Mineral Detectors for Neutrinos and Dark Matter

Sebastian Baum

Stanford University

Can rocks teach us about the history of our Galaxy and what makes up our Universe?

100 Myr old mineral samples from the right geological environments

Imaged with modern nanometer-resolution microscopy

Can rocks teach us about the history of our Galaxy and what makes up our Universe?

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

What is Dark Matter?

[2301.07118]

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] Sharlotte 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 Watanabe[37]

[2301.07118]

Mineral Detection of Neutrinos and Dark Matter. A Whitepaper

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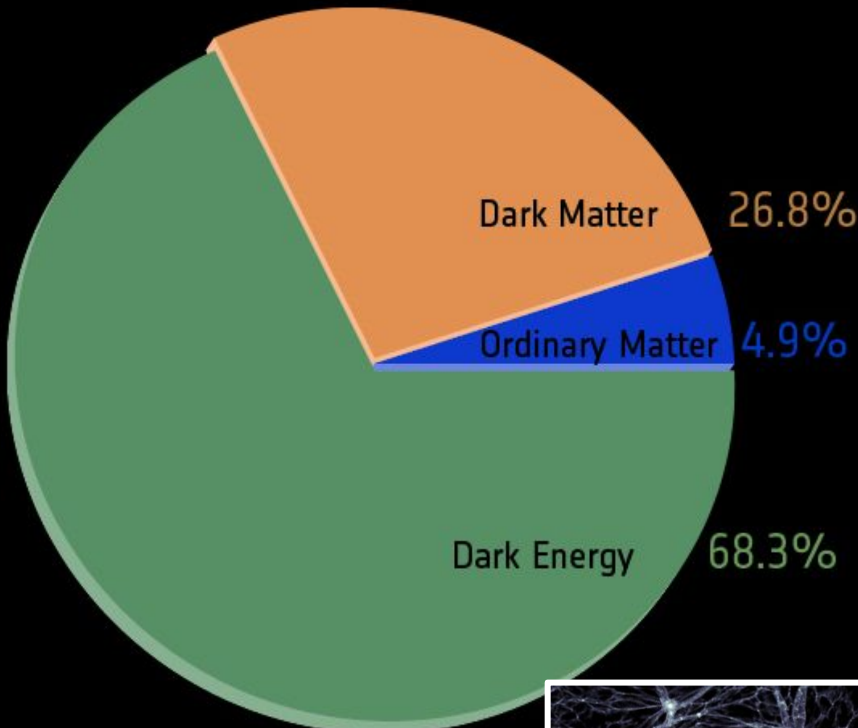
MDvDM community

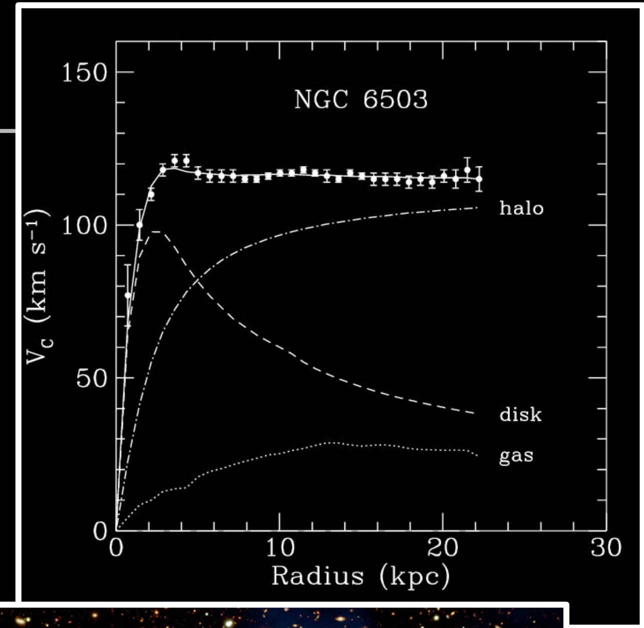
- Astroparticle theorists, experimentalists, geologists, and materials scientists
- Groups across North America, Europe, and Japan
- First meeting in Oct ‘22 at IFPU, Trieste

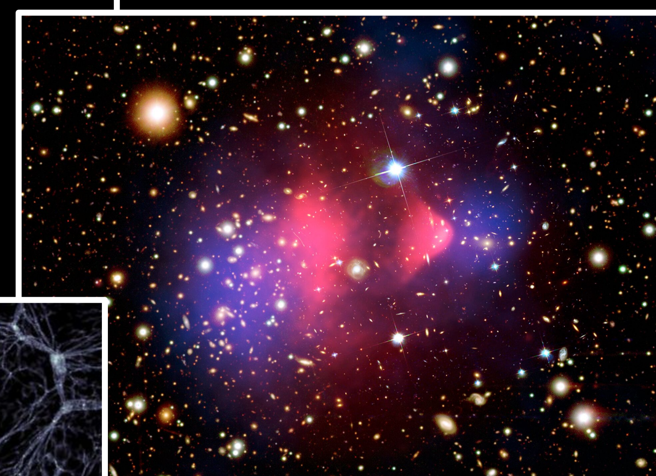
Check out our whitepaper!

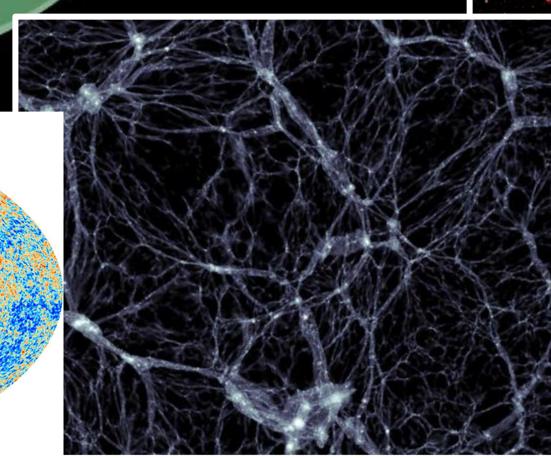
- History of mineral detectors
- Review of scientific potential for (cosmo)particle physics, reactor neutrinos, and geoscience
- Summary of ongoing and planned experimental efforts

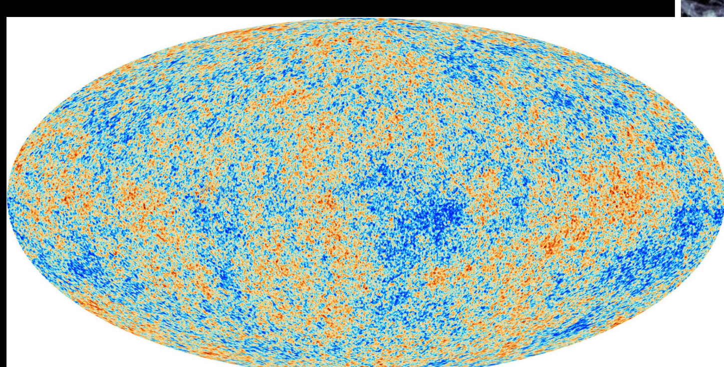
Dark Matter - the missing 85%







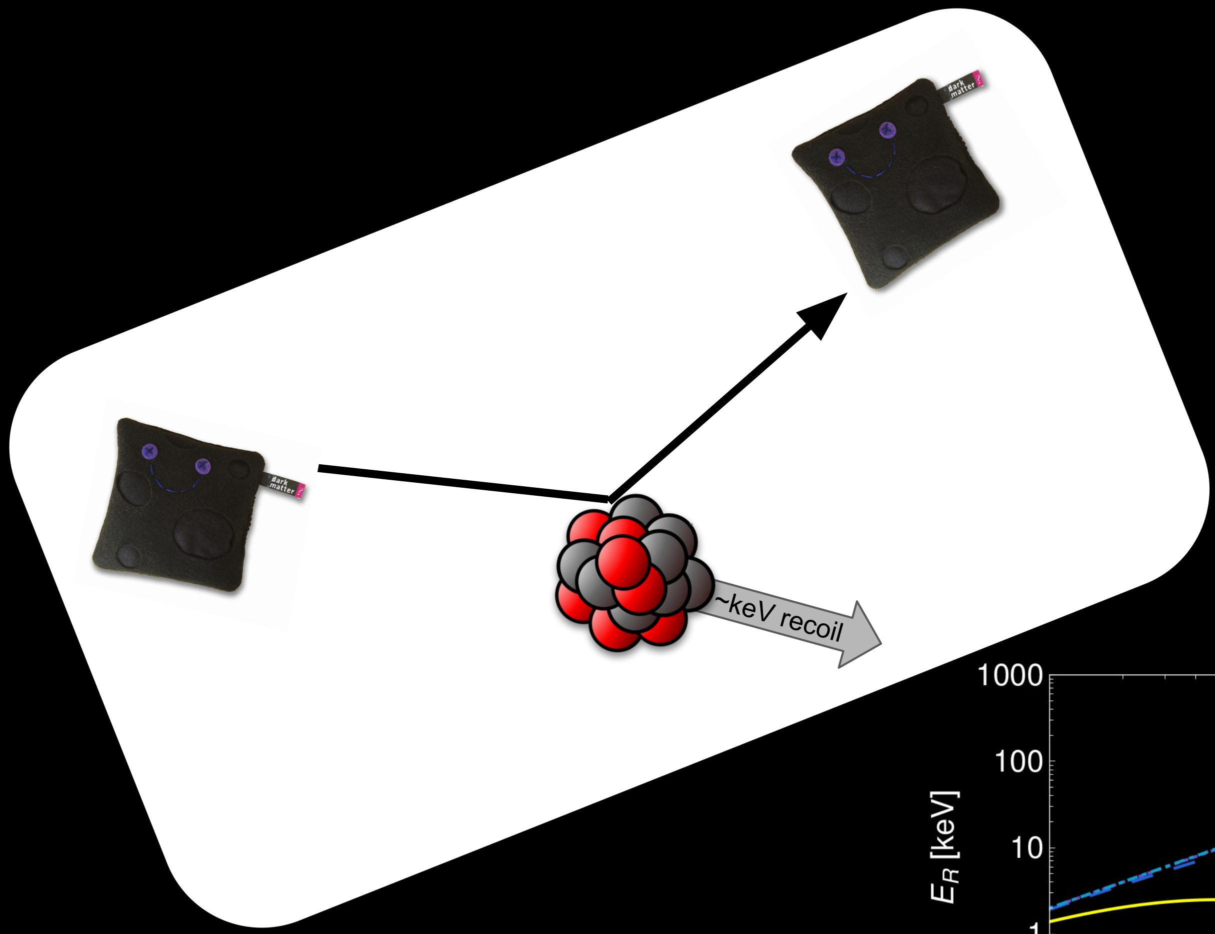


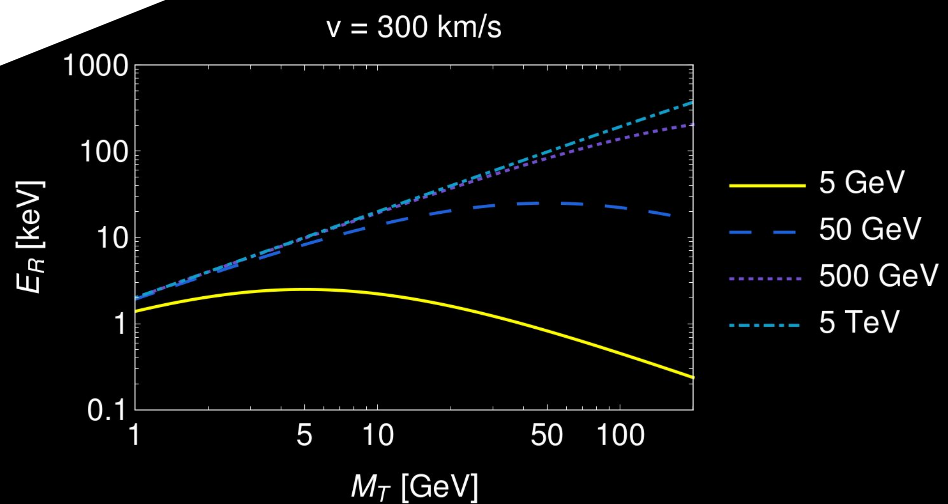


Weakly Interactive Massive Particle (WIMP) DM

Dark Matter could be made up of new particles with mass comparable to ordinary atomic nuclei, and feeble interactions with ordinary matter.

Direct Detection of Dark Matter





How to build a direct detection experiment

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

1987: 750 g of Ge

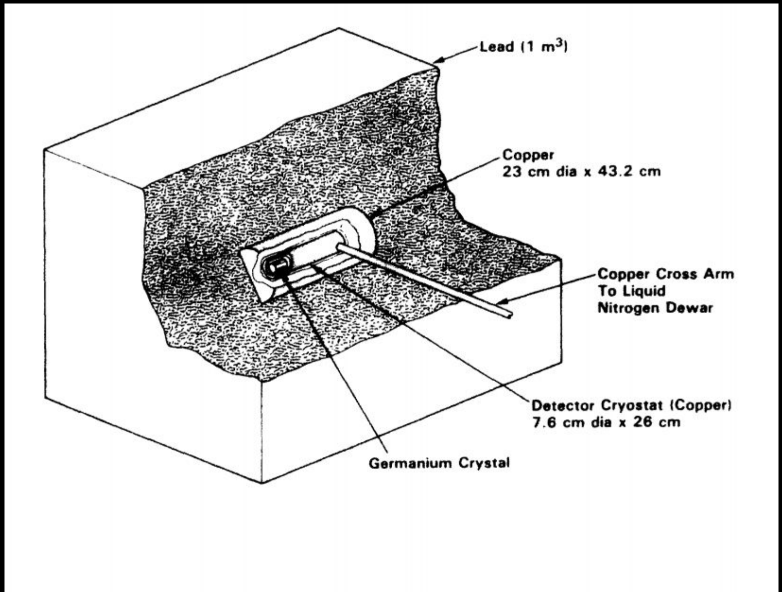
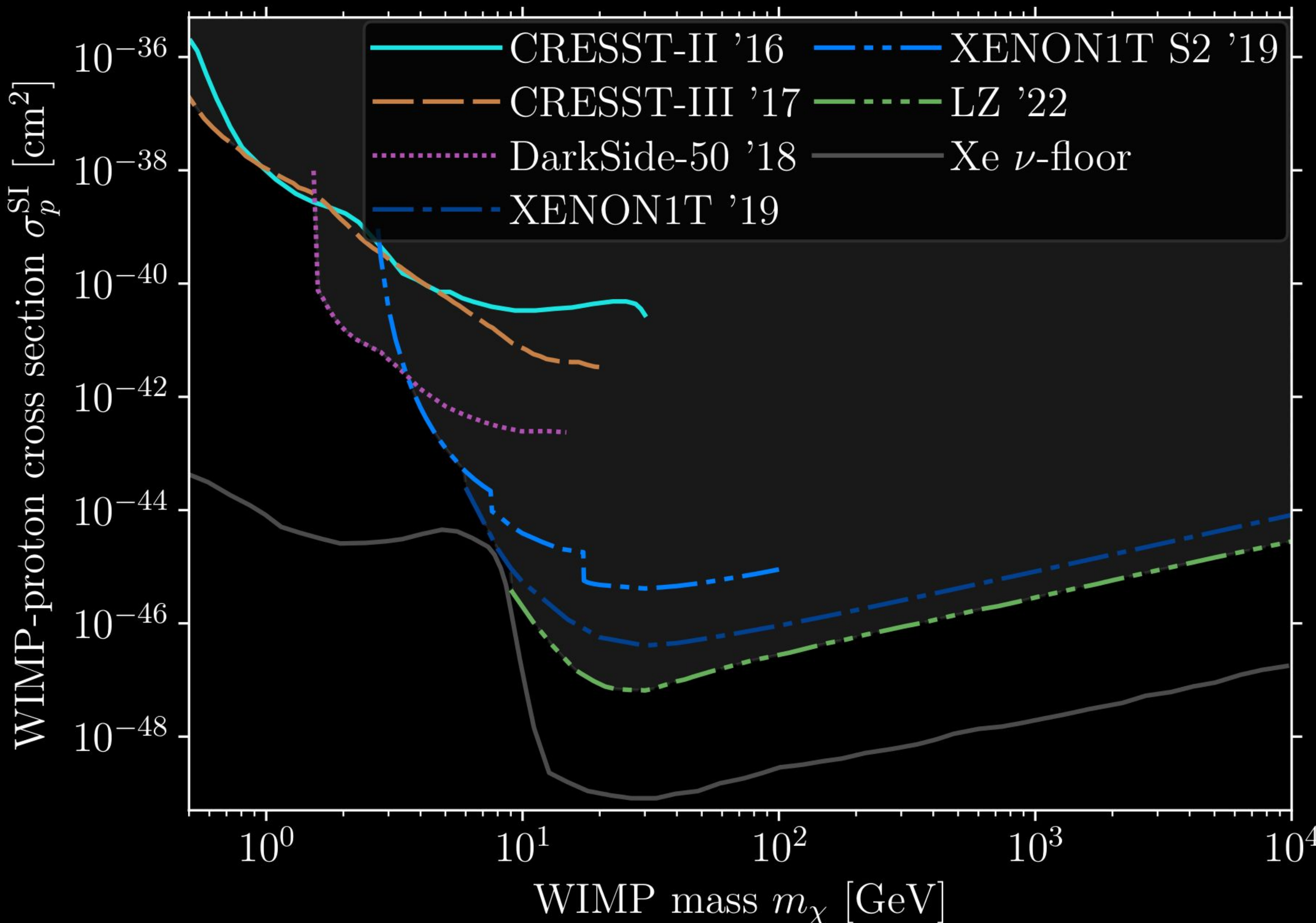


FIG. 1. Ultra-low-background, 135 cm^3 prototype Ge detector with copper inner shield.

[Ahlen+ ‘87, Avignone+ ‘86]

2021: 8 tonnes of Xe

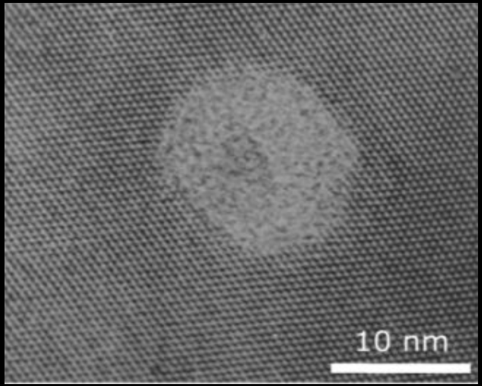
[XENON collaboration]


CRESST-II '16
CRESST-III '17
DarkSide-50 '18
XENON1T '19
XENON1T S2 '19
LZ '22
Xe ν-floor
WIMP-proton cross section σ_p^{SI} [cm^2]
10^{-36}
10^{-38}
10^{-40}
10^{-42}
10^{-44}
10^{-46}
10^{-48}
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}
WIMP mass m_χ [GeV]

Mineral Detectors for Neutrinos and Dark Matter

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

High-resolution TEM

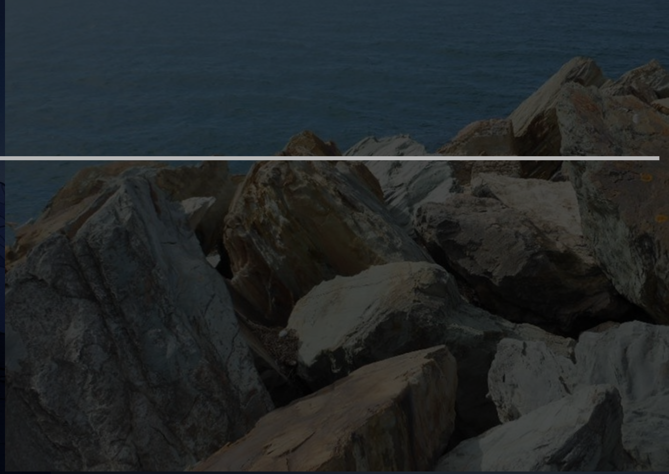


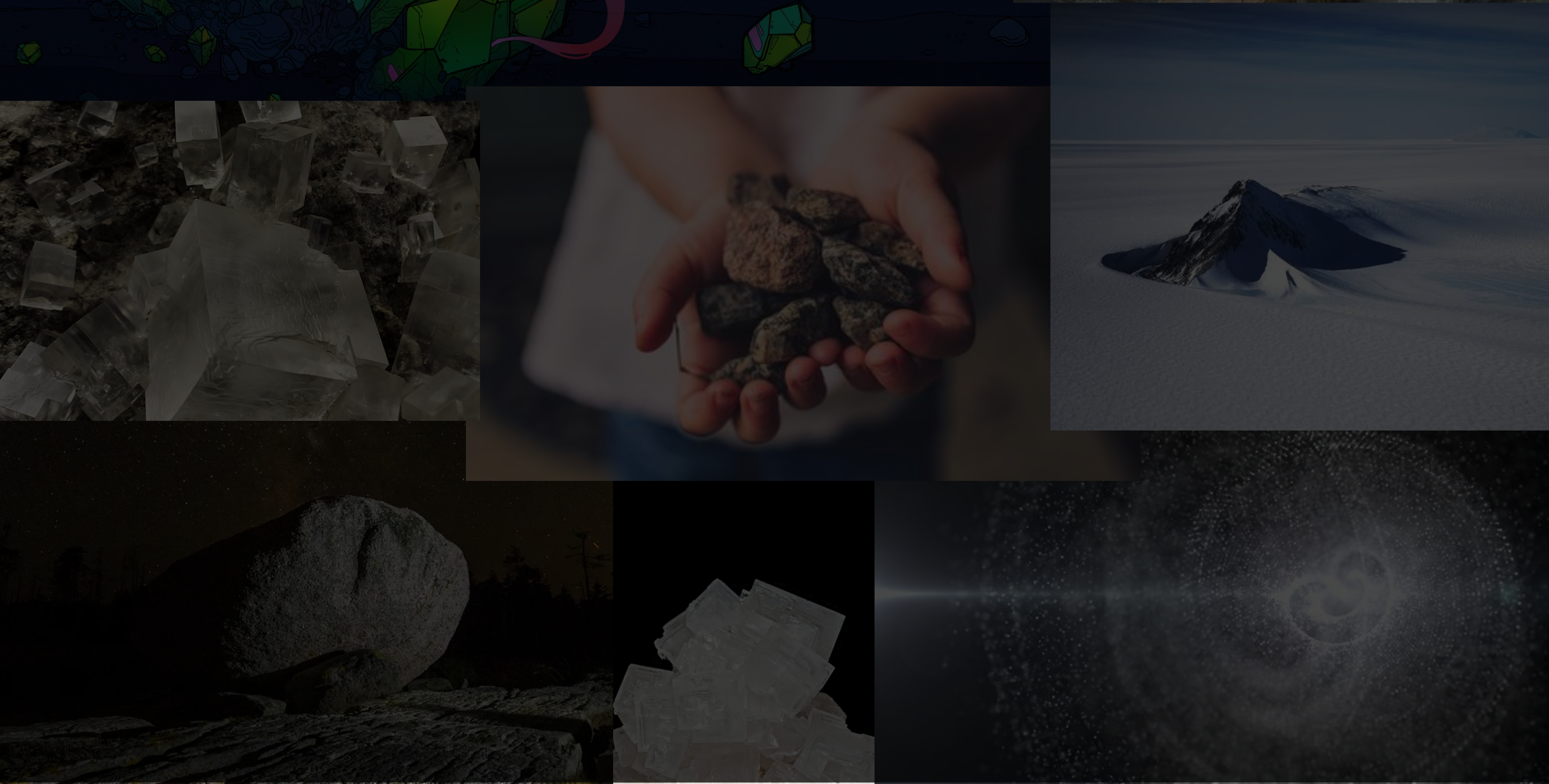
[Toulemonde+ ‘06]

[Price&Walker ‘63]

