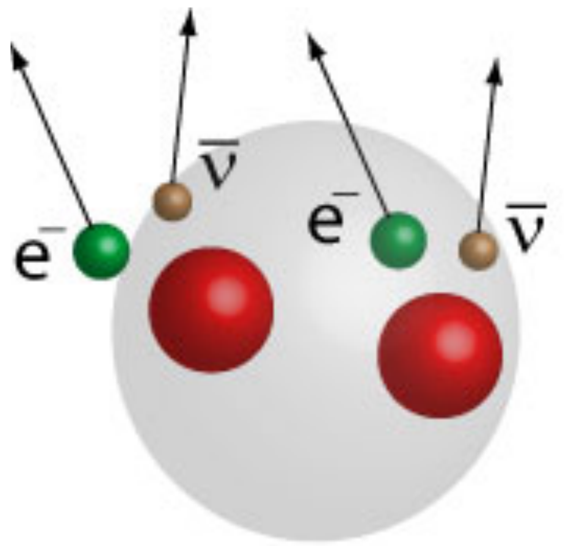
Geant4 simulations for the NEXT experiment and applications

Paola Ferrario (DIPC-Ikerbasque) on behalf of the NEXT Collaboration

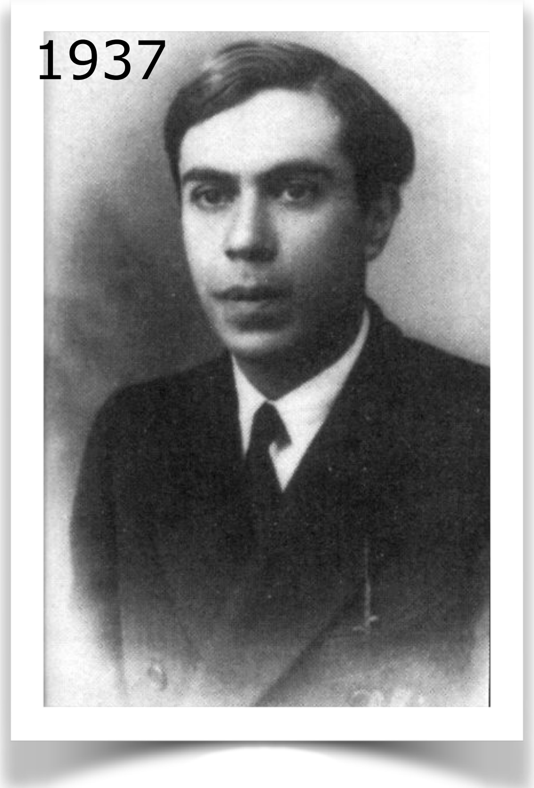
Motivation: neutrinoless double beta decay

- Double beta decay (2n -> 2p + 2e- + 2 antinu) can happen in nuclei where single beta decay is energetically forbidden.
- Observed in a number of isotopes.



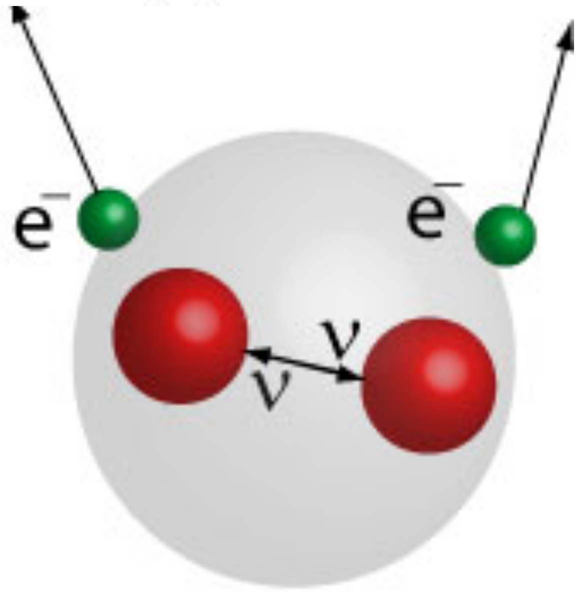
2νββ

Maria Goeppert-Mayer first proposed the two-neutrino double beta decay



Ettore Majorana proposed that neutral 1/2 spin fermions could be their own antiparticle

- If neutrino = antineutrino, no neutrinos are emitted. Conversely, an observation of 0νββ would demonstrate that neutrinos are their own antiparticle.

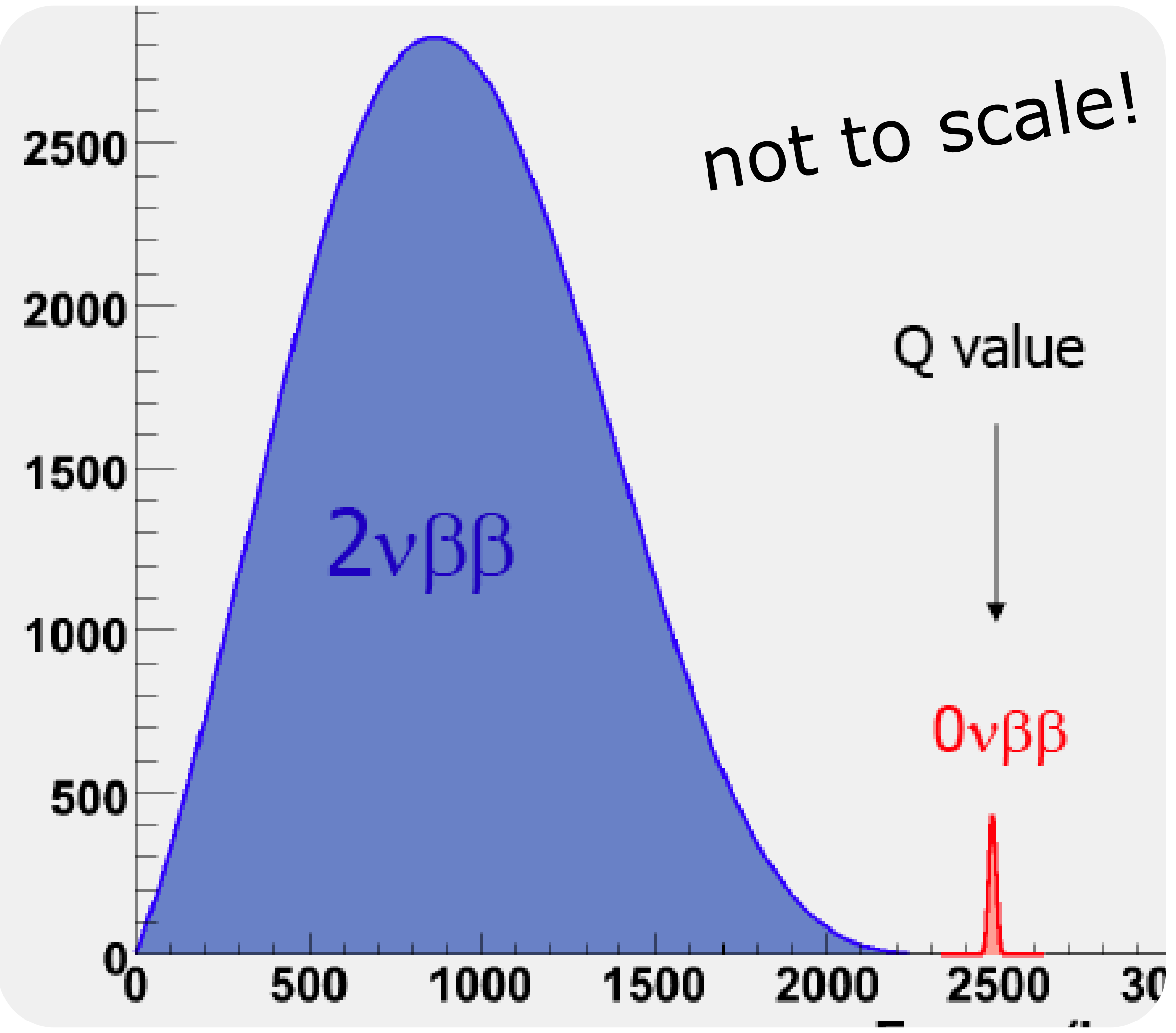


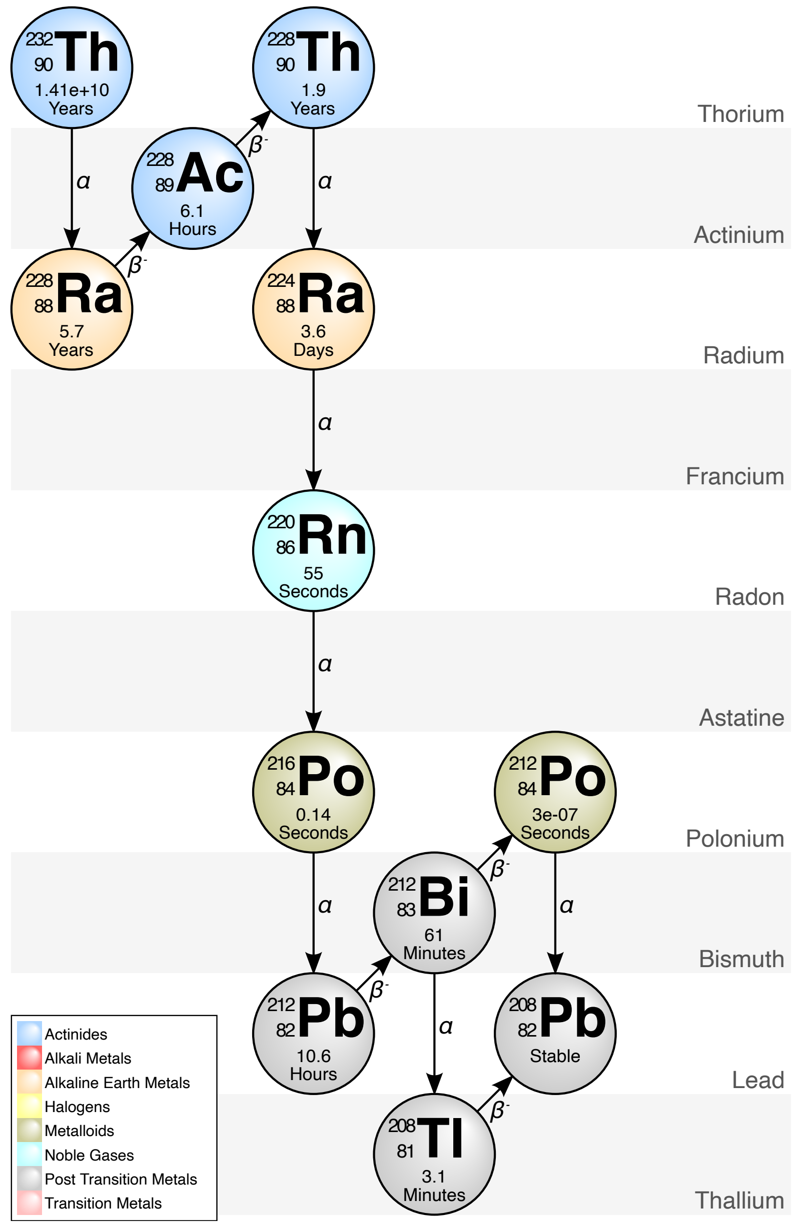
0νββ

- Could explain matter-antimatter asymmetry in the Universe and the smallness of neutrino mass.
- Current limits: 10^{24} - 10^{26} years.

Motivation: neutrinoless double beta decay

- Signature: peak in the sum of the kinetic energy of the two electrons (at the end-point of the 2-neutrino spectrum).

