The ANNIE Experiment

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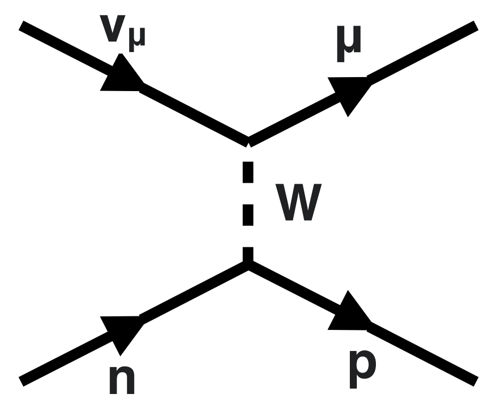
Introduction

- What is ANNIE and what are its aims?
- Why do we need to detect neutrons?
- Progress
- Introducing LAPPDs
- Preliminary results

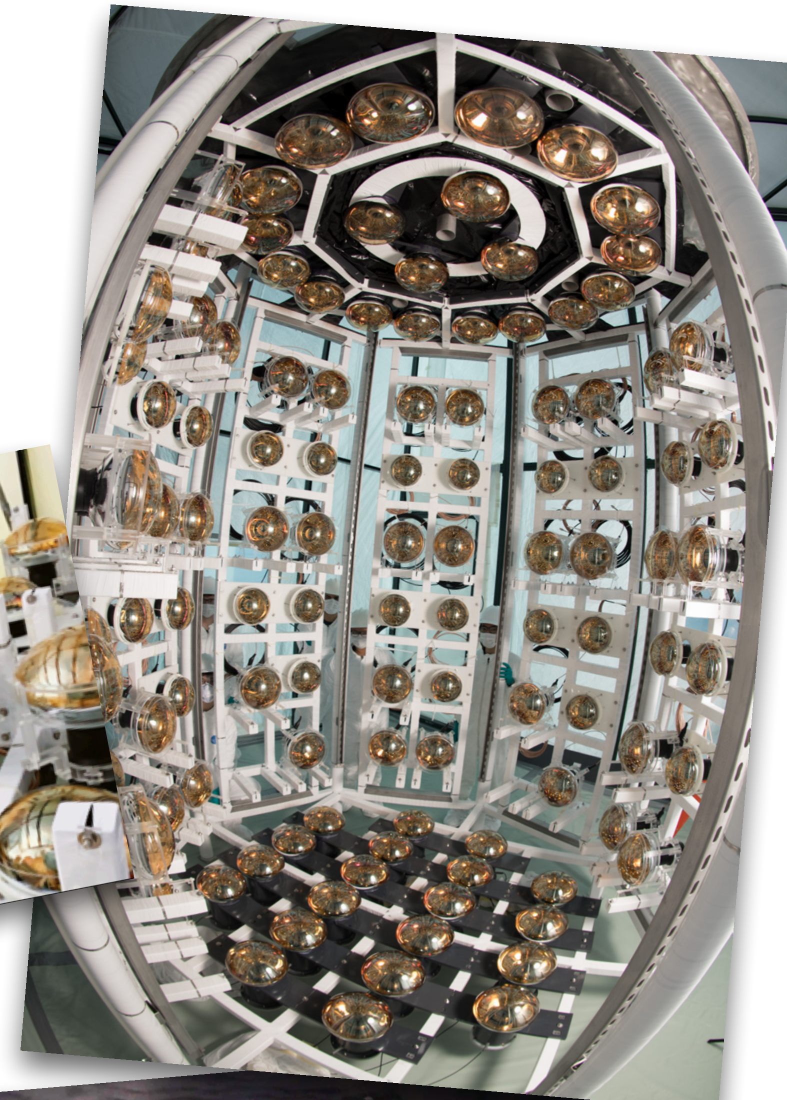
Welcome to the ANNIE collaboration

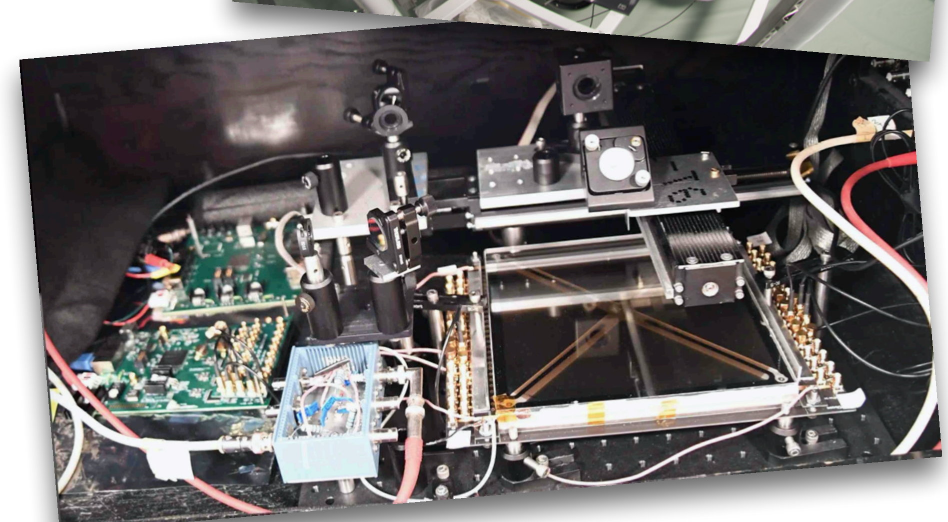
What is ANNIE and what are its main goals?

- ANNIE is the Accelerator Neutrino Neutron Interaction Experiment.
- It will measure the neutron multiplicity of ν_μ interactions as a function of momentum transfer and the ν_μ cross sections on water.
- The complex nature of neutrino-nucleus interactions makes them challenging to model.
  - This results in large systematic uncertainties in long-baseline experiments
  - Unknown contribution of atmospheric neutrino background to proton decay measurements
  - How often do “stealth” atmospheric neutrinos mimic DSNBs?
- Furthermore ANNIE provides a world leading testbed for future technologies:
  - The first use of Large Area Picosecond Photodetectors (LAPPDs) in a running neutrino experiment
  - Potential introduction of a Water-based Liquid Scintillator (WbLS) volume
  - Neutron calibration source provides a prototype for similar implementations in WATCHMAN and THEIA



ν_μ CCQE interaction





Introducing the ANNIE detector

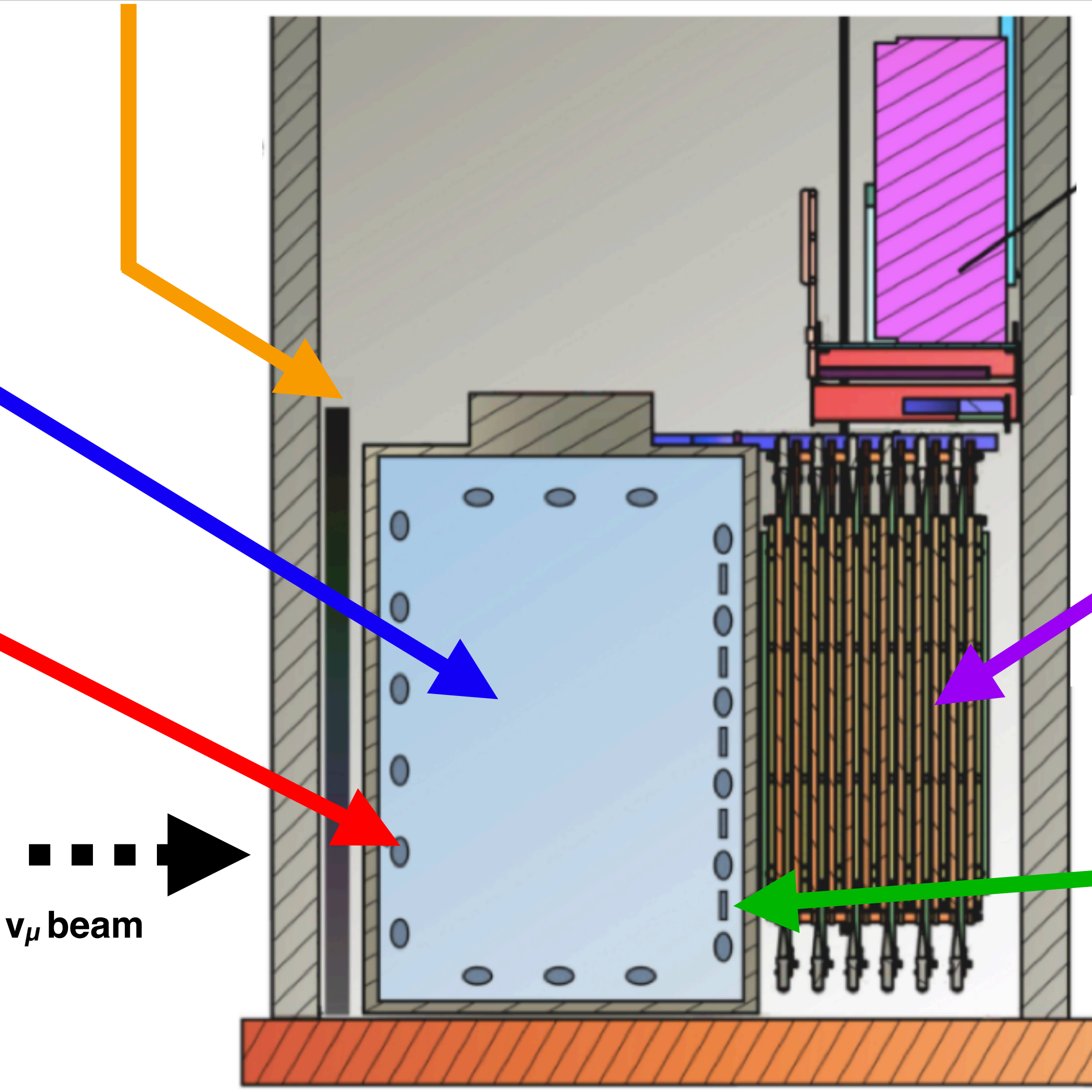
- ANNIE has a 3m diameter and 4m tall cylindrical tank filled with 26 tonnes of gadolinium-loaded (0.1%) deionised water.
- Gadolinium, with its huge neutron capture cross-section (~50,000 barns), enables neutrons to be detected efficiently.

The Front Muon Veto (FMV) consists of 2 scintillator paddle layers and is used to vetos upstream neutrino interactions.

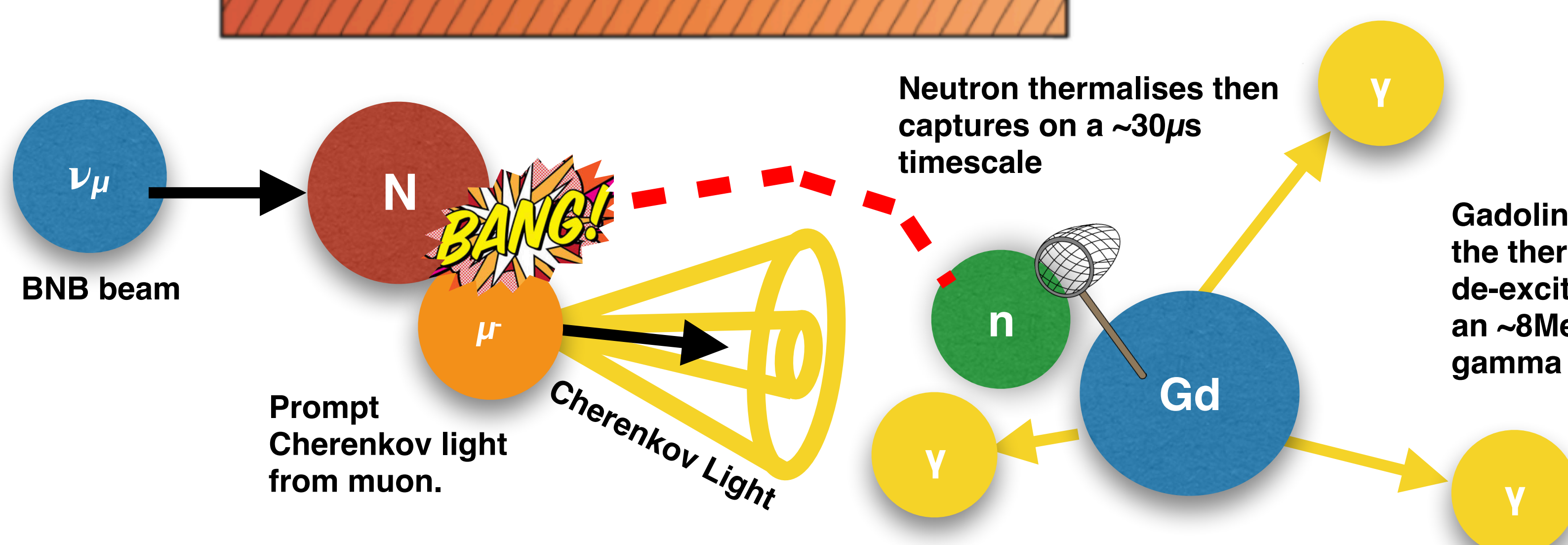
The Muon Range Detector (MRD) consists of 11 layers of scintillator sandwiched between 11 layers of iron. This enables energy and momentum reconstruction of outgoing muons.

