Simulation in rare event search experiments

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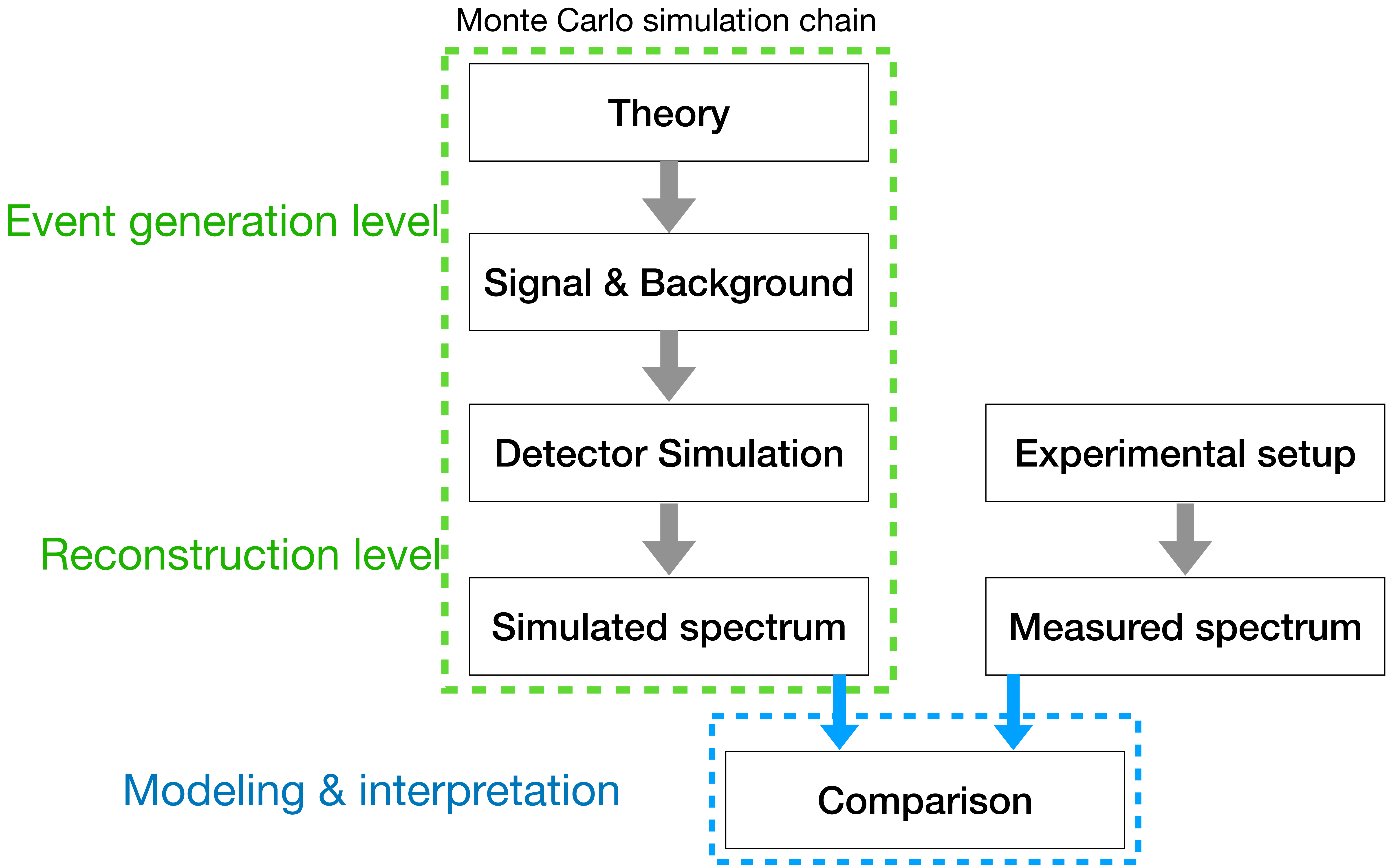
What do we need for rare event search experiments?

- Dark matter interactions and neutrinoless double beta decay occur at extremely low rates
- Key requirements for maximizing the signal-to-background ratio
  - Low backgrounds: underground operation, shielding against external radiation, use of low-radioactive materials, and high radiopurity
  - Low energy threshold and high energy resolution
  - Topological discrimination of signal and background events
- Simulation: quantitative evaluation of backgrounds, detector response, and signal discrimination

Simulation framework

- for interpreting experimental data



Background sources in rare-event experiments

Backgrounds

Cosmogenic

- Induced by cosmic rays, primarily cosmic-ray muons
- Muon-induced secondaries
  - neutrons
  - gammas
  - produced in surrounding rock
- Depends on
  - overburden depth
  - surrounding rock and shielding geometry
- Strongly shaped by detector geometry and veto systems

Radiogenic

- Arise from radioactive decays in
  - detector materials
  - nearby detector structures
  - surrounding rock
- Rock gammas and (α,n) neutrons
- U/Th decay chains and K-40
- Radon and its progeny
- Dominant at low energies

Geant4-based simulation
- for detector simulation approach

- Geant4 is a Monte Carlo toolkit for simulating the passage of particles through matter
- Detector geometry and all relevant materials are explicitly implemented within the Geant4 framework
- Geant4 tracks the transport of particles and interactions in the detector and surrounding structures
- During this transport, the simulation records energy deposition and the production of secondary particles in the sensitive volumes
- From these simulated energy deposits we construct the full detector response to background events
- In this way, all background sources are consistently propagated to detector observables using Geant4-based simulation

