



Paleo-Detectors: An Alternative Approach to Direct Detection

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Supervisor: Katherine Freese, Professor at UT Austin

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Contents

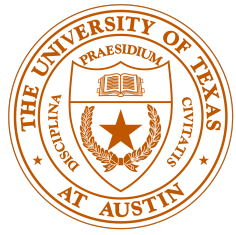


- ❖ Paleo-Detectors: Ancient minerals as Dark Matter detectors
- ❖ Sensitivity Projections for Dark Matter and Neutrino Searches
- ❖ Experimental Progress Toward Paleo-Detectors



Paleo-Detectors: Ancient Minerals as Dark Matter Detectors

The basic concept, the pioneering mica search (1995), and the modern Paleo-Detector program



Paleo-Detectors: Ancient minerals as Dark Matter detectors

- ❖ Paleo-detectors are ancient minerals
- ❖ Extracted from ~ 5 km depth to suppress cosmic-ray backgrounds
- ❖ Typical age ~ 1 Gyr
- ❖ Masses from 10 mg to 100 g
- ❖ Exposure $\sim 10^5$ t $\cdot$ yr
 - ➡ Conventional DD: $\sim 10^2$ t $\cdot$ yr (next decades)
- ❖ Goal: 1 kg of ancient mineral has exposure of Hyper-K with energy threshold of Xenon detectors

ISSUES & EVENTS

Search amps up for signatures of cosmic particles in ancient minerals

Advances in imaging and data handling open new possibilities.

What if a mineral could reveal what it's seen over the millions—or billions—of years it's been sitting deep within Earth? An interdisciplinary global network of scientists is reviving efforts to unlock the secrets that minerals hold. The top goals are to identify dark matter, learn more about neutrinos, and use both as cosmological probes.

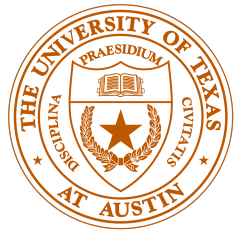
Over epochs, even a tiny grain of sand would be exposed to an enormous flux of neutrinos and dark matter. Using such samples trades mass for time: A 1 g, billion-year-old mineral offers the same total exposure as a 1000-metric-ton tar-

Chris Kelso, a theoretical physicist at the University of North Florida, suggests that looking at the rate of supernova explosions over time is doable in the next five or so years. "We understand the neutrino physics pretty well," he says. "That's an advantage of paleo-detectors—we know there is a signal, so I think we can do this."

Damage tracks

Most approaches to using minerals as paleo-detectors would look at the tracks caused by recoil: When an incident particle hits a nucleus in the mineral, the impacted nucleus is knocked out, leaving a hole and

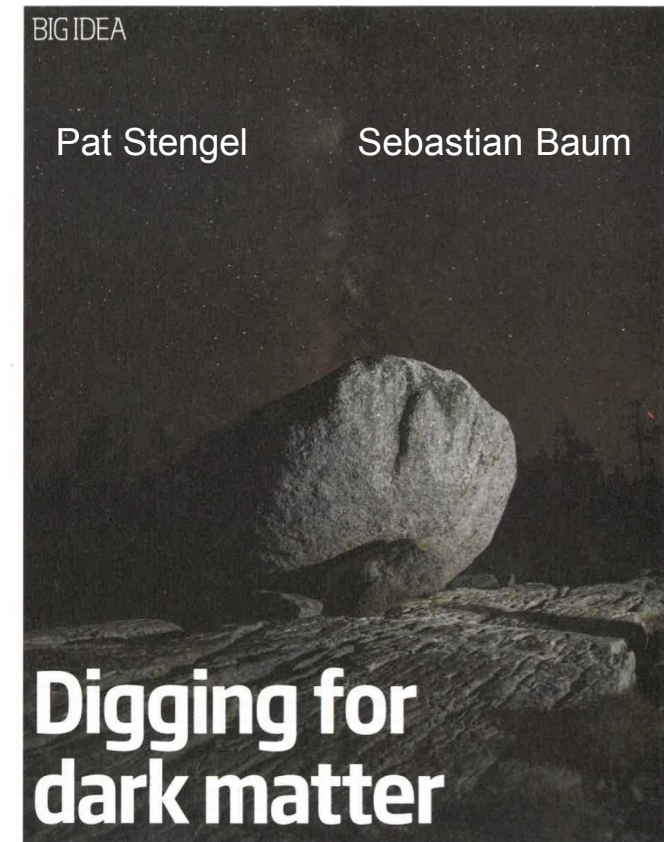




Paleo-Detectors: Ancient minerals as Dark Matter detectors

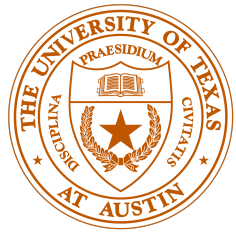
- ❖ Advantage: Replace large detector volume with huge exposure
- ❖ Challenges: Backgrounds, and systematics from geology
- ❖ Dark matter interactions produce nuclear recoil damage tracks in Paleo-detectors
- ❖ Modern nanoscale imaging can reconstruct nanometer-scale tracks in 3D
- ❖ Paleo-detectors: $\mathcal{O}(10^4)$ signal+background events

➡ Direct detection experiments: $\mathcal{O}(1 - 10)$ events



Despite making up most of the universe, we still haven't detected dark matter. A clue could lie buried in ancient rocks, says physicist Sebastian Baum

MOST of our universe is missing. Observations of the smallest galaxies to structures spanning the entire universe show that ordinary matter – the stuff that makes up you, me and everything we see in the cosmos around us – accounts for only one-fifth of all matter. The remaining 80 per cent is a mystery. After decades trying to hunt down this



Muscovite Mica Bounds from 1995

Snowden-Ifft et al. (1995)

↓ DM signal peak is expected

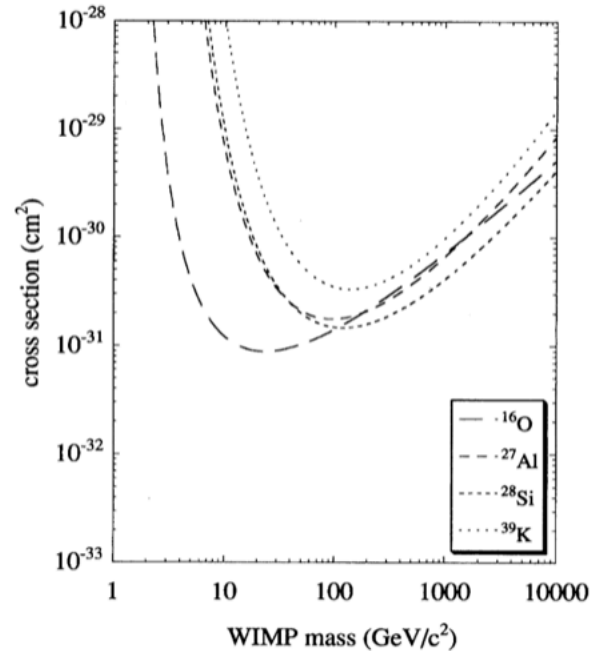
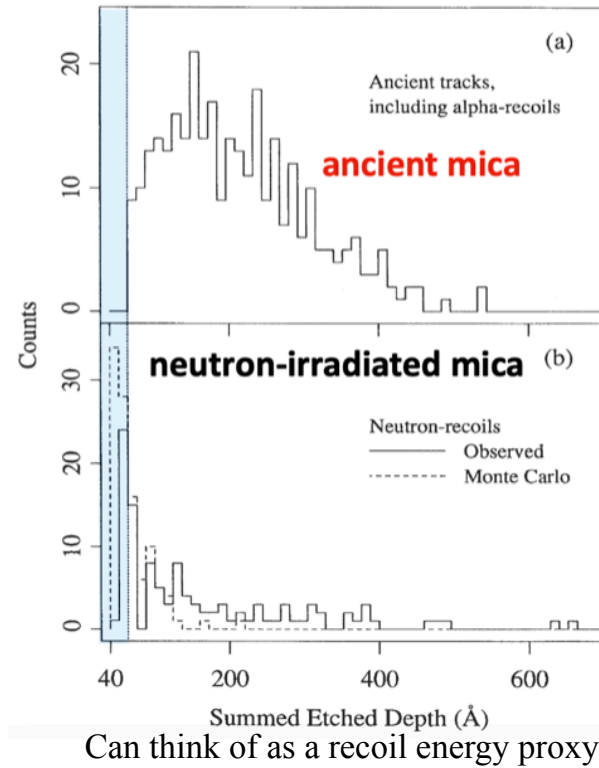


FIG. 4. Exclusion curves for each of the main constituent nuclei of mica. For a given mass, WIMPs with cross sections above these curves are ruled out at the 90% confidence level.

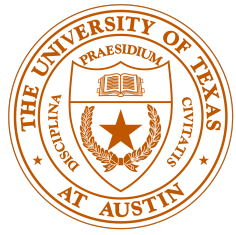
- ❖ No events observed in the smallest pit-depth bins
 - ➡ Region where the WIMP signal was expected to peak
- ❖ Readout technique
 - ➡ Chemical etching enlarges damage tracks
 - ➡ Atomic Force Microscopy (AFM) measures etched pits
- ❖ AFM analogy
 - ➡ Like a record player needle scanning a surface
 - ➡ Reconstructs pit depth with nanometer precision
- ❖ Why revisit paleo-detectors today?
 - ➡ Modern nanoscale imaging
 - ➡ $10^6 \times$ larger exposure



The field was re-ignited in 2018

Katherine Freese and Patrick Stengel re-ignited the field

- ❖ 1806.05991 Searching for Dark Matter with Paleo-Detectors, Baum, Drukier, Freese, Gorski, Stengel
- ❖ 1811.06844 Paleo-detectors: Searching for DM with Ancient Minerals; Drukier, Baum, Freese, Gorski, Stengel
- ❖ 1811.10549 Digging for Dark Matter: Spectral Analysis and Discovery Potential of Paleo-Detectors; KF, Stengel
- ❖ 1906.05800 Paleo-Detectors for Galactic Supernova Neutrinos; Baum, .. Kavanaugh, Stengel, Freese, ... Weniger
- ❖ 2106.06559 New Projections for Dark Matter Searches with Paleo-Detectors, S. Baum, ..., K. Freese, P. Stengel
- ❖ 2603.13629 Projected Sensitivity of Paleo-Detectors to Dark Matter Effective Interactions with Nuclei, D. P. Theodosopoulos, K. Freese, C. Kelso, P. Stengel



The field was re-ignited in 2018

Conference in Trieste: Mineral Detection of Dark Matter and Neutrinos (Oct 17-21)

- The aim of MDDMv is to bring together astroparticle theorists who have been making the scientific case for mineral detection and experimentalists who have initiated preliminary studies of their feasibility. As these searches incorporate various aspects of geology, materials science and astroparticle physics, the participants in MDDMv are a diverse group with expertise encompassing these fields.



The field was re-ignited in 2018

Mineral Detection of Dark Matter and Neutrinos

Oct 17 – 21, 2022
IFPU
Europe/Rome timezone

Overview

Scientific Program and Timetable

Participants

Patrick Stengel

✉ pstengel56@gmail.com

Participants

Participants

Gabriela Araujo (U Zurich)

Sebastian Baum (Stanford)

Yilda Boukhtouchen (Queen's)

Joe Bramante (Queen's)

Thomas Edwards (Johns Hopkins)

Ulrich Glasmacher (Heidelberg U)

Arianna Gleason-Holbrook (Stanford); online

Katherine Freese (UT Austin/Stockholm U)

Shigenobu Hirose (JAMSTEC); online

Patrick Huber (Virginia Tech)

Takenori Kato (Nagoya U); online

Bradley Kavanagh (Cantabria U)

Chris Kenney (SLAC); online

Tatsuhiro Naka (Toho U); online

Paola Sala (INFN Milano)

Patrick Stengel (INFN Ferrara)

Kai Sun (U Michigan)

Reza Ebadi (U Maryland); online

Mineral Detection of Neutrinos and Dark Matter

📅 8 Jan 2024, 03:00 → 11 Jan 2024, 17:00 US/Eastern

📍

👤 Patrick Huber (VT) , Patrick Stengel , Sebastian Baum

Description

Nuclear recoils caused by interactions of Dark Matter or neutrinos can leave latent damage in the crystal structure of minerals. These damage features can be read out using a variety of modern microscopy techniques, ranging from optical (fluorescence) microscopy over X-ray microscopy at accelerator light sources to techniques with sub-nm spatial resolution such as He-ion beam or transmission electron microscopy. Natural as well as laboratory-manufactured minerals have **been** discussed as nuclear recoil detectors for a variety of applications. For example, using the damage features accumulated over 10 Myr – 1 Gyr in natural "paleo-detector" mineral samples, one could measure astrophysical neutrino fluxes (from the Sun, supernovae, or cosmic rays interacting with the atmosphere) or search for a variety of Dark Matter candidates. Using signals accumulated over months to few-years timescales in laboratory-manufactured minerals, one could measure reactor neutrinos or use minerals as Dark Matter detectors, potentially with directional sensitivity. This workshop will bring together theoretical and experimental physicists, material scientists, and geologists to discuss the state of the art of the emerging field of Mineral Detection of Neutrinos and Dark Matter. Particular attention will be given to the progress and plans of experimental studies pursued by groups in Europe, Asia, and America towards unlocking the potential of natural and laboratory-manufactured minerals as passive recorders of keV-scale nuclear recoils.

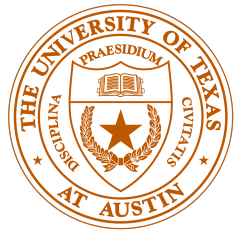
The proceedings of the meeting can be found [here](#).

Registration

🔑 Workshop registration [Register](#)

Participants

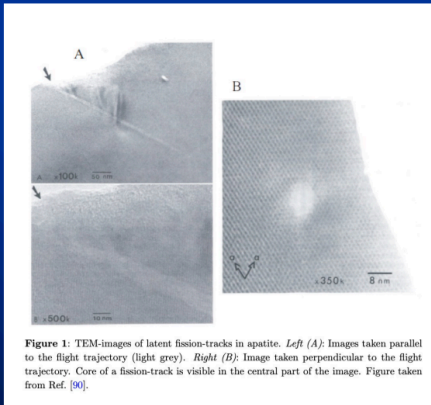
A	Adam Hecht	A	Alexey Elykov	A	Anubhav Mathur	A	Audrey Fung	C	Chris Kelso	D	Daniel Ang
D	David Waters	E	Emilie LaVoie-Ingram	G	Gabriela R. Araujo	J	Janina Hakenmueller	J	Jay Thomas		
J	Joseph Bramante	J	Josh Spitz	K	Kate Scholberg	K	Katherine Freese	K	Katsuyoshi Michibayashi		
L	Lorenzo Caccianiga	M	Maximilian Shen	N	Nathan Higginbotham	N	Noriko Hasebe	P	Patrick Huber		
P	Patrick Stengel	P	Pieter Vermeesch	R	Rosa Luz Zamora Peinado	S	Sebastian Baum	S	Shigenobu Hirose		
S	Shunsaku Horiuchi	T	Tatsuhiro Naka	V	Vassilios Kovanis	V	Vsevolod Ivanov	W	Weixing Li	X	Xingxin Liu
Z	zane cable		+16								



The field was re-ignited in 2018

Mineral Detection of Neutrinos and Dark Matter. A Whitepaper

Recoiling nuclei lead to defects:
Fission tracks, vacancies in crystal lattice, etc



Color Centers:
Vacancies in crystal lattice,
e pairs fill in, get excited and fluoresce,
the crystal changes color

<https://arxiv.org/pdf/2301.07118.pdf>

arXiv > astro-ph > arXiv:2405.01626

Search...
Help | Adv

Astrophysics > Cosmology and Nongalactic Astrophysics

[Submitted on 2 May 2024]

Mineral Detection of Neutrinos and Dark Matter 2024. Proceedings

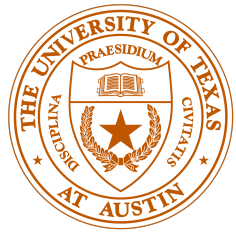
Sebastian Baum, Patrick Huber, Patrick Stengel, Natsue Abe, Daniel G. Ang, Lorenzo Apollonio, Gabriela R. Araujo, Levente Balogh, Pranshu Bhaumik Yilda Boukhtouchen, Joseph Bramante, Lorenzo Caccianiga, Andrew Calabrese-Day, Qing Chang, Juan I. Collar, Reza Ebadi, Alexey Elykov, Katherine Freese, Audrey Fung, Claudio Galelli, Arianna E. Gleason, Mariano Guerrero Perez, Janina Hakenmüller, Takeshi Hanyu, Noriko Hasebe, Shigenobu Hirose, Shunsaku Horiuchi, Yasushi Hoshino, Yuki Ido, Vsevolod Ivanov, Takashi Kamiyama, Takenori Kato, Yoji Kawamura, Chris Kelso, Giti A. Khodaparast, Emilie M. LaVoie-Ingram, Matthew Leybourne, Xingxin Liu, Thalles Lucas, Brenden A. Magill Federico M. Mariani, Charlotte Mkhonto, Hans Pieter Mumm, Kohta Murase, Tatsuhiko 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

MD ν DM community

- Groups across North America, Europe and Japan
- Astroparticle theorists, experimentalists, geologists, and materials scientists

Also check out our whitepaper!
arXiv:2301.07118, 2405.01626

- History of mineral detectors
- Review of scientific potential for particle physics, reactor neutrinos and geoscience



What Minerals should we use?

