CHANDLER: A Technology for Surface-level Reactor Neutrino Detection

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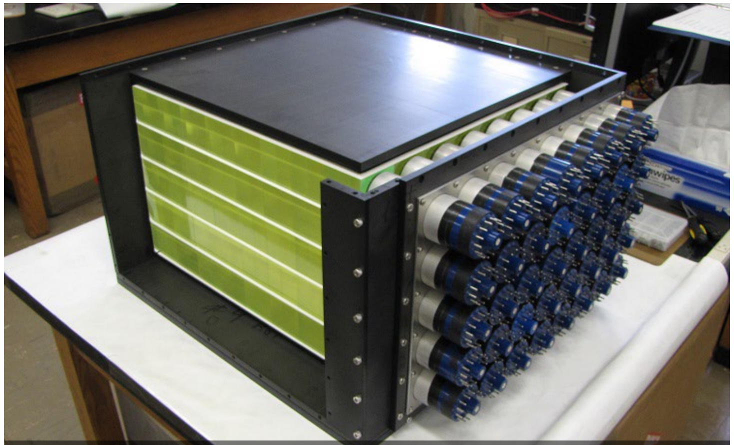
The CHANDLER* Reactor Neutrino Detector

CHANDLER was designed, from the start, to be a robust, mobile detector technology, suitable for a wide range of applications.

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 the neutron capture.

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



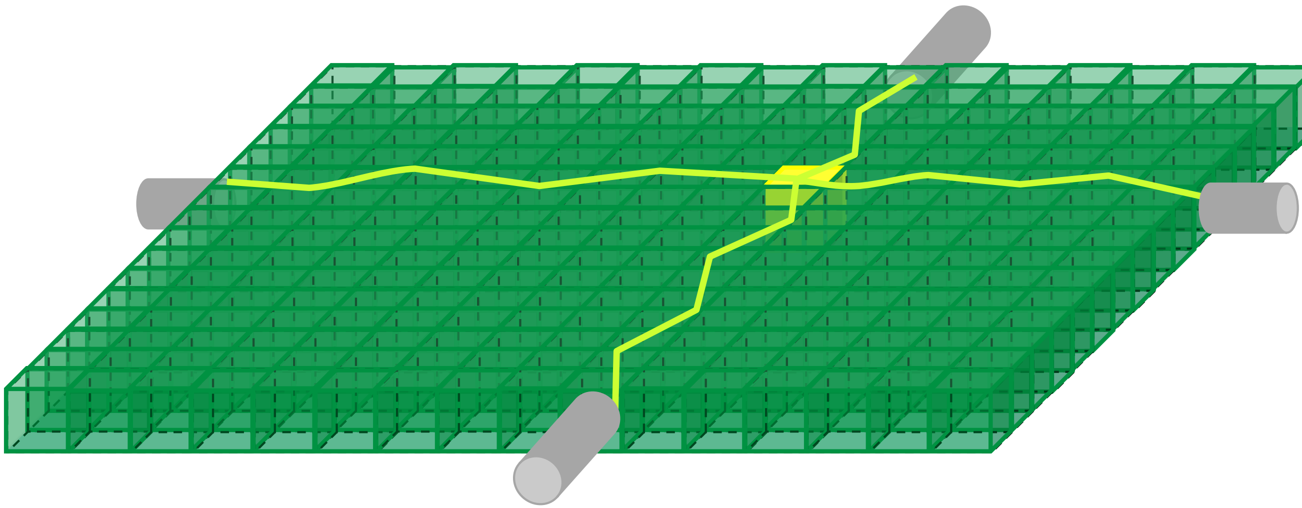
The MiniCHANDLER Prototype, open during assembly to show the cubes and ^{6}Li-doped ZnS sheets

*Carbon Hydrogen Anti-Neutrino Detector with a Lithium Enhanced Raghavan optical lattice

The Raghavan Optical Lattice

The cubes are optically connected in layers, and sandwiched between sheets of ^{6}Li-loaded ZnS scintillator for neutron detection.

Light from the cubes is transported by total-internal-reflection, along the rows and columns of cubes, to the edge of the detector, where it is readout by photomultiplier tubes.



Light from the sheets is absorbed in the cubes and retransmitted by a wavelength-shifter so that it can also be captured by total-internal-reflection.

The Raghavan Optical Lattice allows us to achieve excellent energy and spatial resolution over a large, unbroken detector mass.

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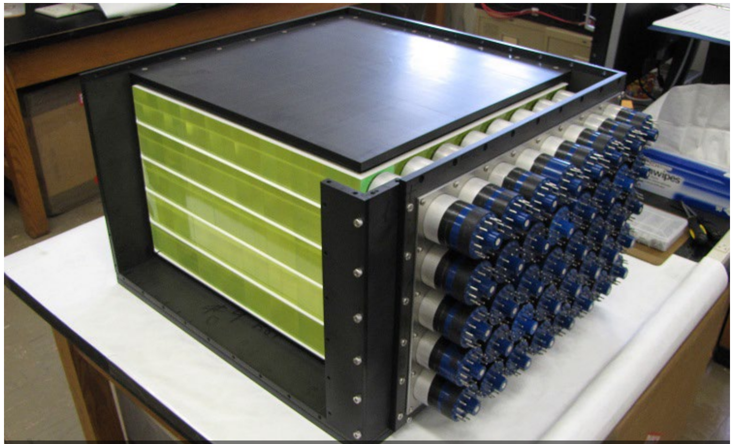
We use this high segmentation to tag the gammas from positron annihilation, and thus reject correlated backgrounds like fast neutrons.



