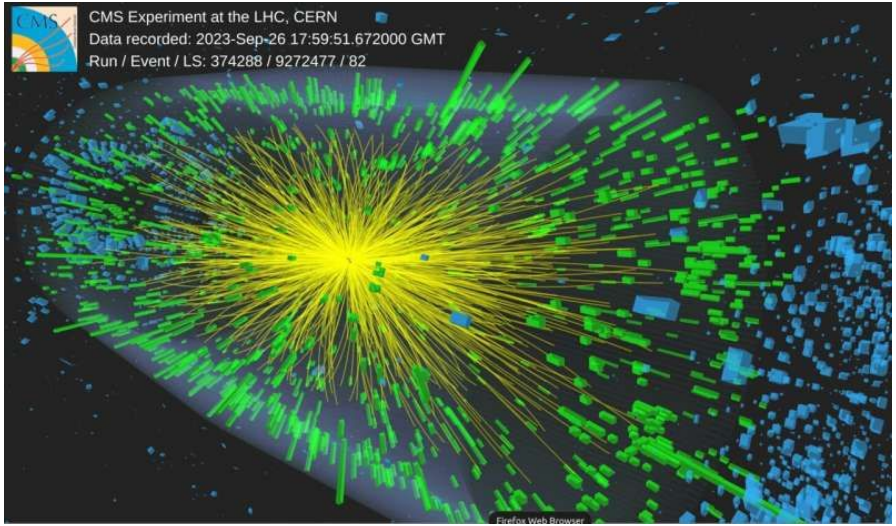
04-07-2026

VIRGINIA TECH



Calorimetric readout of paleo-detectors

with Sam Hedges

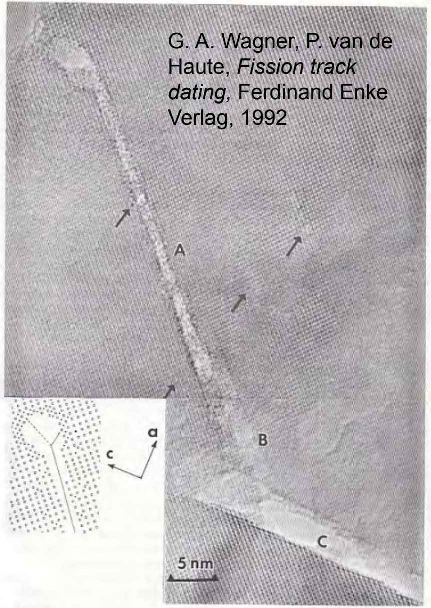
MDvDM 2026
Karlsruhe Institute for Technology
April 14-17, 2026

Patrick Huber
Center for Neutrino Physics at Virginia Tech

NSF
U.S. DEPARTMENT OF ENERGY | Office of Science
NNSA National Nuclear Security Administration
Consortium for Monitoring, Technology and Verification
dnn TECH

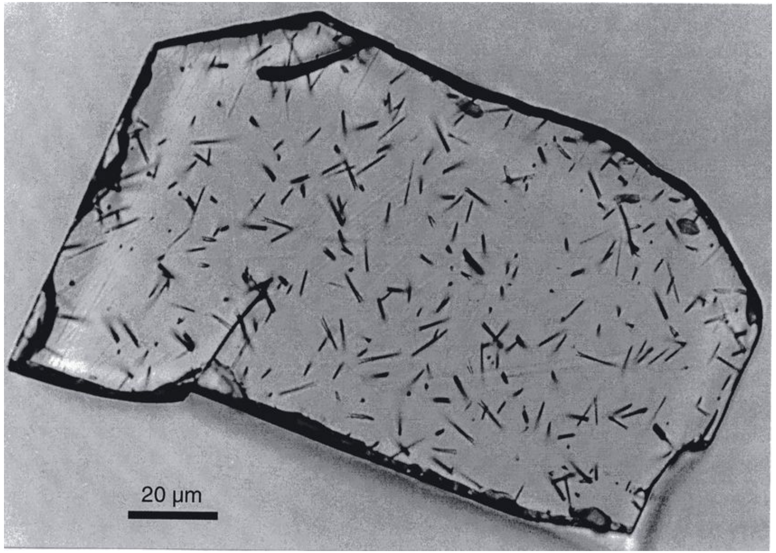
Fission tracks

Solid material damage provides a **persistent** record of nuclear events.



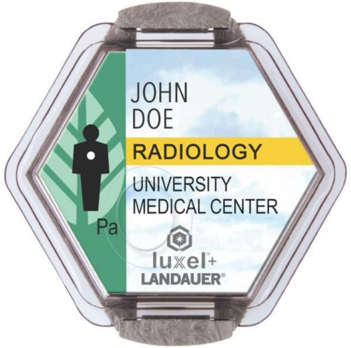
G. A. Wagner, P. van de Haute, *Fission track dating,* Ferdinand Enke Verlag, 1992

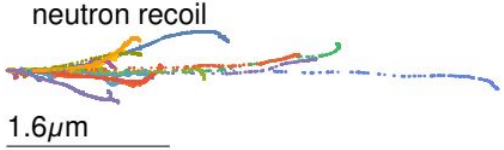
Figure 1.1. Three uranium fission-tracks (A. B and C) making different angles with the (100) plane of zircon (= plane of the picture) observed with high resolution electron microscopy. Arrows indicate sites of point defects. The inset visualizes the formation of the damage track according to Yada *et al.* (1987) together with two major crystallographic directions. (Electron micrograph obtained by courtesy of Dr K. Yada.)

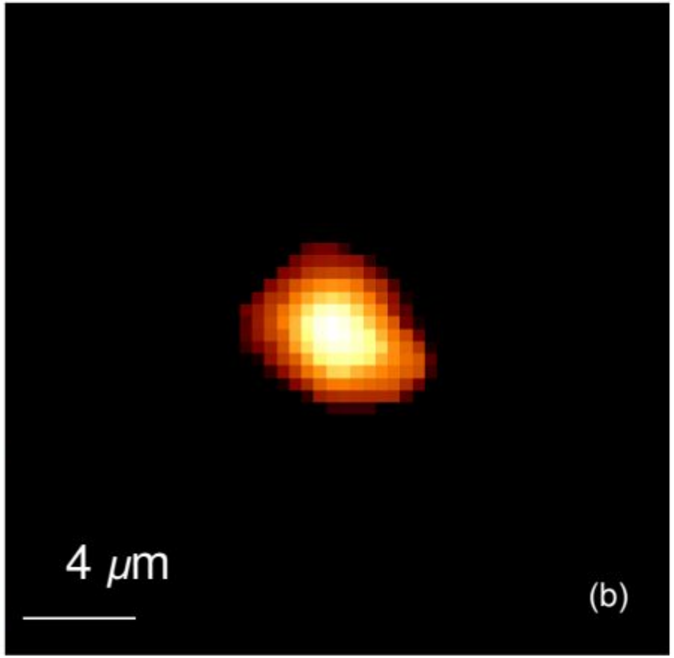


A.J.W. Gleadow et al, Reviews in Mineralogy and Geochemistry **48** 579 (2002).