Cosmogenic backgrounds suppressed in deep boreholes

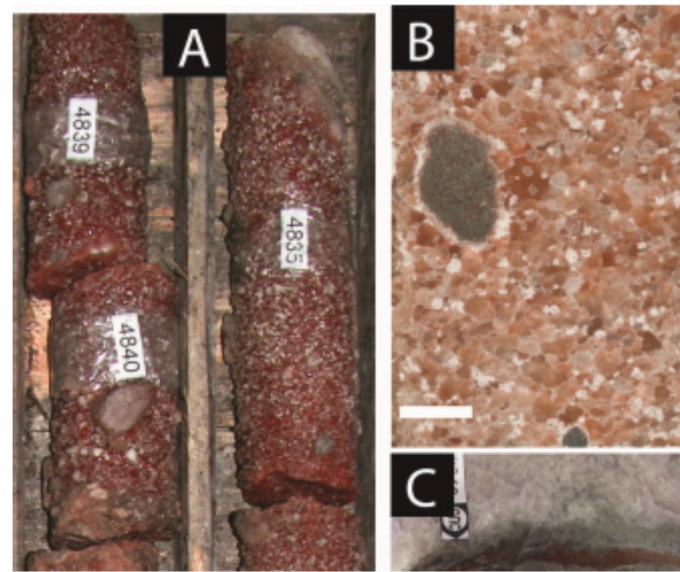
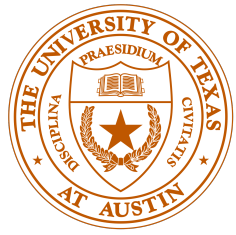


Figure: ~ 2Gyr old Halite cores from ~ 3km, as discussed in Blättler+ '18

Depth	Neutron Flux
2 km	$10^6/\text{cm}^2/\text{Gyr}$
5 km	$10^2/\text{cm}^2/\text{Gyr}$
6 km	$10/\text{cm}^2/\text{Gyr}$
50 m	$70/\text{cm}^2/\text{yr}$
100 m	$30/\text{cm}^2/\text{yr}$
500 m	$2/\text{cm}^2/\text{yr}$

Need minerals with low ^{238}U

- Marine evaporites with $C^{238} \gtrsim 0.01 \text{ ppb}$
- Ultra-basic rocks from mantle, $C^{238} \gtrsim 0.1 \text{ ppb}$



Science goals of Paleo-Detectors

Dark Matter

- ❖ WIMP Dark Matter

 - ➡ WIMPs with mass $\gtrsim 1$ GeV

- ❖ Ultra Heavy Dark Matter

- ❖ Directional detection

- ❖ Dark Matter Substructure

Neutrinos

- ❖ Solar Neutrinos

- ❖ Atmospheric Neutrinos

- ❖ Reactor Neutrinos

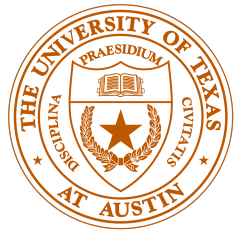
- ❖ Supernova Neutrinos

 - ➡ History of Supernovae in Milky Way

Exotic Signatures

- ❖ Heavy Ionizing Exotica

 - ➡ Magnetic Monopoles



Science goals of Paleo-Detectors

Dark Matter

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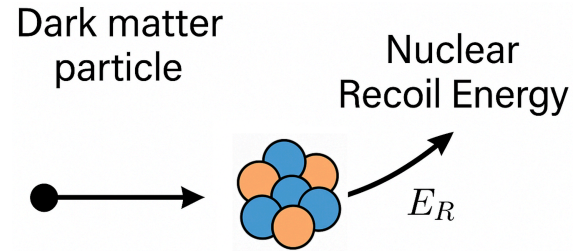


Probing WIMP-Nucleon Interactions with Paleo-Detectors

WIMP-induced track-length spectra, sensitivity projections, mass reconstruction, and interaction discrimination



Nuclear-recoil rate

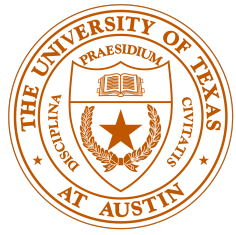


❖ The WIMP-nucleon interaction can be described by the operators of a Non-Relativistic Effective Field Theory

$$\begin{aligned}
 \mathcal{O}_1 &= 1_\chi 1_N & \mathcal{O}_9 &= i \vec{S}_\chi \cdot \left(\vec{S}_N \times \frac{\vec{q}}{m_N} \right) \\
 \mathcal{O}_3 &= i \vec{S}_N \cdot \left(\frac{\vec{q}}{m_N} \times \vec{v}^\perp \right) & \mathcal{O}_{10} &= i \vec{S}_N \cdot \frac{\vec{q}}{m_N} \\
 \mathcal{O}_4 &= \vec{S}_\chi \cdot \vec{S}_N & \mathcal{O}_{11} &= i \vec{S}_\chi \cdot \frac{\vec{q}}{m_N} \\
 \mathcal{O}_5 &= i \vec{S}_\chi \cdot \left(\frac{\vec{q}}{m_N} \times \vec{v}^\perp \right) & \mathcal{O}_{12} &= \vec{S}_\chi \cdot \left(\vec{S}_N \times \vec{v}^\perp \right) \\
 \mathcal{O}_6 &= \left(\vec{S}_\chi \cdot \frac{\vec{q}}{m_N} \right) \left(\vec{S}_N \cdot \frac{\vec{q}}{m_N} \right) & \mathcal{O}_{13} &= i \left(\vec{S}_\chi \cdot \vec{v}^\perp \right) \left(\vec{S}_N \cdot \frac{\vec{q}}{m_N} \right) \\
 \mathcal{O}_7 &= \vec{S}_N \cdot \vec{v}^\perp & \mathcal{O}_{14} &= i \left(\vec{S}_\chi \cdot \frac{\vec{q}}{m_N} \right) \left(\vec{S}_N \cdot \vec{v}^\perp \right) \\
 \mathcal{O}_8 &= \vec{S}_\chi \cdot \vec{v}^\perp & \mathcal{O}_{15} &= - \left(\vec{S}_\chi \cdot \frac{\vec{q}}{m_N} \right) \left[\left(\vec{S}_N \times \vec{v}^\perp \right) \cdot \frac{\vec{q}}{m_N} \right]
 \end{aligned}$$

❖ Differential nuclear–recoil rate:

$$\frac{dR}{dE_R} \quad \leftarrow \quad \begin{aligned} &\text{\# of recoiled nuclei per unit exposure} \\ &\text{Nuclear recoil energy} \end{aligned}$$



Nuclear-recoil rate

Dark matter
particle

Nuclear
recoil Energy

Standard SI operator

$$\mathcal{O}_1 = 1_\chi 1_N$$

$$\mathcal{O}_9 = i \vec{S}_\chi \cdot \left(\vec{S}_N \times \frac{\vec{q}}{m_N} \right)$$

$$\mathcal{O}_3 = i \vec{S}_N \cdot \left(\frac{\vec{q}}{m_N} \times \vec{v}^\perp \right)$$

$$\mathcal{O}_{10} = i \vec{S}_N \cdot \frac{\vec{q}}{m_N}$$

$$\mathcal{O}_4 = \vec{S}_\chi \cdot \vec{S}_N$$

$$\mathcal{O}_{11} = i \vec{S}_\chi \cdot \frac{\vec{q}}{m_N}$$

$$\mathcal{O}_5 = i \vec{S}_\chi \cdot \left(\frac{\vec{q}}{m_N} \times \vec{v}^\perp \right)$$

$$\mathcal{O}_{12} = \vec{S}_\chi \cdot \left(\vec{S}_N \times \vec{v}^\perp \right)$$

$$\mathcal{O}_6 = \left(\vec{S}_\chi \cdot \frac{\vec{q}}{m_N} \right) \left(\vec{S}_N \cdot \frac{\vec{q}}{m_N} \right)$$

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$$\mathcal{O}_{14} = i \left(\vec{S}_\chi \cdot \frac{\vec{q}}{m_N} \right) \left(\vec{S}_N \cdot \vec{v}^\perp \right)$$

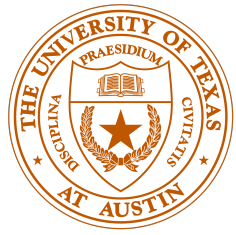
$$\mathcal{O}_8 = \vec{S}_\chi \cdot \vec{v}^\perp$$

$$\mathcal{O}_{15} = - \left(\vec{S}_\chi \cdot \frac{\vec{q}}{m_N} \right) \left[\left(\vec{S}_N \times \vec{v}^\perp \right) \cdot \frac{\vec{q}}{m_N} \right]$$

❖ The WIMP-nucleon interaction can be described by the operators of a Non-Relativistic Effective Field Theory

❖ Differential nuclear-recoil rate:

$$\frac{dR}{dE_R} \quad \leftarrow \quad \begin{array}{l} \text{\# of recoiled nuclei per unit exposure} \\ \text{Nuclear recoil energy} \end{array}$$



Nuclear-recoil rate

Dark matter
particle

Nuclear
recoil Energy

Standard SI operator

Standard SD operator

$$\mathcal{O}_1 = 1_X 1_N$$

$$\mathcal{O}_3 = i \vec{S}_N \cdot \left(\frac{\vec{q}}{m_N} \times \vec{v}^\perp \right)$$

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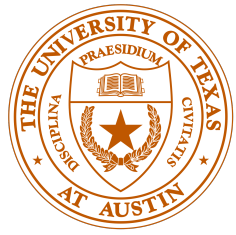
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❖ The WIMP-nucleon interaction can be described by the operators of a Non-Relativistic Effective Field Theory

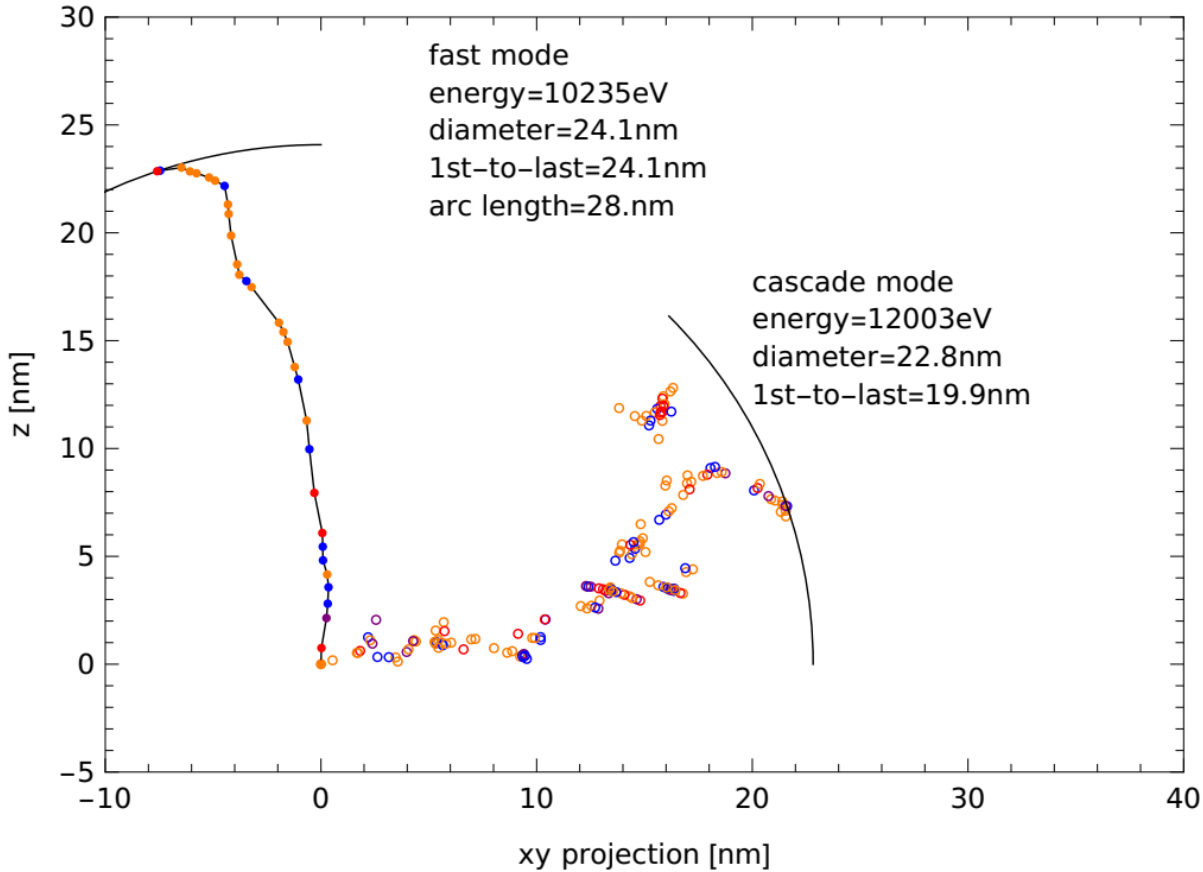
❖ Differential nuclear-recoil rate:

$$\frac{dR}{dE_R} \quad \leftarrow \quad \begin{array}{l} \text{\# of recoiled nuclei per unit exposure} \\ \text{Nuclear recoil energy} \end{array}$$



Track-production rate

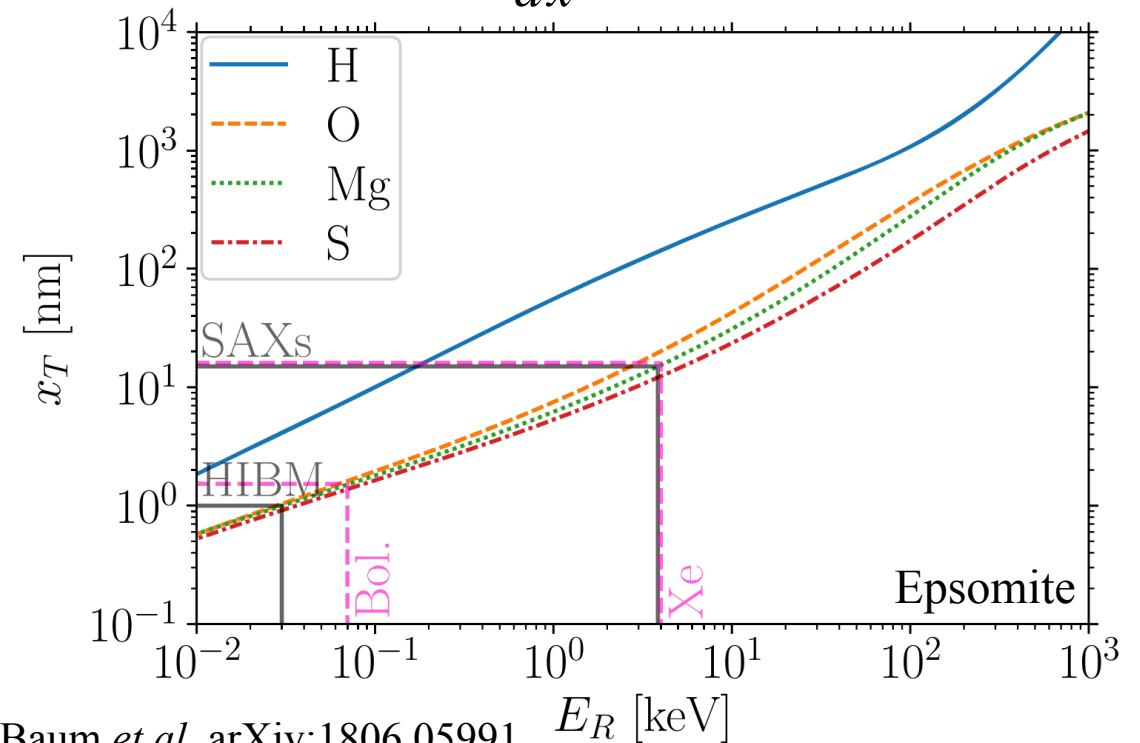
- ❖ We simulate the track lengths with SRIM



- ❖ We assume a one-to-one correspondence

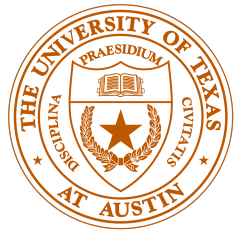
between recoil energy and track length

- ❖ Stopping power $\frac{dE_R}{dx}$ calculated by SRIM:

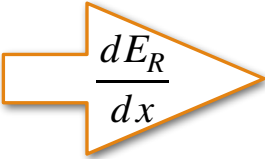


S. Hedges *et al.* arXiv:2605.13659.

S. Baum *et al.* arXiv:1806.05991.



Track-production rate

❖ Differential nuclear–recoil rate: $\frac{dR}{dE_R}$ 

❖ Differential track–production rate in a **mineral**:

of tracks per unit exposure

Nuclear mass ratio

$$\frac{dR_T}{dx_T} = \sum_{N \text{ in Nuclei}} \xi_N \left(\frac{dR}{dE_R} \right)_N \left(\frac{dE_R}{dx_T} \right)_N$$

Track length

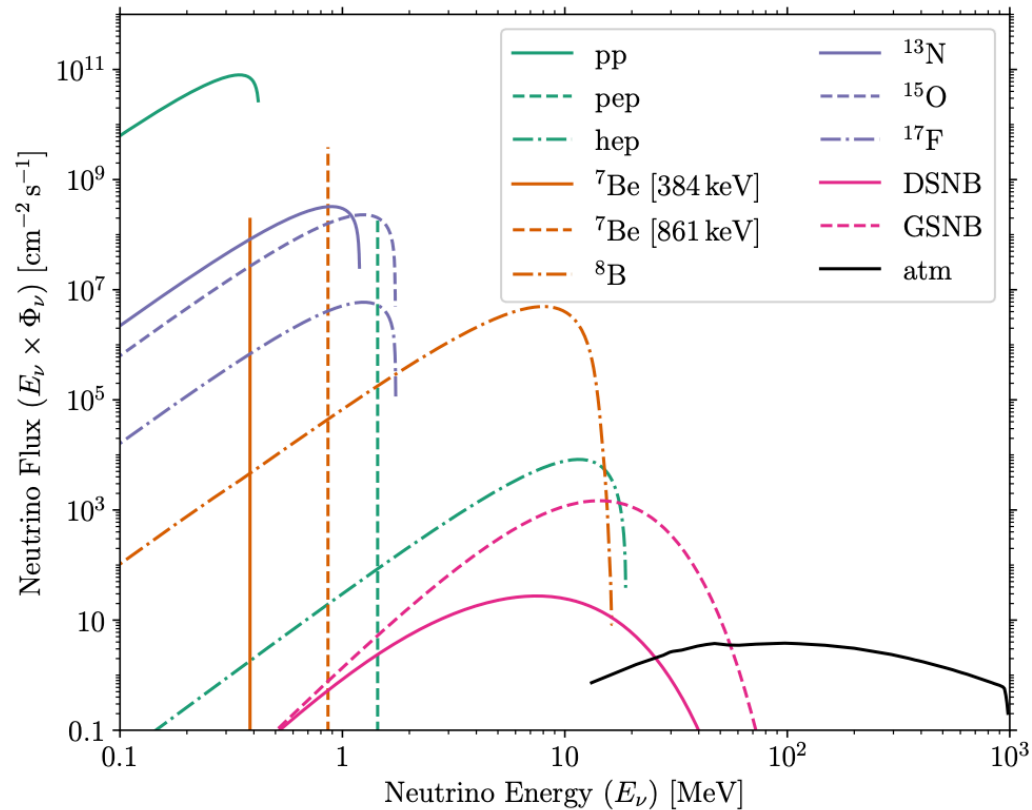
Stopping power for a recoiling nucleus



Backgrounds in Dark Matter Paleo-Detector Experiments

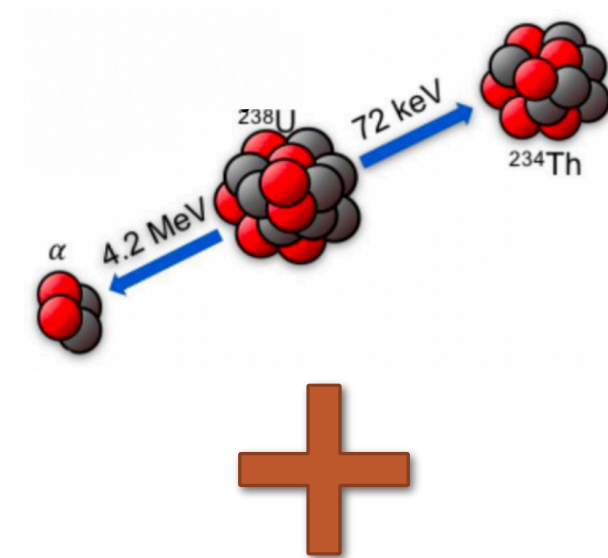
❖ Astrophysical neutrinos

(Sun, supernovae, Earth's atmosphere):



