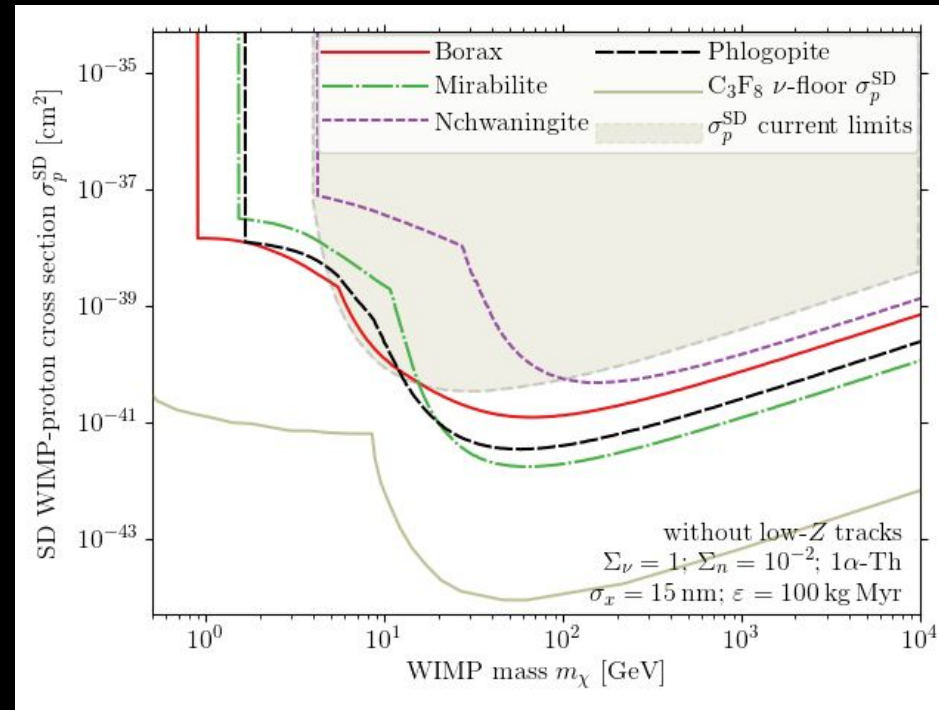
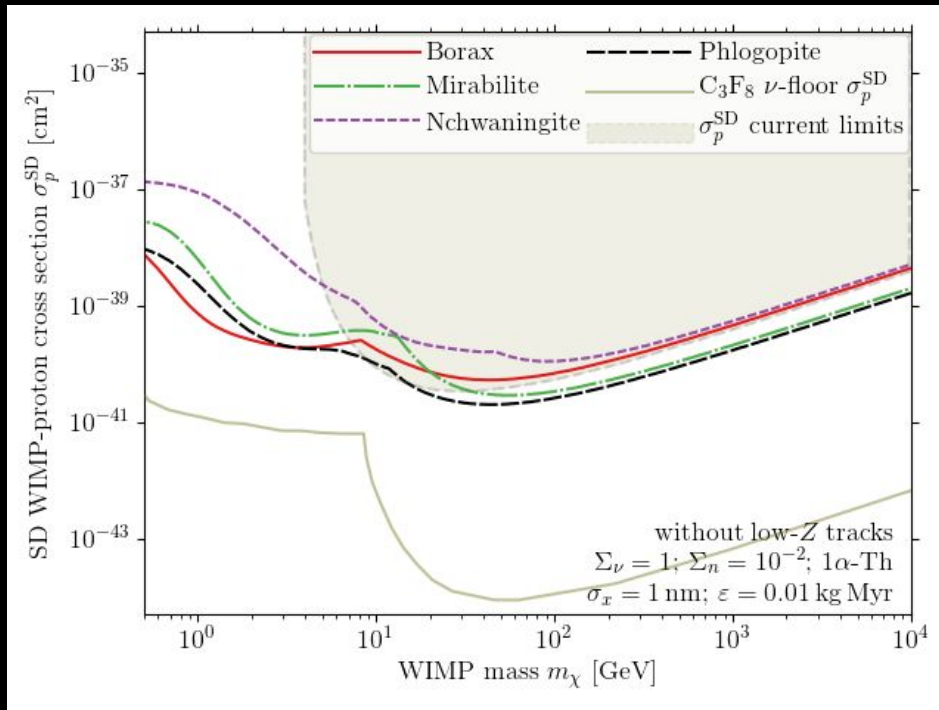
[SB+ '19 (1811.06844)]

