Computing performance from underground physics domain

Eunju Jeon
Center for Underground Physics, IBS
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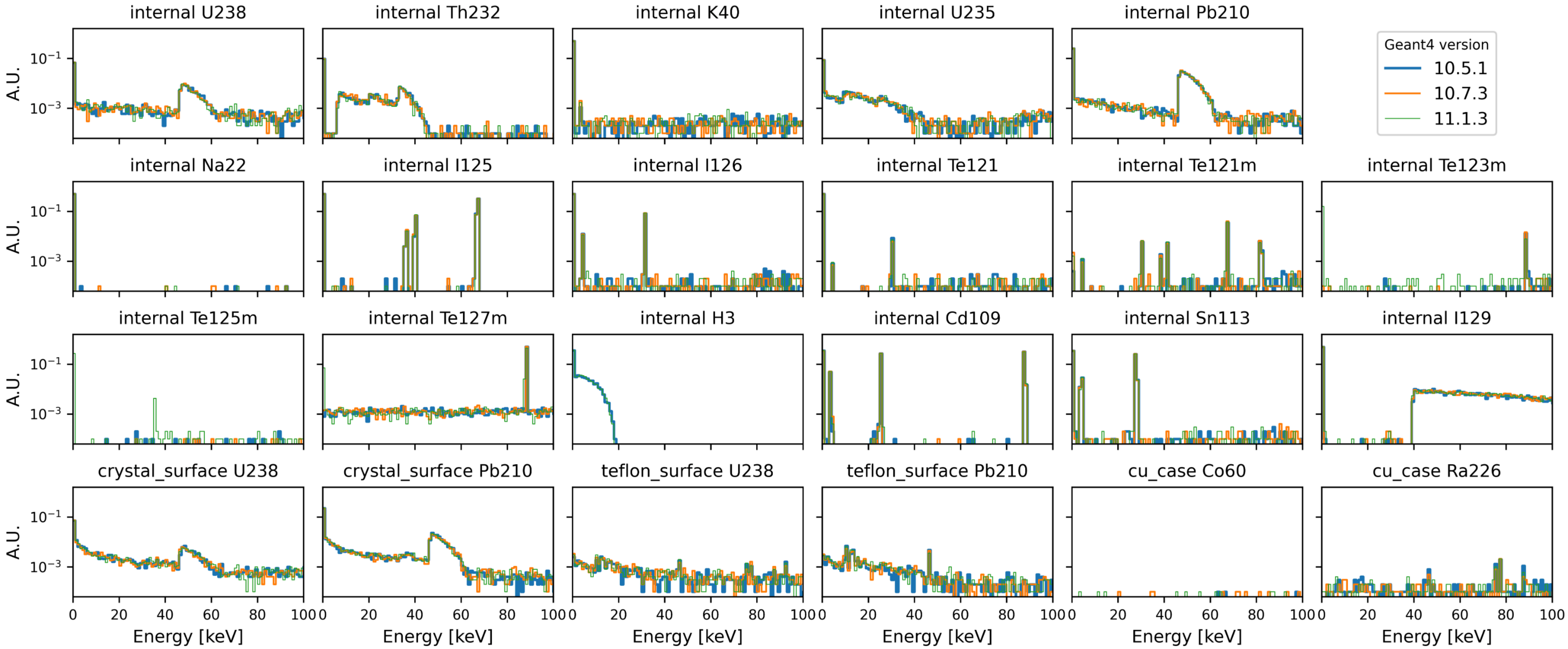
Simulation issues in the rare event searches

like dark matter, 0$\nu\beta\beta$, CEνNS

- Low energy backgrounds (<10MeV): we need reliable background simulations covering different physics scales
    - MeV-scale (nuclear physics): Radioactive decay of contaminants
    - keV-scale (atomic physics): X-ray emission during atomic de-excitation
    - eV-scale (solid state physics): Scintillation photon production, electron/hole-pairs, phonons in the detector
- There was a workshop, VIEWS2024, for users who utilize Geant4 for those simulations
- This presentation focuses our work on the low-energy background simulations for rare events searches at CUP

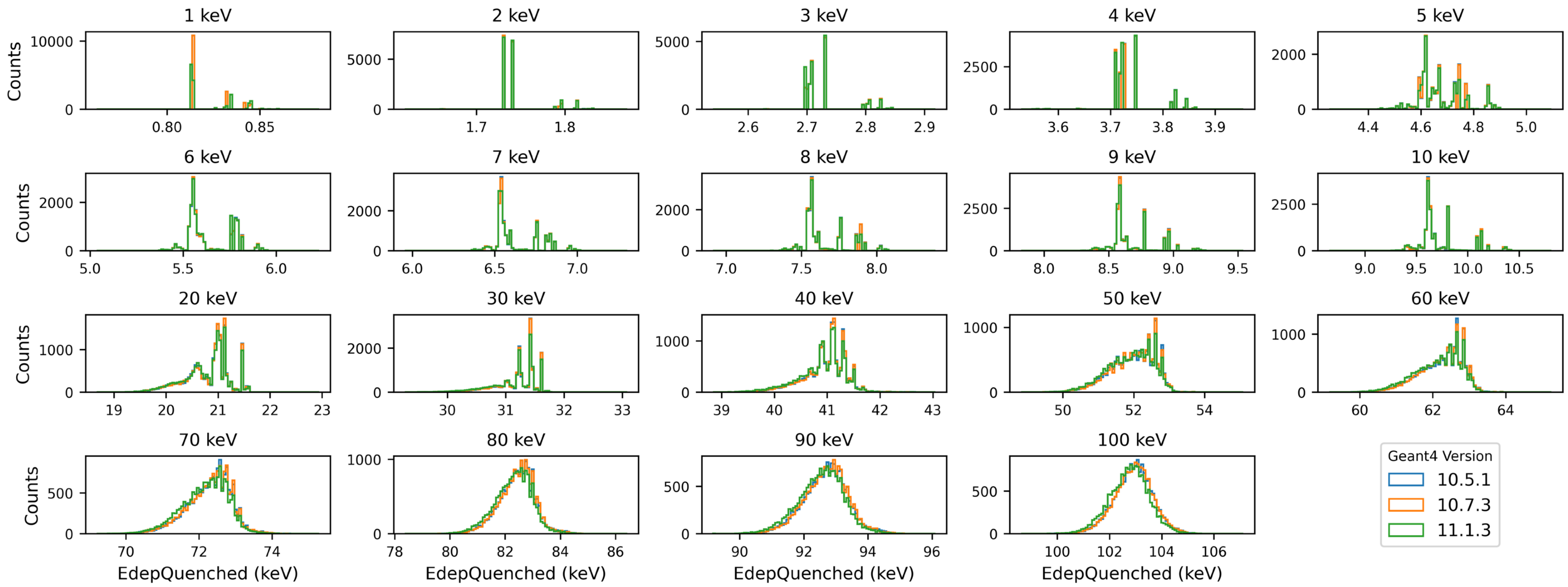
Validation for the migration to Geant4 v11