S. Baum *et al.* arXiv:2301.07118.

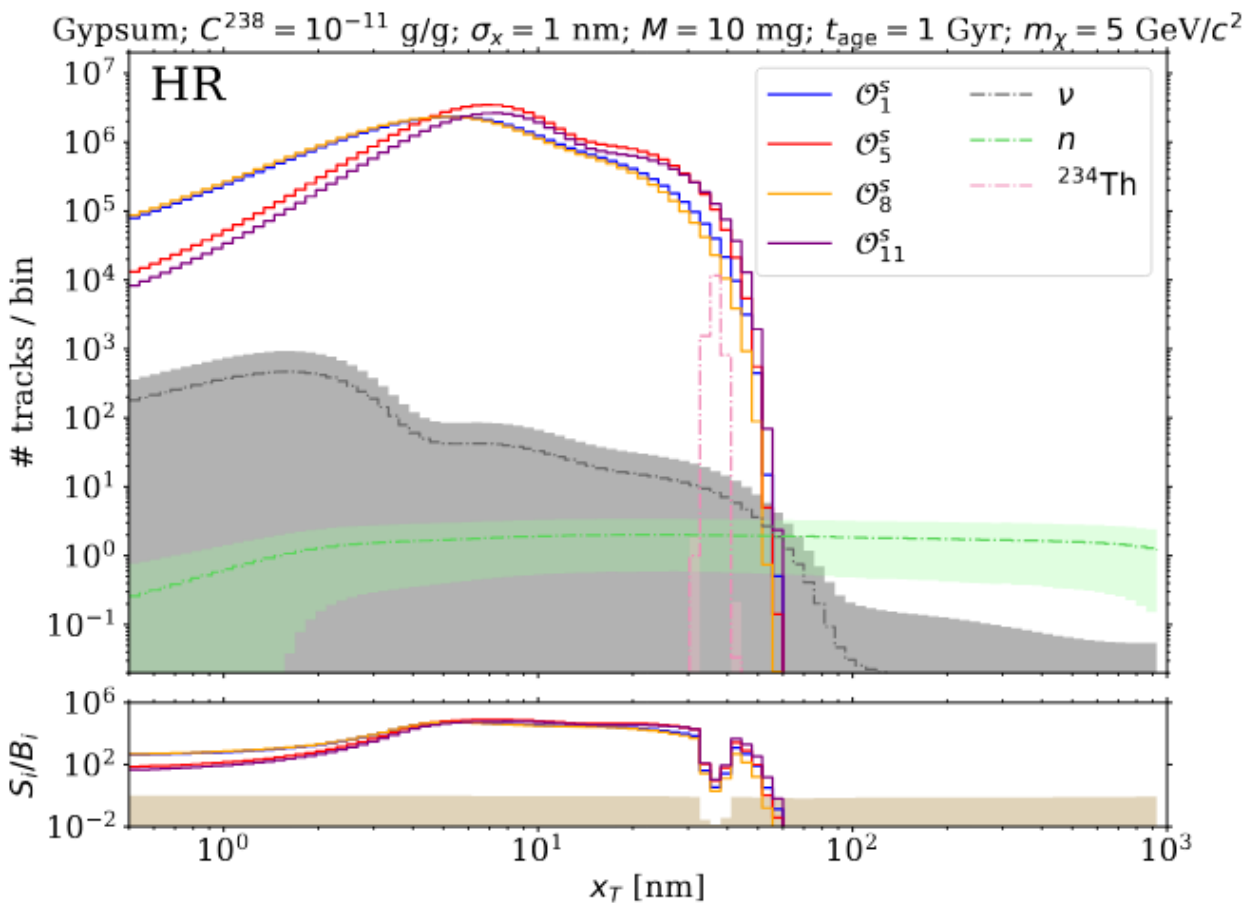
❖ Radiogenics (^{238}U):



Neutrons from spontaneous fission and (α, n) - reaction

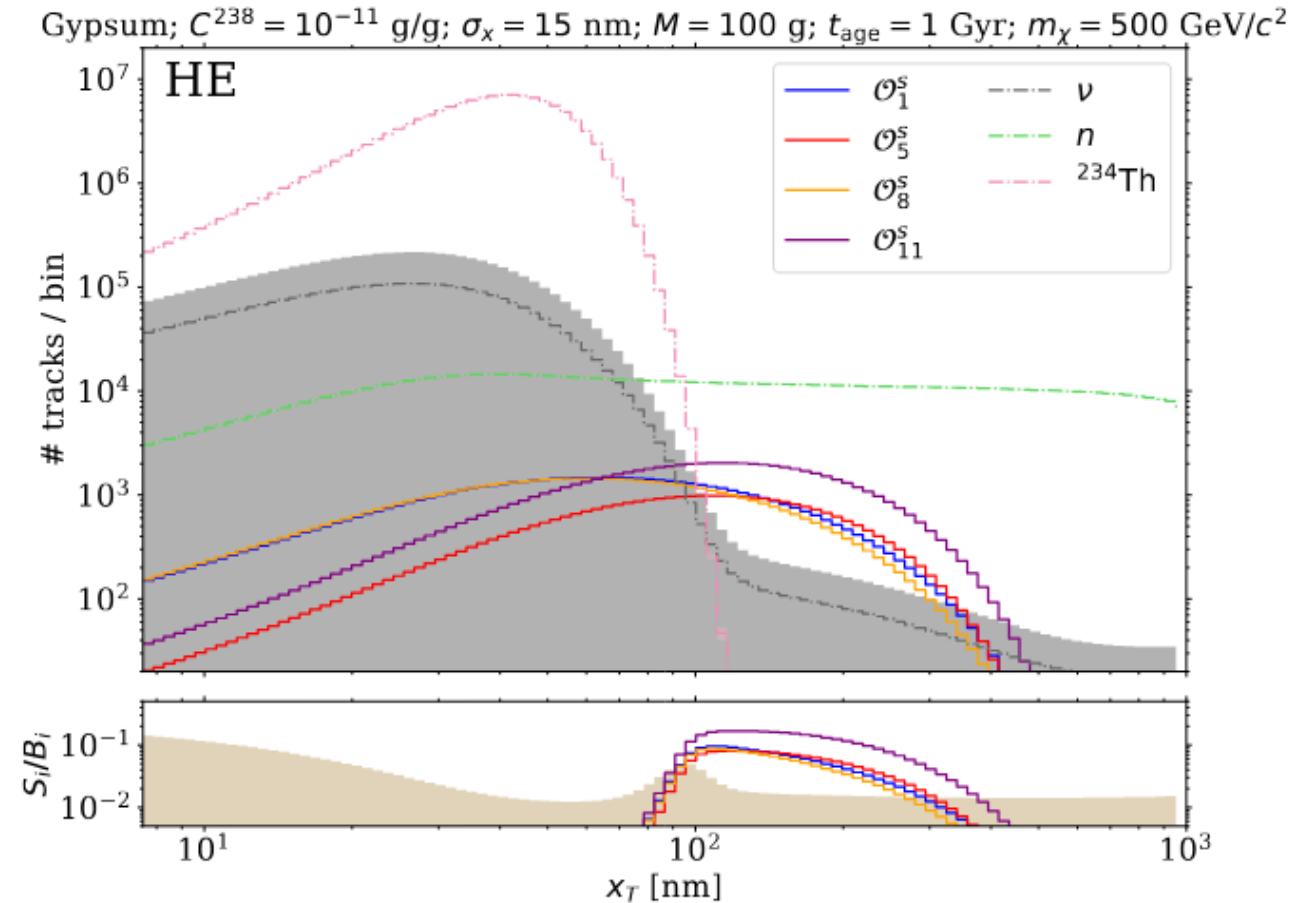


Track-length Spectrum in Paleo-detectors



Left: Coupling constants from **SuperCDMS 2022**

D. P. Theodosopoulos *et al.* arXiv:2603.13629.

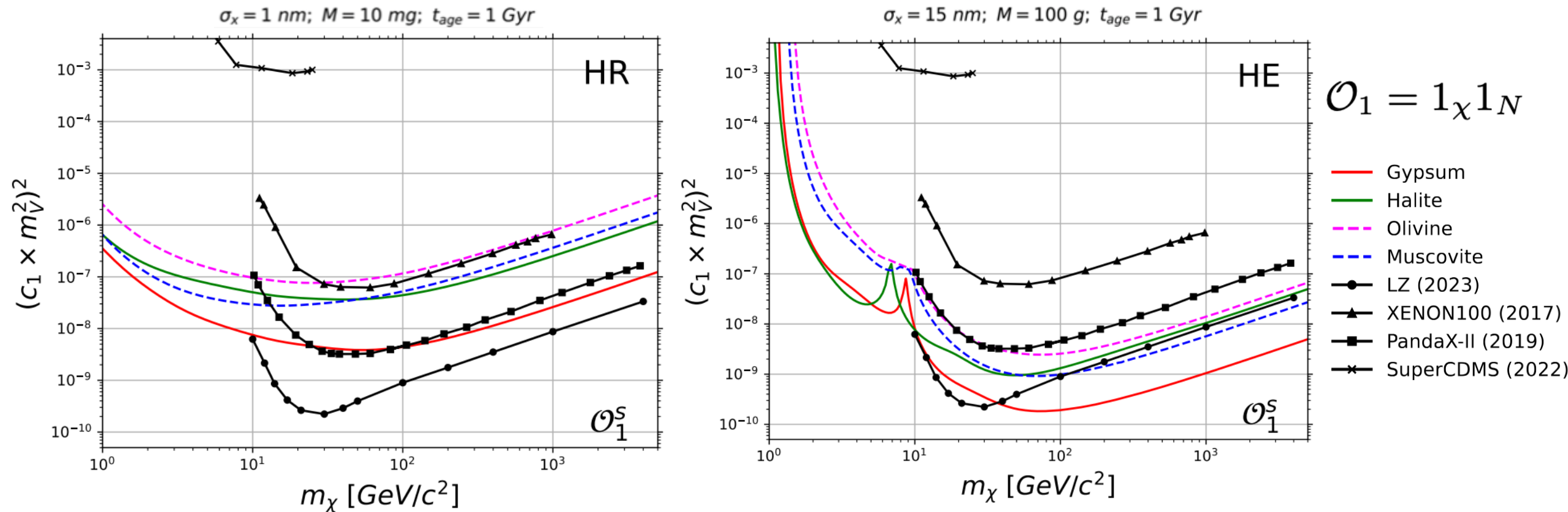


Right: Coupling constants from **LUX-ZEPLIN 2023**



Projected sensitivity of Paleo-Detectors using the standard profile likelihood ratio analysis

❖ Projected 90% CL upper limits on the standard spin-independent ($\mathcal{O}_1$) WIMP-nucleon coupling.

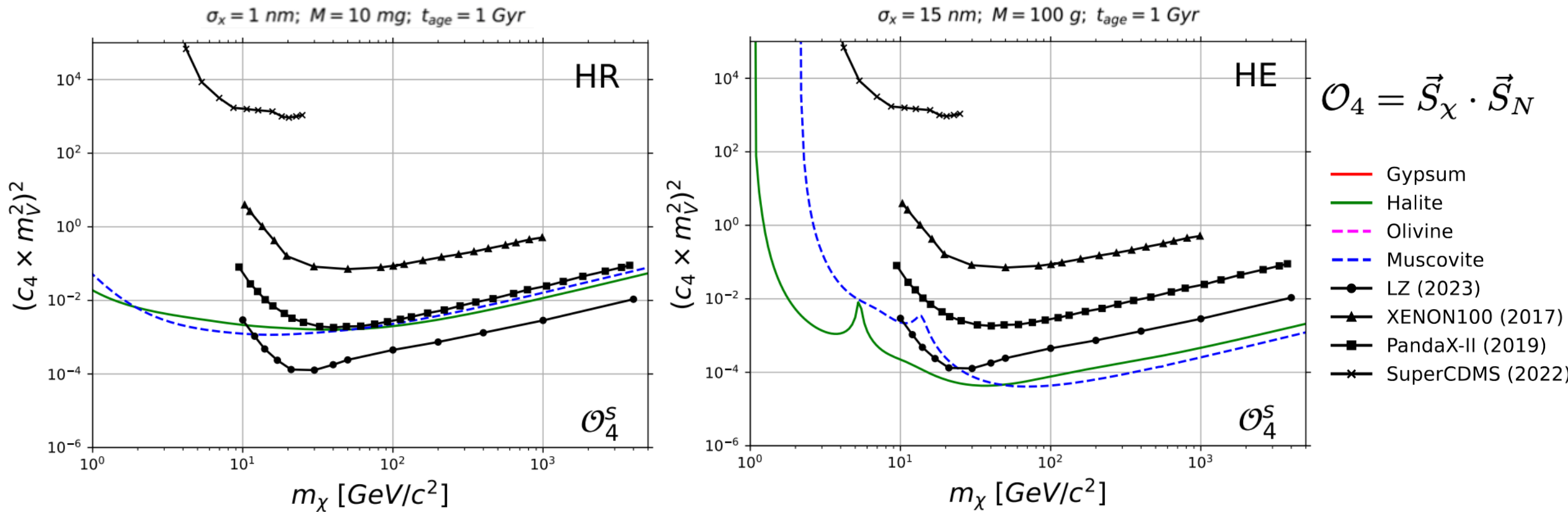


D. P. Theodosopoulos *et al.* arXiv:2603.13629.



Projected sensitivity of Paleo-Detectors using the standard profile likelihood ratio analysis

❖ Projected 90% CL upper limits on the standard spin-dependent ($\mathcal{O}_4$) WIMP-nucleon coupling.

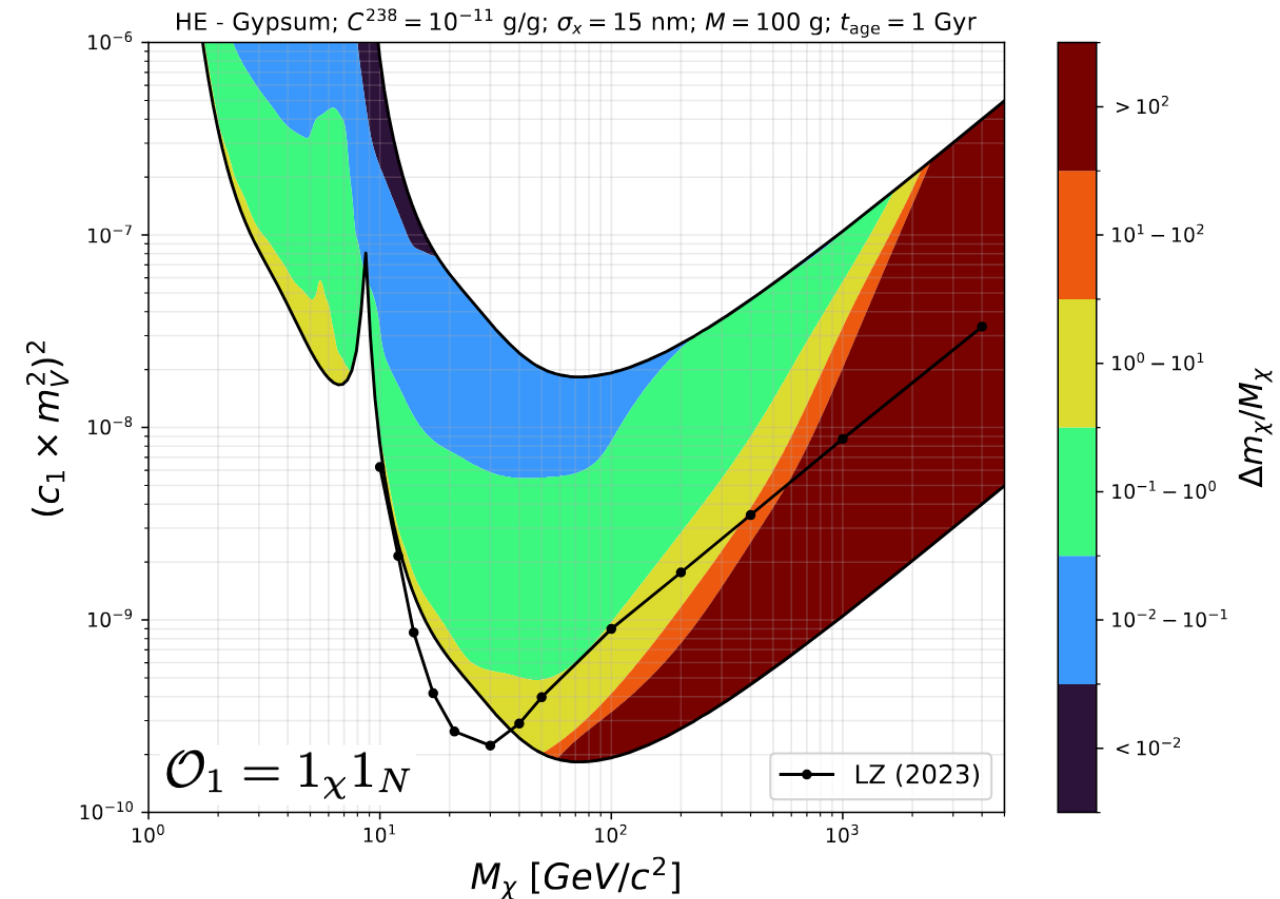
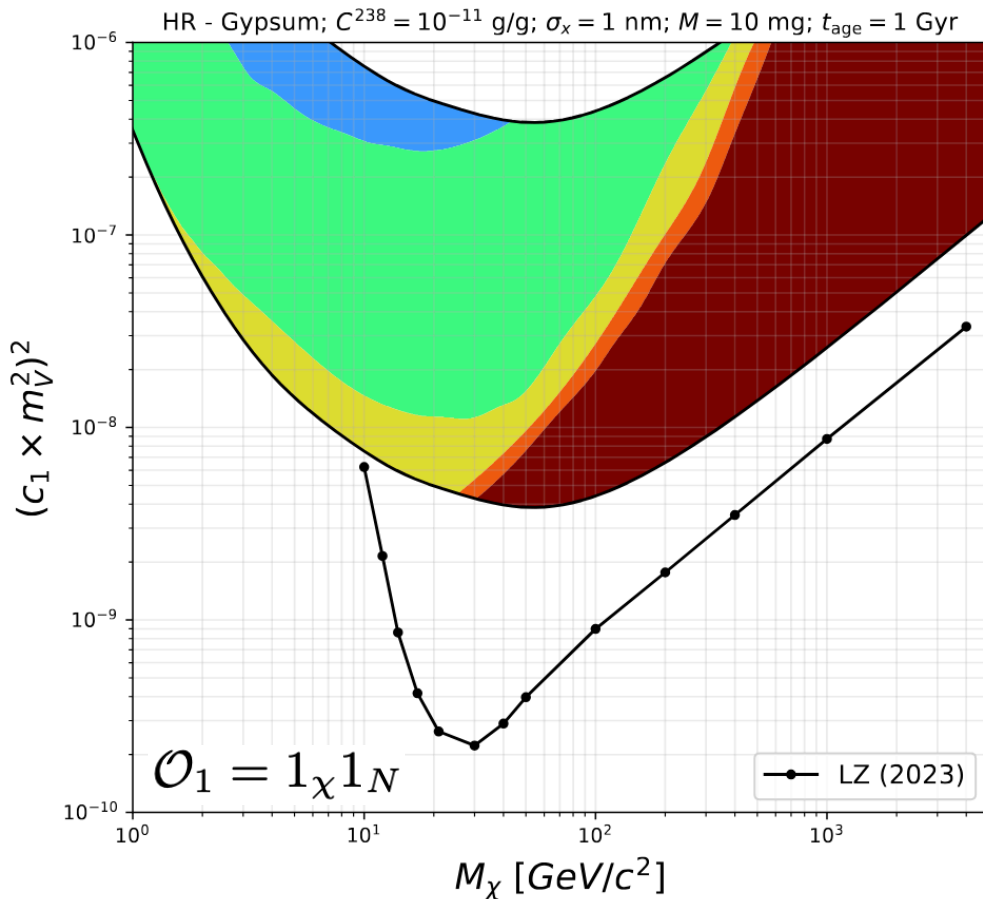


