Simulation of Cosmogenic Backgrounds to nEXO with FLUKA

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WNPPC 2024

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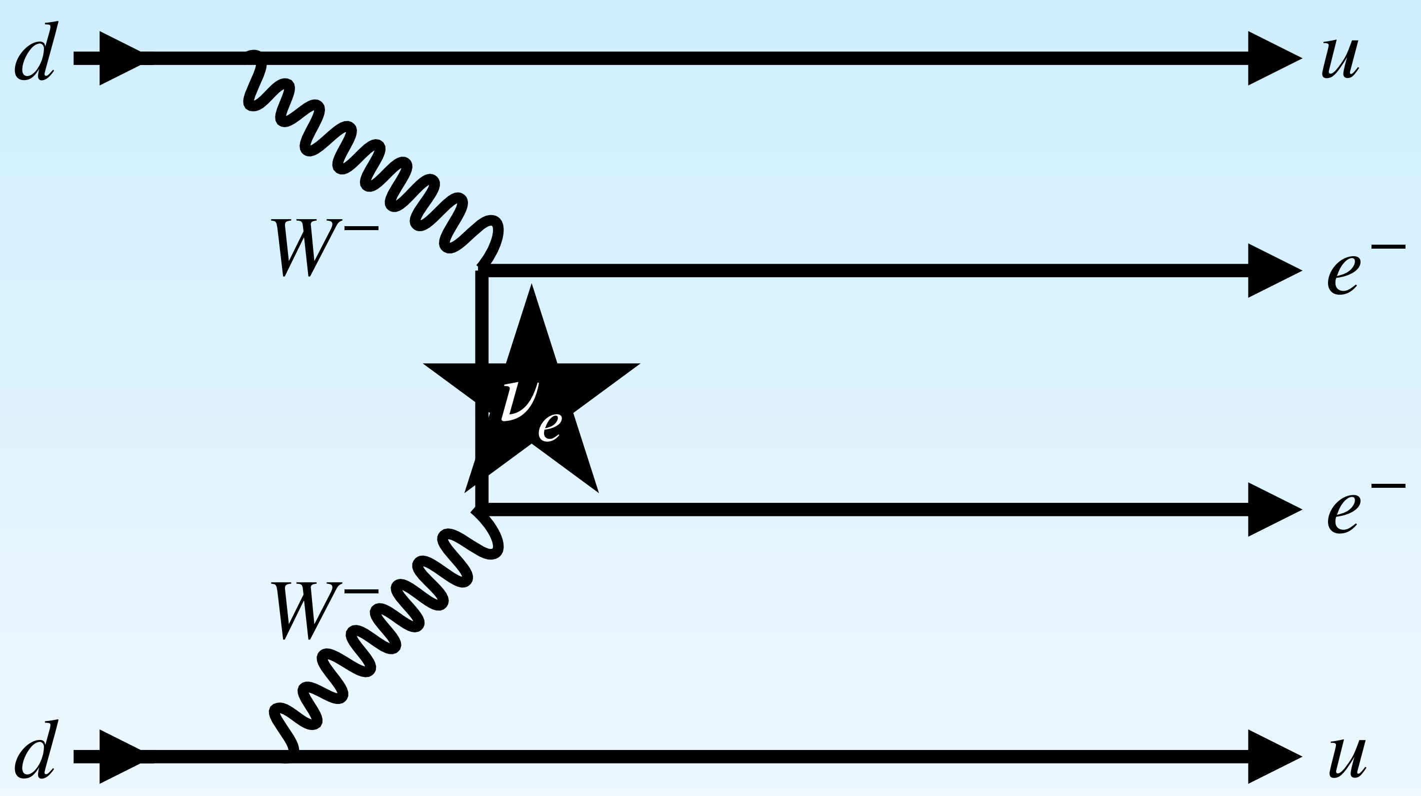
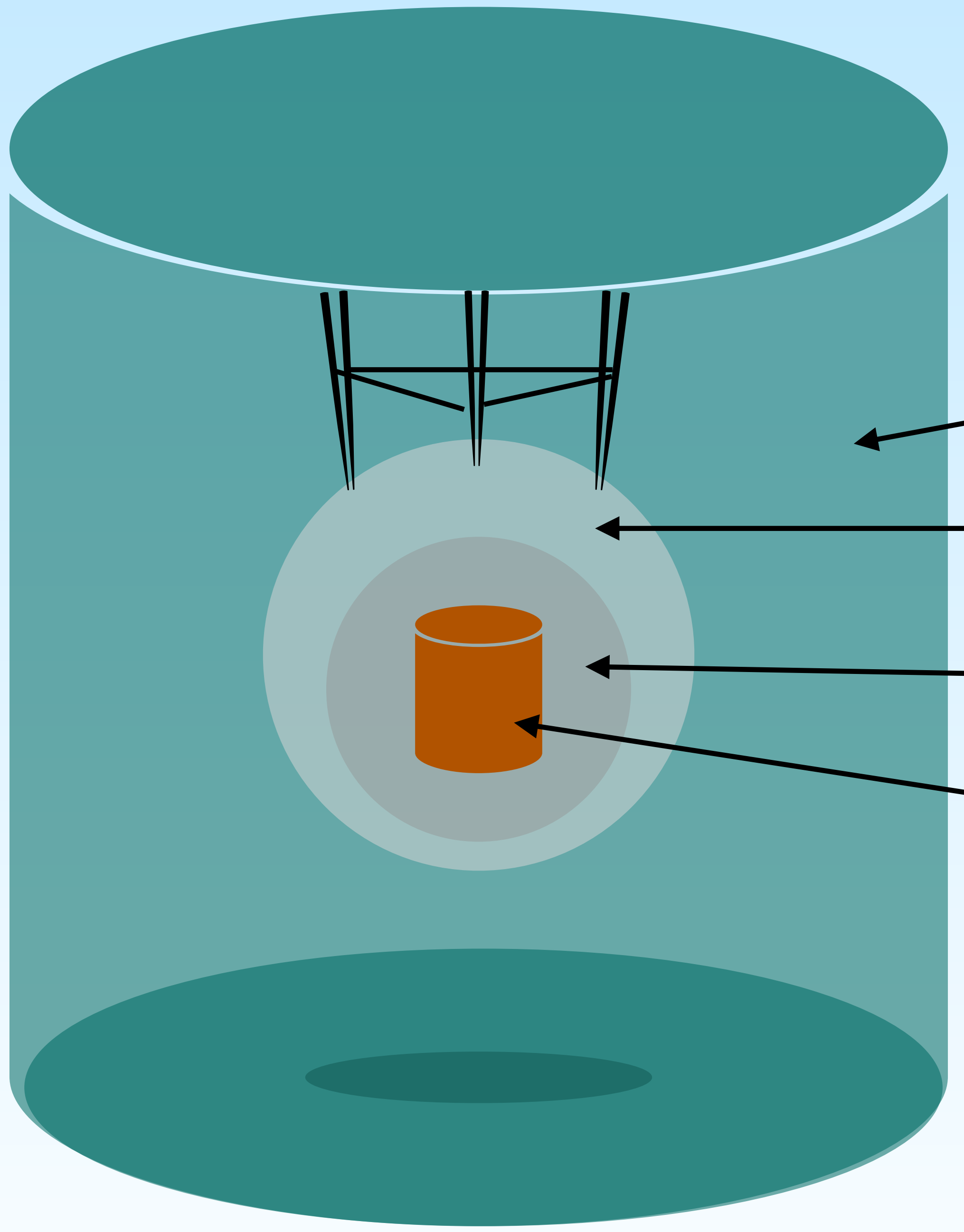
What is nEXO?

