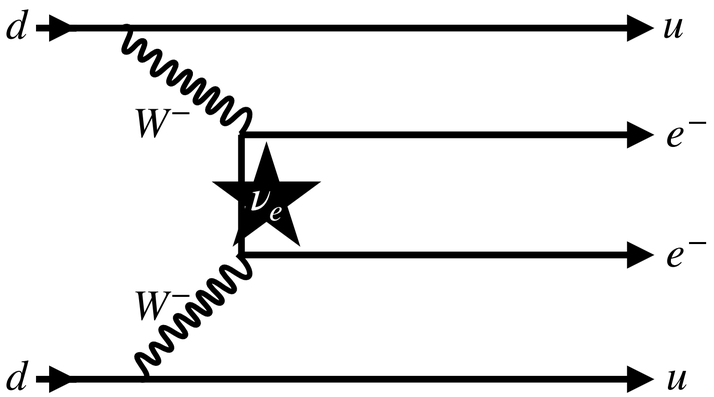
Cosmogenic Simulations for nEXO with G4 and FLUKA

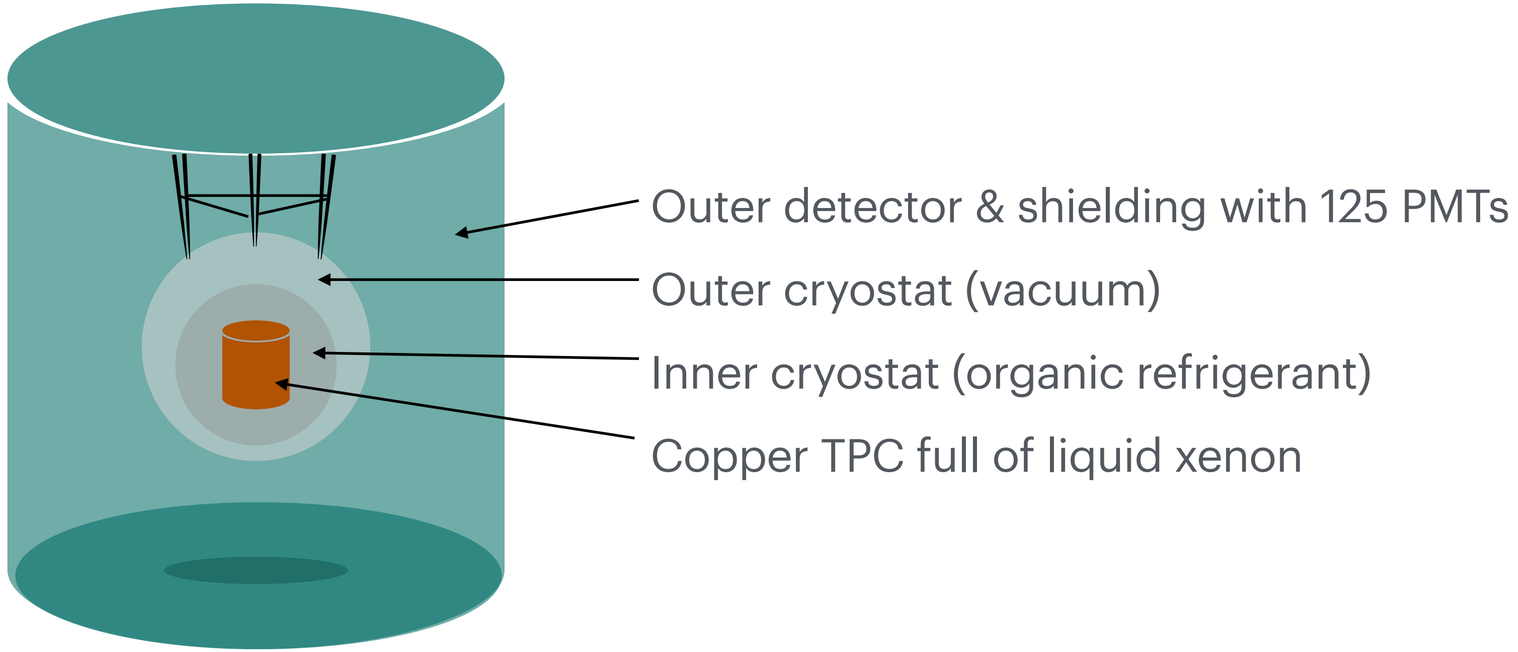
SNOLAB Users Meeting

Regan Ross, June 27, 2024

What is nEXO?

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





See the nEXO Sensitivity paper (2022)

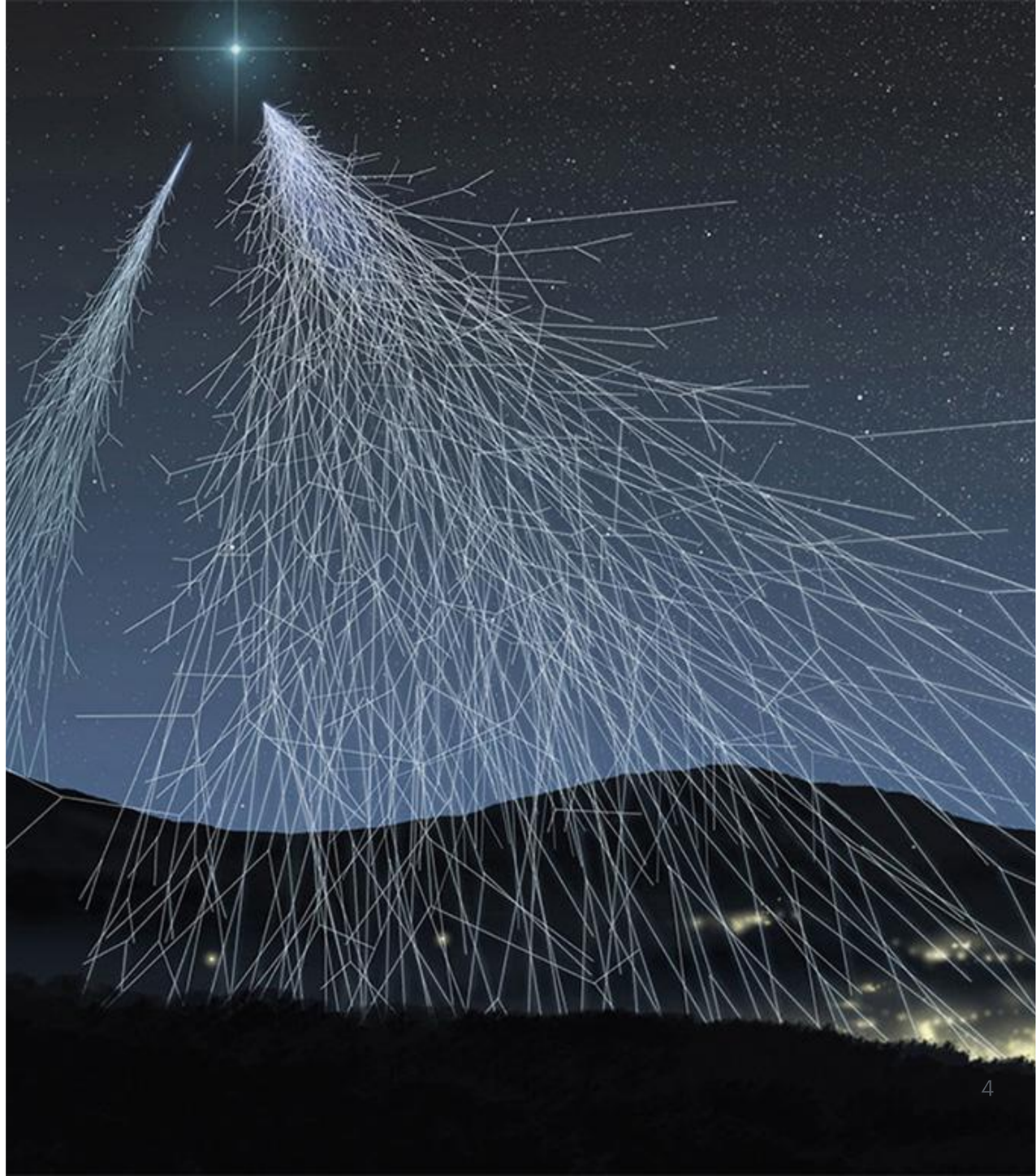
Cosmogenic Background to nEXO

Cosmic Rays!

