DELight Cosmic Backgrounds

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DELight Meeting 26/03/2024

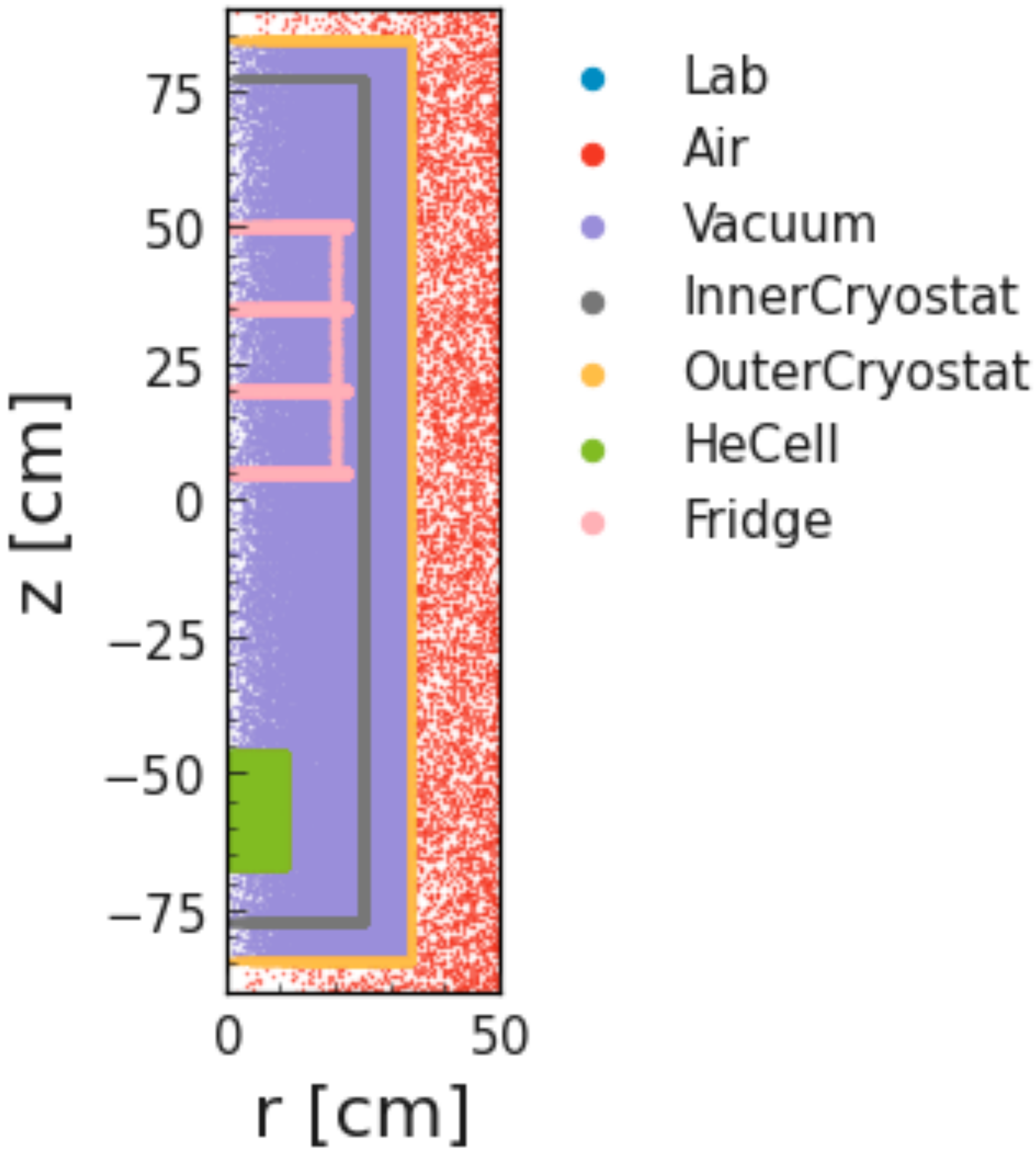
Overview

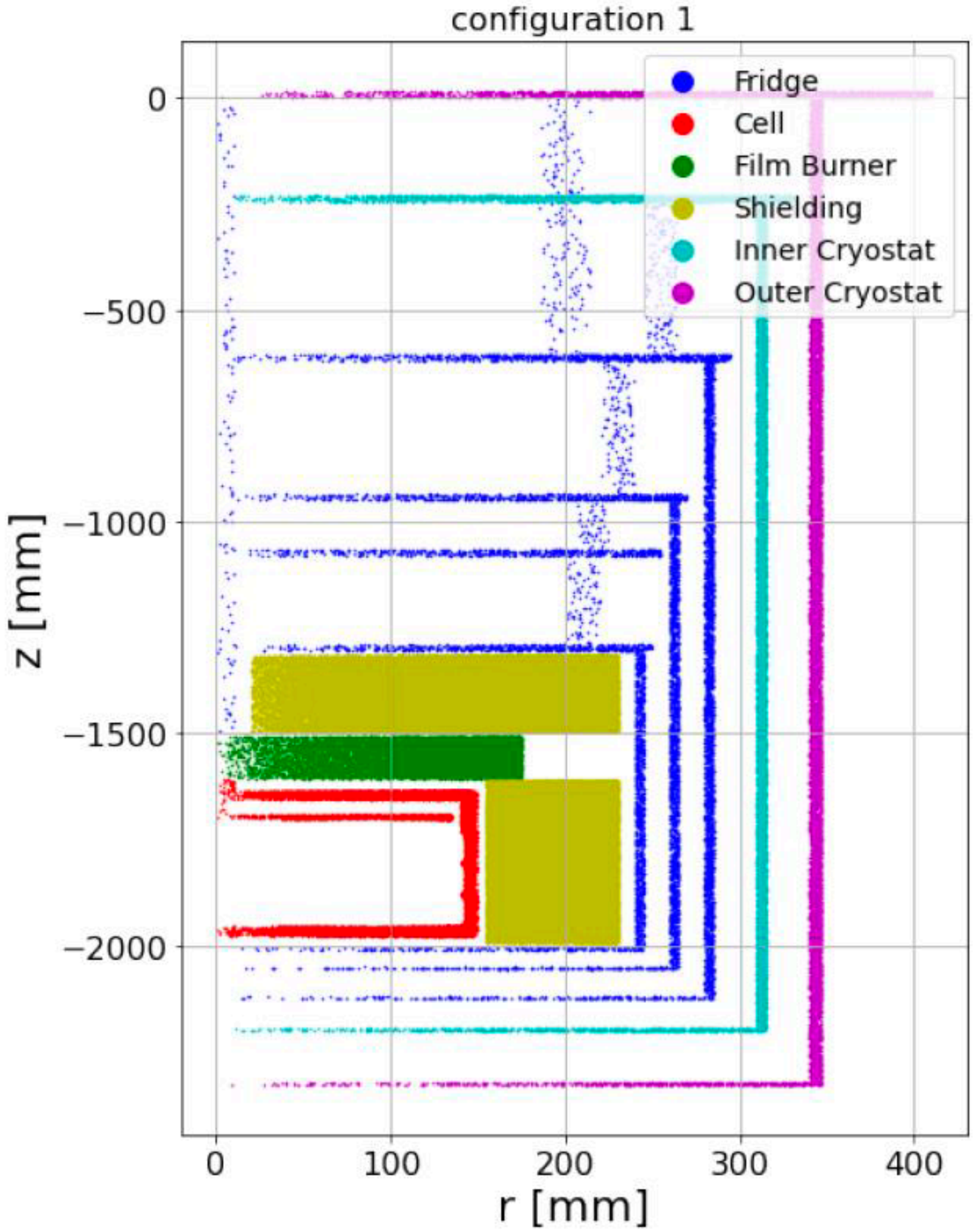
- Cosmic ray showers result in muon and neutron backgrounds at sea level
- Muon backgrounds are attenuated in underground labs, neutron backgrounds are generally removed entirely
- Cosmic neutron backgrounds for DELight have not yet been simulated (as far as I know…)
- Francesco performed preliminary simulations for the muon ER and NR backgrounds
    - Since then, there have been significant updates to detector/cryostat/lab geometry in simulation package
    - + addition of internal (lead) shielding
- Goal: redo the simulations with the updated geometry, extend to lower energies, and check the cosmic neutron background rate

Francesco's Note on ER Simulations

Francesco's Note on NR Simulations

Updated Geometry





Cosmic Muons

Cosmic Muon Spectra

- Cosmic particle flux is given as a function of energy and zenith angle
- Francesco's original simulations used the modified Gaisser formula
  - Not valid for muon energies below 10GeV

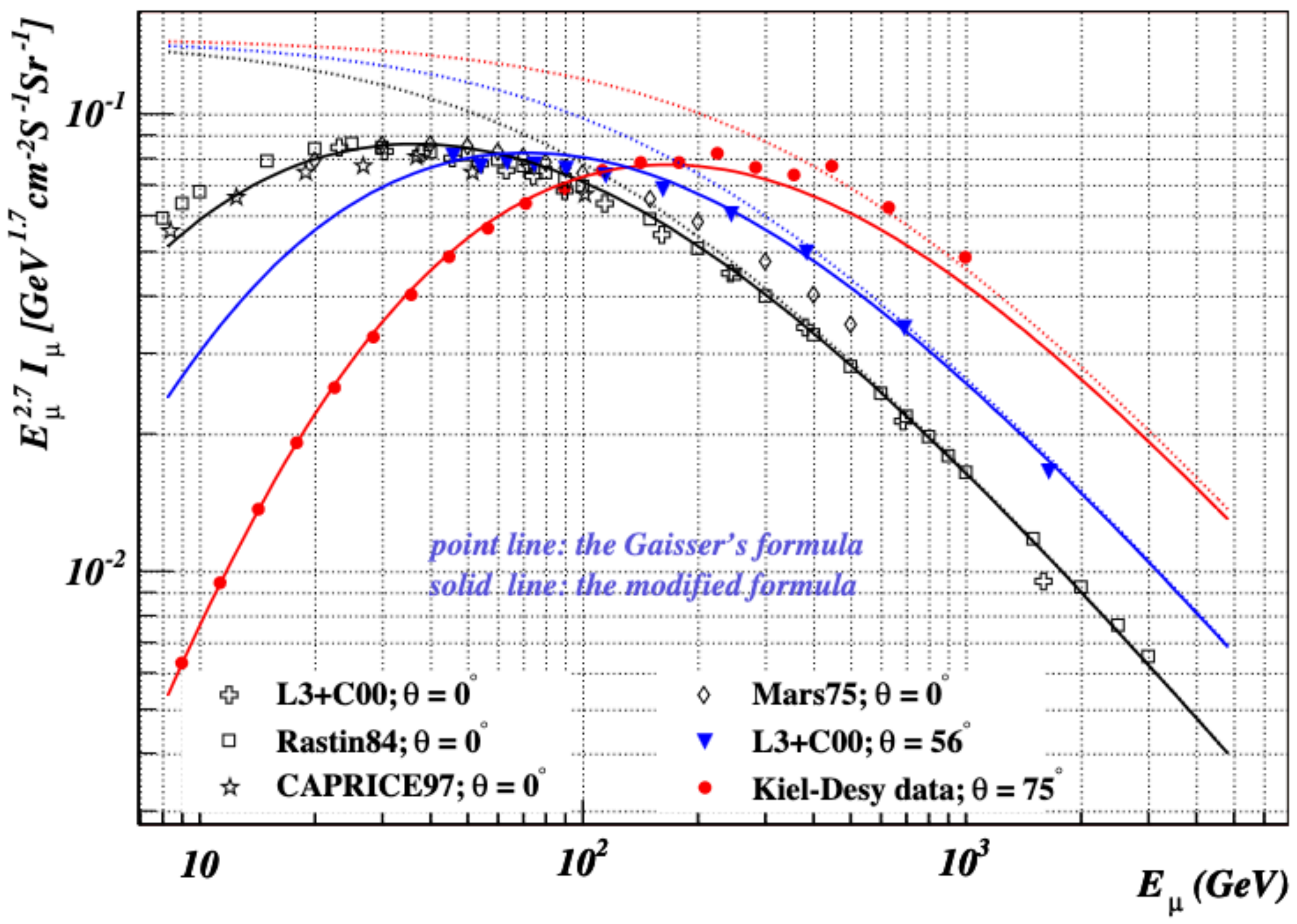
https://doi.org/10.48550/arXiv.1509.06176

Francesco's Note on ER Simulations

Francesco's Note on NR Simulations

$$\cos\theta^* = \sqrt{\frac{(\cos\theta)^2 + P_1^2 + P_2(\cos\theta)^{P_3} + P_4(\cos\theta)^{P_5}}{1 + P_1^2 + P_2 + P_4}}$$

