GEN IV International Forum[SM]

NEUTRINO AND GEN IV REACTOR SYSTEMS

Prof. Jonathan Link
Virginia Tech, USA

19 November 2020

Meet the Presenter

Prof. Jonathan Link received his Ph.D. in particle physics from the University of California Davis in 2001 and was a postdoctoral fellow at Columbia University before joining the Department of Physics at Virginia Tech as a faculty member in 2006. He also has an appointment of affiliated faculty in Virginia Tech's Nuclear Engineering Program.

Prof. Link has been part of several experimental collaborations, including the Daya Bay Reactor Neutrino Experiment, for which he shared the 2016 Breakthrough Prize for Fundamental Physics for his contributions to their discovery of the final neutrino mixing angle.

Currently, Prof. Link is leading an effort to develop a new reactor neutrino detector technology known as CHANDLER, which recently published their first observation of reactor neutrino. The prototype detector used in this study was one of the world's smallest neutrino detectors, and the first mobile reactor neutrino detector. Prof. Link is a member of the executive group for the NNSA-funded NuTools study, which seeks to examine the potential for applications of neutrino detection to nuclear non-proliferation and the nuclear industry.

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What This Talk Will Cover

- The History of Neutrinos and Reactors
- Possible Applications of Neutrino Detection
- Recent Advances in Neutrino Detector Technology

But first, a disclaimer…

Disclaimer

I am a particle physicist, not a nuclear engineer.

We physicist imagine ourselves to be quite clever, but we can be surprisingly naive about the real world.

We hope that our technology can help to bring about a low-carbon future, by enhancing the safety, security, and/or efficiency of nuclear power, but none of us really knows how neutrinos could best be used in the nuclear industry.

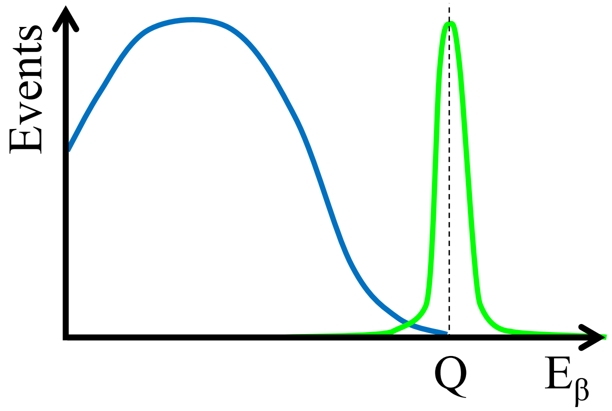
The point of this talk is to raise awareness within the GEN IV community about the information available through reactor neutrino detection, and the relative easy or difficulty of extracting that information.

My hope is that this community can help to identify appropriate problems where neutrino detectors may be a constructive part of the solution.

The Invention of Neutrinos

Neutrinos were first proposed by Wolfgang Pauli in 1930 in an attempt to save energy conservation in beta decay.

$$^{210}_{83}\mathrm{Bi} \rightarrow {}^{210}_{84}\mathrm{Po} + e^- + \nu$$



Adding a third particle in the final state makes it possible for the beta to have any energy less than the maximum.

In order for this particle to go unseen, it had to have **no charge**, **no mass**, and a very **weak interaction** strength: a completely new and unknown type of particle…

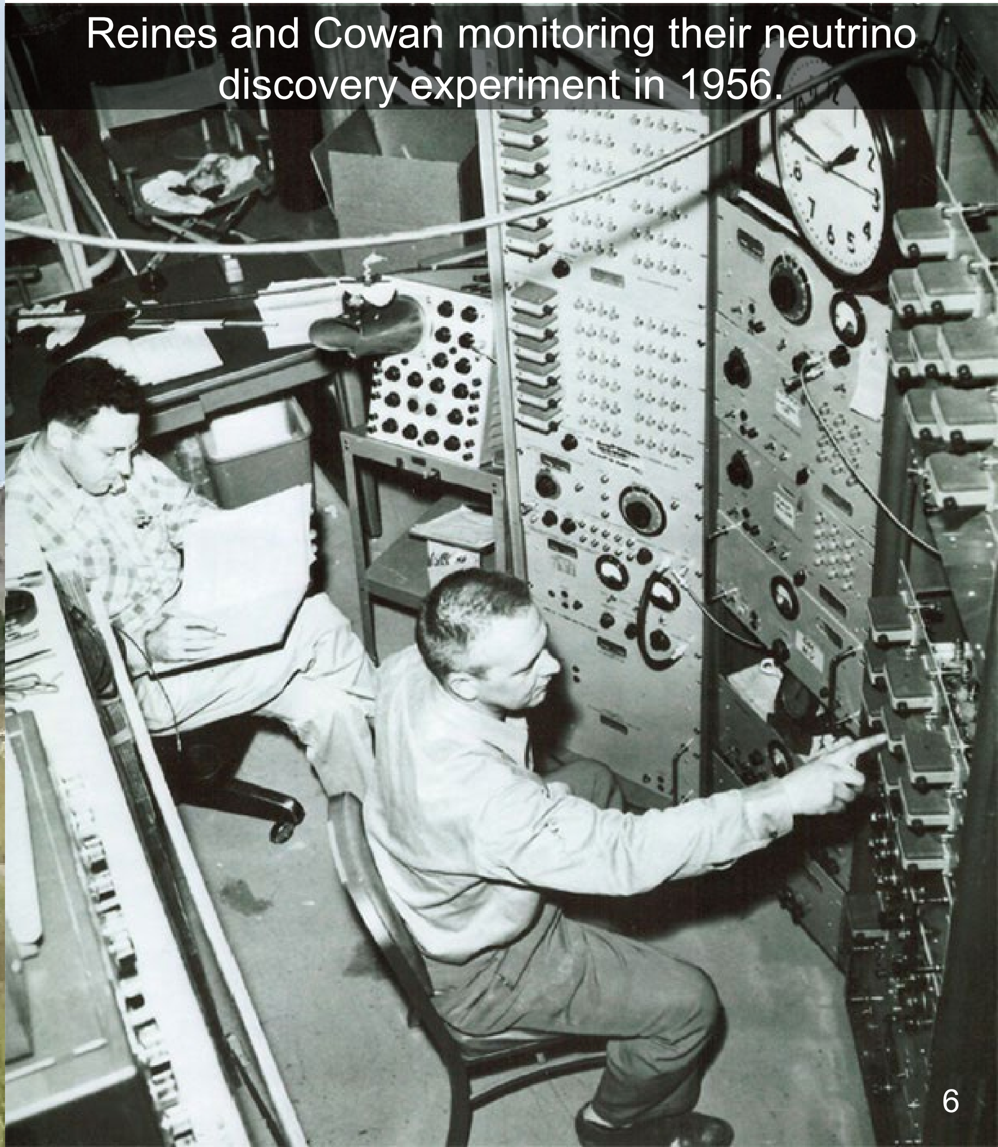
And it would be nearly impossible to detect.

Discovery of the Neutrino

Neutrinos were not discovered until 26 years later.

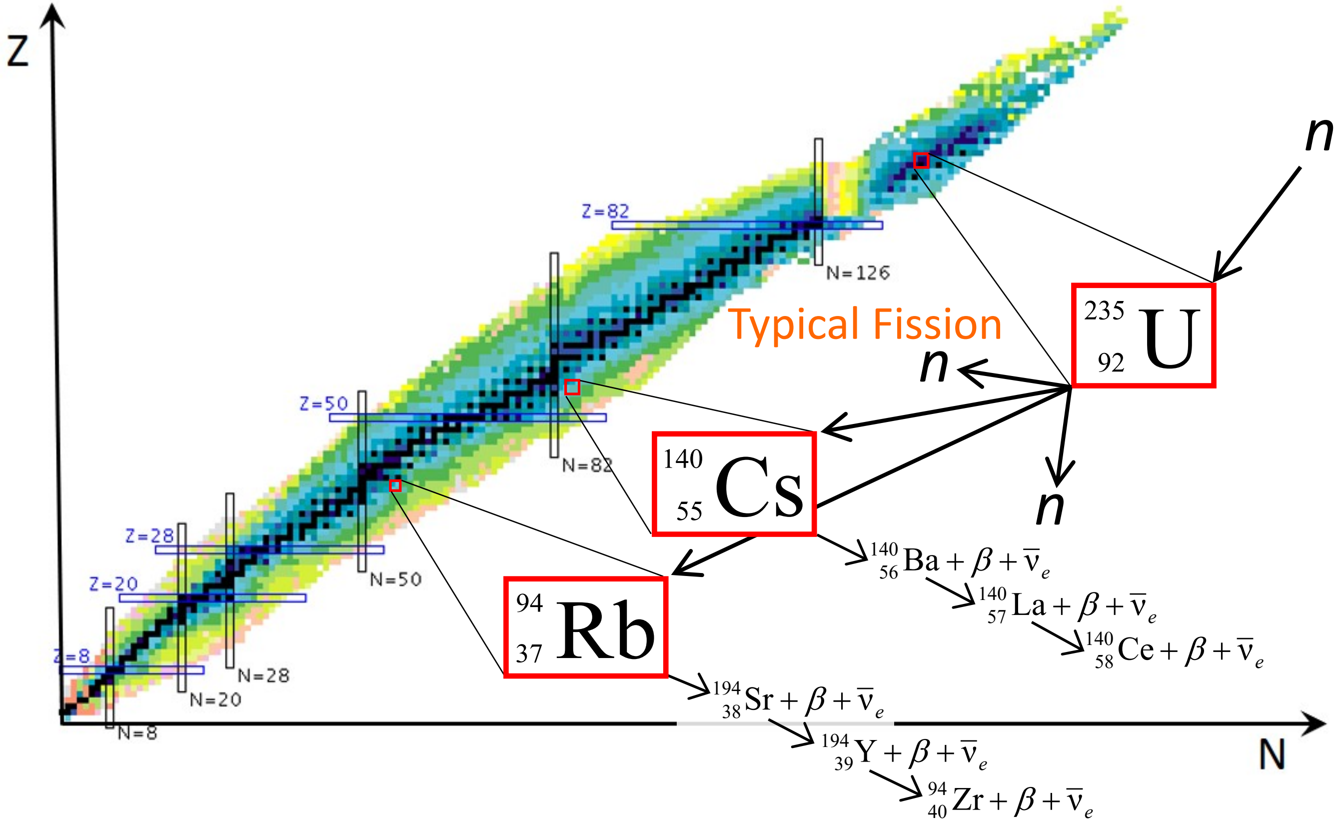
Fred Reines and Clyde Cowan lead the discovery experiment at Savannah River's P Reactor.

Reines and Cowan monitoring their neutrino discovery experiment in 1956.



Reactors as a Neutrino Source

Nuclear reactors are an intense source of electron antineutrinos ($\bar{\nu}_e$). They come from the beta decay of the neutron-rich fission fragments.



A 3 GW thermal reactor produces 6×10^{20} $\bar{\nu}_e$ per second.

Reactors as a Neutrino Source

The neutrinos are emitted isotopically, so their intensity falls off as $1/r^2$.

They are so weakly interacting that they are unaffected by shielding.

They carry information about the fission in the core, like the **reactor power**, the **spatial distribution of fission**, and the **mix of fissile elements** present.

With enough detector mass you could track burn-up from outside the secondary containment, or even outside the security perimeter.

This tracking requires **no input** from the operators, and has **no impact** on reactor operations.

Reactor Neutrino Detection

Electron antineutrinos can be detected through a process known as **inverse beta decay**:

$$p + \bar{\nu}_e \rightarrow n + e^+ \quad \text{(with a 1.8 MeV Threshold)}$$

Organic scintillators are typically used as the detection medium, because they contain lots of free protons, in the from of hydrogen nuclei.

Inverse beta decay results in a **delayed coincidence** signature.

The positron is detected promptly, while the neutron thermalize before it is captured, resulting in a delayed signal.

In an undoped scintillator the neutron will capture on hydrogen, but often the scintillator is doped with things like gadolinium or lithium-6 to enhance capture.