- A search for $0\nu\beta\beta$ in liquid xenon-136
- Half-life sensitivity reach to 1.35×10^{28} years at a 90% C.L.
- 5000 kg of LXe in a time projection chamber (TPC)





Backgrounds to nEXO

1. Intrinsic radioactivity of components
2. Radon outgassing

Quantify:

Radioassays

Measure Rn emanation rates

Mitigate:

Select radiopure materials

3. Exposure based backgrounds
   - During fabrication / transport*
   - Steady state (cosmogenic or local activity)

Quantify:

Simulations

Mitigate:

*Post-installation cool-down time

Shielding

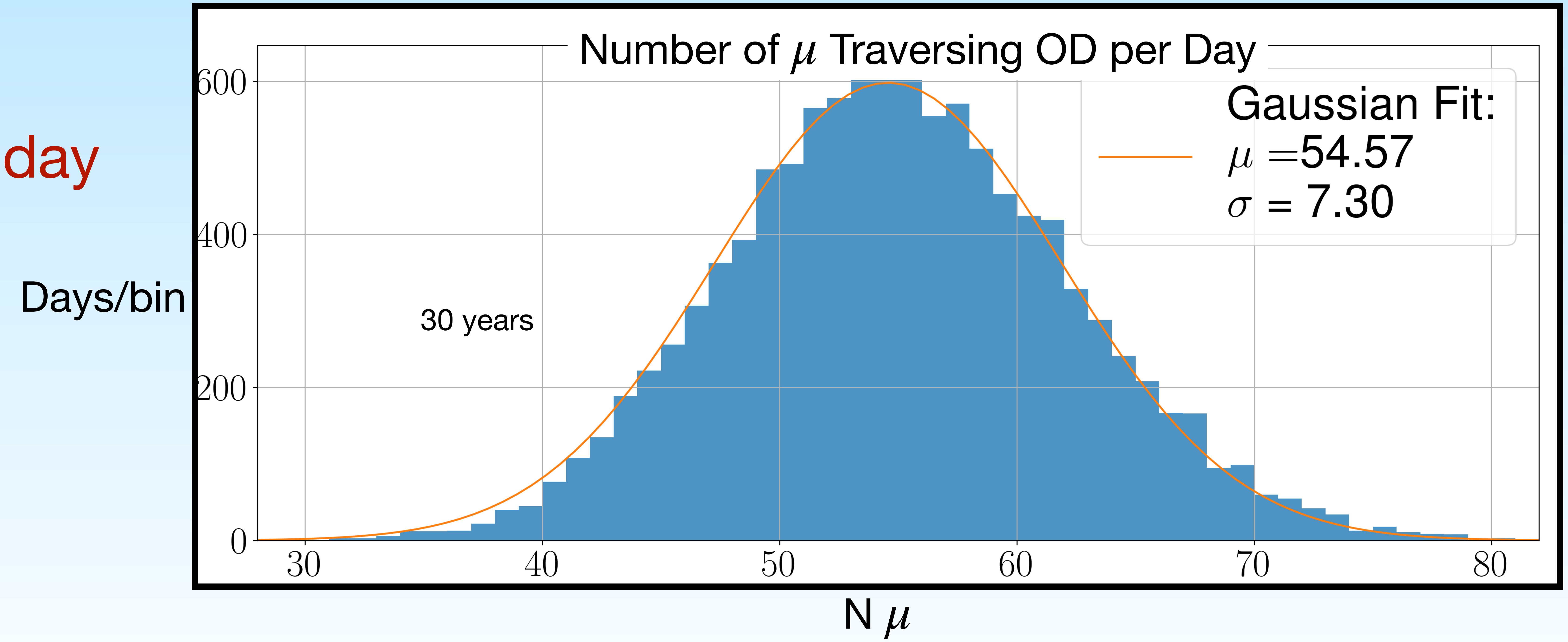
Cosmogenic Backgrounds

SNOLAB overburden reduces μ flux by 2×10^8 compared to surface

… yet we still anticipate between ~55 muons per day through the OD

$\langle E_\mu \rangle \approx 350$ GeV

why are they a problem?



Cosmogenic Backgrounds

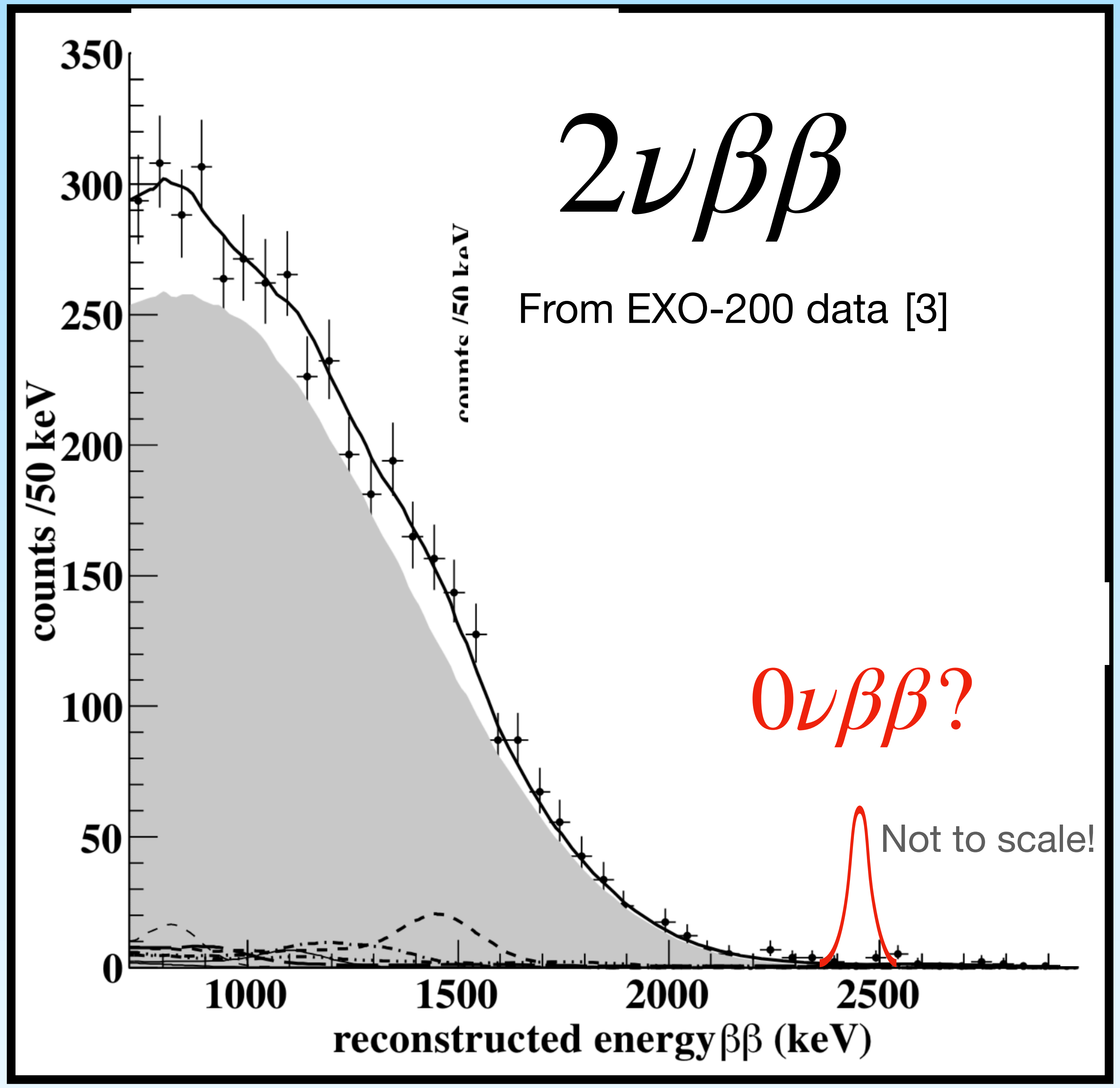
muon spallation:

$$\mu + A \rightarrow n + \ldots$$

leads to neutron capture:

$$^{136}_{54}\text{Xe} \; + \; n \rightarrow \; ^{137}_{54}\text{Xe}$$

producing a signal-like event



$$^{137}_{54}\text{Xe} \; \rightarrow \; ^{137}_{55}\text{Cs} \; + e^- + \bar{\nu}_e \, , \quad Q_\beta = 4173 \text{ keV}, \quad T_{1/2} \approx 3.8 \text{ min}$$

Enter stage right

nEXO’s Outer Detector

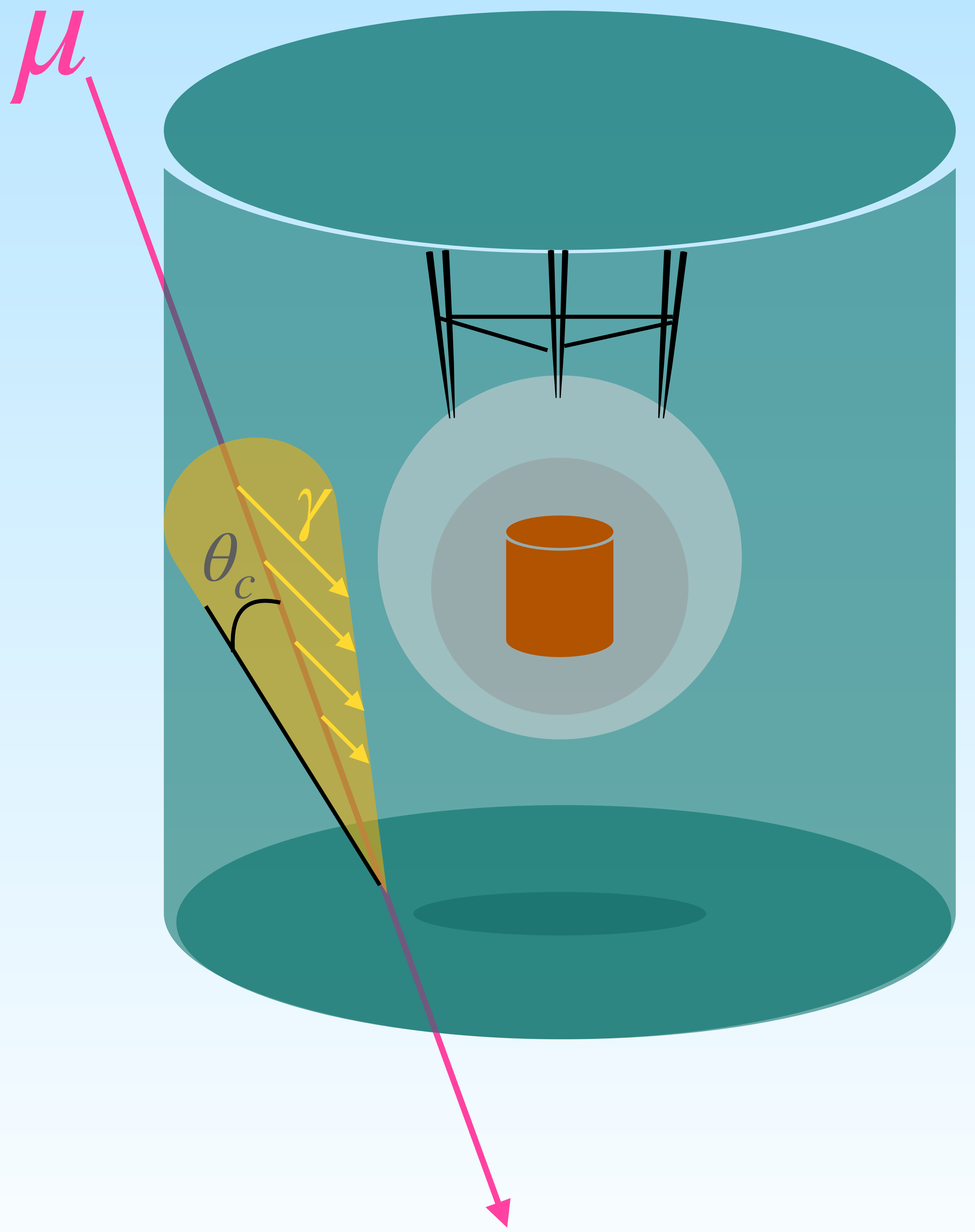
Uses 125 PMTs to detect muons via Cherenkov light whose spectra are given by the Frank-Tamm formula:

$$N = 2\pi\alpha\left(\frac{1}{\lambda_2} - \frac{1}{\lambda_2}\right)\left(1 - \frac{1}{\beta^2 n^3}\right)$$

For $\langle E_\mu \rangle \approx 350$ GeV, $\beta \approx 1$

Average path length and time: $\langle s \rangle \approx 8.6$ m $\quad \langle t \rangle \approx 30$ ns

yielding roughly 1.5×10^5 Cherenkov photons per muon in OD



Simulation Goals

- Quantify the cosmogenic background
- Constrain the activation rate of Xe-136
- Characterize the neutron-inducing muons

What is FLUKA?

- A Monte Carlo particle simulation package
- Implemented in FORTRAN77 (it's been around for a while)

What are possible outputs?