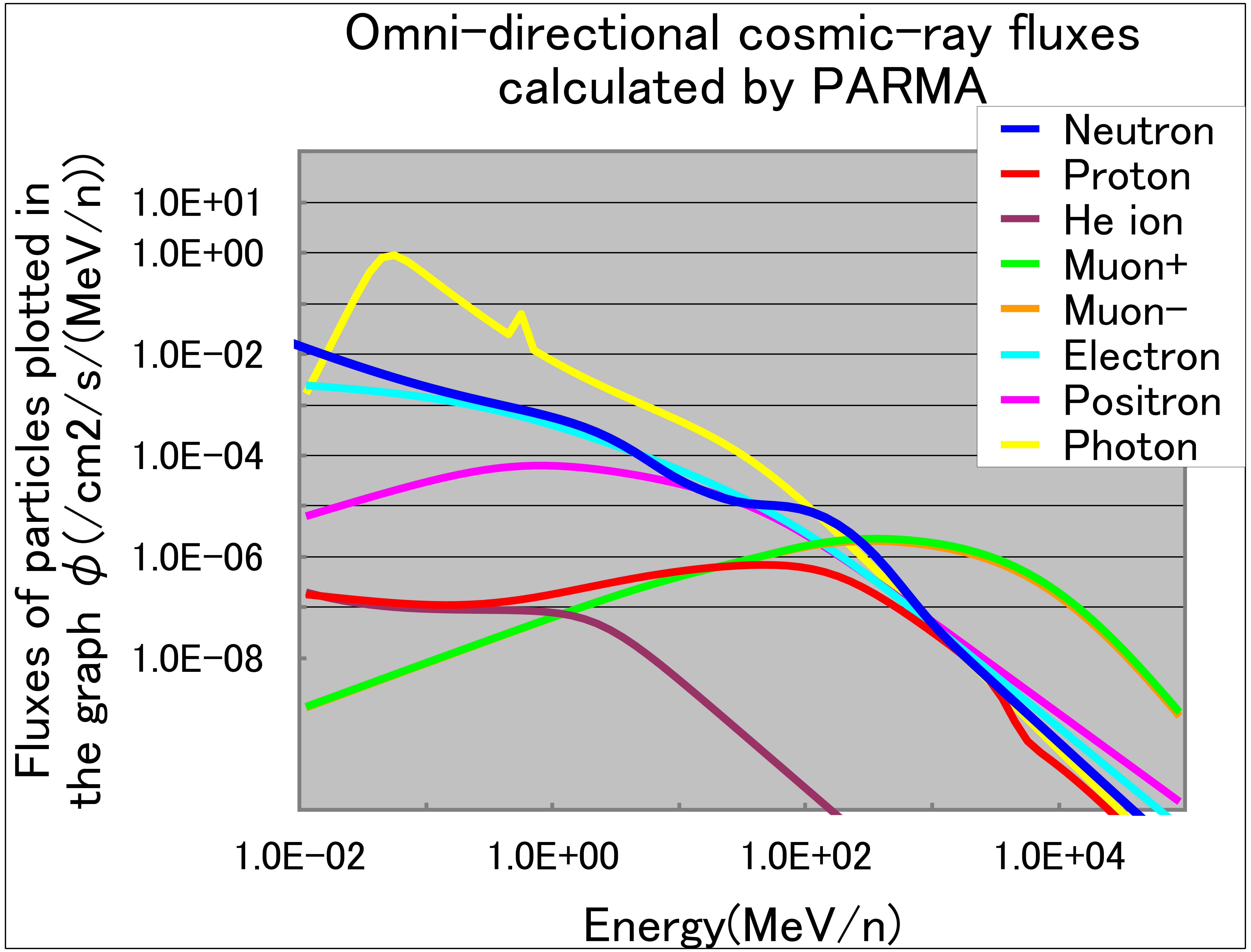
$$\frac{dI_\mu}{dE_\mu} = 0.14\left[\frac{E_\mu}{GeV}\left(1 + \frac{3.64GeV}{E_\mu(\cos\theta^*)^{1.29}}\right)\right]^{-2.7} \times \left[\frac{1}{1 + \frac{1.1E_\mu\cos\theta^*}{115GeV}} + \frac{0.054}{1 + \frac{1.1E_\mu\cos\theta^*}{850GeV}}\right]$$



PARMA Cosmic Ray Flux

EXPACs excel or c++ code: https://phits.jaea.go.jp/expacs/
https://doi.org/10.1371/journal.pone.0160390
https://doi.org/10.1371/journal.pone.0144679
RADIATION RESEARCH 170, 244–259 (2008) 0033-7587/08 544
RADIATION RESEARCH 166, 544–555 (2006) 0033-7587/06

- Began with extension to lower energies using PARMA C++ code
  - Analytical model that takes into account location, elevation, and solar flux
  - Based on MC simulations of initial cosmic rays
  - Very coarse binning



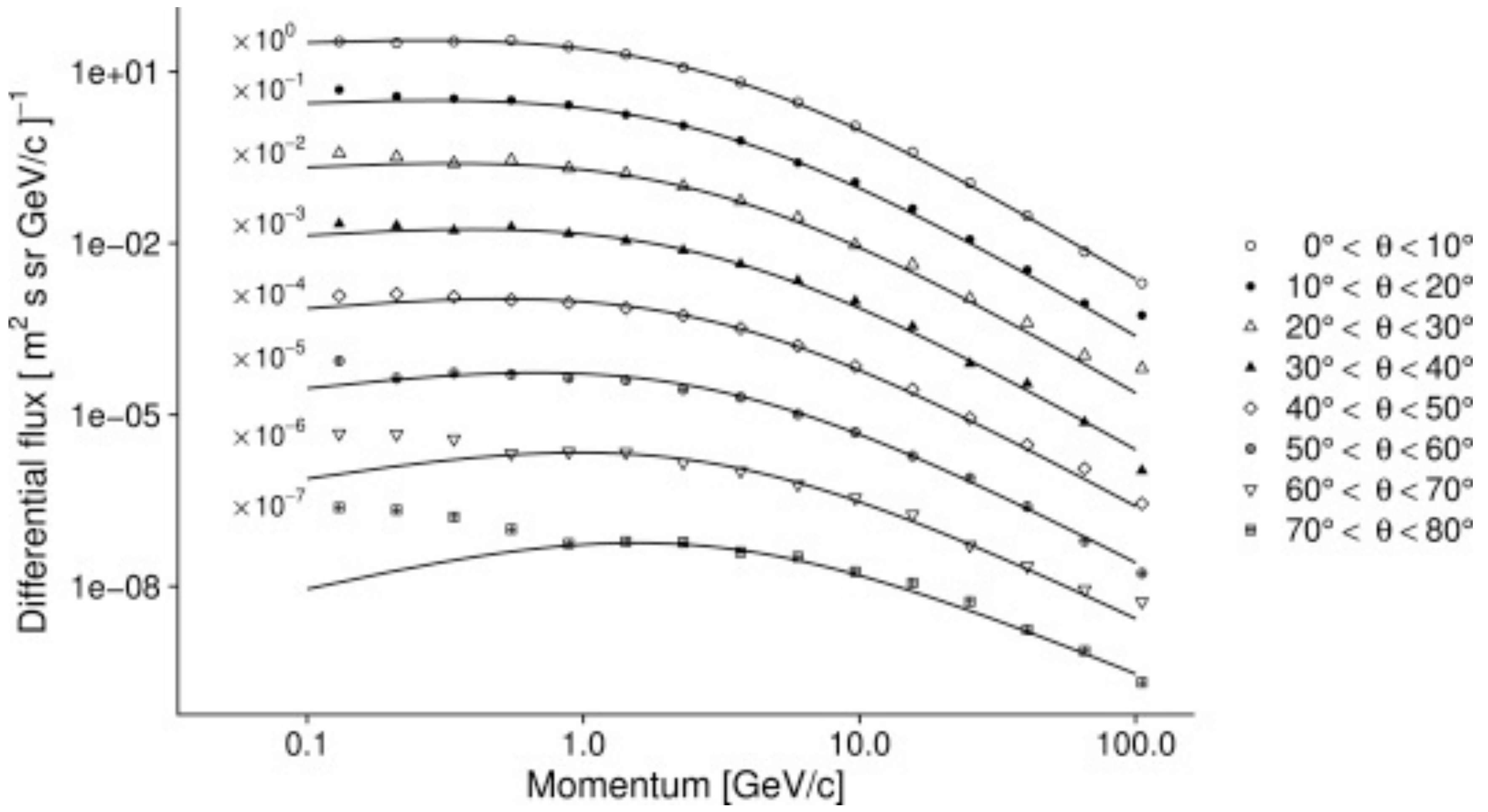
EcoMug: An Efficient COsmic MUon Generator for cosmic-ray muon applications

D. Pagano, G. Bonomi, A. Donzella, A. Zenoni, G. Zumerle, N. Zurlo, Nucl. Instrum. Methods Phys. Res. A., Volume 1014, 2021, 165732

- Switched to EcoMug for the muon simulations
  - Parameterization based on data

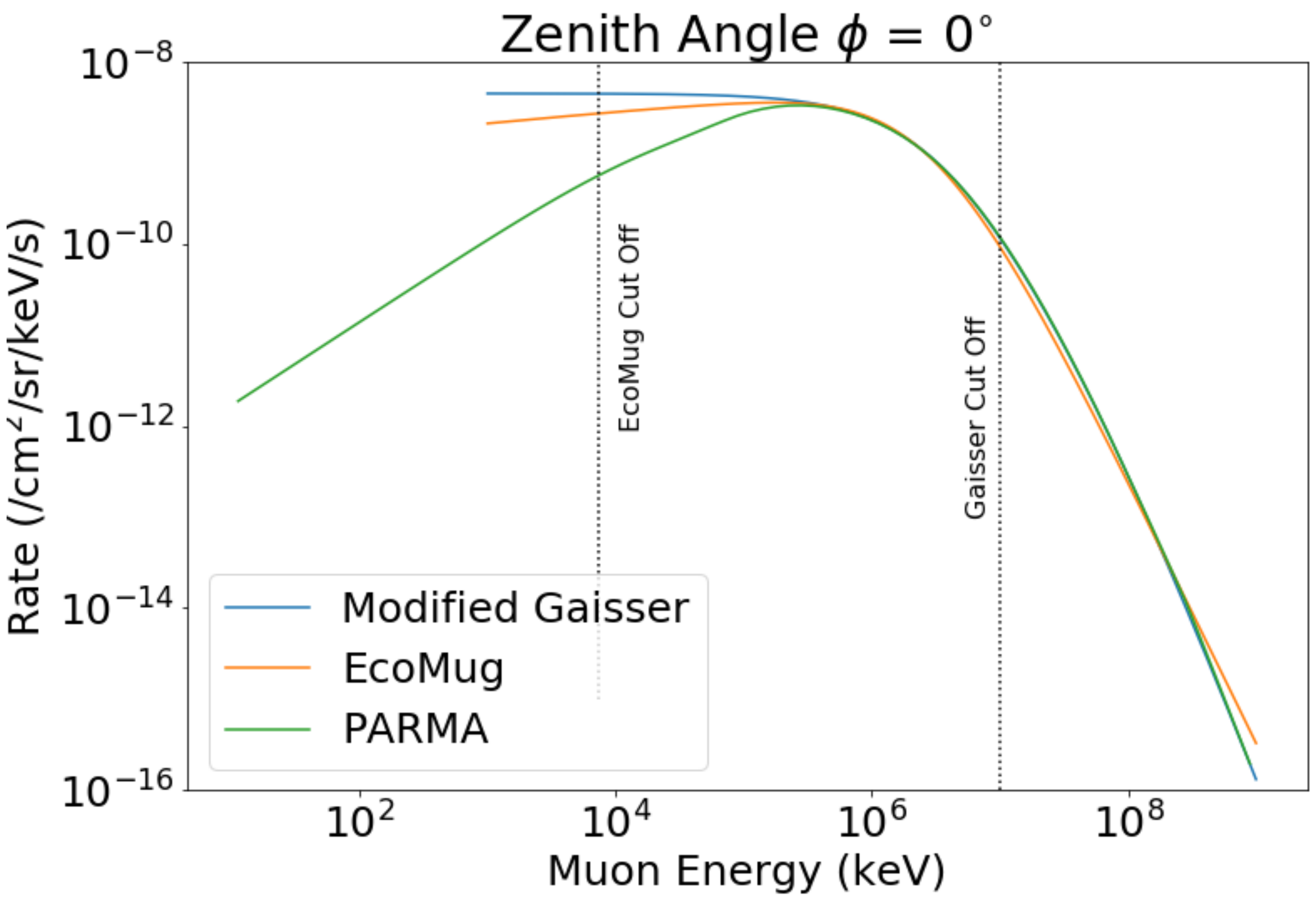
$$J = \left[1600 \cdot \left(\frac{p}{p_0} + 2.68\right)^{-3.175} \cdot \left(\frac{p}{p_0}\right)^{0.279}\right] \cdot (\cos\theta)^n \cdot \frac{1}{\mathrm{m^2 \cdot s \cdot sr \cdot GeV/c}},$$

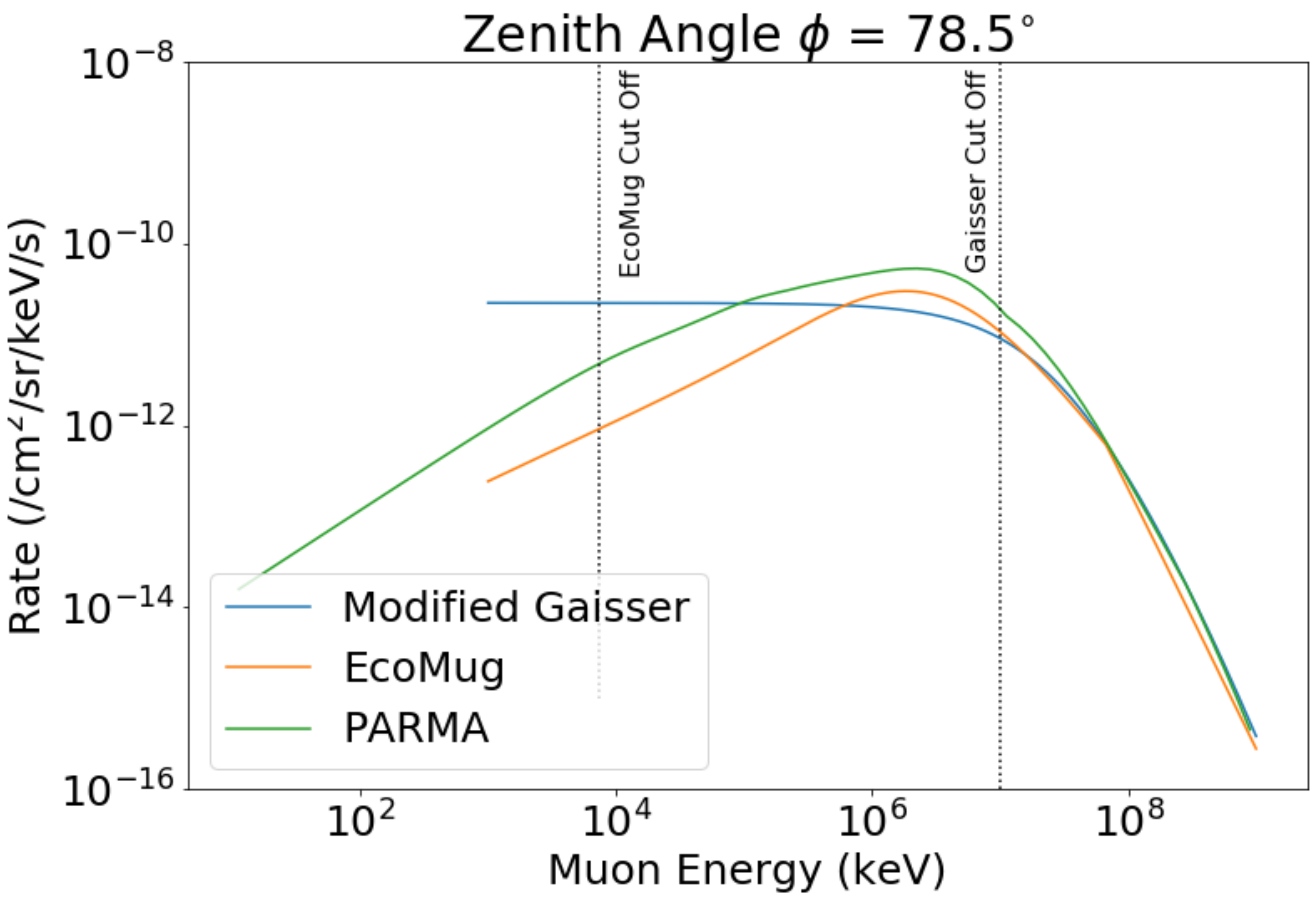
- Valid down to momenta of 0.04GeV/c (energy = 0.007GeV/c^2)
- Allows generation of spectra on three different surfaces - very useful for keeping nearly horizontal muons without having to simulate a massive sky
  - Sky, hemisphere, cylinder
- Assumed μ^+/μ^- charge ratio: 1.28
- Readily implemented in Geant4