Calorimeters





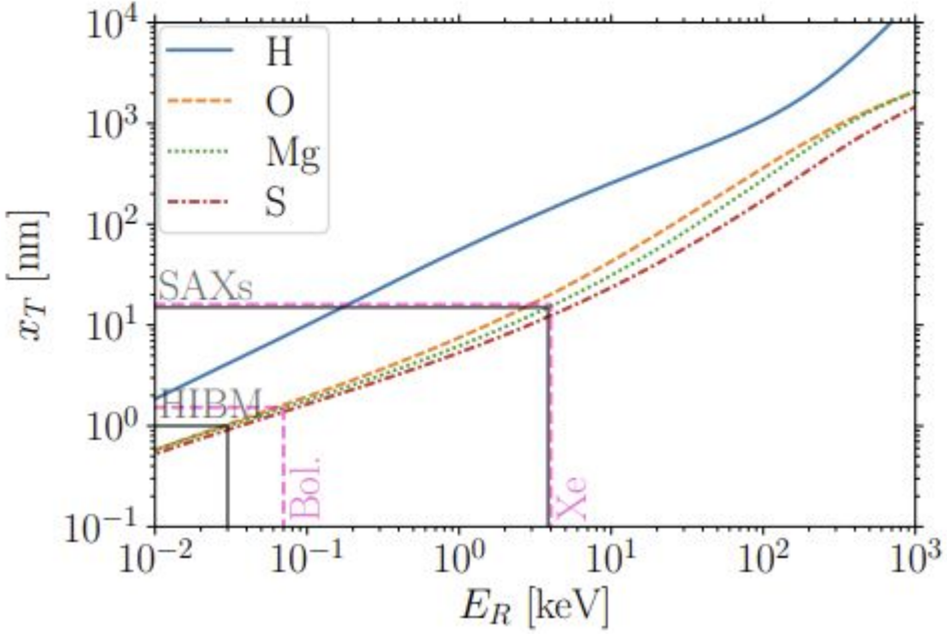


Araujo, *et al.*, arXiv:2503.20732

Stopping power

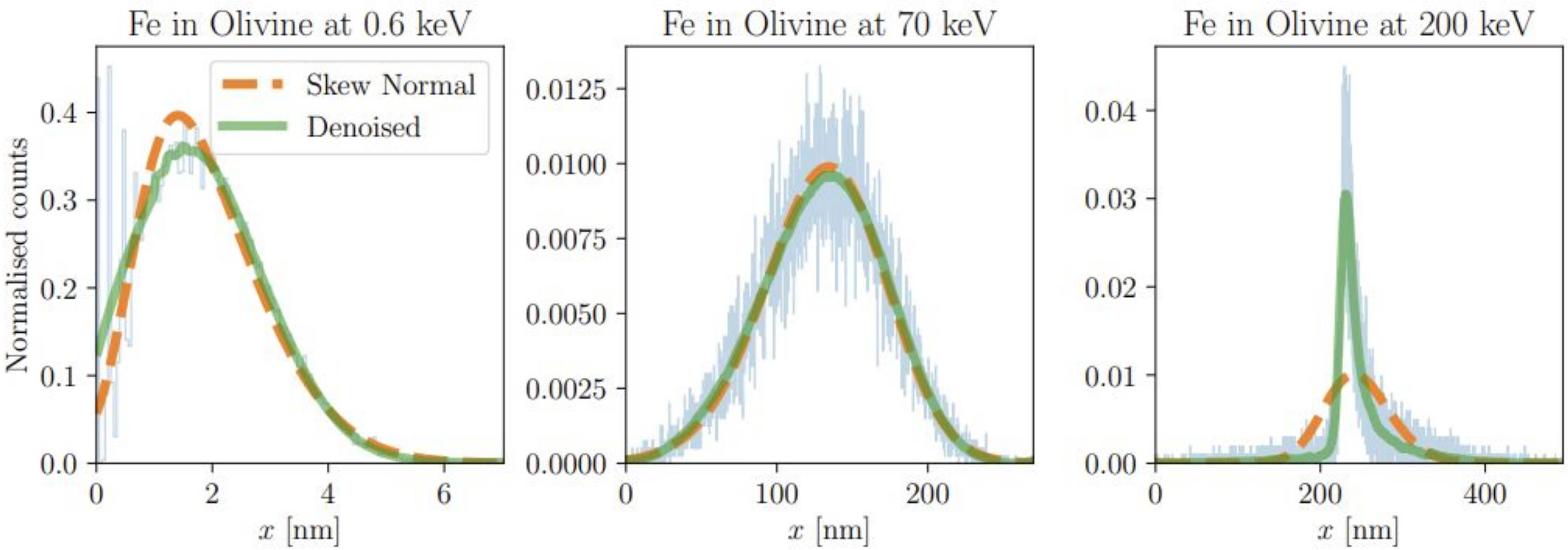
Baum, Drukier, Freese, Górski, Stengel in their seminal 2018 paper phrase track length in terms of stopping power

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



Baum, Drukier, Freese, Górski, Stengel, Phys.Lett.B **803** (2020) 135325

“Real” tracks using SRIM



Fung, Lucas, Balogh, Leybourne, Vincent, Phys.Rev.D **112** (2025) 4, 043040

SRIM again

S. Agarwal,Y. Lin, C. Li, R.E. Stoller, S.J. Zinkle, NIMB **503**, (2021), 11-29.

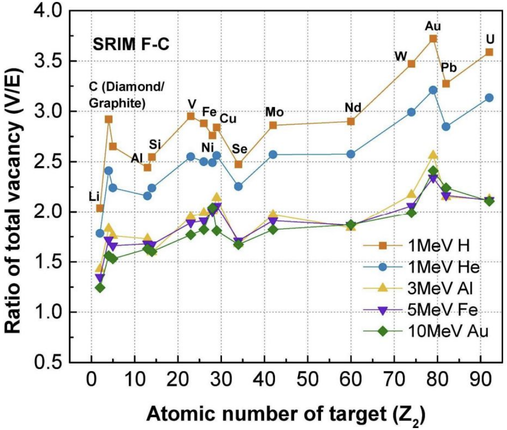


Fig. 6. The ratio of vacancy production from vacancy.txt file to damage energy method for the SRIM F-C option (integrated over the full ion range). Five different projectiles H, He, Al, Fe, and Au (Z_1=1 to 79) were examined on 16 different targets with varied Z_2 from 3 (Li) to 92 (U).

