October 2022

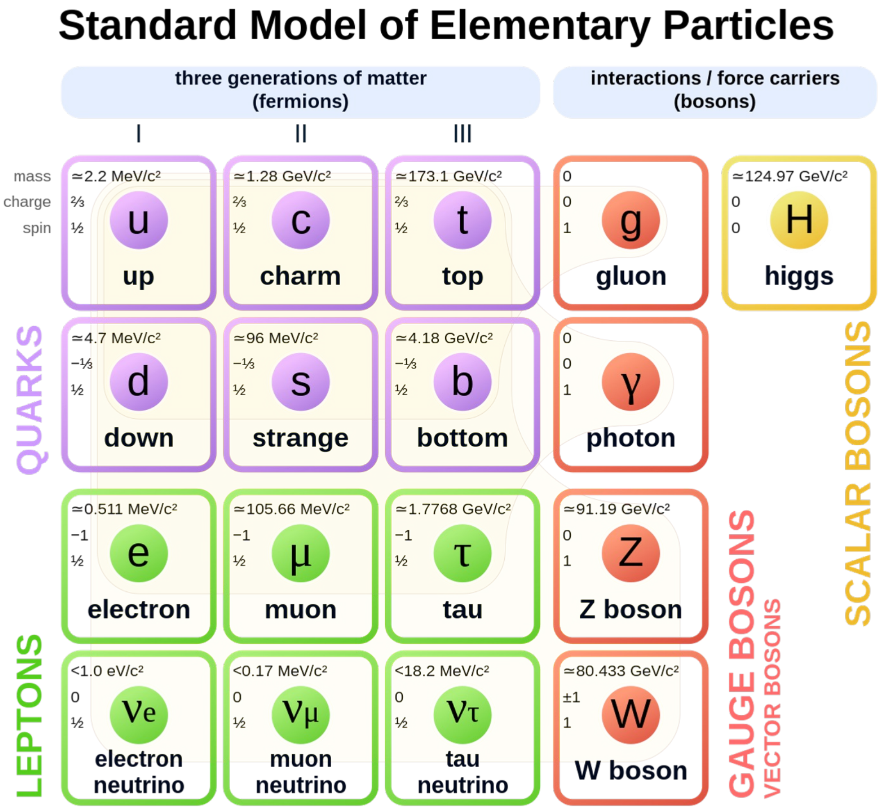
Beyond the Standard Model: Neutrinos and Medical Imaging

Dalton Myers, Wonseok Bae, Kyle Klein, Firas Abouzahr
The University of Texas at Austin

Outline:
-NOvA Test Beam Analysis: Dalton Myers
-LEGEND-1000: Wonseok Bae
-Novel PET Designs: Firas Abouzahr
-TPPT: Kyle Klein

Neutrino Physics

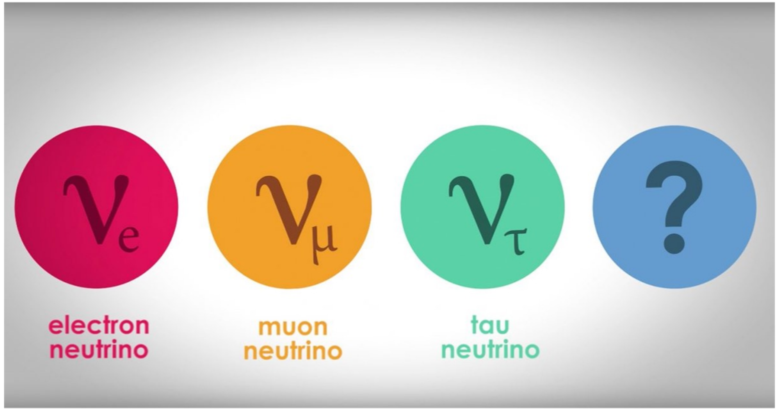
- First postulated by Pauli in 1930 & named by Enrico Fermi
- Modeled as massless by Steven Weinberg in 1967 (A Model of Leptons)
- Neutrino oscillations in late 1990s
- First particle physics beyond the Standard Model
- ***Many* open questions to answer…**



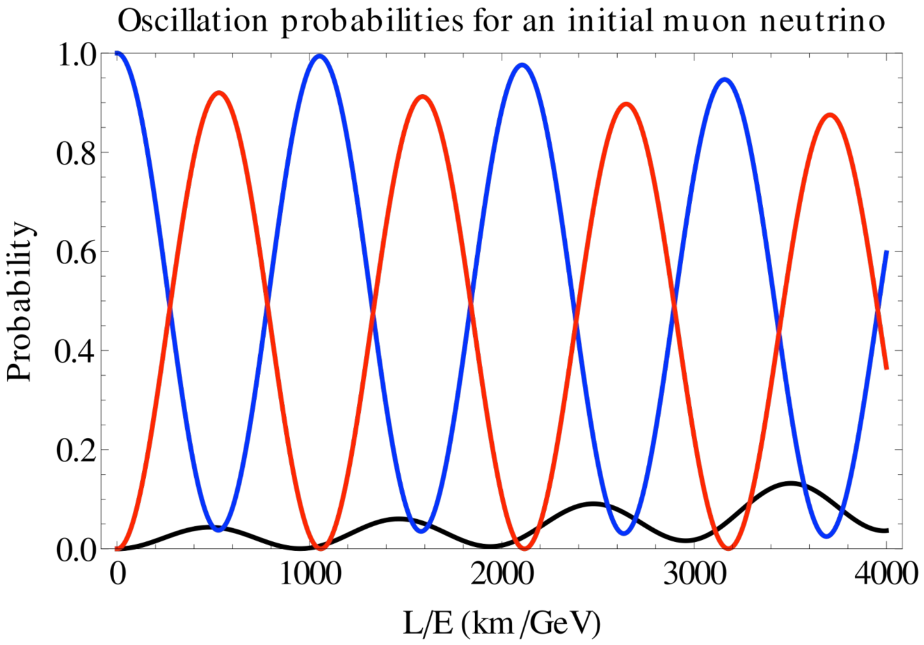
Open Questions in Neutrino Physics

- Majorana or Dirac neutrinos?
- Neutrino Masses?
- CP Violation with neutrino CP Phase?
- Reactor antineutrino anomaly?
- 4th-generation (sterile) neutrinos?
- Origin of ultra-high energy Neutrinos?

And Many More!!!



Neutrino Oscillations

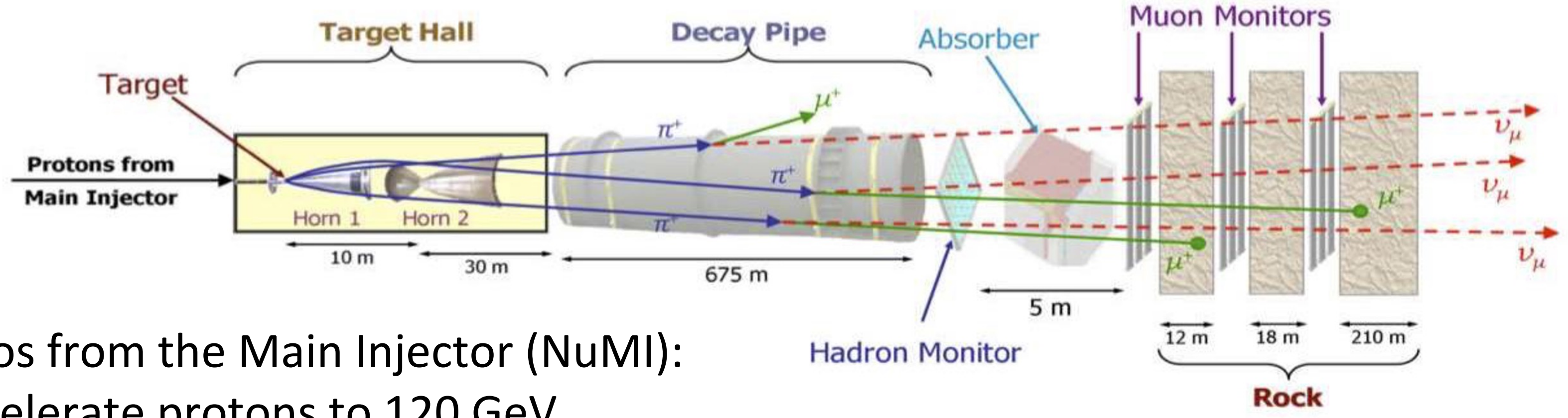


$$P_{\alpha\to\beta,\alpha\neq\beta} = \sin^2(2\theta)\,\sin^2\left(1.27\frac{\Delta m^2 L}{E}\frac{[\mathrm{eV}^2]\,[\mathrm{km}]}{[\mathrm{GeV}]}\right)$$

Oscillation frequency set by Δm^2 ; Max oscillation probability set by mixing angles ; Need to measure 3 of each