Comparison of Different Muon Flux Parameterizations

- There are some differences between the different muon flux parameterizations





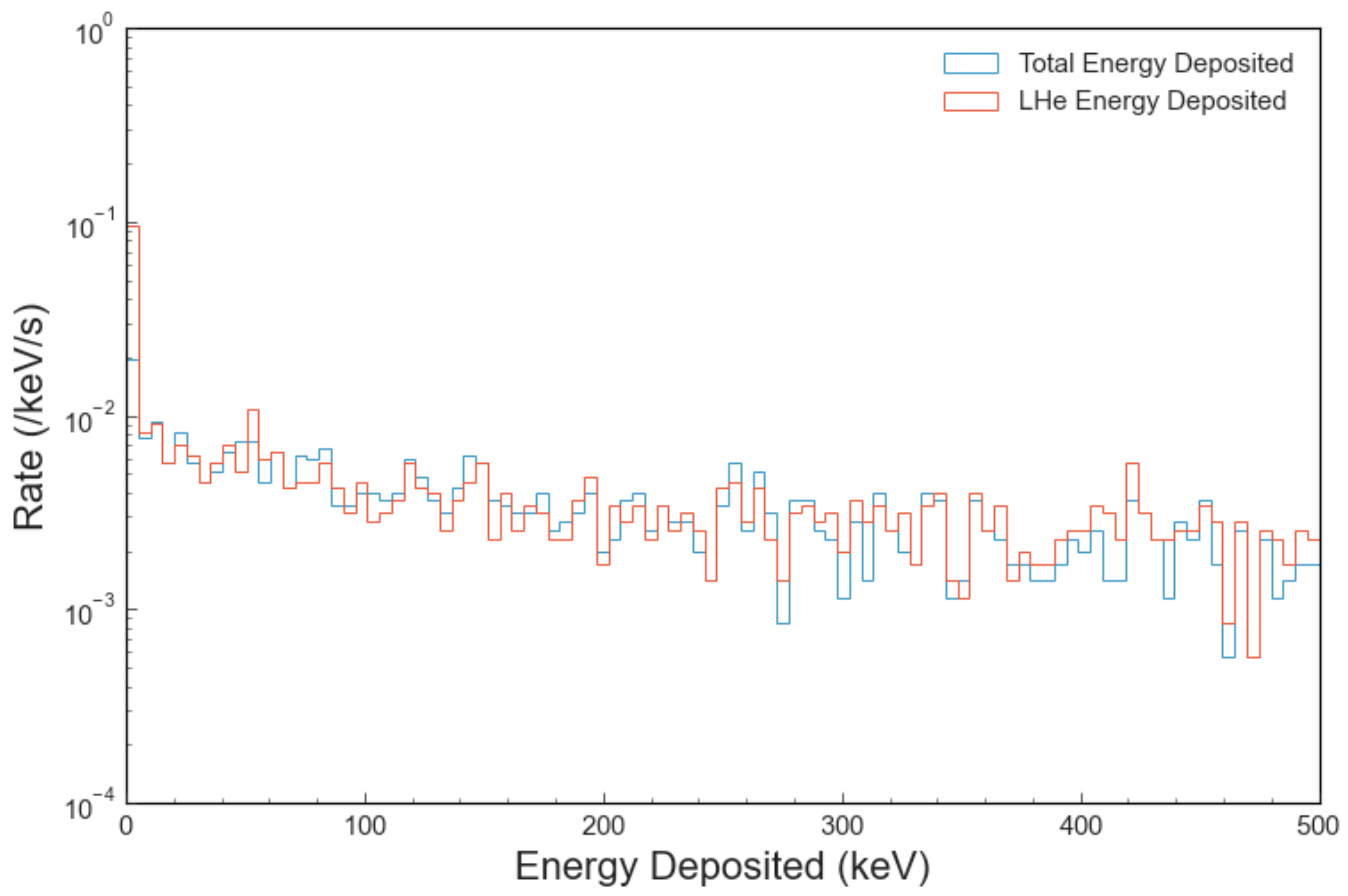
Note on Simulation Primary ‘Efficiency’

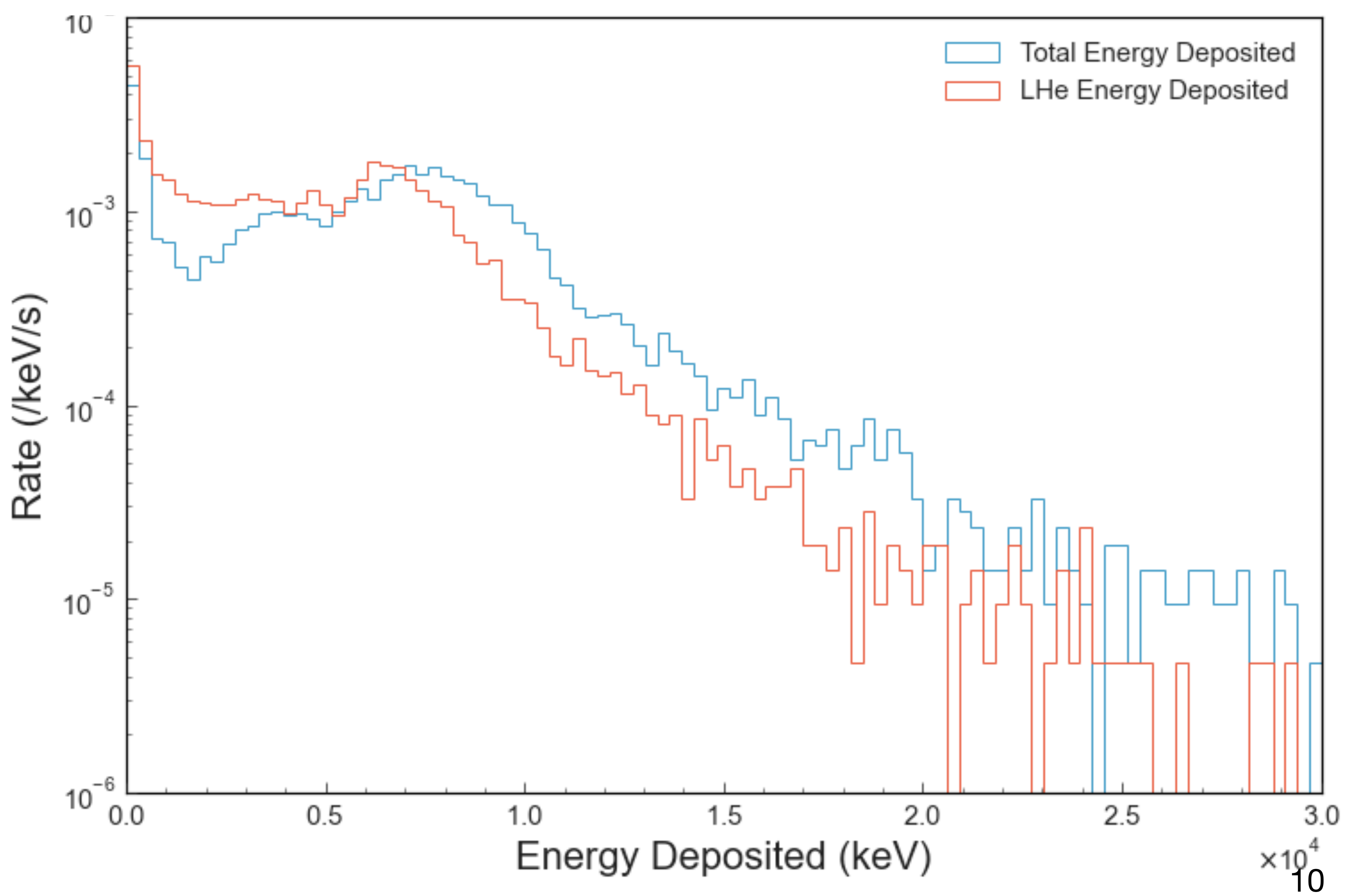
- Using EcoMug is slightly less efficient that the previous method in Francesco’s simulations
    - Previous method: generate X primaries at random positions in the lab and project them backwards to a sphere outside of the lab
- EcoMug method: generate X primaries on a hemisphere slightly larger than the lab
    - Some primaries will never make it into the lab based on their angular distribution

EcoMug Muon Simulation - Results

- 20 x 500k = 1e7 primaries, some uncertainty on the simulation time, but currently lower than the statistical uncertainty
- Assumed rate at sea level
- Most NRs are between 100-1000 keV
- Total rate shouldn't be problematic for the DAQ, but we see a higher NR rate than initially suggested by Francesco's simulations

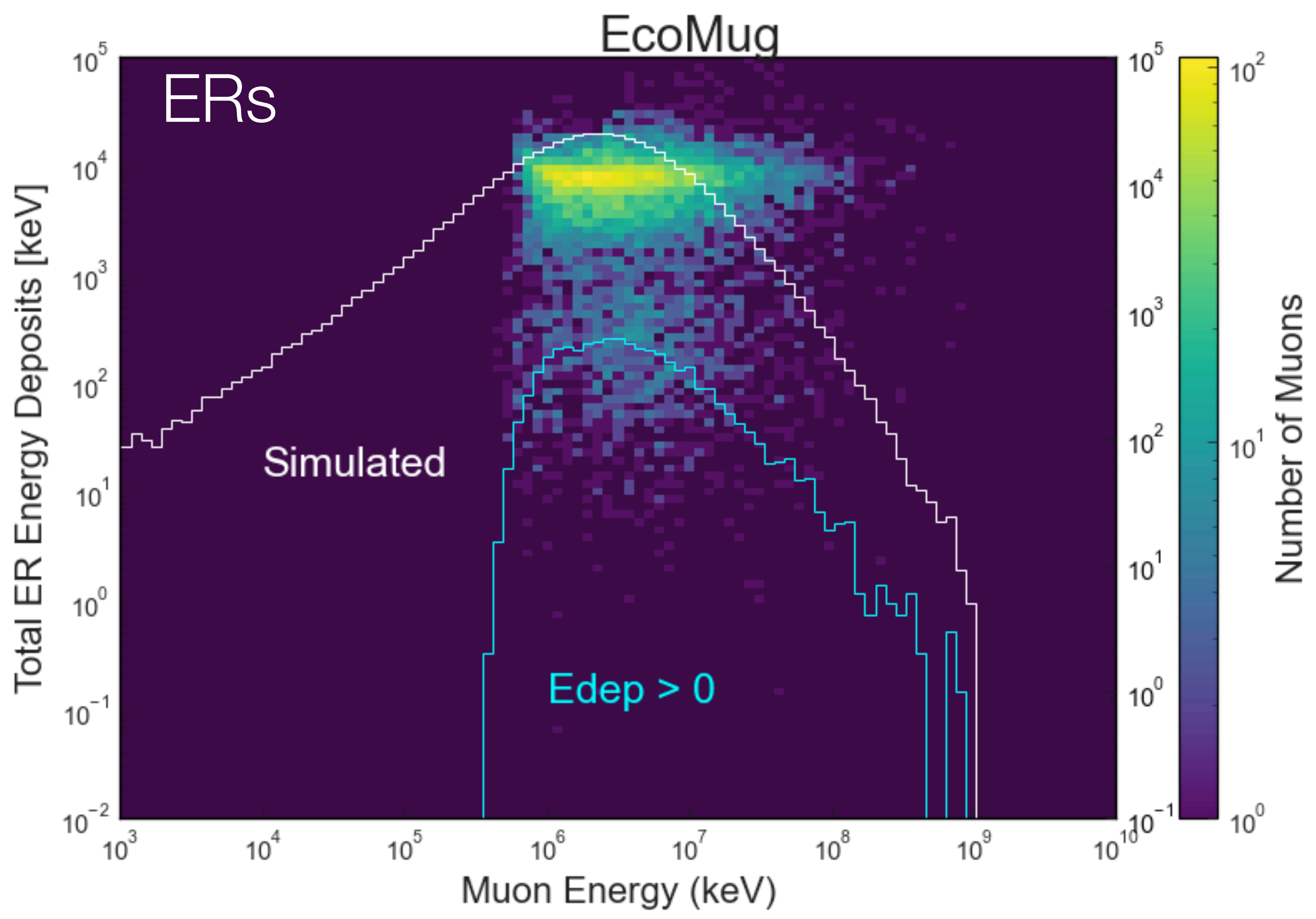
Rate [Hz]	mu+	mu-	Total
ER>0	7.48	6.31	13.79
NR>ER	0.04	0.49	0.52
NR between (10eV,100keV)	0.003	0.064	0.067
Total	7.48	6.31	13.79