- Neutron energy, position, direction, generation, muon-parent & attributes
    - Activation — Count of *Residual* nuclei per primary — *Stopping* nuclei
        - Using ENDF σ for ^{136}Xe(n,γ)^{137}Xe
    - By region: either TPC, or everything within OD boundary

Muon Source

~~Monochromatic? Collimated? Isotropic?~~

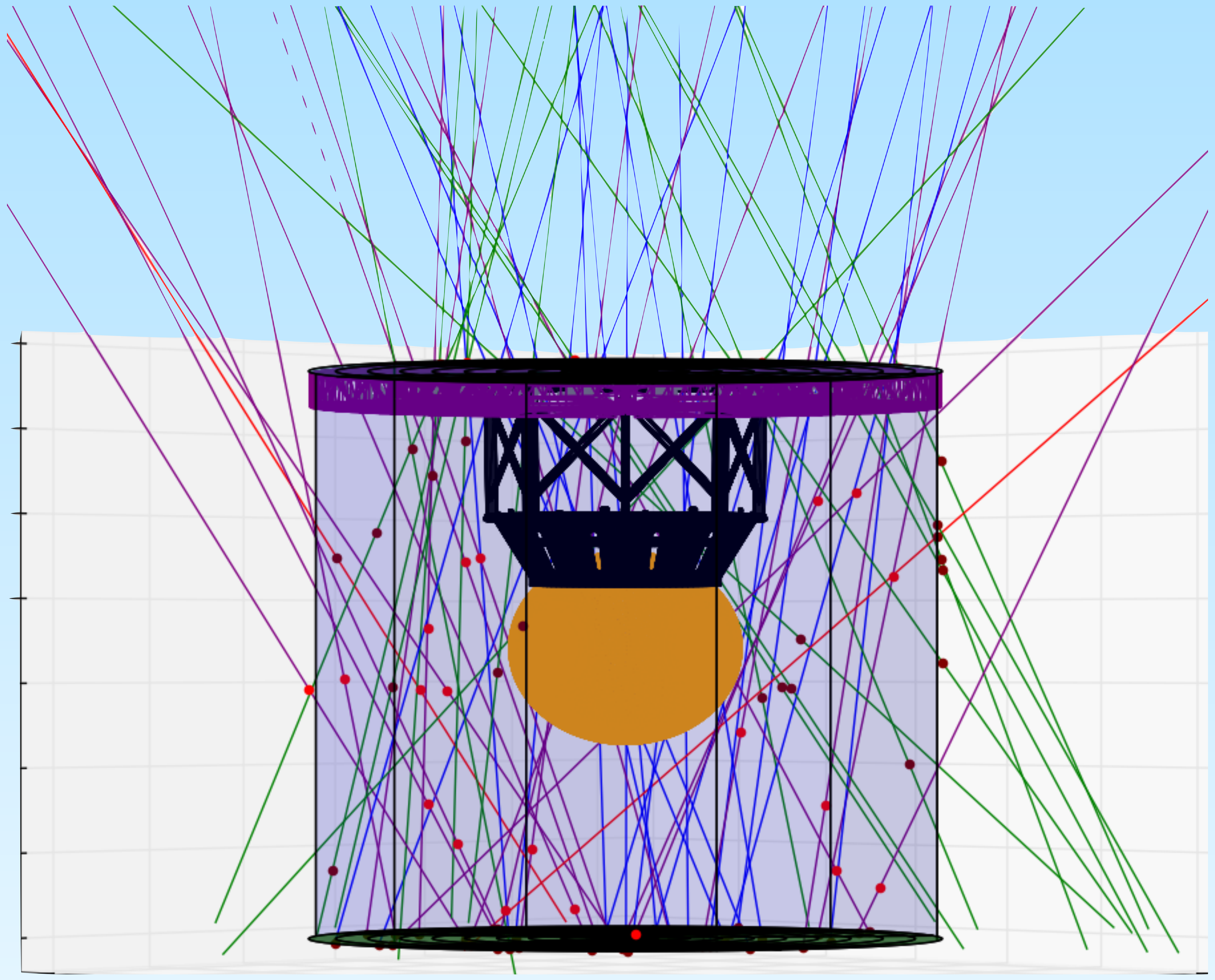
- Zenith angle from Mei and Hime [4]

$$I(\theta, X) = \left(I_1 e^{-X/\Lambda_1 \cos\theta} + I_2 e^{-X/\Lambda_2 \cos\theta}\right) \sec\theta$$

- Energy E_μ sampled from Gaisser:

$$\frac{dN}{dE_\mu d\Omega} \approx 0.14 E_0^{-2.7} \left(\frac{1}{1 + \frac{1.1 E_\mu \cos\theta}{115 GeV}} + \frac{0.054}{1 + \frac{1.1 E_\mu \cos\theta}{850 GeV}} \right)$$

- Instantiated on a disk above the OD



An average day of muons @ nEXO

Activation Rates

43.5 years simulated

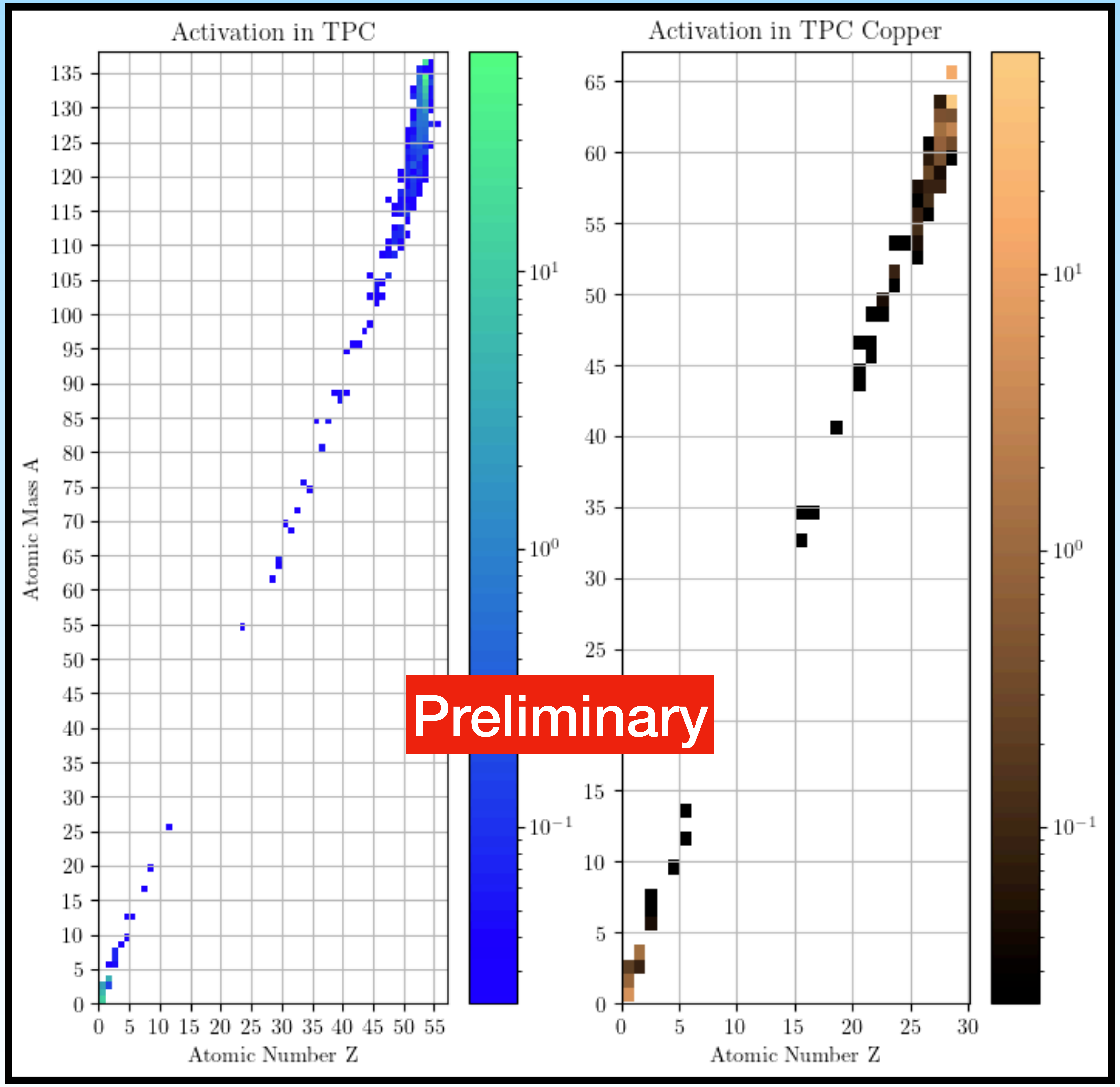
Small ROI

Production rates:

Xe-137— 21.86 atoms/yr

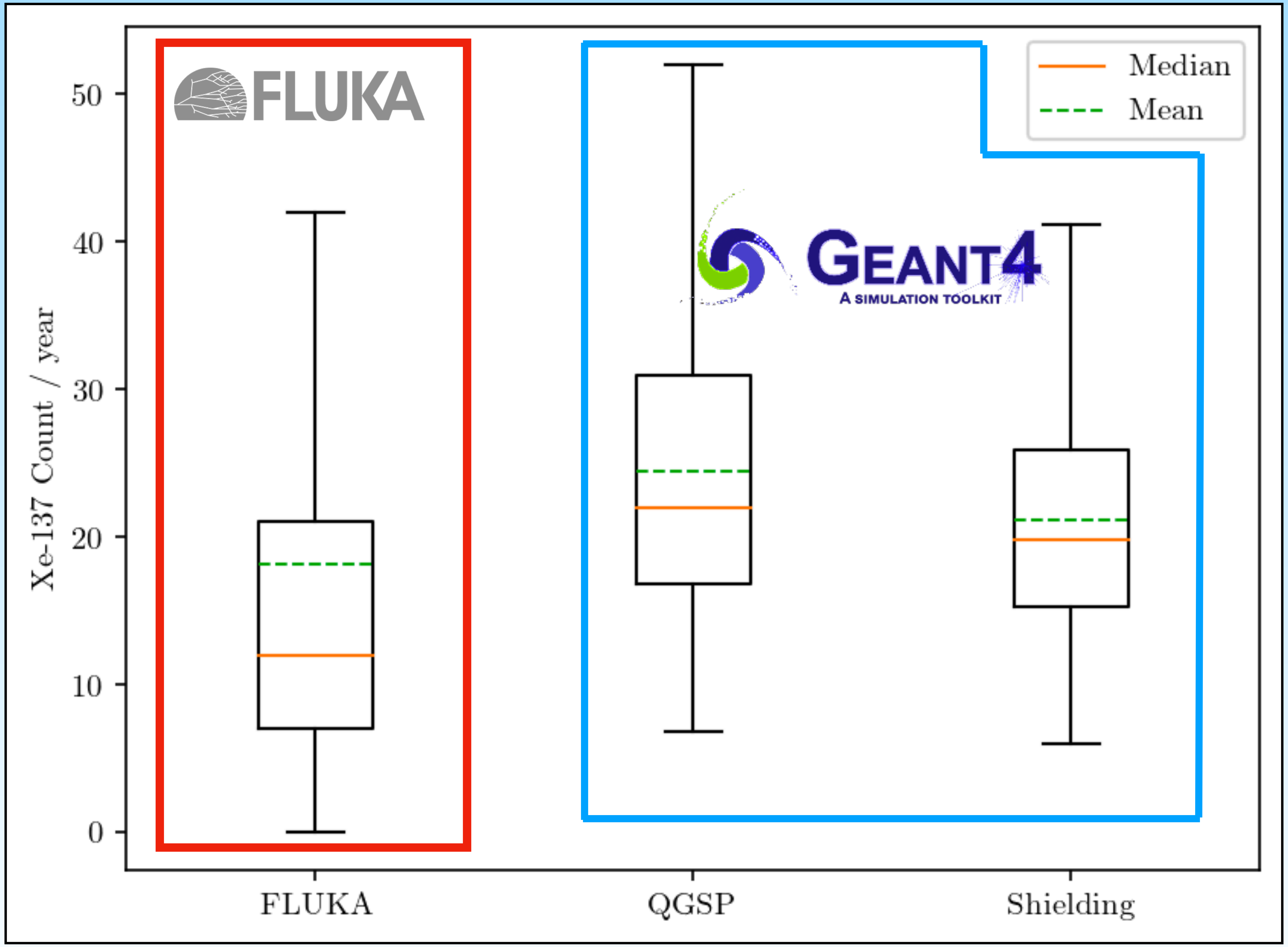
Cu-64— 63.46 atoms/yr

Cu-66— 13.69 atoms/yr



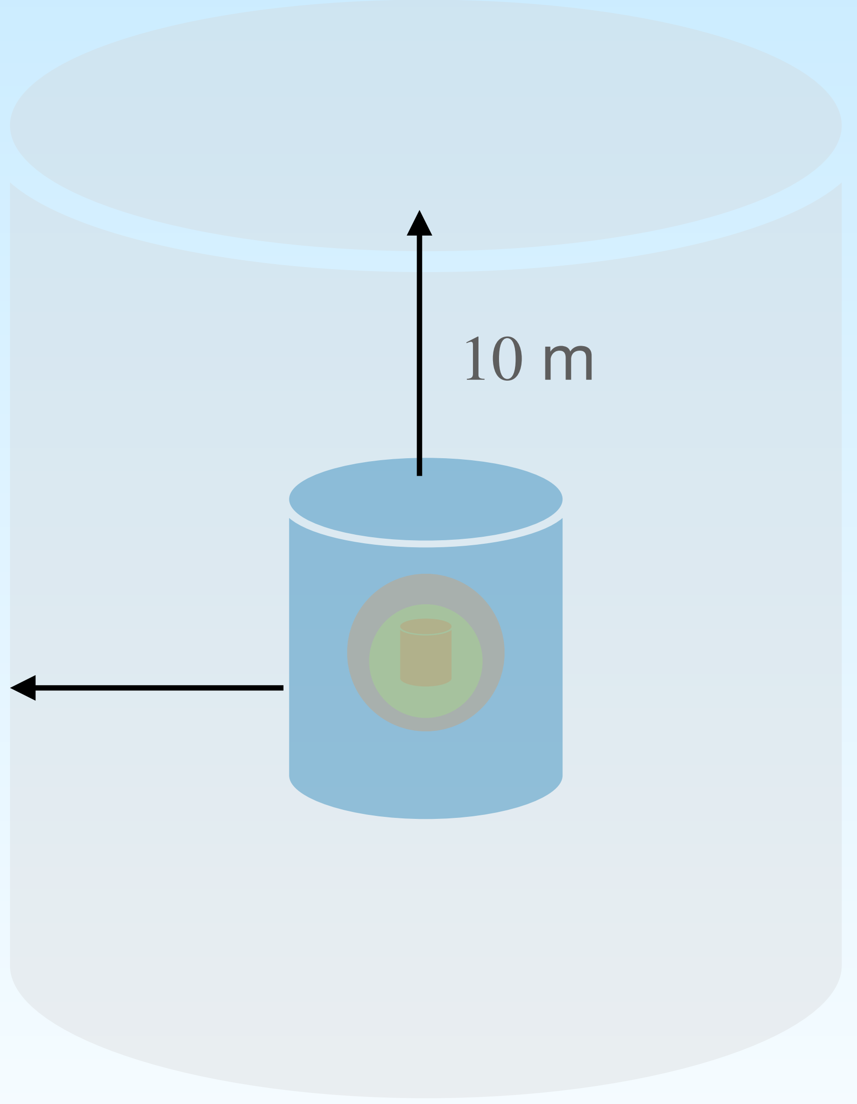
Xe-137 Activation

Activation rates for Xe-137 are consistent with other simulations based on GEANT4