The water volume is instrumented with 132 PMTs, giving a 20% photocathode coverage

5 LAPPDs with sub-cm spacial, and ~60ps temporal, resolution are to be installed imminently. This will further enhance reconstruction capabilities.

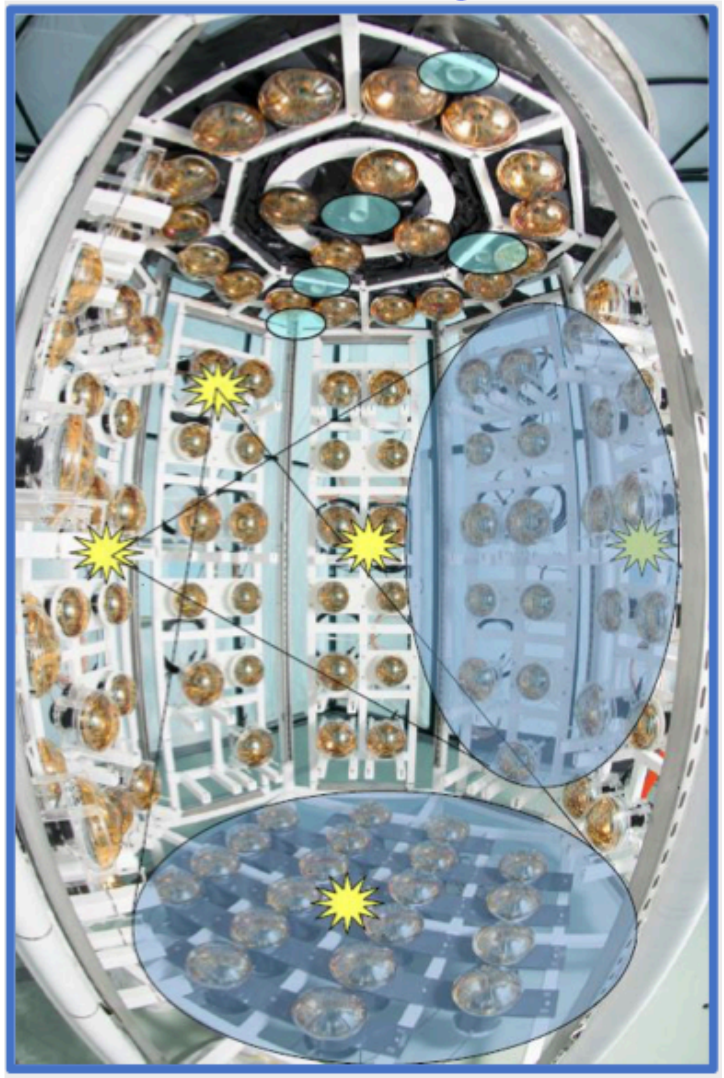


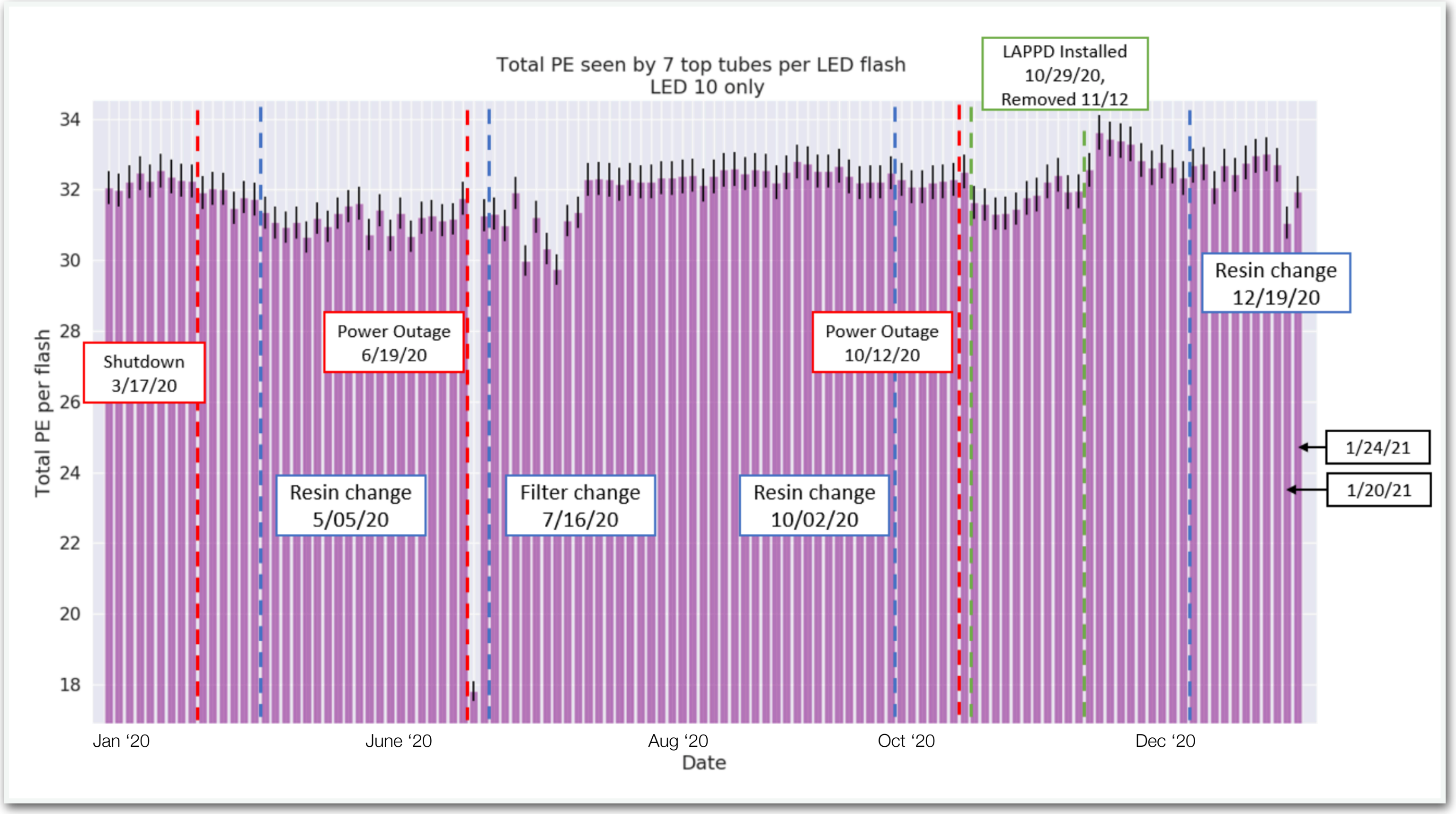
- Located 100m downstream in the Booster Neutrino Beam (BNB) at Fermilab.
- ~26,000 charged-current ν_μ interactions in the fiducial volume per year.



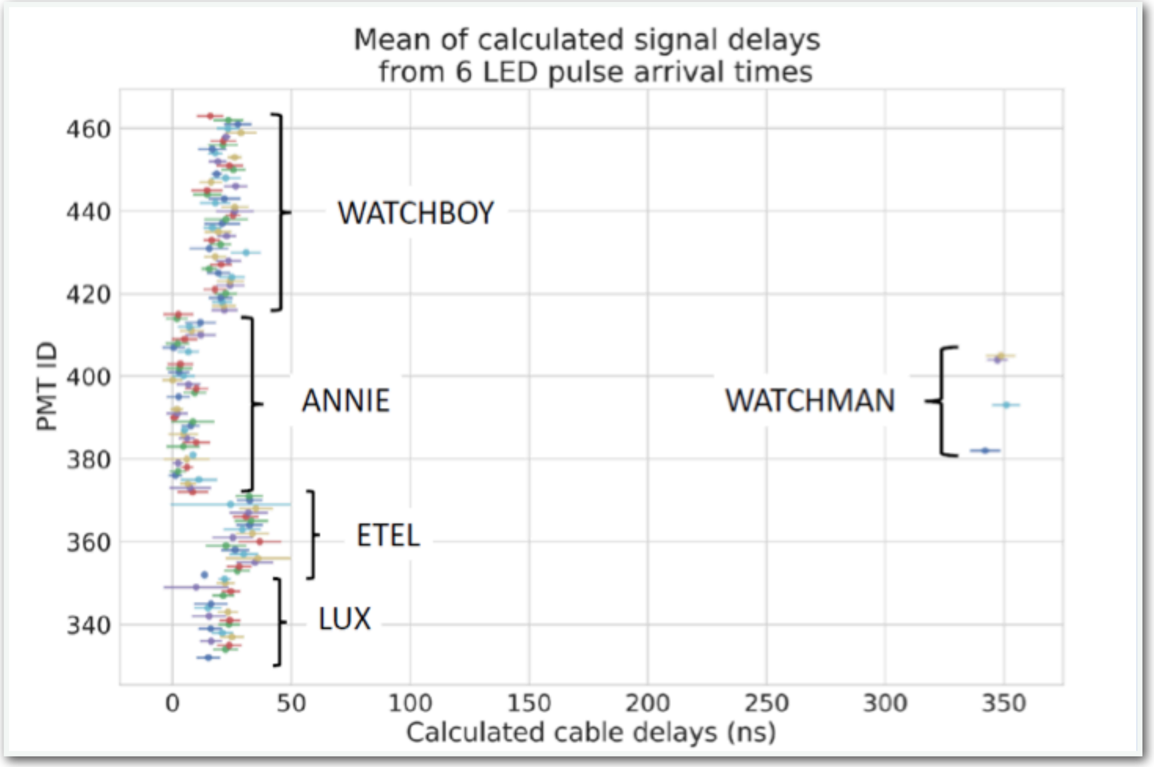
Optical calibration techniques

- 6 LEDs installed in the tank.
- Essential for setting uniform PMT gains.
- Enabled the determination of cable delays.
- Used to periodically monitor the water transparency.