Good resolution, small target mass

- 1 nm spatial resolution
- Exposure: (10 mg) x (1 Gyr)

Larger target mass, worse resolution

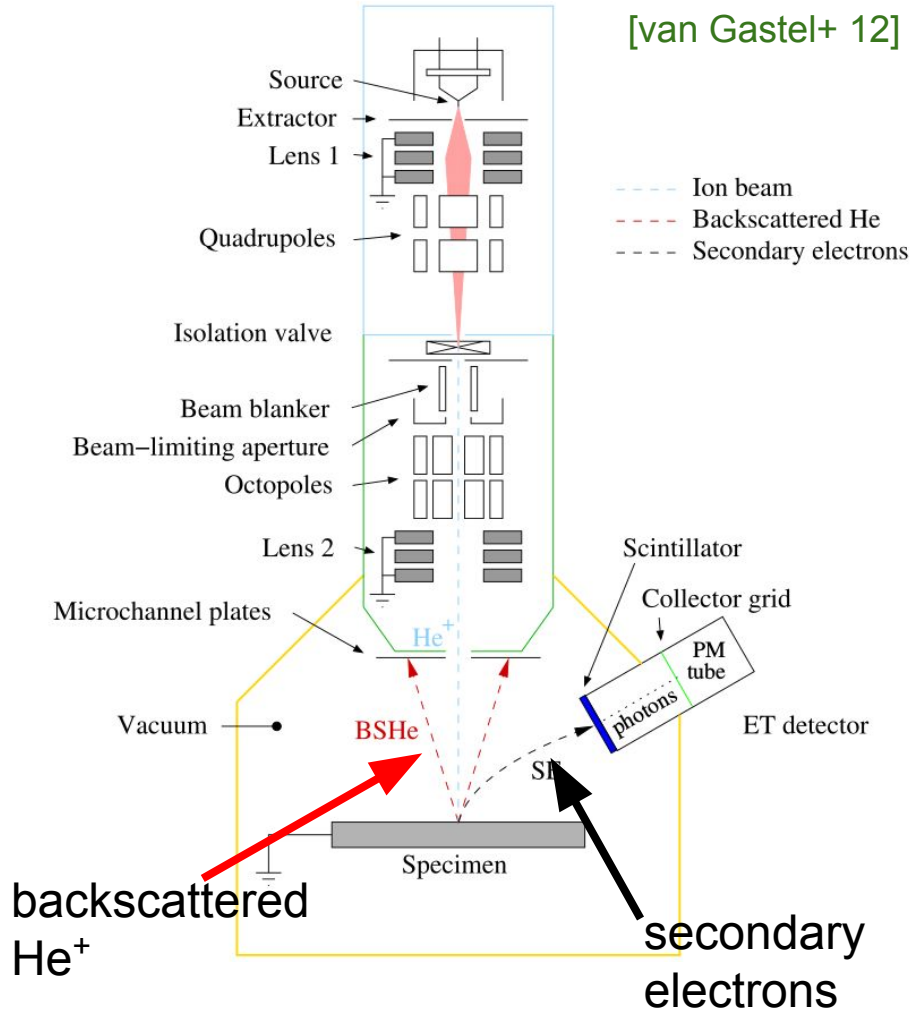
- 15 nm spatial resolution
- Exposure: (100 g) x (1 Gyr)



Borax -- $\text{Na}_2(\text{B}_4\text{O}_5)(\text{OH})_2 \cdot 8(\text{H}_2\text{O})$
 Mirabilite -- $\text{Na}_2\text{SO}_4 \cdot 10(\text{H}_2\text{O})$