Stopping power in SRIM is computed using the "quick mode", basis for paleo-spec and most of the subsequent literature.

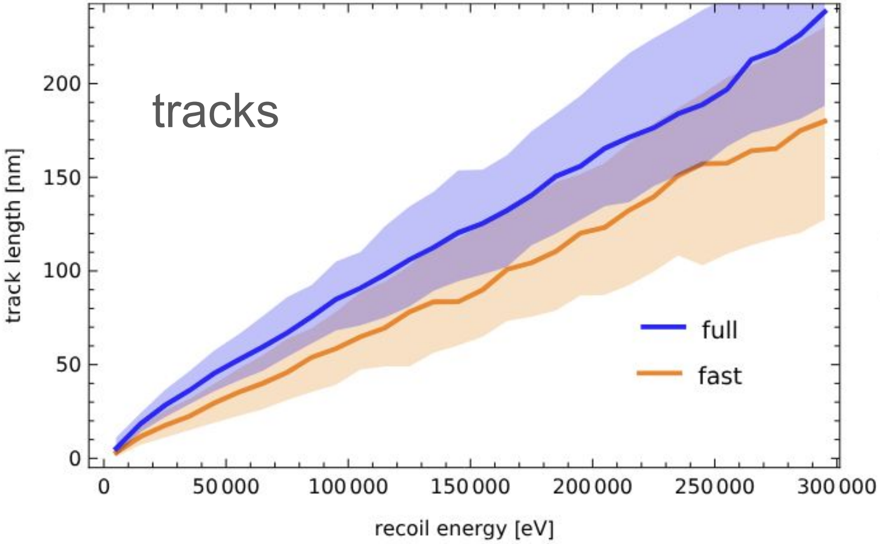
Long standing issue with SRIM

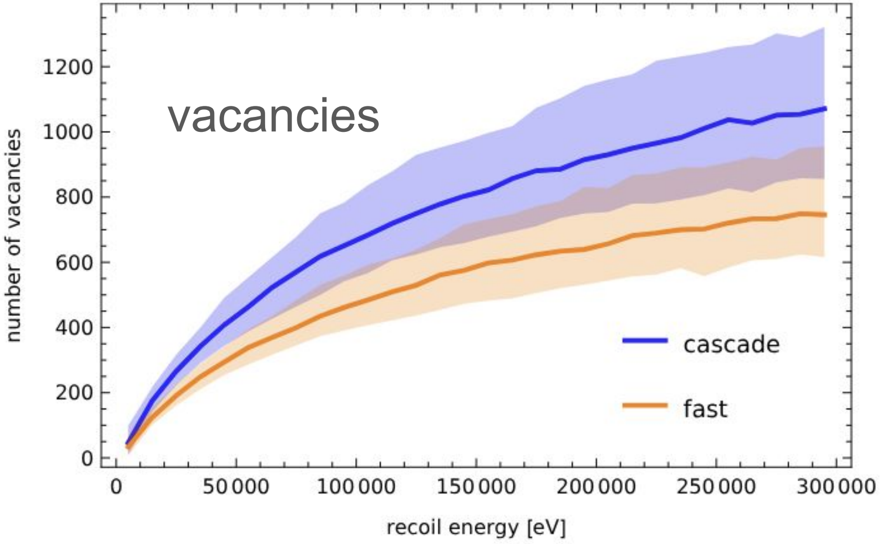
- Full cascade mode **should** capture physics more accurately
- **BUT** full cascade mode and quick mode are not consistent

The culprit seems to be some internal bug that misses replacements, where a vacancy is filled by an interstitial, in the full cascade mode.

J.F. Ziegler, M.D. Ziegler, J.P. Biersack, Nucl. Instruments Methods Phys. Res. Sect. B Beam Interact. with Mater. Atoms. 268 (2010).