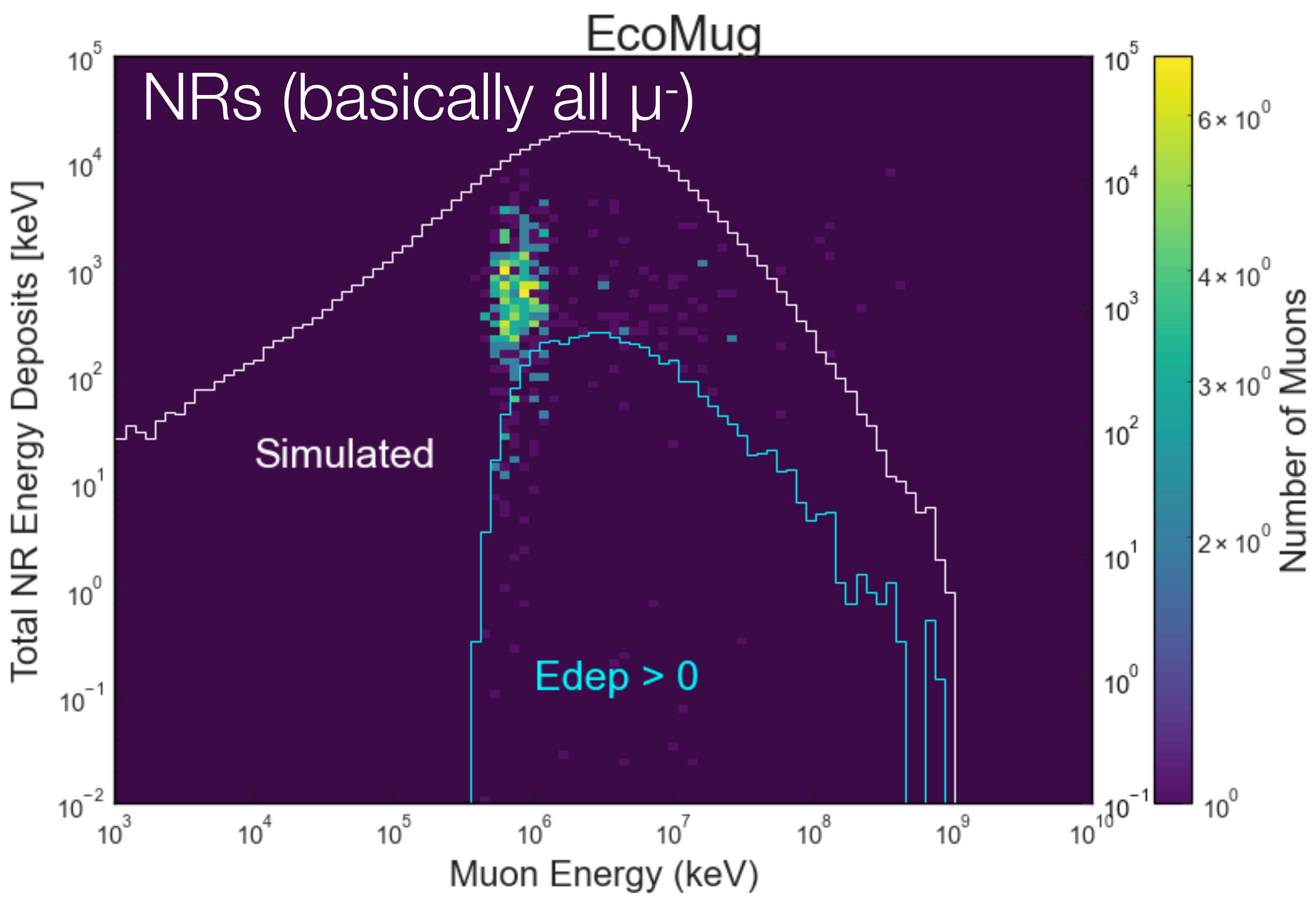




EcoMug Muon Simulation - Energy Deposition

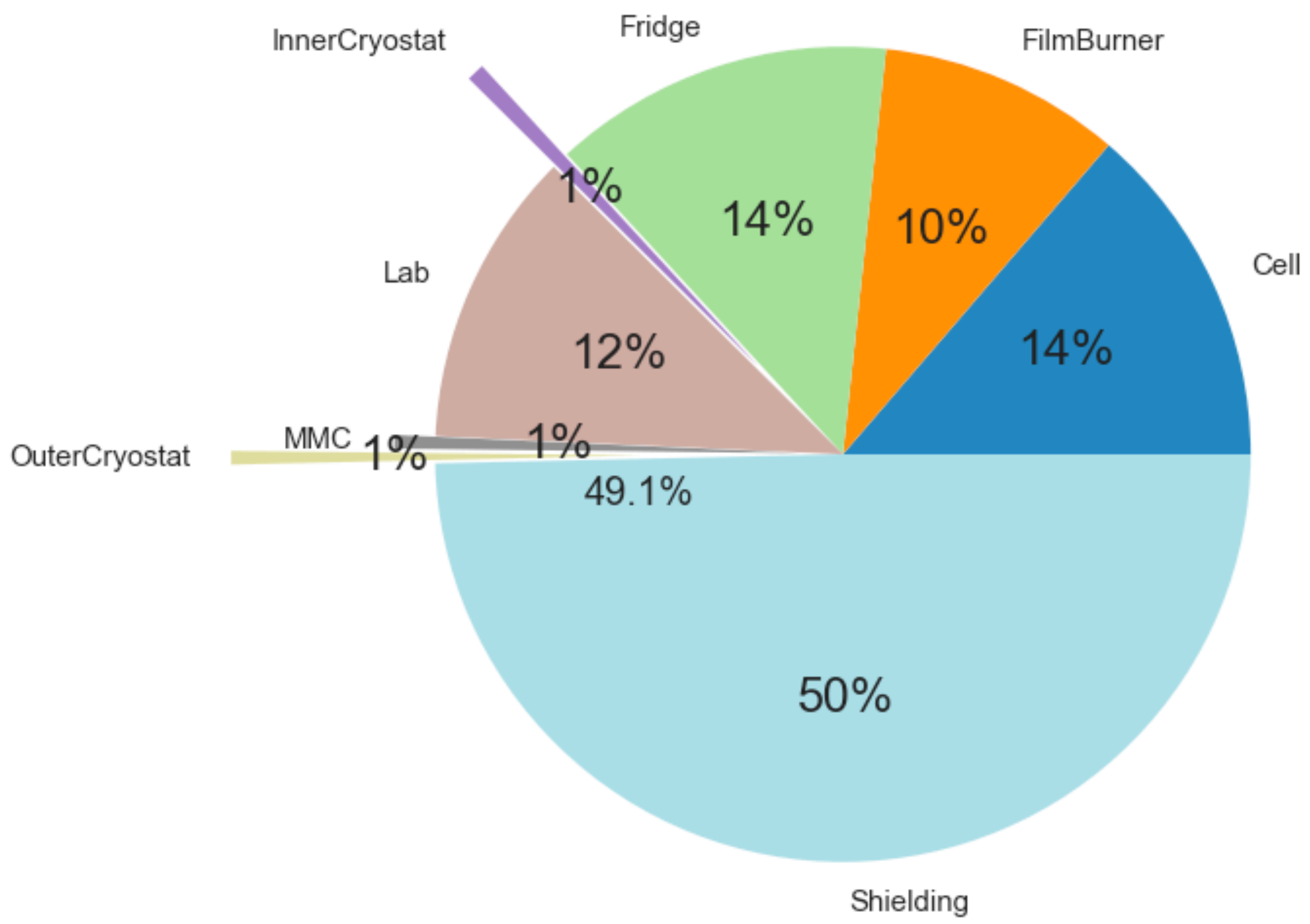
- Sensitive volumes include LHe and MMCs. Rate from primaries with E<10GeV is significant
- Little effect from primaries with energy <1e5 keV where the PARMA and EcoMug parameterizations differ most
- NR events are almost all from negative muon capture

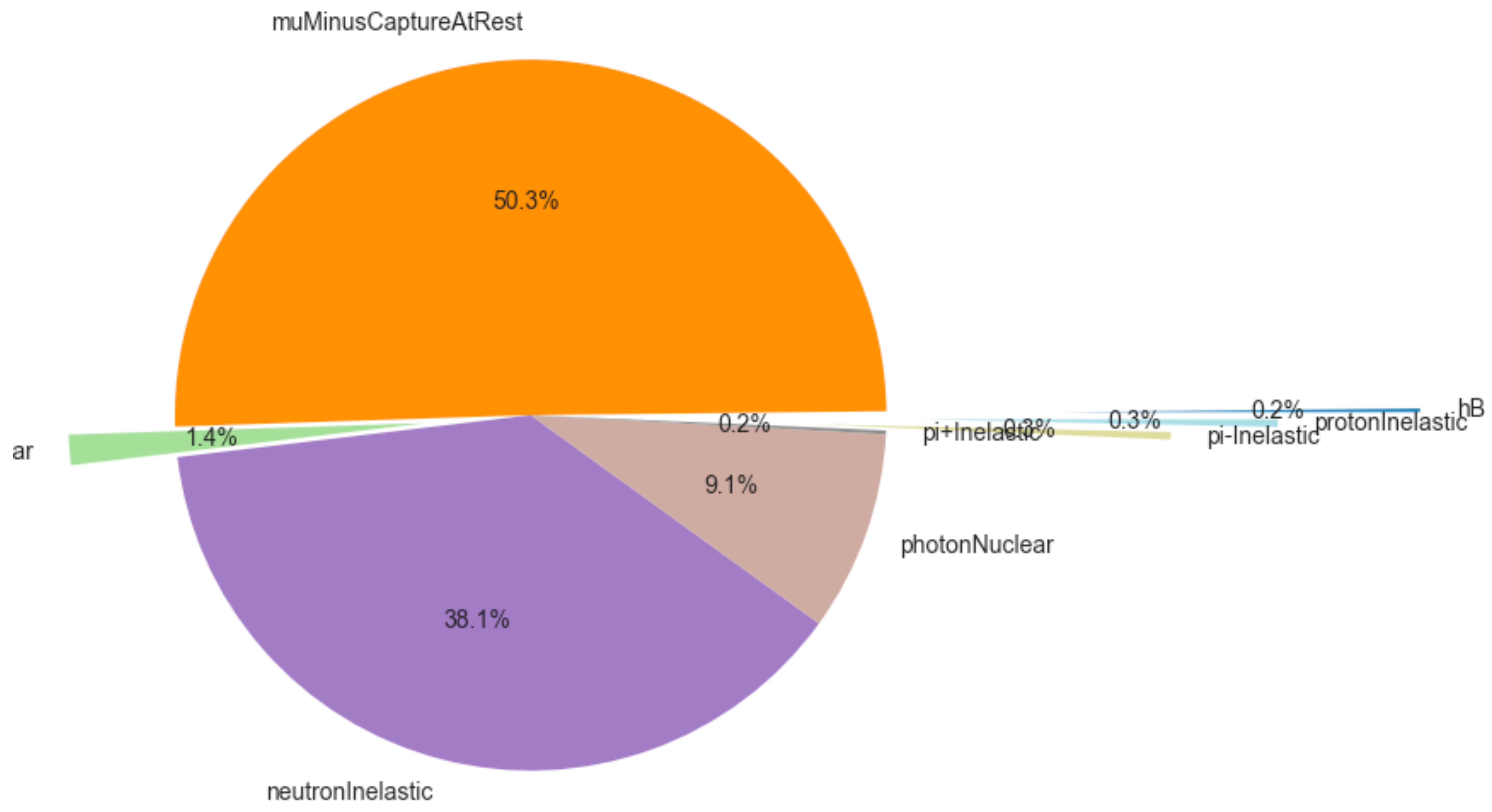




EcoMug Muon Simulation - Neutrons

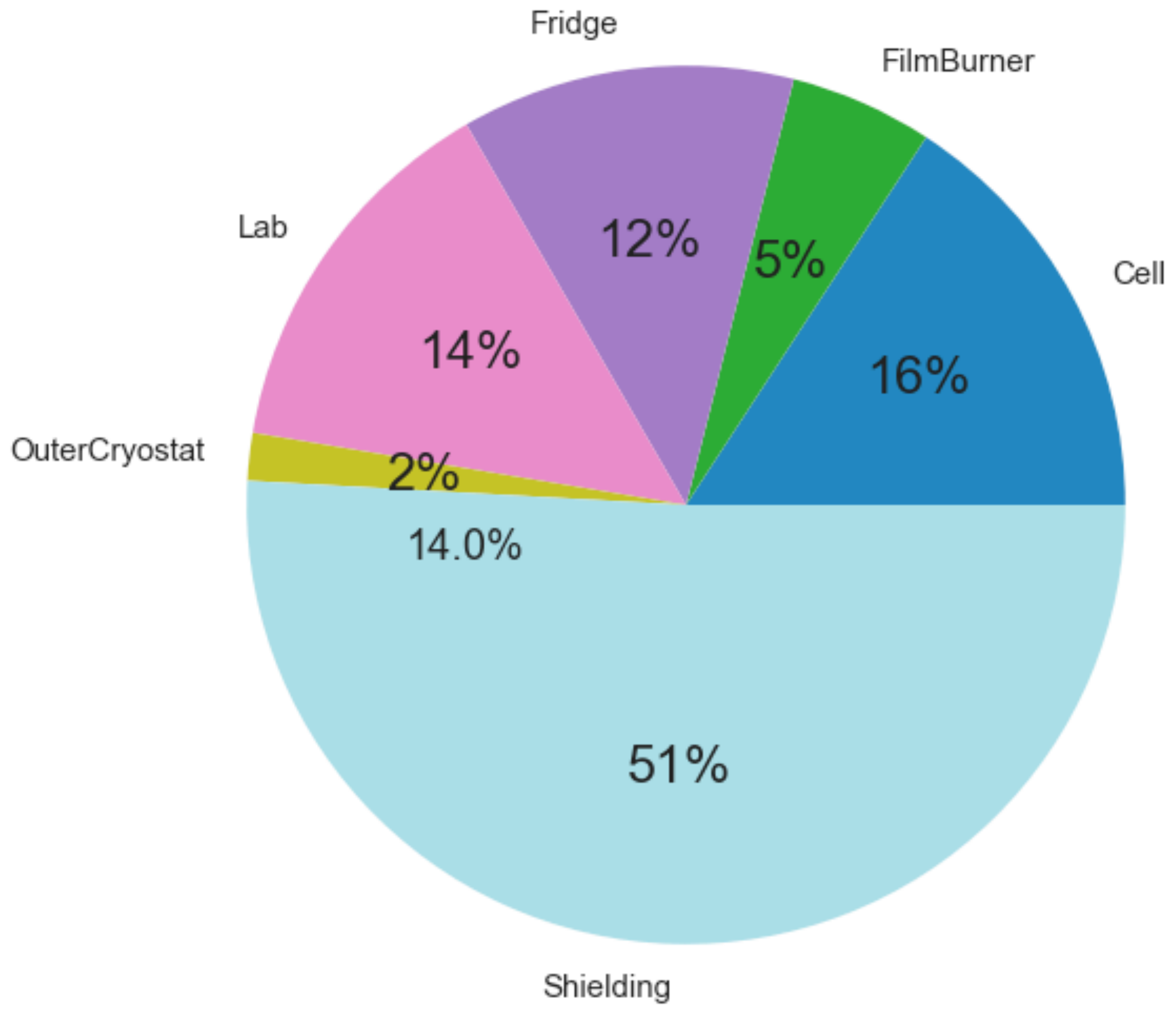
- Total of 562 neutrons produced, majority produced in the shielding
- Dominant production process - negative muon capture (low energy muons)

