Geant4 usage for AMoRE

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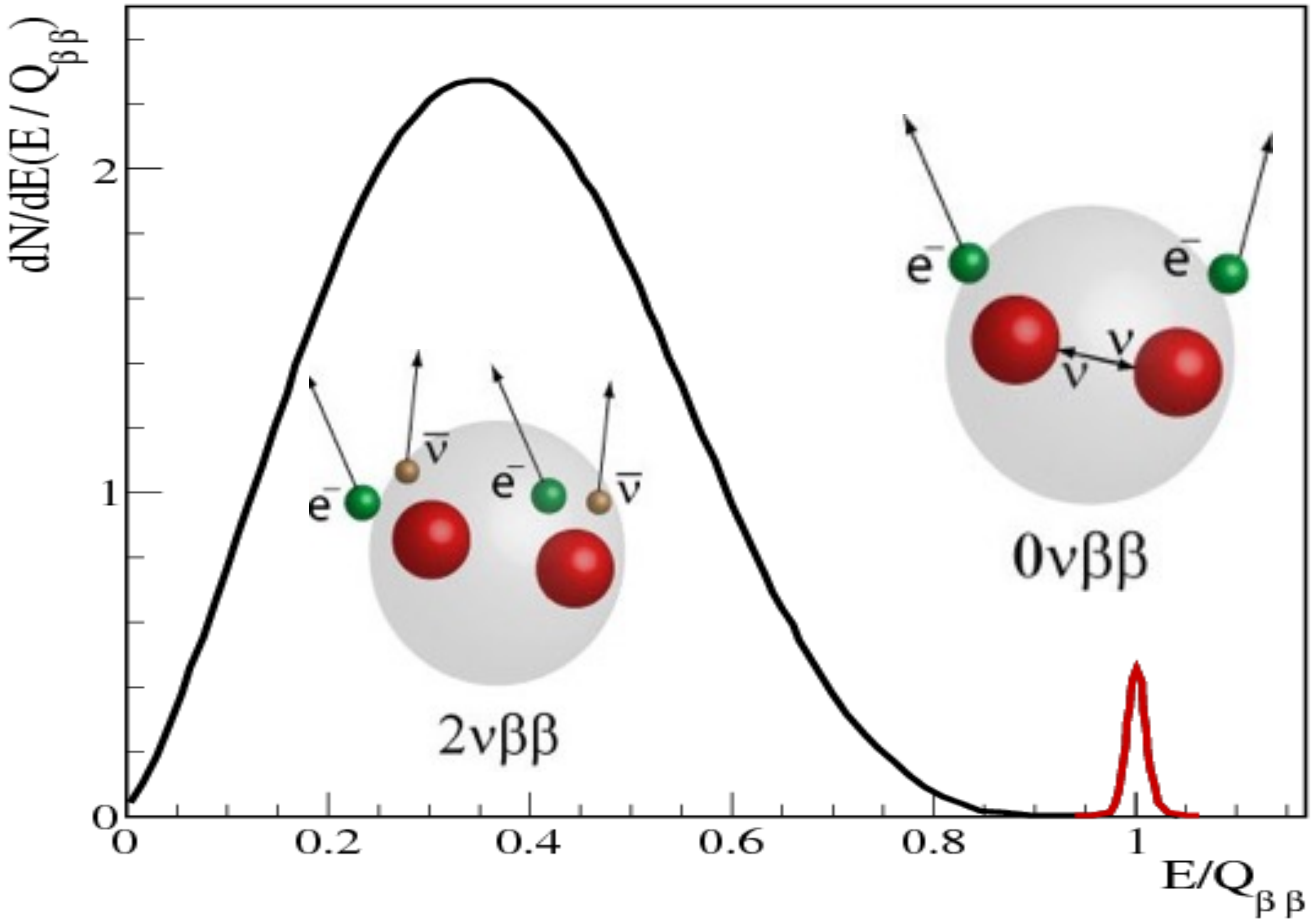
AMoRE project

Collaboration members

And others…

AMoRE (**A**dvanced **Mo**-based **R**are process **E**xperiment)

It aims at searching for neutrinoless double beta decay (0vββ)



- To determine whether the neutrino is a Majorana particle
- To test the existence of lepton number violating process
- To estimate the absolute neutrino mass scale

For light neutrino exchange model:

$$[T^{0\nu}_{1/2}]^{-1} = G_{0\nu}\,|M_{0\nu}|^2 \left(\frac{m_{\beta\beta}}{m_e}\right)^2$$

Half-life measured; Phase factor; Nuclear matrix element; Effective 0νββ neutrino mass, < $m_{\beta\beta}$>

$$\langle m_{\beta\beta}\rangle = \left|\sum_{i=1}^{3} U_{ei}^2 m_i\right|$$

- If the decay rate of the 0vββ is precisely measured, the absolute neutrino masses can be calculated → It helps to determine neutrino mass hierarchy

(for zero background)

$$T^{0\nu}_{1/2} \propto M \cdot T$$

(for finite background)

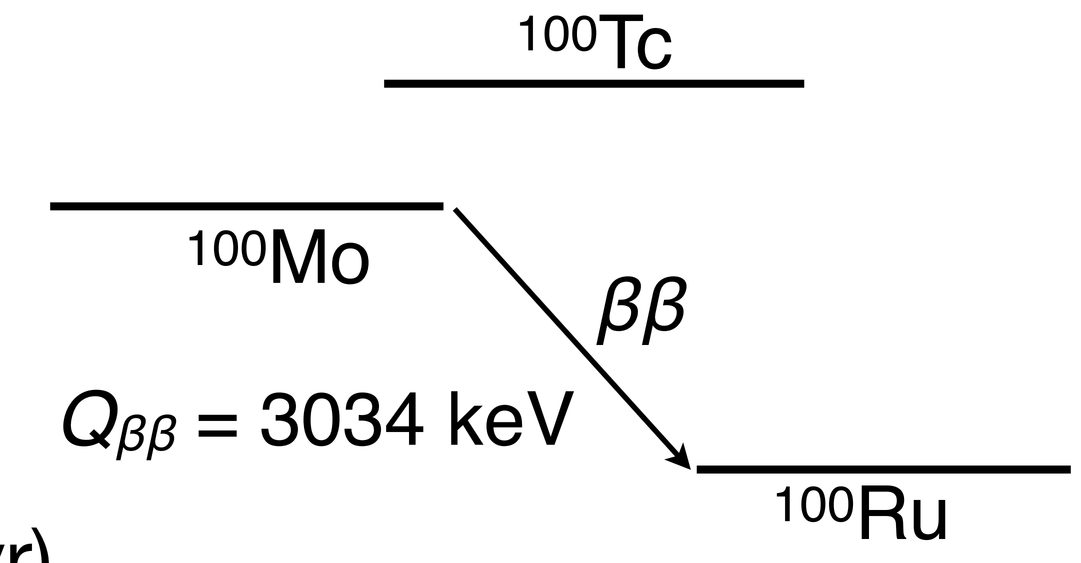
$$T^{0\nu}_{1/2} \propto \sqrt{\frac{M \cdot T}{B \cdot \Delta E}}$$

- Half-life limits are proportional to the detector mass M and DAQ time T, if finite background, sqrt(MT)
- To discover a sharp peak @ Q-value:
  - **Good energy resolution**
  - **Extremely low background**

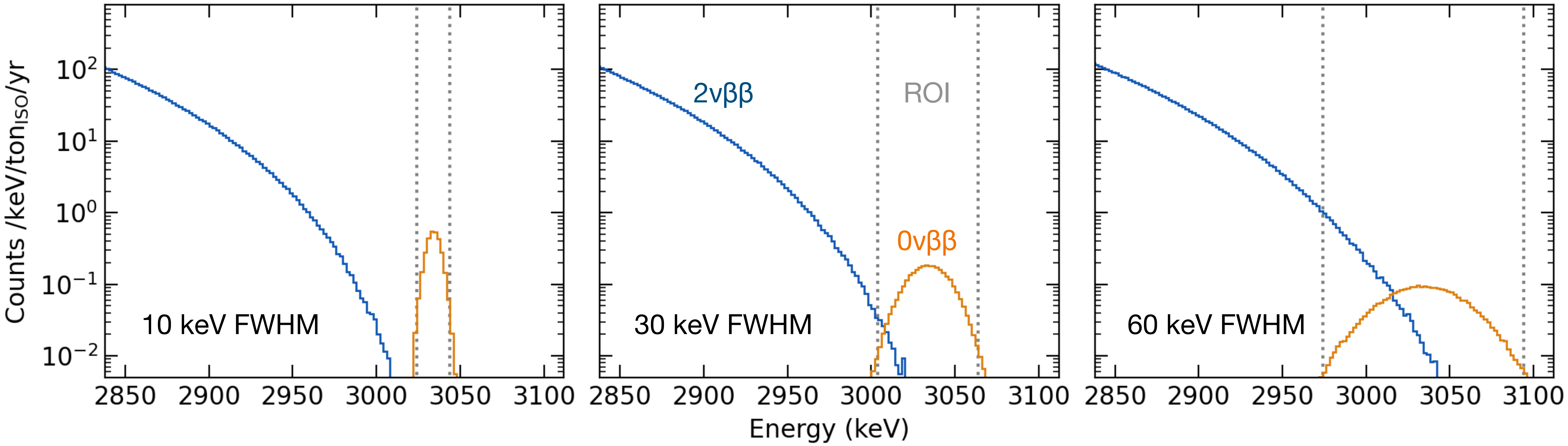
Energy resolution and background

for experimental sensitivity

- Understanding of background and its reduction
  - Careful choice of detector/shielding components' materials.
  - Heavy shielding: deep underground; Pb, B, CH, Rn free air, μ-veto,…
- Irreducible background: 2νββ ➔ energy resolution ➔ cryogenic (phonon) detector

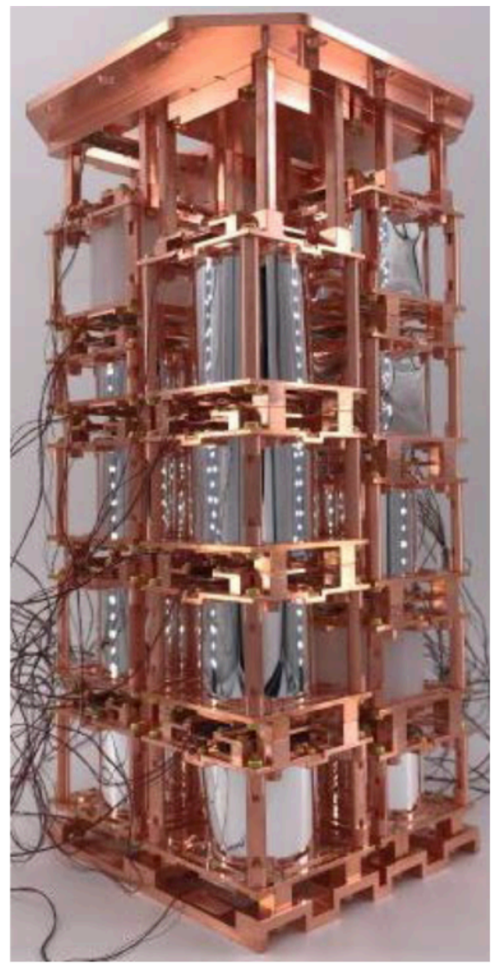
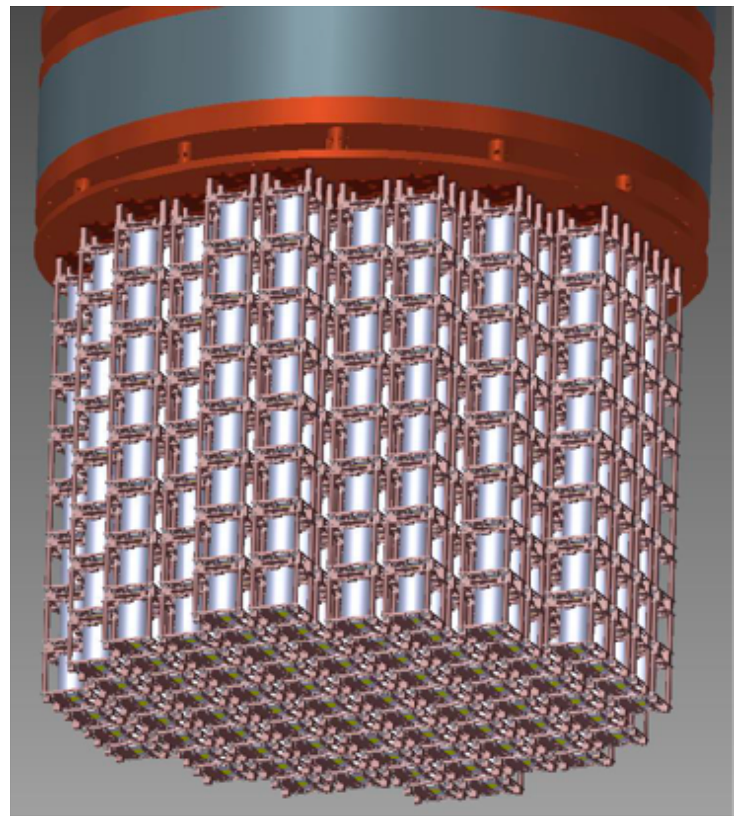


Assuming 100% absorption efficiency, 10^{-8} 0νββ branching ratio ($\tau_{0\nu}$~10^{27} yr)



AMoRE project in three phases

TAUP2023

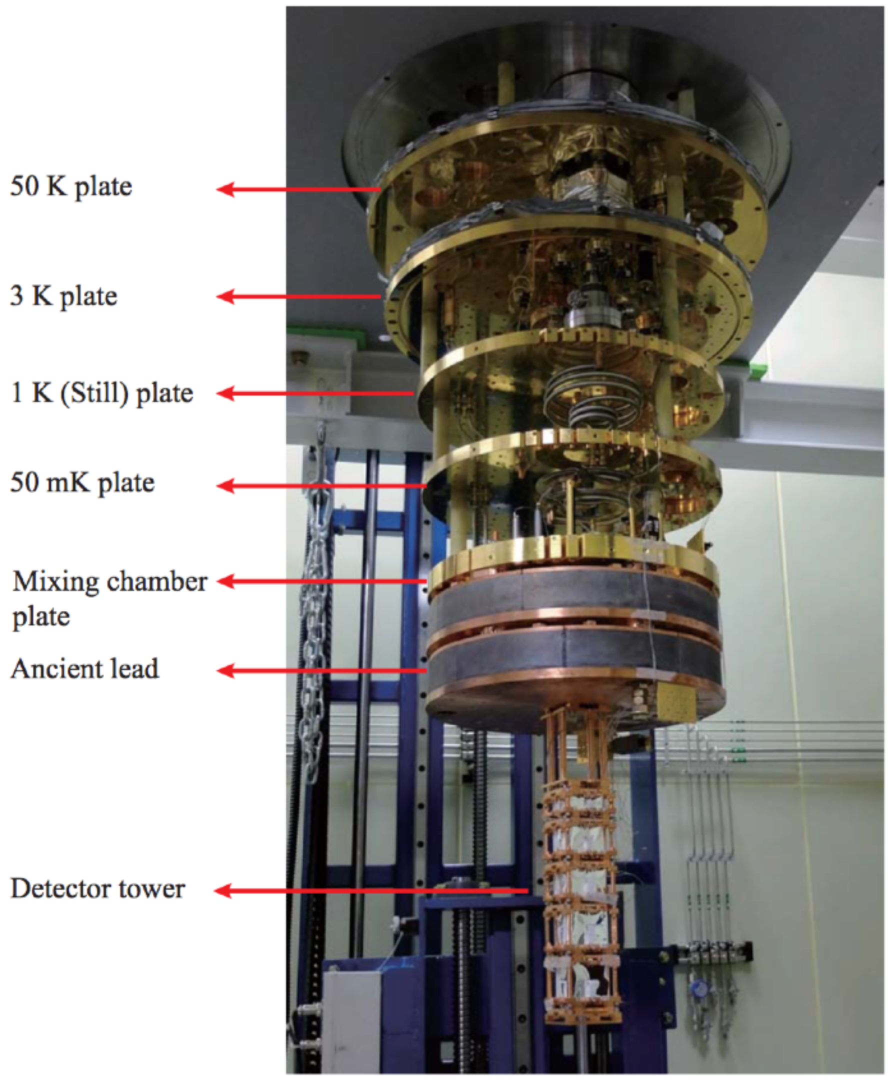
	AMoRE-pilot	AMoRE-I	AMoRE-II
Crystal Tower			
Crystal	CMO	CMO, LMO	LMO
Crystal Mass (crystal #)	1.9 kg (6)	6.2 kg (18)	178 kg (596)
Live exposure	~ 0.32 $kg_{Mo\text{-}100}\cdot yr$ ×12	~ 4 $kg_{Mo\text{-}100}\cdot yr$ ×120	> 500 $kg_{Mo\text{-}100}\cdot yr$
Background rate at ROI (counts/keV/kg/year)	0.5 ×1/15	0.03 ×1/200	~10^{-4}
Expected T1/2 sensitivity (year)	> 3.0×10^{23} (90% C.L.)	> 3.4×10^{24} (90% C.L.)	5×10^{26}
Expected <mββ>(meV)	600-1000	210-370	18-31
Location	Y2L	Y2L	Yemilab
Schedule	2015-2018	2020-2023	2024-2029