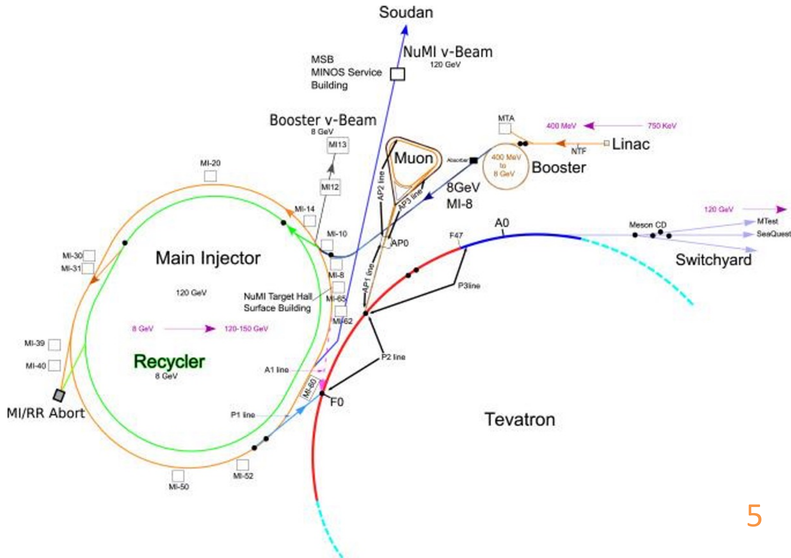
Neutrino oscillations occur because: 1) neutrinos are massive & 2) the neutrino mass eigenstates $\nLeftrightarrow$ flavor eigenstates

Neutrino Beam:

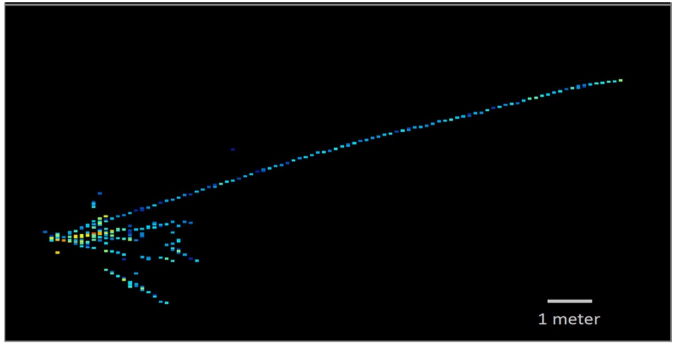


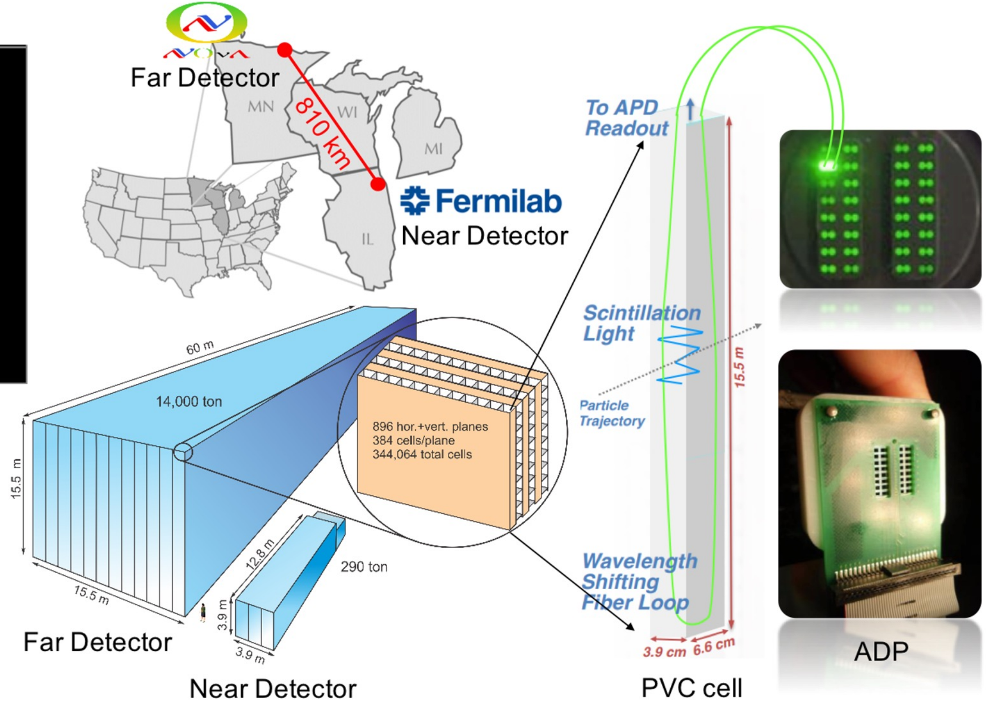
Neutrinos from the Main Injector (NuMI):

1. Accelerate protons to 120 GeV
2. Impact protons on carbon target
3. Focus $\pi^{\pm}$ (charge set by magnetic horn current)
4. Let $\pi^{\pm}$ decay → $\mu^{\pm} + \nu_{\mu}$
5. Absorb $\mu^{\pm}$ (natural rock)



NOvA



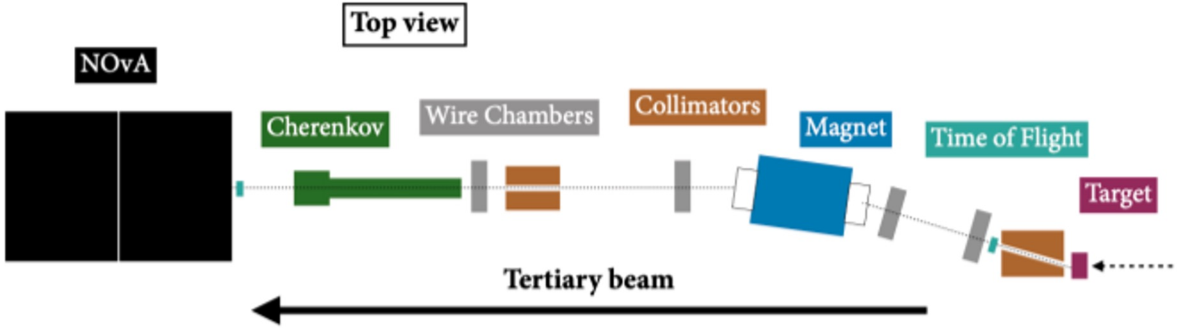


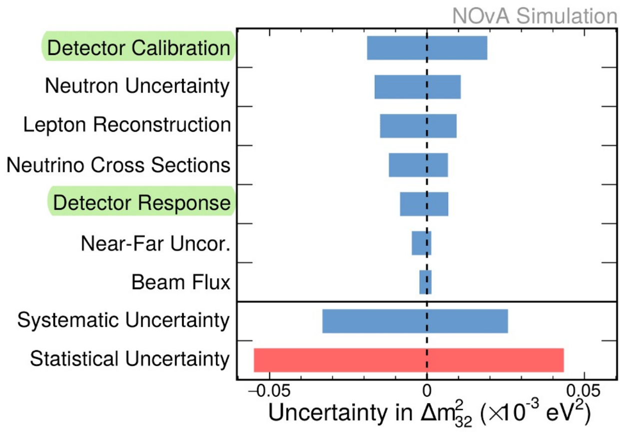
- 2 Detectors
  - ND (Fermilab)
  - FD (Ash River, MN)
- PVC Cells filled with scintillant each with 1 loop of fiber

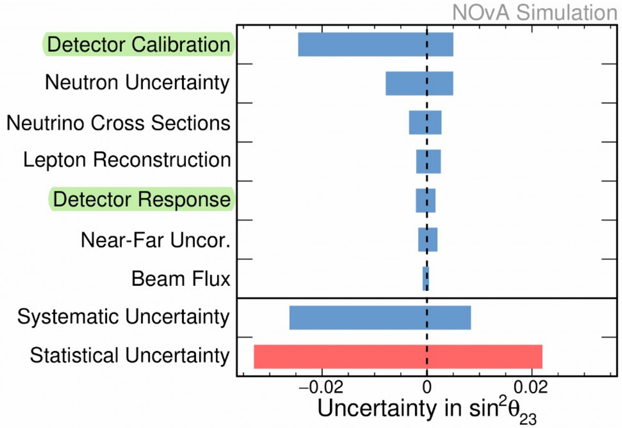
Recent Results

$$\Delta m^2_{32} = (+2.41 \pm 0.07) \times 10^{-3}\mathrm{eV}^2,$$
$$\sin^2\theta_{23} = 0.57^{+0.03}_{-0.04},$$
$$\delta_{CP} = (0.82^{+0.27}_{-0.87})\pi.$$