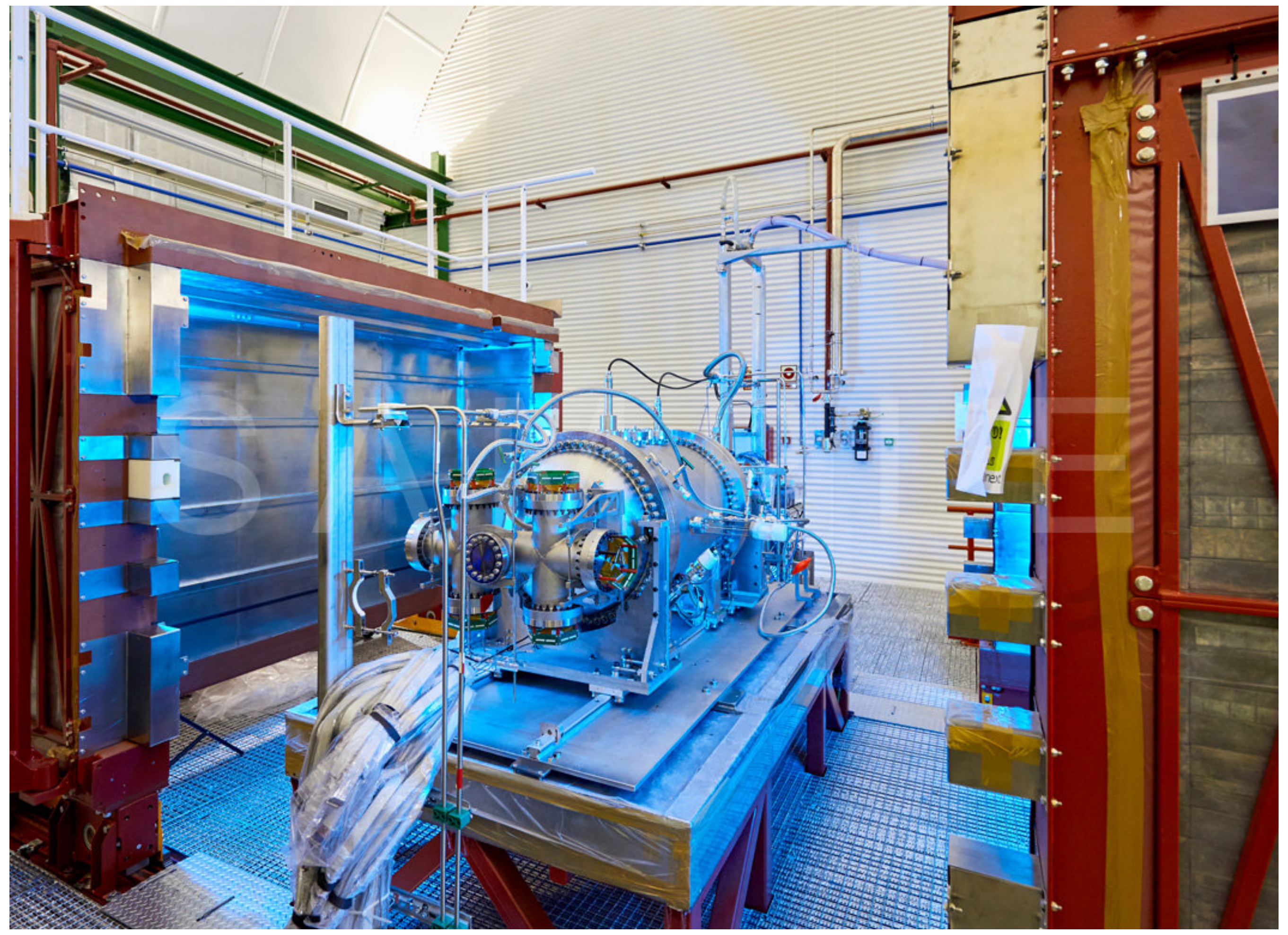


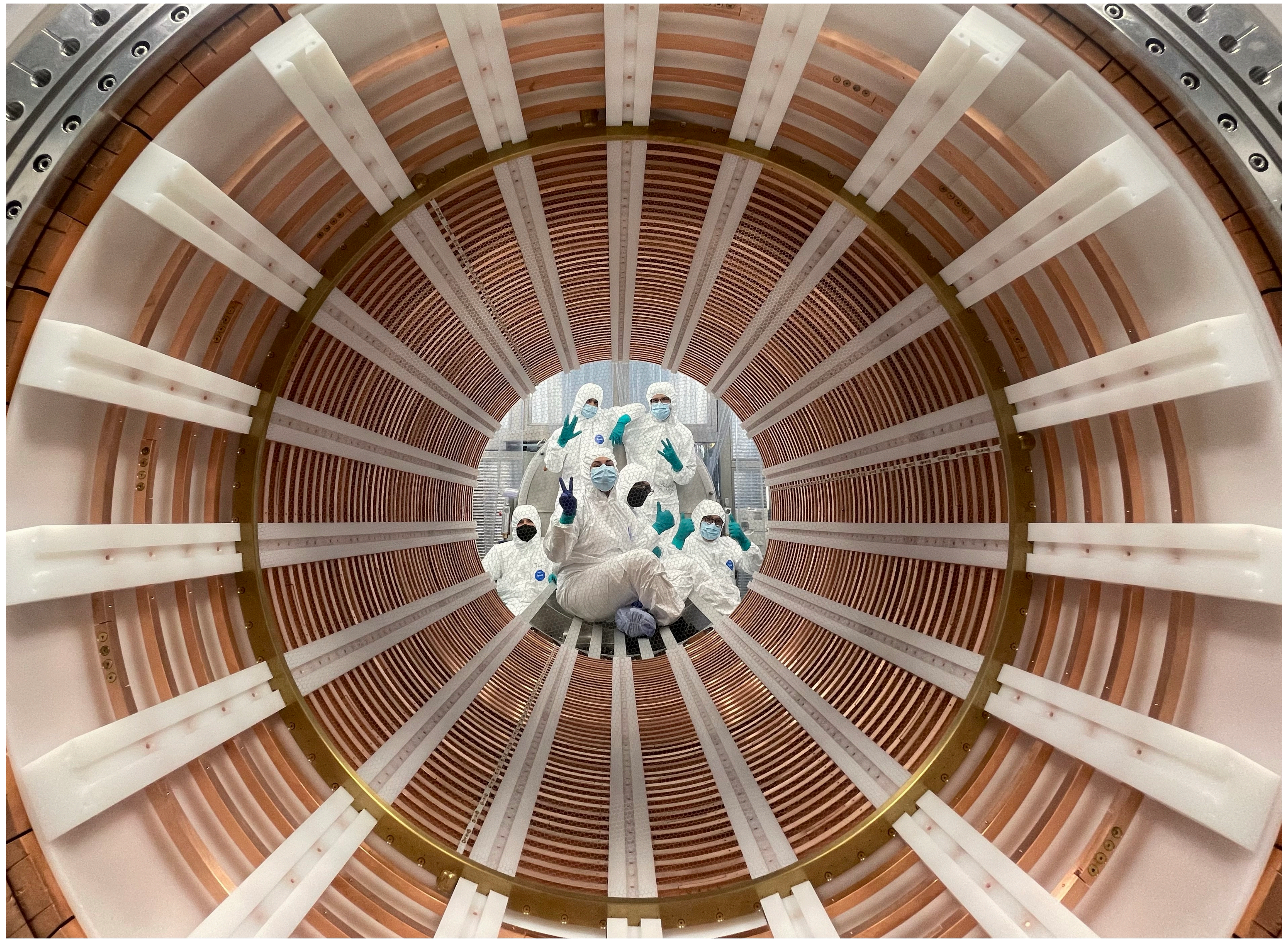


- Background: electrons coming from Compton and photoelectric interactions of gammas from natural radioactivity (up to 3 MeV) or from cosmogenic origin (muons and neutrons).

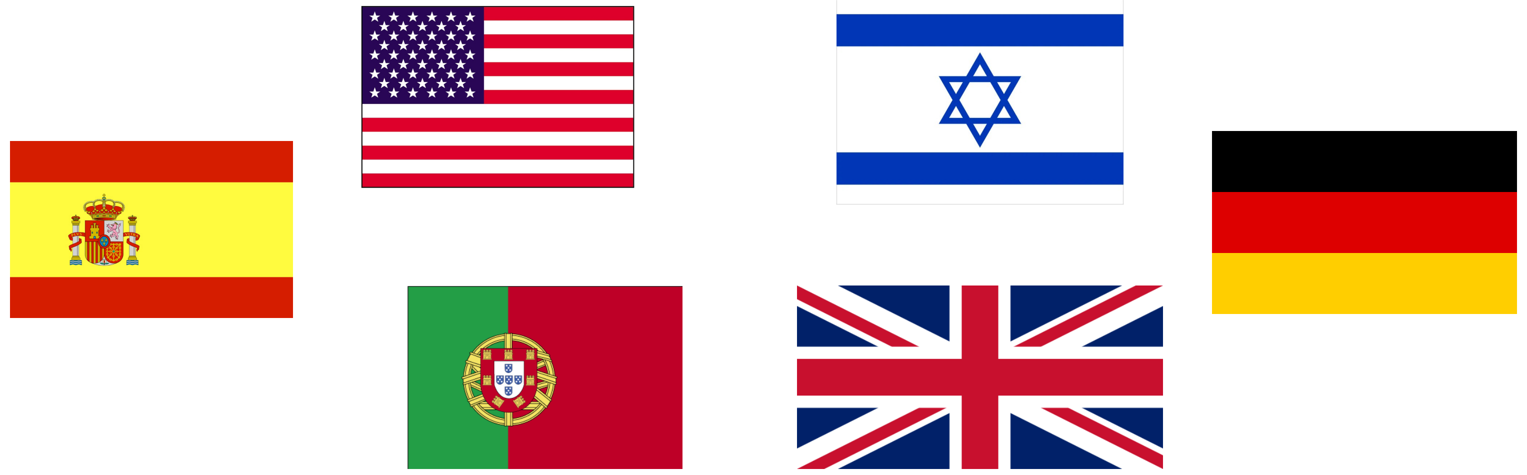
- Experiments with large masses, extremely low environmental background, excellent energy resolution, extra background/signal discrimination.

NEXT: Neutrino Experiment with a Xenon TPC



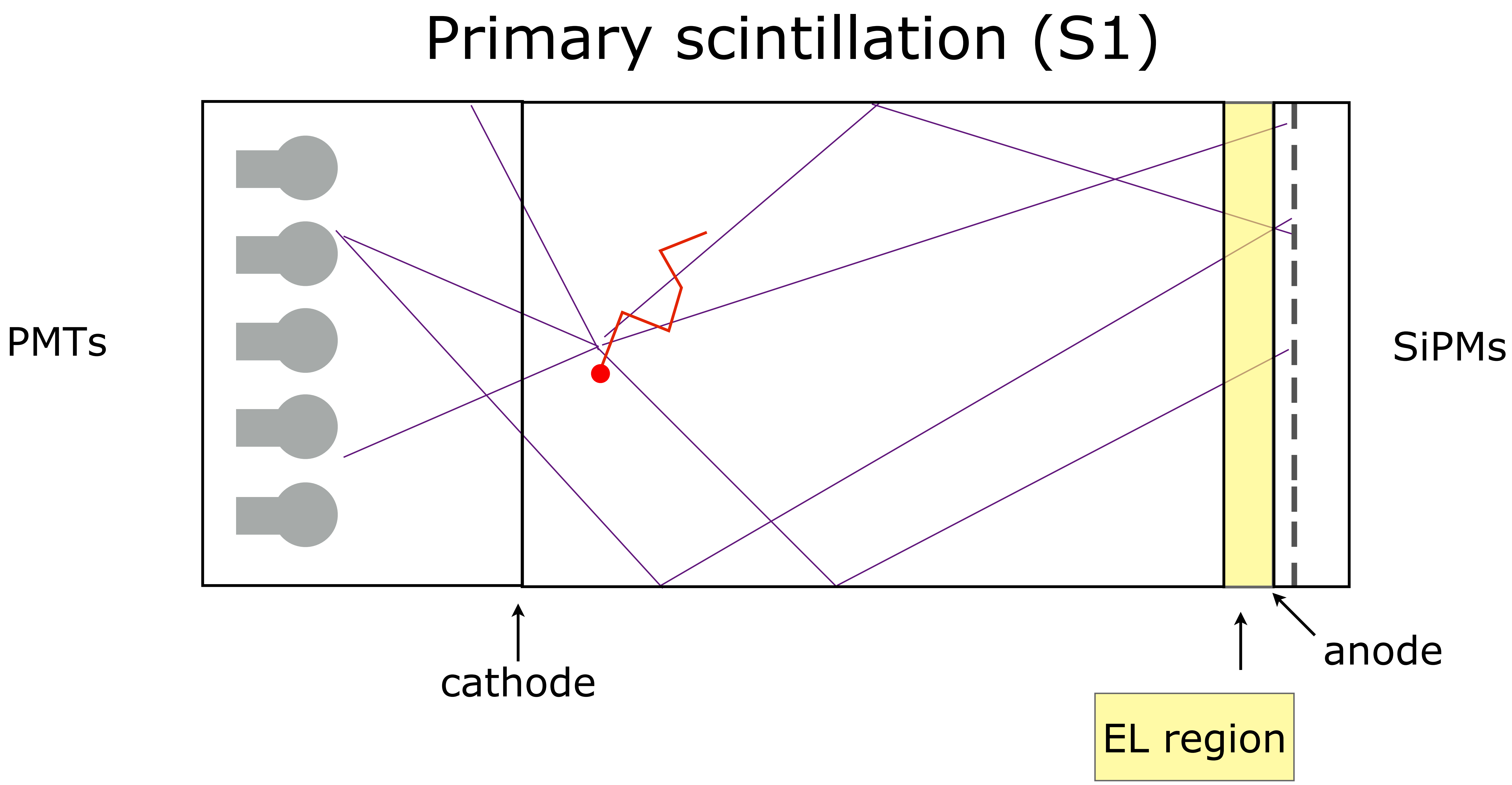


- International collaboration.
- Located at the Canfranc Underground Laboratory (Spain).
- NEXT-100 detector currently being commissioned.



NEXT: Neutrino Experiment with a Xenon TPC

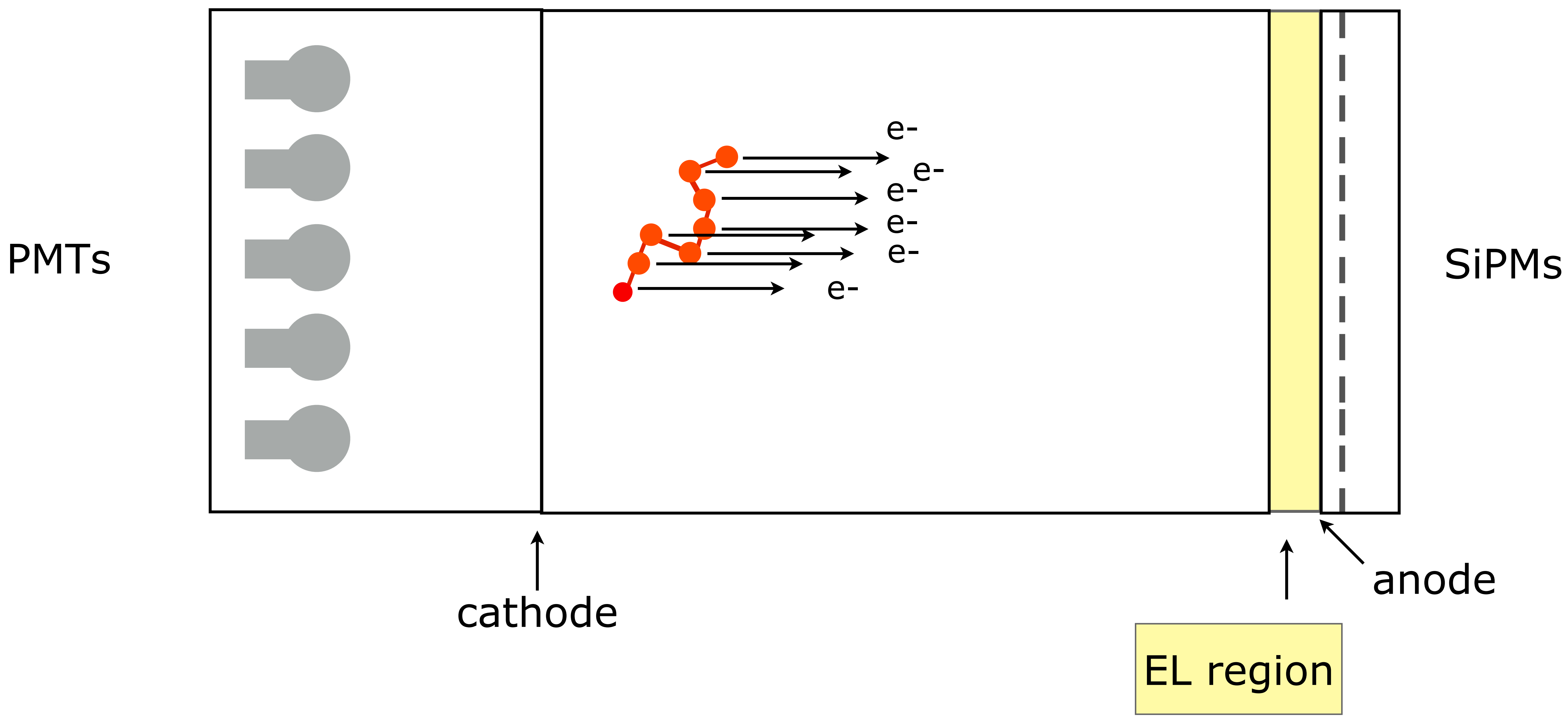
- Time Projection Chamber with high pressure gaseous xenon (10-15 bar).
- Peak energy: 2.458 MeV.
- Electron tracks as an additional discrimination tool between signal and background.



NEXT: Neutrino Experiment with a Xenon TPC

- Time Projection Chamber with high pressure gaseous xenon (10-15 bar).
- Peak energy: 2.458 MeV.
- Electron tracks as an additional discrimination tool between signal and background.