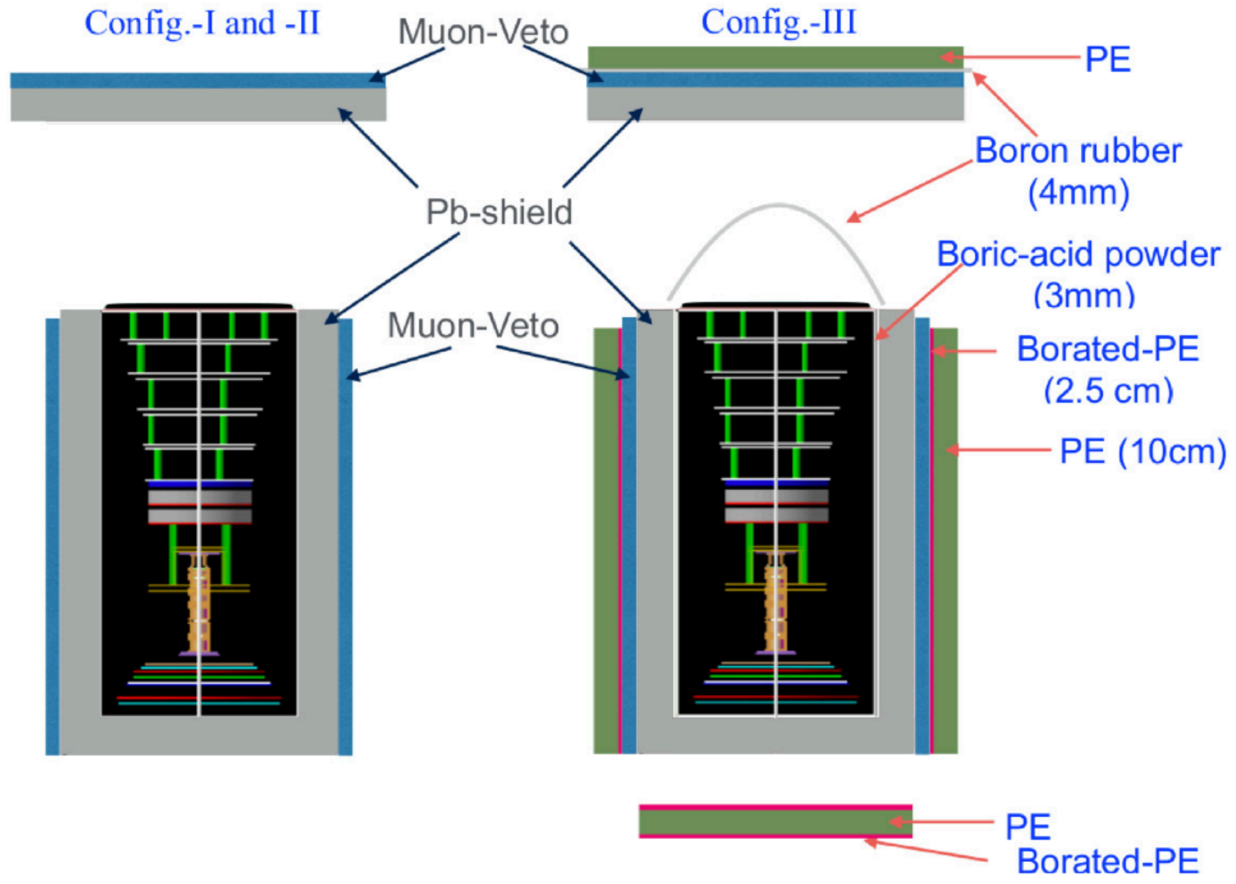
Status of the progress

A5 at Y2L

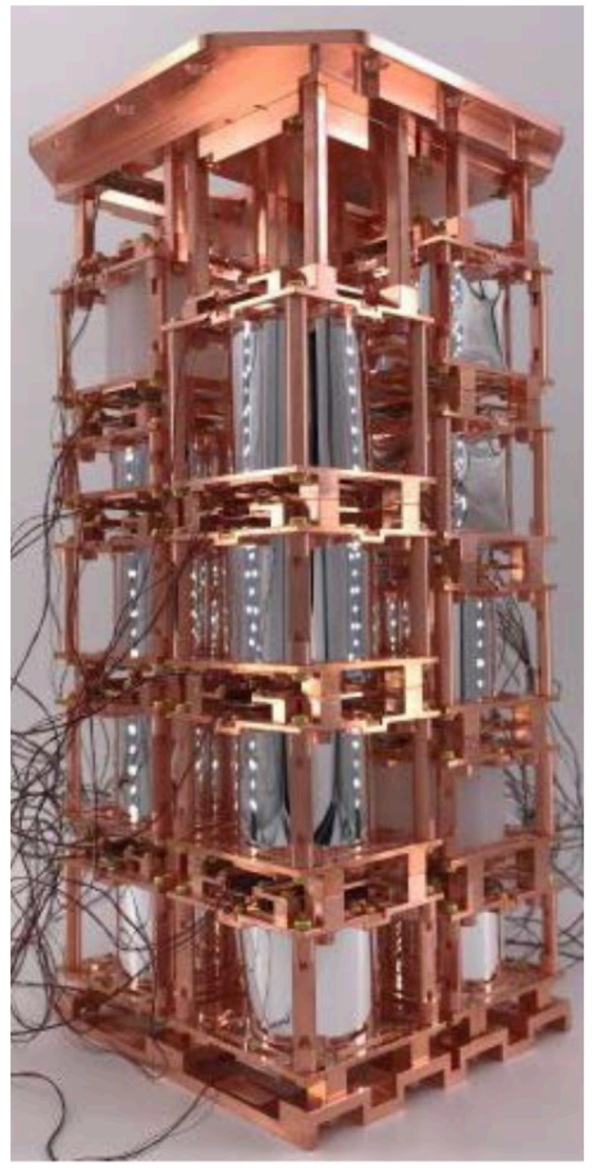
AMoRE-Pilot

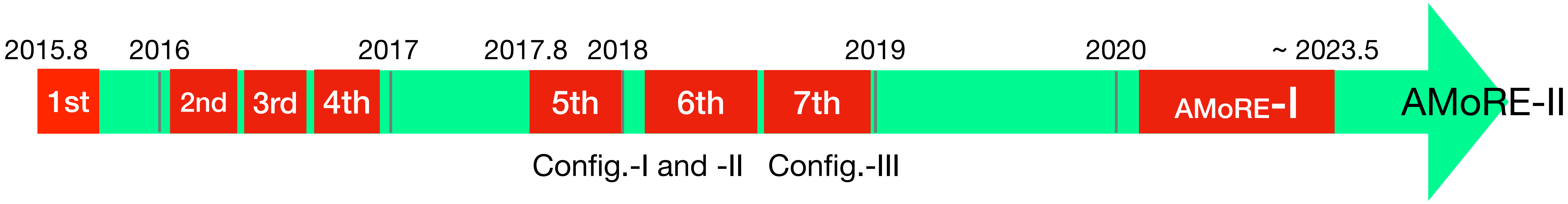
July 2015





AMoRE-I

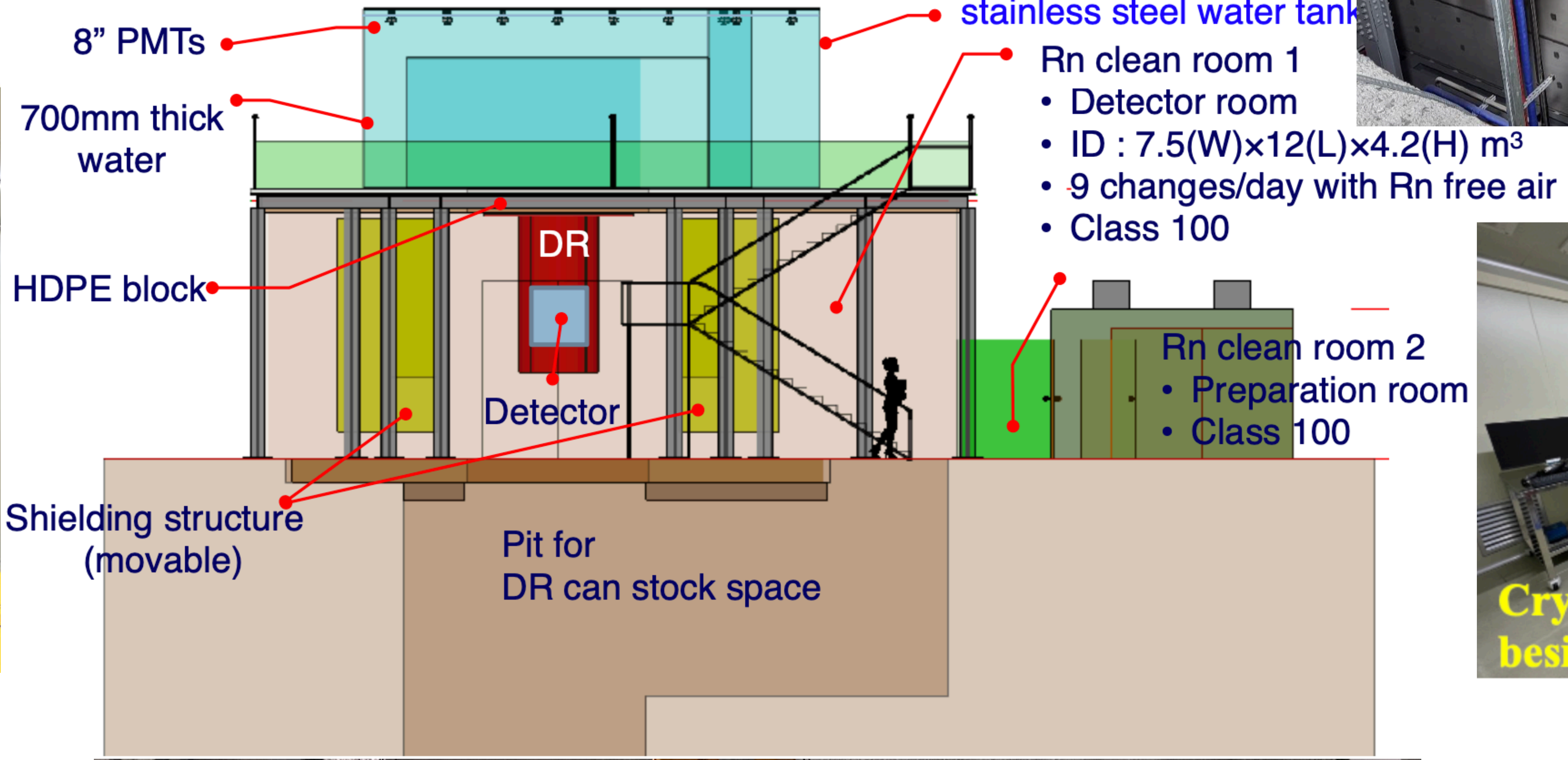


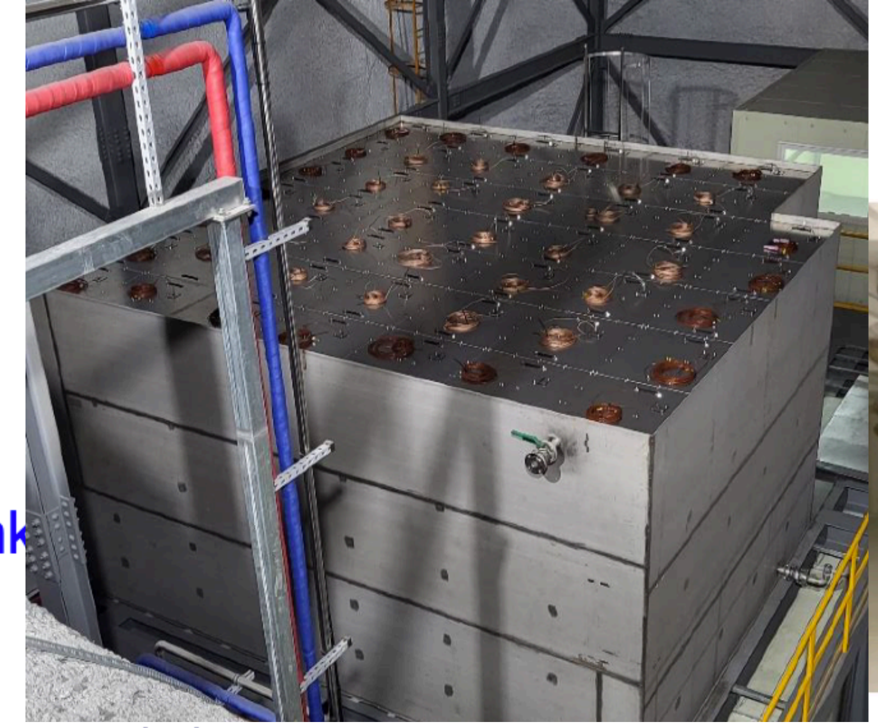


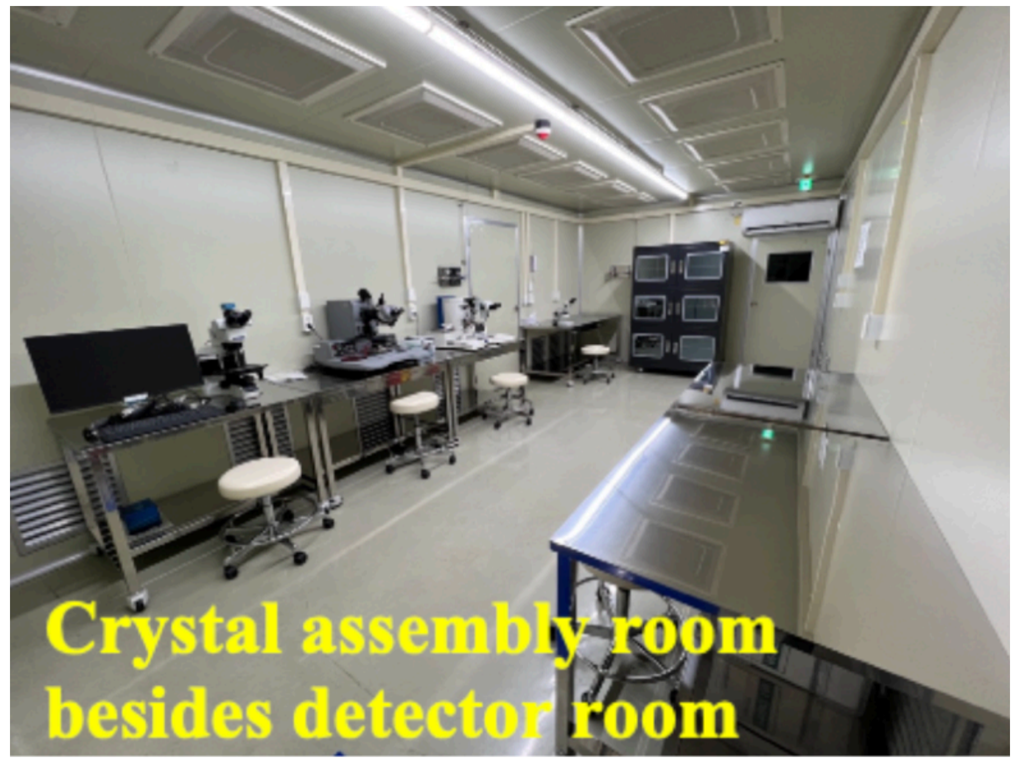
- Two vibration reduction systems were installed
- Background level was reduced by replacing radioactive components and adding additional γ/n shield layers, based on the Geant4 simulation studies

