



PALEODETECTION: FOSSIL RECORDS OF NEW PHYSICS IN ANCIENT MINERALS

based on arXiv: 2504.08885 and on ongoing work

Collaborators:

Physics: Aaron Vincent (Queen's), Shohei Okawa (APCTP), Jinheung Kim (KIAS)

Geology: Matthew Leybourne, Sharlotte Mkhonto

Mechanical Engineering and Material Science: Levente Balogh, Thalles Lucas

asia pacific center for
theoretical physics



QCUMBER

QUEEN'S CENTRE FOR
UNDERSTANDING MINERALS BY
BLASTING THEM WITH
EXCESSIVE RADIATION



Queen's
UNIVERSITY

THE LANDSCAPE OF PALEODETECTION

Limits on Dark Matter Using Ancient Mica

D. P. Snowden-Ifft,* E. S. Freeman, and P. B. Price*
Physics Department, University of California at Berkeley, Berkeley, Ca.
(Received 20 September 1994)

- WIMP dark matter
- Ultra heavy dark matter
- Solar neutrinos for testing SSM, BSM neutrino interactions
- DSNB
- Proton decay
- DM Sub-halos
- etc. ... see MDvDM white paper (2301.07118), proceedings 2024 (2405.01626) and 2025 (2508.20482)

Mineral Detection of Neutrinos and Dark Matter. A Whitepaper

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Thalles Lucas,⁹ William F. McDonough,^{37,38,39} Mason C. Marshall,^{15,40}
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Erwin H. Tanin,¹⁶ Aaron Vincent,⁹ Nikita Vladimirov,⁵⁰ Ronald L. Walsworth,^{14,15,40}
and Hiroko Watanabe³⁷

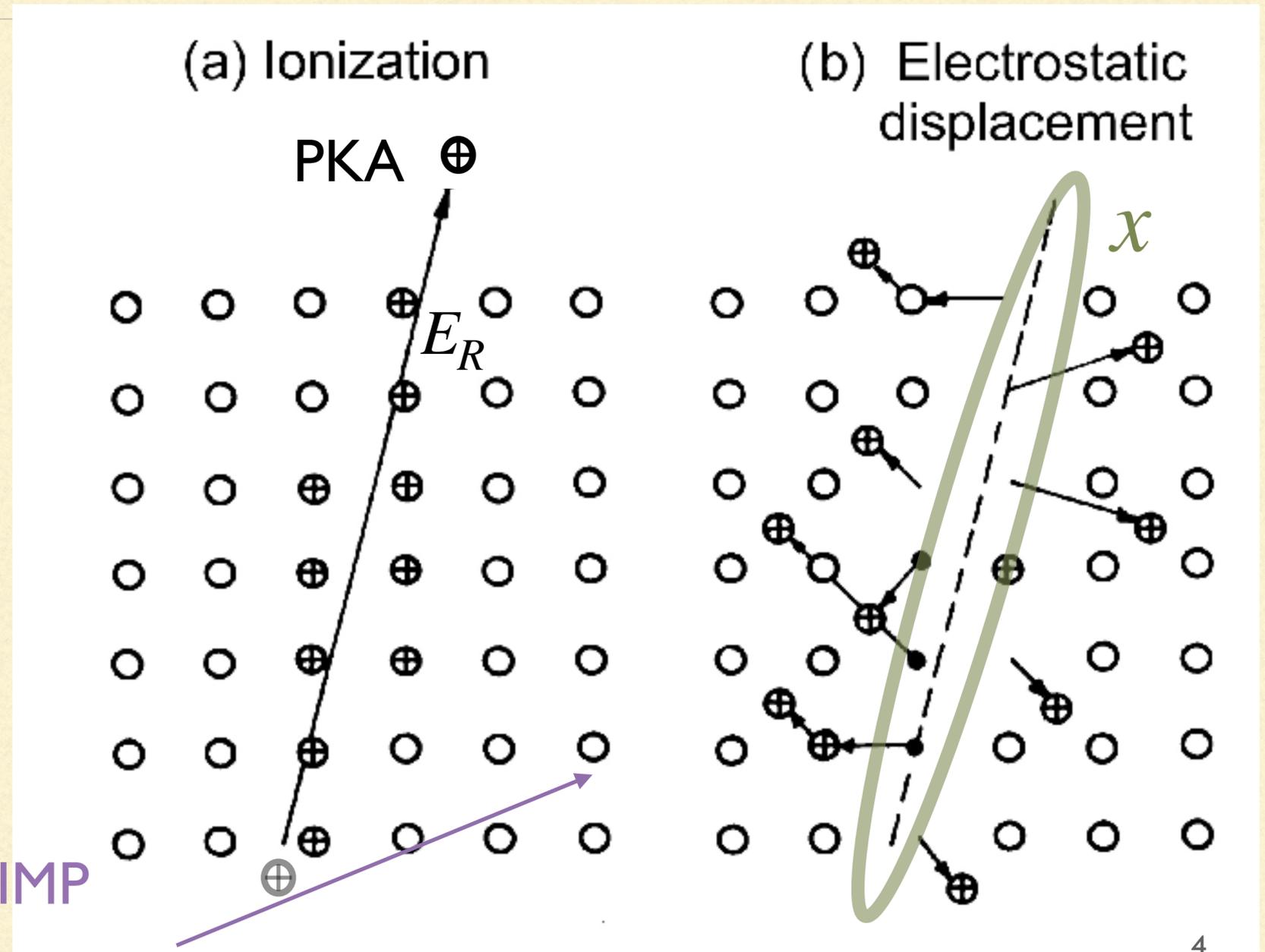
Link to MDvDM 2026: <https://indico.kit.edu/event/5425/>

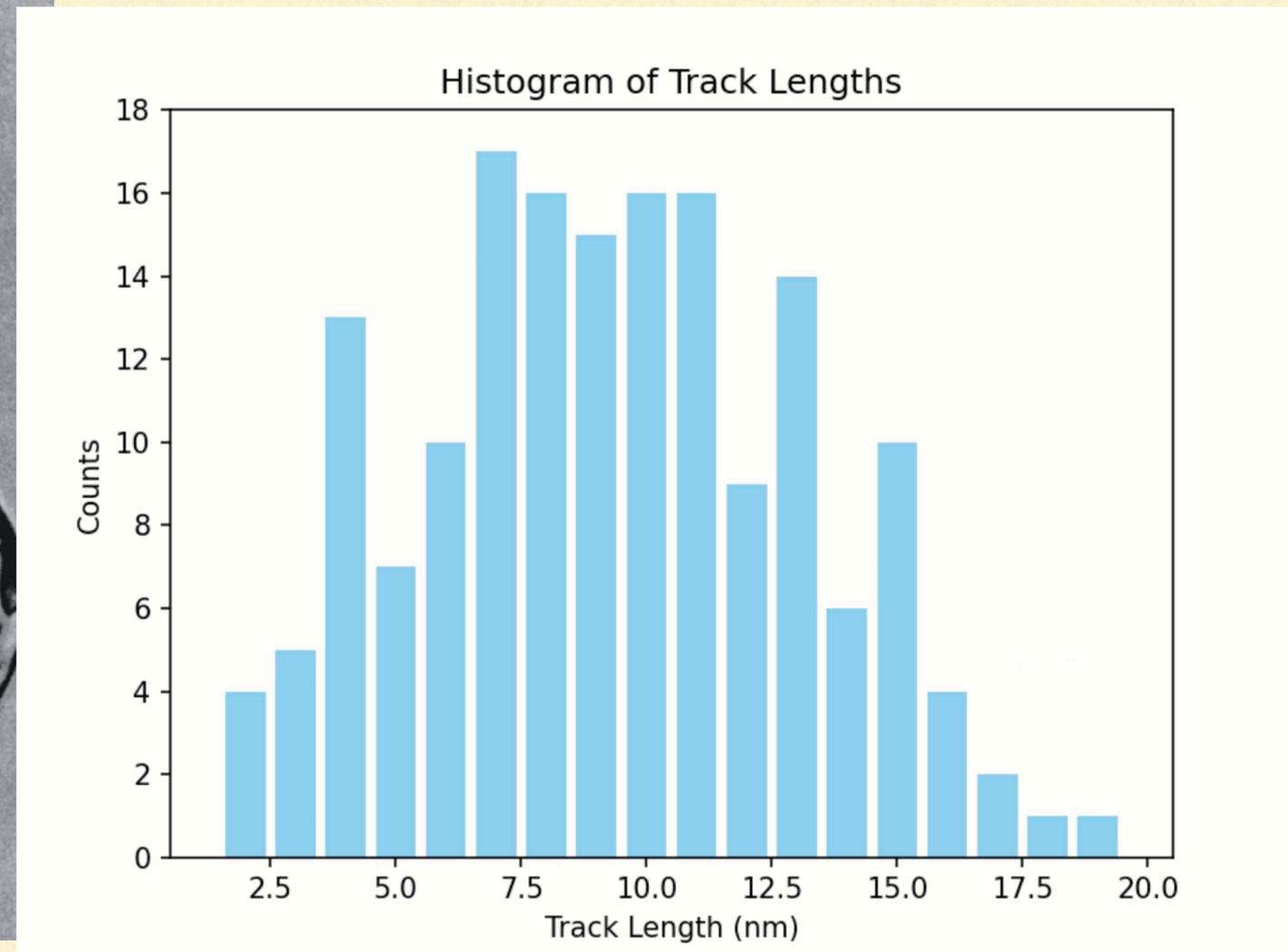
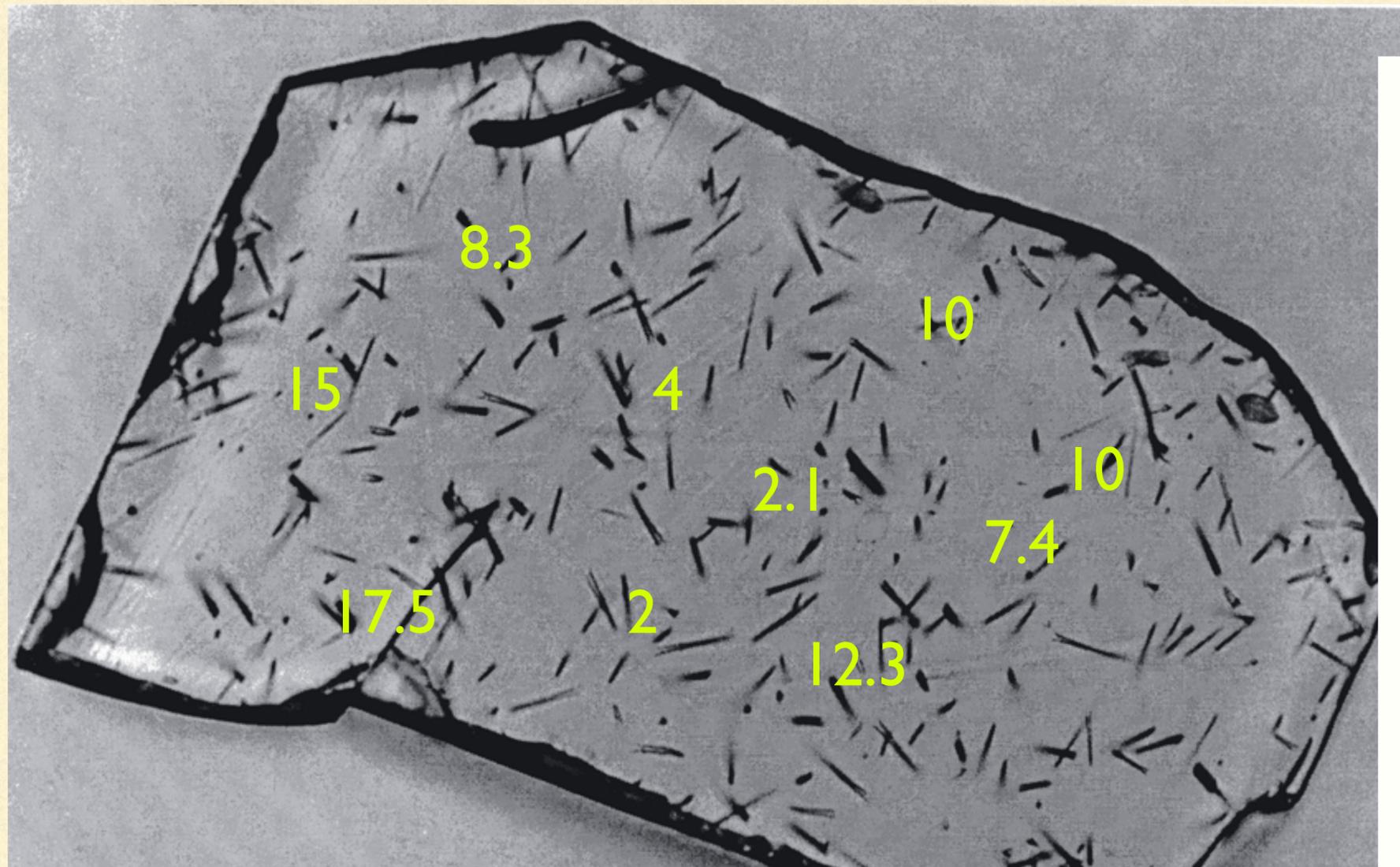
I. WIMP DARK MATTER

DAMAGE TRACKS

- Incident particles leave latent damage to crystal structure
- Preserved crystal damage over Gyr timescale
- Infer particle incident energy and flux from track length (and its distribution), track counts and vacancy defects

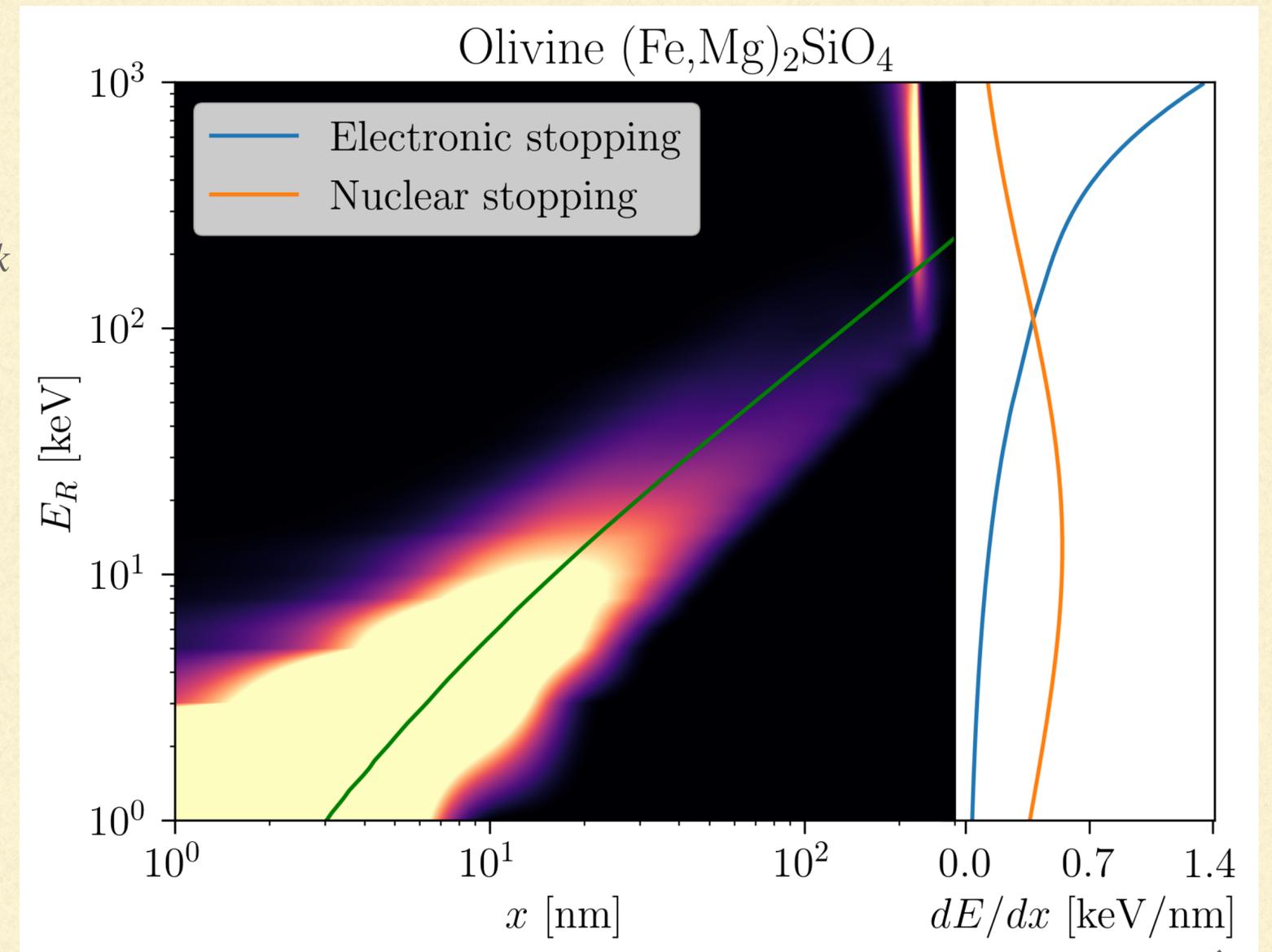
WIMP





RECOIL ENERGY-TRACK LENGTH RELATION

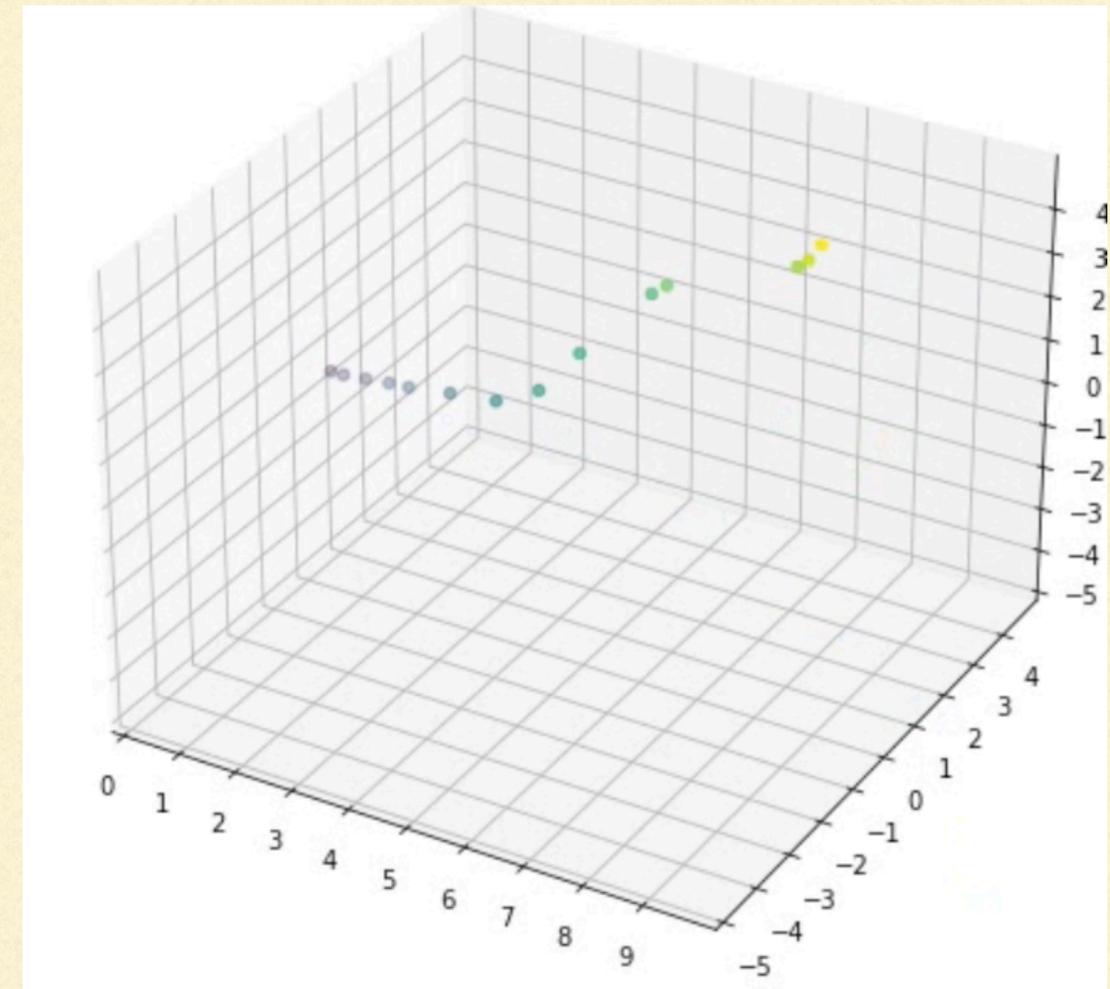
- $\frac{dR}{dx}(x) = \sum_{i=1}^{\text{compositions}} \int dE_R \frac{dR_i}{dE_R}(E_R) \mathcal{P}_i(x | E_R) \times \mathcal{P}_{i,track}$
- $\mathcal{P}_i(x | E_R)$: the probability of track length x given a recoil energy E_R
- $\mathcal{P}_{i,track}$: the probability that a track is formed



TRIM (TRANSPORT OF IONS IN MATTER)

- a Monte Carlo program that calculates interactions of ions with amorphous targets
 - simulates cascades of produced by irradiated ions
 - record the locations of all collisions between irradiated ions and target atoms
- e.g. irradiate a 5keV ion in Olivine 40000 times