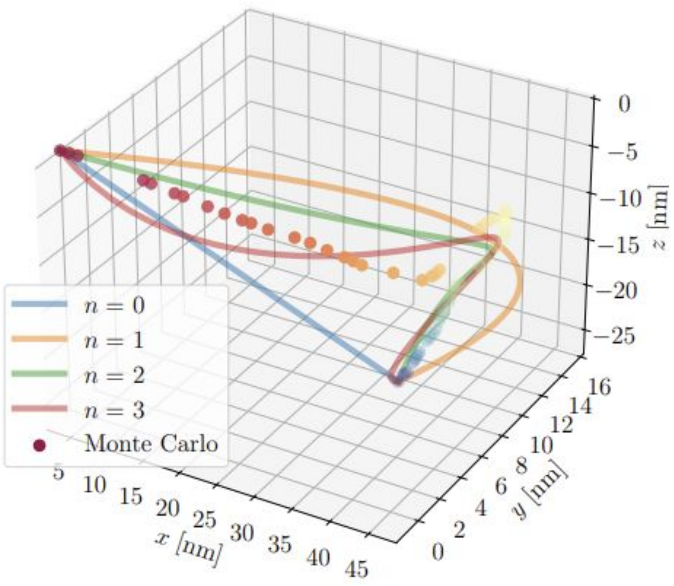
Tracking energy



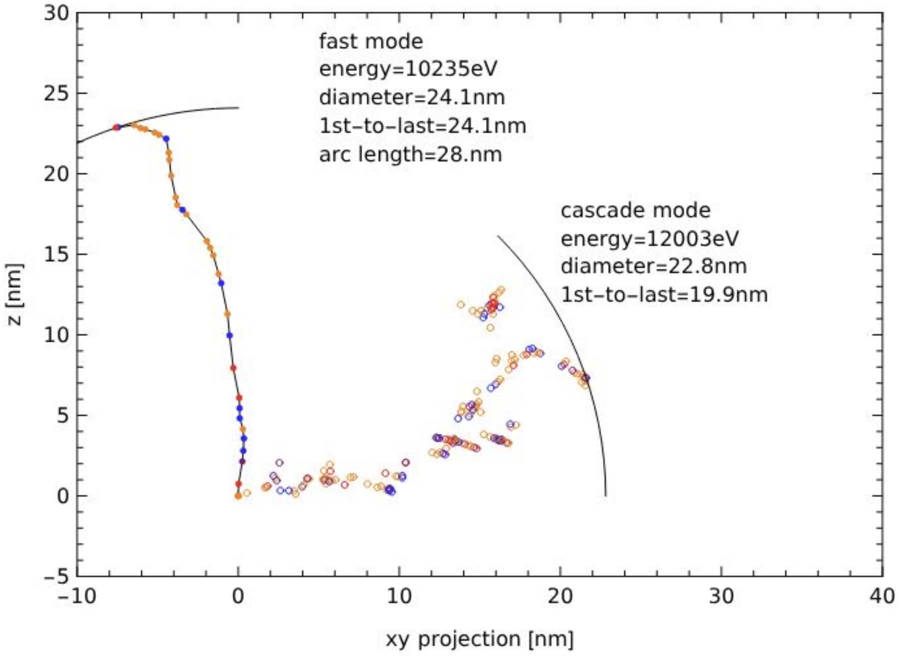


We assume that vacancies of all atomic species contribute equally.

Defining length

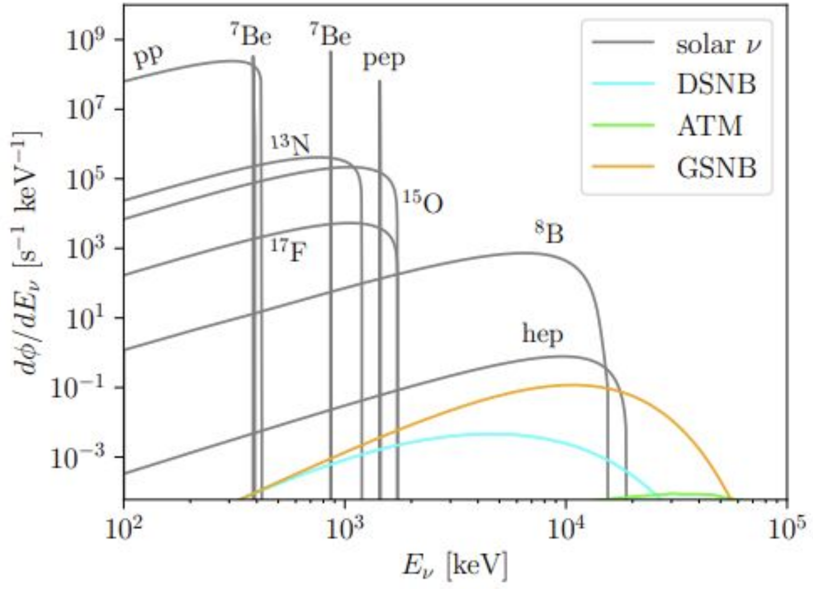


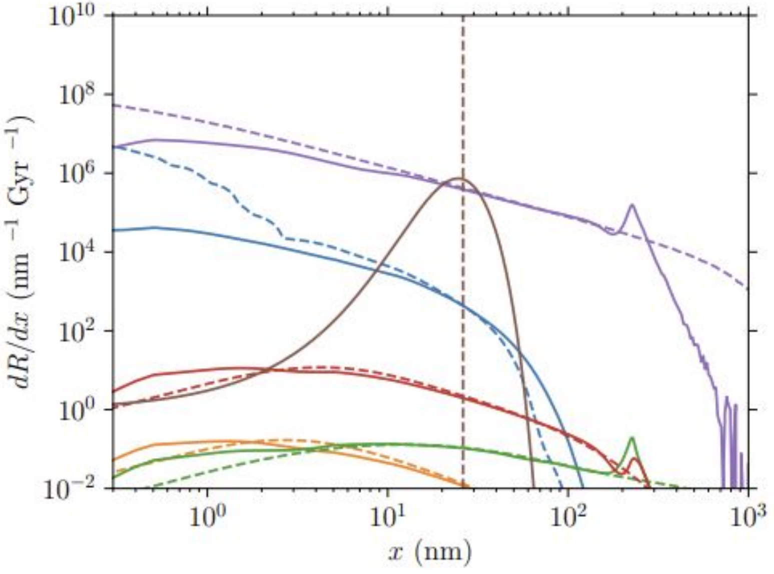
Fung, Lucas, Balogh, Leybourne, Vincent,
Phys.Rev.D **112** (2025) 4, 043040



Longest distance between any two vacancies - diameter.

Backgrounds





Figures from Fung, Lucas, Balogh, Leybourne, Vincent, Phys.Rev.D **112** (2025) 4, 043040

Sensitivity estimates

We use olivine as target.

We assume that each vacancy counts the same.

Light yield is varied between 1 p.e. to 10 p.e. per vacancy.

Camera noise and intrinsic defects are studied as well.