AMoRE-II at Yemilab

- Muon detector installed
- DR inside heavy sheilding with Pb, PE, and water



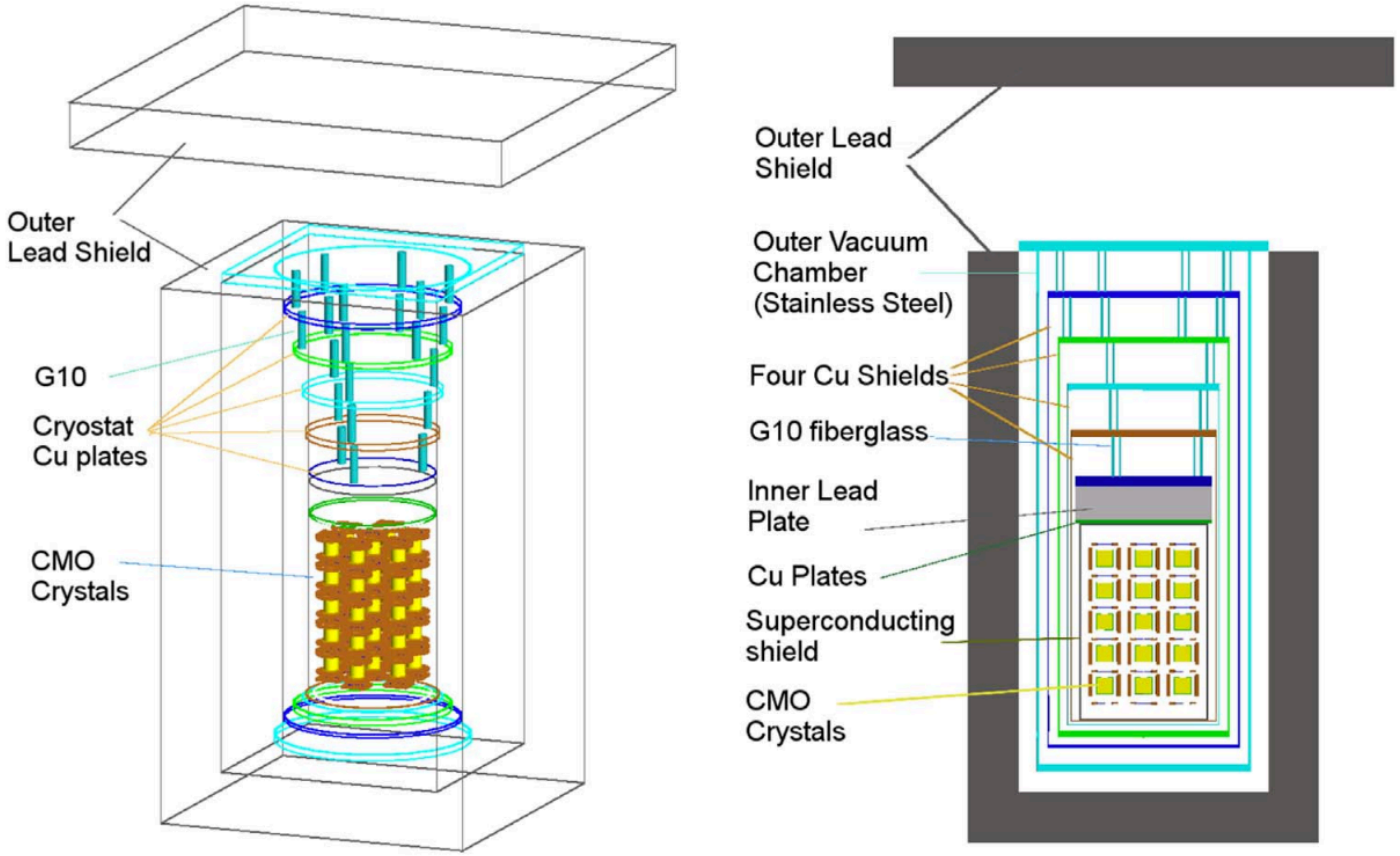




Simulations of background sources

- We simulated background sources inside the crystals, surrounding materials, outer shielding, and rock walls and estimated their background rate
- Based on the Geant4 simulations, the detector shielding design is optimized, and materials used for the detector system are selected and replaced