energy range 0-100 keV



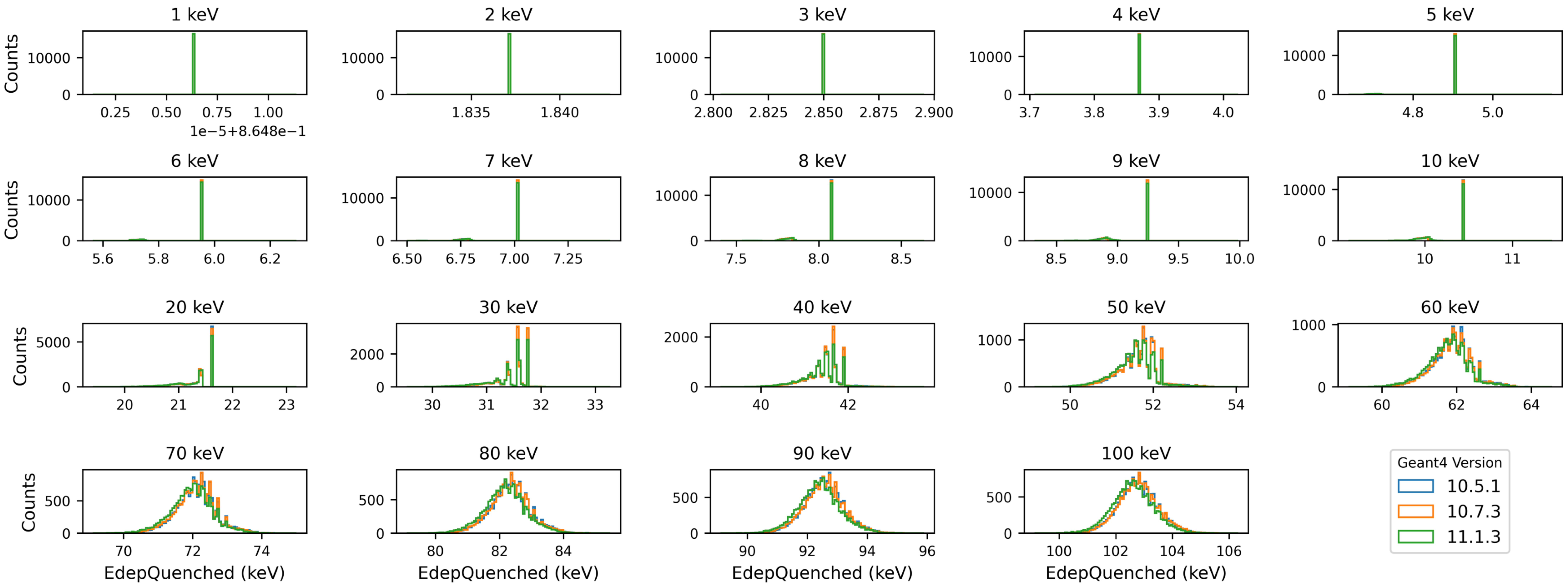
For gammas

1keV to 100keV



For electrons

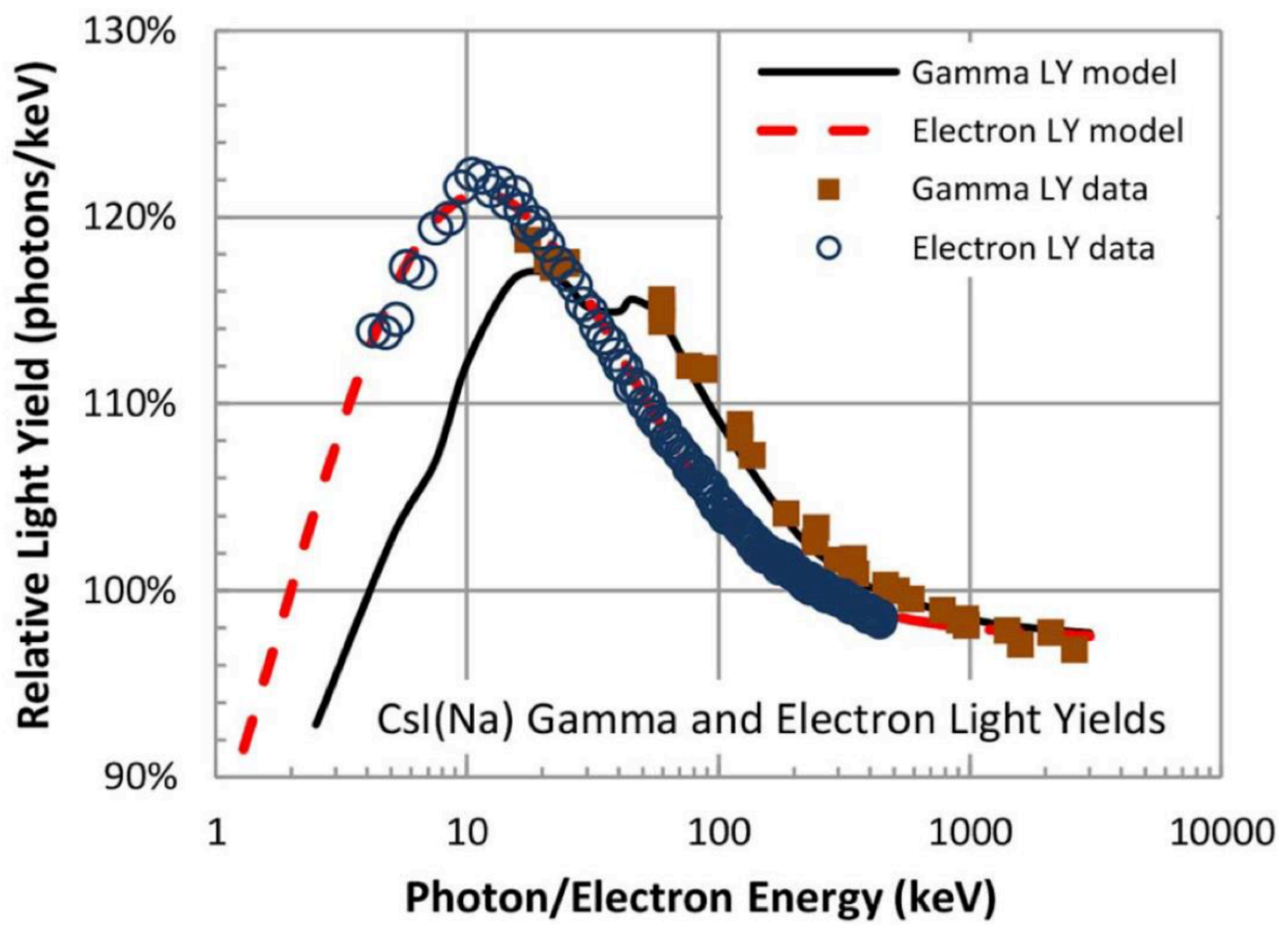
1keV to 100keV



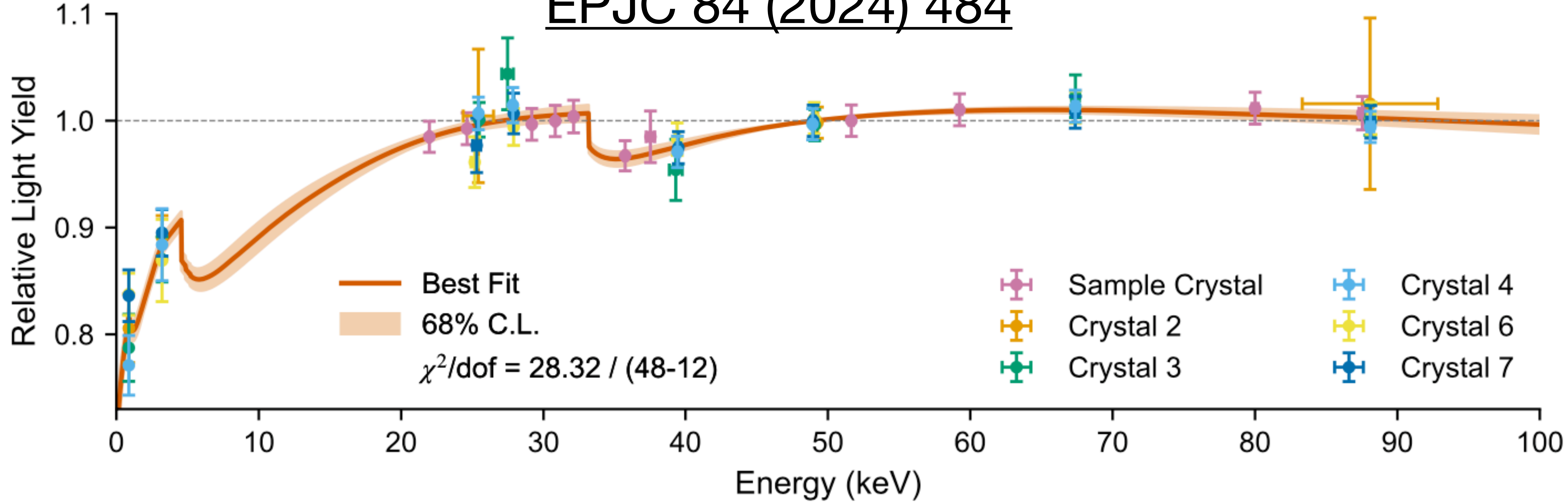
Nonproportionality (nPR) of NaI(Tl)

- It is well known that the relationship between the energy of incident particles (γ, e-) and the light yield in NaI(Tl) is not linear

Payne, IEEETrans.Nucl.Sci.623, 1429 (2015)

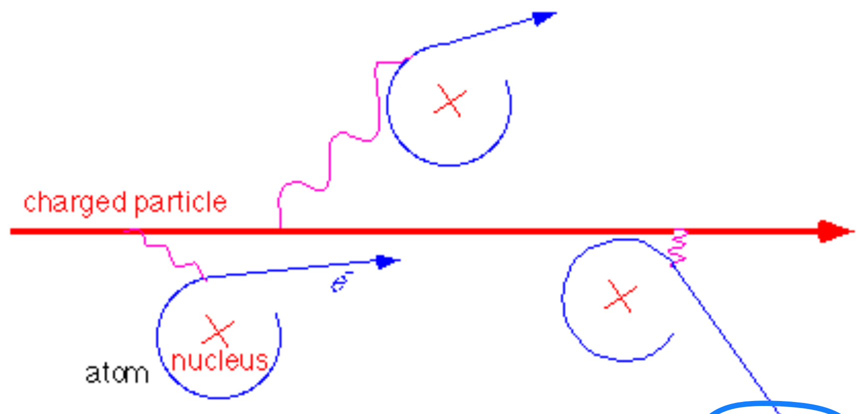


EPJC 84 (2024) 484



Implementation of nPR in the simulation package

- We have measured nPR for gamma rays