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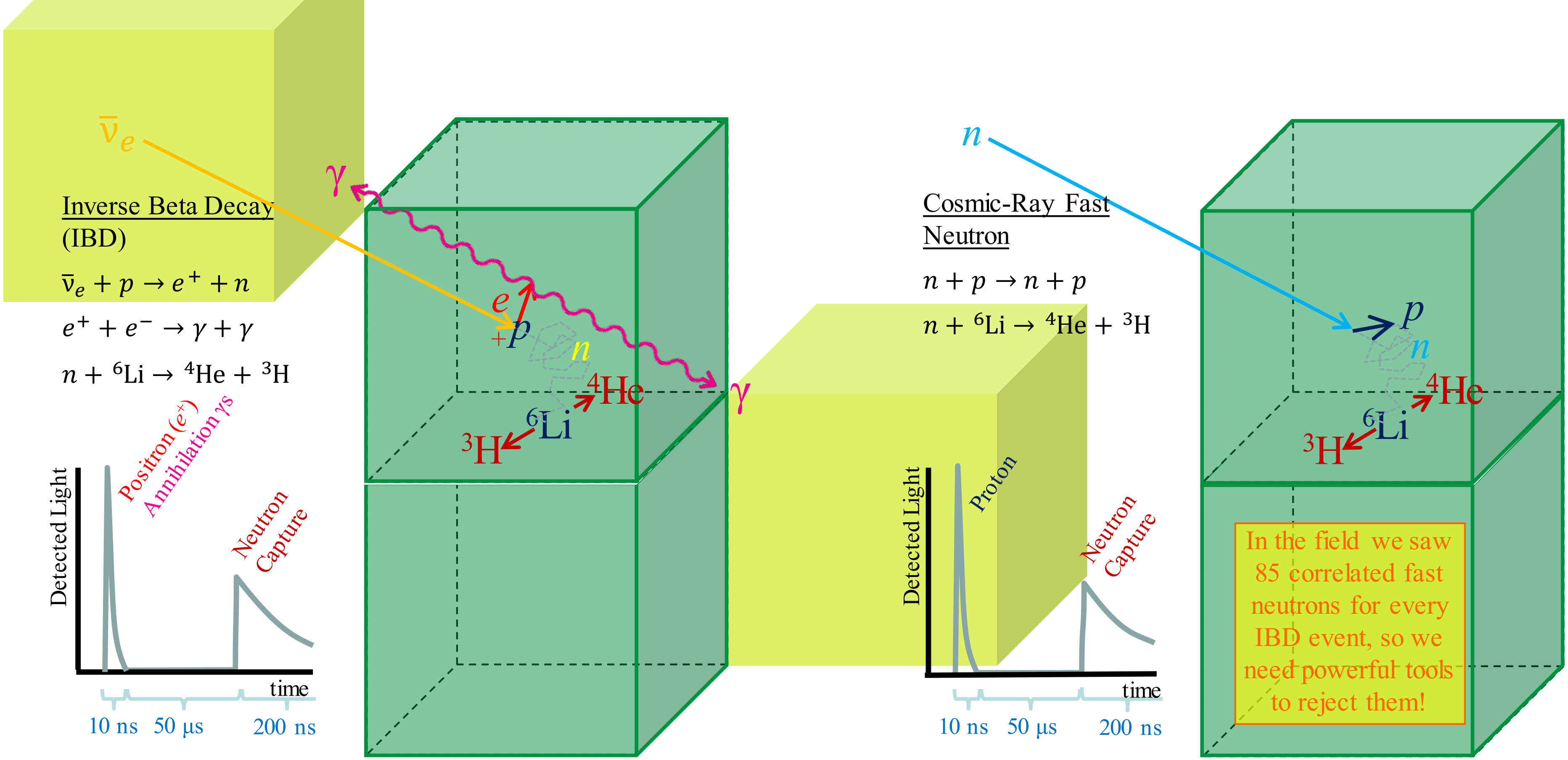
The Signal and the Noise

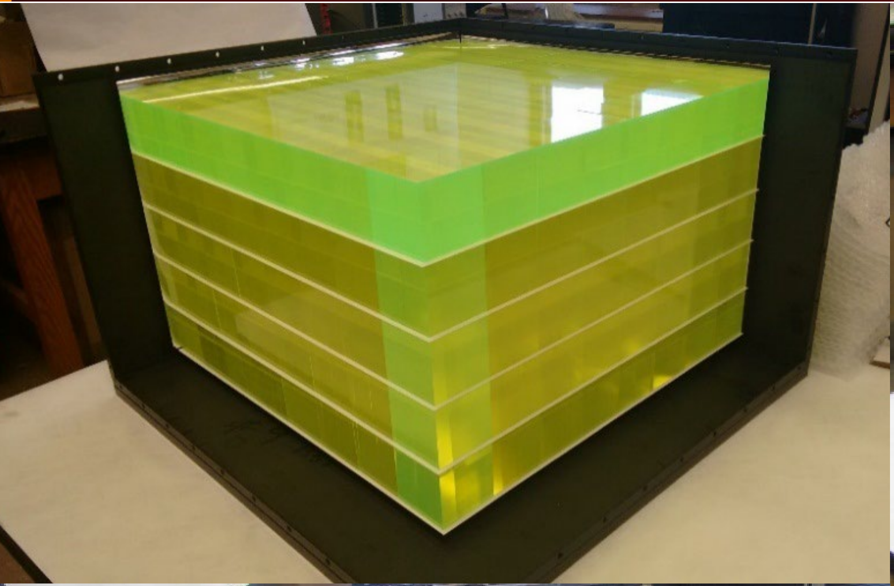
High segmentation allows us to tag the positron annihilation gammas interacting in neighboring cubes.

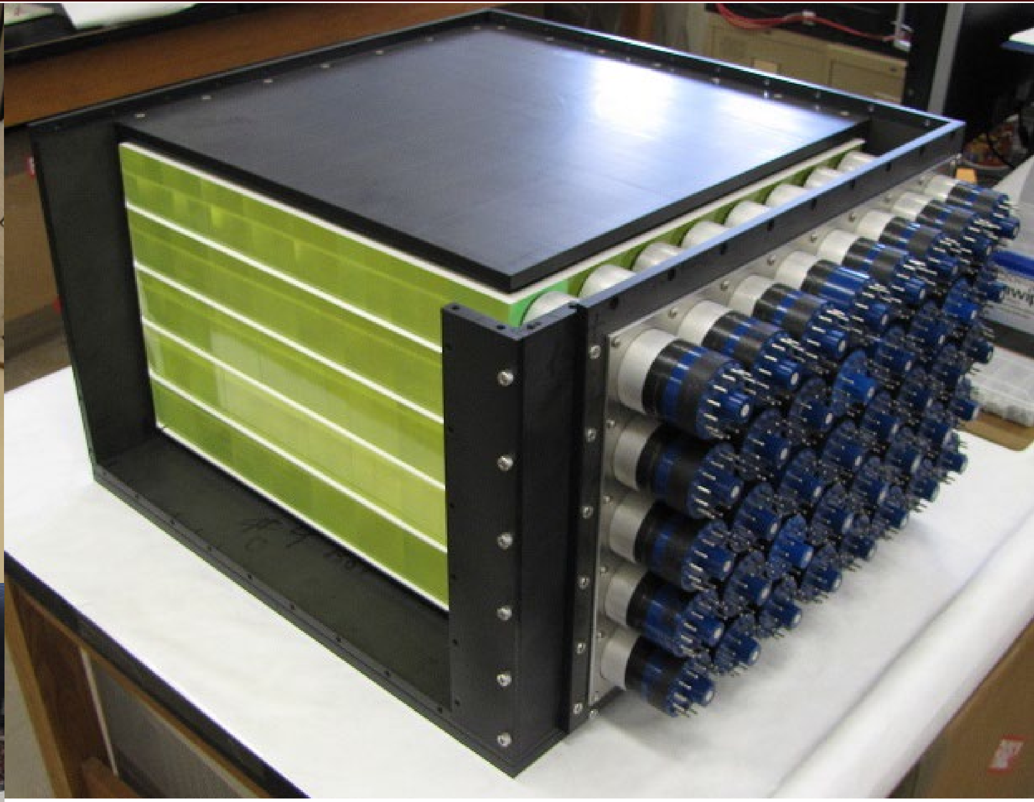
Neutrons are tagged by the slow scintillation decay time of the zinc sulfide scintillator (200 ns vs 10 ns).