Nchwaningite -- $\text{Mn}_2\text{SiO}_3(\text{OH})_2 \cdot (\text{H}_2\text{O})$
 Phlogopite -- $\text{KMg}_3\text{AlSi}_3\text{O}_{10}\text{F}(\text{OH})$

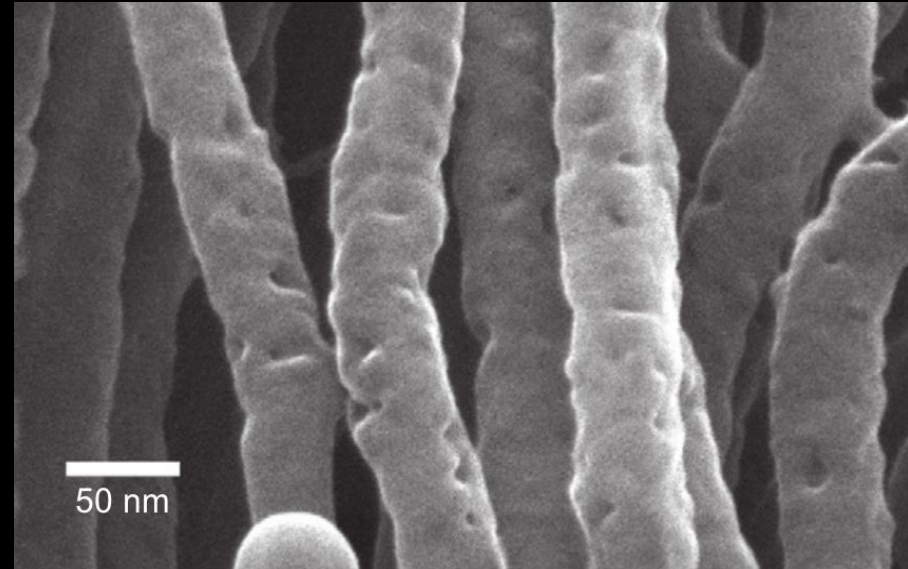
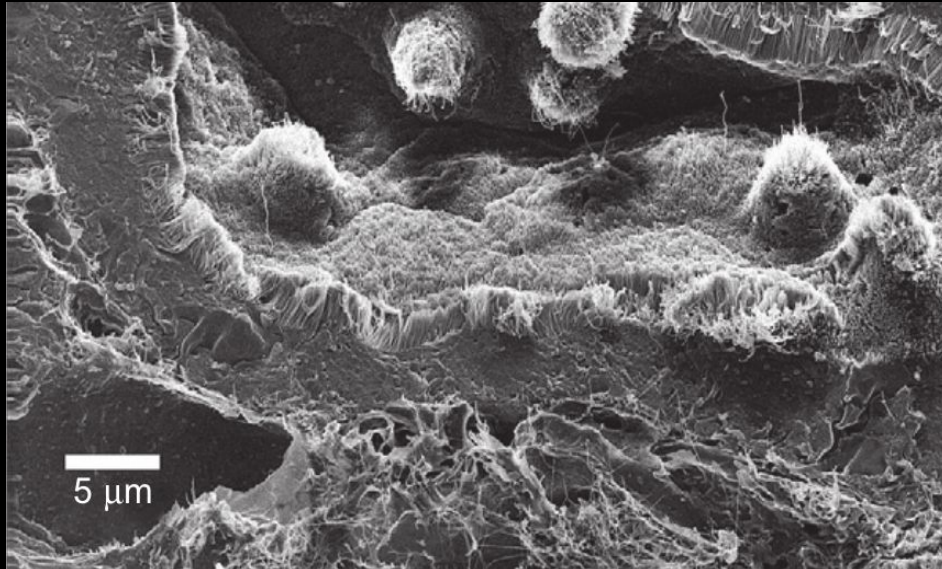
Read-Out Methods (ii): He-Ion Beam Microscopy