Variation in total photoelectrons detected by top PMTs when flashing the bottom PMT to assess water transparency

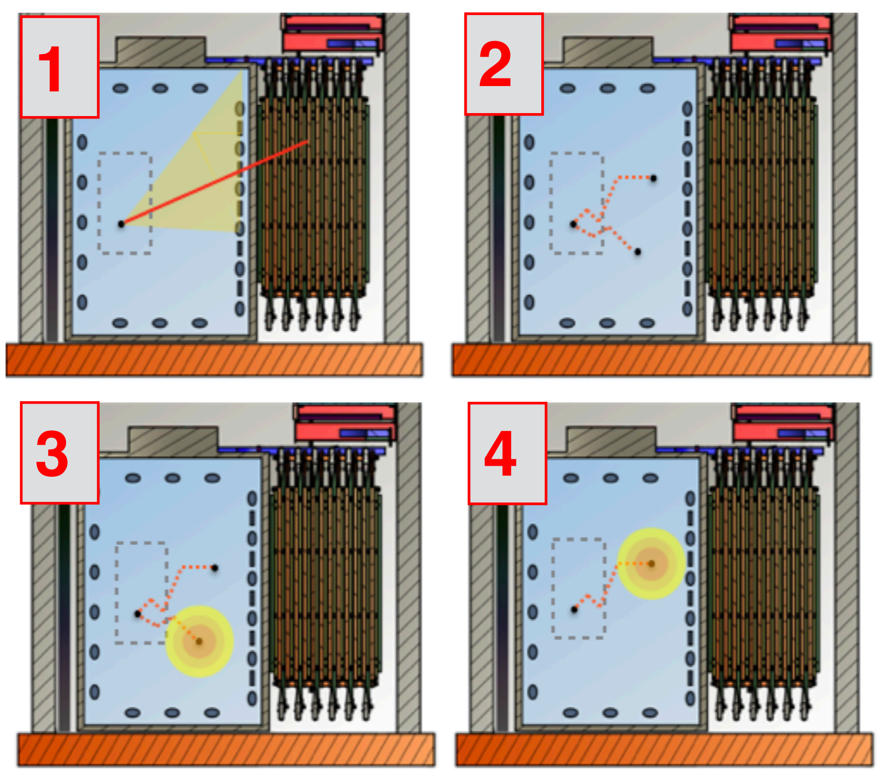


Methodologies have been developed to fully characterise the PMTs

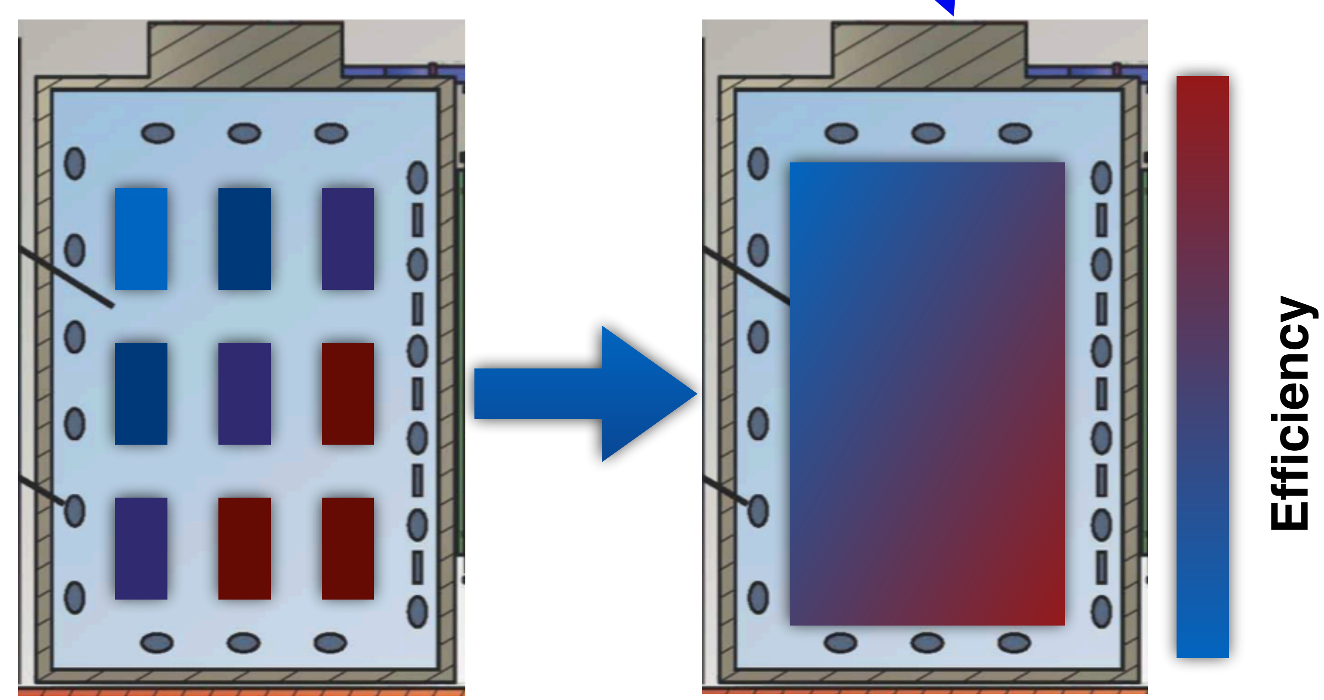
ANNIE's neutron capture detection efficiency must be precisely mapped

- To achieve ANNIE's main goals, it is imperative that we fully understand the position-dependent neutron capture efficiency
- By designing and deploying a neutron source at specific locations within the tank, the efficiency as a function of position can be mapped.
- Thus, we need to design a calibration source that produces a single neutron AND can be tagged.

To measure neutron multiplicities, ANNIE's position-dependent neutron detection efficiency must be well measured.



1. **A prompt muon interacts in the fiducial volume, producing a Cherenkov ring and a track in the MRD.**
2. **Final state neutrons are produced. Scattering and thermalising.**
3. **& 4. After ~10s μs each neutron is captured on Gd, producing an 8 MeV gamma cascade.**

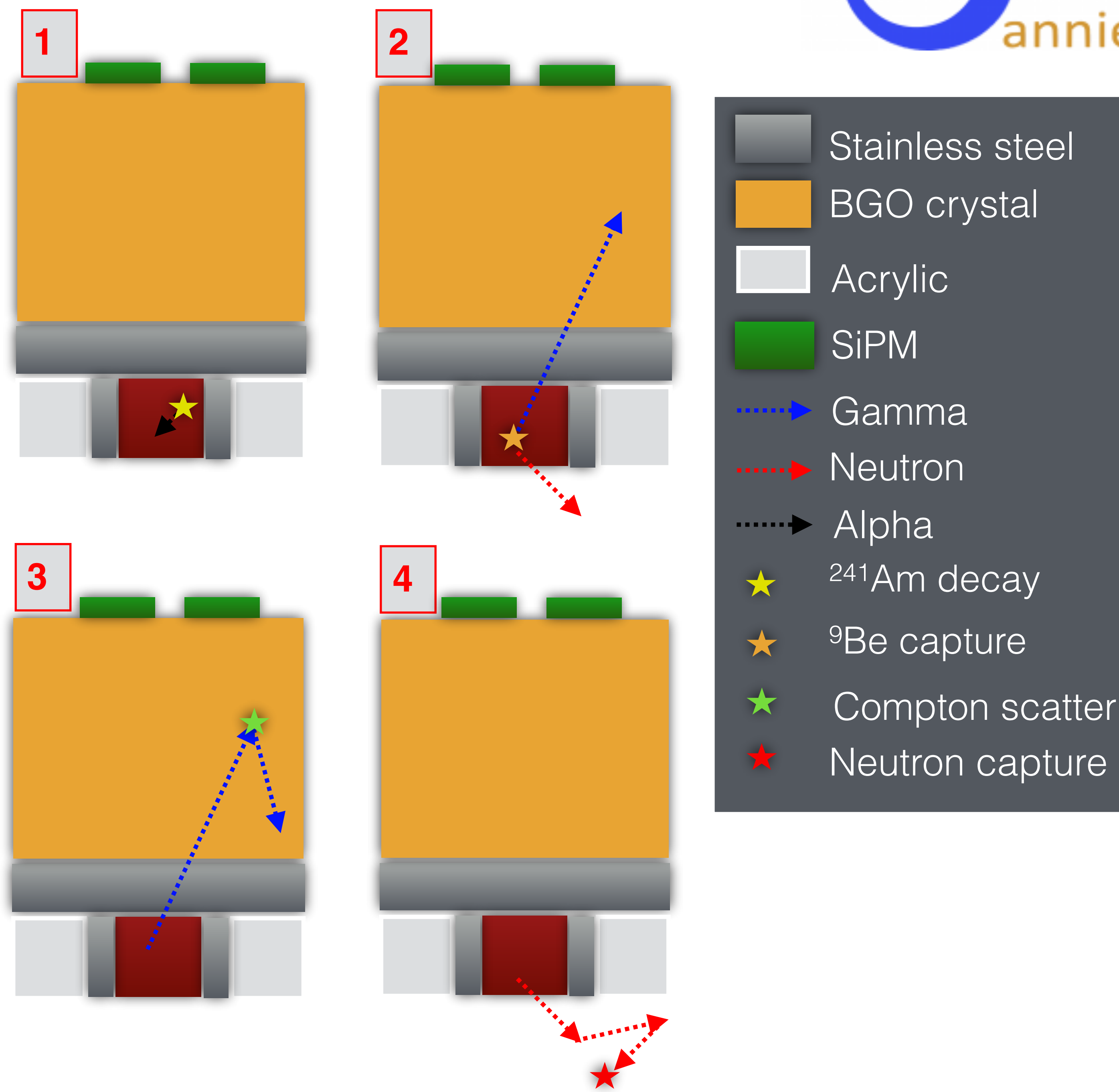


By placing a calibration source throughout the detector....

...the neutron capture detection efficiency will be mapped.

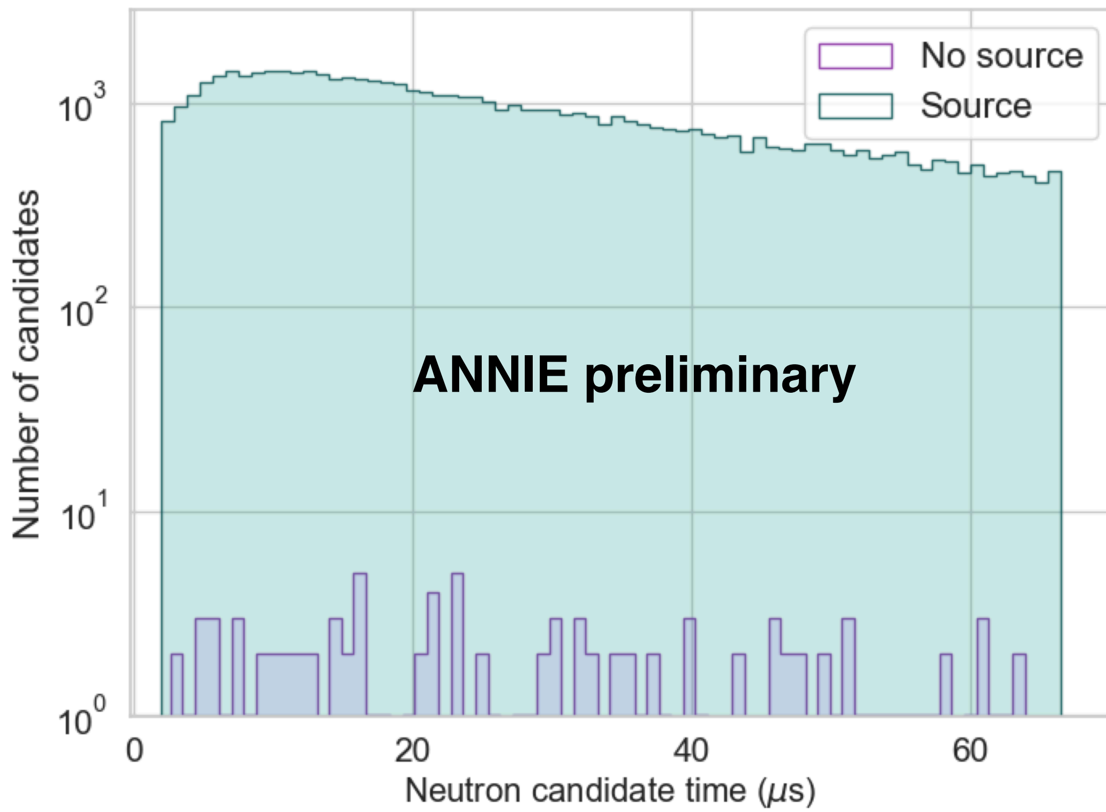
Introducing the AmBe source…

- The AmBe source is a mixture of ^{241}Am and ^{9}Be.
- Produces a neutron and a 4.44 MeV gamma.
- SiPMs and a bismuth germanium oxide (BGO) crystal are used to detect this gamma.
  - High light yield of ~8500 photons per MeV.
  - Emits in a favourable wavelength regime (480 nm peak emission with a range of 375-650 nm).
  - Dense (7.13 g/cm^3), increasing Compton scatter likelihood.
- The neutron detection efficiency is then determined by searching for the 8MeV gamma cascade produced upon capture.

