Neutron shielding studies for underground large detectors

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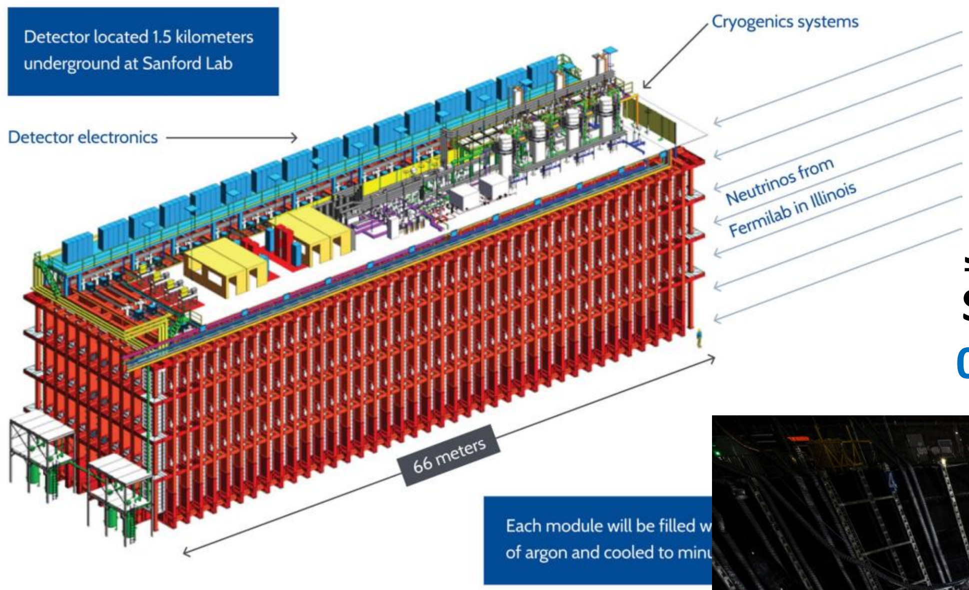
Rare event searches – the need for large detectors

- Neutrino Physics (mass hierarchy, oscillasions, supernovae explosion bursts...)
- Dark matter searches
- Proton decay
- Neutrinoless double-beta decay

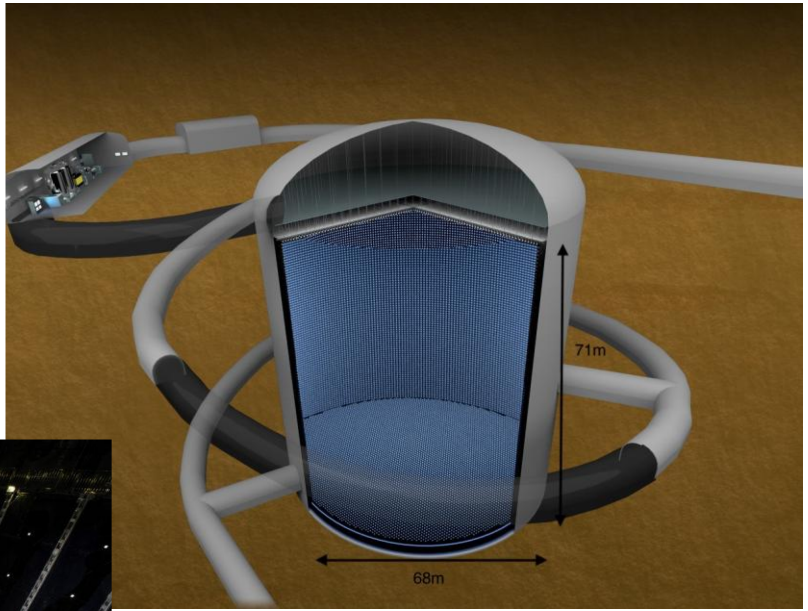
All these searches require large detectors to increase the probability of detection. We require different detection techniques based on the searches we want to do (TPC detectors, Cherenkov detectors, scintillator detectors).

Experiments that use large detectors



<u>DUNE experiment</u> – LAr TPC detectors
1.5 km underground

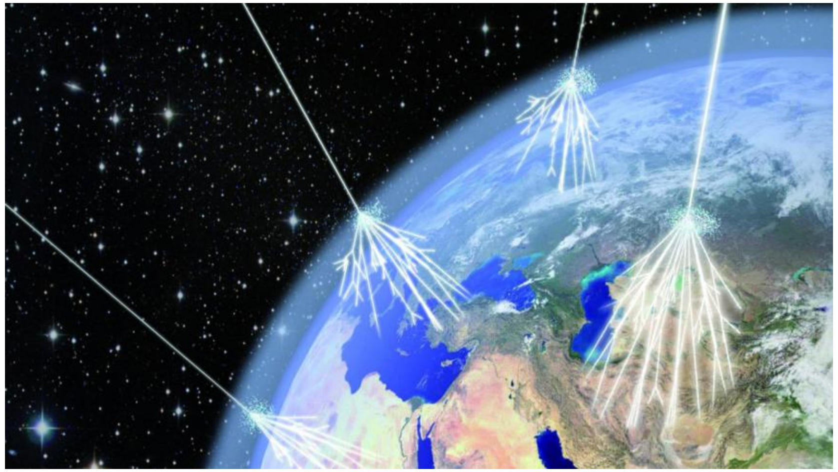
<u>JUNO experiment</u> -
Scintillator detector
0.7 km underground



<u>HyperKamiokande experiment</u> -
Cherenkov detector
0.65 km underground

Main background sources

Cosmic Rays



Radioactive decay

Radioactive series (Th-232, U-238, U-235), K-40, ...

https://www.pngegg.com/en/png-pxanf

https://news.uchicago.edu/explainer/what-are-cosmic-rays

Main background sources

Cosmic Rays

Highly reduced underground!!

Only muons from cosmic rays can penetrate deep underground

Radioactive decay

Radioactive series (Th-232, U-238, U-235), K-40, ...

Alphas, electrons, neutrons, photons

https://www.pngegg.com/en/png-pxanf
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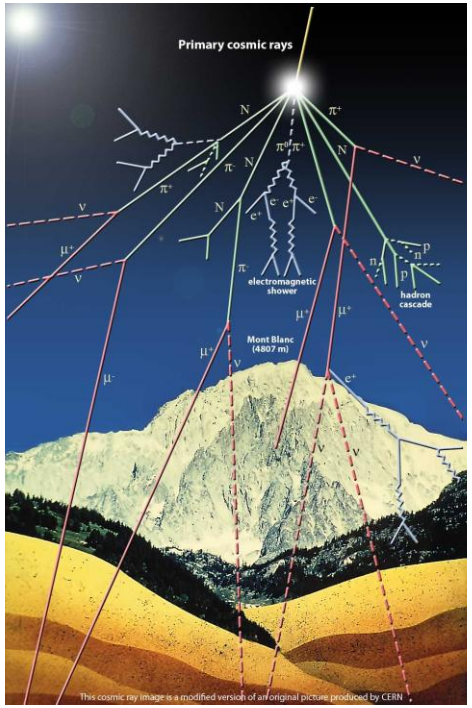
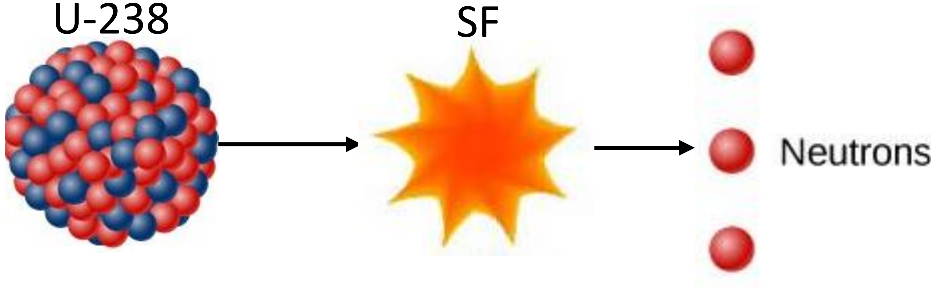
Underground neutrons

- There are three different neutron sources underground:

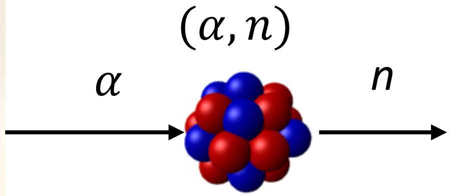
Neutrons generated by Cosmic Muons

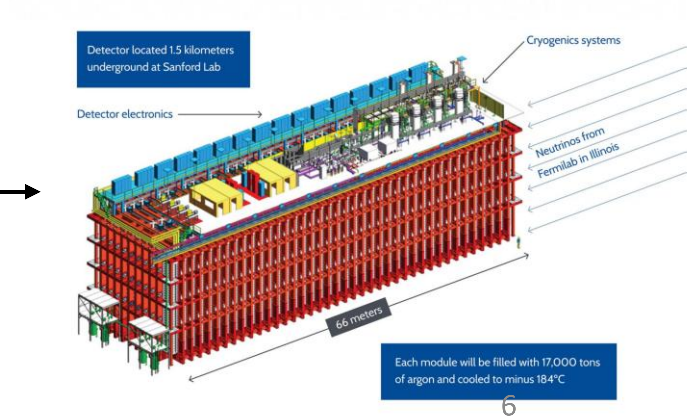


Spontaneous Fission of U-238



Neutrons from (α, n) reactions





https://tomasobecerra.medium.com/the-muons-particle-detectors-5056d7751b65
https://fensfeltet.no/en/hva-brukes-de-til/
https://lbnf-dune.fnal.gov/how-it-works/detectors-and-computing/

Neutron background

Neutrons can...

