UCLA College | Physical Sciences
Physics & Astronomy

Simulating Dark Matter Detection with GEANT4 and G4VR

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Cali-X TPC

- Incident particle interacts with xenon nucleus → scintillation light (S1) detected by photomultiplier tubes (PMTs)
- Interaction ionizes atoms, freeing electrons, which travel upward due to electric field
- Electrons reach the top → produce second signal (S2)
- Timing of S1 and S2, PMT data used to reconstruct initial particle trajectories

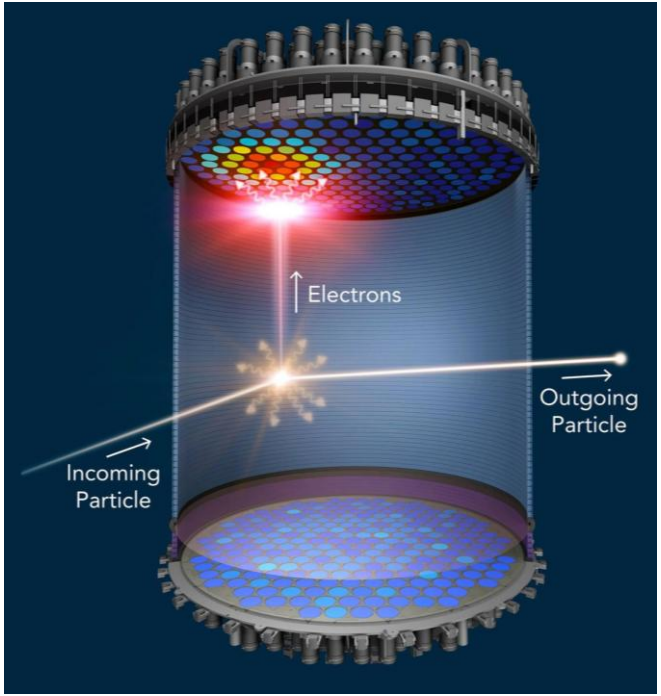


Fig. 1: Example of scintillation process in LZ detector [8]

Cali-X TPC

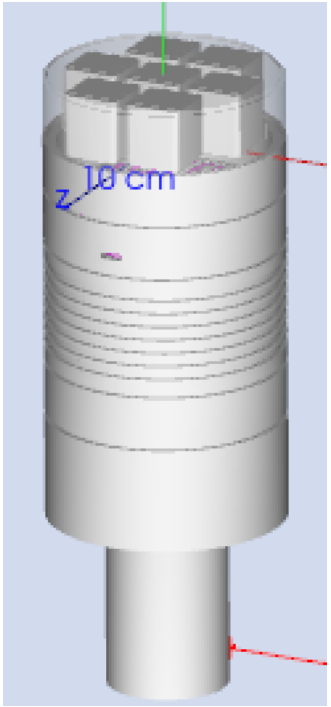


Fig. 2: GEANT4 Simulation of Cali-X TPC

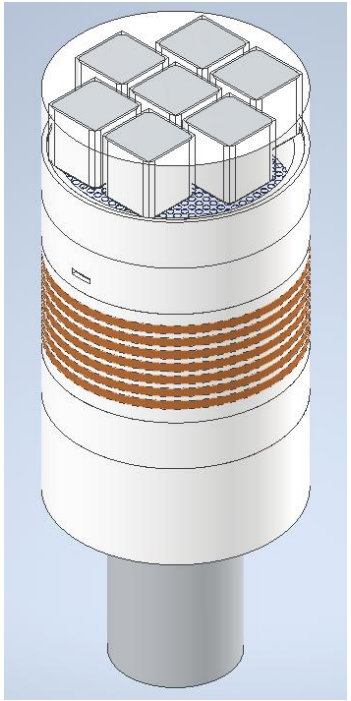


Fig. 3: CAD Drawing of Cali-X TPC [4]

What is GEANT4?