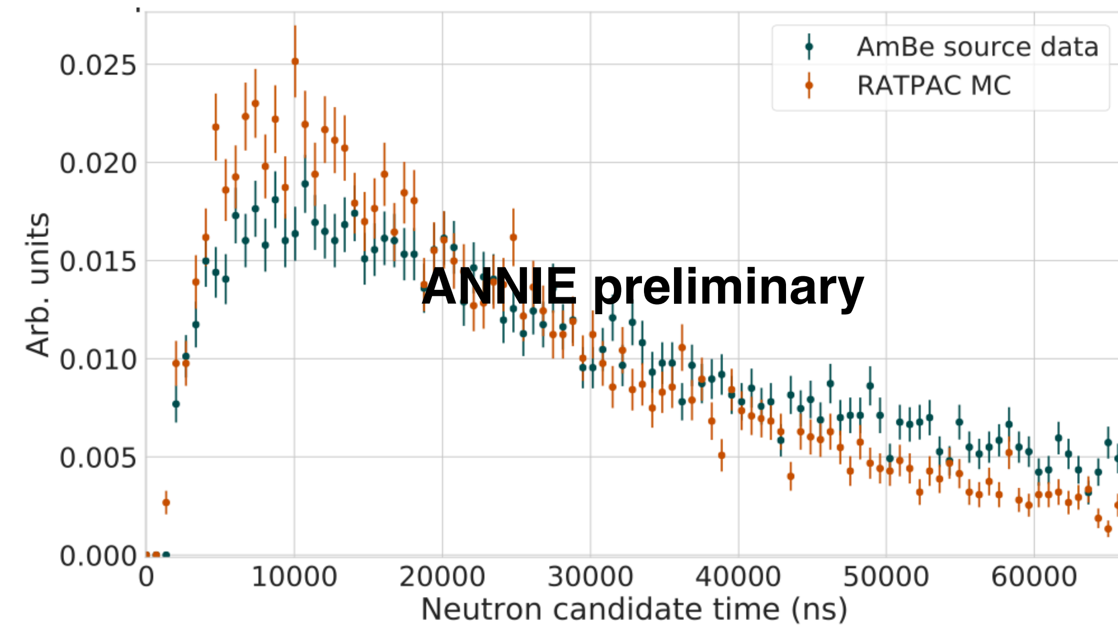


1. **^{241}Am decays to ^{237}Np via alpha emission (half-life = 432.2 yr).**
2. **^{9}Be can capture the emitted alpha to produce ^{12}C* and a neutron. ^{12}C* produces a prompt 4.44MeV gamma.**
3. **4.44 MeV gamma can Compton scatter in the BGO crystal - this gives us a trigger.**
4. **Neutron thermalises in ANNIE and is captured on Gd.**

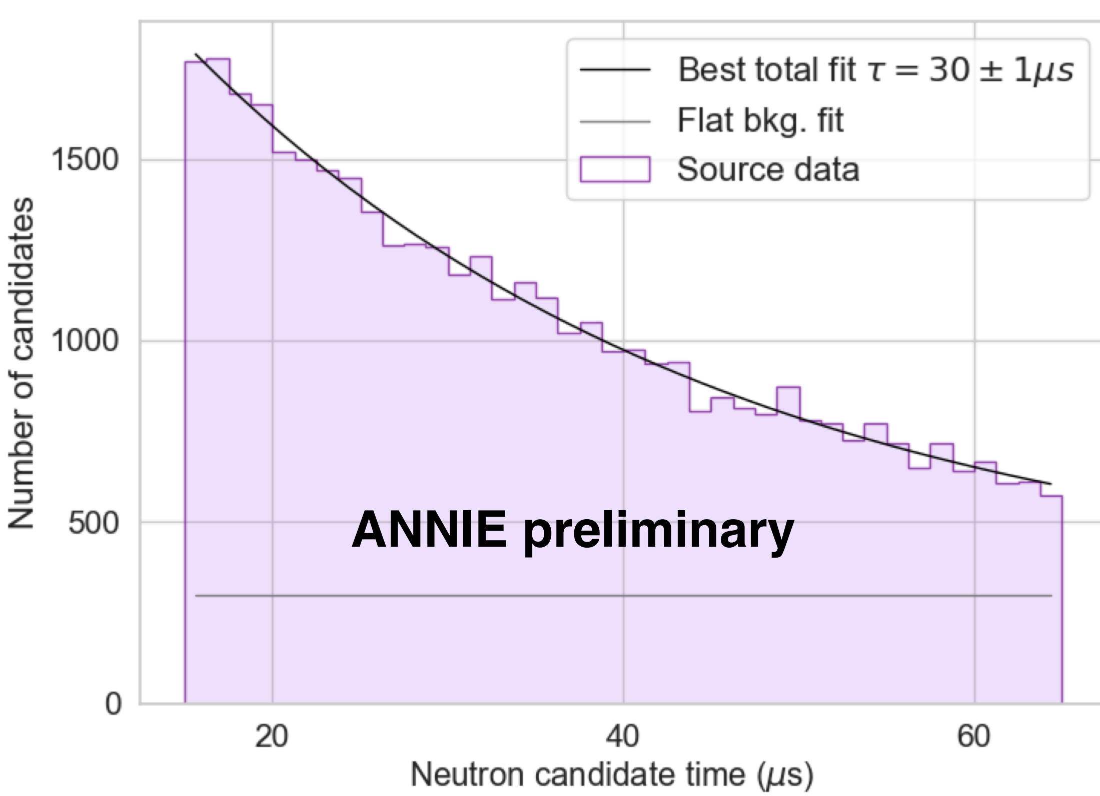
ANNIE's first detection of neutrons



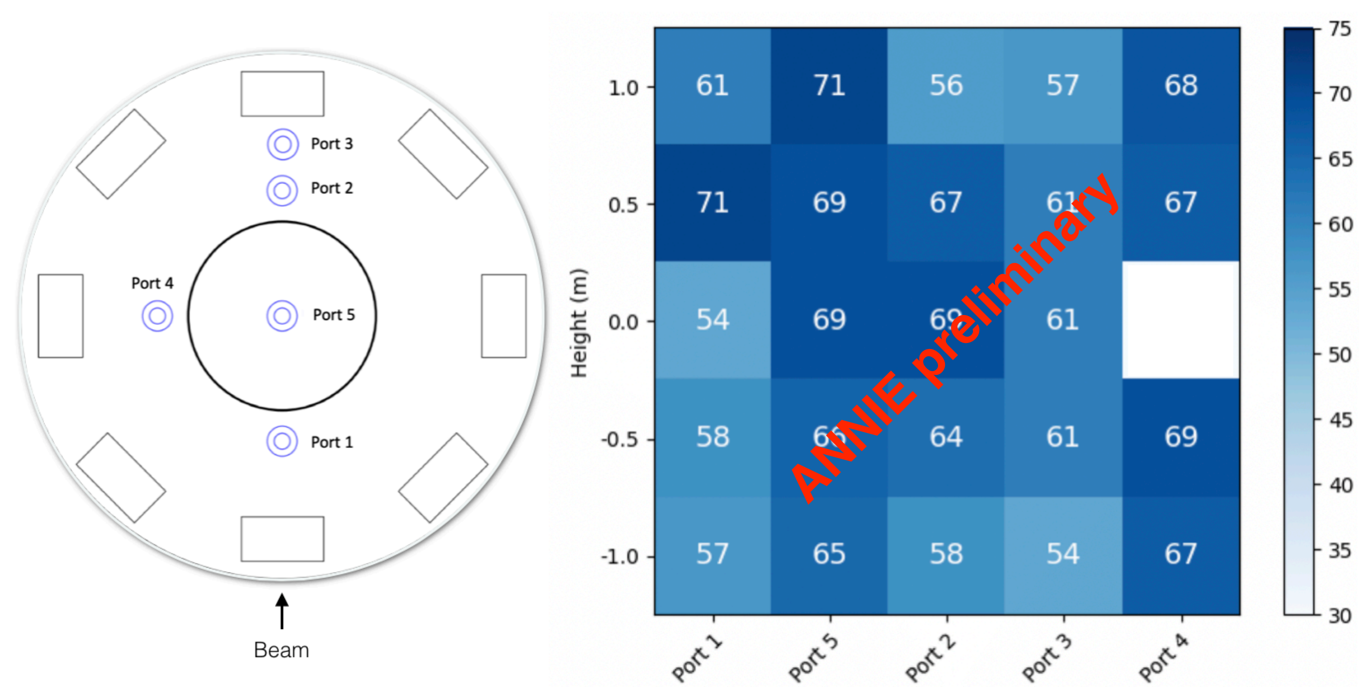
Reconstructed neutron capture candidates with and without AmBe source deployed



Data/MC comparison of neutron candidate time for a central deployment



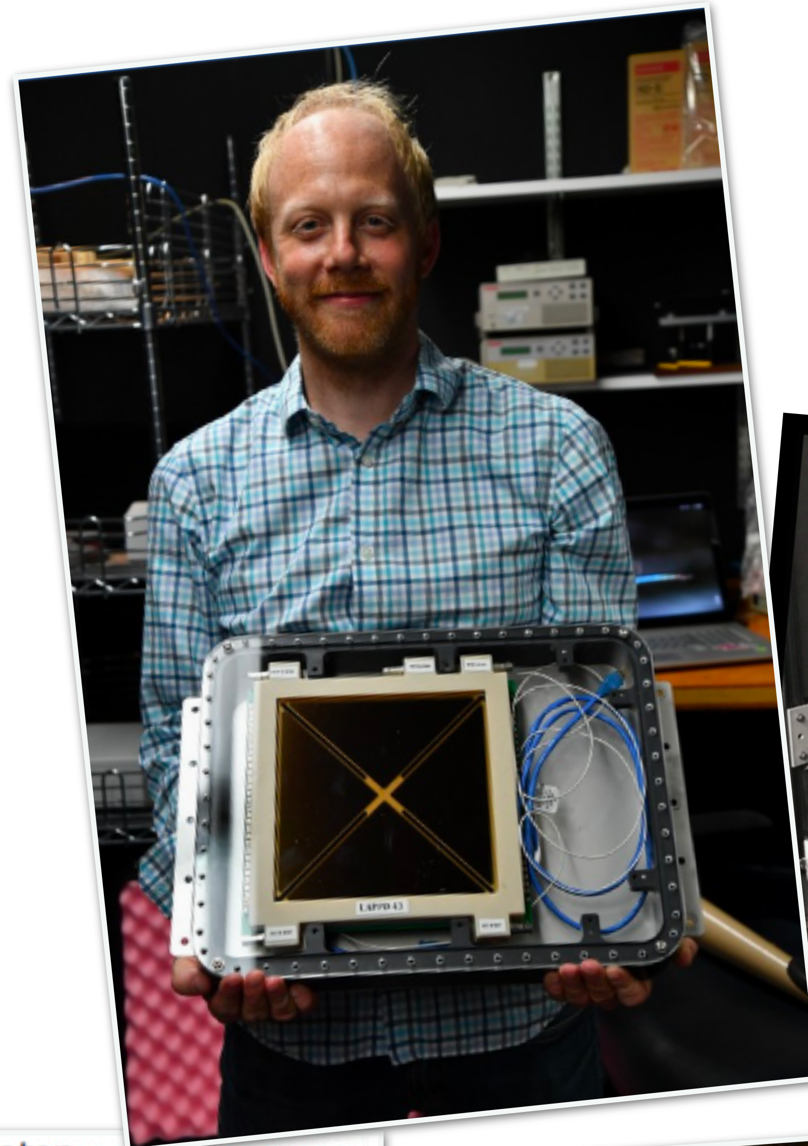
The expected neutron capture timescale has been observed