- get captured in the detector walls or in the active volume and this leads to gamma emission.
- undergo inelastic scatterings that lead to gammas.
- induce different reactions such as (n,α), (n,p) etc.
- mimic the signal expected for dark matter searches through recoil.

Neutrons can be shielded with...

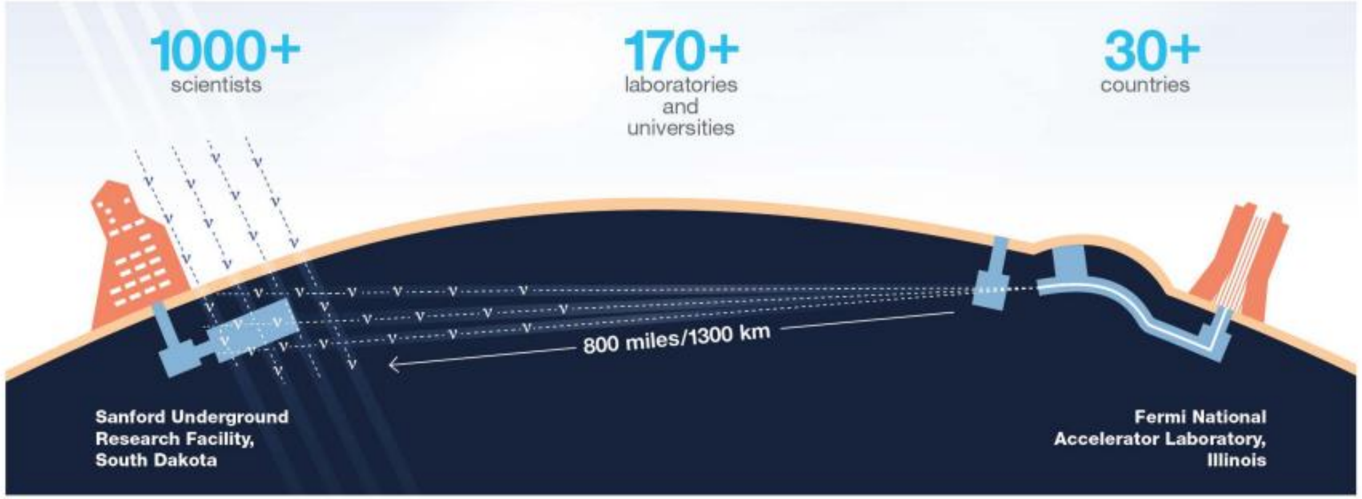
- materials with high hydrogen content (water, HDPE, paraffin...) because hydrogen has the mass comparable with the mass of neutron
- materials with high boron content (Borated HDPE, boron carbide...) because natural boron has the isotope B-10 with high neutron cross-section ($\sigma(n,tot)=3846$ b for thermal neutrons).

What is DUNE?

Fermilab

Sanford Underground Research Facility

- **Dual-site experiment** for the study of neutrino oscillations, supernova burst neutrinos, nucleon decay, atmospheric neutrinos…
  - **Near Detector** to measure the unoscillated neutrino spectrum and flux constraints
  - **Far detector**: 4 x 10 kt (fiducial) LAr TPC modules (single phase and/or dual phase)
- **High purtity ν_μ beam:** ~1.2 MW, upgradeable to 2.4 MW



- DUNE aims at answering fundamental questions

Origin of Matter
Origin of the matter-antimatter asymmetry (CP violation)

Unification of forces
Observation of the rare signal of proton decay

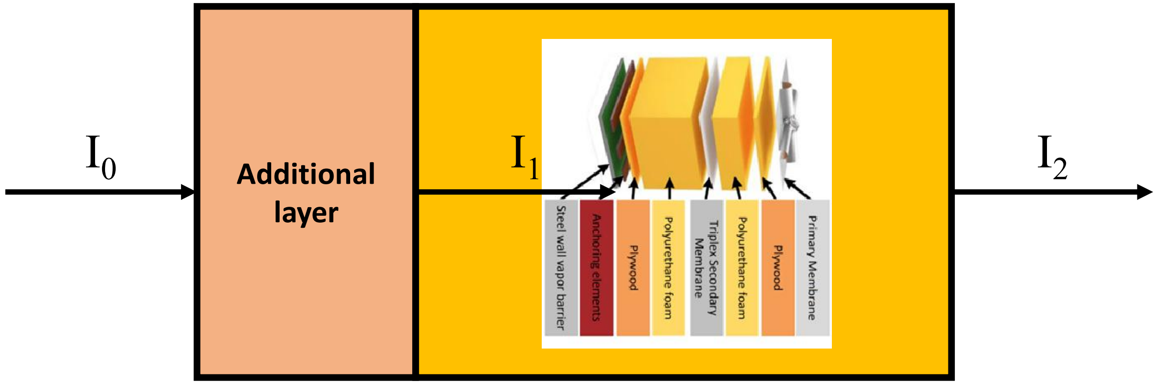
Black hole formation
Gigantic streams of neutrinos emitted by exploding stars

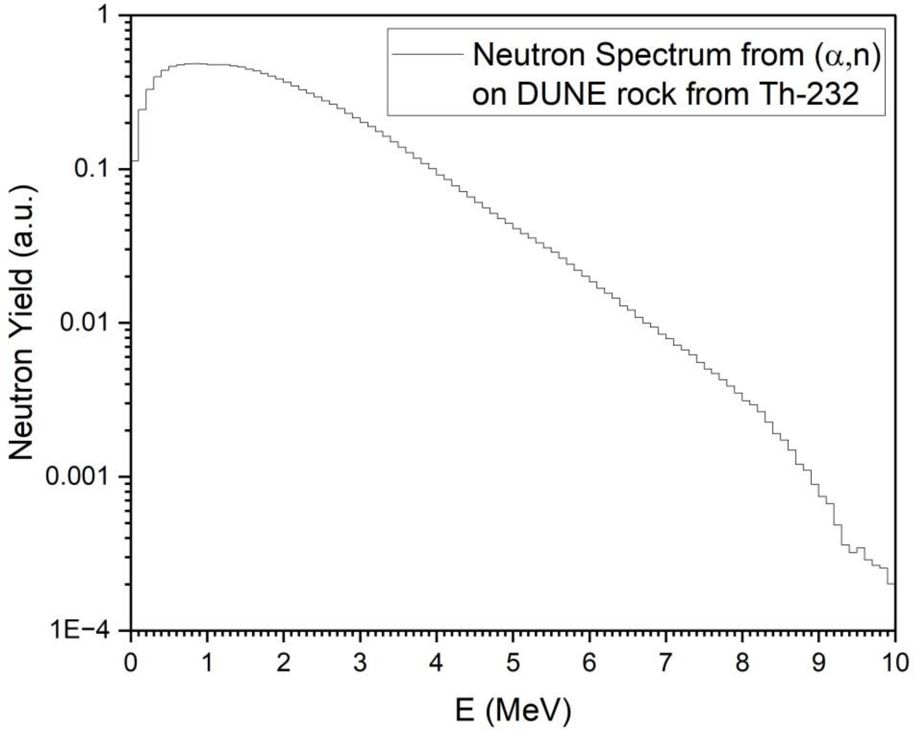
DUNE Collaboration, B. Abi, and M. Parvu et al. The DUNE far detector interim design report, volume 3: Dual-phase module, 2018.