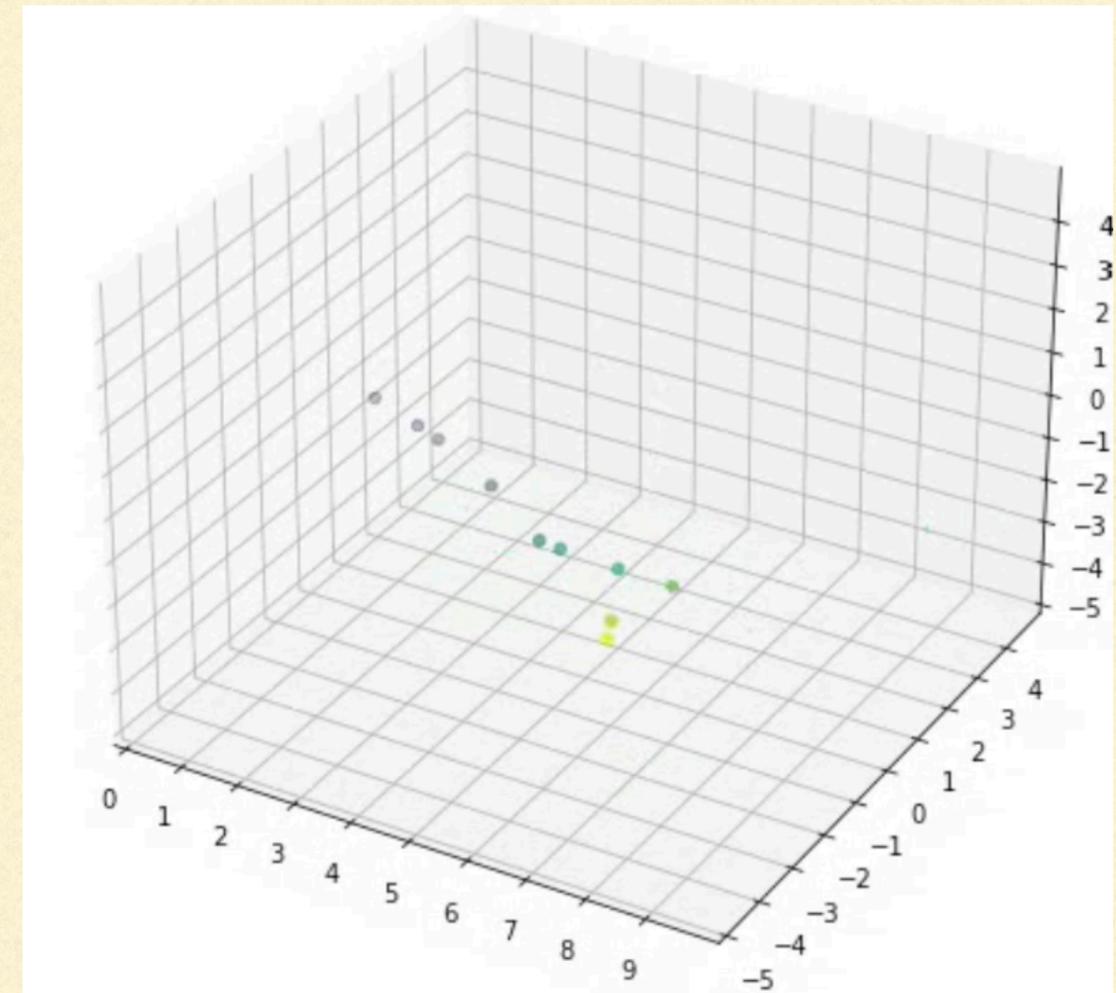
5 keV Fe in Olivine



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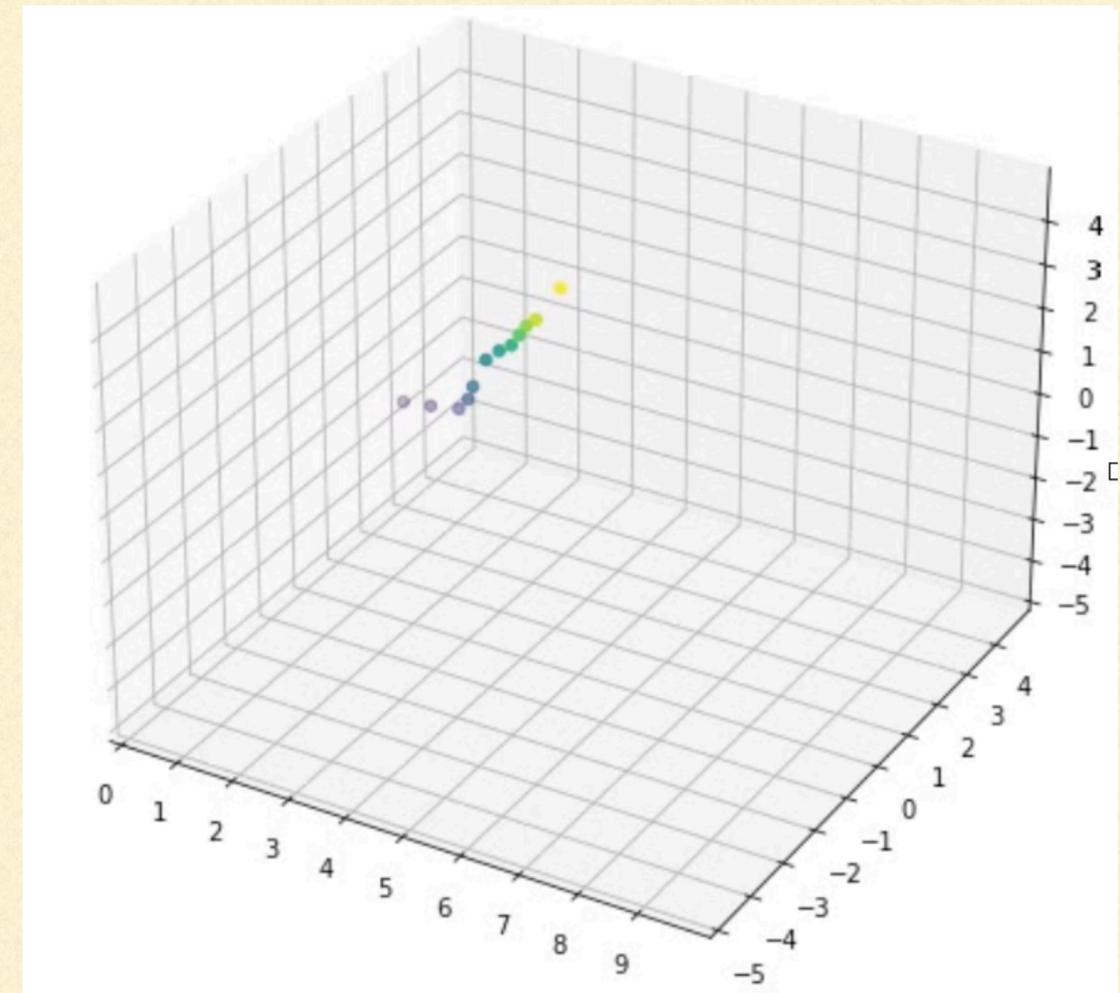
5 keV Fe in Olivine



TRIM (TRANSPORT OF IONS IN MATTER)

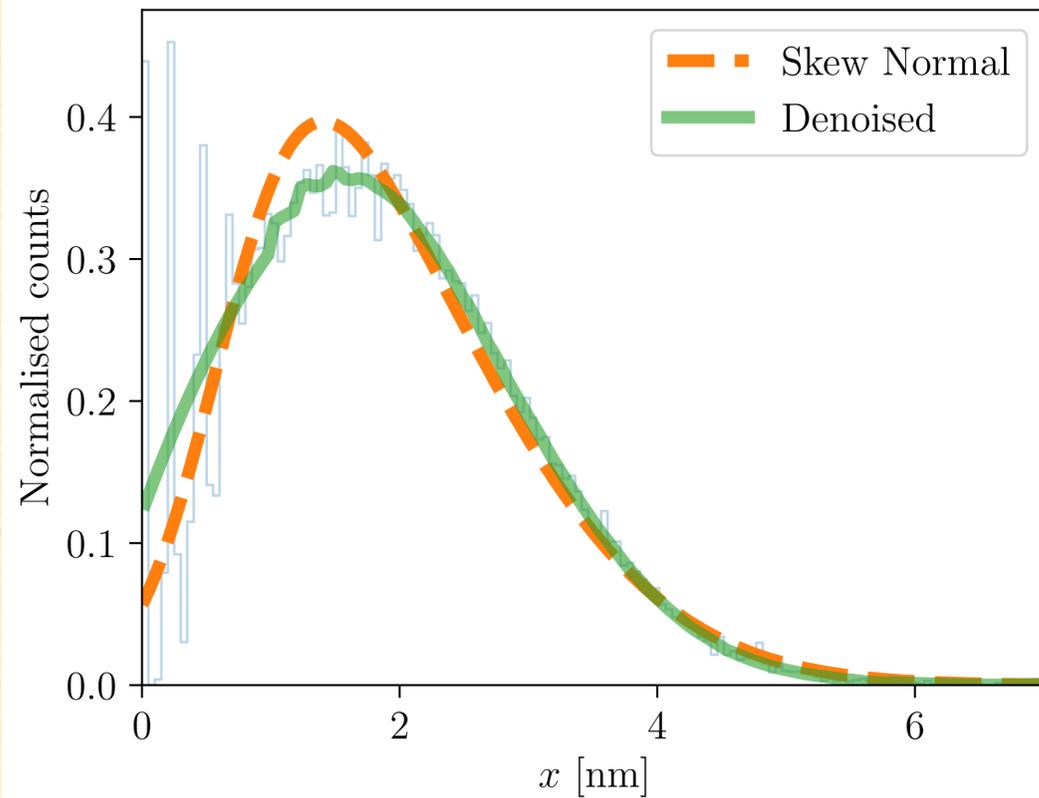
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5 keV Fe in Olivine

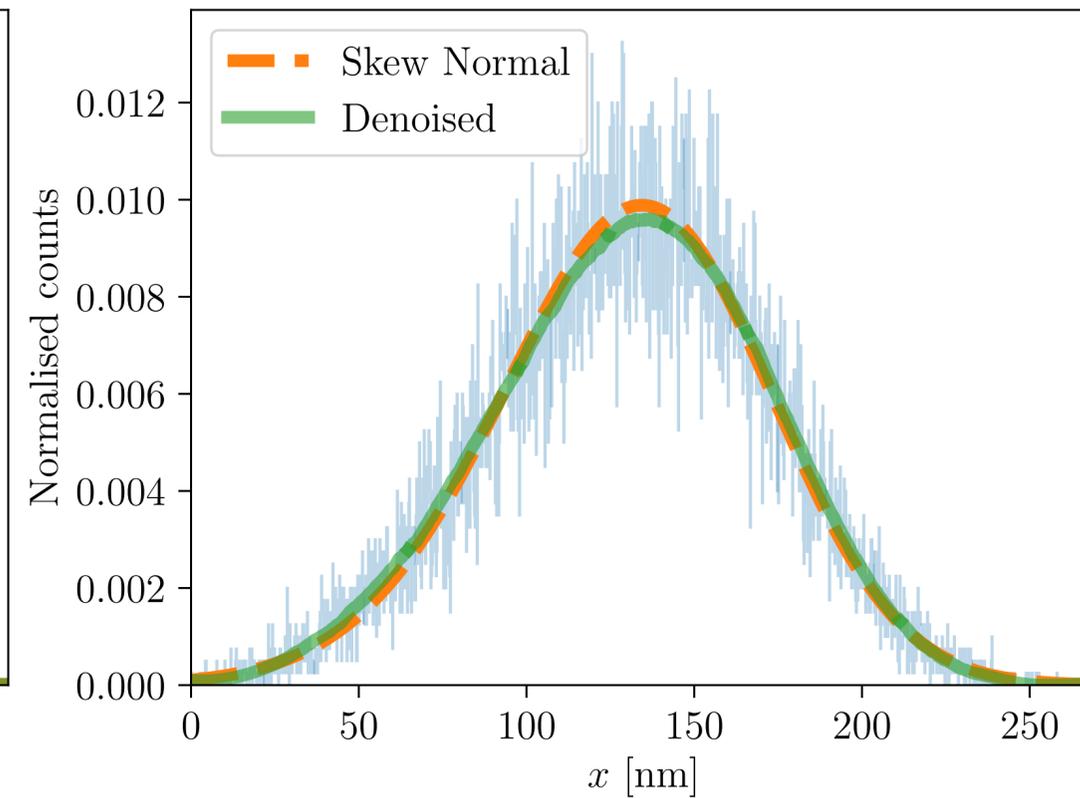


I. TRACK LENGTH DISTRIBUTION $\mathcal{P}_i(x | E_R)$ OF Fe IN OLIVINE $(\text{Mg, Fe})_2 \text{SiO}_4$

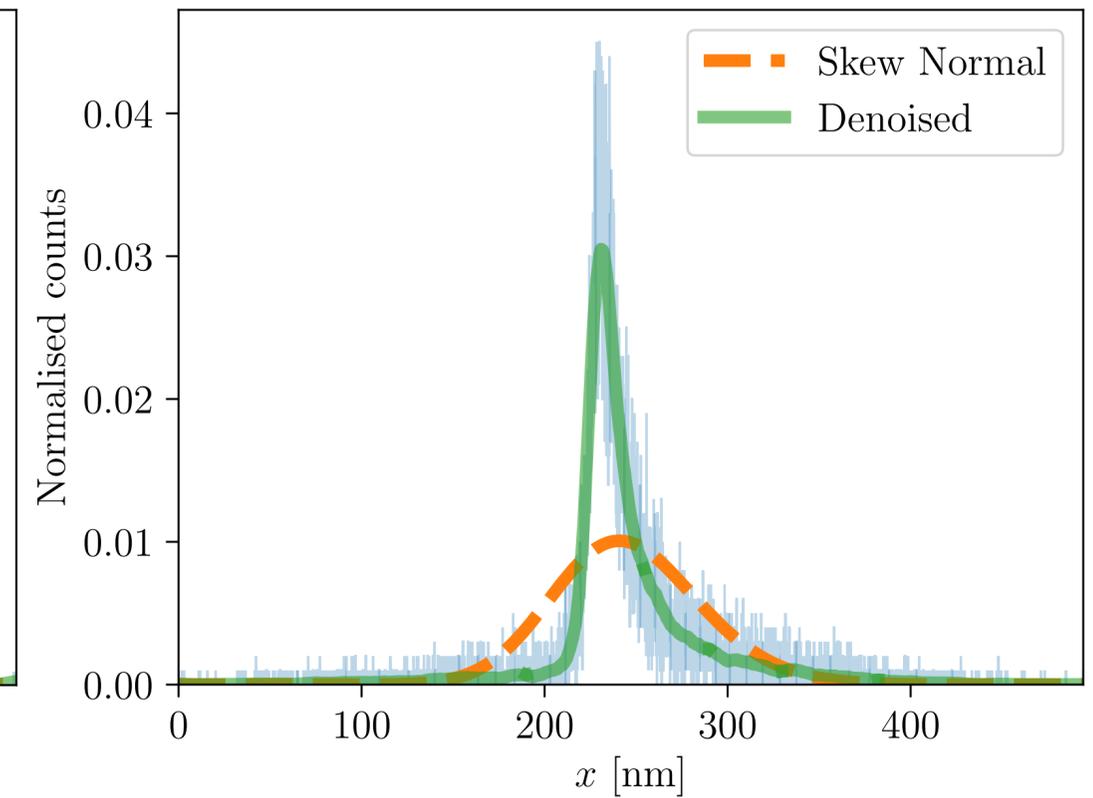
Fe in Olivine at 0.6 keV



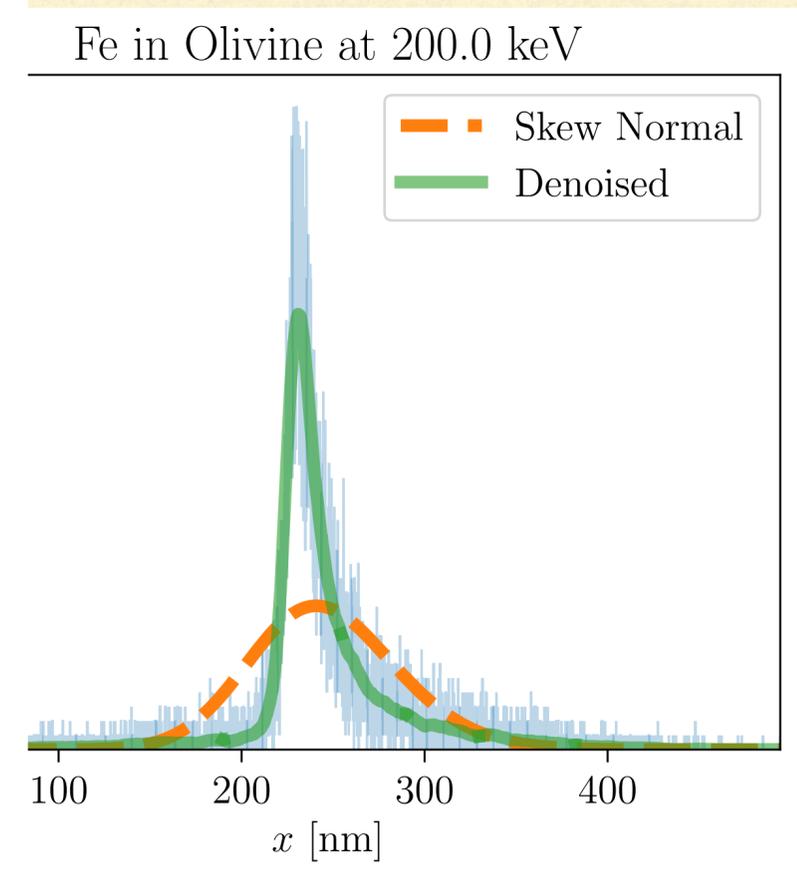
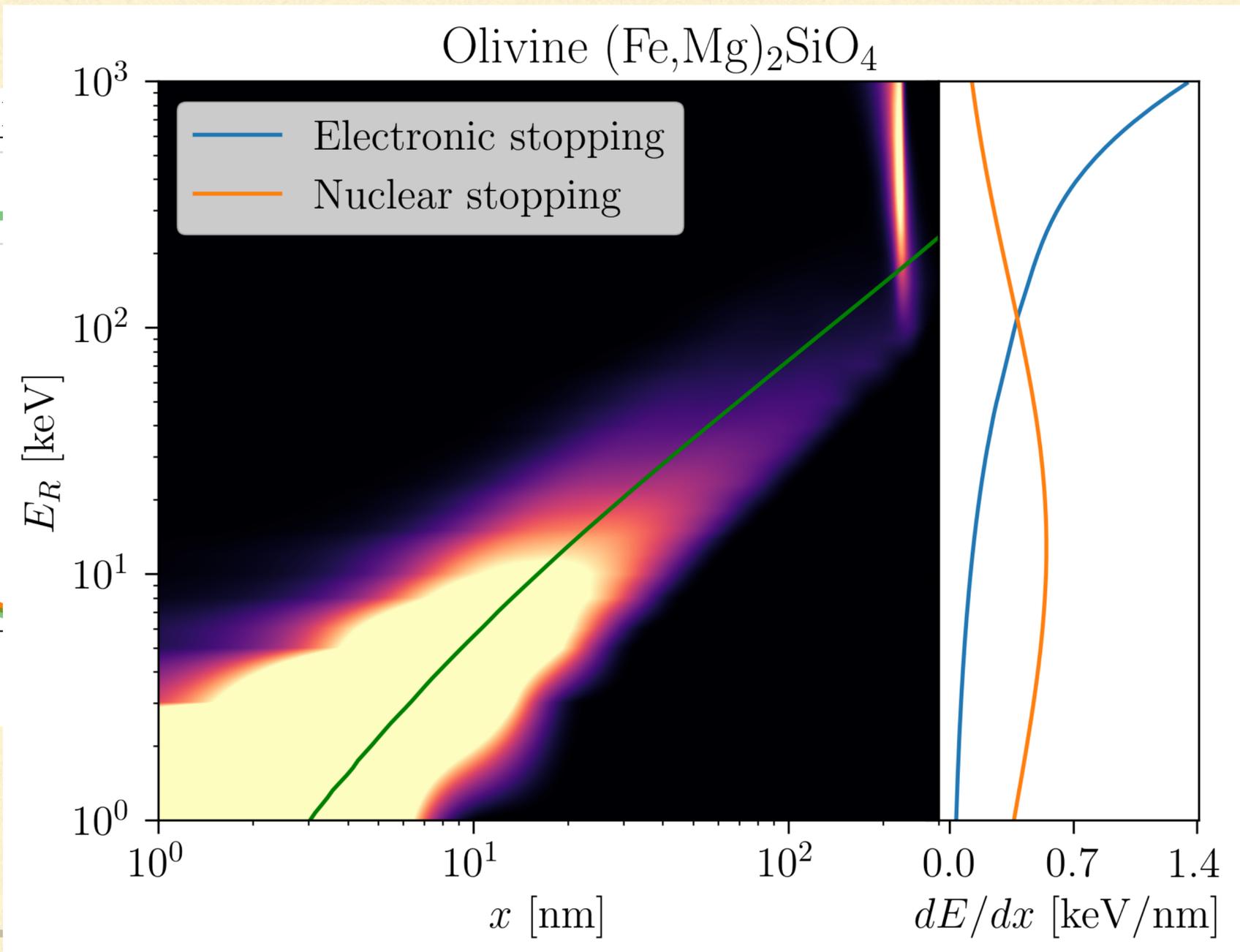
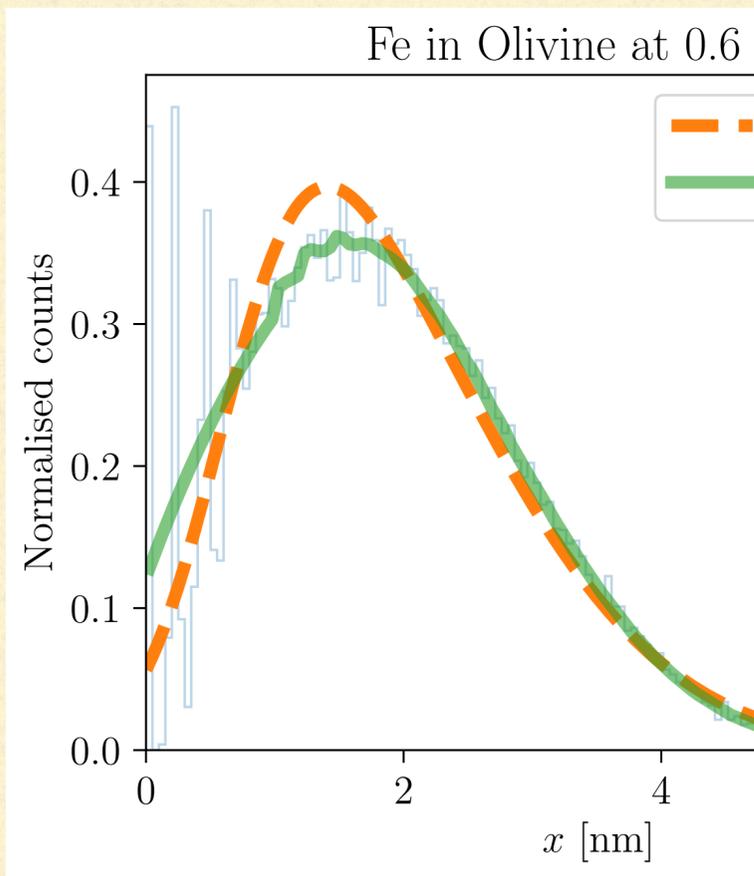
Fe in Olivine at 70.0 keV



