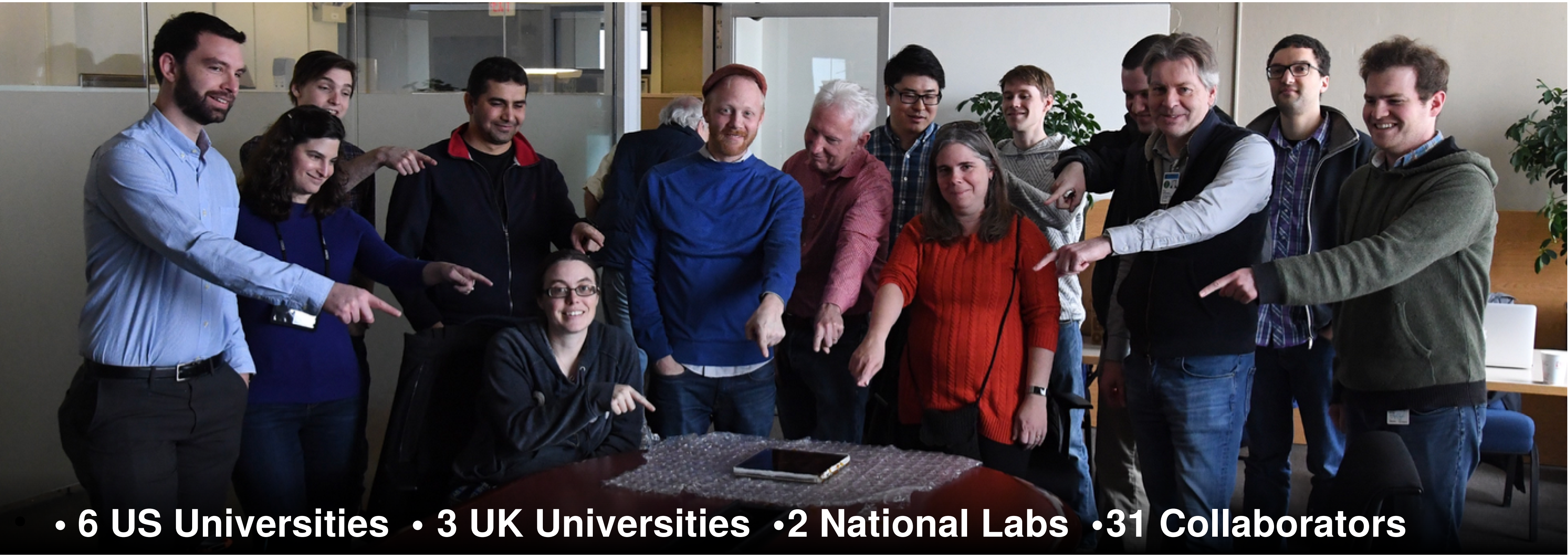
Accelerator **N**eutrino **N**eutron **I**nteraction **E**xperiment

Marcus O'Flaherty, University of Sheffield UK
on behalf of the ANNIE Collaboration

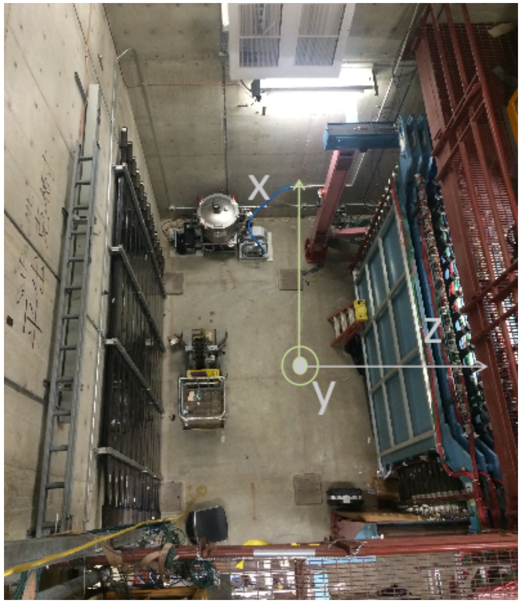
Who is Annie?

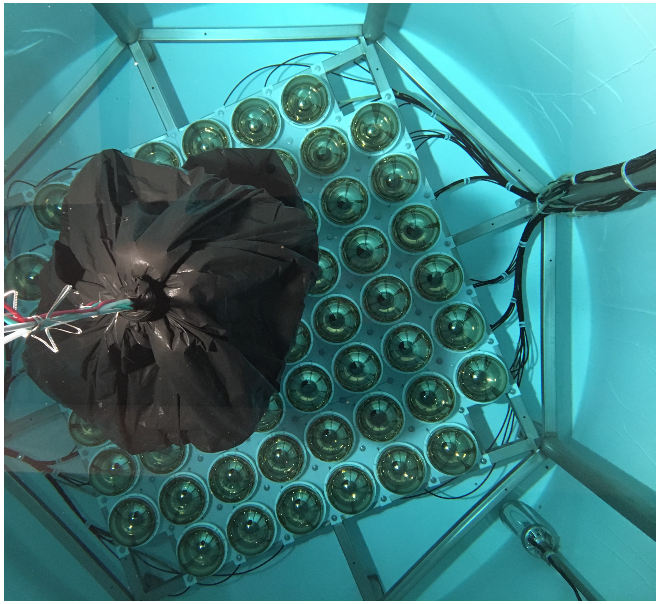


- Fermi National Accelerator Laboratory
- Lawrence Livermore National Laboratory
- Iowa State University
- Ohio State University
- Queen Mary University of London
- University of California at Berkeley
- University of California at Davis
- University of California at Irvine
- University of Chicago, Enrico Fermi Institute
- University of Edinburgh
- University of Sheffield

What is ANNIE?