FLUKA simulations (simplified geometry)

- 7 materials (with different thicknesses x = 5cm -> 30cm at intervals of 5 cm): Water, HDPE, Borated Polyethylene (2%, 5%, 10% and 30%), Boron Carbide.

- Each simulation has 10^7 neutron primaries which follow the energy spectrum from (α,n) reactions from Th-232 simulated for the SURF cavern where the DUNE far detectors will be placed.

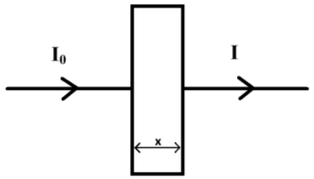




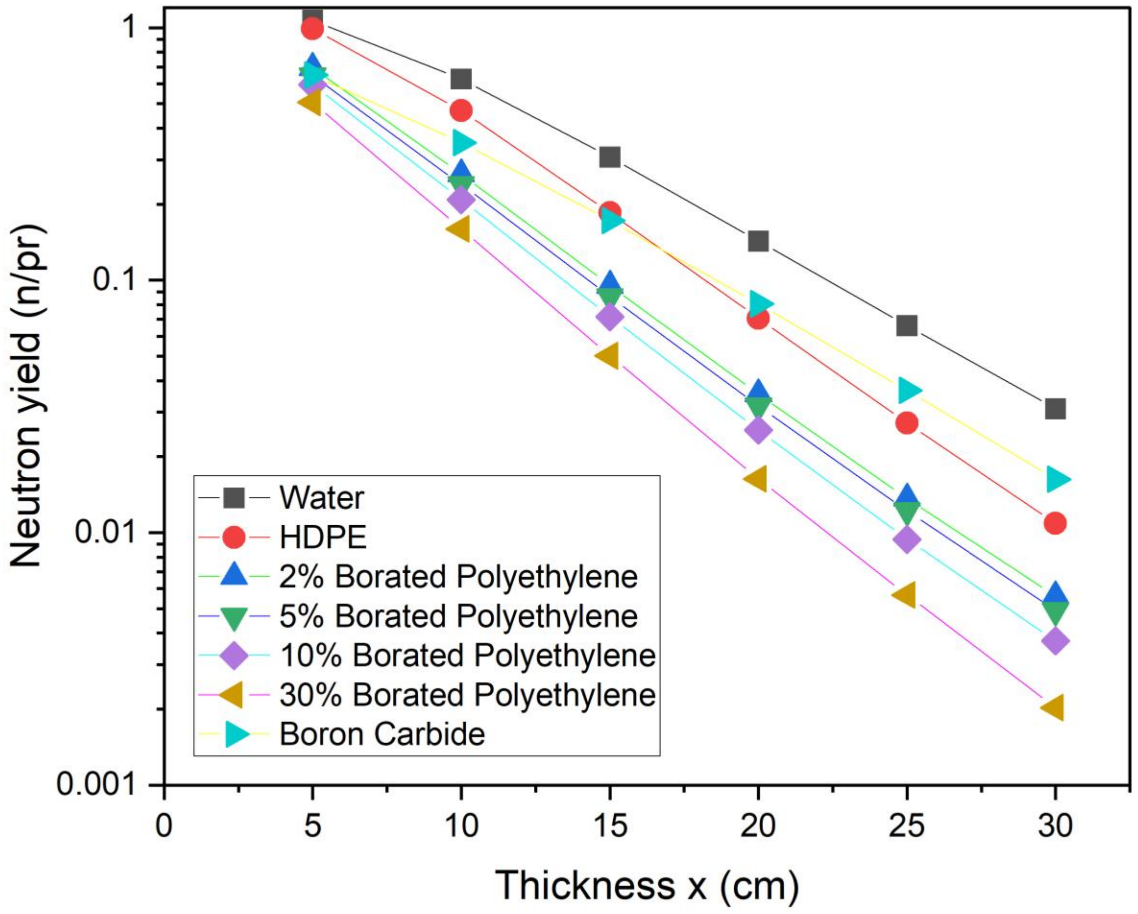
SOURCES4 calculations from [1]

[1] https://arxiv.org/abs/2408.10910

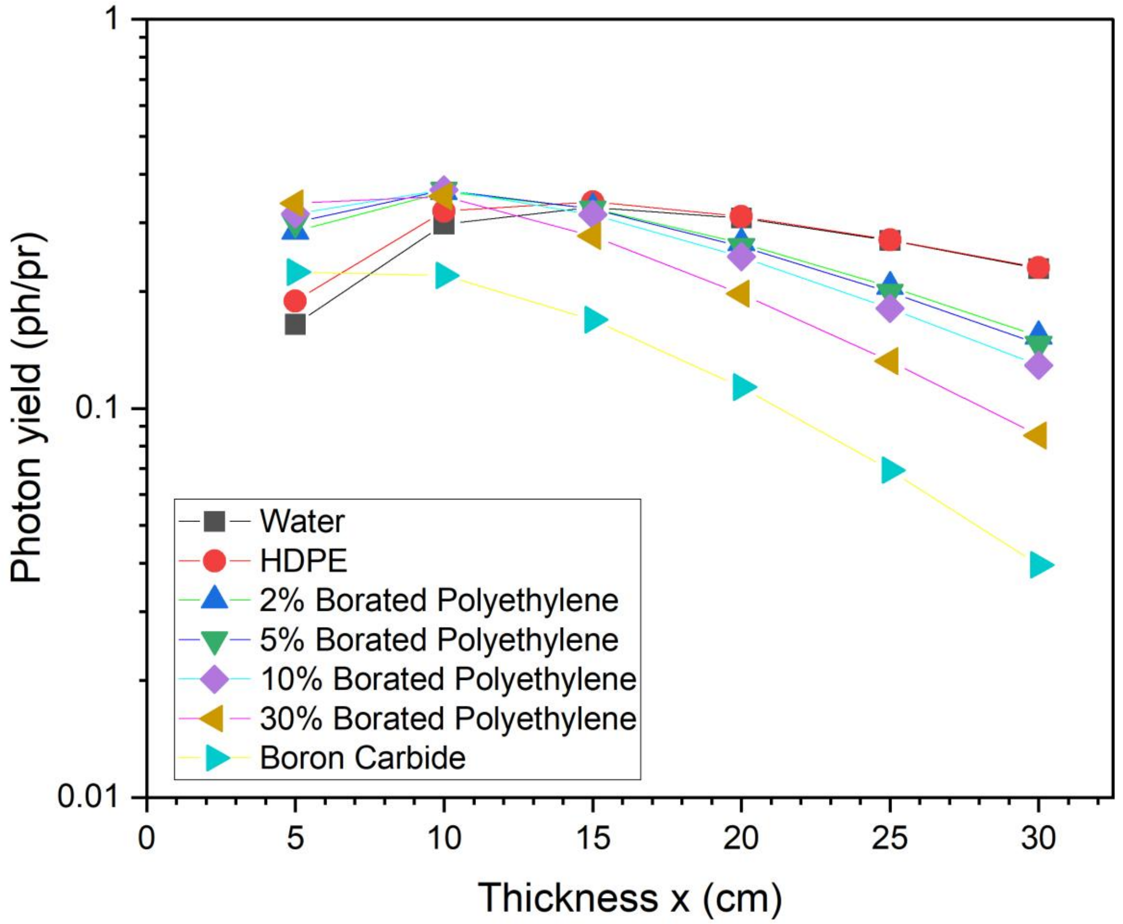
First scenario – passing the additional layer



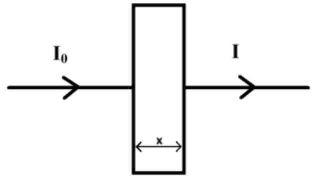
Number of neutrons per primary passing the layer