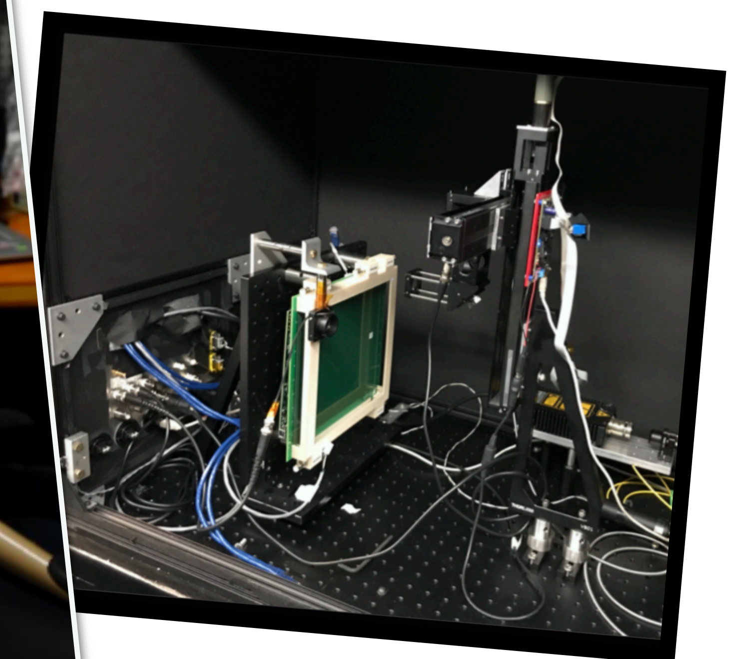


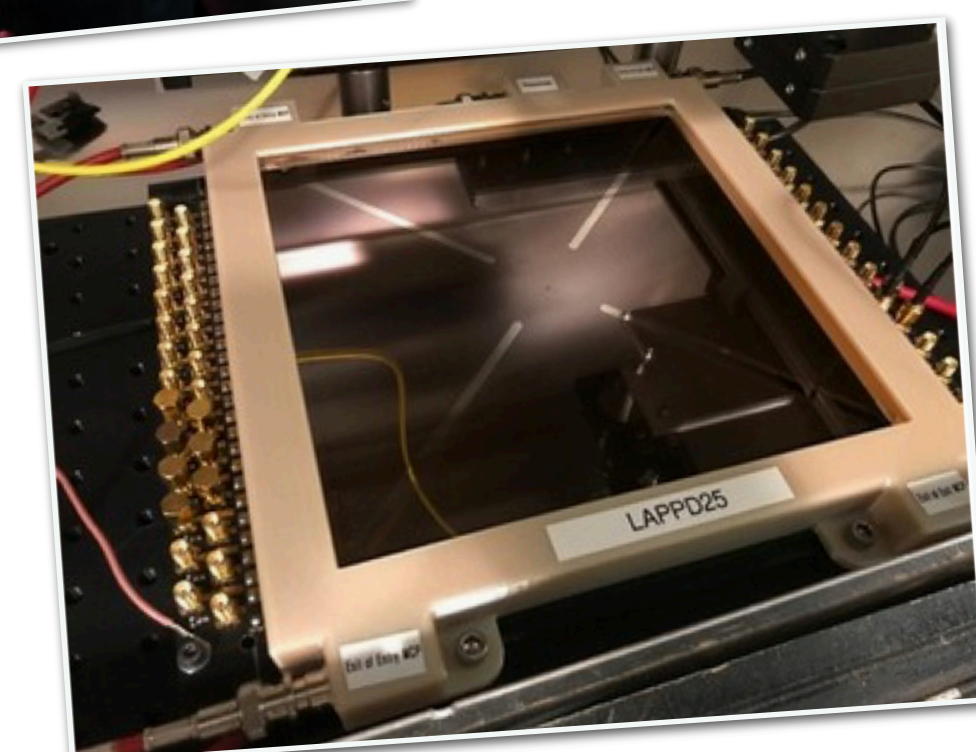
Position dependent neutron capture efficiency has been been measured to be consistent with expectations

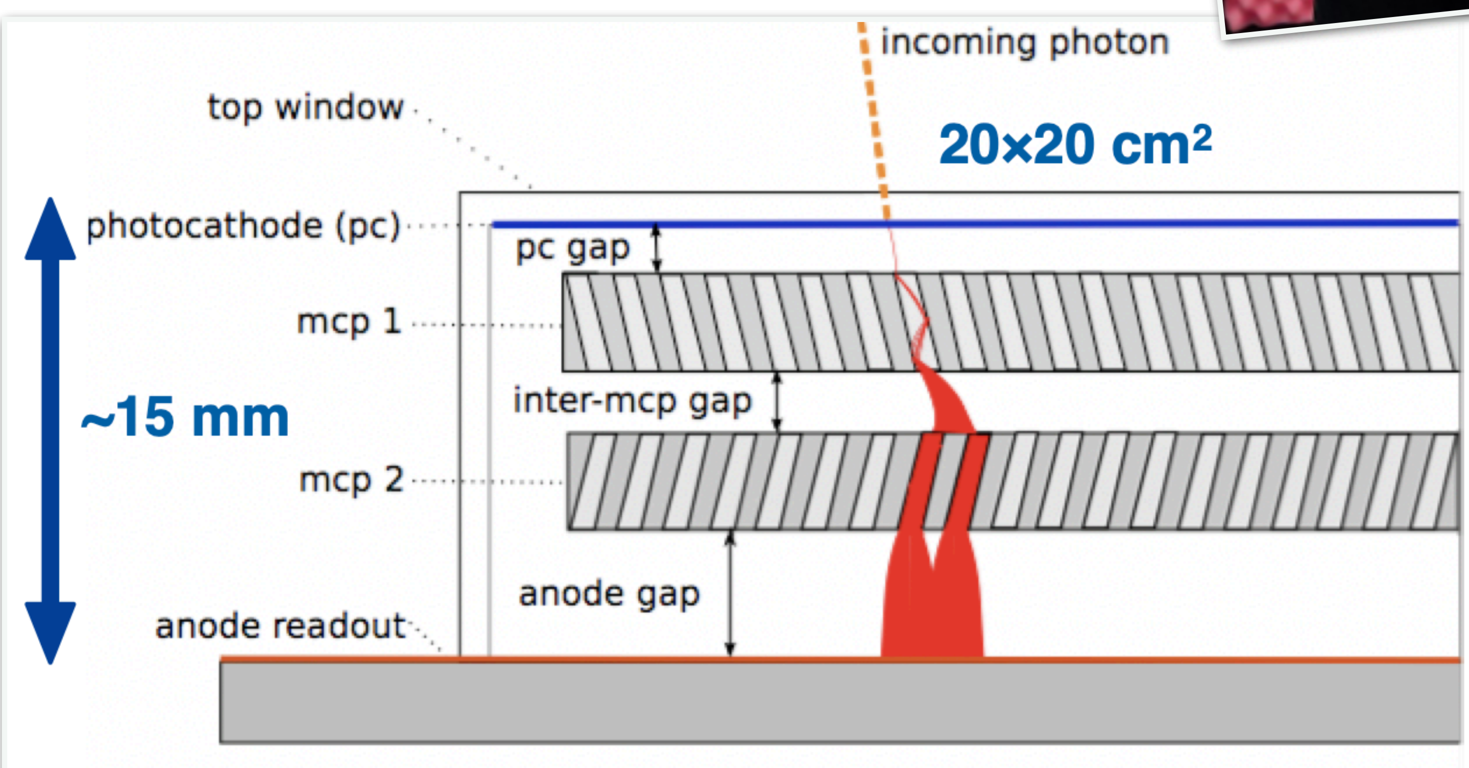
LAPPDs

- Large-area picosecond photodetectors (LAPPDs) are cutting-edge photodetectors.
- Consist of strips of micro channel plates.
- Sub-cm spacial and ~60ps timing resolution.
- > 20% quantum efficiency.
- ANNIE has 5 on hand ready for installation.