- GEANT4 = GEometry ANd Tracking 4
- “Toolkit for the simulation of the passage of particles through matter”
- C++ based platform that uses Monte Carlo methods to simulate interactions between particles

Designing the Simulation

DETECTOR GEOMETRY

- Can manually build volumes in C++ or import CAD files

3 Types of Volumes

- Solid
  - Shape of component
- Logical
  - Material, visual attributes, detection properties
- Physical
  - Location, orientation

PARTICLES AND SOURCES

- Particle Gun
  - Point source
  - Specified direction, momentum
  - Best for simple monoenergetic sources
- General Particle Source (GPS)
  - Point or volume source
  - Better for more complex sources

Designing the Simulation

PHYSICS AND FIELDS

- Specify desired physics
- Reduce computational cost
- prevent unwanted interactions (e.g. gravitational force)
- Implement electric fields in liquid xenon
- Implement Noble Element Simulation Technique (NEST) package to accurately determine photon and electron yields from scintillation

```
RegisterPhysics (new G4OpticalPhysics());
RegisterPhysics (new G4DecayPhysics());
RegisterPhysics (new G4RadioactiveDecayPhysics());
RegisterPhysics (new G4HadronElasticPhysicsHP());
RegisterPhysics (new G4HadronPhysicsQGSP_BIC_HP());
RegisterPhysics (new G4IonElasticPhysics());
RegisterPhysics (new G4IonPhysics());
RegisterPhysics (new G4StoppingPhysics());
RegisterPhysics (new G4EmLowEPPhysics());
RegisterPhysics (new G4StepLimiterPhysics());
```