The rain of particles will never cease

- About 1000 per m^2 per second hit Earth's atmosphere corresponding to
- roughly 1 μ (muon) per cm^2 per minute at sea-level (s.l.) (among other things).
- If you could see them (if they were slow and macroscopic) they'd look like a light rain.
- Would be an irreconcilable background to nEXO at their sea-level flux.

See PDG on cosmic rays



Cosmic Rays

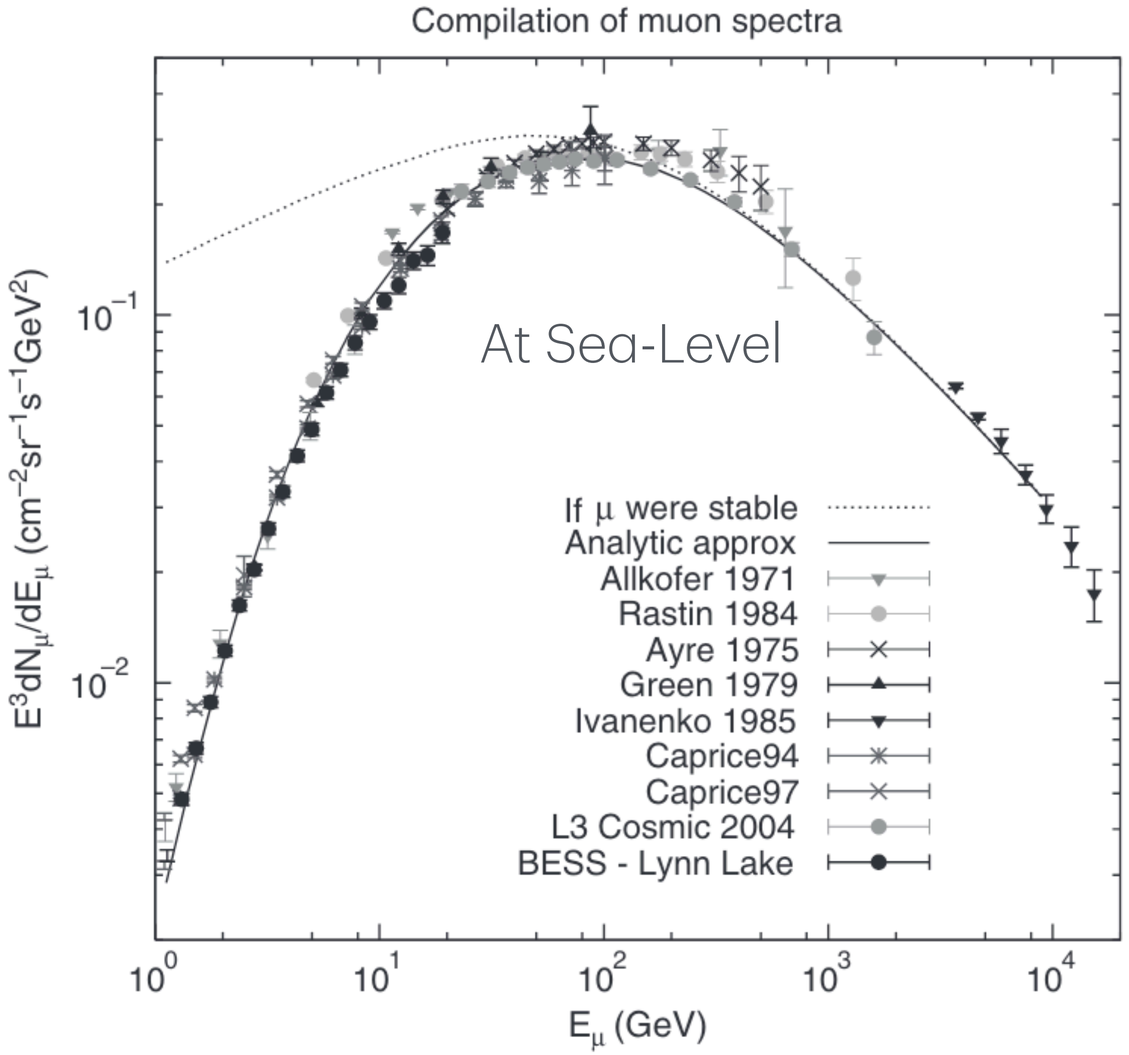
will present a background to nEXO— though not a dominant one.

- At SNOLAB, the muon flux is reduced by a factor of roughly 50 million.
- Backgrounds to nEXO are categorized:
  - 1. Intrinsic radioactivity of the stuff the detector is made of
  - 2. Outgassing of radon from the xenon (or materials wet by the xenon)
  - 3. Creation of radio-nuclides after commissioning (activation)

See the nEXO Sensitivity paper (2022) and the EXO-200 Cosmogenics paper

The Trouble with Muons

- μ's are very penetrating. They come with high energies: $\langle E_\mu \rangle \approx 4$ GeV @ s.l.
- They produce *fast* neutrons via:
  - muon spallation
  - muon-neutron elastic scattering
  - muon-induced EM showers
  - $\mu + A \rightarrow n \ + \ldots$



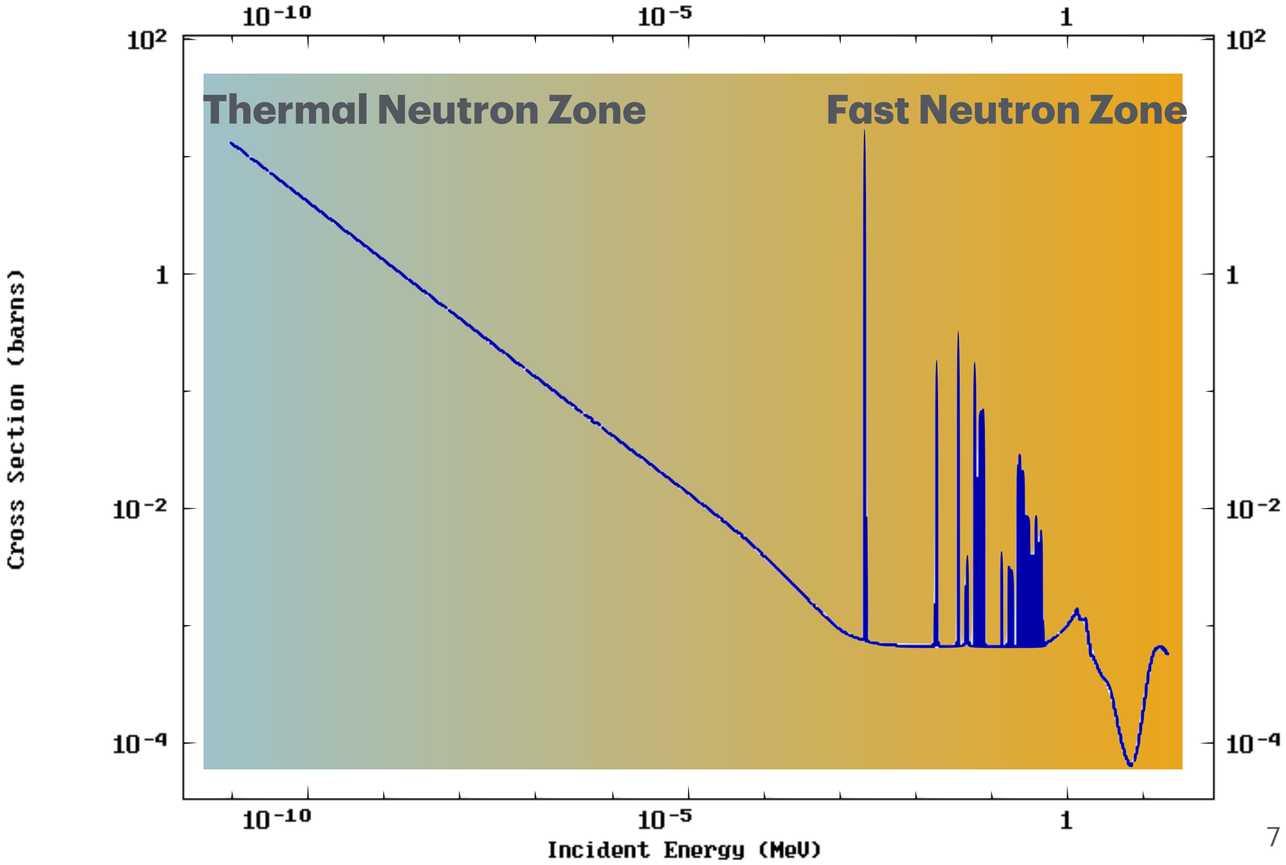
See Gratta's Neutron Production from Cosmic Ray Muons and Gaisser's *Cosmic Rays and Particle Physics*