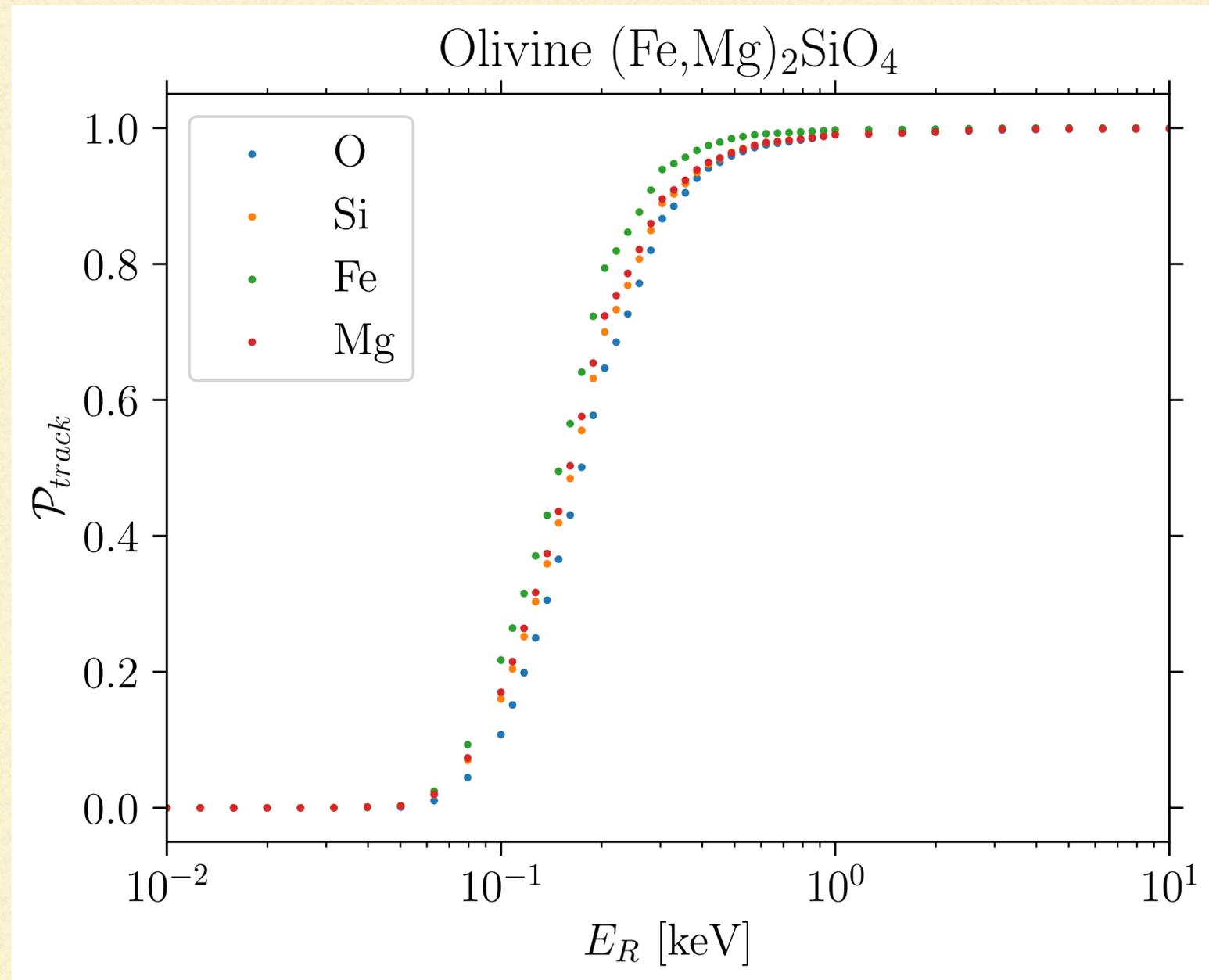
Fe in Olivine at 200.0 keV



I. TRACK LENGTH DISTRIBUTION $\mathcal{P}_i(x | E_R)$ OF Fe IN OLIVINE $(\text{Mg, Fe})_2 \text{SiO}_4$

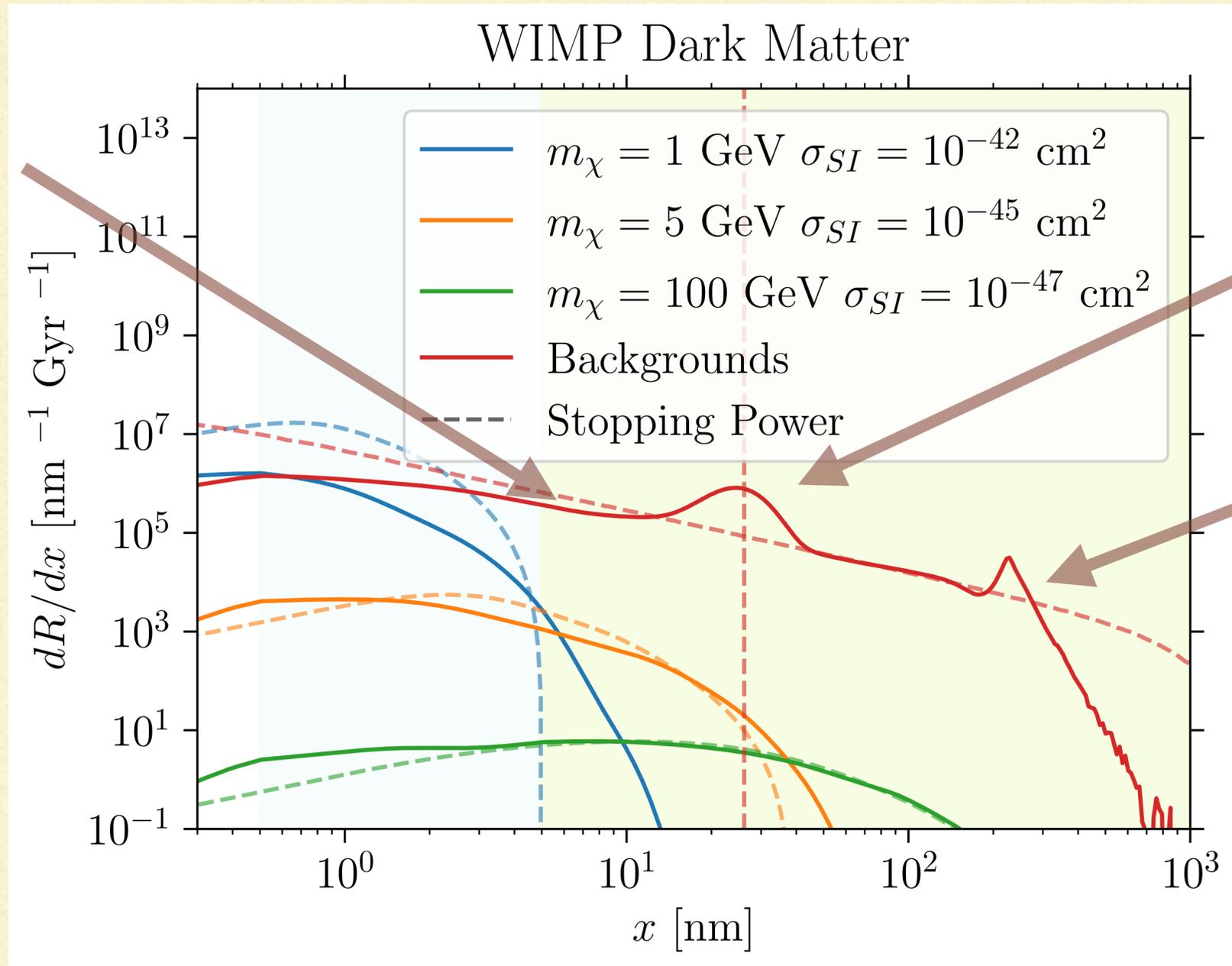


II. PROBABILITY OF TRACK FORMATION $\mathcal{P}_{i,track}$



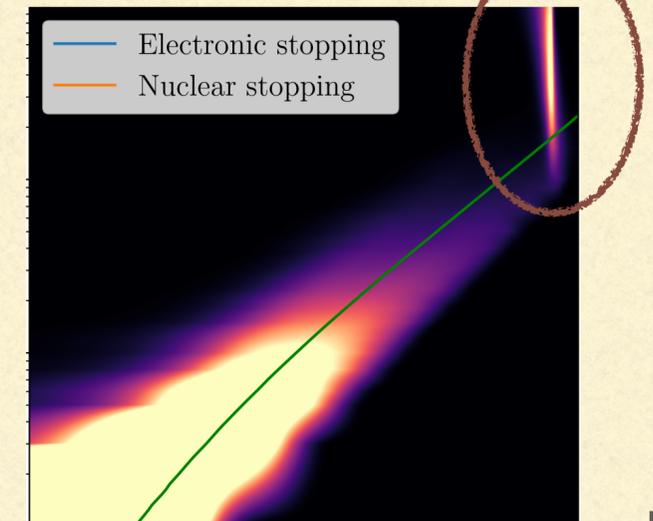
WIMP TRACKS

- Neutrons from ^{238}U
- Solar ν
- atm ν

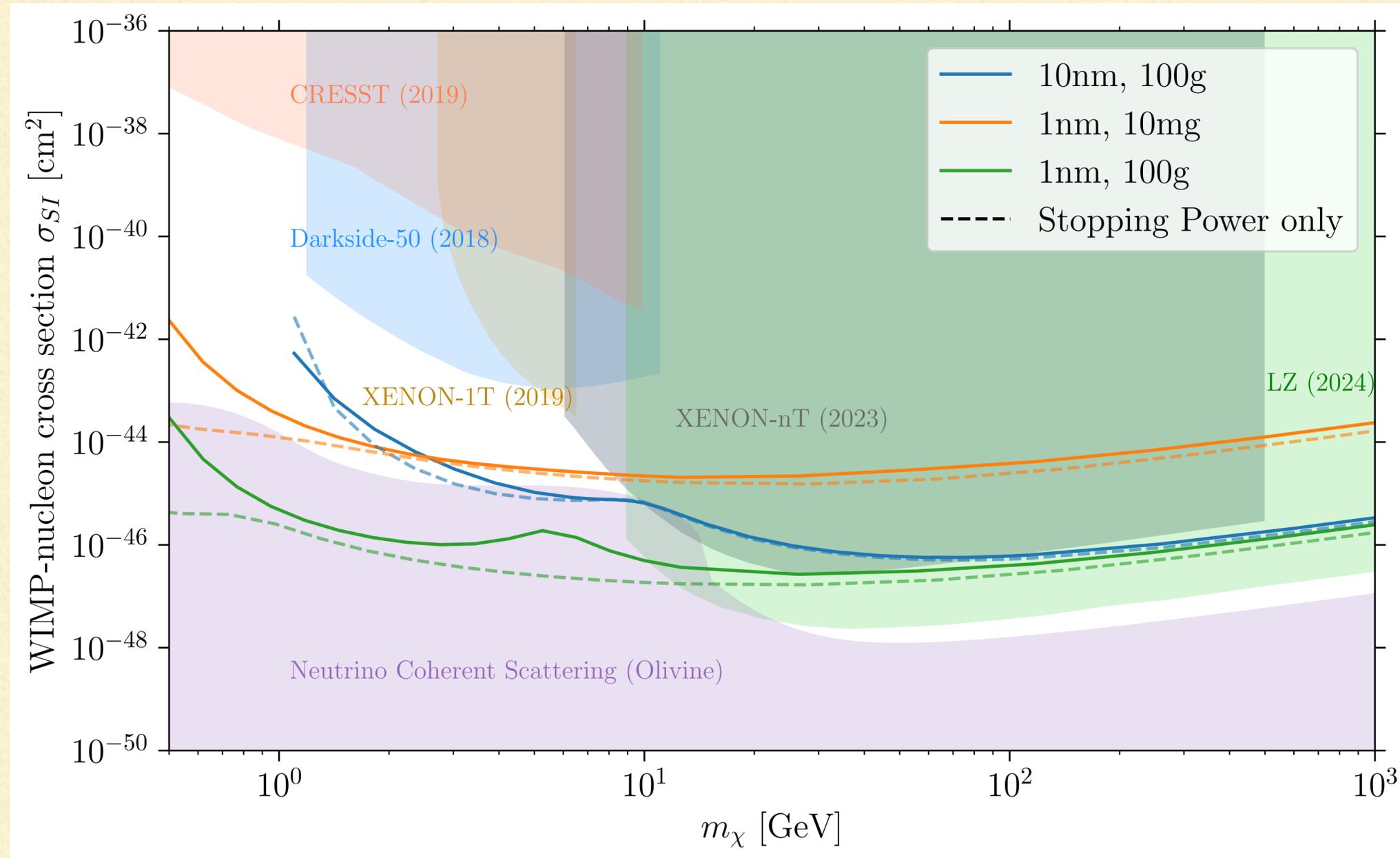


^{234}Th at 72 keV

$x \approx 200 \text{ nm}$ pile up



WIMP PROJECTED LIMITS



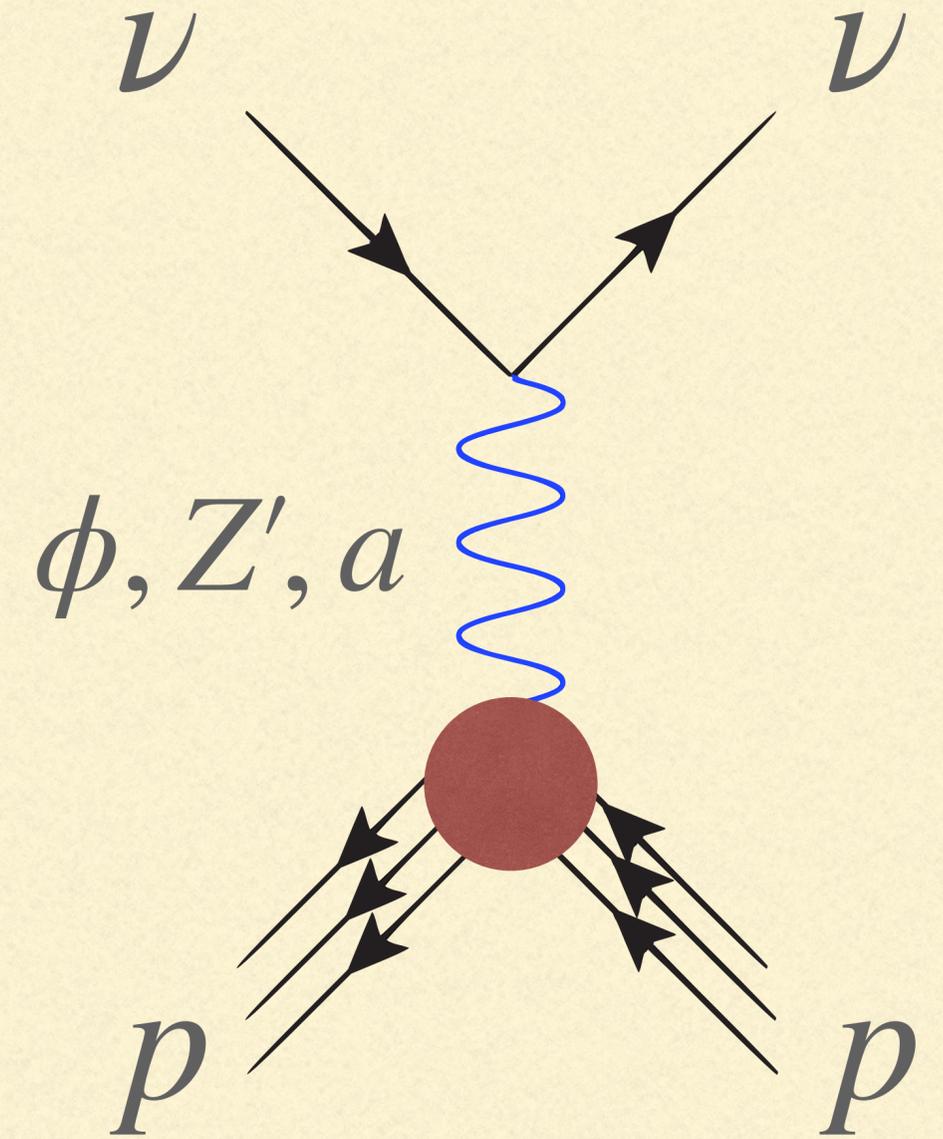
II. NEW LIGHT MEDIATORS

NON-STANDARD NEUTRINO INTERACTIONS WITH CE ν NS

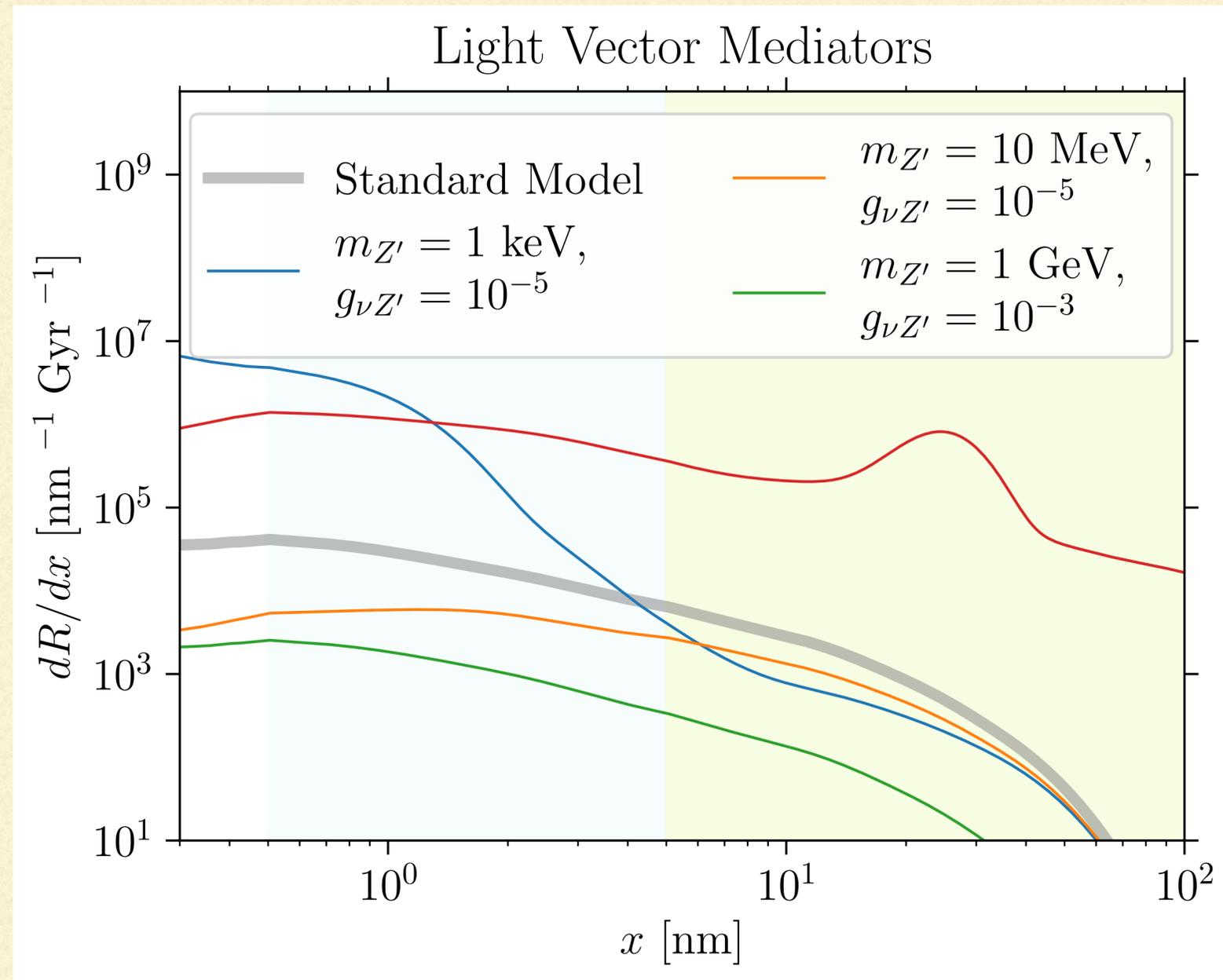
- $$\left(\frac{d\sigma}{dE_R}\right)_\phi = \left(\frac{d\sigma}{dE_R}\right)_{SM} + \frac{Q_s'^2 m_N^2 E_R}{4\pi E_\nu^2 (2E_R m_N + m_\phi)^2}$$
- $$\left(\frac{d\sigma}{dE_R}\right)_{Z'} = \left(\frac{d\sigma}{dE_R}\right)_{SM} - \frac{G_F m_N Q_\nu Q_\nu' (2E_\nu^2 - E_R m_N)}{2\sqrt{2}\pi E_\nu^2 (2E_R m_N + m_{Z'}^2)}$$

$$+ \frac{Q_\nu'^2 m_N (2E_\nu^2 - E_R m_N)}{4\pi E_\nu^2 (2E_R m_N + m_{Z'}^2)^2}$$
- $$\left(\frac{d\sigma}{dE_R}\right)_a = \left(\frac{d\sigma}{dE_R}\right)_{SM} + \frac{G_F m_N Q_a Q_a' (2E_\nu^2 + E_R m_N)}{2\sqrt{2}\pi E_\nu^2 (2E_R m_N + m_a^2)}$$