D. P. Theodosopoulos *et al.* arXiv:2603.13629.



Dark Matter Mass Reconstruction

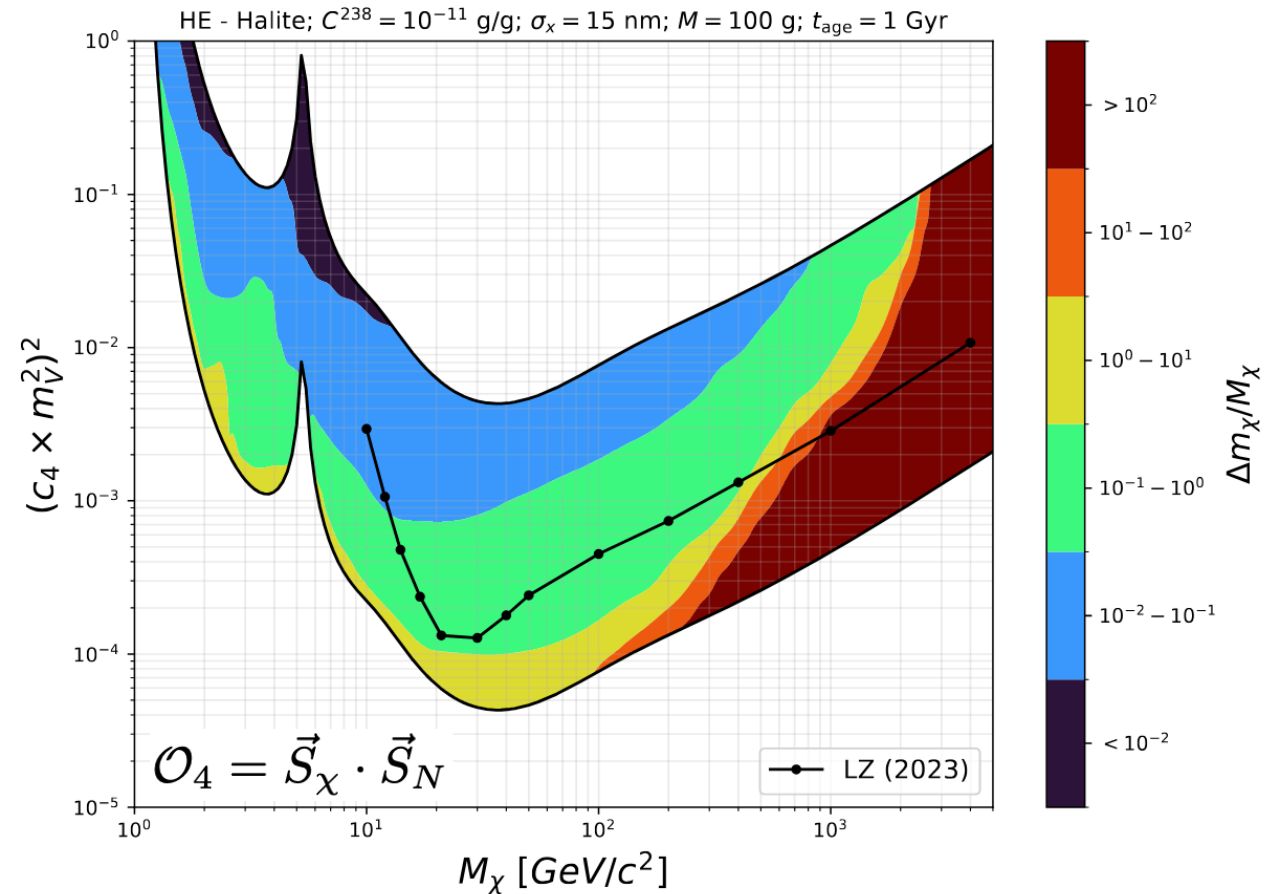
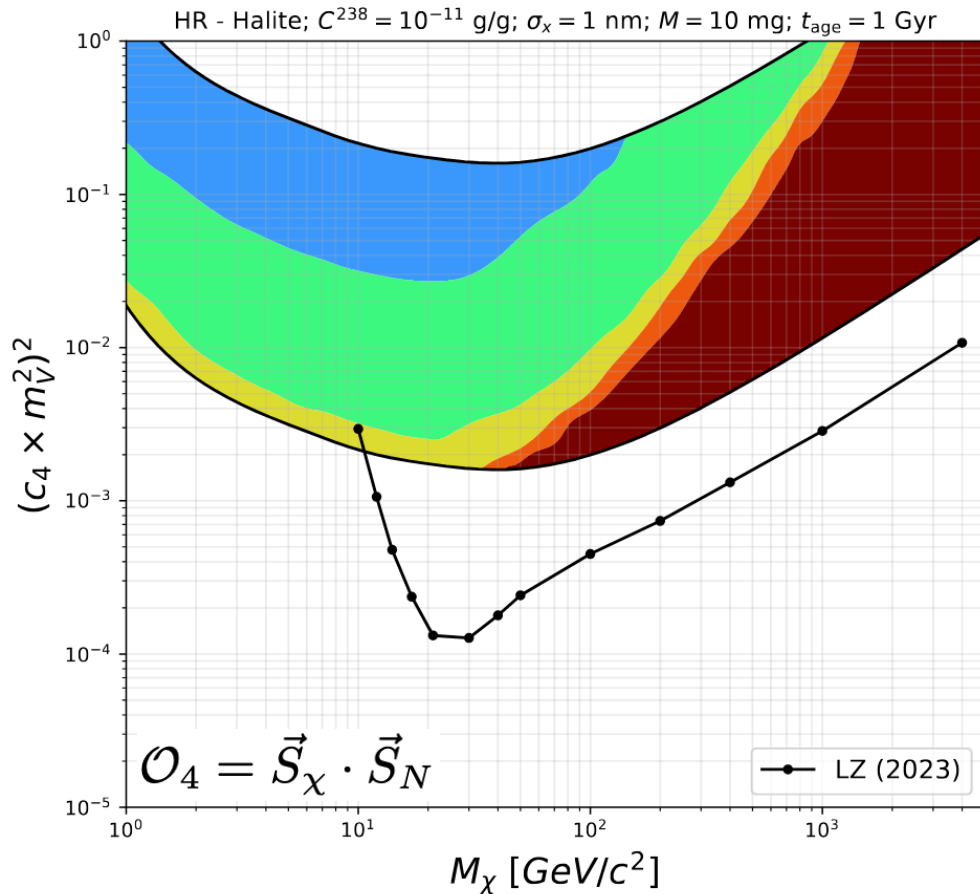
❖ Projected 2σ constraints on dark matter mass





Dark Matter Mass Reconstruction

❖ Projected 2σ constraints on dark matter mass

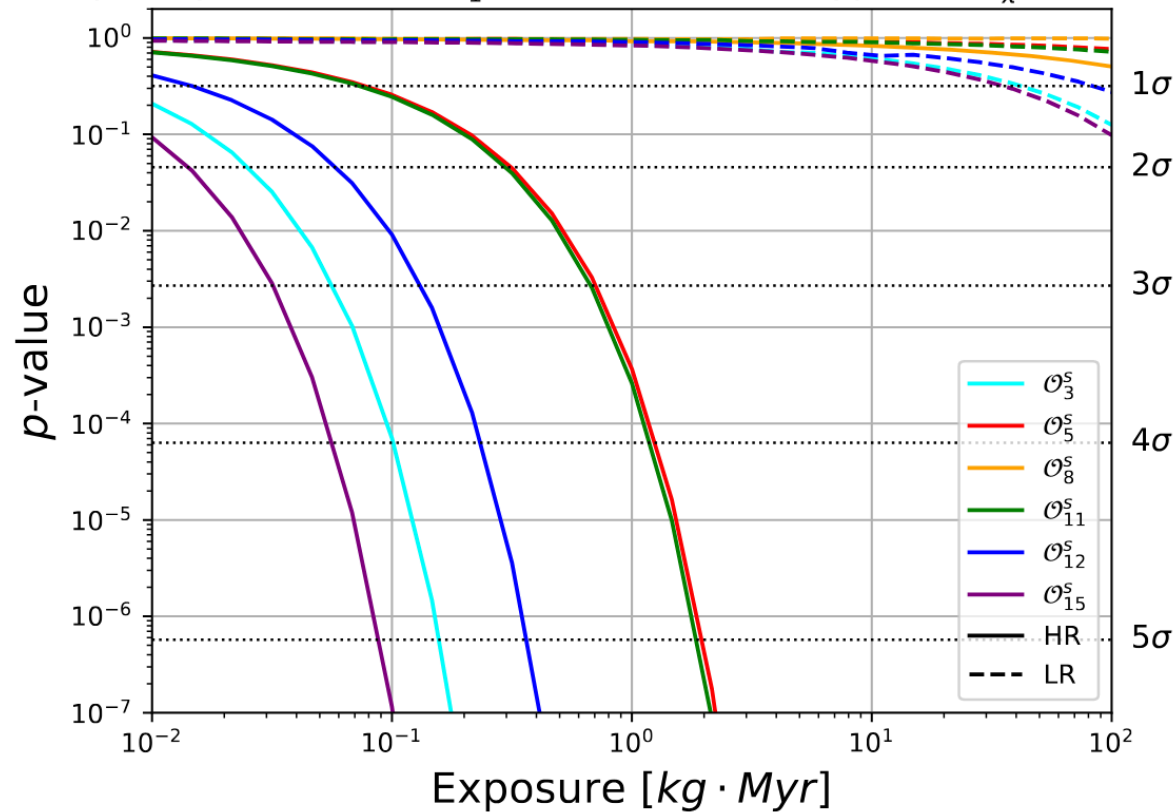




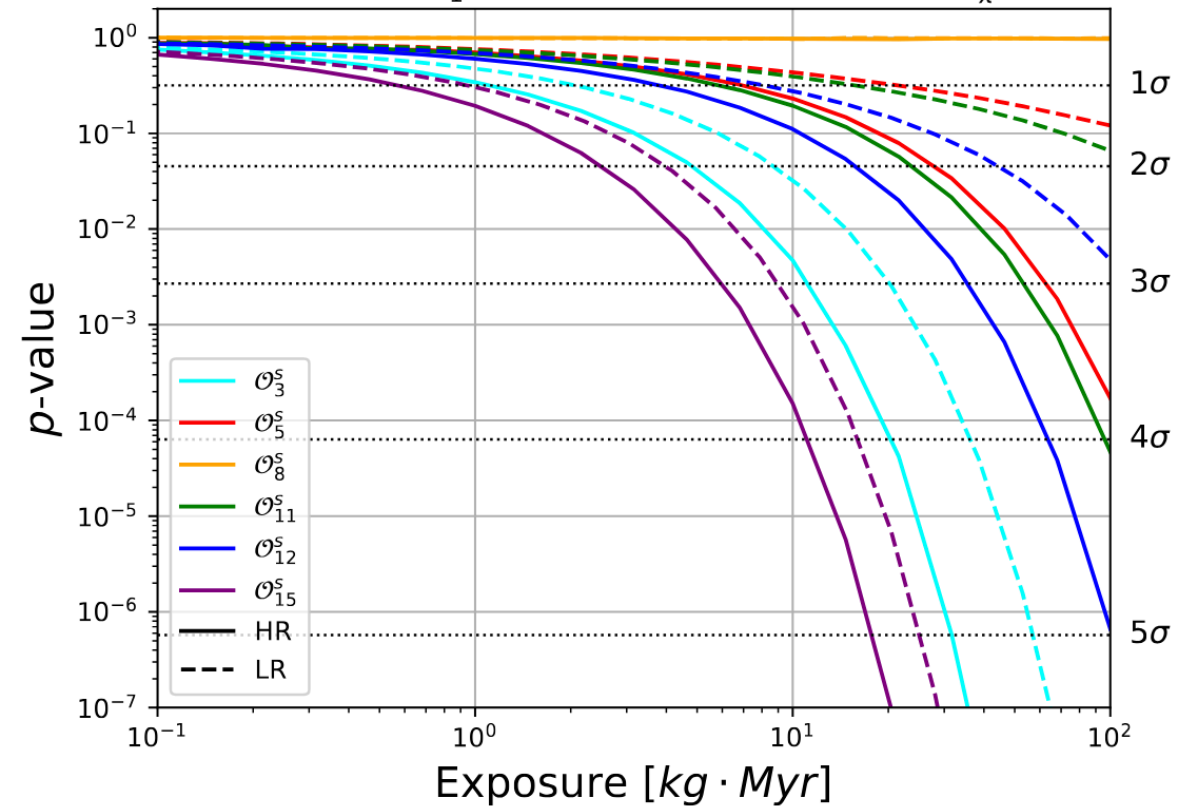
Discriminating Dark Matter Interactions

- ❖ Rejecting **standard SI** interactions $\mathcal{O}_1$ assuming a hypothetical signal generated by a **non-standard** operator $\mathcal{O}_j$.

Rejecting standard SI ($\mathcal{O}_1^S$) interactions with Gypsum; $m_\chi = 5 \text{ GeV}/c^2$



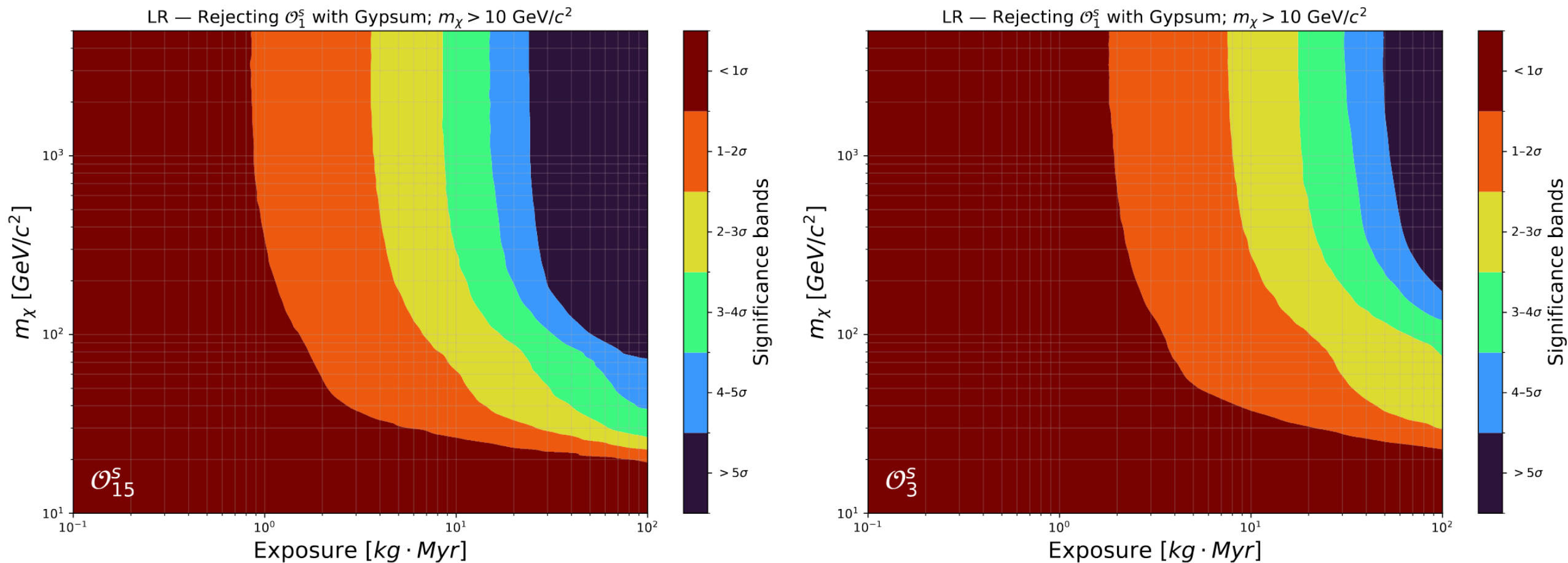
Rejecting standard SI ($\mathcal{O}_1^S$) interactions with Gypsum; $m_\chi = 500 \text{ GeV}/c^2$



HR (High Resolution) $\rightarrow \sigma_x = 1 \text{ nm}$, LR (low resolution) $\rightarrow \sigma_x = 15 \text{ nm}$