$\mu \rightarrow n \Rightarrow$ trouble

Why do we care about the rogue neutrons?

- muons produce neutrons
- neutrons capture on Xe-136
- Xe-137 β decays
- its spectrum overlaps that for $0\nu\beta\beta$
- background!

$^{136}\mathrm{Xe}(n,\gamma)^{137}\mathrm{Xe}$ Cross Section



Evaluated Nuclear Data Files (ENDF) database

Cosmogenic activation of nEXO's xenon

muon spallation:

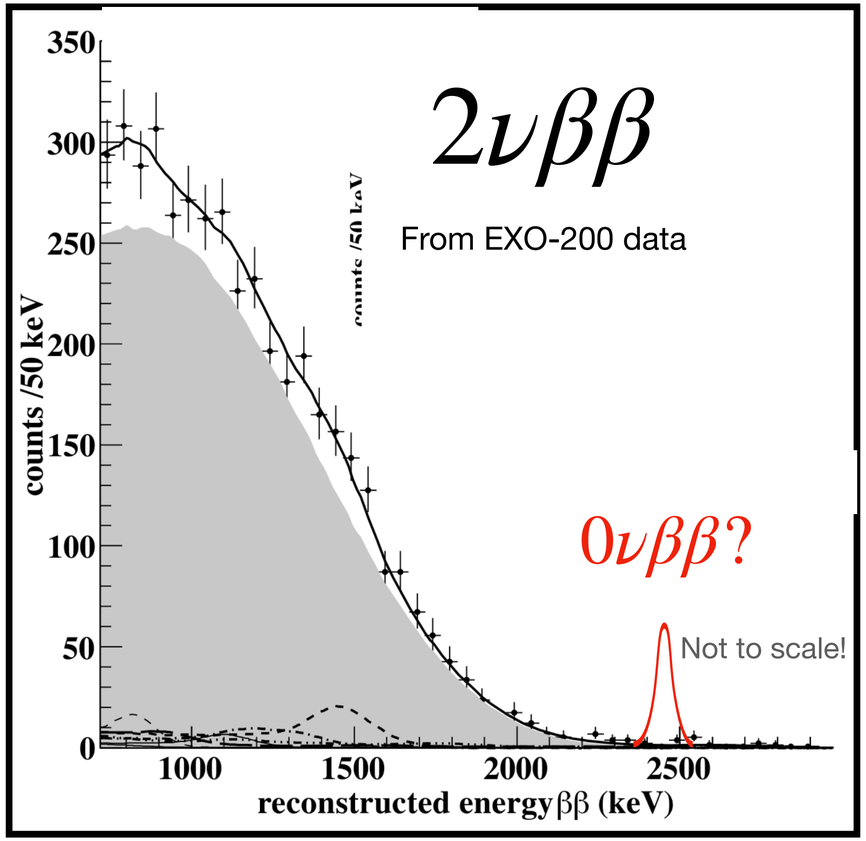
$$\mu + A \rightarrow n + \ldots$$

leads to neutron capture:

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

producing a signal-like event

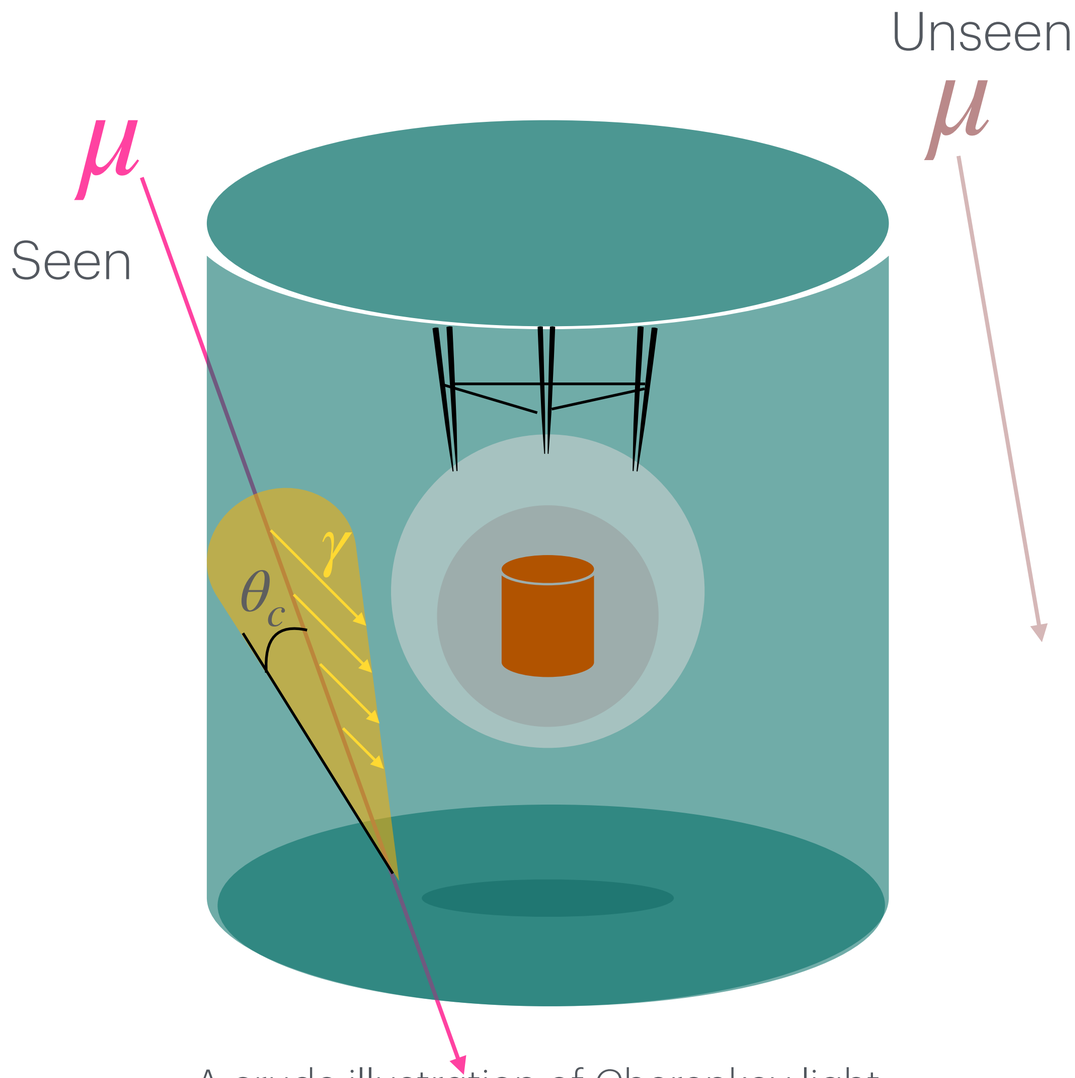
$$^{137}_{54}\mathrm{Xe} \rightarrow {}^{137}_{55}\mathrm{Cs} + e^- + \bar{\nu}_e\,, \quad Q_\beta = 4173\ \mathrm{keV}, \quad T_{1/2} \approx 3.8\ \mathrm{min}$$



Quantifying Activation

What do we want to know?