- But, when e- and γ are emitted together, calibration becomes more challenging ➔ our detector response is a mixture of e-/γ interactions with matter
- It would be ideal if nPR is included in the simulation package ➔ we embedded nPR in Geant4 (very preliminary)



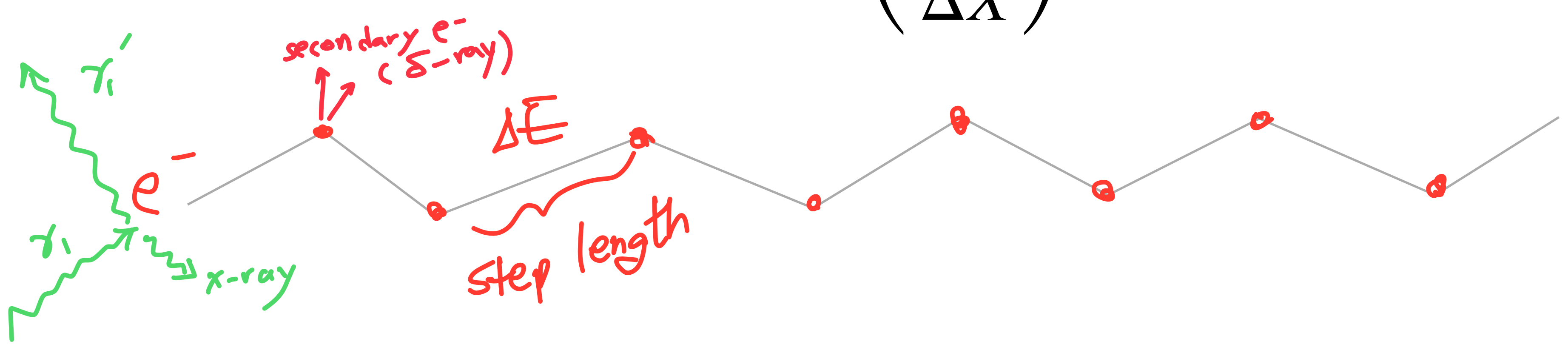
Energy absorption by NaI(Tl) via electron Ionization

Optical photon production

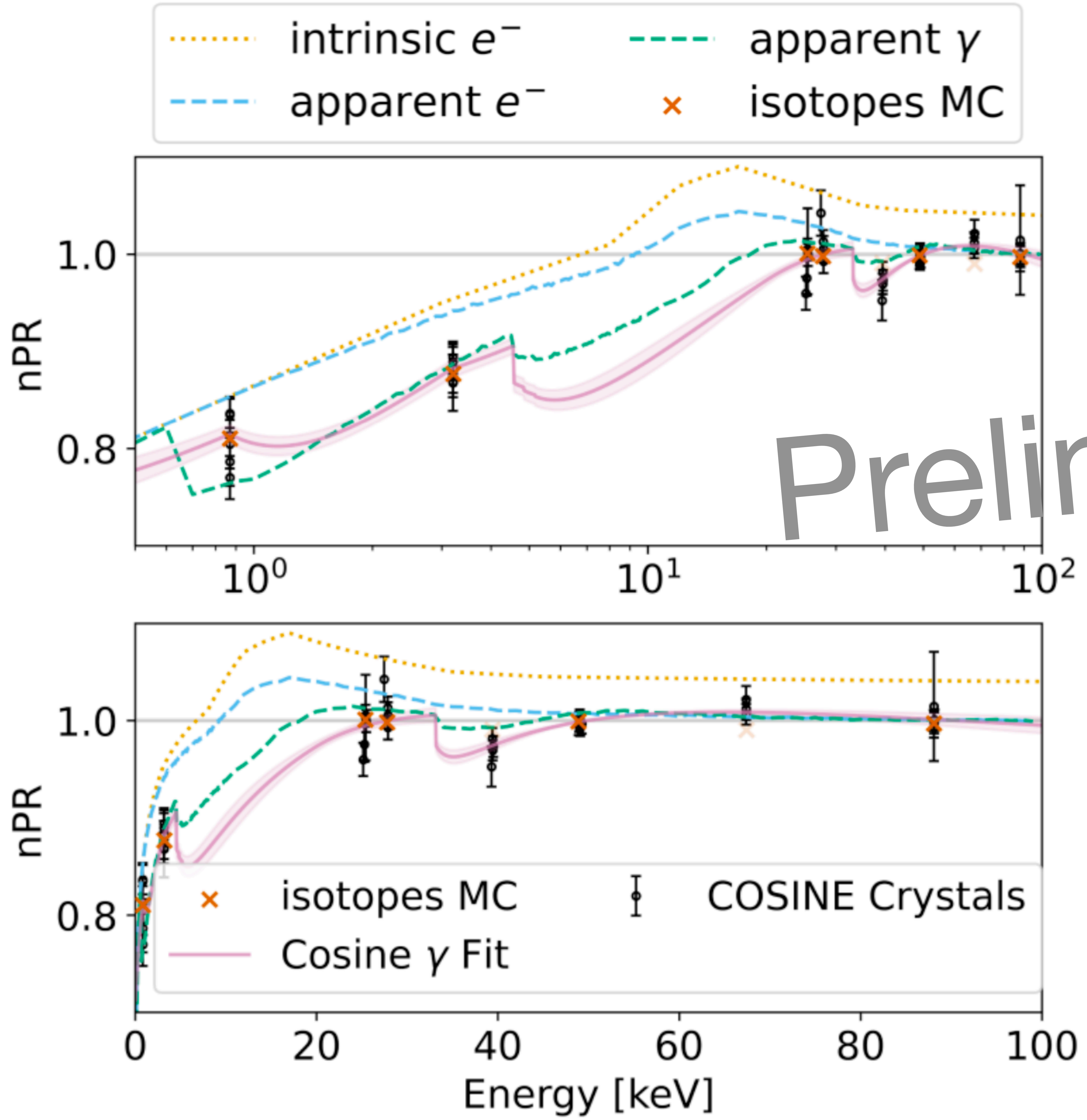
Optical photon, λ >> atomic spacing, and treated as waves:
subject to reflection, refraction, …
➔ it takes much CPU time to track all the photons in the simulation