- 26 ton Gd-loaded water Cherenkov detector
- Upstream veto
- Downstream Muon Range Detector (MRD) from SciBooNE
- Located 100m from the Fermilab Booster Neutrino Beam (BNB) target





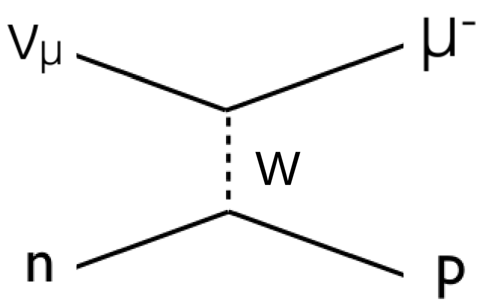
Physics Motivations

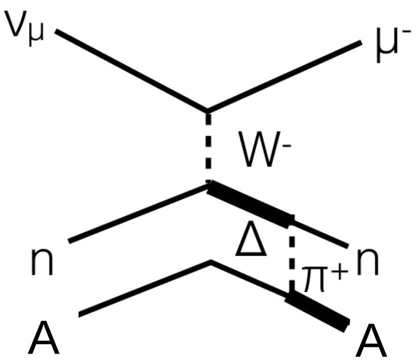
ANNIE will measure final state neutron multiplicity

as a function of topology and kinematics in the 0.5 – 3 GeV range

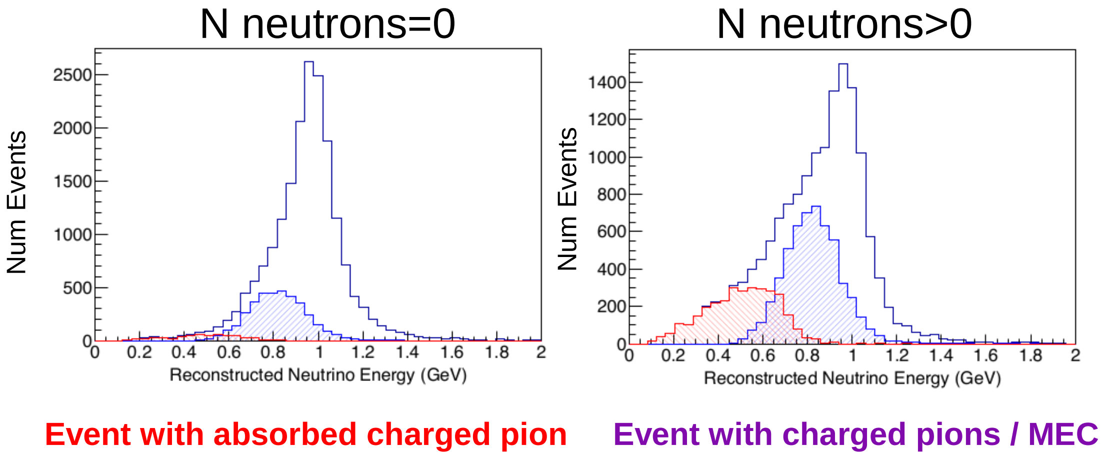
This measurement is **complementary to liquid Argon** proton multiplicity measurements

- **A key quantitative measure for theoretical model validation**
- When final state neutrons are not accounted for the neutrino energy is under-estimated, resulting in an **asymmetric bias in reconstructed energy**
- Knowledge of multiplicity is key to **reducing these systematics**





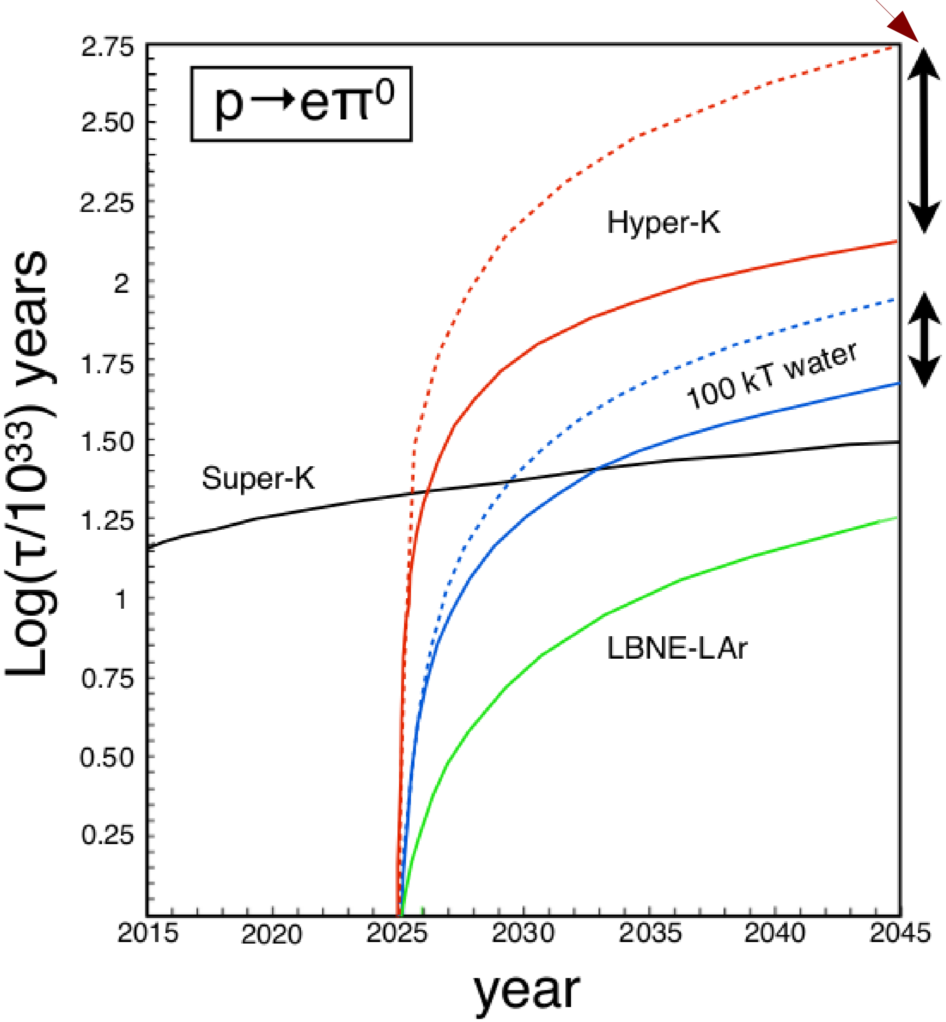
Genie simulations of 1GeV ν_μ



Physics Goal: II

- Atmospheric neutrino interactions are a key **background in proton decay experiments**
- >90% of proton decay events produce no neutrons
- Many neutrino background events will produce one or more neutrons
- Neutron multiplicity measurements will **improve background modelling** improving confidence in no-neutron events