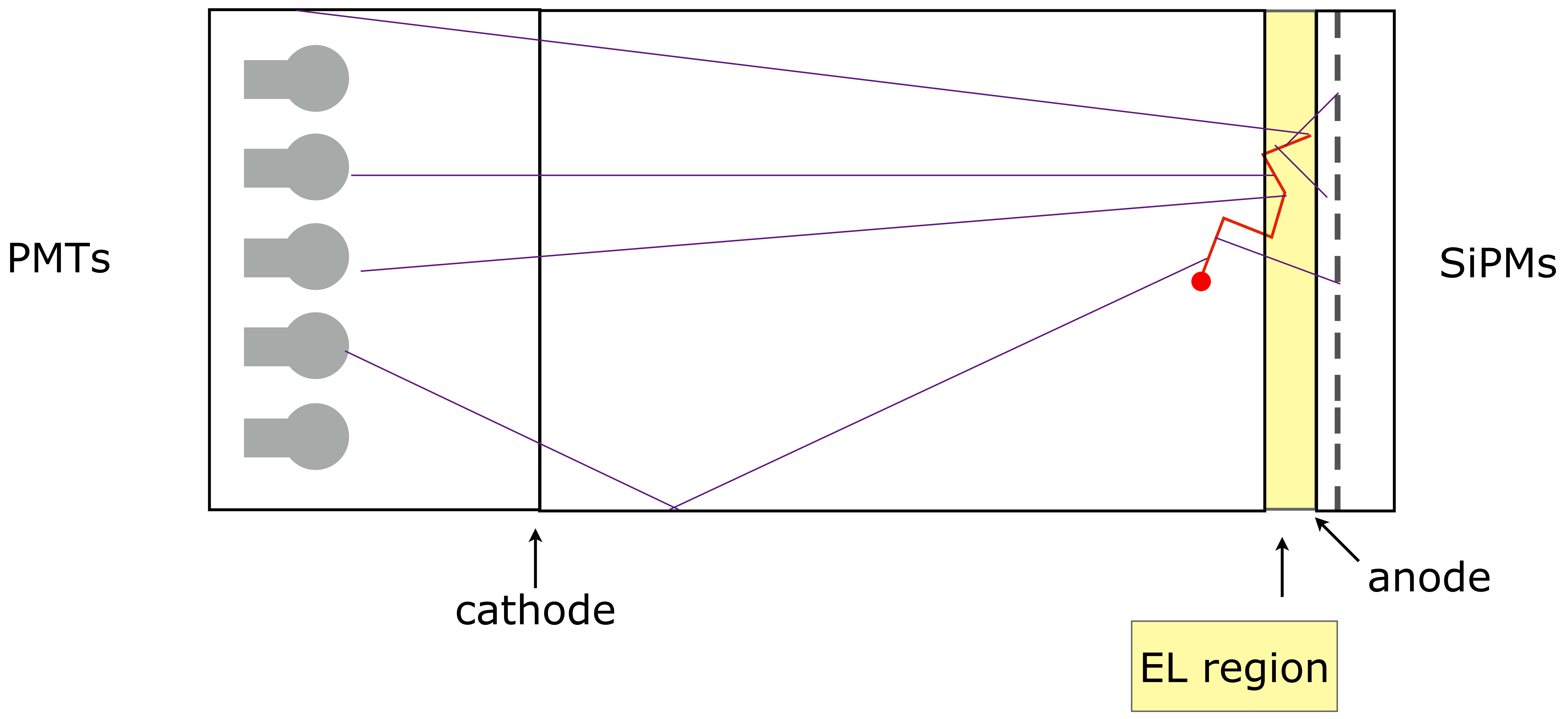
Ionization and drift



NEXT: Neutrino Experiment with a Xenon TPC

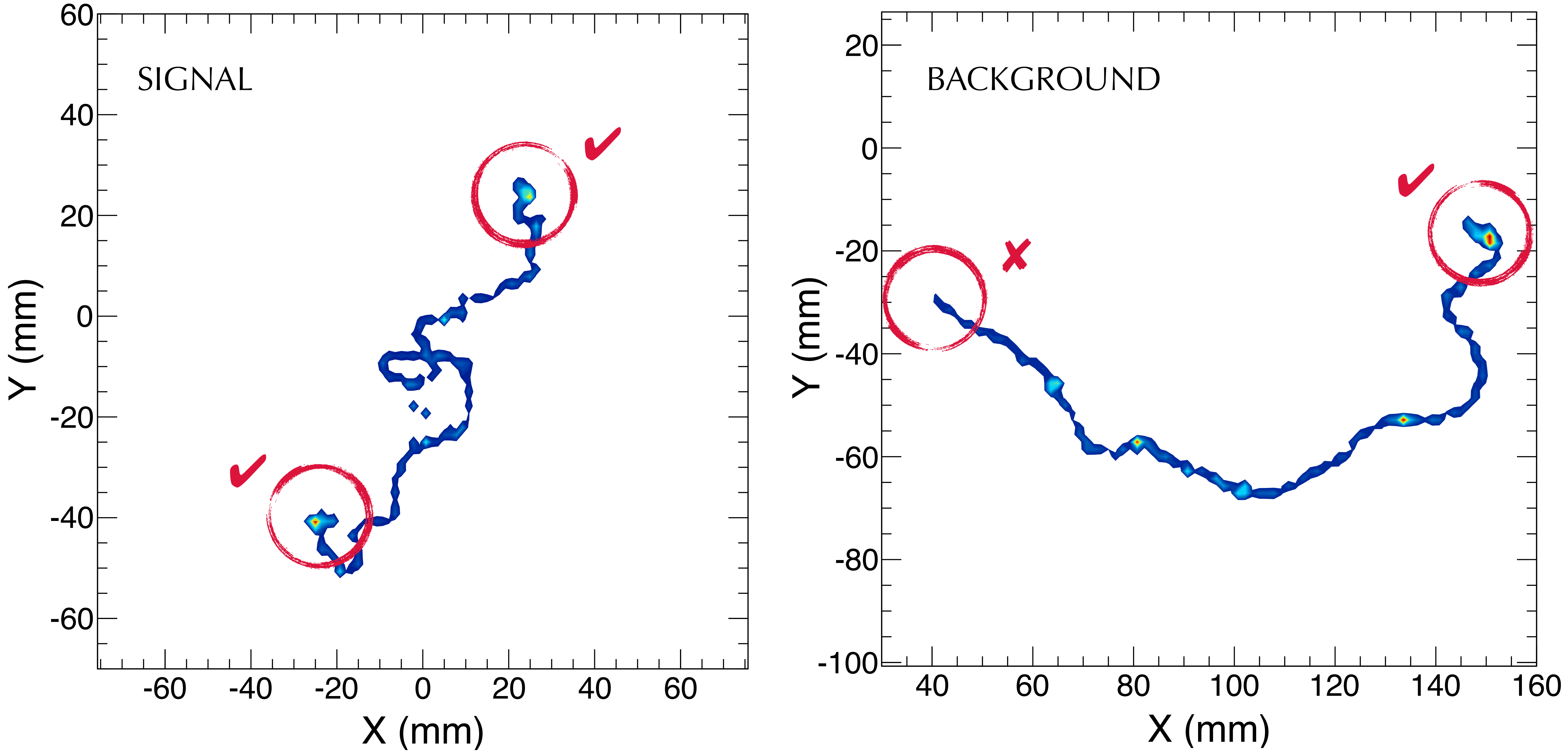
- Time Projection Chamber with high pressure gaseous xenon (10-15 bar).
- Peak energy: 2.458 MeV.
- Electron tracks as an additional discrimination tool between signal and background.

Secondary scintillation (S2)



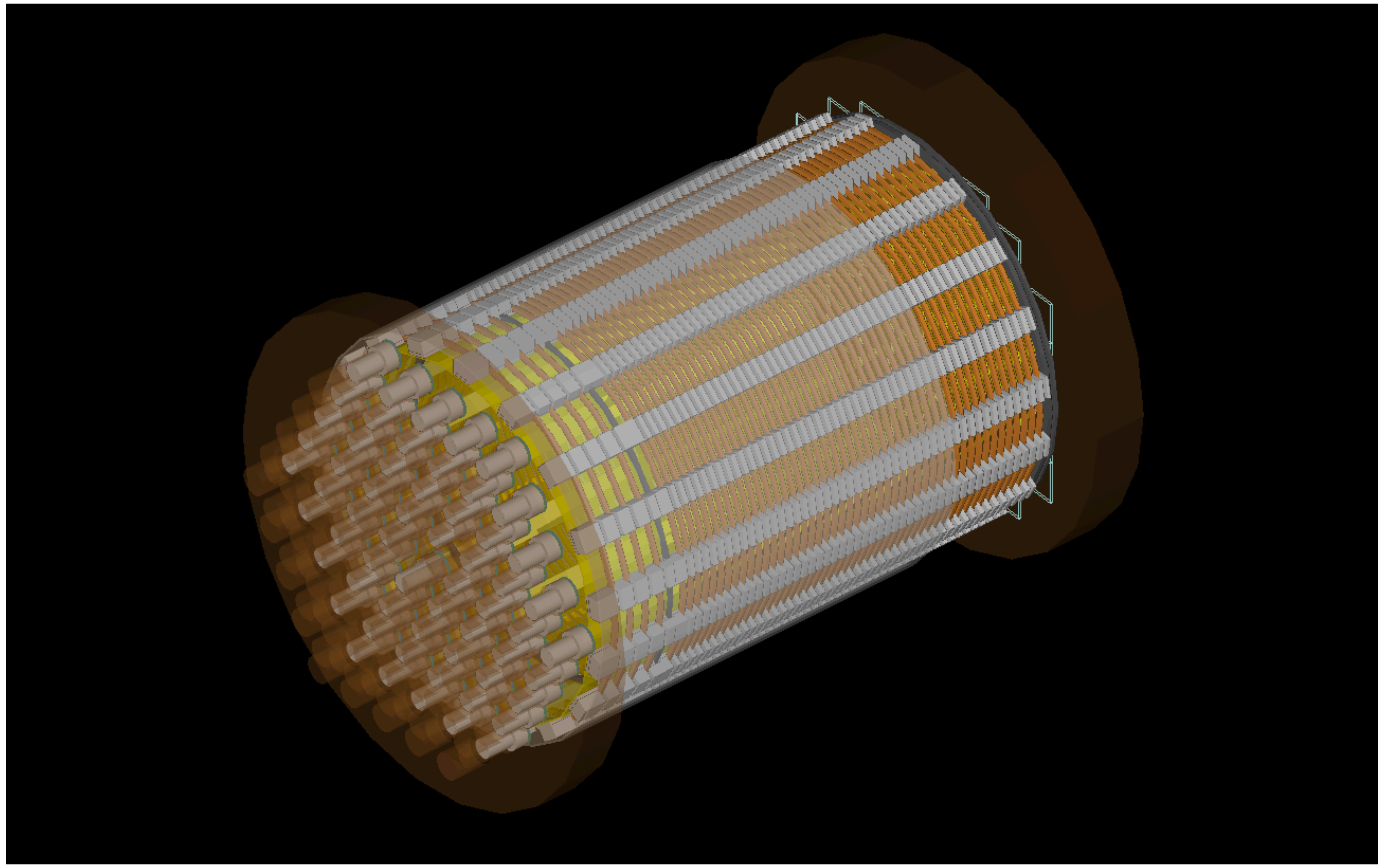
Why Monte Carlo simulation

- Guide the design and upgrades of detectors.
- Help the development of reconstruction and analysis algorithms.
- Help explain effects visible in data and not understood.
- Essential to build a realistic background model to measure neutrino(less) double beta decay.



NEXUS: Geant4-based NEXT Monte Carlo code

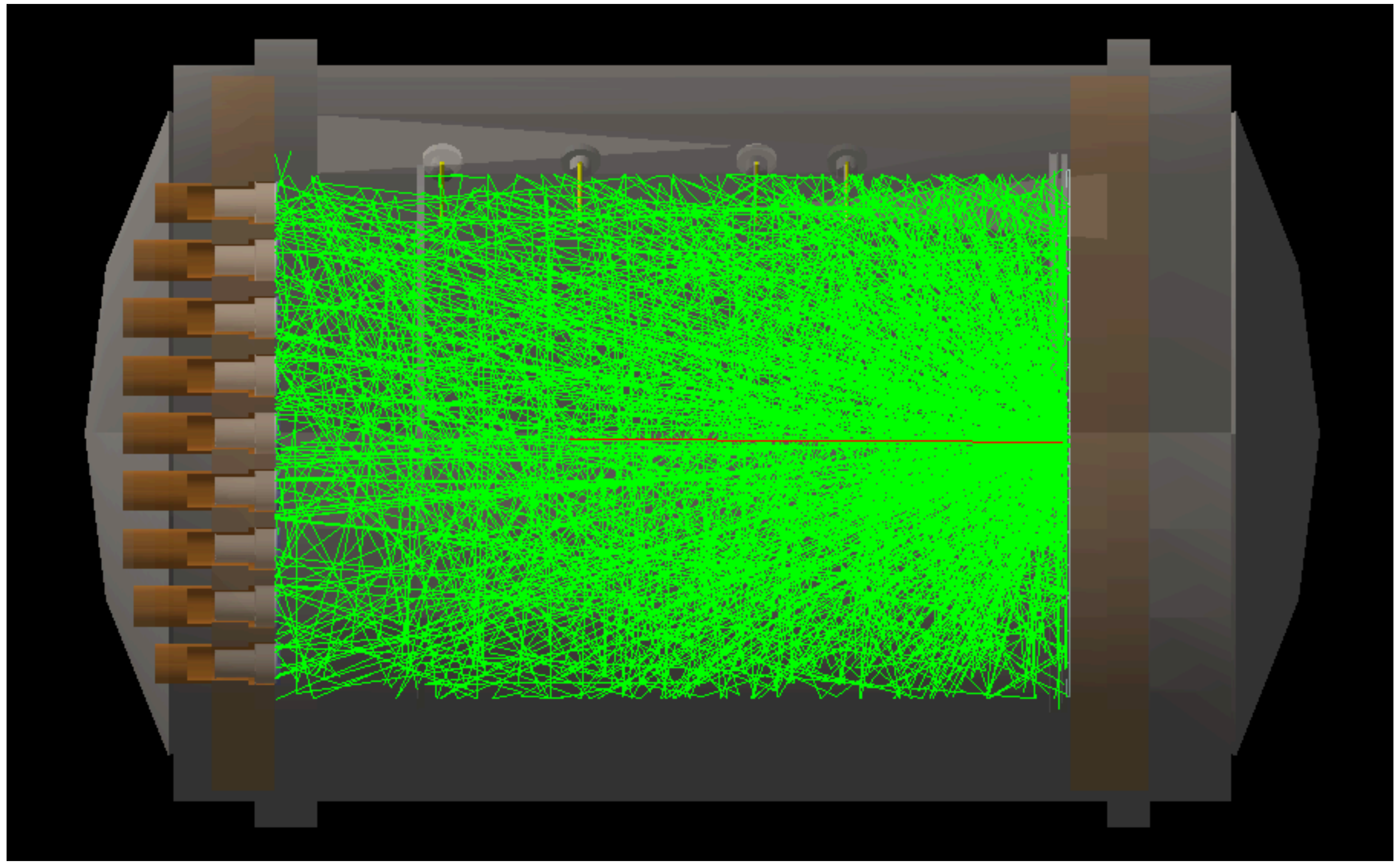
Interior of the NEXT-100 detector



- Custom geometries, actions, materials and physics processes.
- Code available in GitHub: https://github.com/next-exp/nexus

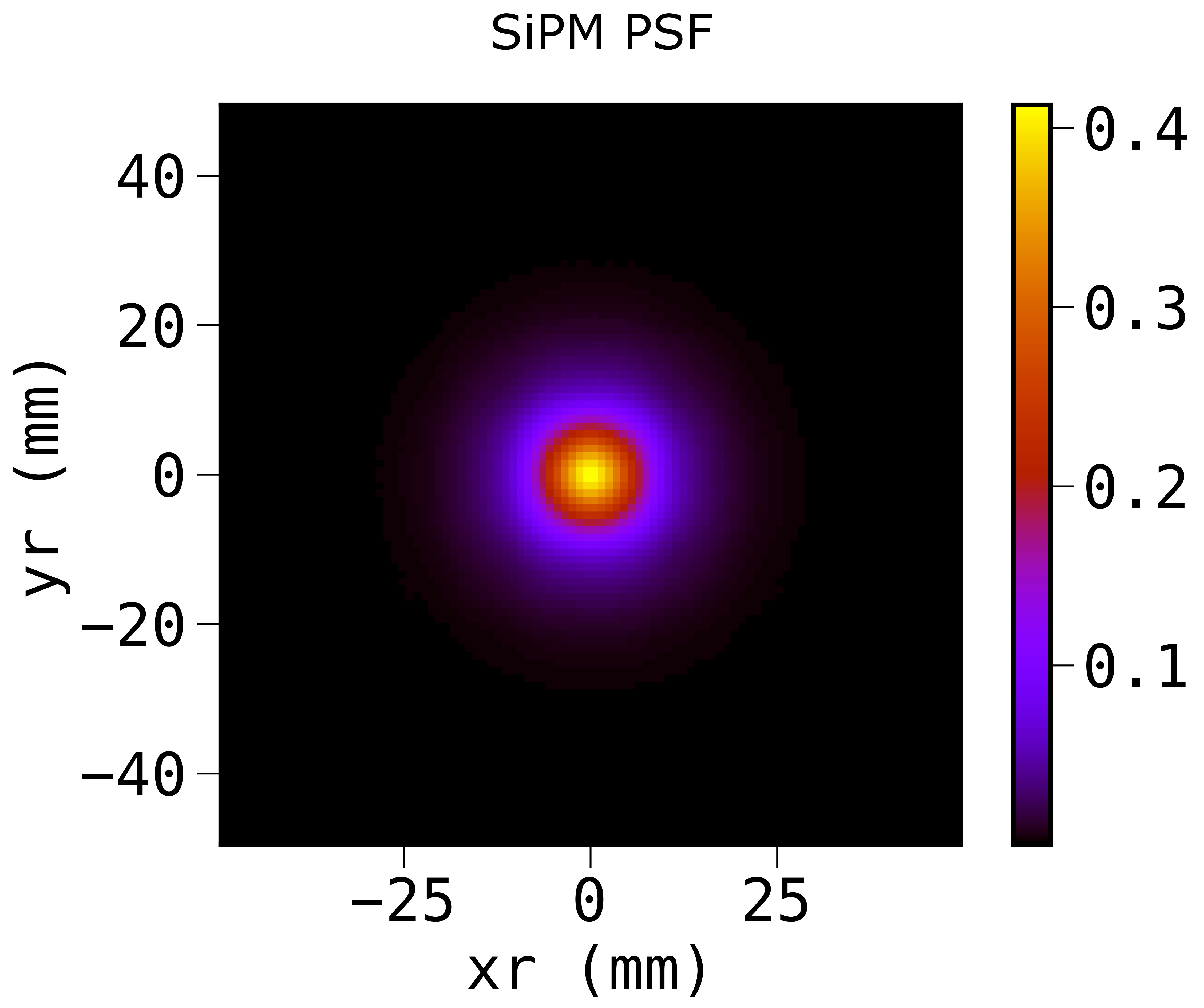
Custom-made physics processes

- Everything after gamma/electron interactions.
- Ionization, electron drift, electroluminescence (EL), photoelectric effect of optical photons on metal grids.
- Input by our own measurements (drift velocity, longitudinal and transversal diffusion, scintillation yield…) or literature (EL yield, GXe Fano factor, PTFE reflectivity…).
- After propagation, the optical photons that have hit a photosensor are registered according to a photodetection efficiency and saved for posterior analysis.