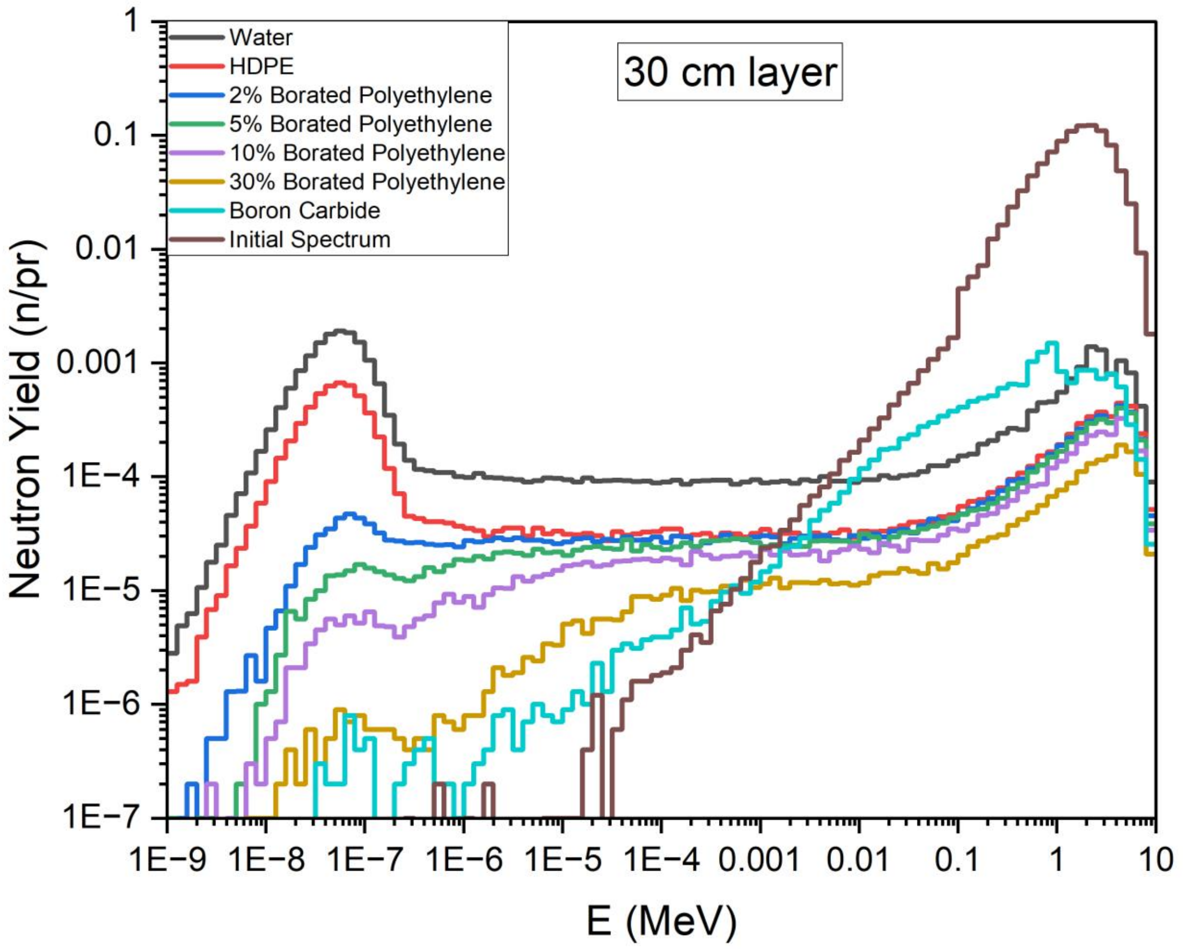
Number of photons (generated) per primary passing the layer



First scenario – passing the additional layer of 30cm



Number of neutrons per primary passing the layer



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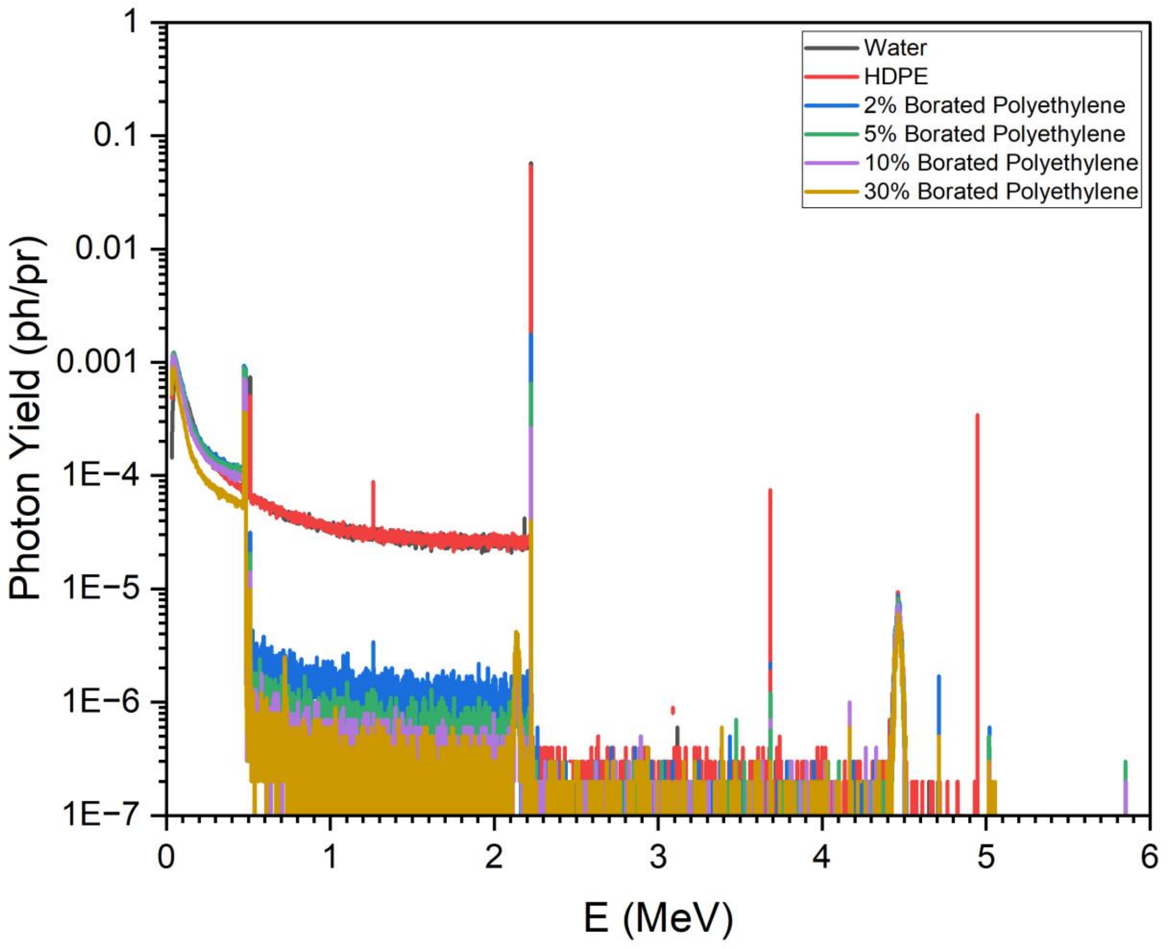
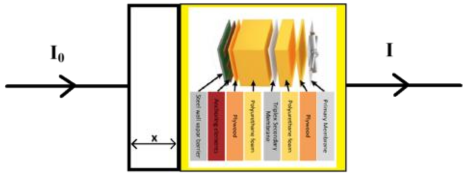
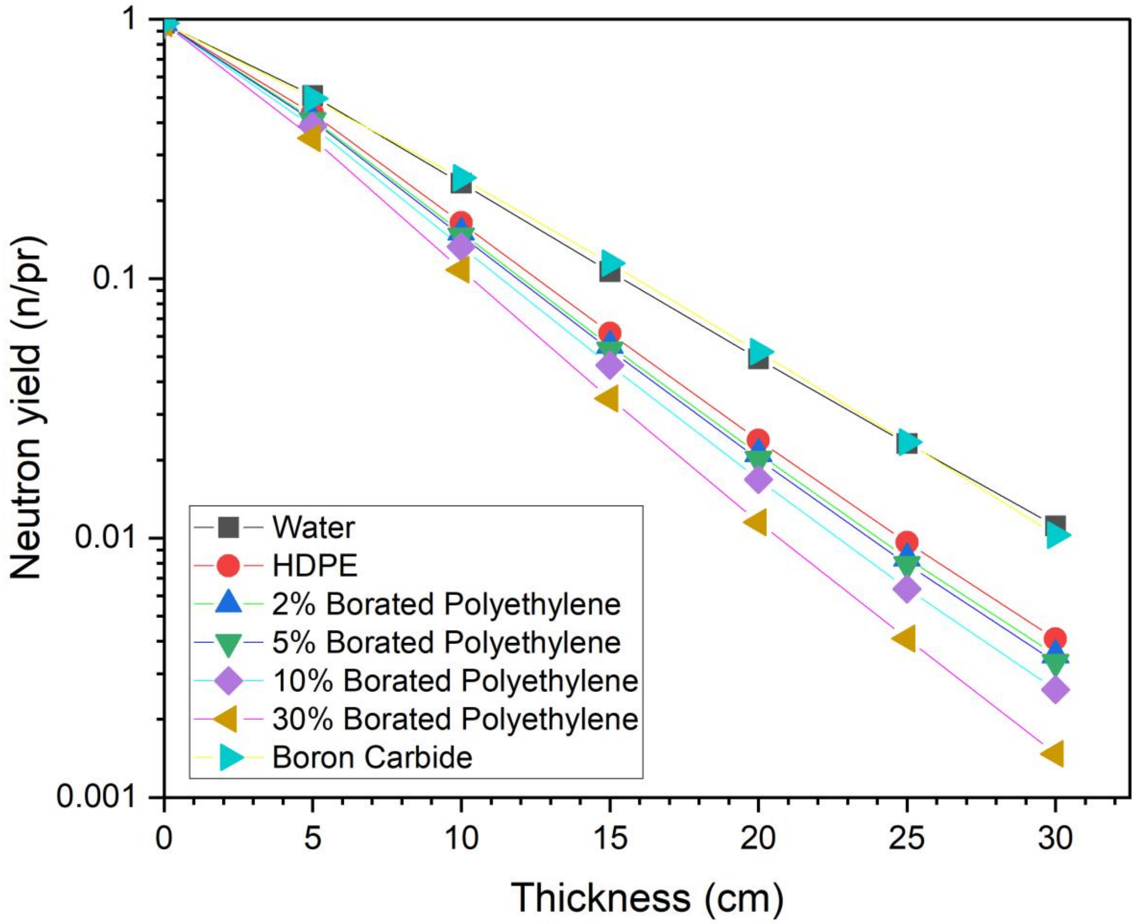