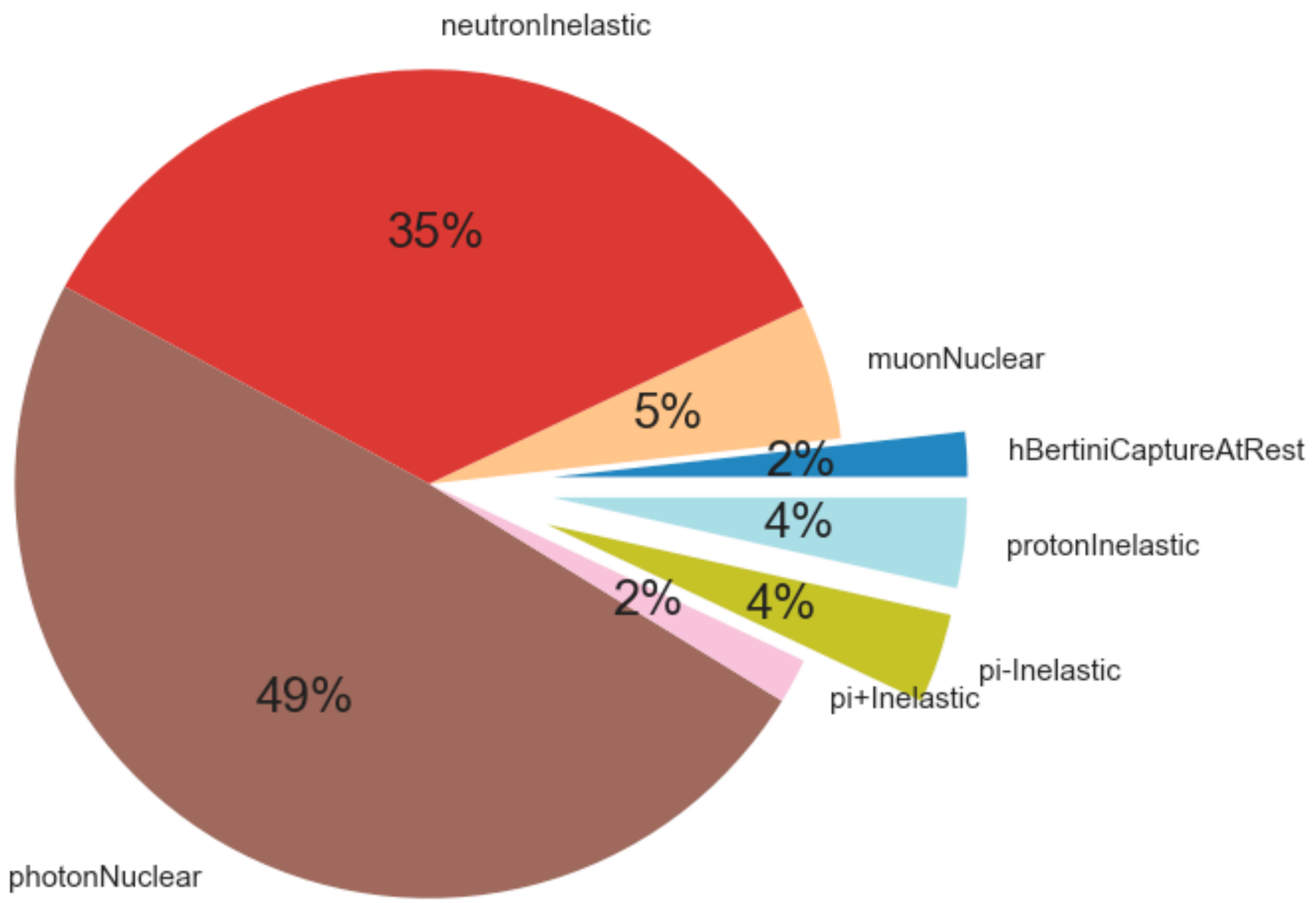




EcoMug Muon Simulation - Neutrons

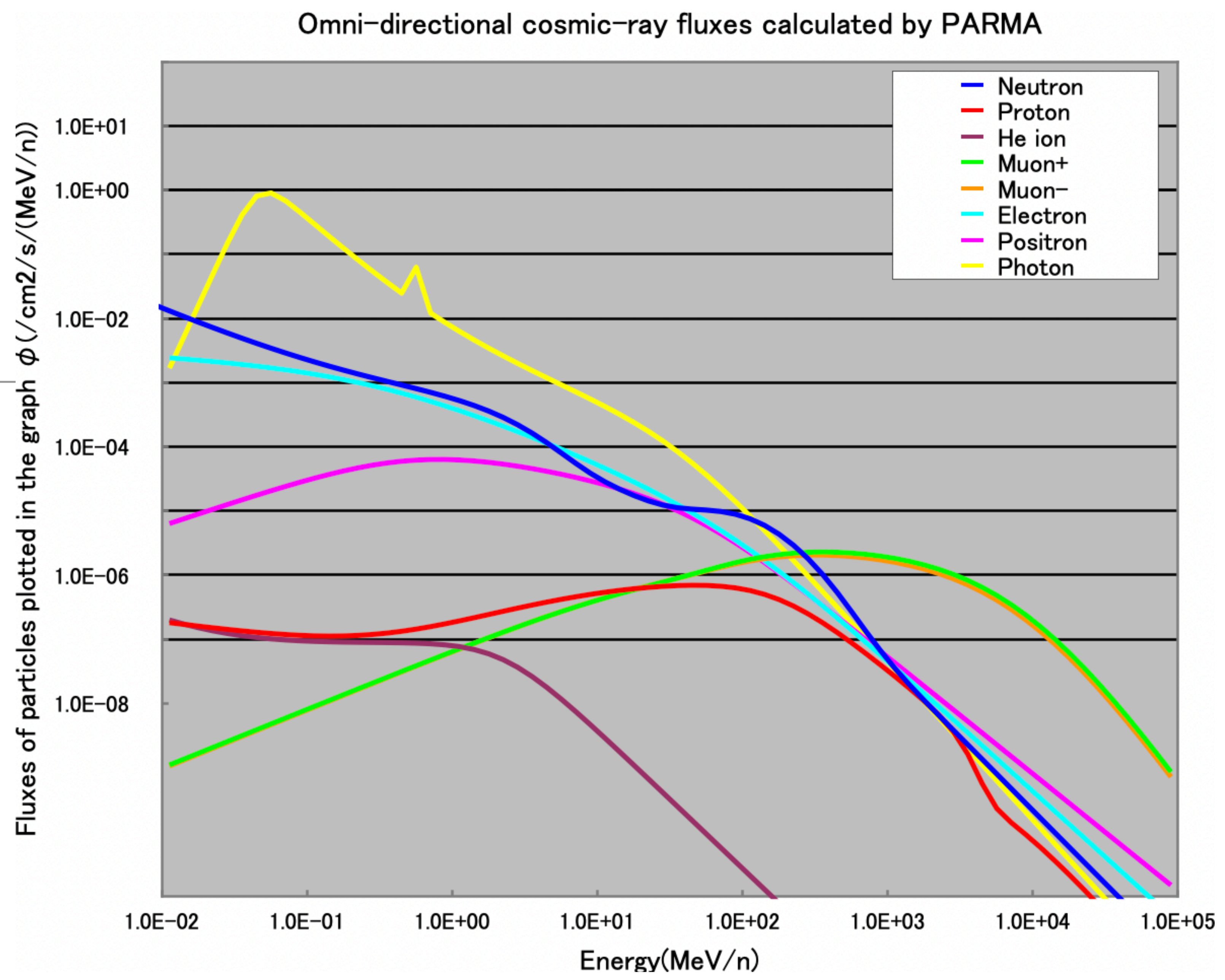
- Same plots for primary muons with energy > 10GeV, only 62 neutrons
- No negative muon capture (also why the NR rate is so much higher than in Francesco's original simulations)





Cosmic Neutrons - Very Preliminary, Needs Corrections

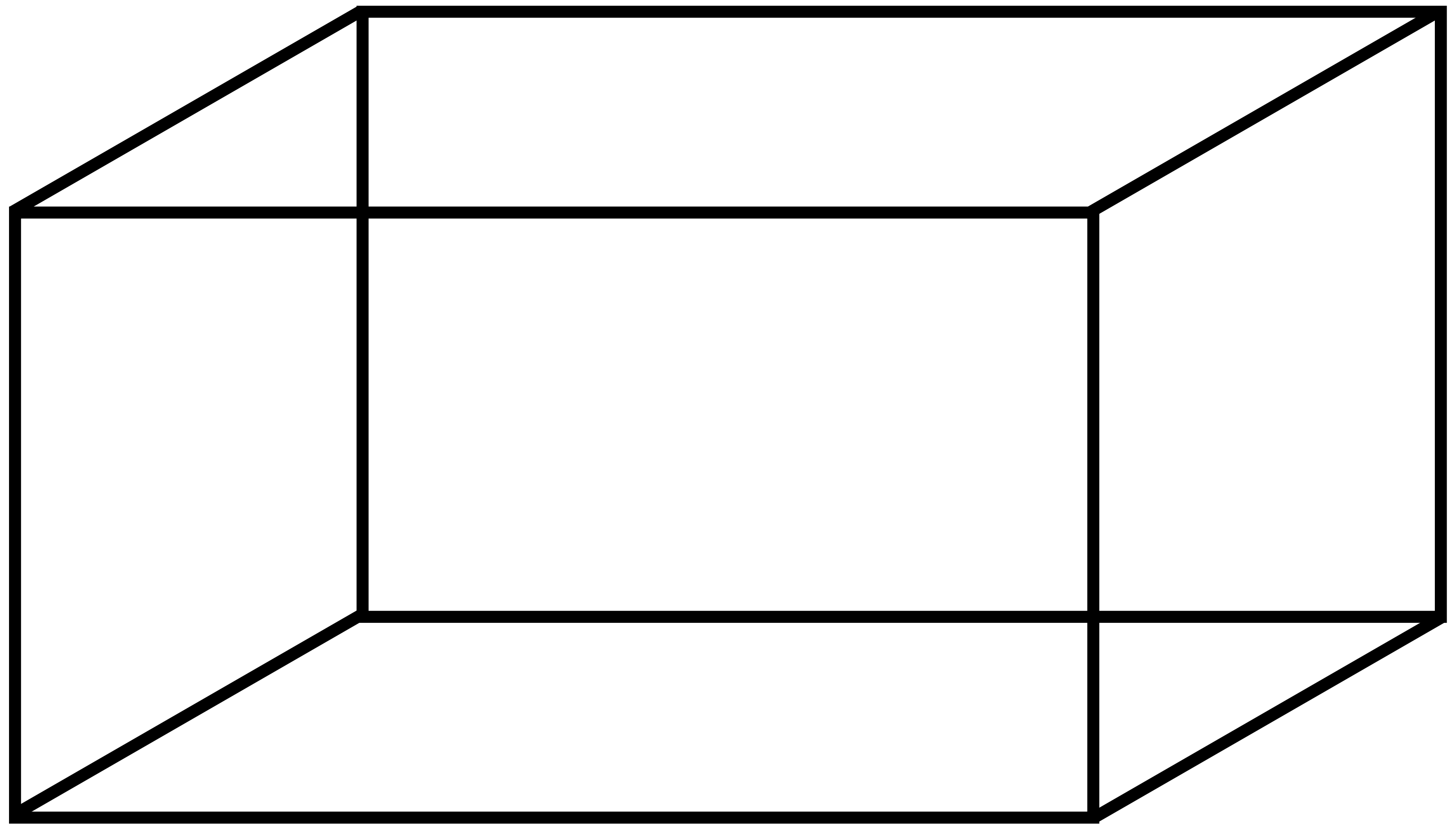
Cosmic Neutron Spectrum



- Spectrum from PARMA code
- Coarse binning
- Simulation performed à la Francesco's original simulations
  - N positions drawn in lab geometry
  - Draw energy and zenith angle from PARMA distribution
  - Project back onto a hemisphere outside of the lab volume
  - Note: unlike muons, backscatter is important for neutrons - these are projected to the floor for now

The Flux Calculation

- Flux through a given surface is integrated over the area element d**A** and unit direction of particle, **r**



$$F_{general} = \int d\Omega \int d\mathbf{A} \cdot \hat{\mathbf{r}} \int dE \frac{dI}{dE}(E, \phi)$$

$$= \int_0^{2\pi} d\theta \int_0^{\pi} \sin(\phi) d\phi \int d\mathbf{A} \cdot \hat{\mathbf{r}} \int dE \frac{dI}{dE}(E, \phi)$$