Critical points: optical photon propagation

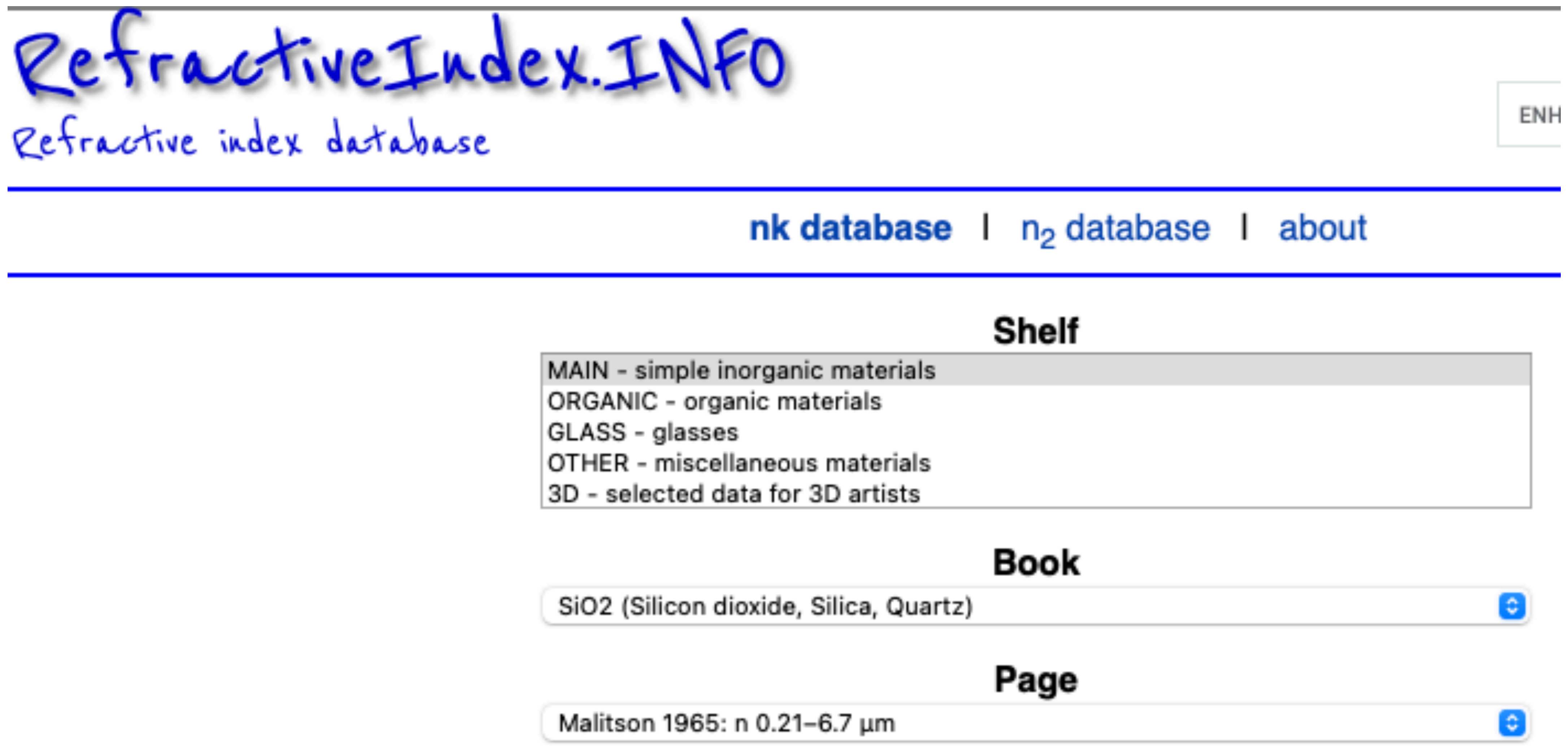
- Huge amount of CPU time, mainly due to photon propagation.
- 1 bb0nu event = 10^5 ie-, 10^3 photons per ie- —> 10^8 photons, 1 hour of CPU.
- Generation of look-up tables (PMT response) or point-spread functions (SiPM response).
- Used outside Geant4 in a python-based framework.

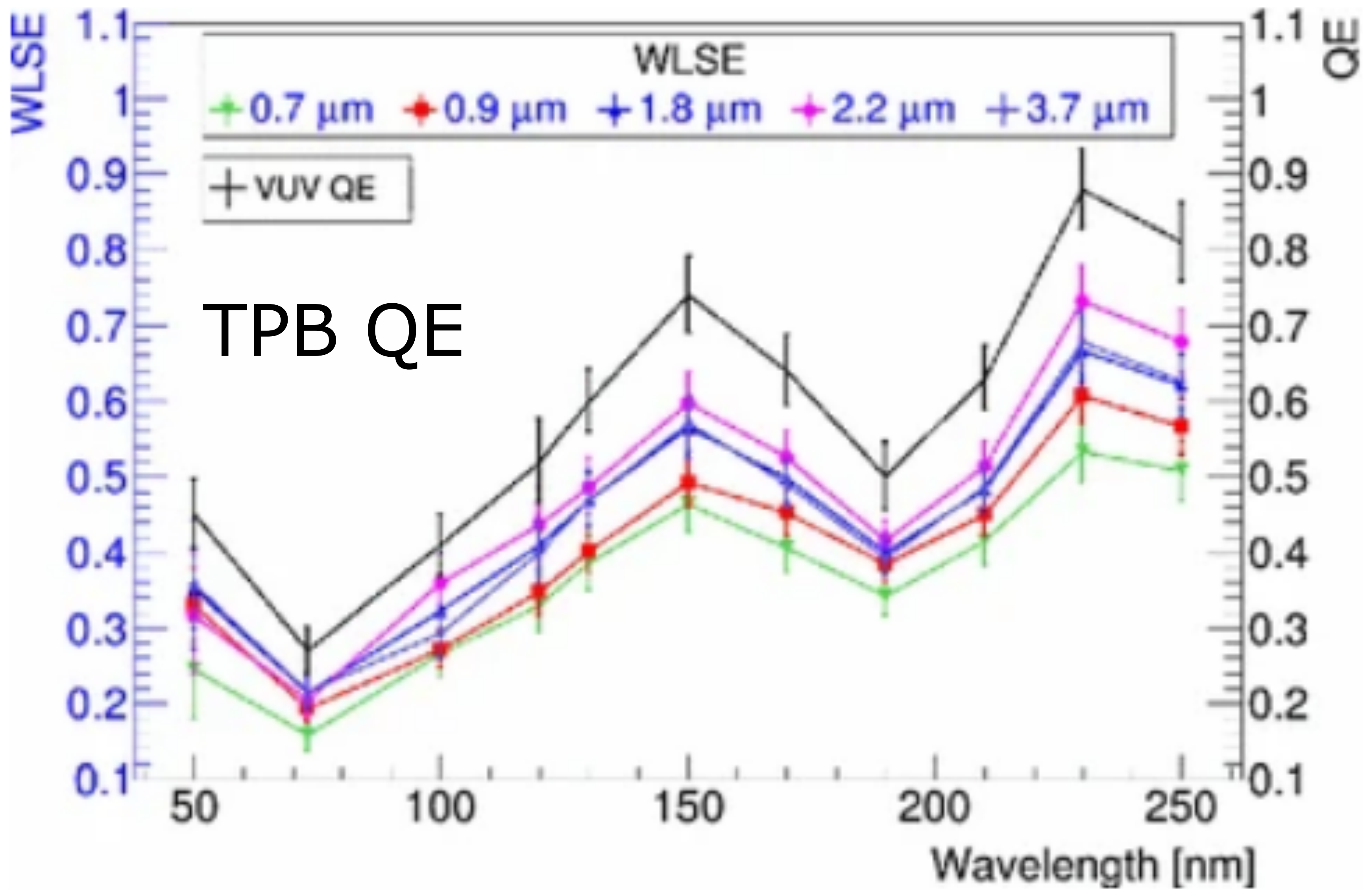


- Exploring Opticks to exploit GPU performance and avoid look-up tables whatsoever.

Critical points: optical material properties

- Material properties such as reflectivity, refractive index, wavelength shifting efficiency… affect significantly the amount of collected light.
- Extremely difficult to find information that is applicable to one’s specific case.
- Very few measurements in the VUV range (Xe peak ~172 nm).
- Need for a global effort of measurements/shared information among G4 users.



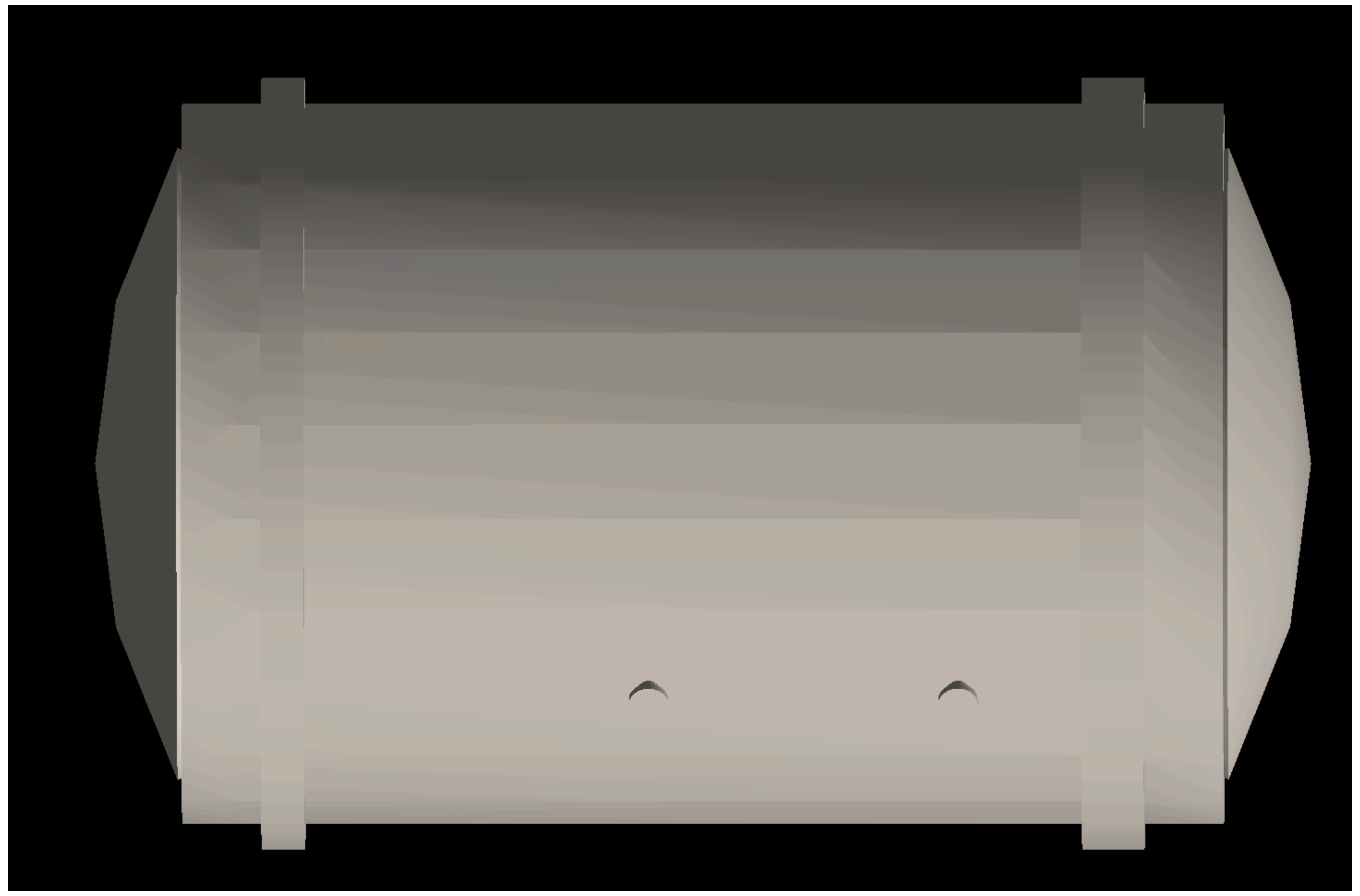


Eur. Phys. J. C **78**, 329 (2018)

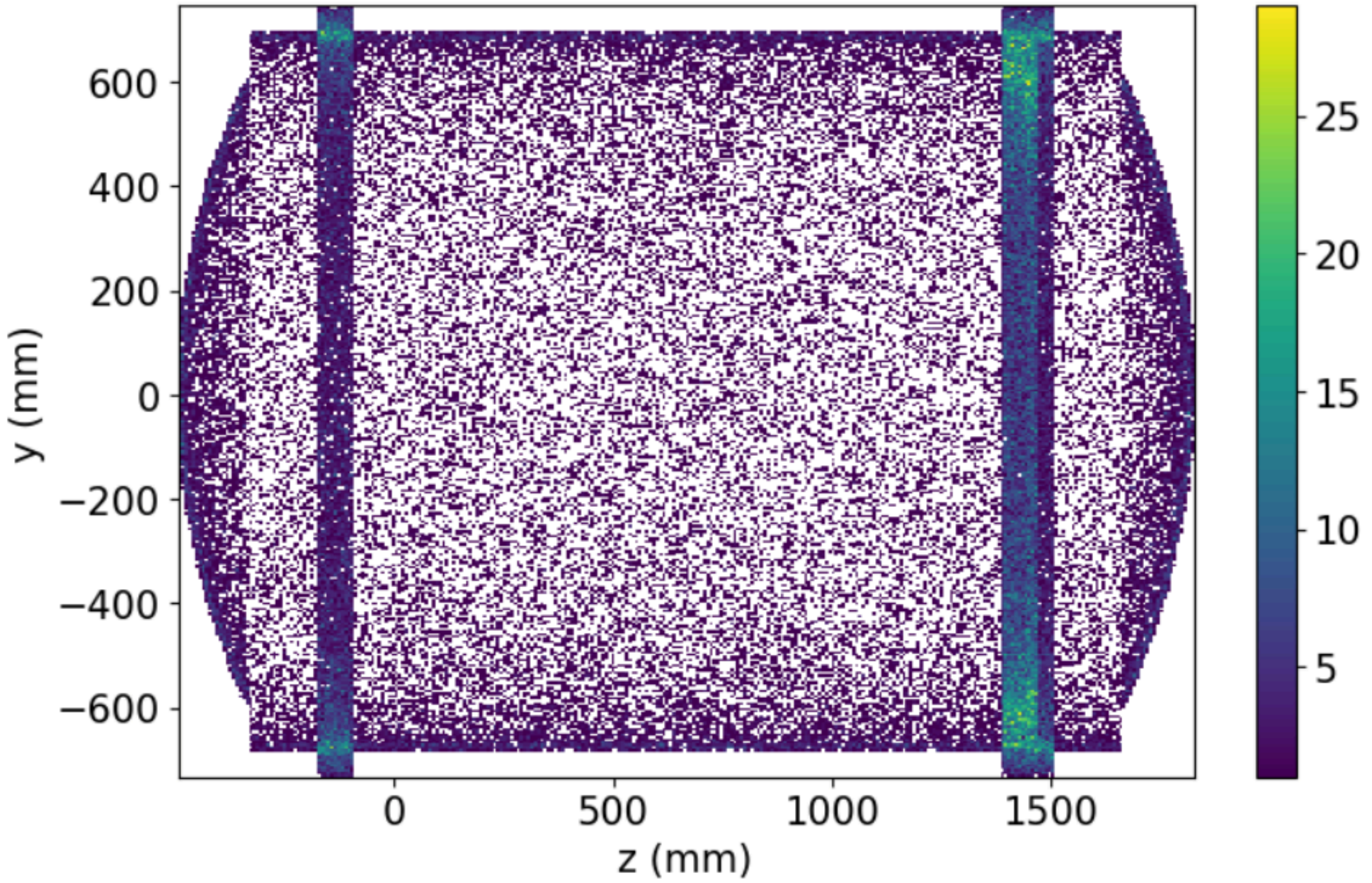
Critical points: vertex generators

- For background models, decays need to be simulated from a large variety of volumes with different and complicated shapes.
- We build our own vertex generators starting from simple shapes (cylinder, box, sphere…).
- Very prone to errors.