Nucl. Instrum. Meth. A 855 (2017) 140-147

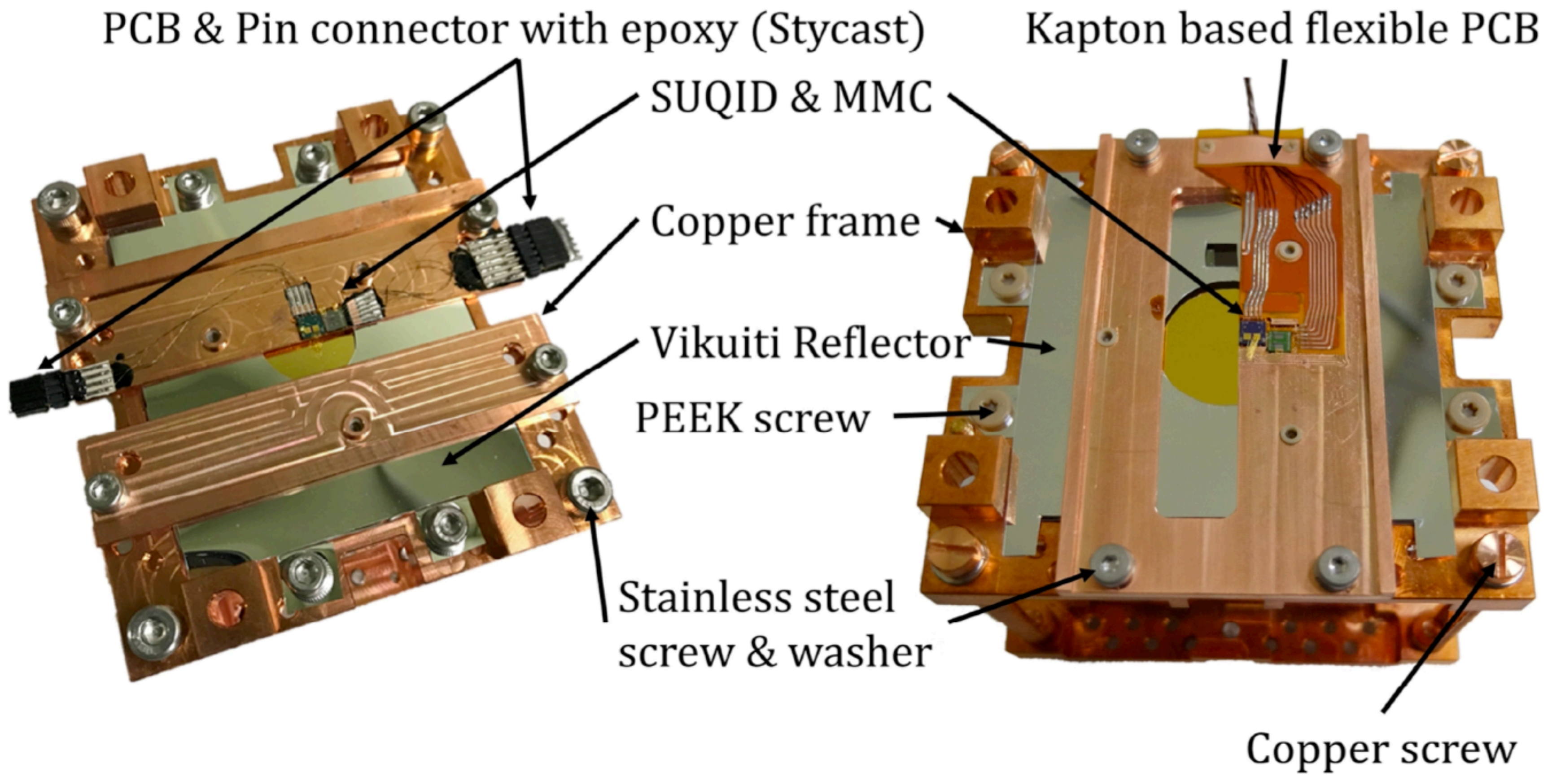


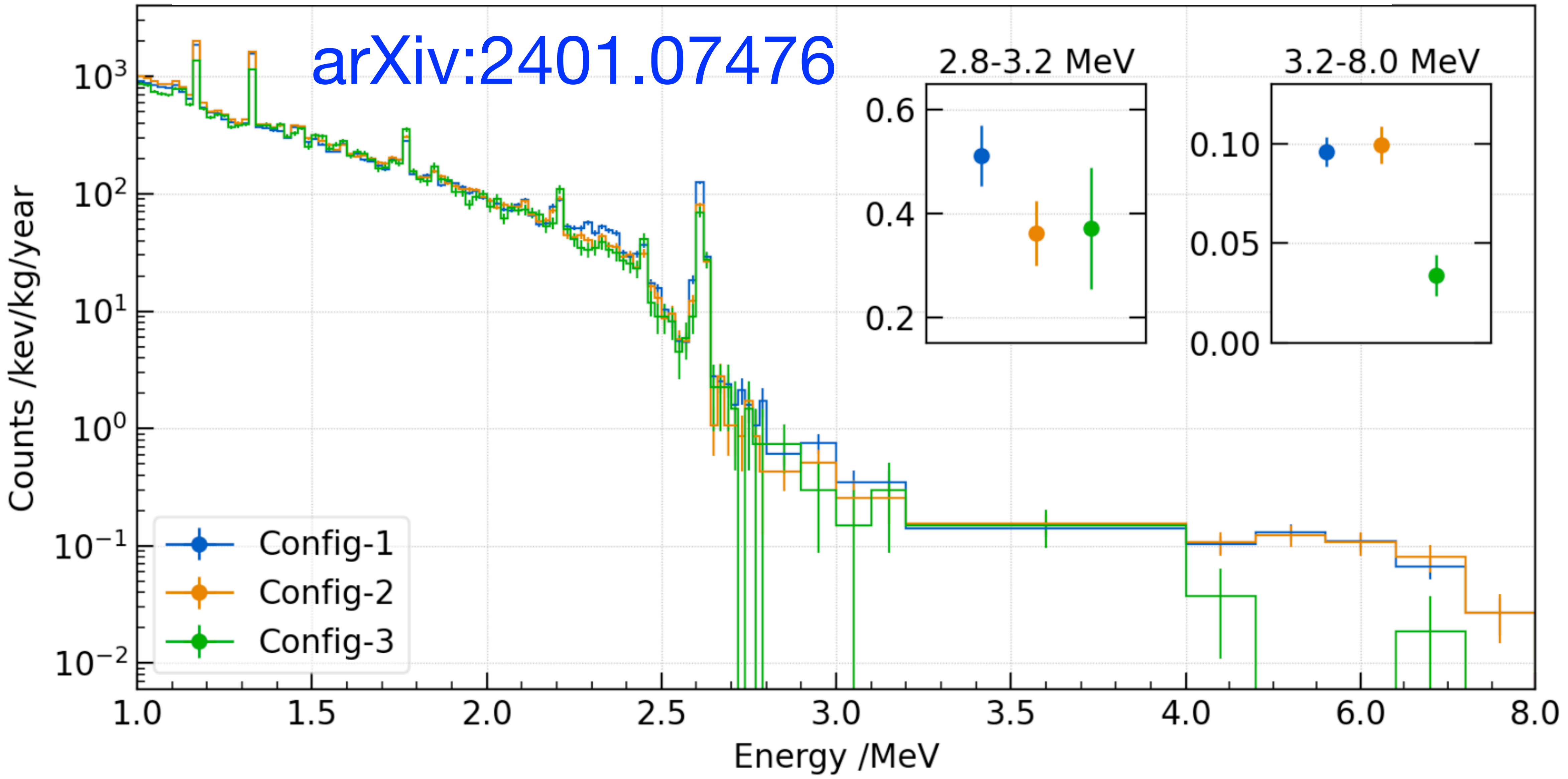
Reducing backgrounds in AMoRE-Pilot

Configurations 1, 2, and 3

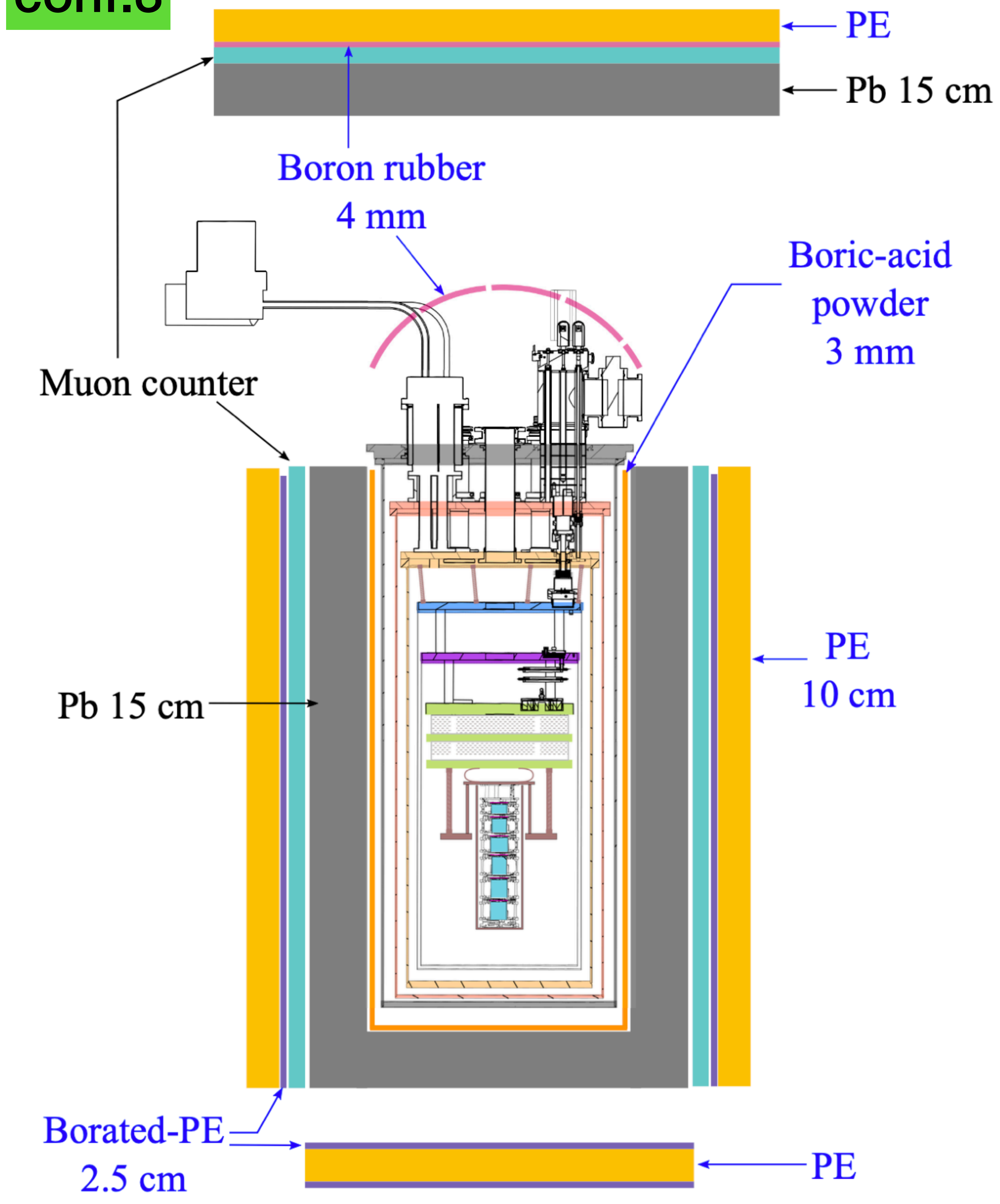
conf.1

conf.2





conf.3

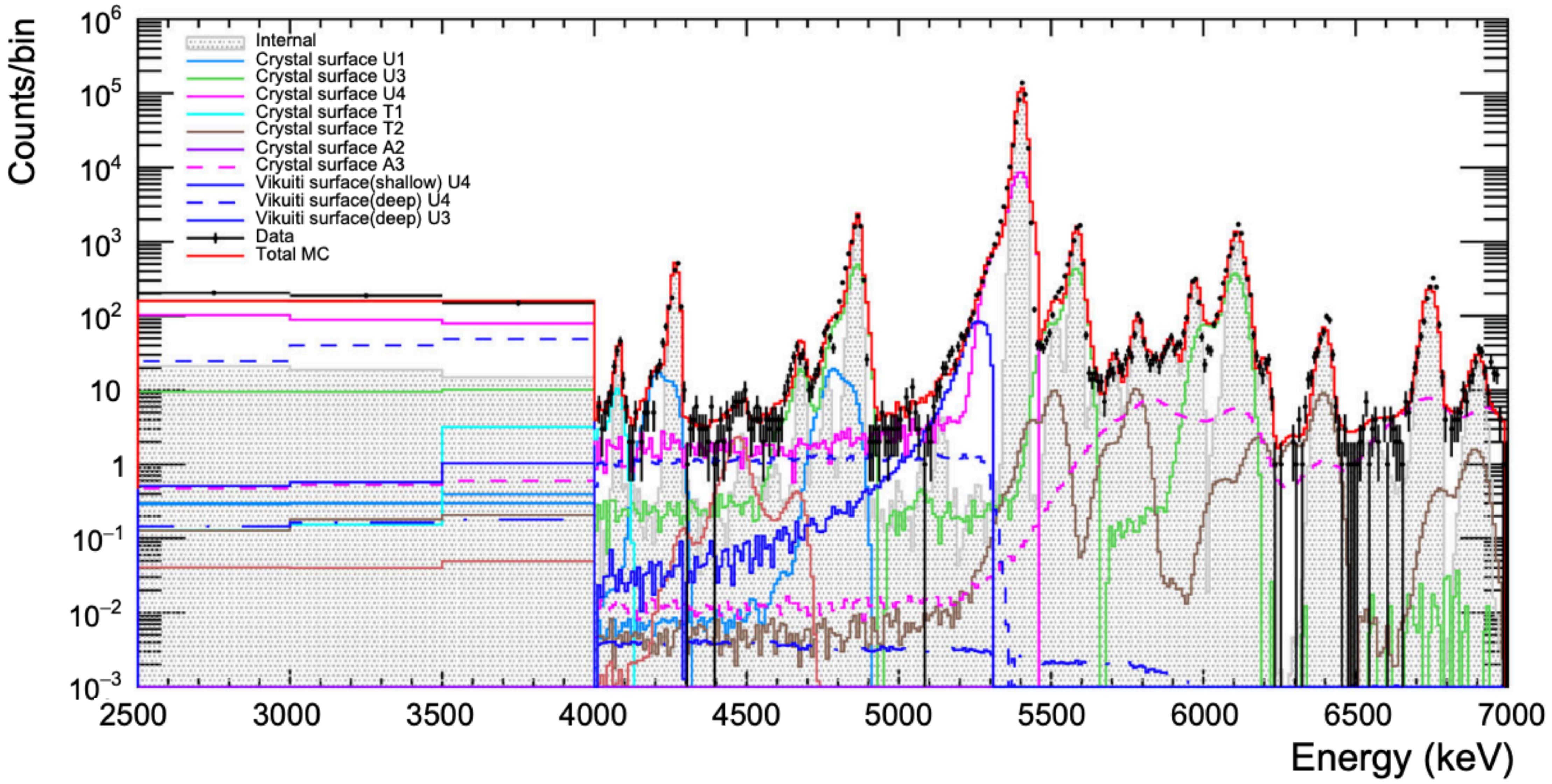


Background modeling for AMoRE-pilot

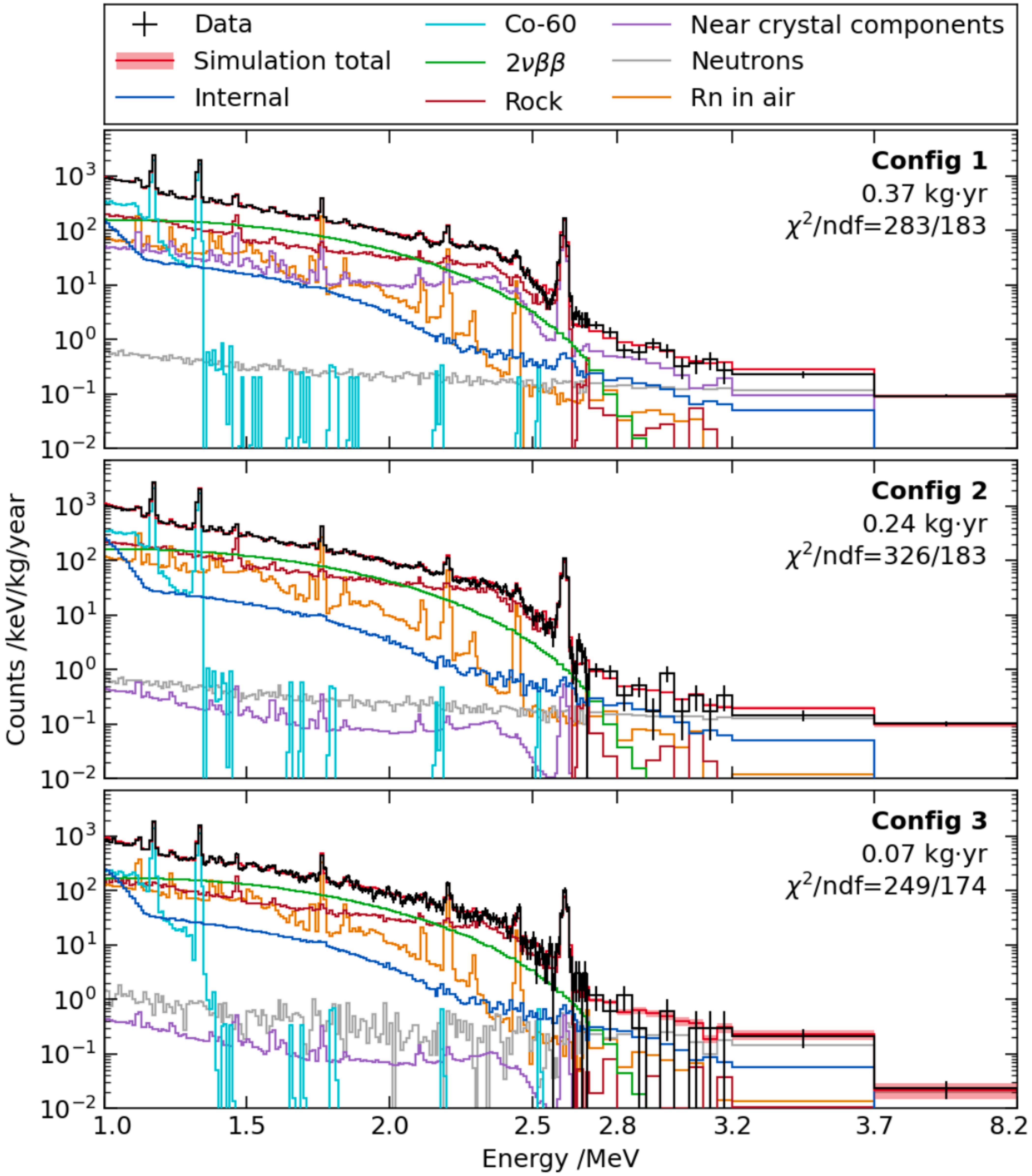
- ***β/γ*** spectrum: Rn in the air, gamma from rock, and neutron-induced events are dominant

- Alpha analysis provides activity levels from both surface and bulk contaminations