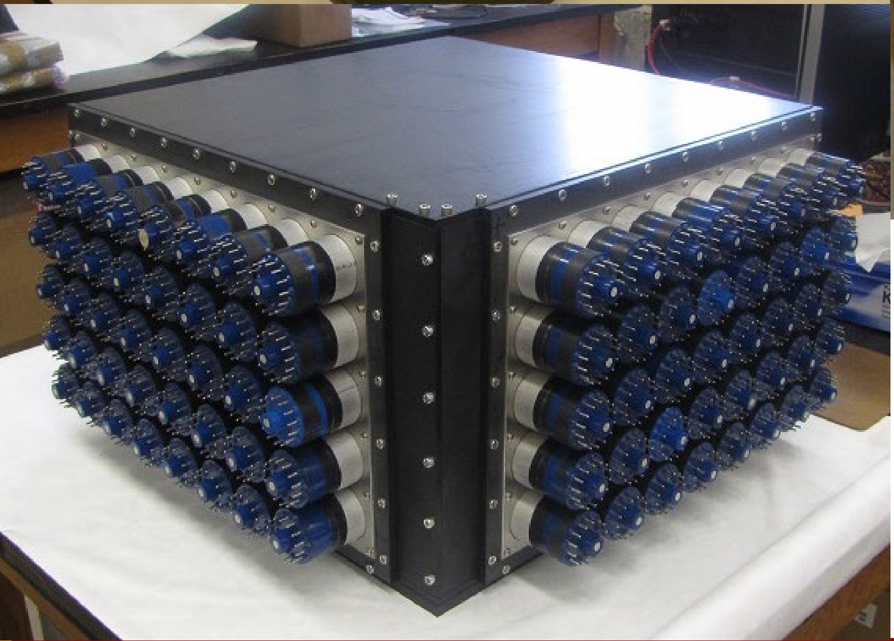
The time ordered coincidence of the positron and the neutron tag separates IBDs from background.



MiniCHANDLER in Pictures







The 80 channel MiniCHANDLER detector was completed in fall 2016.

It was commissioned and installed in our Mobile Neutrino Lab…

The Mobile Neutrino Lab

The MiniCHANDLER prototype was installed in our Mobile Neutrino Lab and deployed to the North Anna Nuclear Generating Station.

MiniCHANDLER would become:

1. The first demonstrated mobile neutrino detector,
2. The first unshielded reactor neutrino detector, and
3. One of the world's smallest neutrino detectors.

The Mobile Neutrino Lab at North Anna

The MiniCHANDLER Analysis

Phys. Rev. Applied 13, 034028 (2020)

The IBD Event Selection

The inverse beta decay candidates include all positron-like events in the 1000 μs preceding a neutron.

The positron candidate energy is reconstructed from the pattern of PMT light collected in each detector plane.

We apply a spatial separation cut between the positron and neutron.

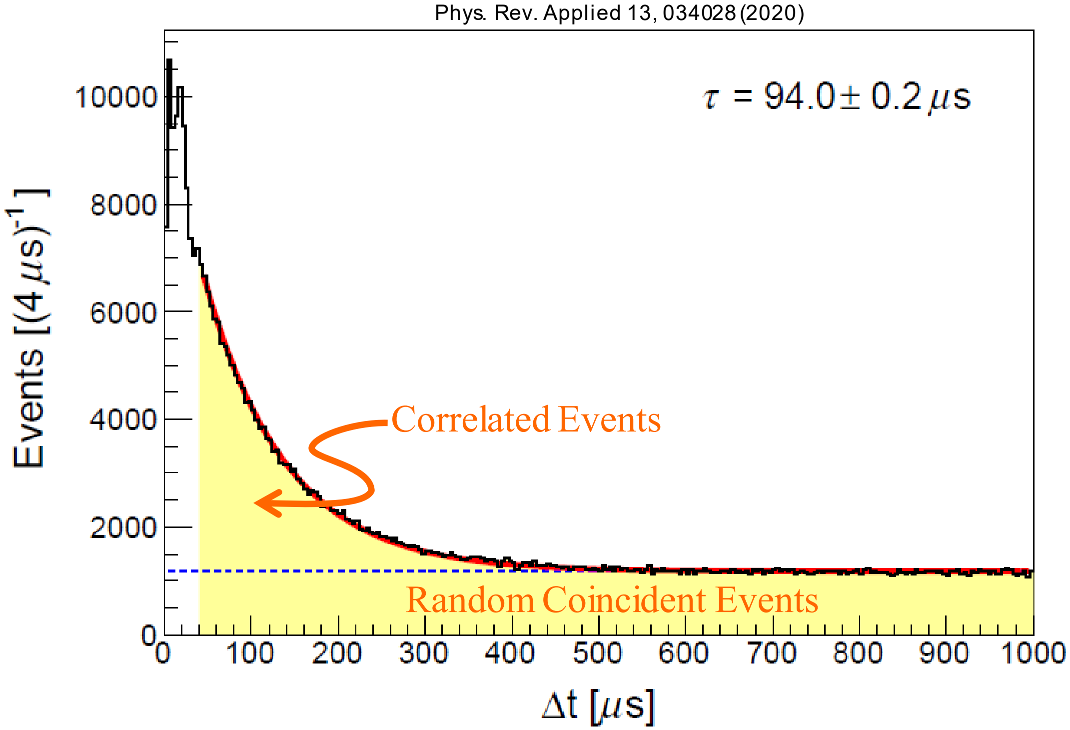
Topological selections are used to reject multiple proton recoils and tag evidence of the annihilation gammas:

1. Total energy outside the primary cube <1 MeV
2. No single cube outside the primary cube with E>511 keV
3. At least one cube outside the primary with energy >100 keV

Fitting Δt for Correlated Events

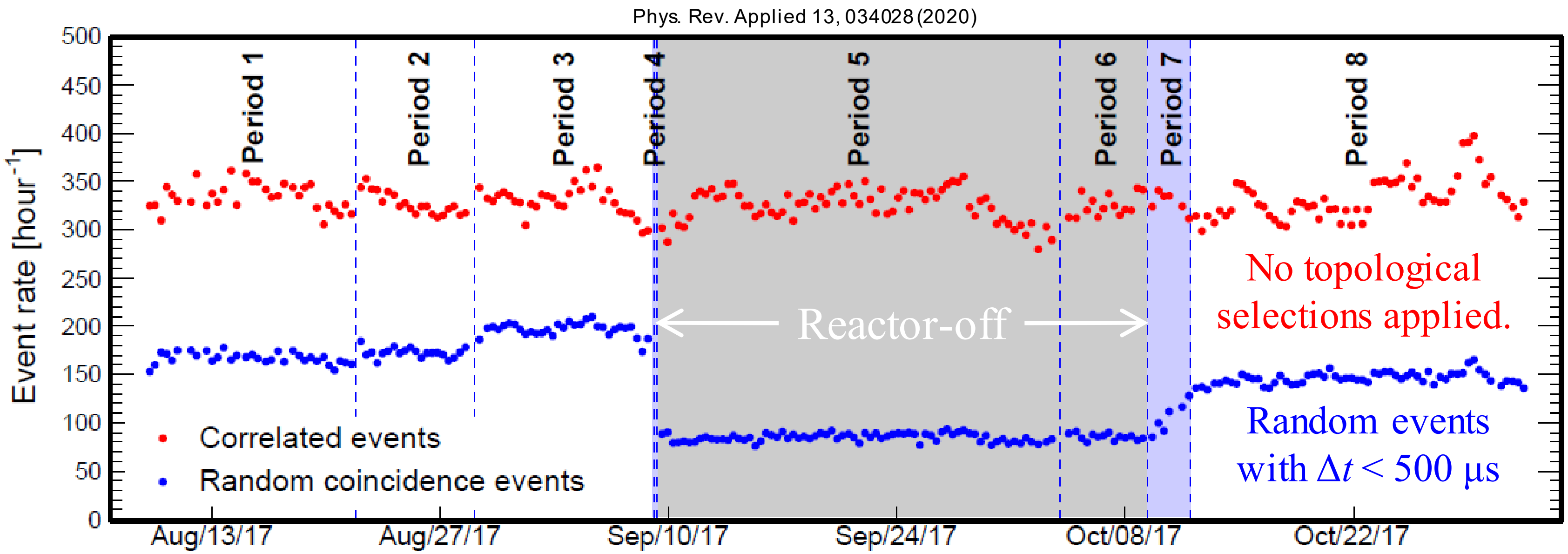
We then sorted our IBD candidates into energy bins of 1 MeV.