geometry



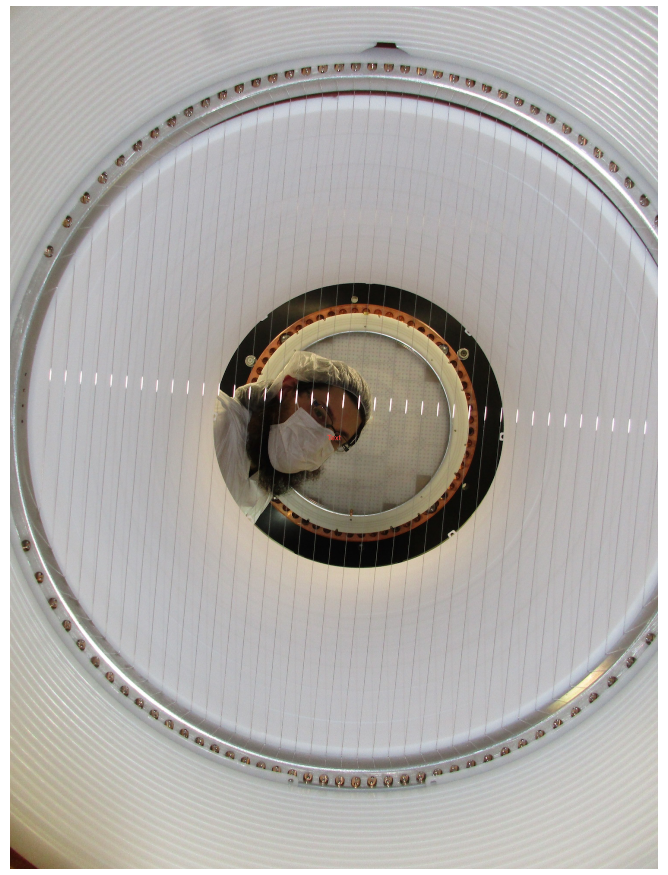
vertices

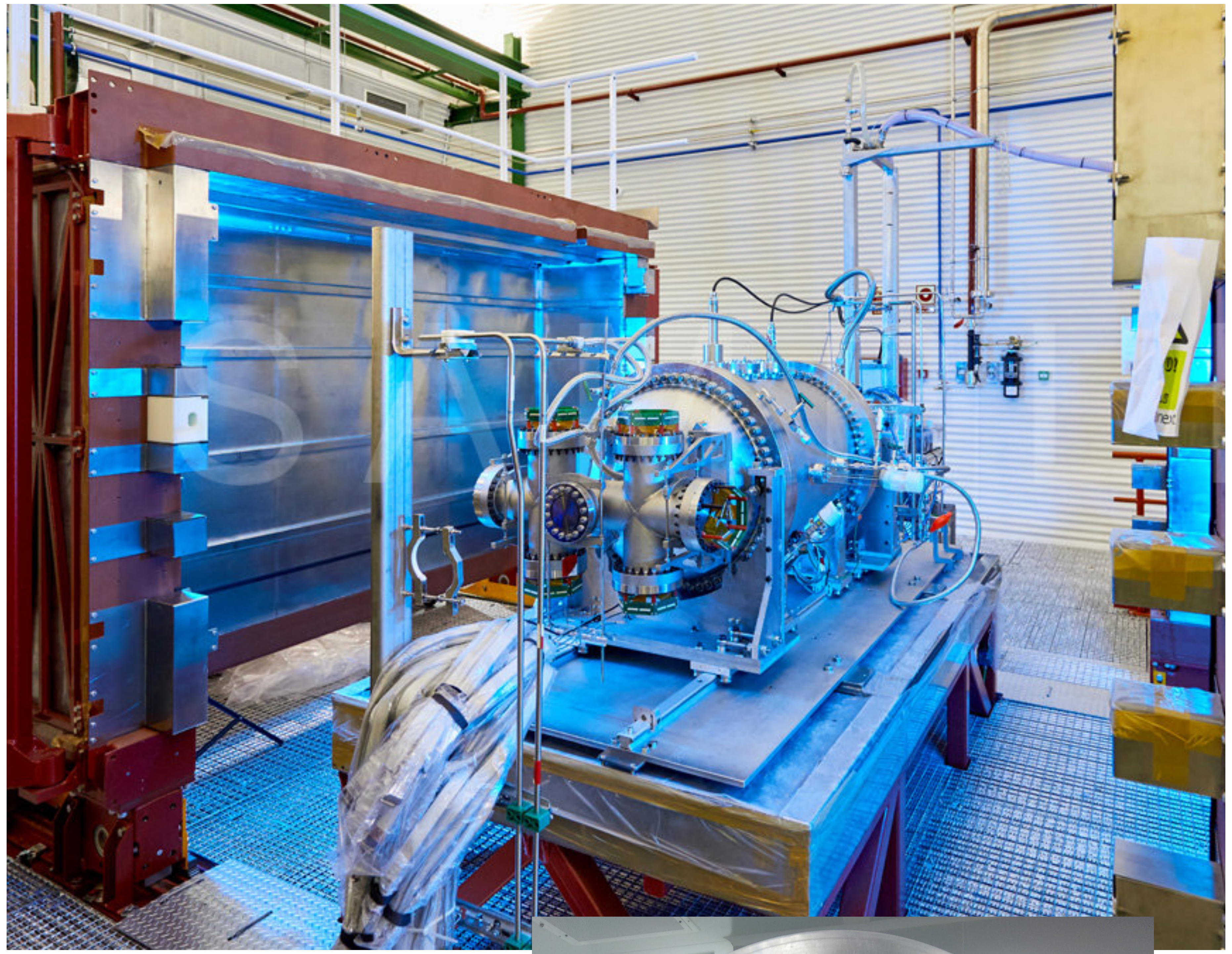


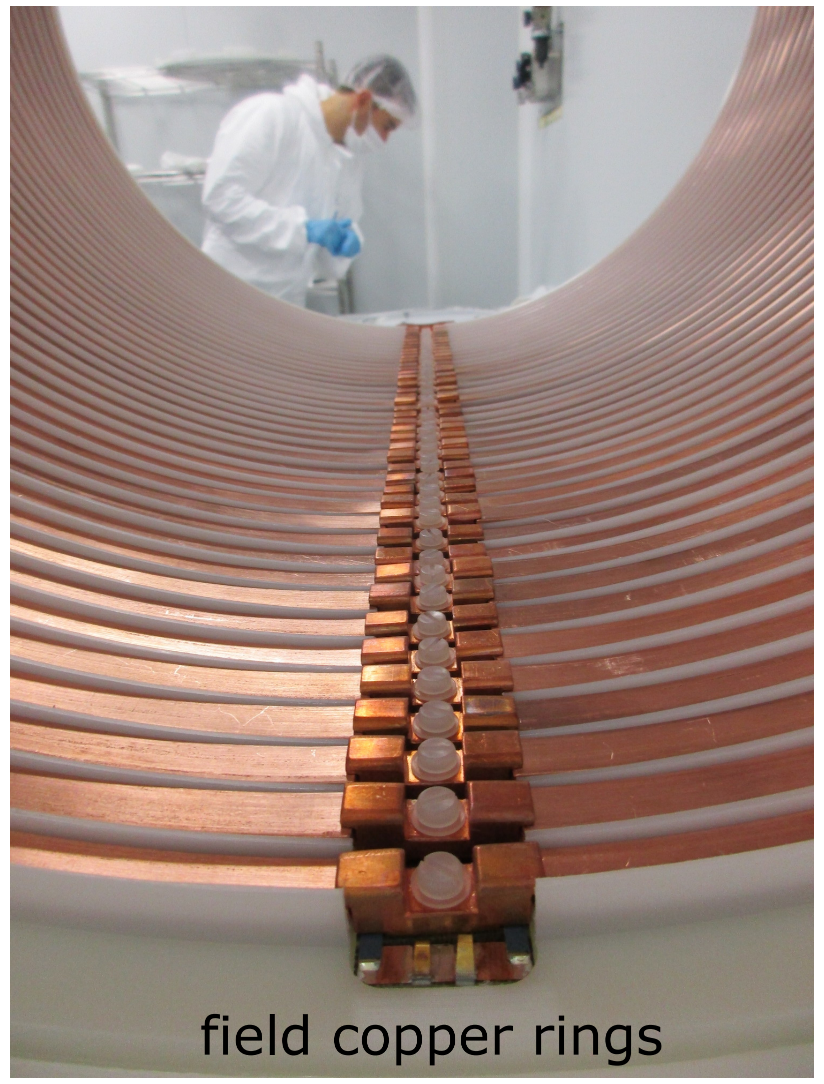
- Extremely useful if Geant4 could build its own vertices, given a physical volume.