Estimated improvement with neutron tagging



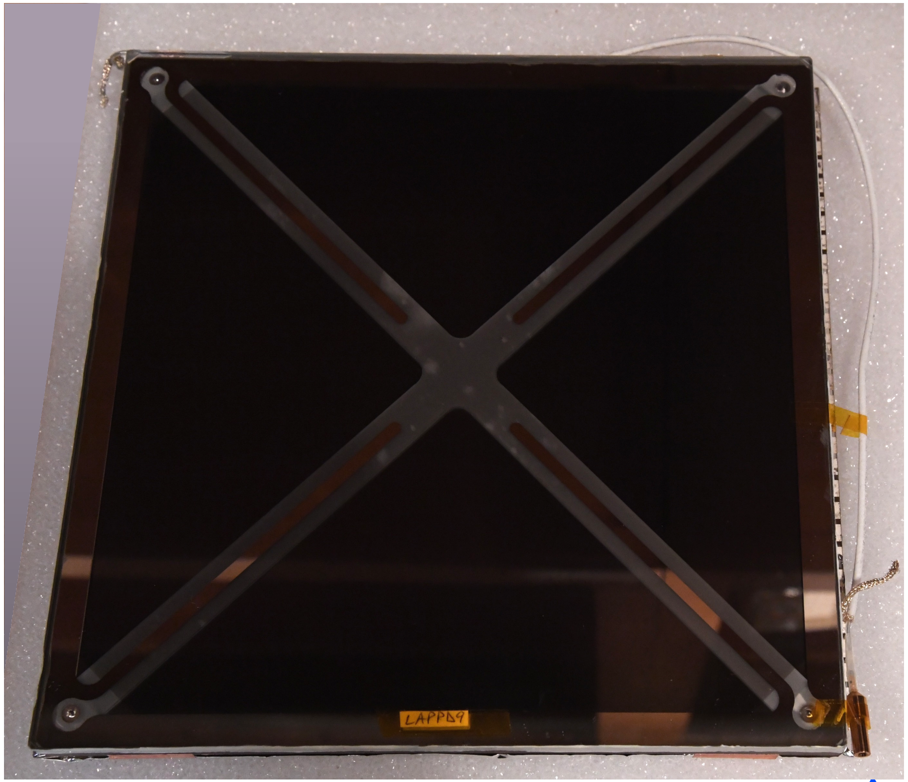
Anghel, I. et al., arXiv 1504.01480

Technical Goals: I

- **First application of LAPPDs** (Large Area Picosecond Photo Detectors) in particle physics
  - Implementing multi-tile readout electronics
  - Integration into a hybrid DAQ framework with conventional PMTs
  - Development and demonstration of reconstruction capabilities
  - Crucial to allow ANNIE to distinguish multi-track events to reject pion production

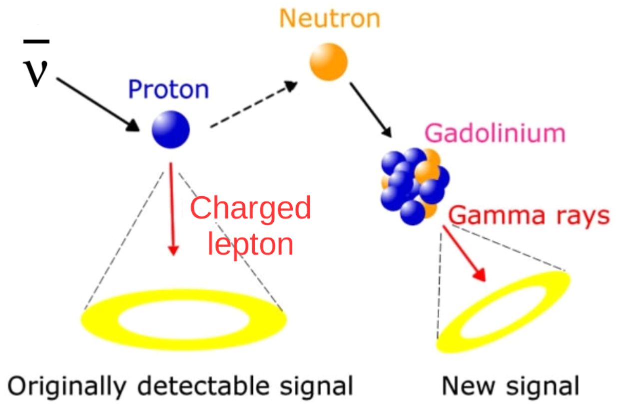
<u>LAPPD Technical Specifications</u>

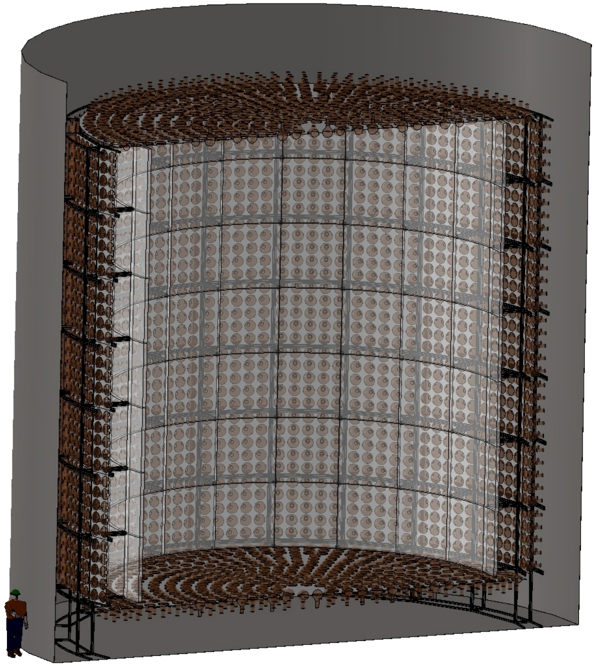
- 20cm x 20cm active area
- Gain of $>10^6$
- <60ps single pe resolution, <5ps multi-pe timing resolution
- mm-cm level spatial resolution (X-Y planes)
- 20+% QE with ~15% uniformity
- Low dark noise levels



Technical Goals: II

- ANNIE is also the **first neutrino beam experiment to use Gd-loaded water** for neutron tagging
- ANNIE will **demonstrate event reconstruction** and long term stability testing of interest for future Gd loading projects