In each bin, the positron-neutron Δt distribution was fitted with an exponential plus flat distribution,



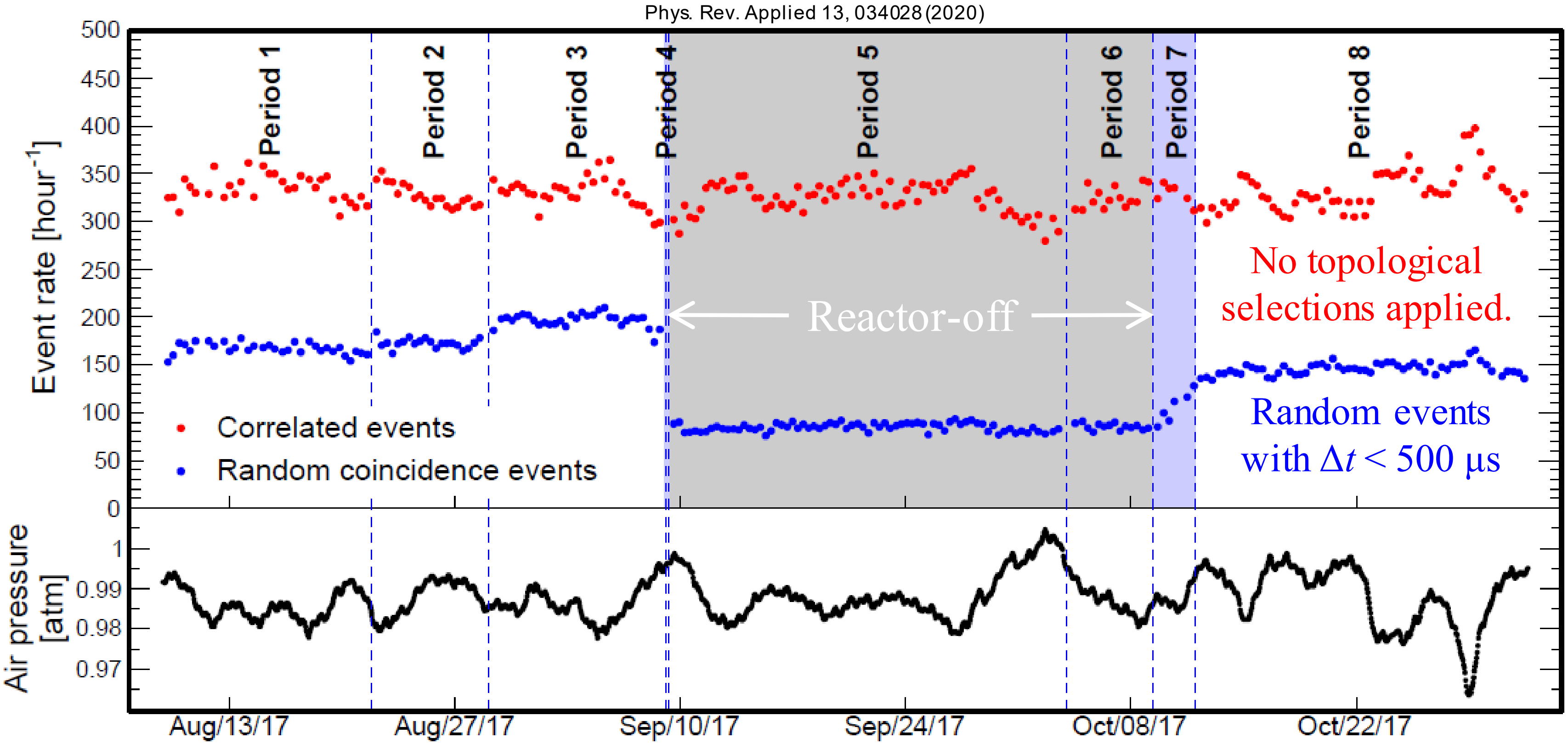
This is how we extracted the time-correlated event rate as a function of the positron candidate energy.

Time Correlated Fast Neutrons



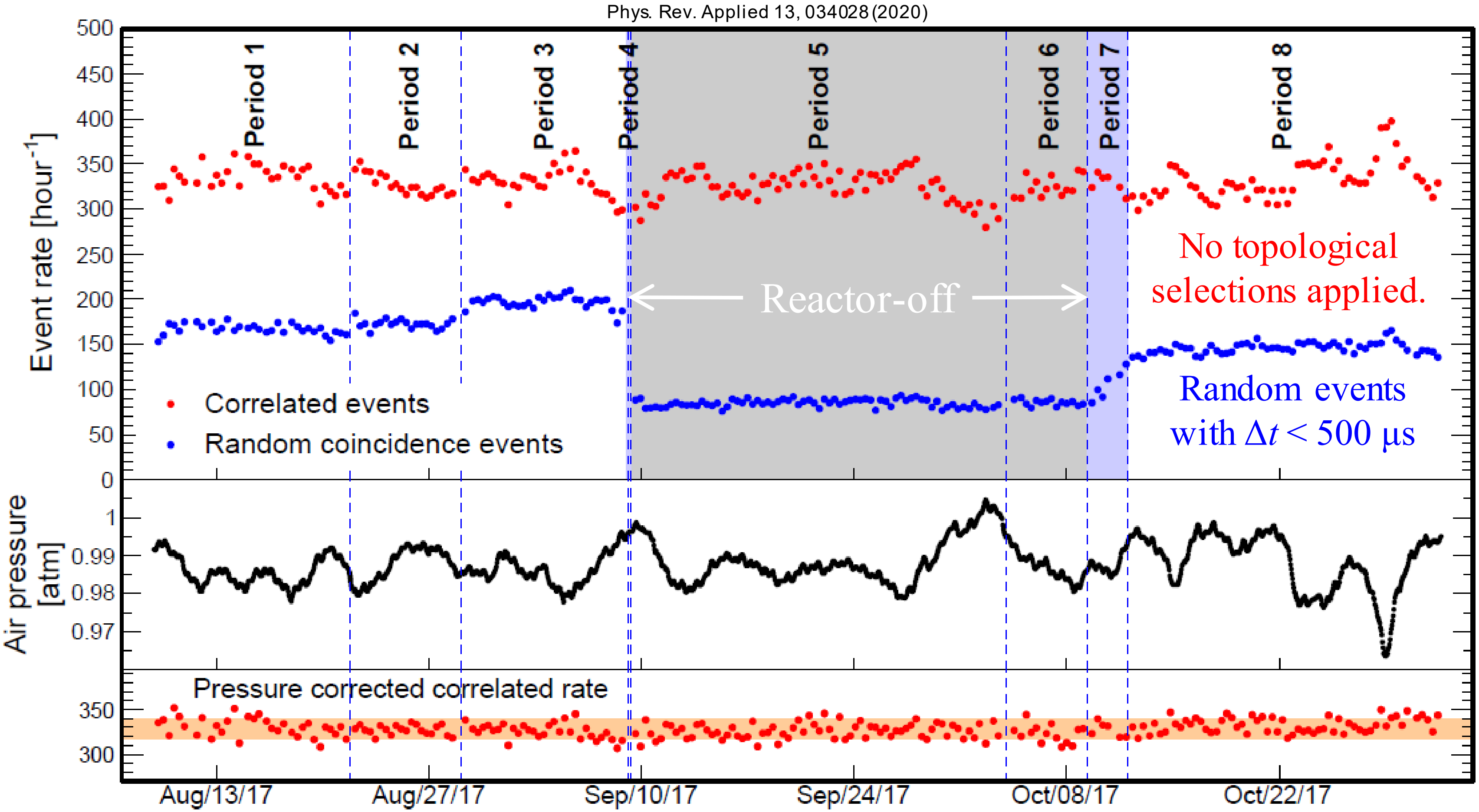
Most of the time correlated events are fast neutrons, and their rate is independent of the reactor power.