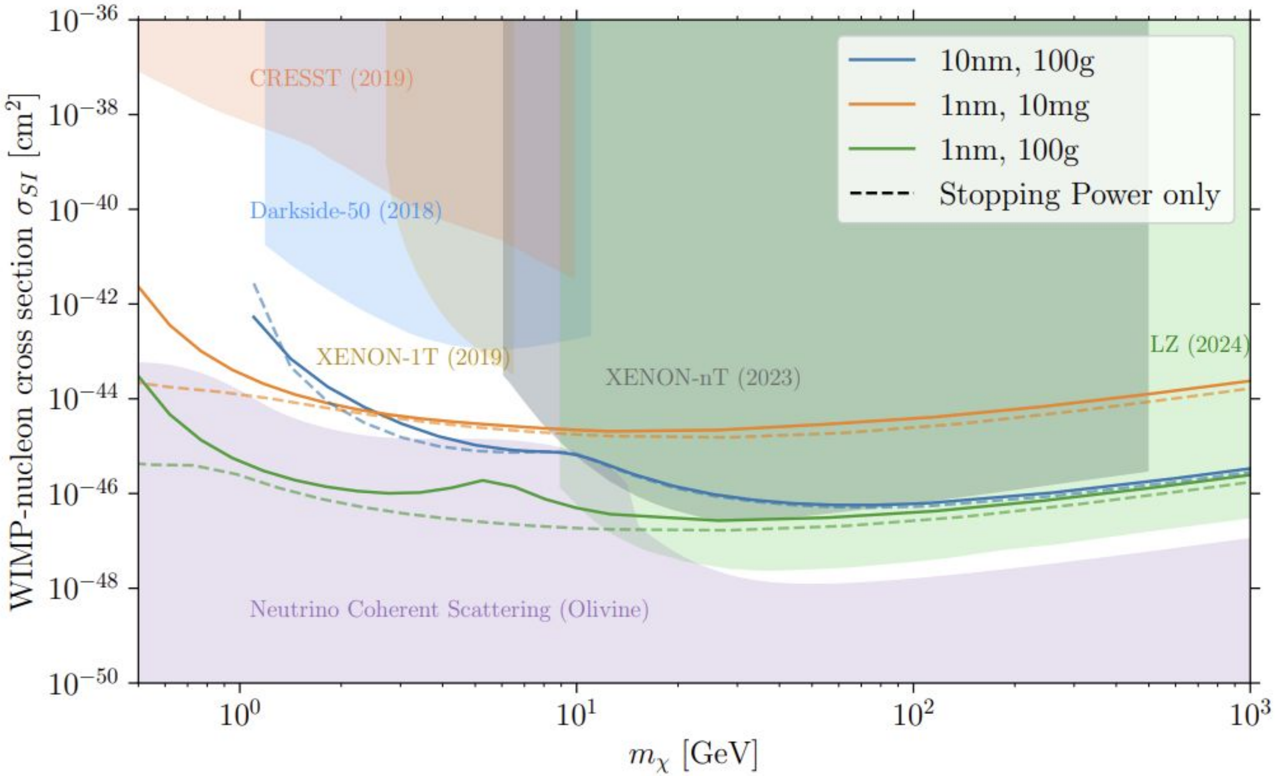
We use 100g 1Gyr exposure, this is 3 orders of magnitude above Darwin or XLZD!

We generally follow the approach in Fung, Lucas, Balogh, Leybourne, Vincent, Phys.Rev.D 112 (2025) 4, 043040 for signal, backgrounds and systematics and use paleo-spec for neutron backgrounds.

Parameter n_i	**Error** σ_i
$\nu_{\rm solar}$ flux	14%
$\nu_{\rm DSNB}$ flux	100%
$\nu_{\rm GSNB}$ flux	100%
$\nu_{\rm ATM}$ flux	100%
^{238}U concentration	1%
Mineral age t	5%
Mineral mass $m_{\rm olivine}$	0.01%

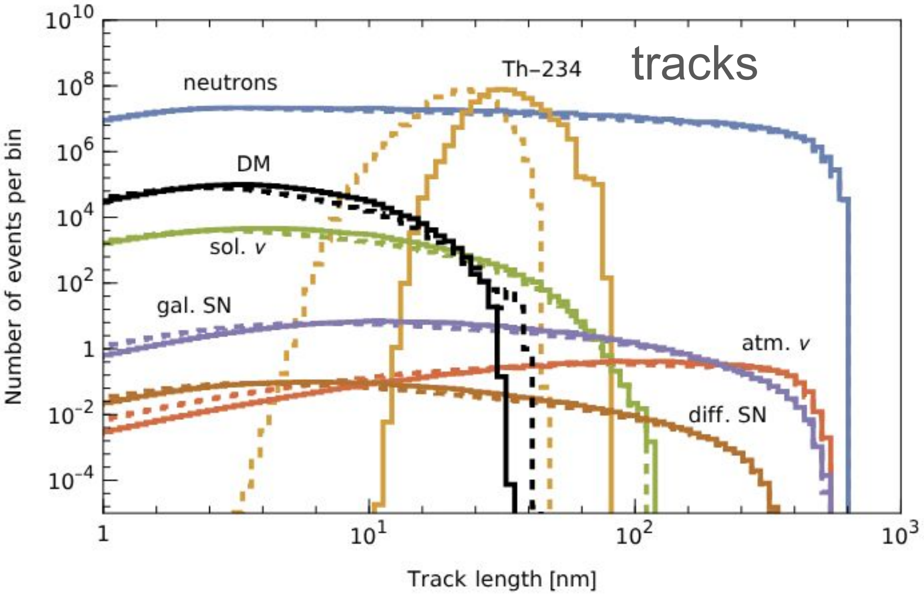
DM sensitivity

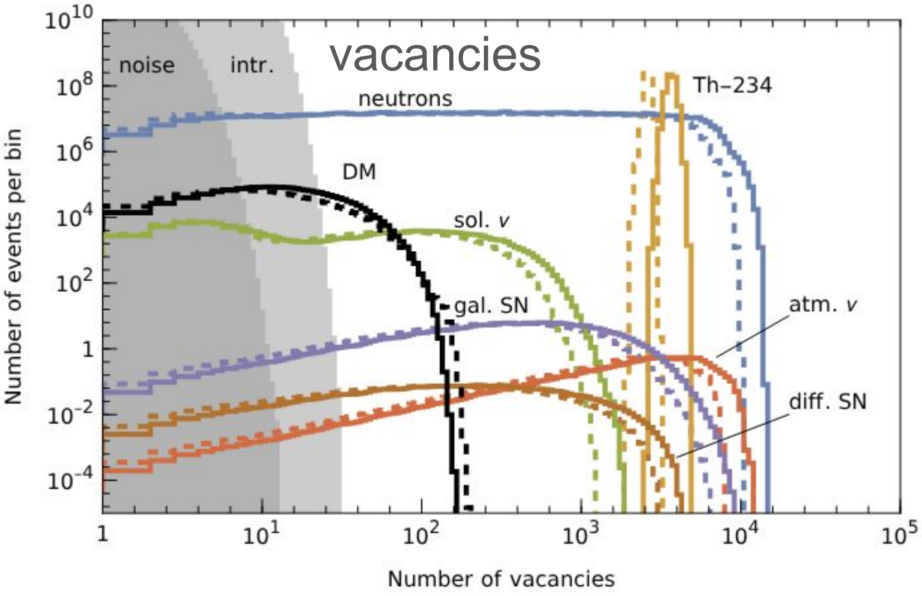
"Real" tracks provide less sensitivity for low-mass DM.