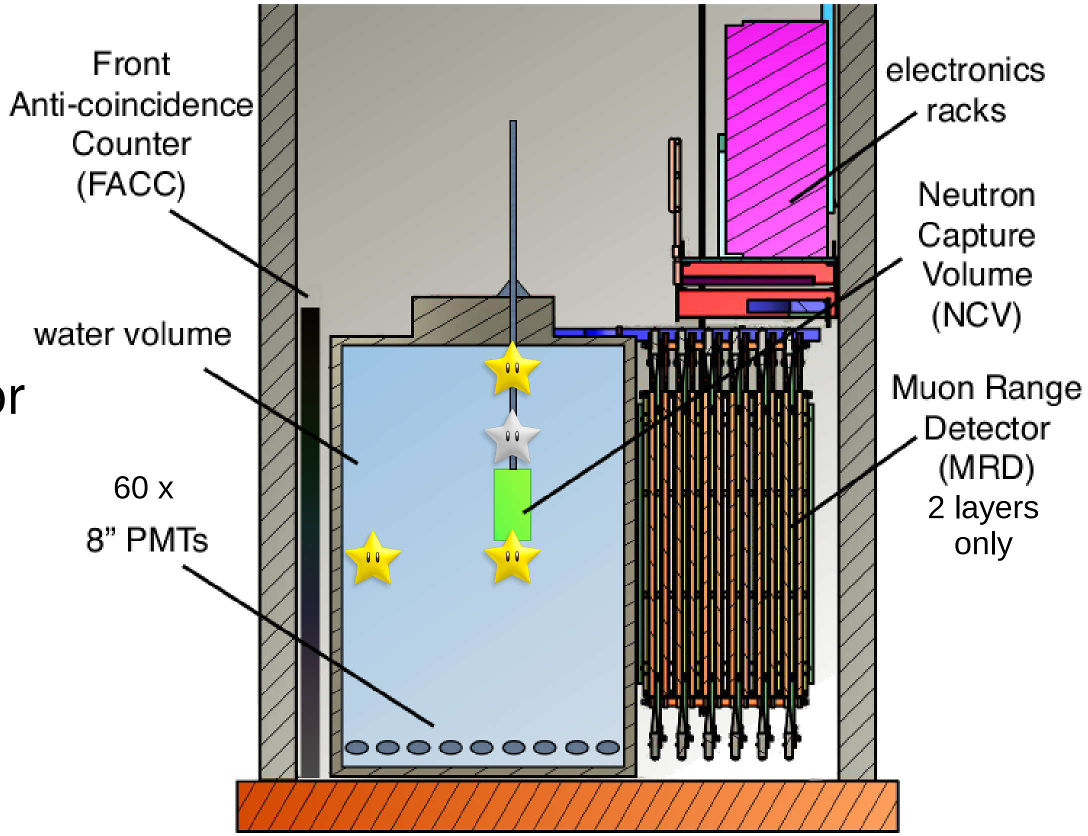


Watchman

Experiment Progress

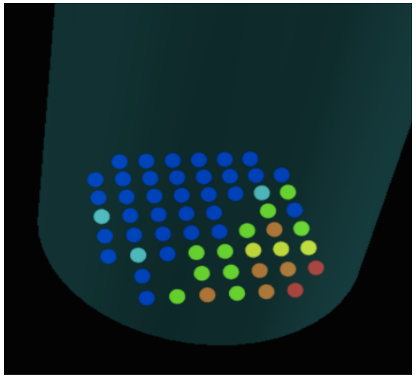
- Construct the detector
- **Assess levels of neutron backgrounds from dirt interactions and sky-shine**
- Pure water (no Gd), movable sub-volume of Gd-doped liquid scintillator
- NCV optically isolated from tank, watched by 2 PMTs
- Tank PMTs act as muon veto

Phase I: June 2016 - 2017

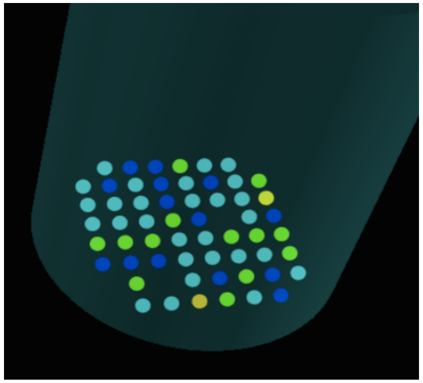


Phase I Results

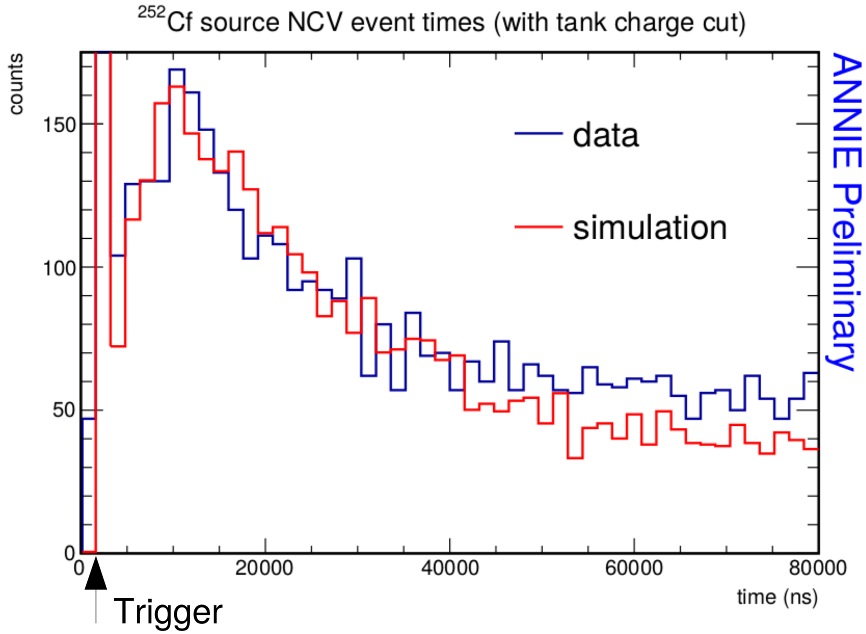
- Observed and reconstructed neutron captures, both beam events and a ^{252}Cf calibration source
- Strong suppression of skyshine neutrons seen with increasing depth
- Conservative estimates suggest <2% of beam spills produce a background neutron capture in the fiducial volume of Phase II
- More data to be collected, but levels are confirmed low enough for Phase II physics