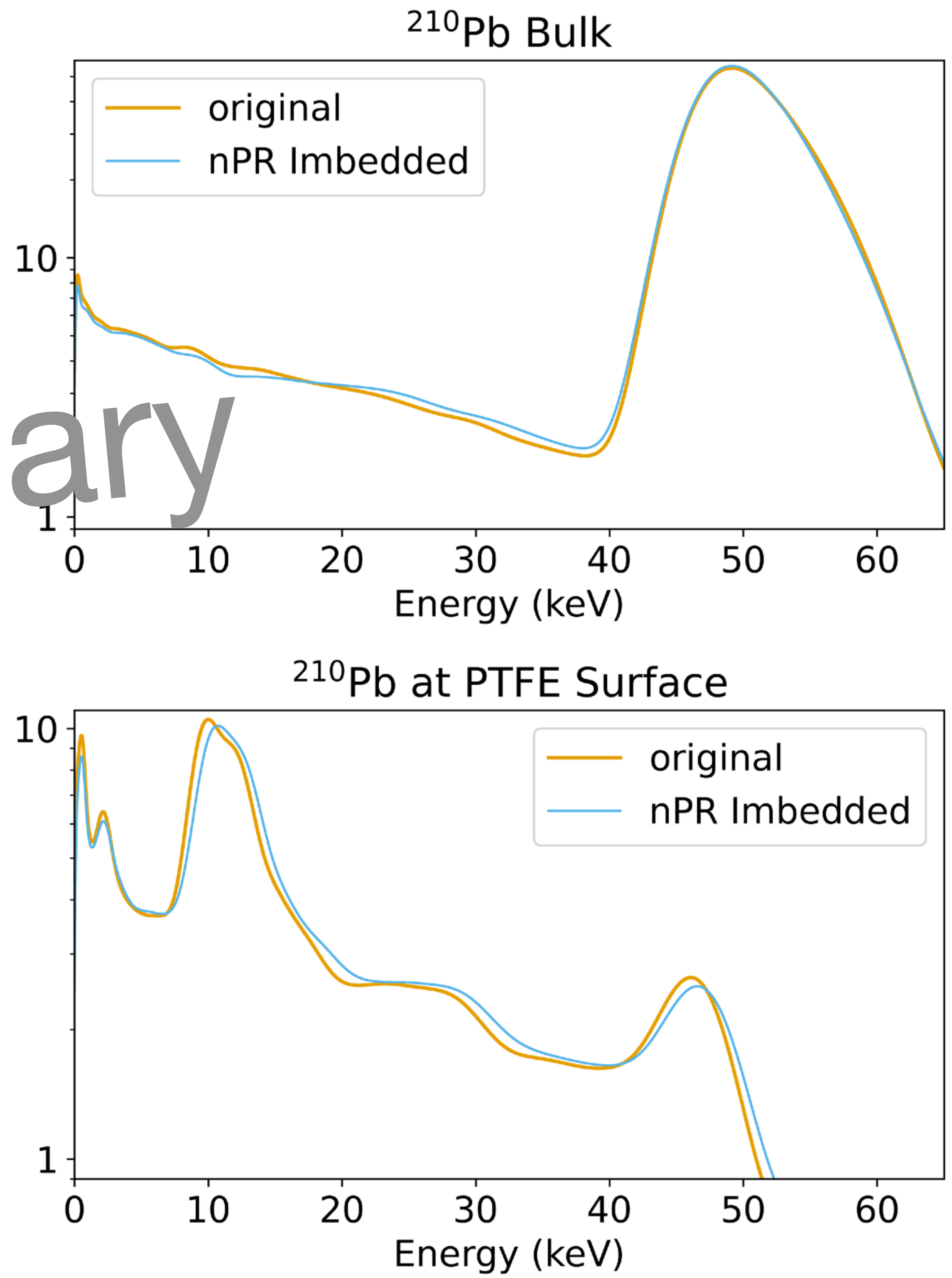
We will model the light production as a function of dE/dx of electrons in a given step of the simulation, using the experimentally measured nonproportional light output curve for electrons

$$L(E) = \Sigma_{steps} f\left(\frac{\Delta E}{\Delta X}\right) \Delta E$$



Comparison of simulation results applied by the empirical curve and using embedded in Geant4





Preliminary

Low-energy X-ray emissions

induced by interacting with materials

- Low-energy X-ray emission lines can be induced by interacting with detector materials, leaving energy deposits in the crystal
    - Lines at 8.038 and 8.905 keV due to K-shell transitions in the copper encapsulator
    - Lines around 35 keV due to K-shell transitions of Ba induced by PMT borosilicate glass when generating ^{238}U from the entire PMT body
- To ensure accurate background modeling, we will include this process for all the detector materials when simulating background sources