Fig. 4: GEANT4 physics lists included in experiment

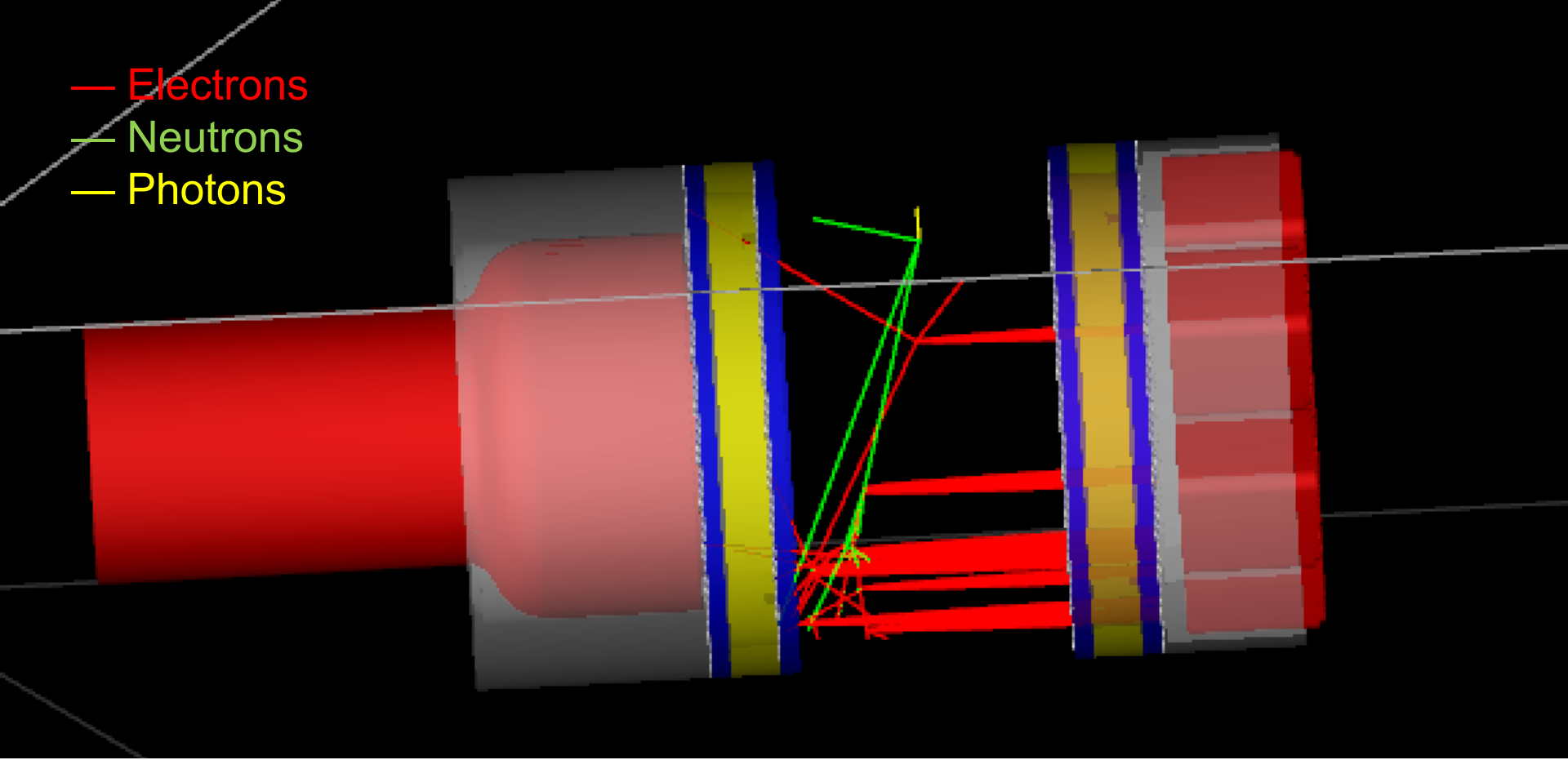


Fig. 7: S2 event as seen in GEANT4 viewer

Visualization in Virtual Reality

- G4VR is a visualization tool developed by Benjamin Jobilal that allows GEANT4 runs to be viewed in virtual reality
- View energy depositions in specific volumes, energy depositions of specific tracks
- Time evolution for GEANT4 example scenes
- G4XR saves scene geometry as a .glb file and each run as an individual .csv file
- This data is stored on a local server and parsed by G4VR to produce the scenes we see in VR