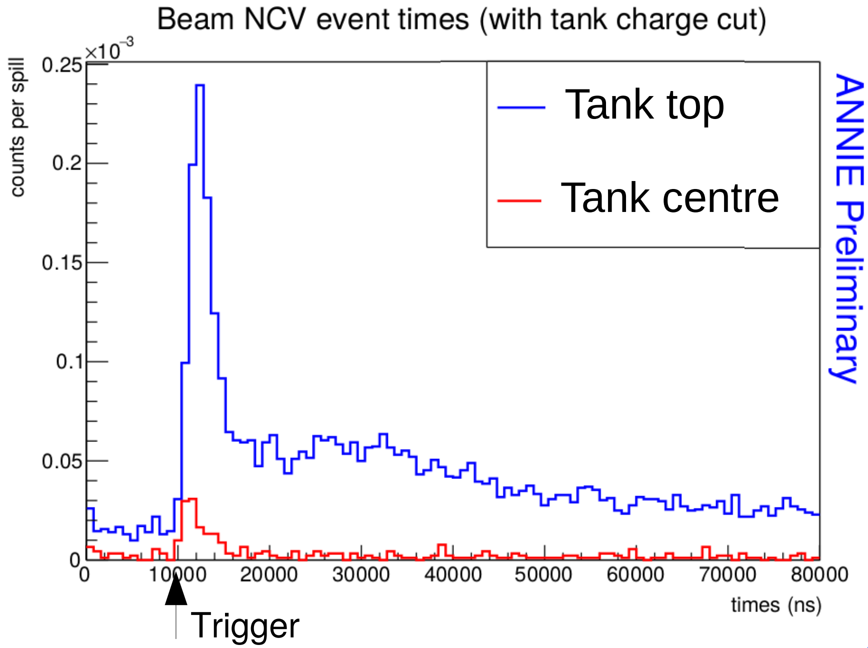


Cosmic μ candidate



Neutrino candidate

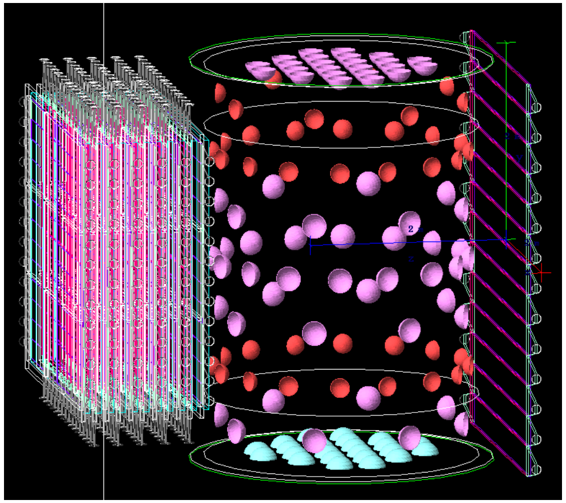




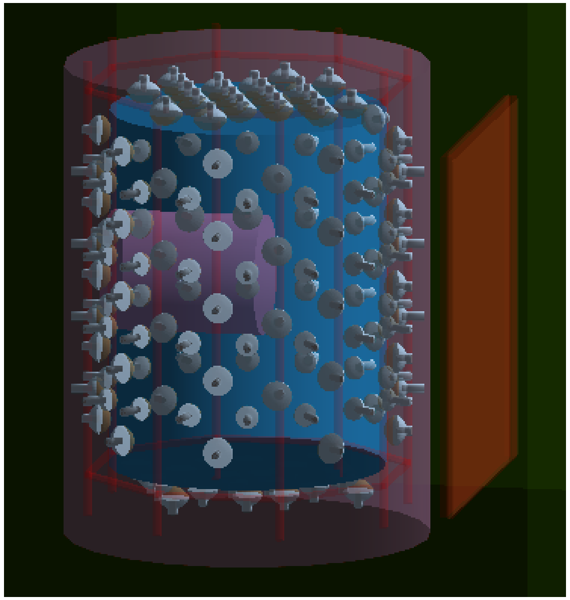
Simulations

- Detector simulation with RAT-PAC (Watchman, SNO+, Theia) and WCSim (Hyper-K)
- Flux simulation with GENIE v 2.12
- Assessment of Phase II physics capabilities
  - Neutron detection efficiency
  - MRD kinematic acceptance
  - Tank PMT / LAPPD number and placements
- Various reconstruction avenues being investigated
  - Custom timing residual minimisation algorithm
  - Bonsai
  - FitQun
  - Machine Learning

WCSIm geometry



RAT-PAC geometry – V. Fischer



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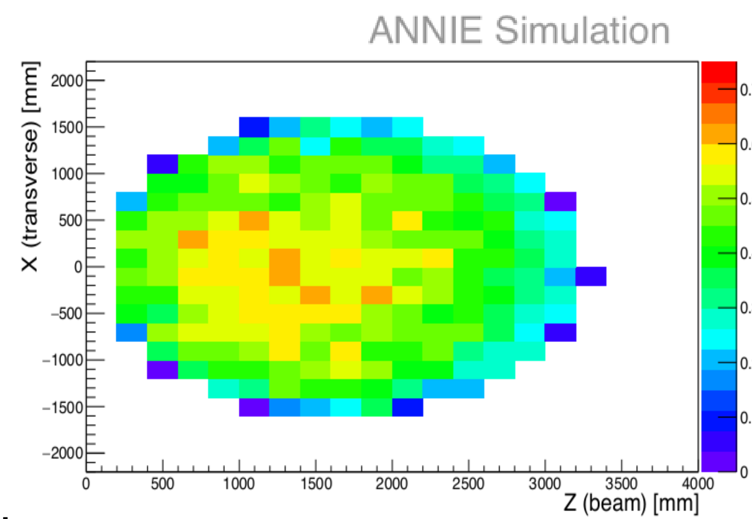

Neutron detection efficiency vs neutrino interaction position within 2m fiducial y axis region, 10pe threshold

V. Fischer, U.C. Davis

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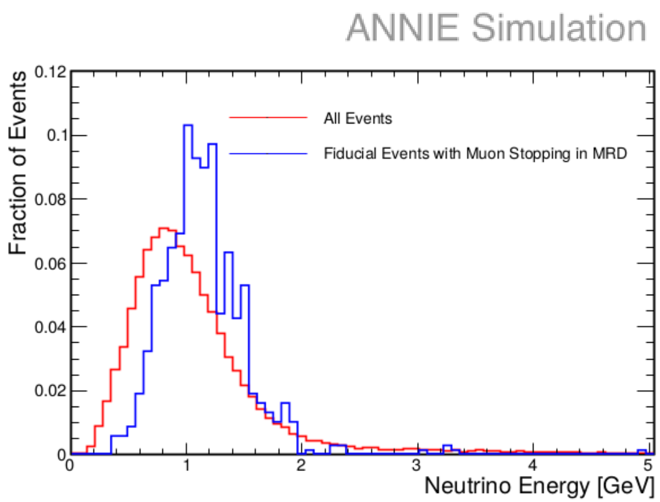