Read-Out Methods (ii): He-Ion Beam Microscopy

Overview & Zoom-in of rodent kidney

[Hill+ '12]



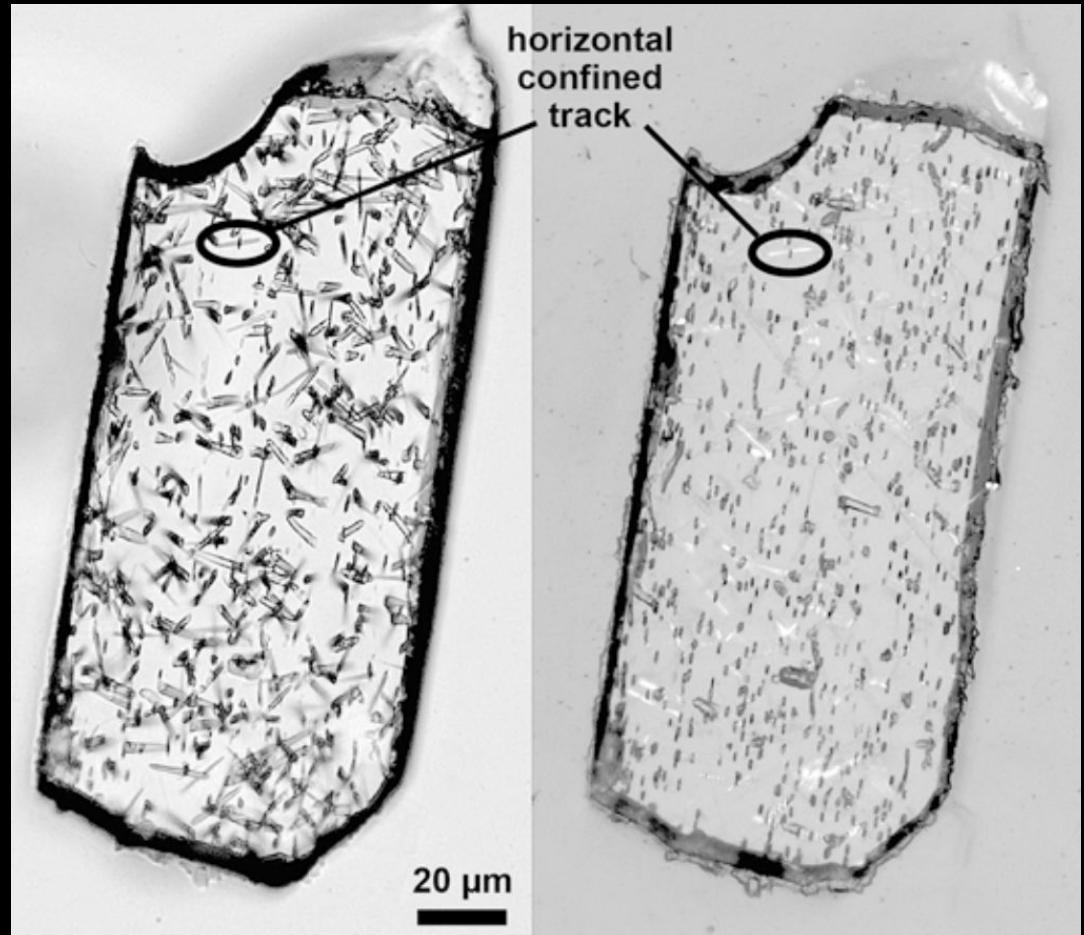
Read-Out Methods: Optical Microscopy

Etched fission tracks in Apatite

transmission

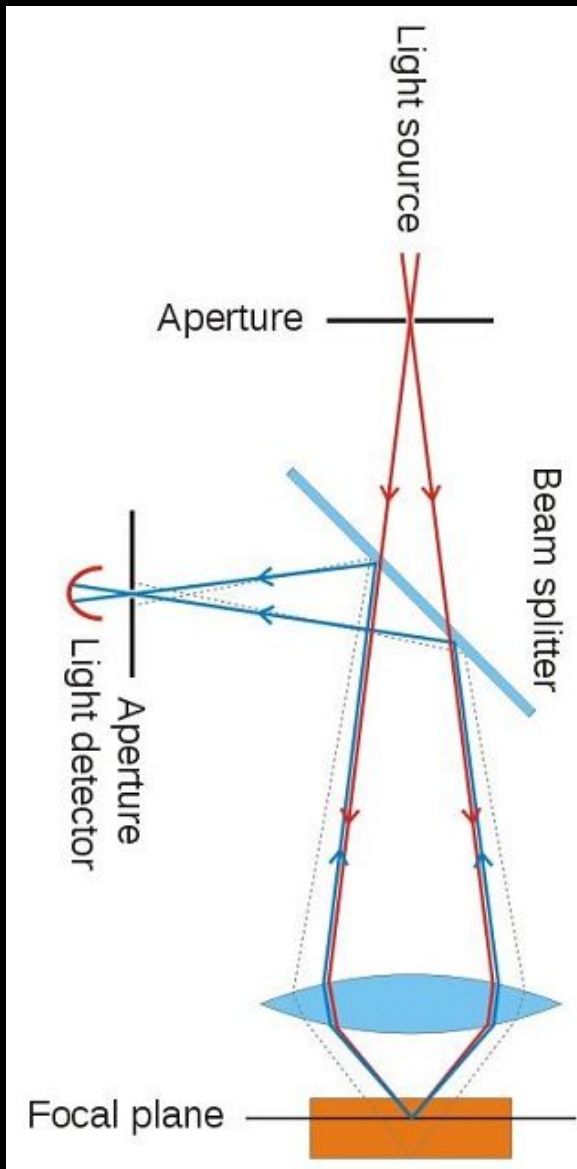