Cosmic-ray muon simulation

Surface muon flux

- Modified Gaisser parameterization

Mountain profile / Overburden

- MUSIC/MUTE

Muon propagation in rock

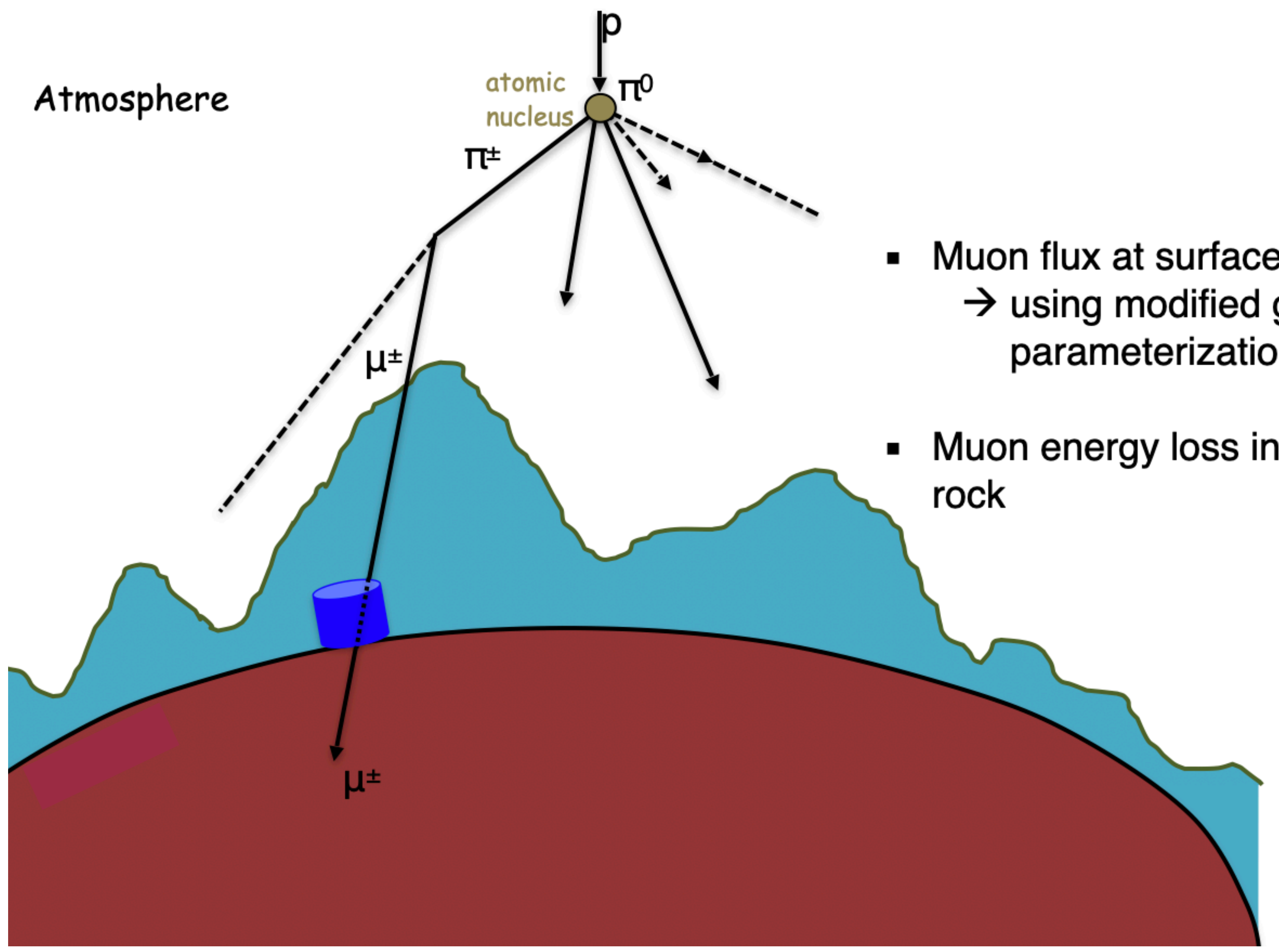
- MUSIC/MUTE

Underground muon spectrum + muon-induced secondaries

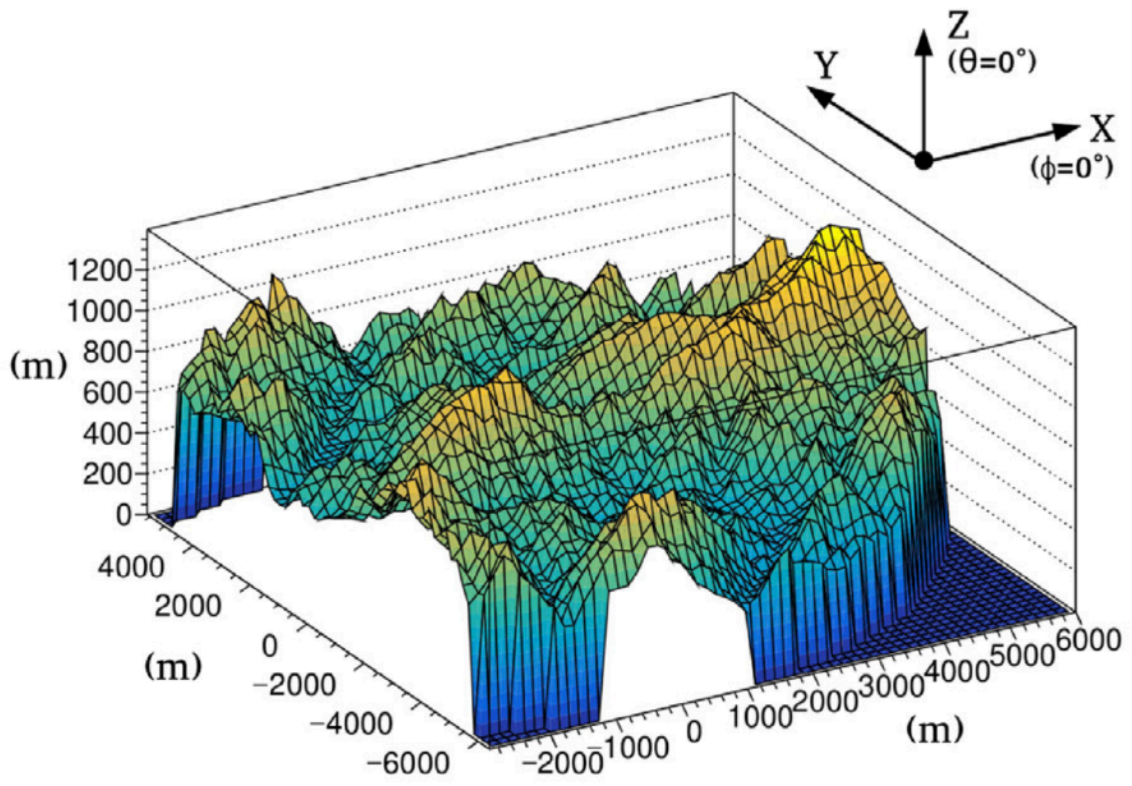
- GEANT4/FLUKA

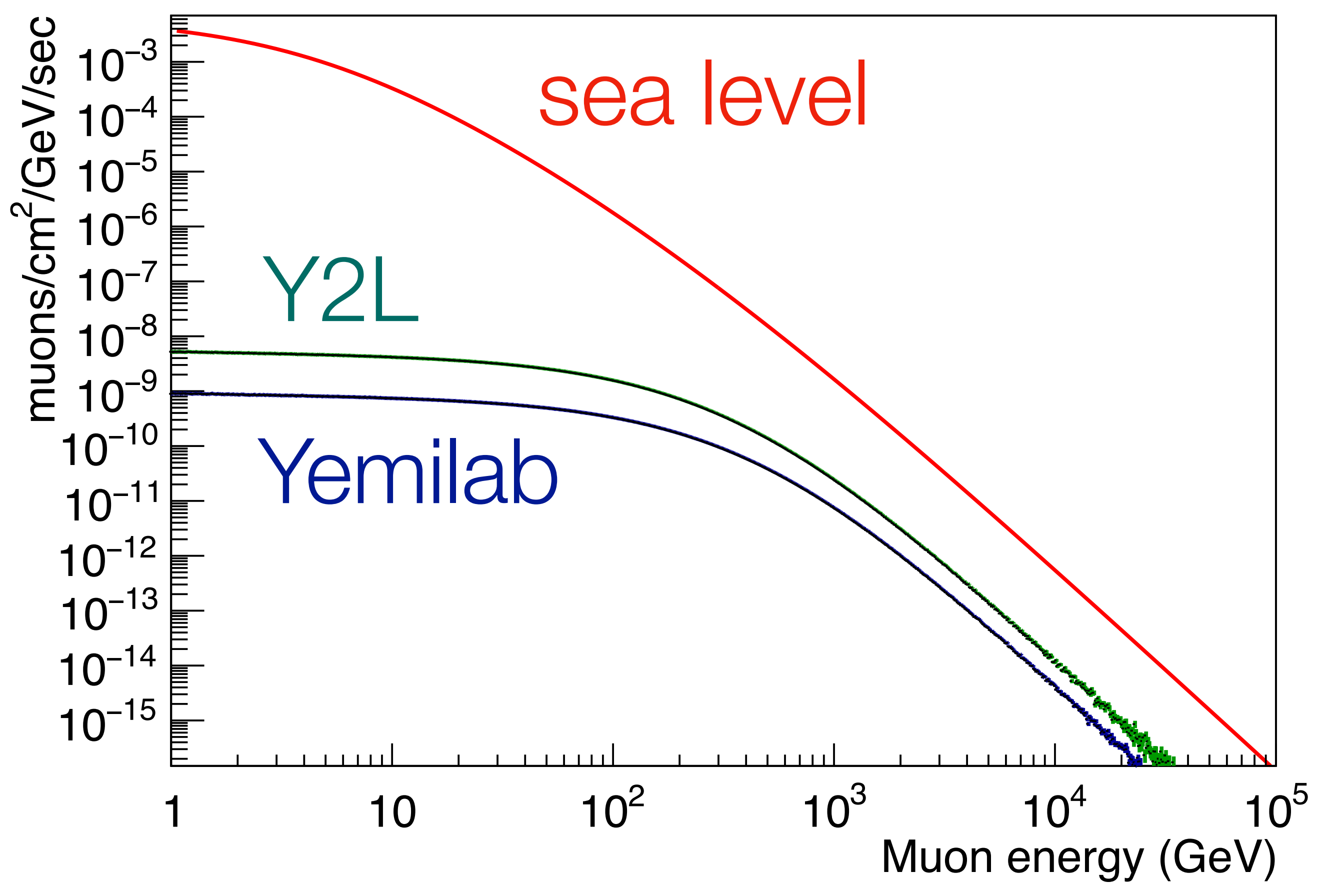
Detector & shielding & muon veto

- GEANT4

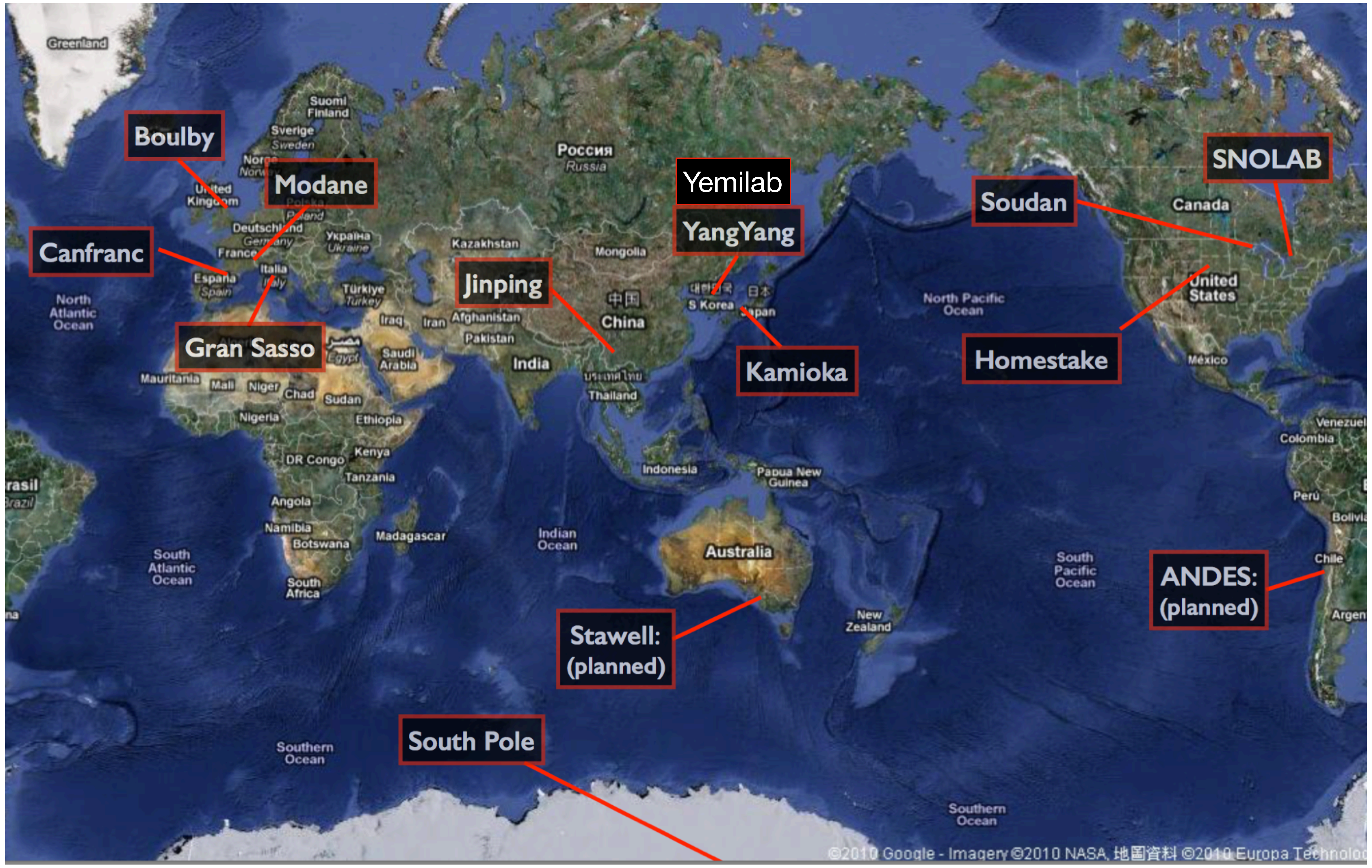


- Muon flux at surface
  → using modified gaisser parameterization
- Muon energy loss in the rock

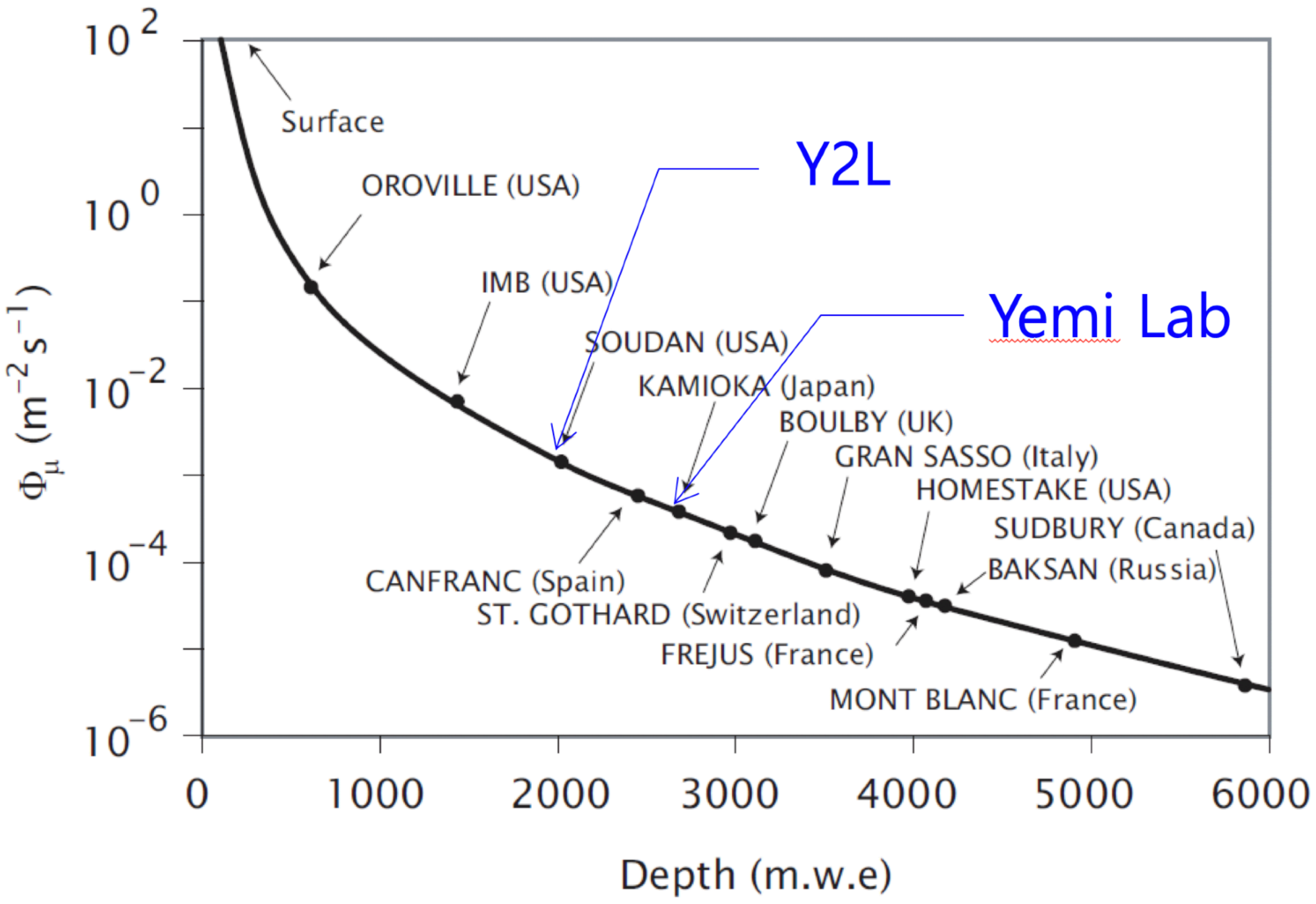




Deep underground laboratories in the world



~ 10^5 reduction



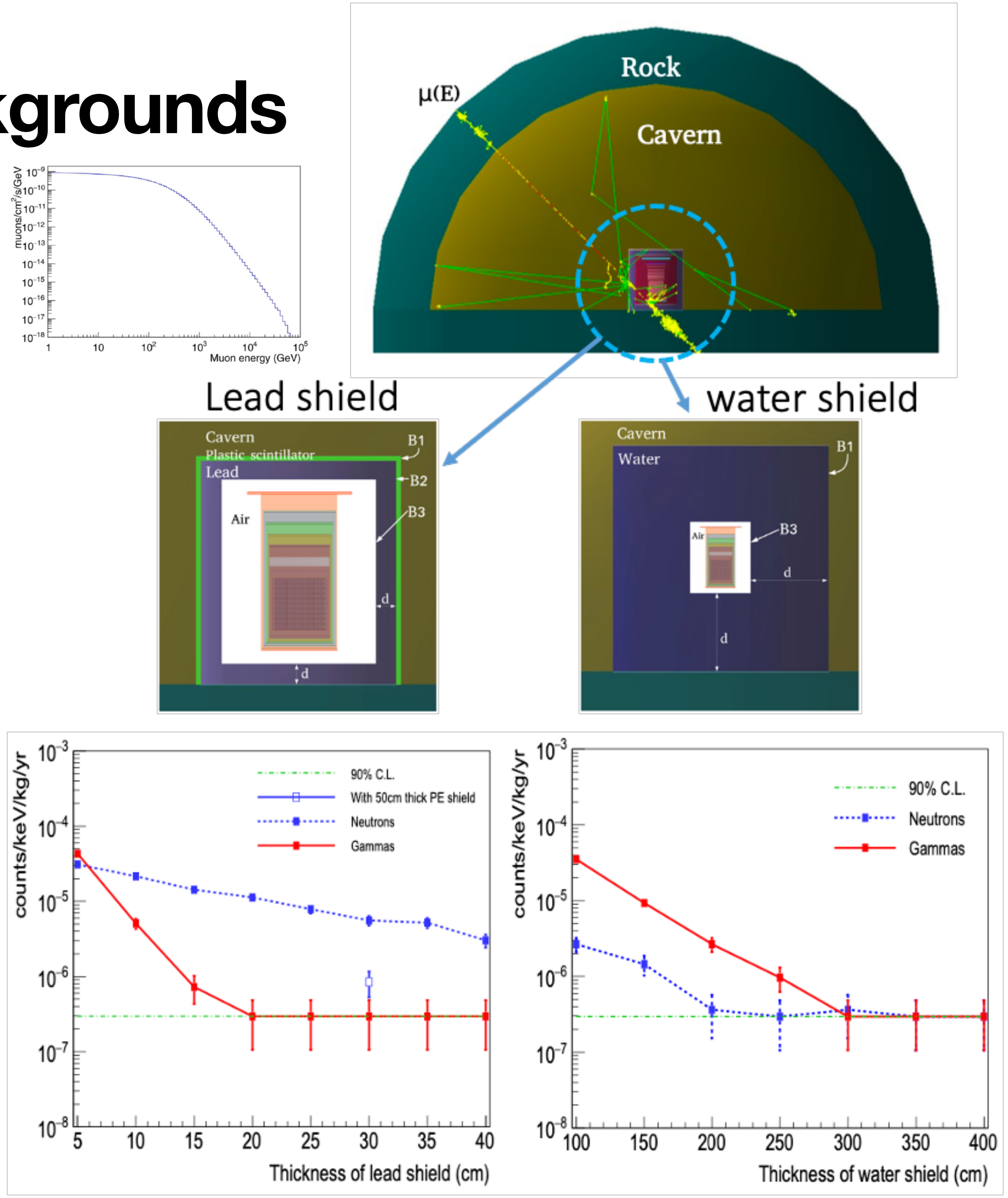
Simulation-driven background mitigation and detector design

- External background mitigation
  - Passive shielding
    - rock overburden
    - lead, copper, polyethylene, water
  - Active background rejection
    - muon veto systems
    - anticoincidence techniques

- Simulation enables
  - Quantification of background attenuation and secondary production
  - Evaluation of veto efficiency for cosmogenic backgrounds
  - Optimization of trade-offs between background reduction and signal acceptance

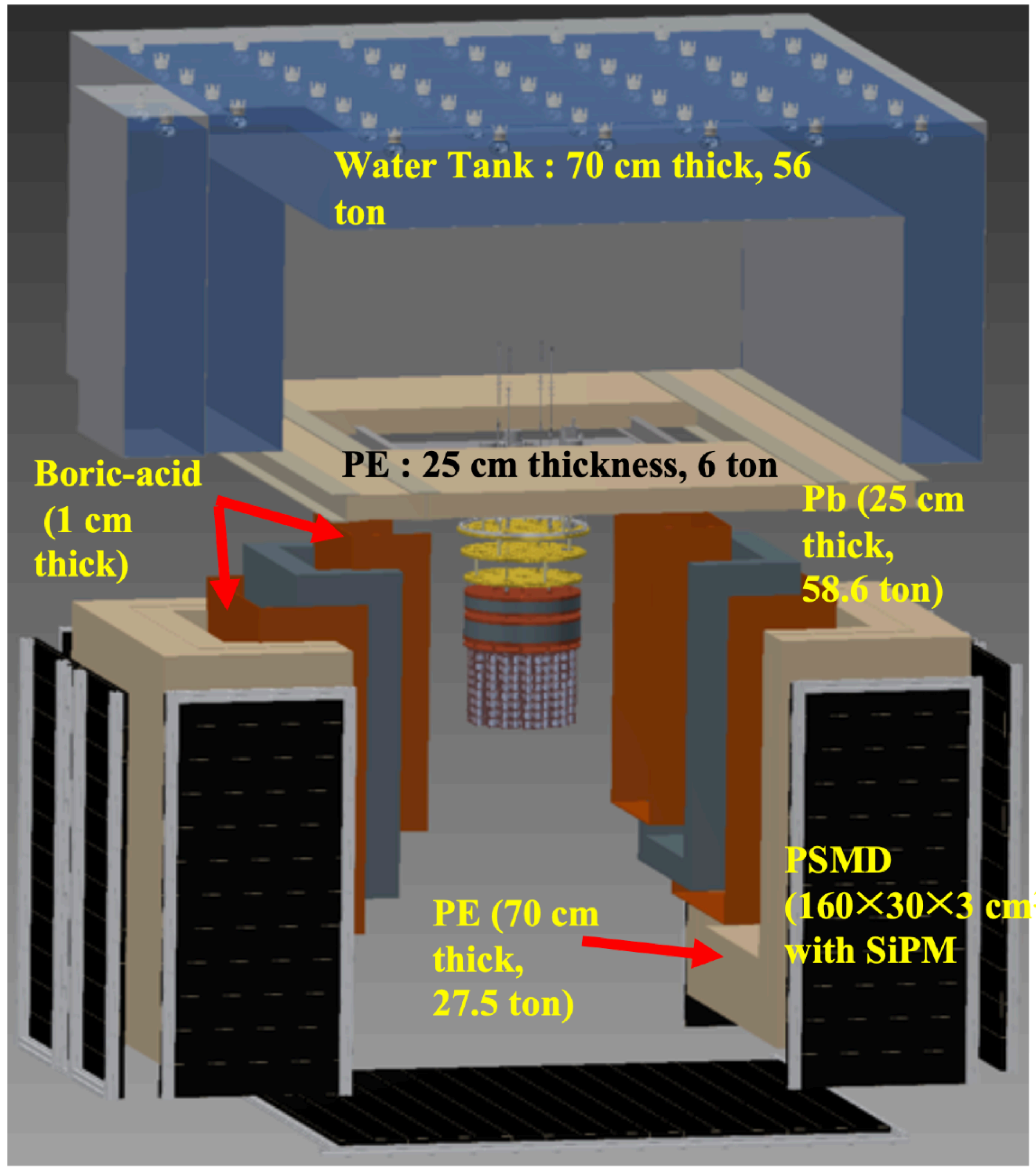
Muon and muon-induced backgrounds

- We simulated cosmic muons and muon-induced particles
- We estimated single-hit event rate in the (2–8) MeV with several shielding thicknesses applied for both lead shielding and water tank shielding when muon veto efficiency is given
- 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