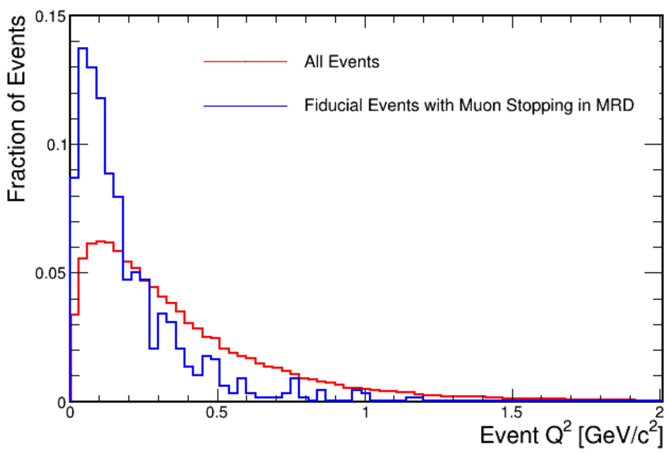

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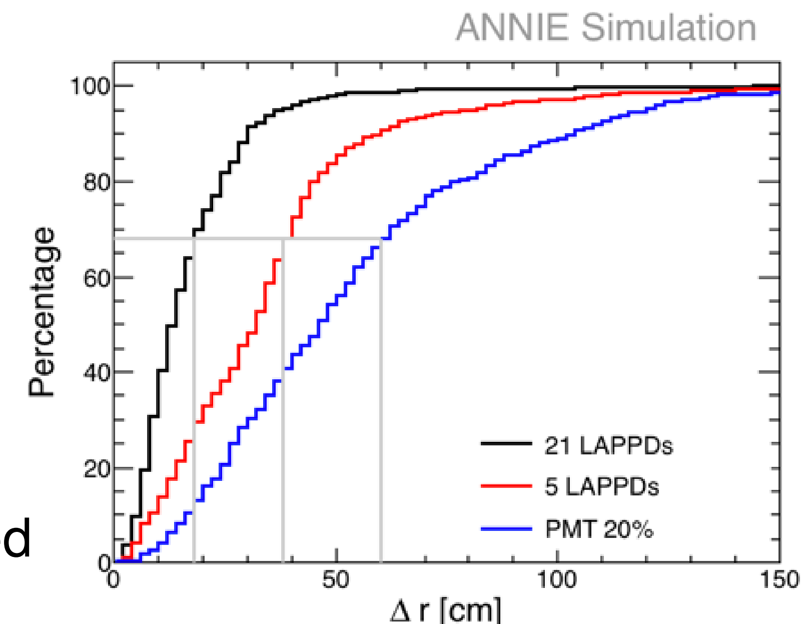
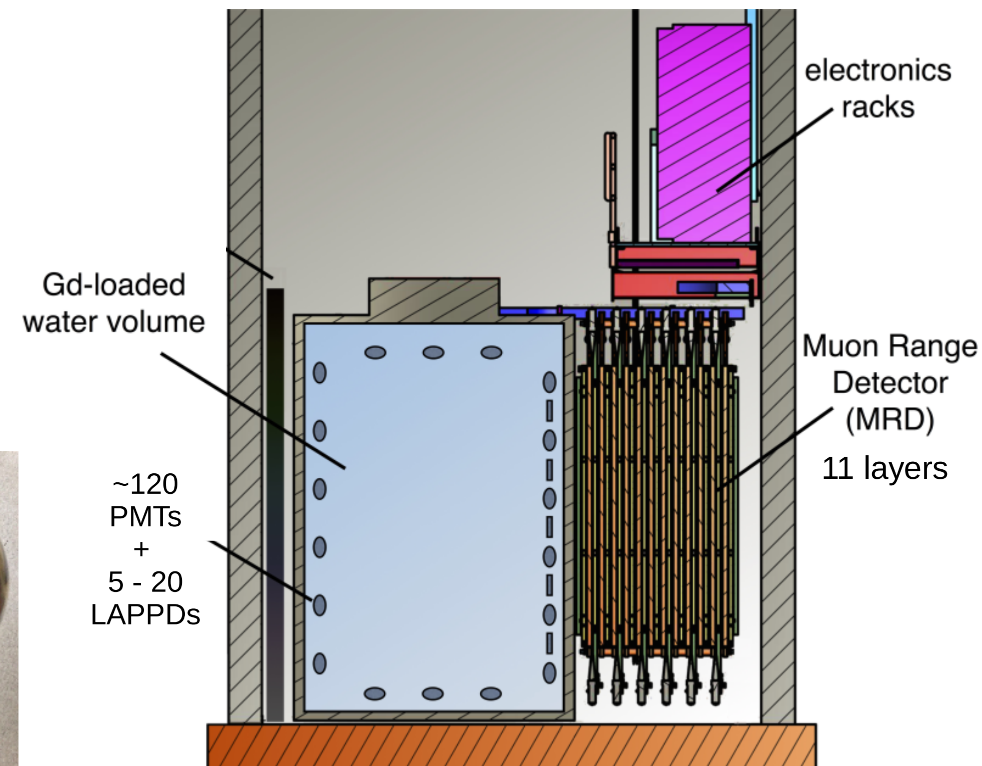


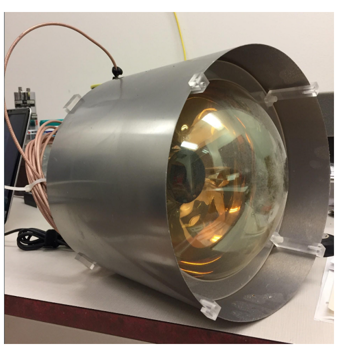
120 PMTs – 67% of events within ~60cm
5 LAPPDs – 67% of events within ~38cm
21 LAPPDs – 67% of events within ~18cm

Looking Ahead

Phase II: Fall 2017 - 2021

- **Upgrade the detector**
- ~120 PMTs covering all tank faces
- Fully refurbished 11-layer MRD
- Associated DAQ + HV channels
- 0.2% $Gd_2(SO_4)_3 \rightarrow$ 0.1% Gd by weight
- LAPPDs as they become available