Second scenario – DUNE cryostat with the additional layer



Number of neutrons per primary entering the LAr



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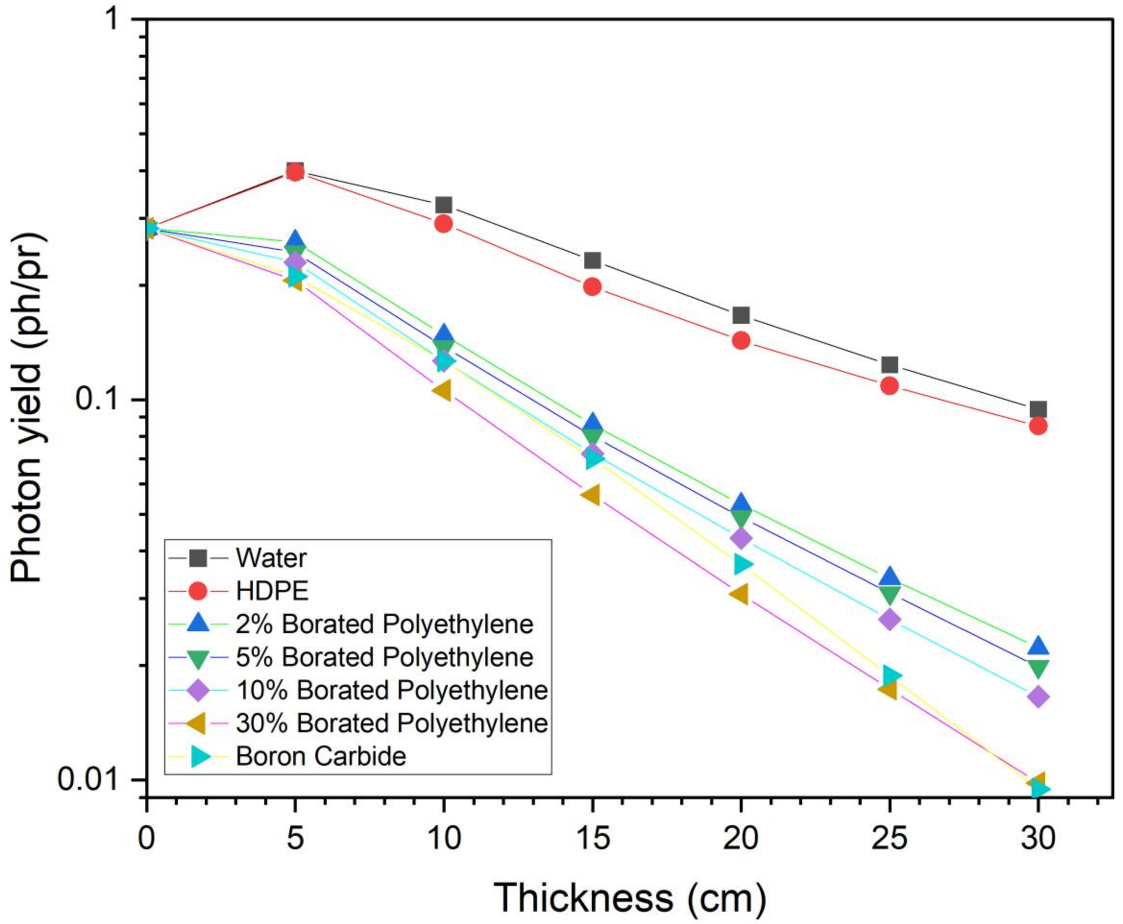
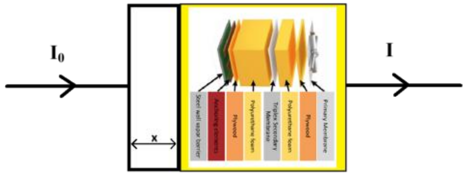
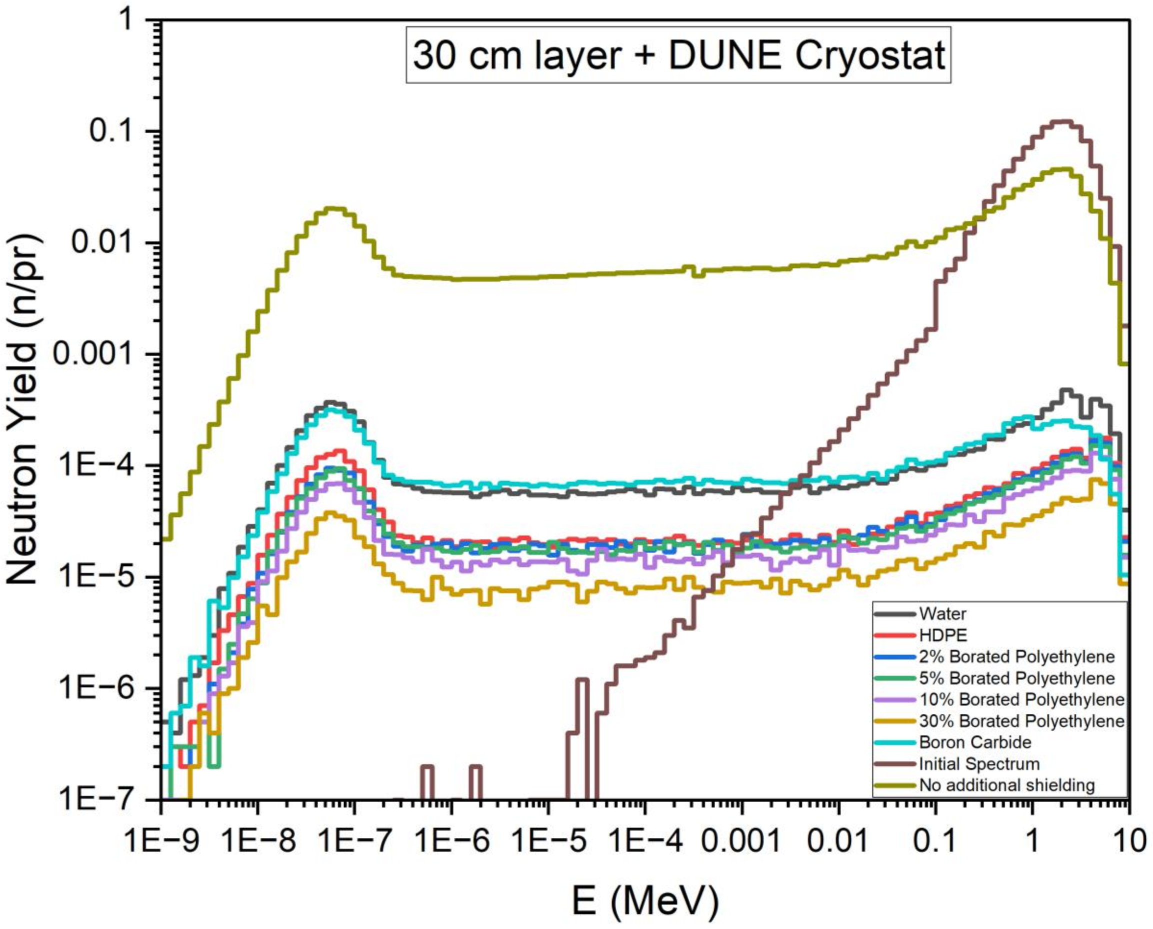