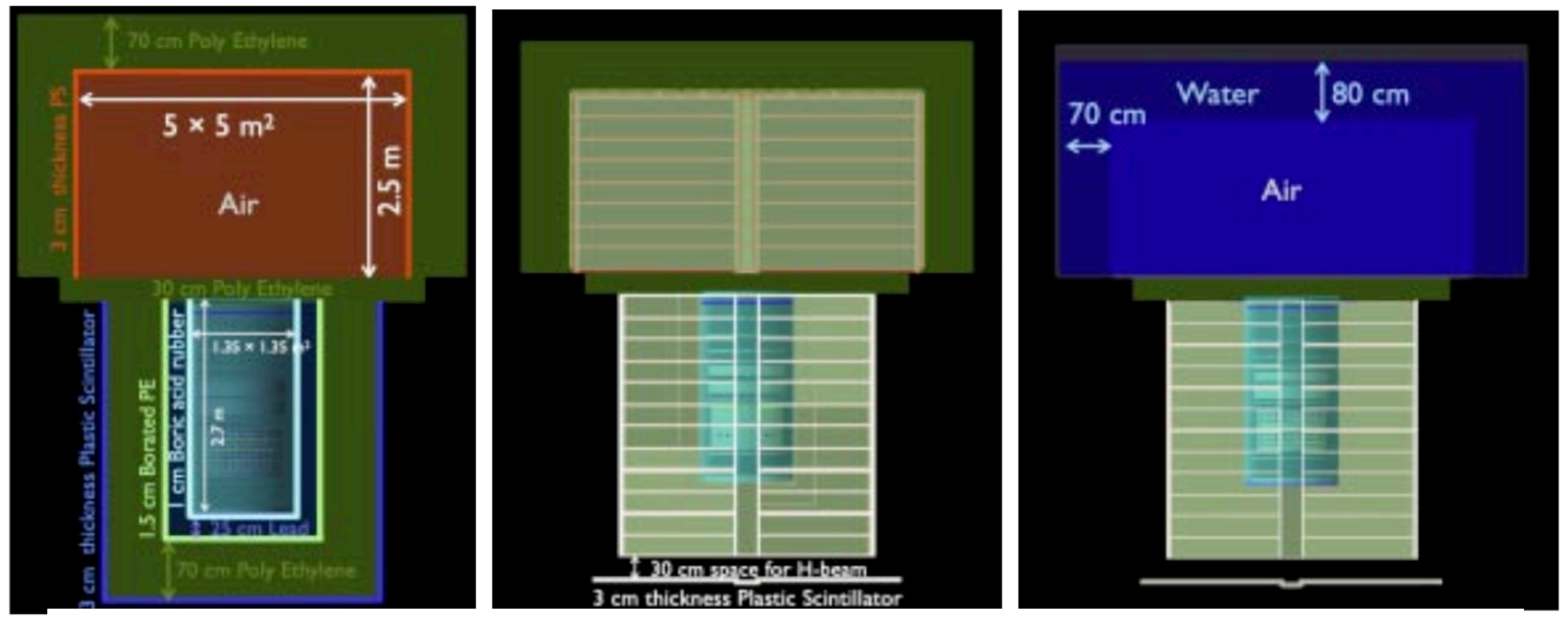


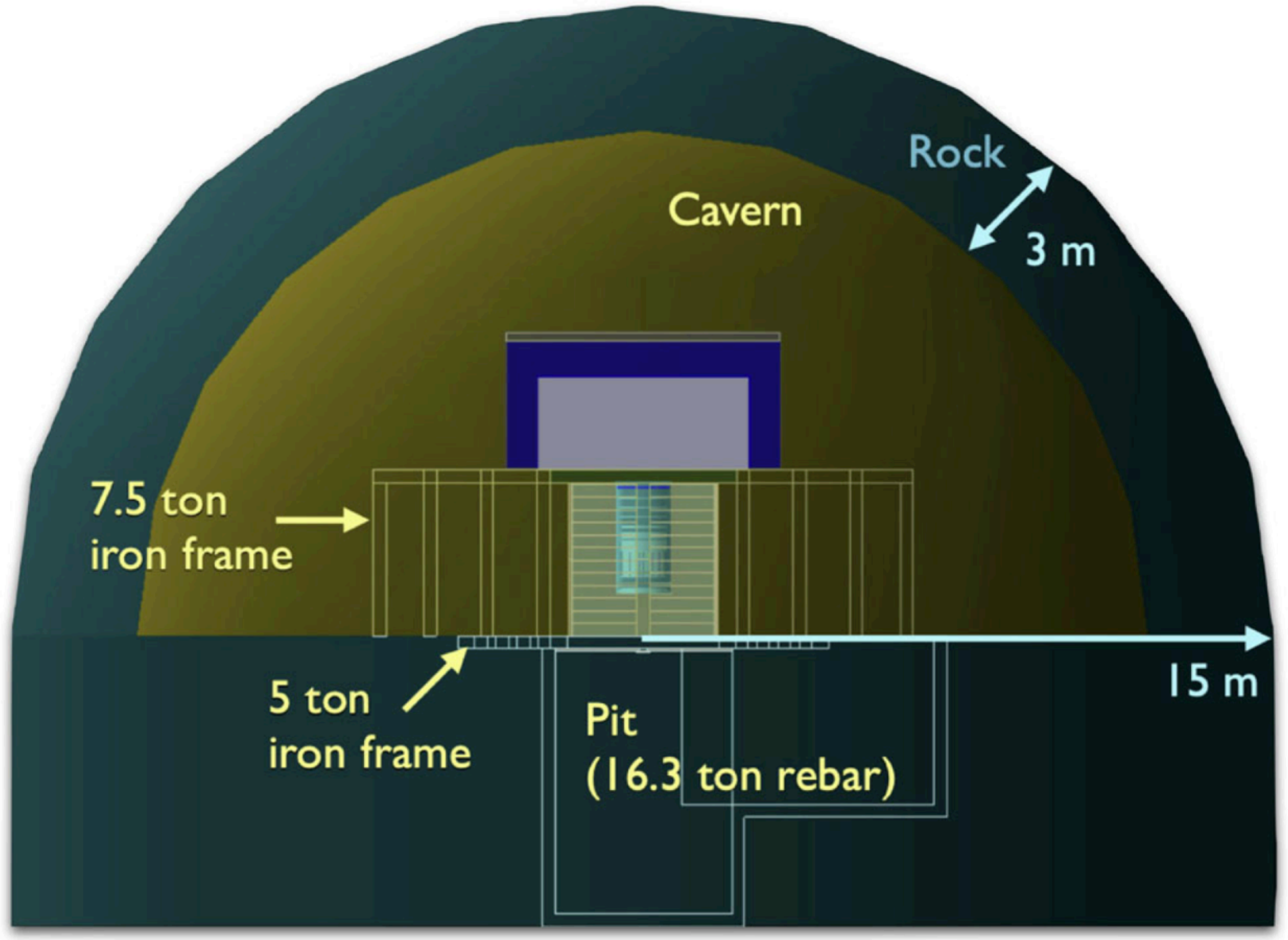
Shielding structure and muon veto system
- for the detector design

- GEANT4-based study was performed to specify the thickness and layers of the various shielding materials. All of those parameters are reflected in the design of the AMoRE-II construction.
- New concepts for veto system were evaluated in simulation before construction
    - Water Cherenkov detector with active muon veto capability is installed above the cryostat
    - Plastic scintillator detector panels are installed on the four sides and the bottom of the cryostat