Reactor Neutrino Backgrounds

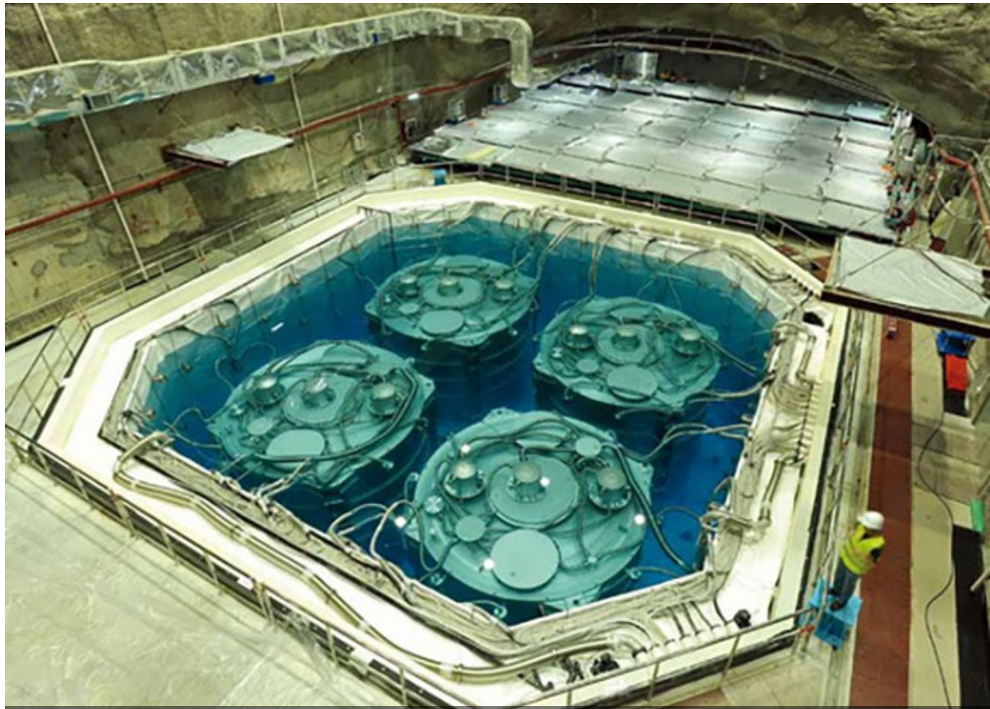
The weak signal from neutrino interactions can easily be overwhelmed by cosmic-rays and conventional radiation.

The delayed coincidence eliminates the vast majority of background.

The remaining backgrounds are things like **random coincidences** and **cosmic-ray fast neutrons**.

A fast neutron hits a proton in the scintillator causing a recoil that mimics the positron in an inverse beta decay.

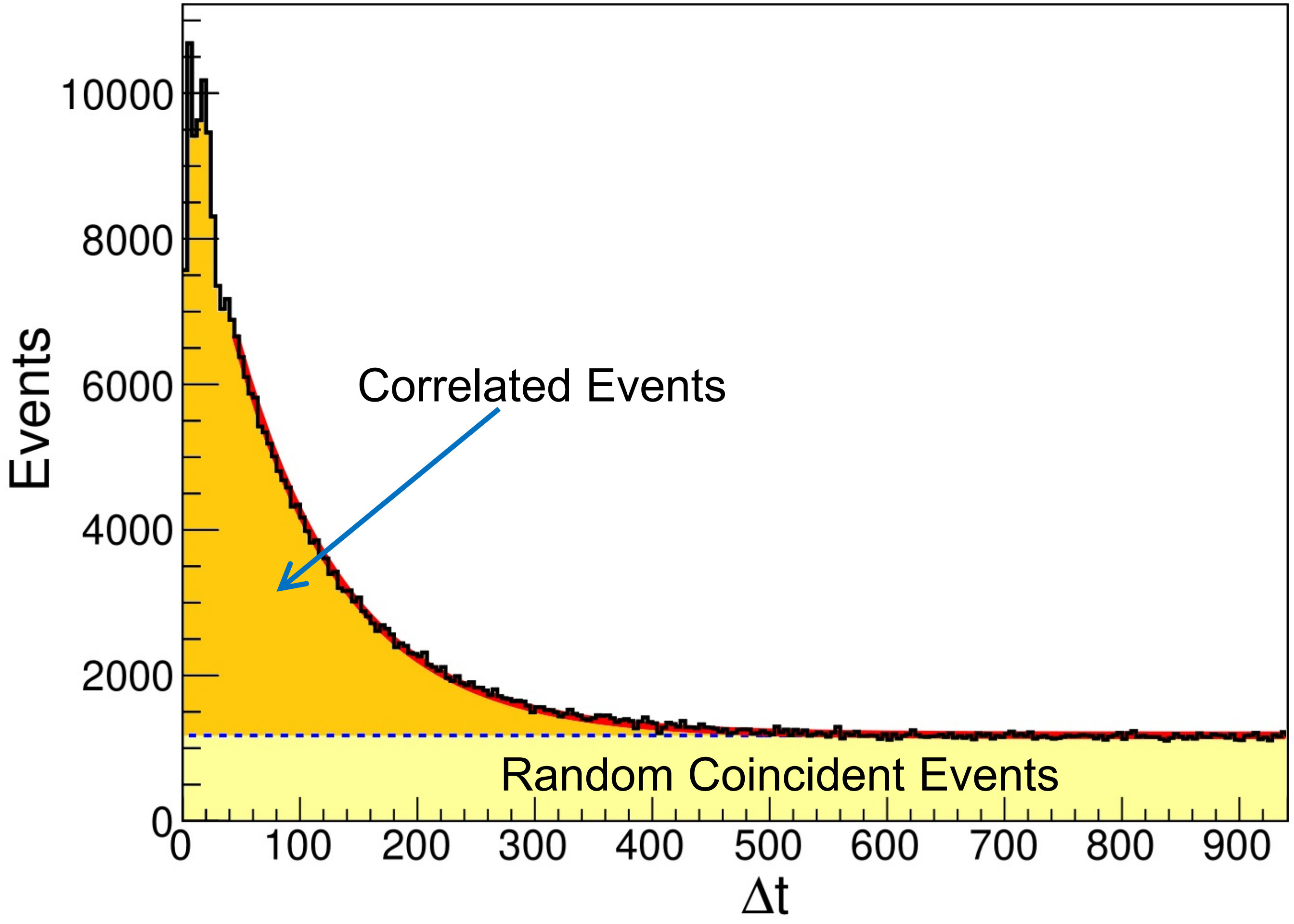
The coincidence is completed when the neutron thermalizes and is captured in the detector.



The Daya Bay Reactor Neutrino Experiment

To control backgrounds, neutrino detectors are often located deep underground and surrounded by layers of low activity shielding materials.

Reactor Neutrino Backgrounds



Random coincident events have no structure in the time separation between the prompt and delayed signals,

But correlated events, including **fast neutrons** and **inverse beta decay**, have an exponentially decaying neutron capture time.

As a result, fast neutrons are the more serious background concern.

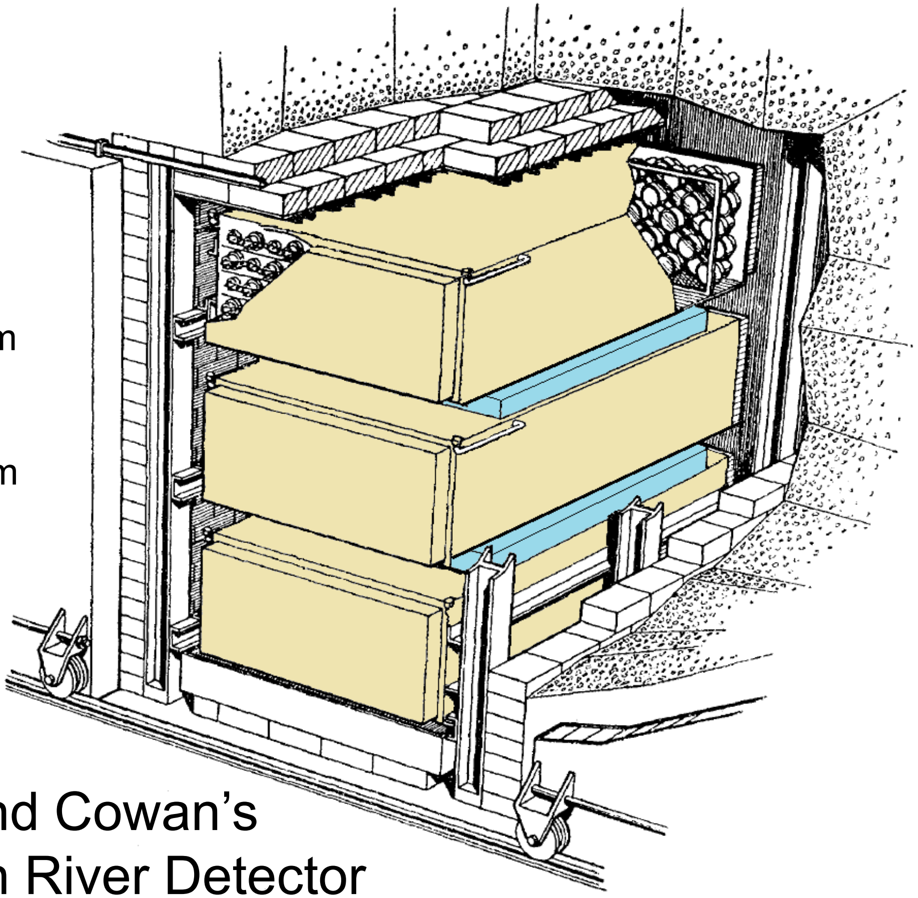
Discovery of the Neutrino

Reines and Cowan used a layered detector to pick out the specific signatures of the positron and neutron from inverse beta decay.

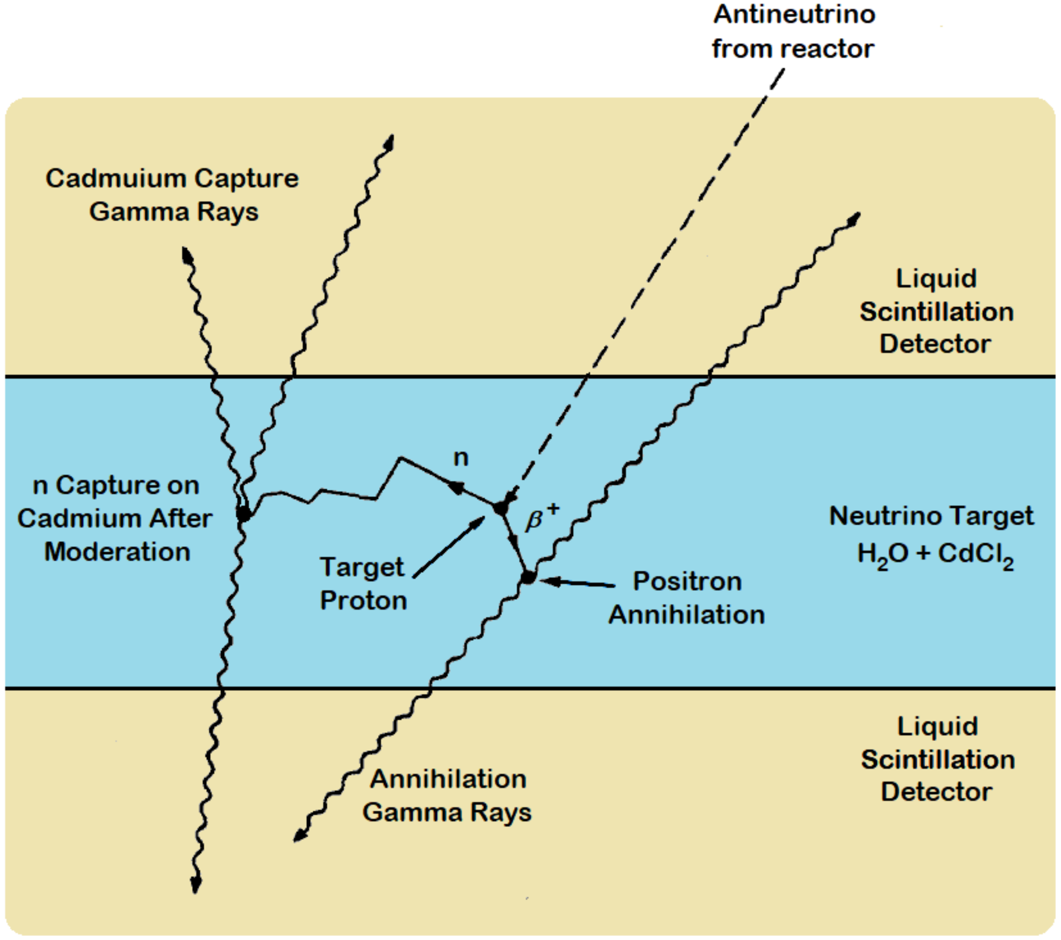
12 meters underground

11 meters from the reactor

Used cadmium for neutron capture



Reines and Cowan's Savannah River Detector



By tagging the positron annihilation gammas, they filtered out fast neutrons.