- What is the activation rate of Xe-136 in the TPC due to muons?
- What are the activation rates of other detector constituents— namely copper or refrigerant?
- How many of the activations are due to muons we *can't see?*



A crude illustration of Cherenkov light being produced by a muon

See Frank & Tamm's Legendary Paper

Simulations with FLUKA & GEANT4

Simulating Muons

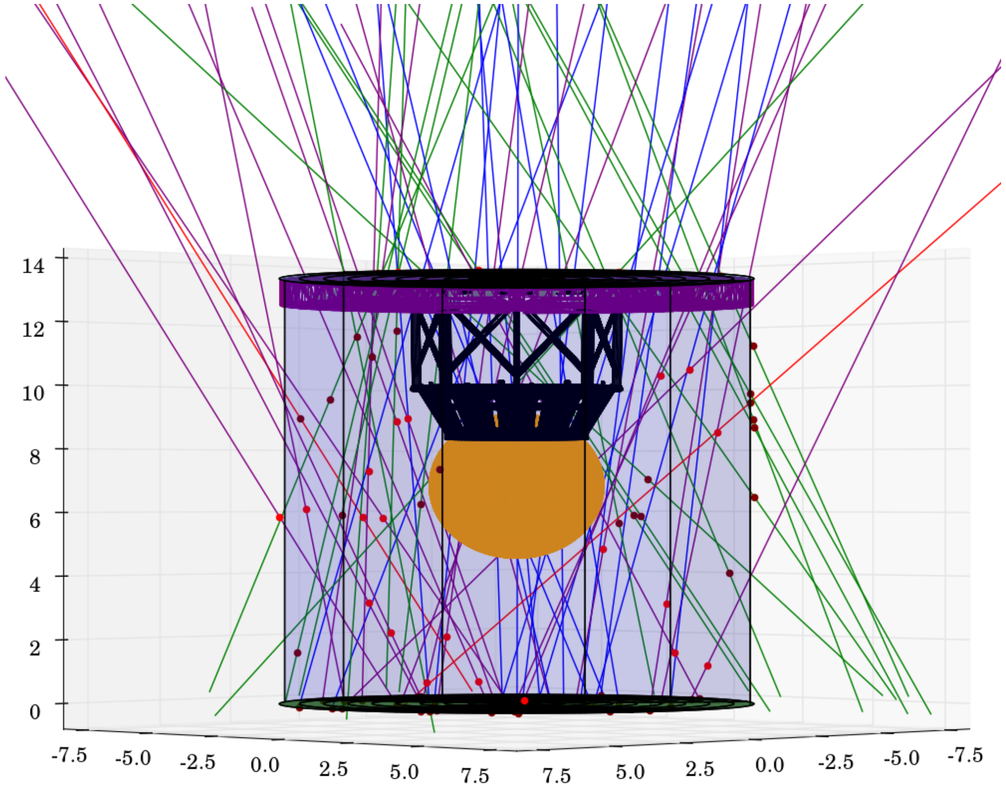
A Menu

- **CRY** (**C**osmic-**R**ay Simulation Librar**y**); Based on parameterization of galactic proton energies
- **MUSIC** (**Mu**on **Si**mulation **C**ode); For high energy muons propagating through rock
- **MUSUN** (**Mu**on **S**imulations **Un**derground); **MUSIC** but simplified for underground labs
- **MUTE** (**Mu**on Intensi**t**y Cod**e**); Based on **MCEQ** at sea-level and **PROPOSAL** for propagation.
- Or… write your own mini Monte Carlo.

Simulating Muons

What we did

- Presuppose azimuthal symmetry (flat overburden)
- Choose a **zenith angle** θ (see Mei & Hime)
- $I_{th}(h,\theta) = \left(I_1 e^{\left(-h_0 \sec(\theta)/\lambda_1\right)} + I_2 e^{\left(-h_0 \sec(\theta)/\lambda_2\right)} \right) \sec(\theta)$
- Given zenith angle, choose an **energy** (Gaisser)
- $$\frac{\mathrm{d}N_\mu}{\mathrm{d}E_\mu} \approx \frac{0.14 E_\mu^{-2.7}}{\mathrm{cm}^2\ \mathrm{sec}\ \mathrm{sr}\ \mathrm{GeV}} \left\{ \frac{1}{1 + \frac{1.11 E_\mu \cos\theta}{115\mathrm{GeV}}} + \frac{0.054}{1 + \frac{1.11 E_\mu \cos\theta}{850\mathrm{GeV}}} \right\}$$

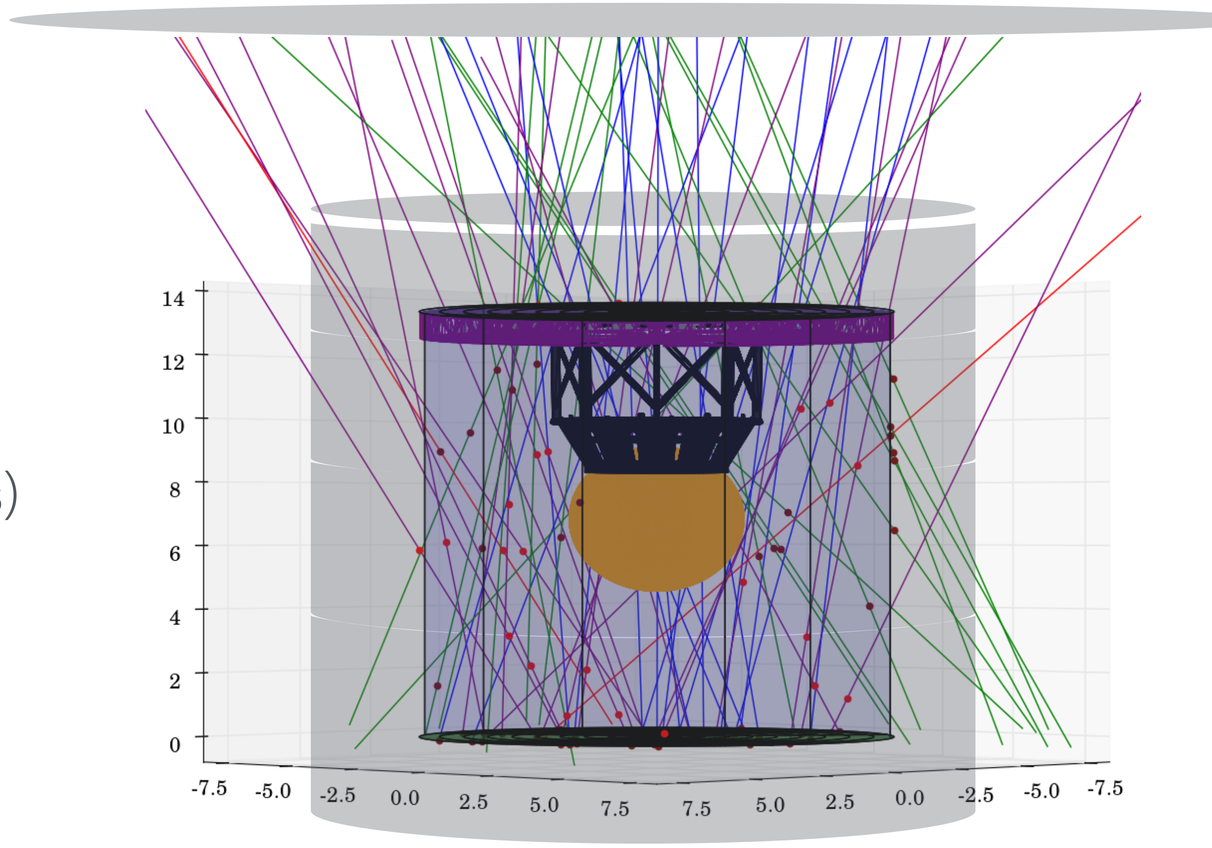


An average day's worth of muons hitting nEXO (~55)