Paleo-Detectors

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





Paleo-Detectors

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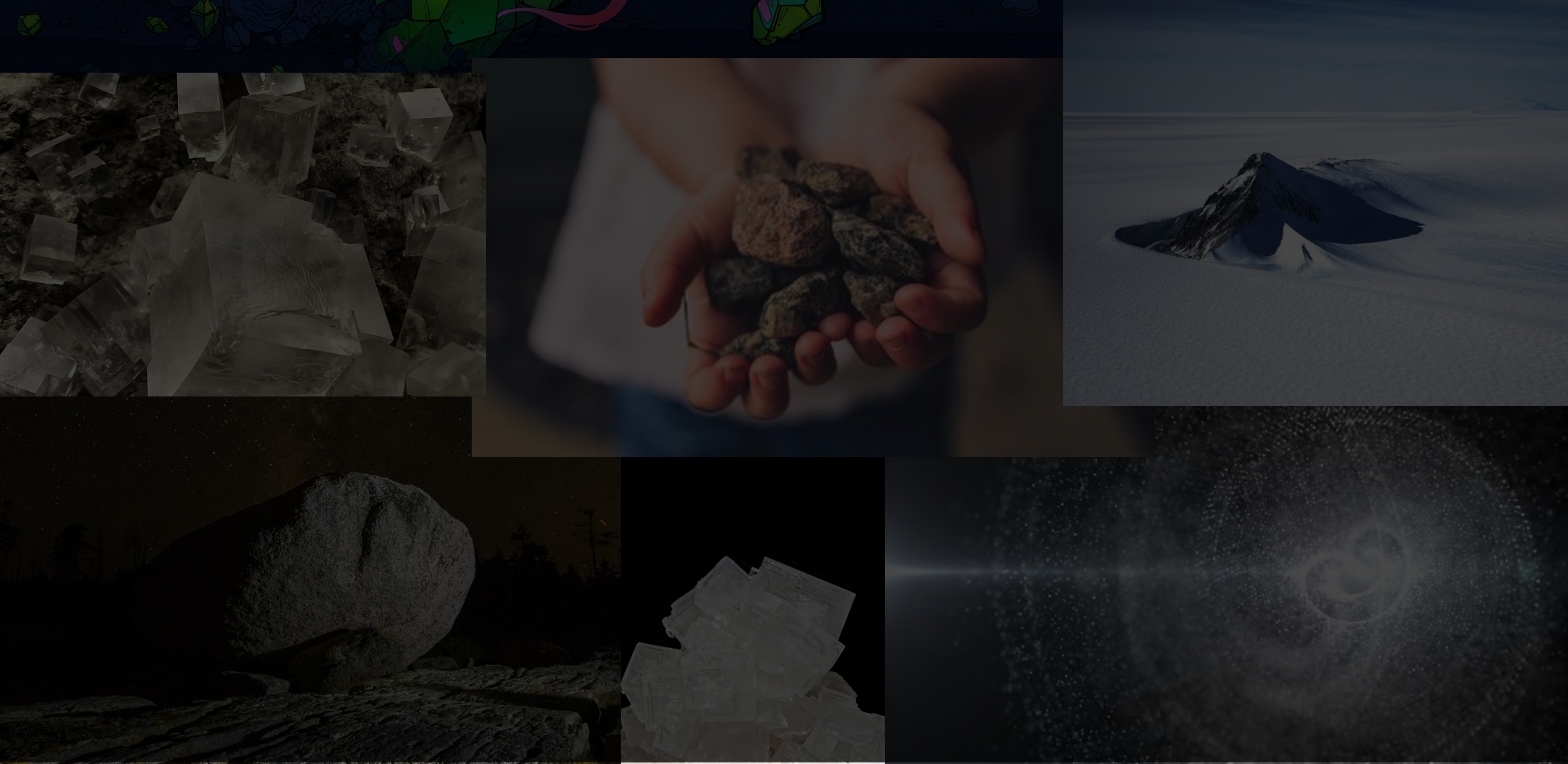
- Once created, damage tracks can be preserved for $\gg 10^9$ years



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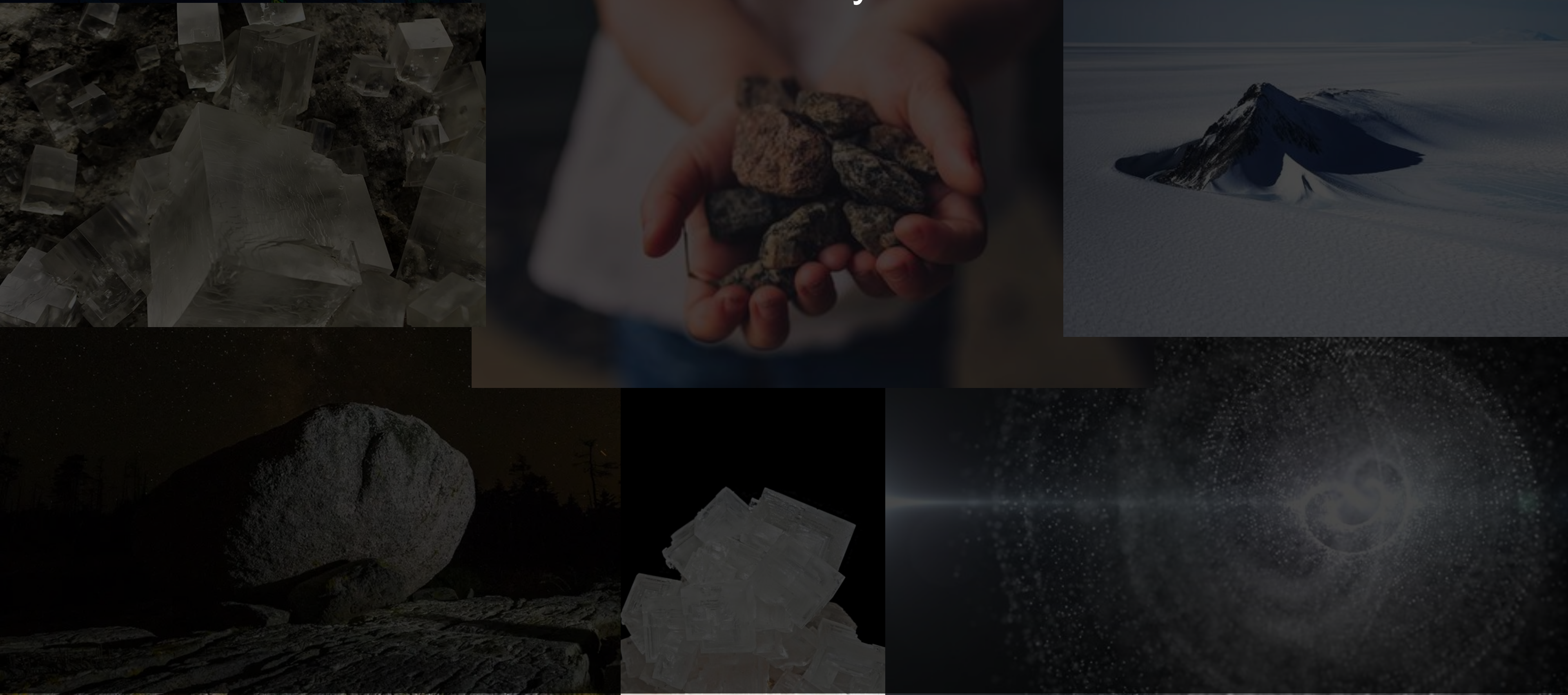

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- Modern microscopy technology allows for nanometer-scale resolution!

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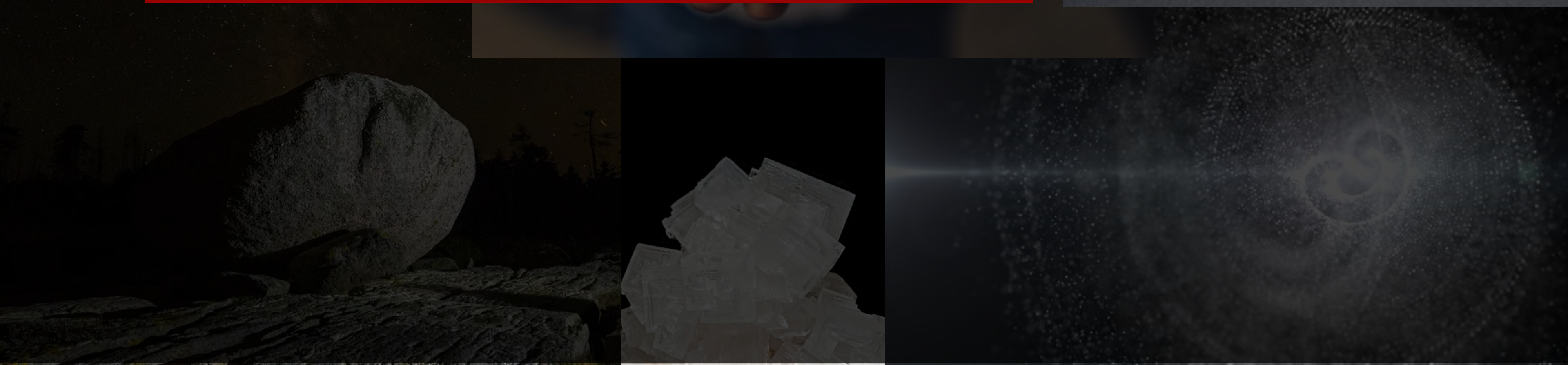
Exposure through time

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



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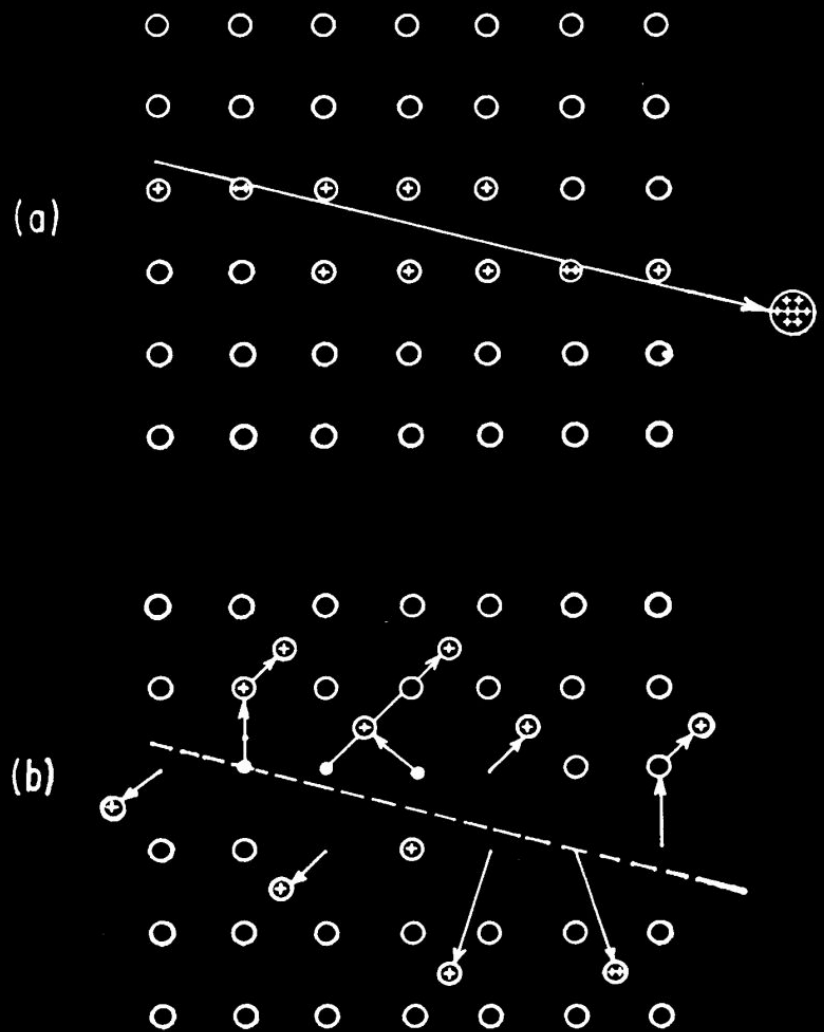
Exposure through time

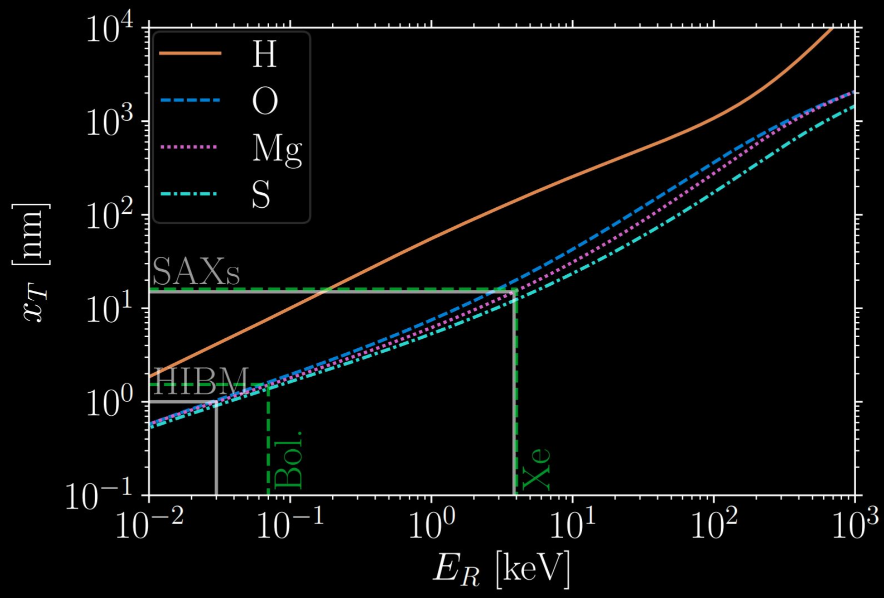
$100\ \text{g} \times 1\ \text{Gyr} = 10\ \text{kilotonne} \times 10\ \text{yr}$

$\lesssim$ keV recoil thresholds

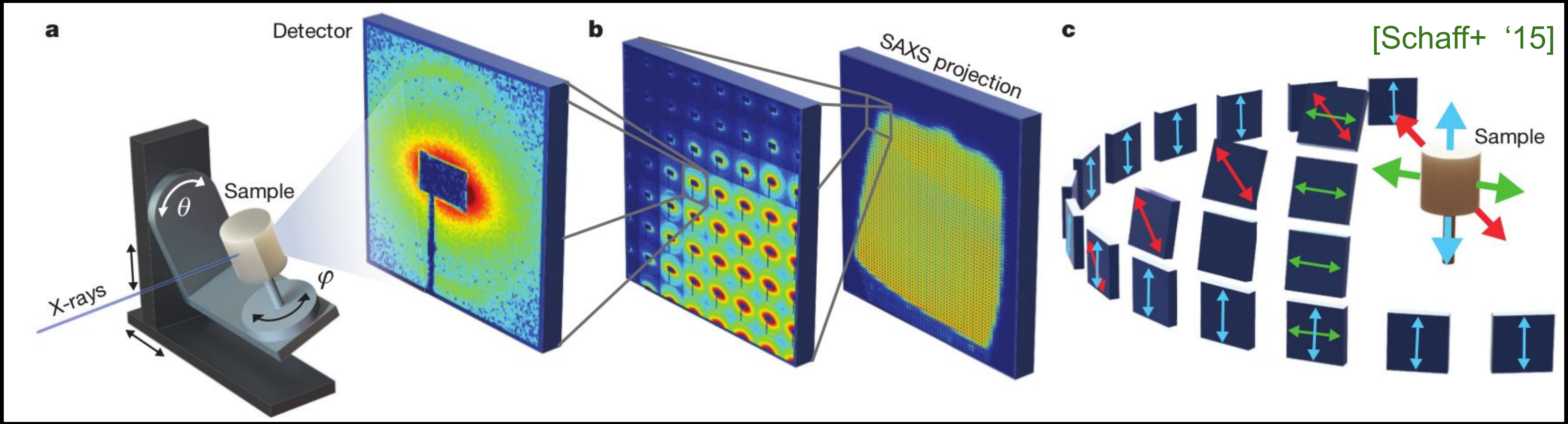
Damage (tracks) from recoiling nuclei

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





Read-Out Methods (i): X-ray Ptychography



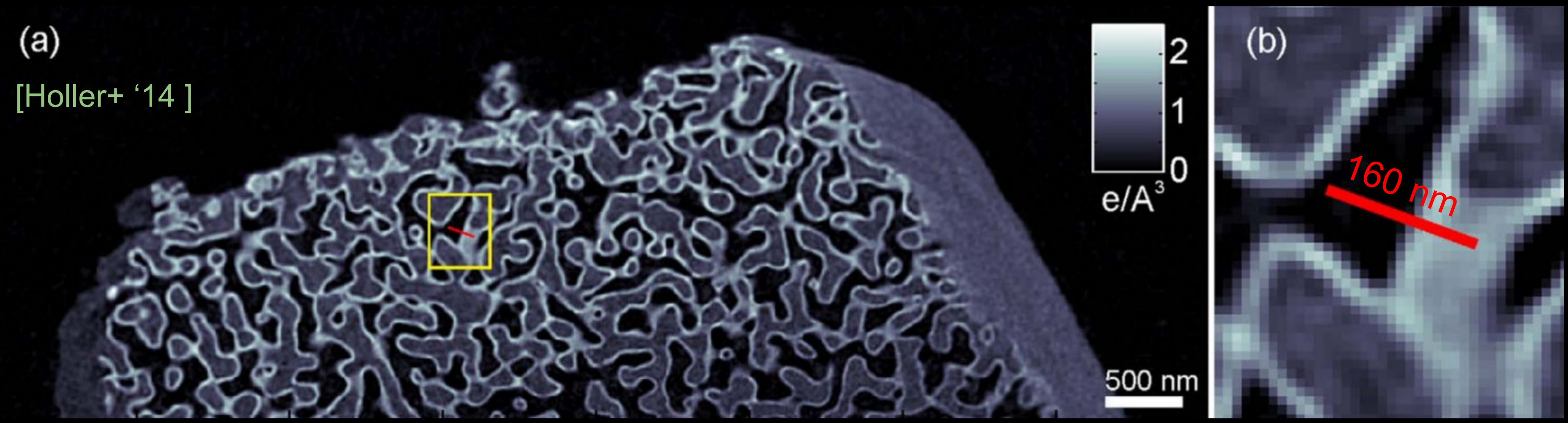
Single "pixel" of sample

Combine "pixels" into 2D picture

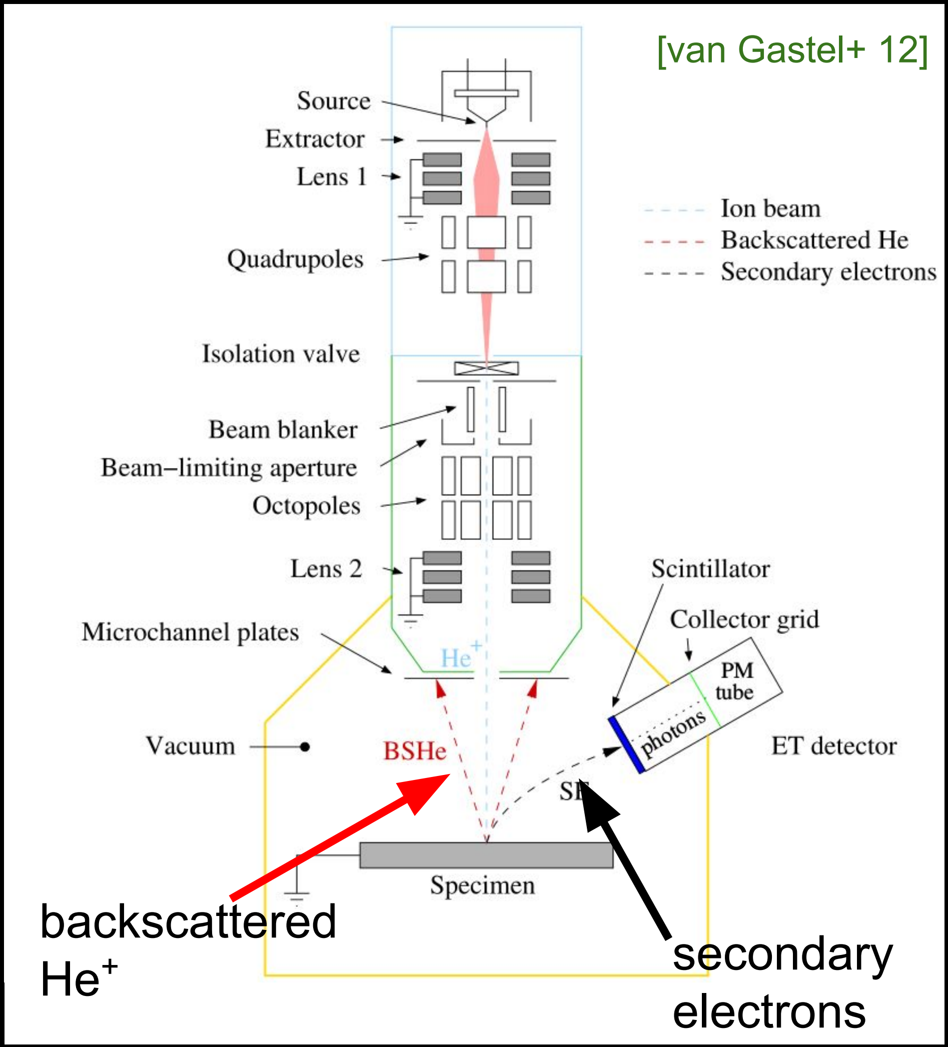
Reconstruct 3D image from 2D pictures

Read-Out Methods (i): X-ray Ptychography

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



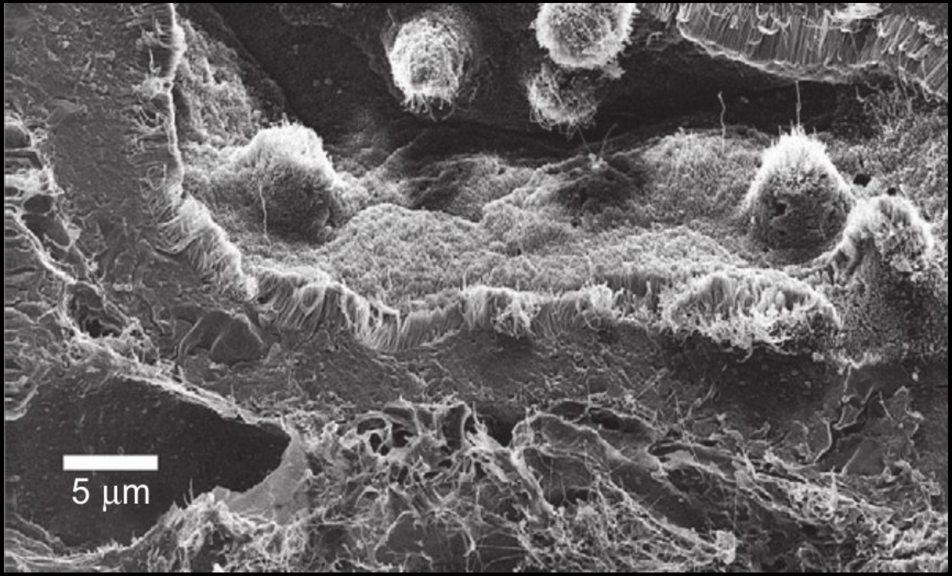
Read-Out Methods (ii): He-Ion Beam Microscopy

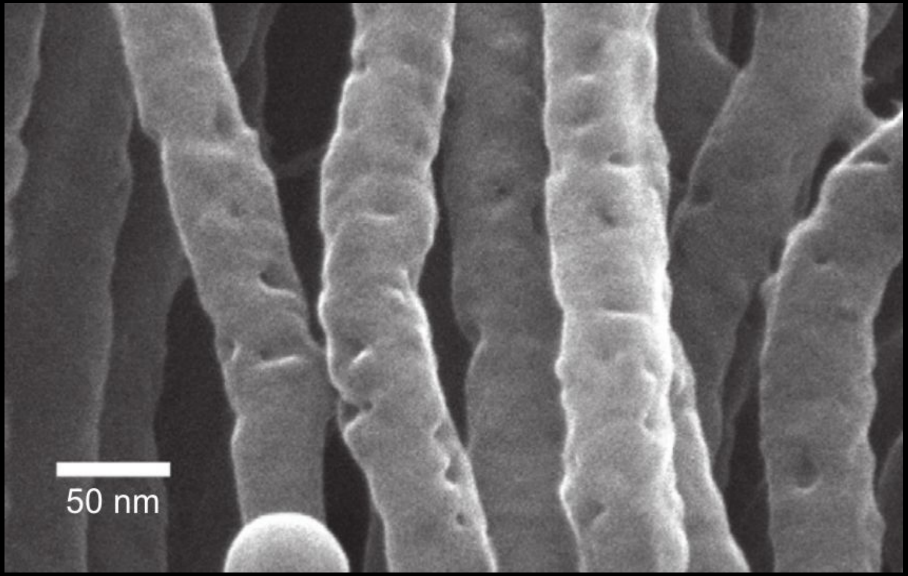


Read-Out Methods (ii): He-Ion Beam Microscopy

Overview & Zoom-in of rodent kidney

[Hill+ ‘12]