Fung, Lucas, Balogh, Leybourne, Vincent, Phys.Rev.D **112** (2025) 4, 043040

Signal and background distributions





Solid - full cascade moder, dashed - quick mode

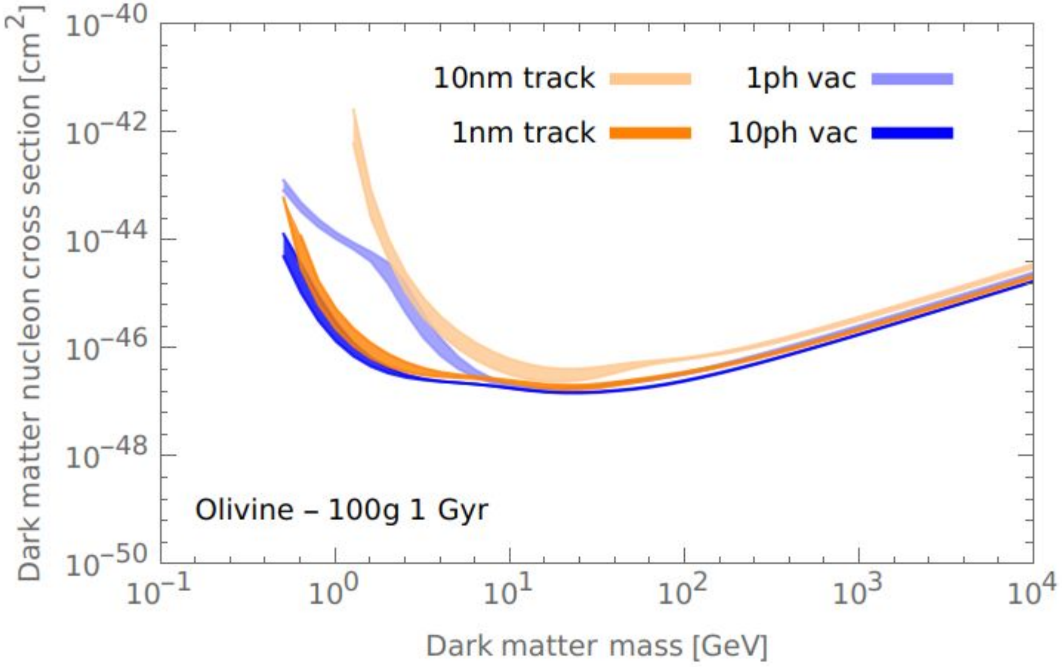
Noise is from camera,
1ppb intrinsic defects.

DM sensitivity

Depends on the readout performance –

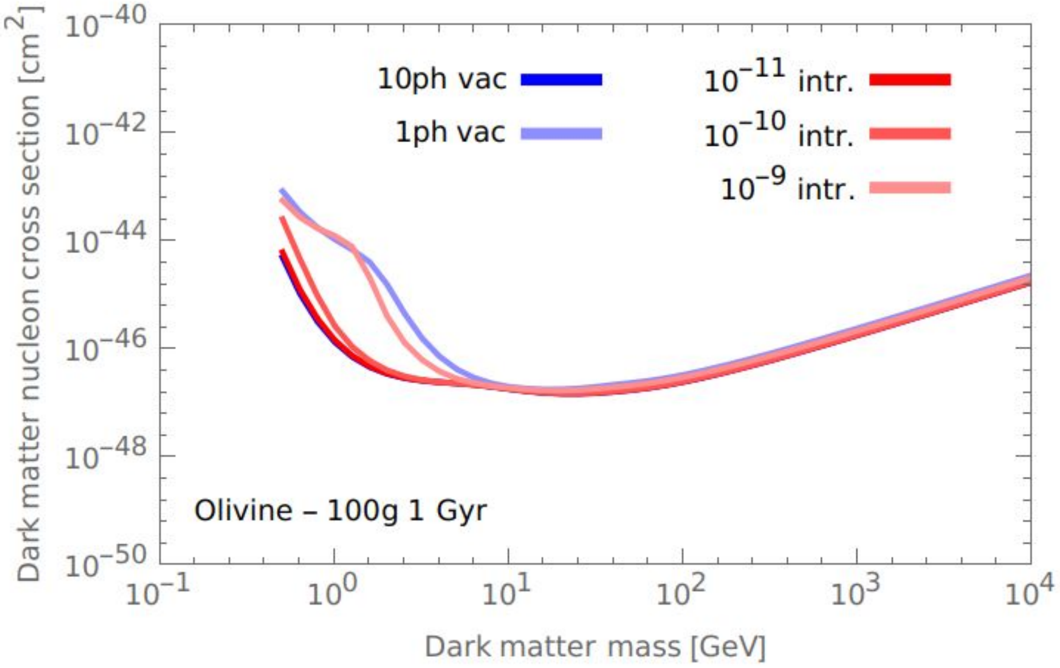
overall tracks and vacancies provide very similar sensitivity.

Bands: difference between full cascade mode and quick mode



Intrinsic defects

Intrinsic defects matter for low-mass sensitivity once they reach 1ppb concentration.



dE/dx measurements by combining

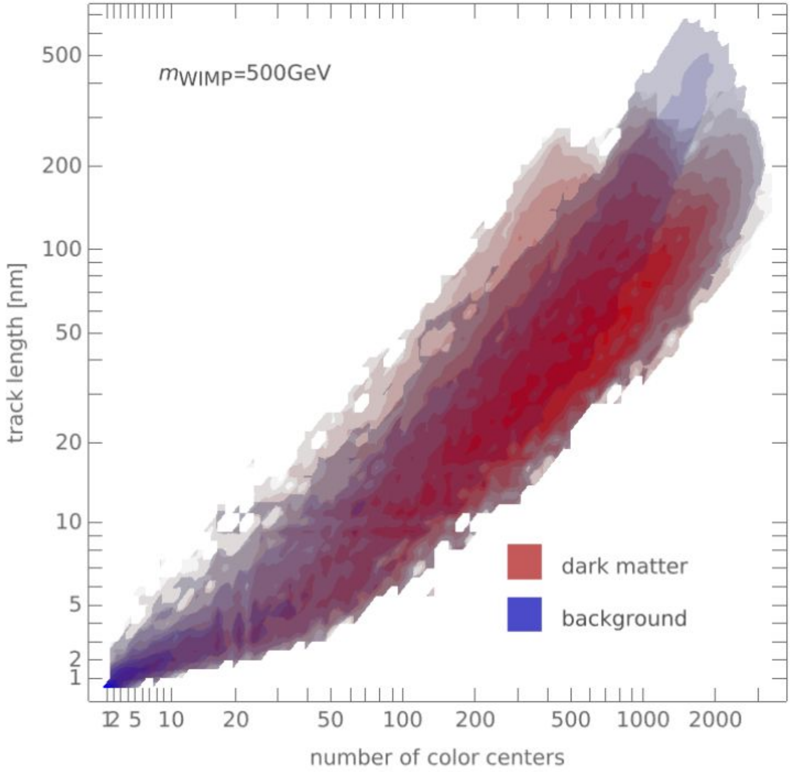
Neutron cross section very similar for all atomic species.