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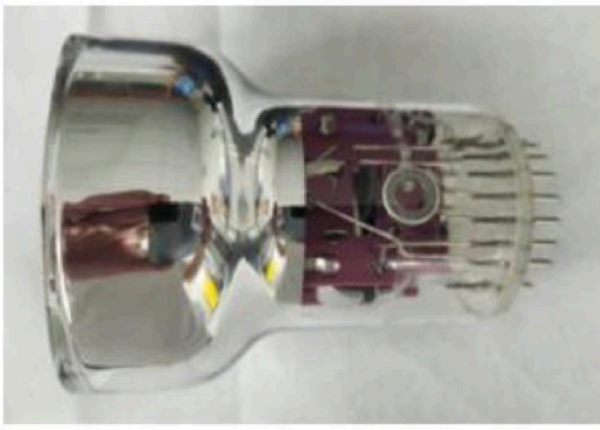
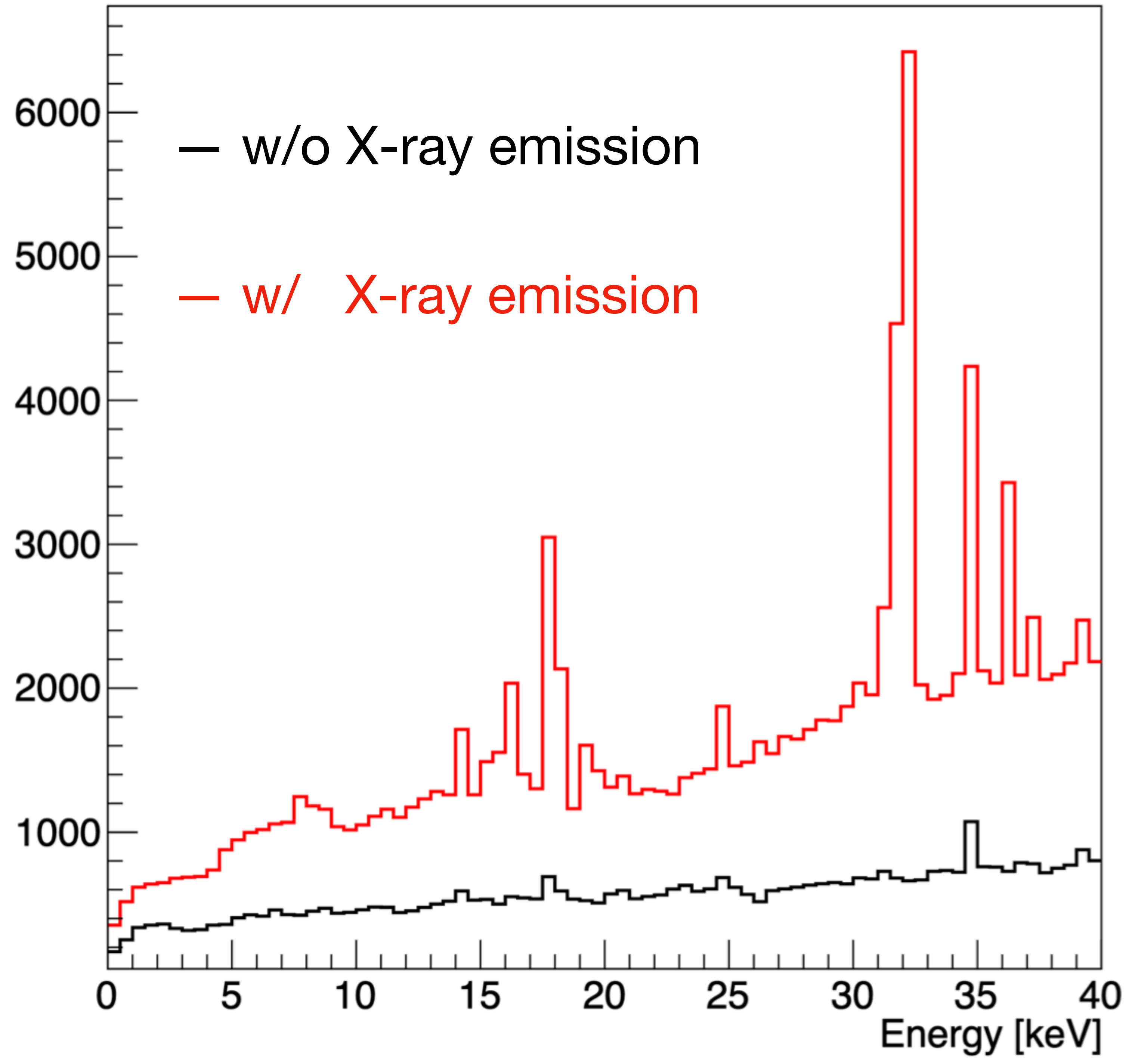
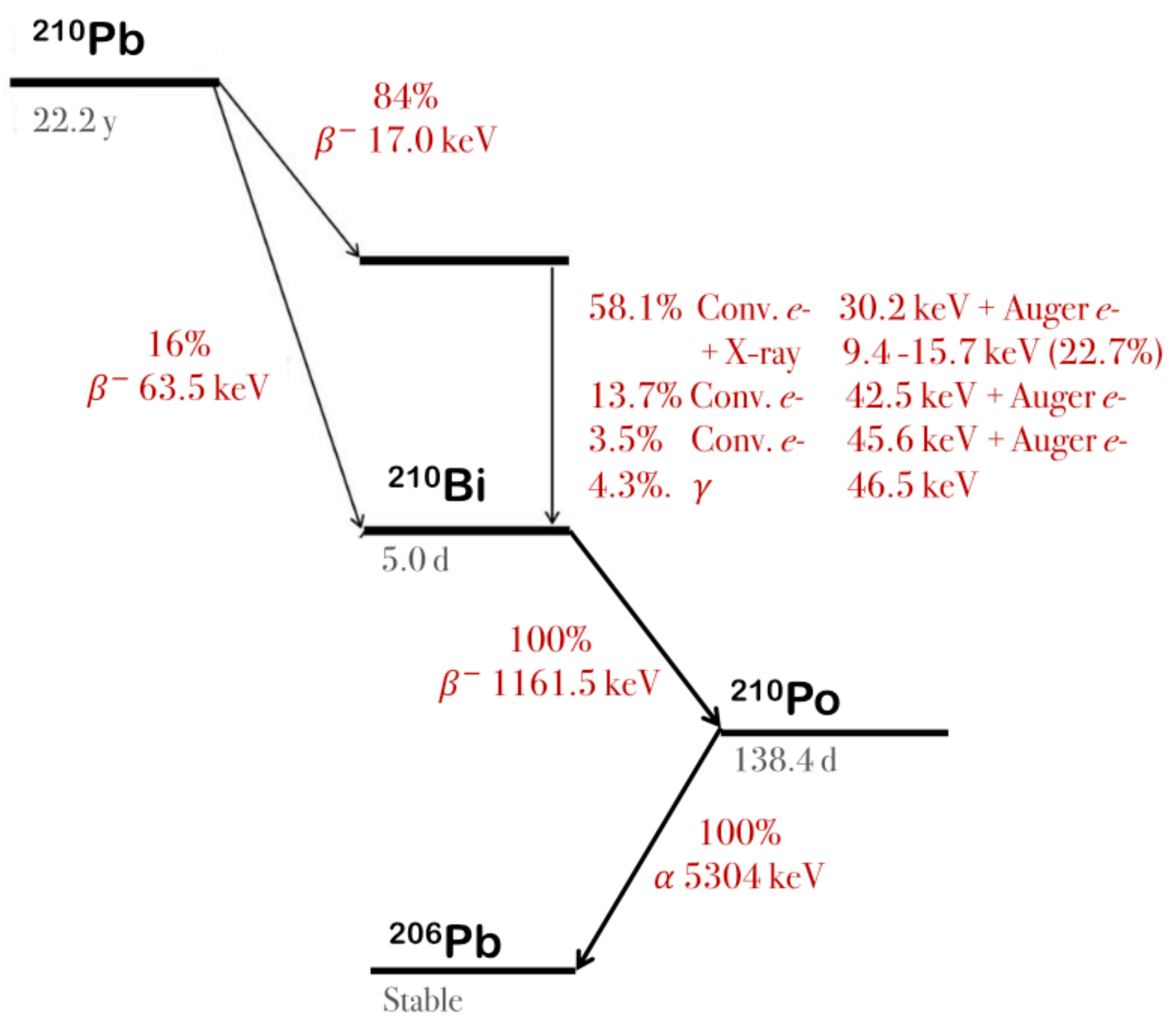