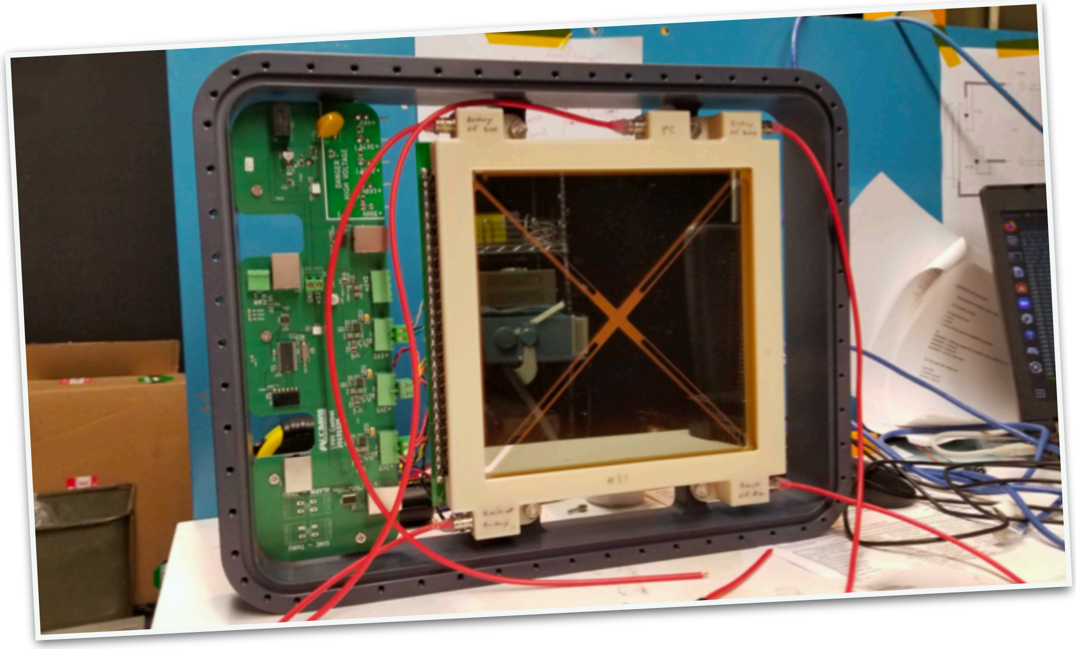


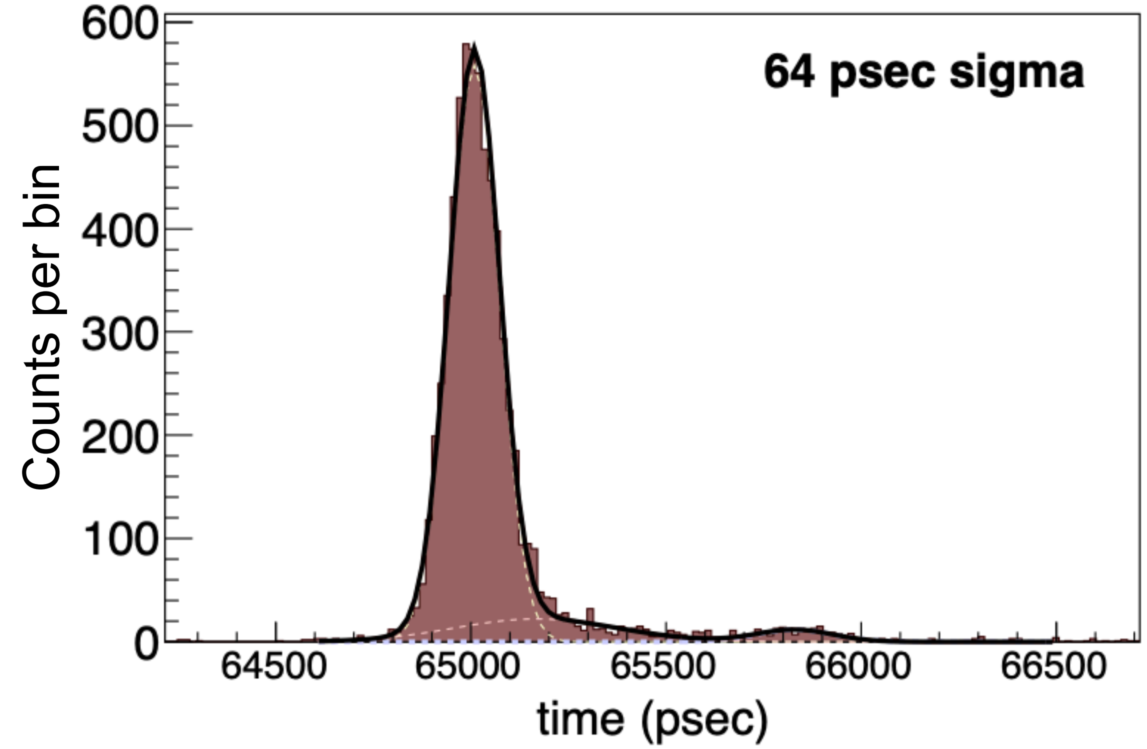




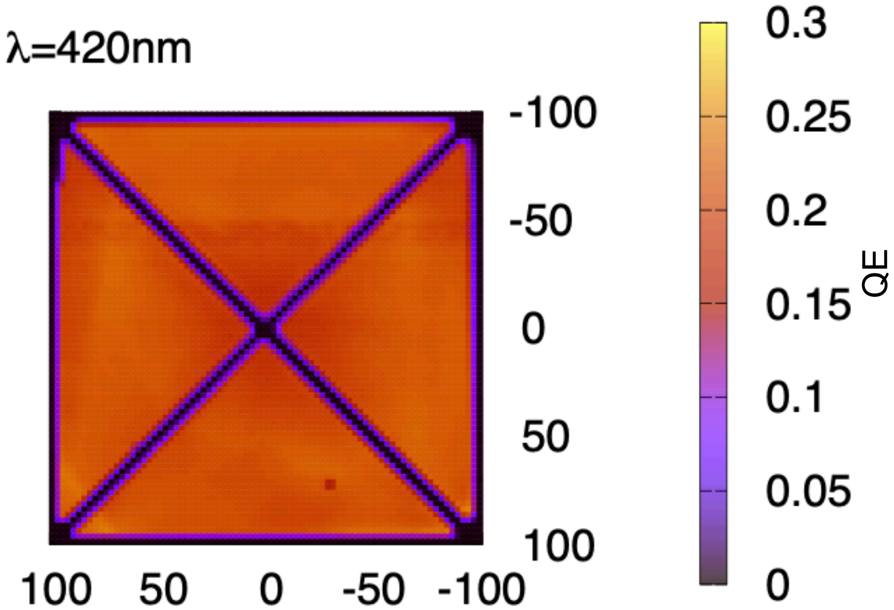


LAPPDs have next-generation performances

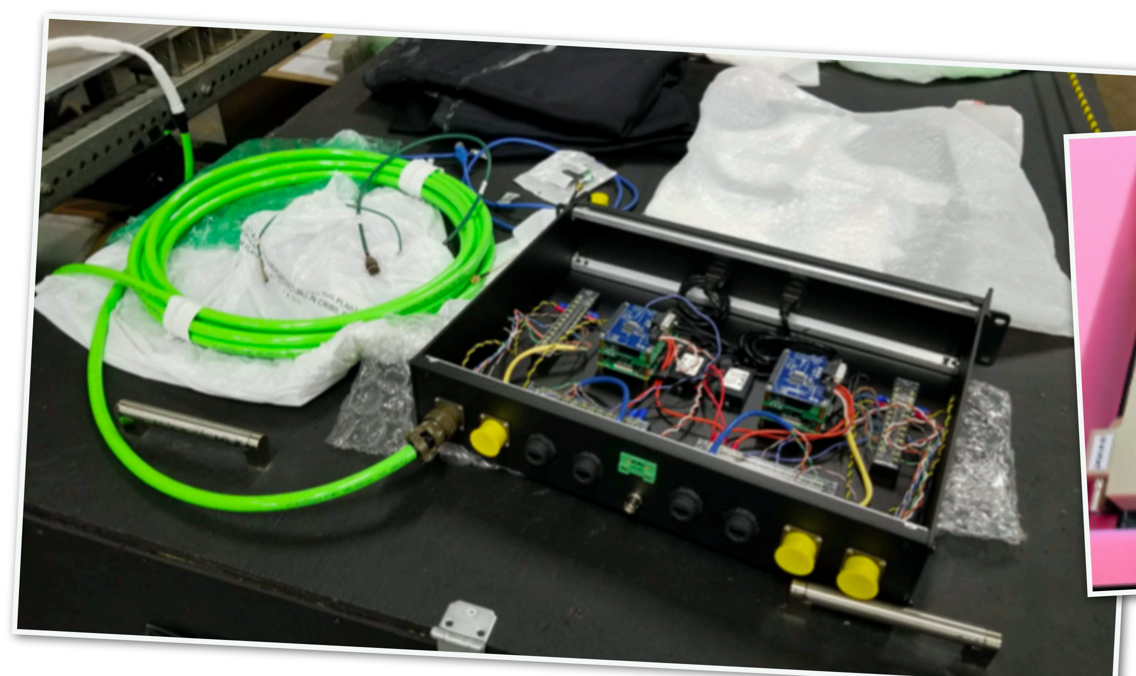




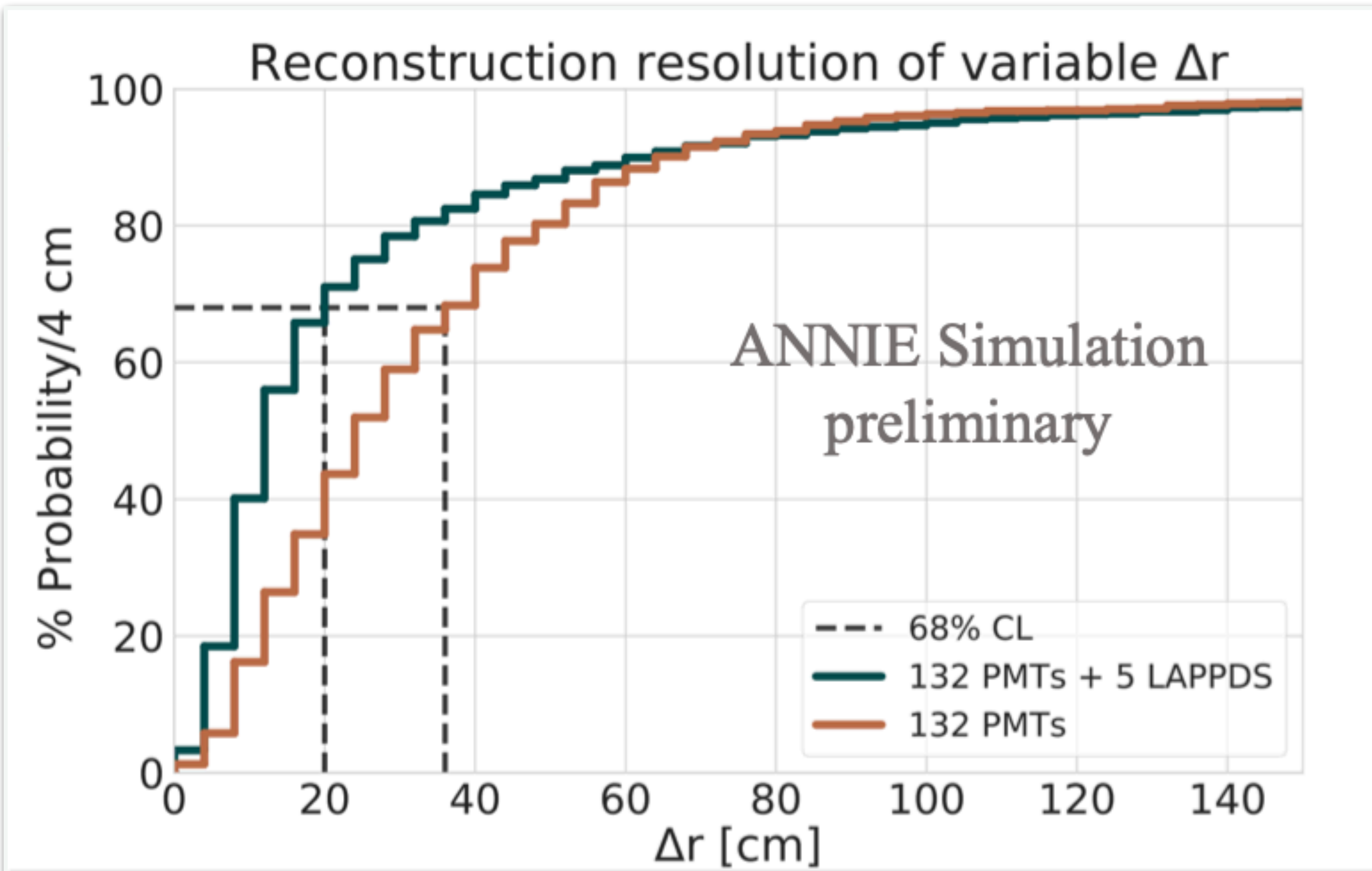
Pico-second level LAPPD timing resolution has been achieved



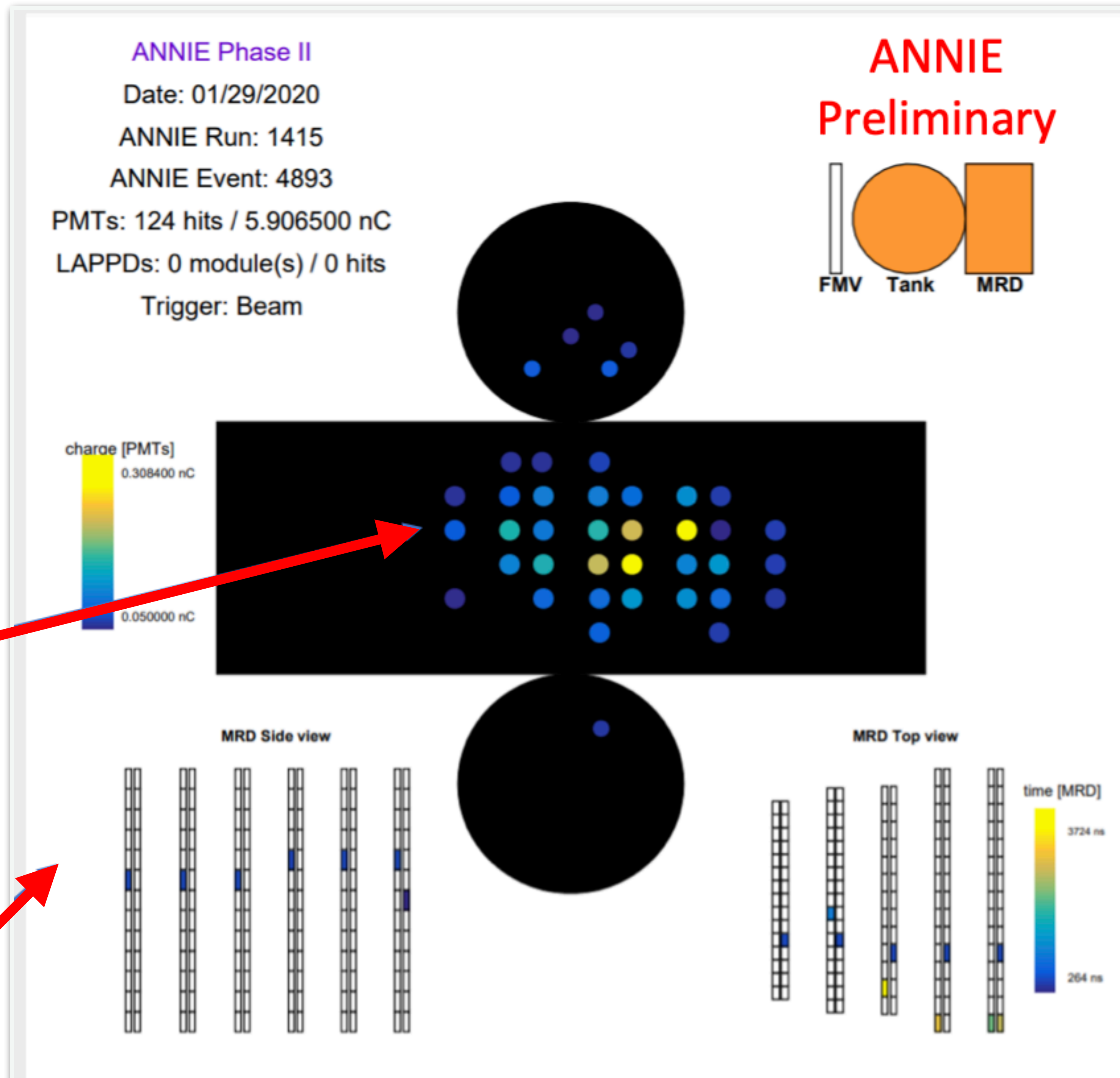
Homogeneous LAPPD quantum efficiency as a function of position