Readout methods: an incomplete list

Throughput

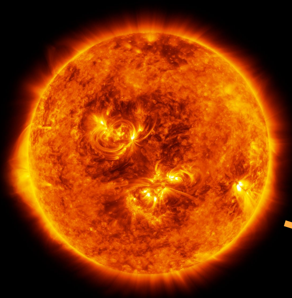
- Optical microscopy
  - Chemical etch + optical (phase contrast) imaging
  - Fluorescence microscopy of color centers (superresolution)
- X-ray microscopy
  - Soft X-ray scattering (table top)
  - Hard X-ray microscopy (synchrotron/FEL) (ptychography!)
- Scanning Probe Microscopy
  - Atomic Force Microscopy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

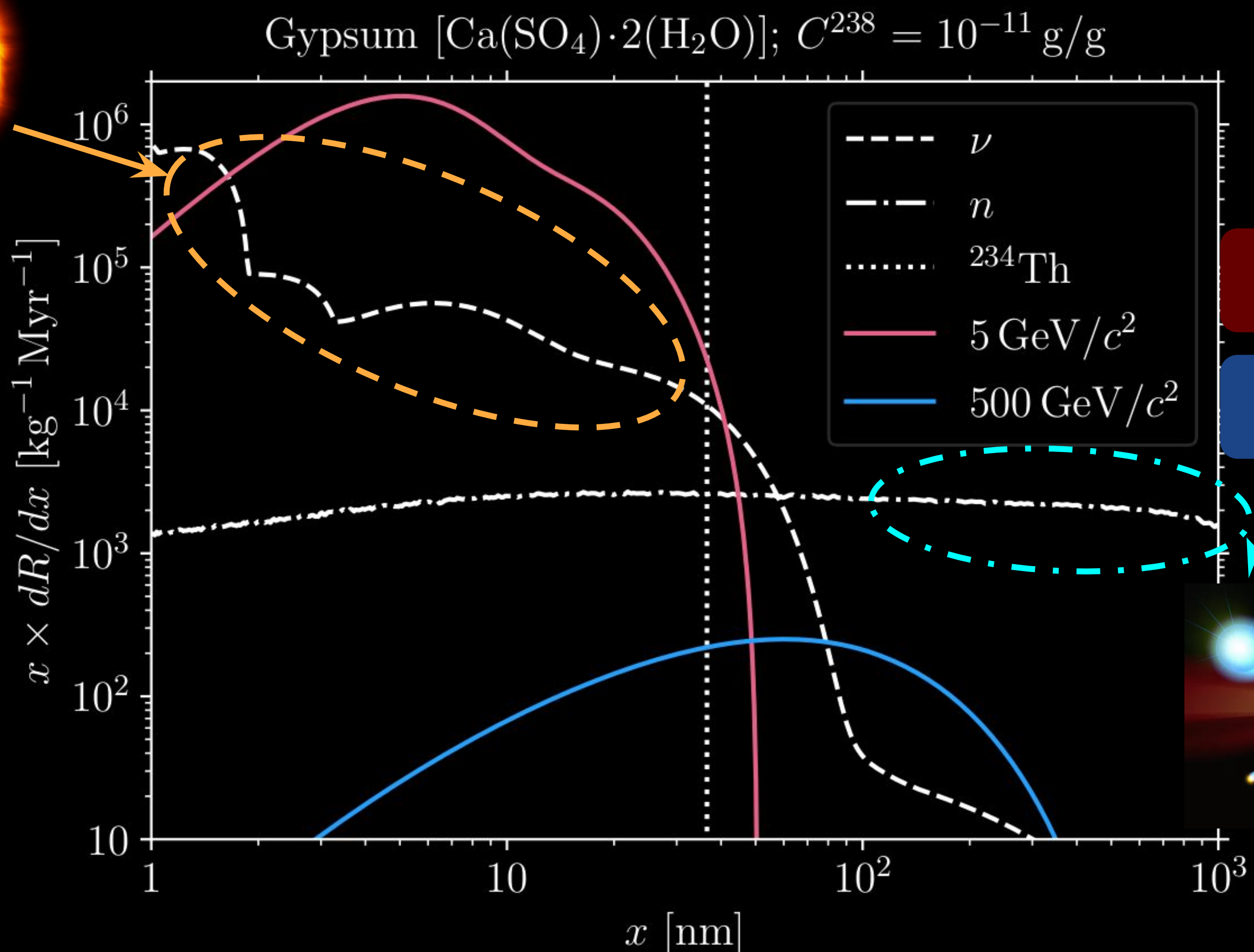
Spatial Resolution

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?

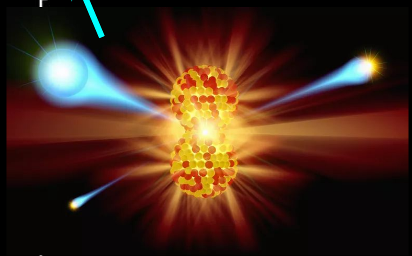
Use track length spectrum to pick up DM signal



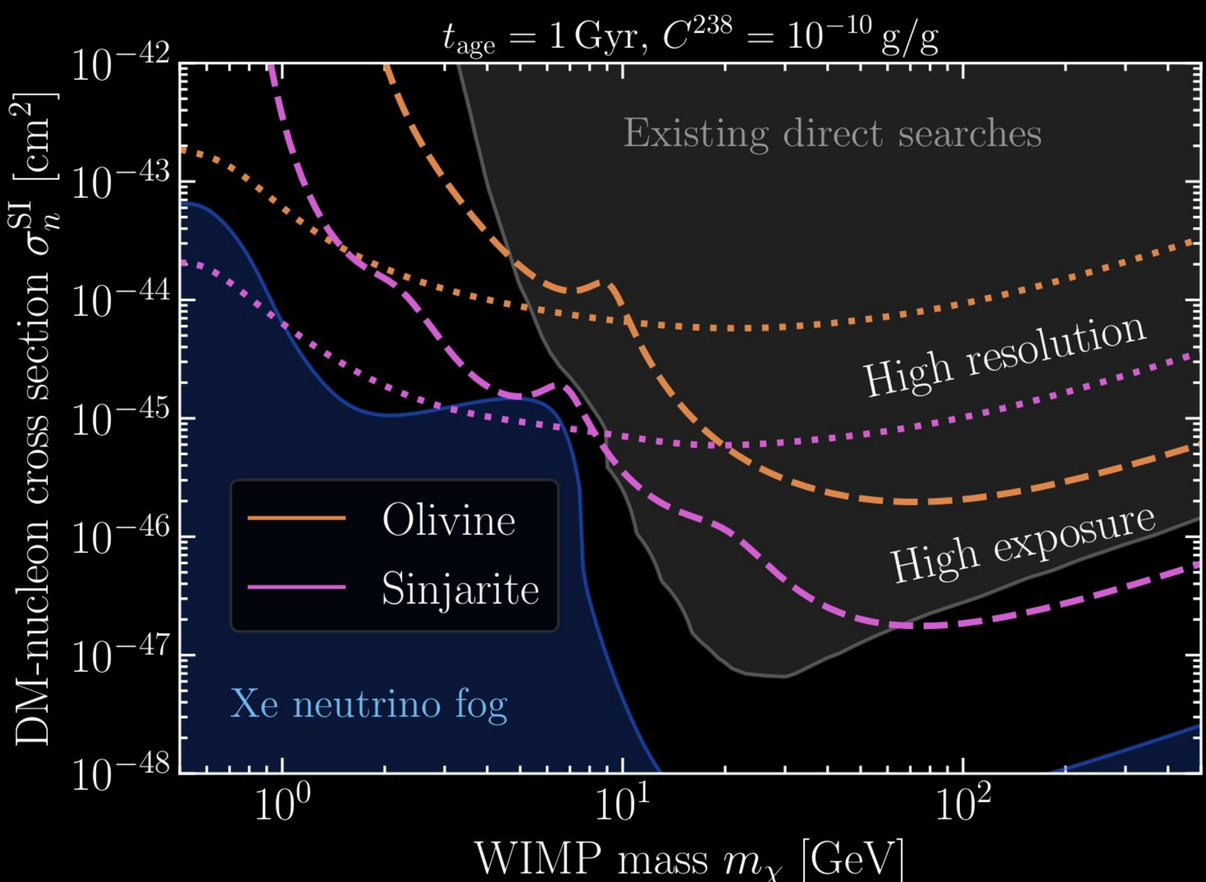


$\sigma_p^{SI} = 10^{-43}$ cm^2

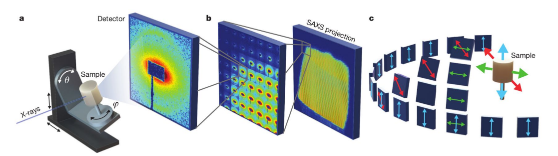
$\sigma_p^{SI} = 10^{-46}$ cm^2



Dark Matter Sensitivity Projections



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



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

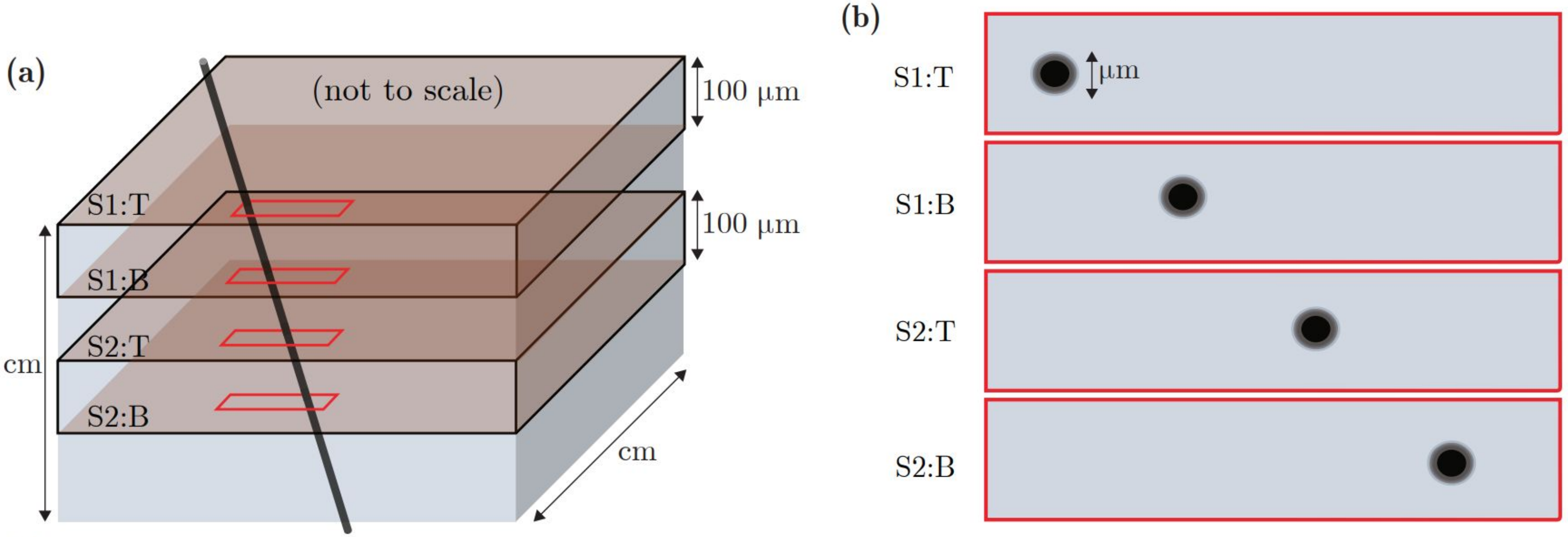
Paleo-detectors for composite DM detection

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

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

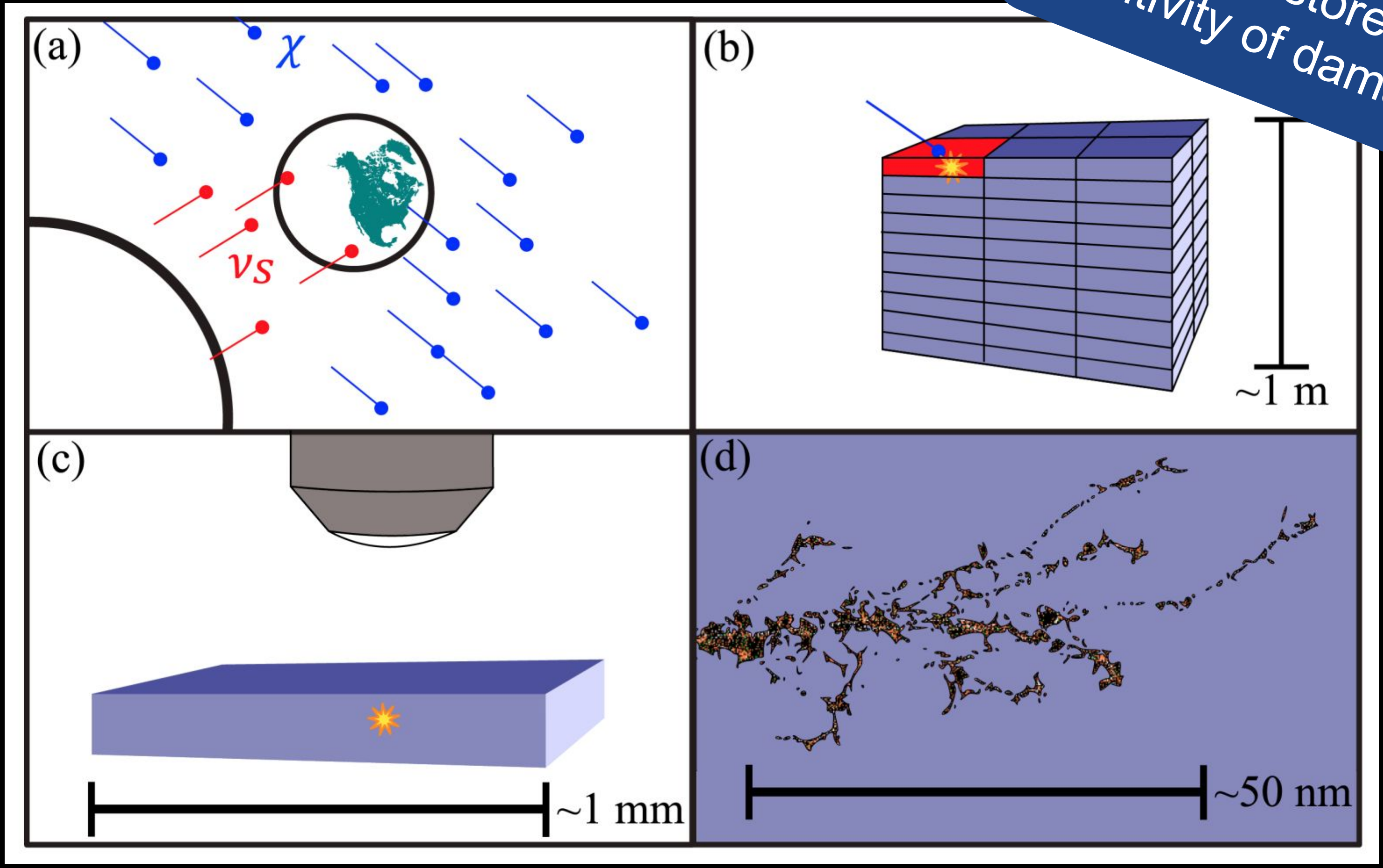
Ultra-Heavy Dark Matter Search with Electron Microscopy of Geological Quartz

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,¶]



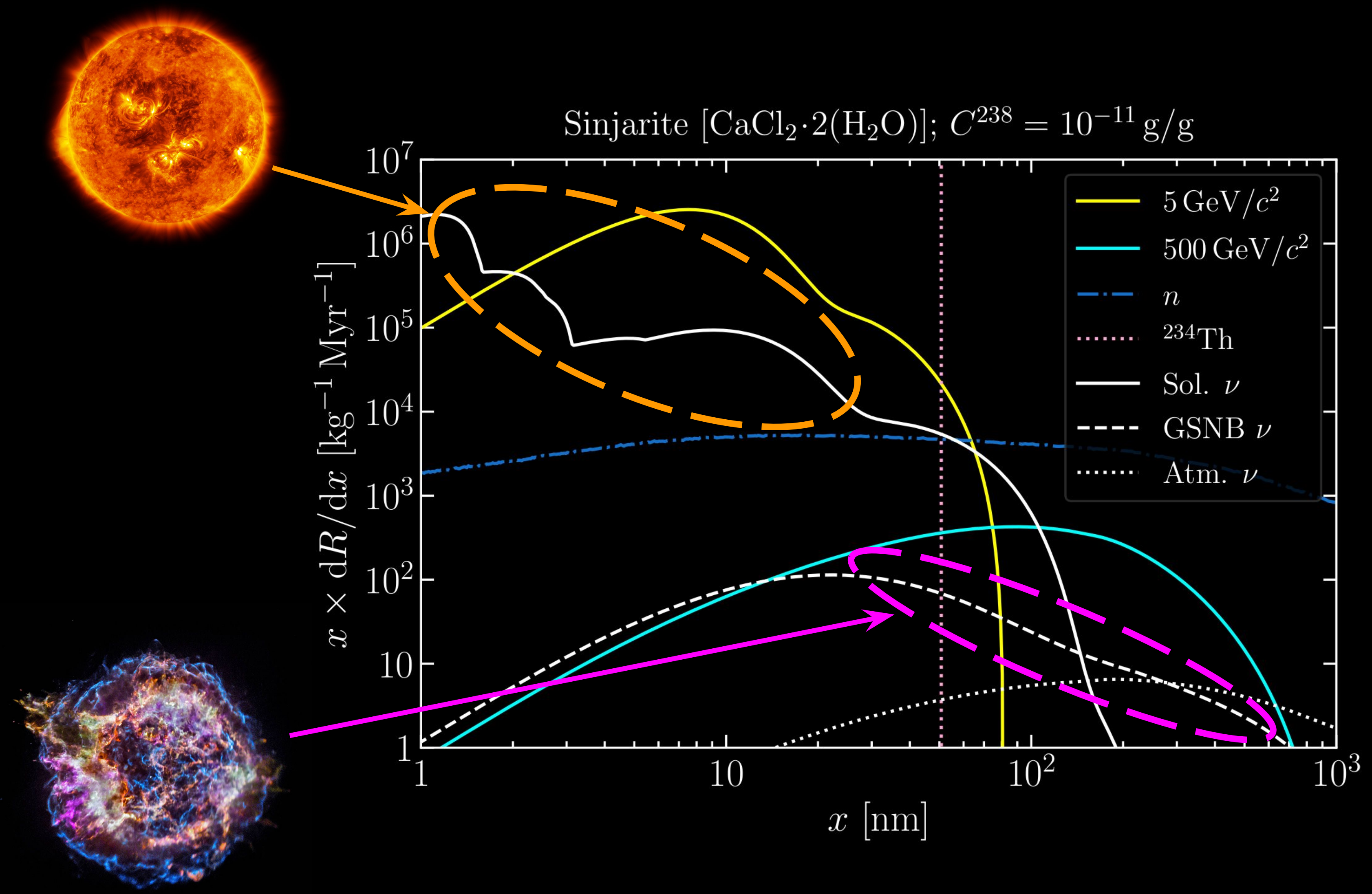
Mineral Detectors for as directional DM detectors?

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

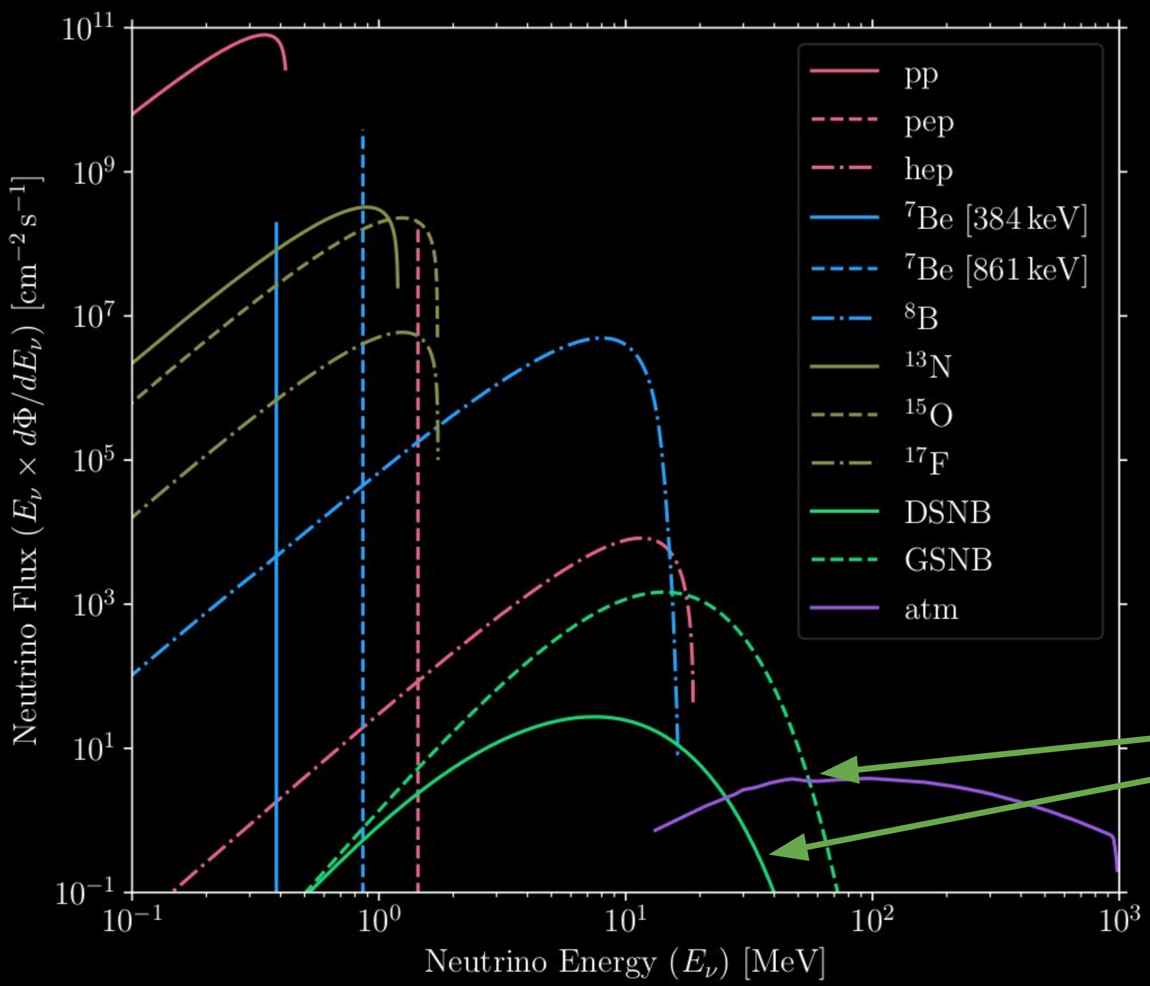


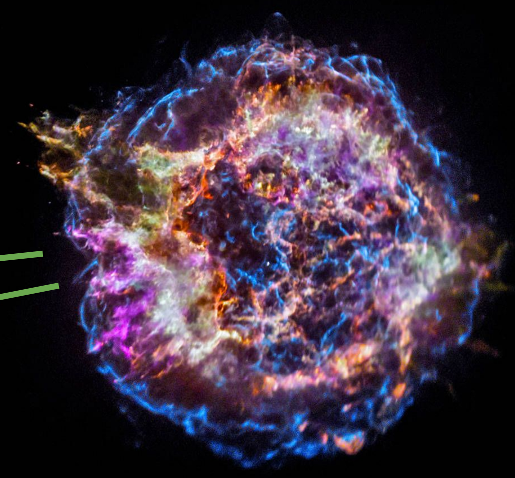
Time-tag restores directional sensitivity of damage track!