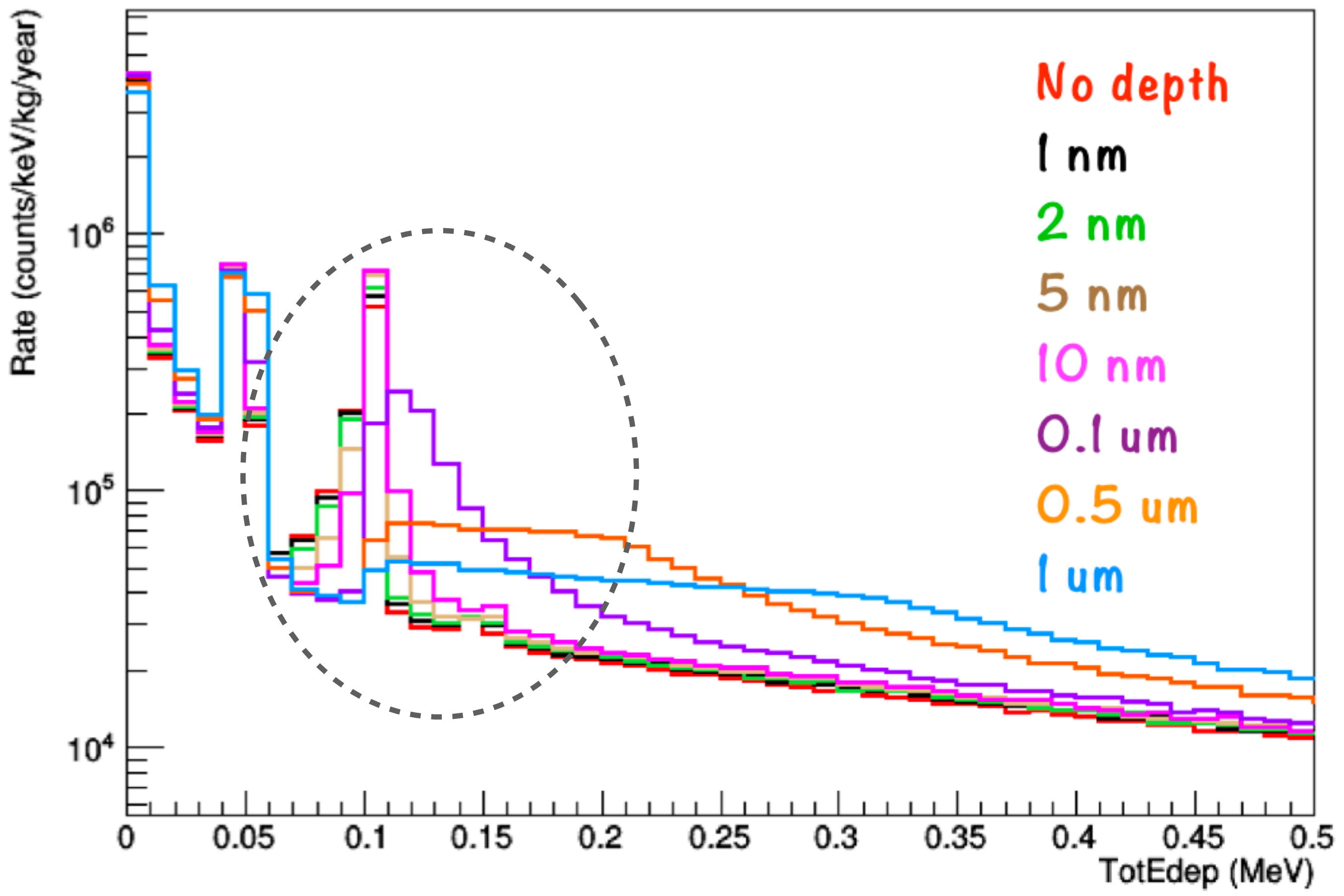
Nuclear recoil events

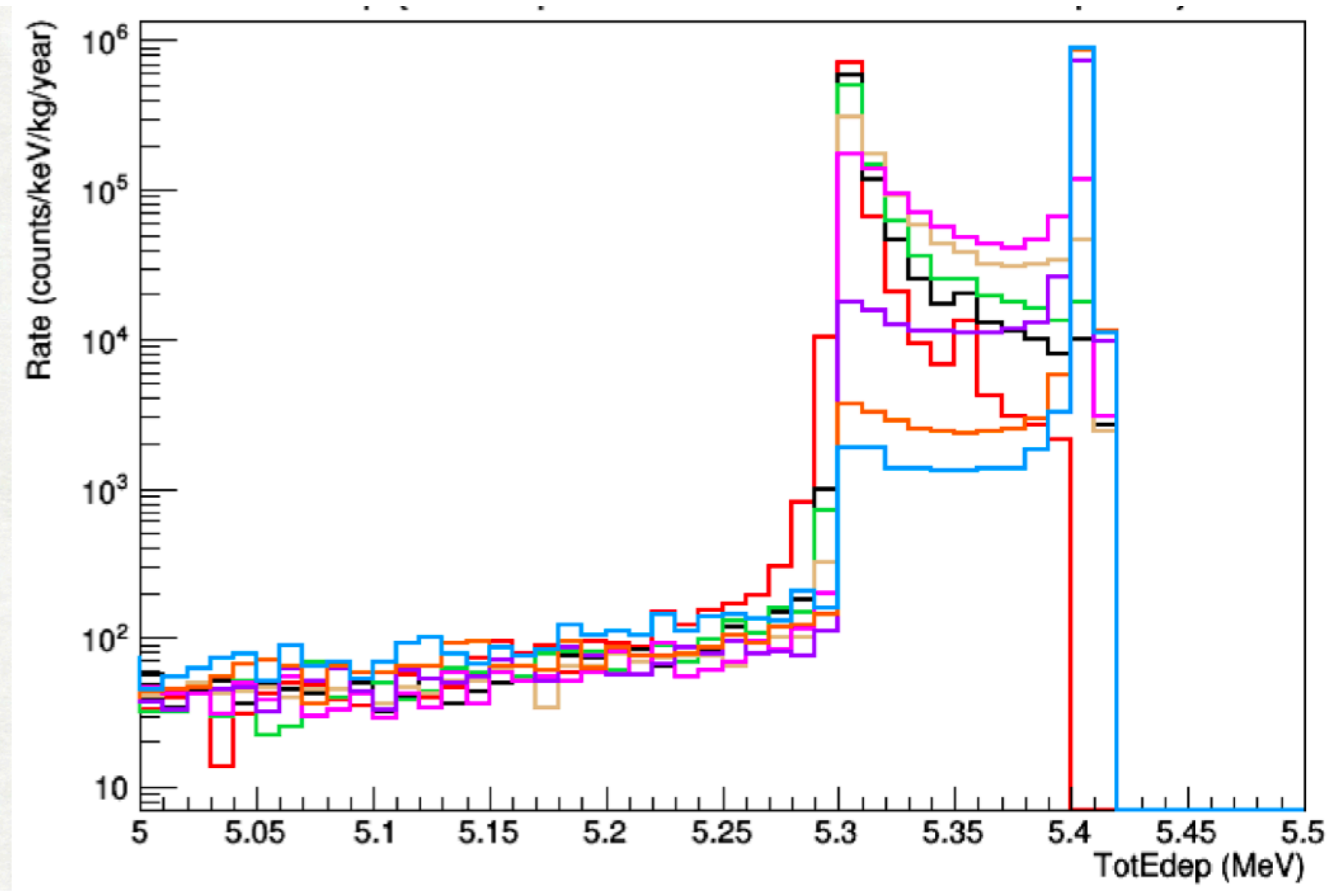
quenching effect

- Nuclear recoils of Na and I in NaI(Tl) scintillator are well-understood and established
- However, nuclear recoil events due to the recoiling of ^{206}Pb from alpha decay of the surface contamination are under study
- We need to understand their quenching effect and plan to apply it to the simulations in the near future