reflection

- Widely available
- Cheap
- Resolutions of a few 100 nm
- Requires etching



[Thomson '16]

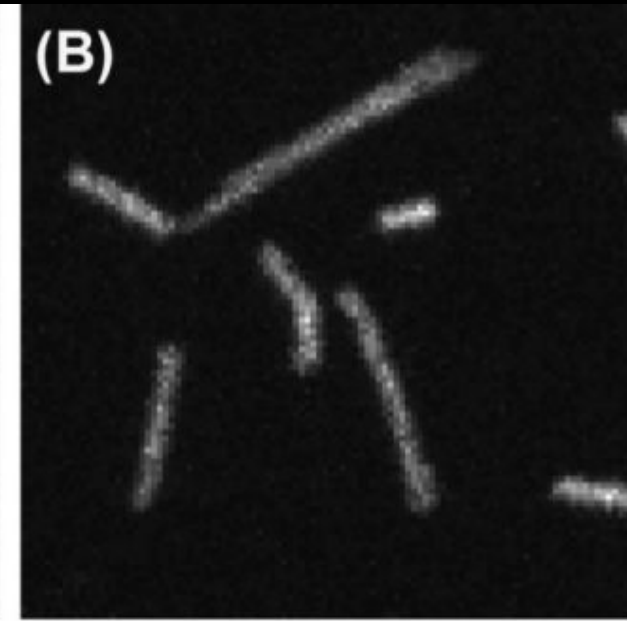
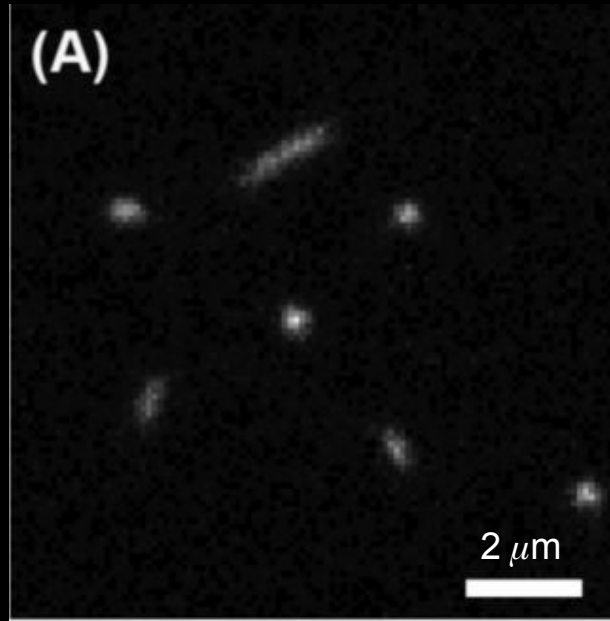
Read-Out Methods: Confocal Microscopy