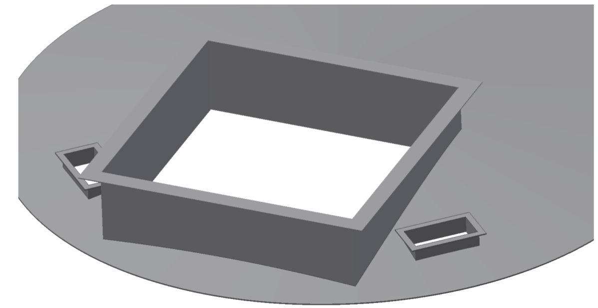

Watchboy R7081

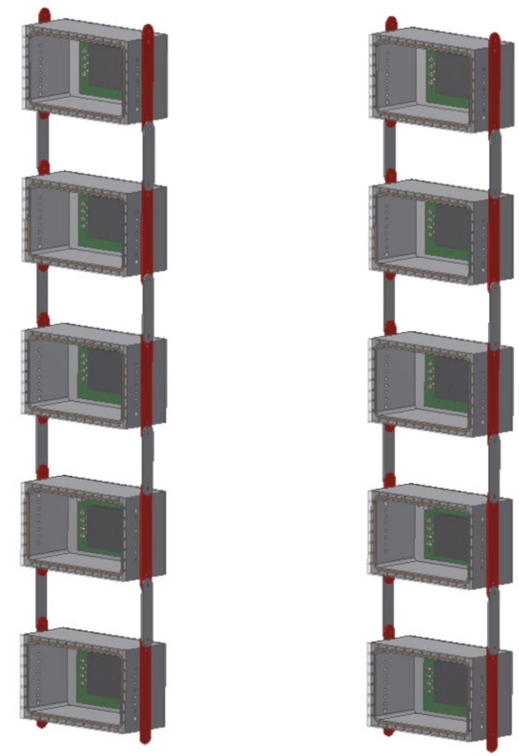

LUX R7081

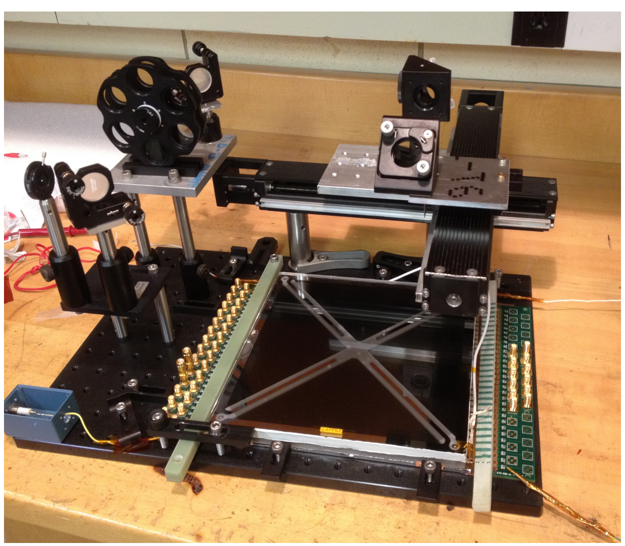

ETEL D784KFBL

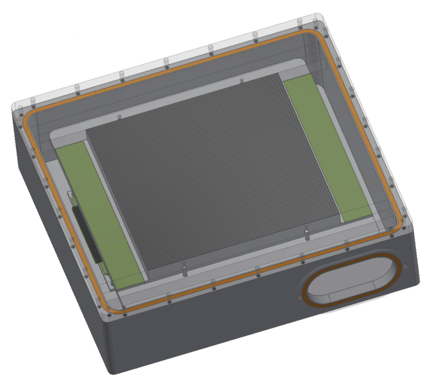
LAPPD Preparation

- Expect 5 LAPPDs in first year of Phase II
- Design of submersible housing by UC Davis
- Removable cassette mechanism to allow LAPPDs to be added or removed with ease
- Response characterisation and vertical integration of DAQ with ISU test stand





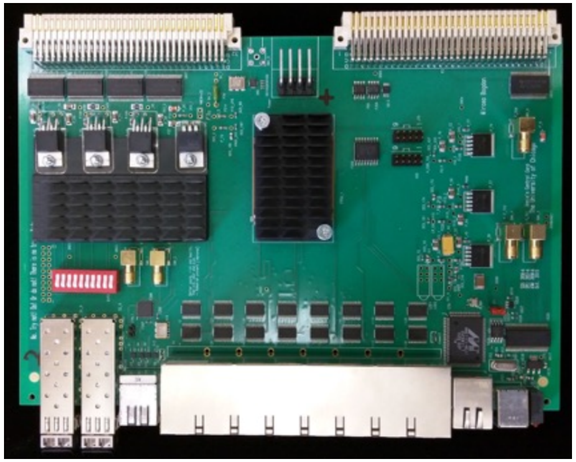




Data Acquisition

- ANNIE will require a dual readout design to accommodate fast digitizers for LAPPDs alongside deep buffered PMT data required to contain delayed neutron captures
- PMTs digitized by VME-based ADC system at 500MHz
- LAPPDs digitized by 'ACDC' board housing five PSEC-4 sampling ASICs, giving 10GHz digitization on a total of 30 readout channels
- Interface to the DAQ system is provided by a central card, which may interface 8 nodes – ACDCs or other central cards

ACDC Card
Eric Oberla, University of Chicago



ANNIE Central Card
https://arxiv.org/abs/1607.02395

Phase II Timeline

Fall 2018 – Year 1

- Gd in water
- Full MRD
- 5 LAPPDs, installed as available
- Focus on CCQE-like events

2019 – Year 2

- Up to 20 LAPPDs
- Expanded range of topologies to include CC, NC and inelastic scattering

2020 – Years 3+

- Further data taking
- ANNIE Phase III?
- Water-based Liquid Scintillator (Theia) R&D?