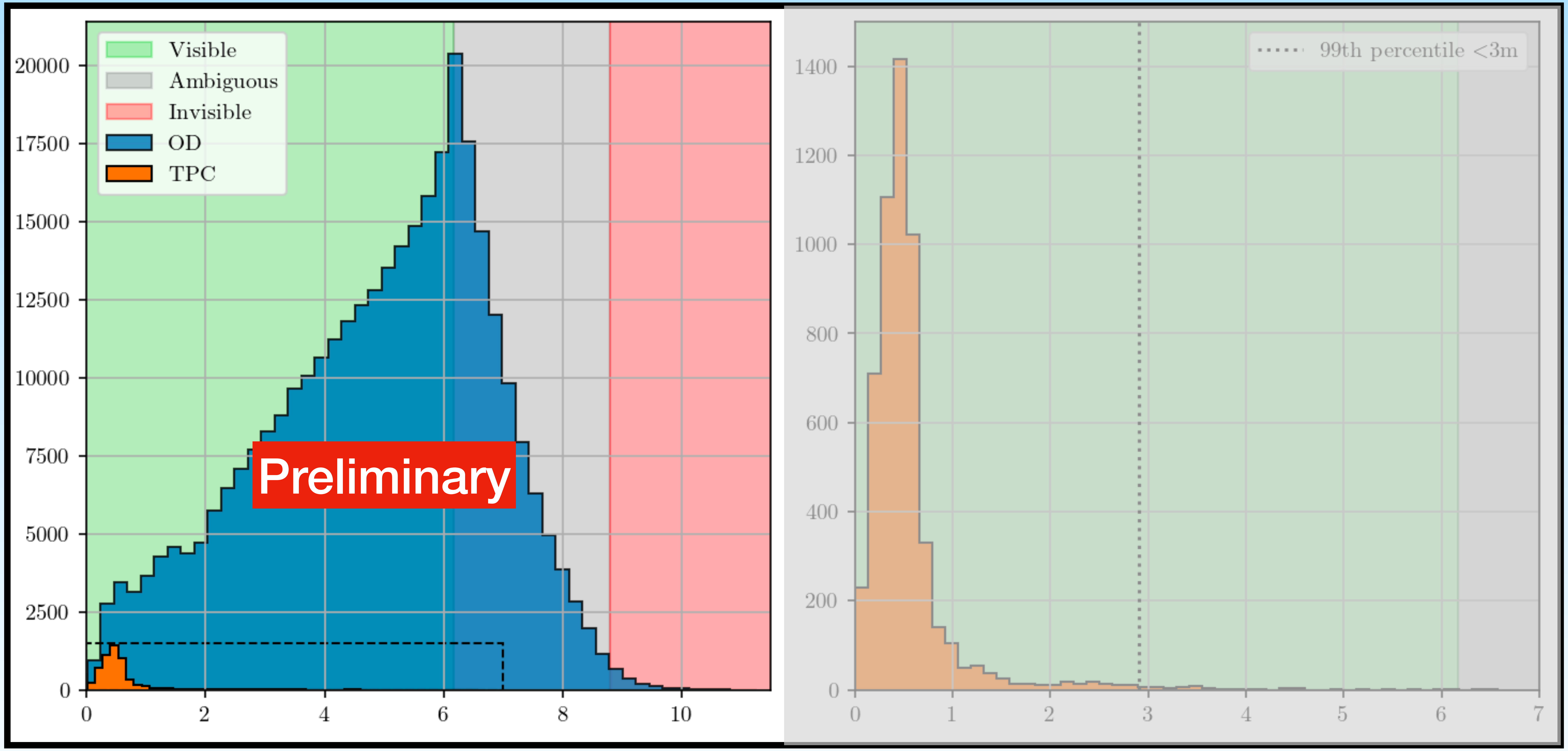


Muon Impact Parameters

Counts of μ that produce neutrons in the respective volumes



~150 yr of fluxes

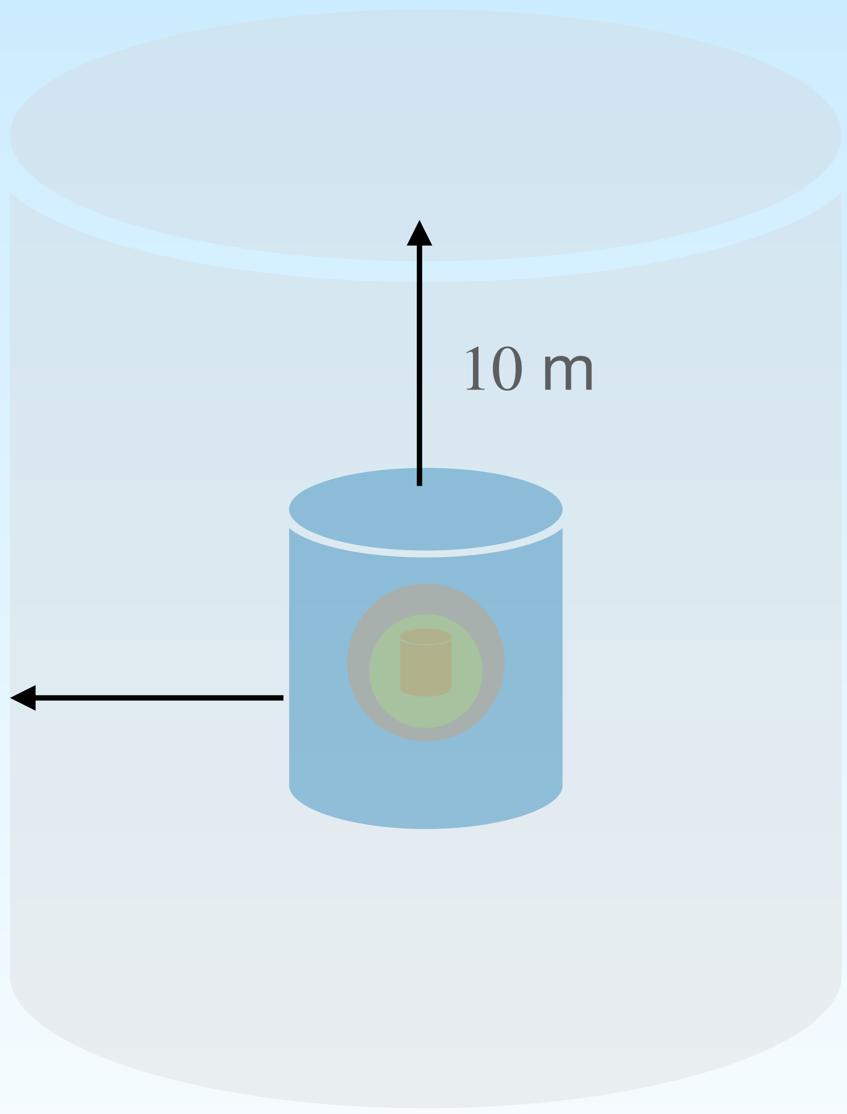


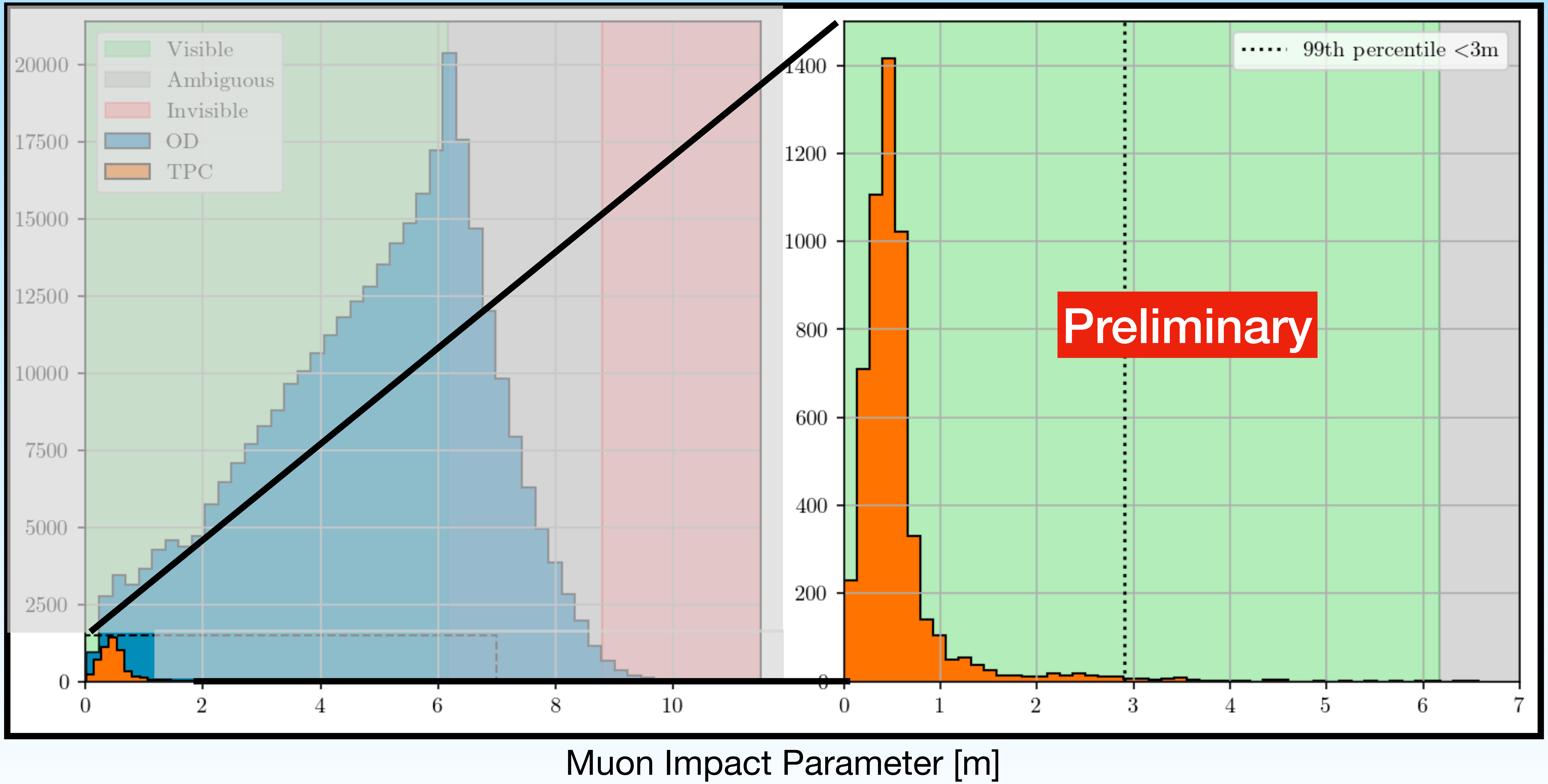
Muon Impact Parameter [m]

Muon Impact Parameters

~150 yr of fluxes

Counts of μ that produce neutrons in the respective volumes





Conclusions

- Muons that produce TPC backgrounds traverse the OD - we can *see* them
- Activation rates have been quantified and are consistent with GEANT4
- We don't have to worry about muon-induced showers in surrounding rock

Acknowledgements

Thank you for listening!

Thanks are also owed to:

- nEXO Outer Detector Group:
  Thomas Brunner, Ubi Wichoski, Erica Caden, Al Odian, Samin Majidi, Soud Al Kharusi
- Broader nEXO Collaboration
- WNPPC Organizers

Natural Sciences and Engineering Research Council of Canada
Conseil de recherches en sciences naturelles et en génie du Canada
Canada

References

1. nEXO Collaboration et al., NEXO: Neutrinoless Double Beta Decay Search beyond 10^{28} Year Half-Life Sensitivity, J. Phys. G: Nucl. Part. Phys. 49, 015104 (2022).

2. S. Al Kharusi, A Water-Cherenkov Muon Veto for the nEXO Neutrinoless Double Beta Decay Experiment, PhD Thesis, McGill University, 2023.

3. EXO Collaboration et al., Observation of Two-Neutrino Double-Beta Decay in ^{136}Xe with the EXO-200 Detector, Phys. Rev. Lett. 107, 212501 (2011).