What about those neutrinos?



Paleo-Detectors for Galactic Supernovae

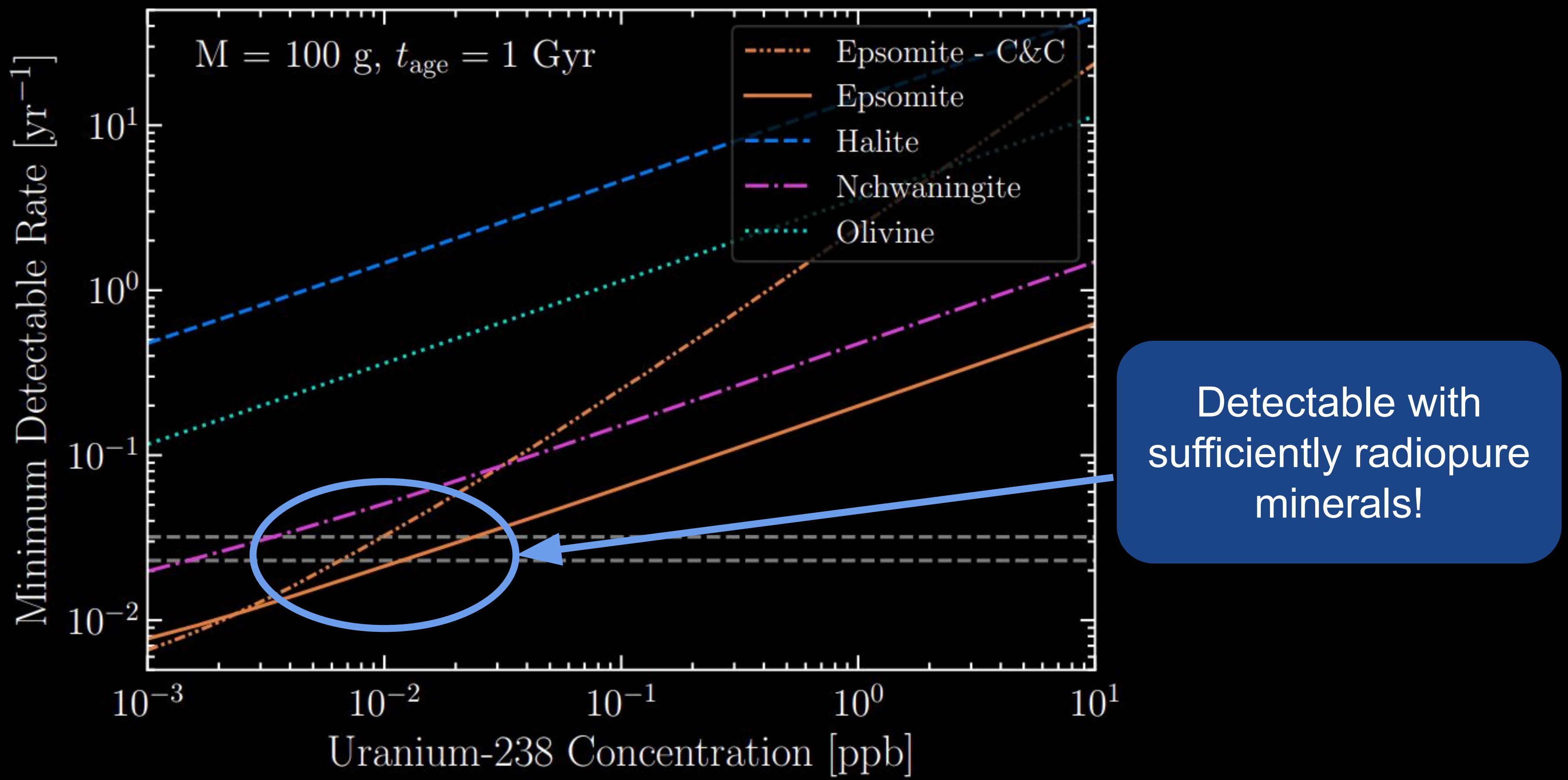




[NASA/CXC/SAO]

Measuring the Galactic Supernova Rate?

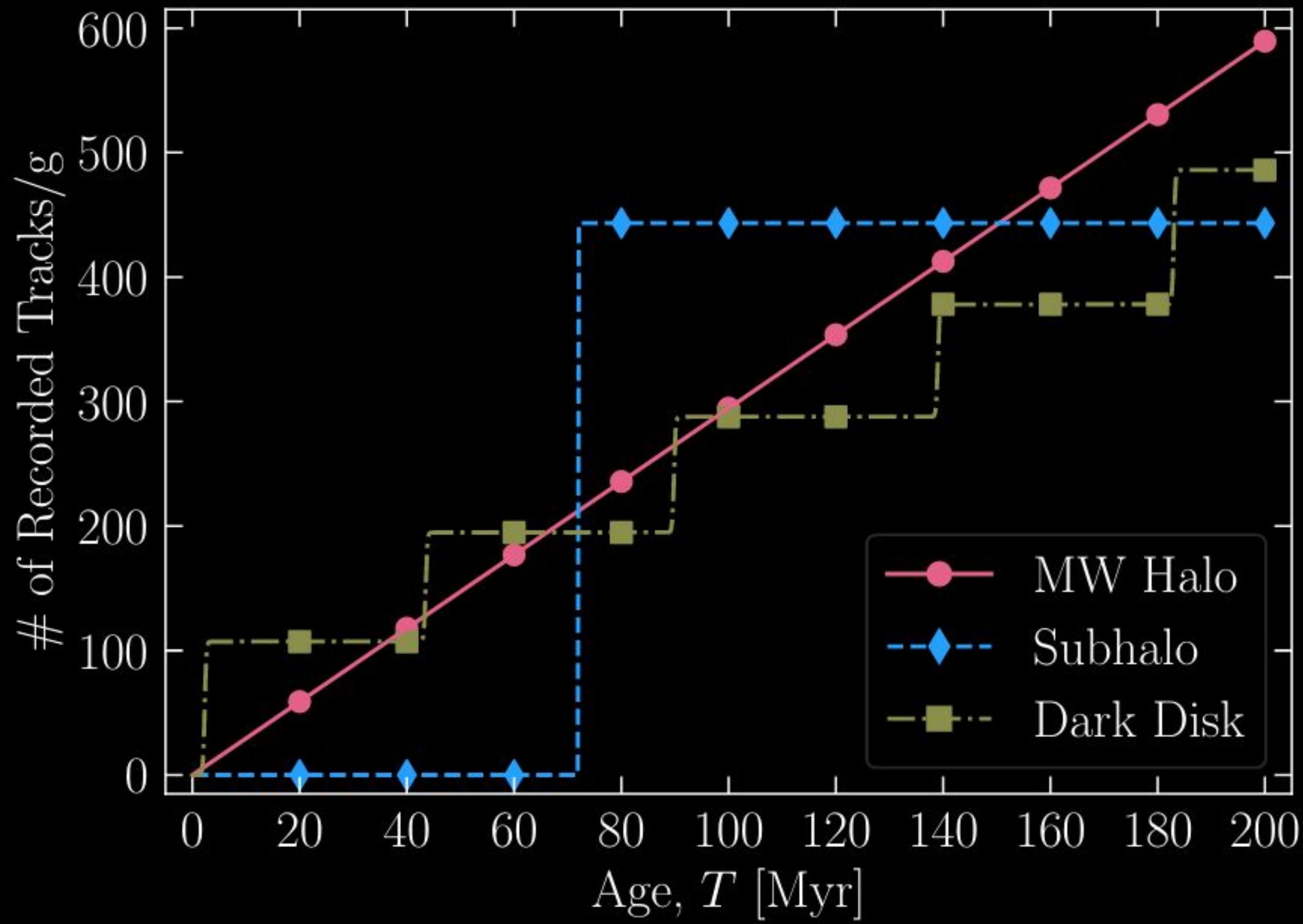
[**SB**+ 1906.05800]



- Halite -- NaCl
- Epsomite -- $MgSO_4$•$7(H_2O)$
- Olivine -- $Mg_{1.6}Fe_{0.4}(SiO_4)$
- Nchwaningite -- $Mn_2SiO_3(OH)_2$•(H_2O)

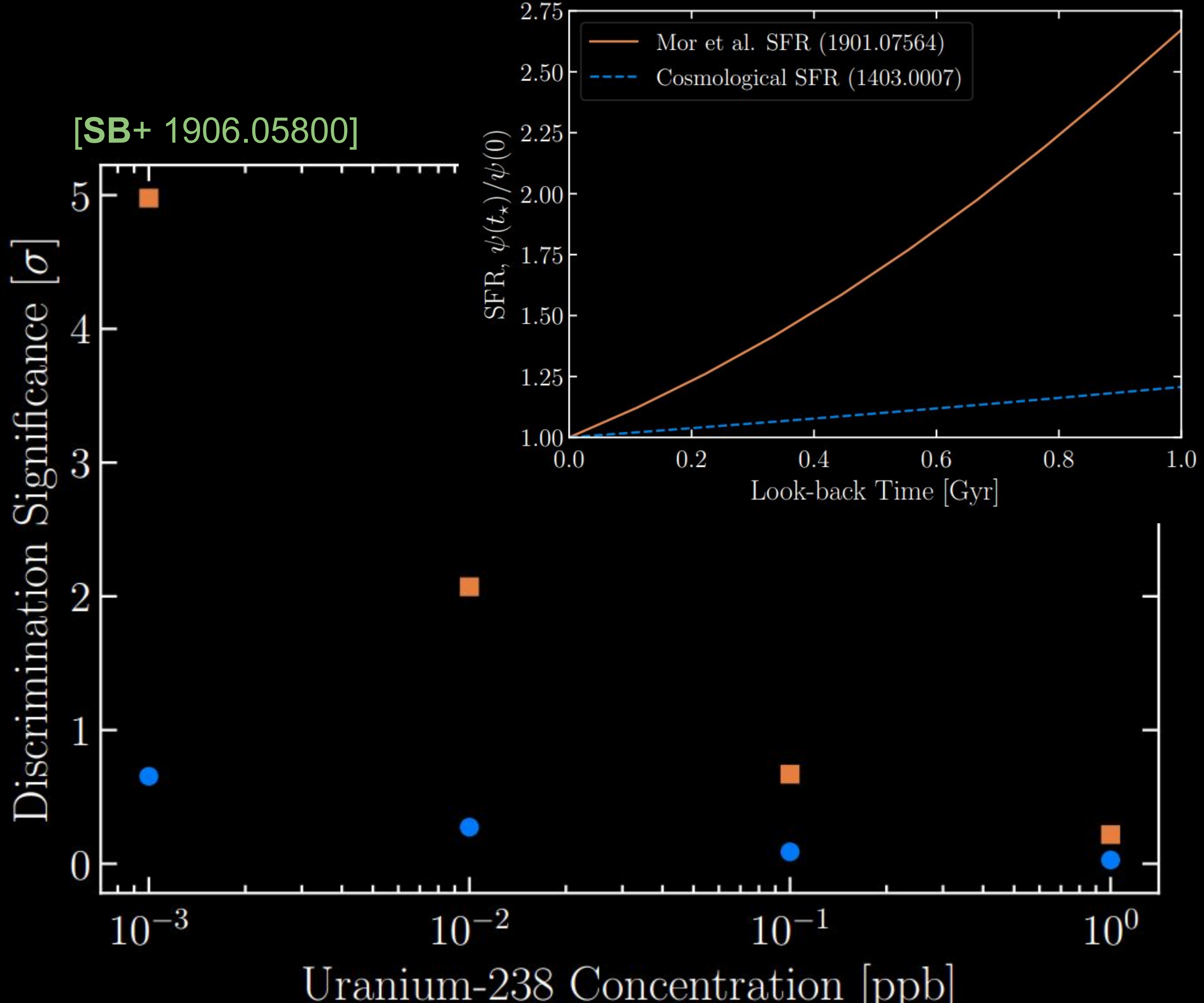
Beyond the rate: Time-varying Signals

[**SB**, DeRocco, Edwards, Kalia, 2107.02812]



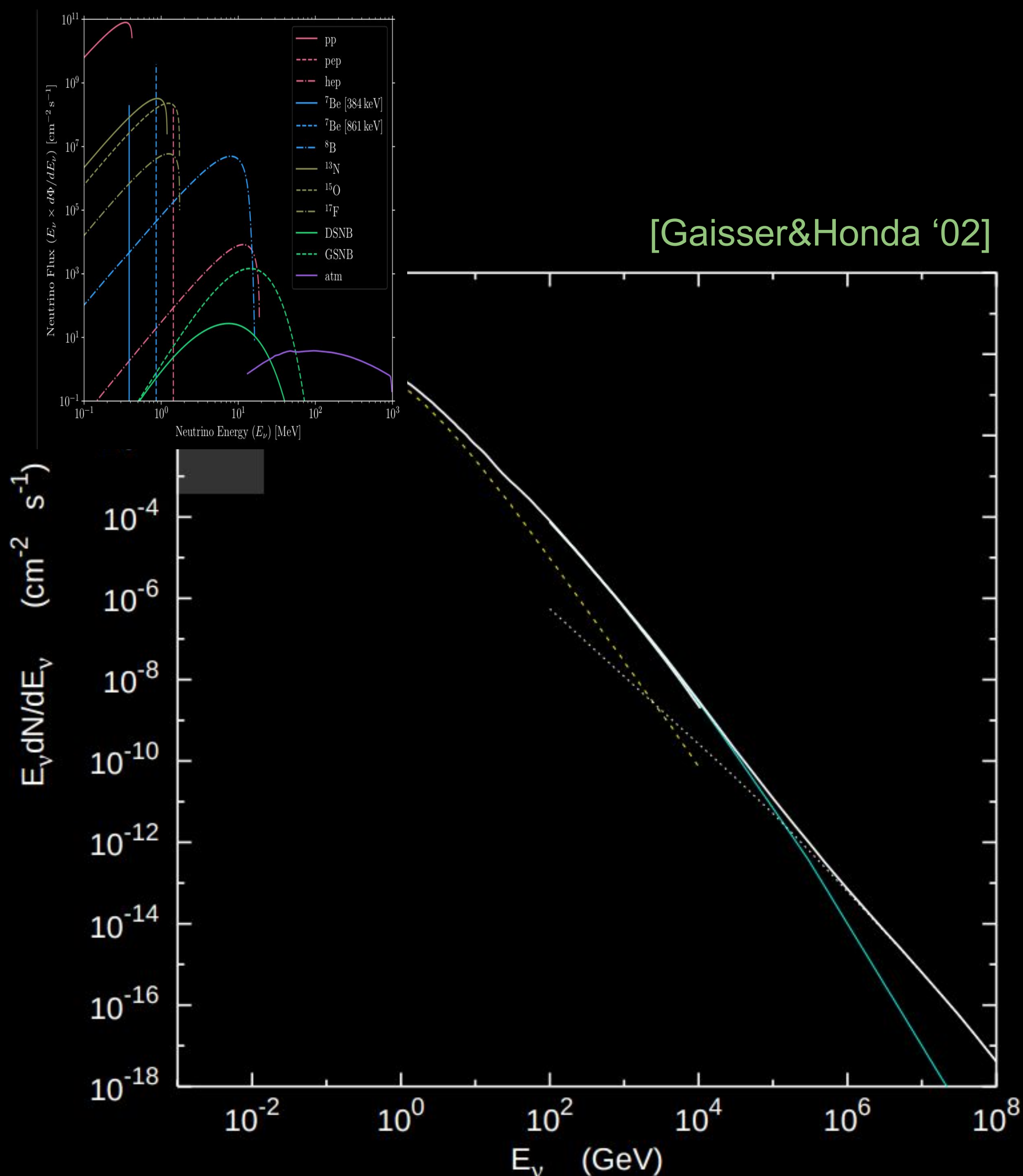
Learning about the Time-Dependence of the SN rate?

[SB+ 1906.05800]



Epsomite -- $MgSO_4 \cdot 7(H_2O)$

What About a Little More Energetic Neutrinos?



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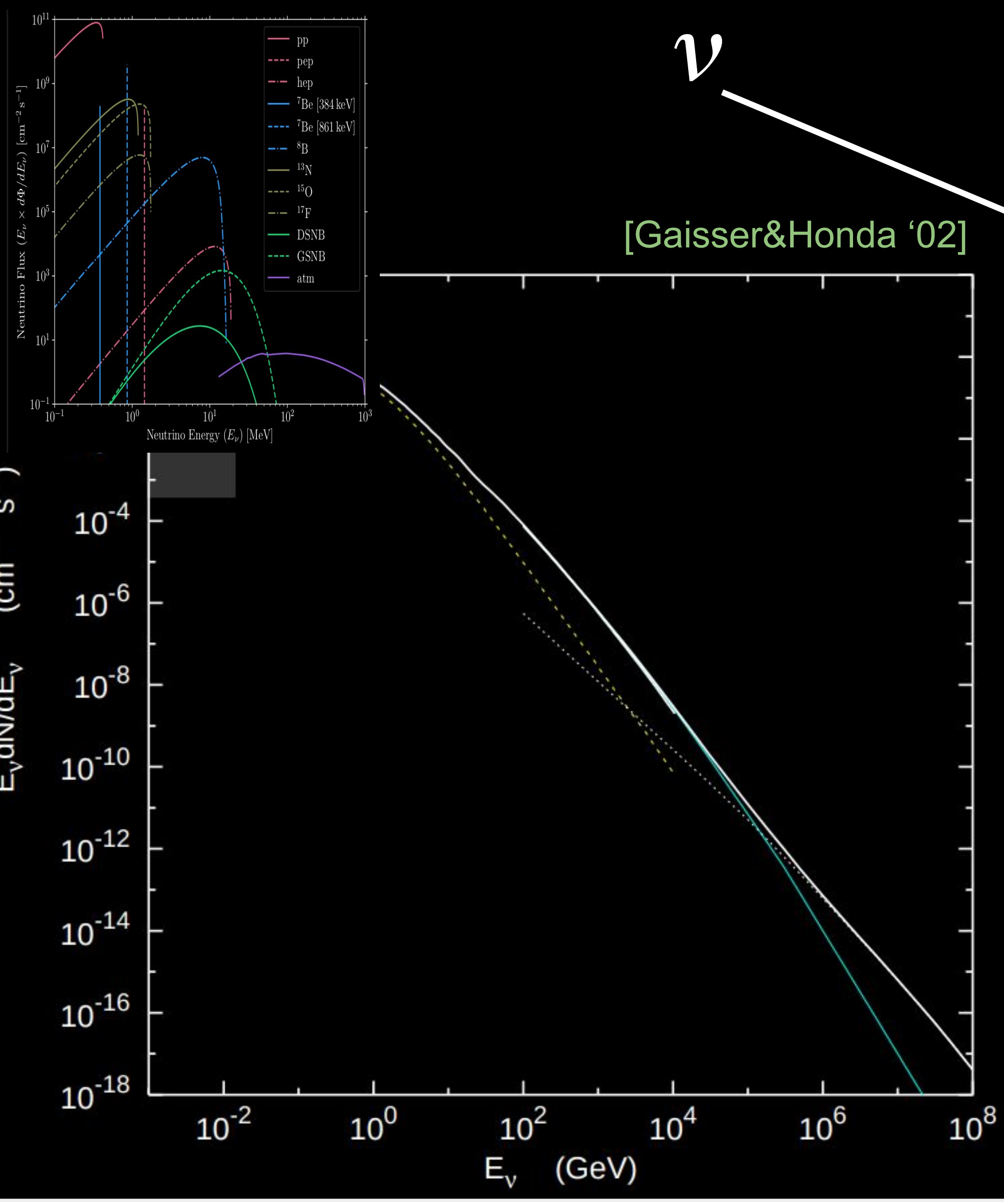
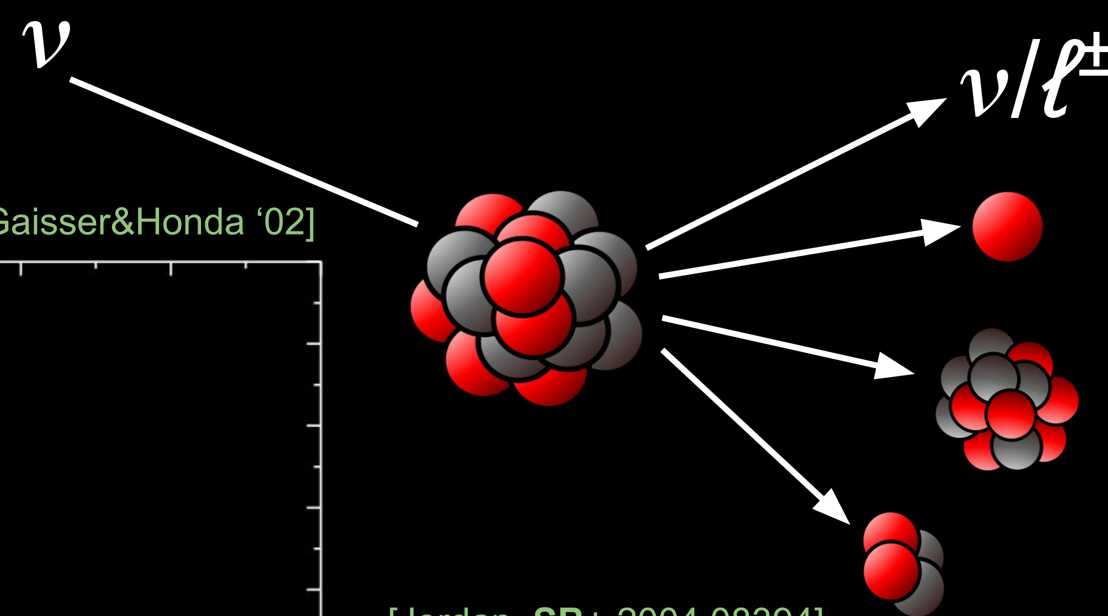
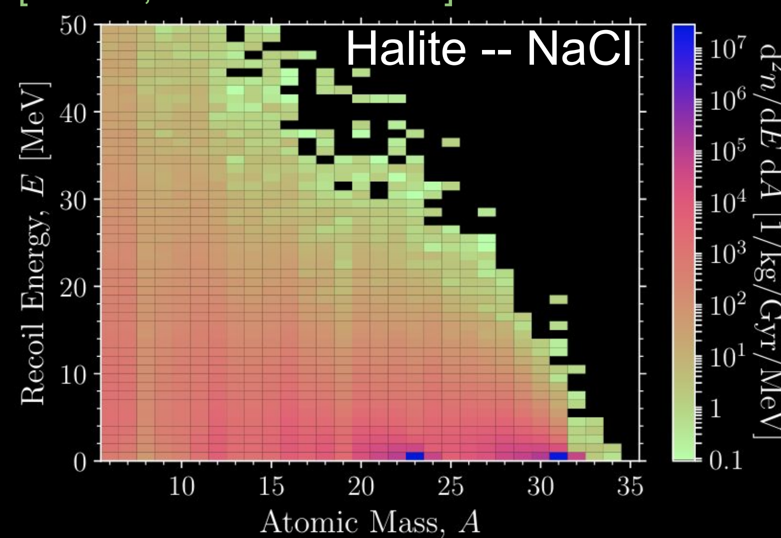
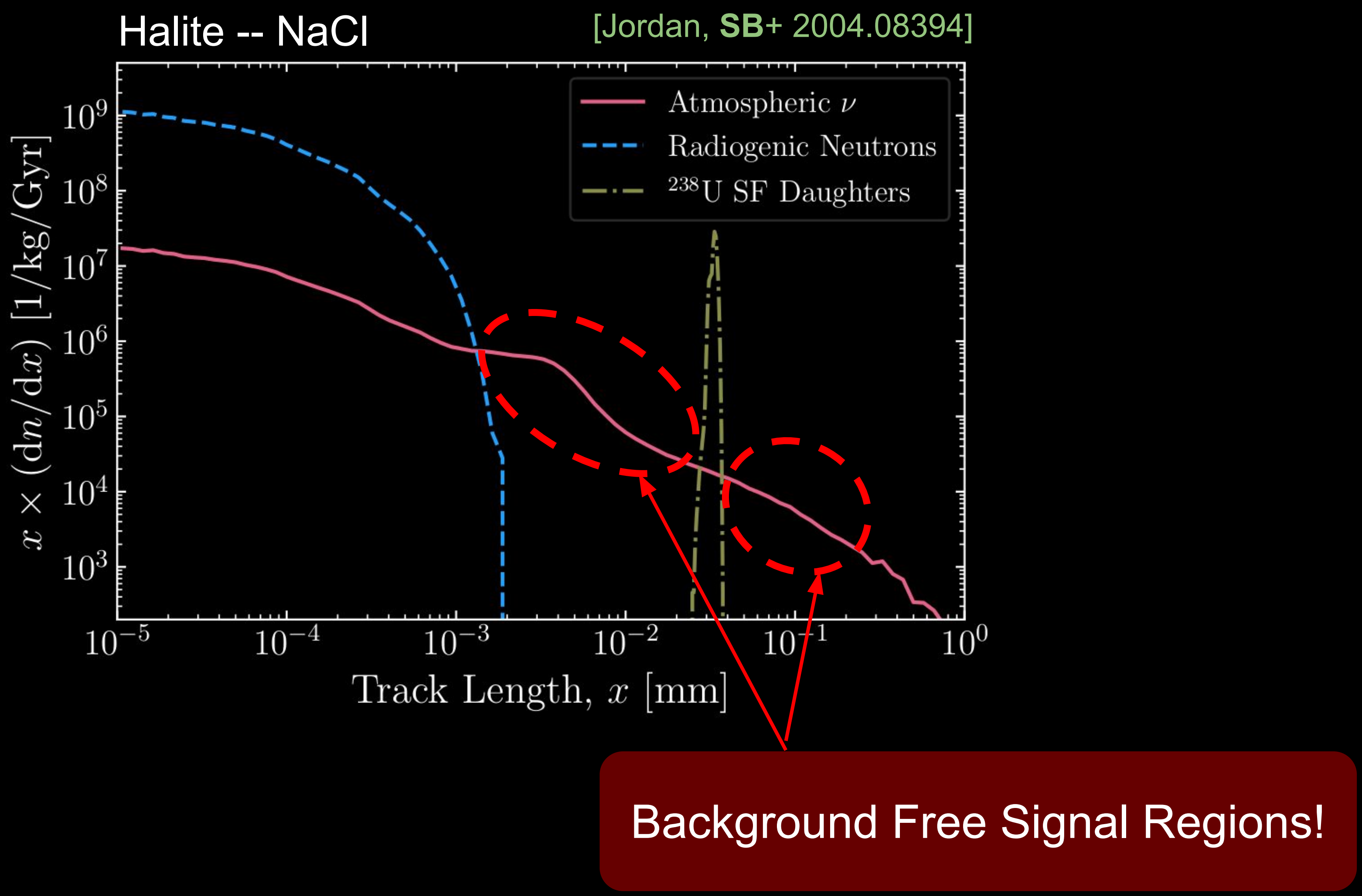