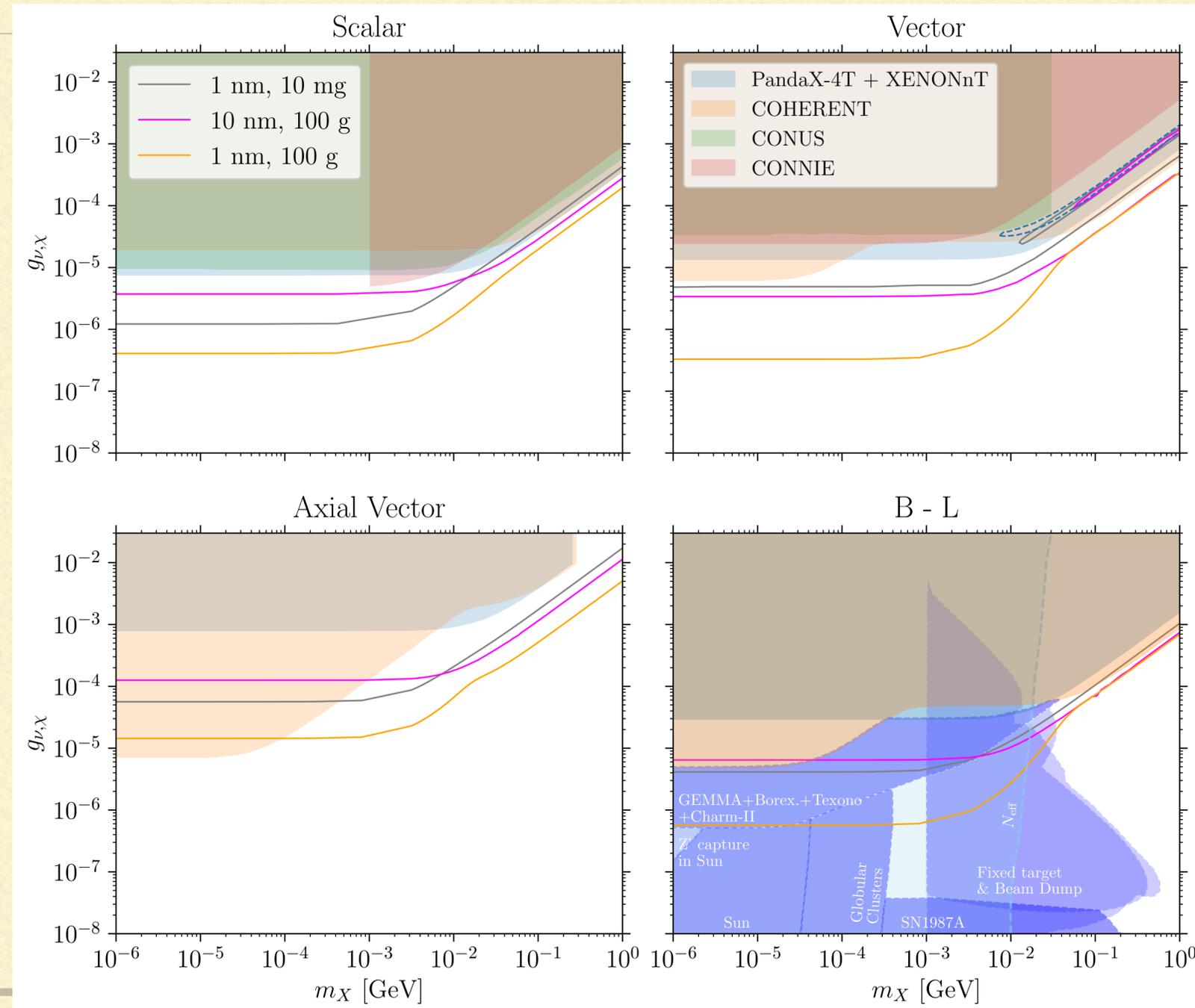
$$- \frac{G_F m_N Q_\nu Q_a' E_\nu E_R}{2\sqrt{2}\pi E_\nu^2 (2E_R m_N + m_a^2)} + \frac{Q_a'^2 m_N (2E_\nu^2 + E_R m_N)}{4\pi E_\nu^2 (2E_R m_N + m_a^2)^2}$$



NEUTRINOS TRACK DISTRIBUTIONS

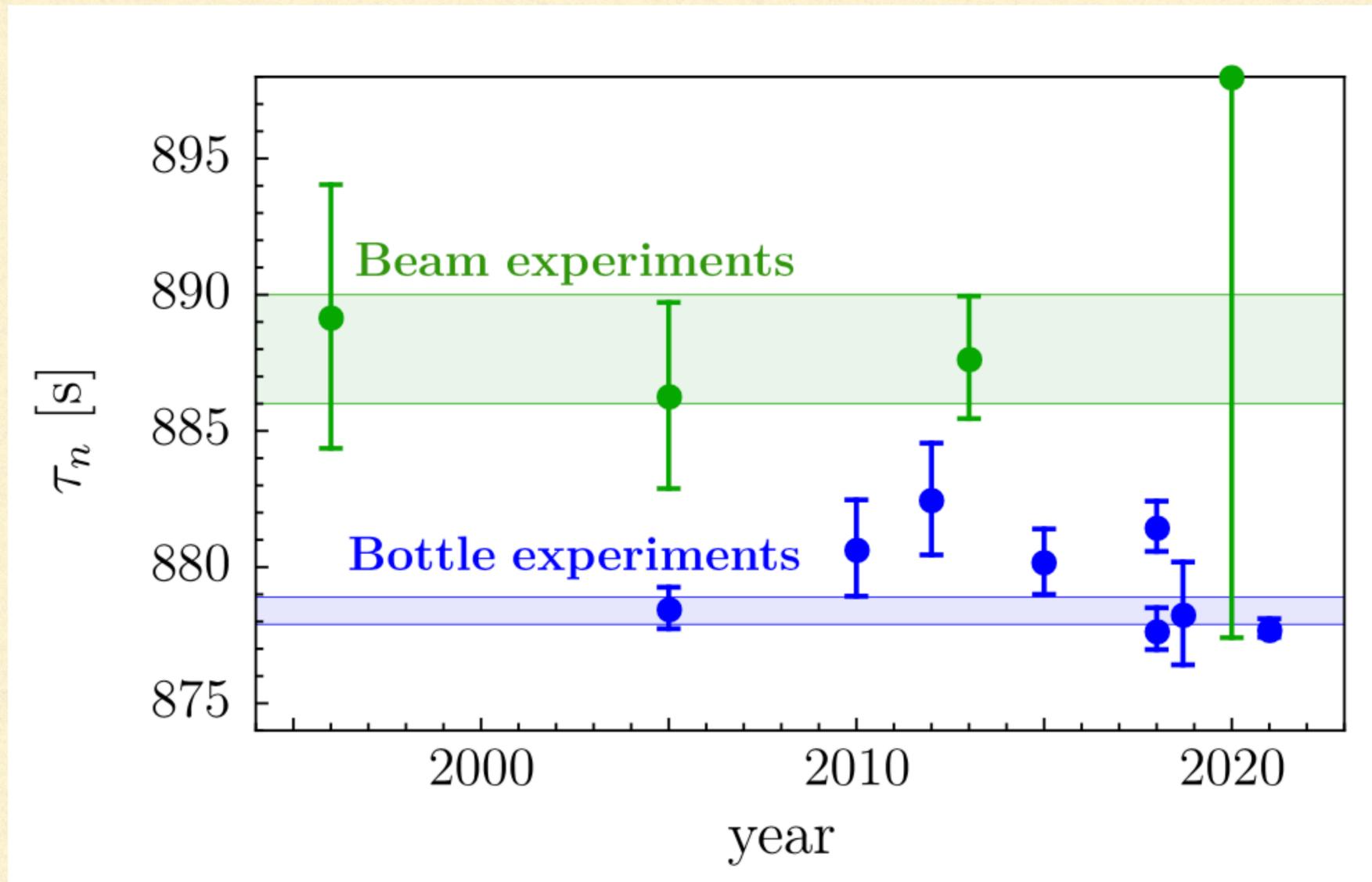


PROJECTED LIMITS FOR NEW MEDIATORS



III. NEUTRON DECAY

THE TENSION



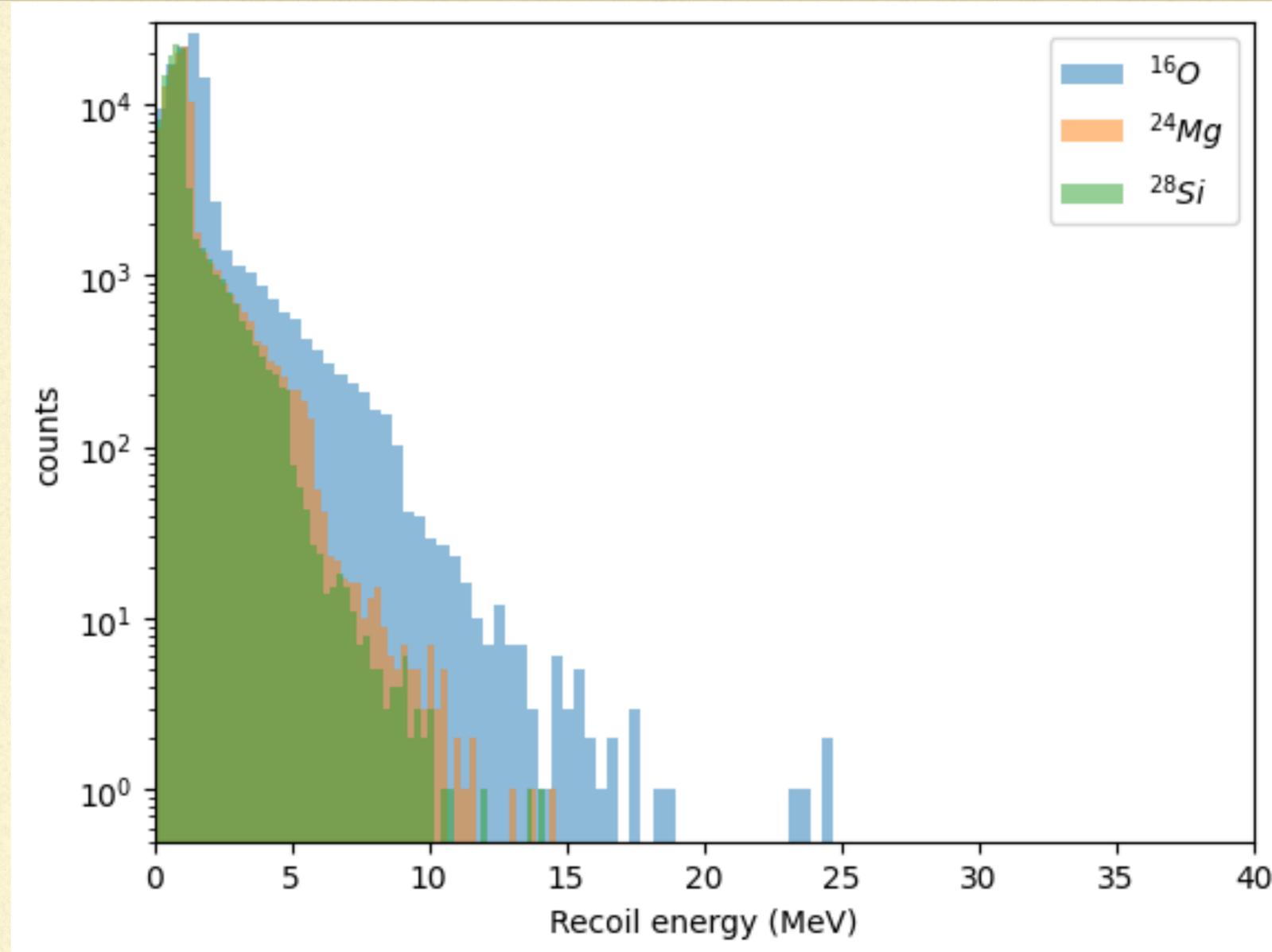
$$\tau_n^{\text{bottle}} = \tau_n^{\text{beam}} \times \text{Br}(n \rightarrow p + X) \leq \tau_n^{\text{beam}}$$

$$\text{Br}(n \rightarrow p + X) \approx 99\%$$

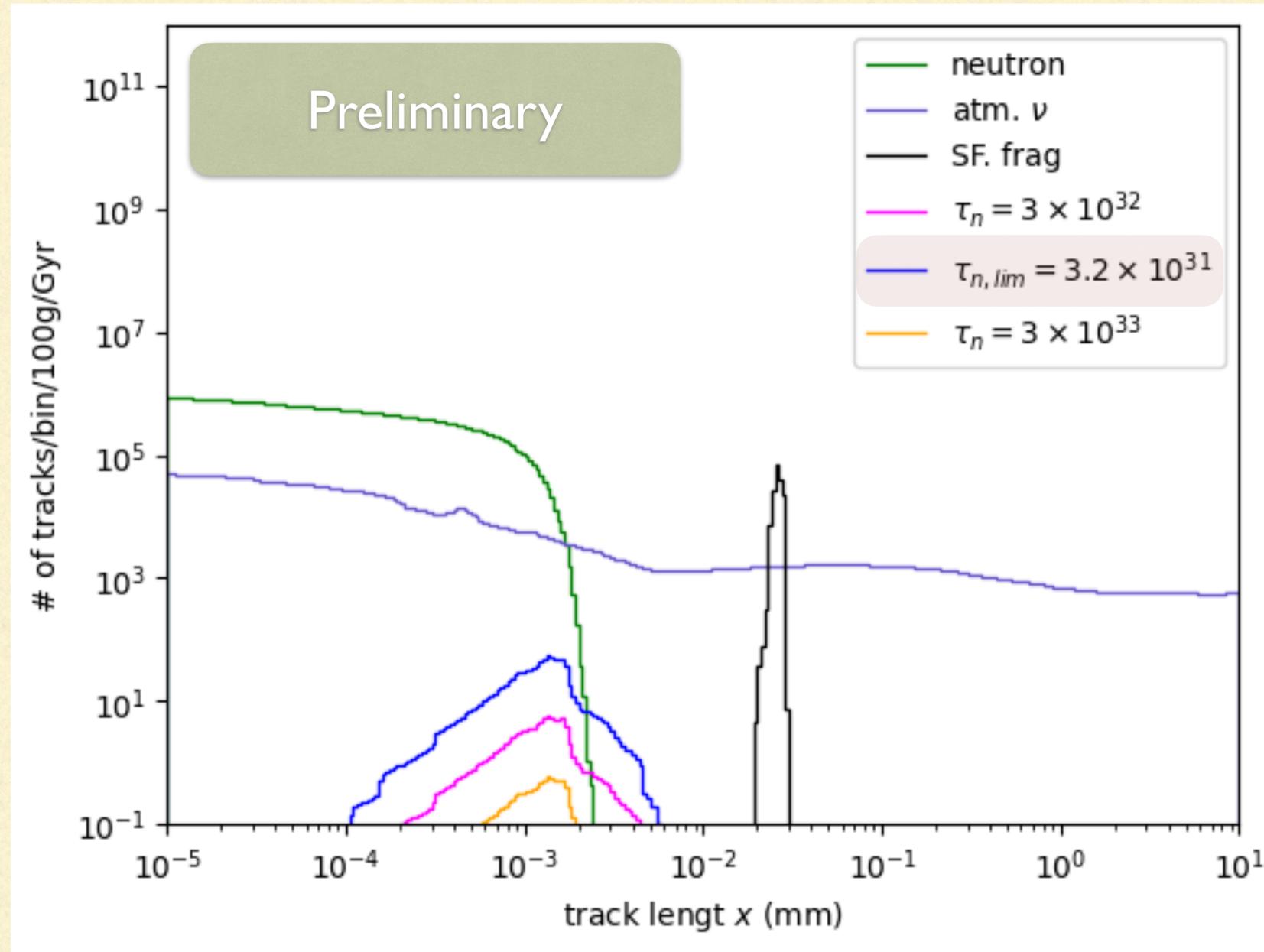
$$\text{Br}(n \rightarrow \text{not } p) \approx 1\%$$

- $n \rightarrow$ invisible, e.g.
 - $n \rightarrow 3\nu$
 - $nn \rightarrow \nu\nu$
 - etc.
- $n \rightarrow$ BSM, e.g.
 - $n \rightarrow \chi\gamma$
 - $n \rightarrow \chi A'$
 - etc.

NUCLEAR RECOIL SPECTRA



TRACK LENGTH DISTRIBUTION

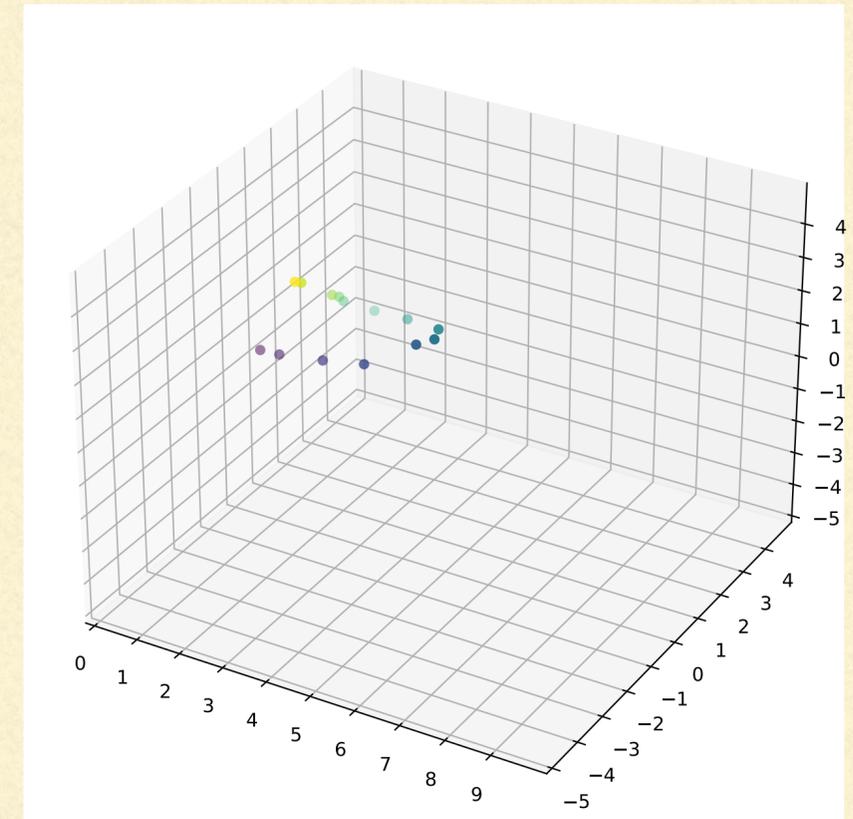
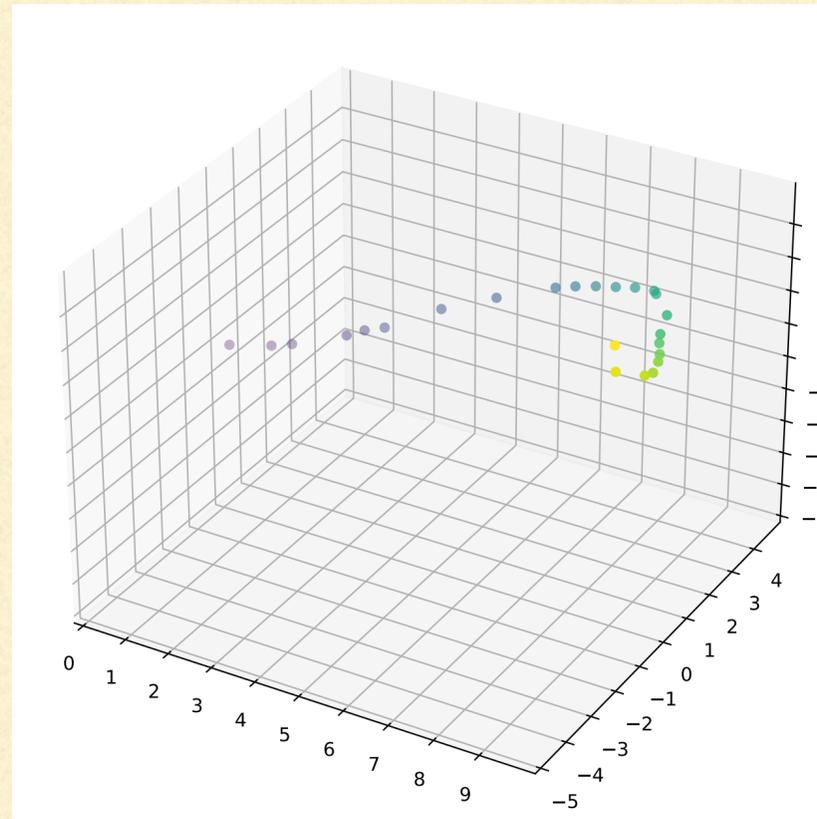


TRACK READOUT

- Optical fluorescence microscope (UV-visible)
 - Colour centers
 - Density of CC → signal brightness
- X-ray
 - Large volume scans (kg-scale / cm-scale)
 - Non-destructive readout
- TEM/STEM
 - Very detailed imaging: fraction of nm resolution