DM cross section scales a A².

dE/dx is higher for higher-A nuclei.

Comparing number of vacancies to track length provides a measure of dE/dx.

Opportunities to distinguish different DM interactions?

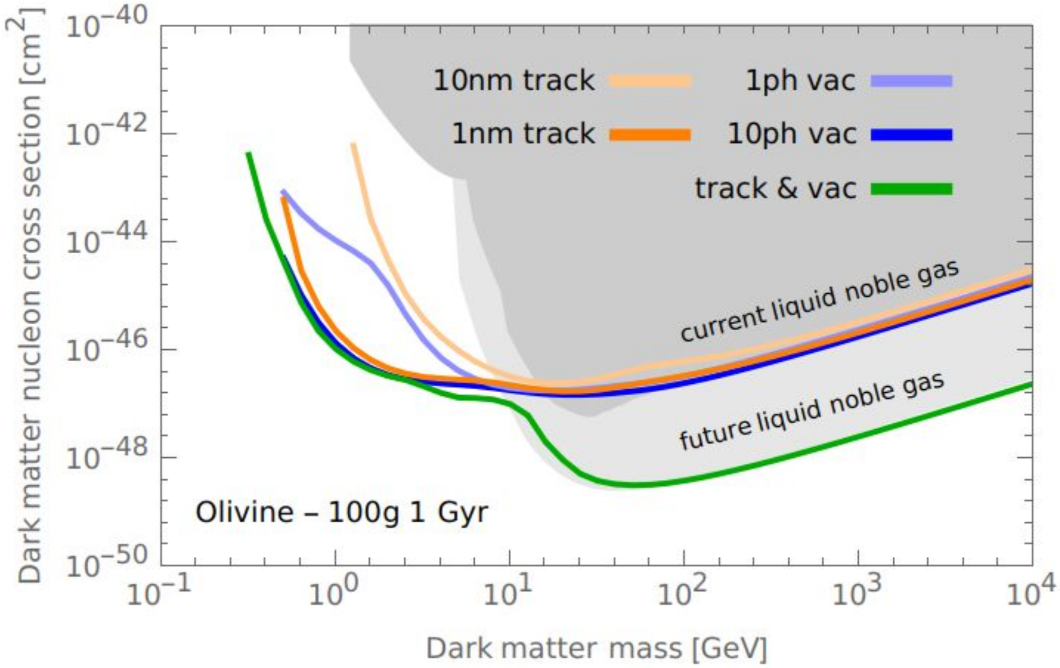


Combining tracks & vacancies

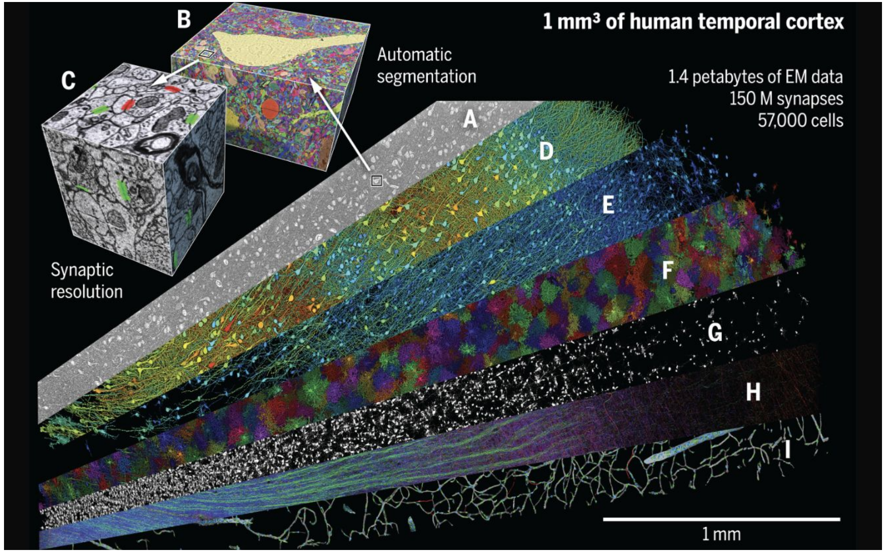
Light gray – current liquid noble gas

Dark gray – future liquid noble gas

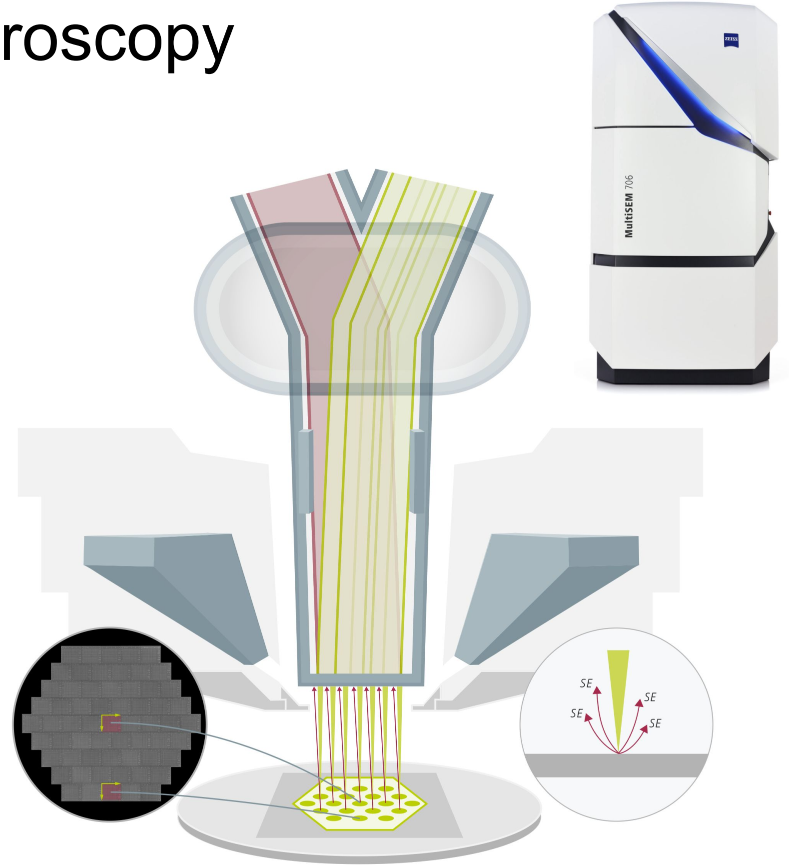
Combined analysis could rival large future liquid noble gas detectors.