The NOvA Test Beam

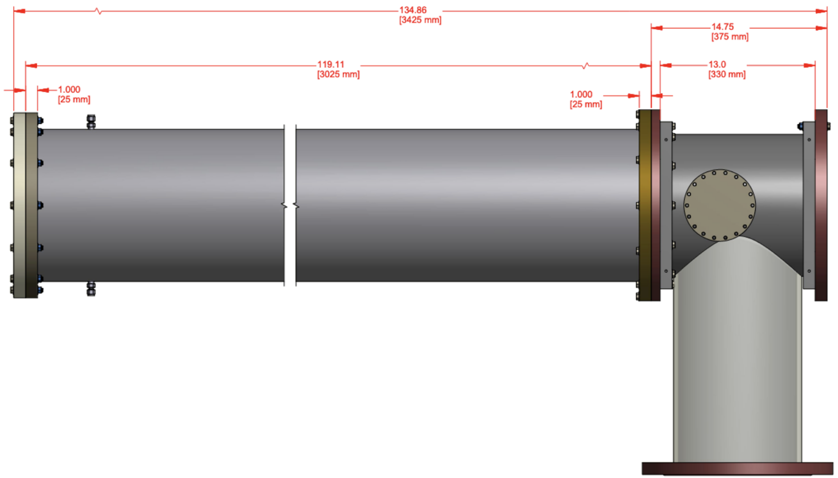


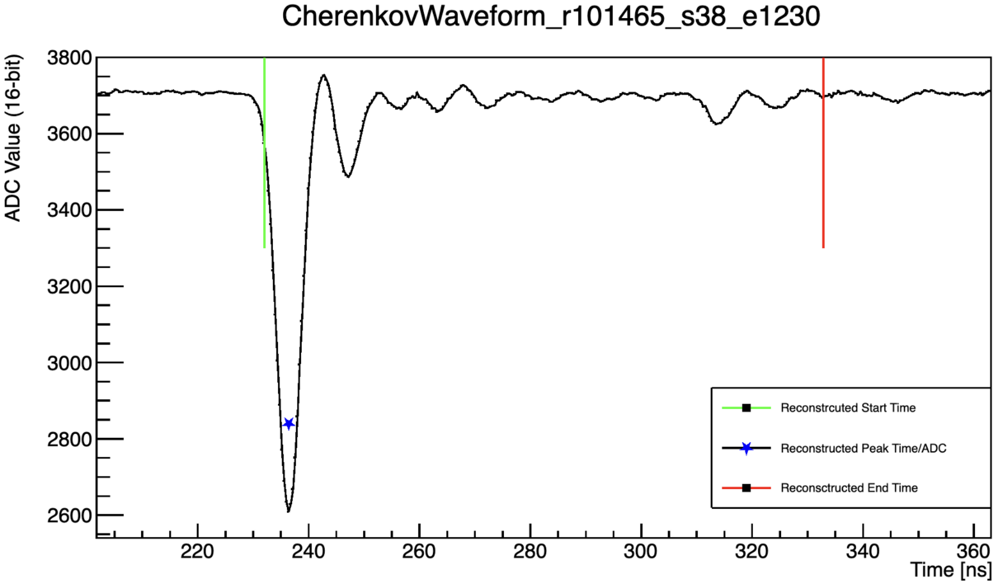




- *Critical importance* to reduction of systematic uncertainties
- Looking at e, μ, π, K, and p → ***not neutrinos***
- Beamline-measuring components measure particles before they enter a scaled-down NOvA detector
- Better understanding of inputs → better reconstruction

The NOvA Test Beam Cherenkov Detector

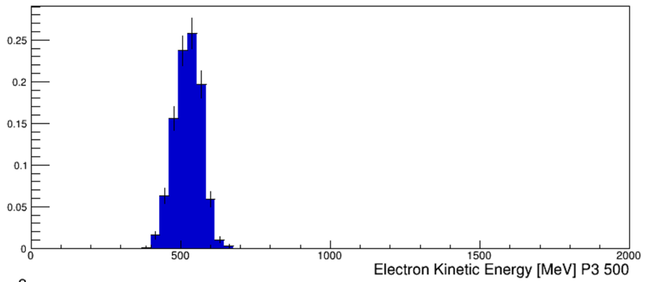


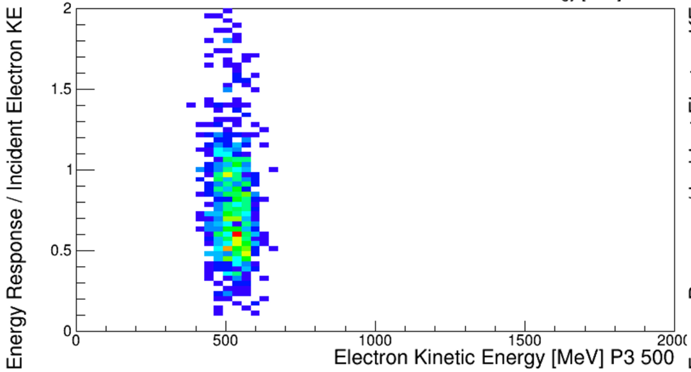


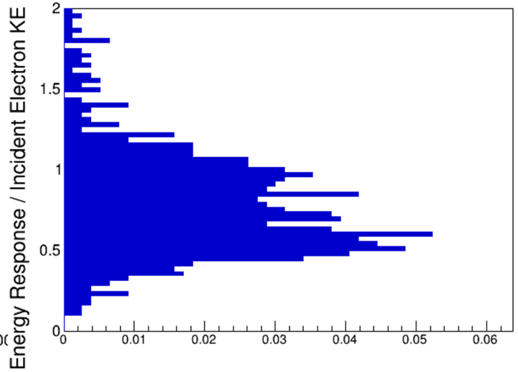
- Designed and built at the UTKL lab
- Tags Electrons by searching for “flashes” of Cherenkov light
- Potential for improvement of electron selection

The NOvA Test Beam Electron Energy Response

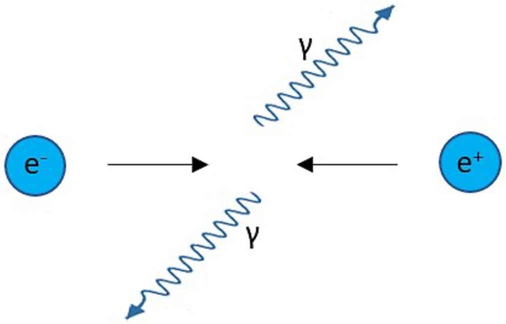
- Characterizing relationship of input particle energy to particle energy response
- More precise calibration → less systematic uncertainty on primary-goal measurements → better limits on primary-goal measurements without any change to NOvA







Neutrinoless Double Beta Decay



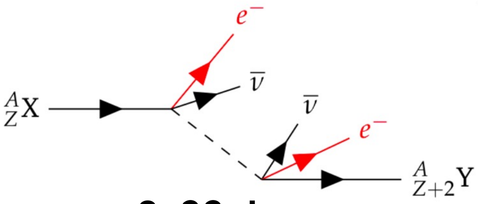
- **Particle** and **antiparticle** collide
→ **Annihilation** and energy is released.

  At the beginning of the universe, **matter and antimatter** were created in equal quantities. If they had remained the **same amount**, they would have annihilated and the **universe would not exist.**

- Something caused an **imbalance between matter and antimatter** → More matter than antimatter.

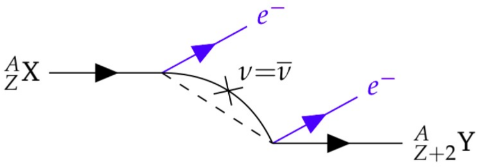
- **Majorana fermion** is a particle that is its own antiparticle. Since neutrinos are the only neutral particles in the standard model, they could be Majorana particles.

- If and only if neutrinos are Majorana particles, **neutrinoless double beta decay** is possible.



2vββ decay

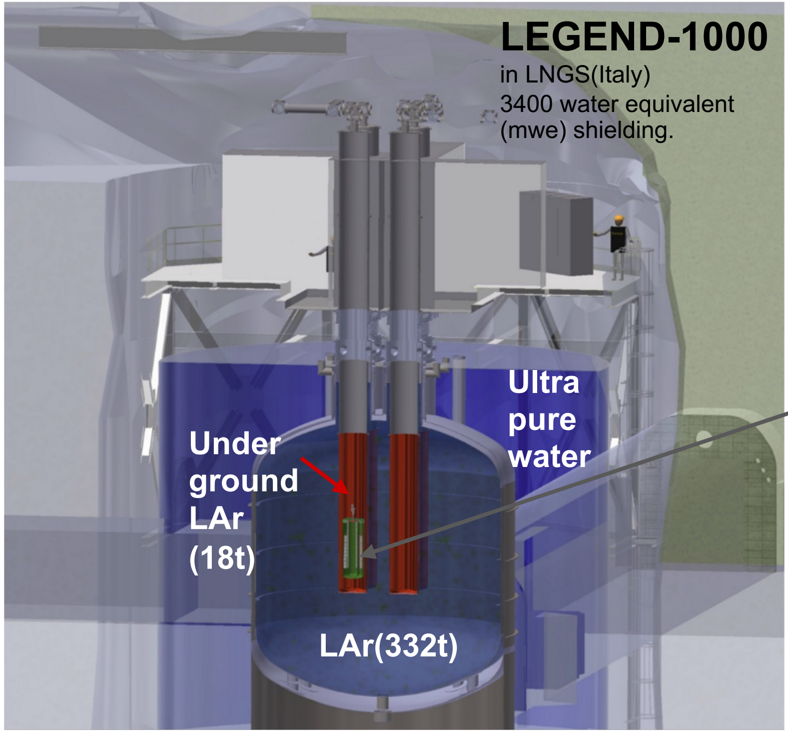
two particles and **two antiparticles** emitted



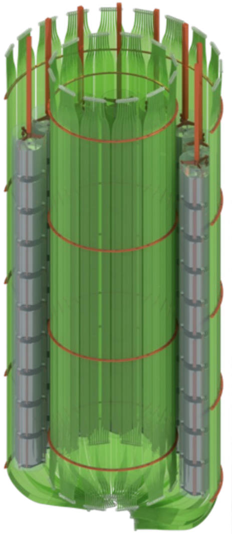
0vββ decay

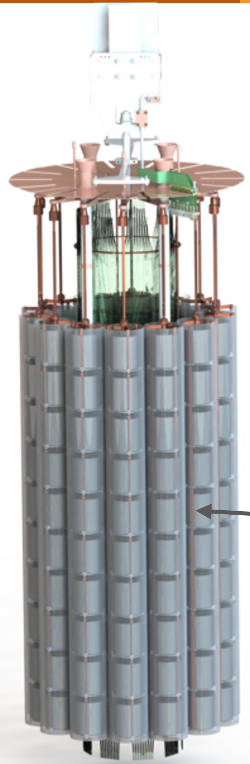
(Lepton number violation)