Time Correlated Fast Neutrons



The fast neutron rate is inversely correlated with atmospheric pressure.

Time Correlated Fast Neutrons



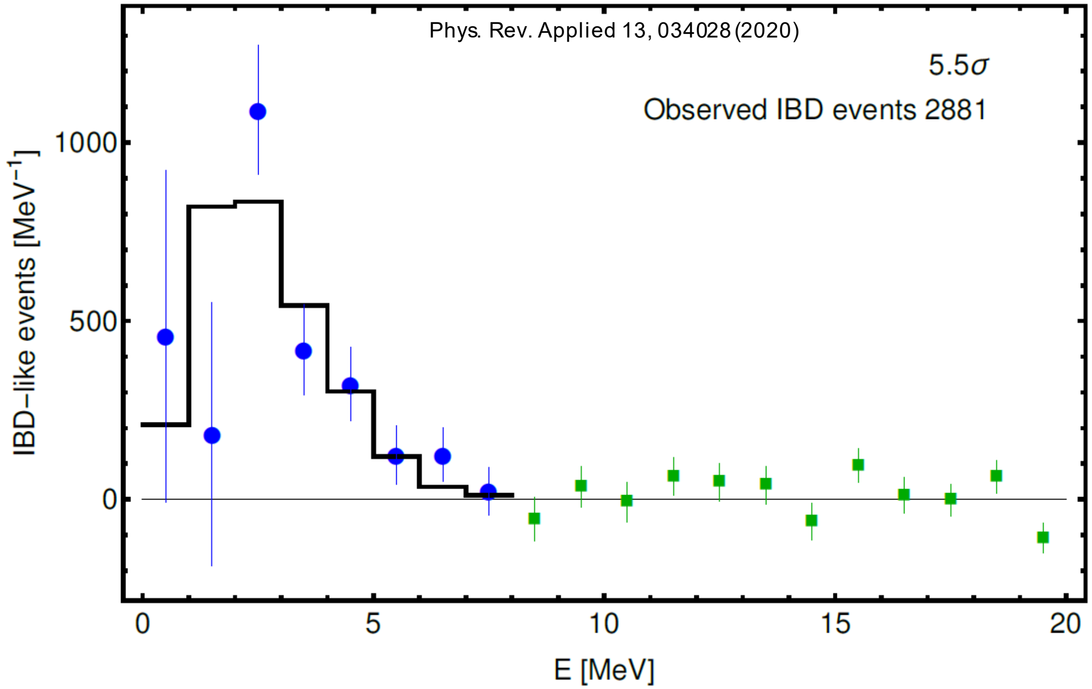
After a pressure correction, we found that the average correlated rate in the reactor-off period was lower than in reactor-on by about 4 events/hour.

Which is consistent with the expected inverse beta decay rate.

The IBD Analysis Results

To further eliminate the correlated background, we performed a reactor-off subtraction.

We used energy bins beyond the signal region (from 8 to 20 MeV) to scale the reactor-off absolute rate to match the reactor-on rate.

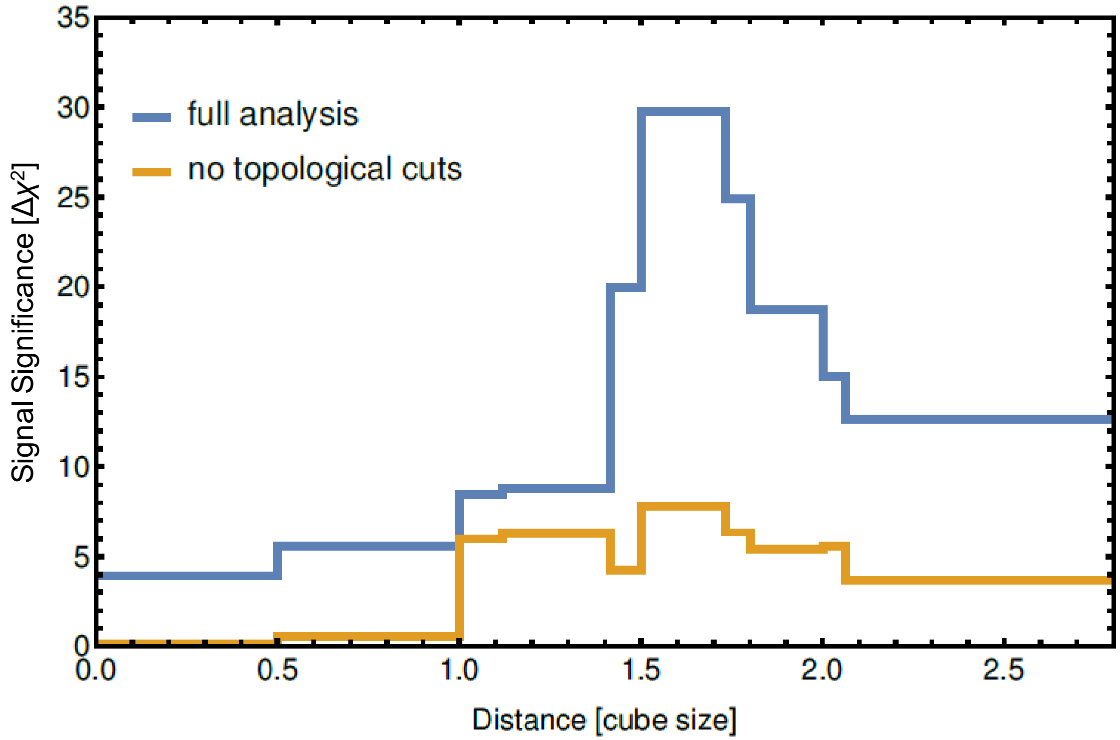


The excess below 8 MeV are neutrino events.

We fit this excess to the inverse beta decay spectrum from Monte Carlo (black histogram).

Topological Selection

The topological selections were essential to extracting a significant signal in MiniCHANDLER:



These selections will improve dramatically with the improved optics.

And, a larger detector will better contain the annihilation gammas and multiple proton recoils.