[Jordan, **SB**+ 2004.08394]



Cosmic Rays & Atmospheric Neutrinos



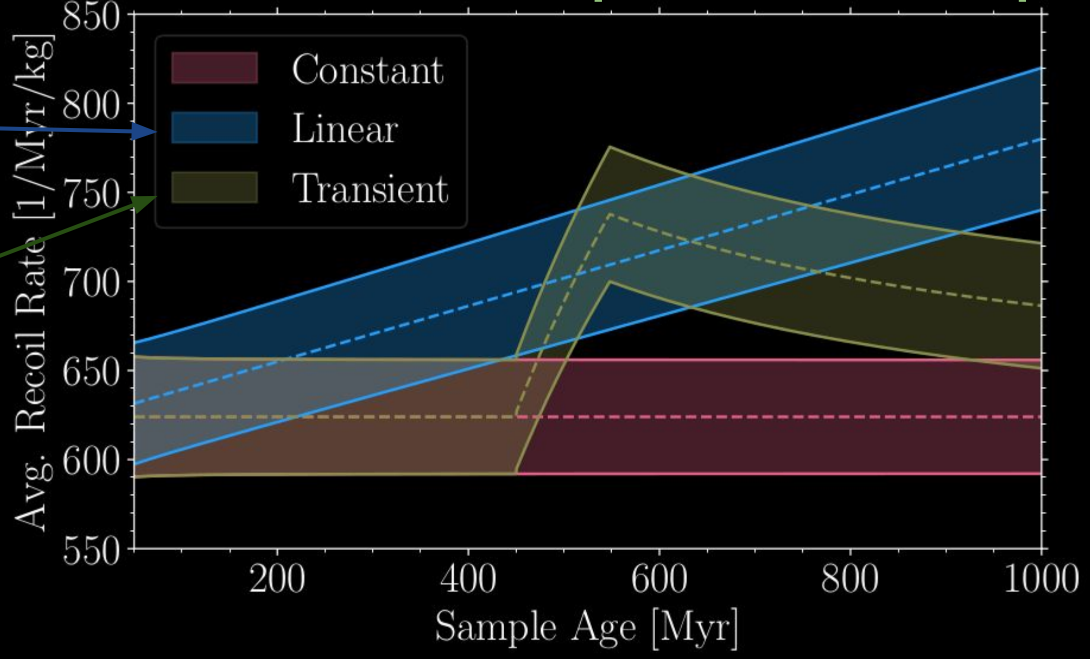
Cosmic Rays & Atmospheric Neutrinos

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

50% drop over 1 Gyr

100% enhancement for 100 Myr

[Jordan, **SB**+ 2004.08394]

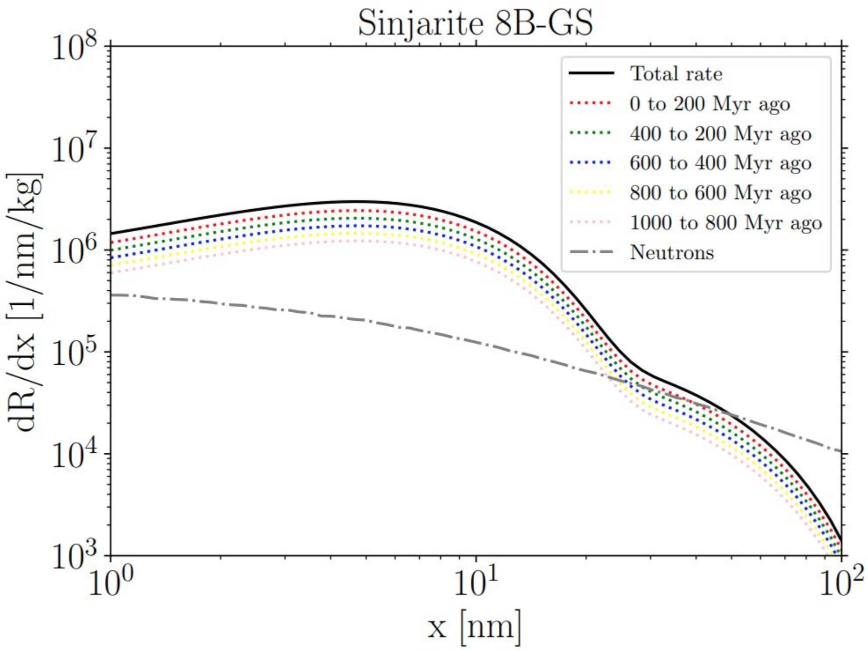


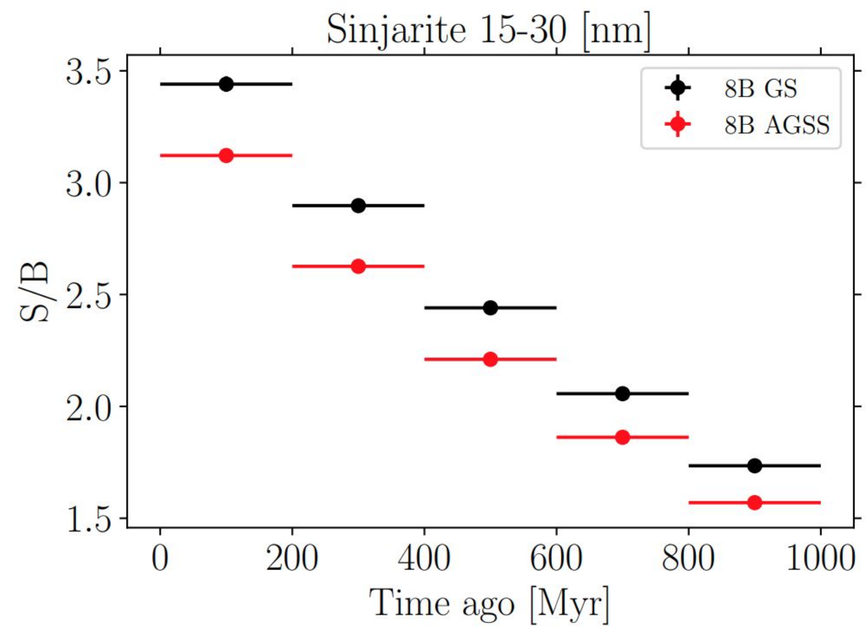
What about a little less energetic neutrinos?

[2102.01755]

Measuring solar neutrinos over Gigayear timescales with Paleo Detectors

Natalia Tapia-Arellano[1,*] and Shunsaku Horiuchi[1,†]



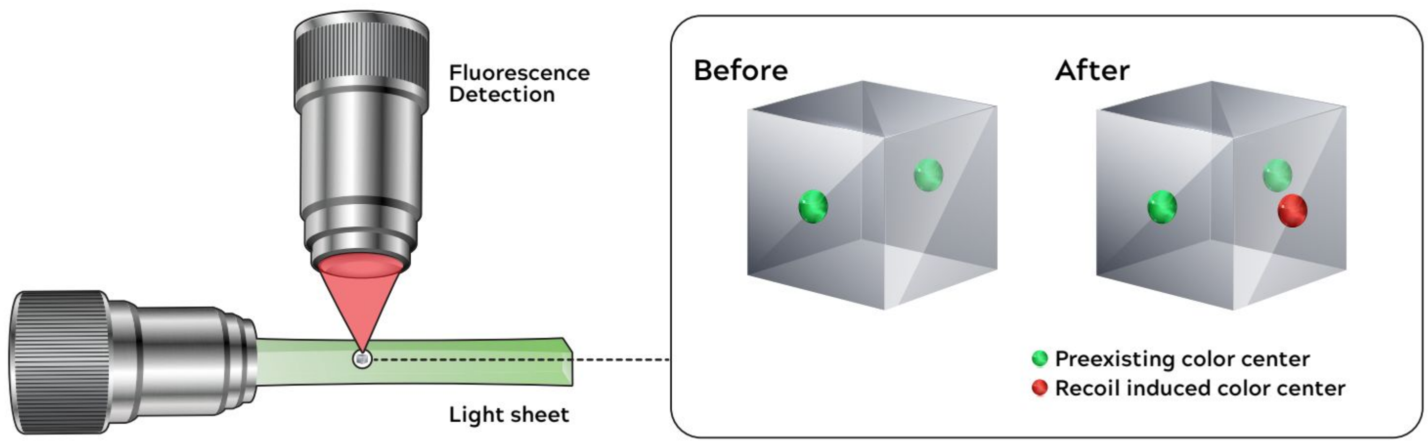


What about man-made neutrinos?

[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?

Ongoing and planned feasibility studies

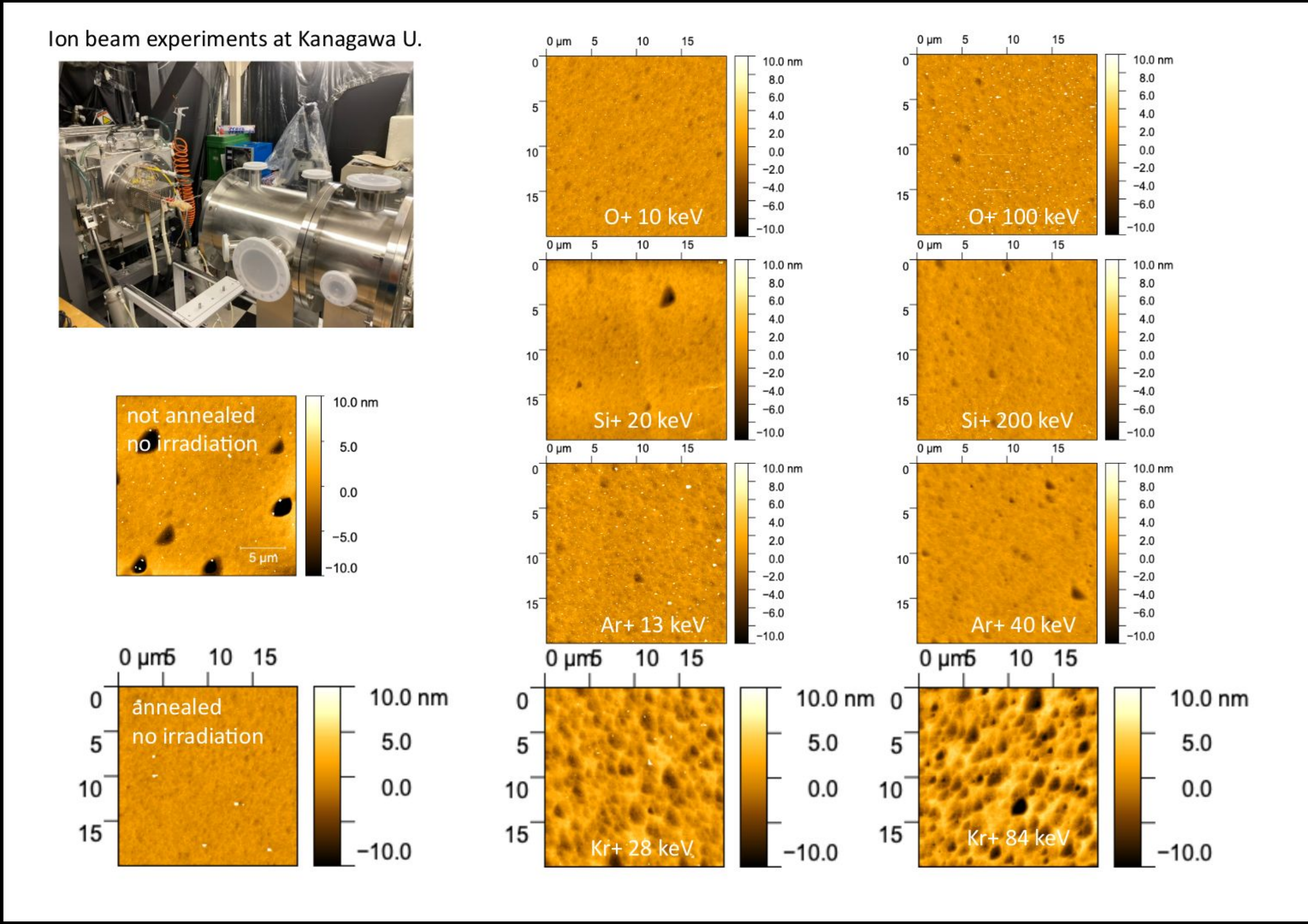
- SLAC
    - Irradiate samples (mica, silicon, …) with ~10 keV - 1 MeV ions
    - Image with electron beam tomography, chemical/sputter-etch + AFM, coherent X-ray imaging @ LCLS-II, …
- JAMSTEC
    - Irradiate samples (gypsum, mica, olivine…) with ~10 keV - 200 MeV ions
    - Image with SEM, TEM, chemical 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

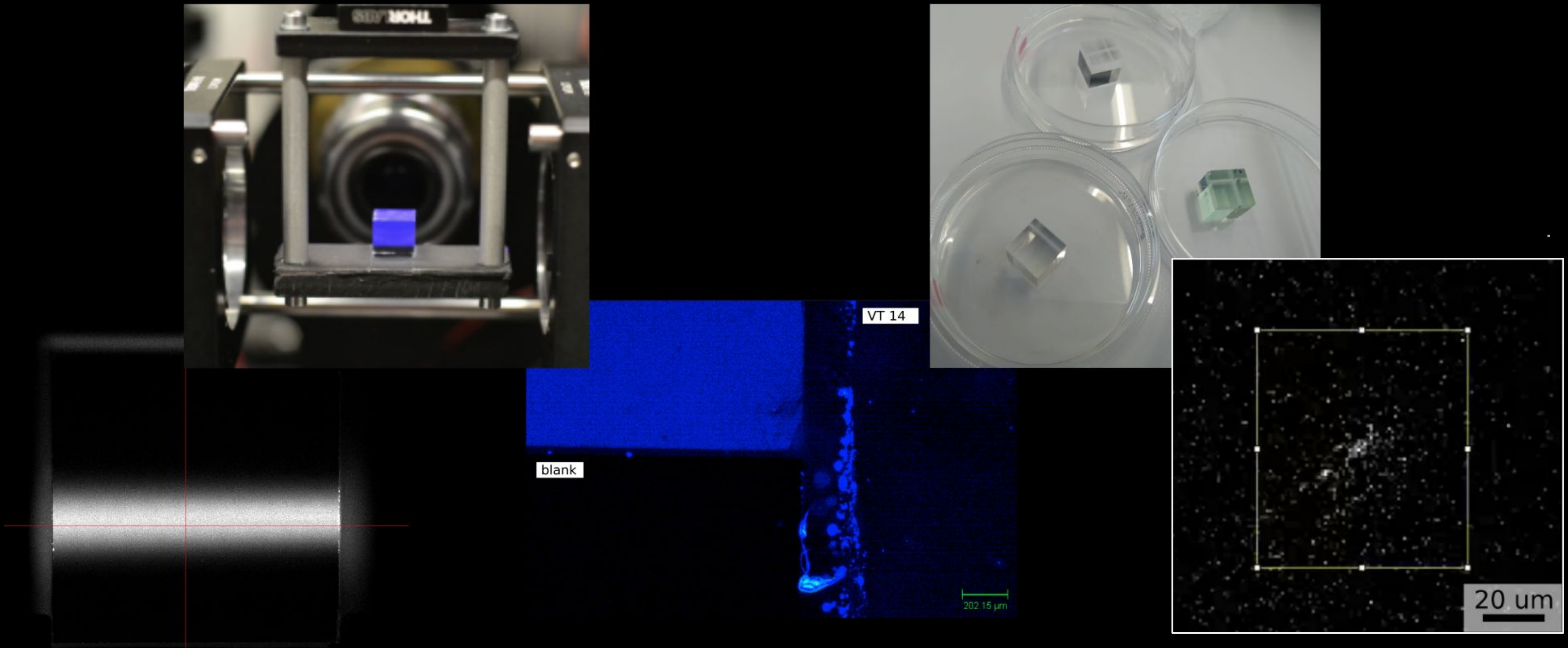
Feasibility studies by Shigenobu Hirose @ JAMSTEC

- Chemical etch + atomic force microscopy (AFM)



Feasibility studies: Gabriela Araujo+ @ U Zurich

- Fluorescence (light sheet) microscopy



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!

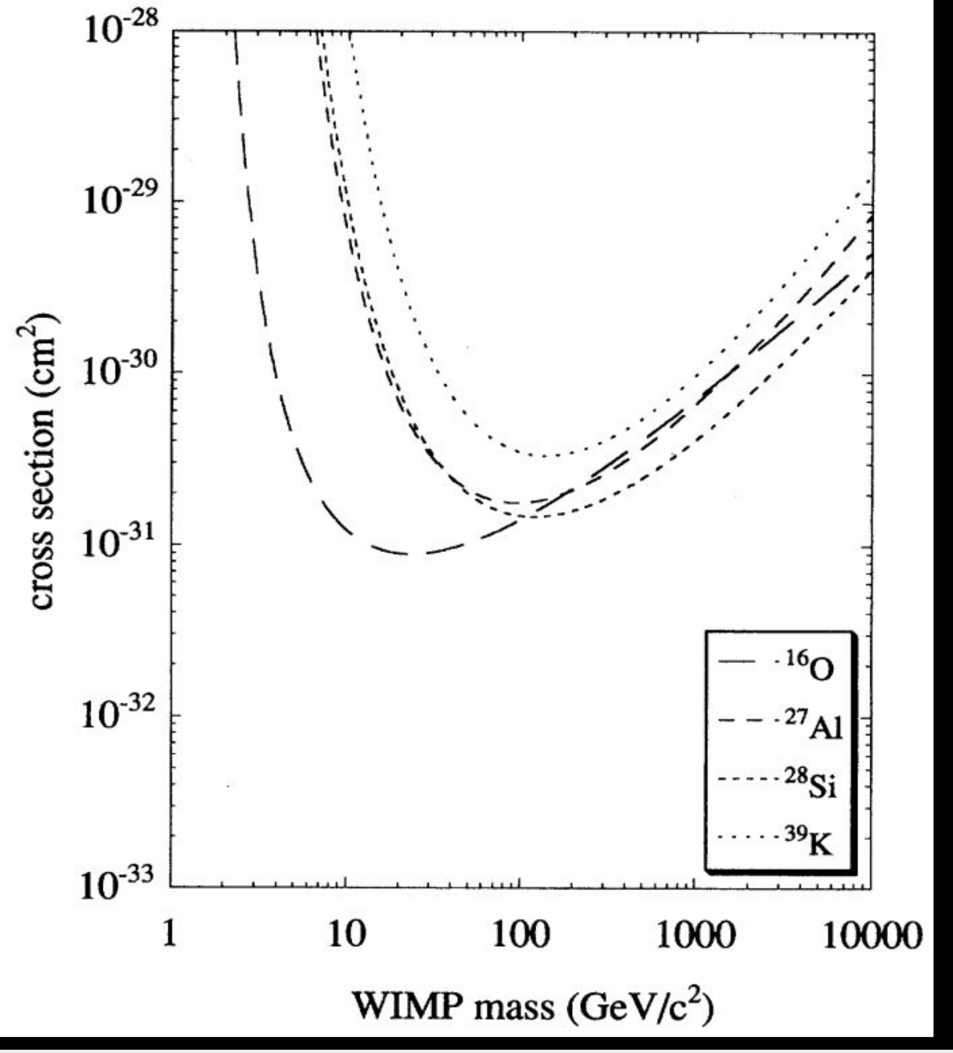
What was the Milky Way’s star formation rate 500 million years ago?

What is Dark Matter?

VOLUME 74, NUMBER 21 PHYSICAL REVIEW LETTERS 22 MAY 1995

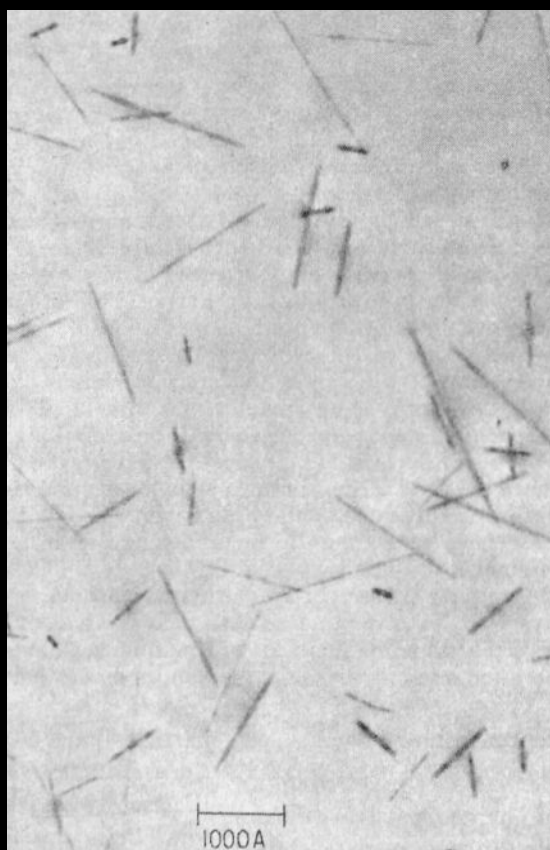
Limits on Dark Matter Using Ancient Mica

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



What has changed?