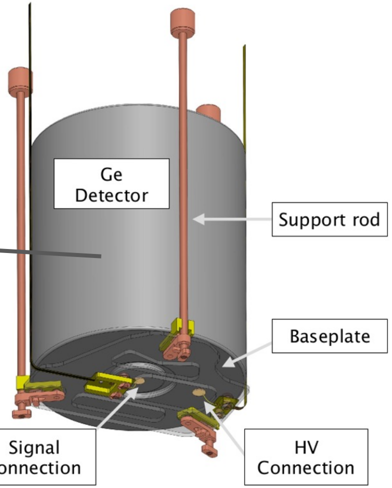
Only two particles emitted



LEGEND-1000 pCDR





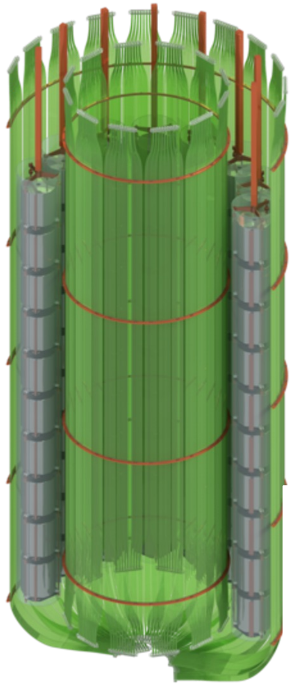


LAr Veto System
→ UTKL Research

Detector Arrays

Ge Detector

Fiber Model



LEGEND-200

1. The **background** near Germanium crystal should be eliminated by detecting those.

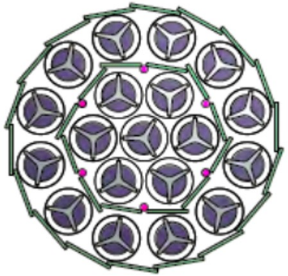
1. All this systems are submerged in Liquid Argon, so the main background is LAr scintillation UV light

1. Fiber coating material shifts the UV light to blue light. Fiber material shifts blue light to green light.

1. Photodetector has a high efficiency to detect green light.

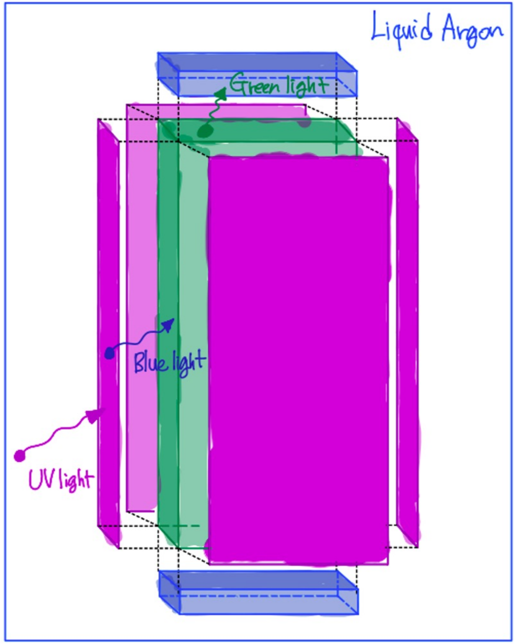
1. So, **UV light(LAr) → blue light(Coating) → green light(Fiber) → detection(SiPM)**

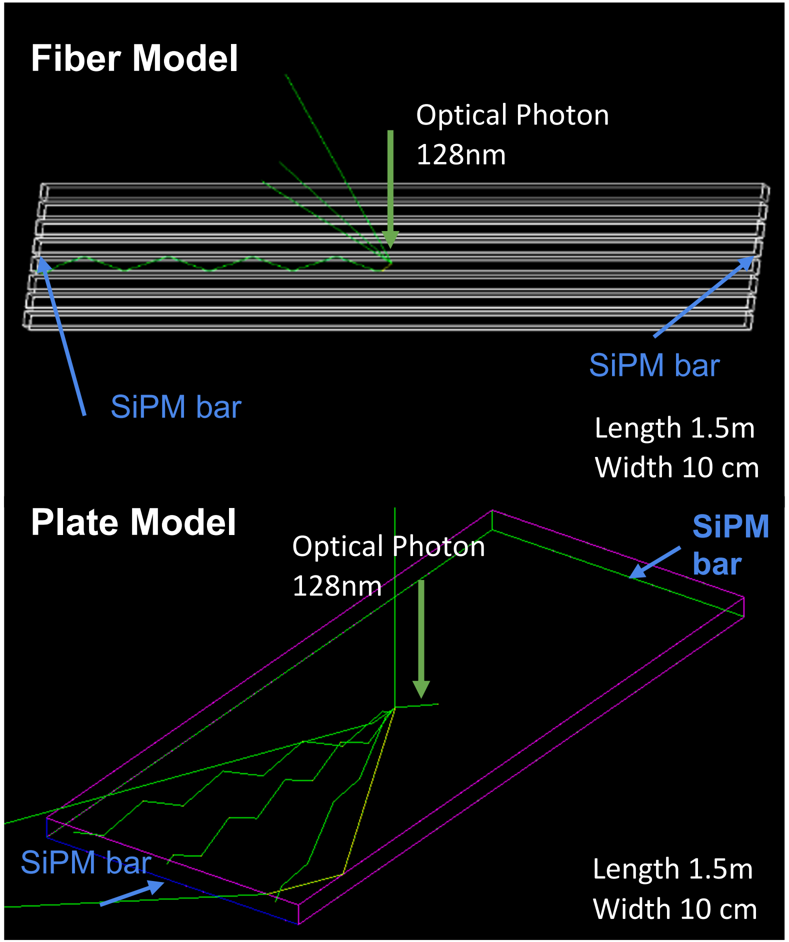
Plate Model



The plate model may able to achieve

1. Better space coverage → **Better global photodetection efficiency**
1. Better radio-purity →**Lower background noise**

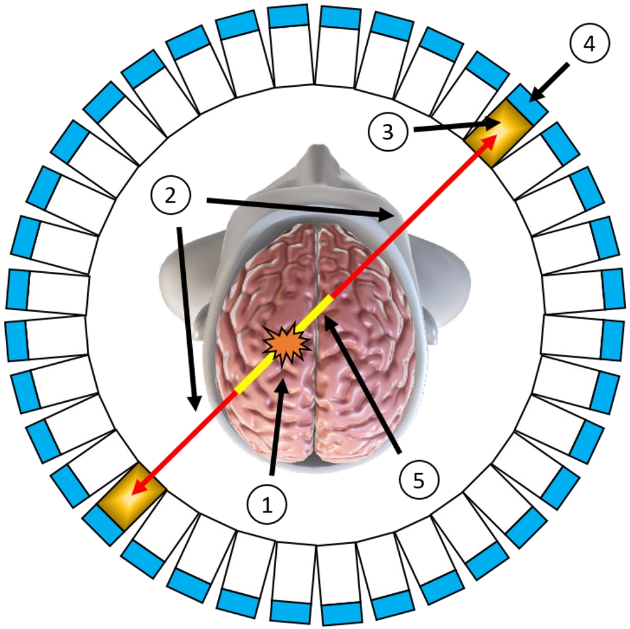




- Simplified simulation but the same condition for fiber/plate.
  -SiPM coupling constant: 100%
  -SiPM detection efficiency: 100%
  -Ignore LAr attenuation.
- Plate shows **~47% better** photo detection efficiency than fiber model.
- We will move to build the set-up and measurement of photo detection efficiency and radio-purity.
- Even without graduate level physics & math, There is a lot of chance to contribute and learn.

Positron Emission Tomography (PET)

- Image Patients from “inside-out”!
  - Patients are injected w/ positron-producing radio-pharmaceutical
- Scintillators convert gamma rays to “optical photons” for better detection efficiency
  - optical photons then detected using Silicon Photomultipliers (SiPMs)



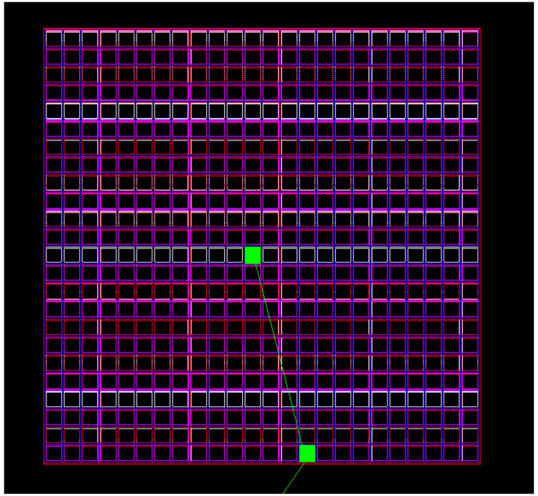
1: Positron annihilates with electron to produce a gamma pair
2: Gamma pair travels to the detector along the Line of Response (LOR)
3: The gammas are detected and converted to optical photons via scintillators
4: The optical photons are detected by SiPMs
5: Based on the detector response, we can localize the annihilation along the LOR