Eur. Phys. J. C 81 (2021) 837

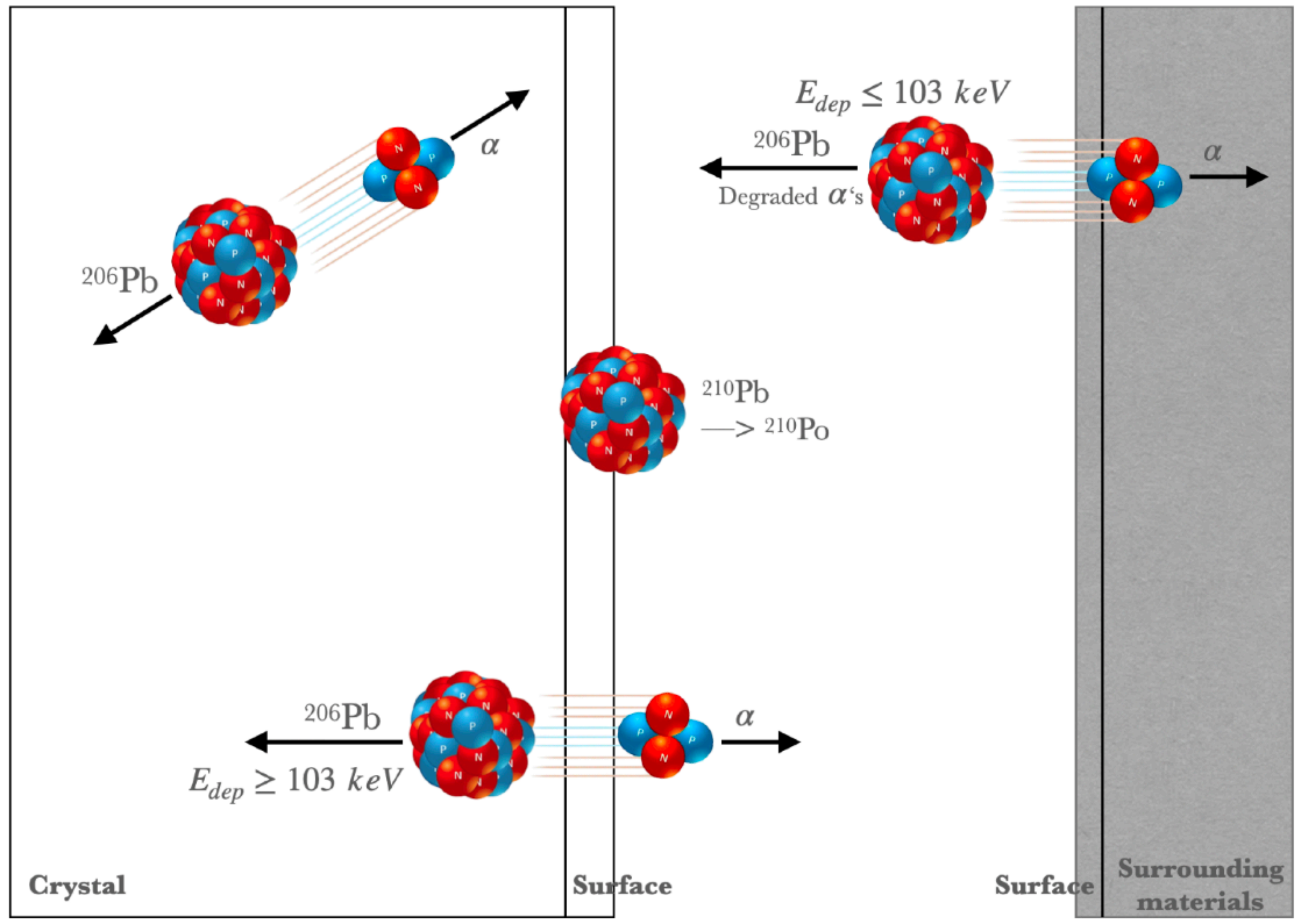


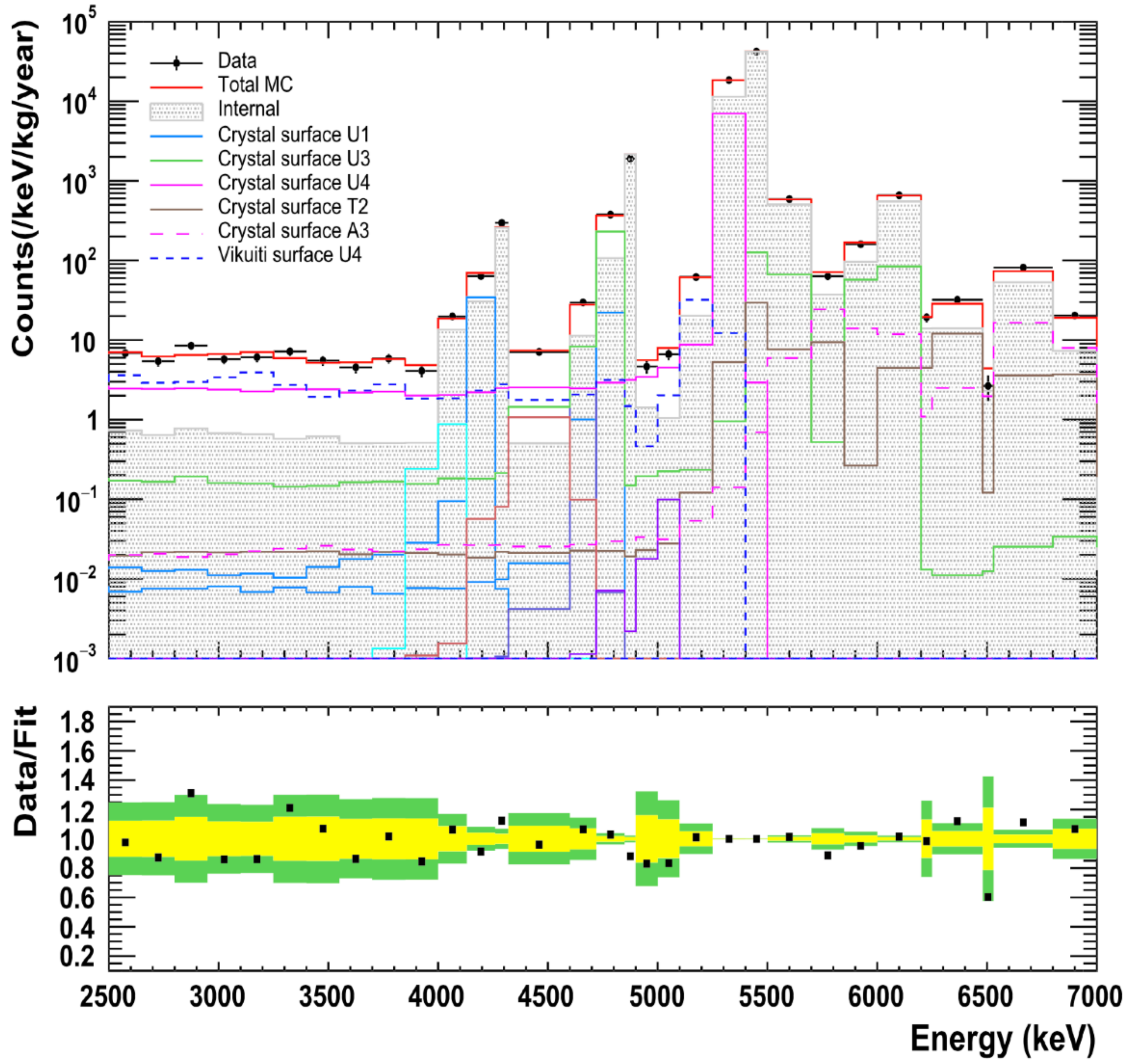
arXiv:2401.07476

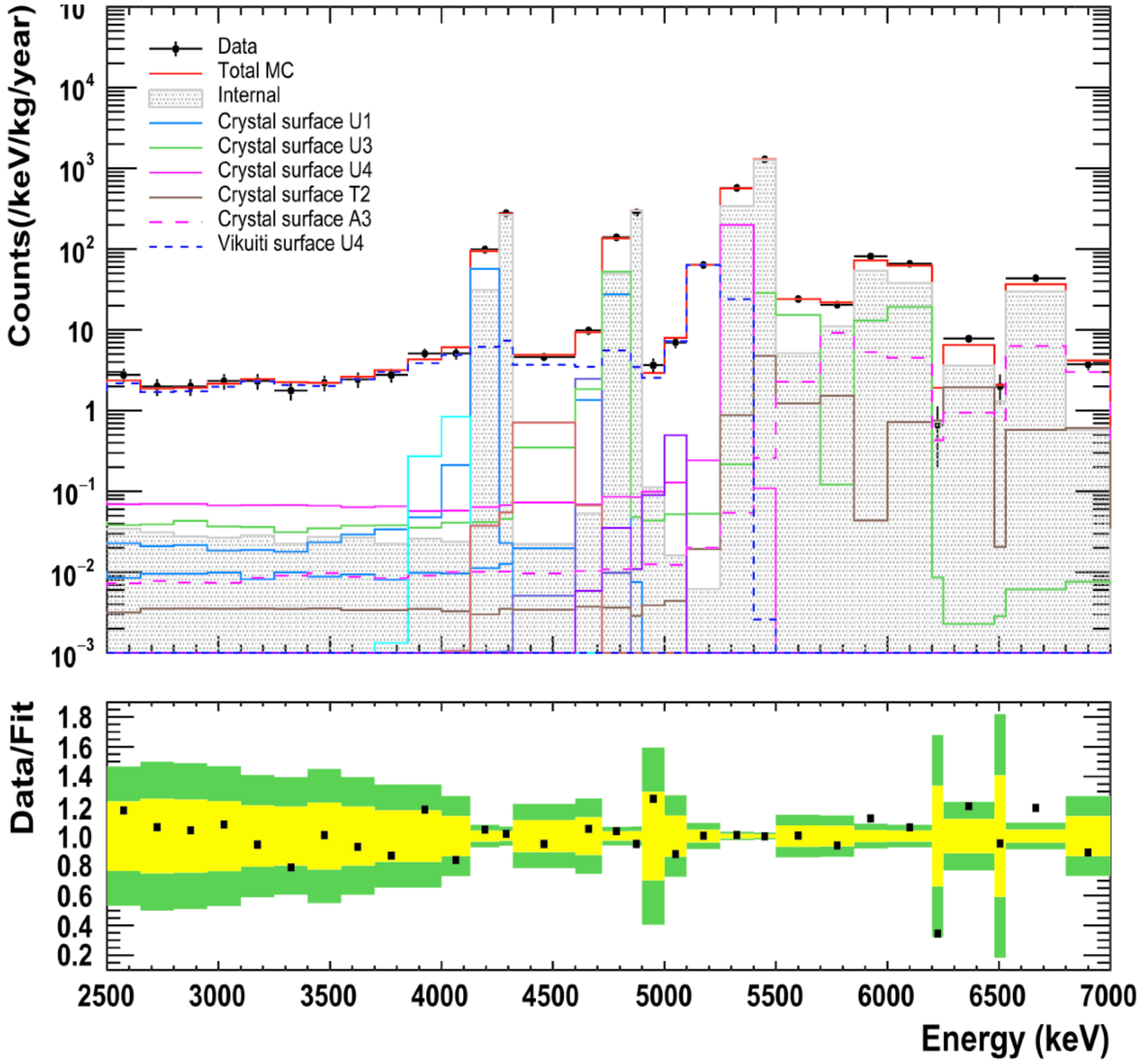


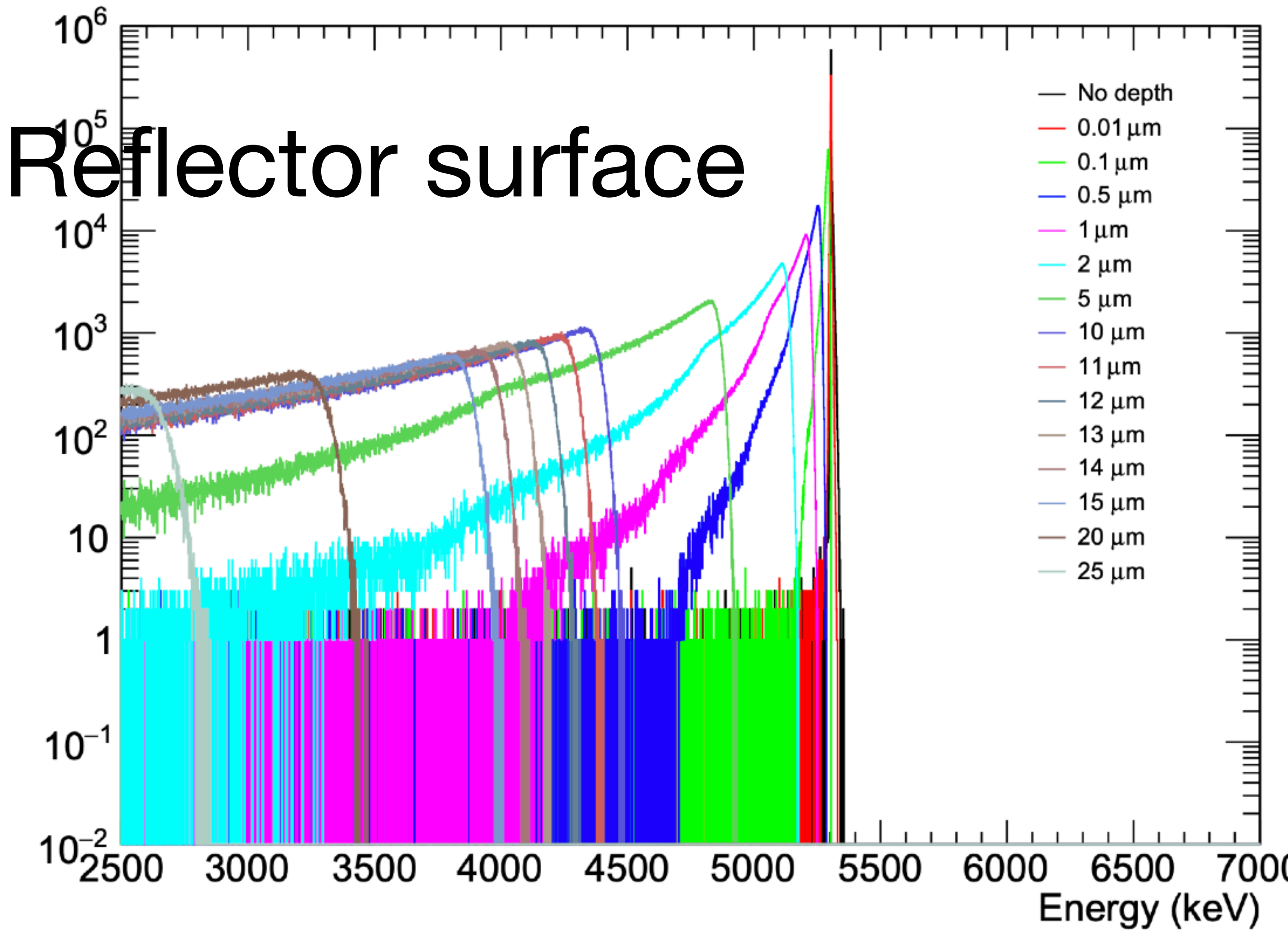
Surface contamination

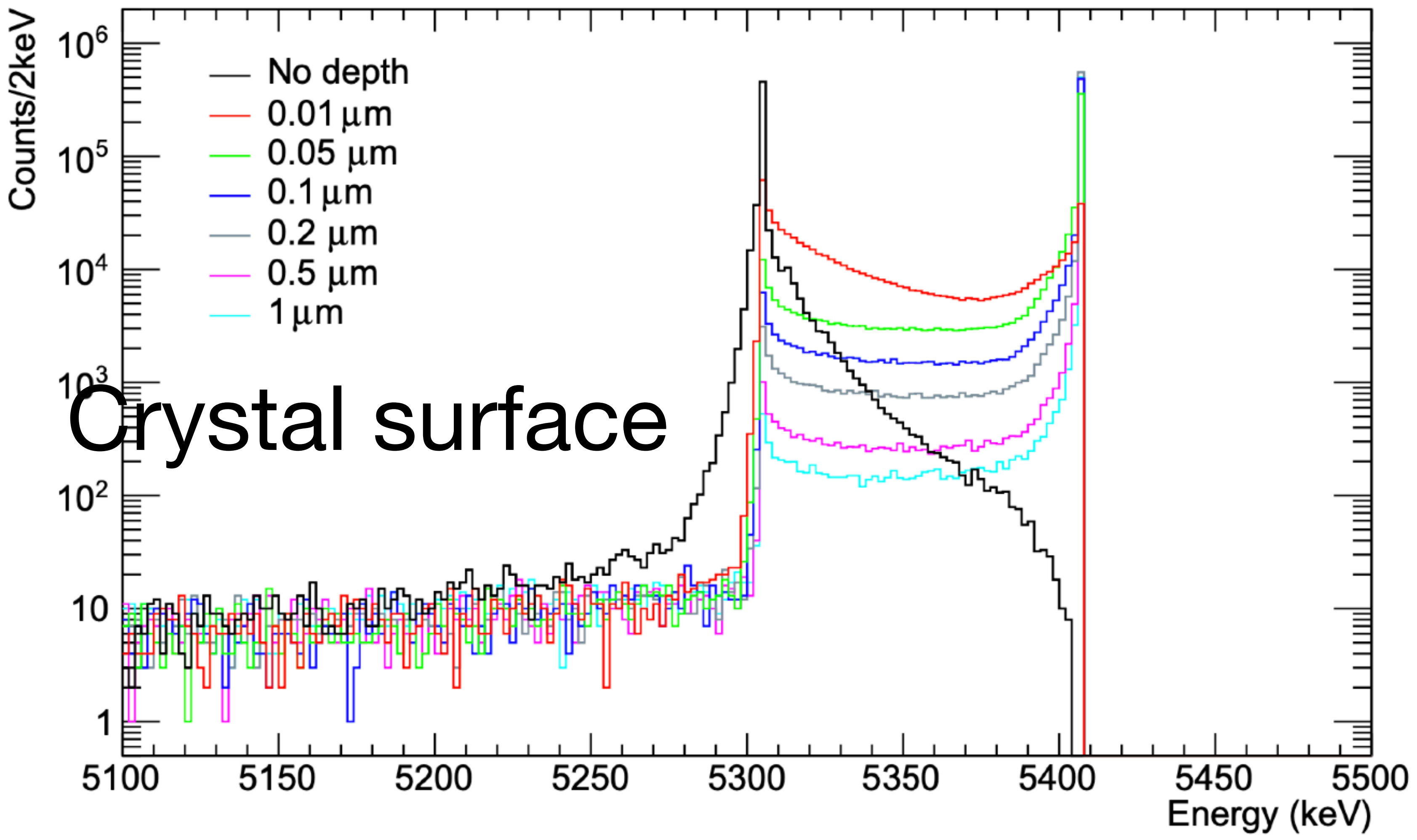
- 5304 keV alpha energy can be deposited in the crystal surface when the ^{206}Pb surface recoil escapes
- Since we do not know the depth profile of the surface contaminants, we modeled the background spectrum in variable bins covering spectral shape change due to energy loss of 0~100 keV