Fission fragment tracks
in synthetic Mica, TEM

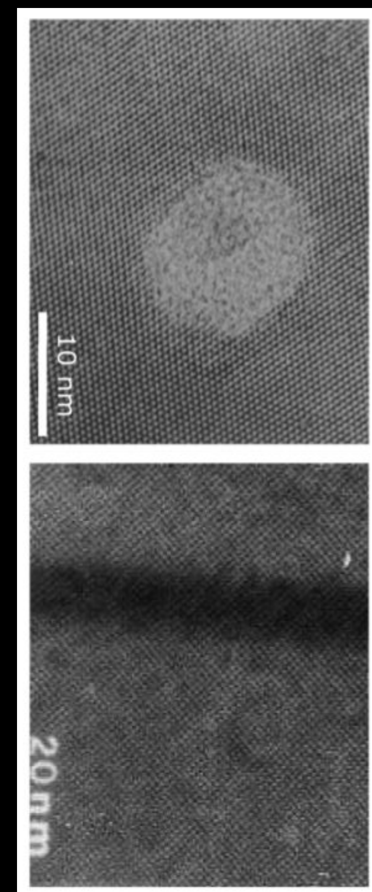


[Price&Walker '63]

High-resolution TEM
pictures of ion tracks

Pb on Mica

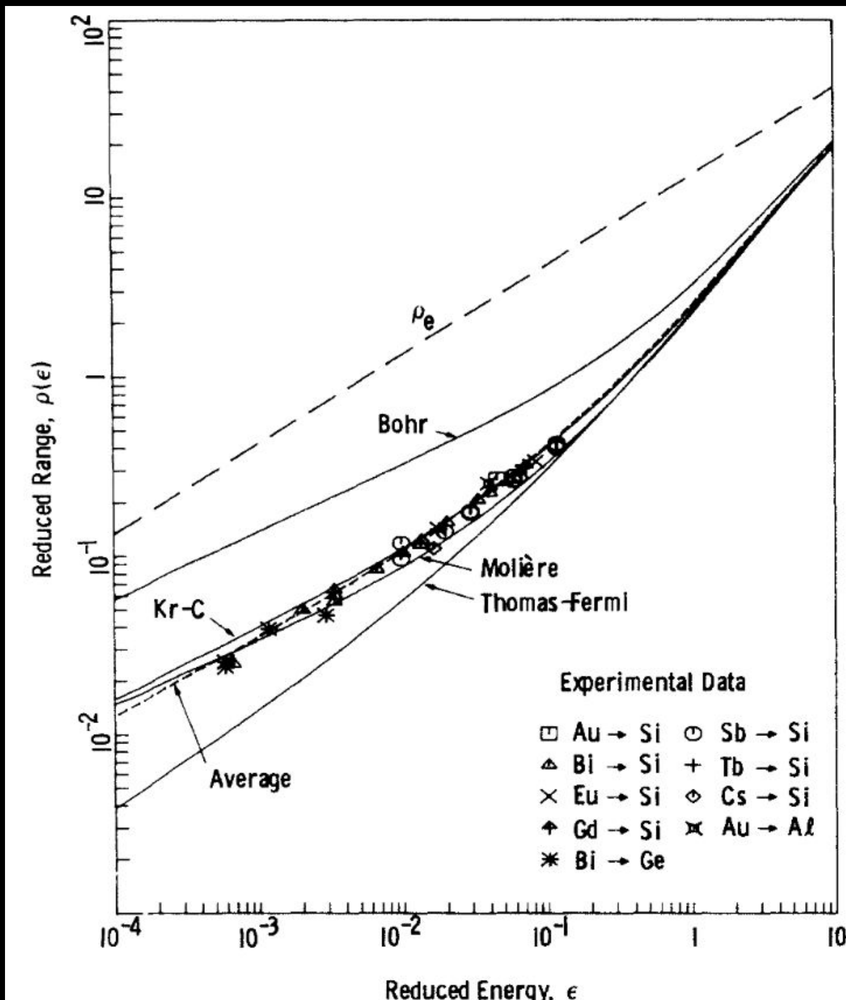
Xe on $Y_3Fe_5O_{12}$



[Toulemonde+ '06]

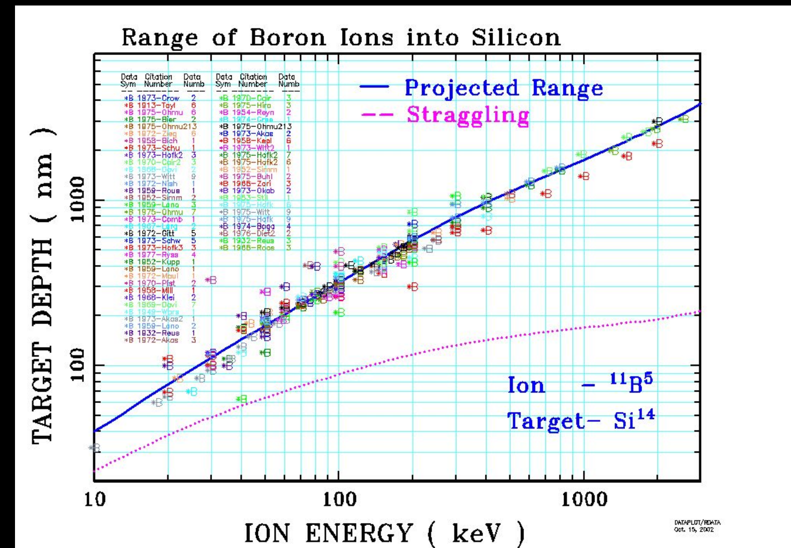
Ion Range Calculations

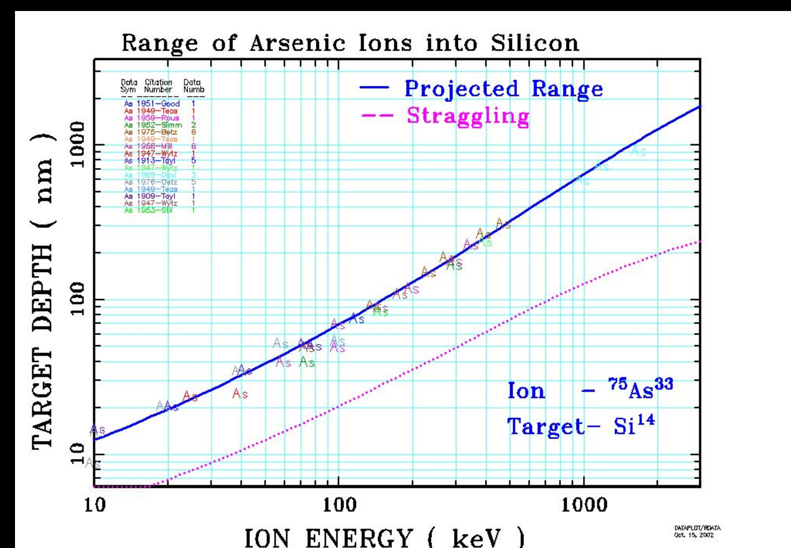
Semi-analytic treatment



[Wilson,Haggmark,Biersack +76]

SRIM



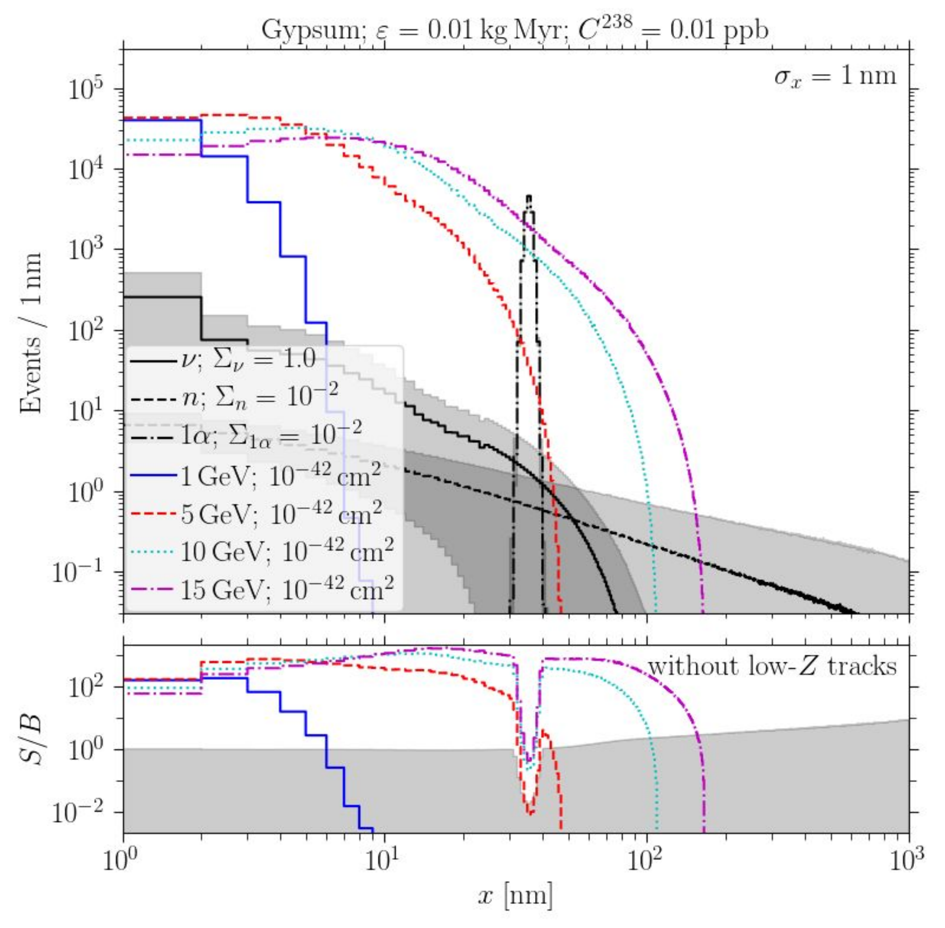


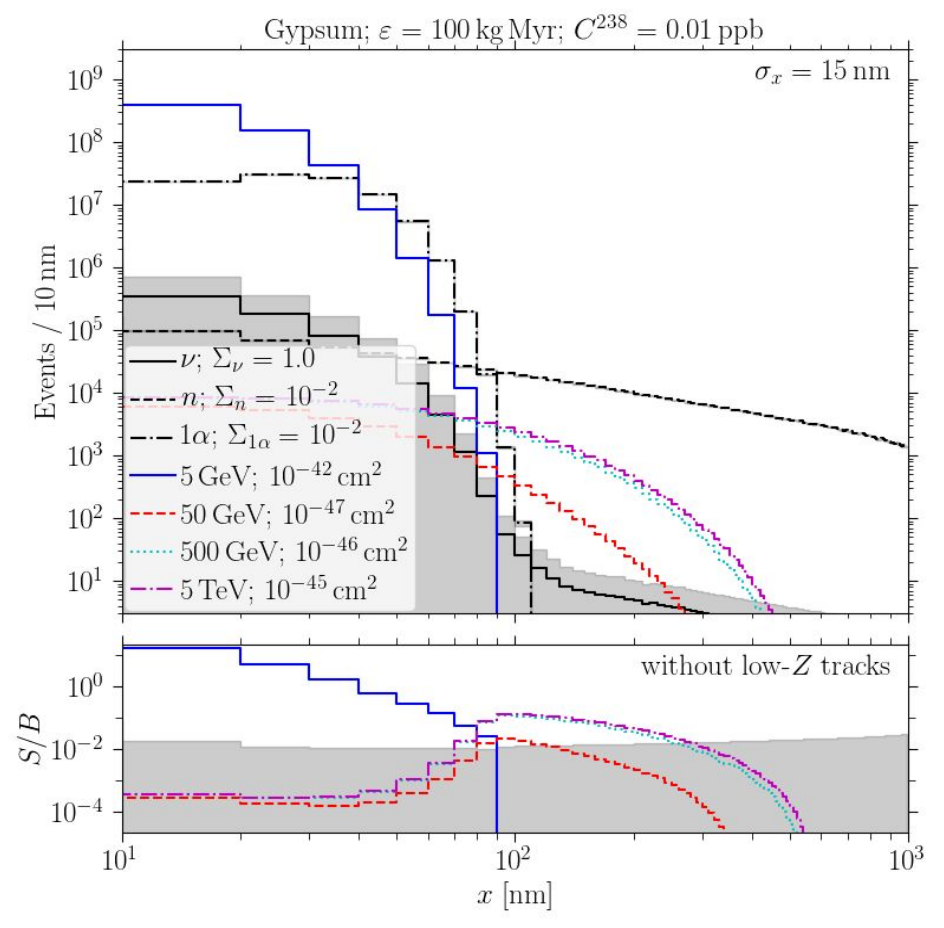
Dark Matter Against The Rest

[SB+ ‘19 (1811.06844)]

High-Resolution read-out
- 1 nm spatial resolution
- Exposure: (10 mg) x (1 Gyr)

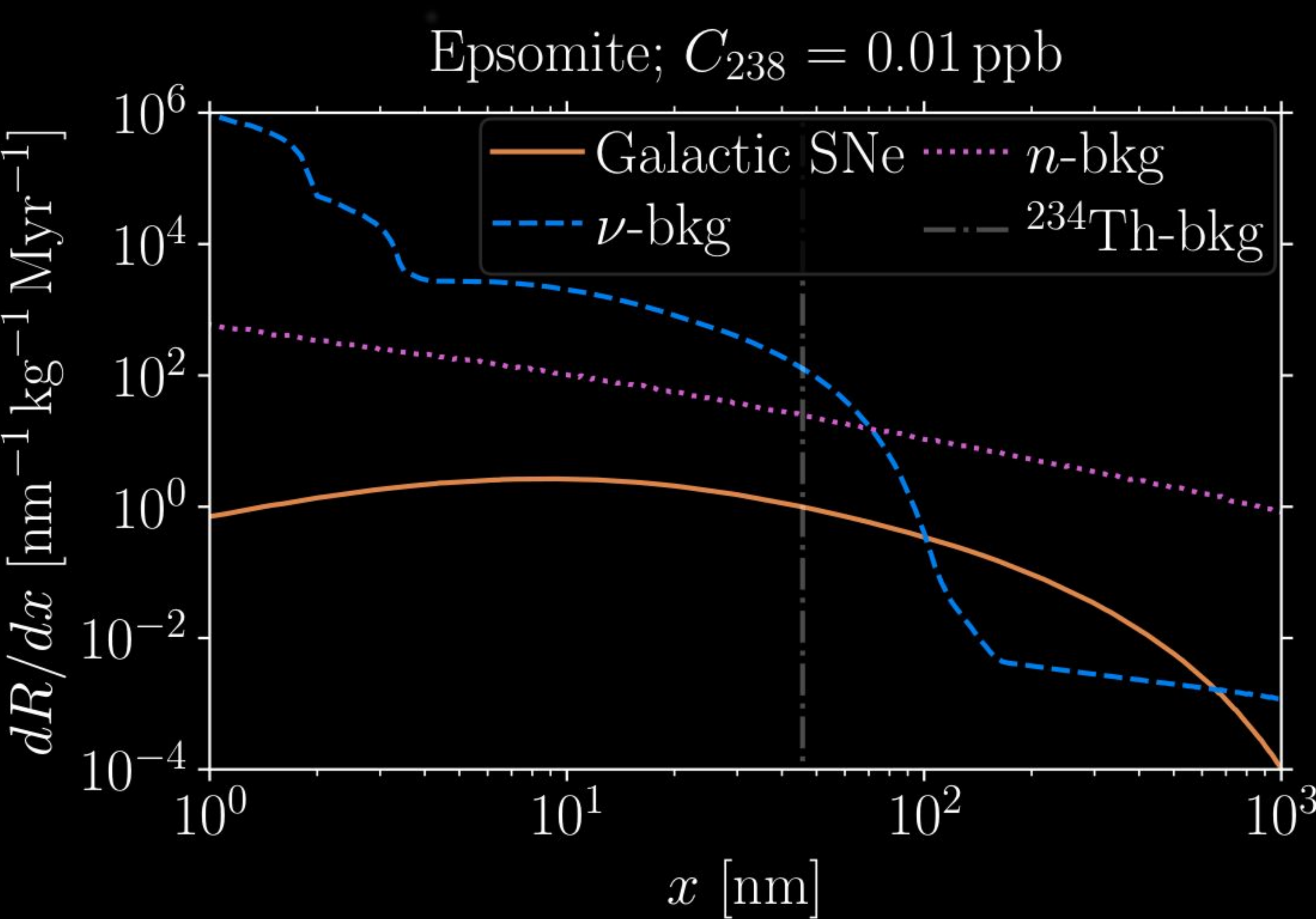
Low-Resolution read-out
- 15 nm spatial resolution
- Exposure: (100 g) x (1 Gyr)





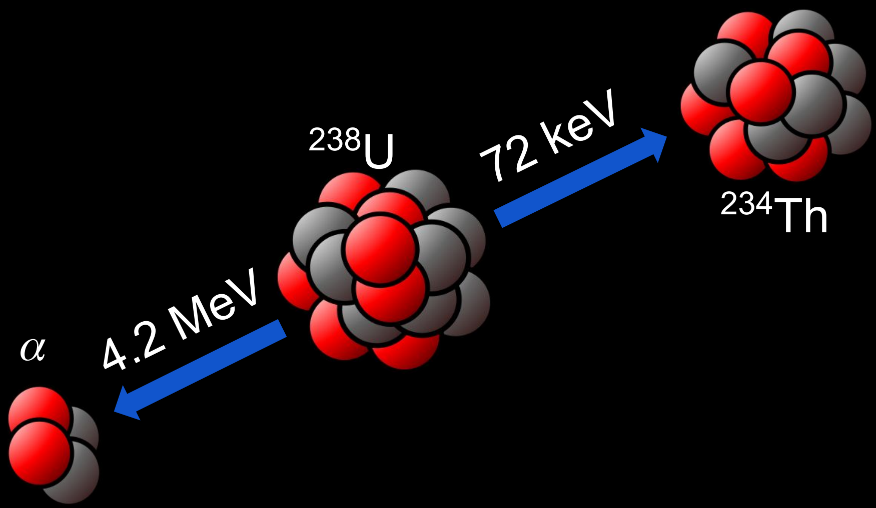
Backgrounds vs Supernova Neutrinos

Epsomite -- $MgSO_4 \bullet 7(H_2O)$



Radioactive Backgrounds: Single-α

$$^{238}\mathrm{U} \xrightarrow{\alpha} {}^{234}\mathrm{Th} \xrightarrow{\beta^-} {}^{234\mathrm{m}}\mathrm{Pa} \xrightarrow{\beta^-} {}^{234}\mathrm{U} \xrightarrow{\alpha} {}^{230}\mathrm{Th} \xrightarrow{\alpha} {}^{226}\mathrm{Ra} \xrightarrow{\alpha} {}^{222}\mathrm{Rn} \xrightarrow{\alpha} \ldots \longrightarrow {}^{206}\mathrm{Pb}\,.$$



Nucleus	Decay mode	$T_{1/2}$
^{238}U	α	4.468×10^9 yr
	SF	8.2×10^{15} yr
^{234}Th	β^-	24.10 d
$^{234\mathrm{m}}$Pa	β^- (99.84 %) IT (0.16 %)	1.159 min
^{234}Pa	β^-	6.70 d
^{234}U	α	2.455×10^5 yr
^{230}Th	α	7.54×10^4 yr
^{226}Ra	α	1600 yr
^{222}Rn	α	3.8325 d

$$n_{1\alpha}^{238} = n_{238}^{0} \frac{T_{1/2}^{234}}{T_{1/2}^{238}} = 1.4 \times 10^9\,\mathrm{kg}^{-1} \left(\frac{C^{238}}{0.01\,\mathrm{ppb}} \right)$$

Sensitivity Projections: SD Proton-Only

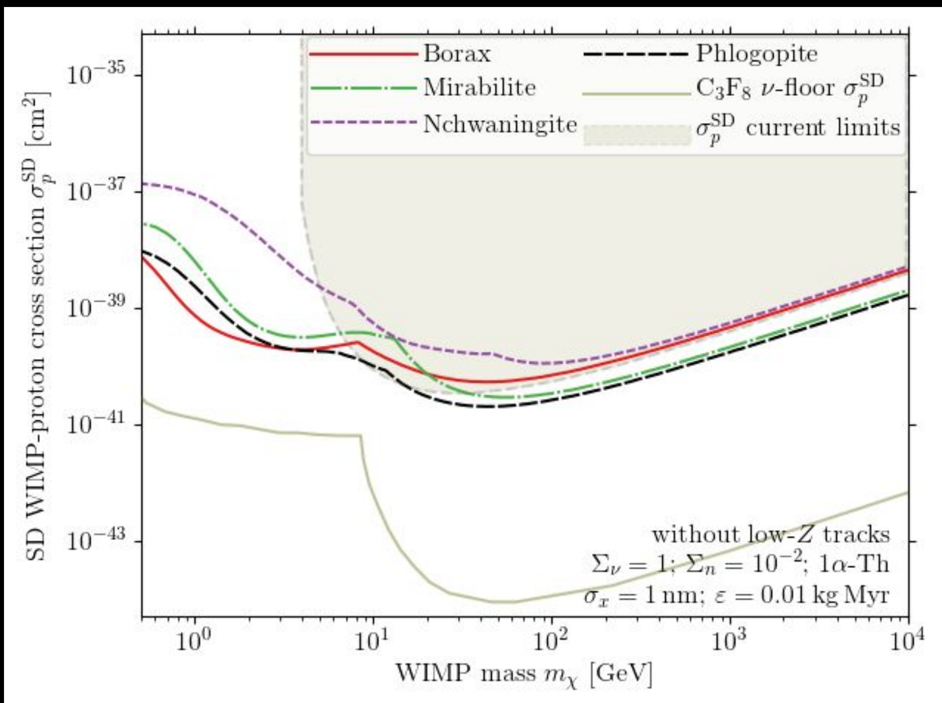
[SB+ ‘19 (1811.06844)]

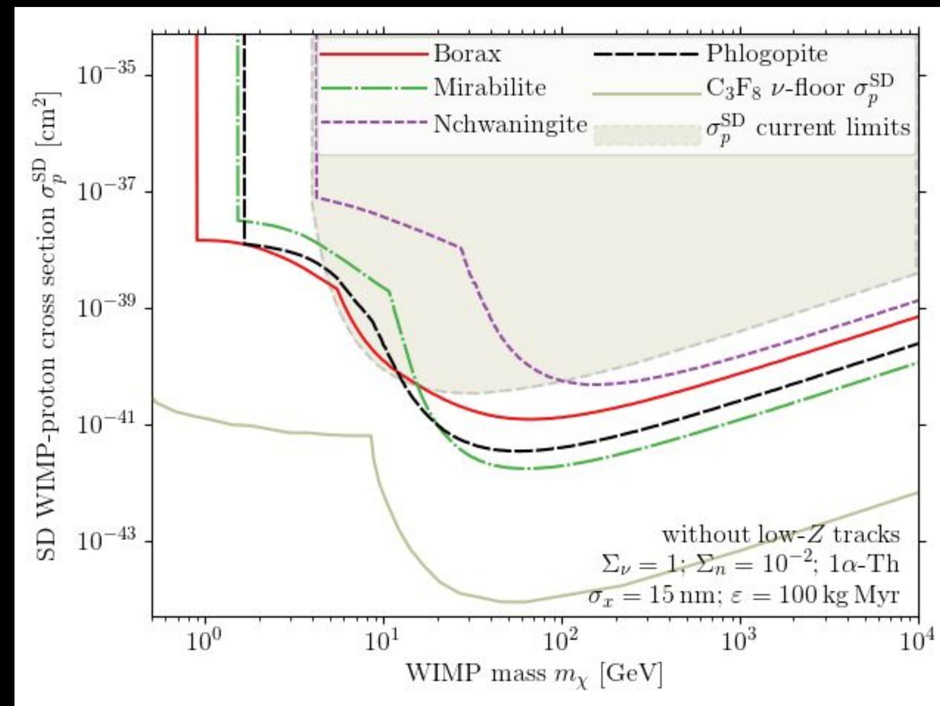
Good resolution, small target mass

- 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)