Only 5 LAPPDs will produce a significant improvement in reconstruction accuracy



ANNIE is now collecting data



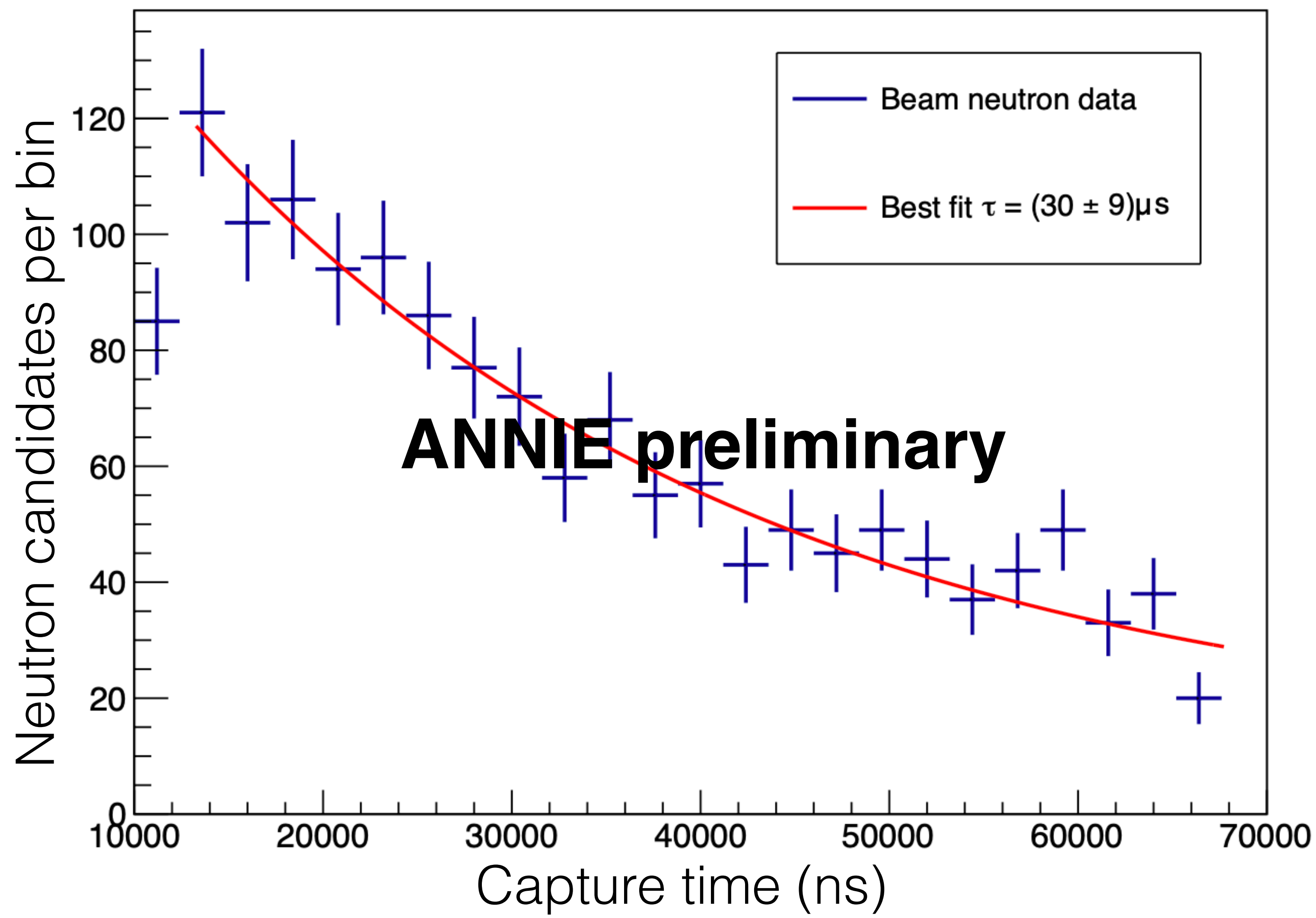
Cherenkov disk

Muon track in MRD

A candidate CCQE event - ANNIE's golden signal for the determination of the neutron multiplicity

We have now detected our first beam-related neutrons

- Analysis of the current data taking run is currently underway.
- Beam related neutron capture time is consistent with the AmBe run.
- Muon momentum reconstruction in agreement with MC expectations.
- First results of the neutron multiplicity expected upon the completion of the current beam run.



Conclusions

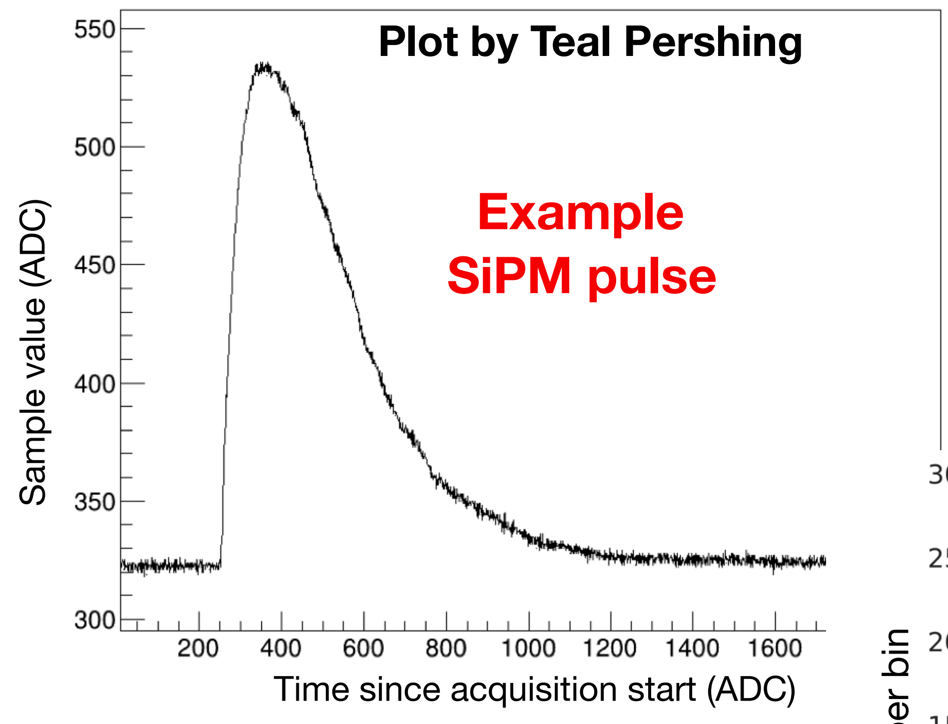
- ANNIE will measure the neutron multiplicity of neutrino interactions in water as a function of momentum transfer.
- This is important to constraining systematic errors for future neutrino experiments.
- Commissioning and calibration are now complete.
- Installation of LAPPDs, a world first in a running neutrino experiment, is imminent.
- Now taking physics quality beam data.
- Analysis is underway with results expected later this year.

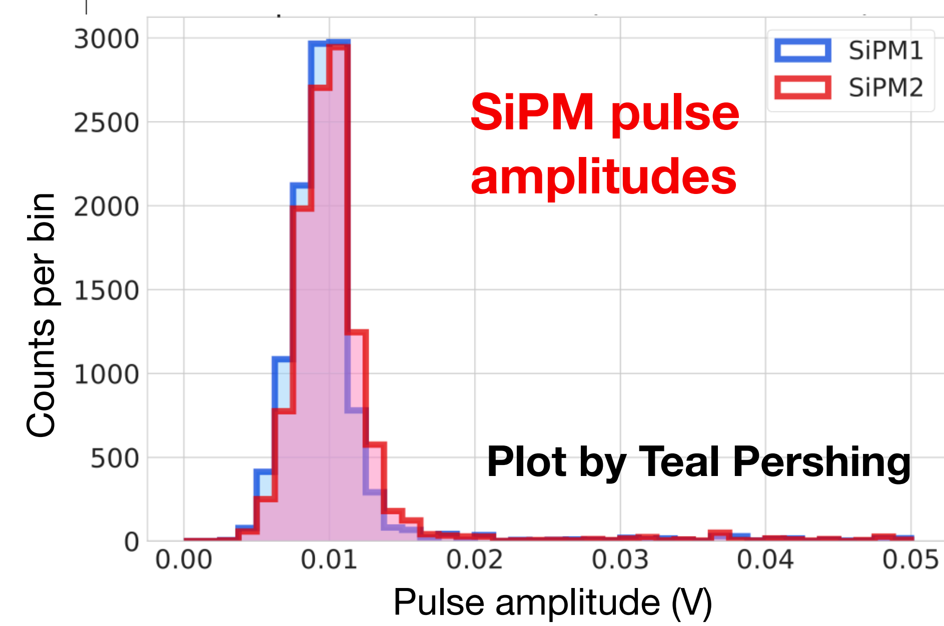
Backup

AmBe data selection

SiPM cuts

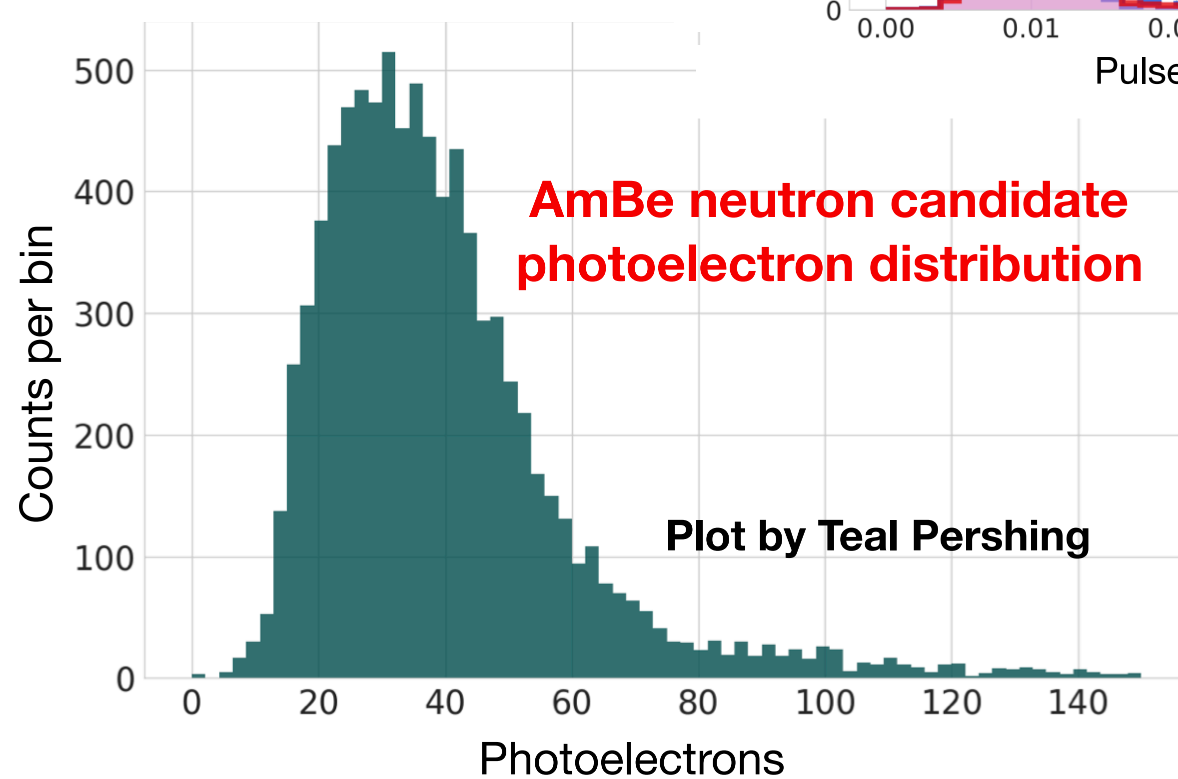
- Both SiPMs trigger in coincidence (with 6mV amplitude)
- Only one pulse in each SiPM acquisition





Tank activity

- No neutron candidates within 2μs of SiPM trigger - reduces through-going muon background
  - A “candidate” occurs when at least 5 PMTs see a pulse within 50ns.