First underground detector: NEXT-White

Field cage + PTFE reflectors

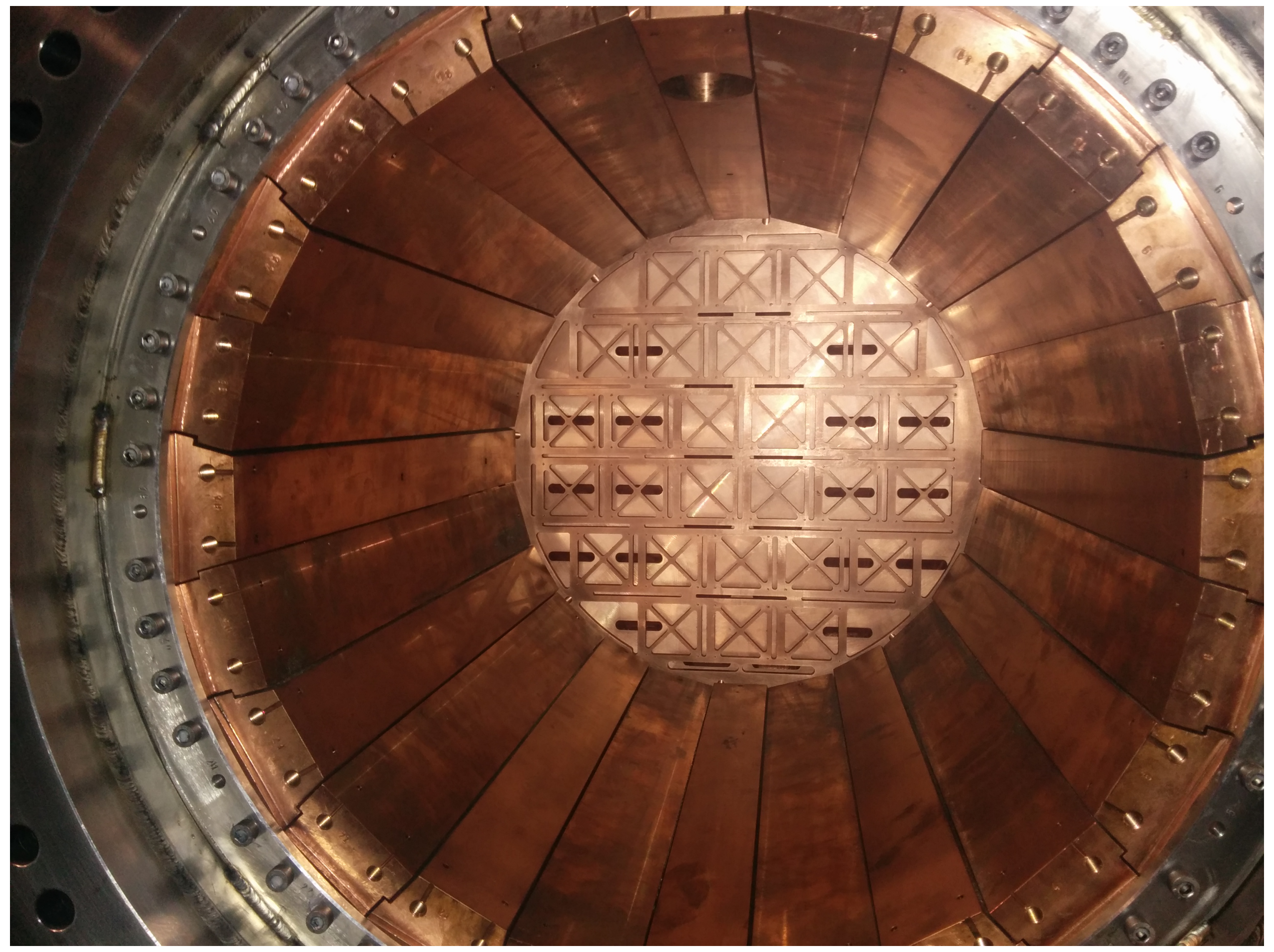




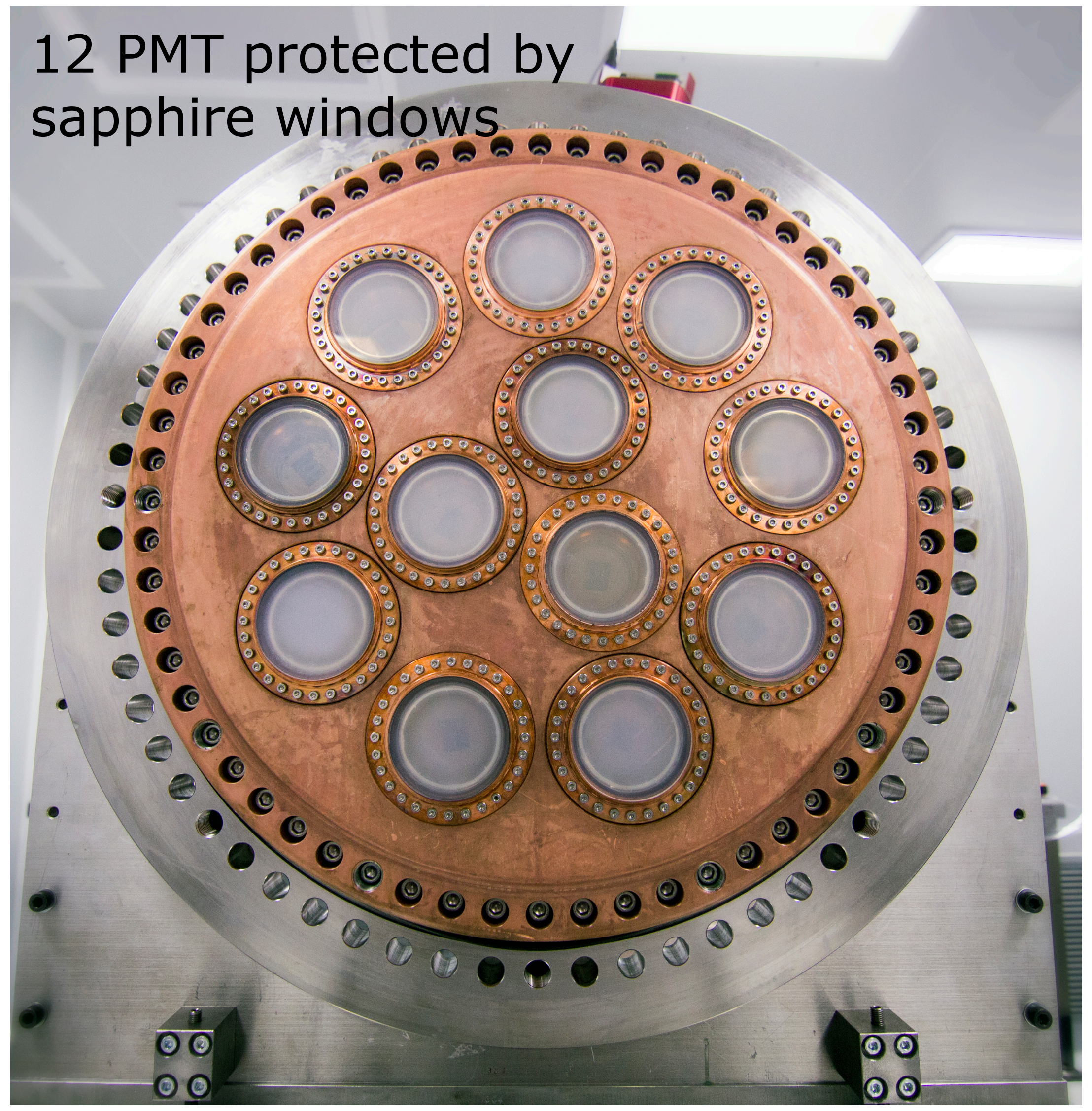


field copper rings

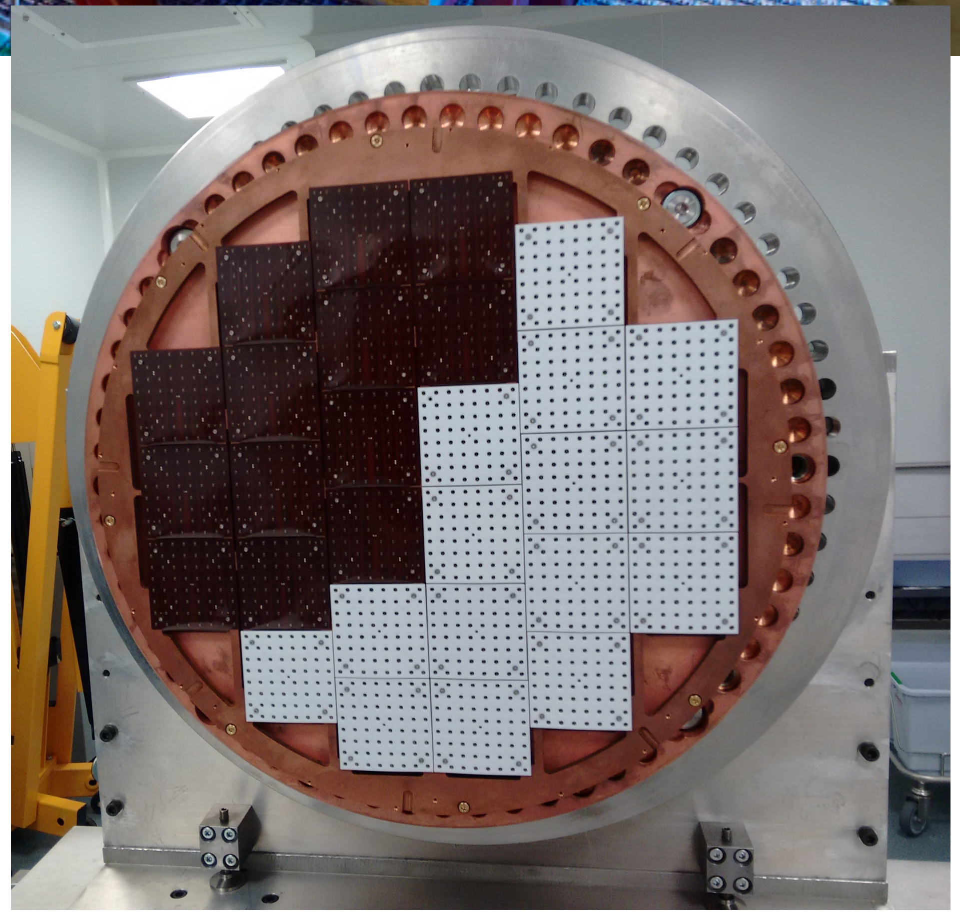
inner copper shielding



12 PMT protected by sapphire windows

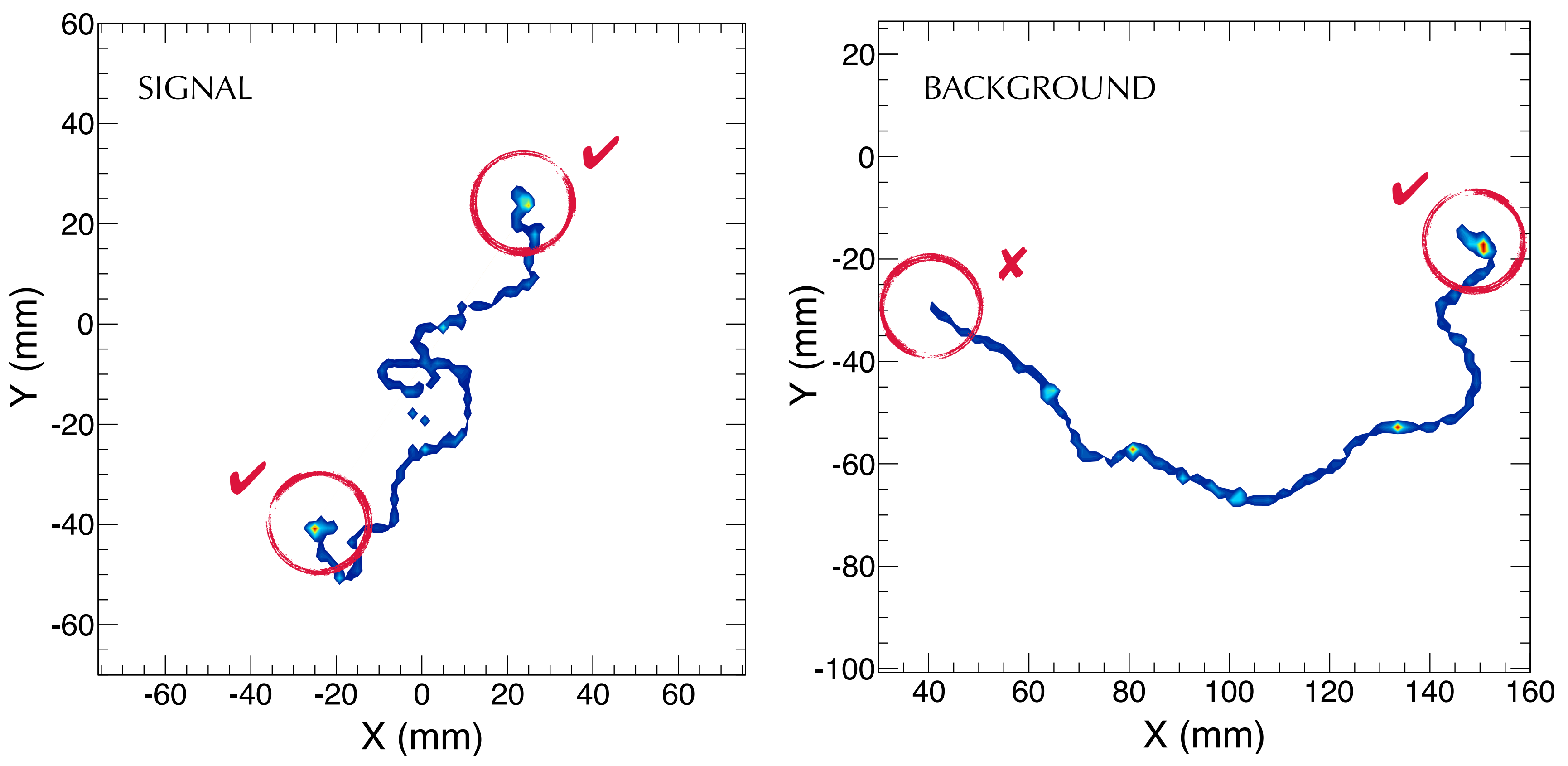


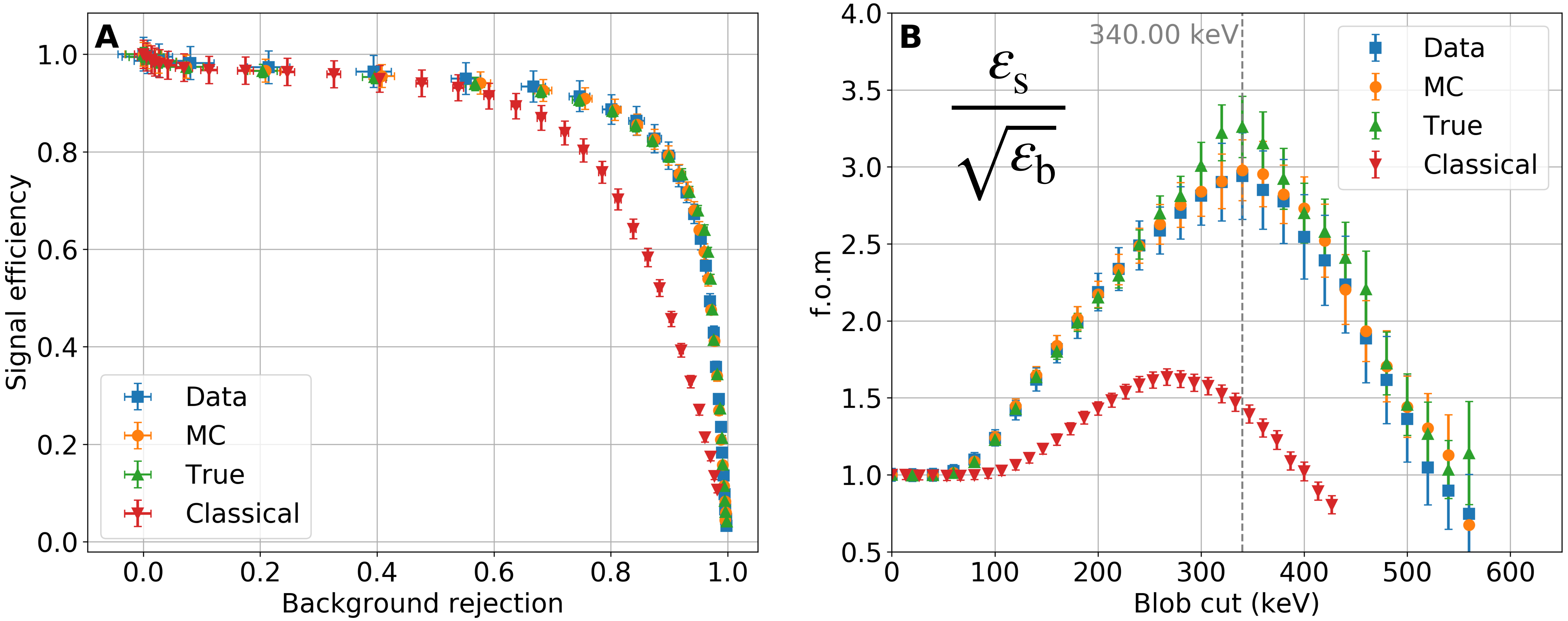
SiPMs at 1 cm pitch, PTFE masks for reflectance



- ~5 kg radiopure detector.
- Aims: background and bb2nu measurement.

Monte Carlo simulations in NEXT-White



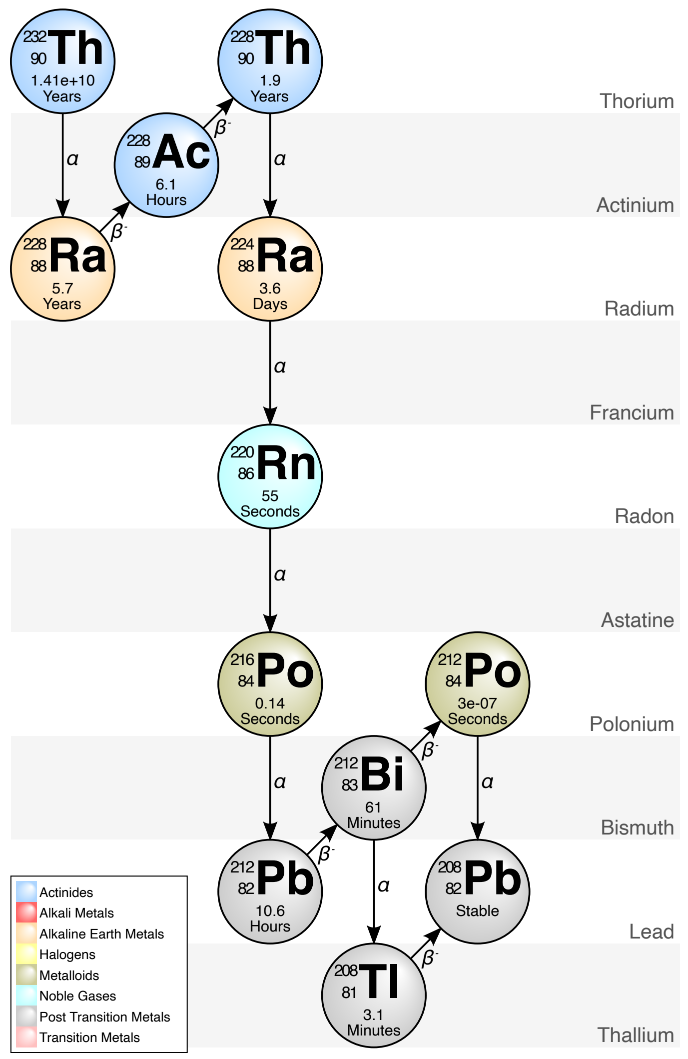


The NEXT Collaboration (A. Simón et al.) *JHEP* 07 (2021) 146

- MC used to optimize the "topological cut" which rejects single-electron vs double-electron tracks.
- Evaluated on calibration data, using electron-positron pair from Tl-208.
- Good agreement with data.