Simulated configurations for veto system

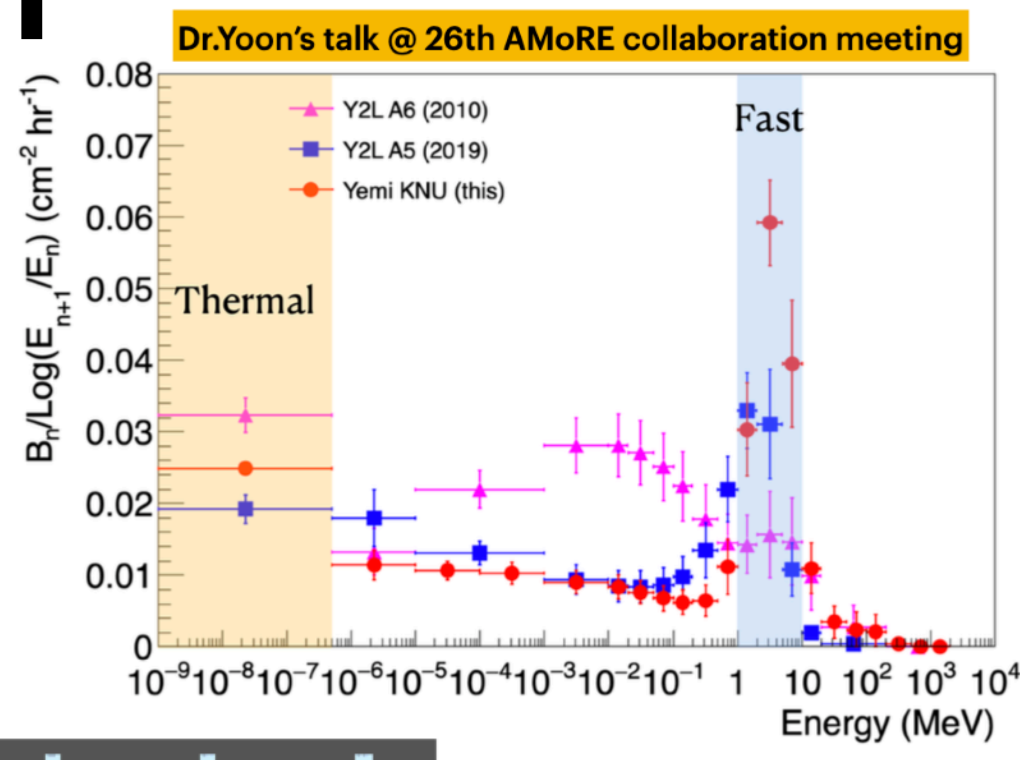


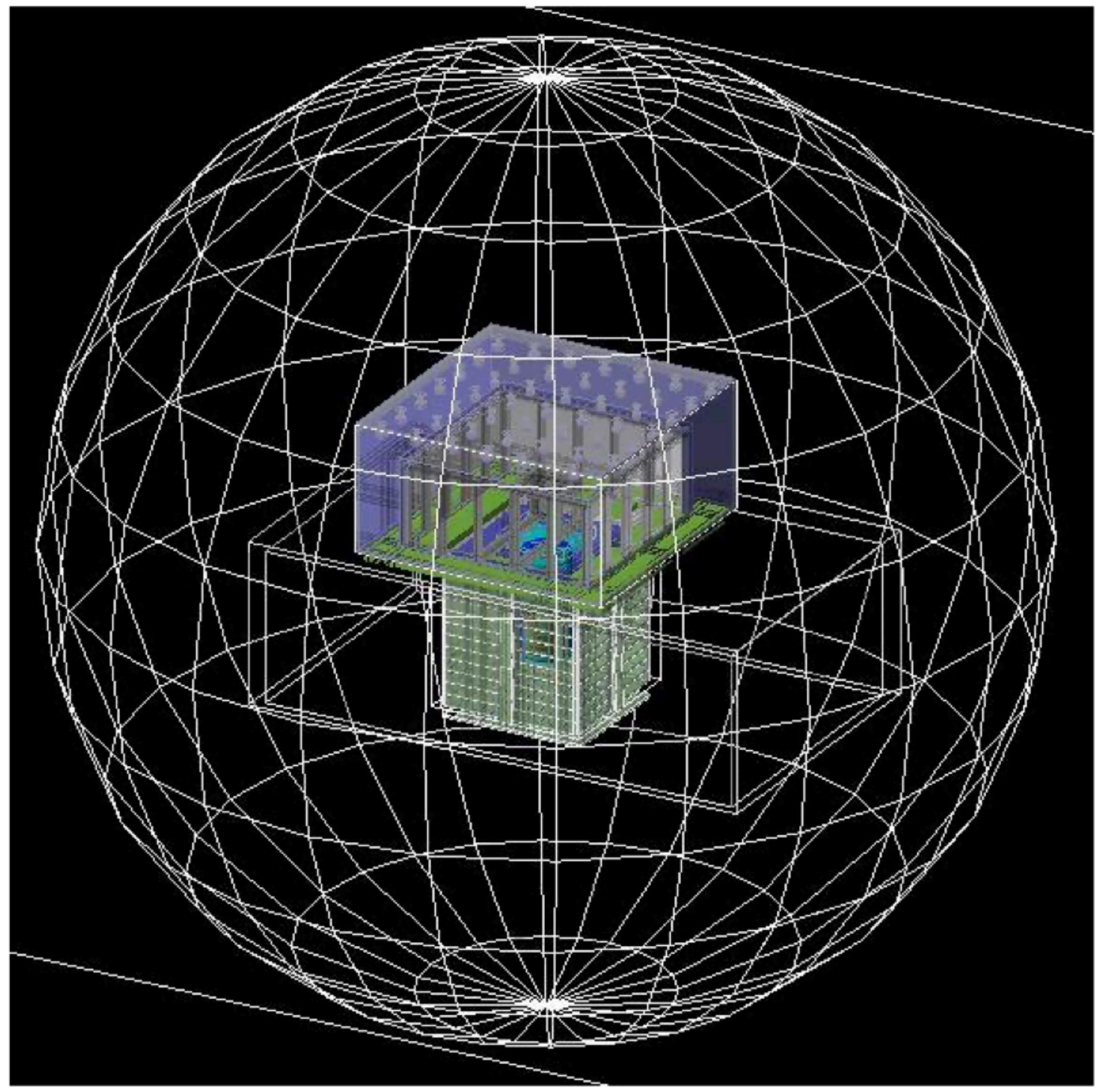


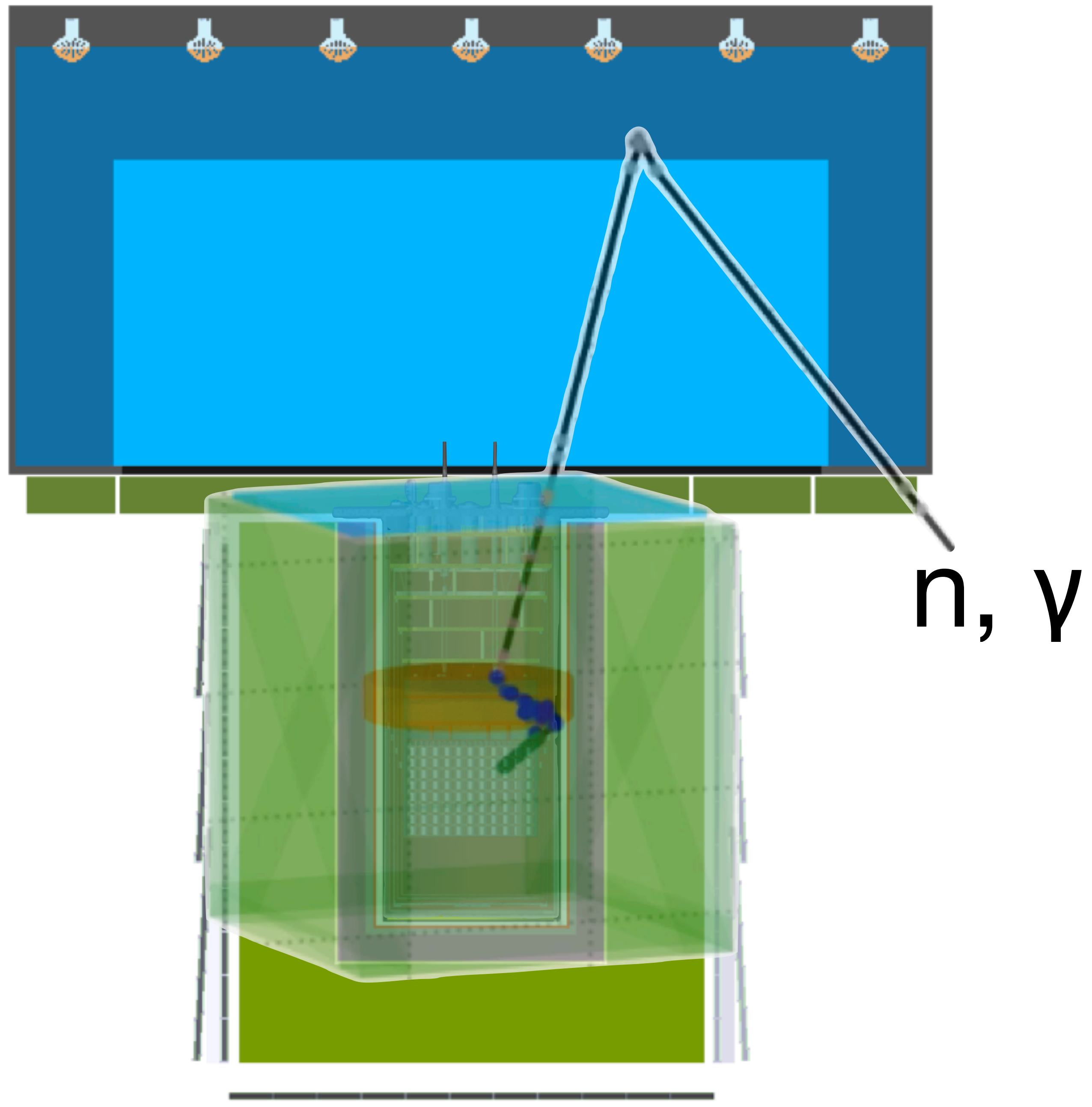
Rock gammas and environmental neutrons

- for shielding design optimization

- Rock radioactivity produces
  - Neutrons (<10 MeV)
  - Gamma rays (< 4 MeV)
- Rock radioactivity (U, Th, K) and environmental neutrons must be measured on site
- Shielding optimization relies on rock assays and detailed simulations of the shielding geometry





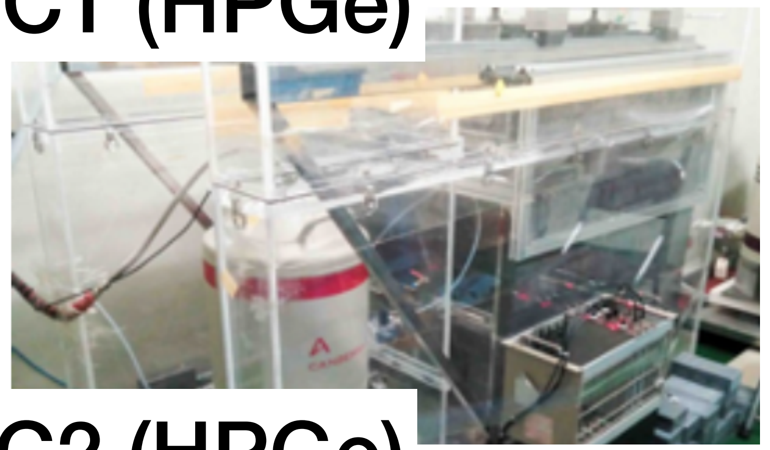


Detector geometry and radiogenic background

- Detector and shielding materials produce radiogenic background
- Their activities are measured (HPGe, α counters, ICP-MS) and put into a detailed geometry model
- Simulation shows which parts dominate the background and how to improve the design

Radioactivity measurement

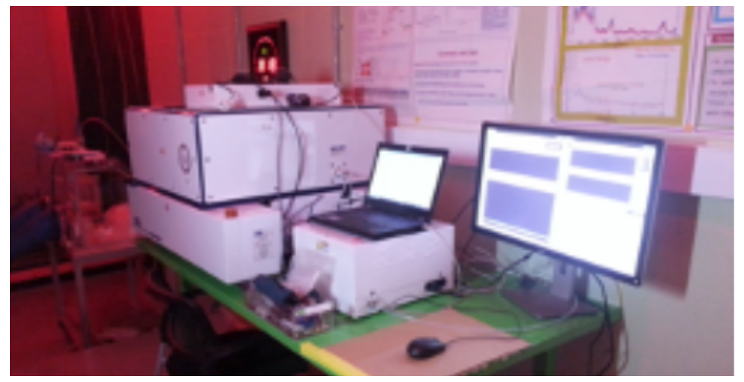
CC1 (HPGe)



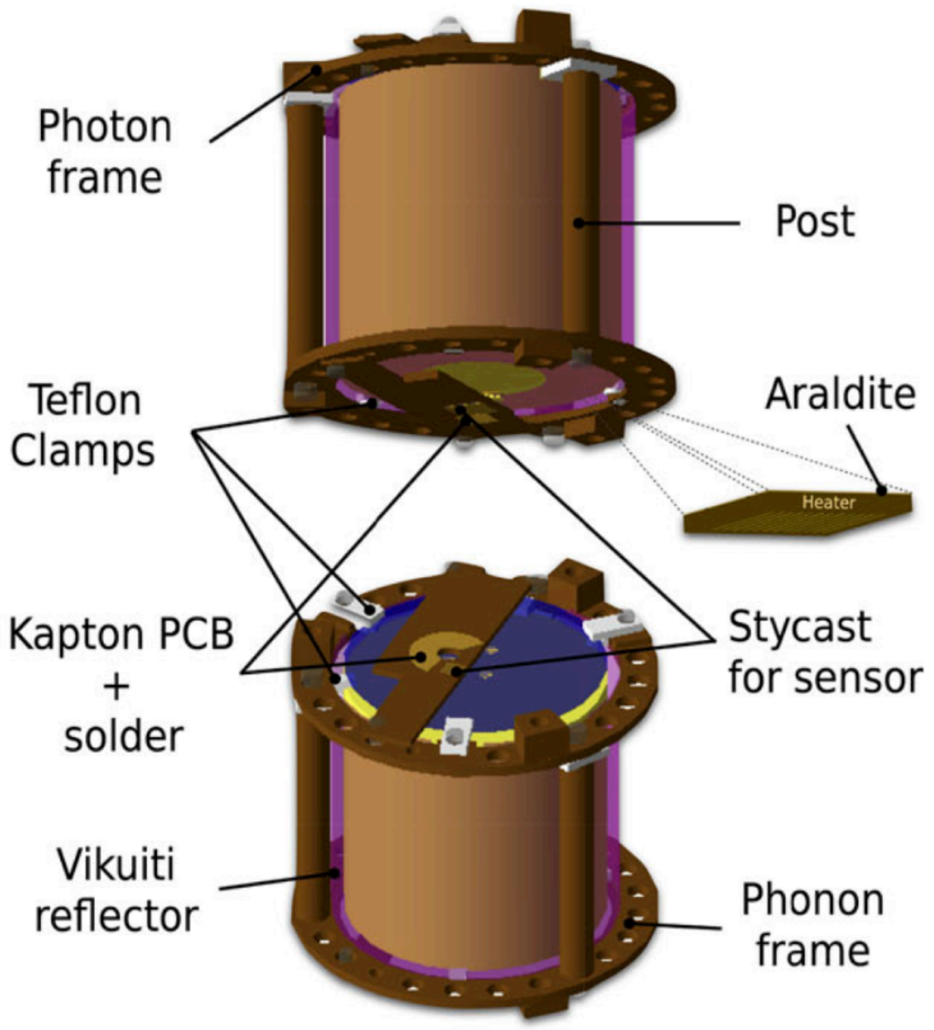
CAGE (14 array HPGe)

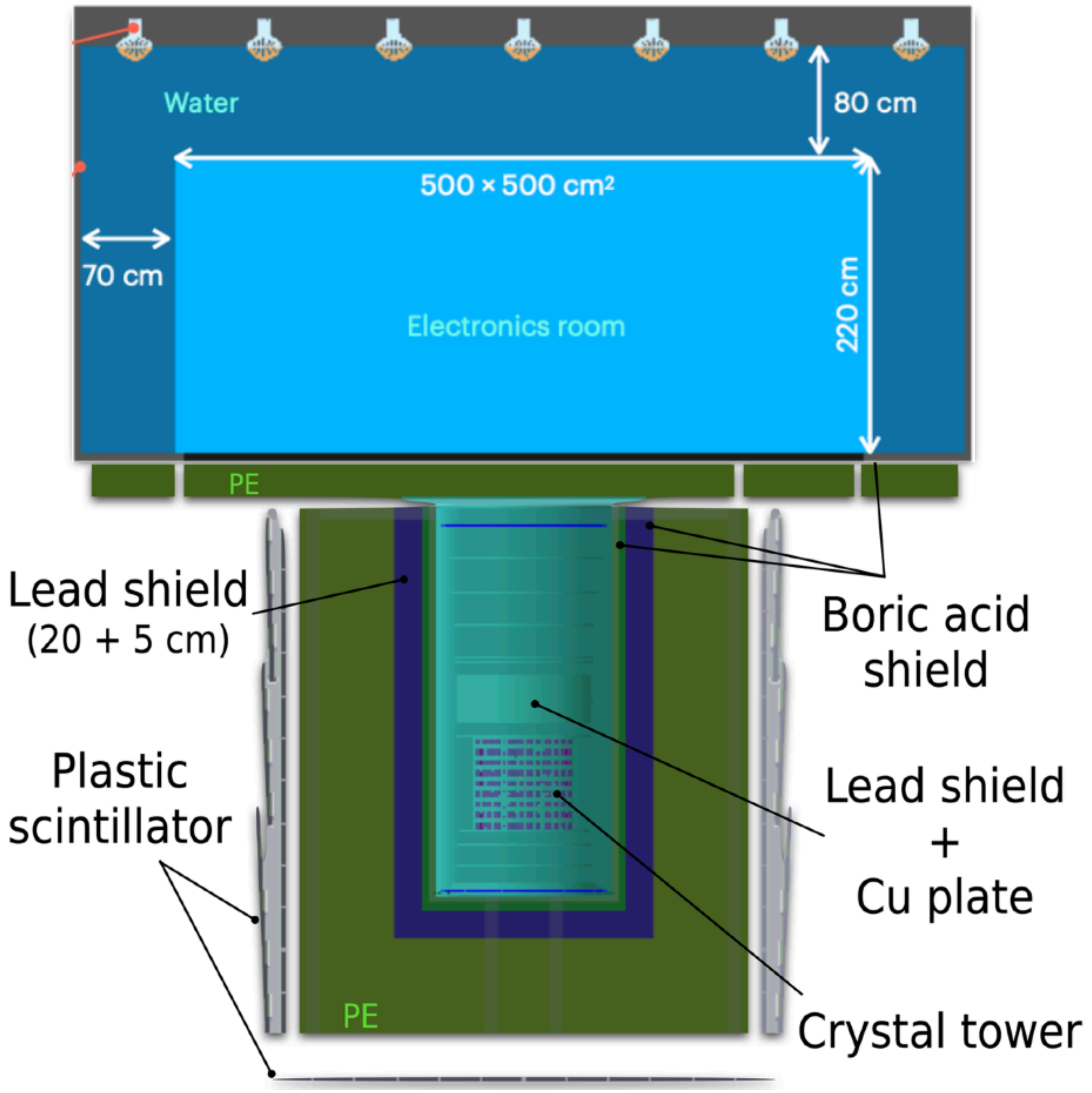
CC2 (HPGe)