Neutrino Physics at Reactors

Since the original discovery experiment, there have been dozens of distinct reactor neutrino experiments.

Among other things, they have

- Studied different types of neutrino interactions,
- Searched for the neutrino magnetic moment, and
- Searched for and studied **neutrino oscillations**.

Neutrino oscillations are the most important discovery in particle physics in the last 40 years, and this is where reactor neutrinos have made their greatest contribution to science.

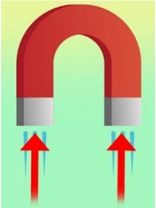
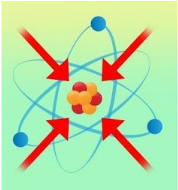
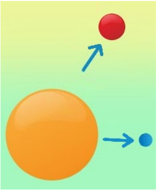
Before discussing this, we'll need a quick introduction to particle physics…

Particle Physics

Particle physics is the study of **fundamental particle** and **forces**.

There are four fundamental forces:

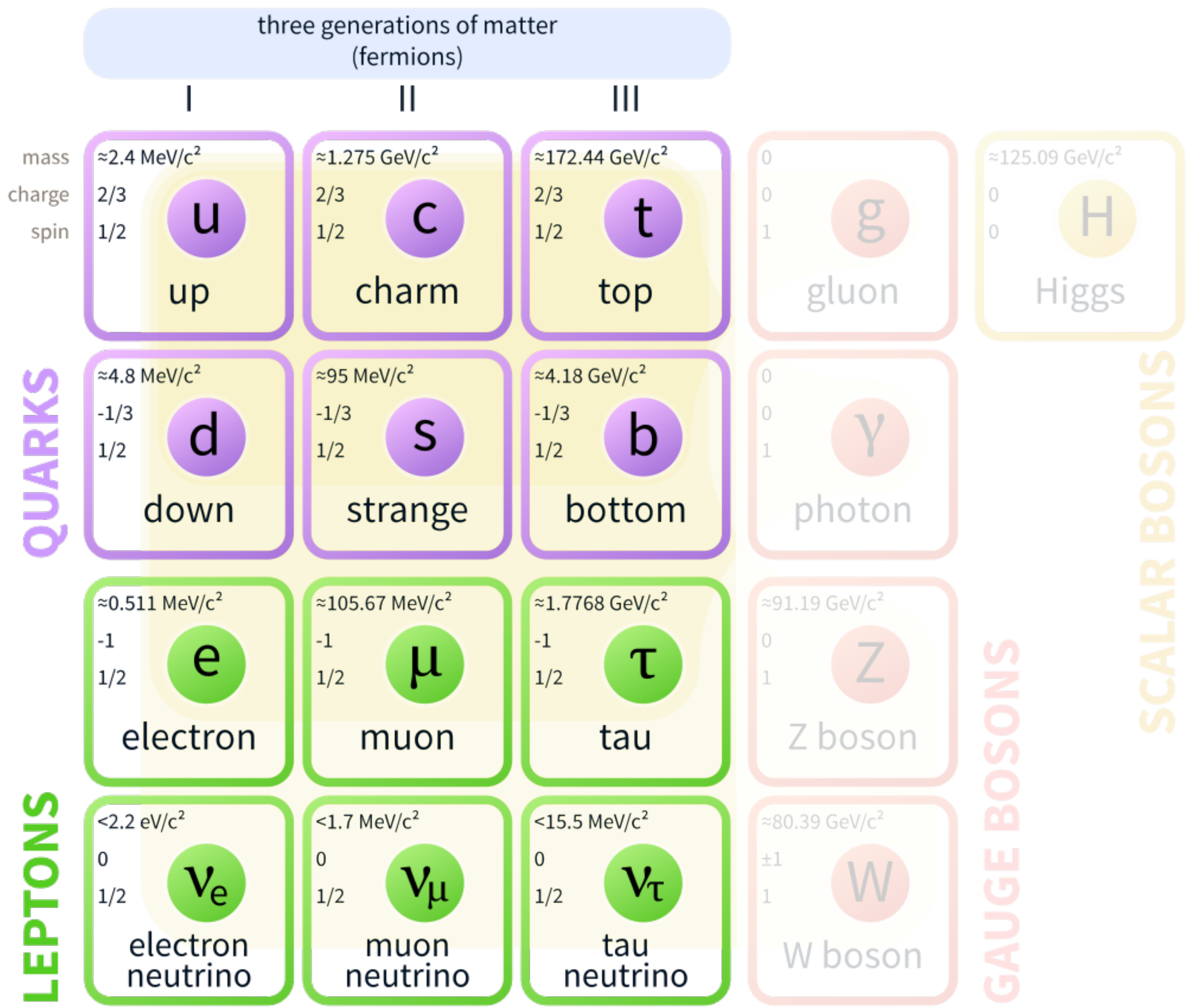
1. Gravity
2. Electromagnetism
3. The Strong Nuclear Force
4. The Weak Nuclear Force

Neutrino interactions are weak because they only feel the Weak Nuclear Force (and perhaps gravity, but that’s not relevant at the scale of particle physics).

Neutrinos and Particle Physics

Standard Model of Elementary Particles



The spin ½ particles include 6 quarks and 6 leptons.

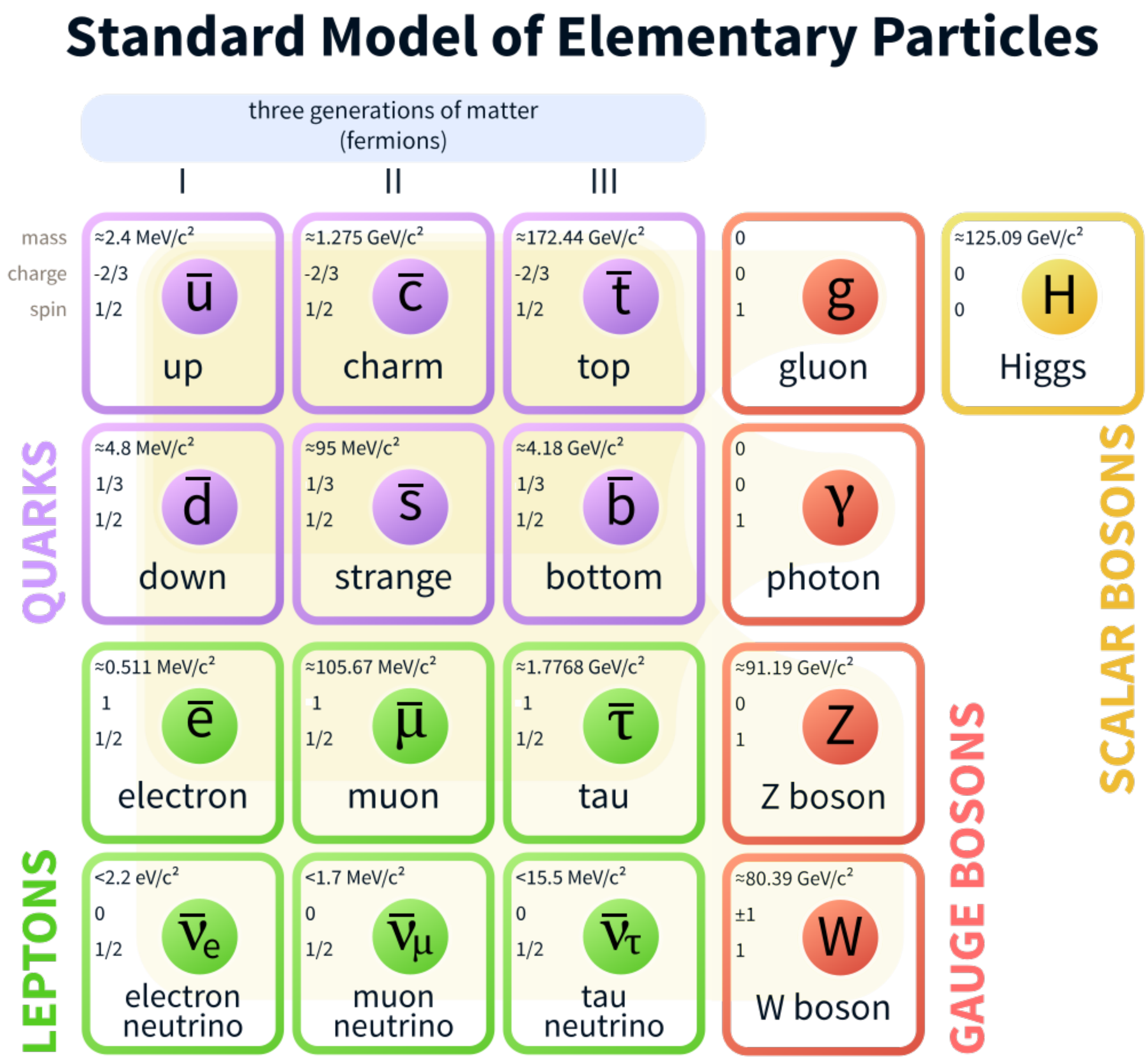
These come in three generations which get progressively heavier, but otherwise have the same properties.

The spin 1 gauge bosons which mediate the forces.

The Higgs boson is responsible for giving the other particles mass.

Neutrinos and Particle Physics

Antimatter



Every particle has an antimatter counterpart.

We denote antimatter with a bar.