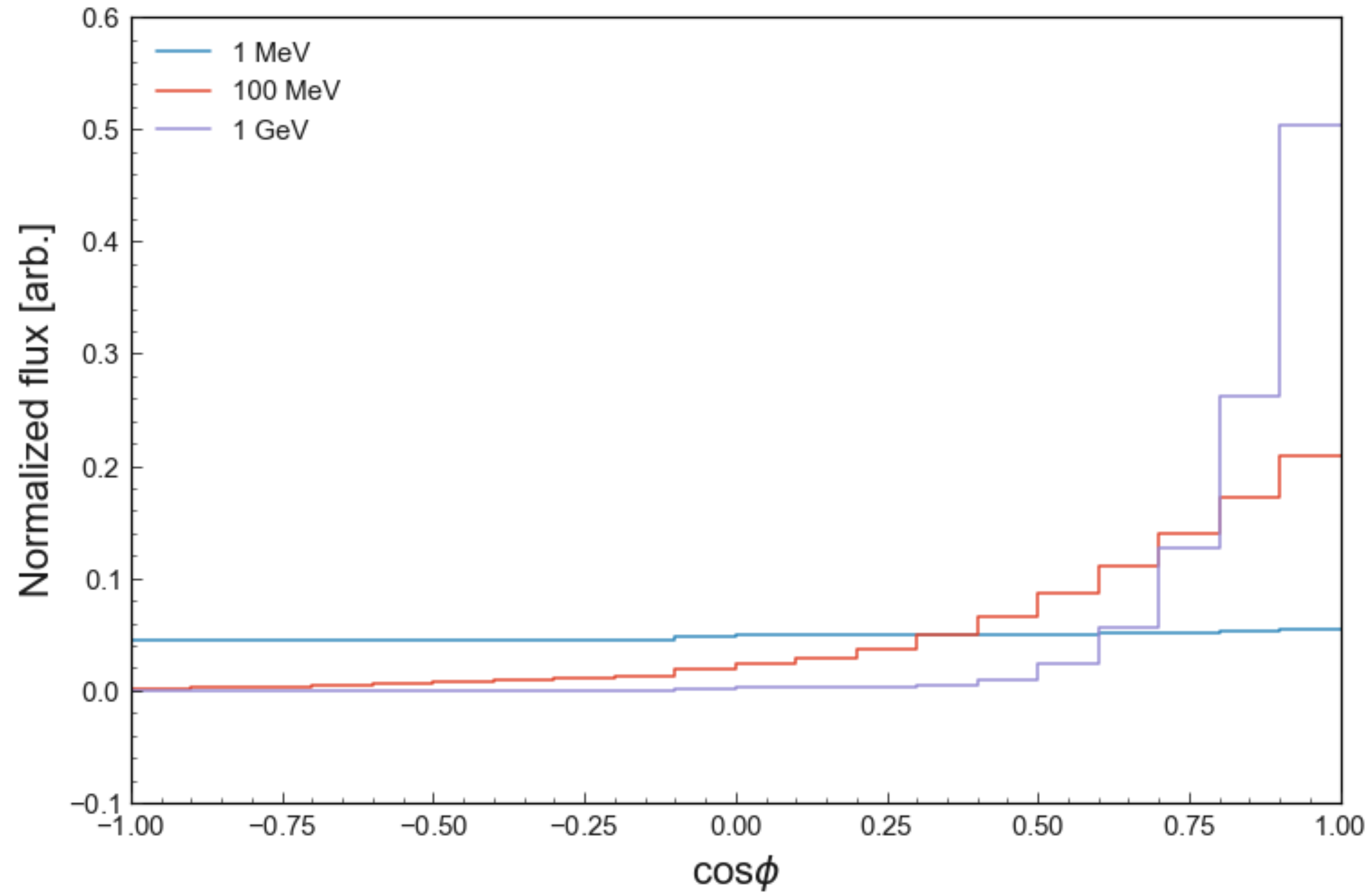
$$\hat{\mathbf{r}} = \sin\phi\cos\theta\hat{\mathbf{x}} + \sin\phi\sin\theta\hat{\mathbf{y}} + \cos\phi\hat{\mathbf{z}}$$

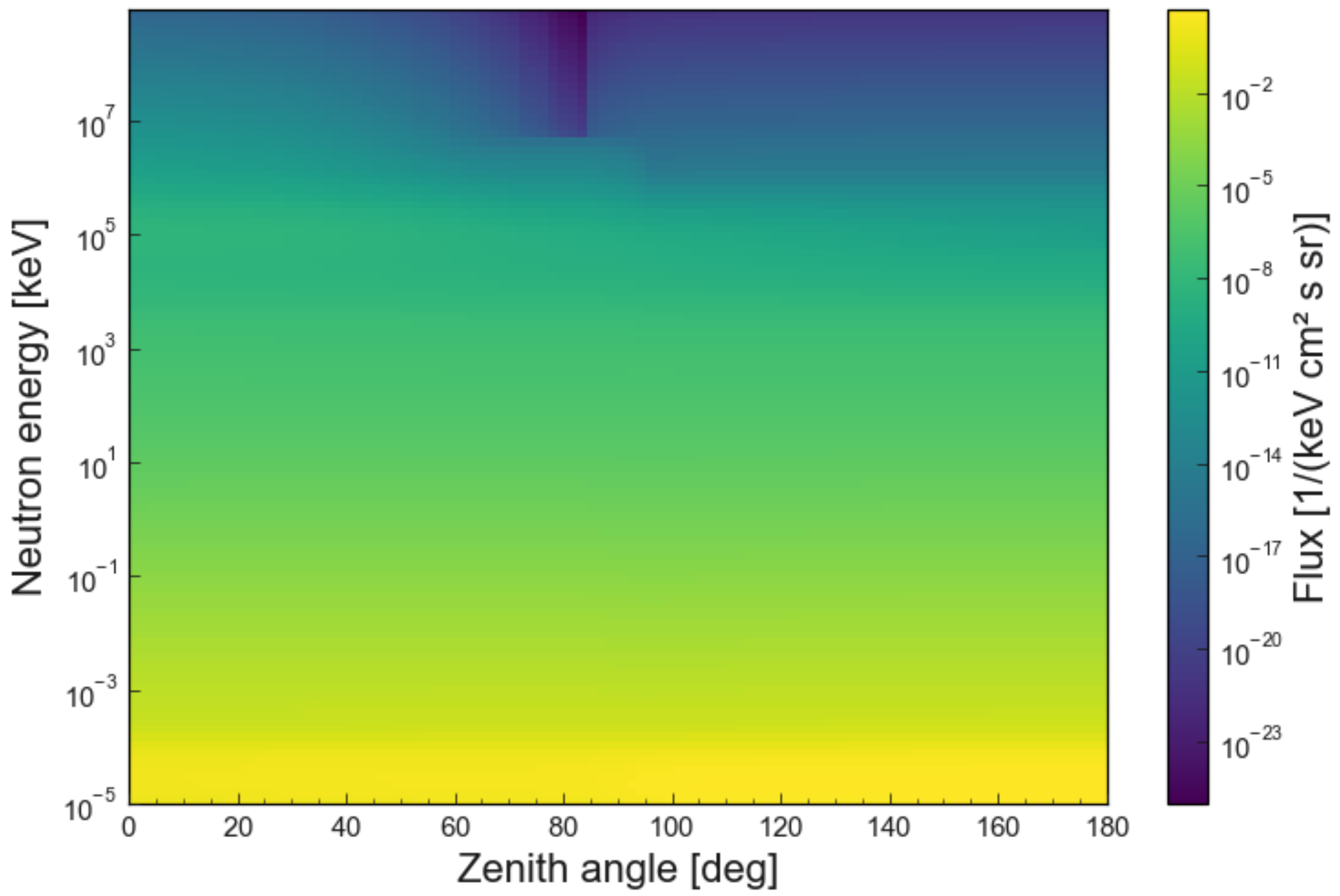
- Flux is assumed to be isotropic in the polar direction θ