α -tracks in $\text{Al}_2\text{O}_3:\text{C},\text{Mg}$ (without etching!)

Single picture

Longest projection of 3D

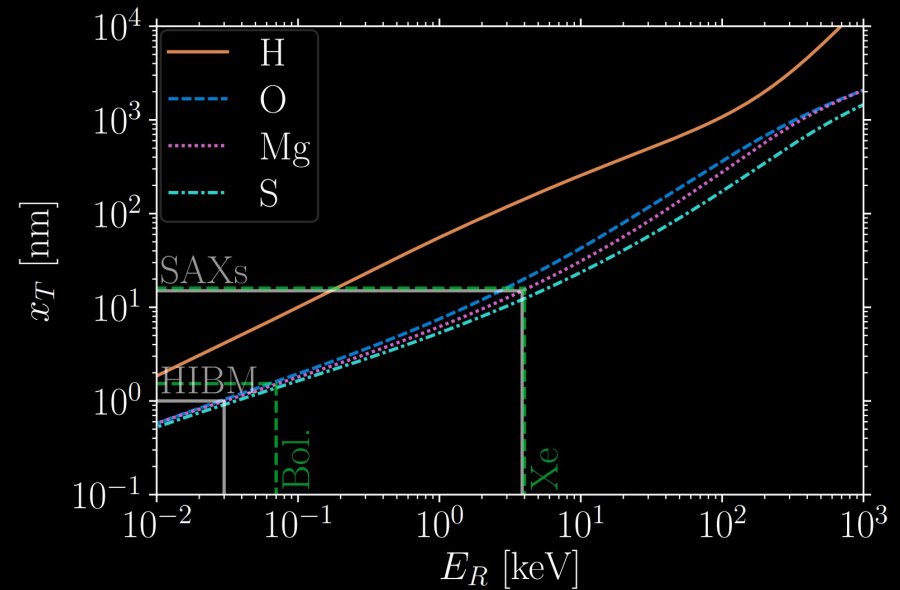
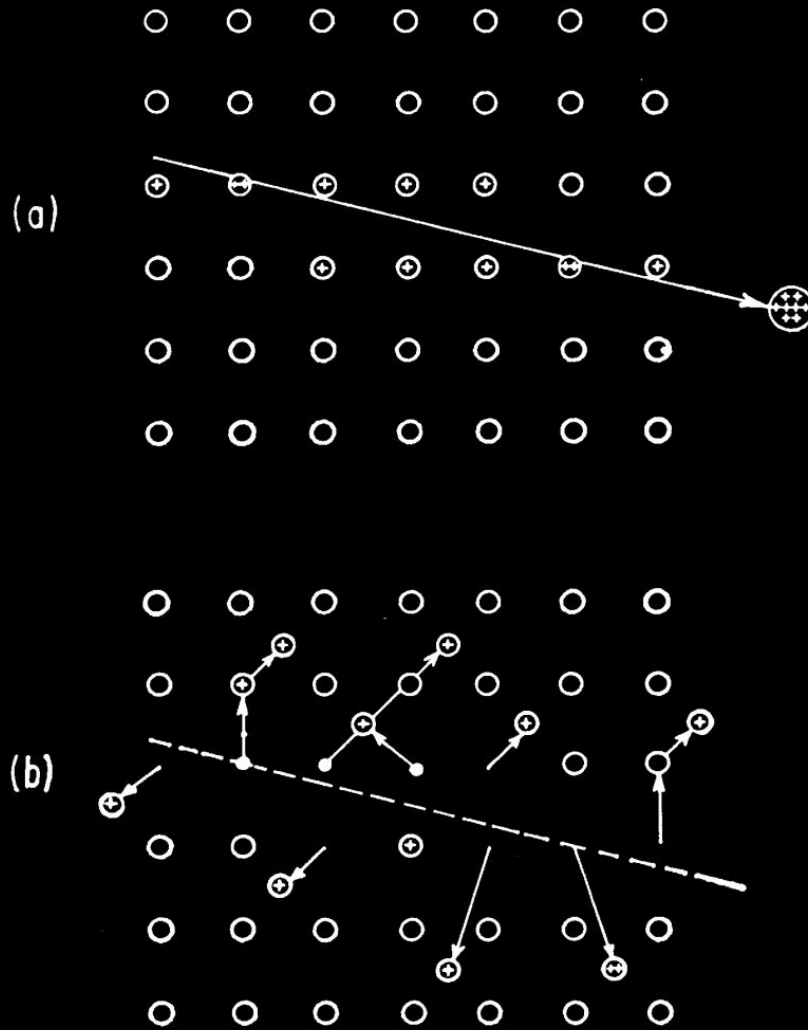