CHANDLER Future Prospects

Future Upgrades

Going from MiniCHANDLER to full CHANDLER, there are several known enhancements:

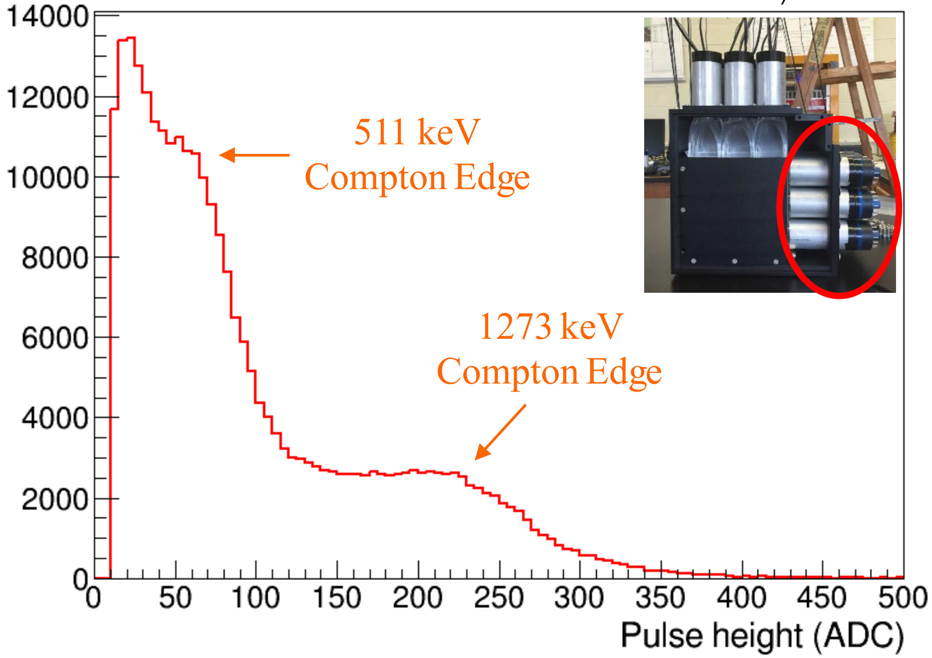
1. New optics: improves energy resolution, pattern recognition and background rejection.

MiniCHANDLER Upgrades: New Optics

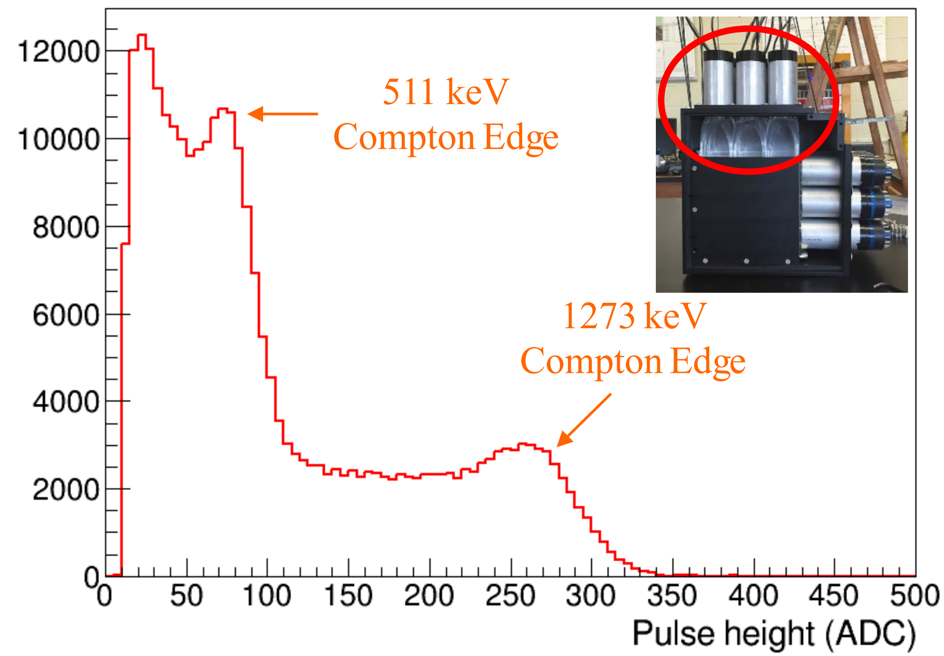
We rebuilt our MicroCHANDLER prototype with half new optics.

We used a ^{22}Na source to compare the energy response in the new and old optics.

Old PMT (As used in the original MiniCHANDLER)



New PMT with lightguide



The new light collection improves the energy resolution by at least a factor of 2.

The annihilation gamma Compton edge and continuum are now distinct features.

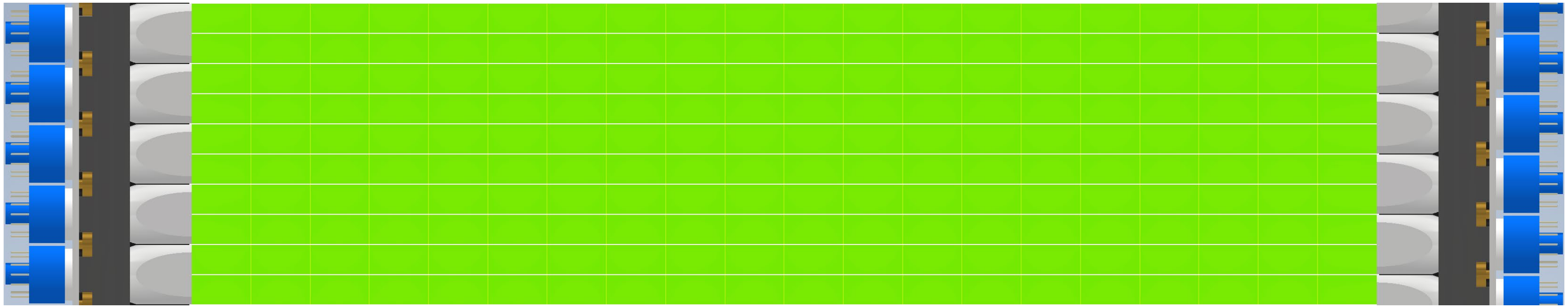
Future Upgrades

Going from MiniCHANDLER to full CHANDLER, there are several known enhancements:

1. New optics: improves energy resolution, pattern recognition and background rejection.
2. Larger detector: faster event accumulation and better detection efficiency from neutron and annihilation gamma containment.
3. PMTs on four sides: improves the pattern recognition and the energy resolution.
4. Half cubes: increases ^{6}Li tagging efficiency and lowers the random coincident background rate.

Half Cubes

The half cubes upgrade doubles the effective ^{6}Li density in the detector.



The opposing PMTs are offset by a half-cube to take advantage of the extra spatial information.

Configuration	^{6}Li Capture	Time to 90% Capture	Volume for 90% Capture
Full Cubes	51%	229 μs	37 cubes
Half Cubes	69%	120 μs	24.5 cubes

The half cubes upgrade increases the ^{6}Li capture efficiency by 35%, but it only increases the cost of the detector by only 12%.

Half cubes lowers the capture time and capture spatial separation, which reduces the random coincident background rate.