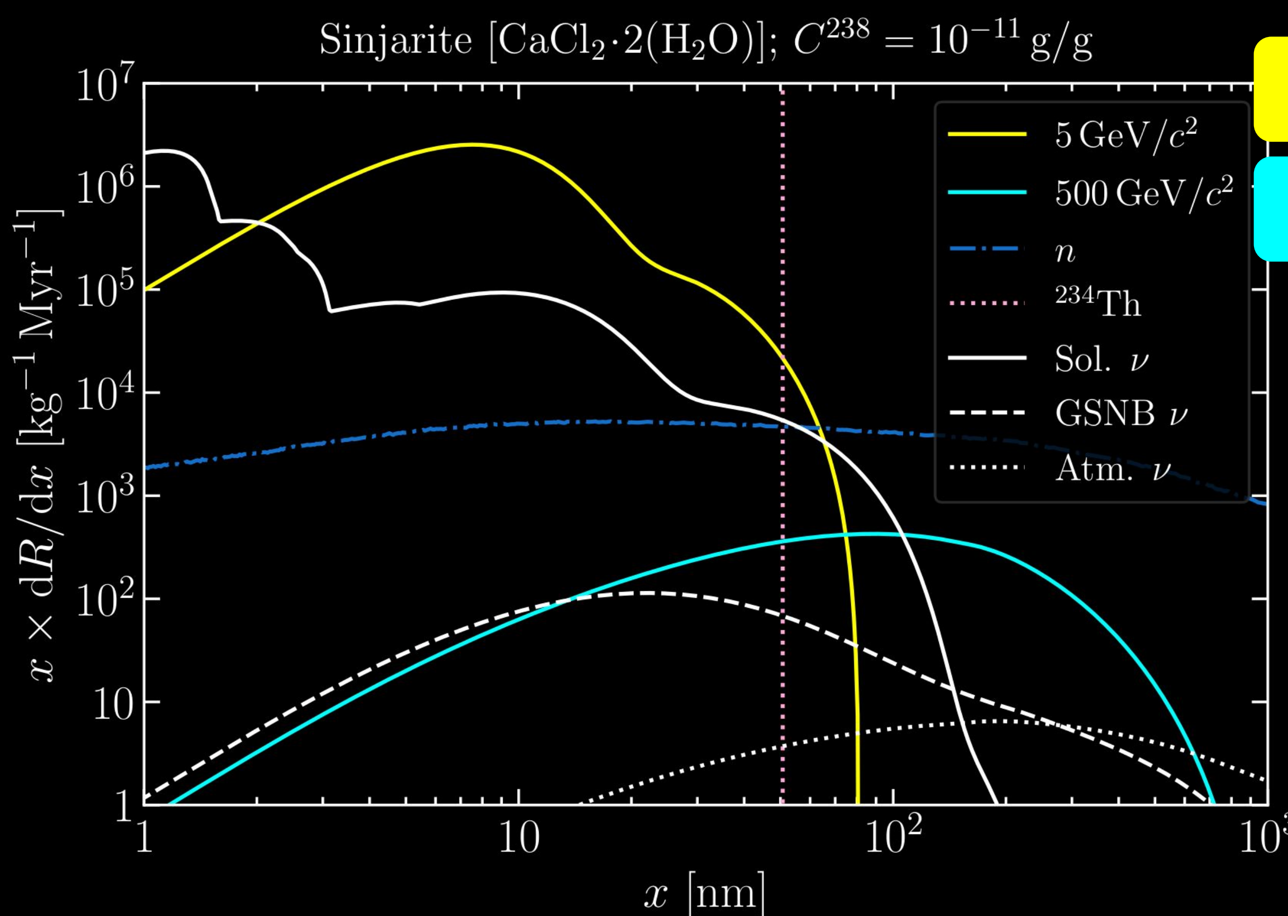




Borax -- $\mathbf{Na_2}(\mathbf{B_4}O_5)(OH)_2 \cdot 8(H_2O)$
Mirabilite -- $\mathbf{Na_2}SO_4 \cdot 10(H_2O)$

Nchwaningite -- $\mathbf{Mn_2}SiO_3(OH)_2 \cdot (H_2O)$
Phlogopite -- $\mathbf{K}Mg_3\mathbf{Al}Si_3O_{10}\mathbf{F}(OH)$

Track Length Spectra

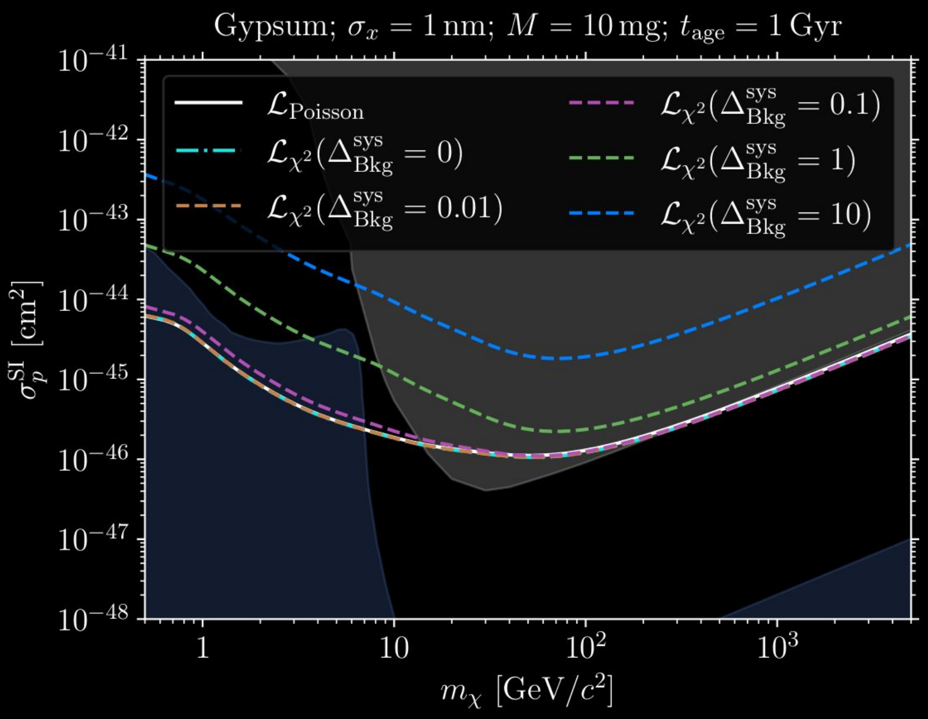


$\sigma_p^{SI} = 10^{-43}$ cm^2

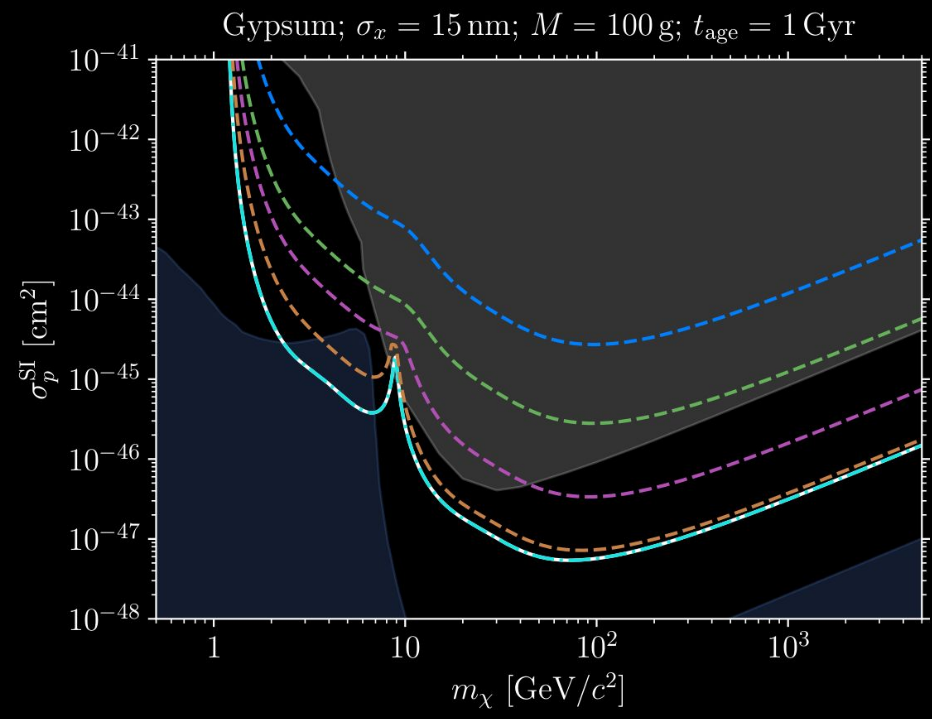
$\sigma_p^{SI} = 10^{-46}$ cm^2

Robustness Against Errors in Background Shape

“High Resolution”

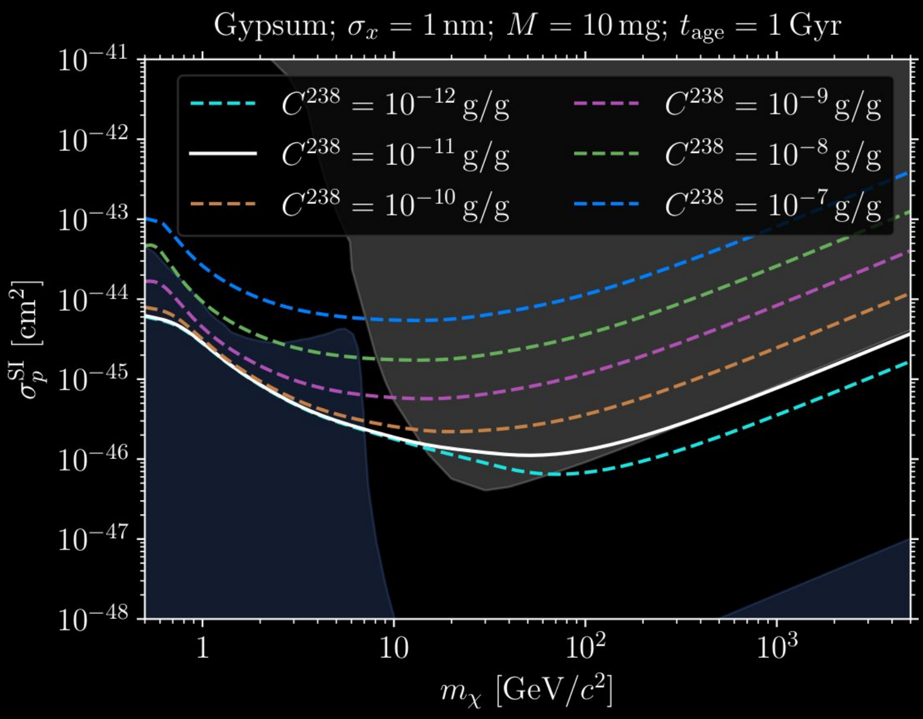


“High Exposure”

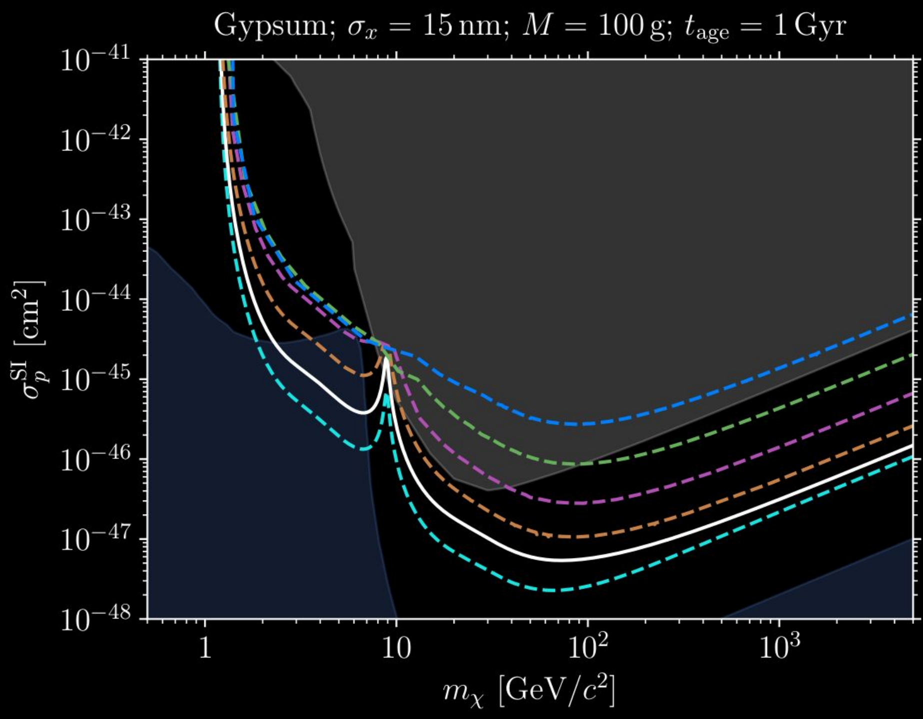


DM sensitivity for different radiopurities

“High Resolution”

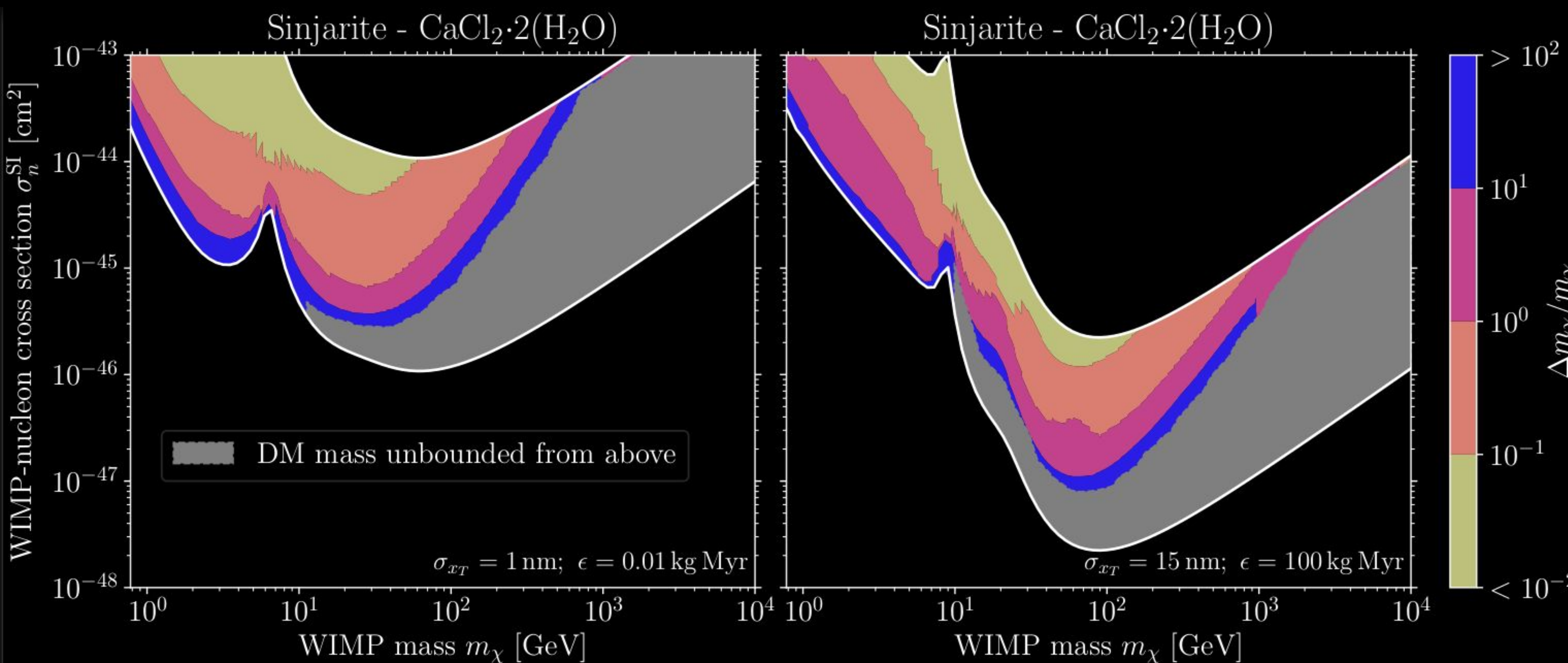


“High Exposure”



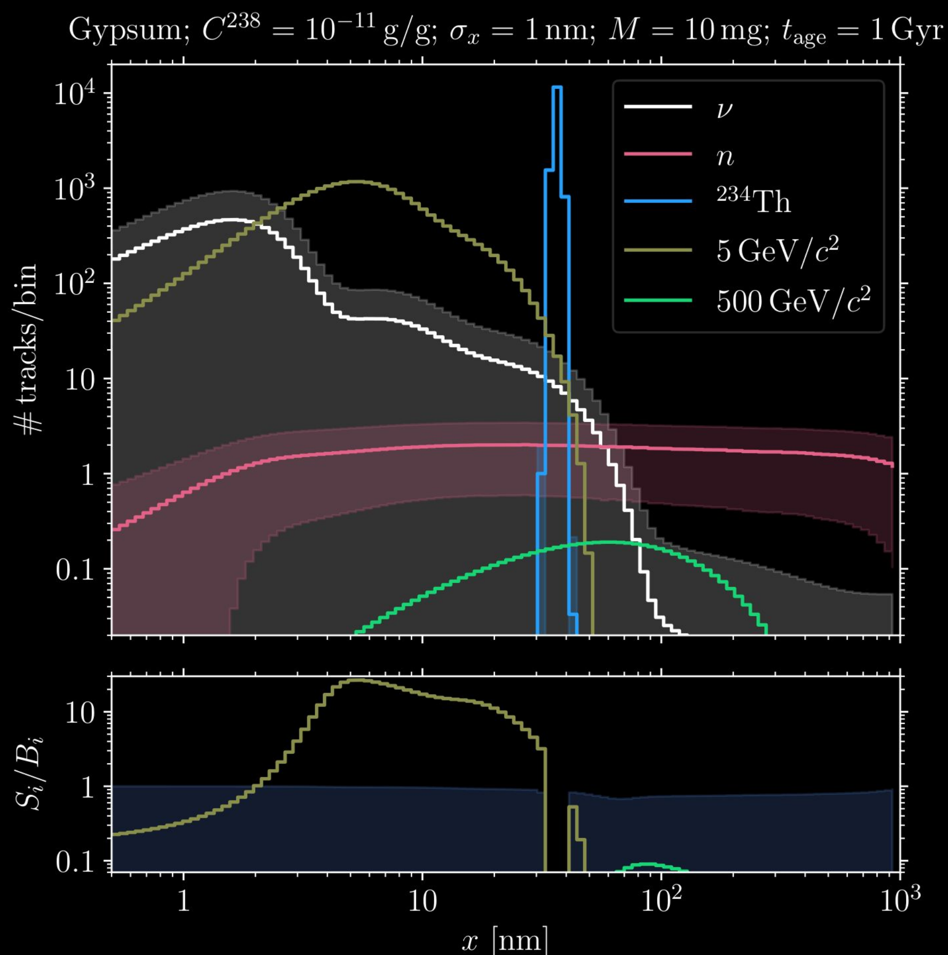
Measuring the Dark Matter mass

[Edwards, SB+ 1811.10549]

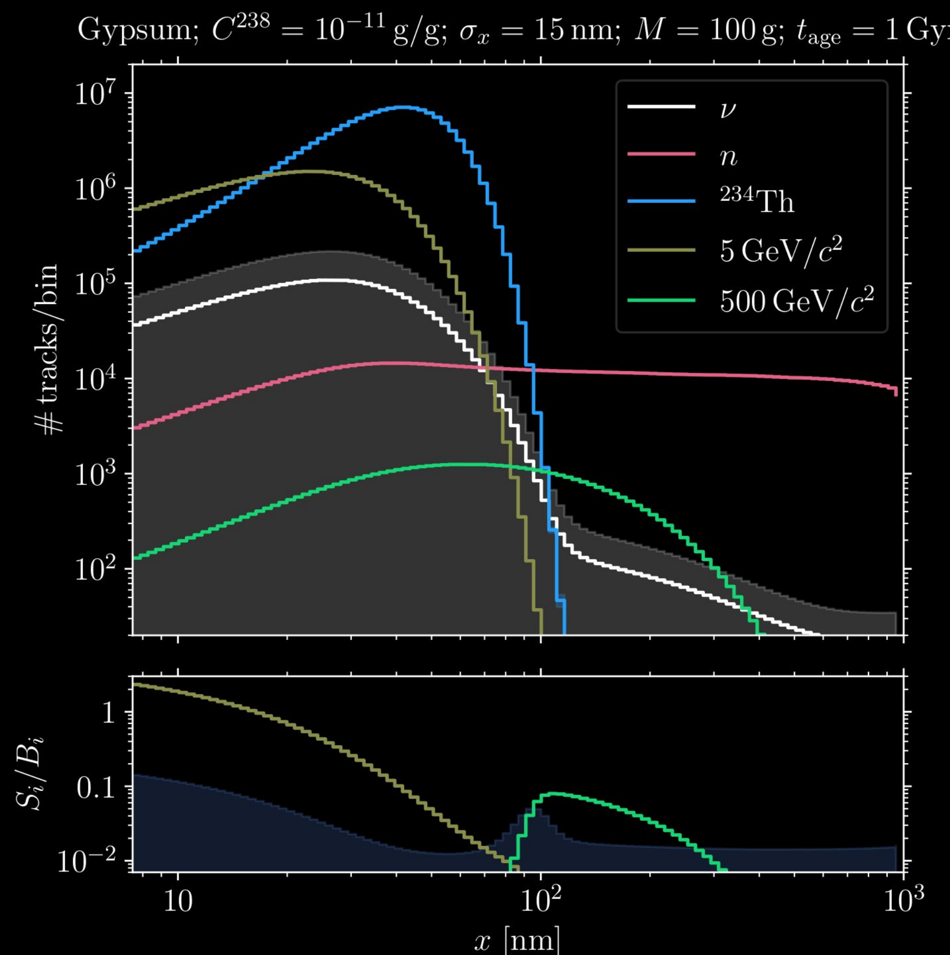


Digging a Signal out of the Background

"High Resolution"



"High Exposure"