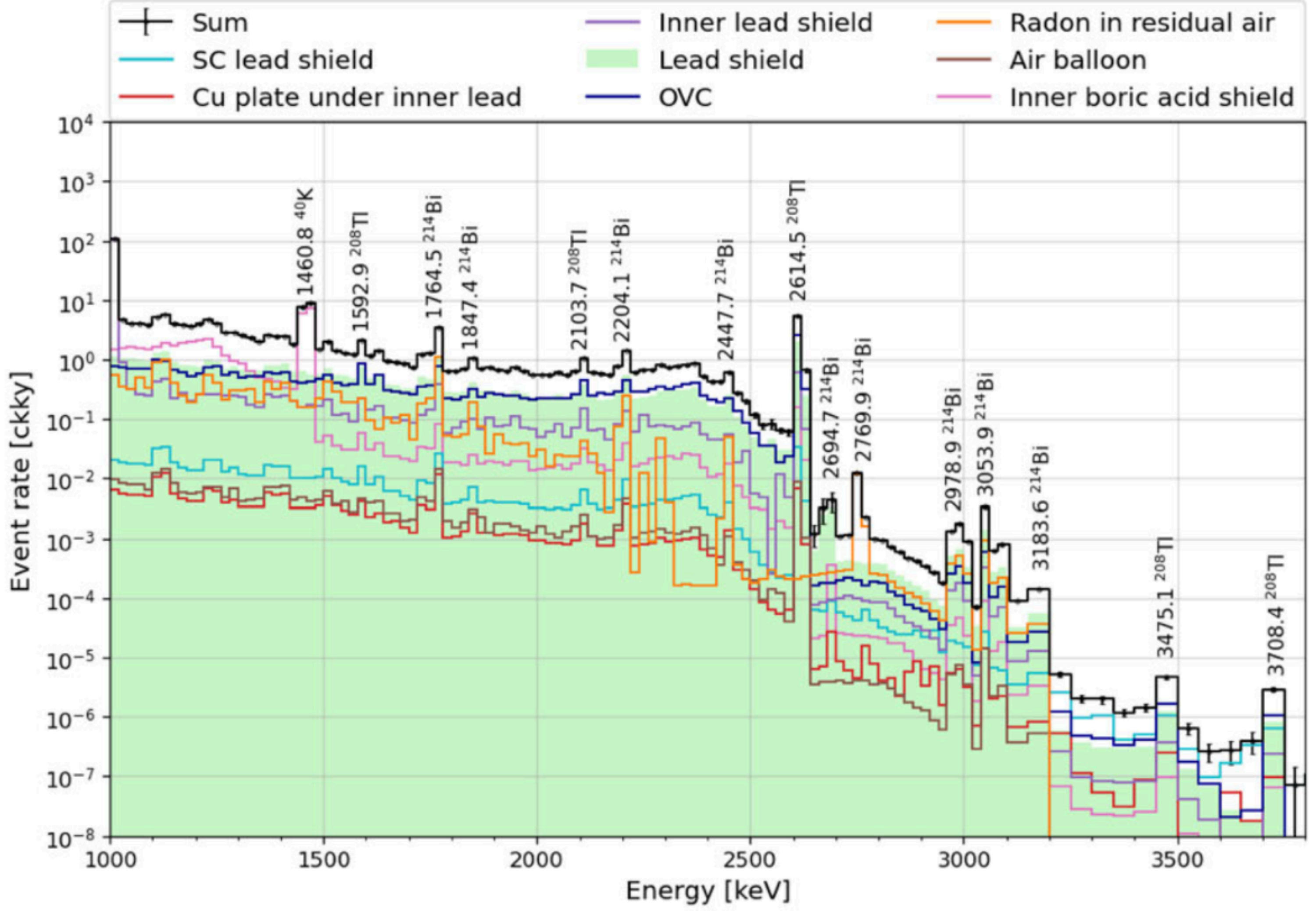
α ionization counter (XIA)

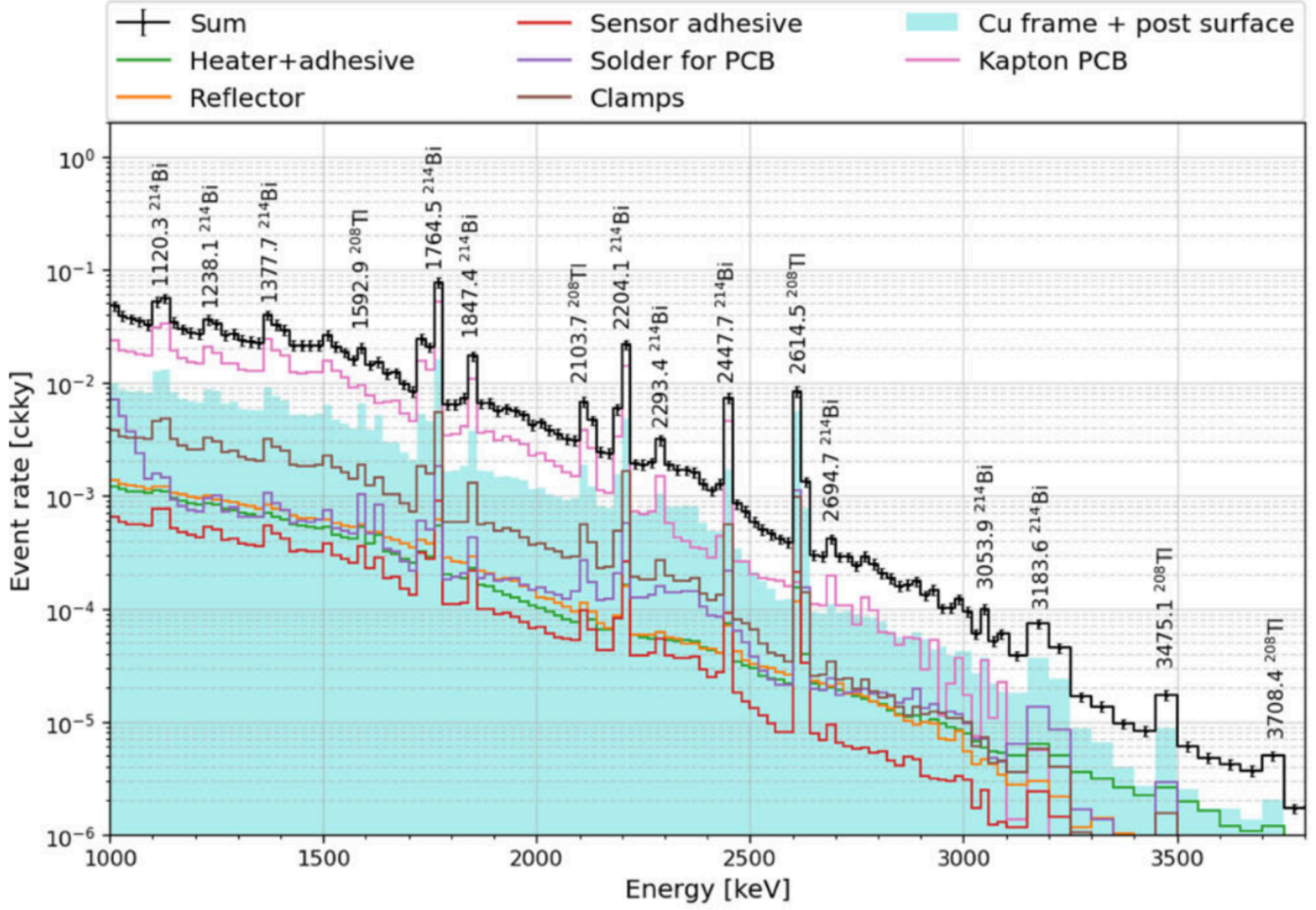


ICP-MC (Alilent 7900)





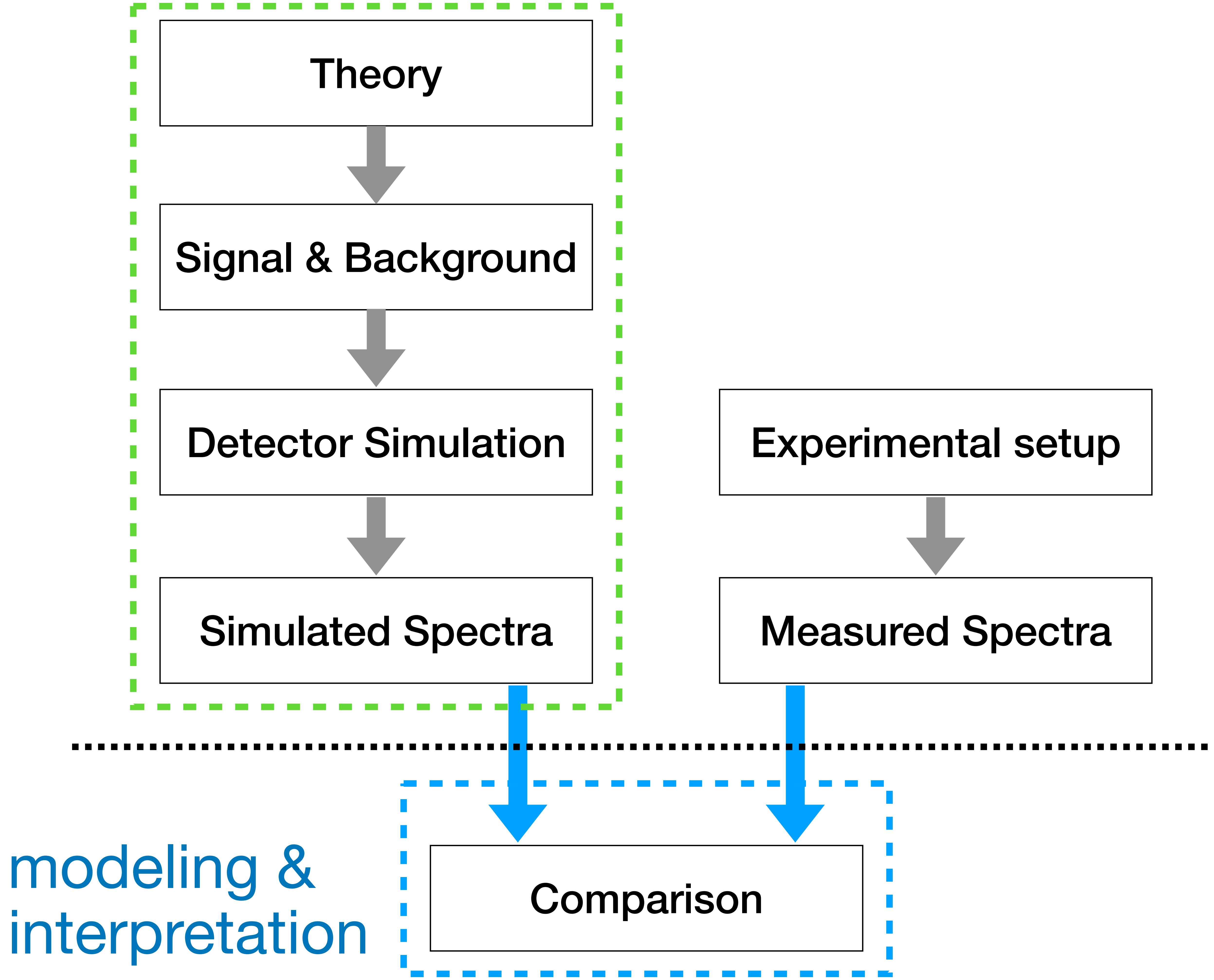




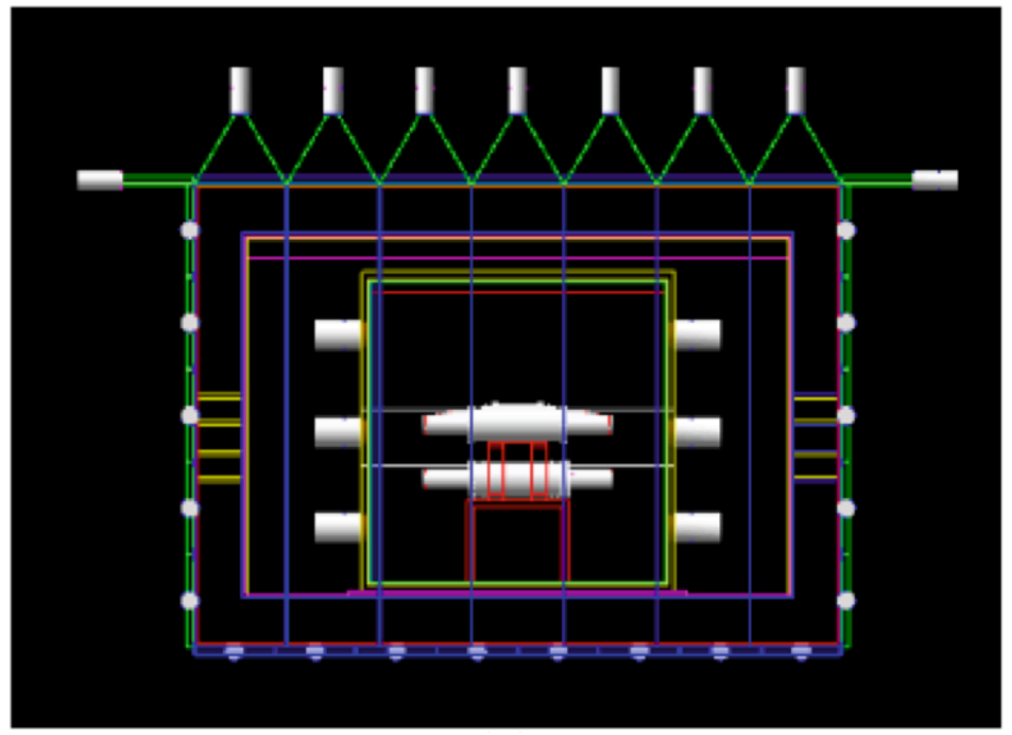
From bakground simulations to background modeling

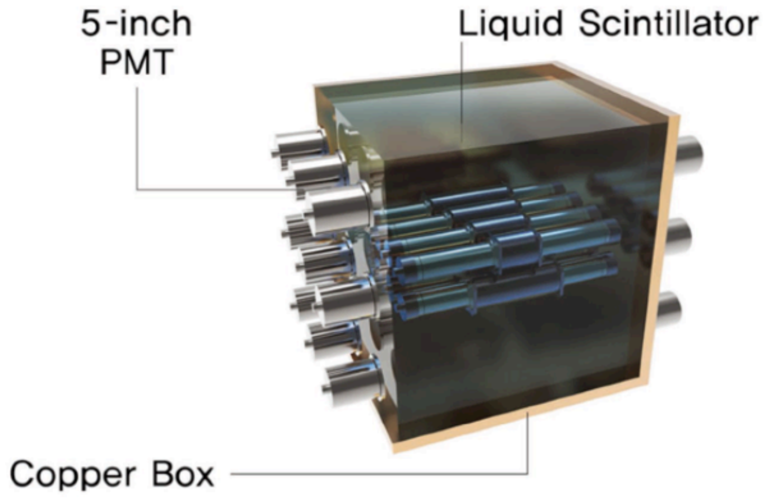
- simulation framework

- Background simulations
  - Individual background sources are generated and propagated through the full detector geometry
  - At the reconstruction level we obtain simulated spectra for each background component
- Background modeling
  - All simulated background components are added to obtain a total spectrum that can be directly compared with the data
  - The total simulated spectrum is fitted to the measured data, providing a quantitative decomposition of backgrounds and a basis for interpretation