Simulating Muons

What we did

- Choose a point on a disk above nEXO in the norite rock from which to propagate the muon
- Simulate only those that pass within a particular target volume (solve some parametric equations)
- Assign a muon charge (assuming fixed +/- ratio)



An average day's worth of muons hitting nEXO (~55)

Muons get passed to

- A multi purpose particle simulation code
- Comprehensive physics built-in by default
- A license required from CERN
- Implemented in FORTRAN77
- Sources external cross section libraries
- Treatment of neutrons down to thermal energies
- Particle ancestry NOT easily accessible

- A toolkit for *building* simulations
- Users must choose specific physics processes to include
- Open source, implemented in C++
- Sources external cross section libraries
- Highly customizable
- Particle ancestry easily accessible

Muons get passed to

FLUKA

Version 4-4.0

- Precision defaults PRECISIO(n)
- PHOTONUC(lear): interactions enabled
- MUPHOTON: muon photonuclear interactions enabled
- Neutron transport floor: $10\ \mu$eV
- Low-energy point-wise cross sections activated for all materials (LOW-PWXS)

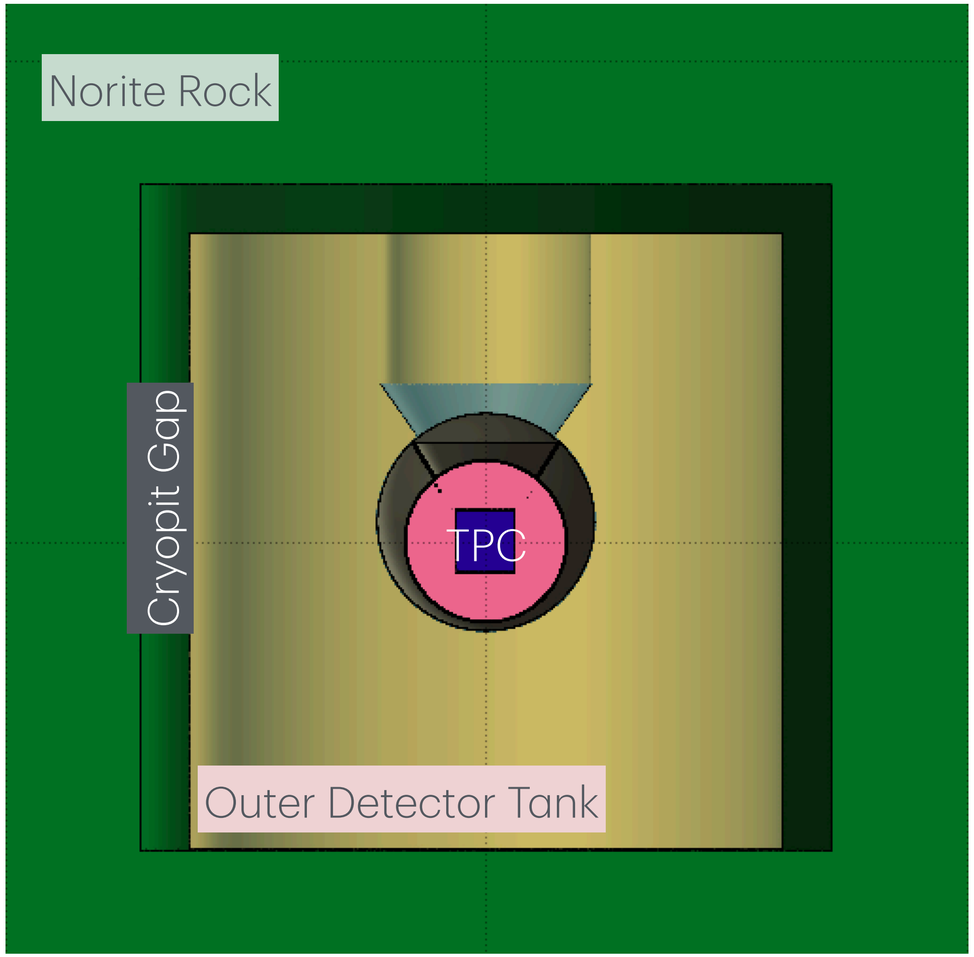
GEANT4
A SIMULATION TOOLKIT

Version 10.7

- Three standard physics lists deployed:
  - QGSP_BERT_HP
  - QGSP_BIC_HP
  - Shielding

For reference:
- KamLAND-Zen cosmogenics paper (FLUKA)
- DARWIN cosmogenics paper (GEANT4)

nEXO Geometry in FLUKA



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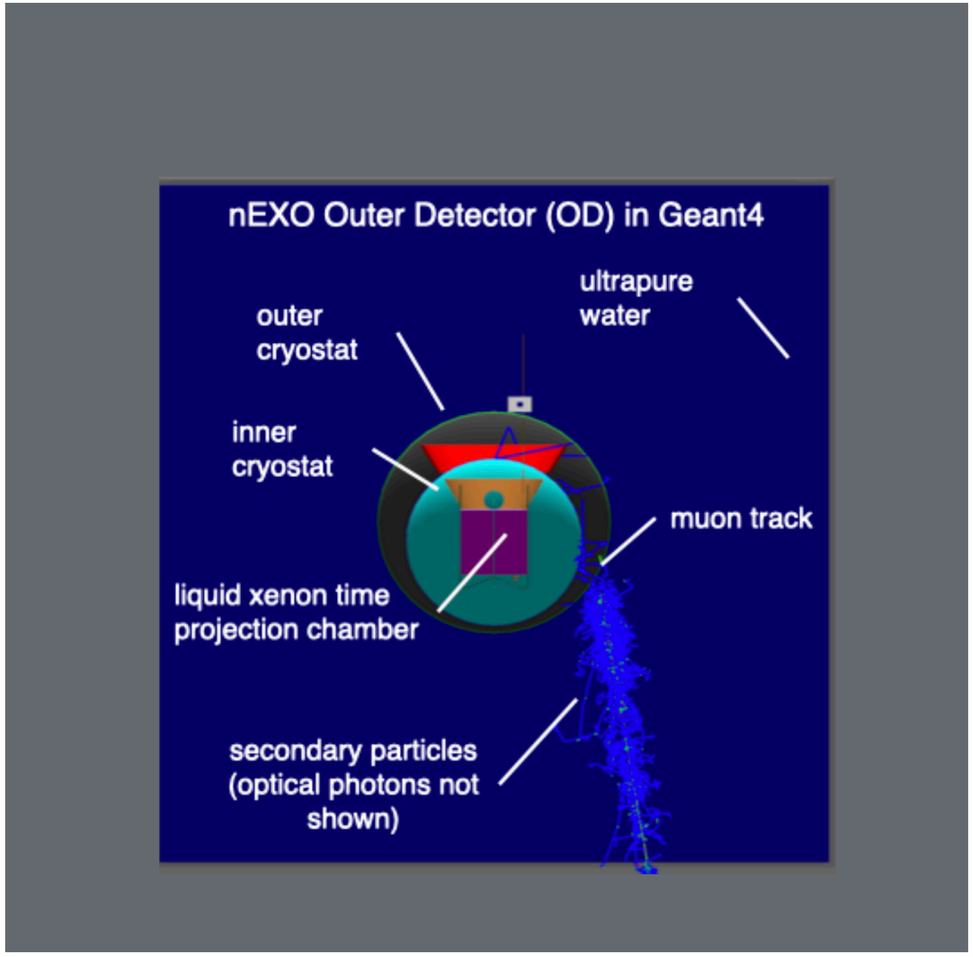