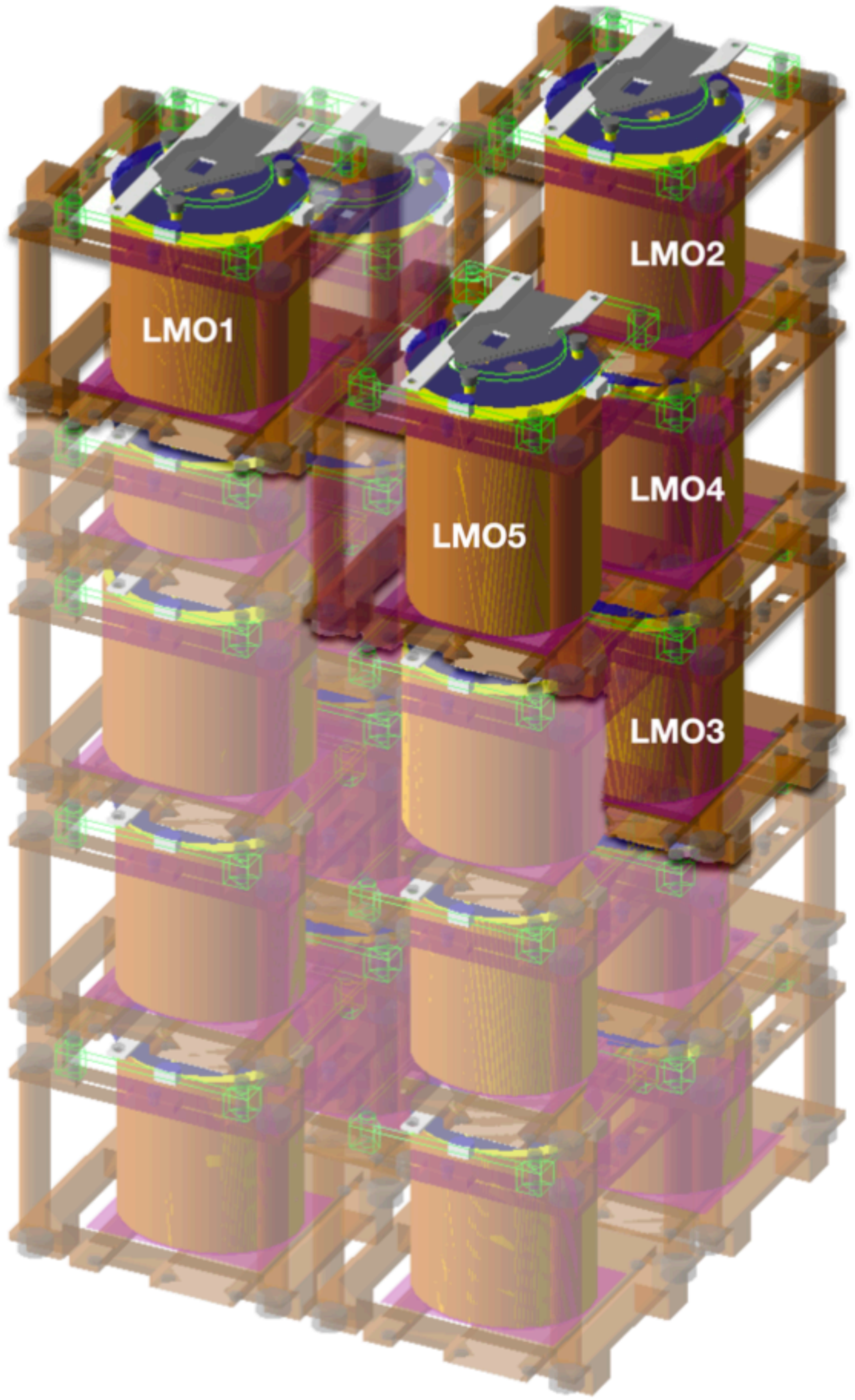


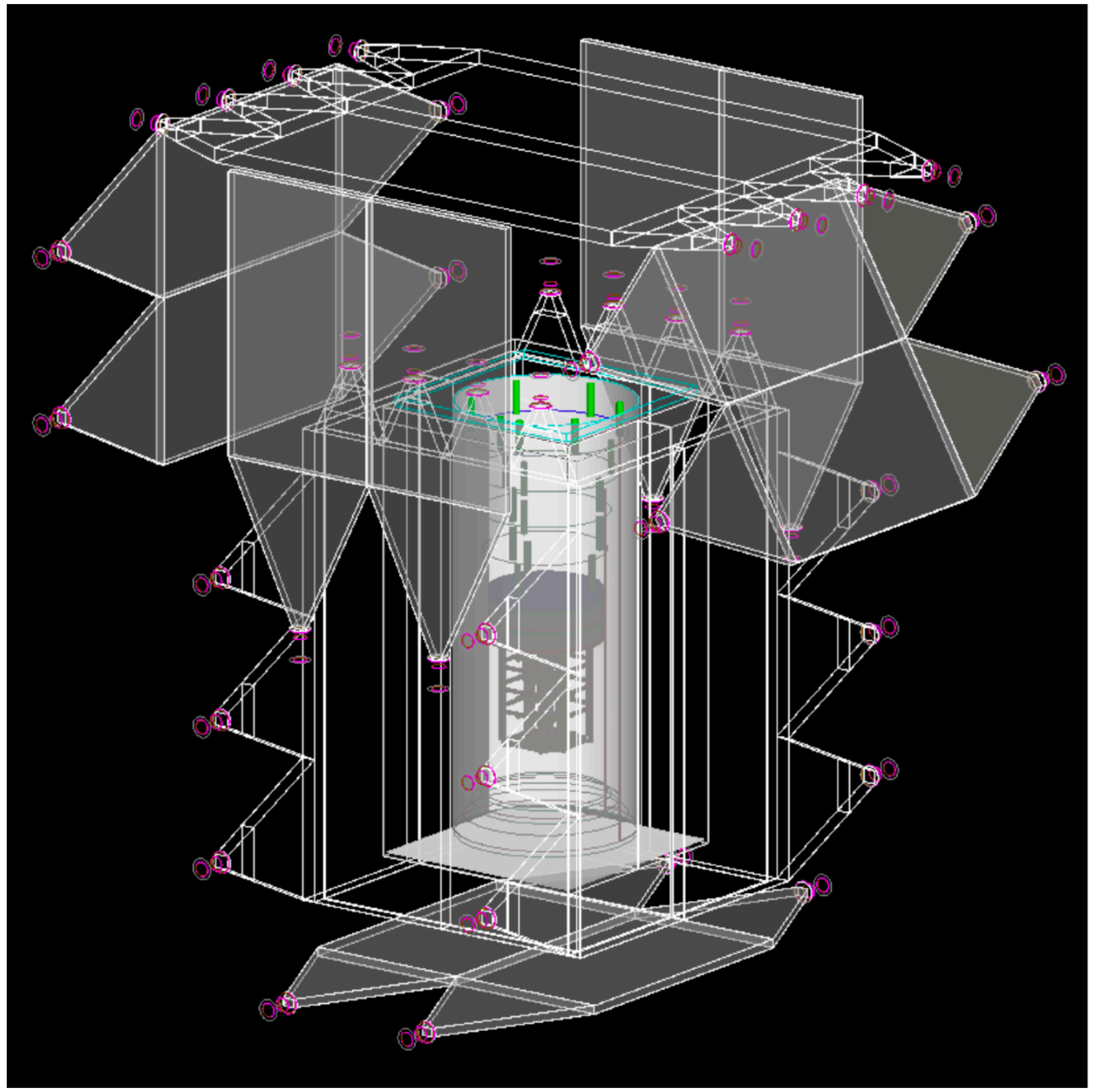




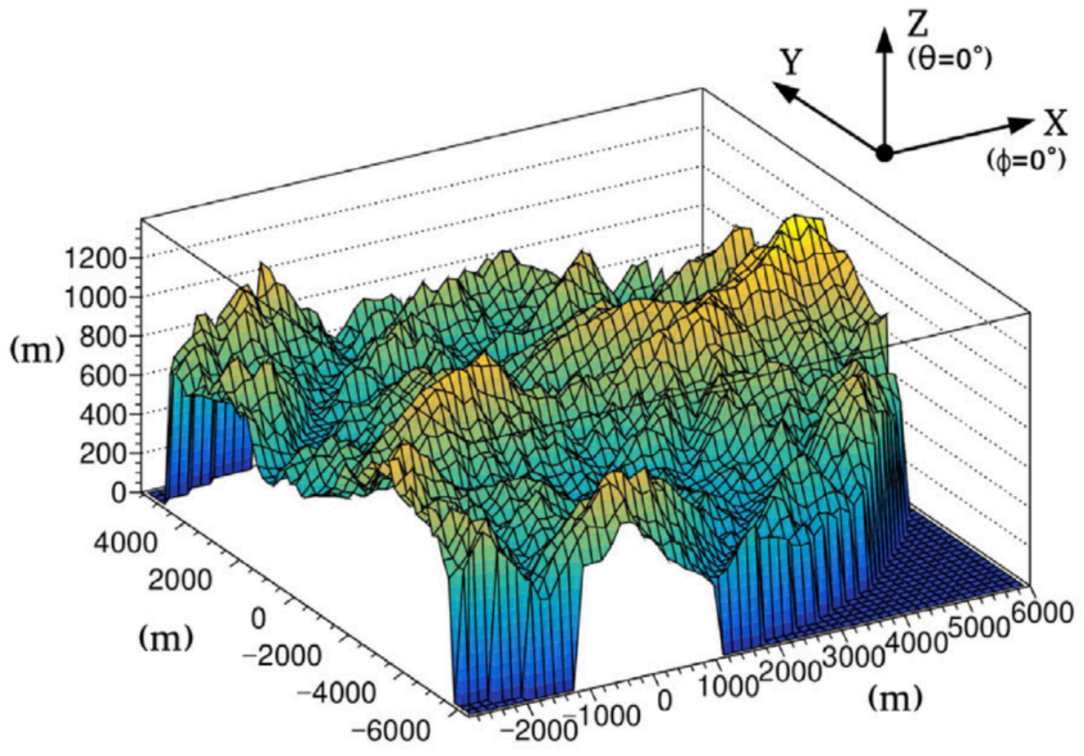
Reducing backgrounds in AMoRE-I

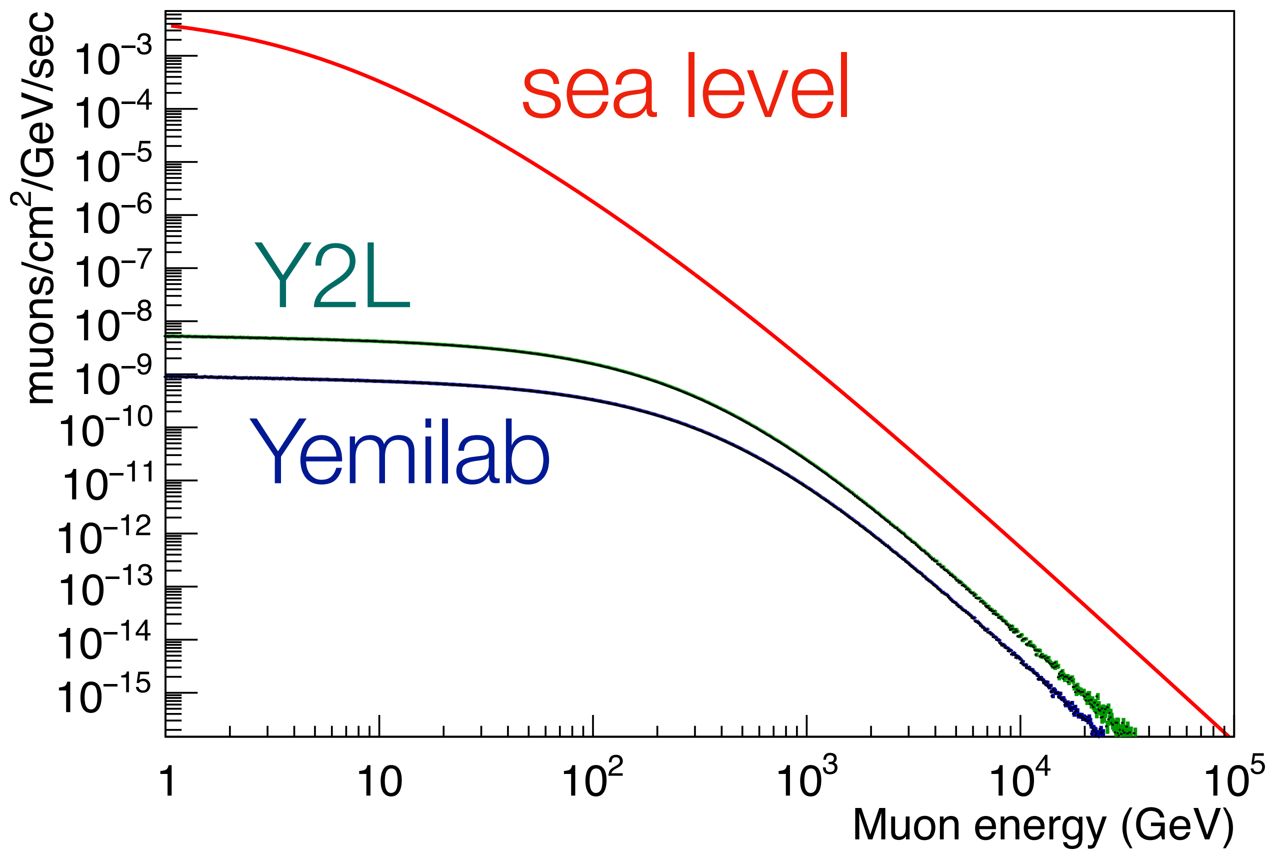
- 6 CMO (1.89 kg)
  ➔ 13 CMO (4.58 kg) + 5 LMO (1.61 kg)
  ➔ total crystal mass = 6.19 kg, ^{100}Mo mass = 3.0 kg
- Shielding enhancements:
  - Outer Pb: 15 ➔ 20 cm
  - neutron shields: boric acid silicon + more PE/B-PE
- More muon counter coverage and a more stable supply of Rn-free air
- Estimated background level in ROI was lowered from 0.5 in AMoRE-Pilot to 0.03 counts/keV/kg/year
  ➔ Geant4-based background modeling is in progress



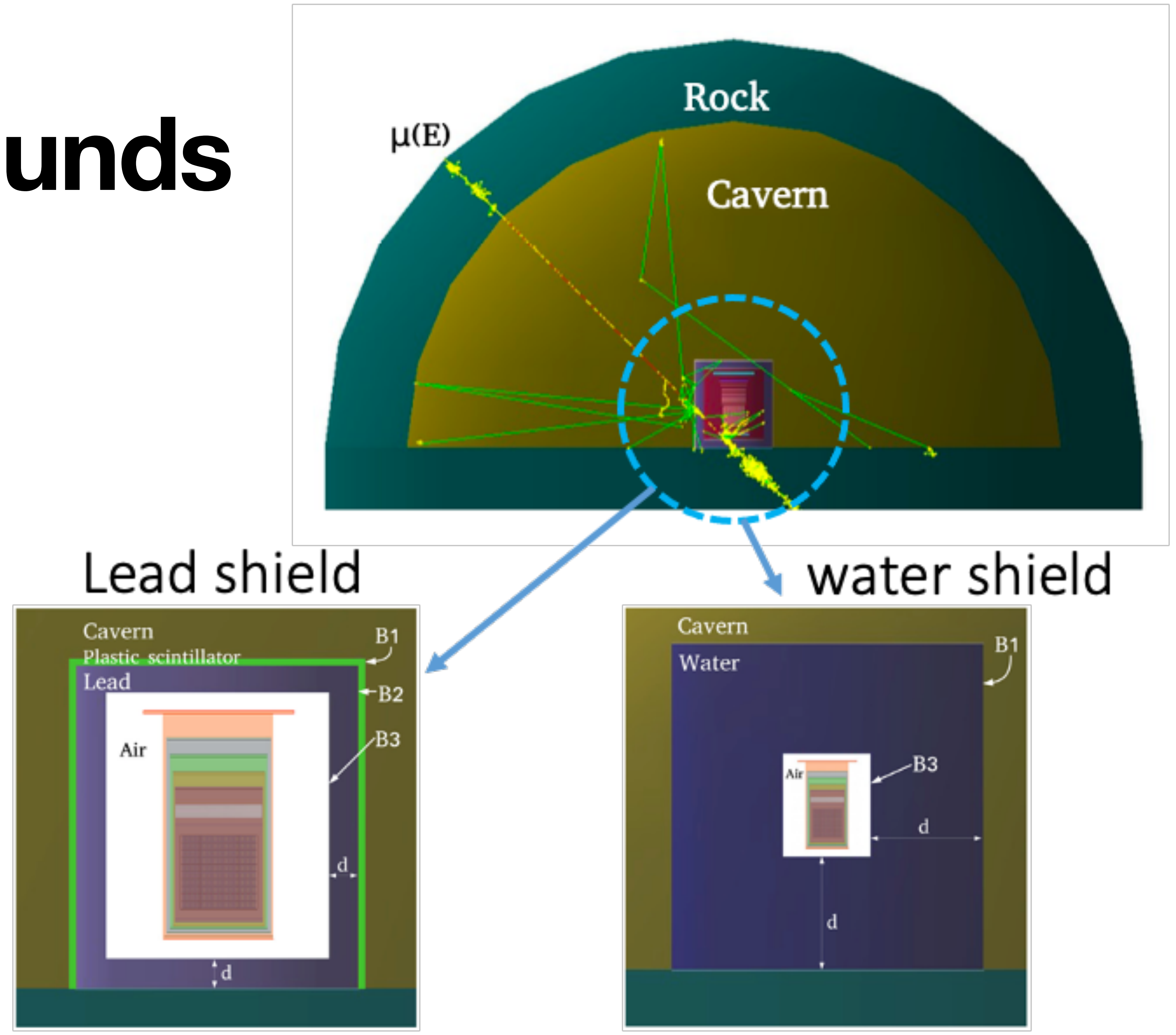


Neutron and muon-induced backgrounds

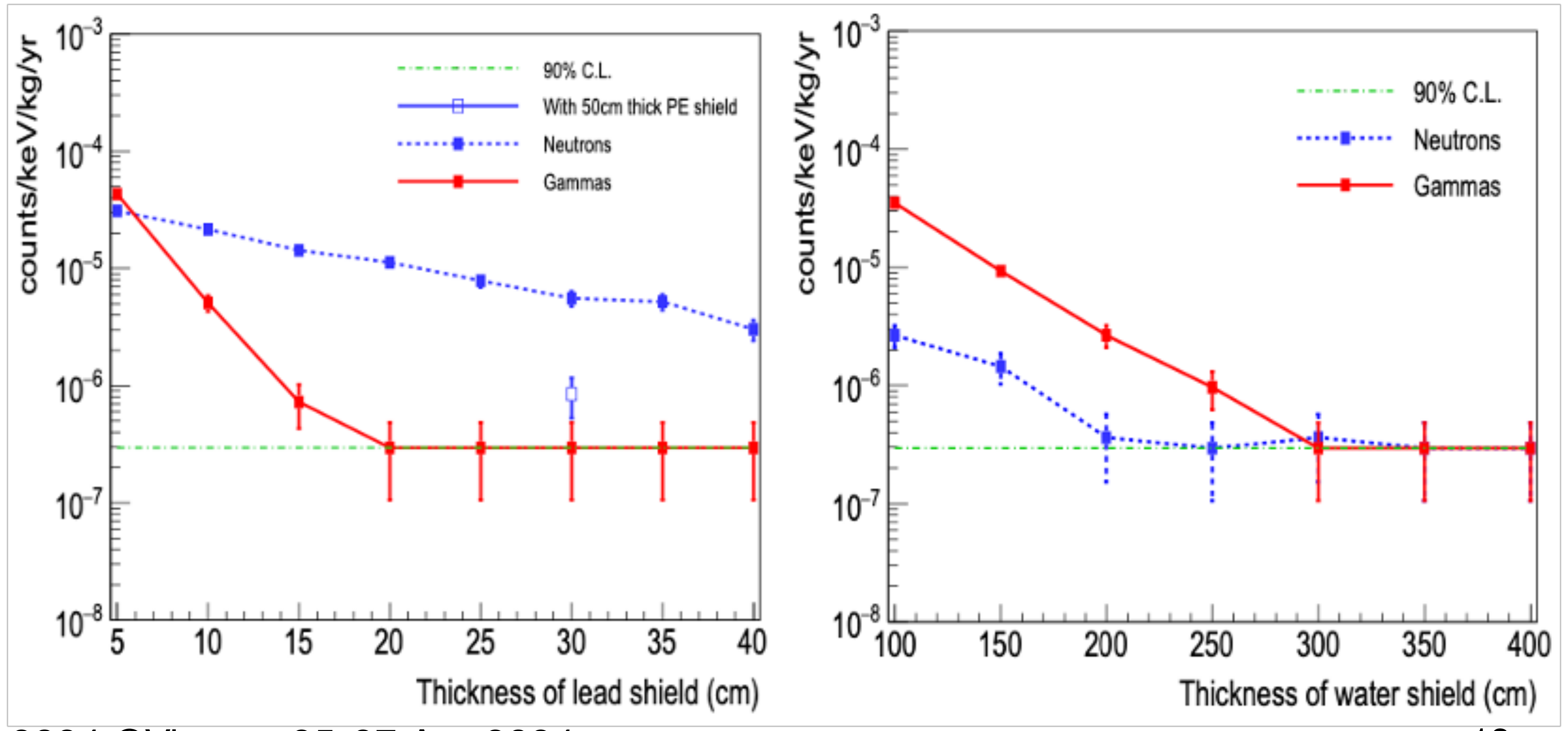




Astropart. Phys. 114 (2020) 60-67



- We simulated cosmic muons and neutrons from the rocks surrounding the cavern
- We estimated single-hit event rate in the (2–8) MeV with several shielding thicknesses applied for both lead shielding and water tank shielding
- Thickness of shielding layers has been optimized
- Due to the difficulty of implementing a cryostat in the water shielding, we decided to go for lead shielding