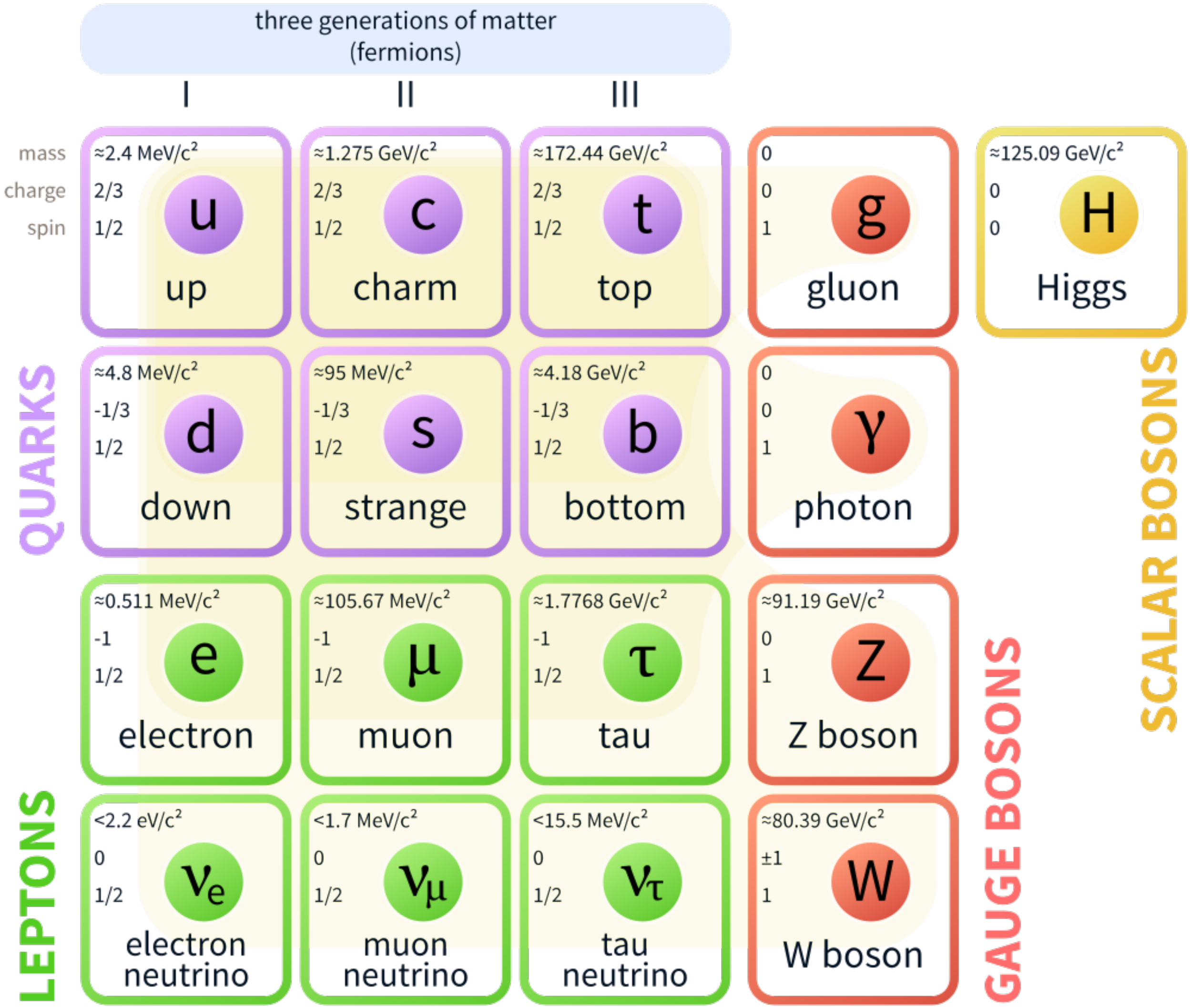
Antimatter particles have the opposite sign charge relative to their matter counterpart.

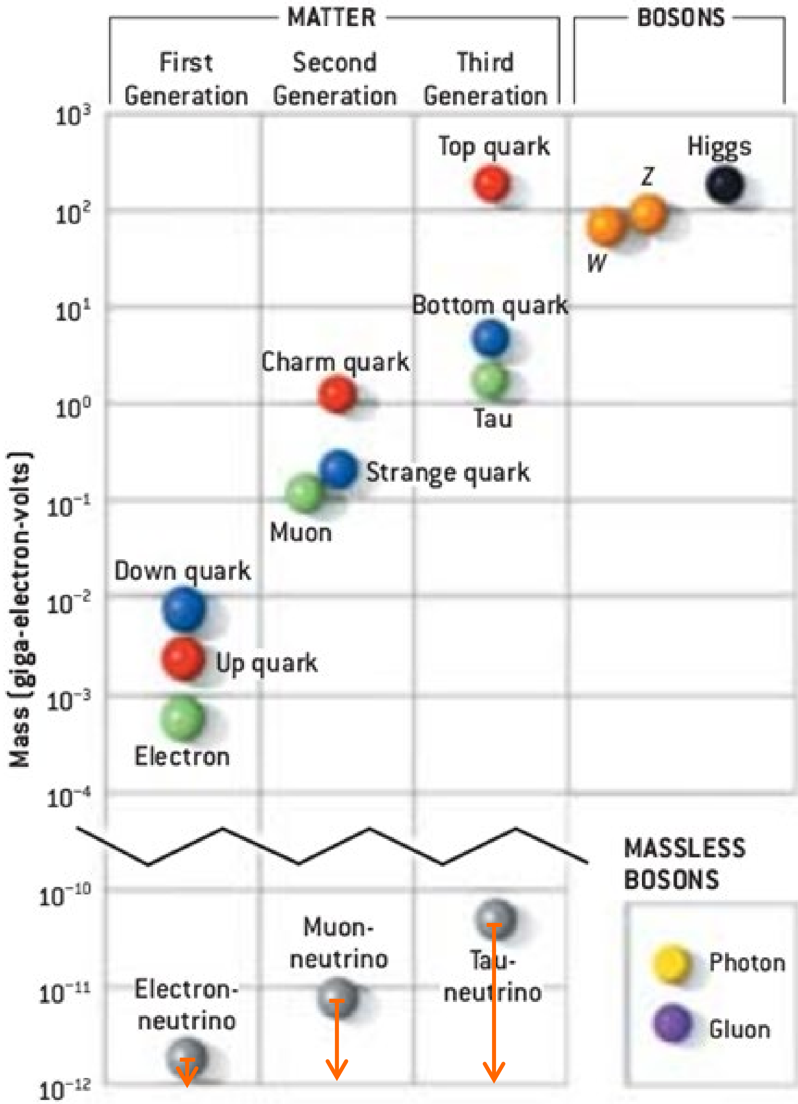
The neutral bosons are their own antimatter.

But there are both neutrinos and antineutrinos.

Neutrinos and Particle Physics

Standard Model of Elementary Particles

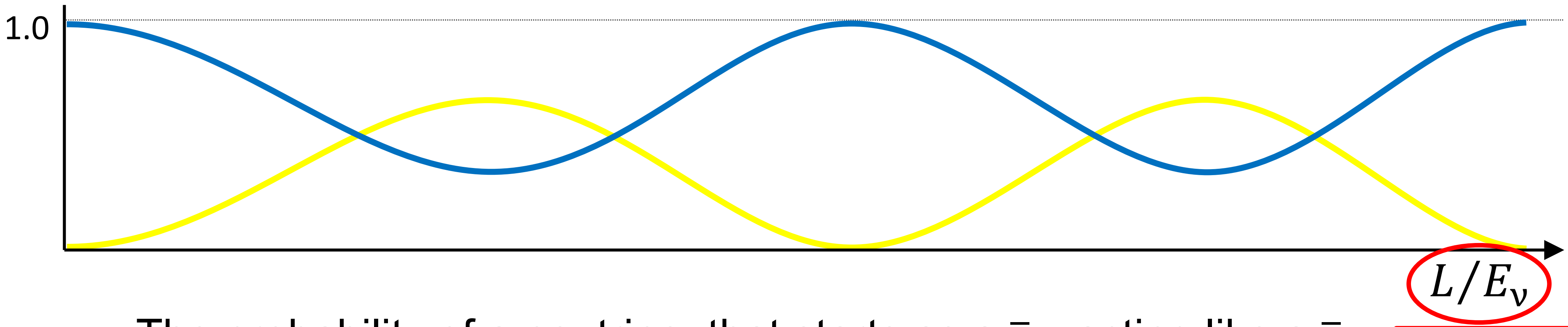




Neutrino Oscillations

If neutrinos have mass, then the three types of neutrinos can mix with each other in a sinusoidal pattern.

As a simple example, it might look something like this:



— The probability of a neutrino, that starts as a $\bar{\nu}_e$, acting like a $\bar{\nu}_e$

— The probability of a neutrino, that starts as a $\bar{\nu}_e$, acting like a $\bar{\nu}_\mu$

Neutrinos oscillate as a function of the distance traveled divided their energy

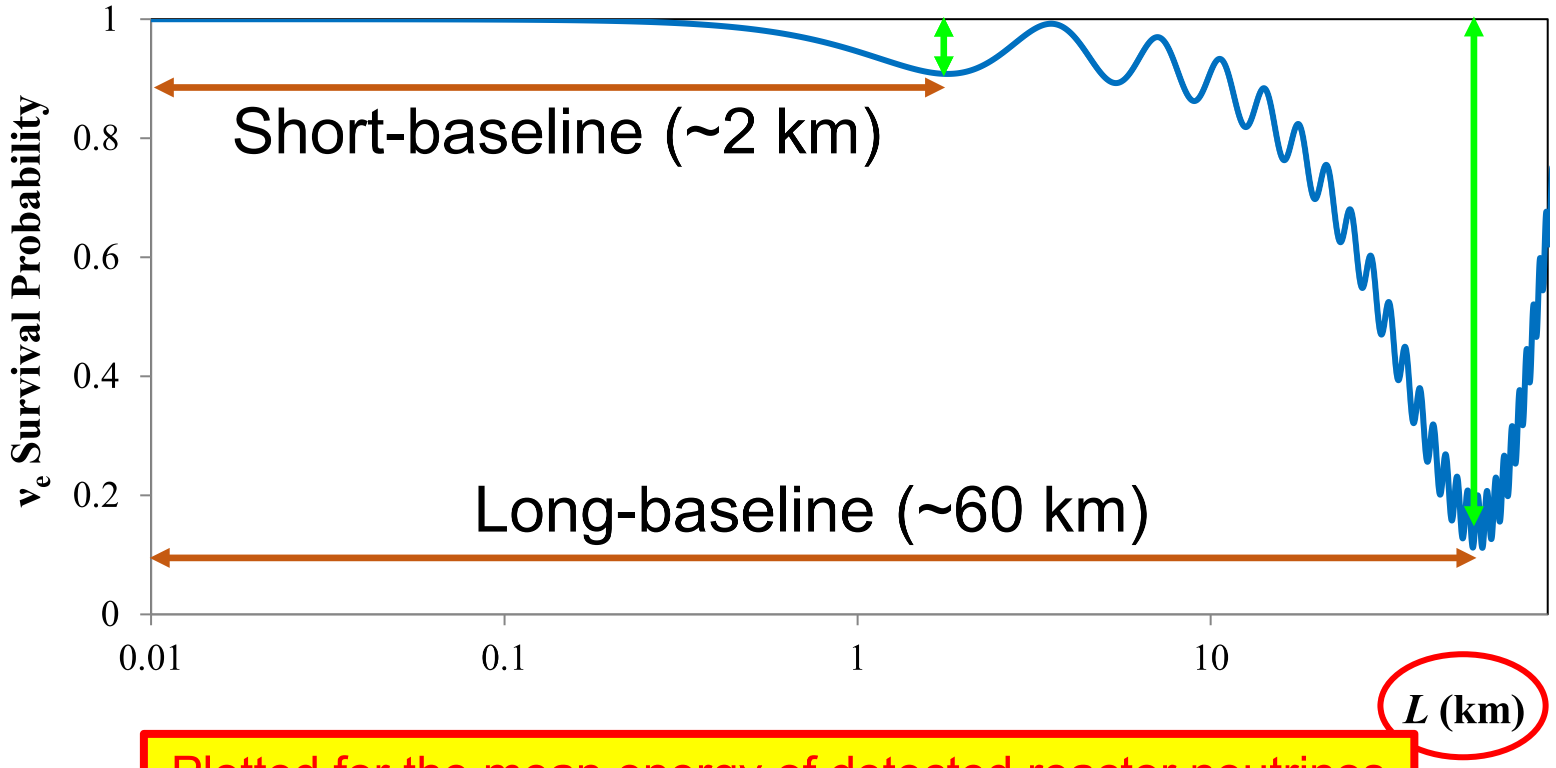
Inverse beta decay is only sensitive to electron antineutrinos.

So acting like a muon antineutrino means that we won't see it in our detector.

Neutrino Oscillations

Electron neutrinos (and antineutrinos) undergo two types of oscillations.