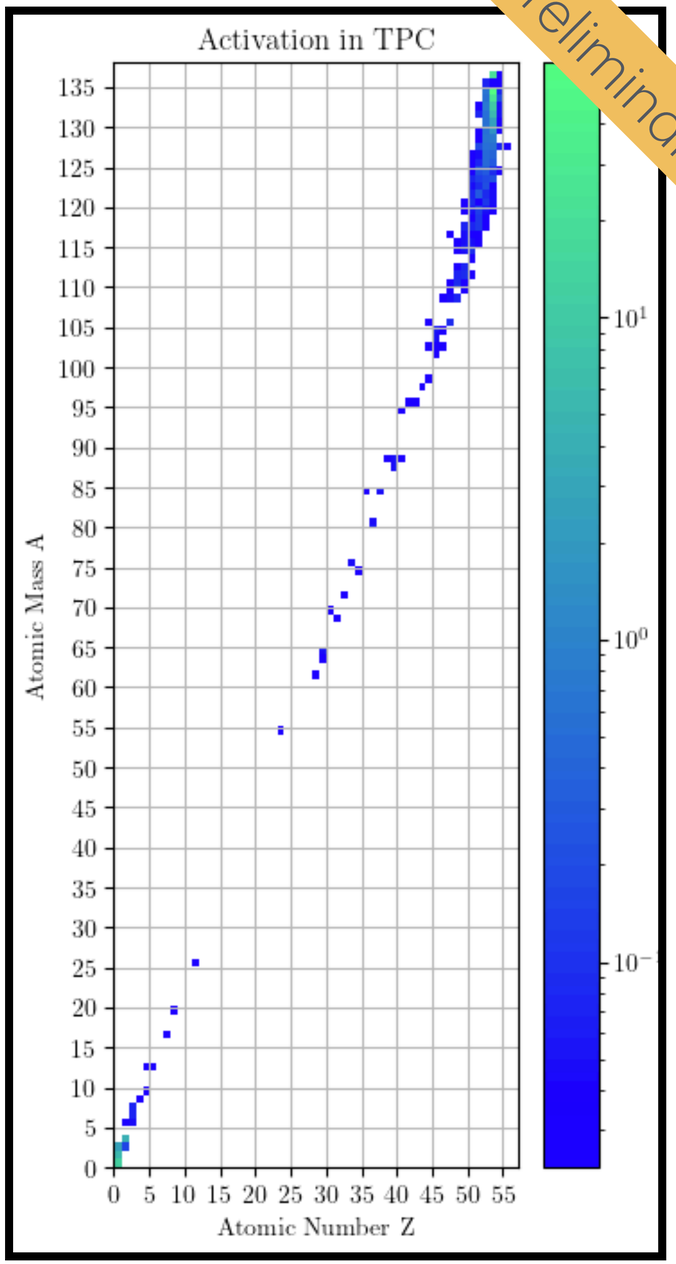
FLUKA Outputs

Built-in Scoring

- *Residual Nuclei* (stopping nuclei in a given region)

Custom Scoring

- Neutron attributes scored by region
- Neutrons produced vs muon impact parameter
- Neutron-muon parent relationship



Preliminary

Activation

Atoms per Year

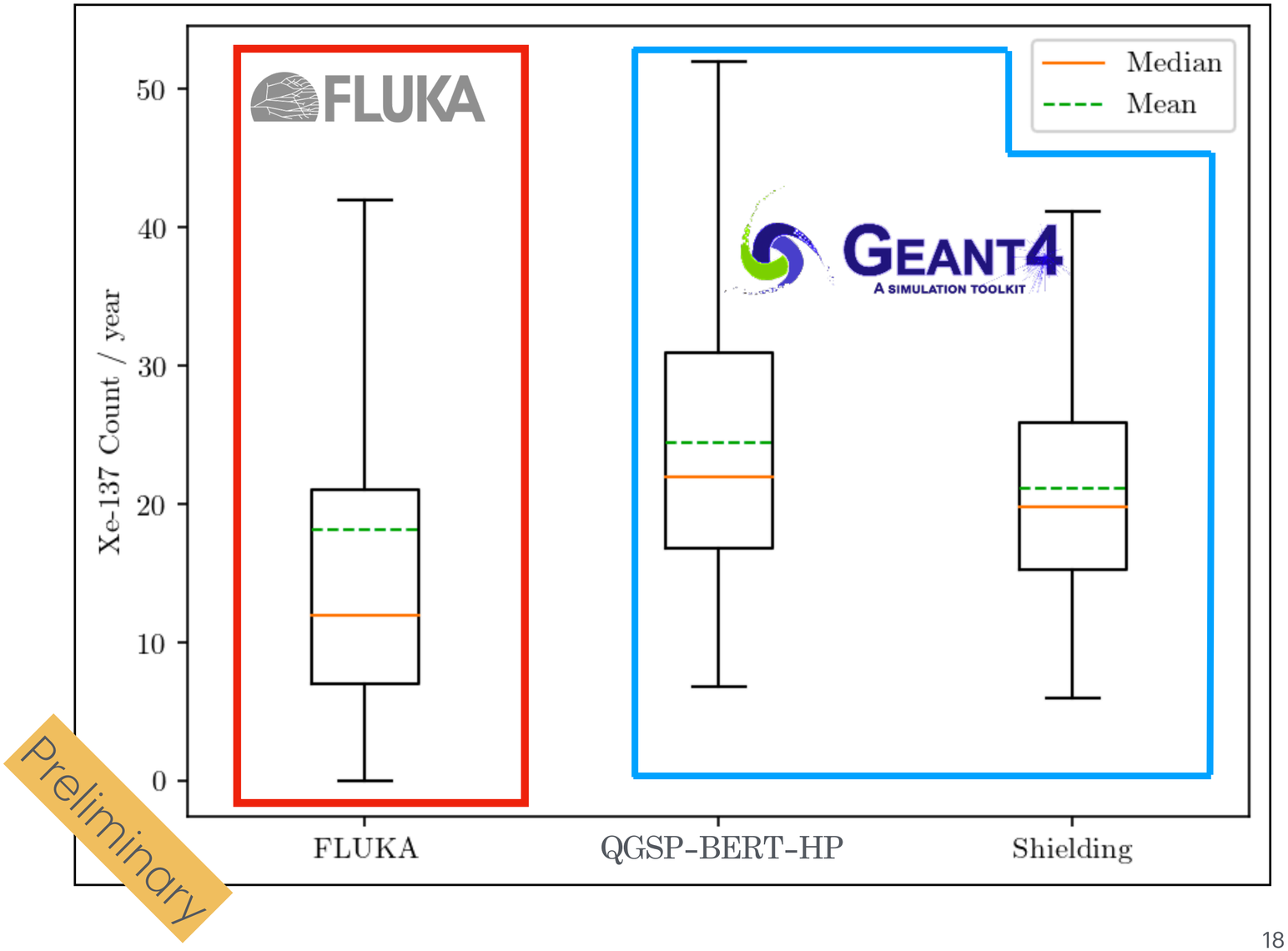
Production rates (FLUKA).