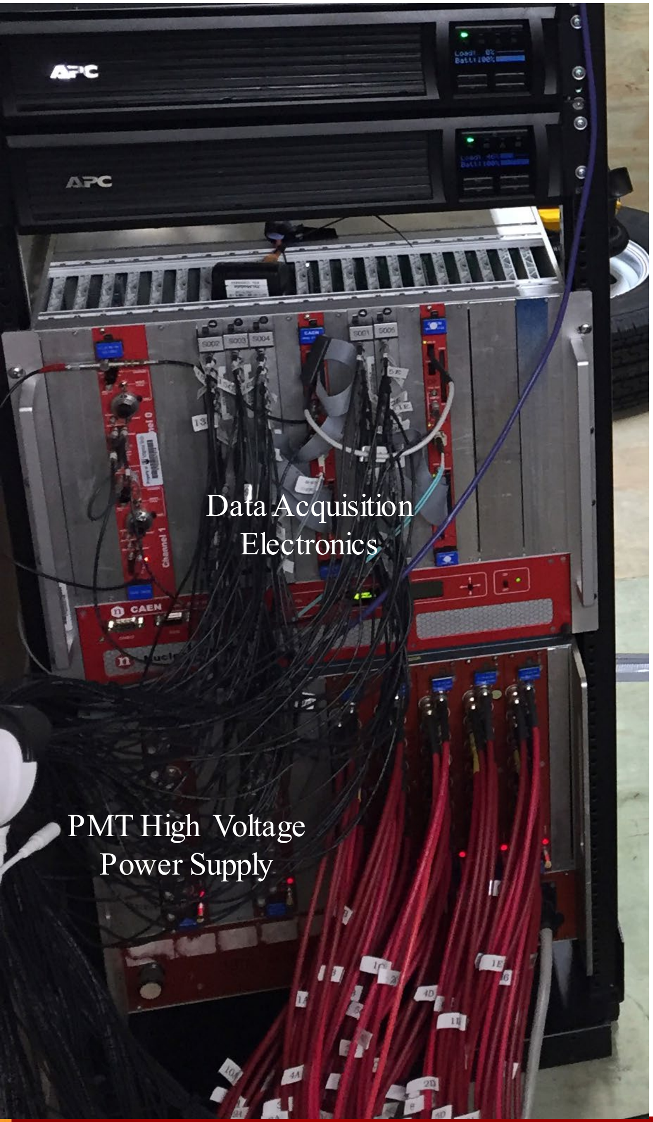
Future Upgrades

Going from MiniCHANDLER to full CHANDLER, there are several known enhancements:

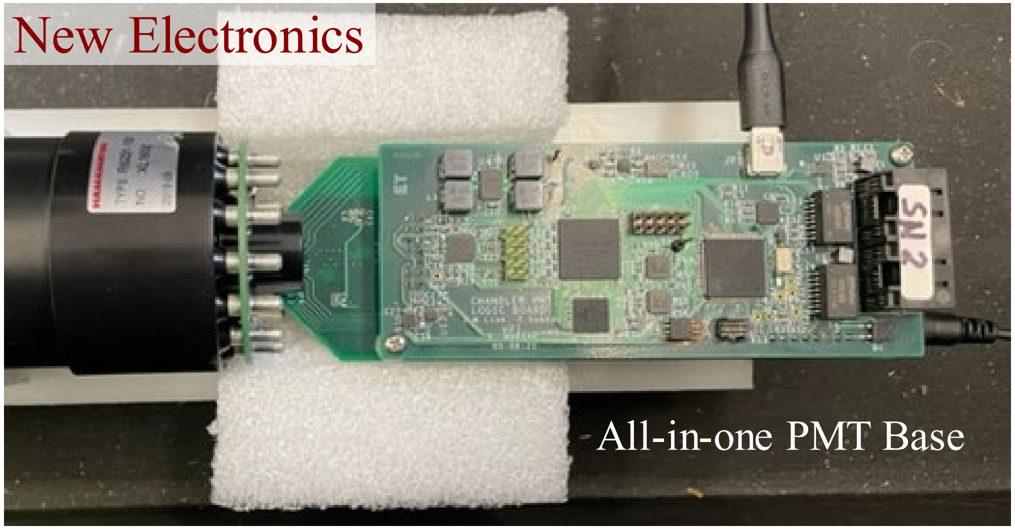
1. New optics: improves energy resolution, pattern recognition and background rejection.
2. Larger detector: faster event accumulation and better detection efficiency from neutron and annihilation gamma containment.
3. PMTs on four sides: improves the pattern recognition and the energy resolution.
4. Half cubes: increases ^{6}Li tagging efficiency and lowers the random coincident background rate.
5. Electronics upgrade: lowers cost, improves data quality and pattern recognition.

Electronics Upgrade

Old Electronics



We are pursuing a major upgrade to our electronics.



This base puts the high voltage, digitizer and a fully programmable trigger, all at the PMT.

- Uses power over Ethernet
- No channel-to-channel crosstalk
- No signal attenuation
- ADC dynamic range goes from 12 bits to14 bits
- Dynamic trigger threshold for superimposed hits
- On-board, programmable neutron/positron ID

Future Plans

We're upgrading MiniCHANDLER for a redeployment this spring at North Anna.

This upgrade includes new PMTs and light guides, a new voltage-divider base, and one plane of half cubes.

Unfortunately, we will not have the all-in-one base for this deployment; a consequence of the global semiconductor crisis.

This deployment will test improved event selections based on the improved energy resolution.

CHANDLER is one of two technologies under consideration in the Mobile Antineutrino Demonstrator project.

This may be a path to the first ton-scale CHANDLER detector.

Thoughts on Nuclear Data Needs

Isotope Specific Antineutrino Spectra

As Daya Bay has shown, the different fissile and fissionable isotopes have different antineutrino spectra, and I believe that this is the key to most neutrino applications in reactor monitoring:

Tracking Burn-up: Measures the evolution of the fissile isotopes through spectral changes.

Measuring Power: But first you have to know where you are in the burn-up.

Identifying Material Diversions: Looks at the neutrino spectra, before and after shutdowns or fueling activities, and compares to expectations from the declared activities.

Fitting the observed spectrum with the isotope-specific reference spectra would gives the most complete picture of what's going on in the core.

How Do We Get These Reference Spectra?

Through an analysis of direct antineutrino measurements.

Even if you take a maximalist view of what can be achieved by theory and database calculations, the spectra would need to be verified by antineutrino measurements.

The uranium-235 spectrum can be directly measured in HEU reactors, but the other isotopes require a fit-based extraction.