Second scenario – DUNE detector wall with the additional layer of 30 cm



Number of neutrons per primary entering the LAr



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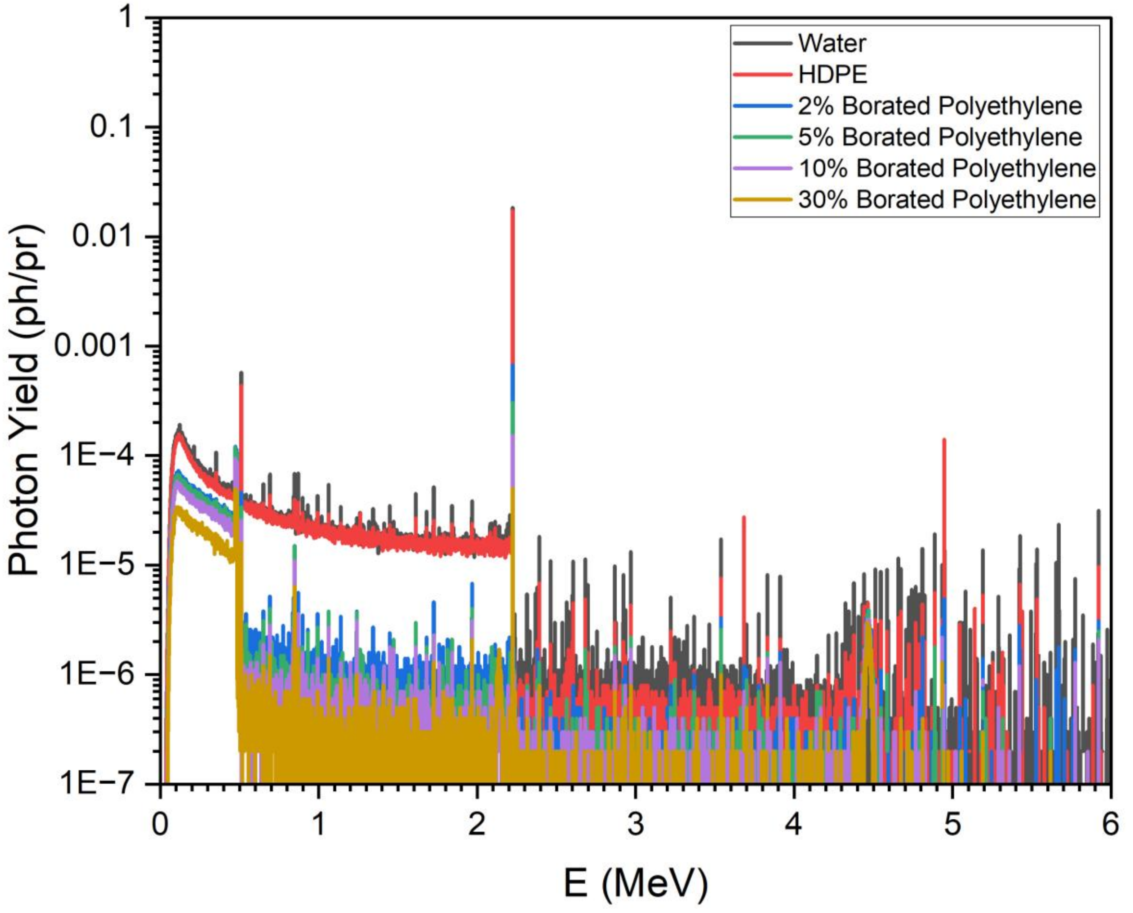

Why new and more complex simulations are required?

- At the level of just comparing the capabilities of these materials as shields against neutrons and photons (produced by the neutrons interactions) these simulations were useful.
- However, because the neutron beam is oversimplified (assumed to be uni-directional and originating from a single point) two important factors are neglected:

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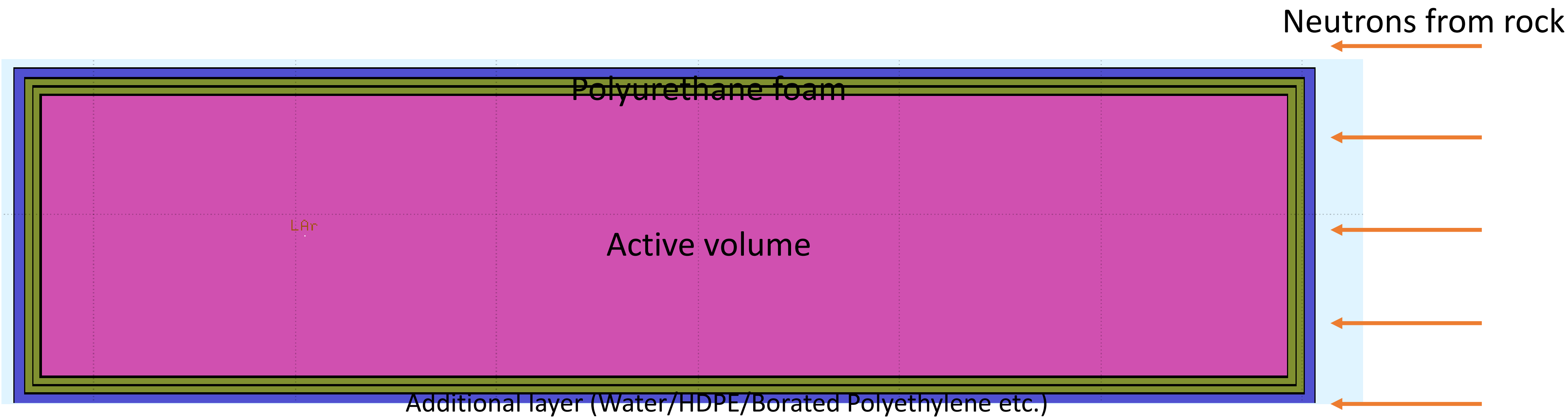