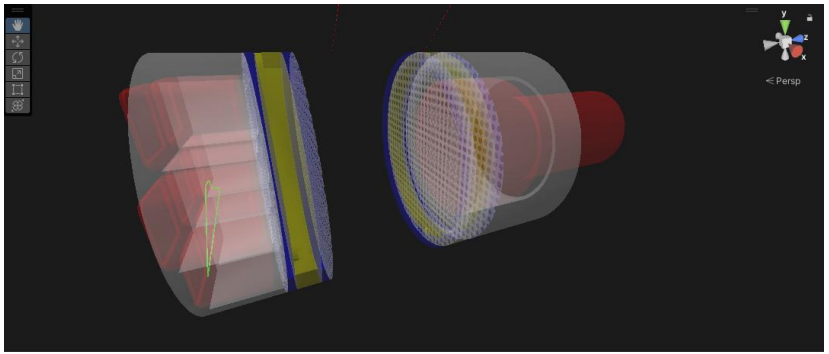


Fig. 8: CALI-X TPC as seen in G4VR

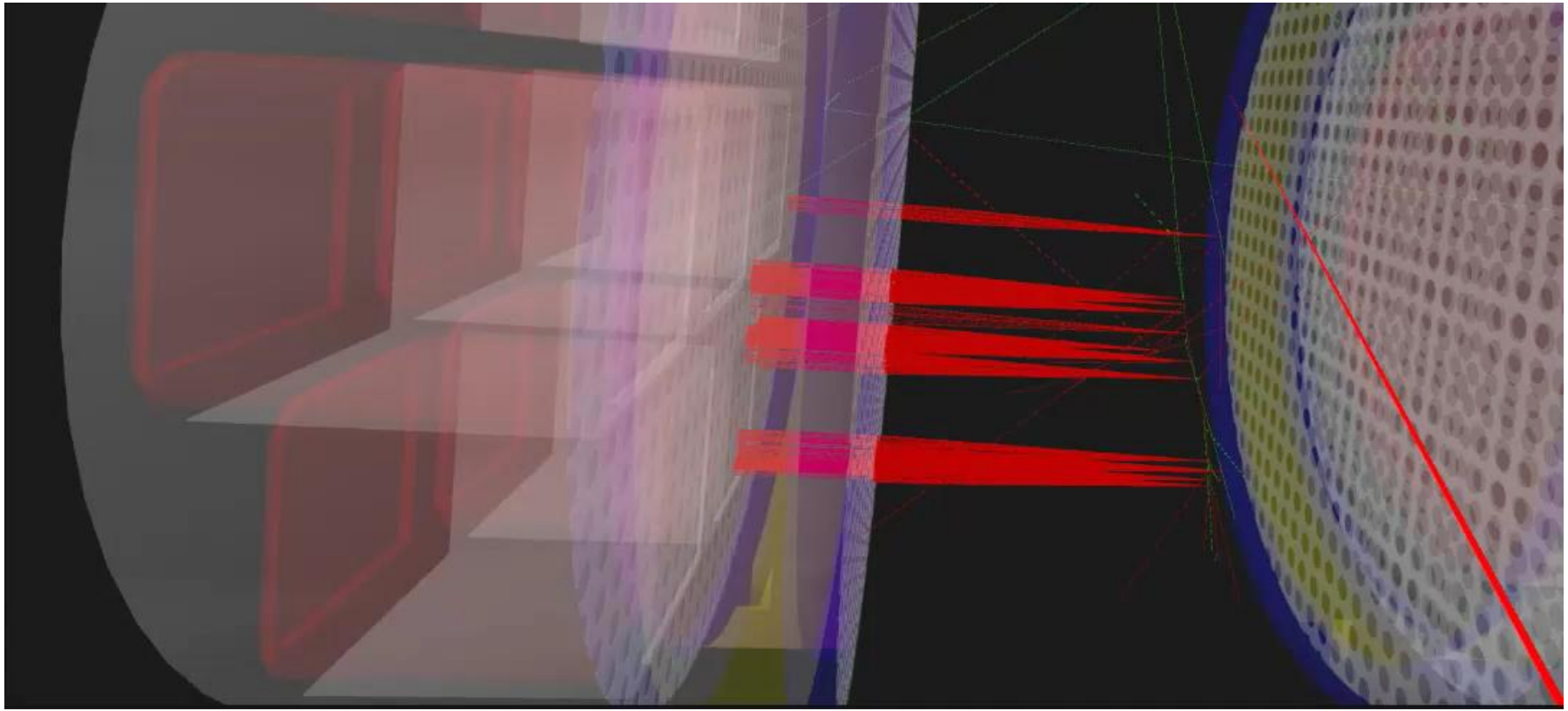


Fig. 8: Example event in GEANT4 simulation viewed in virtual reality via G4VR

Simulating Dark Matter in GEANT4

DMG4

- DMG4 is a GEANT4 add-on developed by Mikhail Kirsanov
- Simulates dark matter production in electron, muon, and positron beams
- Plan to implement this in simulation when testing additional sources

NEST

- NEST has options for simulating yields for WIMP collisions
- Plan to explore this further to see what impacts it can have

Next Steps

- Test more sources to try to replicate results from real detector (AmBe, DD, tritium, etc.)
- Compare electron drift time and drift velocity to real-world results
- Validate scintillation signal ratios
- Create completely accurate visualization of electric field lines inside the TPC using FEniCS software