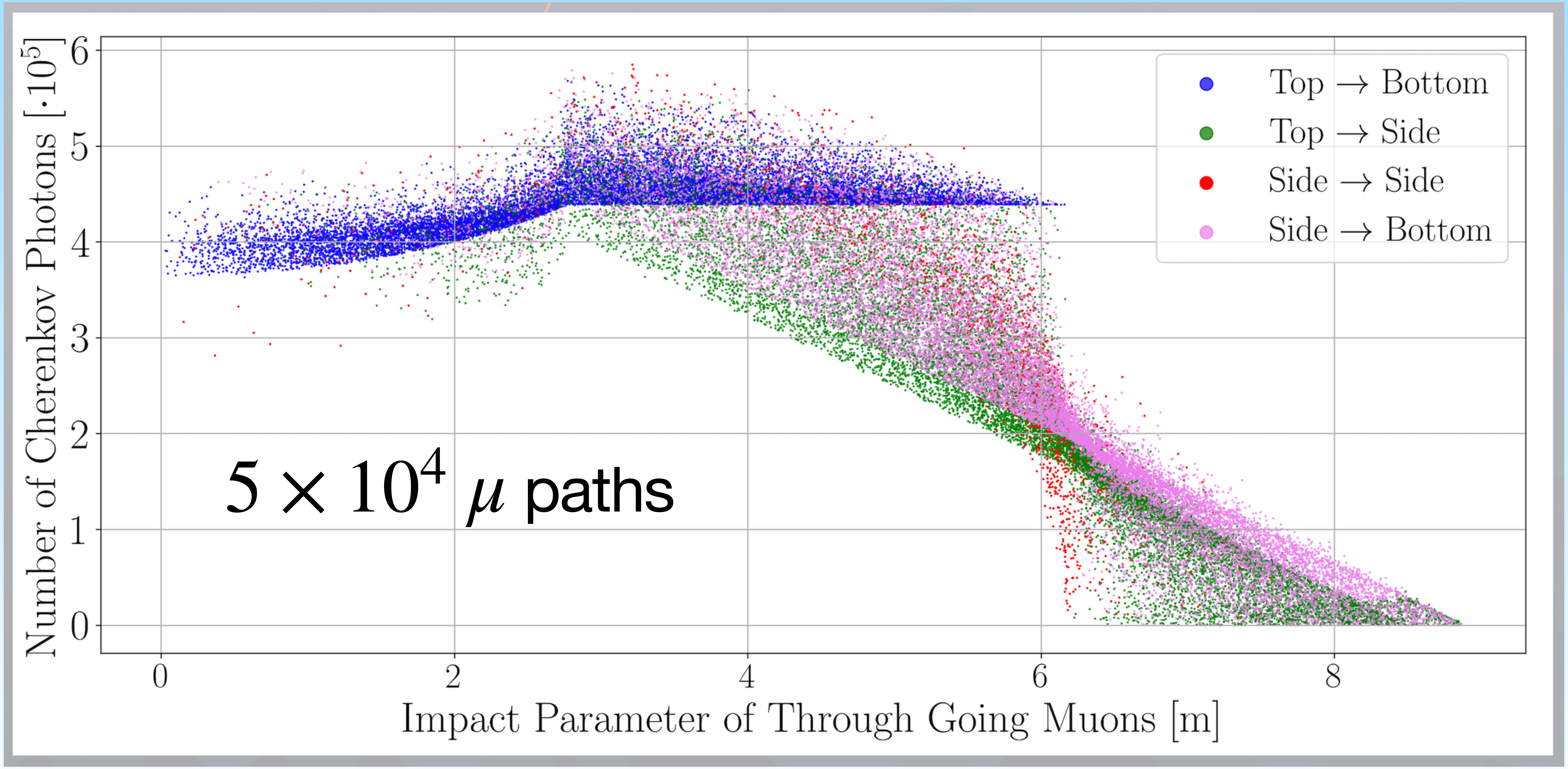
4. I. Frank and Ig. Tamm, Coherent Visible Radiation of Fast Electrons Passing Through Matter, in Selected Papers, edited by I. E. Tamm, B. M. Bolotovskii, V. Ya. Frenkel, and R. Peierls (Springer, Berlin, Heidelberg, 1991), pp. 29–35.

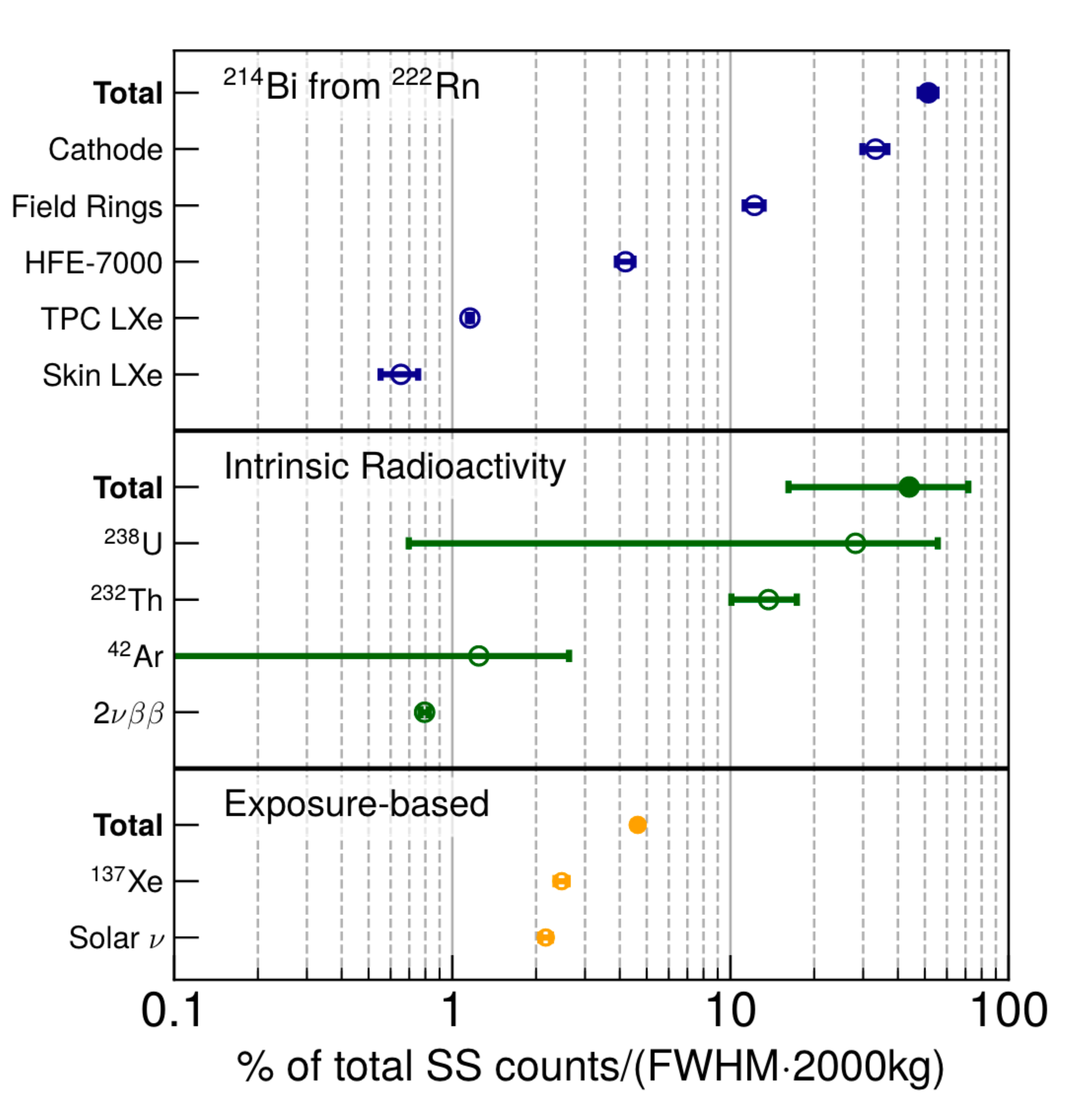
5. D.-M. Mei and A. Hime, Muon-Induced Background Study for Underground Laboratories, Phys. Rev. D 73, 053004 (2006)

6. T. K. Gaisser, R. Engel, and E. Resconi, Cosmic Rays and Particle Physics, Second edition (Cambridge University Press, Cambridge, 2016).

7. FLUKA collaboration, ”New Capabilities of the FLUKA Multi-Purpose Code”, Frontiers in Physics 9, 788253 (2022).

Bonus: Cherenkov Photons vs Impact Parameter




Total
Cathode
Field Rings
HFE-7000
TPC LXe
Skin LXe
214Bi from 222Rn
Intrinsic Radioactivity
Total
238U
232Th
42Ar
2νββ
Exposure-based
Total
137Xe
Solar ν
0.1
1
10
100
% of total SS counts/(FWHM·2000kg)