[Kouwenberg+ '18]

- Widely available
- Resolution $\sim 100\ \text{nm}$
- Requires fluorescent targets

Damage (tracks) from recoiling nuclei

Ion Explosion Spike [Fleischer, Price, Walker '65]

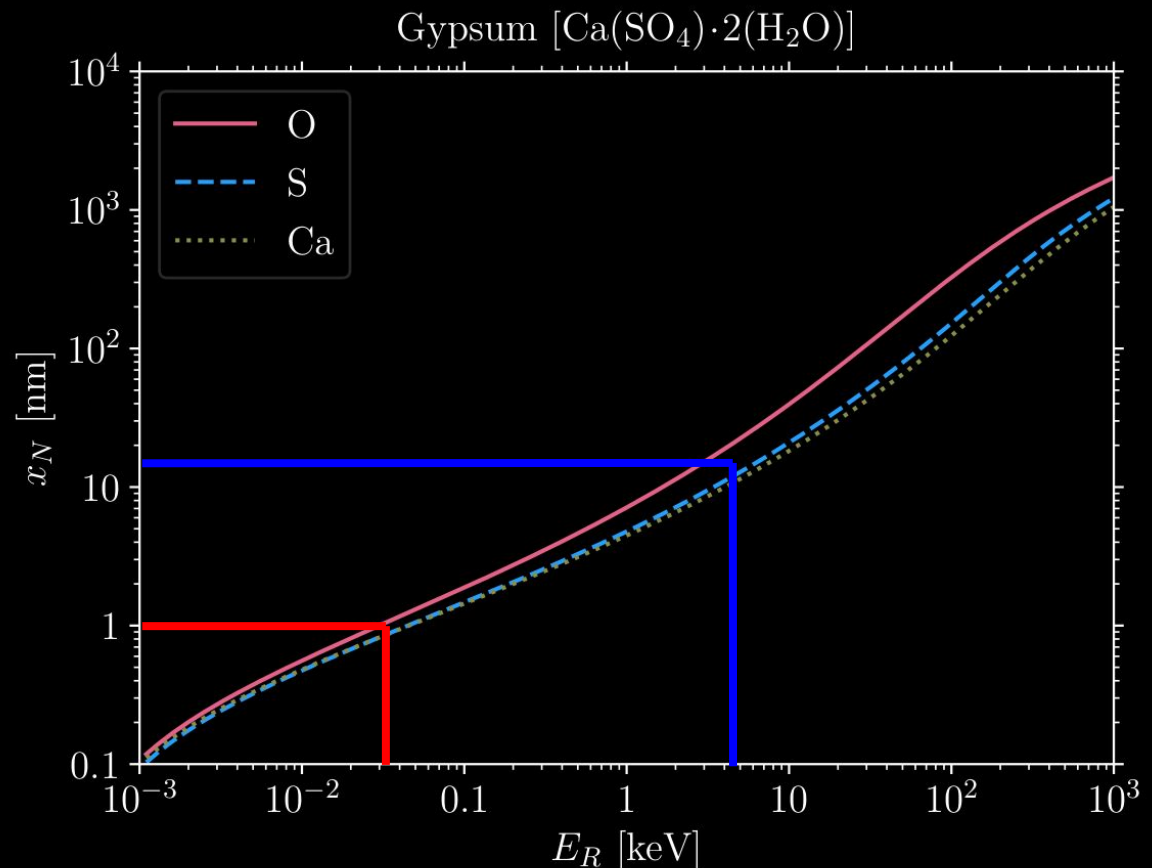


From Recoil Energies to Track Length