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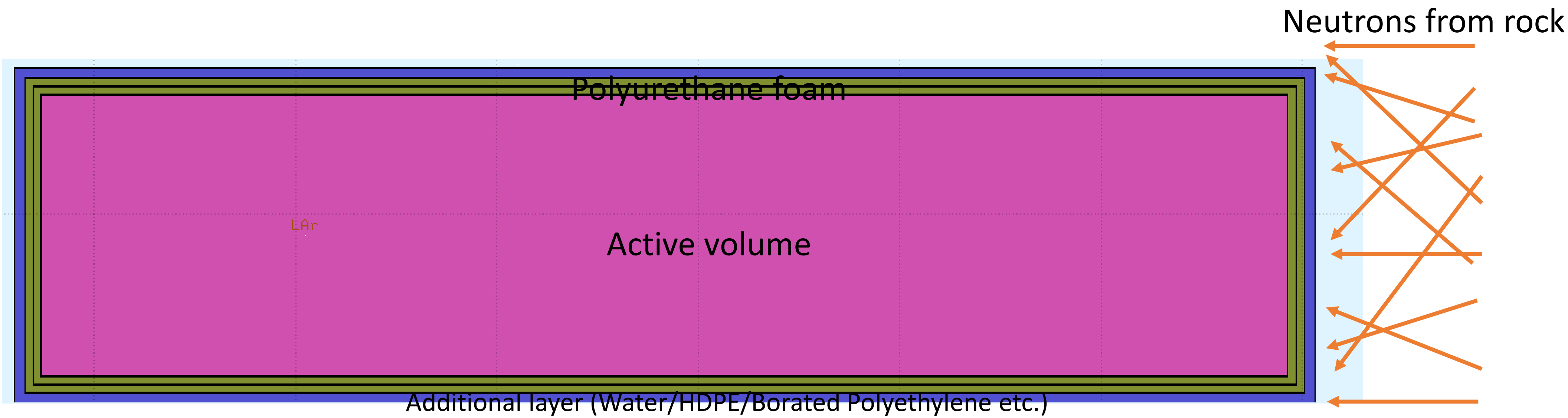
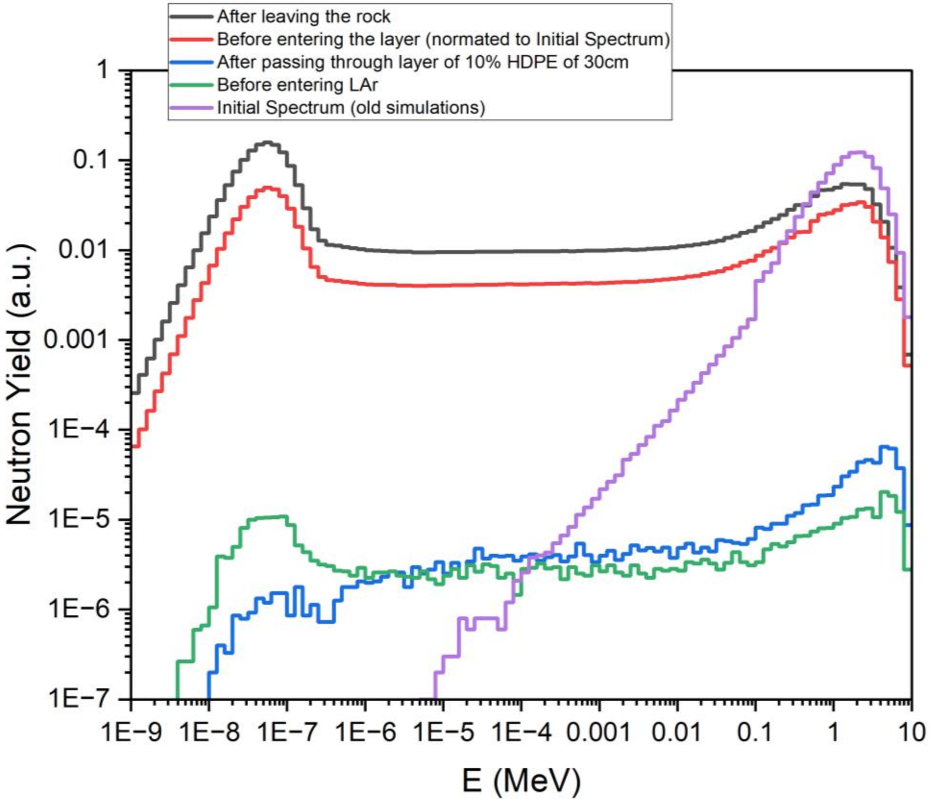
  - Geometric effects arising from the difference in dimensions of the layers covering the active volume.
  - The angular distribution of neutrons interacting with the first layer - in a realistic setup, neutrons arrive from multiple directions and do not all hit the first layer at normal incidence.



Why new and more complex simulations are required?

- The neutron spectrum was considered without traversing the rock/air before reaching the layers.

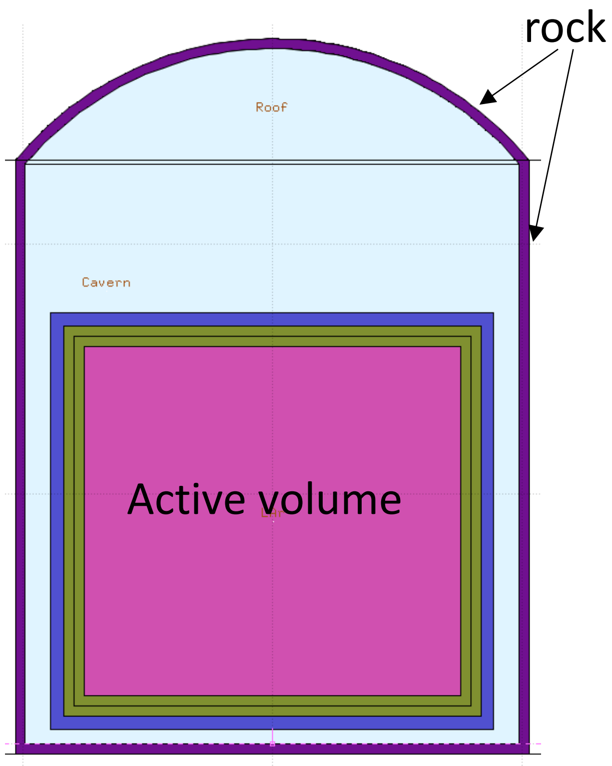
Neutrons transported through rock



https://news.uchicago.edu/story/colossal-caverns-fermilabs-dune-experiment-have-been-fully-excavated

New simulations in FLUKA

- A geometry (in scale) of the cavern and the detector was implemented.
- The neutrons are generated isotropically in the rock with the initial spectrum from SOURCES4.



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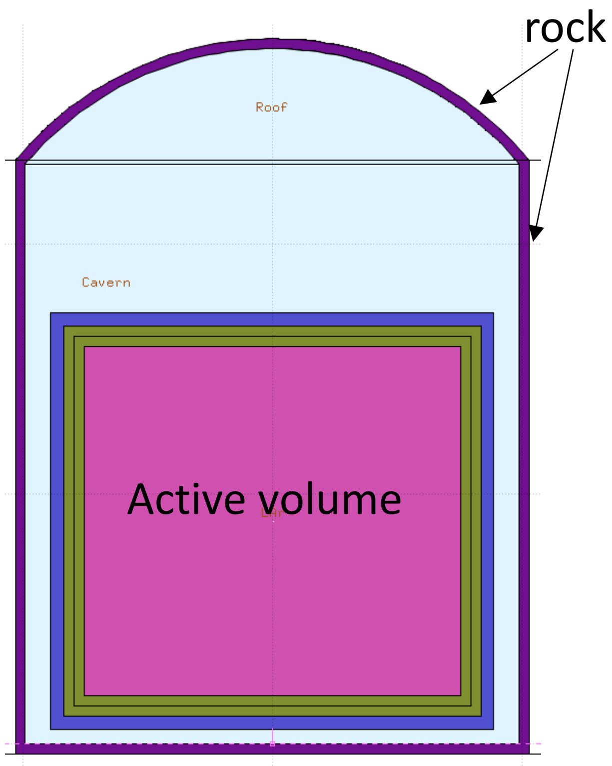
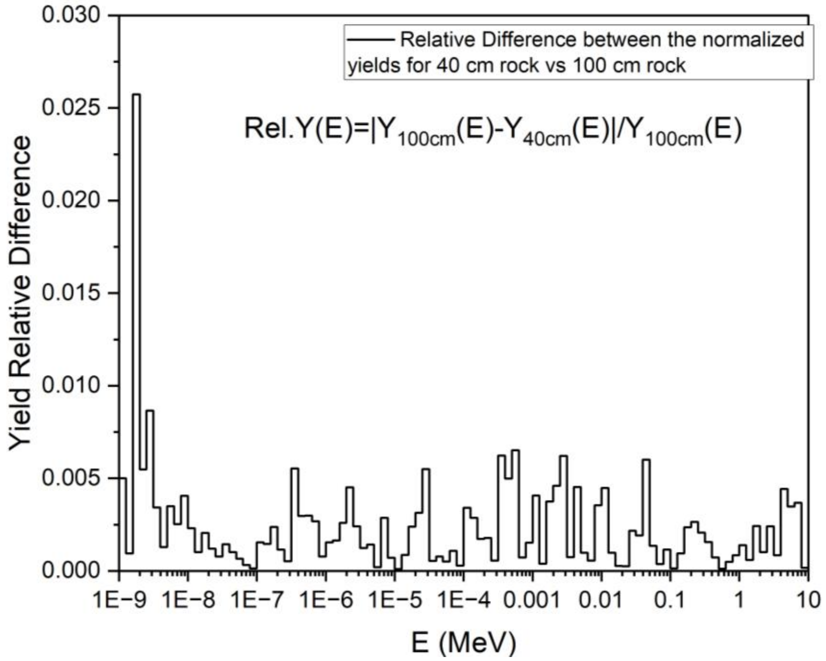