Discriminating Dark Matter Interactions



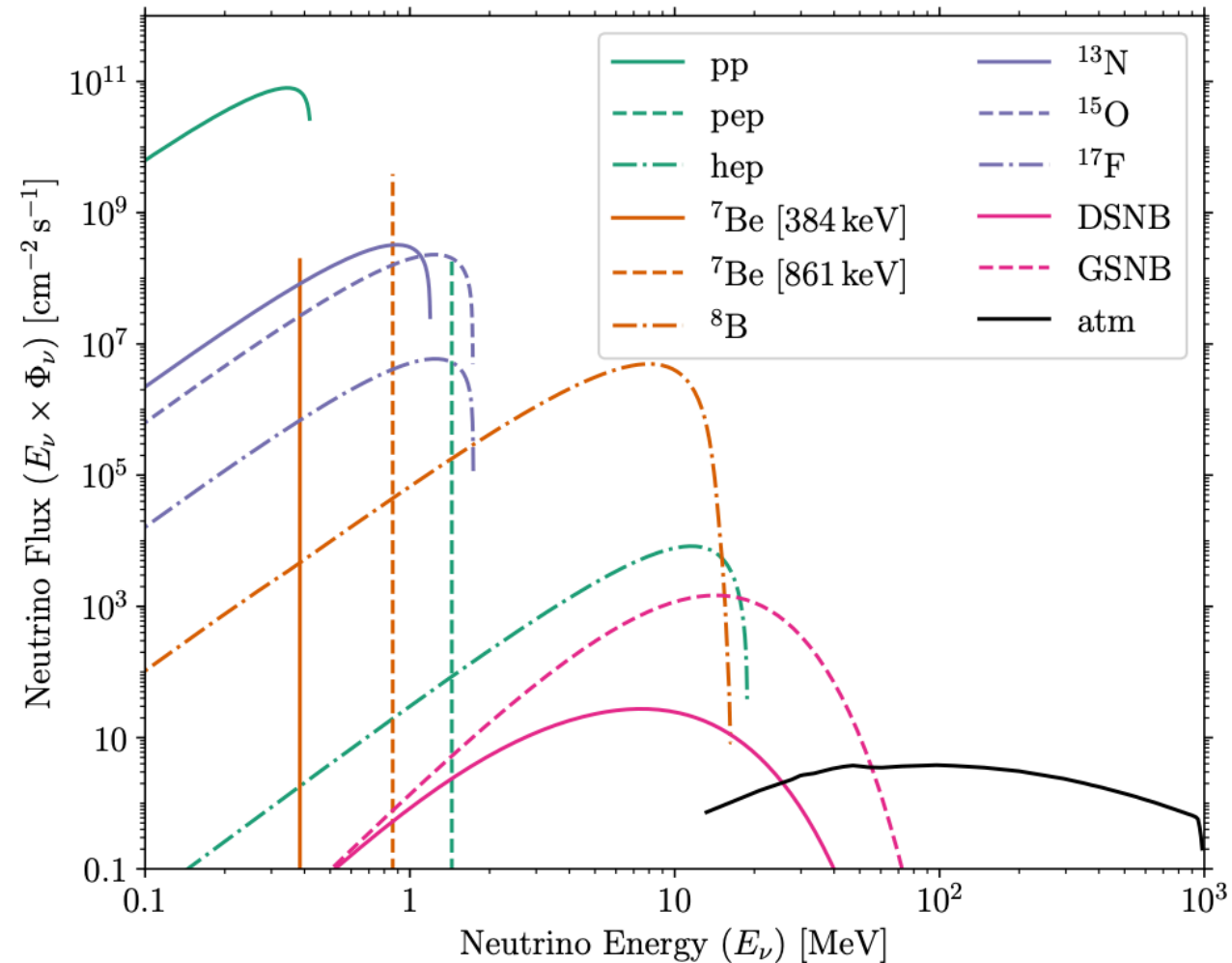


Paleo-Detectors as Neutrino Detectors

Probing Supernova, Atmospheric, and Solar Neutrinos



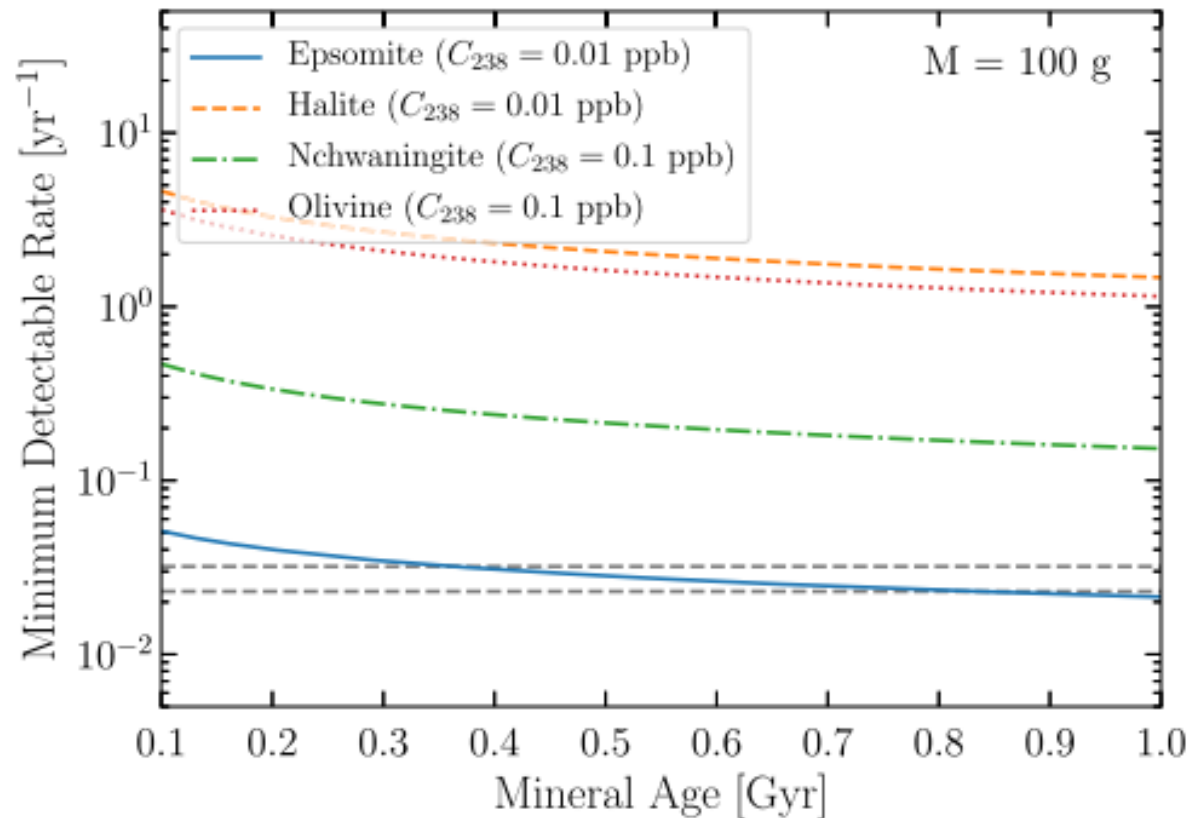
Paleo-Detectors as Neutrino Detectors





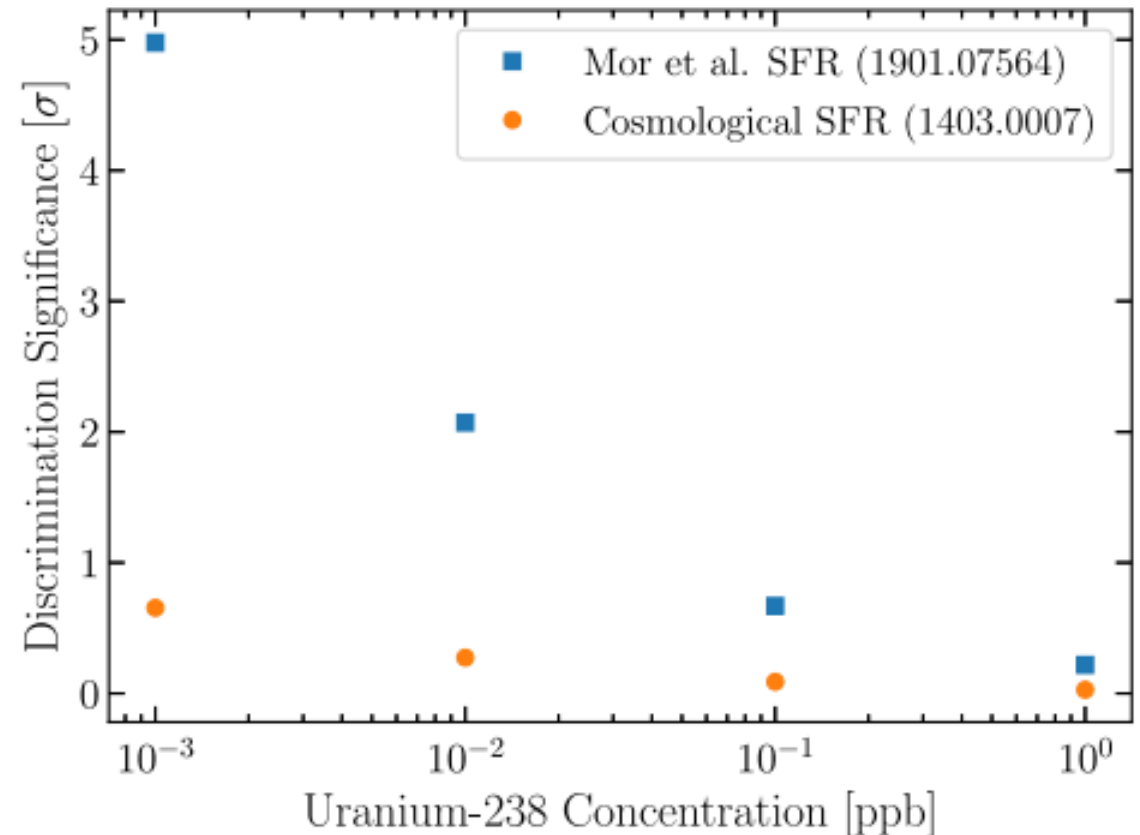
Paleo-Detectors for Galactic Supernova Neutrinos

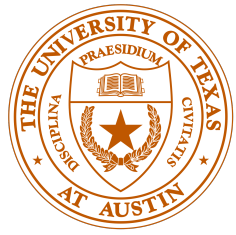
- ❖ Minimum galactic core collapse supernova rate which could be detected at 3σ in paleo-detectors.



S. Baum *et al.* arXiv:1906.05800.

- ❖ Significance levels for discriminating between benchmark galactic star formation rate models.

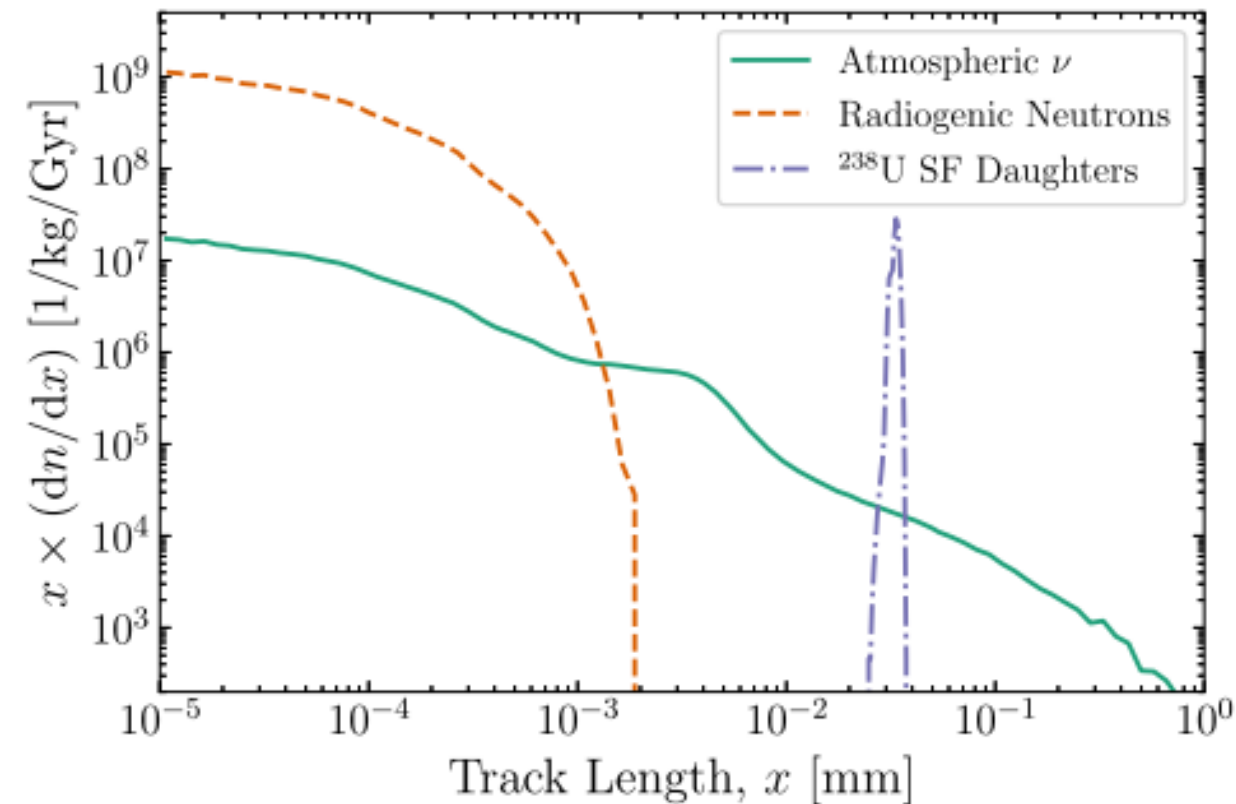




Paleo-Detectors for Atmospheric Neutrinos

❖ Atmospheric neutrino spectrum:

Background-free region for $x \gtrsim 1 \mu\text{m}$



J. R. Jordan *et al.* arXiv:2004.08394.

❖ Radiogenic neutron-background confined to low $x \lesssim 2 \mu\text{m}$, regardless of target mineral.

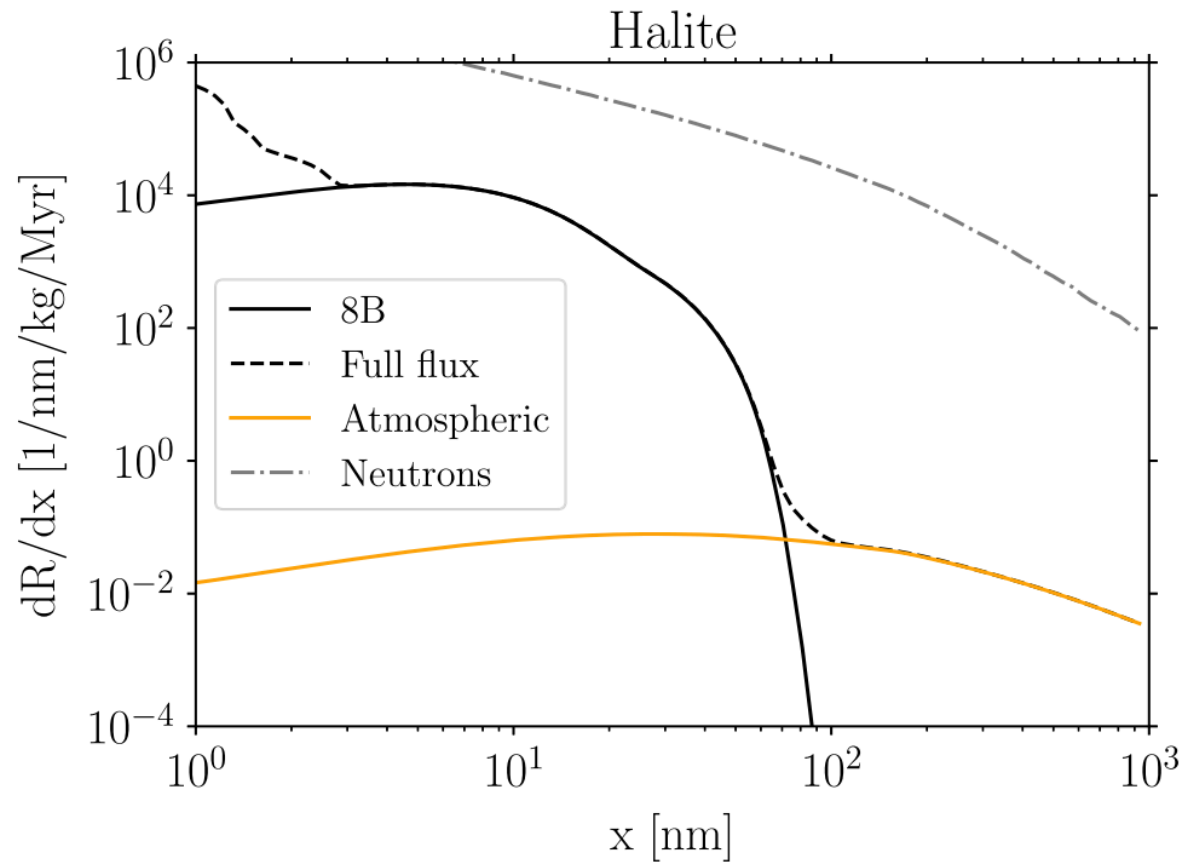
❖ Subdominant systematics:

- ➡ the heliomagnetic field, is modulated much faster than the geological timescales
- ➡ Changes in the Earth's atmospheric composition and density over the past ~ 1 Gyr do not affect atmospheric neutrino searches with paleo-detectors.

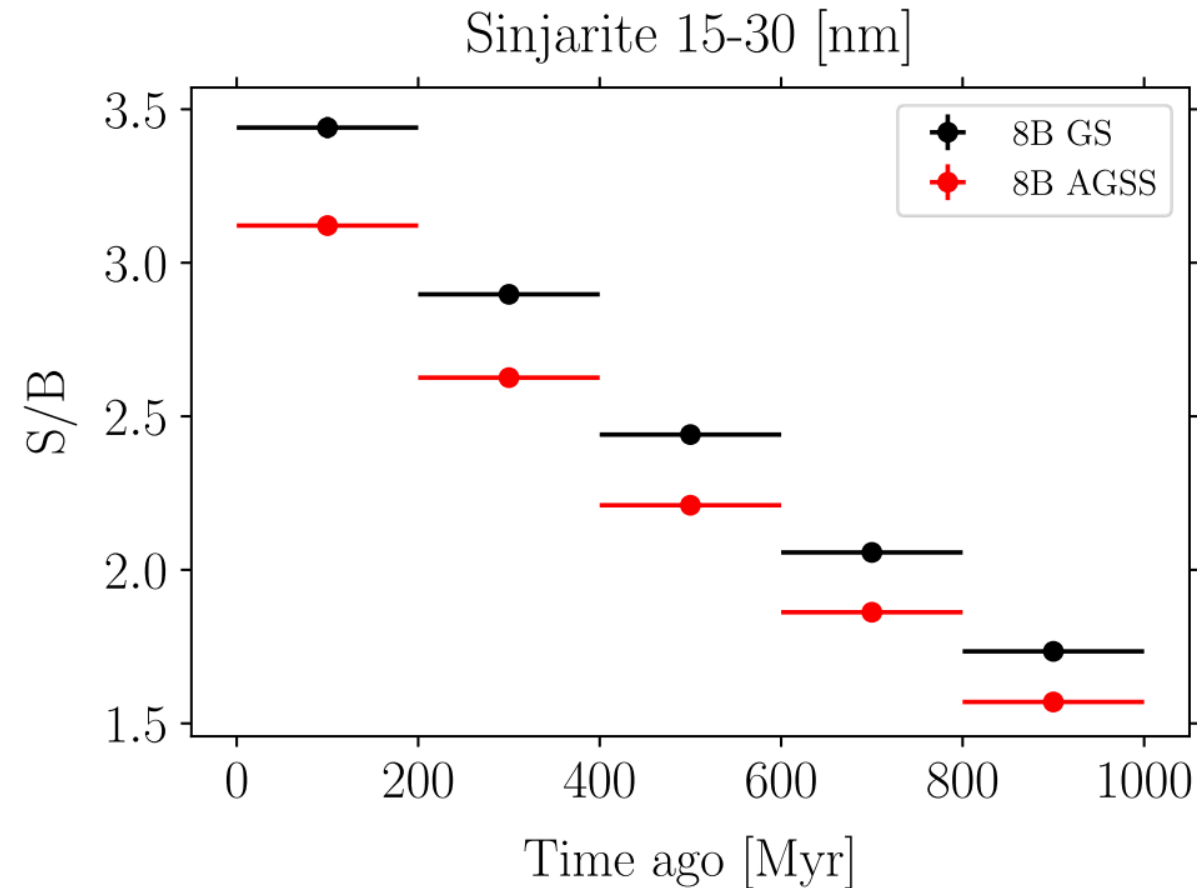


Paleo-Detectors for Solar Neutrinos

❖ Solar neutrino (8B) spectrum:



❖ Signal-to-background ratio for two solar metallicity scenarios:



N. Tapia-Arellano *et al.* arXiv:2102.01755.



Experimental Efforts

Worldwide Efforts Toward Realizing Paleo-Detectors



Experimental Effort Worldwide

U. Maryland

Using color centers for directional WIMP dark matter detection

Daniel Ang

dga@umd.edu

Queens U.

Using tracks to search for WIMP and ultraheavy dark matter

Joseph Bramante

joseph.bramante@queensu.ca

SLAC

Using X-ray diffractive imaging to search for WIMP and neutrino tracks

Arianna Gleason-Holbrook

ariannag@stanford.edu

U. North Florida

Searching for WIMP dark matter and supernova neutrino tracks

Chris Kelso

ckelso@unf.edu

U. Michigan

Searching for tracks from atmospheric neutrinos

Joshua Spitz

spitzj@umich.edu

U. Texas at Austin/Stockholm U.

Theoretical studies and early planning stages for experimental work

Katherine Freese

ktfreese@utexas.edu

PALEOCCENE

Searching for solar/reactor neutrinos and lighter WIMPs using color centers

Patrick Huber

pahuber@vt.edu

INFN Milan/U. Milan

Searching for cosmic ray induced tracks

Lorenzo Caccianiga

lorenzo.caccianiga@mi.infn.it

KIT/U. Heidelberg

Searching for WIMP dark matter and atmospheric neutrino tracks

Alexey Elykov

alexey.elykov@kit.edu

UC London

Preliminary experimental studies of neutrino track detection

David Waters

d.waters@ucl.ac.uk

JAMSTEC

Searching for WIMP dark matter tracks in mica

Shigenobu Hirose

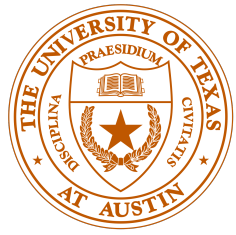
shirose@jamstec.go.jp

Toho U./Nagoya U.