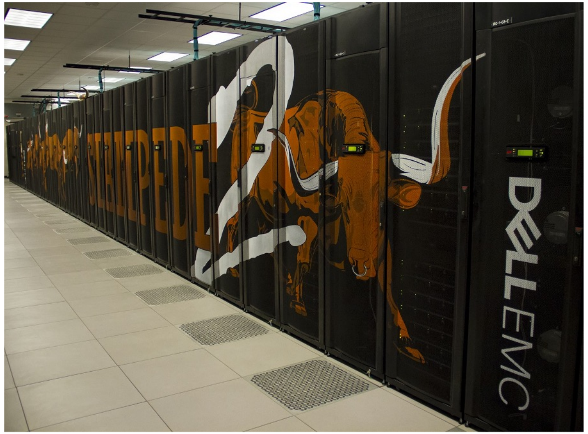
Simulation in GEANT4

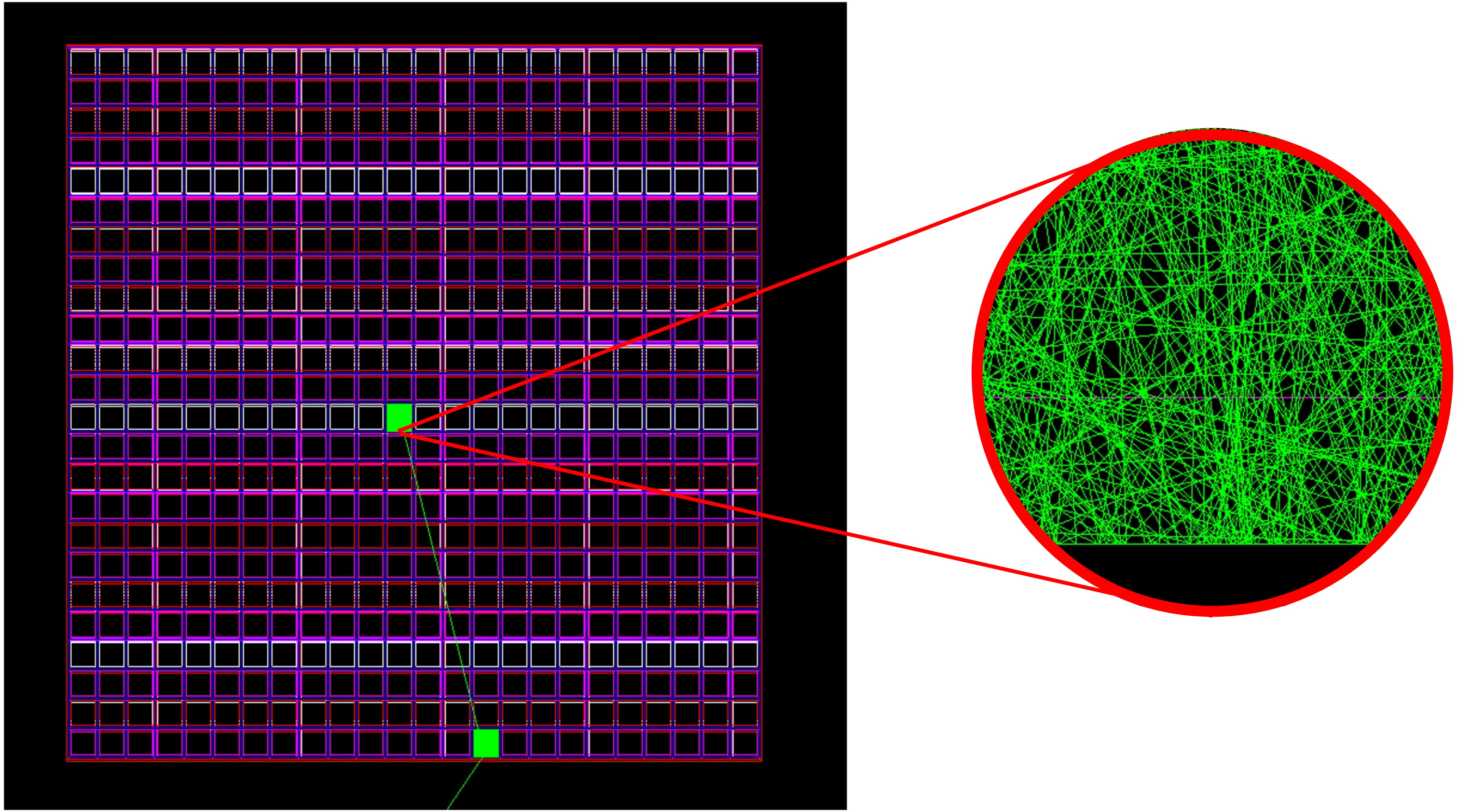
- Novel designs/modifications to PET scanners are constantly being proposed.
  - To acquire grants to test them, we need proof they will work!

- Scanners are expensive....
  - crystals alone can cost ~$100,000!

- We use Monte Carlo particle physics software to simulate PET scanner performance, and run it on the Stampede2 Supercomputer at TACC.





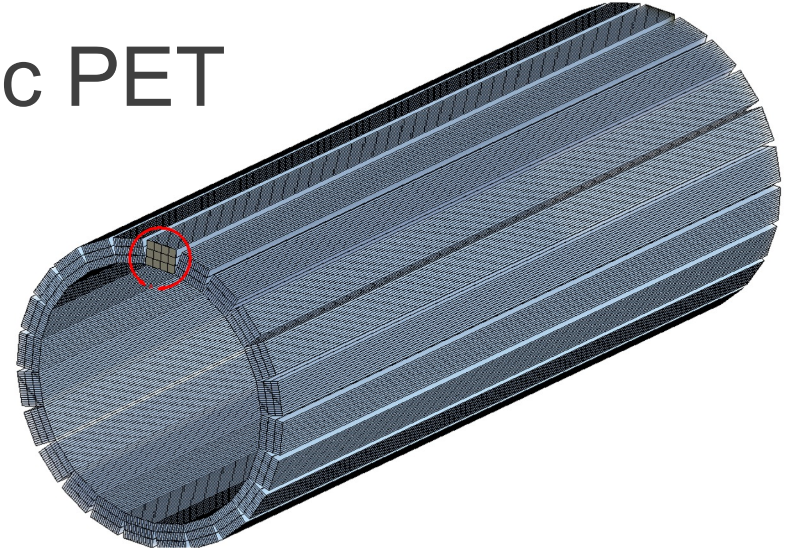


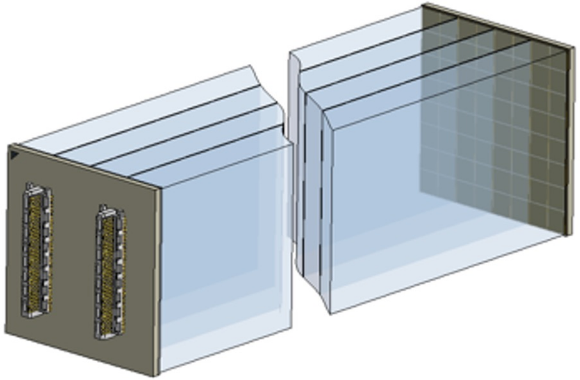
Novel PET Simulations: Plastic PET

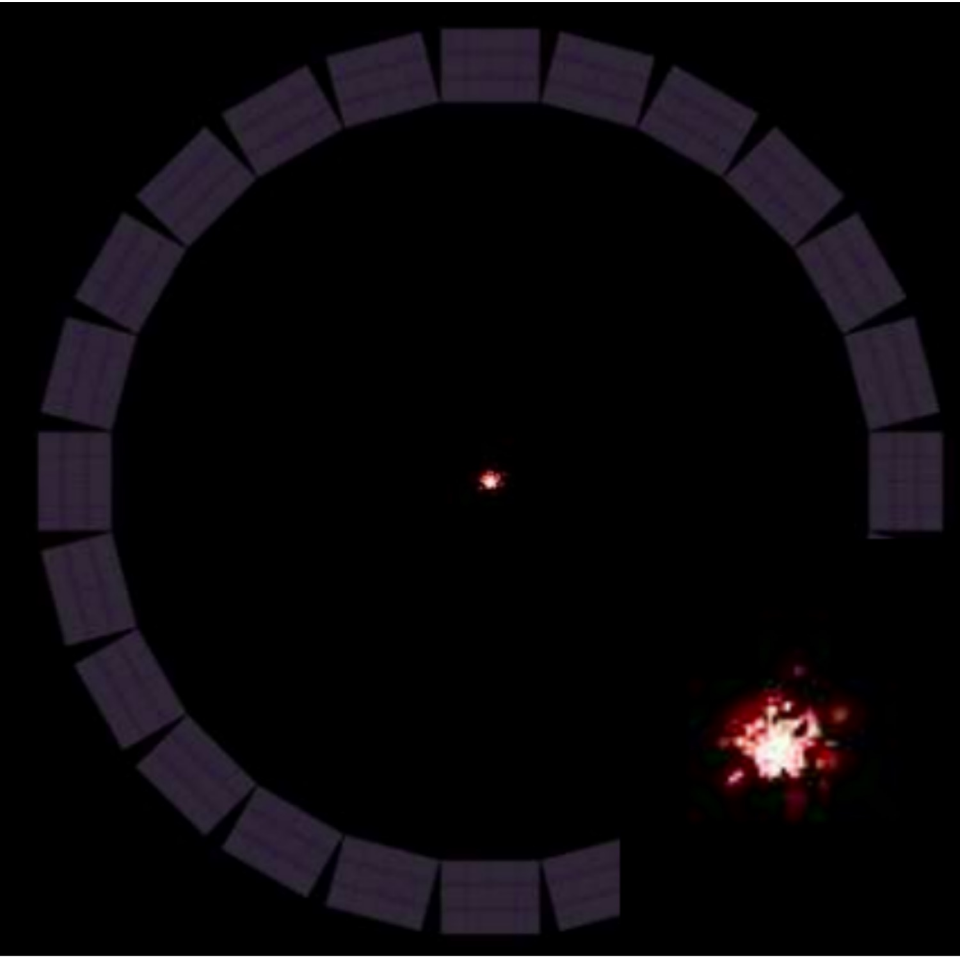
- Full Body PET Scanners are expensive!
    - Top of the Line Siemens Biograph Quadra > $4.5 Million