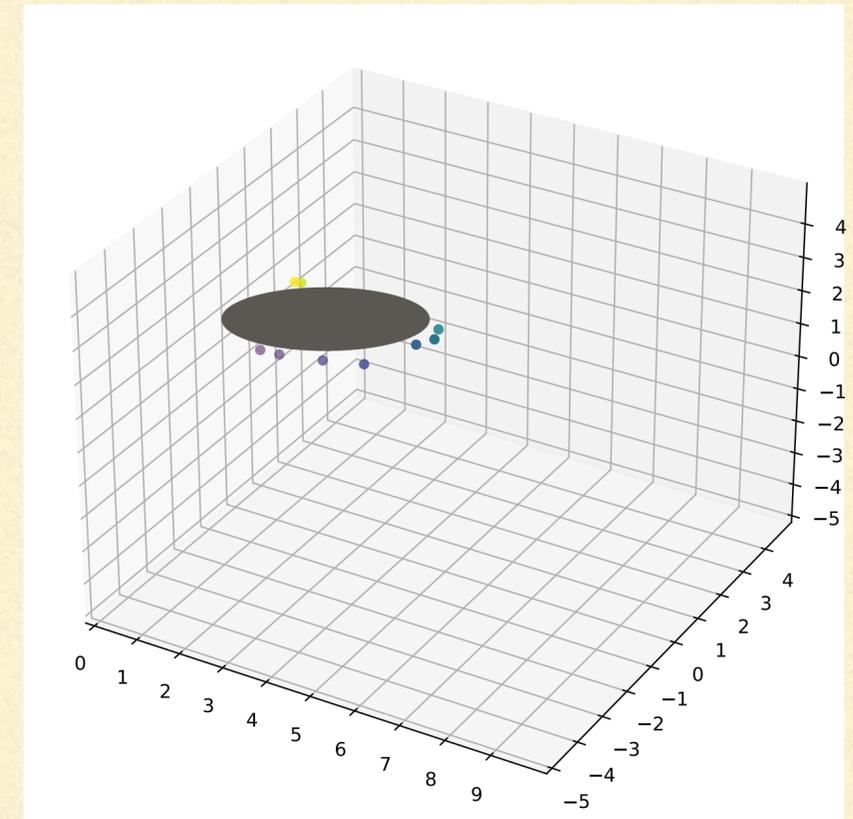
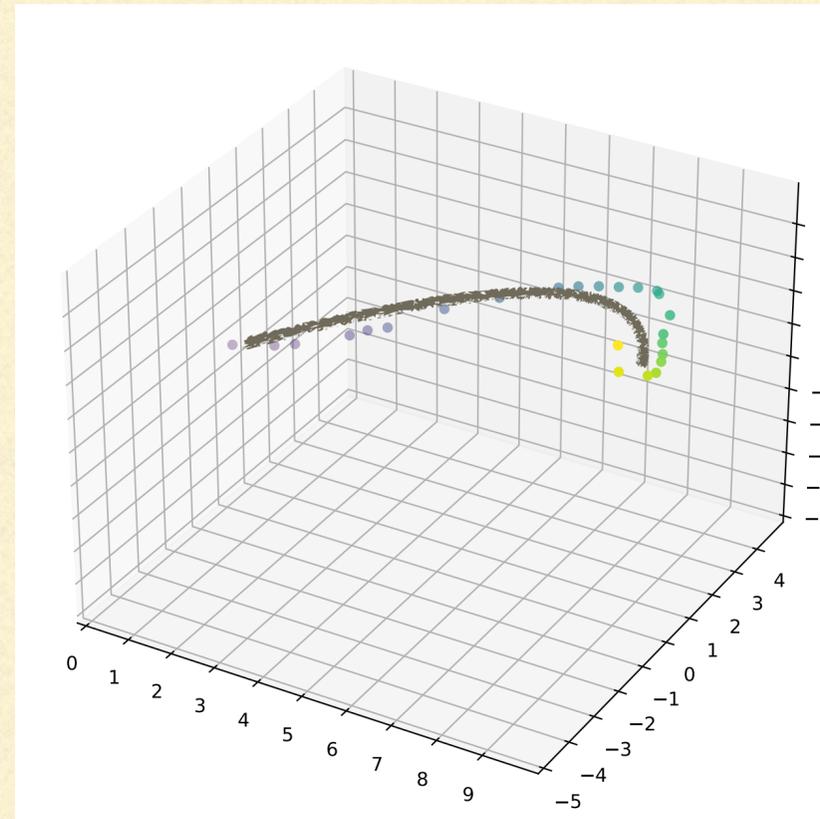
CHALLENGES

- Definition of a track
- Background
- Crystal damage modelling
- Readout
- Annealing



CHALLENGES

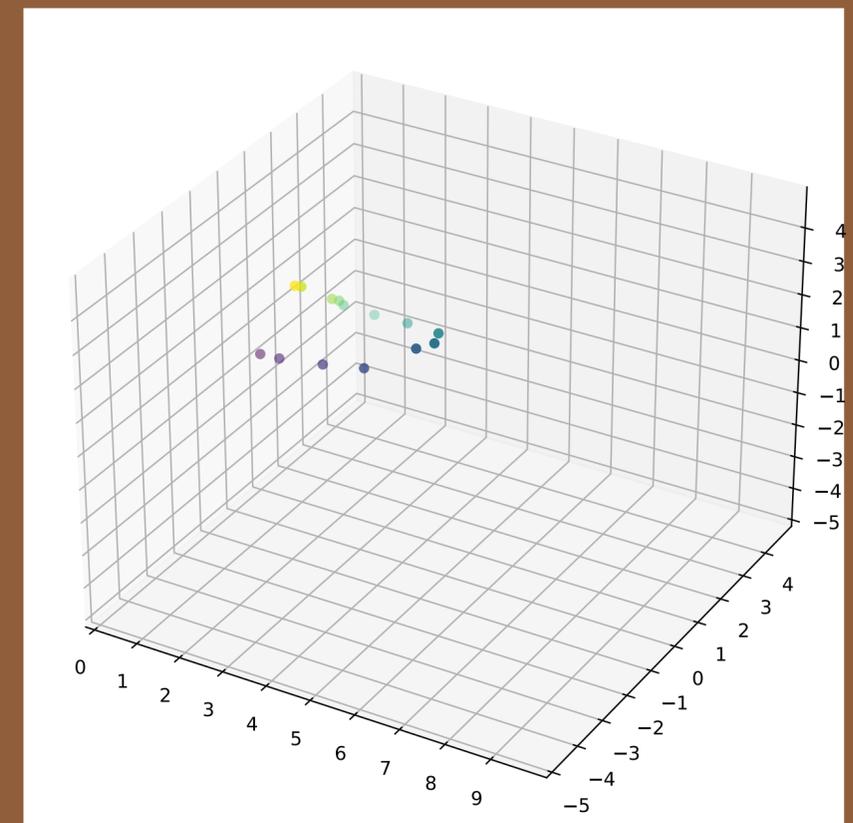
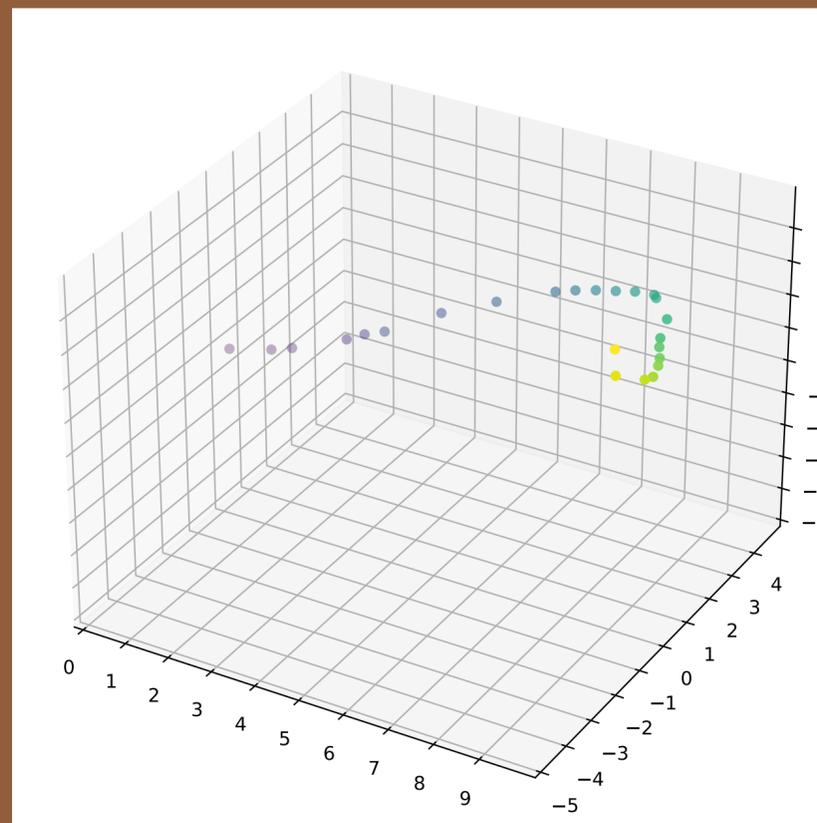
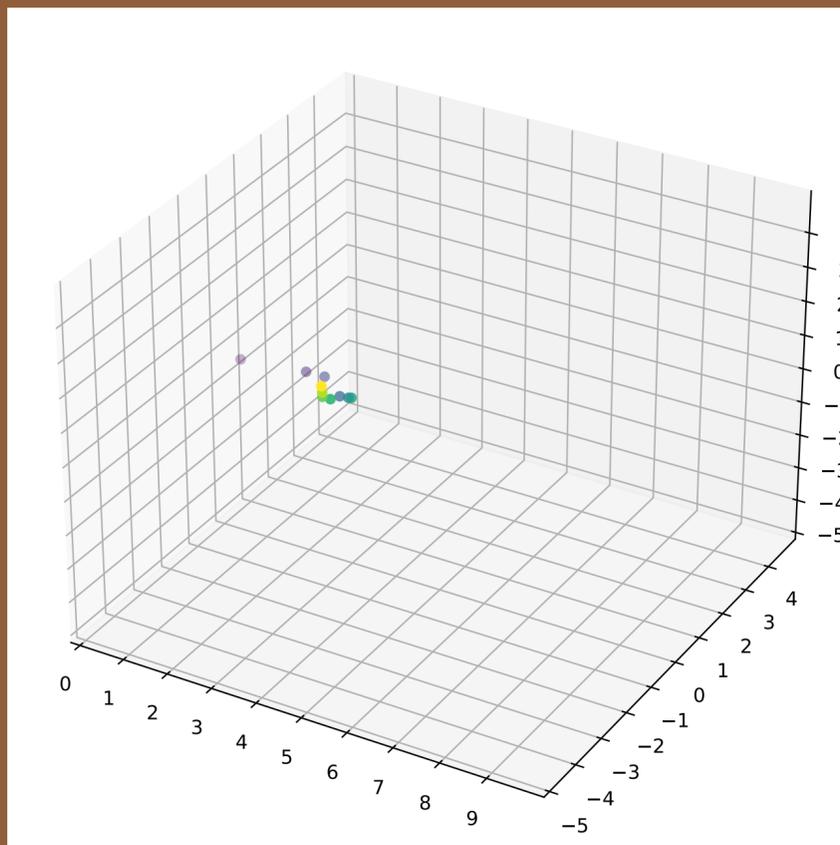
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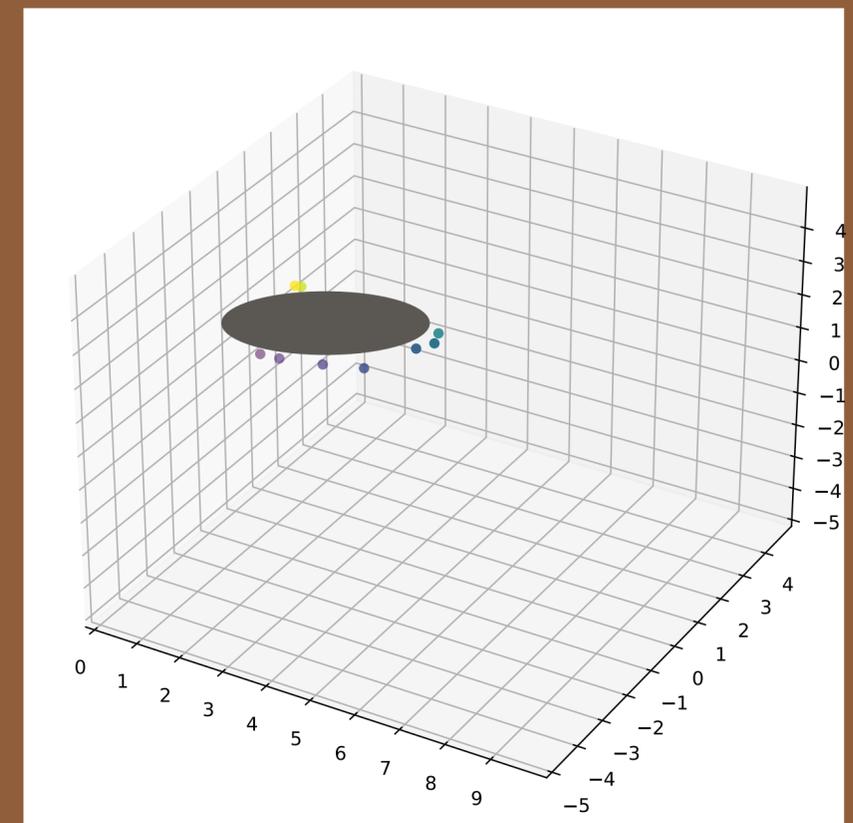
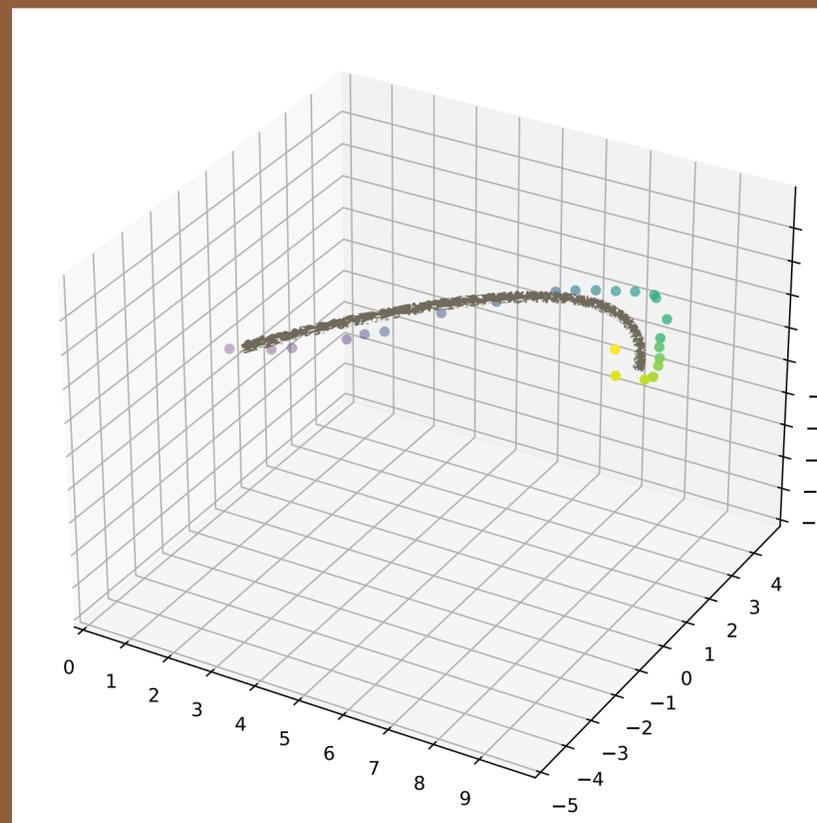
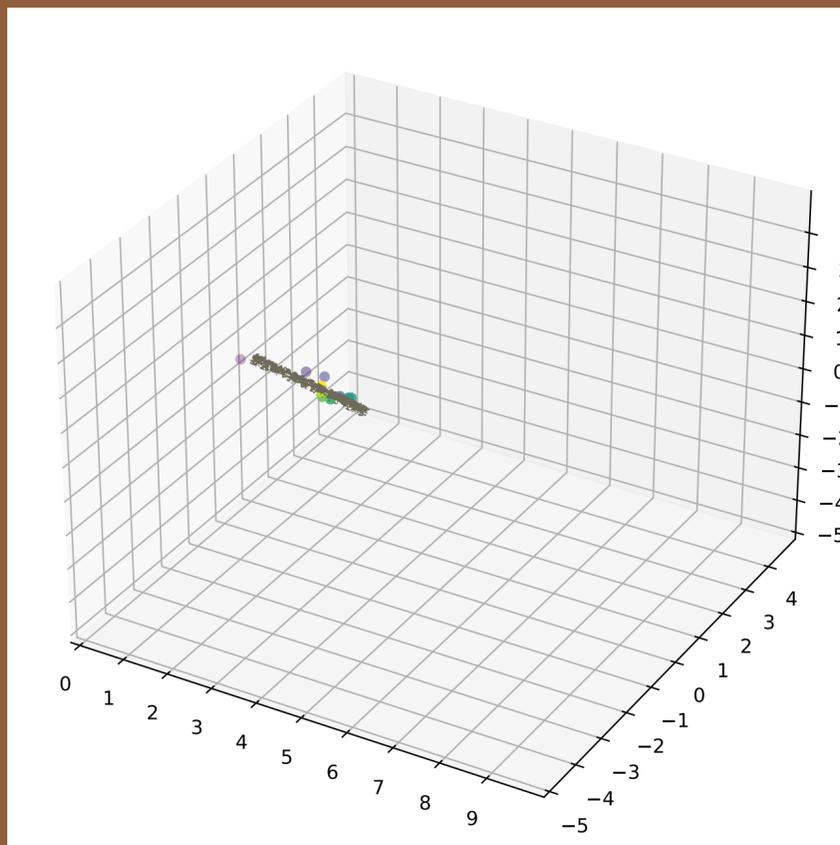
THANK YOU FOR LISTENING

BACK-UP SLIDES

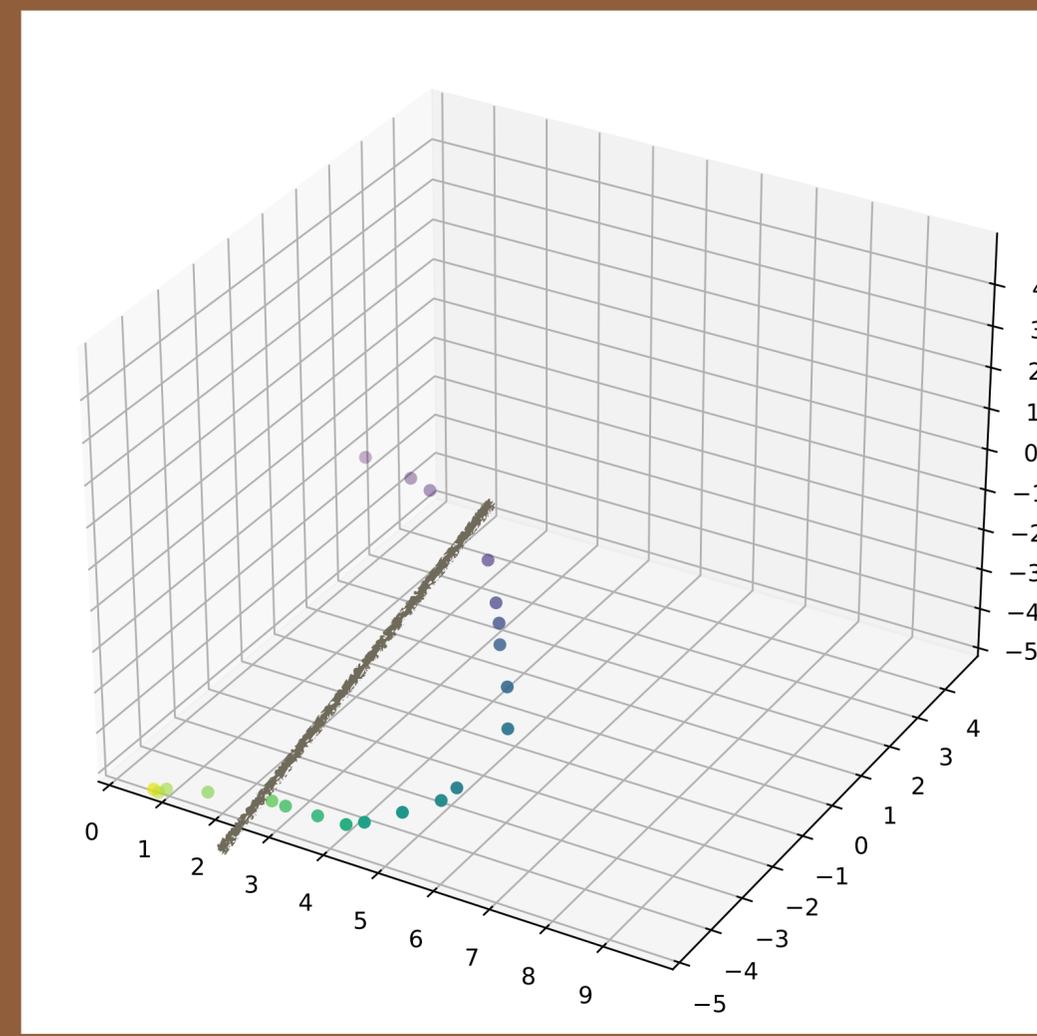
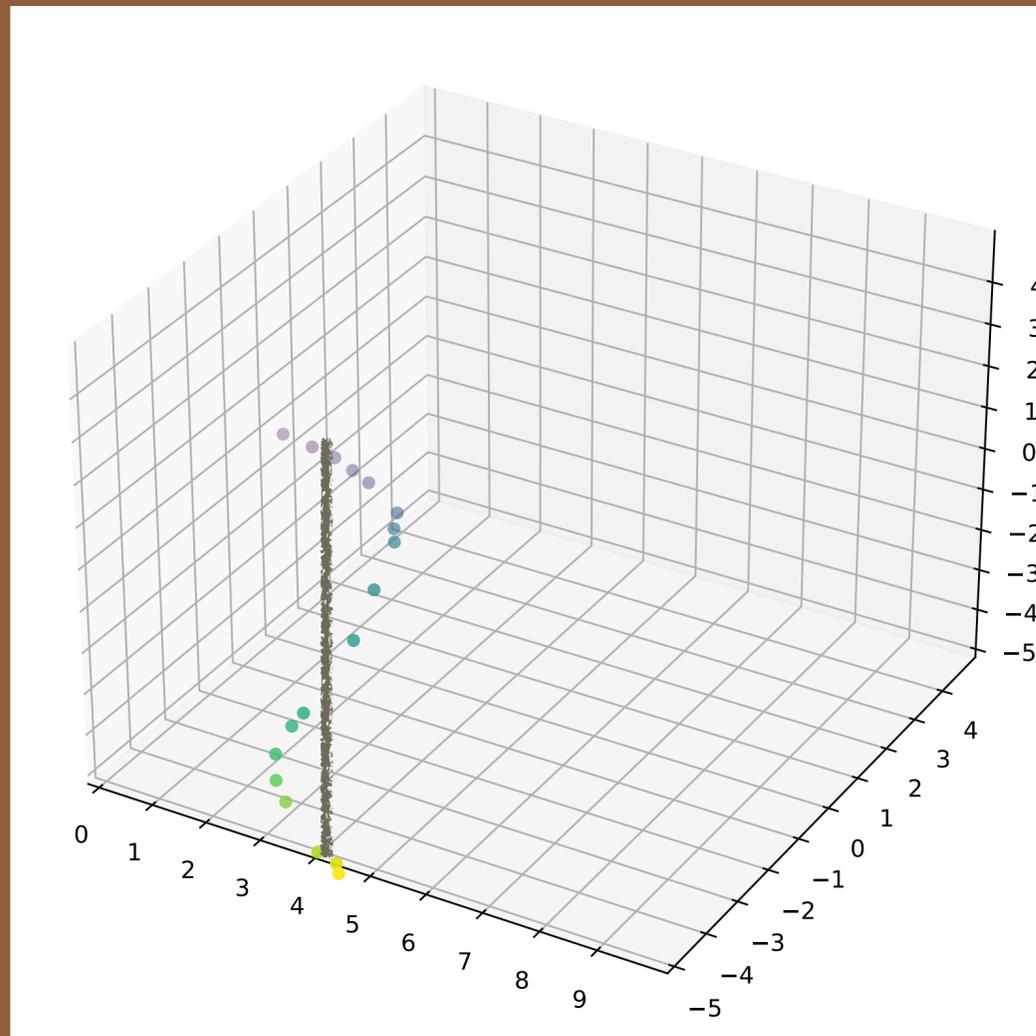
DEFINING TRACK LENGTH