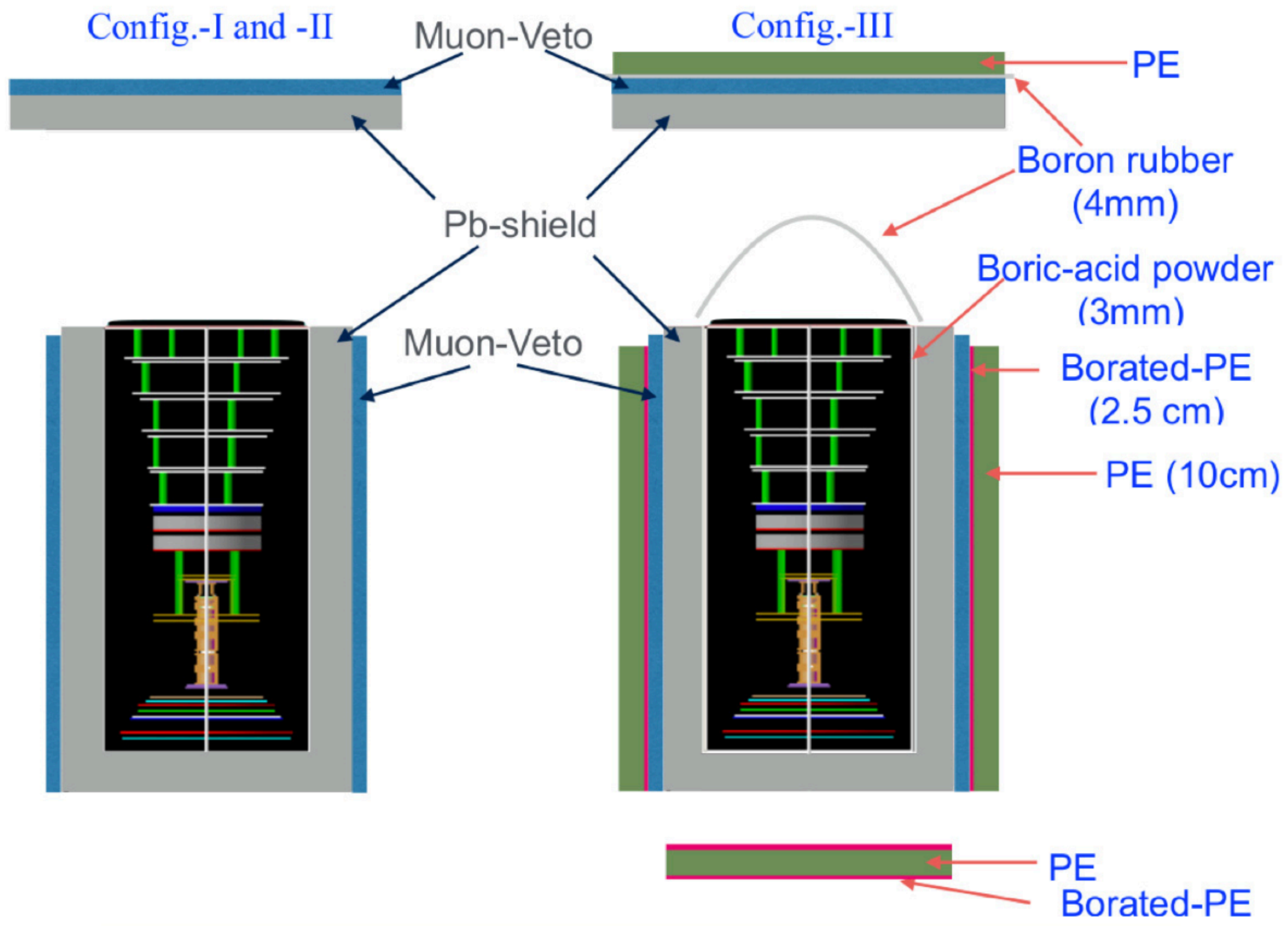


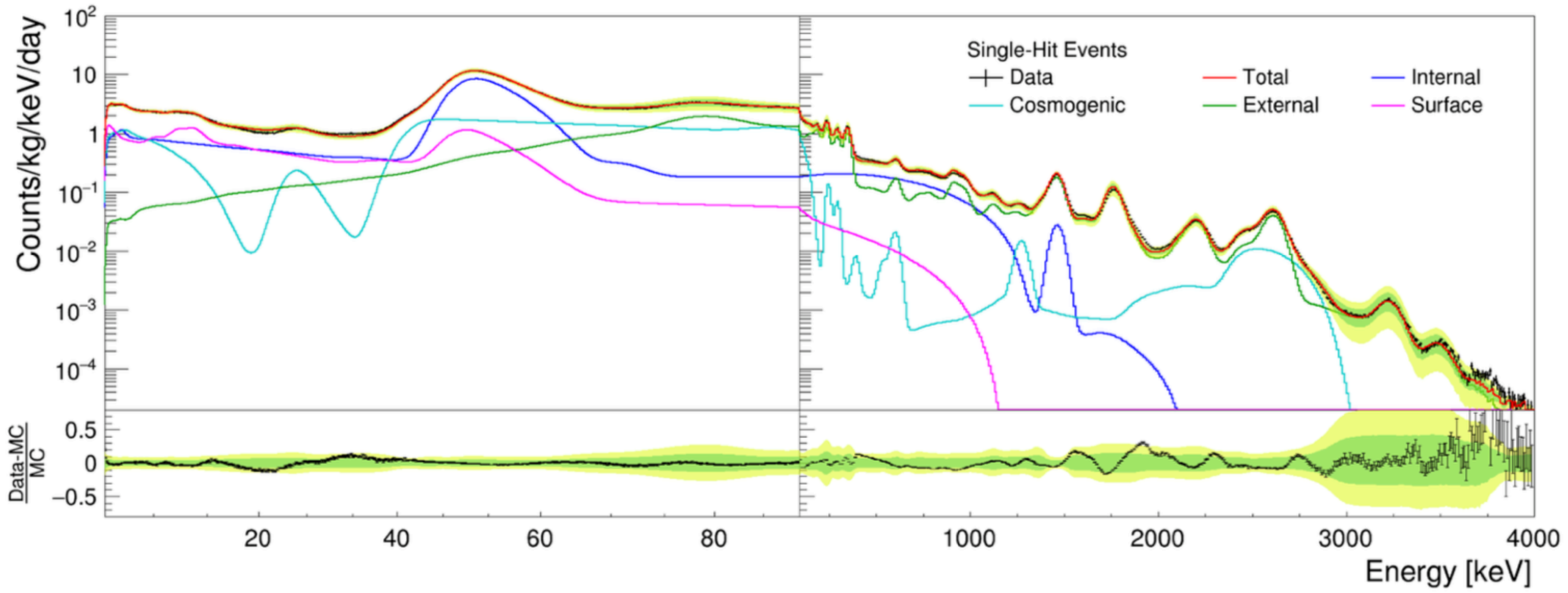
Background modeling

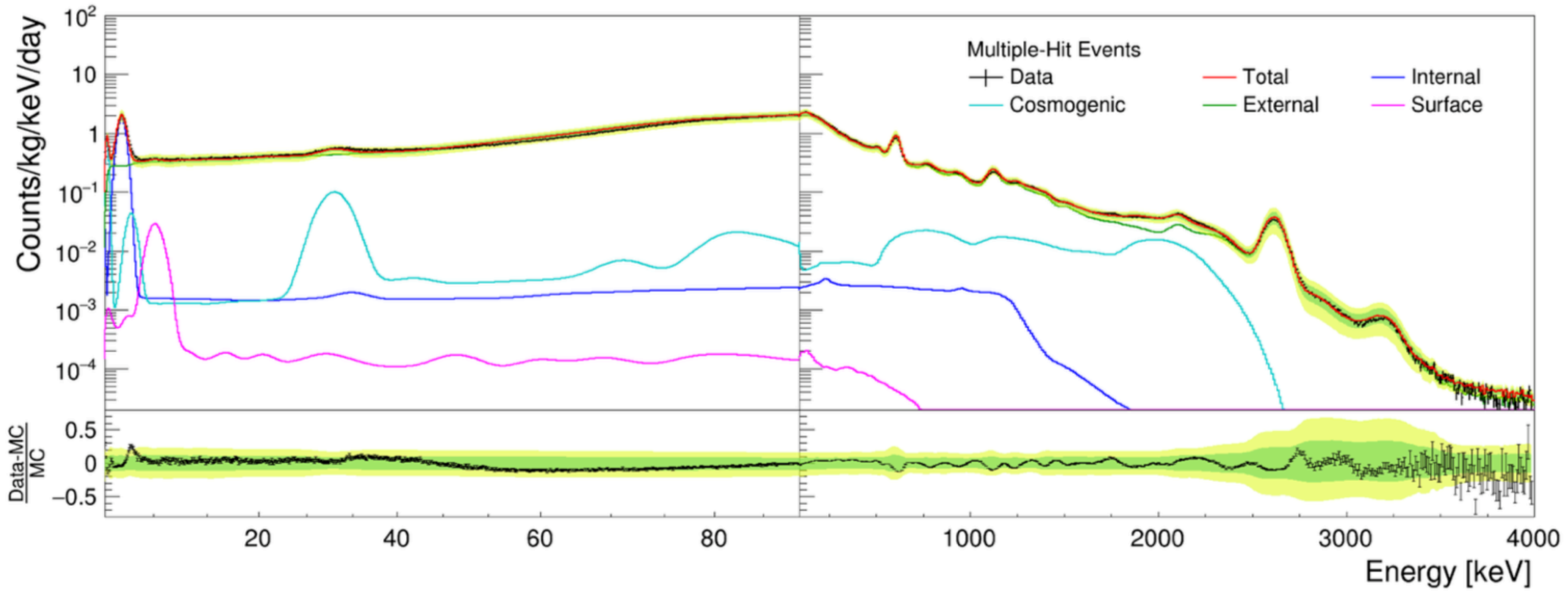


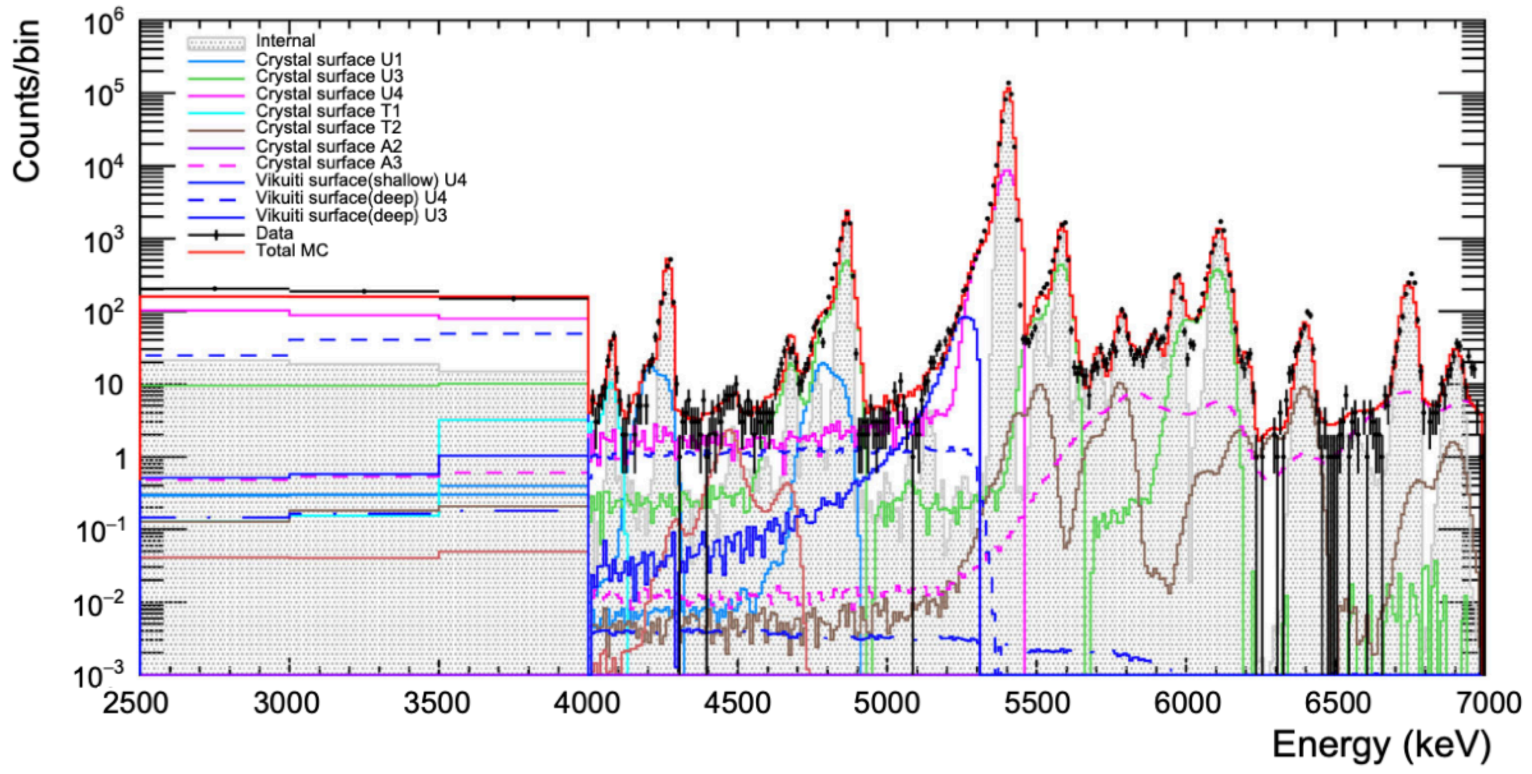


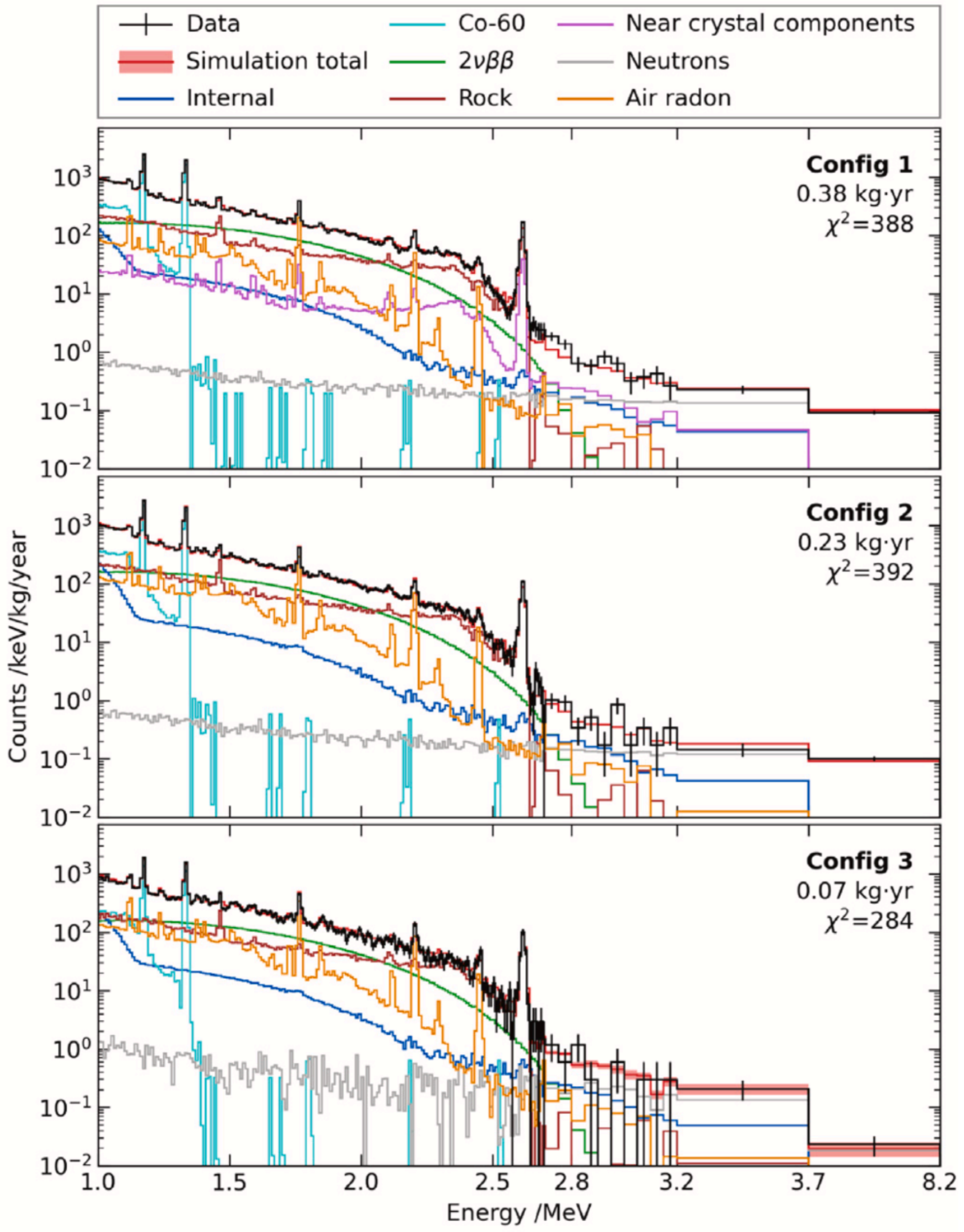
- We model the measured background by simulating all relevant sources in the full detector geometry and fitting the total spectrum to data
- For COSINE-100, this approach reproduces the observed spectra and enables quantitative tests of possible WIMP signals
- For AMoRE-Pilot, three configurations were studied; simulation-based background models guided changes in materials, shielding, and crystal surface treatment, and the impact of each configuration was confirmed by fitting the simulated background model to the measured spectra