Xe-137— 21.86 atoms/yr (β)

Cu-64— 63.46 atoms/yr ($\beta\pm$, γ)

Cu-66— 13.69 atoms/yr ($\beta\pm$, γ)

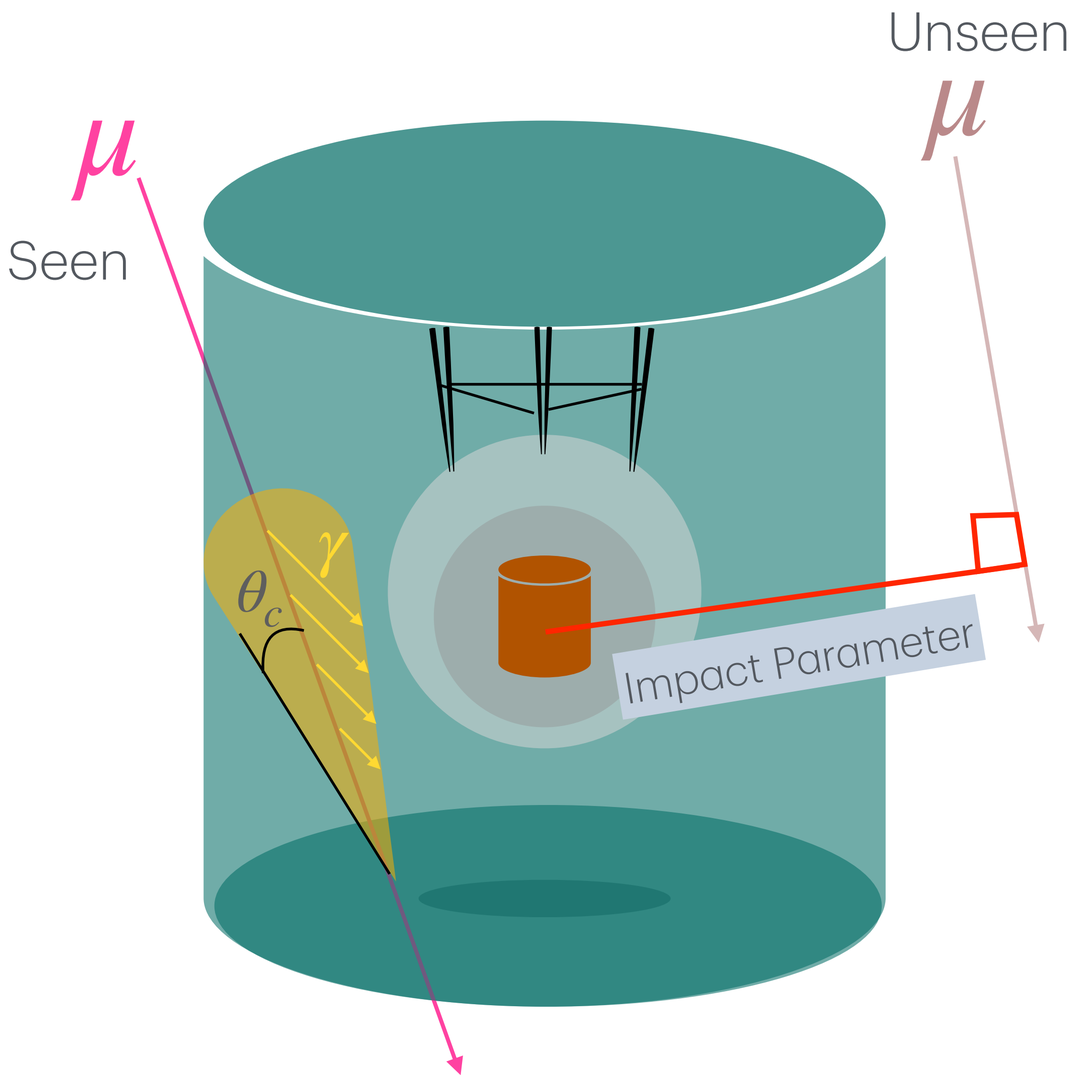
Xe-137 Production



Impact Parameter

Defined

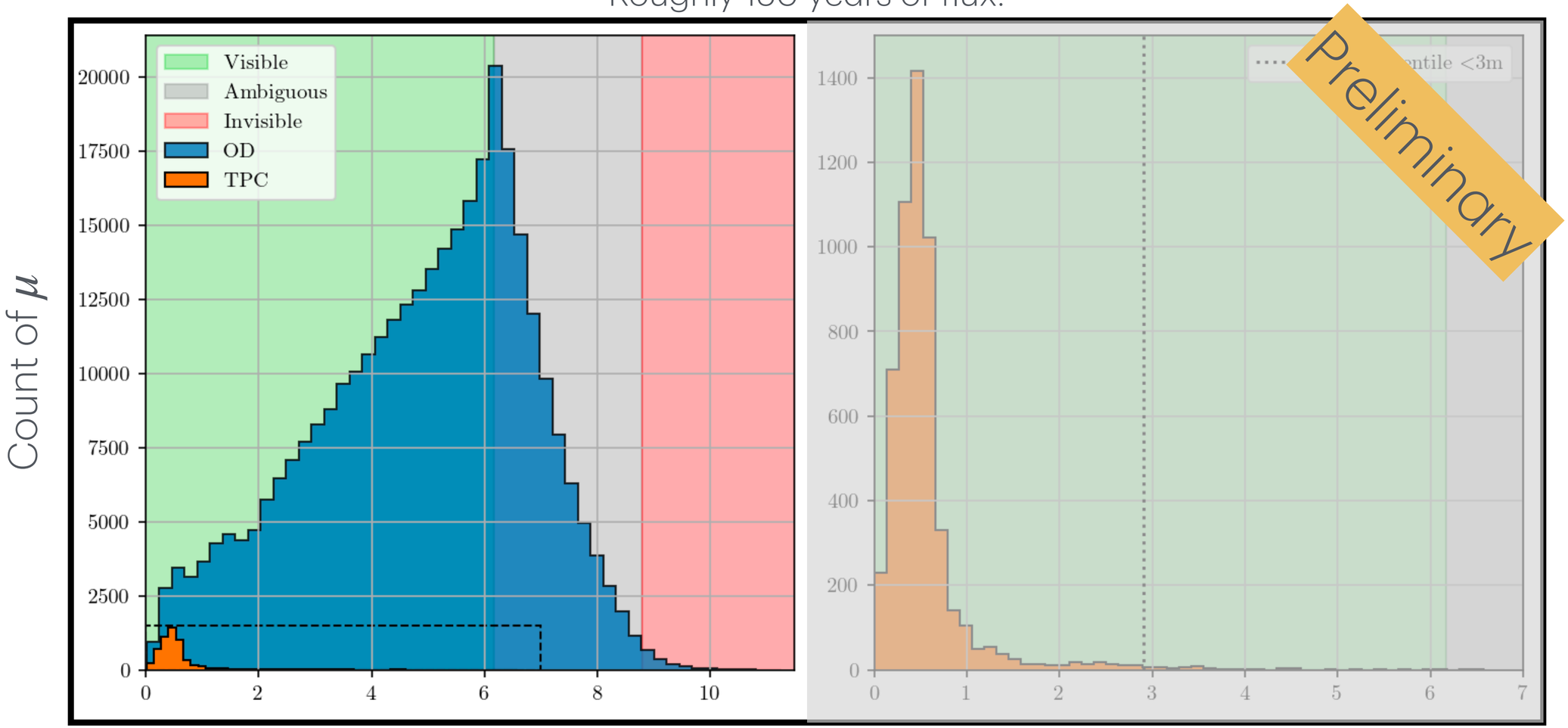
The distance of closest approach of a muon track (~ straight line) to the centre of nEXO's TPC.



Impact Parameters

How many muons that we don't see sent neutrons into nEXO?

Roughly 150 years of flux.