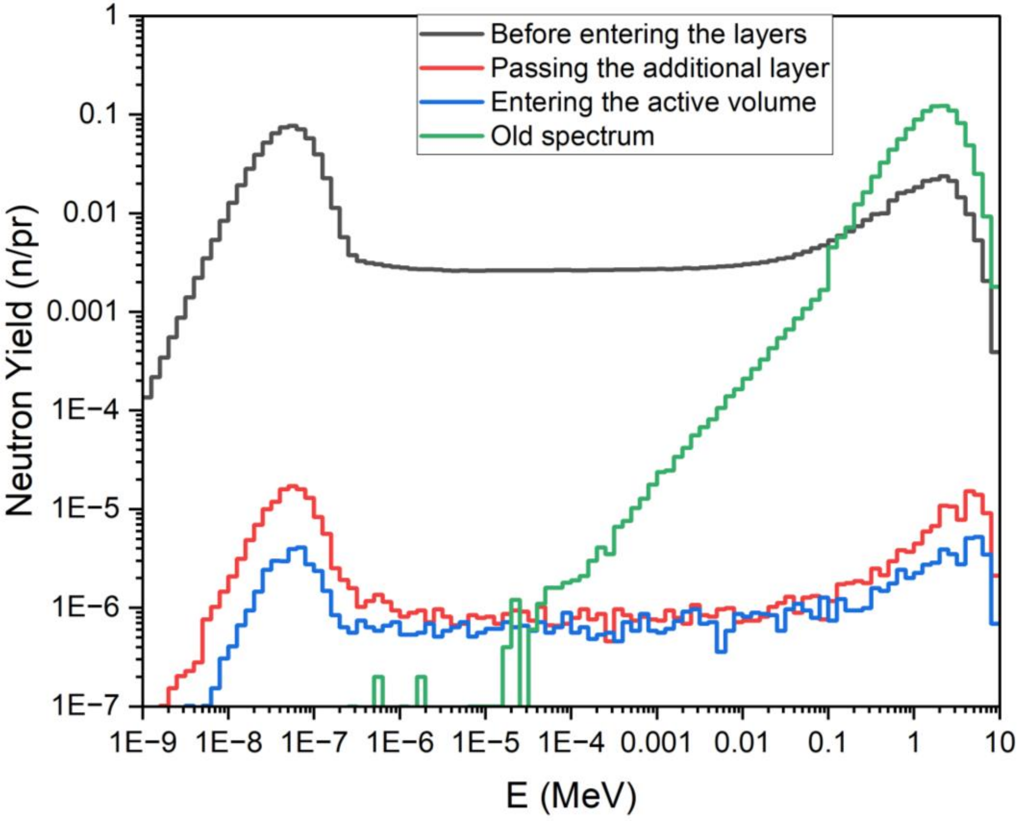


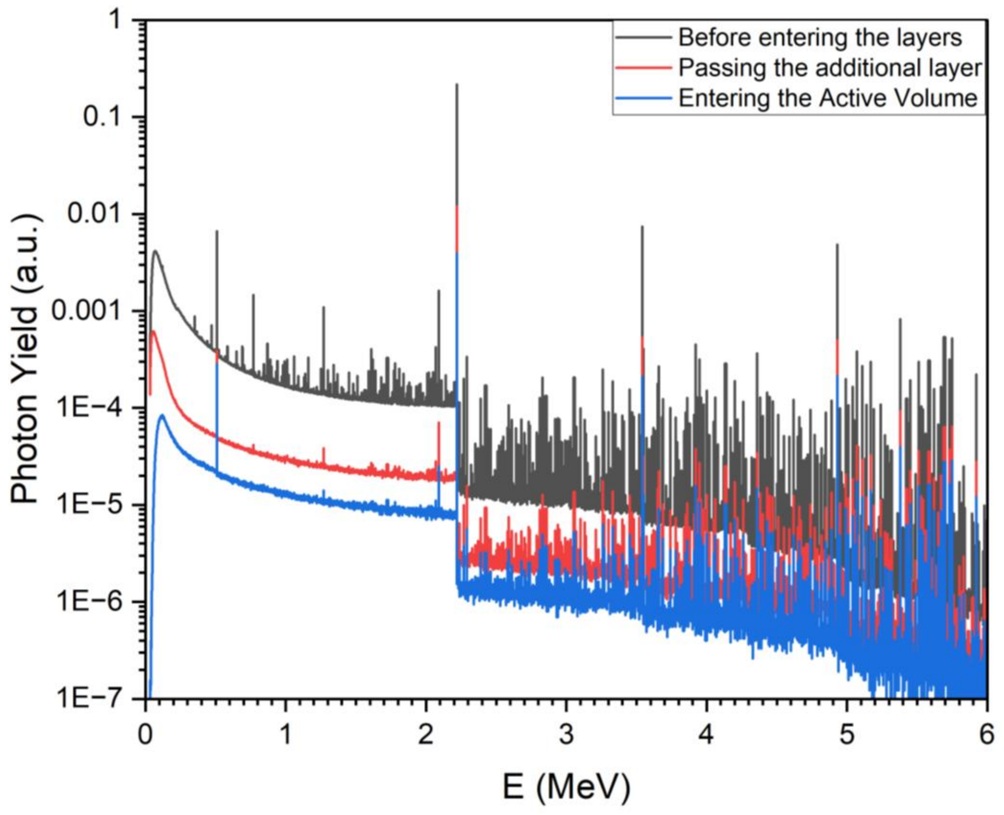
- The 40 cm thickness of the rock is enough to prevent any significant deviation in the exiting neutron spectrum compared to that observed with greater rock thicknesses, such as 100 cm.

Preliminary results

- The very large dimensions of the geometry lead to huge number of primaries required for good statistics in our simulations -> very long simulations.

New simulations with 50cm water layer





Summary and outlook

- Regarding neutron shielding, 30% Borated Polyethylene is by far the best material (between the materials discussed) that can be used, however it’s quite expensive.
- Cheaper materials with closer capabilities are 2% or 5% Borated Polyethylene, HDPE or even water!
- Combinations of these materials can be found to highly increase the quality/price ratio.
- New simulations will greatly improve our results, giving more realistic and reliable results.
- A neutron source of Pu-Be from the Faculty of Physics, University of Bucharest could be used to confirm our results.

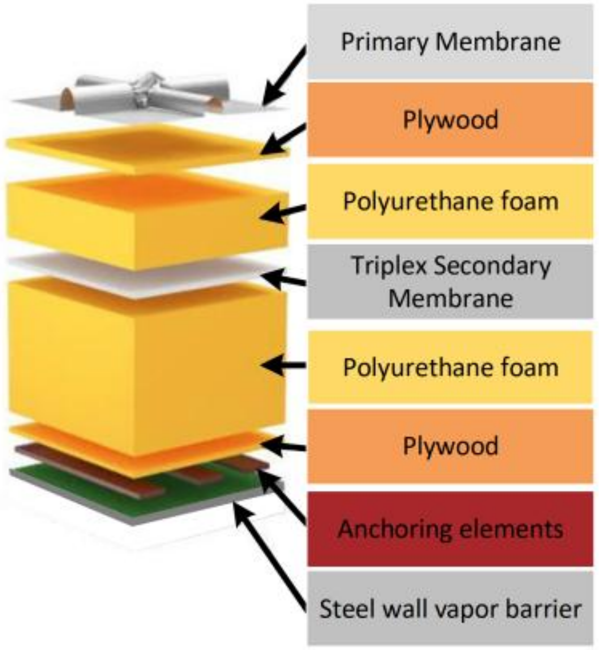
Thank you for your attention!

I sincerely thank the organizing committee of CSSP2025 for the opportunity to participate and present my work here!

Questions?

Backup slides

DUNE Cryostat and some materials



Material
Polyurethane Foam H(6.0%), C(64.6%), O(23.9%), N(5.6%)
Stainless Steel (SS304L) Fe(66.76%), C(0.16%), Cr(19.99%), Ni(9.31%), Mn(1.97%), Si(1.48%), P(0.05), S(0.05%), Al(0.22)
S460ML Fe(95.35%), Mn(1.7%), Ni(0.8%), Si(0.6%), Cu(0.55%), C(0.18%), P(0.03%), S(0.025%), Al(2e-8%), N(0.025%), Nb(0.05%), V(0.12%), Ti(0.05%), Cr(0.3%), Mo(0.2%)
Mean DUNE Rock O(58.742%), Fe(1.501%), Mn(0.03%), Ca(0.112%), K(1.554%), Si(19.854%), Al(4.94%), Mg(3.58%), Na(0.692%), H(8.996%)
Polyethylene H(14.371%), C(85.629%)

arXiv:2312.09104