Petascale Scanning Electron Microscopy



Shapson-Coe *et al.*, Science **384** (2024) eadk4858



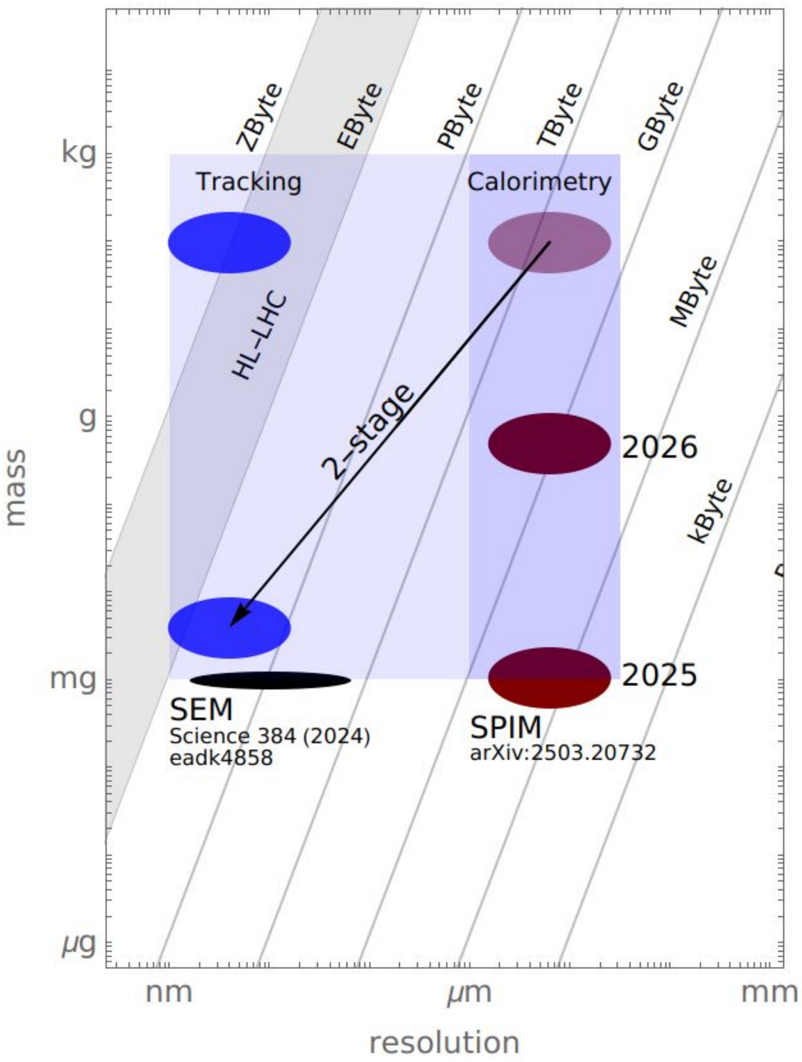
~ 1 milligram of human brain

Zeiss MultiSEM 706

100 grams is a lot…

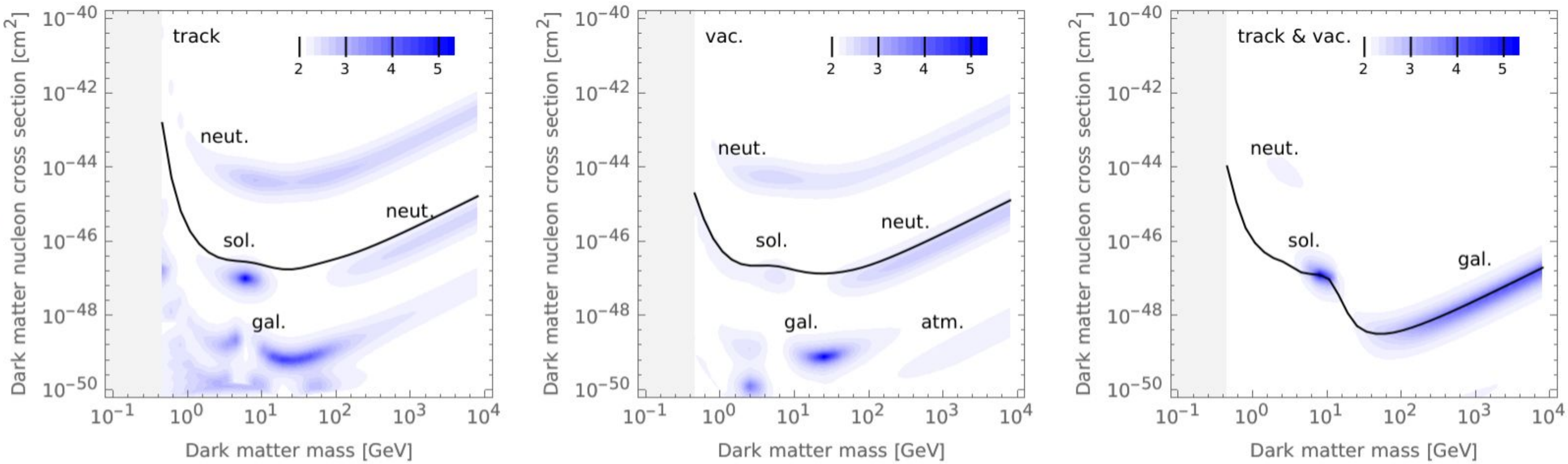
…but a lot less if done in stages

- Still HL-LHC data volumes
- How do we isolate 1 billion ROIs?



Neutron fog

Following O'Hare Phys. Rev. Lett. **127,** 251802 (2021).



$$n = (\mathrm{d}\ln\sigma/\mathrm{d}\ln N)^{-1}$$

At the limit we still have 1,000 to 100,000 DM events.

Summary

- Presented first calorimetric analysis based on full SRIM simulations.
- SRIM mode differences do not change results very much
- Full range of backgrounds included.
- Light yield, camera noise and intrinsic defects appear as new parameters.
- Calorimetric analysis is a natural fit for SPIM.
- Provides overall very similar sensitivity envelope to state-of-the-art track-based analyses.
- Combination of tracking & calorimetry provides powerful neutron rejection.
- Two stage approach makes data rates and track analysis less challenging.