The different oscillations are characterized by their amplitudes and periods:



Plotted for the mean energy of detected reactor neutrinos

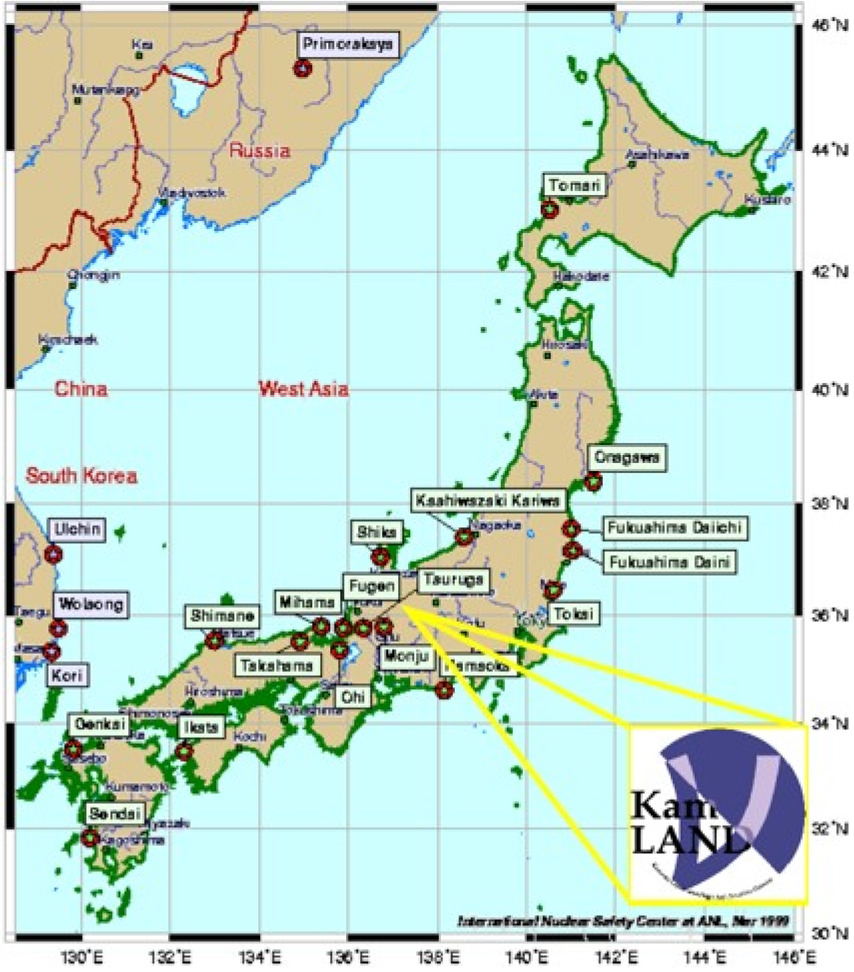
The amplitudes tell us about the strength of the mixing.

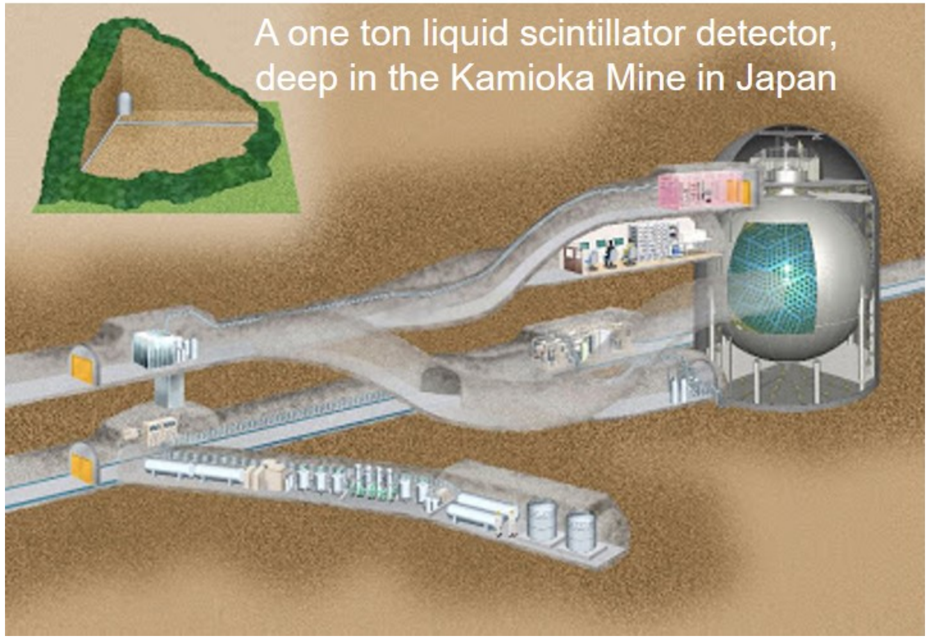
The periods tell us about the masses of the neutrinos.

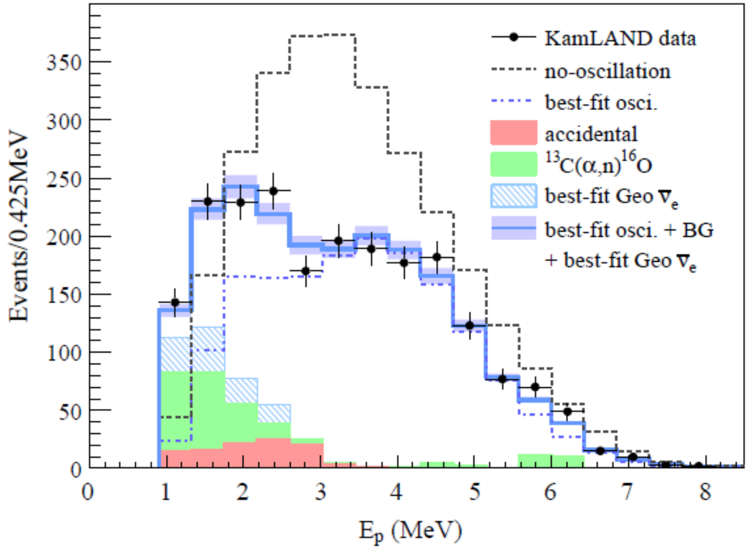
Reactor experiments have made critical measurements for both types of oscillations…

The KamLAND Experiment

The KamLAND experiment used neutrinos from all the reactors in Japan.





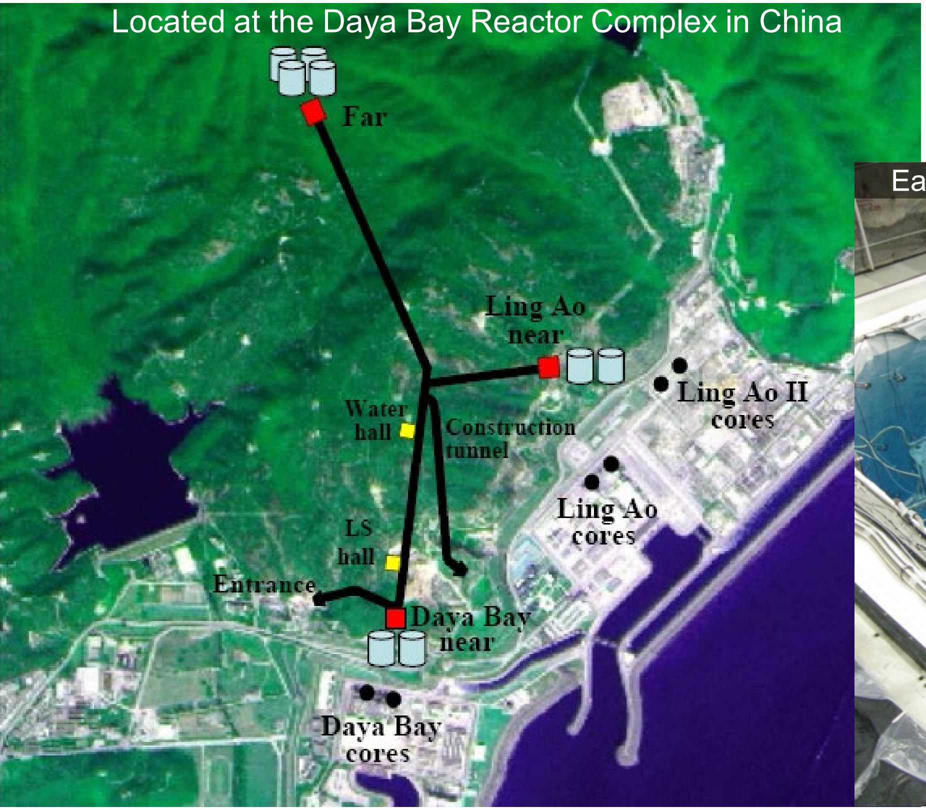


KamLAND measured the long-baseline oscillation period.

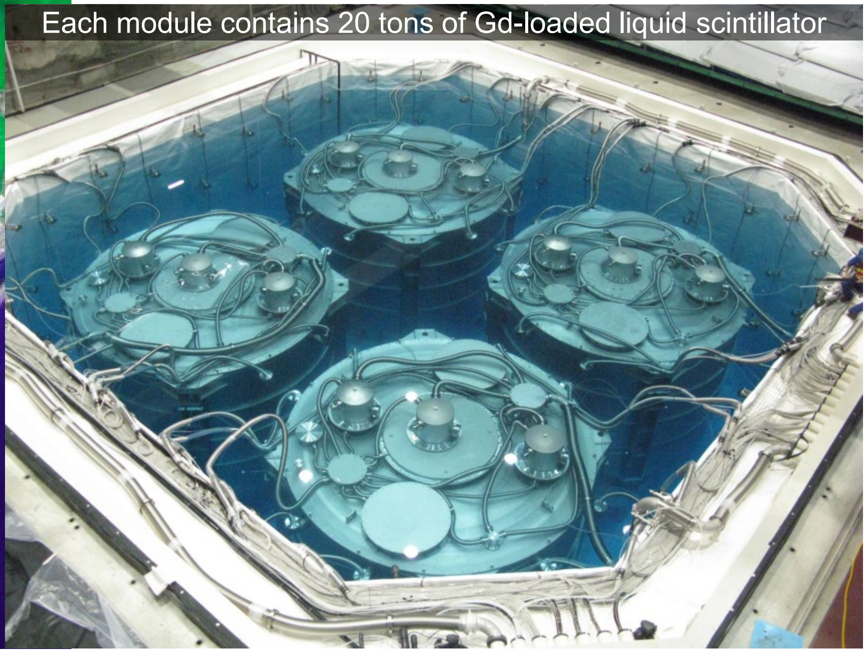
This type of oscillation had previously been observed with neutrinos from the Sun.

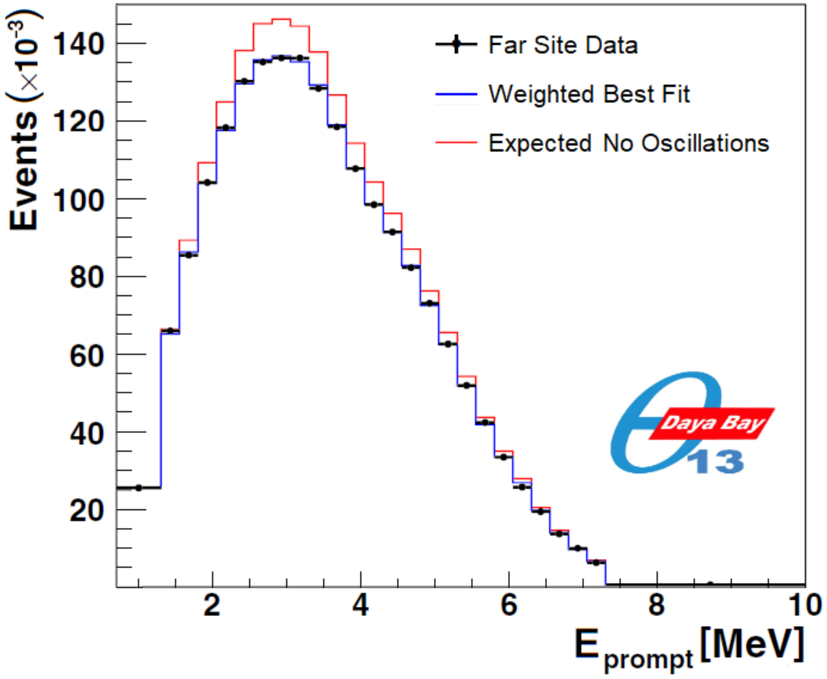
The Daya Bay Experiment

Studied the short-baseline oscillation, and measure the smallest oscillation amplitude.