Searching for ultraheavy dark matter tracks

Tatsuhiro Naka

tatsuhiro.naka@sci.toho-u.ac.jp



DMICA: A Modern Revival of the Mica Dark Matter Search



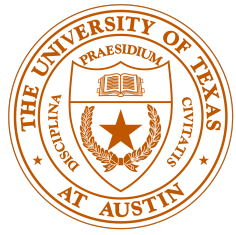
DMICA: exploring Dark Matter in natural muscovite MICA

Shigenobu Hirose

Japan Agency for Marine-Earth Science and Technology (JAMSTEC)

Collaboration with:

Natsue Abe¹ Qing Chang¹, Takeshi Hanyu¹, Noriko Hasebe², Yasushi Hoshino³, Takashi Kamiyama⁴,
Yoji Kawamura¹, Kohta Murase⁵, Tatsuhiro Naka⁶, Kenji Oguni¹, Katsuhiko Suzuki¹, Seiko Yamasaki⁷
(JAMSTEC¹, Kanazawa U², Kanagawa U³, Hokkaido U⁴, Penn State⁵, Toho U⁶, AIST⁷)



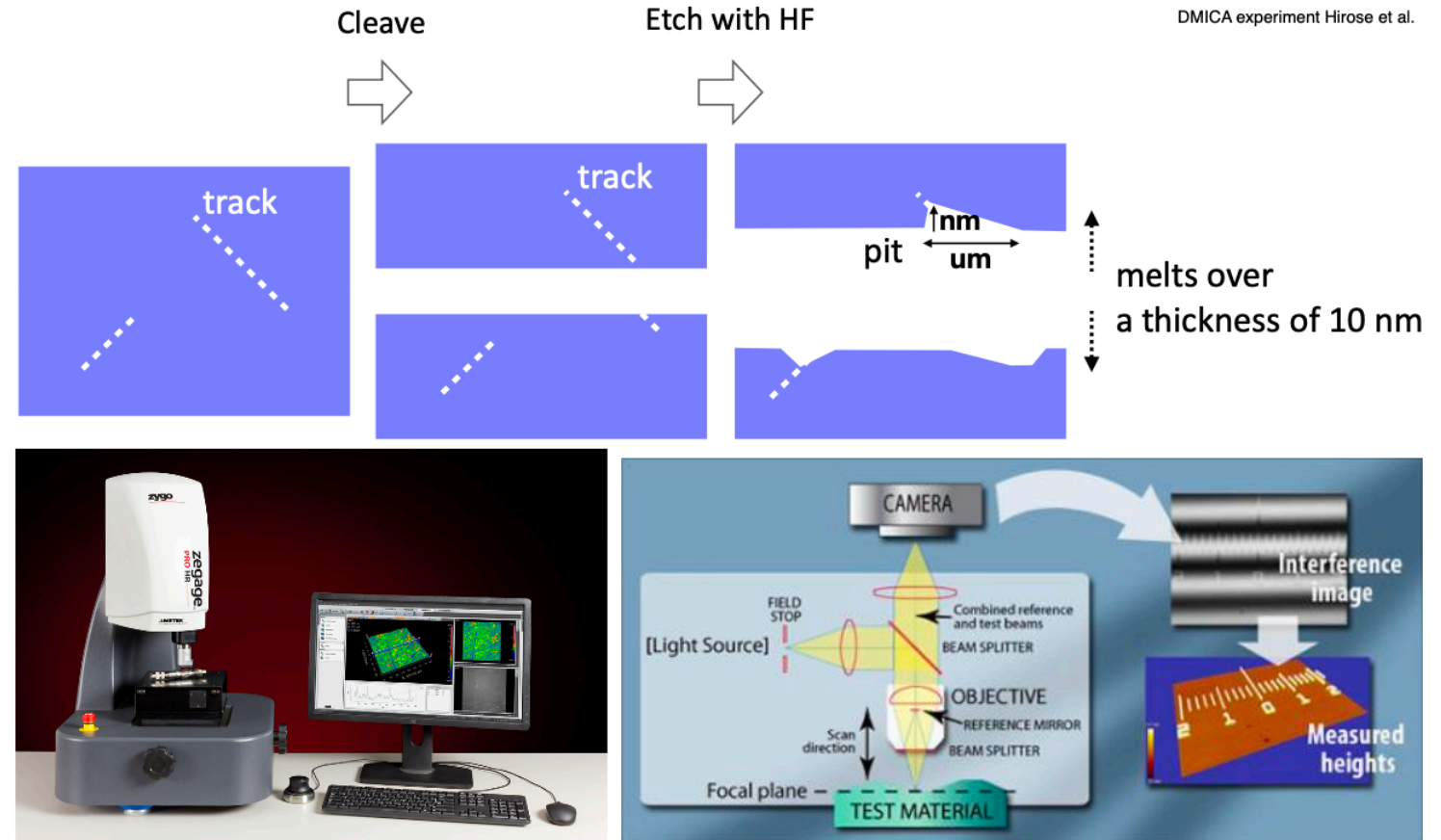
DMICA: A Modern Revival of the Mica Dark Matter Search

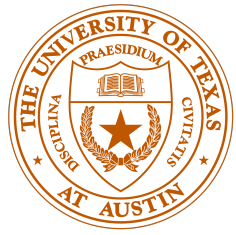
- ❖ Replace slow AFM scanning with high-throughput optical profilometry

➡ Use laser instead of AFM's mechanical needle

★ Projected exposure $\sim 1 \text{ ton} \cdot \text{yr}$

★ Still a few orders of magnitude less sensitive than XENON1T





NSF GRANT FOR 2.5M

NSF GCR Mineral Detection of Dark Matter

Robert Bodnar, Judah DiStefano, Samuel Hedges,
Patrick Huber, Vsevolod Ivanov, Giti Khodaparast,
Brenden Magill, Maverick Morrison, Thomas O'Donnell,
Abigael Parks, Arjun Uppal, Keegan Walkup
Virginia Tech, USA

Igor Jovanovic, Emilie LaVoie-Ingram, Josh Spitz, Kai
Sun, Katie Ream, Andrew Calabrese-Day
University of Michigan, USA

Chris Kelso, Greg Wurtz
University of North Florida, USA

Arianna Gleason, Sulgiye Park, Kazu Terao
SLAC National Accelerator Laboratory, USA

Katherine Freese, Dionysius Theodosopoulos
University of Texas, Austin, USA

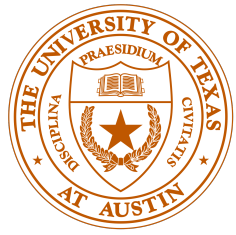
Patrick Stengel
Jozef Stefan Institute, Slovenia

Laura Baudis, Nikita Vladimirov, Christian Wittweg,
University of Zurich, Switzerland

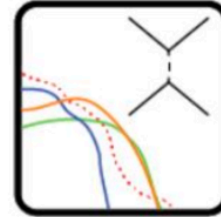
William McDonough
University of Maryland, USA

Xianyi Zhang
Lawrence Livermore National Laboratory, USA

Jay Thomas
Syracuse University, USA

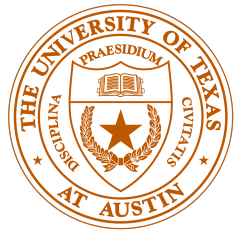


NSF GRANT FOR 2.5M



Universität
Zürich^{UZH}





MOORE FOUNDATION 1.5M at the University of Michigan



Atmospheric Neutrino and Dark Matter Detection at the University of Michigan

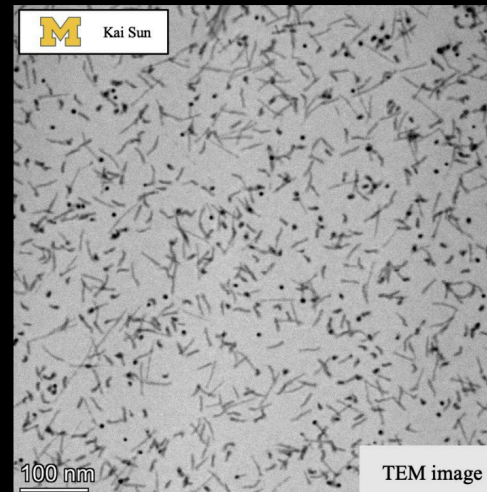
PI: Josh Spitz, spitzj@umich.edu

RA: Emilie LaVoie-Ingram, emlavoie@umich.edu

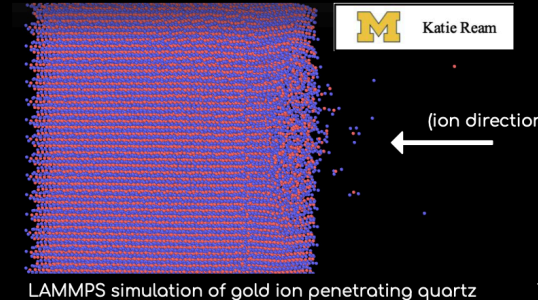
- Ion irradiation of various minerals to study morphology of nuclear recoil damage tracks
- TEM imaging for high resolution measurements
 - Currently testing x-rays for high throughput, high resolution track imaging at U-M and SLAC
- Automatic track detection algorithm
- LAMMPS molecular dynamics simulations to study track formation
- GEANT4 simulations to study cosmogenic neutron background in ancient minerals as a function of rock overburden

GORDON AND BETTY
MOORE
FOUNDATION

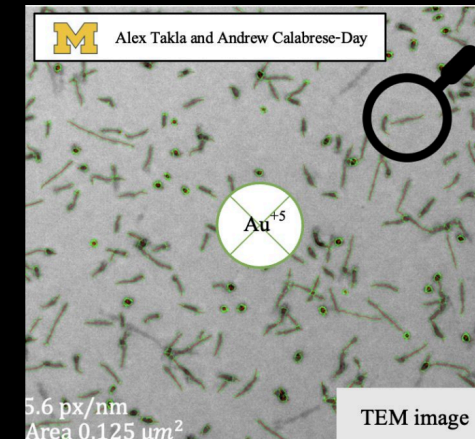
SPITZ
GROUP



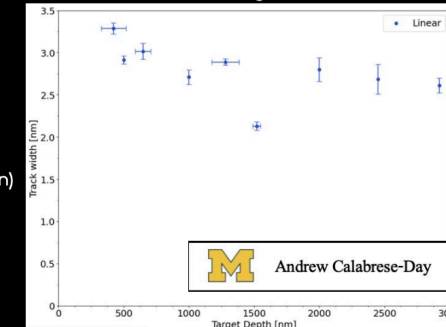
Gold ion tracks in olivine



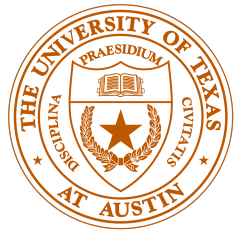
LAMMPS simulation of gold ion penetrating quartz



Automatic track detection algorithm



Track width v. depth data for gold irradiated olivine



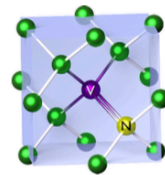
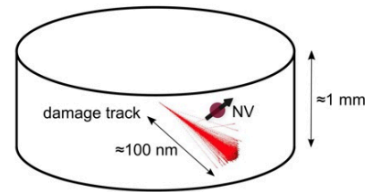
Mineral detection at the University of Maryland



Mineral detection at the University of Maryland: Directional detection of neutrinos and dark matter with quantum diamond sensors

qtc.umd.edu

Lead personnel: Prof. Ronald Walsworth, Dr. Daniel Ang (dga@umd.edu)



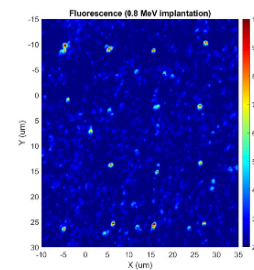
Nitrogen-vacancy center

- WIMP dark matter particles and neutrinos can induce nuclear recoils that leave 10-100 nm damage tracks in diamond
- **Goal:** locate and characterize damage track with nitrogen-vacancy (NV) quantum sensors embedded in the diamond to deduce energy and direction of initial particle
- Directionality allows distinguishing WIMPs from the solar neutrino background
- Requires state-of-the-art quantum diamond microscopy techniques at the micro- and nanoscales
- See [Ebadi et al., AVS Quantum Sci. 4 \(4\): 044701 \(2022\)](#)

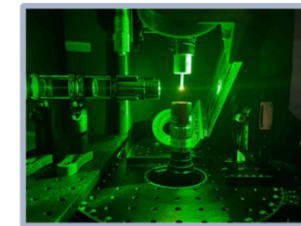


Current research activities

- Experiments creating and detecting artificial ion-induced damage tracks (at Sandia National Lab)
- Developing light-sheet quantum diamond microscope (LS-QDM) for high-speed, high-resolution diamond scanning
- Developing NV super-resolution imaging techniques to resolve and characterize individual damage tracks at the nanoscale



Single ion impact damage sites



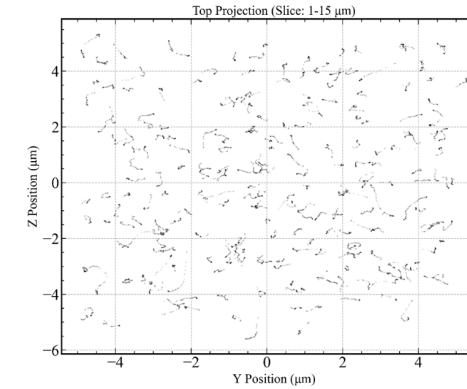
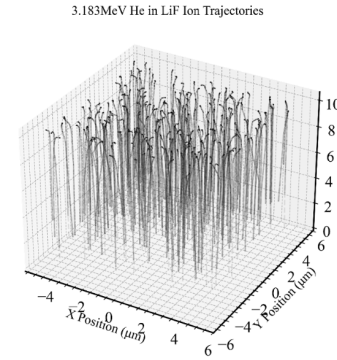
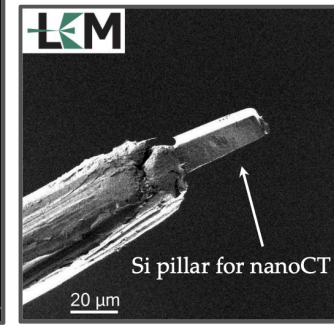
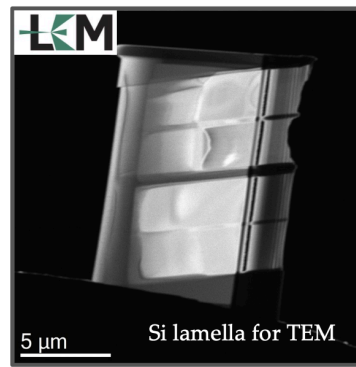
LS-QDM @ UMD



Karlsruhe Institute of Technology

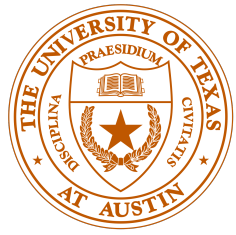
Contact: alexey.elykov@kit.edu

Sample preparation & imaging



Track simulation & analysis

- **Collaborative project** - KIT institutes (astroparticle, microscopy) & Uni. Heidelberg (geology)
- **Experimental studies** of natural & artificial samples (irradiated & blank), accompanied by simulations
- **Establish** the techniques for **imaging** & **analysis** of **particle-induced tracks** in minerals



EURECApd Project

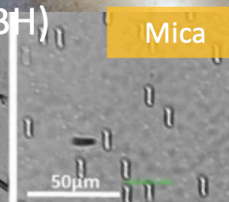
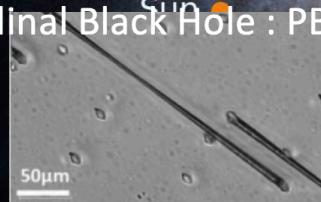
EURECApd project



Toho U., Nagoya U., Kyoto U. Kanagawa U. JAMSTEC

Ultra Heavy Dark Matter

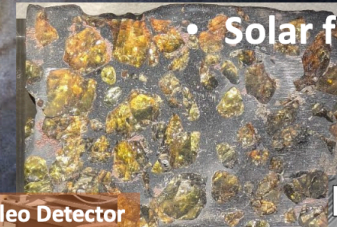
- composite dark matter
e.g., Q-ball, quark, nugget, nuclearite •
- Magnetic Monopole
- (Primordial Black Hole : PBH)



Mica

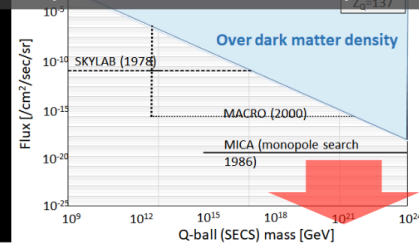
Ultra Heavy Element

- meteorite analysis
- Transuranium element
- r-process in Neutron star merger (NSM)
- Accelerator mechanism
- Solar flare



Solar flare

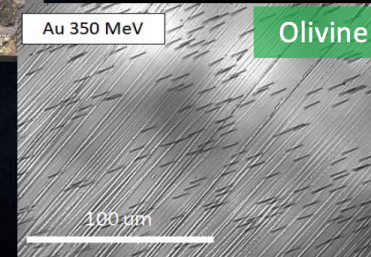
The deepest search for ultra heavy dark matter



Automatic scanning system for Paleo Detector

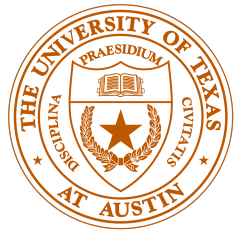


High speed scanning and imaging processing system based on the nuclear emulsion technology



Au 350 MeV

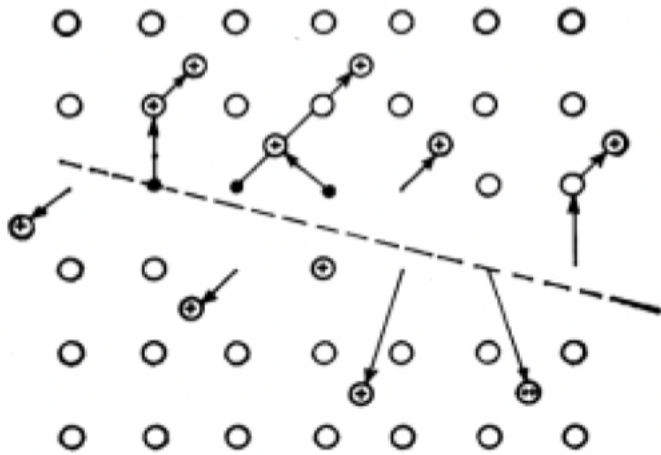
Olivine



Nuclear Recoils Leave Permanent Damage Tracks in Minerals

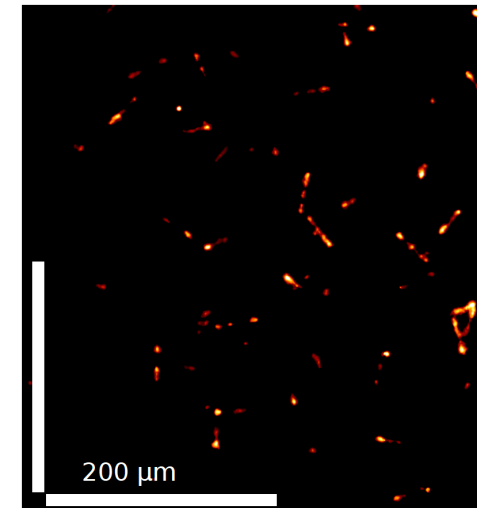
❖ Ionization Tracks: (for recoils > 100 eV)