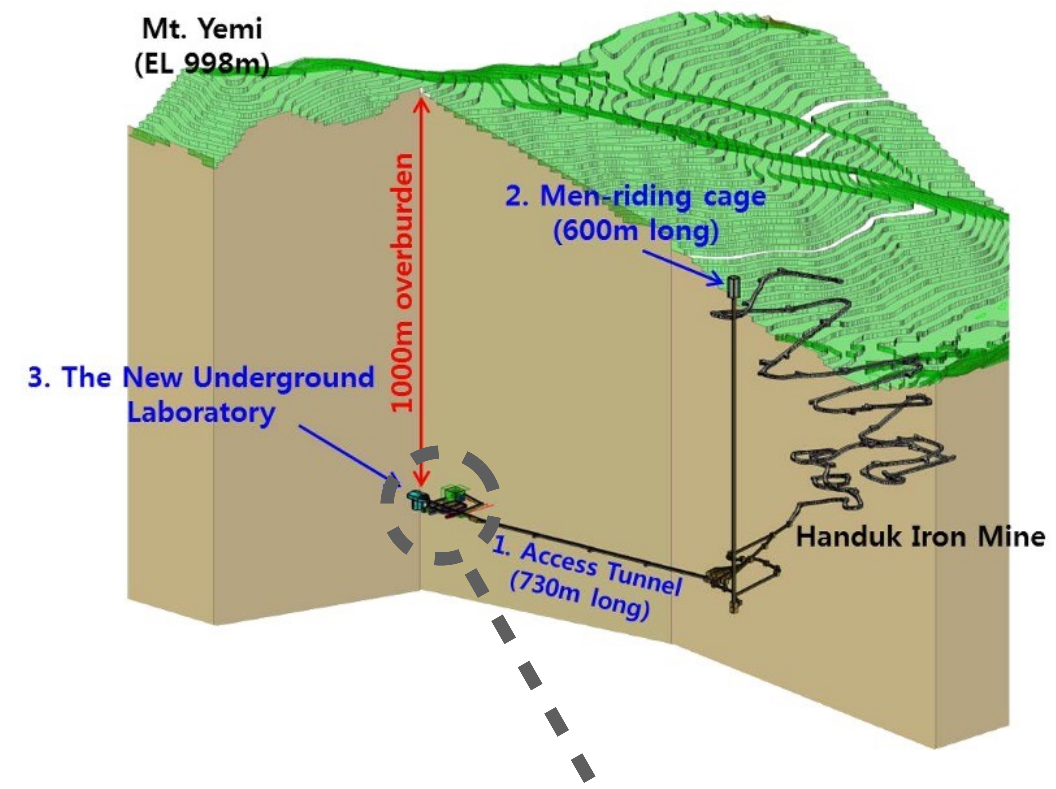
$$^{210}\text{Po} \xrightarrow{138d} {}^{206}\text{Pb}(103\ \text{keV}) + \alpha(5.3\ \text{MeV})$$

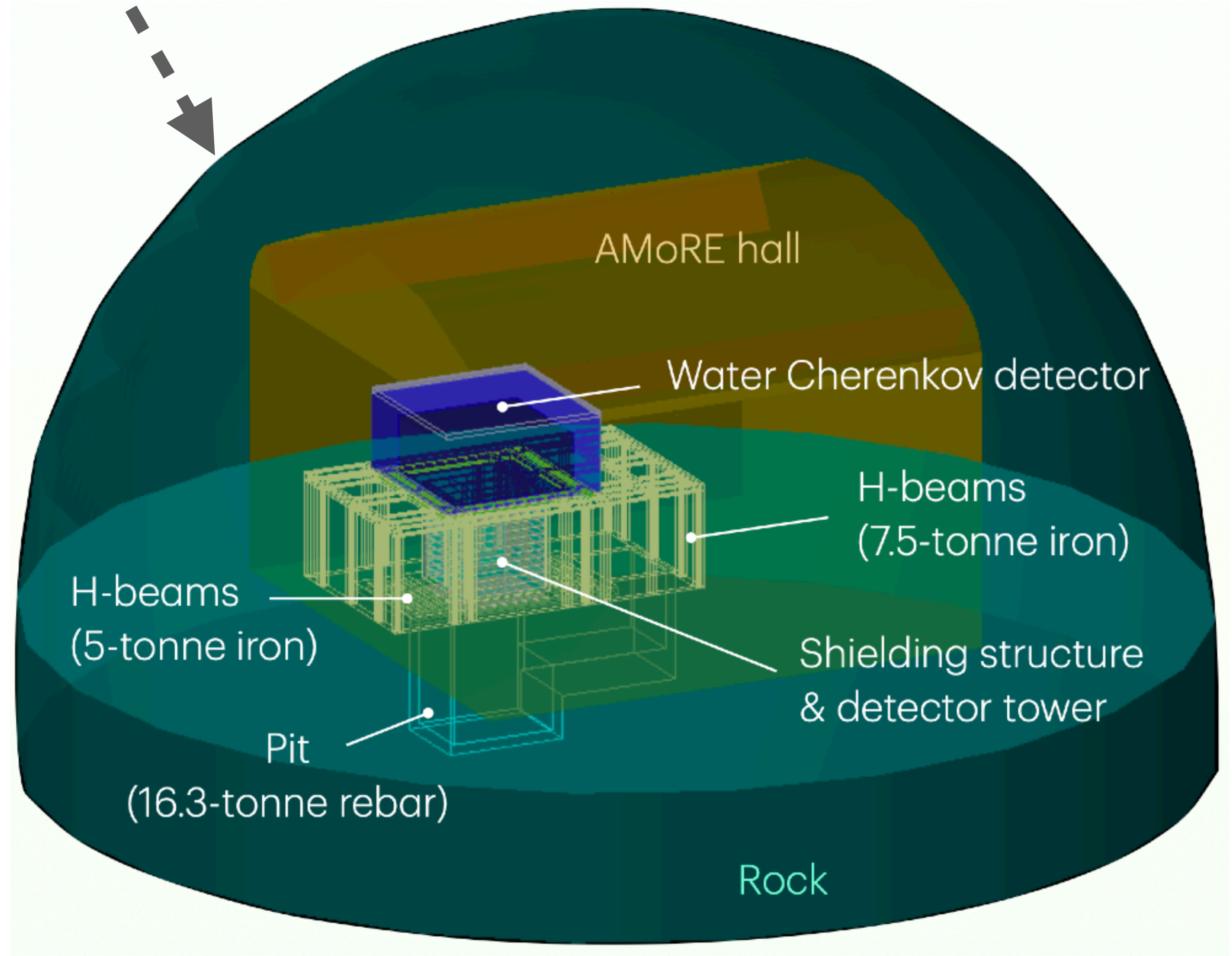




Water Cherenkov detector using ParallelWorld library

- AMoRE is an experiment to search for neutrinoless double-beta decay
- Water Cherenkov muon detector (WCMD) is used to veto background events induced by cosmic ray muons
- WCMD was constructed using the ParallelWorld library
- Currently, photon simulations are being conducted to study the backgrounds induced by muons using the water Cherekov detector
- Multithreading for photon simulation is under testing ➔ results occasionally save successfully to the ROOT output file but intermittently fail
- We plan to use GPU-based photon simulation to improve speed in the near future