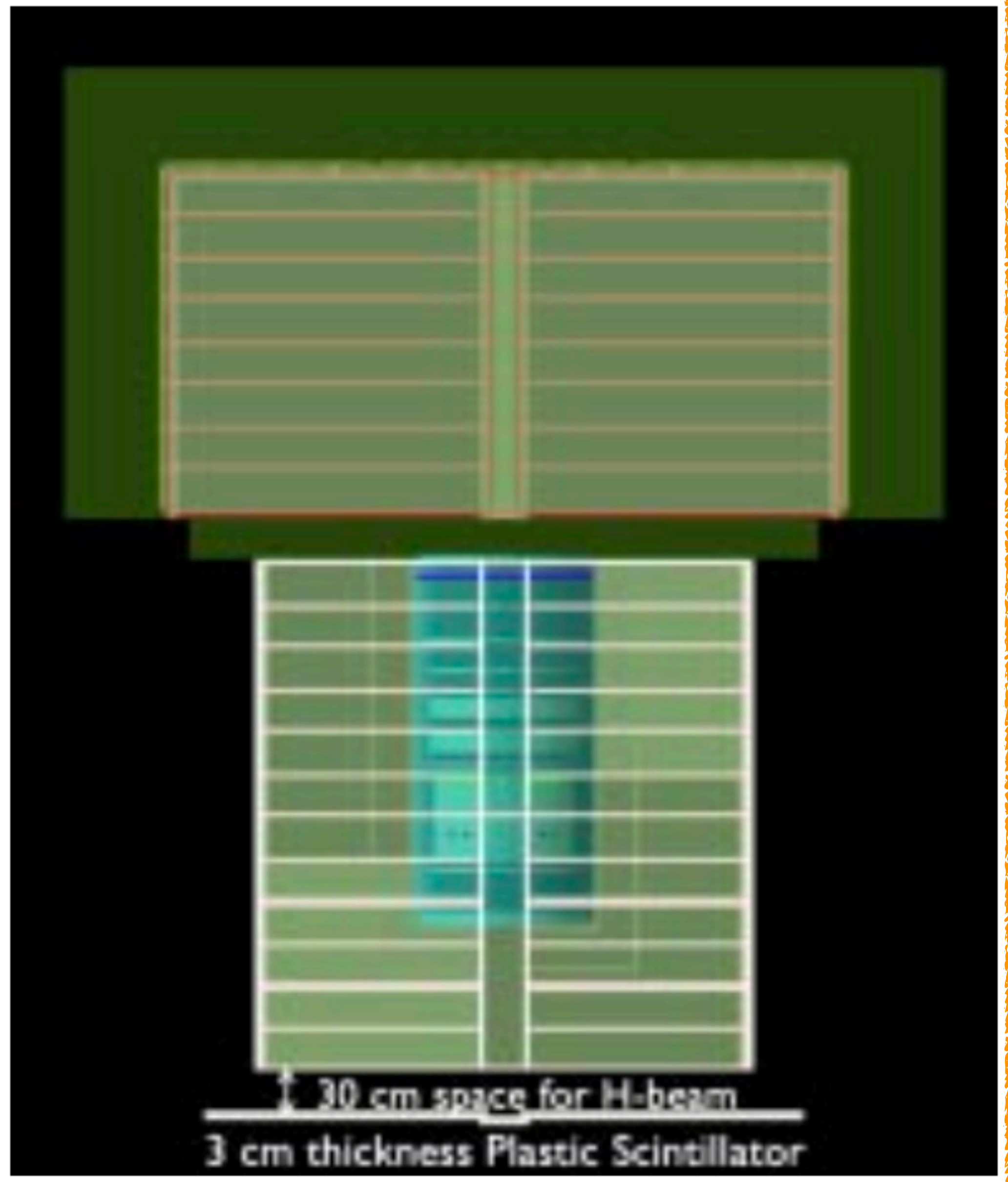


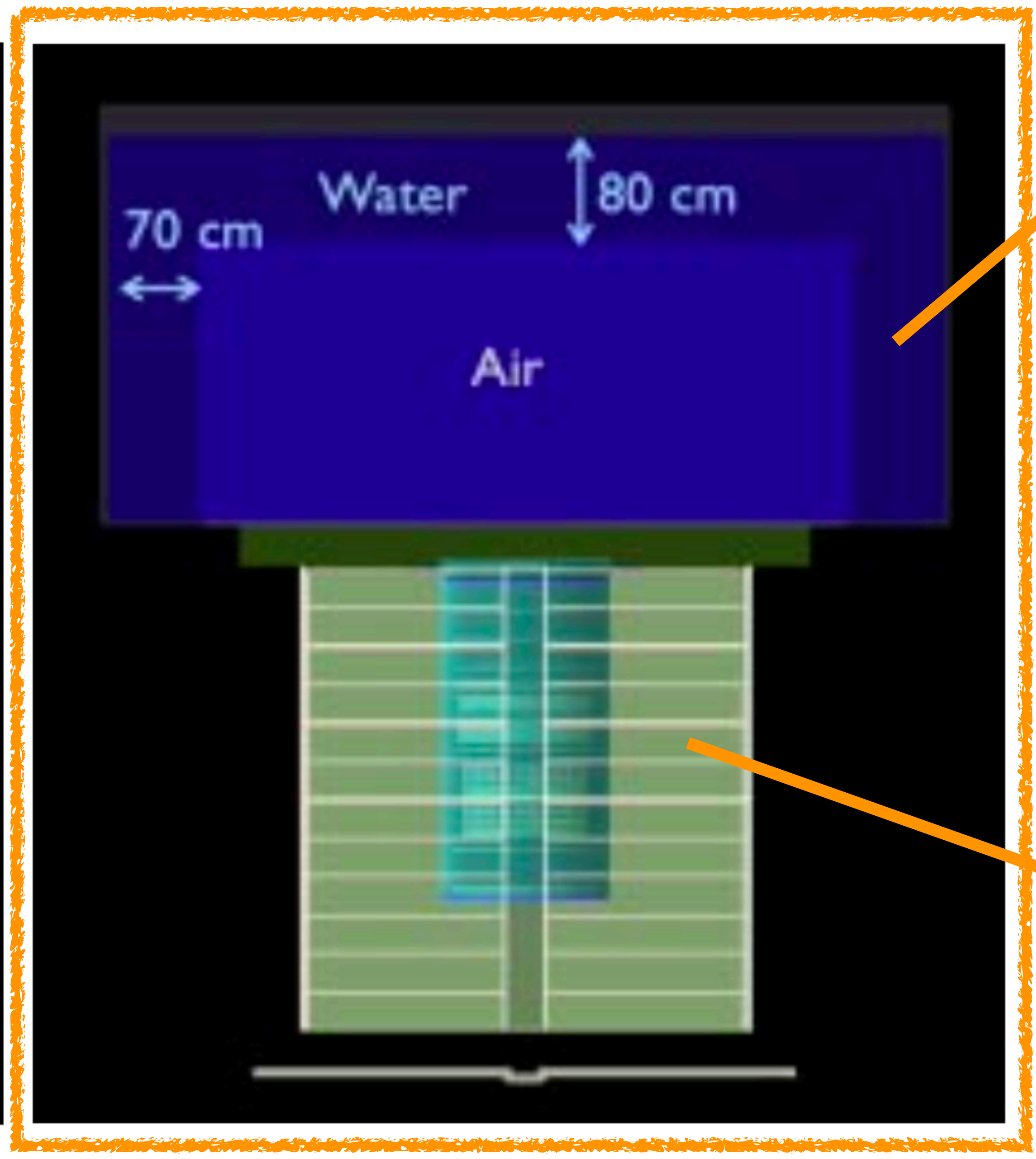
Muon veto system

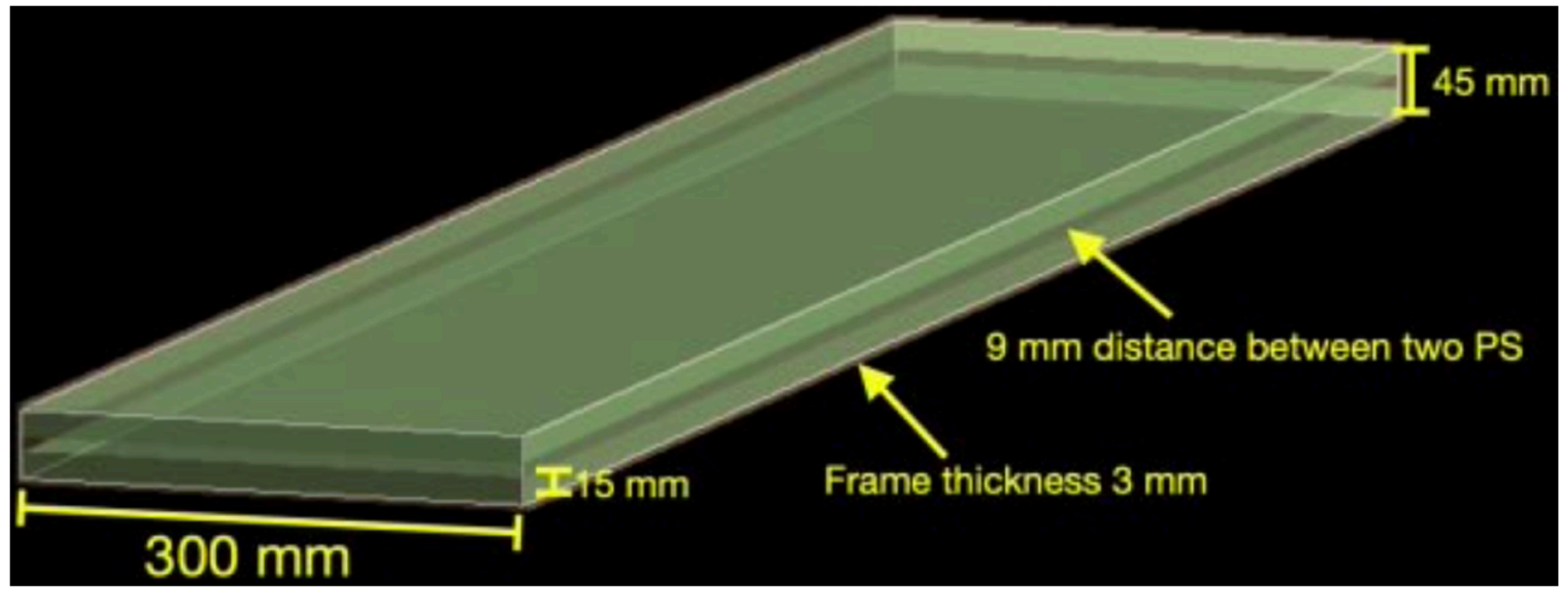
- We compared the water Cherenkov detector with the plastic scintillator detector for the above part of the cryostat

➔ water Cherenkov detector with an active muon veto capability has been selected

Il Nuovo 35. Cimento 45 C (23) (2022)