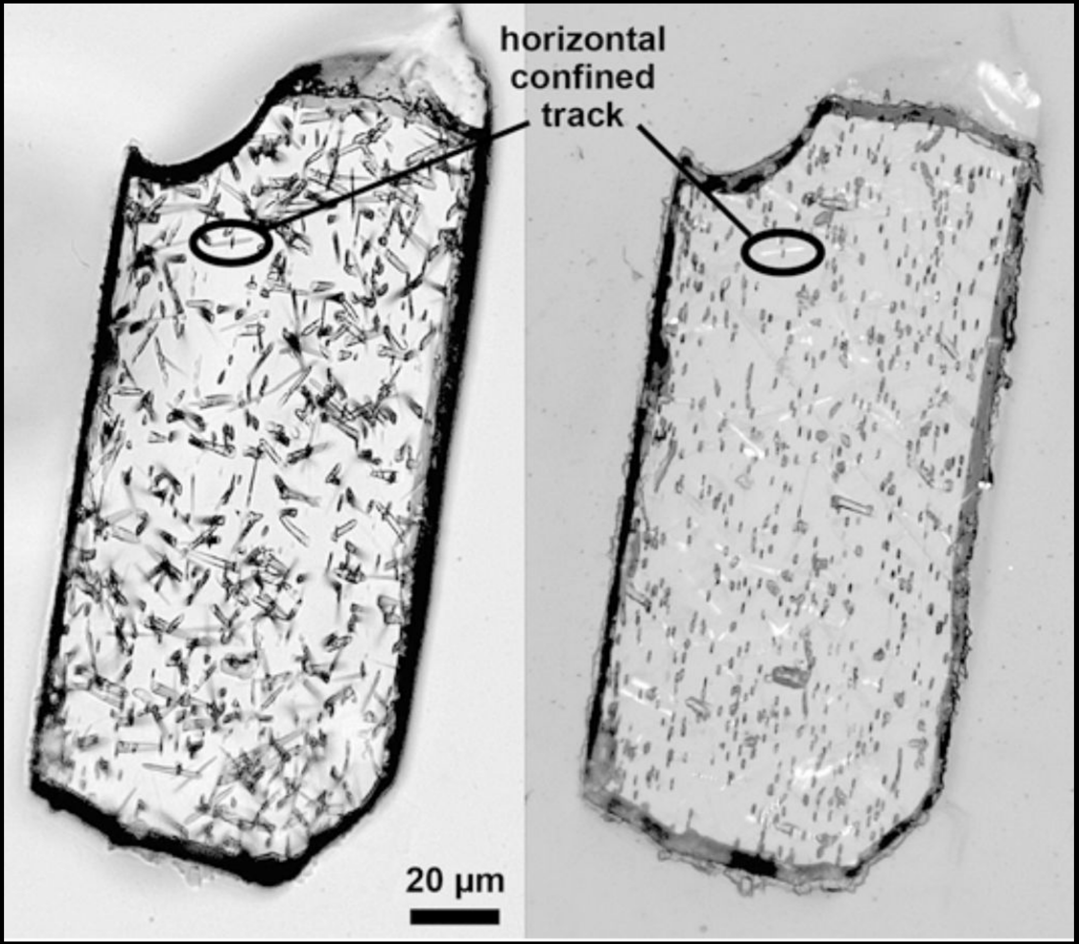


Read-Out Methods: Optical Microscopy

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

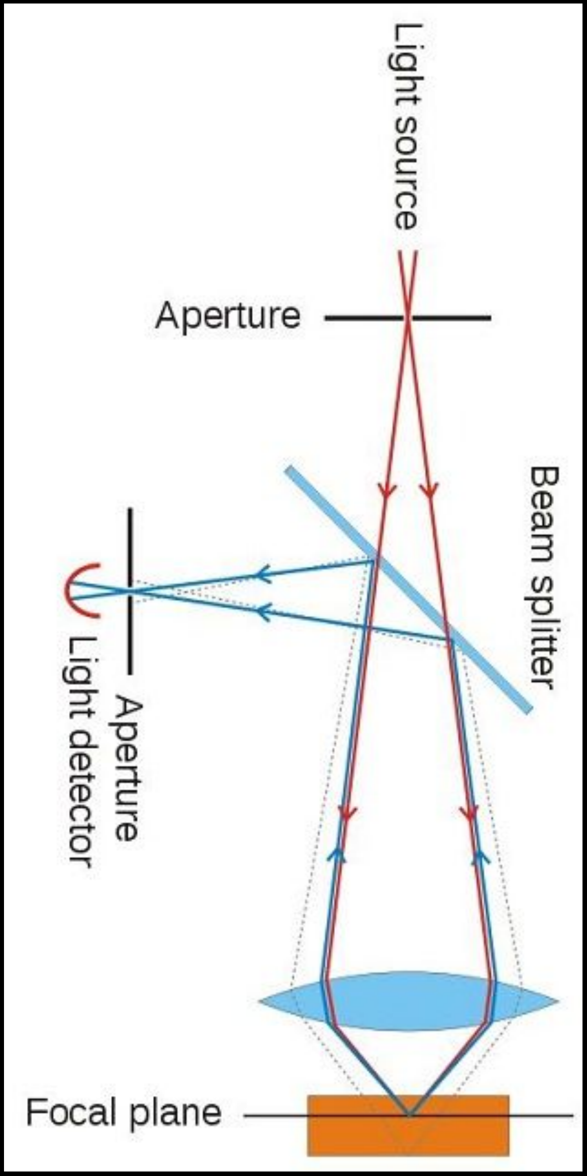
Etched fission tracks in Apatite

transmission reflection



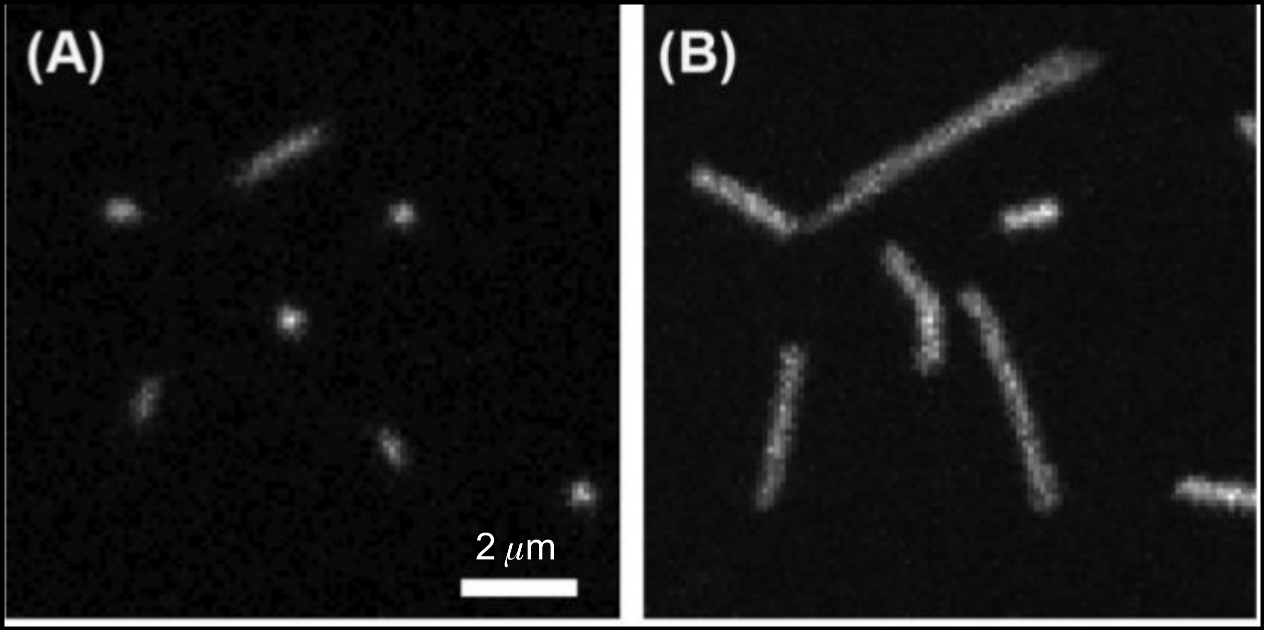
[Thomson ‘16]

Read-Out Methods: Confocal Microscopy



α-tracks in Al_2O_3:C,Mg (without etching!)

Single picture | Longest projection of 3D

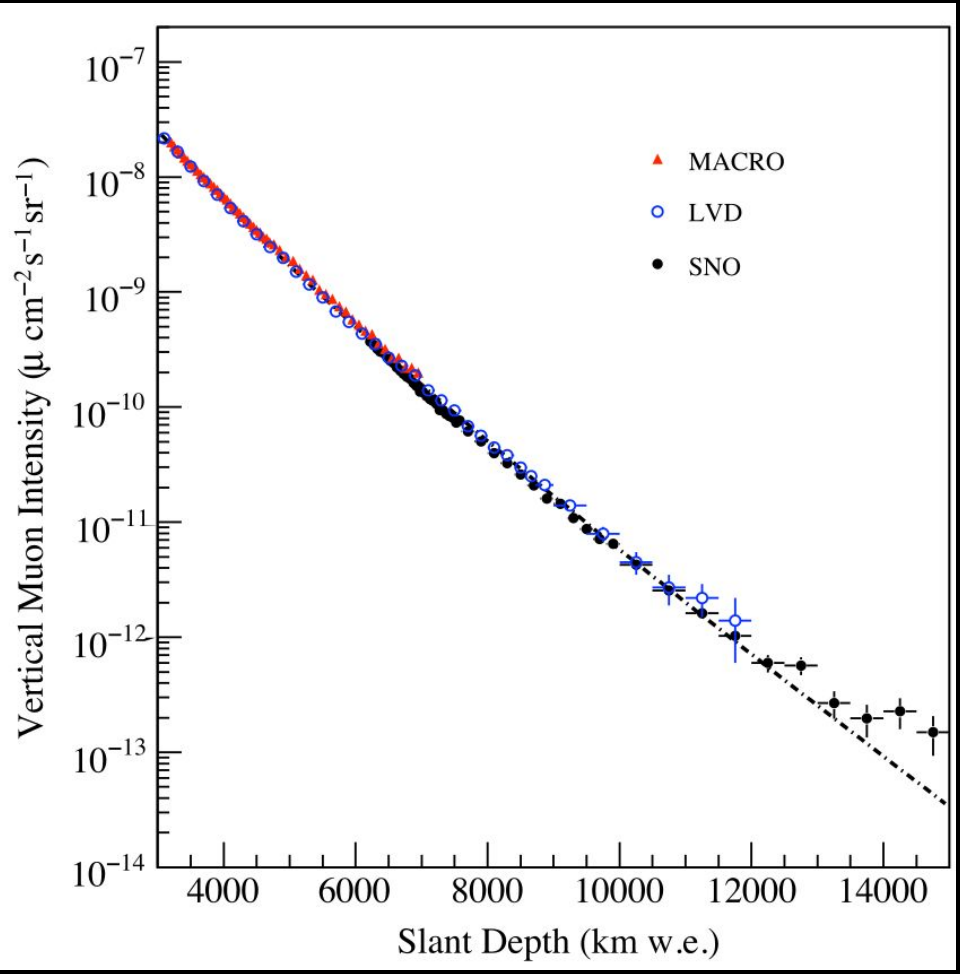


[Kouwenberg+ ‘18]

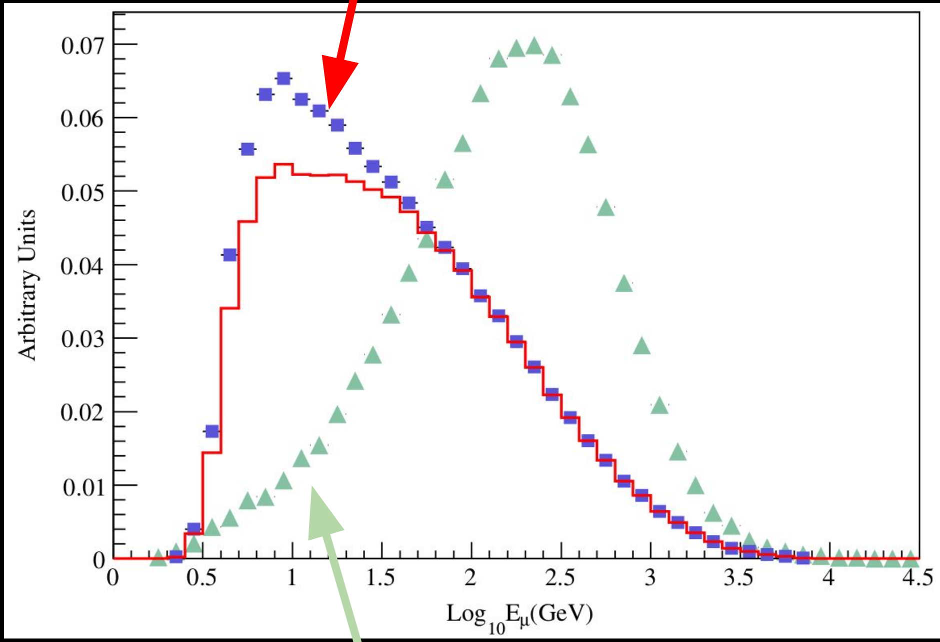
- Widely available
- Resolution ~100 nm
- Requires fluorescent targets

Neutrons from Atmospheric Neutrinos

[Aharmim+ '09]



muons from atmospheric neutrinos
w/o (w) neutrino oscillations



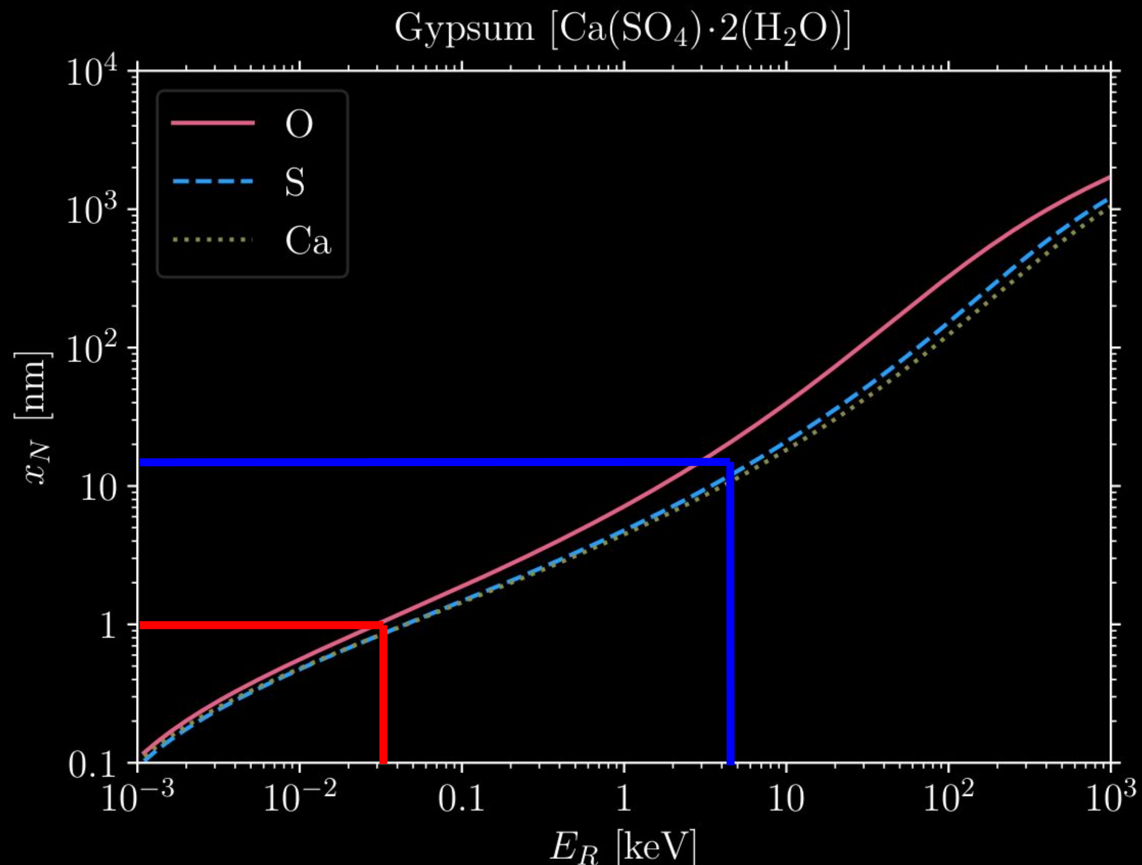
cosmic-ray muons
(@ 6 km w.e)

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

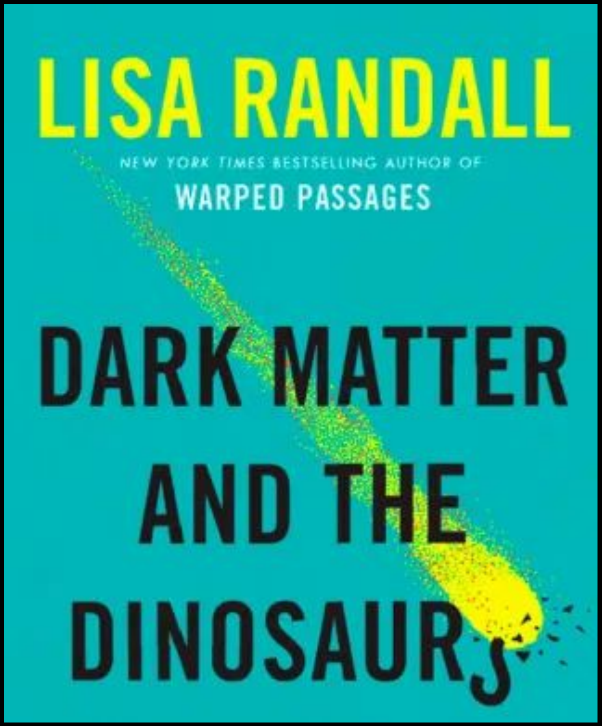
- Electronic stopping (off electron clouds)
- Nuclear stopping (off other nuclei)

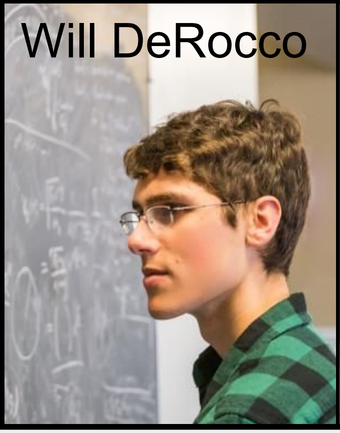


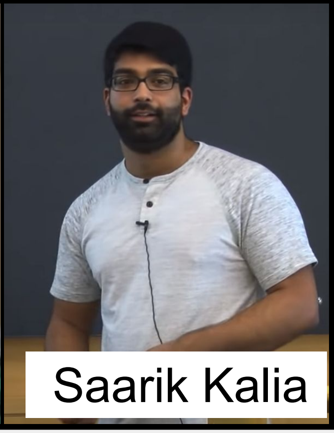
[SB, DeRocco, Edwards, Kalia, 2107.02812]

Time-Dependent Dark Matter Signals?

[Springel+ (Aquarius) '08]

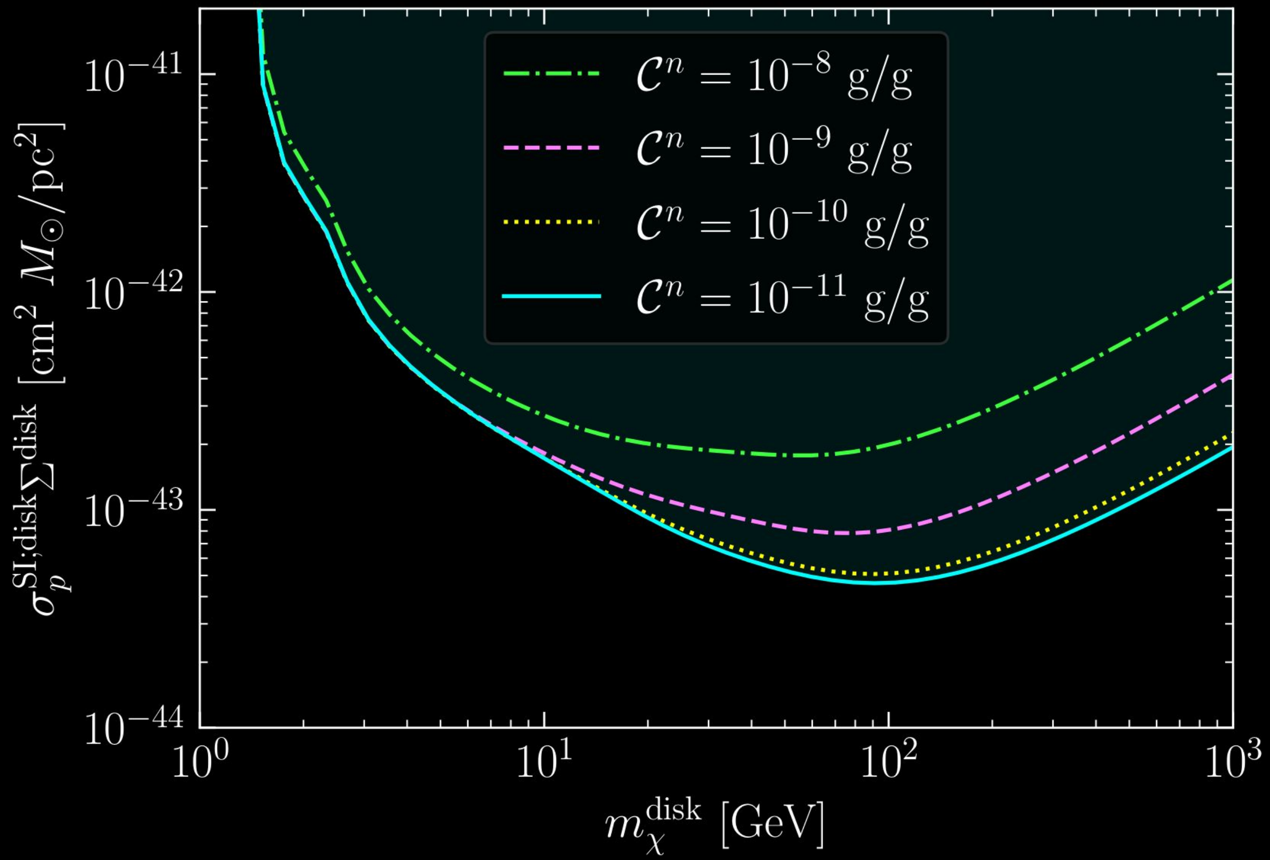






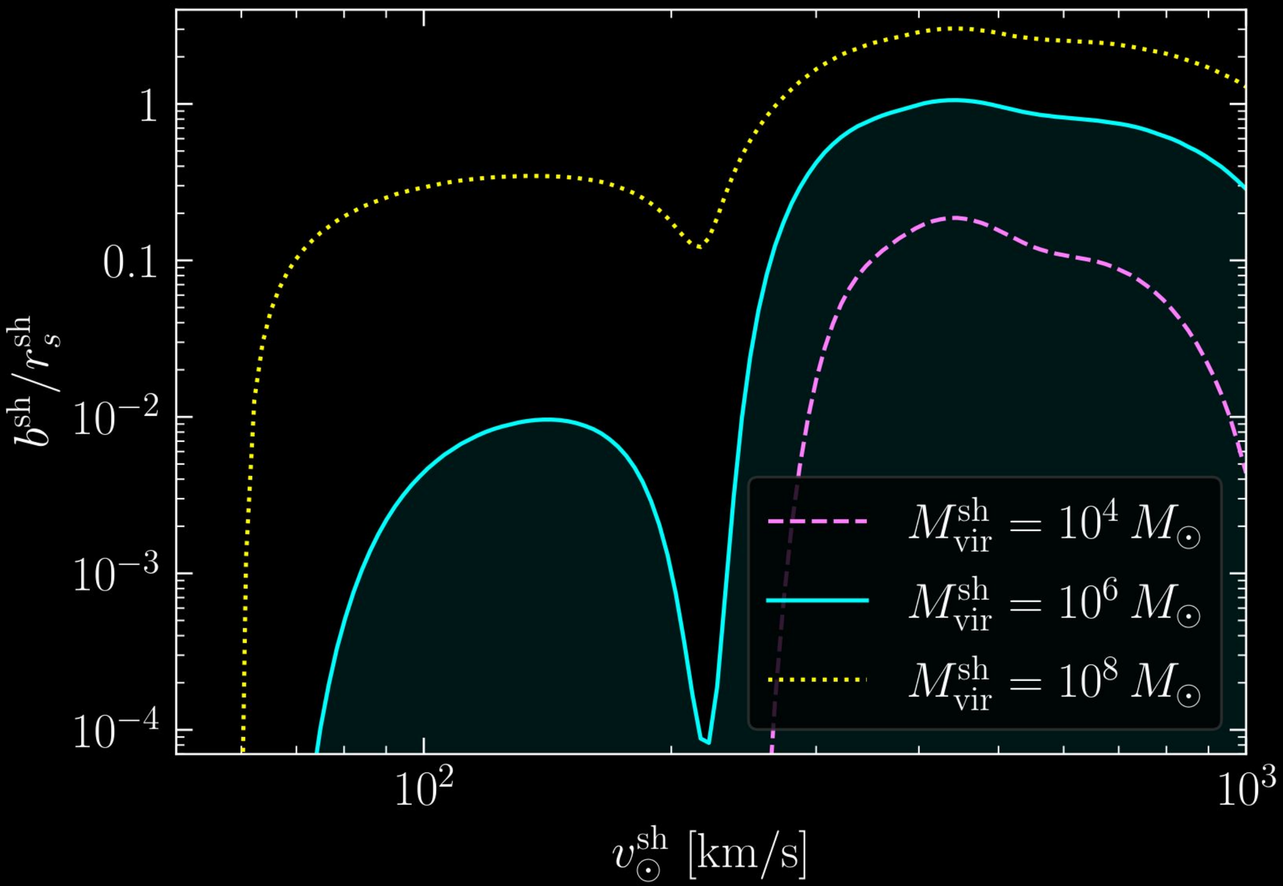
[SB, DeRocco, Edwards, Kalia, 2107.02812]

Could we see a dark disk?



- Gypsum [Ca(SO4)•2(H2O)]
- "High-Resolution" scenario
- 5 samples with ages T^n = {20, 40, …, 100} Myr

What if we went through a subhalo?



- Gypsum [Ca(SO4)•2(H2O)]
- “High-Exposure” scenario
- 5 samples with ages T^n = {200, 400, …, 1000} Myr