Monte Carlo simulations in NEXT-White

- Need for realistic background modelling to extract background and signal (bb2nu) rates.



simulation of the decay of relevant isotopes → probability of detecting a background event

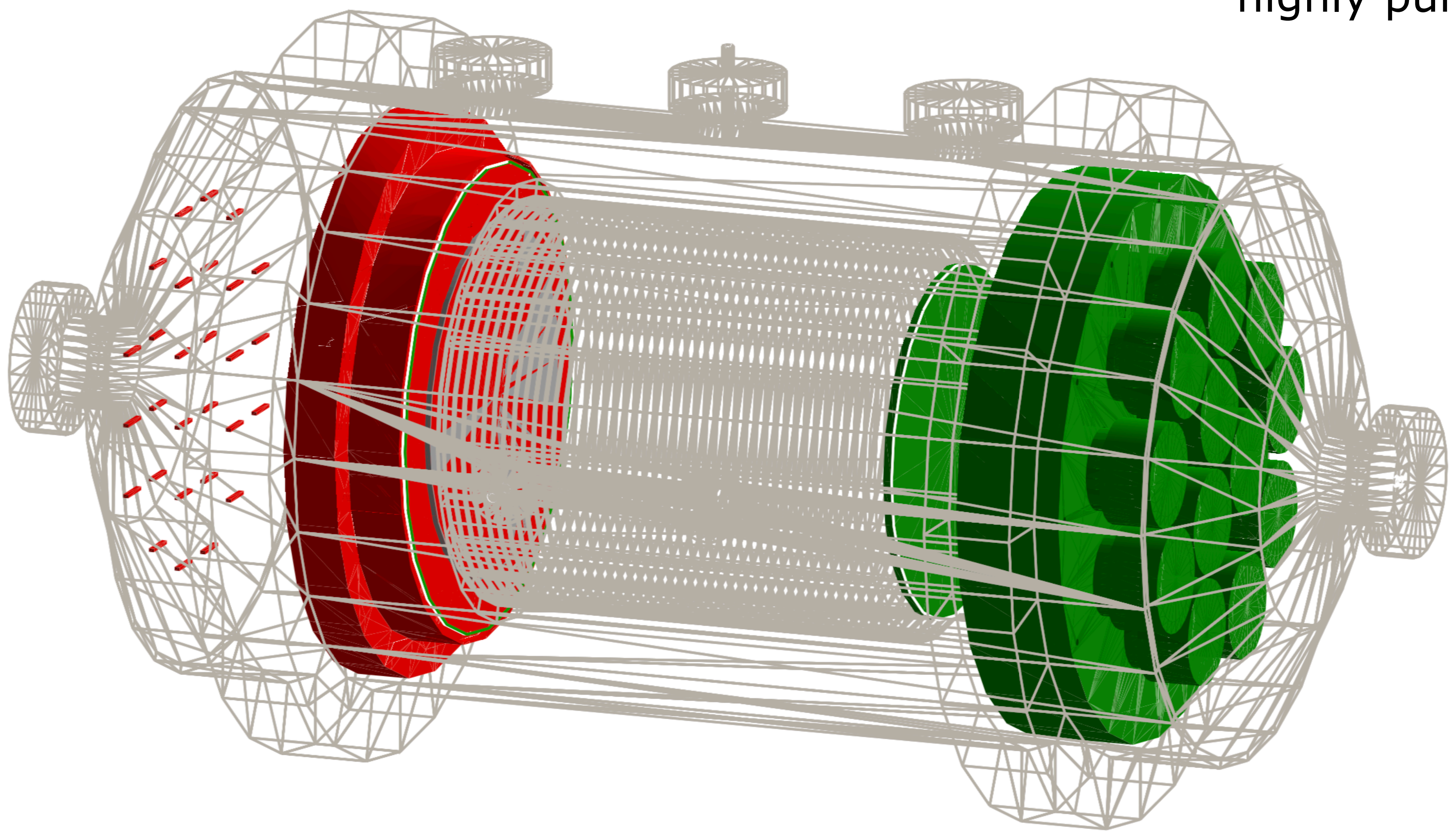
+

radioactivity screening of all materials in the detector → activity of the material

=

expected background contribution

highly pure Ge detectors

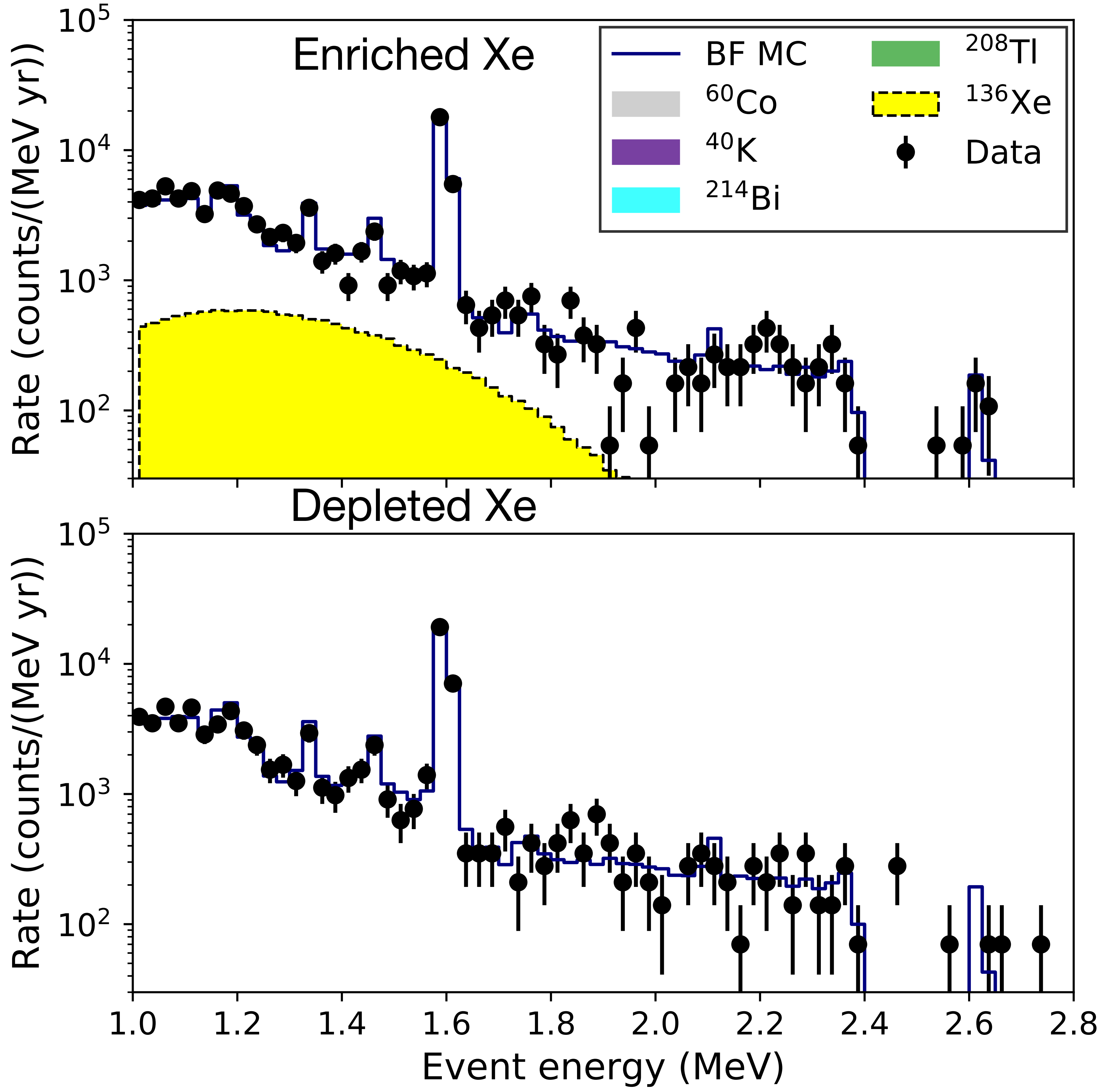


- 23 different volumes and 4 isotopes (^{214}Bi, ^{208}Tl, ^{60}Co, ^{40}K) for radiogenic background.
- 10^11 events in total.

Monte Carlo simulations in NEXT-White

- Joint fit of depleted and enriched data on the event energy to the background model.

The NEXT Collaboration (P. Novella et al.) *Phys.Rev.C* 105 (2022) 5, 055501



Best fit rates for ^{136}Xe: $334 \pm 78 \pm 54$ count/year

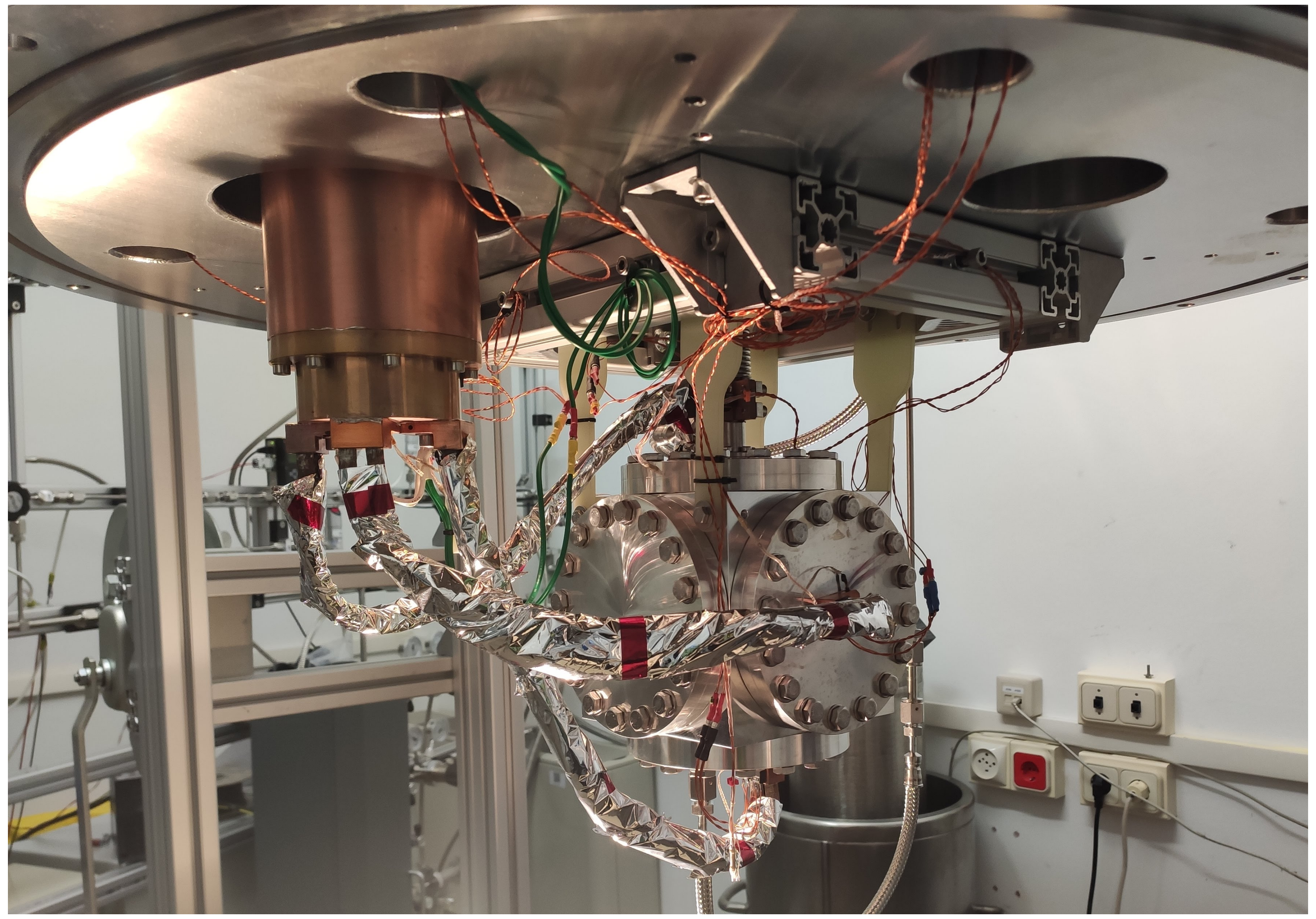
isotope	rate (μHz)
± ^{214}Bi	6 3
± ^{208}Tl	40 2
± ^{60}Co	14 2
± ^{40}K	10 2

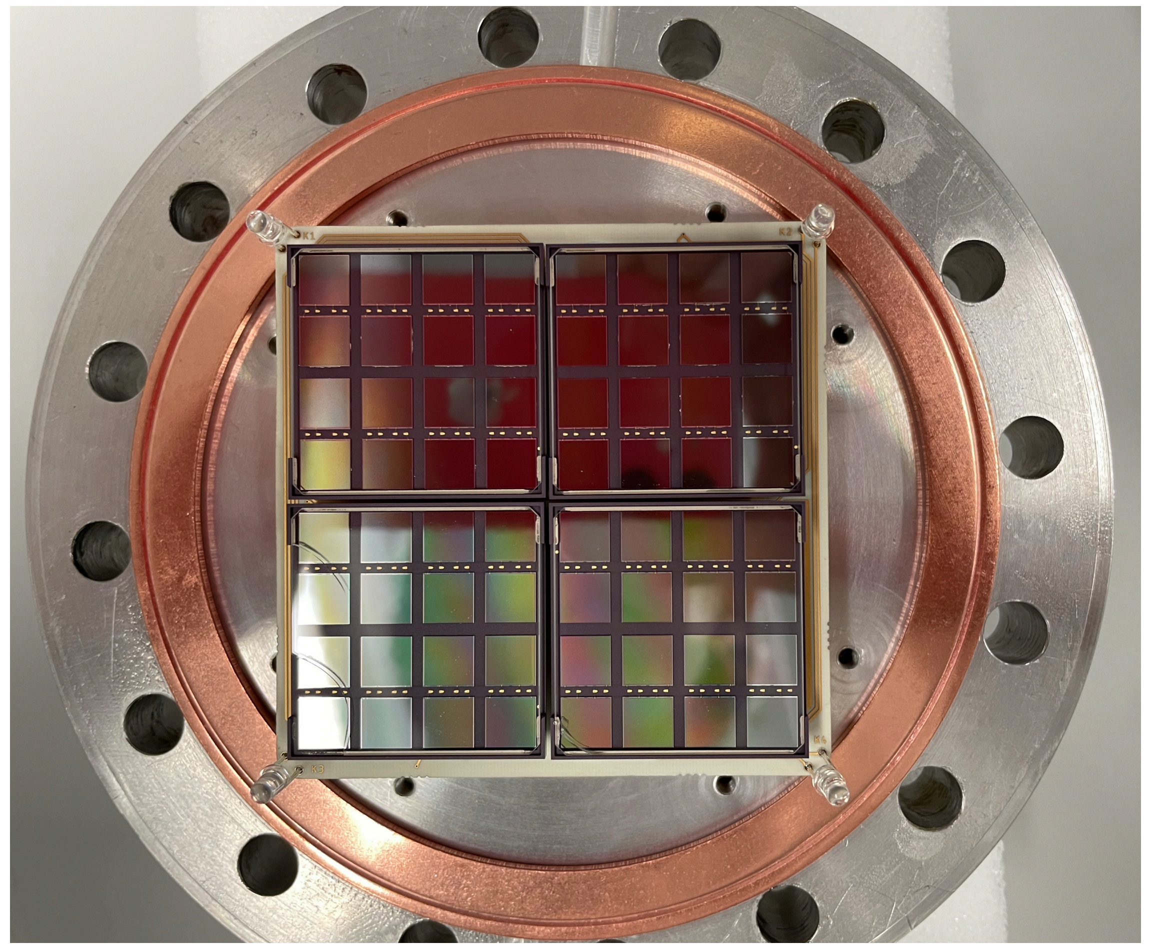
- Compatible with direct subtraction method (much less MC-dependent).

PETALO: a spin-off of NEXT

- Using liquid xenon and SiPMs in PET technology.
- Prototype built and operated at IFIC - Valencia to demonstrate energy and time resolutions.