- ➡ Recoiling nucleus loses energy through ionization and nuclear collisions
- ➡ Atoms are displaced from lattice sites
- ➡ A damaged region is left along the recoil trajectory

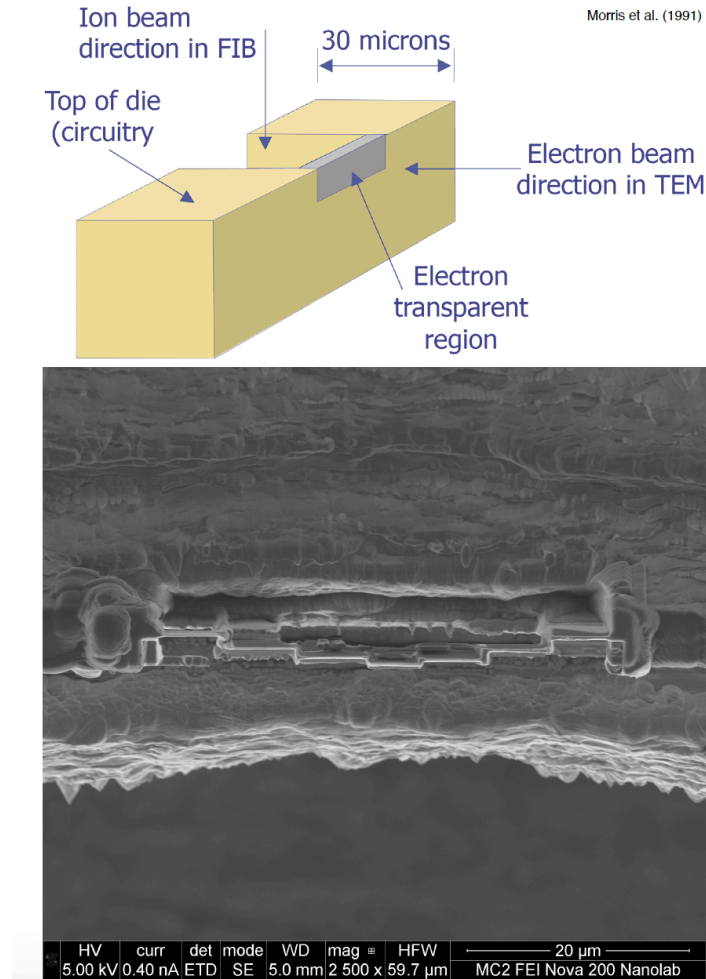
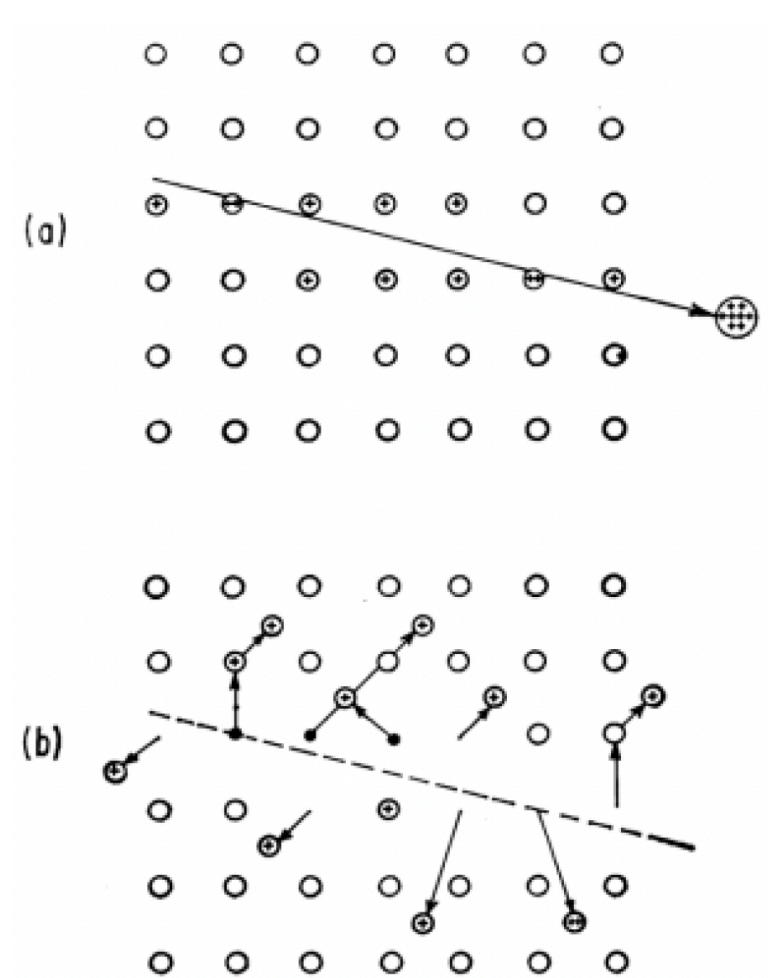


❖ Color Center Defects (for recoils > 10 eV):

- ➡ Recoils create vacancies and lattice defects. Electrons can become trapped at these defects (color centers)
- ➡ Laser excitation causes trapped electrons to fluoresce
- ➡ Map the spatial distribution of defects

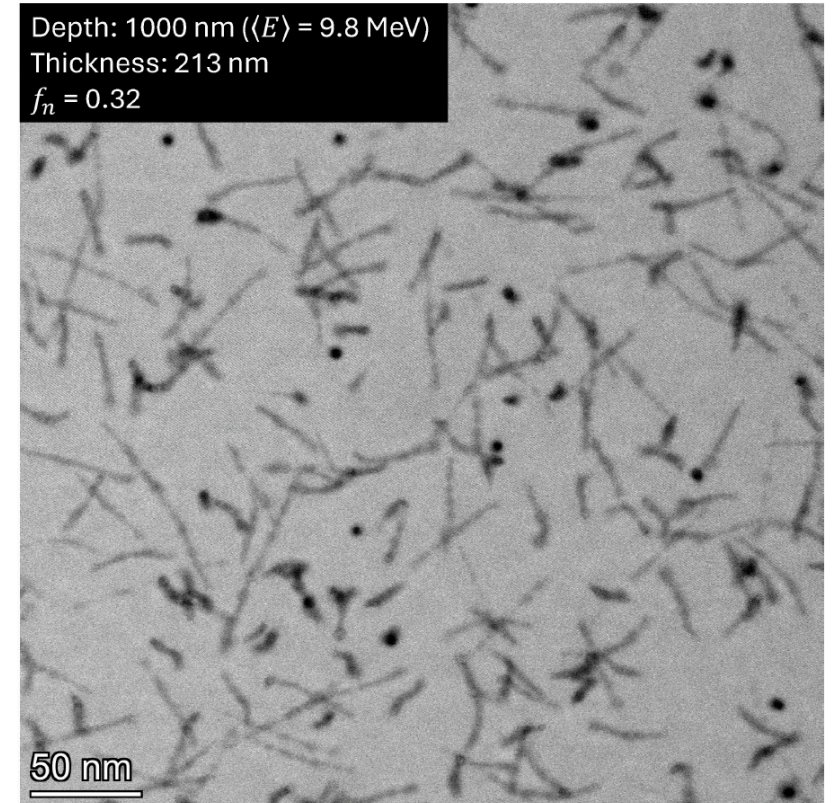


Damage Track Imaging: Direct Imaging of Recoil Tracks



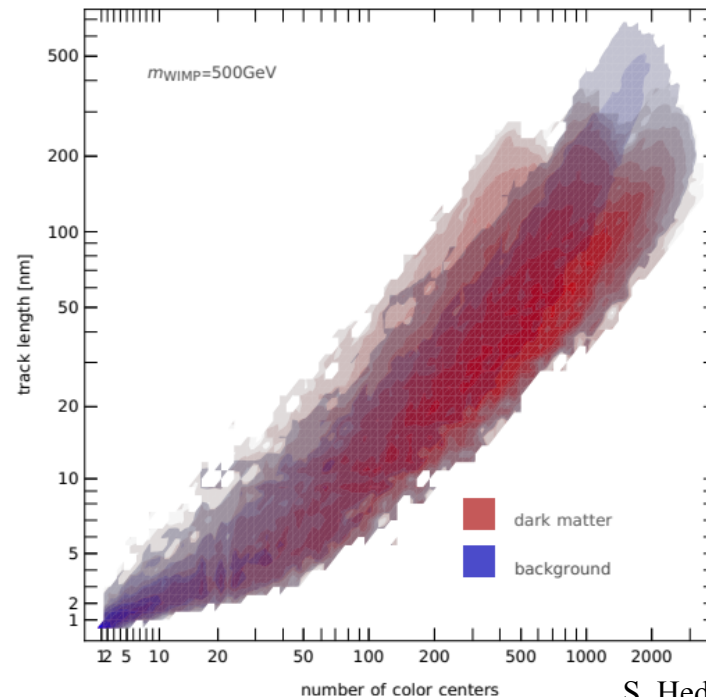
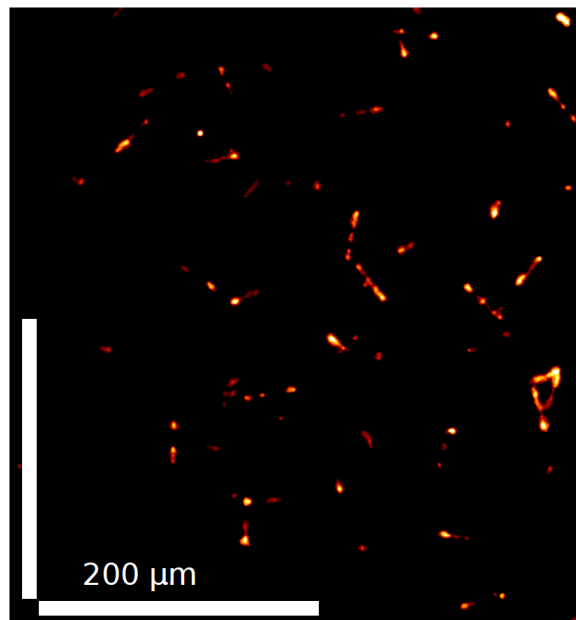
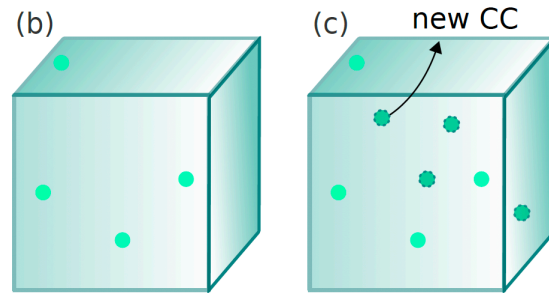
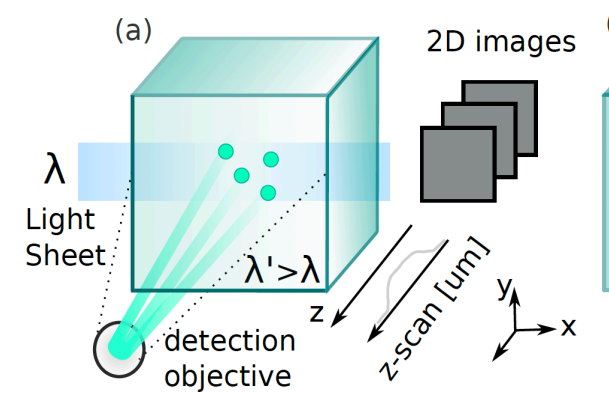
A. Calabrese-Day *et al.* arXiv:2604.09732.

A. Calabrese-Day *et al.* arXiv:2604.09732.



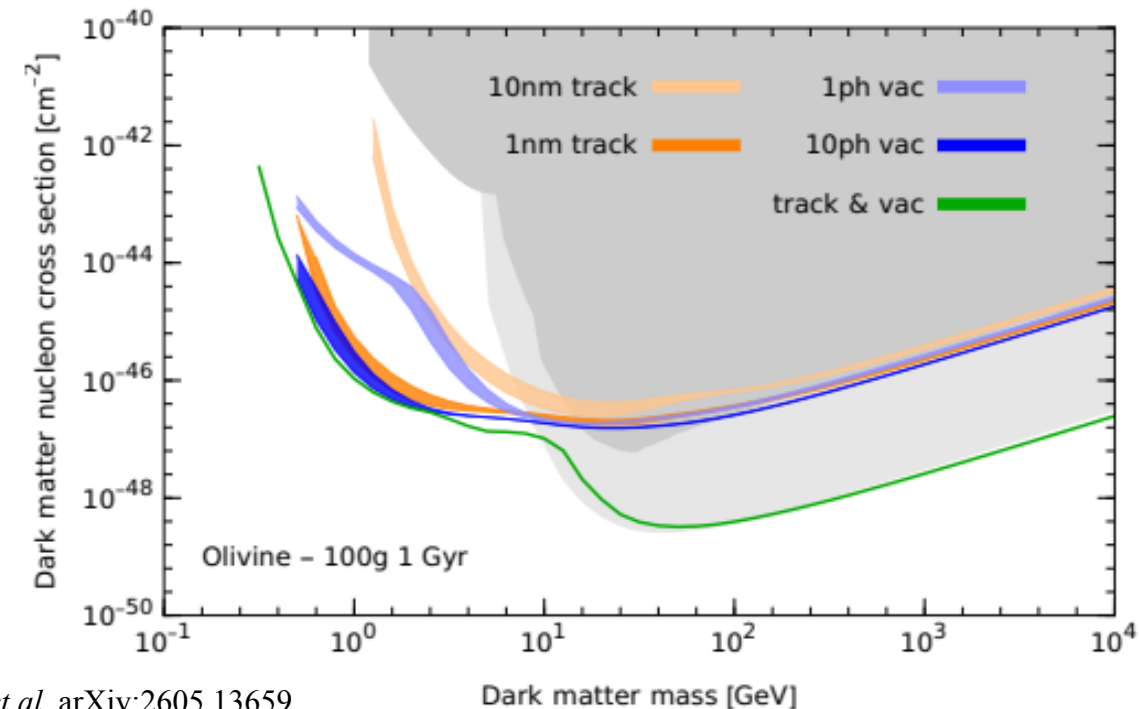
- ❖ No etching to enhance tracks
- ❖ 2D imaging of tracks at depth
- ❖ Track formation, morphology

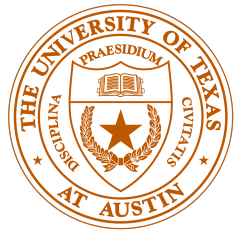
Color Center Imaging: Optical Readout of Crystal Defects



S. Hedges *et al.* arXiv:2605.13659.

- ❖ 3D imaging of CCs in bulk
- ❖ Low ionizing CC tracks
- ❖ Could scan $\sim \text{cm}^3$ in hours

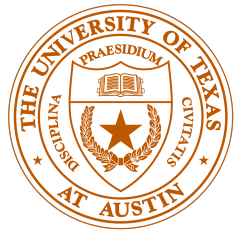




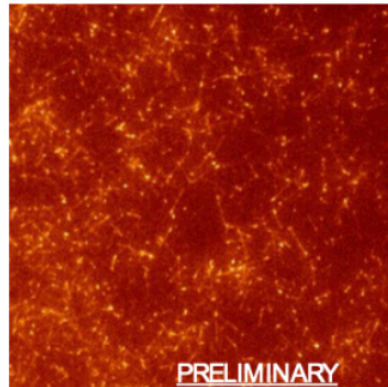
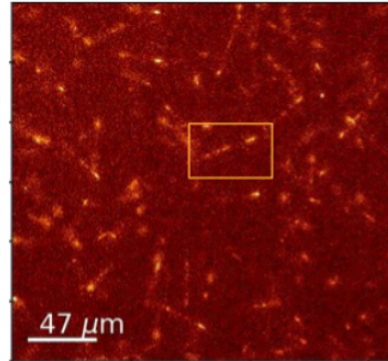
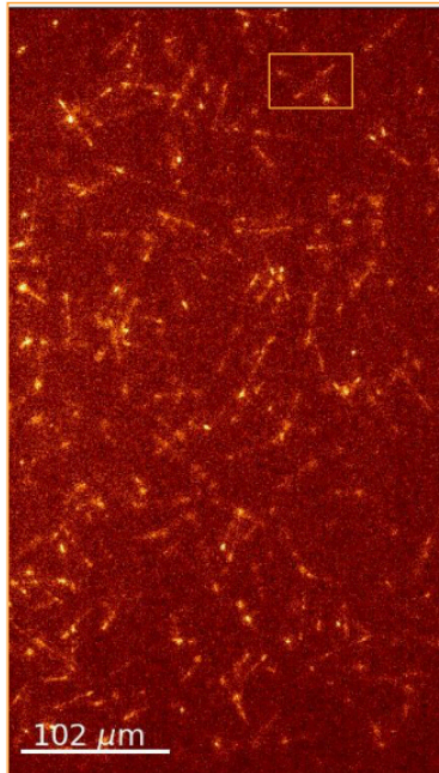
Reactor Monitoring with Color Centers, Patrick Huber



- ❖ Nuclear safeguards and nonproliferation
- ❖ Reactor antineutrino spectra depend on fuel composition
 - ➡ Potentially distinguish civilian power production from plutonium breeding
- ❖ Advantages of color-center detectors
 - ➡ Passive operation
 - ➡ No continuous monitoring
 - ➡ No cryogenics or electronics
- ❖ Concept
 - ➡ Bury a box with calibrated crystals near a reactor
 - ➡ Retrieve and read out months later



Fission Tracks from Irradiation of LiF with Thermal Neutrons



TRITIUM + ALPHA: some tracks show sizes according to expected. Tritium track (~33 μm) and alpha track (~6 μm).



IMAGING AT at millimeters INSIDE THE CRYSTAL! (USUALLY NOT POSSIBLE WITH OTHER MICROSCOPY TECHNIQUES)

IRRADIATION OF LiF WITH FAST NEUTRONS PRODUCE SHORT (A FEW MICRONS) TRACKS AND SOME AMOUNT OF FISSION TRACKS CAUSED BY SLOWER NEUTRONS



Universität
Zürich^{UZH}

PALEOCCENE
Araujo et al.

See tracks of color centers at mm depth inside sample
These are z-stacks. Proof of principle.