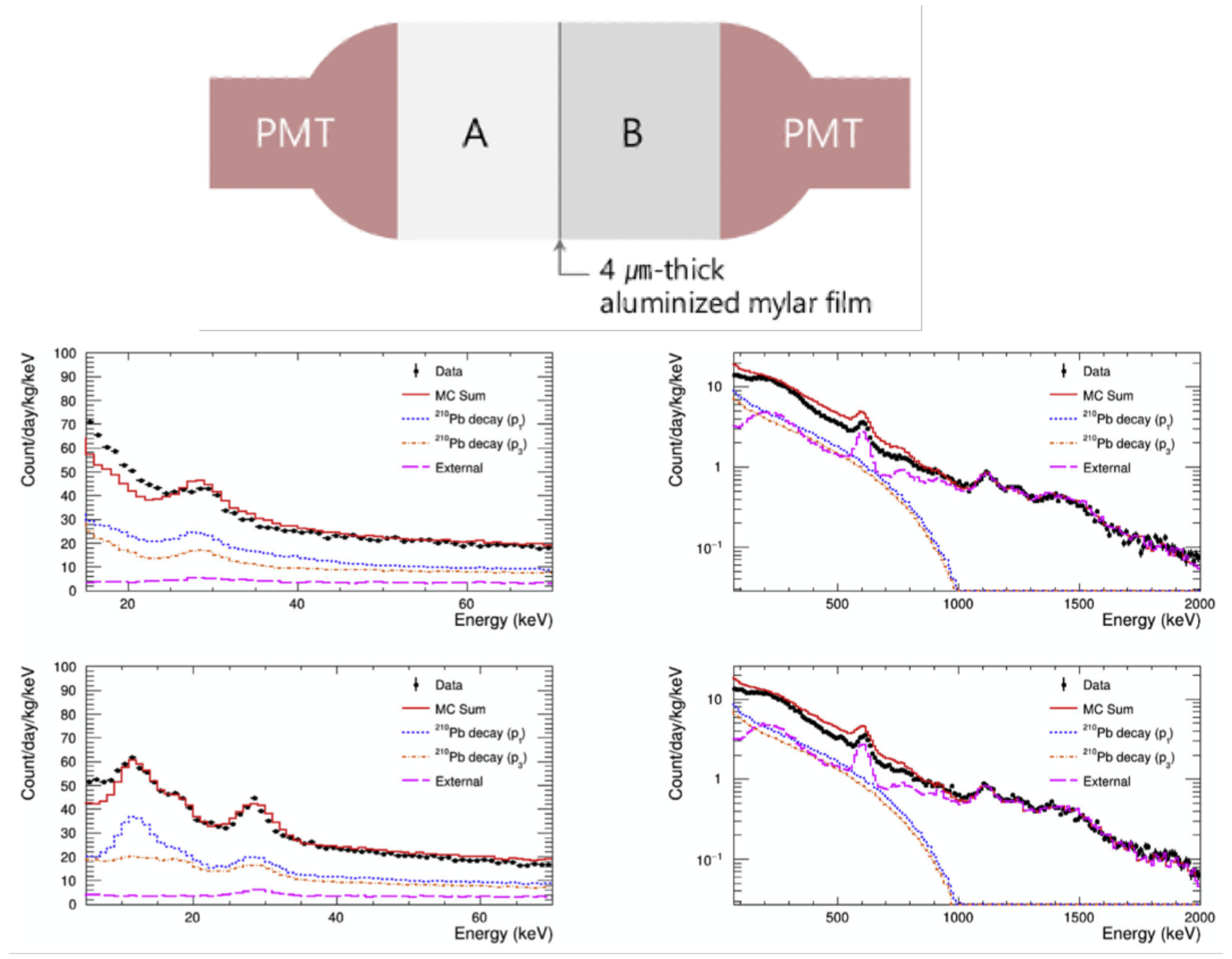


Simulation for R&D studies

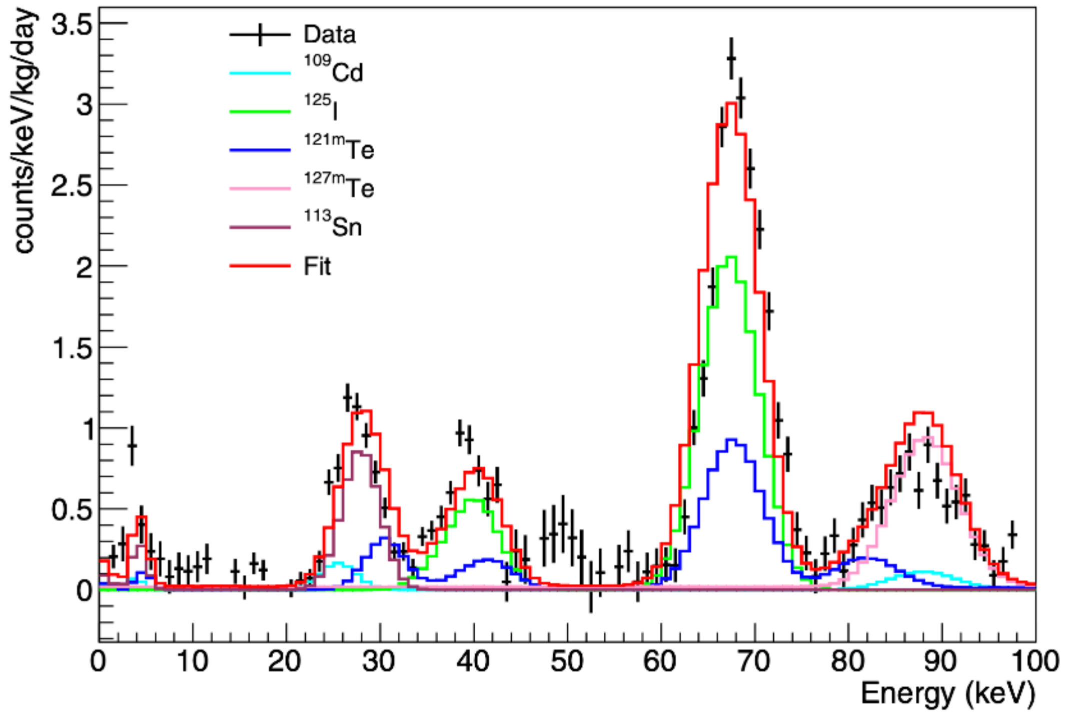
- for better background understanding

- Improving background modeling requires a more precise and quantitative understanding of the major background contributors
- Using a common simulation framework, we study
  - crystal backgrounds (bulk and surface),
  - time-dependent cosmogenic isotopes,
  - scintillator nonproportionality embedded directly in the detector response simulation