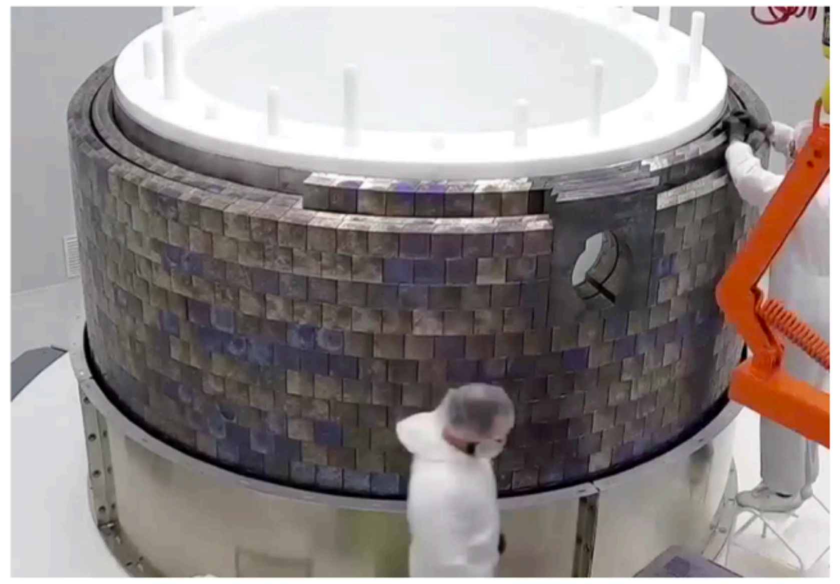
Background simulation with heavy shield layers

- Heavy shield layers such as thick leads are used to minimize the background level
- To ensure sufficient statistical sampling of events inside the lead shield, Geant4's importance biasing is recommended, as it can improve simulation efficiency significantly
- We plan to apply Geant4's importance biasing when simulating gamma interactions with a heavy lead shield for the AMoRE experiment

(Birgit Zatschler @VIEWS24)

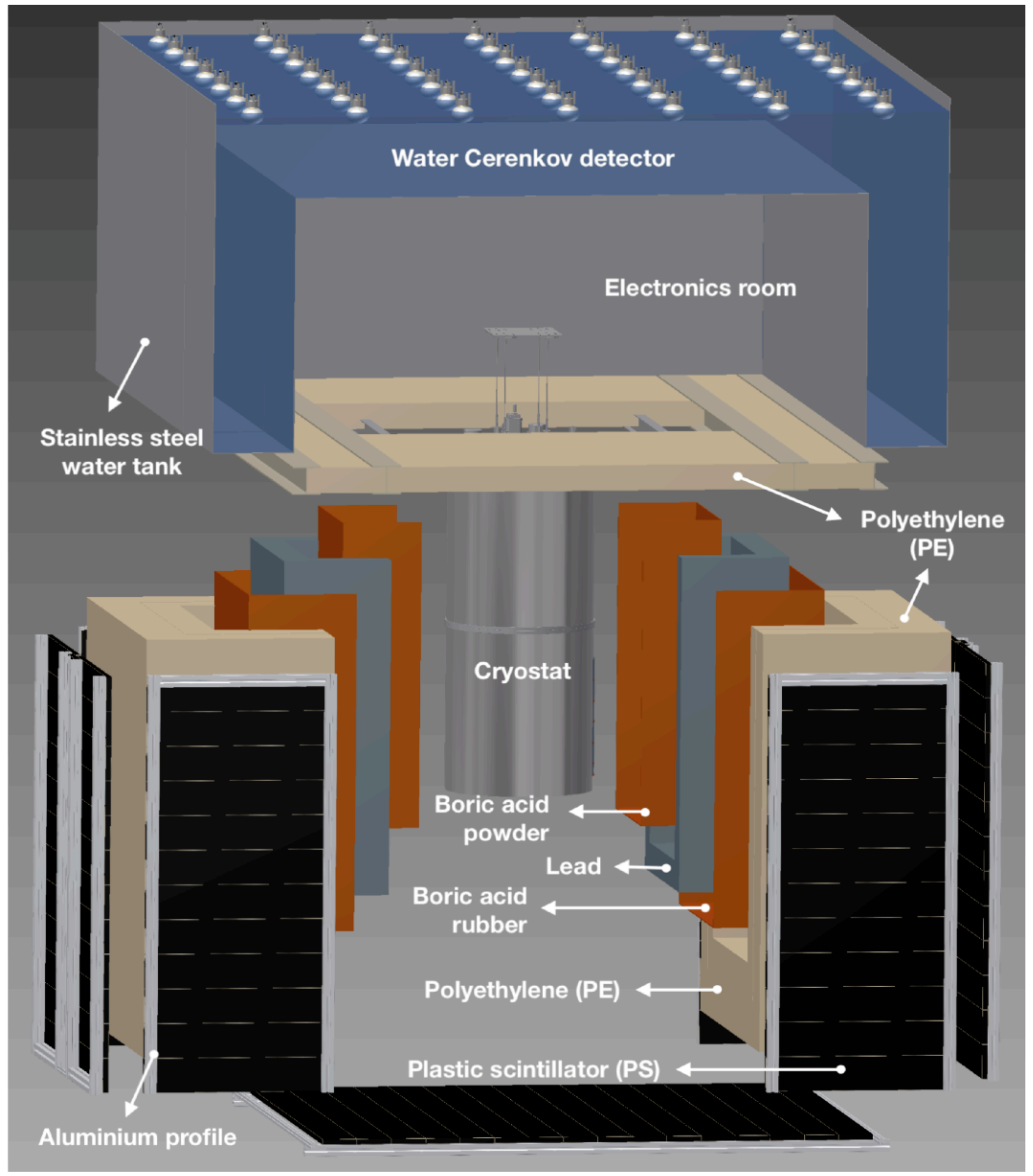
SuperCDMS lead shield simulation in SuperSim

- Graded lead shield:
  - Ultra low background (ULB): 0 - 1 cm – 0.3 Bq/kg
  - Low background (LB): 1 - 10 cm – 21 Bq/kg
  - Regular background (RB): 10 - 20 cm – 157 Bq/kg
- Simulating radioactive contaminations inside the lead shield (e.g. ^{210}Pb) or in volumes surrounding the lead shield (e.g. ^{40}K in Al Radon Barrier) would consume ~ $\mathcal{O}$(10k) of cpu years.



➔ application of Geant4's importance biasing

AMoRE shielding and muon detector system



Summary

- Background understanding in low-energy region < 10MeV
  - crucial for rare events searches like dark matter, $0\nu\beta\beta$, CEνNS
  - utilizing Geant4 for simulations to study the backgrounds
- Facilitated migration to version 11
  - compared low-energy background spectra between version 11 and previous versions for migration
- Current work
  - implementing the nonproportionality in NaI(Tl) crystals into Geant4-based simulation codes and obtained the preliminary results
  - studying the quenching effect of ^{206}Pb recoil from the alpha decay of surface contamination
- Current testing and optimization
  - testing low-energy X-ray emission lines induced by interacting with nearby detector materials
  - testing multithreading for photon simulations
  - applying Geant4's importance biasing for the gamma background simulations with heavy shielding materials