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

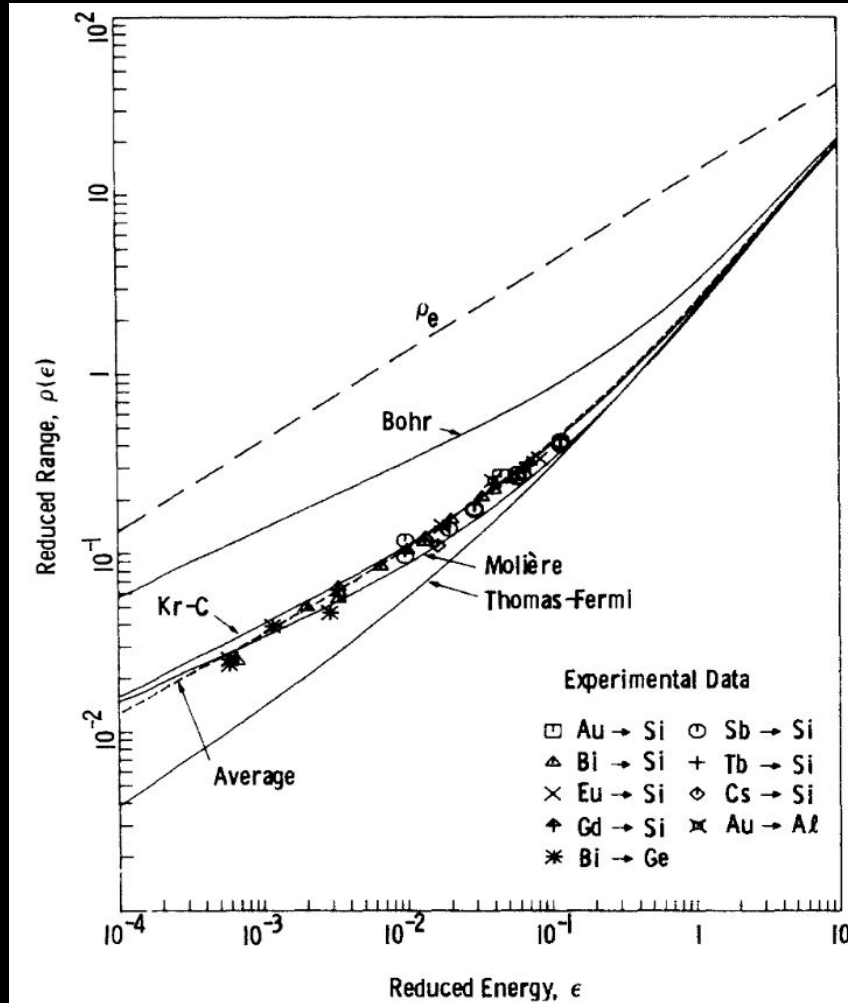
Energy loss due to

- Electronic stopping (off electron clouds)
- Nuclear stopping (off other nuclei)



Ion Range Calculations

Semi-analytic treatment



[Wilson,Haggmark,Biersack +76]

SRIM