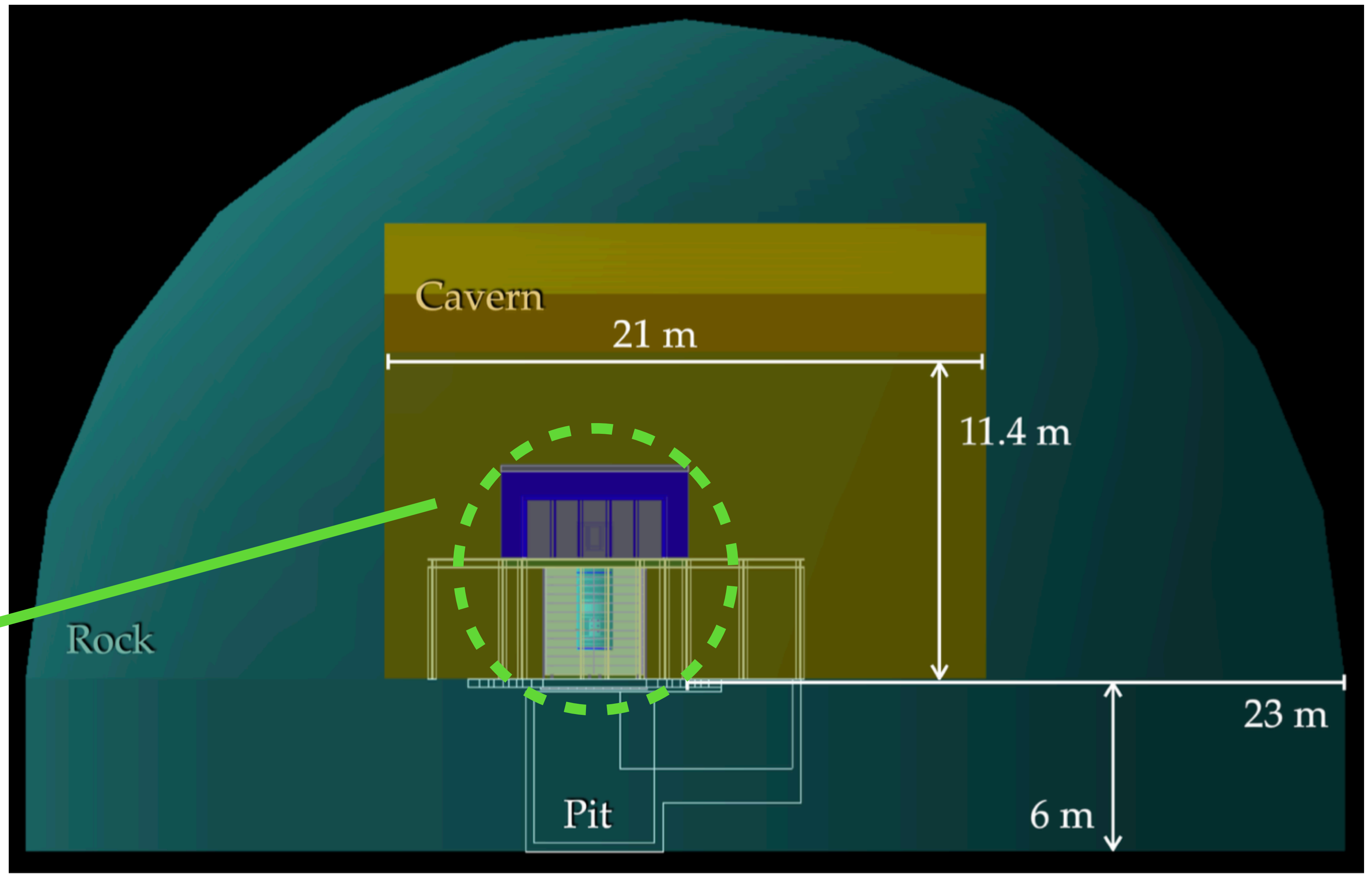


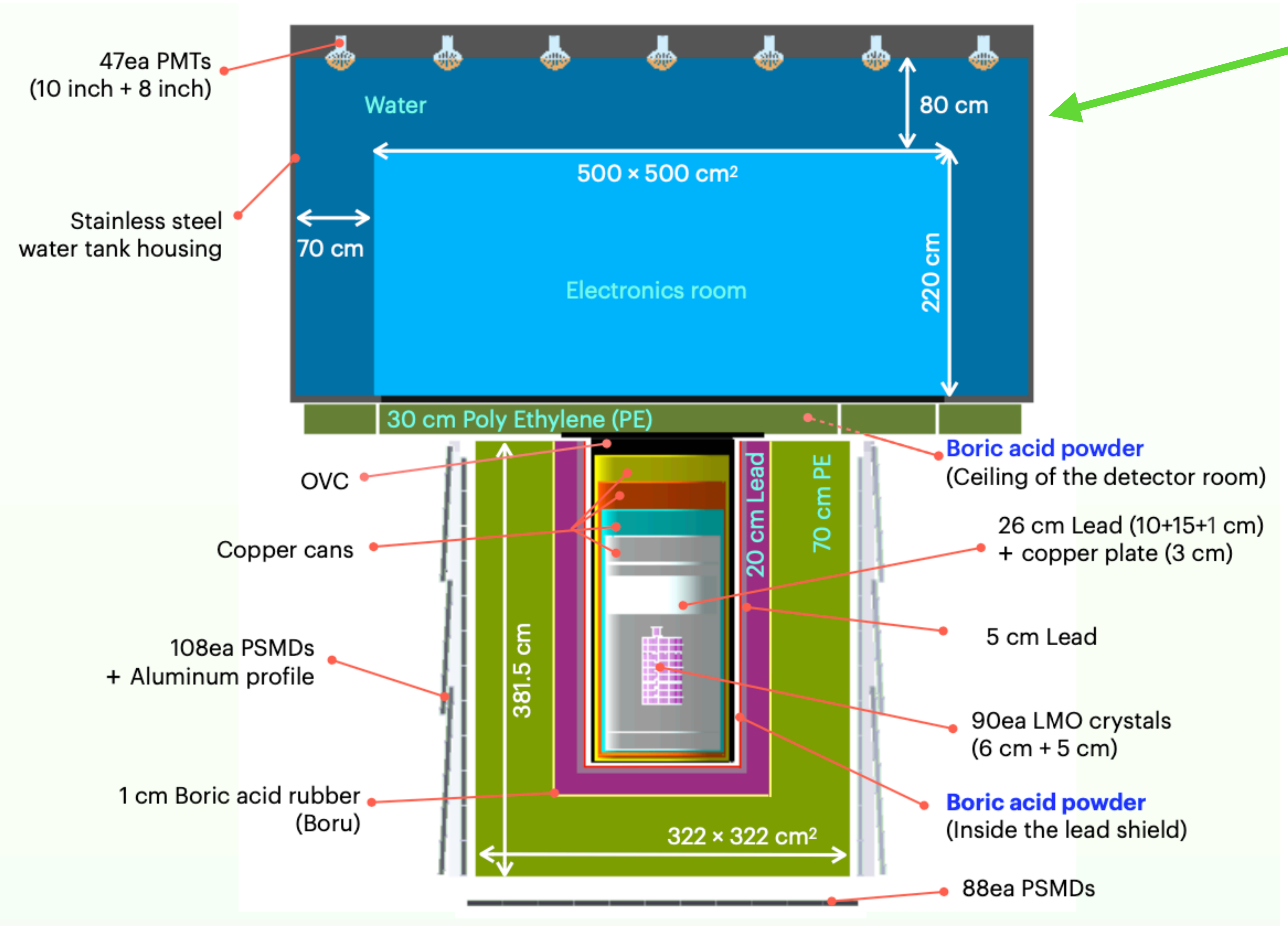


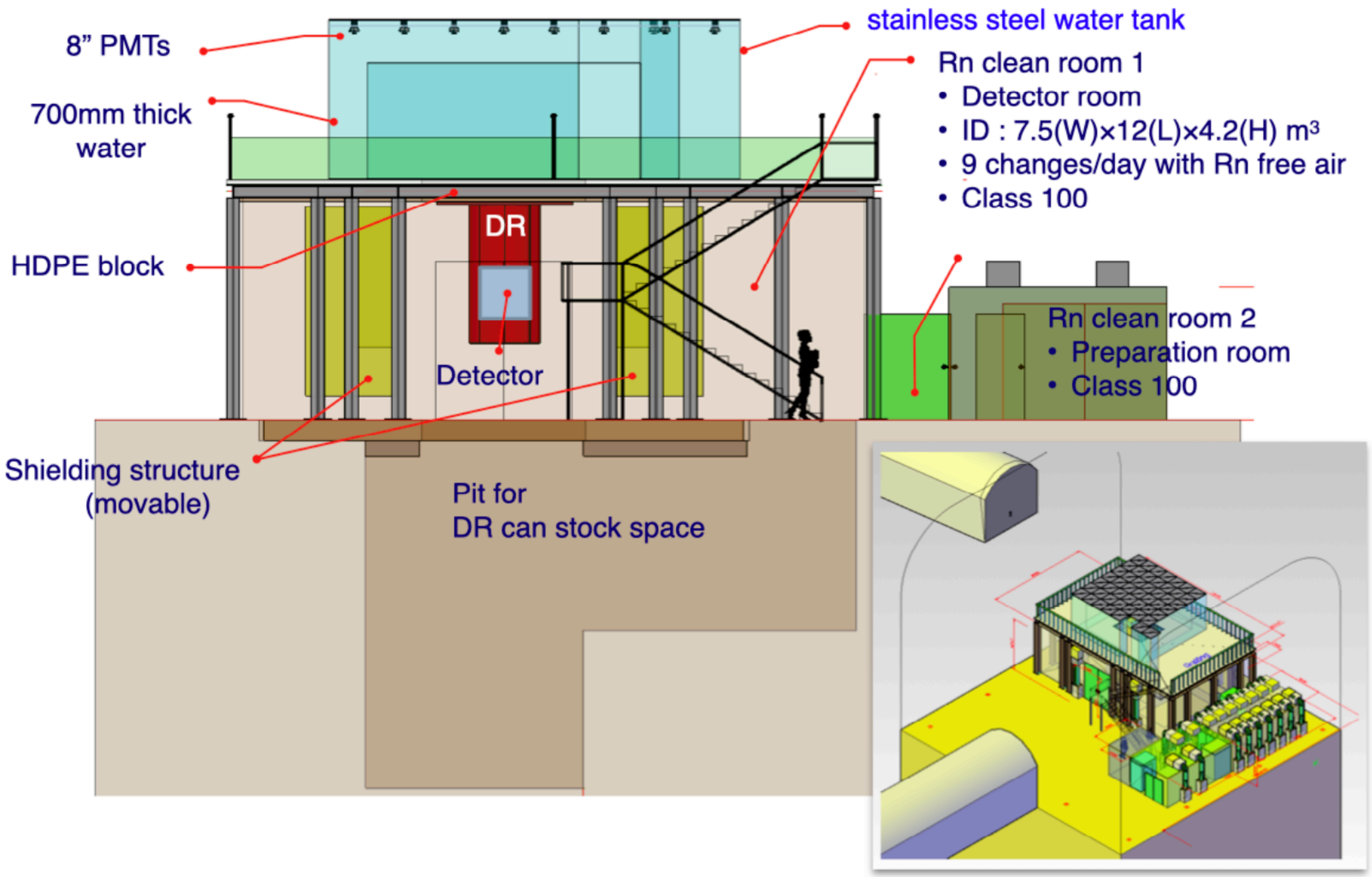
Water Cherenkov detector

Plastic scintillator

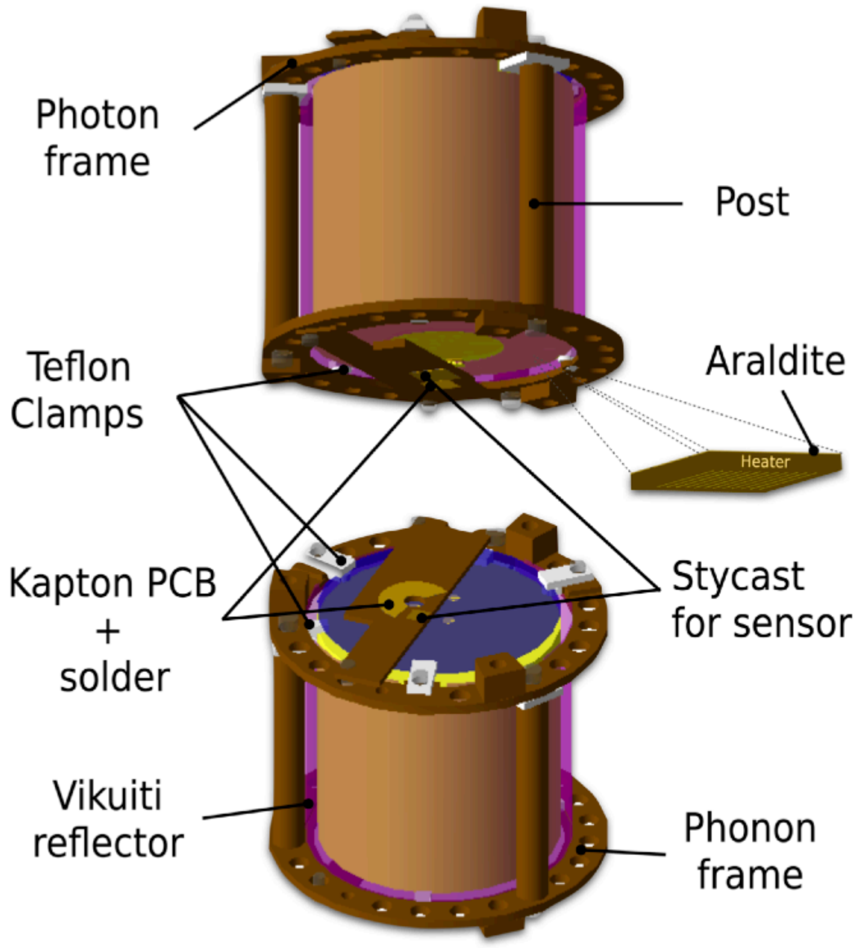
AMoRE-II simulation



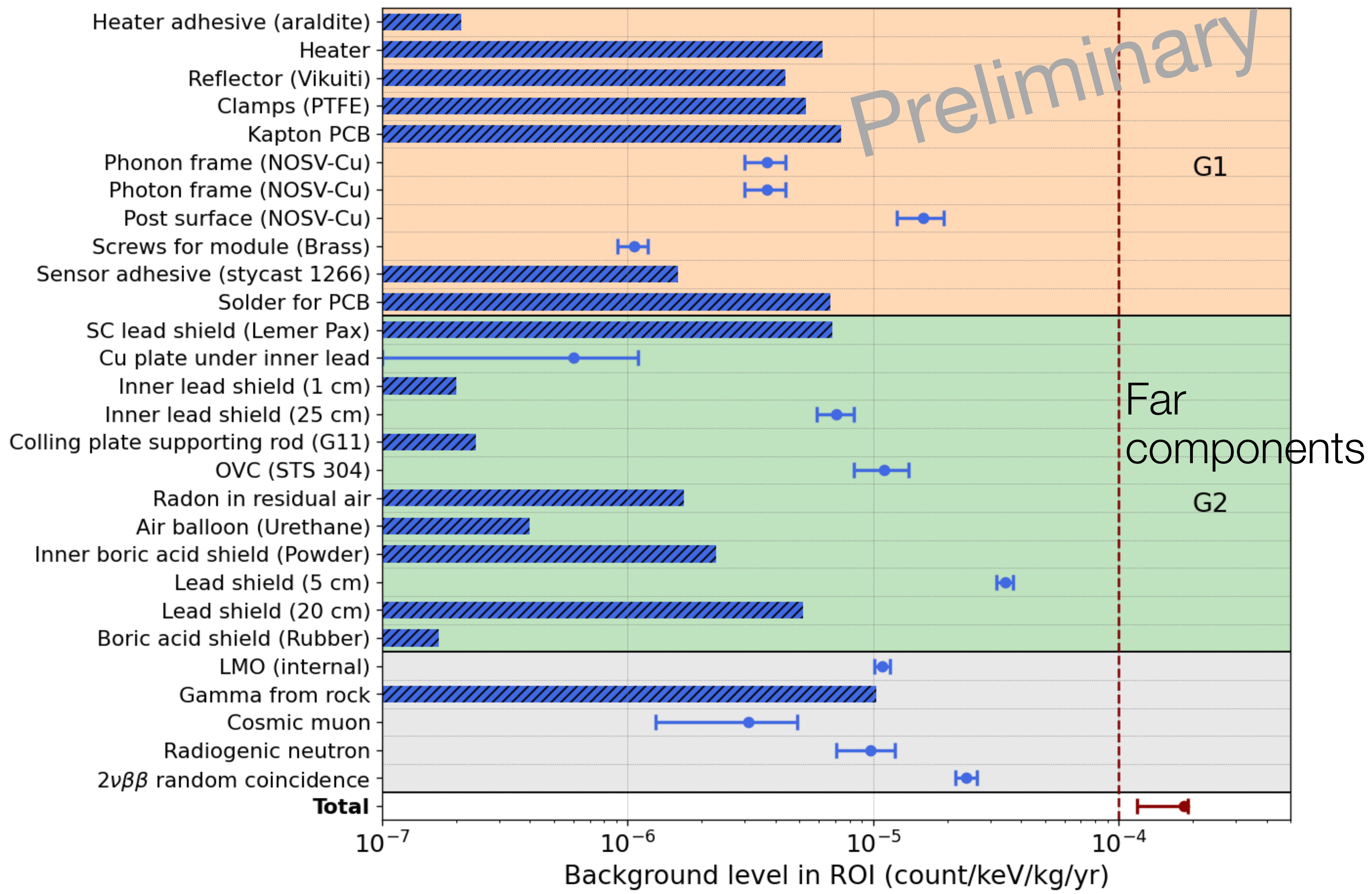


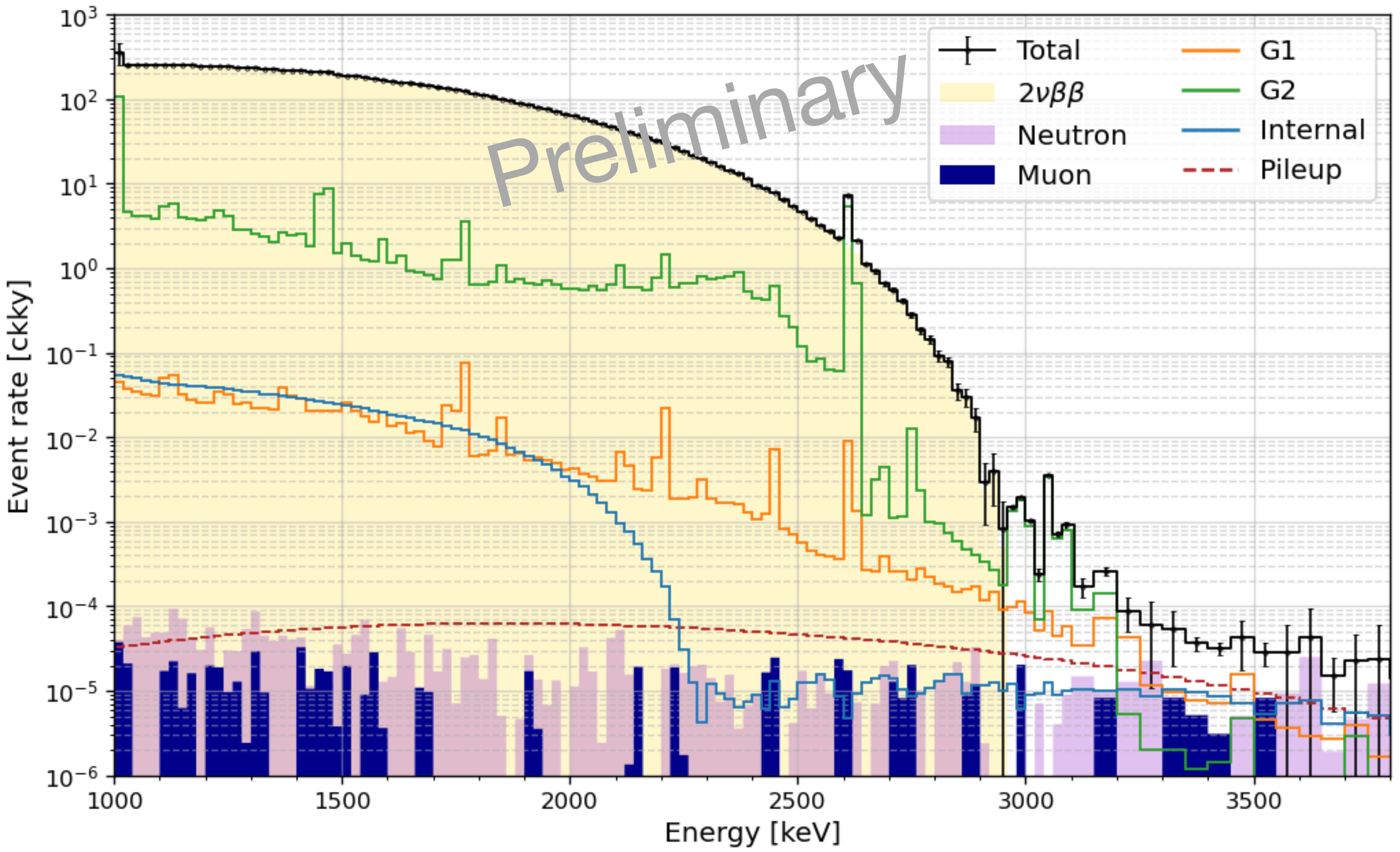


Background estimation



Near components (G1)





Summary

- Based on background simulations using Geant4, we gained a comprehensive understanding of detector performance and background components during the AMoRE-pilot and AMoRE-I phases
  - We replaced radioactive components with purer materials and added additional γ/n shield layers
  - We lowered the background level in ROI in AMoRE-I from 0.5 in AMoRE-Pilot to 0.03 counts/keV/kg/year
- For AMoRE-II, we conducted intensive background simulations based on Geant4 and estimated it to be 1.8×10^{-4} counts/keV/kg/year, which meets the requirement