Modelling the neutron multiplicities to extract the true detection efficiency

Position dependent multiplicity

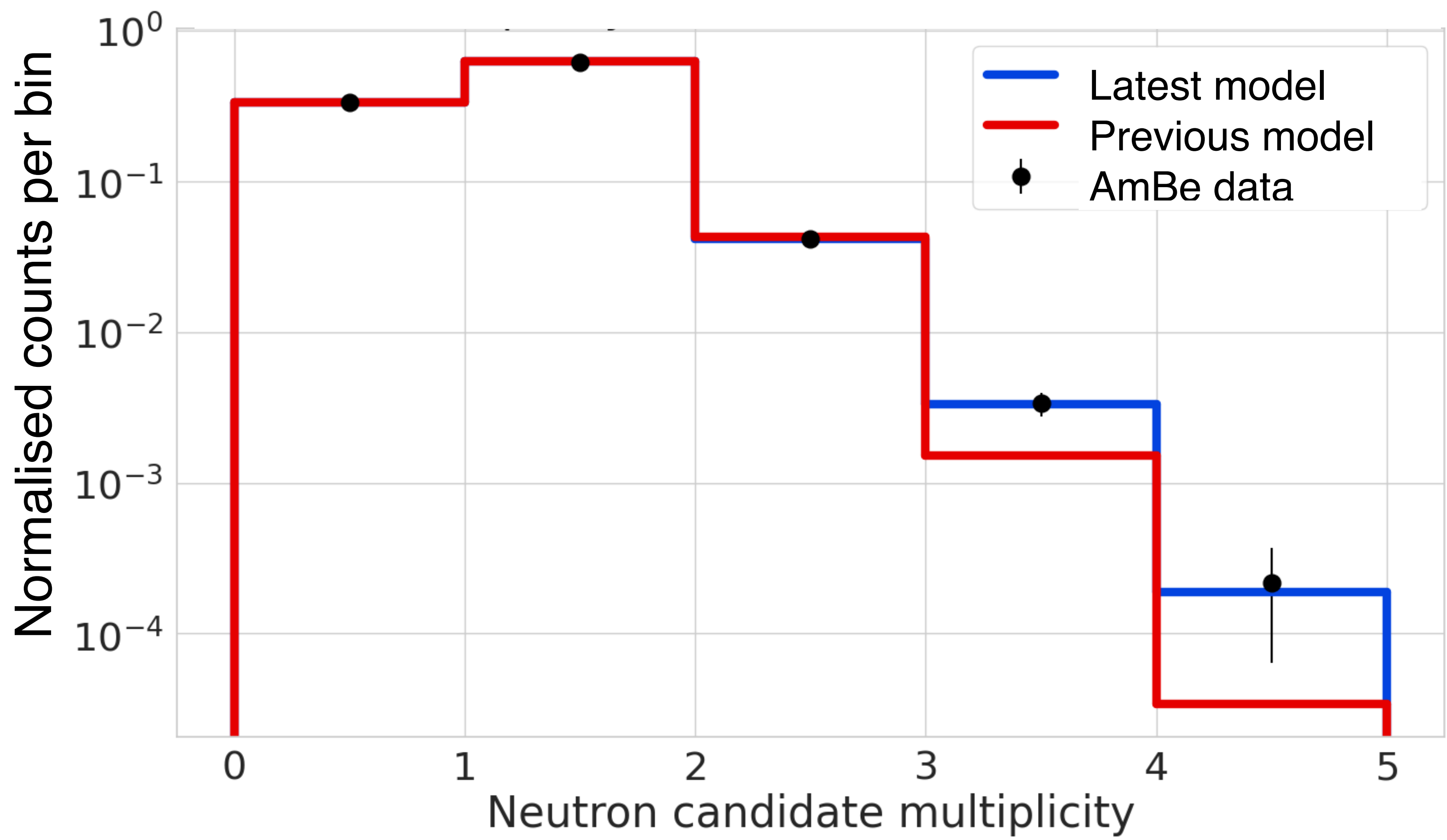
Uncorrelated background

Uncorrelated neutron-gamma pairs from AmBe source

$$M(x) = B(n;\epsilon_n) + \frac{\lambda_b^x e^{-\lambda_b}}{x!} + \frac{\lambda_{un}^x e^{-\lambda_{un}}}{x!} + \left(\frac{\lambda_\gamma^x e^{-\lambda_\gamma}}{x!} + M_{\gamma n}(n_\gamma)\right)$$

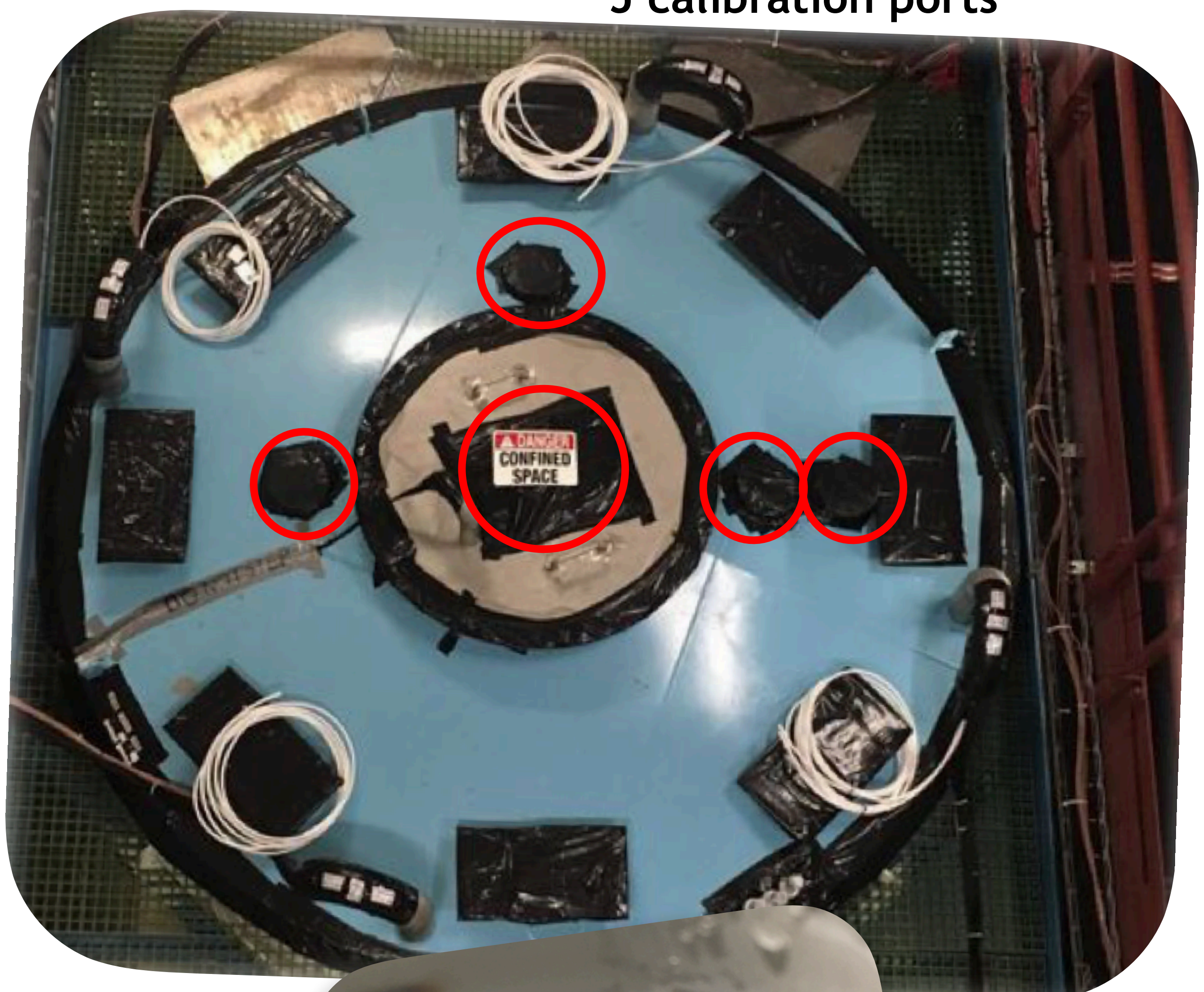
Bernoulli distribution for a given neutron detection efficiency

Uncorrelated neutrons from AmBe source

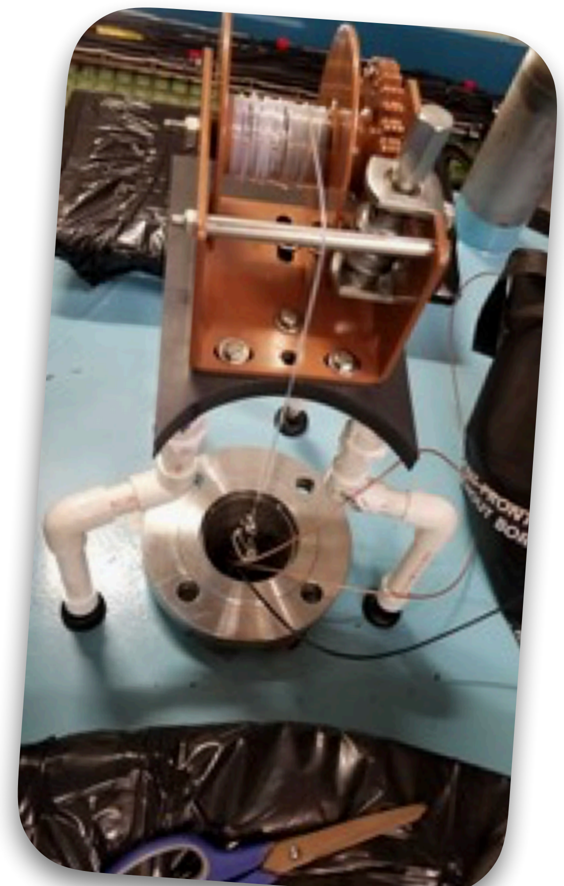


The calibration campaign has begun!

5 calibration ports

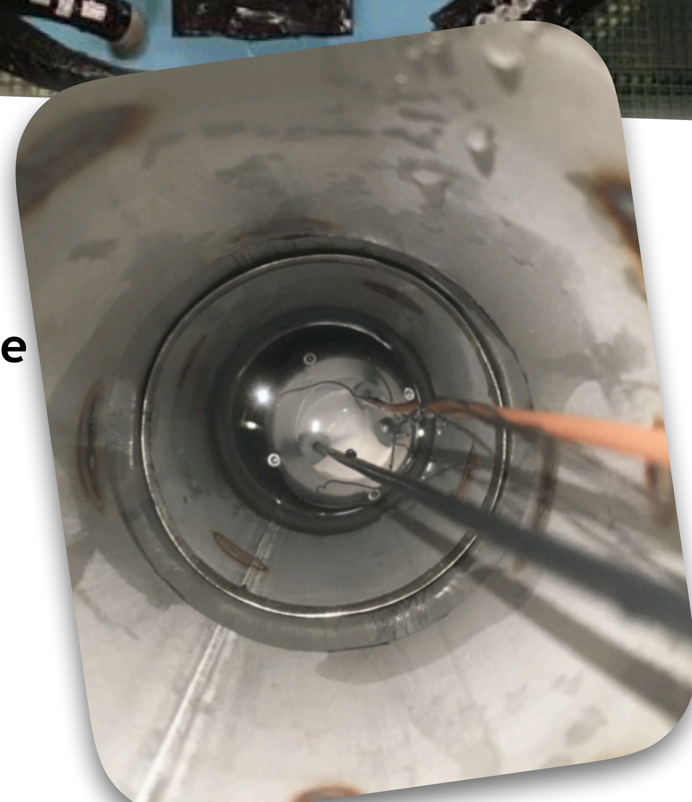


Deployment winch



UVT acrylic container

Submerging the AmBe source container



SiPM electronics board