DEFINING TRACK LENGTH

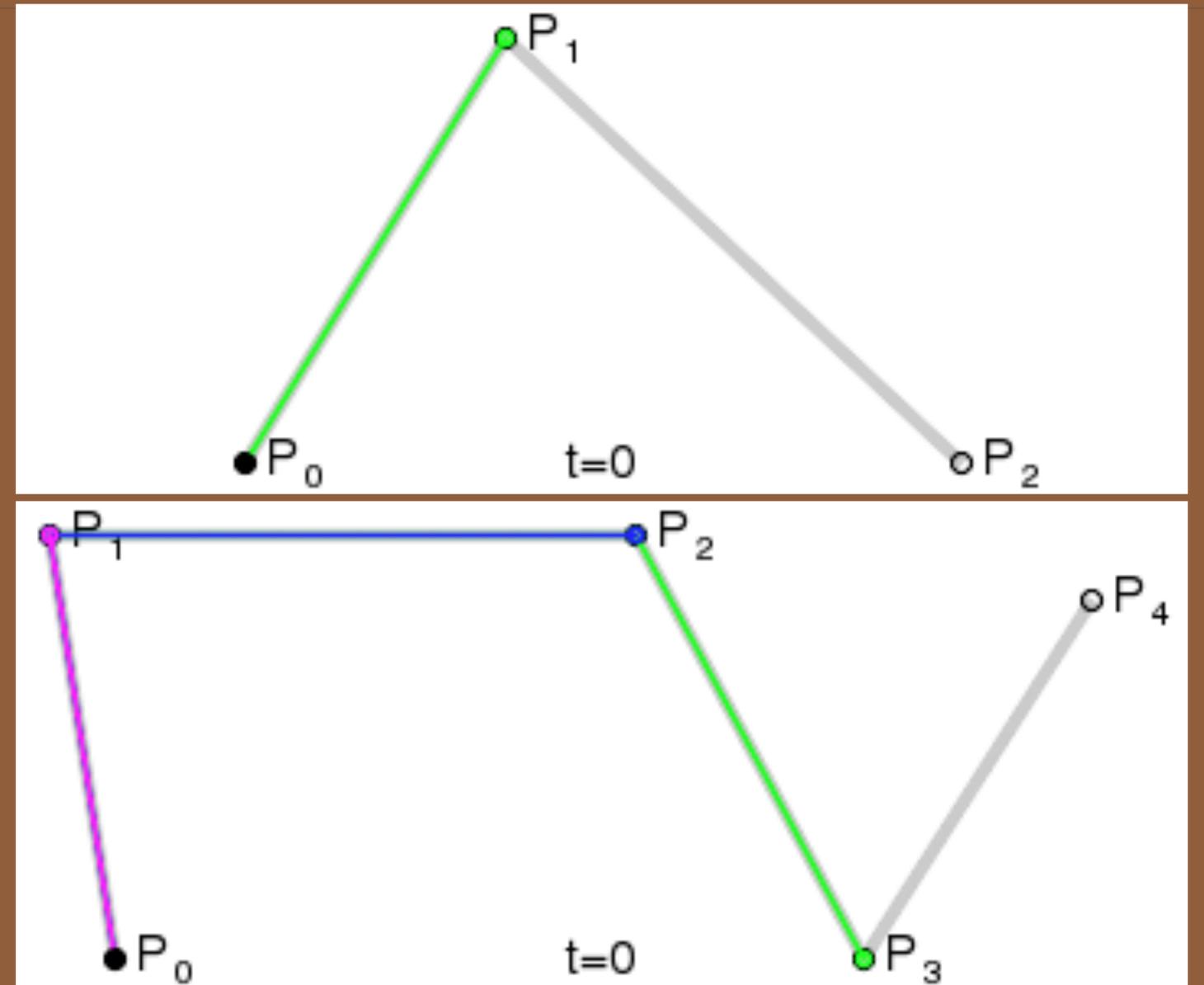


PRINCIPAL COMPONENT PROJECTION



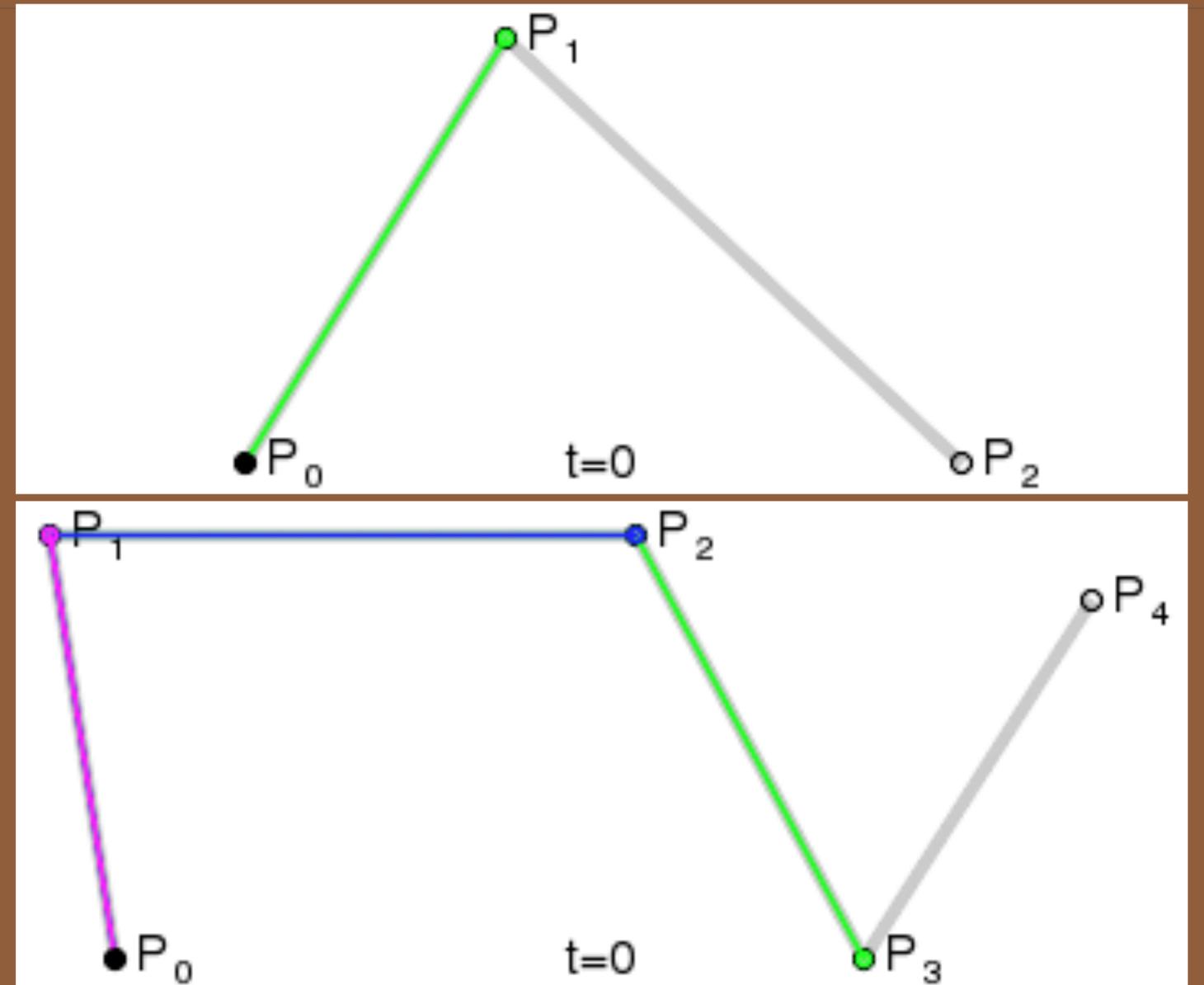
BEZIER CURVE FITTING

- defined by control points
- $\mathbf{B}(t) = \mathbf{P}_0 + t(\mathbf{P}_1 - \mathbf{P}_0), 0 \leq t \leq 1$
- better fits to arbitrary geometric features
- controllable resolution

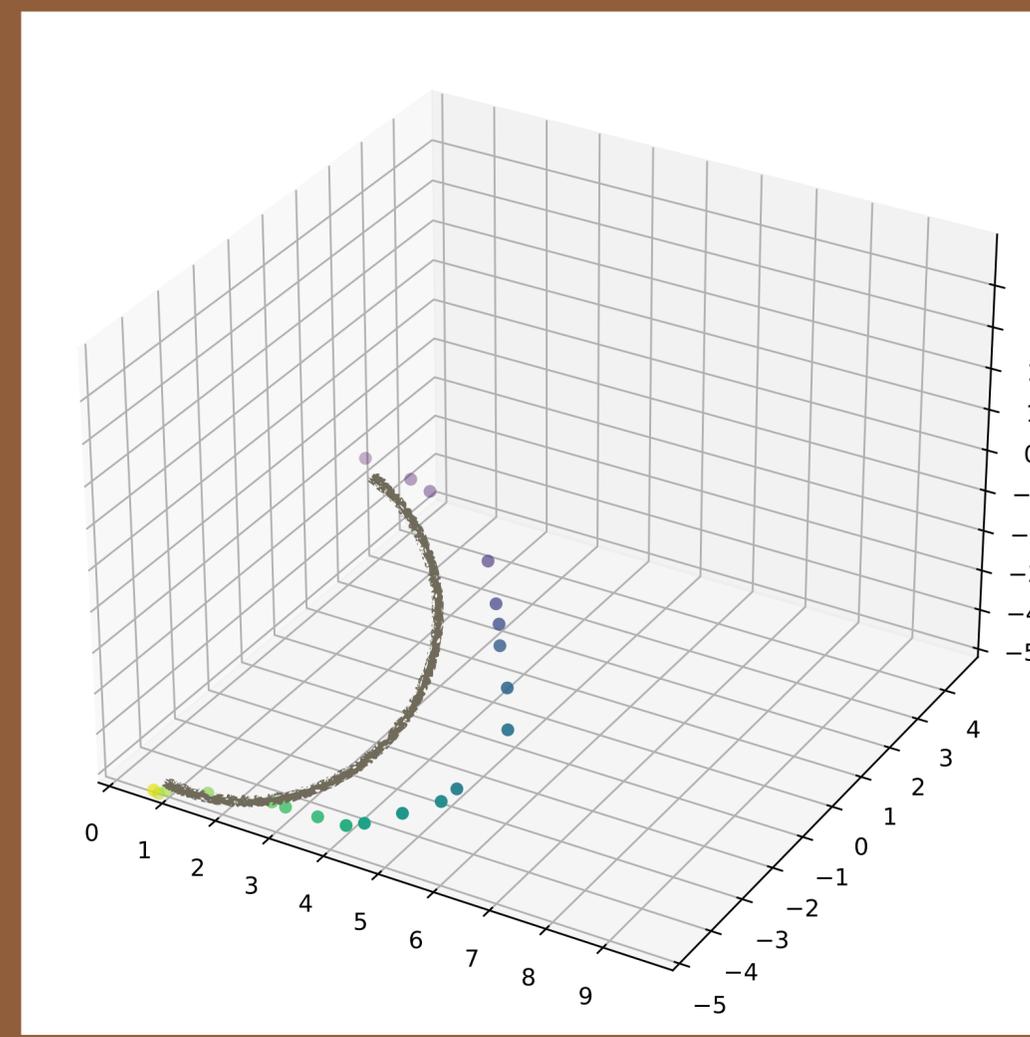
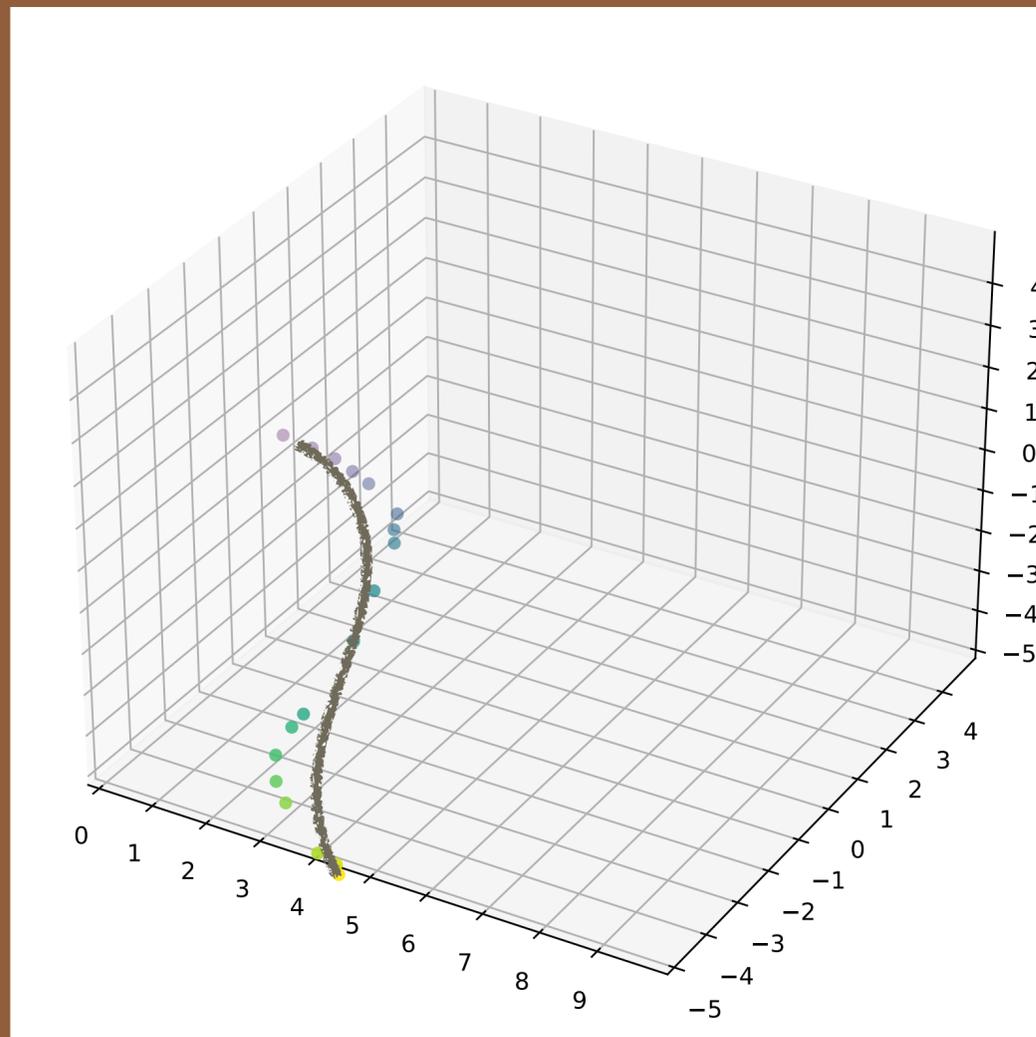


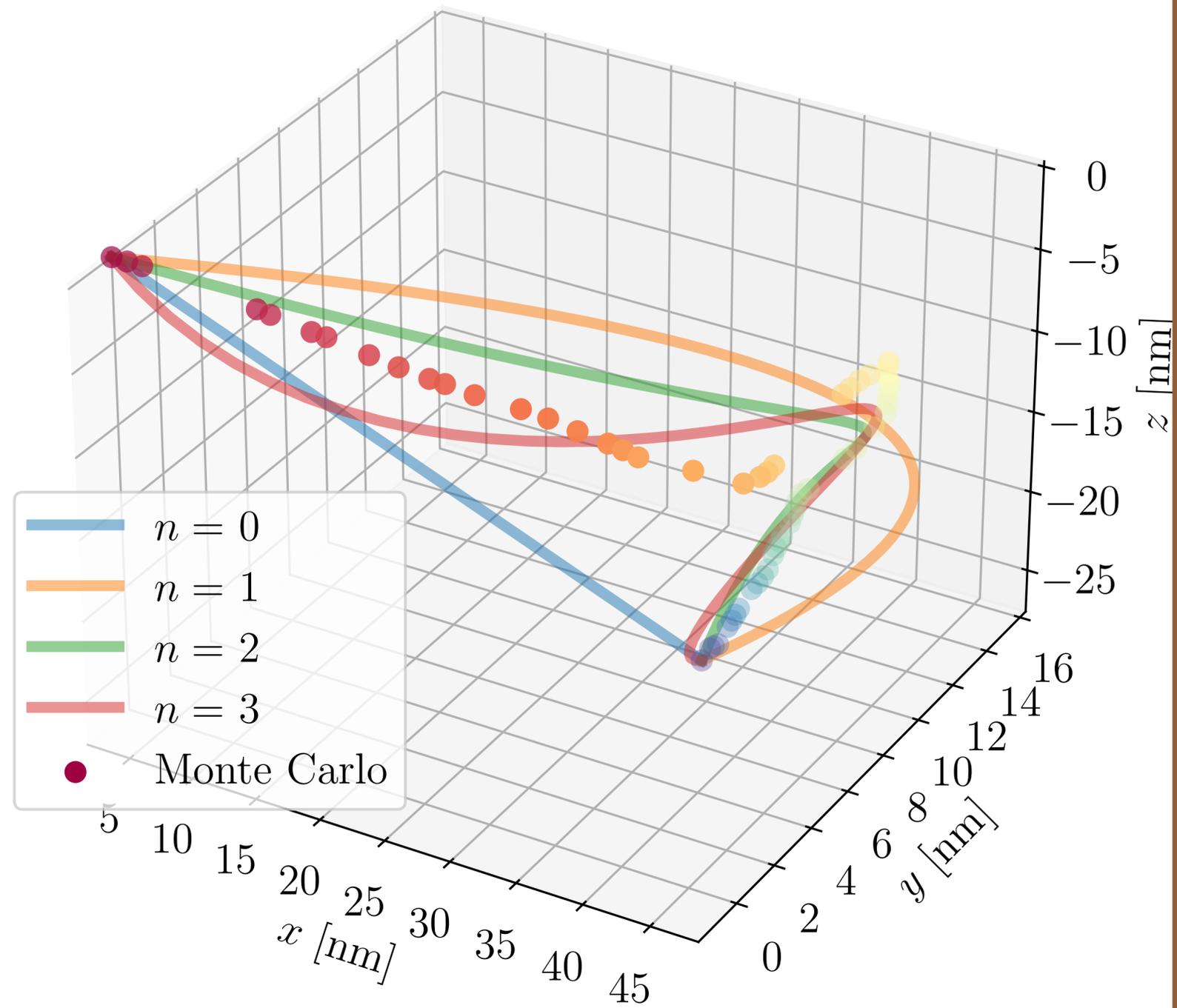
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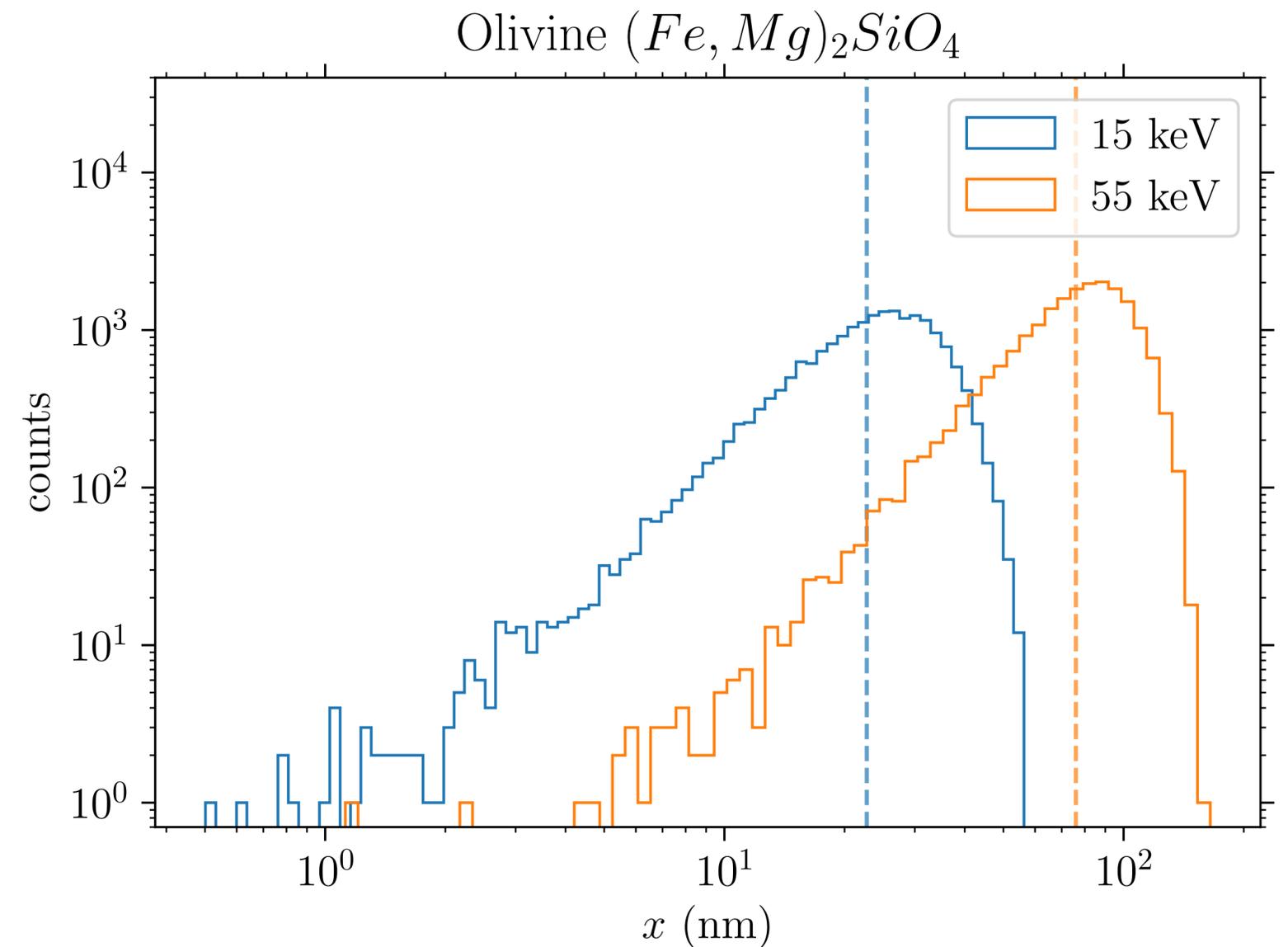
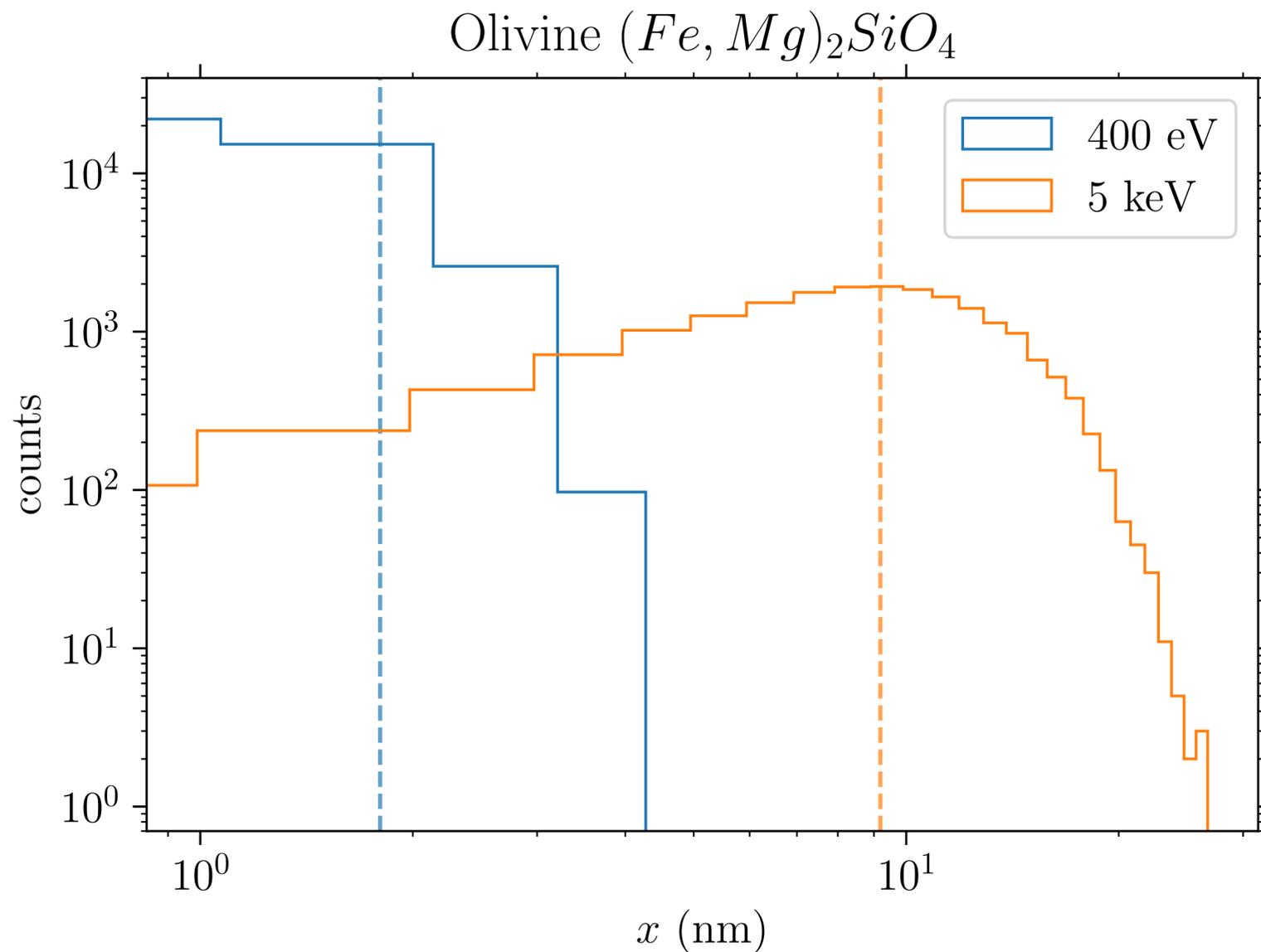