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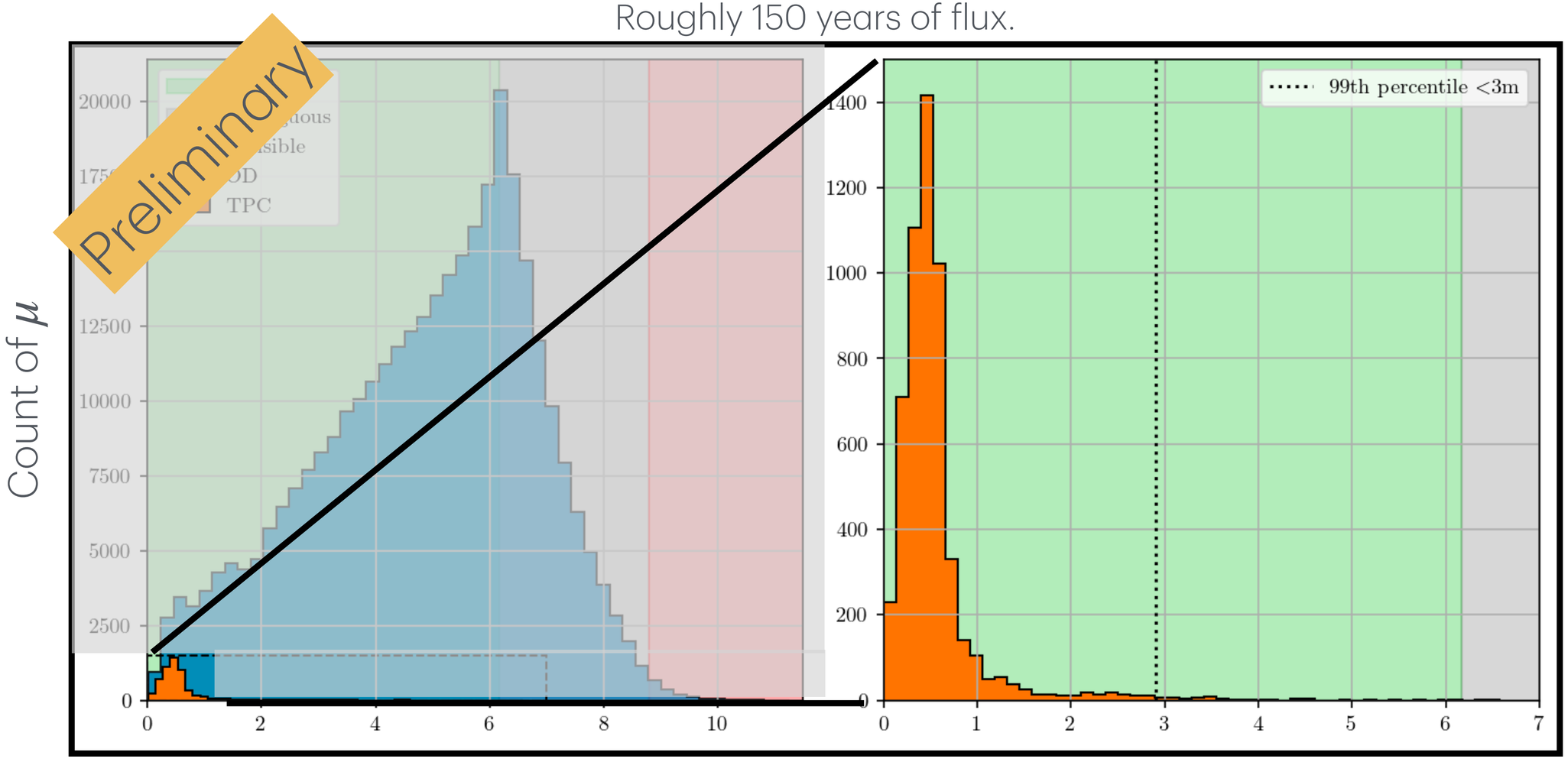
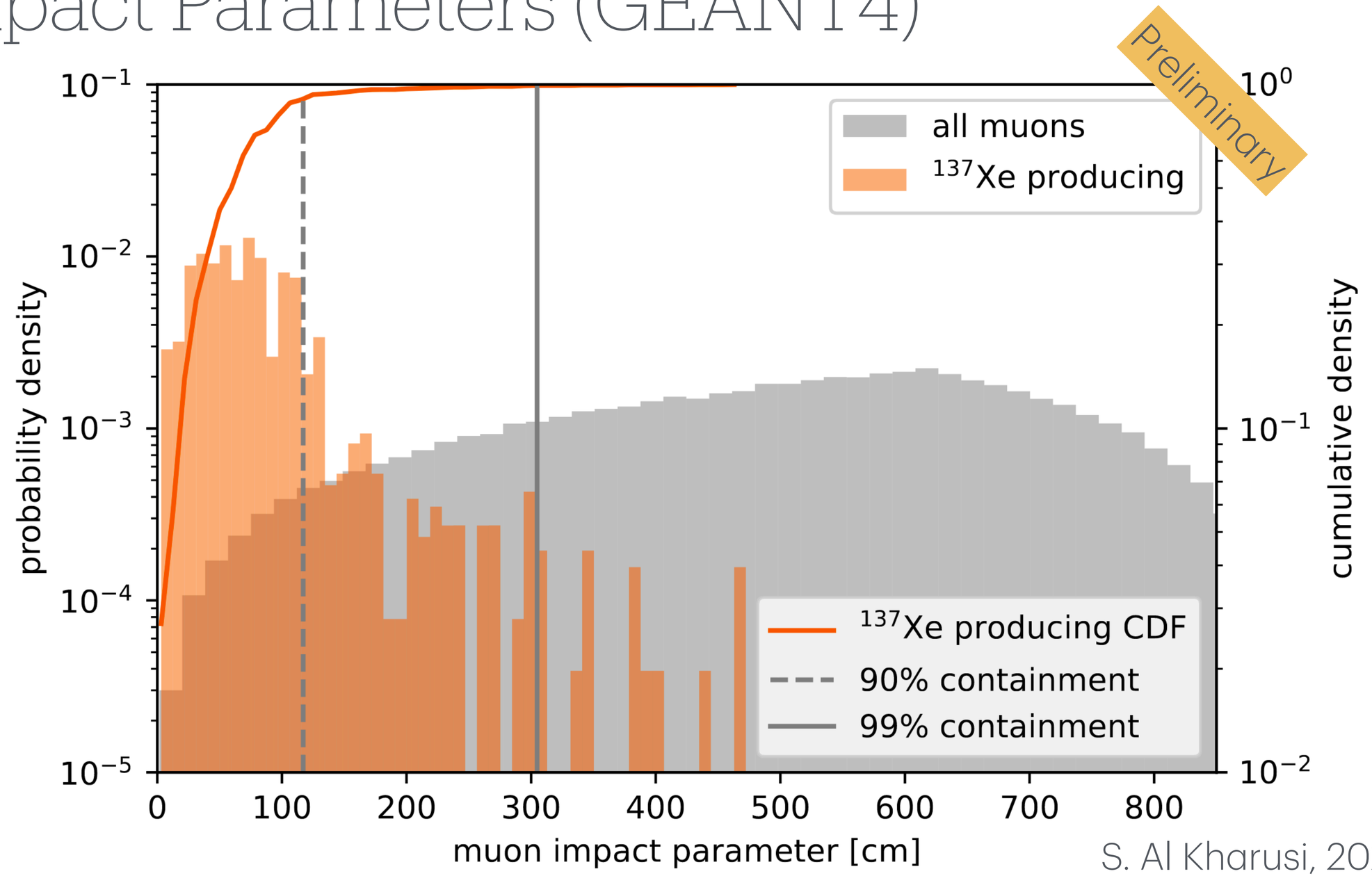


Impact Parameters (GEANT4)



S. Al Kharusi, 2023

Thank you for listening!

I'm happy to take your questions.

Thanks are also owed to the organizers, the nEXO collaboration, and the Brunner group at McGill.

Please contact me if you have any other questions:

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