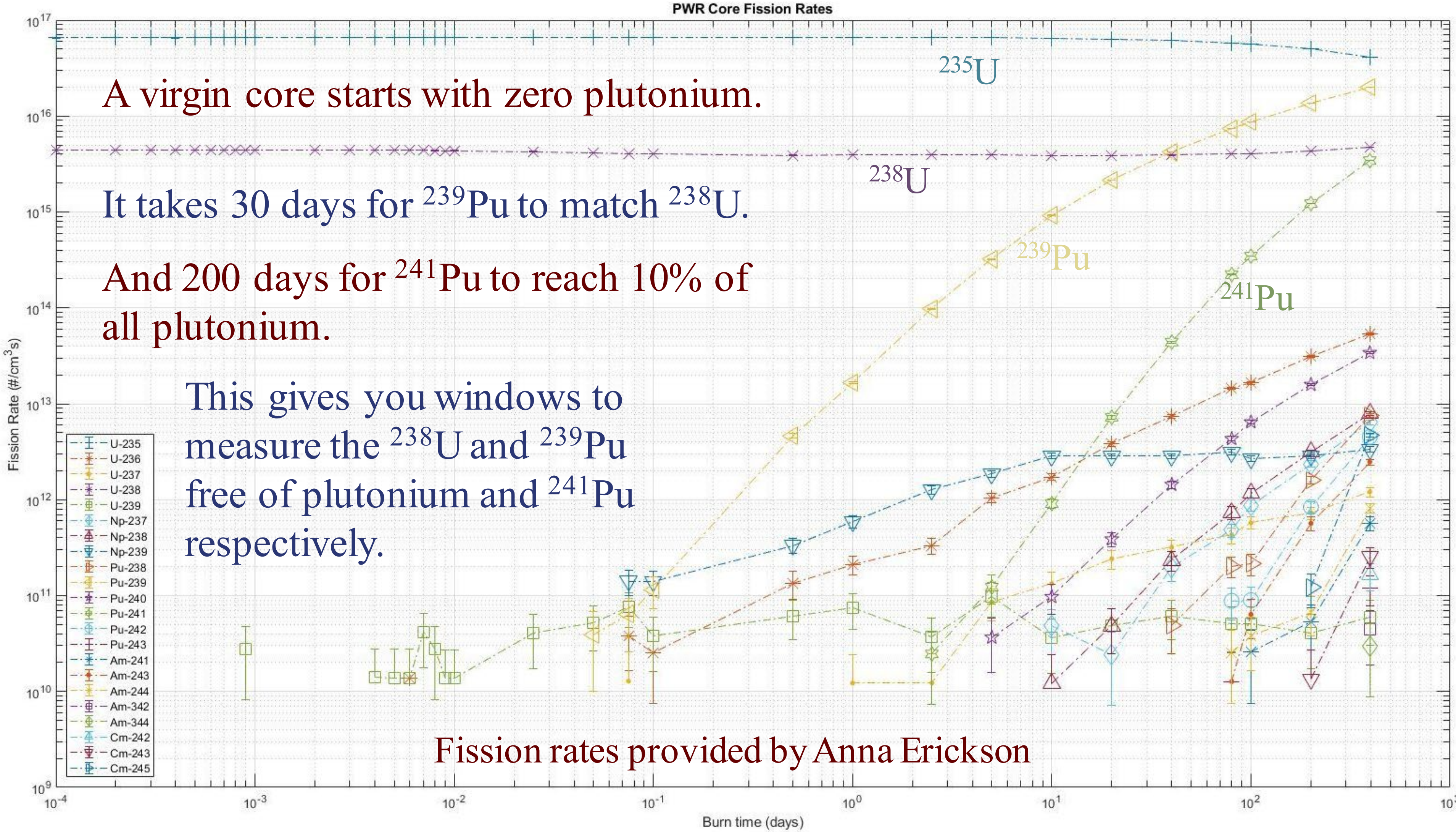
This requires data from different types of reactors, and/or different periods in the fuel cycle, which maximizes variations in the mix of fission rates.

Homework:

What are the most impactful reactor types for determining these reference spectra and where can we access them?

Virgin Core Example

Vogel 3 & 4 are two new reactors coming online in 2023 and 2024.



A virgin core starts with zero plutonium.

It takes 30 days for ^{239}Pu to match ^{238}U.

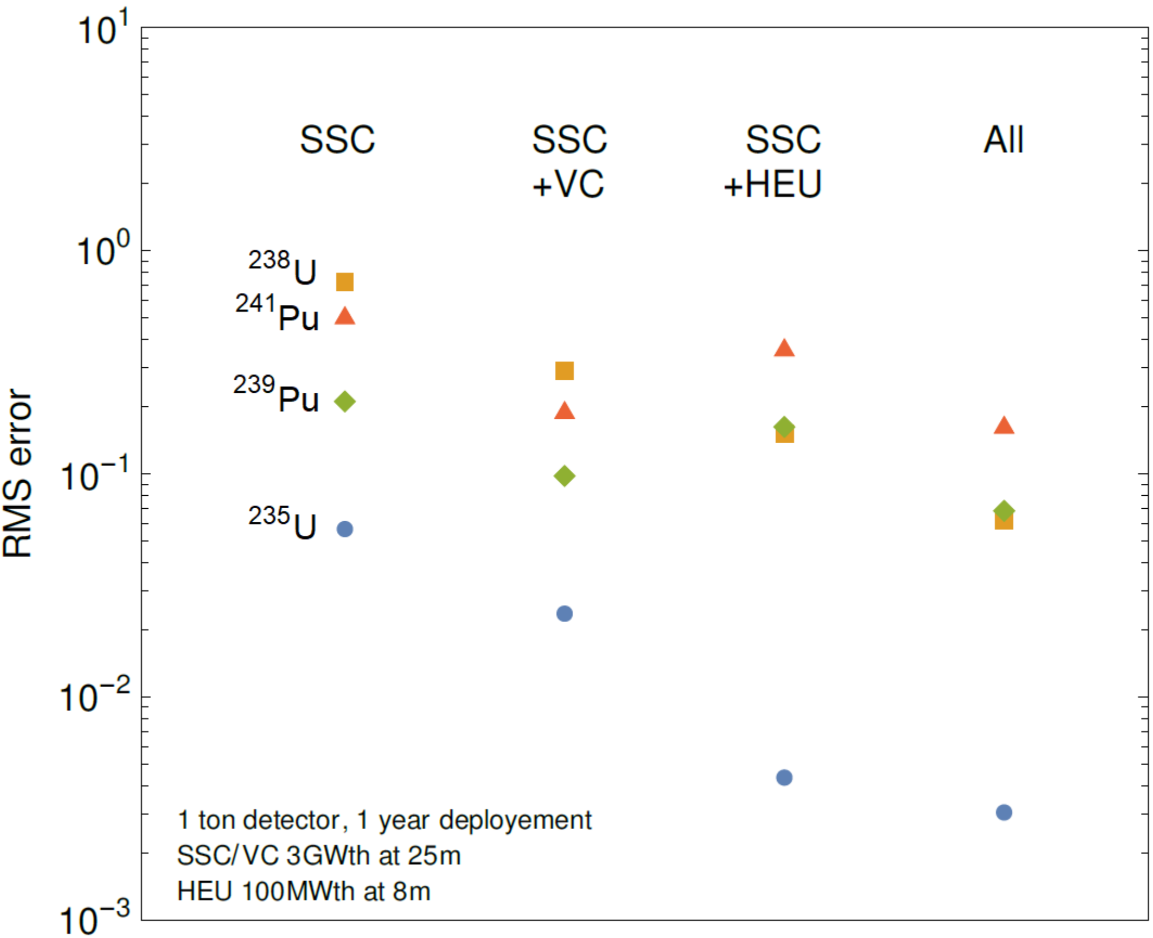
And 200 days for ^{241}Pu to reach 10% of all plutonium.

This gives you windows to measure the ^{238}U and ^{239}Pu free of plutonium and ^{241}Pu respectively.

Fission rates provided by Anna Erickson

Virgin Core Example

In this unpublished study by Patrick Huber, Anna Erickson and JL, we found that adding Virgin Core running to Steady State Core (LEU) improves the flux errors on all four isotopes.



Compared to adding HEU, Virgin Core data significantly improves the errors on ^{238}U and ^{239}Pu.

Combining all three is better still.

Combining a wide range of diverse data sets should be the quickest way to improve the uncertainties on all the reference spectra.

Isotope Specific Antineutrino Spectra

A short list of reactor types that I'd like to see studied includes:

- Heavy water moderated natural uranium (CanDU)
- Mixed oxide fuel (MOX)
- Fast breeder reactor
  (Do we separate fast spectra?)

Are there other reactors types that should be considered?

This program to measure isotope-specific reference spectra should probably be a coordinated worldwide effort.

For example, in North America we don't currently have any operating MOX or fast breeder reactors.