Near detectors were used, because the reactor neutrino flux is poorly understood from theory.

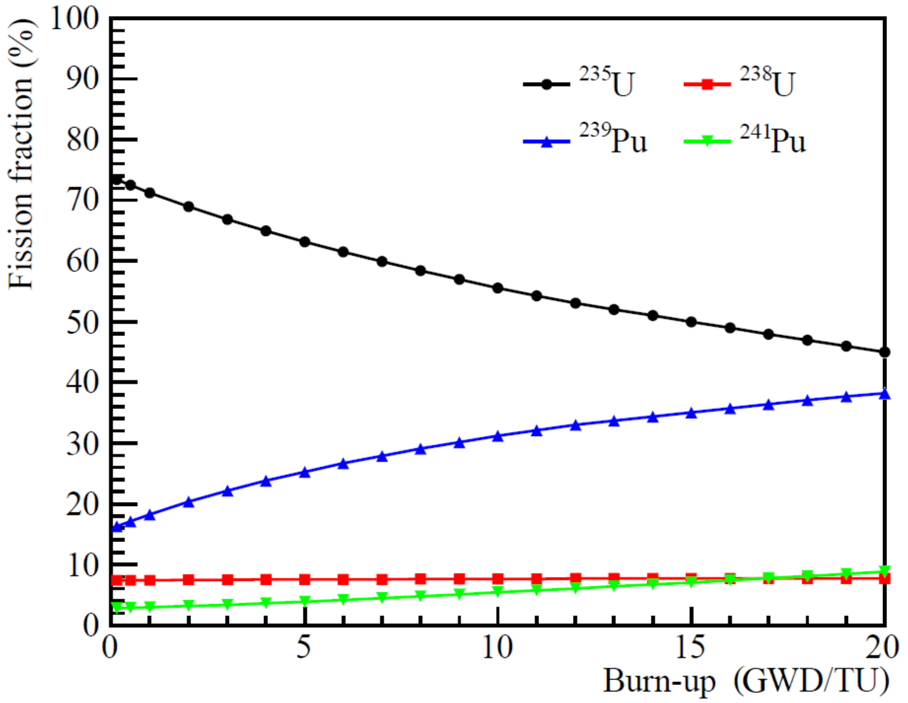


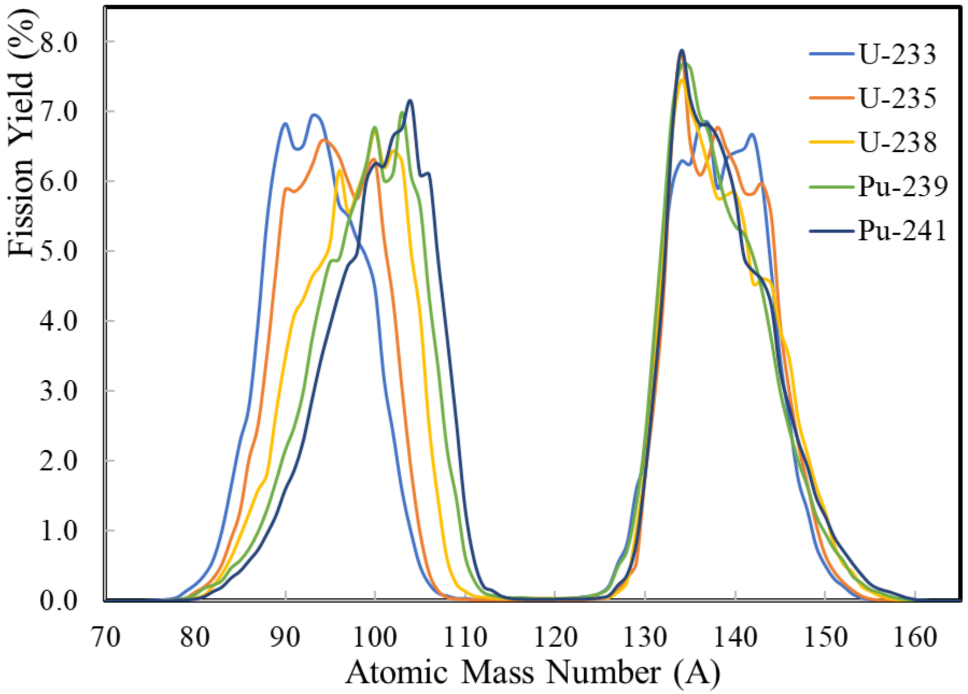


In addition, the Daya Bay Experiment made measurements that have improved our understanding of reactor neutrinos...

Evolution of the Neutrino Spectrum

As the fuel burns in an LEU reactor, the mix of fissile isotopes evolves.



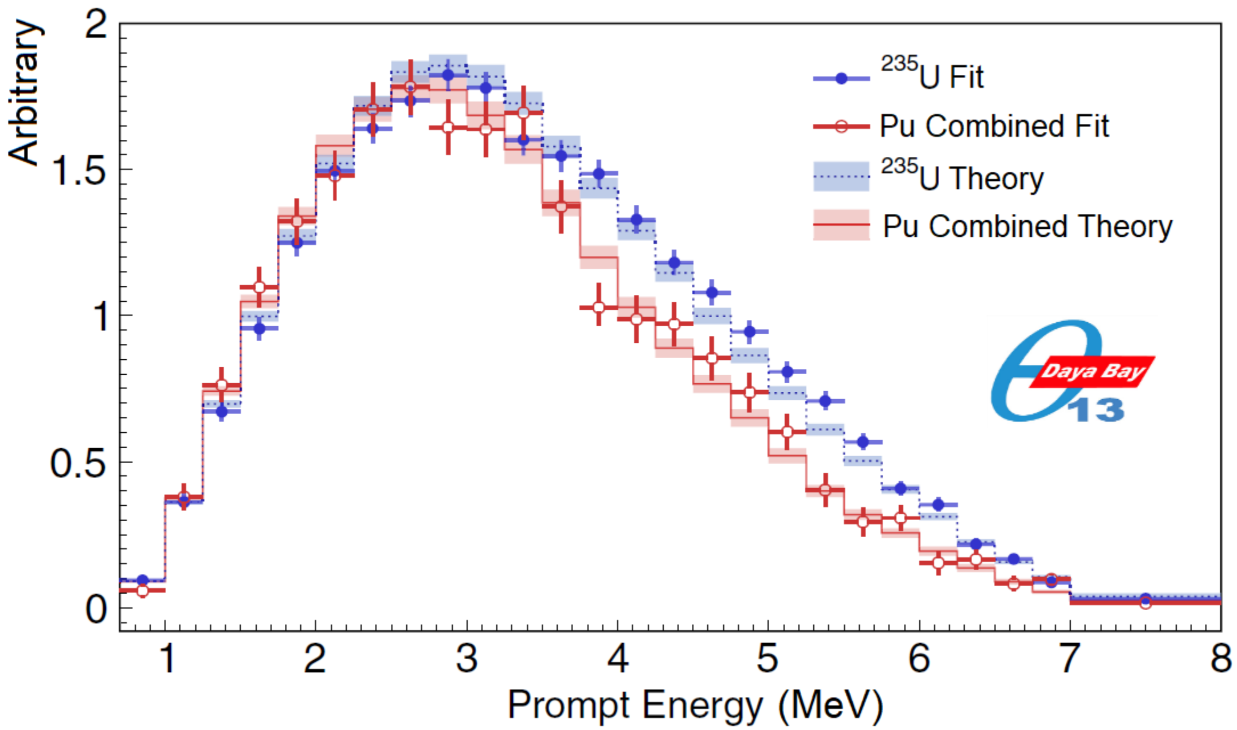


Each fissile isotope makes a slightly different set of fission fragments.

As a result, the neutrino energy spectrum is like a fingerprint for the active mix of fissile isotopes in the core.

Daya Bay Neutrino Spectral Decomposition

Using burn-up data from the reactor operators, the Daya Bay Reactor Neutrino Experiment used neutrinos from one of their near detector sites to decompose the spectrum for the different fissile elements.



The data clearly confirm the fissile element fingerprint hypothesis.

This study was done with detectors located 363 meters away from two cores, with out-of-sync refueling cycles.

Imagine what could be done with a detector at 25 meters, and a single core dominating the neutrino flux.

Functionality for Applications

As we just saw, neutrino detectors can track a reactor's active fissile inventory.

In addition:

- The neutrino detection rate measures the reactor power.
  (When averaged over hours or days, but **not** seconds)

- An array of neutrino detectors may be able to measure the spatial distribution of fission, by triangulation.

- Neutrinos can be used to detect when a reactor is on, even at a significant stand-off.

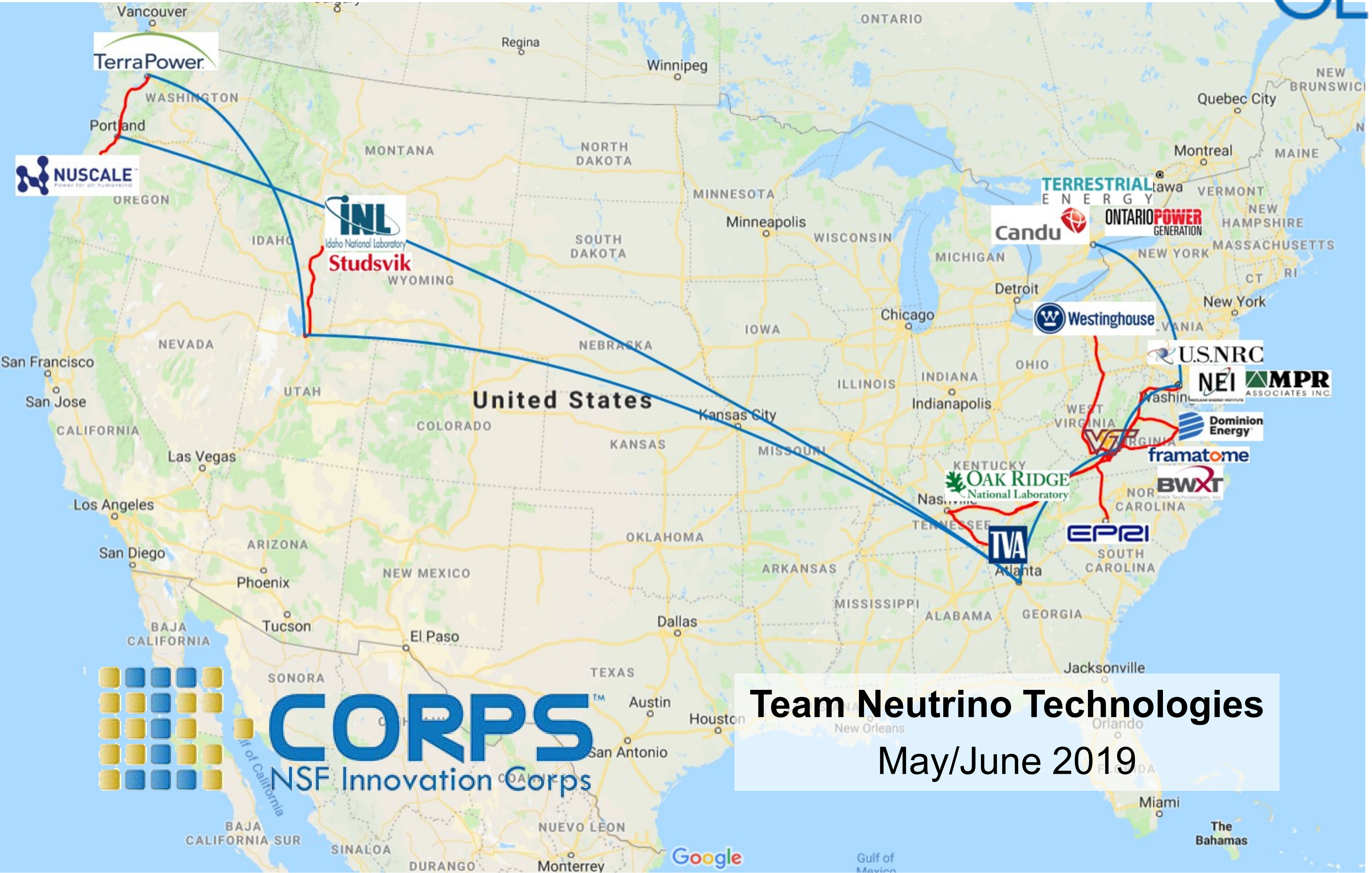
Gathering Data on Applications

Physicists have long thought that reactor neutrino detectors would find applications in reactor monitoring.