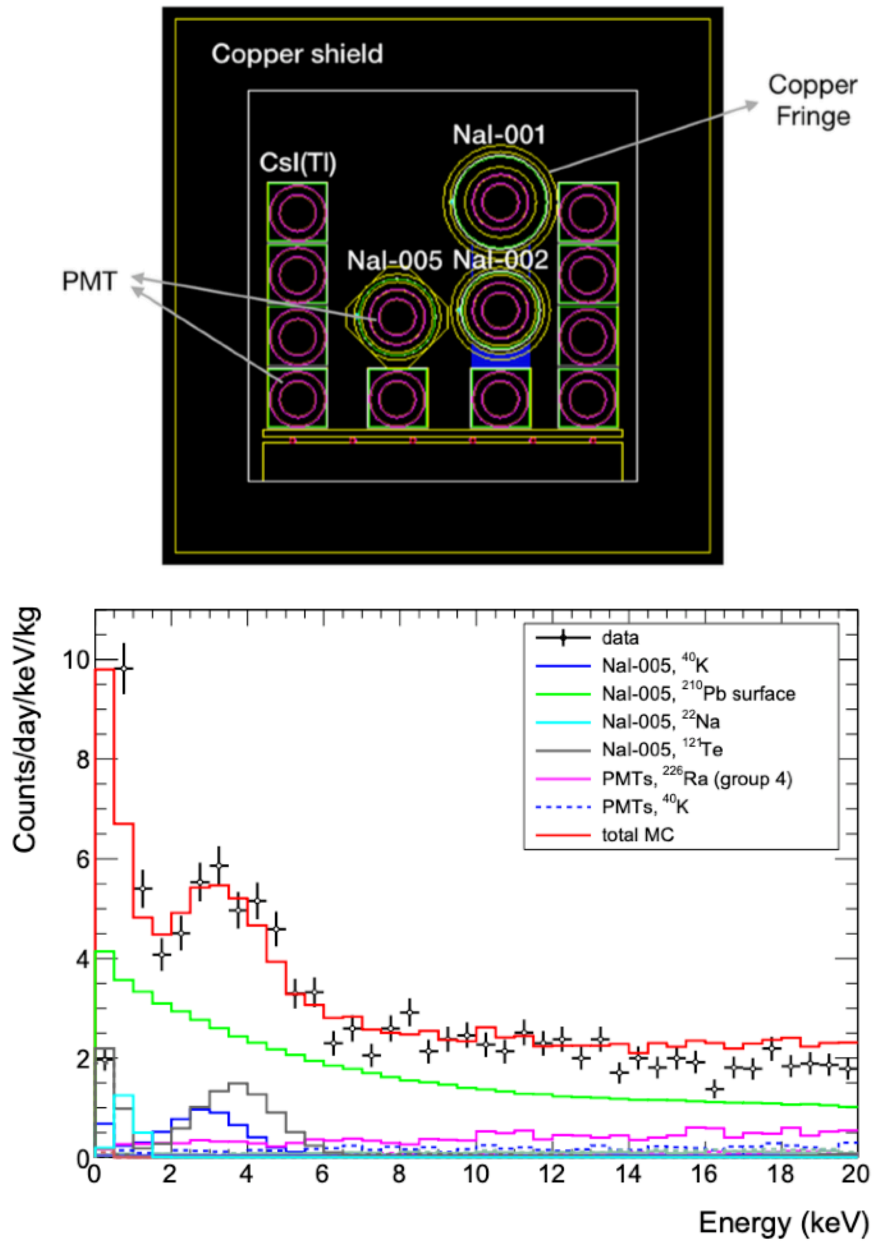
Surface contamination



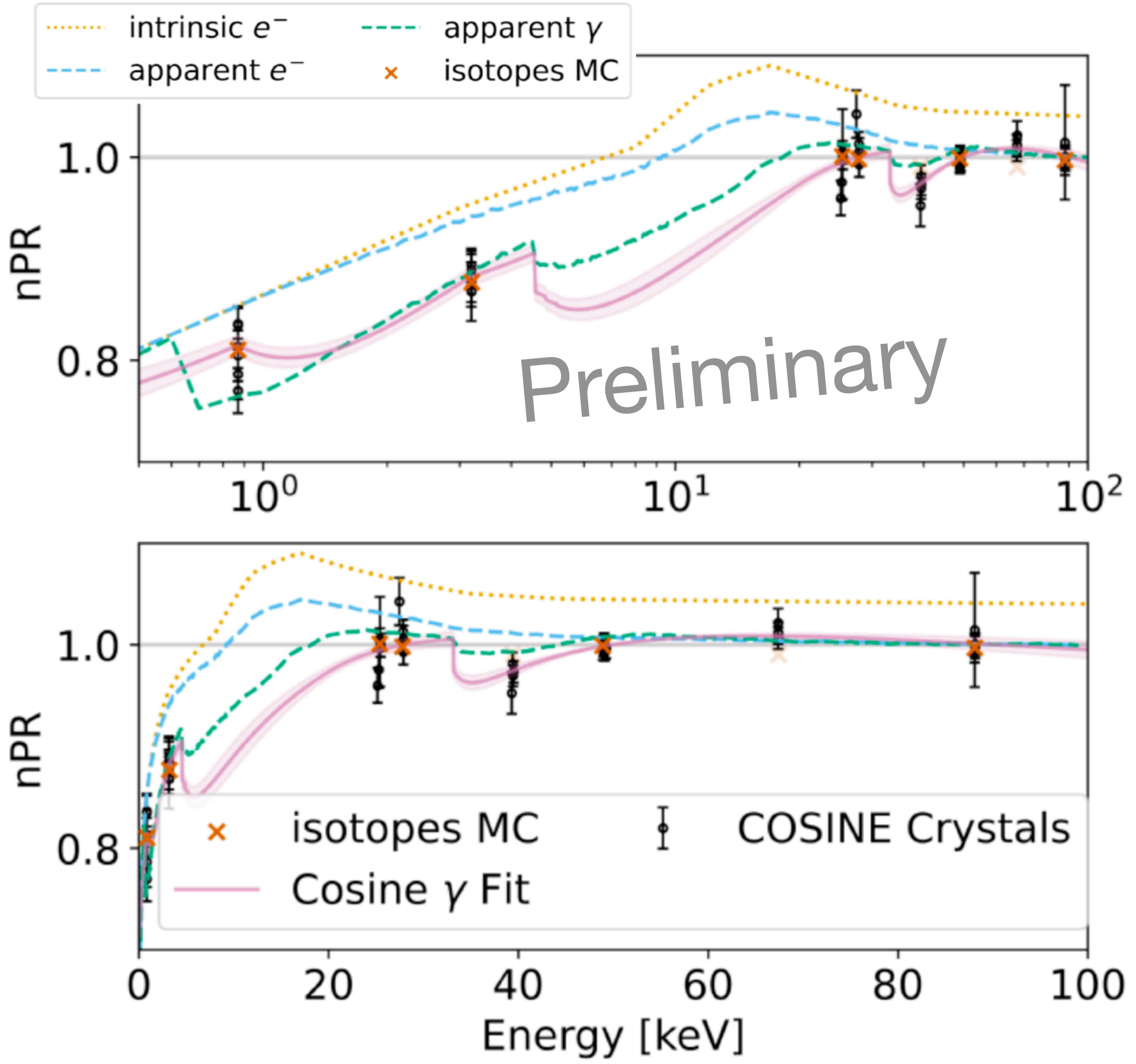
Cosmogenic isotopes



Background modeling

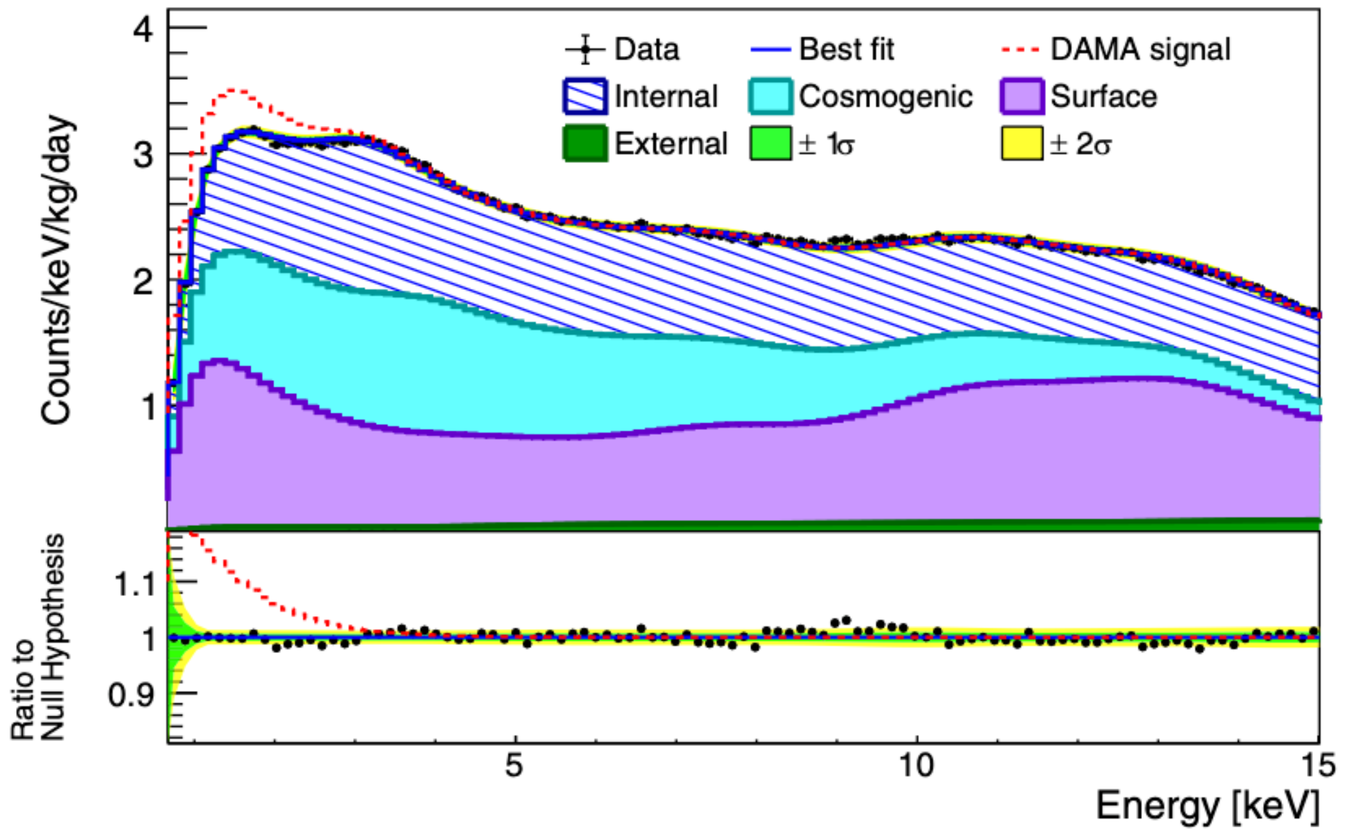


Non-proportionality

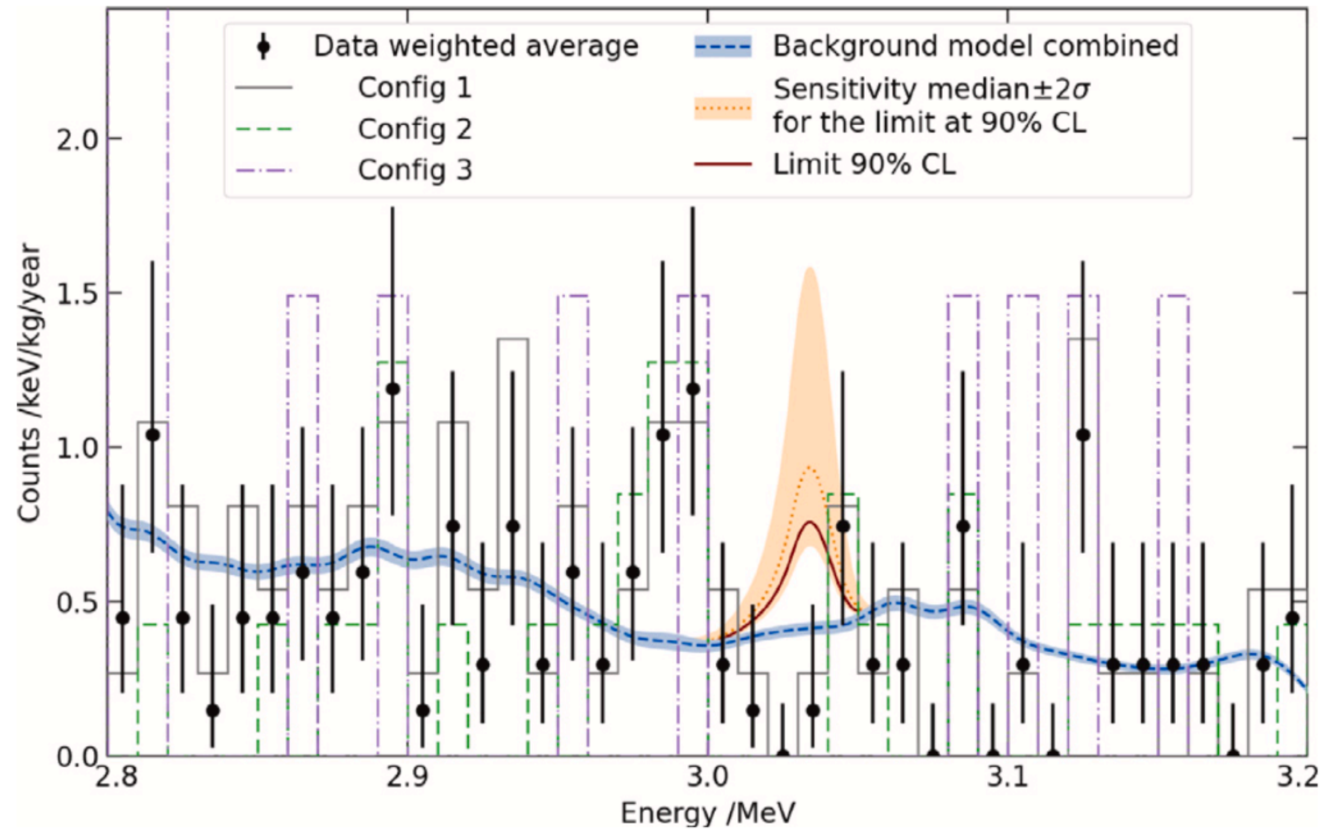


Sensitivity

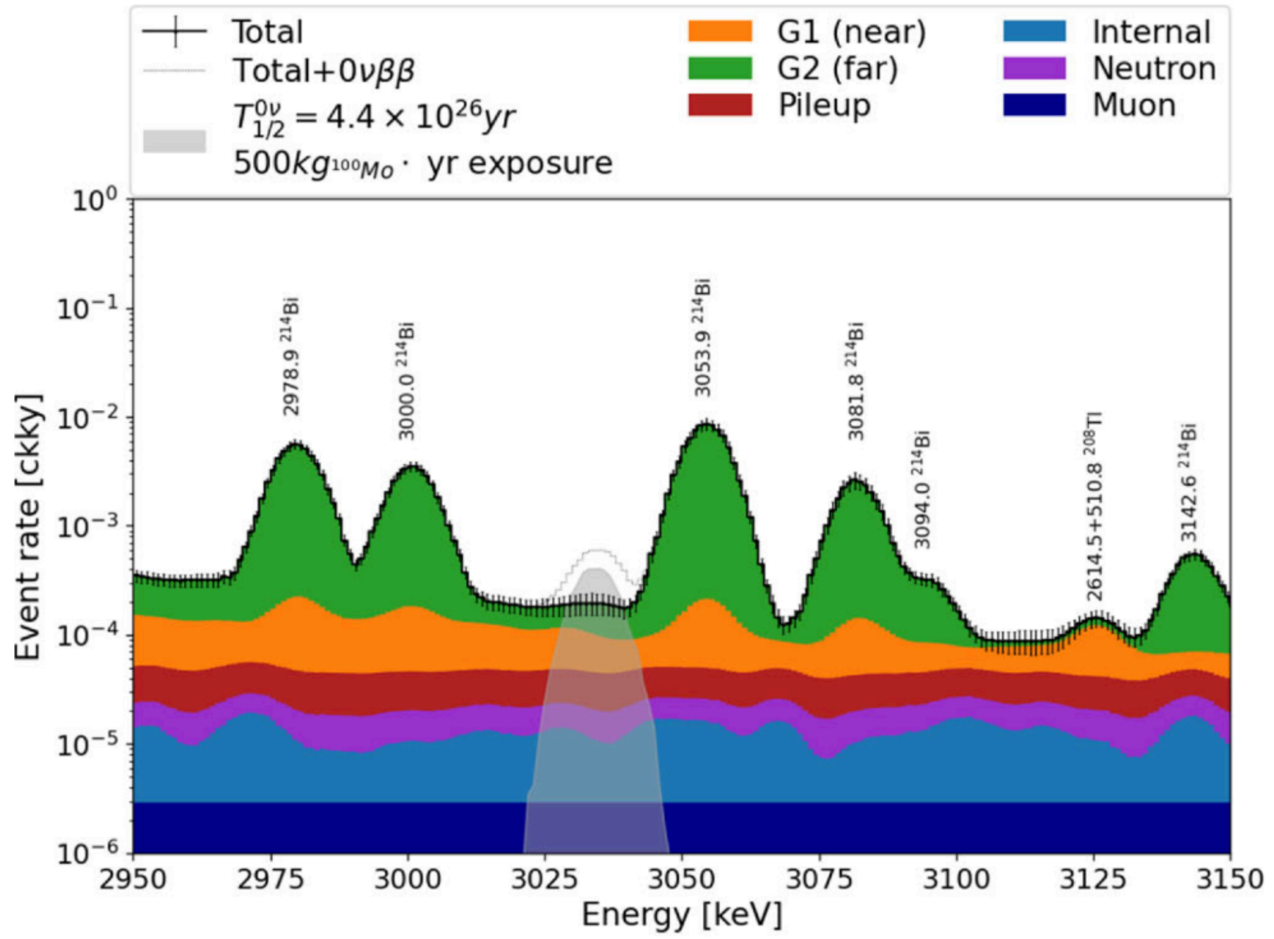
- Validated background models are used as inputs to sensitivity studies:
  - fit (signal+background) to the data to search for rare events
- Systematic uncertainties are estimated and propagated through simulations
- Using these models and uncertainties, pseudo-experiments enables for
  - exclusion limits with quantified confidence
  - discovery potential estimates



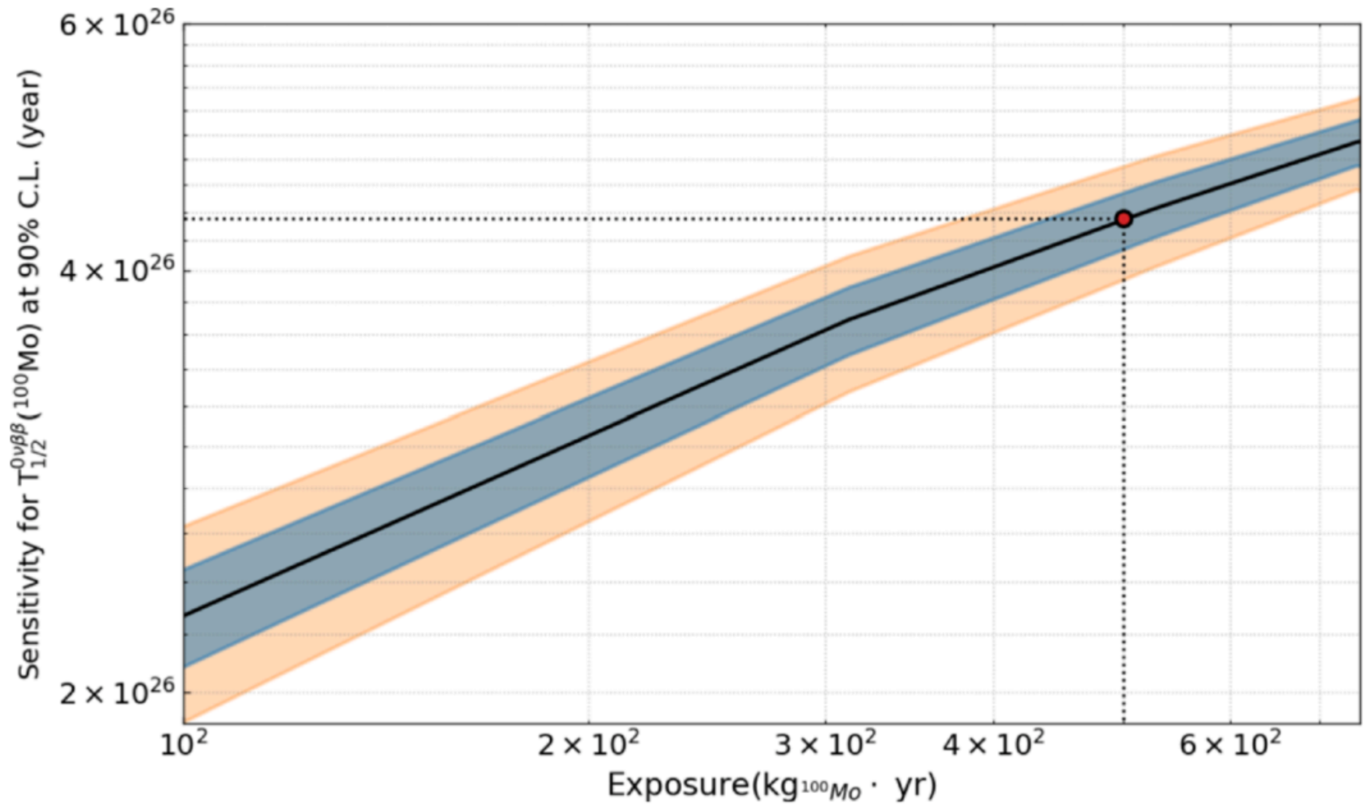
Fit example of the WIMP presence test on COSINE-100 (considering SI and m_χ=11.5GeV/c^2)



AMoRE-pilot ROI spectrum with background model and 0νββ decay signal at 90% C.L. limit



The estimated background of AMoRE-II compared with five years of data.



Expected half-life sensitivity (90% C.L.), obtained from background-only pseudo-experiments based on the estimated background spectrum as a function of exposure

Summary

- Rare-event search experiments require **extreme background control**, beyond what is achievable by experimental design alone
- Simulation provides a **unified framework** connecting background sources, detector geometry, shielding, and veto systems
- Cosmic-ray muons and radiogenic backgrounds must be treated with site-specific and geometry-aware simulations
- Background modeling based on validated simulations is essential for:
    - Detector optimization
    - Reliable background budgets
    - Robust sensitivity projections
- From R&D to final analysis, simulation is a **core component of rare-event experiments**, enabling credible physics results