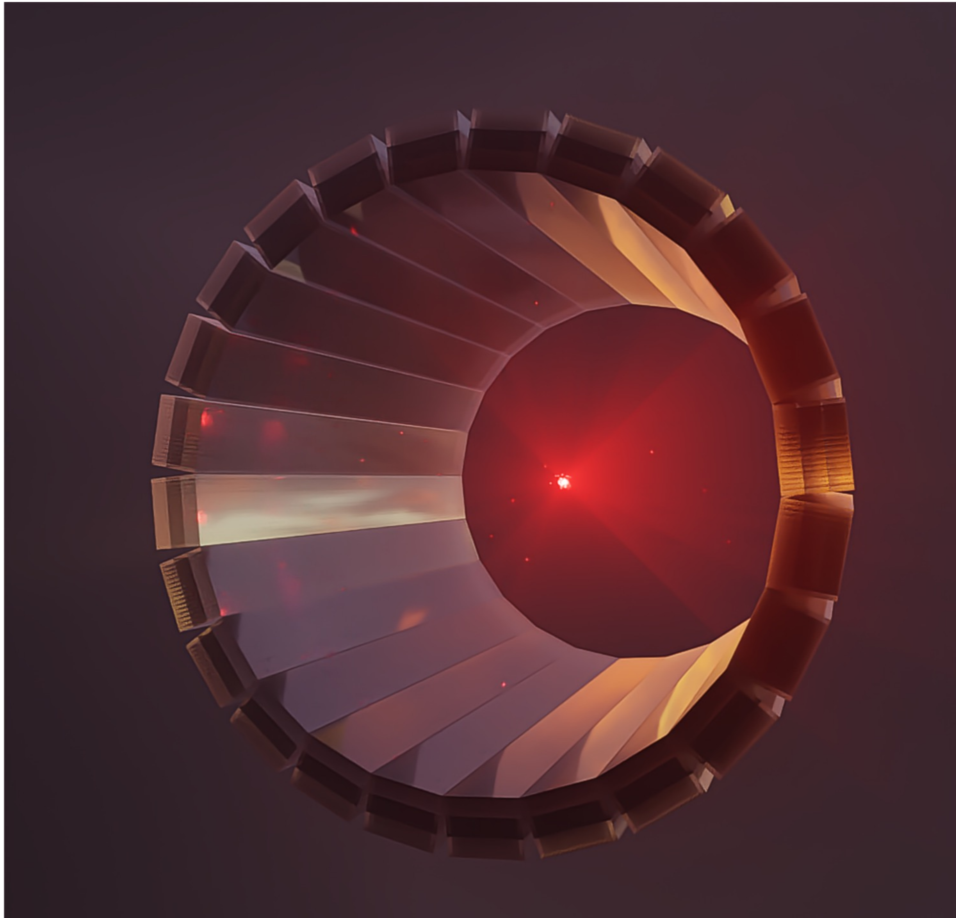
- By using plastic as a scintillant instead of inorganic crystals, the idea is to reduce cost dramatically while retaining the sensitivity benefits of a full body scanner

- There is a reason plastic scintillator is not the choice material for PET scanners, we cannot sacrifice performance!





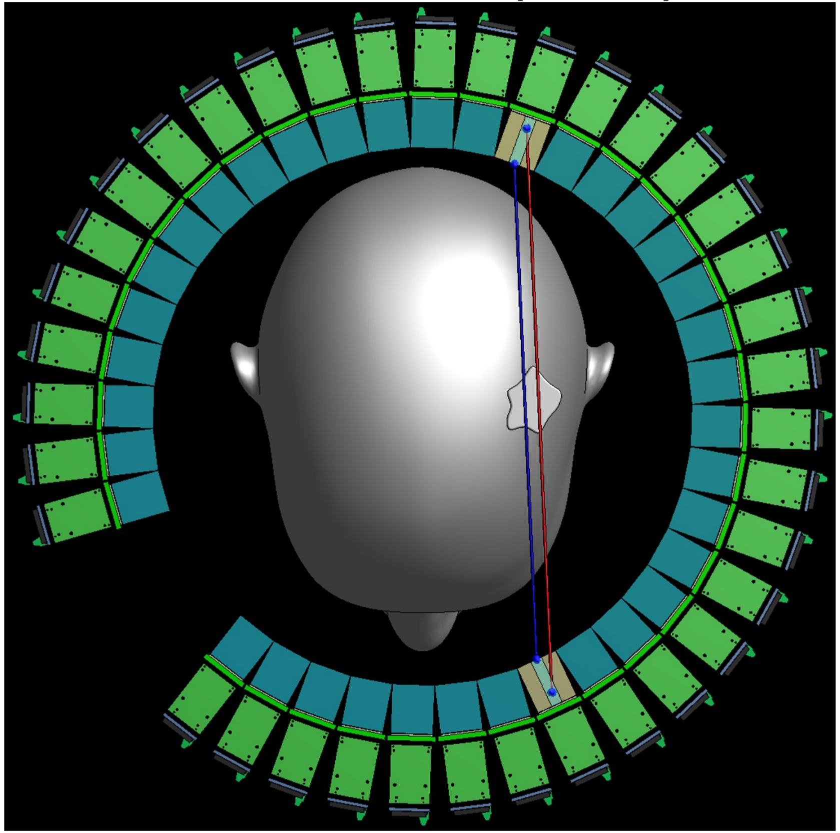




Images courtesy of Akhil Sadam

Novel PET Simulations: Depth of Interaction (DOI)

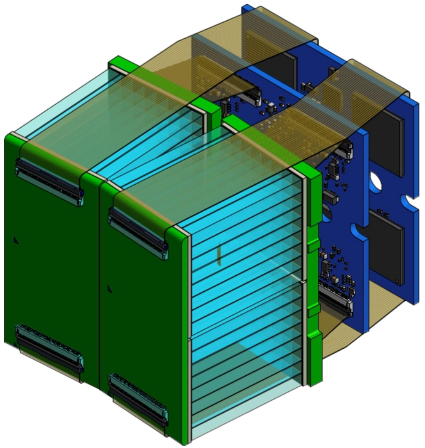
- By knowing the depth at which each gamma ray deposited, we can improve two main aspects of PET imaging:
  - The lines of response (LORs) can be adjusted to better reflect the real gamma pairs (less parallax error)
  - The timing resolution can be improved by reducing the uncertainties associated with light propagation in the crystal

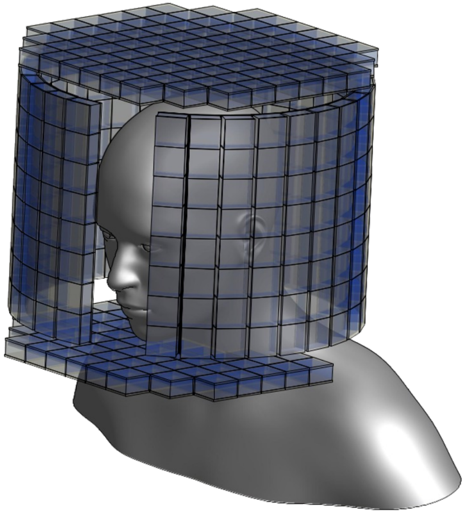


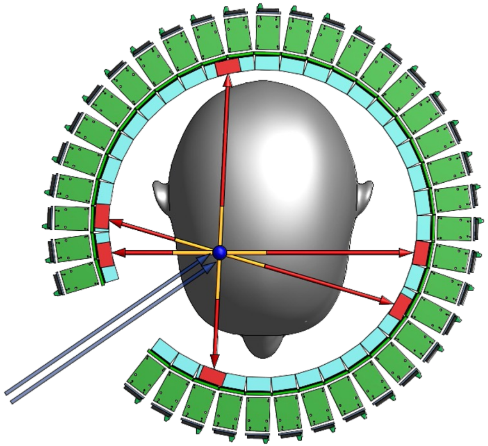
Rendering courtesy of Marek Proga

Novel PET Simulations: Depth of Interaction (DOI)

- To actually get DOI information, we use readout electronics on both ends of the crystal, called double readout (DR)
- We are currently writing an NIH proposal that uses this technology for a brain scanner: Chin Corona Cylinder PET or C^3 PET







Renderings courtesy of Marek Proga

Biomed. Phys. Eng. Express **8** (2022) 025011 https://doi.org/10.1088/2057-1976/ac4f0a