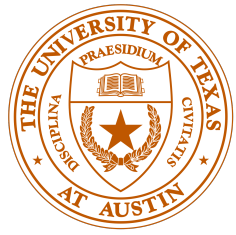
Summary

❖ Paleo-detectors transform ancient minerals into billion-year dark matter and neutrino detectors

- ➡ Typical ages ~ 1 Gyr
- ➡ Effective exposure up to $\sim 10^5$ ton $\cdot$ yr

❖ Sensitivity projections are highly competitive

- ➡ Probe WIMP dark matter with masses $\gtrsim 1$ GeV
 - ★ Explore regions inaccessible (low sensitivity) to other experiments ($1 \text{ GeV} < m_\chi < 10 \text{ GeV}$)
 - ★ For $m_\chi \gtrsim 10 \text{ GeV}$ provide sensitivities comparable to or better than those of existing experiments
- ➡ Large event samples enable mass reconstruction and interaction discrimination



Summary

❖ Paleo-detectors are also neutrino observatories

- ➡ Solar neutrinos
- ➡ Atmospheric neutrinos
- ➡ Supernova neutrinos
- ➡ Potential probes of long-term astrophysical evolution

❖ Experimental progress is accelerating

- | | | |
|------------------------------|---|---------------------------------|
| ➡ Damage-track imaging | ➡ | High resolution, small exposure |
| ➡ Color-center imaging | ➡ | Large exposure, low resolution |
| ➡ 1.5M from Moore Foundation | | |
| ➡ 2.5M from NSF | | |





End of presentation

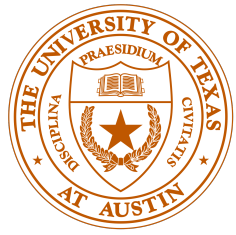
Thank you for your attention!!!



Minerals

Mineral	Composition	Fiducial ^{238}U Concentration [per Weight, g/g]
Gypsum	$\text{Ca}(\text{SO}_4) \cdot 2(\text{H}_2\text{O})$	10^{-11}
Halite	NaCl	10^{-11}
Sinjarite	$\text{CaCl}_2 \cdot 2(\text{H}_2\text{O})$	10^{-11}
Epsomite	$\text{Mg}(\text{SO}_4) \cdot 7(\text{H}_2\text{O})$	10^{-11}
Olivine	$\text{Mg}_{1.6}\text{Fe}_{0.4}^{2+}(\text{SiO}_4)$	10^{-10}
Muscovite	$\text{KAl}_2(\text{AlSi}_3\text{O}_{10})(\text{F}, \text{OH})_2$	10^{-10}
Phlogopite	$\text{KMg}_3\text{AlSi}_3\text{O}_{10}\text{F}(\text{OH})$	10^{-10}
Nchwaningite	$\text{Mn}_2^{2+}\text{SiO}_3(\text{OH})_2 \cdot (\text{H}_2\text{O})$	10^{-10}

D. P. Theodosopoulos *et al.* arXiv:2603.13629.



Track-length Spectrum in Paleo-detectors

- ❖ The number of tracks in the i -th bin with length $x_T \in [x_{T,i}^{\min}, x_{T,i}^{\max}]$ reads:

Mineral mass $\times$ mineral age

$R \longrightarrow$ # of tracks per unit exposure

$$\mathcal{N}_i = M \times t_{\text{age}} \int dx'_T W(x'_T; x_{T,i}^{\min}, x_{T,i}^{\max}) \frac{dR}{dx_T}(x'_T)$$

Probability of measuring the true length x'_T to be between $x_{T,i}^{\min}$ and $x_{T,i}^{\max}$

- ❖ The window function is: $W(x'_T; x_{T,i}^{\min}, x_{T,i}^{\max}) = \frac{1}{2} \left[\text{erf} \left(\frac{x'_T - x_{T,i}^{\min}}{\sqrt{2} \sigma_x} \right) - \text{erf} \left(\frac{x'_T - x_{T,i}^{\max}}{\sqrt{2} \sigma_x} \right) \right]$
- ❖ We take the probability of measuring x_T from a true length x'_T to be Gaussian-distributed with variance σ_x^2 and mean value x'_T , where σ_x is the read-out resolution of the Paleo-Detector.



Projected sensitivity of Paleo-Detectors using the standard profile likelihood ratio analysis

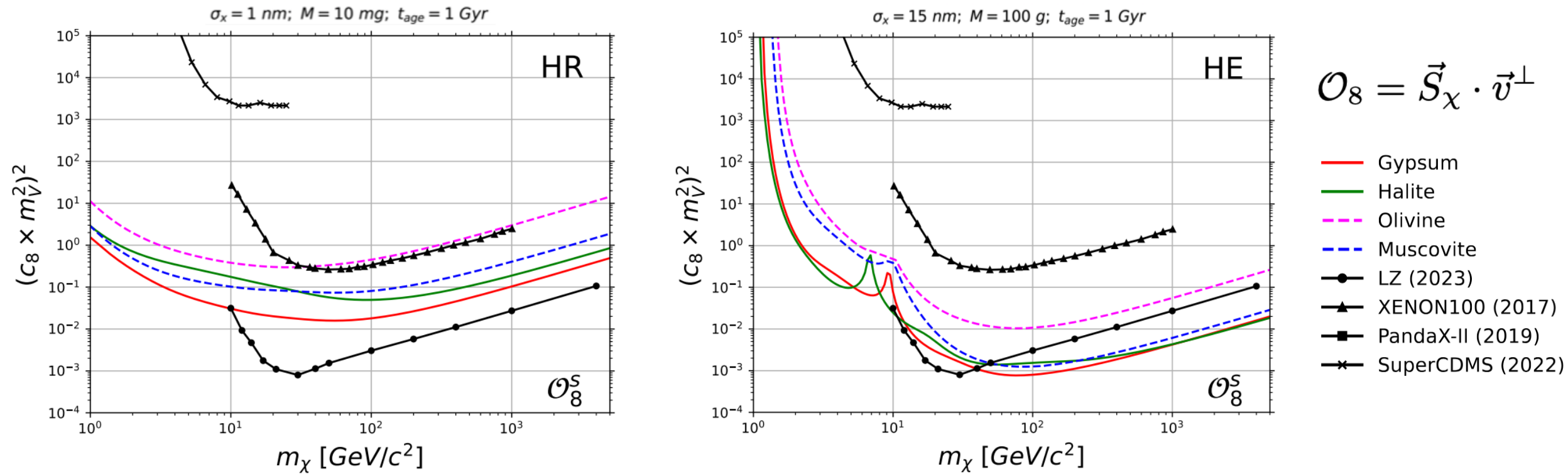


Figure 9: Projected 90% CL upper limits on the spin-independent ($\mathcal{O}_8^S$) WIMP-nucleon NREFT coupling constants in the HR (left) and HE (right) scenarios. Also shown are the limits from the experiments LUX-ZEPLIN (2023), XENON100 (2017), PandaX-II (2019), and SuperCDMS (2022).¹

[1] D. P. Theodosopoulos *et al.* arXiv:2603.13629.



Projected sensitivity of Paleo-Detectors using the standard profile likelihood ratio analysis

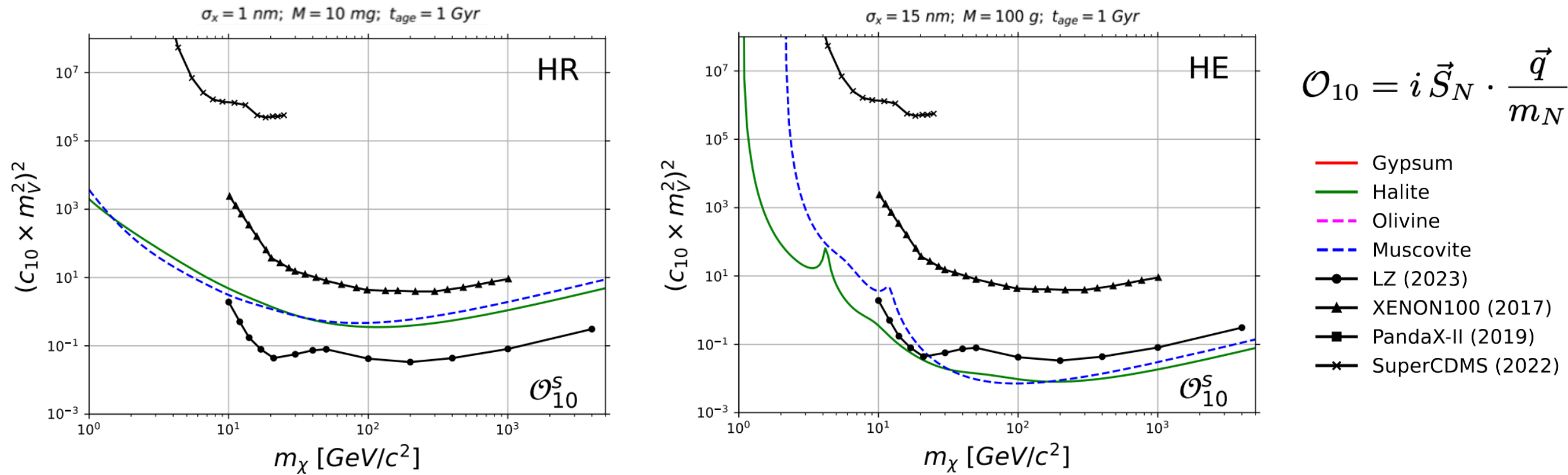


Figure 10: Projected 90% CL upper limits on the spin-dependent ($\mathcal{O}_{10}^s$) WIMP-nucleon NREFT coupling constants in the HR (left) and HE (right) scenarios. Also shown are the limits from the experiments LUX-ZEPLIN (2023), XENON100 (2017), PandaX-II (2019), and SuperCDMS (2022). ¹

[1] D. P. Theodosopoulos *et al.* arXiv:2603.13629.

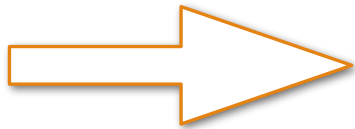


WIMP-Nucleon Inelastic Interactions¹

❖
$$\mathcal{L}_{\text{int}} = \sum_{N=n,p} \sum_i c_i^{(N)} \mathcal{O}_i \chi^+ \chi^- N^+ N^-$$

❖ Mass splitting: $\delta_m \equiv m_{\chi,\text{out}} - m_{\chi,\text{in}}$

❖ For inelastic scattering ($m_{\chi,\text{out}} > m_{\chi,\text{in}}$)



$$\chi^+ \neq \chi^- \quad \text{and} \quad N^+ \equiv N^-$$

❖
$$\vec{v}^\perp \longrightarrow \vec{v}_{\text{inel}}^\perp = \vec{v}^\perp + \frac{\delta_m}{|\vec{q}|^2} \vec{q}$$

[1] G. Barello *et al.* arXiv:1409.0536.



WIMP-Nucleon Inelastic Interactions

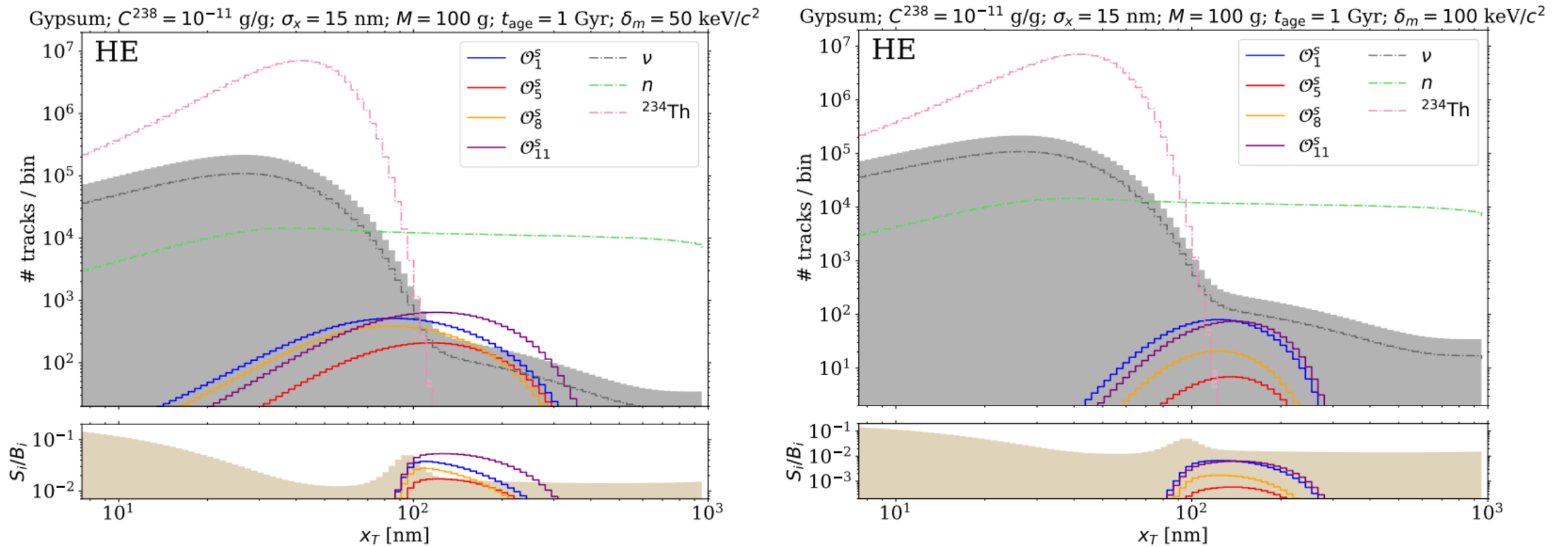


Figure 11: Track length spectrum for inelastic scattering from a 500 GeV/c² WIMP in the HR (left) and HE (right) scenarios. The normalization is compatible with the upper limits from LUX–ZEPLIN (2023).¹

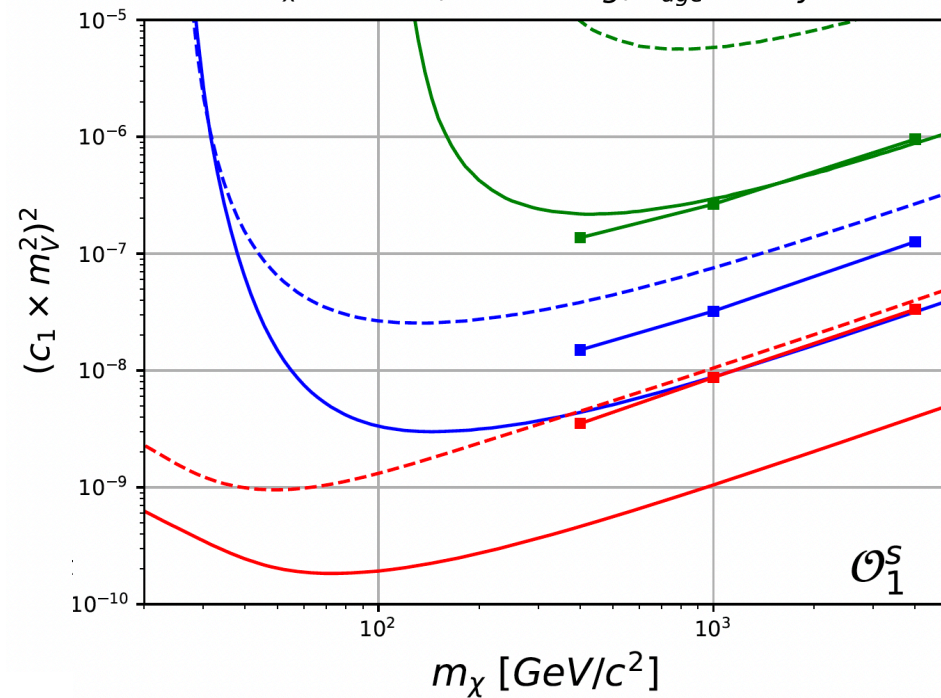
[1] D. P. Theodosopoulos *et al.* arXiv:2603.13629.



WIMP-Nucleon Inelastic Interactions

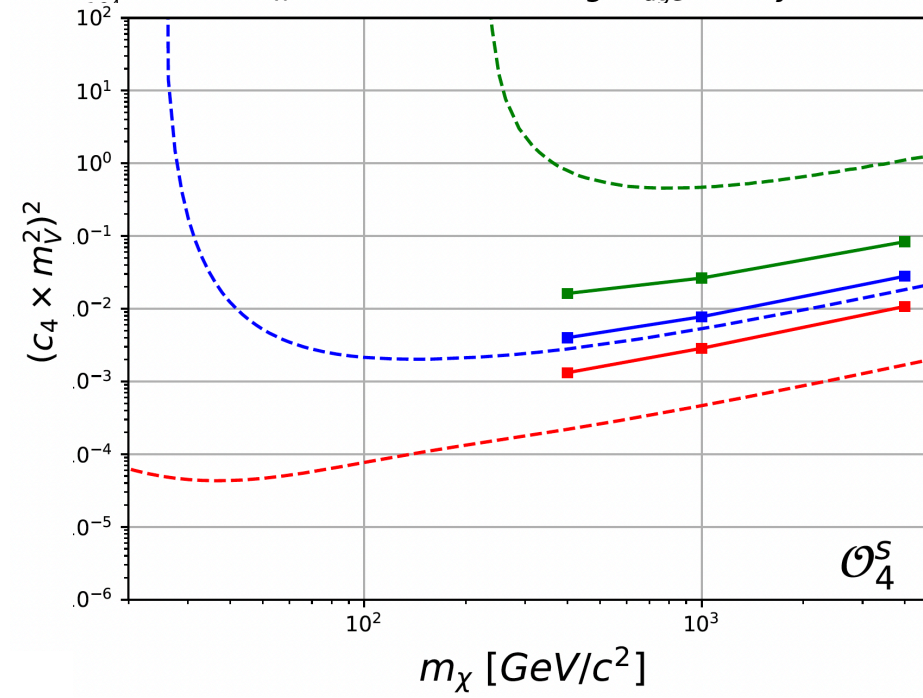
$$\mathcal{O}_1 = 1_\chi 1_N$$

$\sigma_x = 15 \text{ nm}; M = 100 \text{ g}; t_{\text{age}} = 1 \text{ Gyr}$



$$\mathcal{O}_4 = \vec{S}_\chi \cdot \vec{S}_N$$

$\sigma_x = 15 \text{ nm}; M = 100 \text{ g}; t_{\text{age}} = 1 \text{ Gyr}$



- 0 keV
- 50 keV
- 100 keV
- Gypsum
- - - Halite
- LZ (2023)

Figure 12: Projected 90% CL upper limits on the $\mathcal{O}_1^S$ (left panel) and $\mathcal{O}_4^S$ (right panel) WIMP-nucleon coupling constants for inelastic scattering in the HE scenario. Also shown are the NREFT results from the experiment LUX-ZEPLIN (2023).¹

[1] D. P. Theodosopoulos *et al.* arXiv:2603.13629.



Conclusions on the Sensitivity of Paleo-Detectors

❖ Paleo-detectors can achieve better sensitivity than conventional direct detection DM experiments:

- ➡ for $1 \text{ GeV} < m_\chi < 10 \text{ GeV}$, for elastic scattering in the HR ($\sigma_x = 1 \text{ nm}$, $M = 10 \text{ mg}$) scenario, for all NREFT operators
- ➡ for $m_\chi > 10 \text{ GeV}$, for elastic scattering in the HE ($\sigma_x = 15 \text{ nm}$, $M = 100 \text{ g}$) scenario, for most NREFT operates
- ➡ for $30 \text{ GeV} < m_\chi < 400 \text{ GeV}$, for inelastic scattering with $\delta_m < 50 \text{ keV}$ in the HE ($\sigma_x = 15 \text{ nm}$, $M = 100 \text{ g}$) scenario, for most NREFT operates