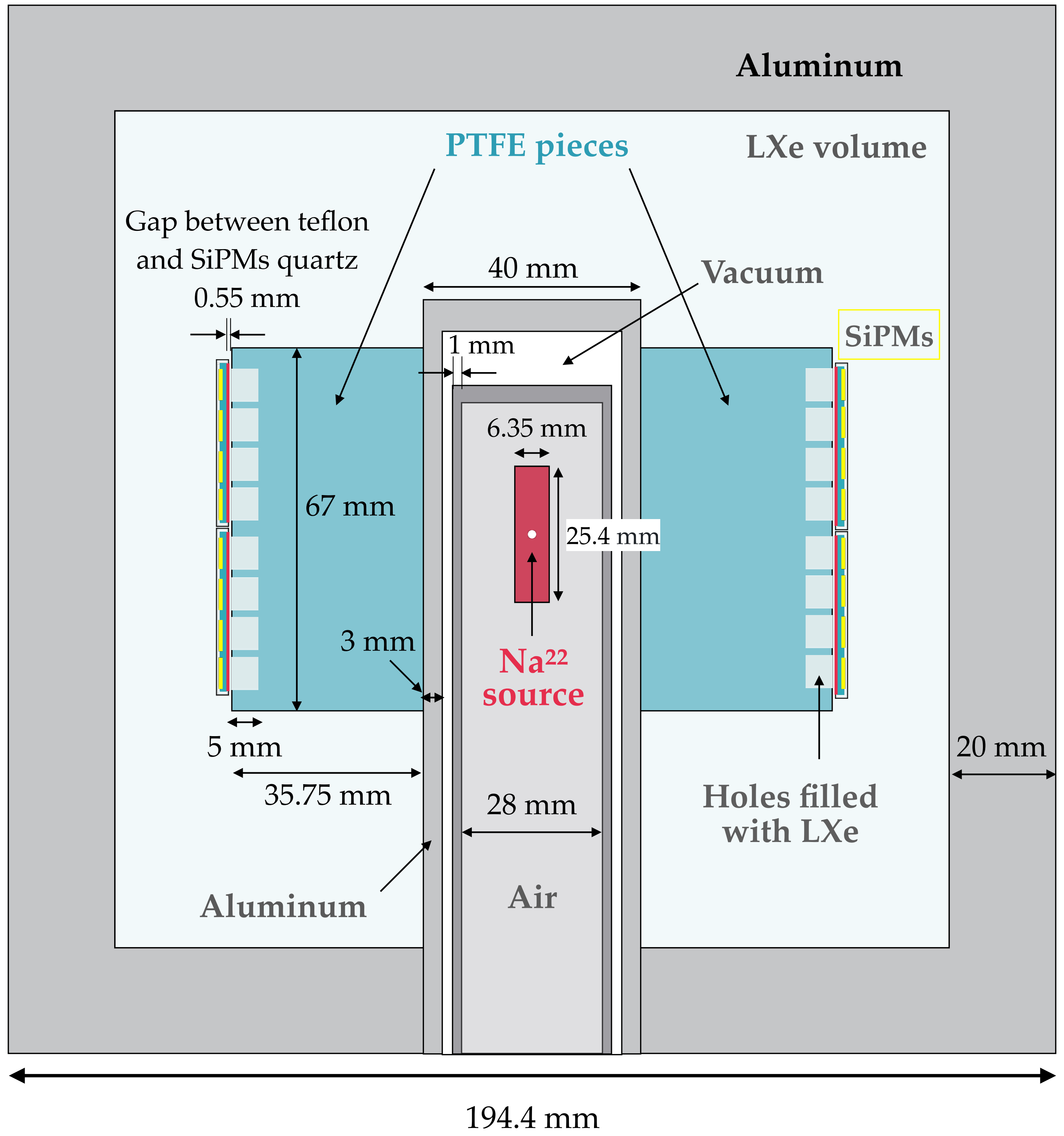
petalo





PETALO: a spin-off of NEXT

- Monte Carlo simulations used to guide the prototype construction and to understand data.
- Software built upon Geant4 and depending on nexus as a third party library (https://github.com/petalo-project/petalosim).



- Only scintillation light —> full simulation is feasible (to a certain extent).
- Detailed simulation of SIPM microcells to study saturation.
- PTFE also present (importance of reflectivity behaviour).

PETALO: a spin-off of NEXT

- Tried to use NEST (Noble Element Simulation Technique) for energy deposition microphysics of LXe (non-linearity of scintillation light).

- ✅ Code successfully linked and working.
- ✅ We contributed to G4 integration code development (https://github.com/NESTCollaboration/nest).

- ❌ G4 integration is not maintained + code not debugged for zero field.

↓

Not using NEST for the moment, our measurements can be useful as input for the code.

Conclusions

- Geant4-based simulations in the NEXT and PETALO experiments.
- Essential to guide detector design, understand the results, direct upgrades.
- Accurate background model crucial for rare event searches.
- Critical points: high CPU-consumption for optical photon tracking, need for accurate material property models/measurements, unified vertex generation.

Conclusions

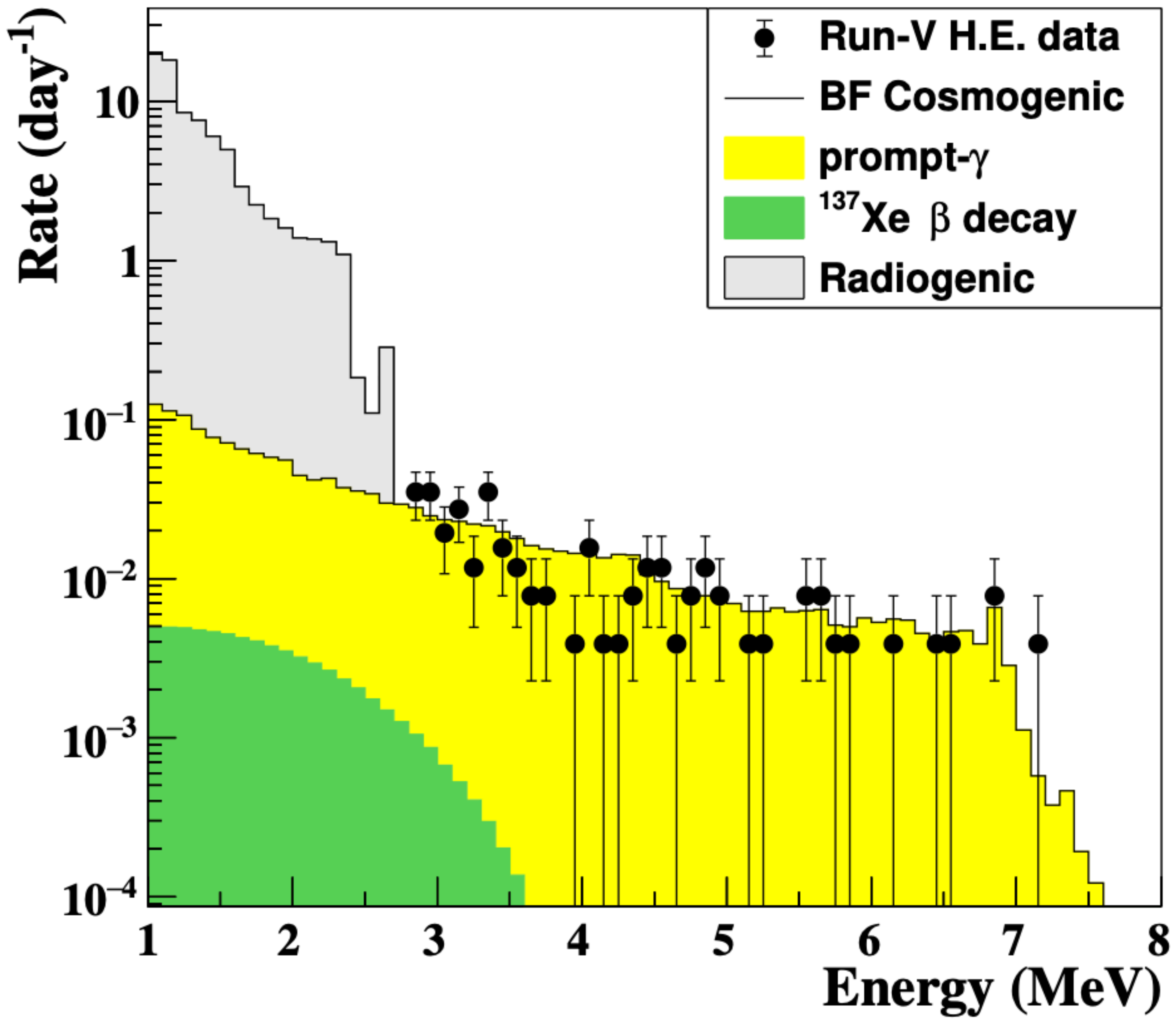
- Geant4-based simulations in the NEXT and PETALO experiments.
- Essential to guide detector design, understand the results, direct upgrades.
- Accurate background model crucial for rare event searches.
- Critical points: high CPU-consumption for optical photon tracking, need for accurate material property models/measurements, unified vertex generation.

Danke schön!

Back-up

Monte Carlo cosmogenic simulations

- Contribution to background from muons and neutron coming from muon spallation.
- Activation of Xe-137 —> beta decay with energy within ROI.
- Negligible for bb2nu measurement (radiogenic much higher) but not for bb0nu.
- Muon veto to be built in NEXT-100 (prototype and simulations ongoing).

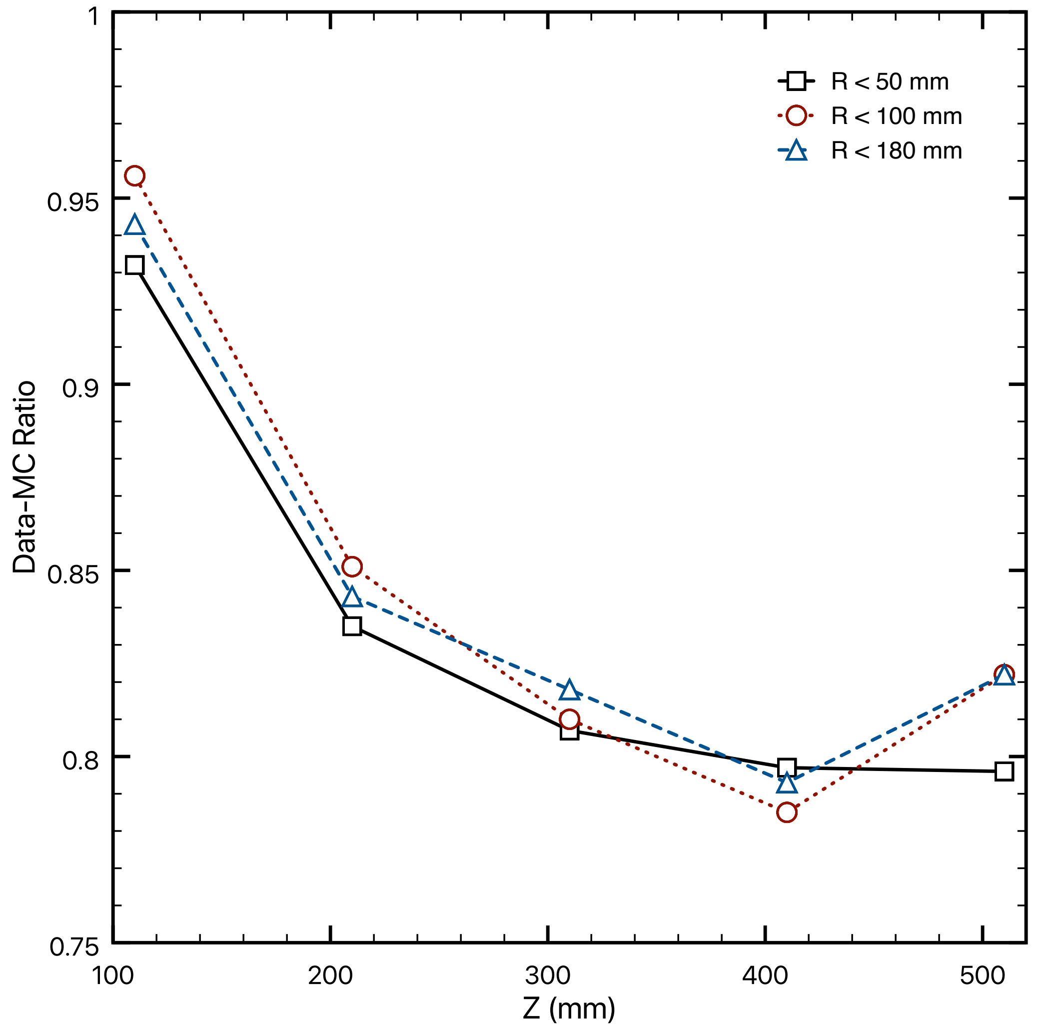


The NEXT Collaboration (P. Novella et al.) *JHEP* 09 (2023) 190

Monte Carlo simulations in NEXT-White

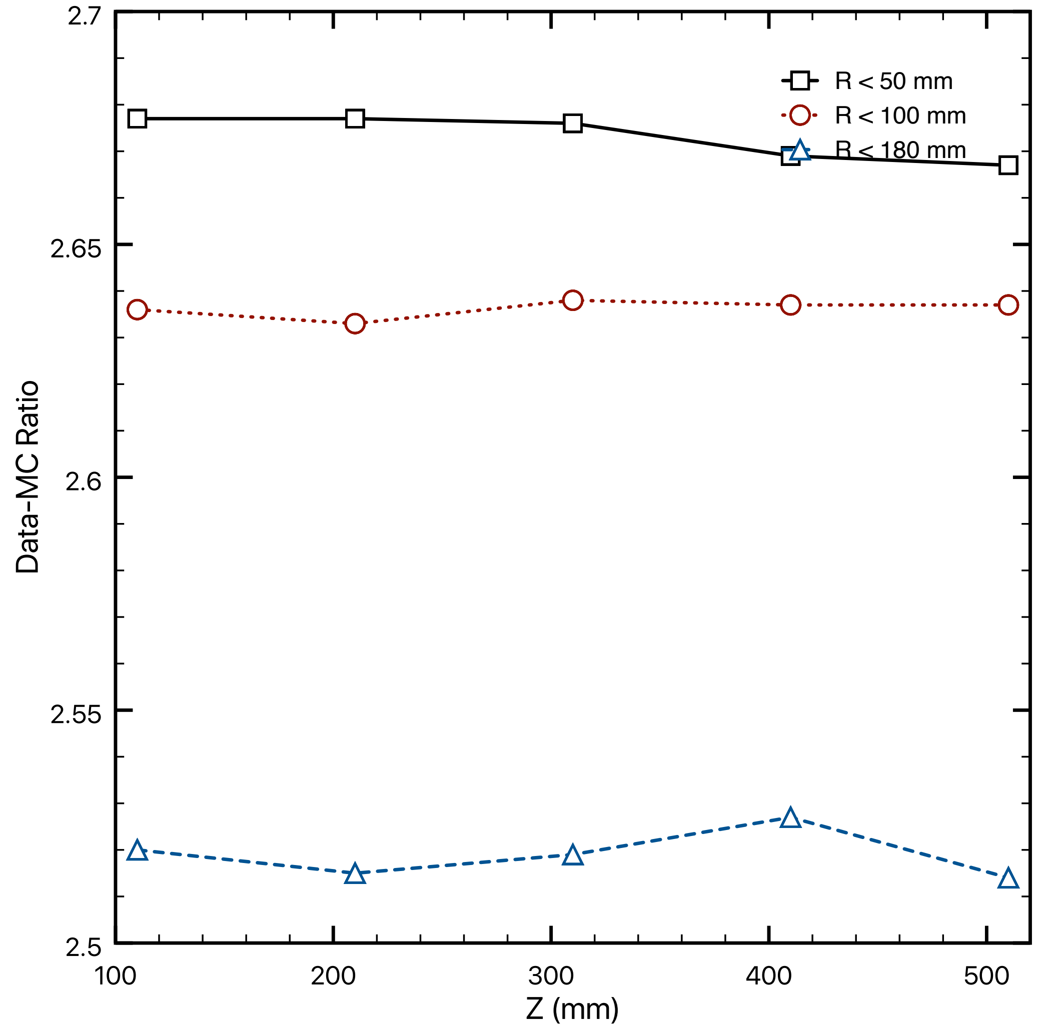
- Data/MC comparison of sensor response to primary and secondary scintillation.

S1 in the PMT sum



agreement within 20%

S2 in the PMT sum



larger discrepancy

- Good agreement for S1 (light produced all over the detector).
- 2.5 more light in data for S2 (issue in EL production, probably).
- Recent upgrade with simulation of reflection of VUV photons on grids —> ~40% more S2 light on PMTs - still large discrepancy.