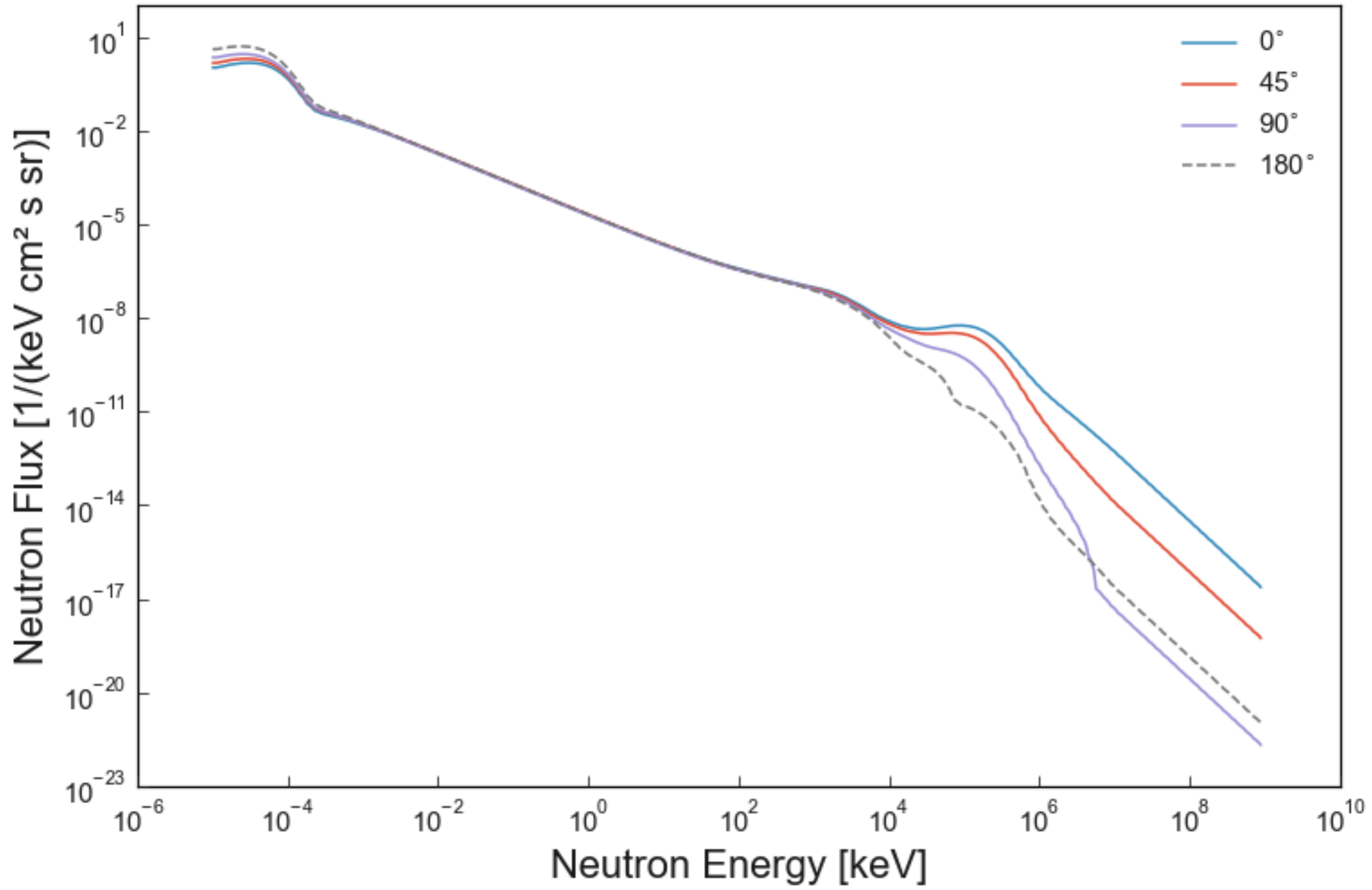
Cosmic Neutrons

- Cosmic neutron flux also given by the PARMA code

- Backscatter is important, unlike for muons



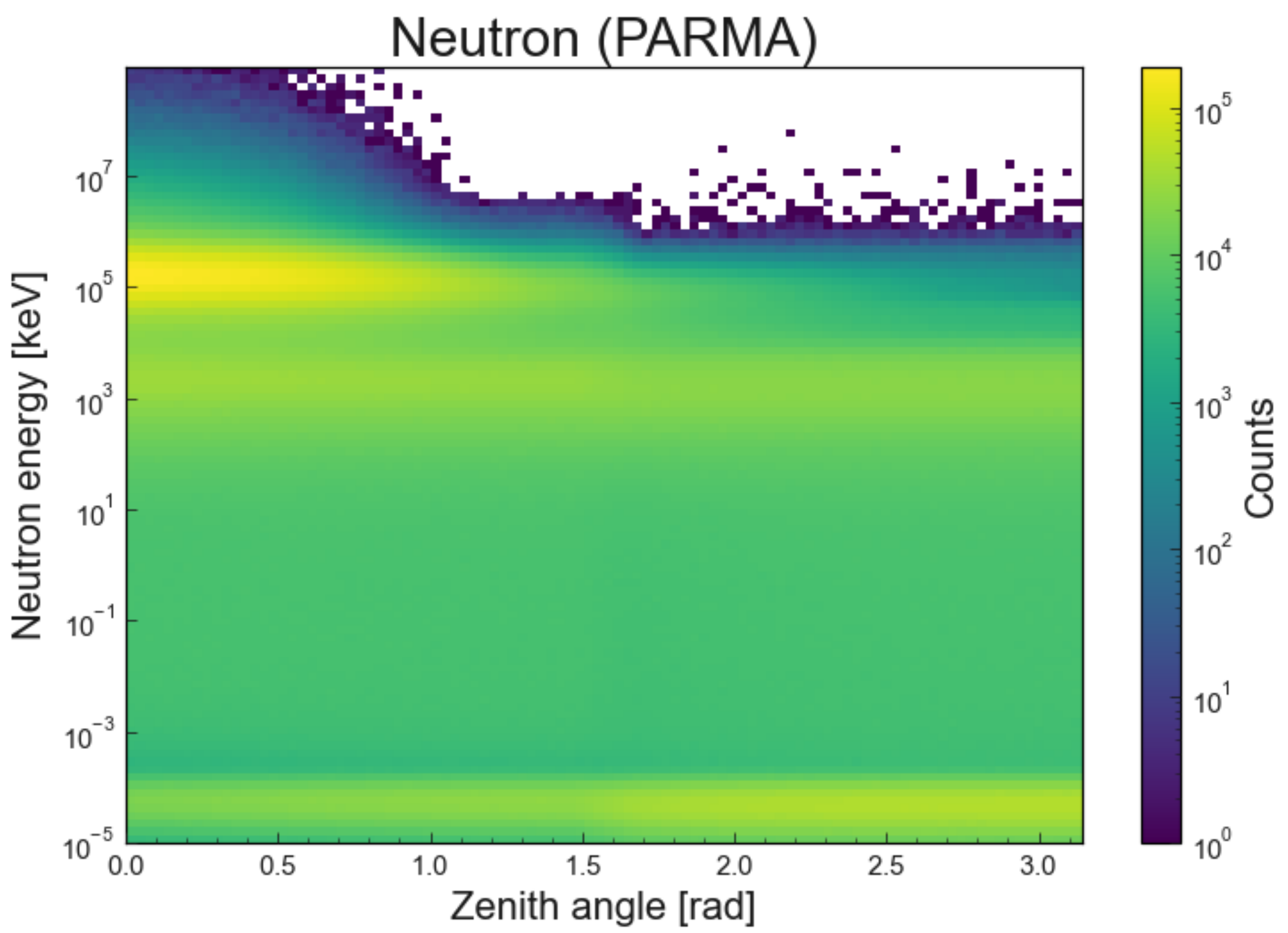


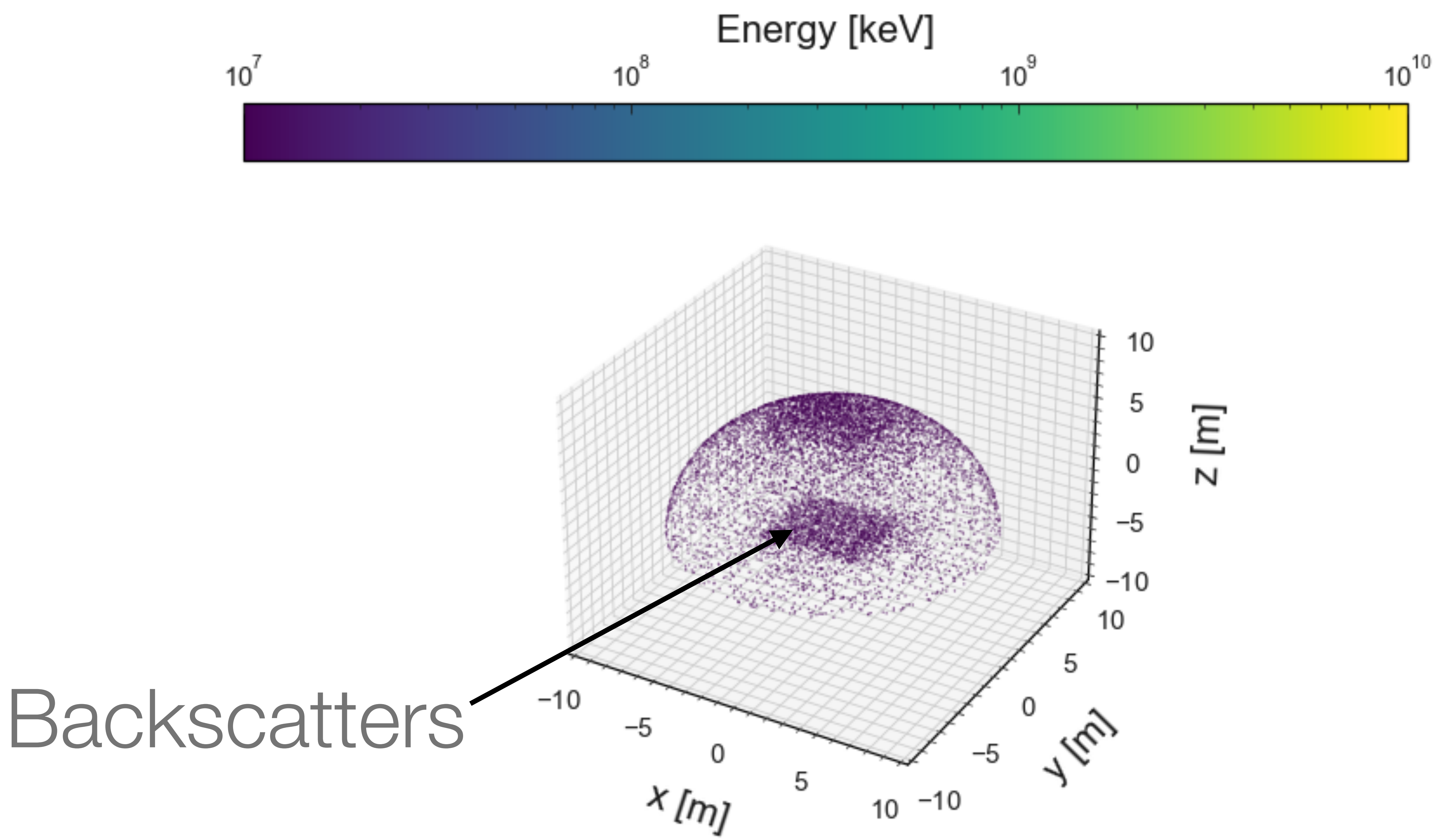


Neutron Simulations - Distribution of Primaries

- Downward-going neutrons are projected back onto a 9m radius hemisphere from a random position in the lab

- Backscattering neutrons are projected onto the floor because the DELight GEANT4 world volume is not defined below this





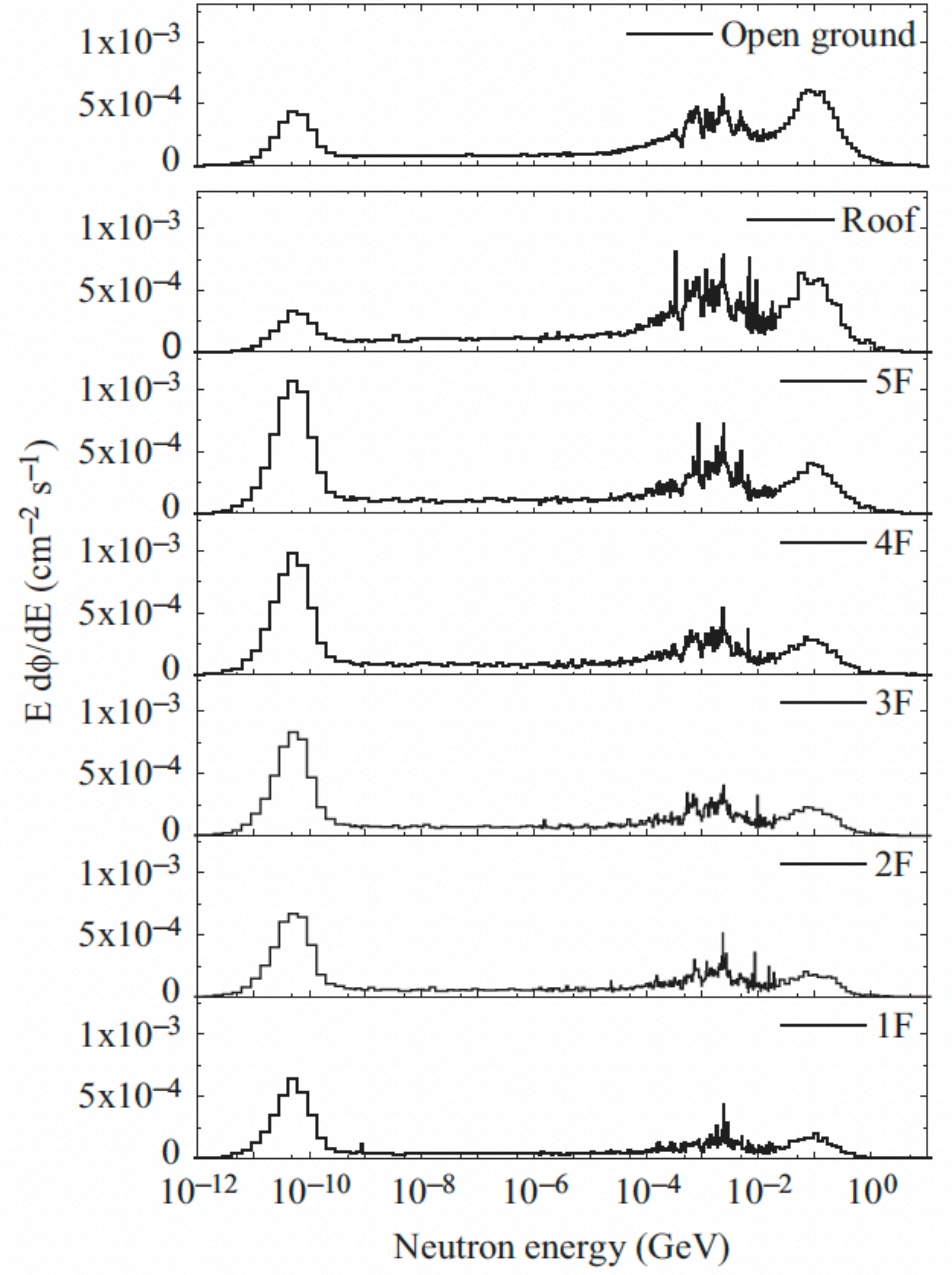
Neutron Simulations - Preliminary Rate

- Using the calculated flux into the lab volume and number of primaries (500k), preliminary interaction rates:
  - 4.5Hz (all non-zero deposits in sensitive volume)
    - 3Hz (all non-zero deposits in sensitive volume from backscattered neutrons)
    - 3.5Hz (deposits with NR>=ER)
      - **0.68Hz with E_{nr} between 10eV and 100keV**
- A little bit worrying…
- How does the building affect the incoming neutrons + backscatters?

Cosmic Neutron Flux In Buildings

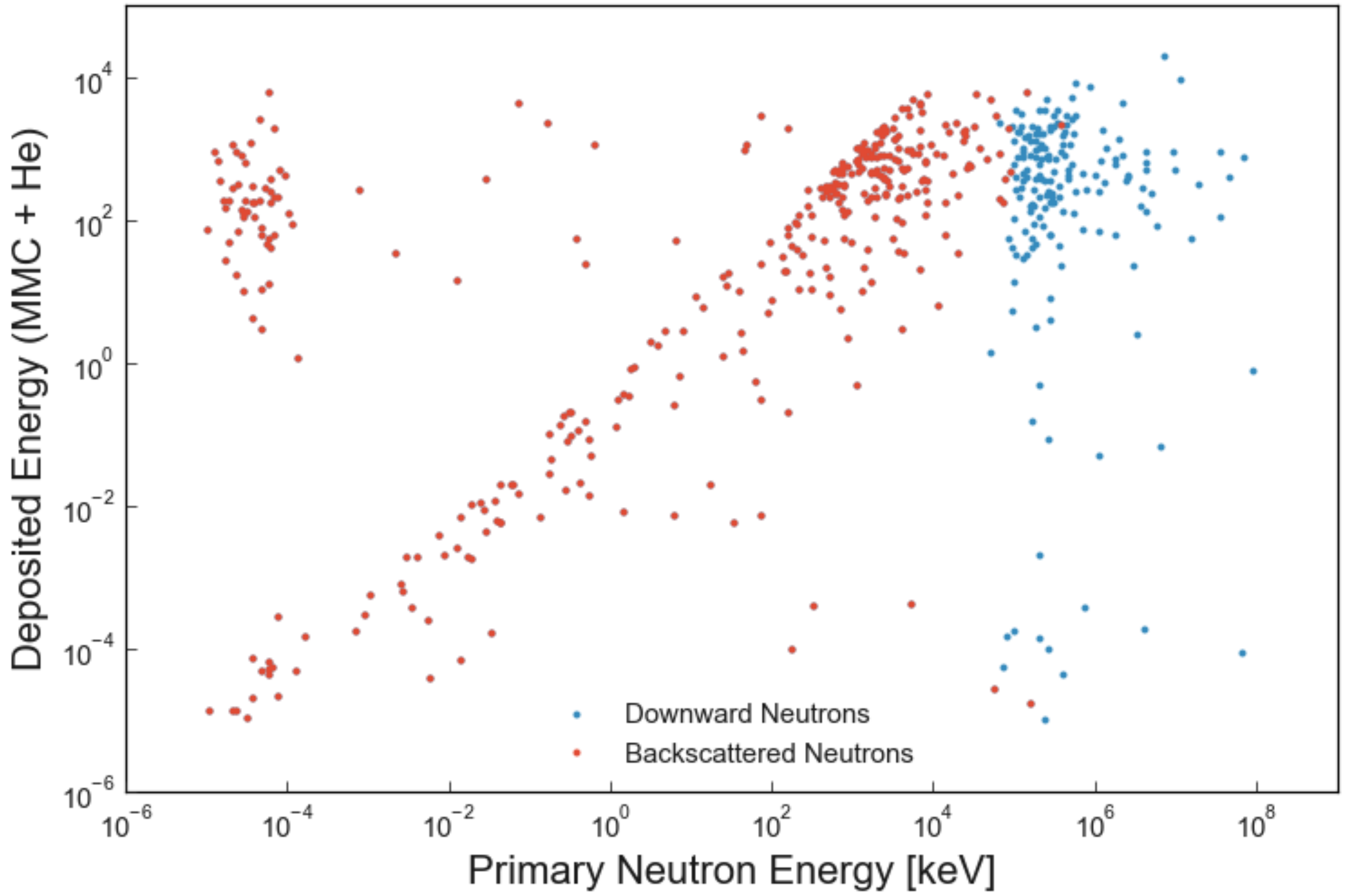
- Study of cosmic neutron measurements on different floors of a 5 story building
- High energy neutrons are attenuated
- Thermal neutron population increases, highest on top floor of the building
- Lab area at HD intended for DELight has only 1 ceiling (asking around for exact building dimensions and materials)