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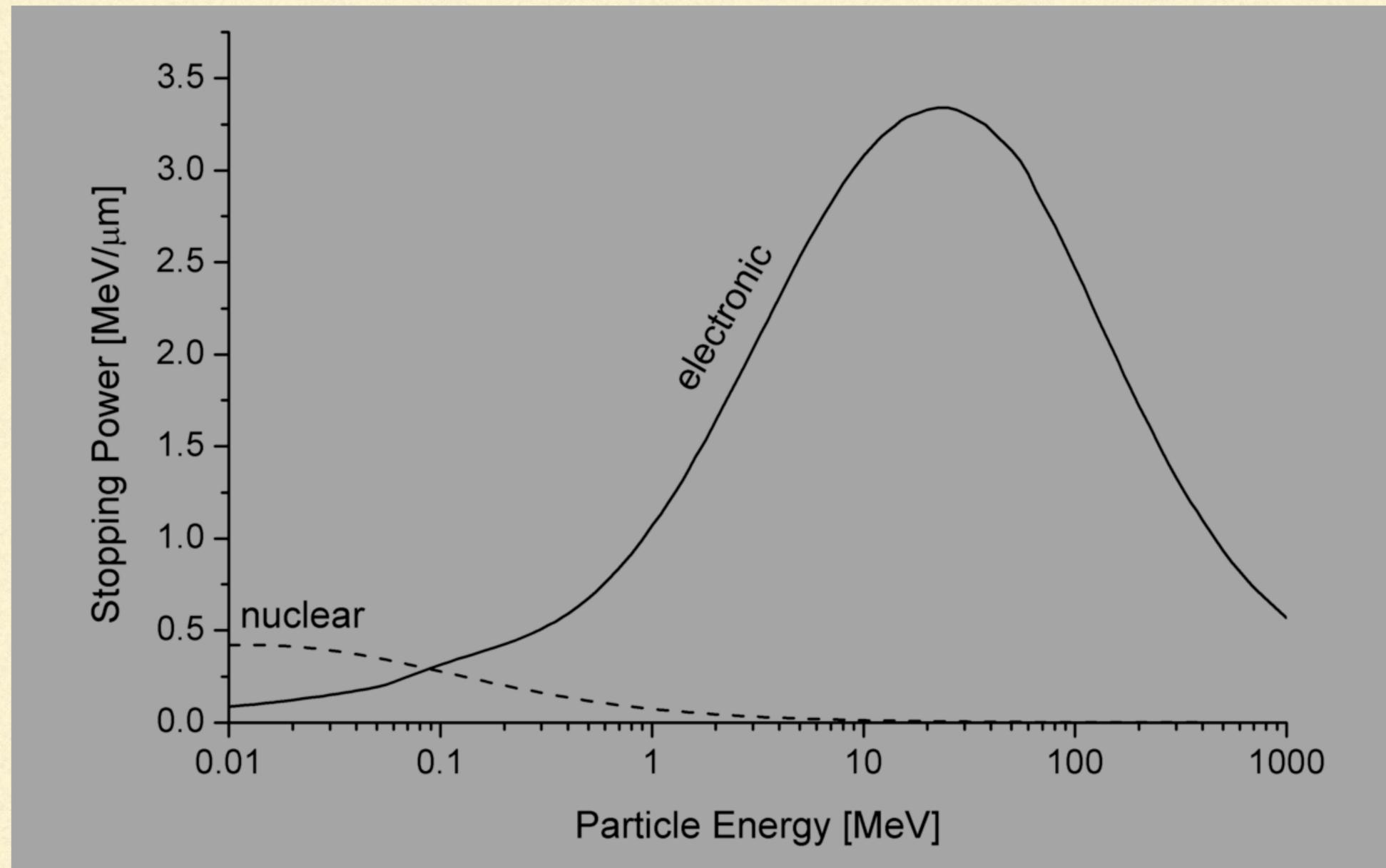




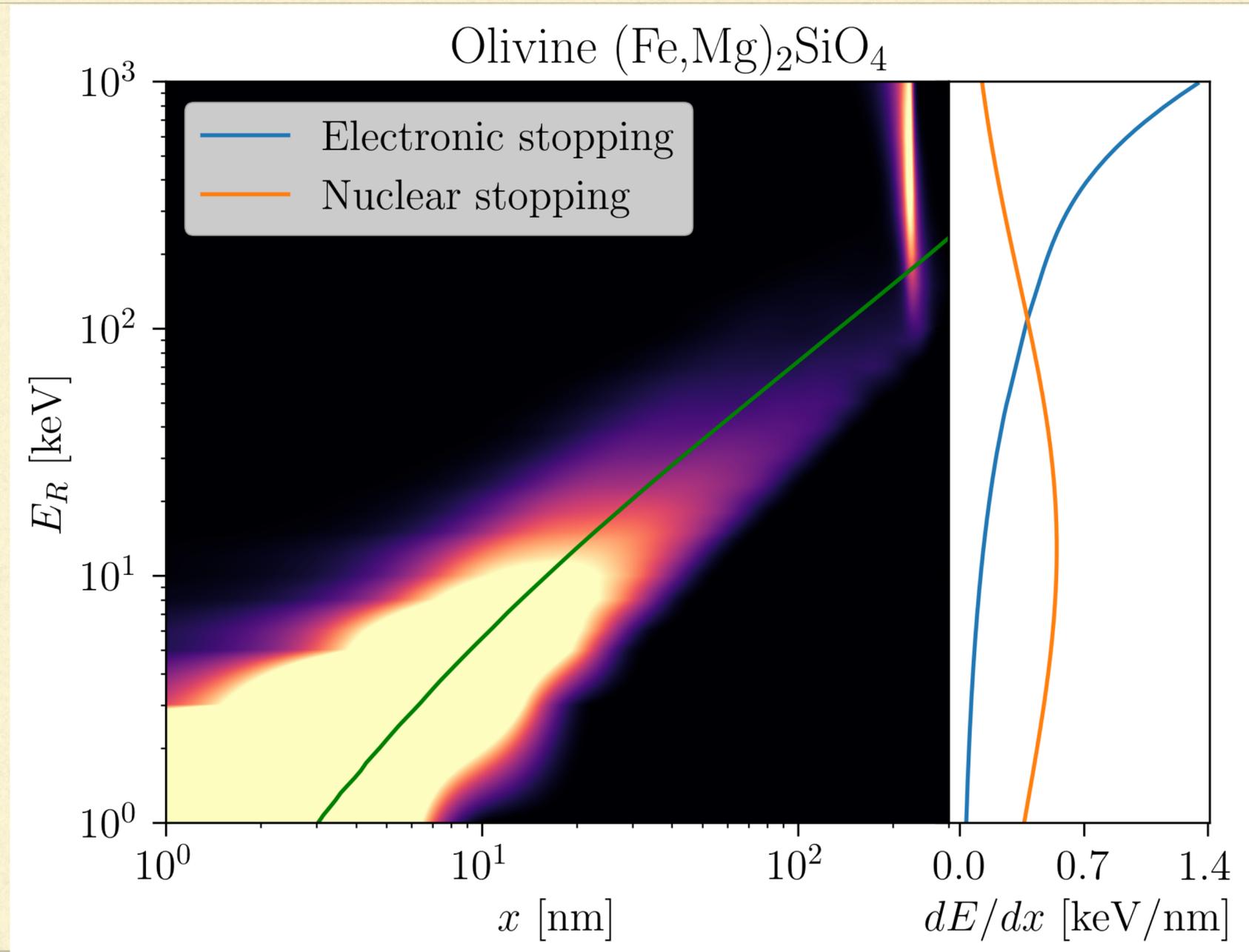
TRACK LENGTH DISTRIBUTION OF **Si** IN OLIVINE $(Mg, Fe)_2 SiO_4$



STOPPING MECHANISM



ONE-TO-ONE VS. 2D DENSITY



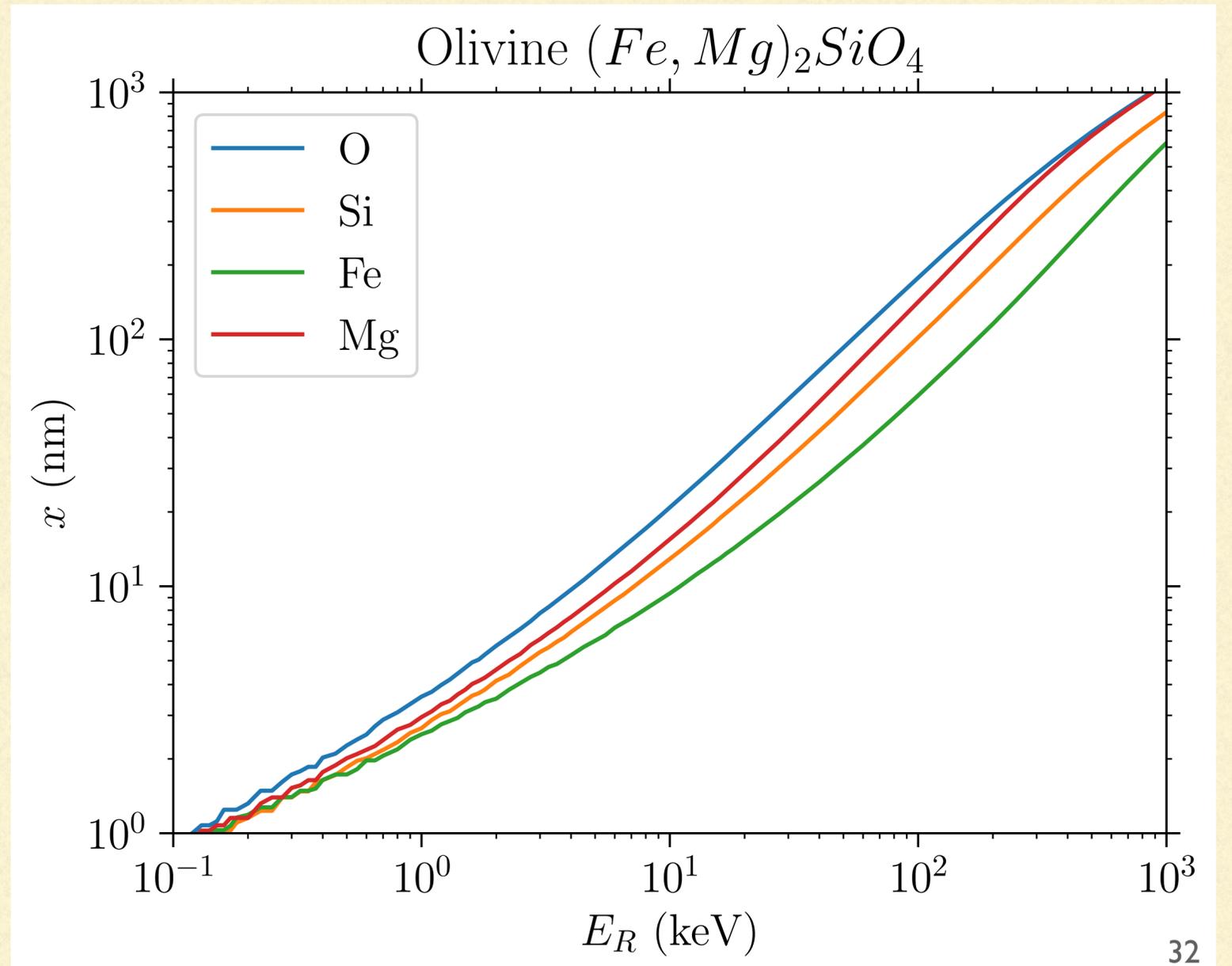
$E_R - X_T$ RELATION

$$\frac{dR}{dx} = \frac{dR}{dE} \times \left| \frac{dE}{dx} \right|$$

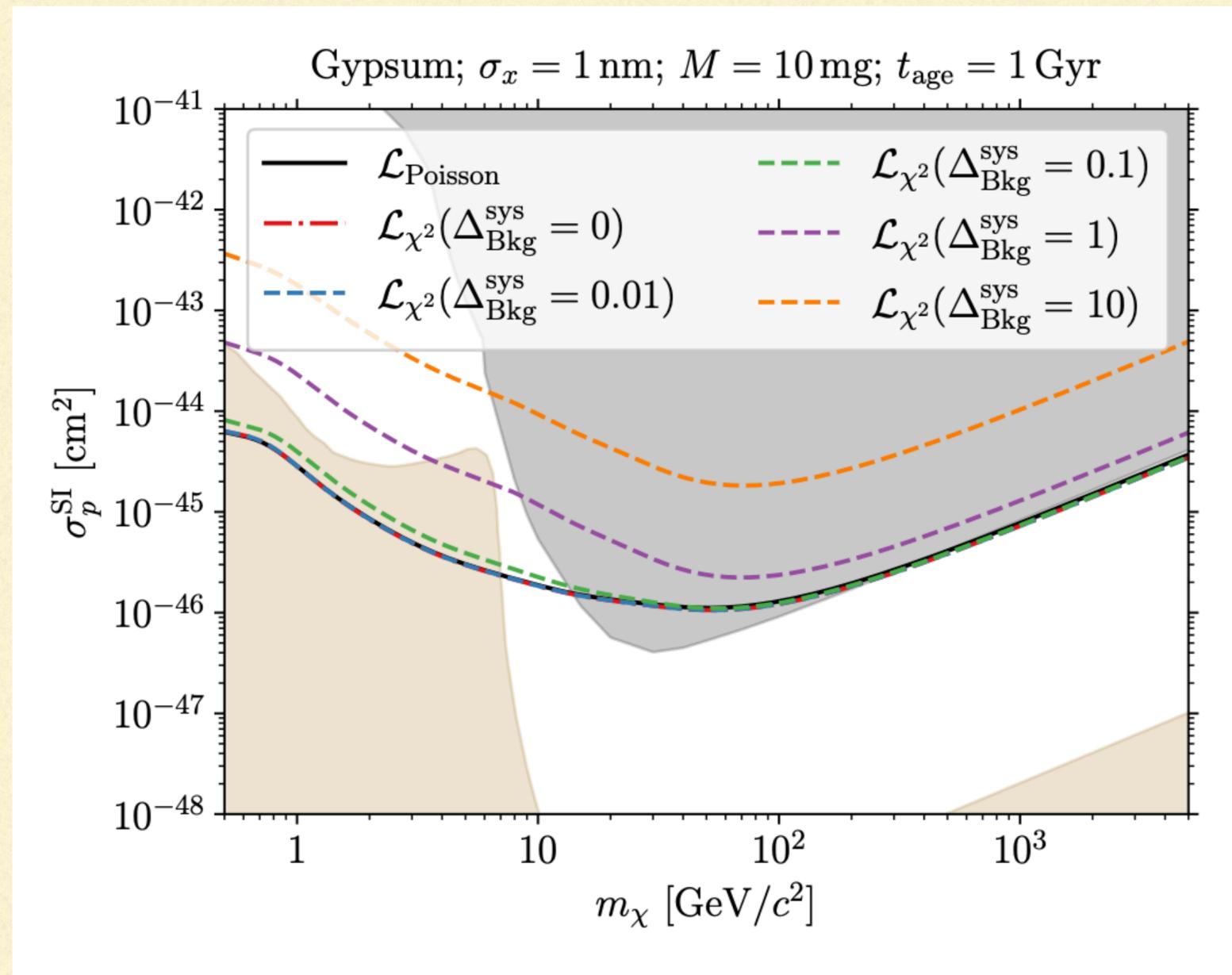
Energy spectrum of
the incoming particle

stopping power of
the target

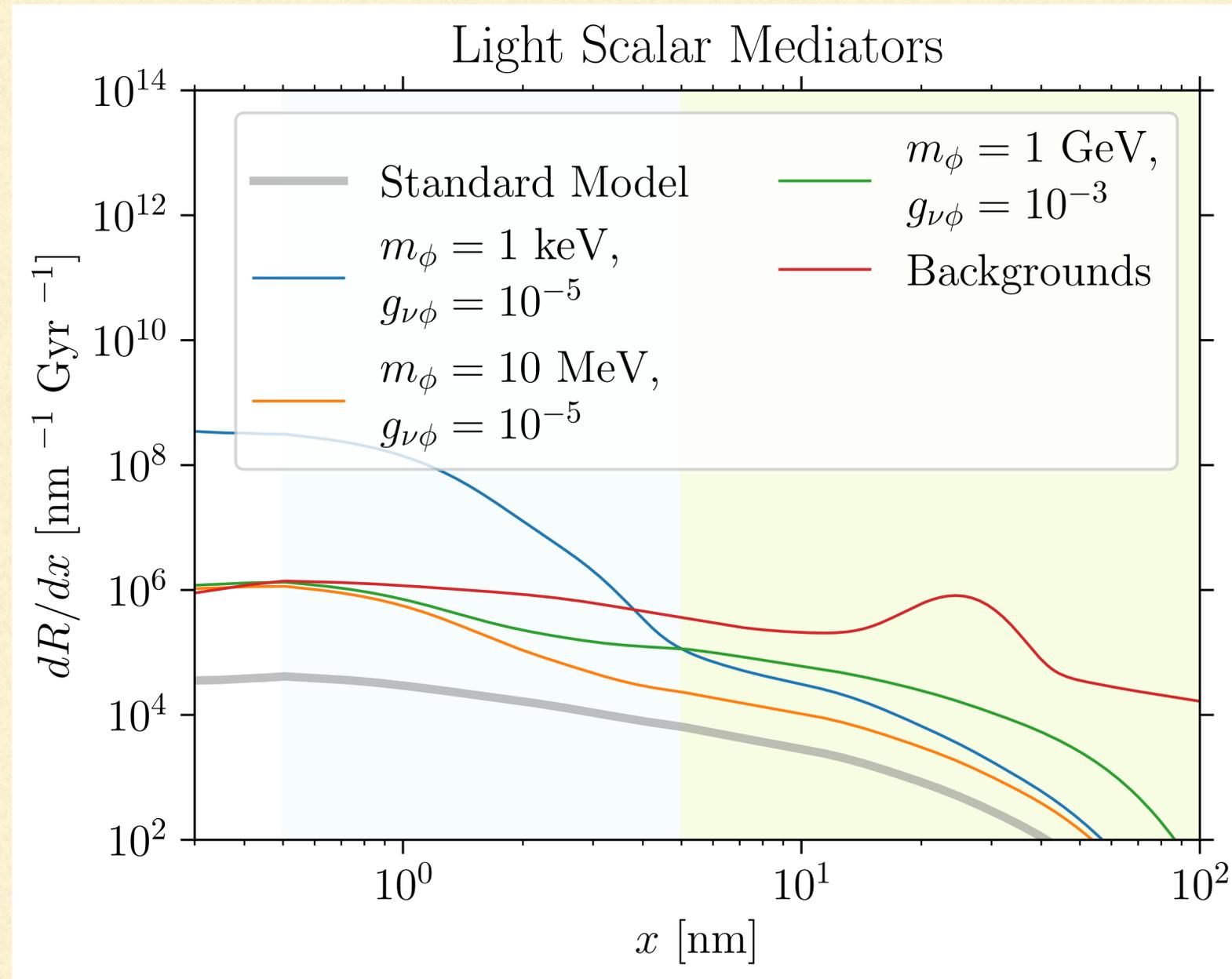
- Stopping power is a statistical average
- Ions of a given recoil energy could give rise to a distribution of track lengths