- The **Applied Antineutrino Physics Conference Series**, has been a regular annual meeting since 2004. Unfortunately, it is mostly physicists talking to each other.
- The NNSA's Office of Defense Nuclear Non-proliferation has commission the ongoing **NuTools Study** (https://nutools.ornl.gov/) to engage with experts in the nuclear industry and nuclear security to assess the viability possible applications.
- Last spring, I lead a team in a study of possible applications funded by the National Science Foundation's **Innovation Corps**.

Gathering Data on Applications

GEN IV International Forum



The NSF's I-Corps program gives inventors training, and money to gather data on commercialization of their technologies.

Participants have seven weeks to dash around the country and interview more than 100 people in the appropriate industrial sectors.

Non-Proliferation Safeguards

In the context of nuclear non-proliferation safeguards several possible applications have been identified:

- Recovery from a loss of continuity-of-knowledge event

  After a diplomatic break down or other interruption in monitoring, neutrinos can determine if plutonium has been removed from the reactor.

- Continuous monitoring of a reactor's operational status

  In the JCPOA, Iran's heavy-water reactor was rendered inoperable. In future agreements short of destroying a reactor, neutrino detectors could be used that a reactor remains off.

- Tracking fissile inventory in operating reactors

  This may enable verification for possible future agreements like a Fissile Materials Cut-off Treaty.

Reactor Instrumentation

Potential applications identified in reactor instrumentation include:

- Neutrino calibrated ex-core neutron detectors

  Inverse beta decay detectors are also excellent neutron detectors. Could ex-core neutrino detectors eliminate the need for in-core neutron detectors, and thus significantly reduce the number of pressure vessel penetrations?

- Tracking the fissile inventory for Gen IV reactors with liquid fuel

  Chemical assay creates a waste stream and sample pulling is a proliferation risk. Neutrino detectors could for low-risk, continuous monitoring.

- Verifying critical status of the core following a beyond design basis accident

  God forbid, if there was an accident and the plant instrumentation is off-line, neutrino detectors could be used to determine if there is an active fission reactor.

Making Applications a Reality

Nuclear security and non-proliferation safeguards, particularly in situations with limited trust, have always seemed like a good starting place for applications.

But the IAEA is understandably reluctant to express a mission need requiring nonexistent or unproven technologies.

Similarly, existing commercial reactors have the instrumentation they need to satisfy regulatory requirements.

Gen IV reactors may have unique needs and an openness to innovative solutions.

So finding use cases in commercial nuclear would help to establish neutrino technologies for security applications.

Past Reactor Neutrino Detectors

So far reactor neutrino detectors have been **delicate research instruments**, requiring ideal conditions and constant attention.

They typically used organic liquid scintillators, which tends to leak and have issues with long-term chemical stability, and flammability

These detectors were large and unwieldy.

They needed the thickest possible overhead shielding to combat cosmic-ray fast neutron backgrounds.

As a result, they were either at some standoff, in an underground cavern, or perhaps constructed *in situ* in a tendon gallery.

These detectors are not suitable for widespread use in applications.

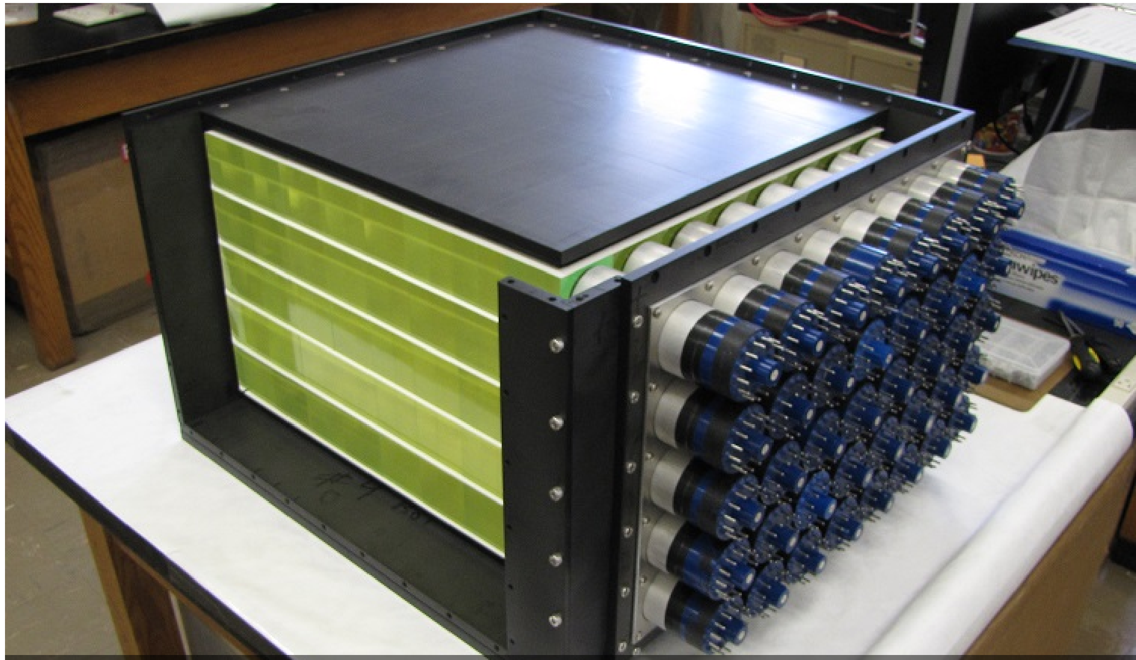
The CHANDLER Reactor Neutrino Detector Technology

CHANDLER was designed, from the start, as a robust, mobile detector technology.

It uses a highly segmented array of plastic scintillating cubes as the neutrino target and positron detector, and thin sheets of lithium-6 doped zinc sulfide (ZnS) scintillator to tag neutron capture.

Light is transported along the rows and columns of cubes by total internal reflection, and readout by photomultiplier tubes.

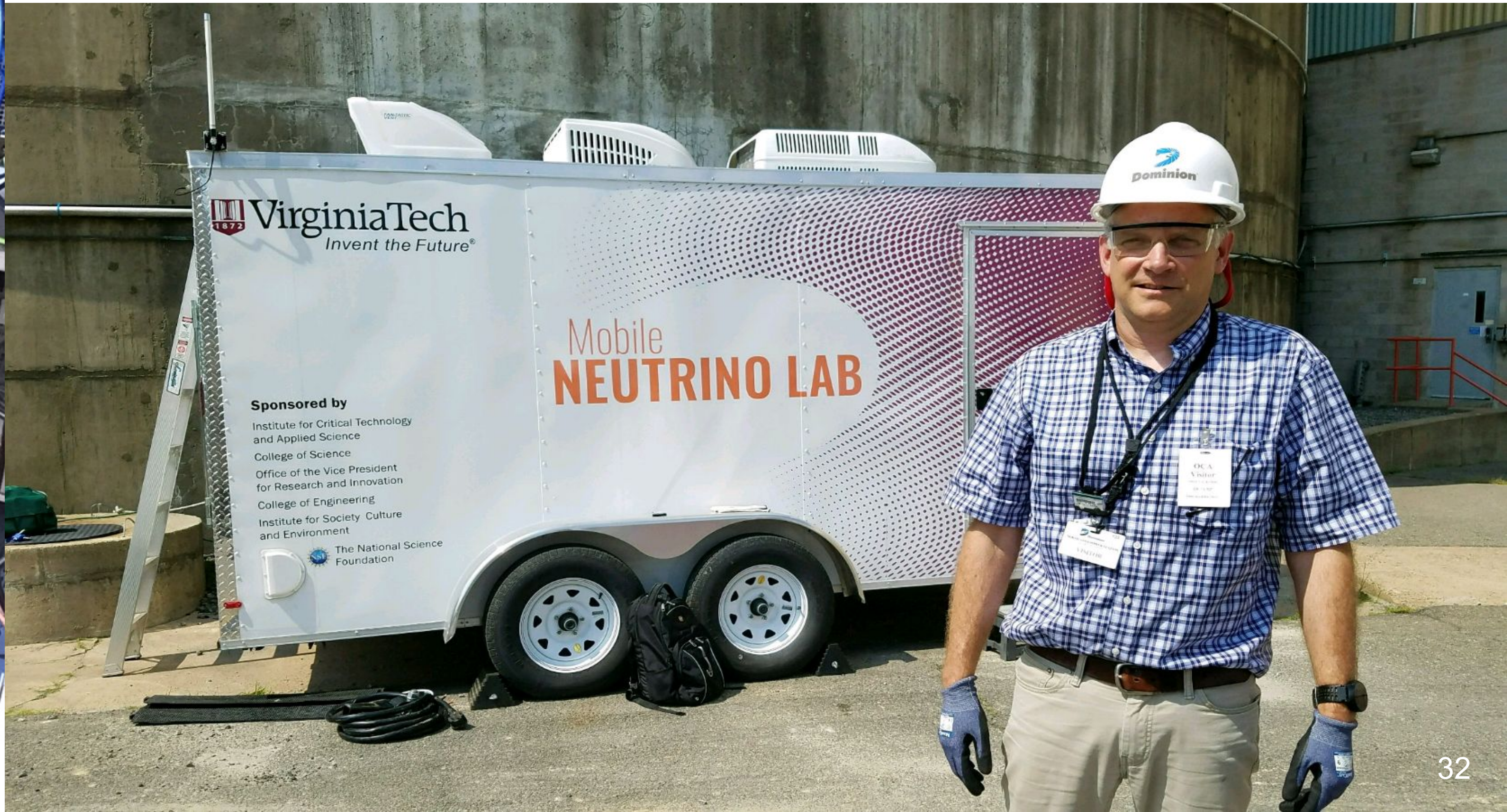
As with the Reines and Cowan experiment, the segmentation is used to tag the gammas from positron annihilation, and thus reject fast neutron correlated backgrounds.



The MiniCHANDLER Prototype, open during assembly to show the cubes and ^{6}Li-doped ZnS sheets

Deployment at North Anna

The MiniCHANDLER prototype was installed in our Mobile Neutrino Lab, deployed to Dominion Power's North Anna Generating Station in Mineral Virginia, and parked just outside their Reactor 2.