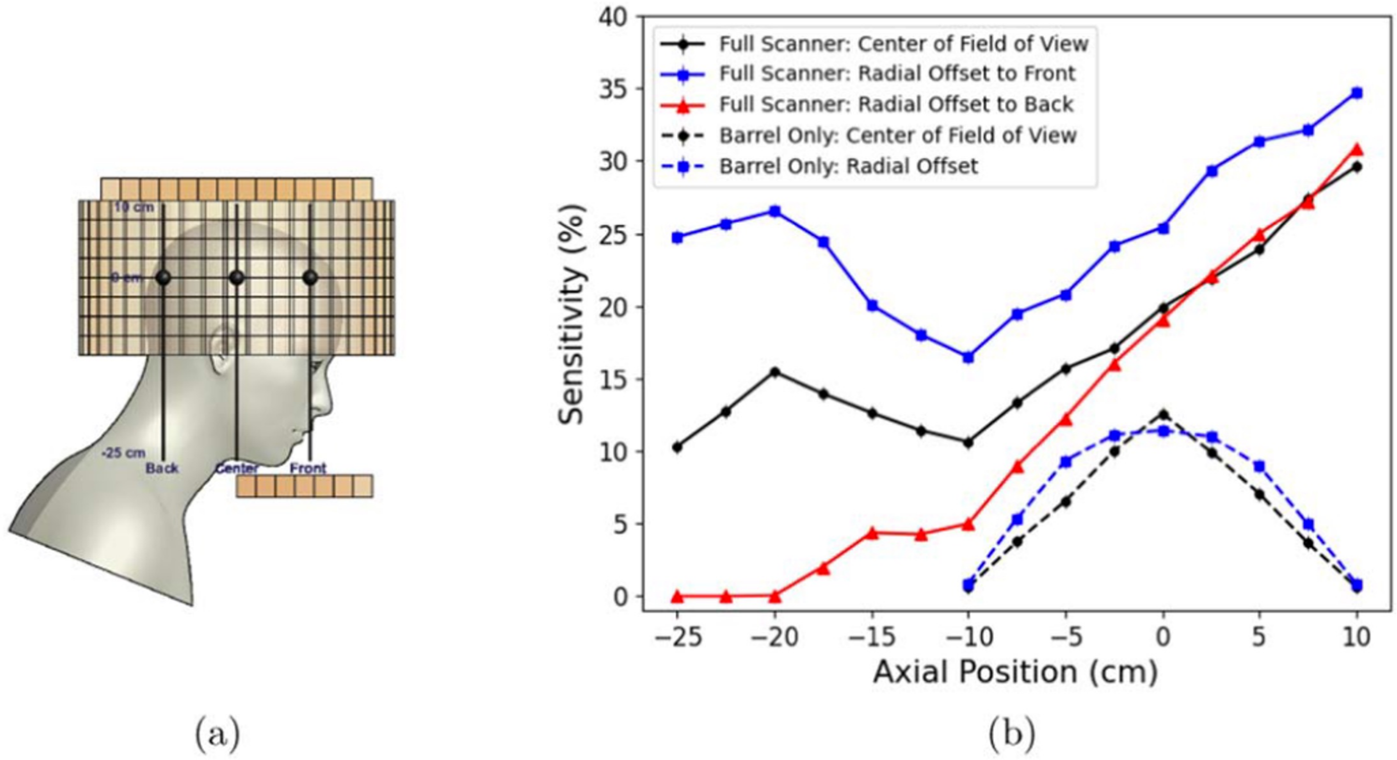
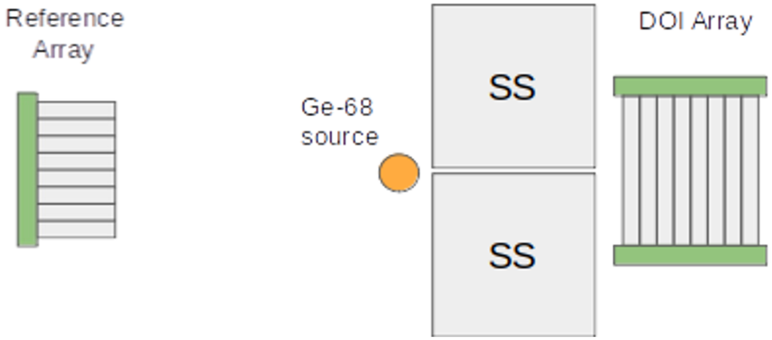


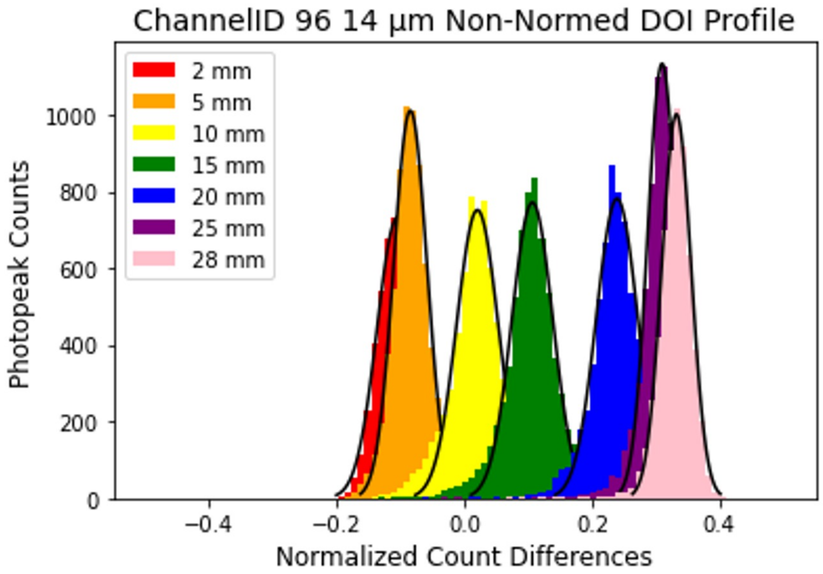
Figure 3. (a) Positions of line sources used for sensitivity predictions. (b) Absolute sensitivities for point sources placed along the line sources, for both the full scanner and barrel module alone, at the center of the radial field of view and at 10 cm radial offsets.

Experimental DOI Research

- We purchased scintillation crystals to study the specifics of obtaining DOI information from double readout crystal arrays and how that depends on crystal surface properties.

- We took data at select depths of interaction to build a full profile of the array

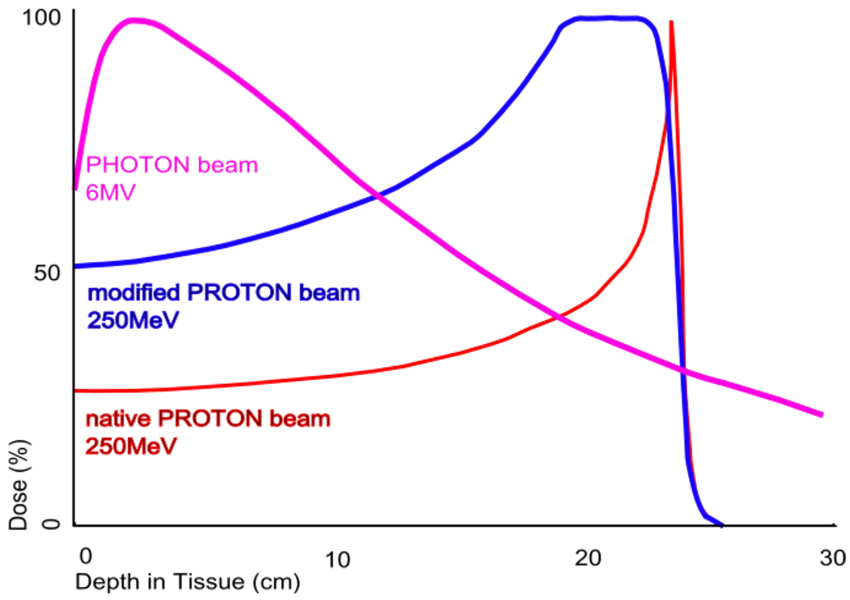




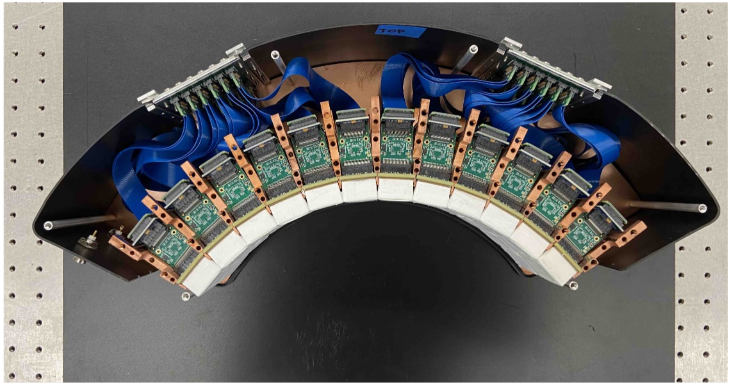
Time of Flight PET for Proton Therapy (TPPT)

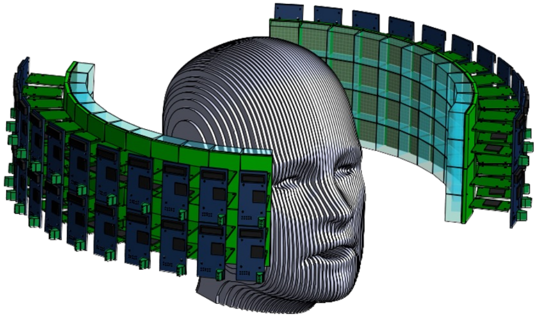
- Proton Therapy is a radiotherapy designed to minimize the damage of healthy tissue
    - Accurately measuring where the beam deposits energy is vital to ensure the treatment is effective and normal tissue is spared i.e. Proton Beam Range Verification