Radiation Protection Dosimetry (2018), Vol. 179, No. 3, pp. 233–243

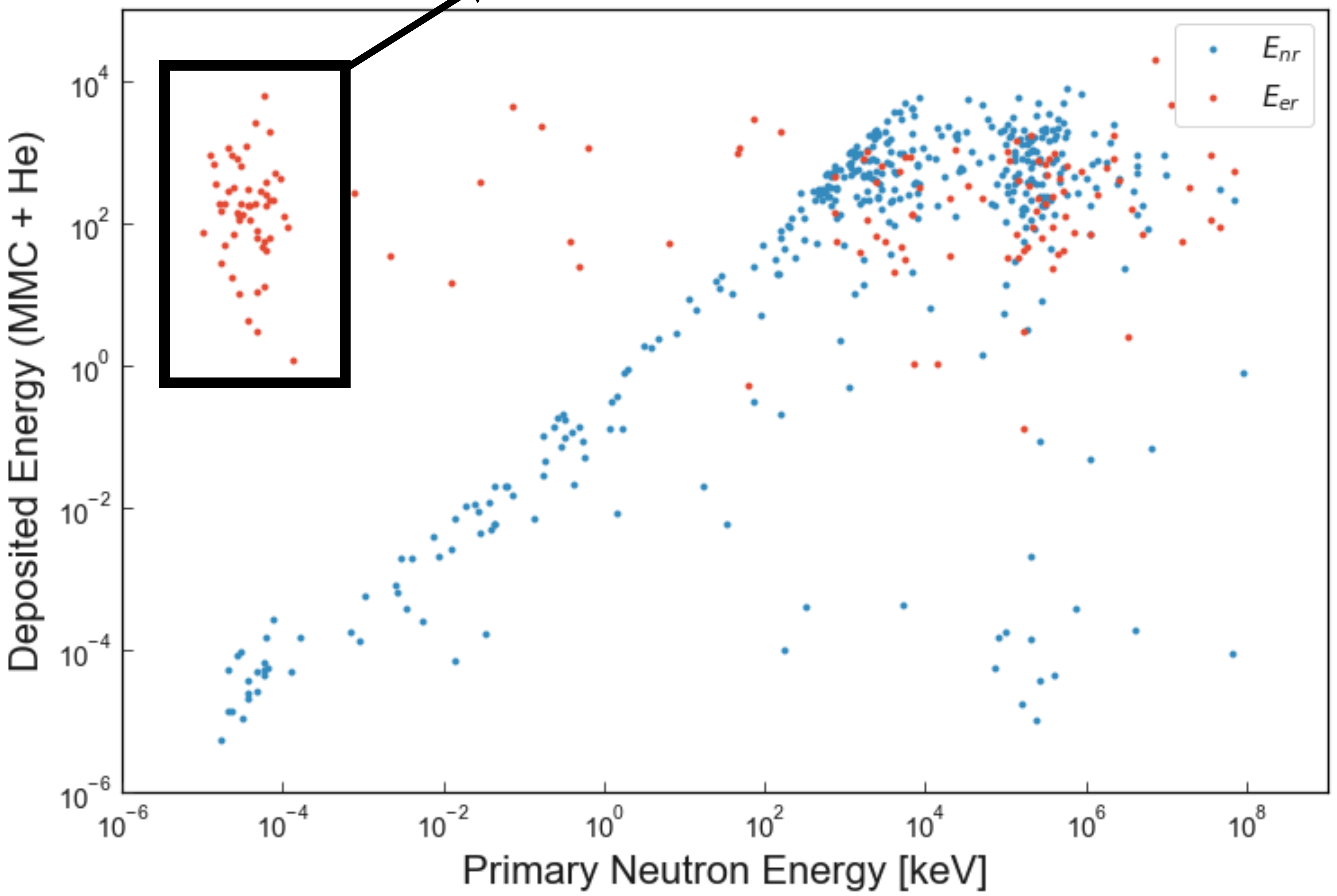


Neutron Simulations - Backscatters

- Most of the energy deposition from back scattered neutrons is from low energy neutrons



e- following neutron capture



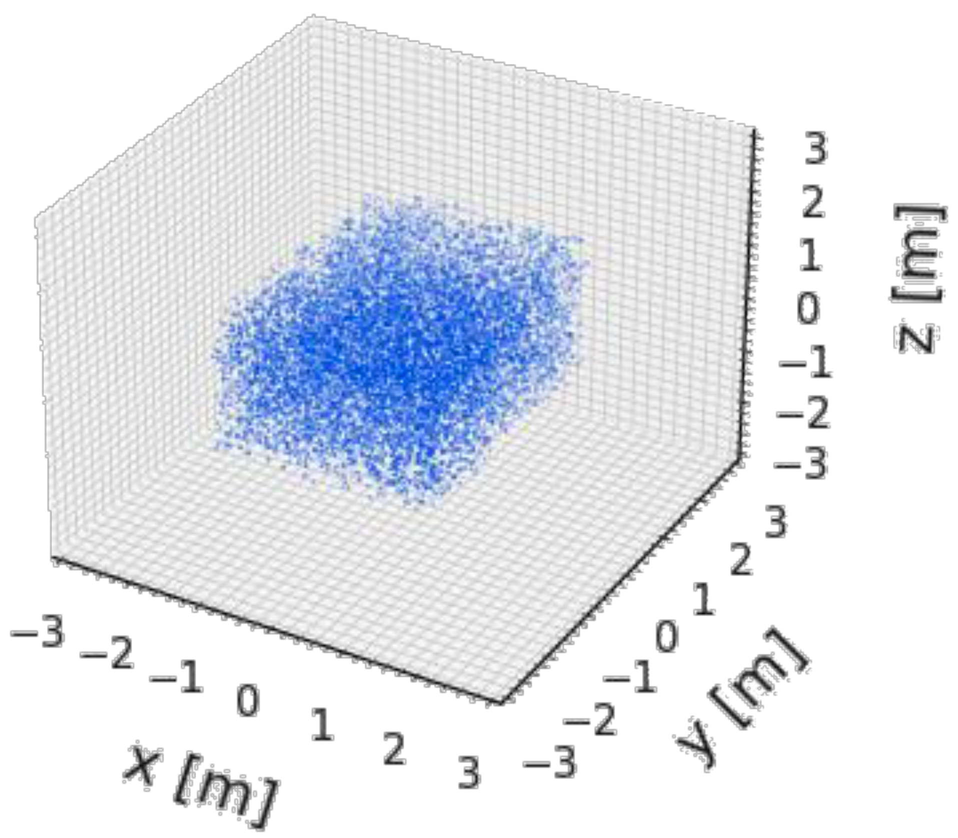
Summary

- Muon rate from lower energy muons is not insignificant, and negative muon capture produces a substantial neutron background
- Cosmic neutron rate at the surface lab also produces a non-negligible background
    - Beginning to investigate shielding options

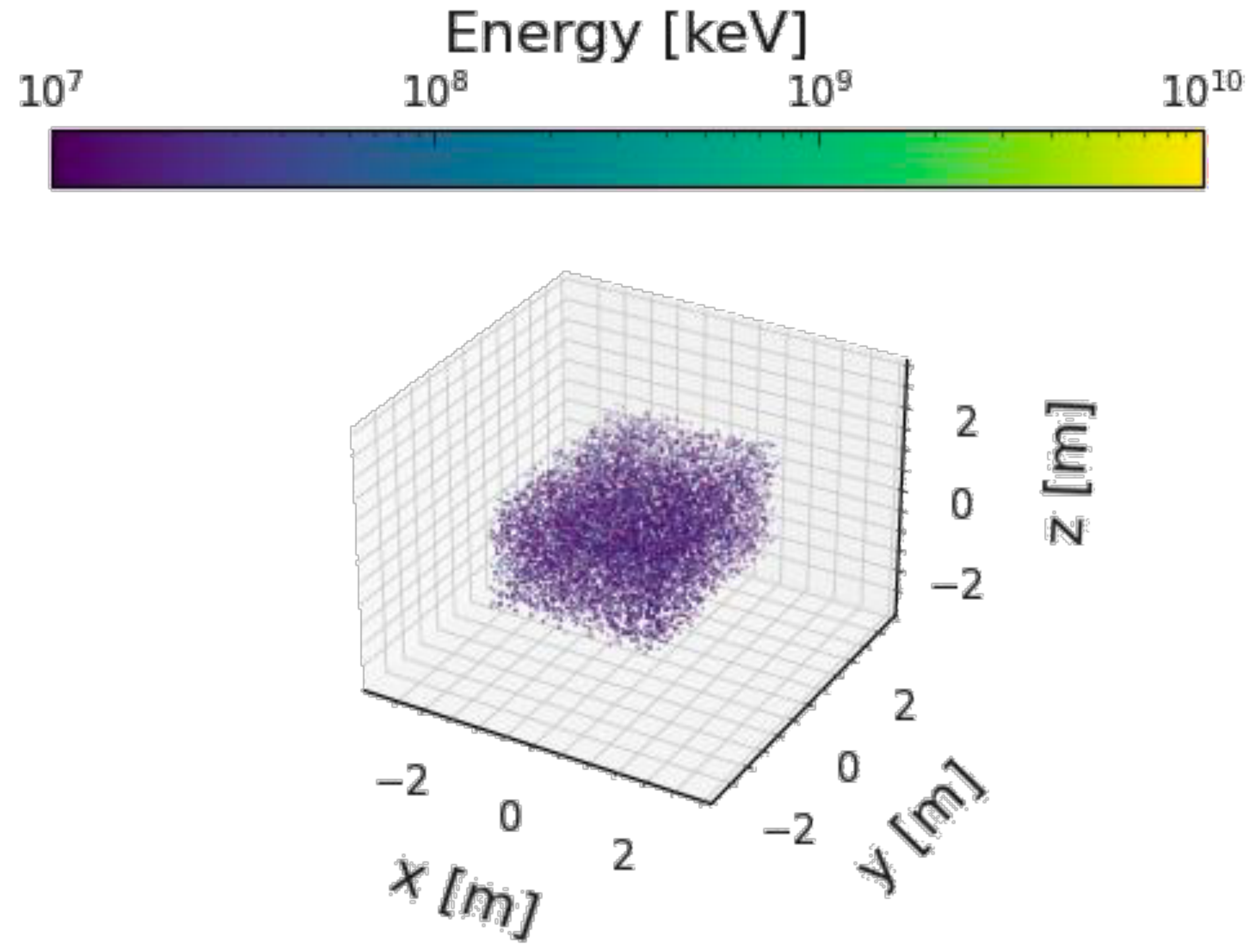
Backup

Francesco’s Original Simulation Method

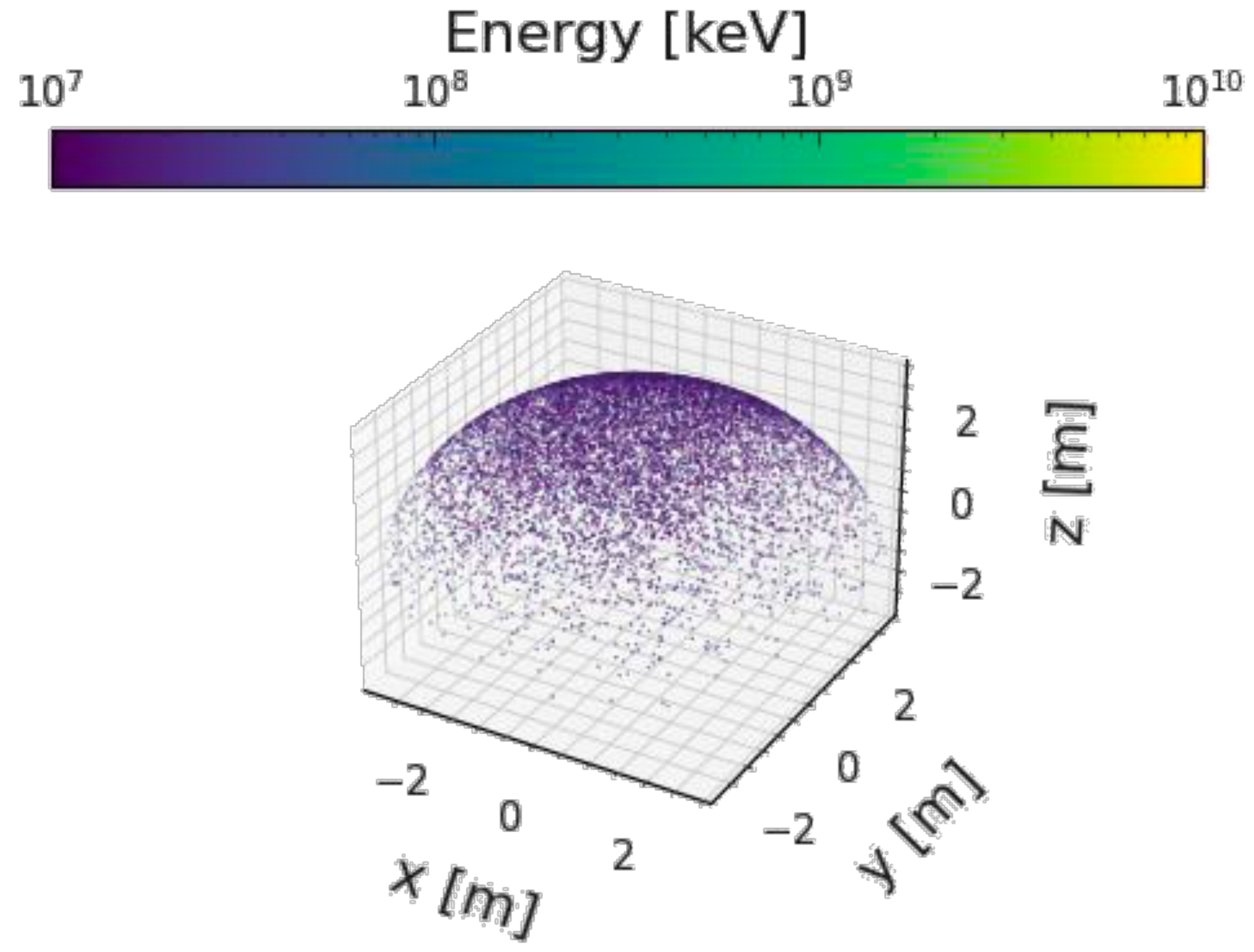
Sample N primary locations in lab



Draw energy and zenith angle for each position



Project to sphere larger than lab walls following the sampled direction



Experimental Data

- Gaisser
  - H. Jokisch, K. Carstensen, et al., Phys. Rev. D19 (1979) 1368. **(Sea level, Hamburg)**
  - H. Jokisch, K. Carstensen, et al., Phys. Rev. Lett. 83 (1999) 4241. **((i) Lynn Lake, Manitoba, Canada (56.5± N, 101.0± W), at an altitude of 360 m above sea level, and a nominal vertical geomagnetic cutoff of 0.5 GV, and (ii) Fort Sumner, New Mexico, (34.3± N, 104.1± W), at an altitude of 1270 m and a cutoff of 4.2 GV)**
  - P. Achardv, O. Adriani, et al., L3 Collaboration, Phys. Lett. B598 (2004) 15.
  - B. C. Rastin, J. Phys. G10 (1984) 1609.
  - C. A. Ayre, J. M. Baxendale, et al., J. Phys. G1 (1975) 584.
- PARMA
  - P. Goldhagen, J. M. Clem and J. W. Wilson, The energy spectrum of cosmic-ray induced neutrons measured on an **airplane over a wide rage of altitude and latitude.** Radiat. Prot. Dosim. 110, 387–392 (2004)
  - T. Nakamura, T. Nunomiya, S. Abe, K. Terunuma and H. Suzuki, Sequential measurements of cosmic-ray neutron spectrum and dose rate at **sea level in Sendai, Japan**. J. Nucl. Sci. Technol. 42, 843–853 (2005).
  - Several others, including some overlap with Gaisser
- EcoMug
  - L. Bonechi, M. Bongi, D. Fedele, M. Grandi, S. Ricciarini, E. Vannuccini, Development of the ADAMO detector: test with cosmic rays at different zenith angles, in: 29th International Cosmic Ray Conference Vol. 9, 2005, pp. 283. **(Possibly sea level Florence?)**