Thank You

References

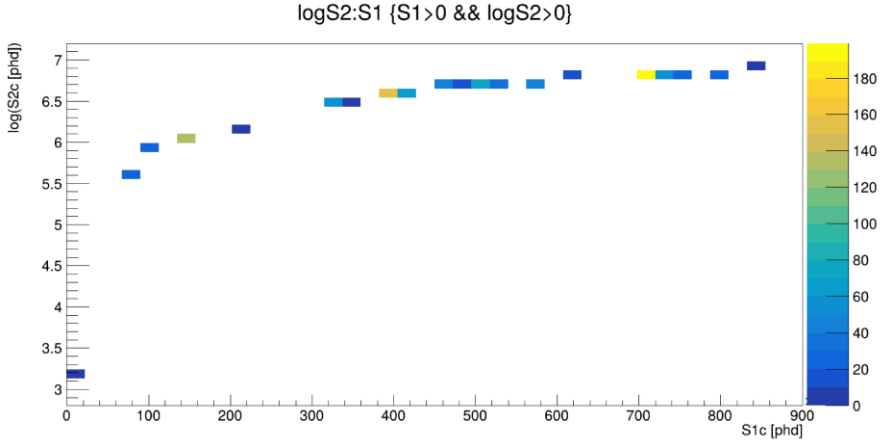
[1] Geant4 - A Simulation Toolkit, S. Agostinelli et al., Nucl. Instrum. Meth. A 506 (2003) 250-303. https://www.sciencedirect.com/science/article/pii/S0168900203013688.
[2] Geant4 Developments and Applications, J. Allison et al., IEEE Trans. Nucl. Sci. 53 (2006) 270-278. https://ieeexplore.ieee.org/xpls/abs_all.jsp?isnumber=33833&arnumber=1610988&count=33&index=7.
[3] Recent Developments in Geant4, J. Allison et al., Nucl. Instrum. Meth. A 835 (2016) 186-225. https://www.sciencedirect.com/science/article/pii/S0168900216306957.
[4] Prototype Detector Final Version, Luca Niu, et al., Kamaha Group, UCLA (2025). https://docs.google.com/presentation/d/15N71nAC3xxZmDA2WFhQfdvlNhiy-njhQEvkuFIxO7SQ/edit?slide=id.p#slide=id.p.
[5] CADMesh GitHub Repository, Christopher Poole, MIT (2020). https://github.com/christopherpoole/CADMesh.
[6] NESTCollaboration/nest: Geant4 Integration Fixes and Updates (v2.0.1beta), Jason Brodsky, Chris Tunnell, M. Szydagis, J Balajth, Vetri Velan, & Junying Huang, (2019). Zenodo. https://doi.org/10.5281/zenodo.2535713.
[7] The LUX-ZEPLIN (LZ) Experiment, D.S. Akerib, et. al., The LZ Collaboration (2019). https://arxiv.org/pdf/1910.09124.
[8] NNSA explores unsolved mysteries of science: What is dark matter?, National Nuclear Security Administration (2018). https://www.energy.gov/nnsa/articles/nnsa-explores-unsolved-mysteries-science-what-dark-matter.
[9] Dark matter detection receives 10-ton upgrade, Eric Hamilton (2017). https://news.wisc.edu/dark-matter-detection-receives-10-ton-upgrade/.
[10] Geant4 Tutorials, Physics Matters (2021-2022). https://www.youtube.com/playlist?list=PLLybgCU6QCGWgzNYOV0SKen9vqg4KXeVL.
[11] CERN ROOT Tutorials, Physics Matters (2020-2022). https://www.youtube.com/playlist?list=PLLybgCU6QCGWLdDO4ZDaB0kLrO3maeYAe.
[12] Fully Geant4 compatible package for the simulation of Dark Matter in fixed target experiments, M. Bondi (2021). https://arxiv.org/abs/2101.12192v3.
[13] First Dark Matter Search Results from the LUX-ZEPLIN (LZ) Experiment, J. Aalbers, et al., (2023). https://arxiv.org/abs/2207.03764.

Backup Slides

Designing the Simulation

DATA COLLECTION

- Data analysis done through ROOT
- Can export histograms, N-tuples,etc.
- Energy depositions, hits, etc. can be analyzed



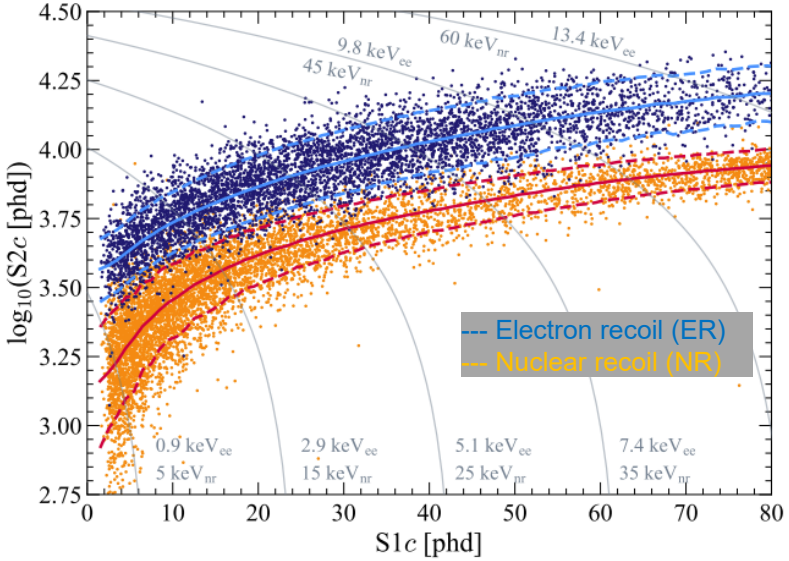


Fig. 5 (Above): Expected ratio of S1 to S2 photons from LZ experiment [13]
Fig. 6 (Left): Ratio of S1 to S2 photons in GEANT4 simulation