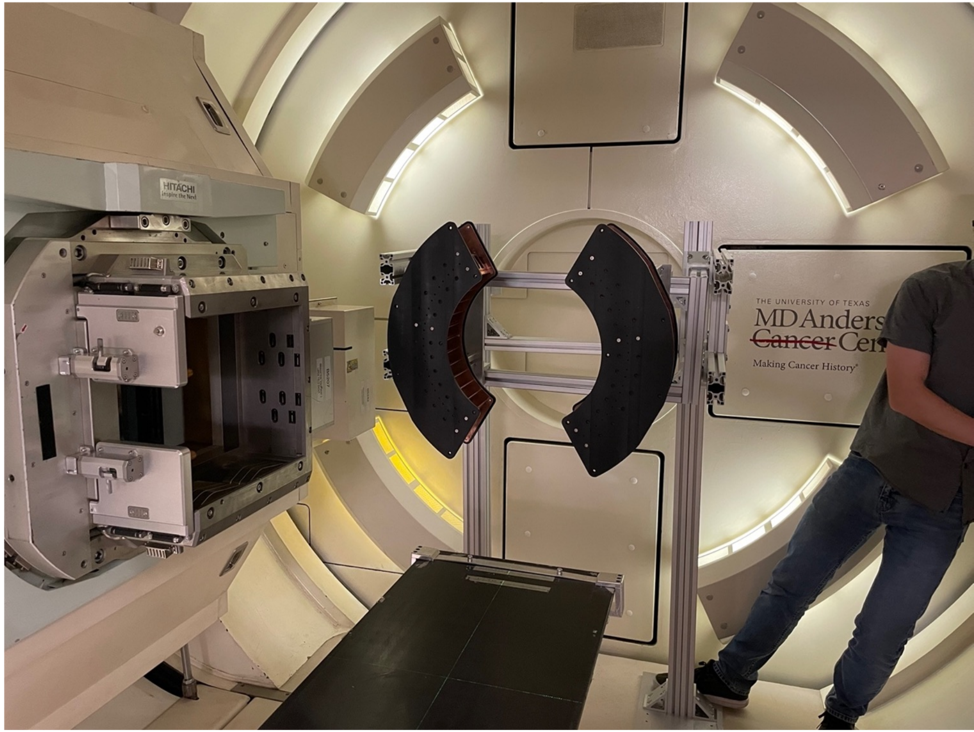
- Our PET system would verify the proton beam deposition by detecting positron emitting isotopes produced by proton beam energy deposition



Time of Flight PET for Proton Therapy (TPPT)

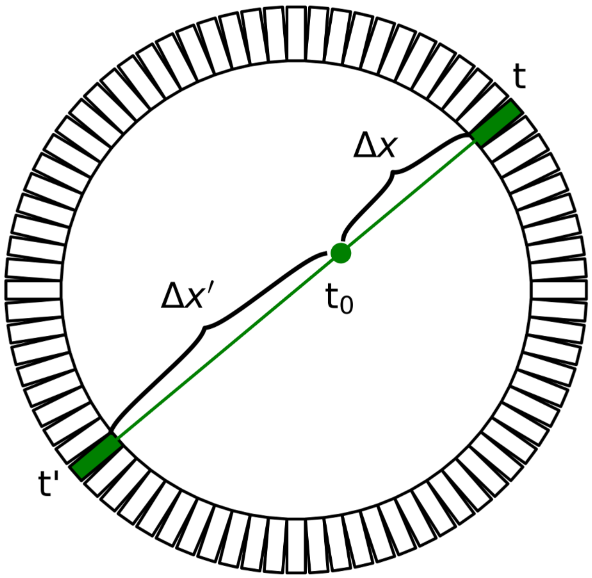






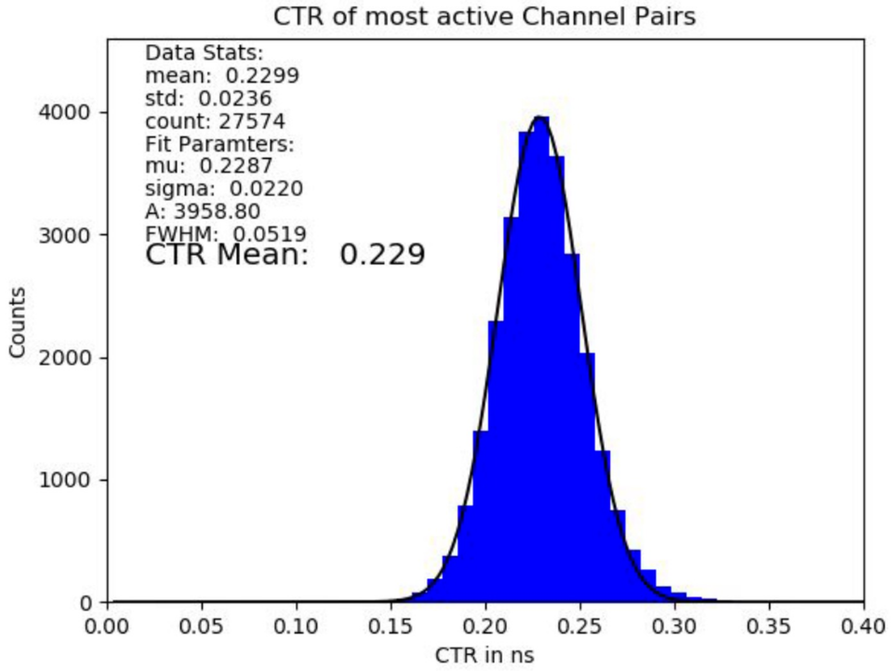
Images and renderings courtesy of Marek Proga

Evaluating the TPPT Scanner

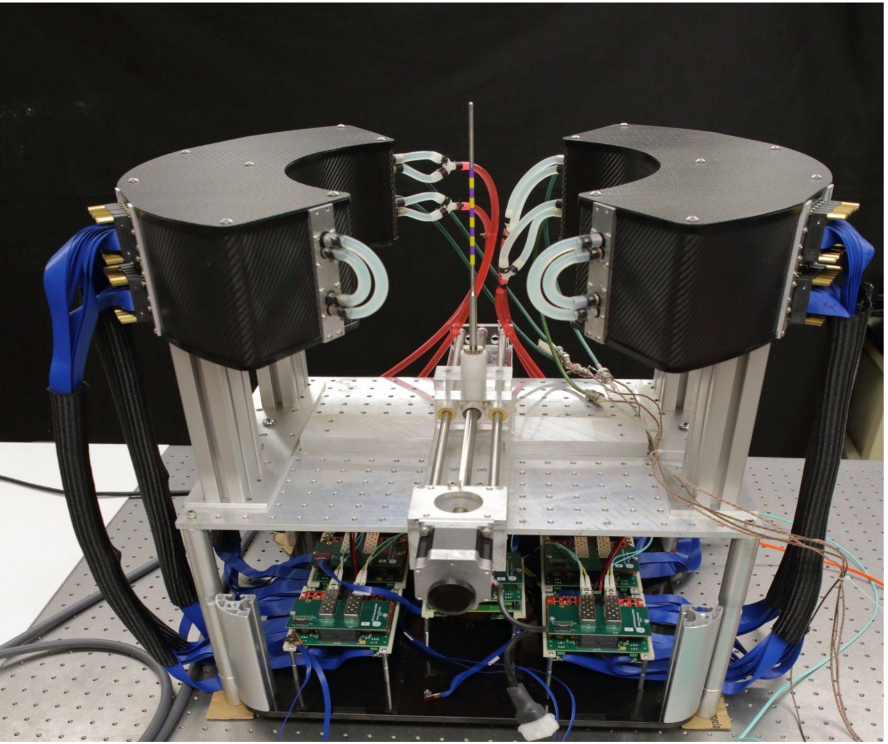


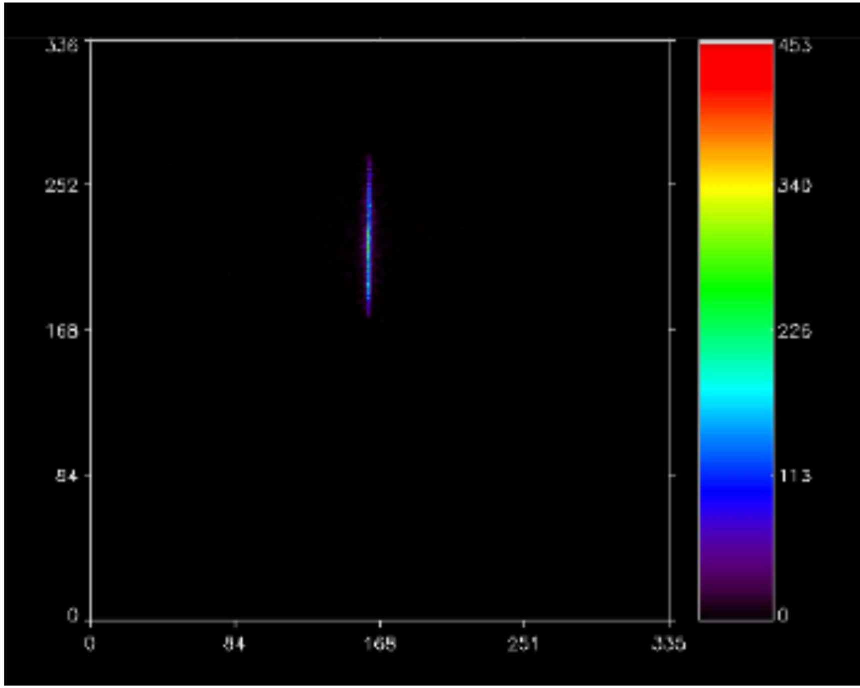
$$\Delta x = c(t - t_0)$$

$$\Delta x' = c(t' - t_0)$$



Evaluating the TPPT Scanner





Interested? Come work with us!

- We're currently looking for motivated students to join the UTKL lab
  - Get involved with data-taking and simulation!
  - Relevant experience for graduate school!
  - Contact: lang@physics.utexas.edu for more details
    - Kyle (PET): kyle.klein@utexas.edu
    - Won (LEGEND): wonseokb@utexas.edu
    - Dalton (NOvA): dgmyers@utexas.edu