SYSTEMATIC UNCERTAINTY

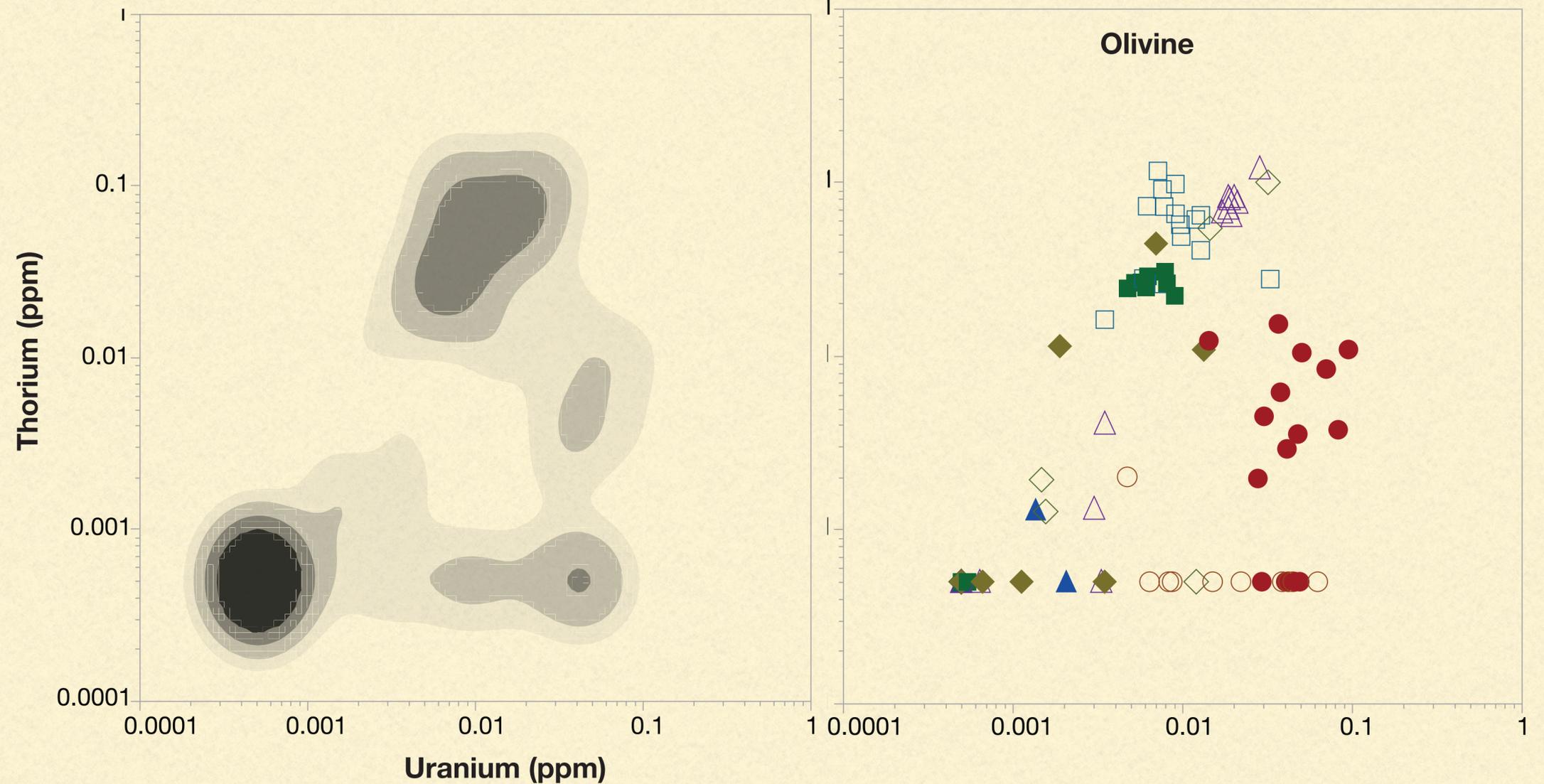


NEUTRINOS TRACK DISTRIBUTIONS

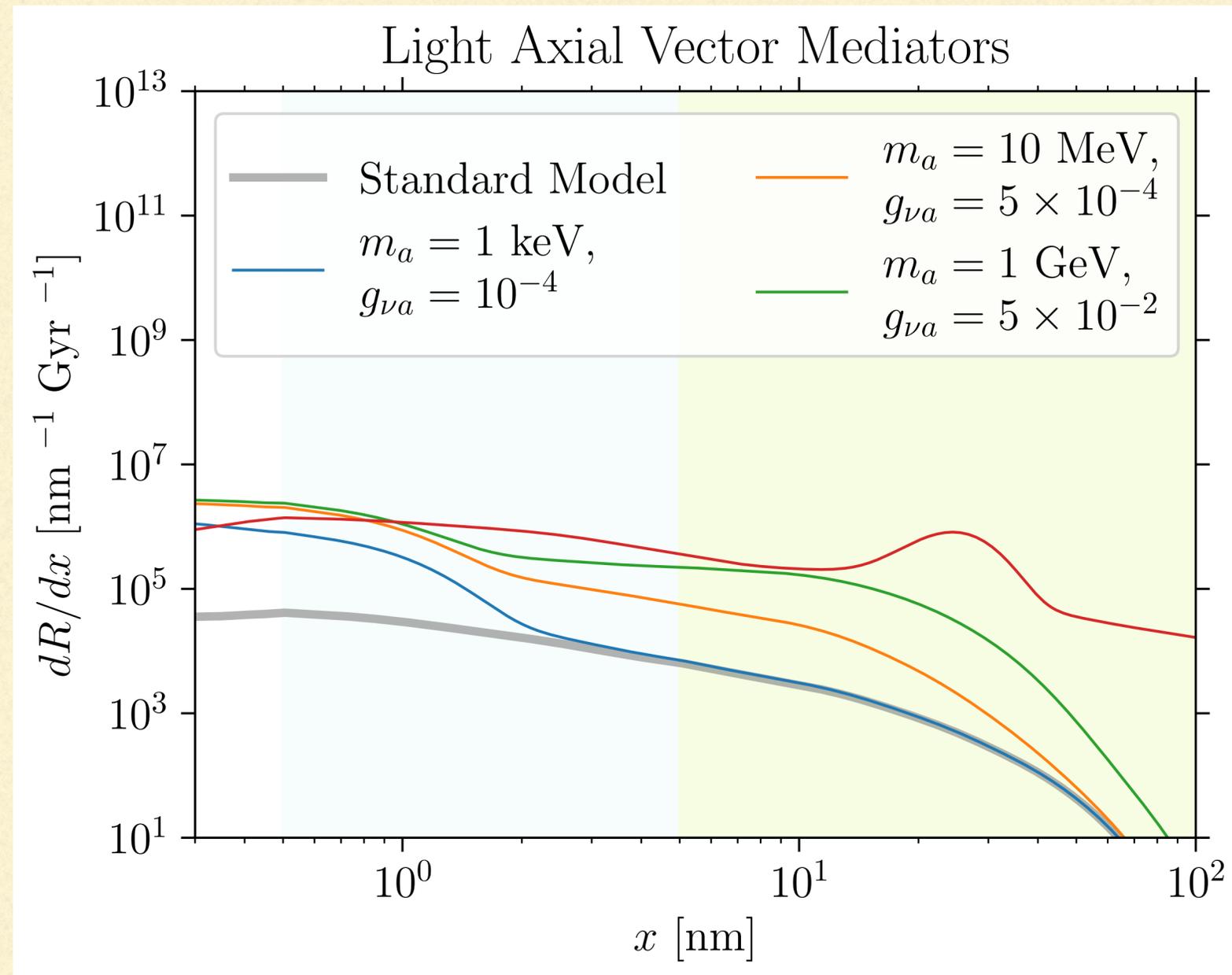


BACKGROUND TRACKS

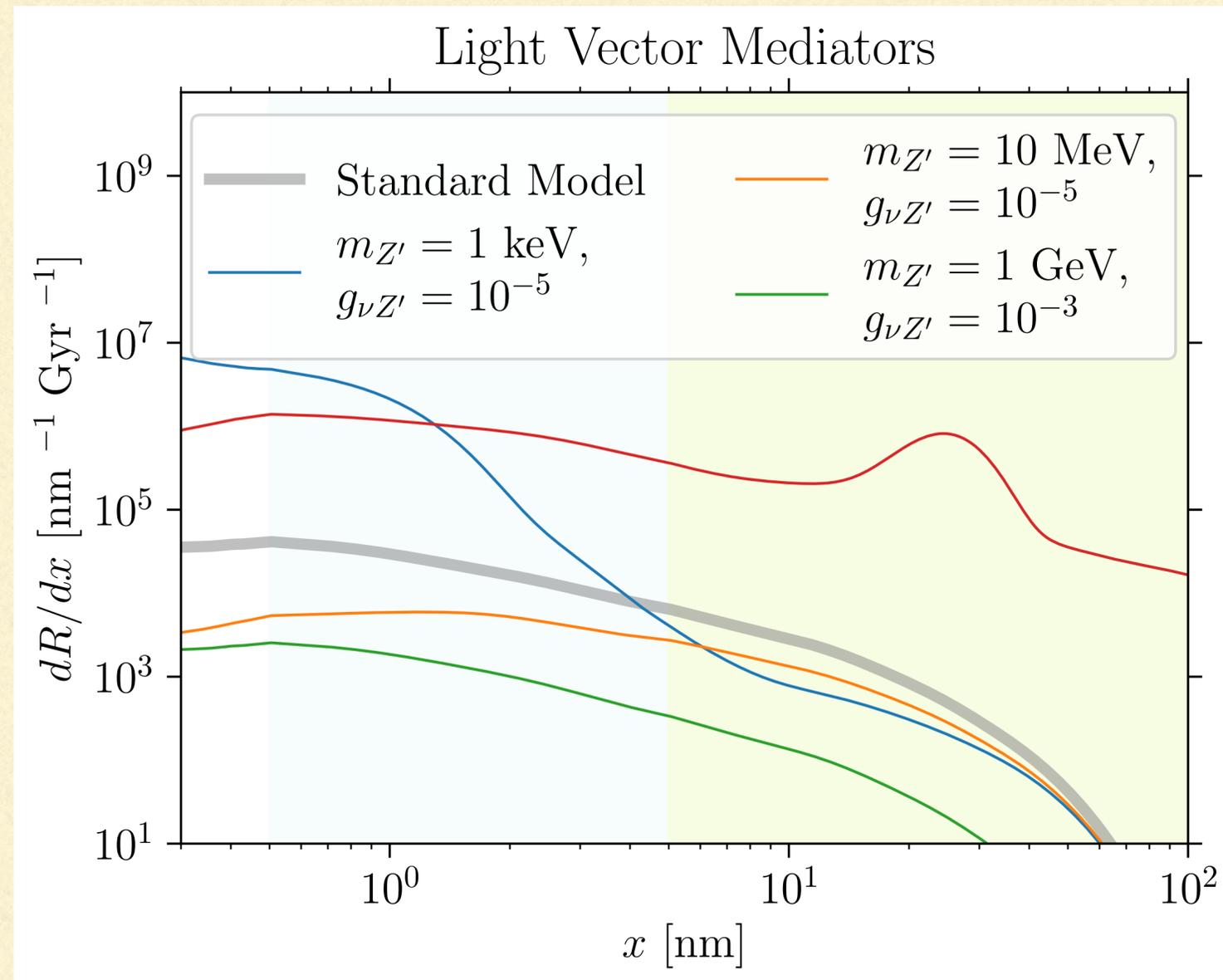
- solar neutrinos
- atmospheric neutrinos
- supernova neutrinos
- neutron from Uranium decay: detection threshold at 0.5 ppb



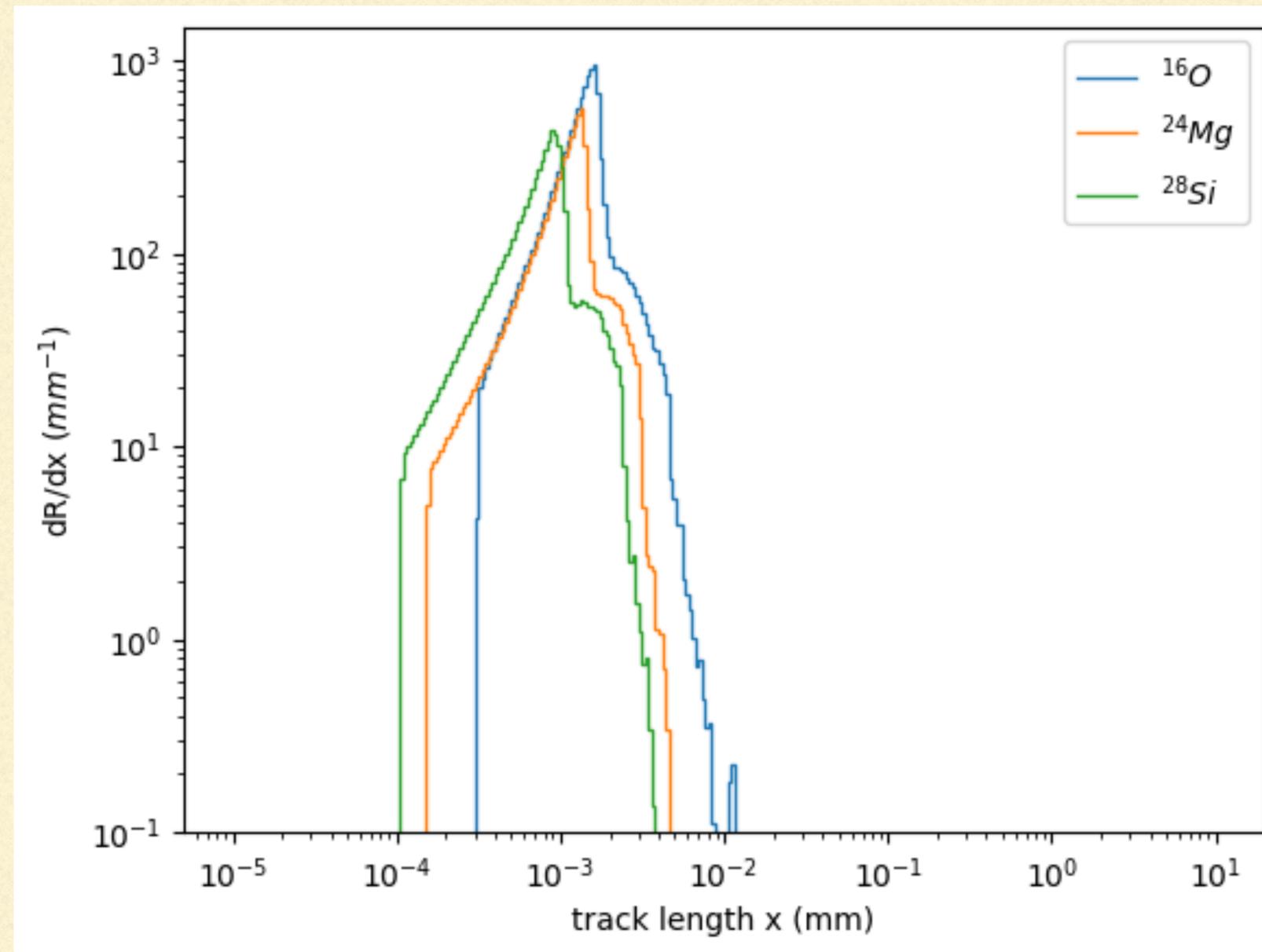
NEUTRINOS TRACK DISTRIBUTIONS



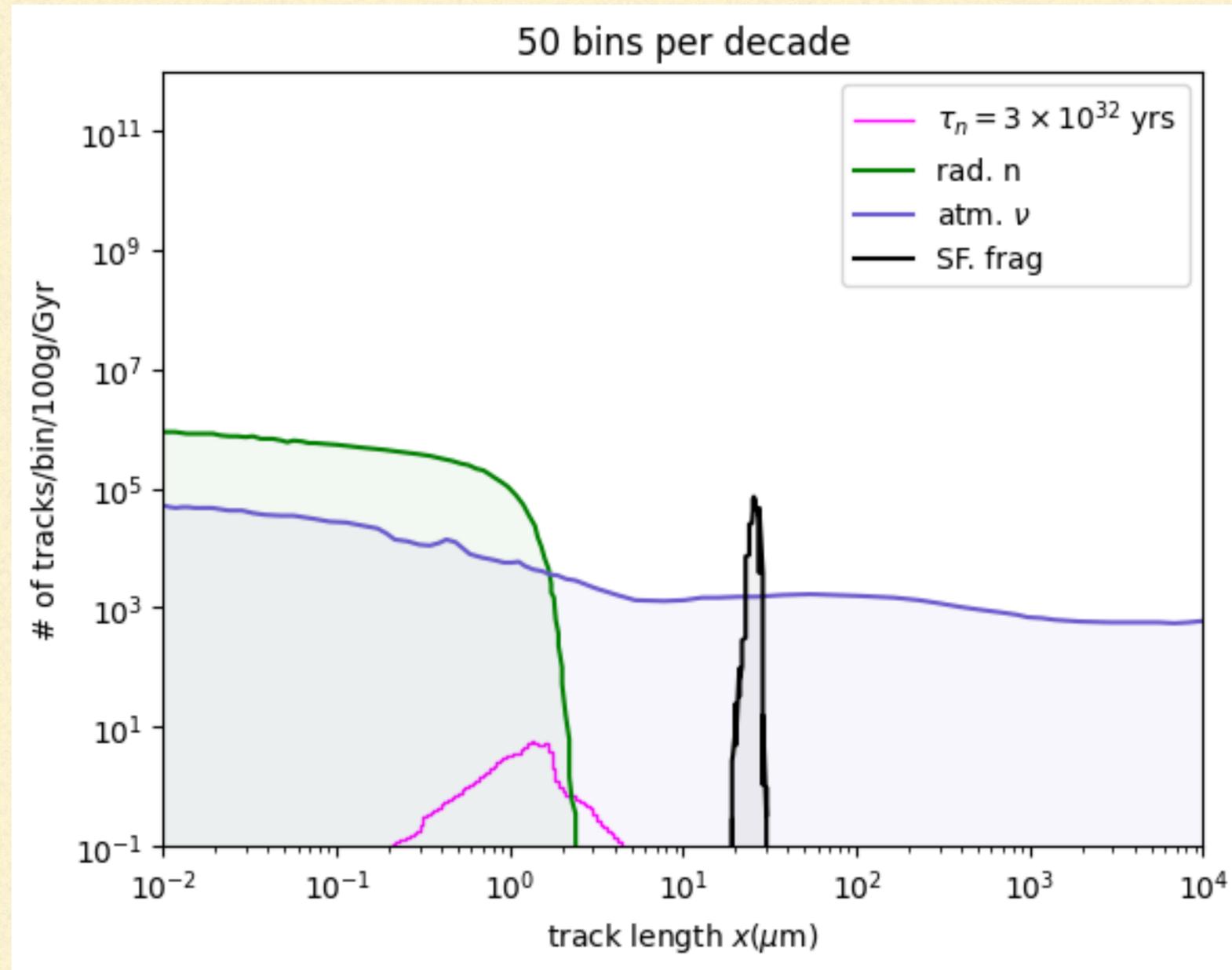
NEUTRINOS TRACK DISTRIBUTIONS



RECOIL NUCLEAR TRACK LENGTH DISTRIBUTION



TRACK LENGTH DISTRIBUTION



IV. NOTHING YET, BUT SUGGESTIONS ARE
WELCOME

TWO MINERAL CANDIDATES

- have low molecular/atomic number → optimised recoil energy
- be suitable for imaging
- be 5 ~ 10 km underground for > 500 Myr
- be able to preserve tracks

- Olivine (Mg,Fe) $_2\text{SiO}_4$

- Has been suggested before (e.g. Drukier et al)
- Not expected to take up much Uranium
- non-hydrous



- Galena (PbS)

- Not used before (as far as we know)
- Not expected to take up much uranium
- non-hydrous



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Ivar Leidus/wikipedia