Deployment at North Anna

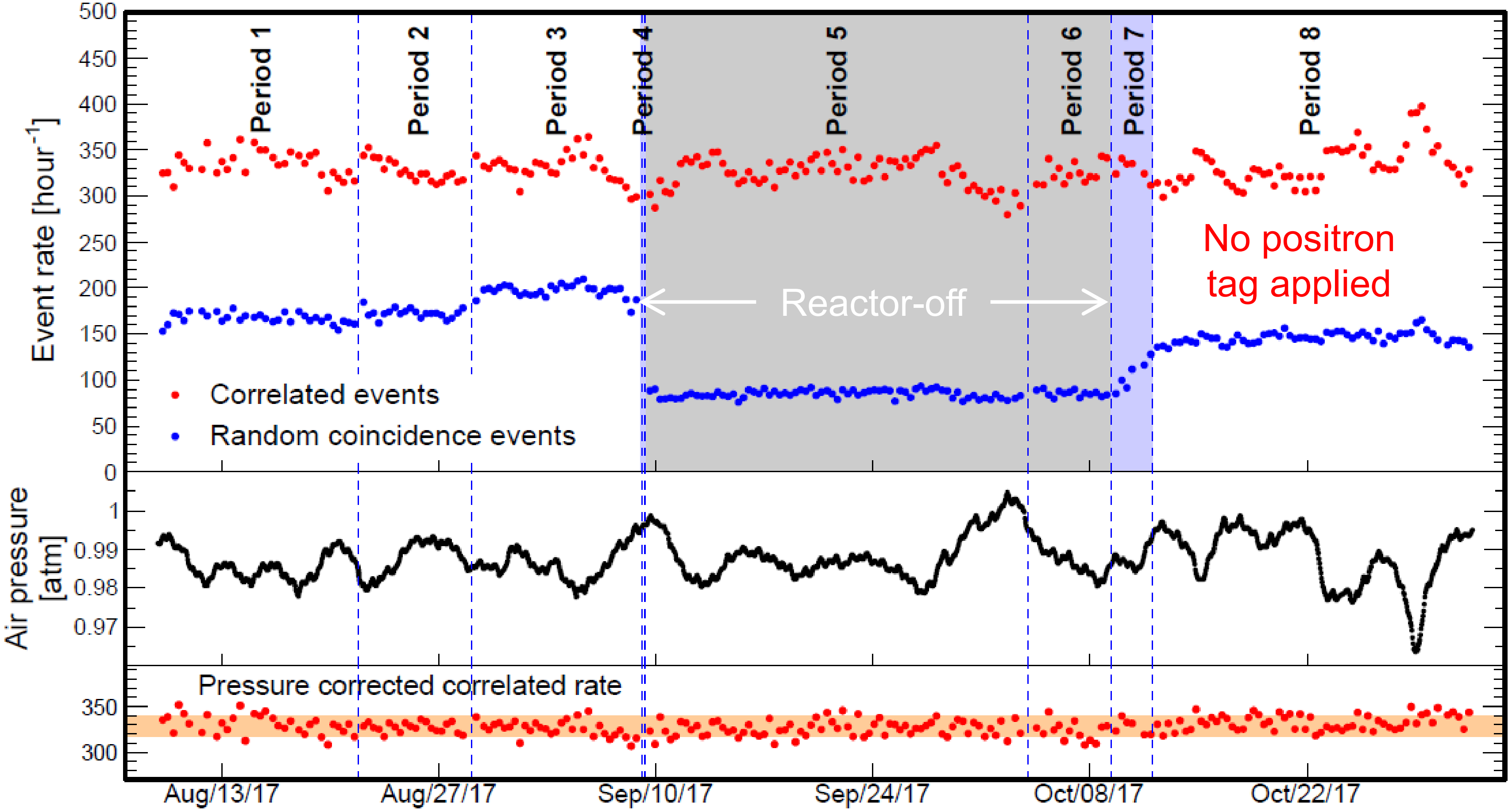
Fast Neutrons in MiniCHANDLER

The fast neutron rate is independent of the reactor power.

Instead, it's inversely correlated with the atmospheric pressure.

After a correction, the average reactor-on correlated rate was found to be 4 events/hour more than with the reactor off.

Which is the expected rate for neutrino events.



In this simple prototype, the positron tag improves the signal-to-noise by about a factor of five!

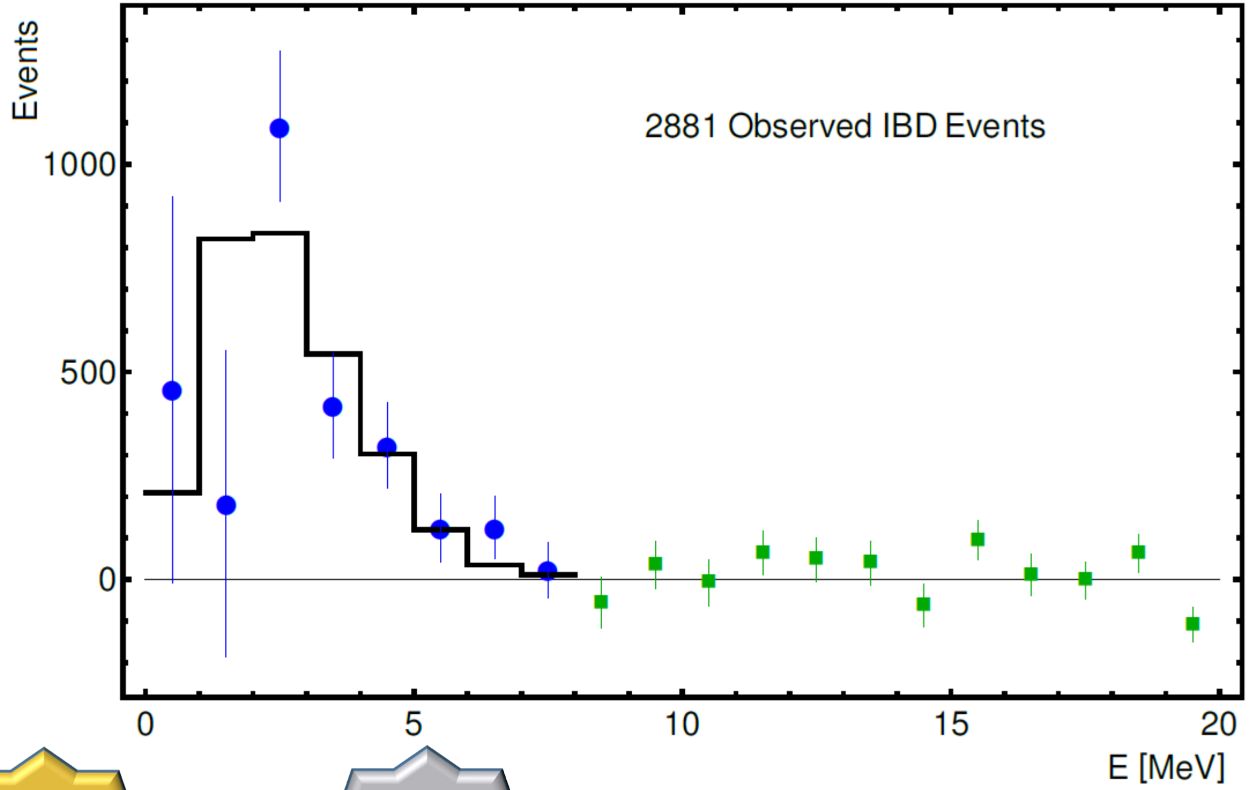
MiniCHANDLER Demonstration

MiniCHANDLER was the **largest detector we could afford** to build and the **smallest detector with a chance to see neutrinos**.

We used surplus photomultiplier tubes, and we had to forgo light-guides that were shown to improve light collection efficiency by 64%.

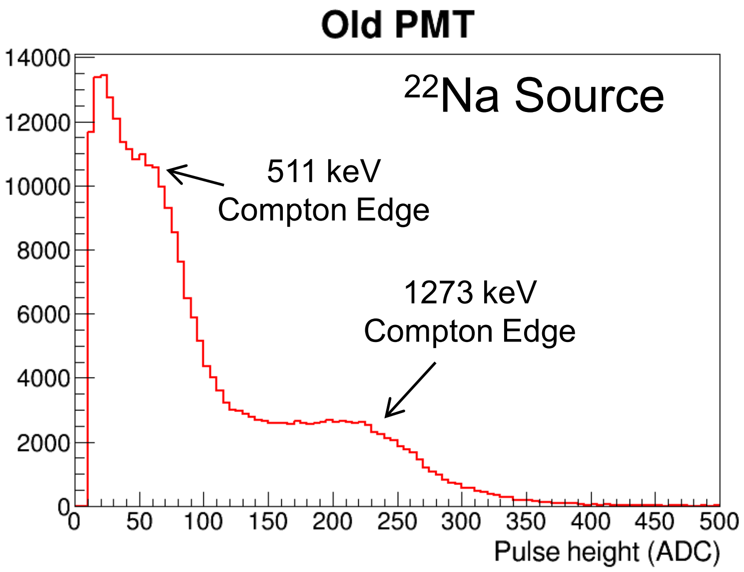
We had no cosmic-ray shielding, and only an inch of boron loaded poly to stop thermal neutron from the reactor.

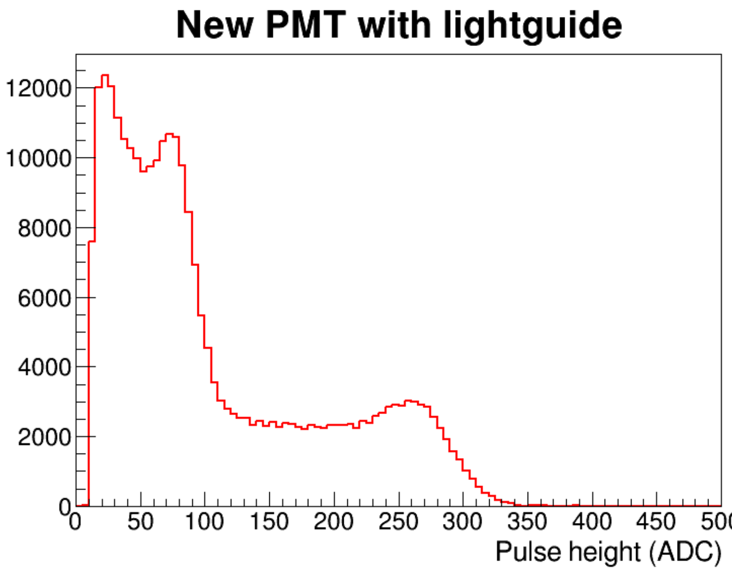
Yet, we succeeded in observing the antineutrino spectrum!



Detector Upgrades

To study the impact of modern PMTs and lightguides, we rebuild our smaller prototype with half new PMTs and lightguides and half old PMTs.






The Micro CHANDLER prototype, testing new PMTs and light guides.

The energy resolution is improved by a factor of 2.

The positron annihilation gammas stand out much more clearly.

Detector Upgrades

Additional planned upgrades will get us the event rates, energy resolution and efficiency needed for a range of entry-level applications.

1. Doubling the number of ^{6}Li-loaded ZnS sheets, which has been shown to improved the neutron detection efficiency by 35%.

2. Increasing to a detector module mass to between 2 and 5 tons will accumulate events at several hundred per hour and more effectively contain neutrons and annihilation gammas.

3. Improved optics, including PMTs on four sides, will increase the signal-to-noise to better than one-to-one, while simultaneously sharpening the fissile-element specific spectral differences.

What Comes Next?

This detector R&D program is just getting started, and there is more we need to learn about the fissile-element specific neutrino spectra.

1. Build a ton-scale detector using our best and most sensitive technology.

2. Use this detector to demonstrate the required sensitivity.

3. Deploy detector modules to a wide variety of reactor types to complete a high-resolution decomposition of the fissile-element specific spectra:
   - Light Water Commercial Reactor
   - HEU Research Reactor
   - CanDU Reactor
   - MOX Fuel Reactor
   - Etc.

4. Continue engagement with the nuclear industry to figure out how this technology can best be used.

Conclusions

1. From the original discovery experiment in 1956, nuclear reactors have played a crucial role in furthering our understanding of neutrinos.

2. We physicists have hopes of giving back to the nuclear industry that has been so kind to us, by developing reactor enabling technologies based on neutrino detection.

3. Advances in detector technology are pointing the way to robust instruments that can operate above ground, and in the environment around an active reactor.

4. The CHANDLER technology is one such detector, and our R&D program seeks to demonstrate its full potential.

5. We need your help to identify promising use cases, and to establish the performance requirements to meet those needs.

GEN IV International Forum℠

Upcoming Webinars

17 December 2020	Development of Multiple-Particle Positron Emission Particle Tracking for Flow Measurement	Dr. Cody Wiggins, University of Tennessee, USA
28 January 2021	MOX Fuel for Advanced Reactors	Dr. Nathalie Chauvin, CEA, France
25 February 2021	Overview of Waste Treatment Plant, Hanford Site	Dr. David Peeler, PNNL, USA