Summary

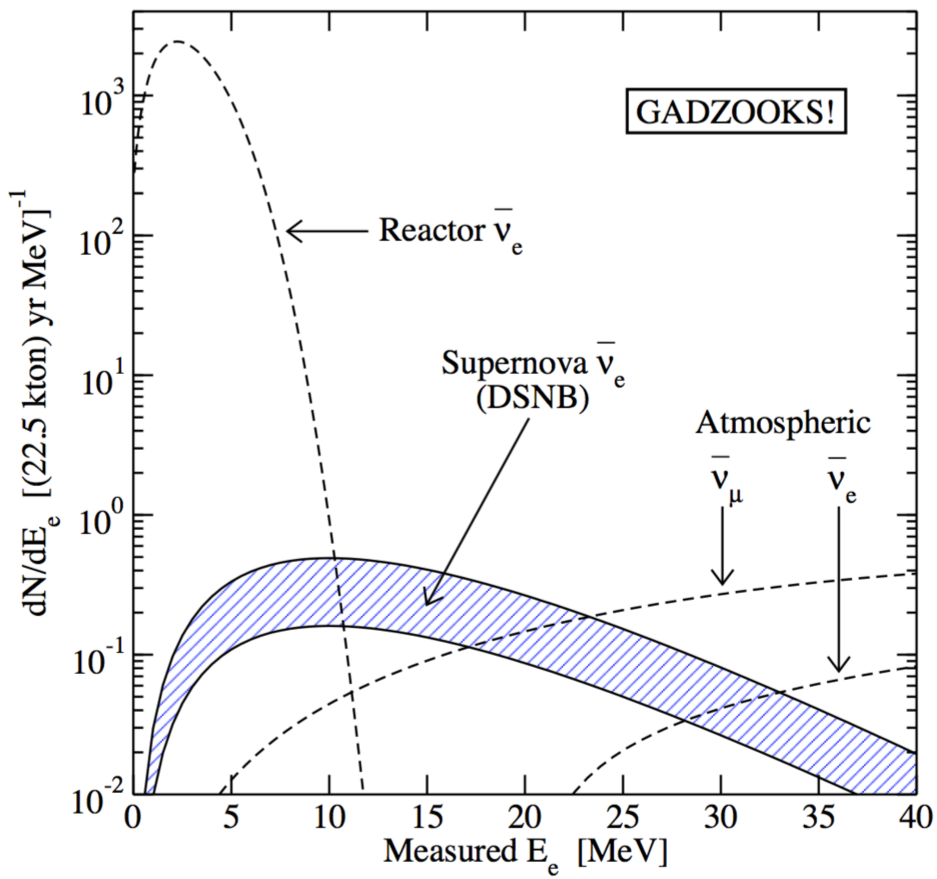
- Measure **neutron multiplicity**, a key handle for testing interaction models of multi-nucleon final states
- Improve understanding of **neutron tagging**, with applications to background tagging in PDK searches
- Implement **LAPPDs** in a particle detector, gaining experience with a next-generation technology

- **Phase I is a success**, results indicate low neutron backgrounds
- Phase II preparation is progressing well
- ANNIE will start taking **physics data in 2018**

Thank you for listening

Physics Goal: III

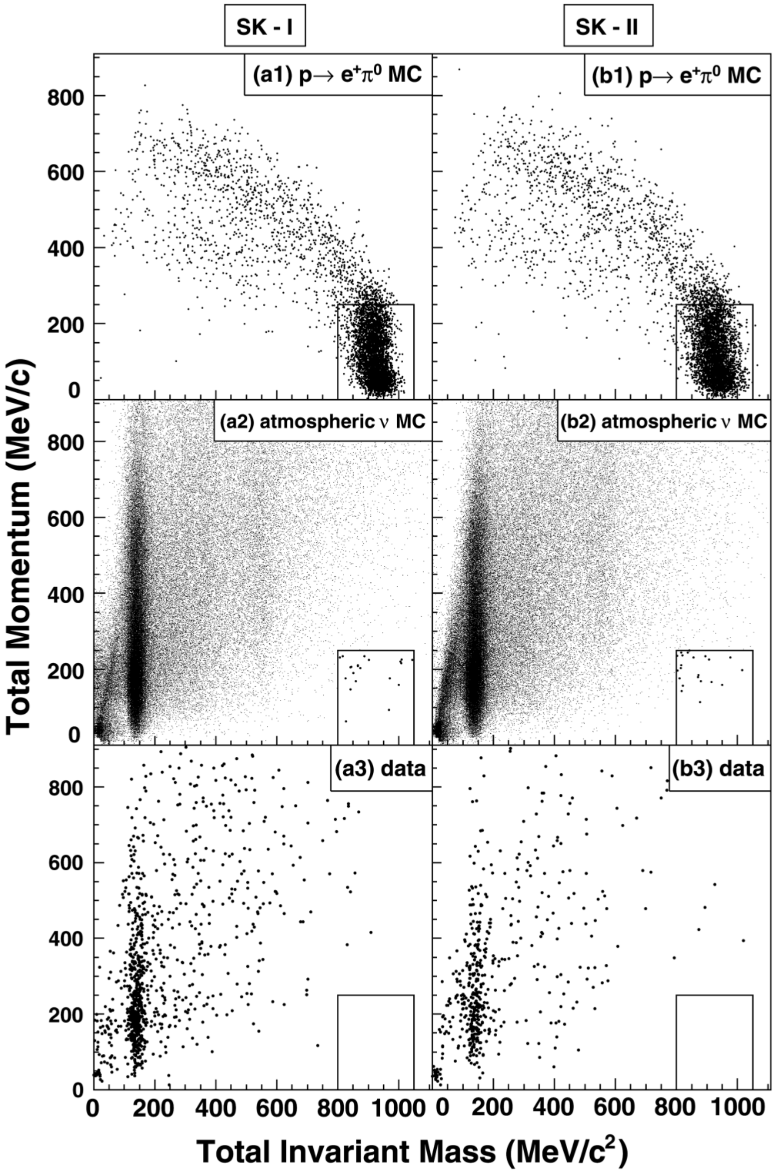
- Atmospheric neutrinos are a background for **Diffuse Supernova Neutrino** detection
- DSNB signal produces exactly 1 neutron
- Atmospheric neutrinos may mimic this signal – dominant background above 20MeV
- But these **background events may also generate neutrons** – knowledge of multiplicity can help account for them
- The energy range here is lower than ANNIE's coverage, but measurements may still be useful for some scenarios
- Background events will typically have higher energy, so neutrons will capture further from the vertex – ANNIE may help characterise this difference



Beacom & Vagins, PRL, 93 (2004) 171101

Proton Decay Backgrounds

- Proton decay events can be selected by requiring, among other criteria, the event have an invariant mass equal to the proton rest mass, and minimal unbalanced momentum
- Plots of signal MC (top), atmospheric neutrino background MC (middle) and data (bottom) show the overlap of background events into the signal region (boxed)
- Background events may generate neutrons through several mechanisms, tagging of which allows the event to be excluded
- Proper modelling requires understanding of neutron multiplicity in atmospheric neutrino interactions
- BNB flux is well matched to this energy range



SK Collaboration. Phys. Rev. Lett. 102 (2009) 141801

It is not enough merely to identify the presence or absence of neutrons

To calculate exclusions and to attribute confidence to discovery, you need to know your fake rate.

$$f = P(0) + P(1)(1-\epsilon) + P(2)(1-\epsilon)^2 + P(3)(1-\epsilon)^3 + \ldots.$$

which depends on...

neutron detection efficiency

and the underlying probability distribution of N neutrons P(N)

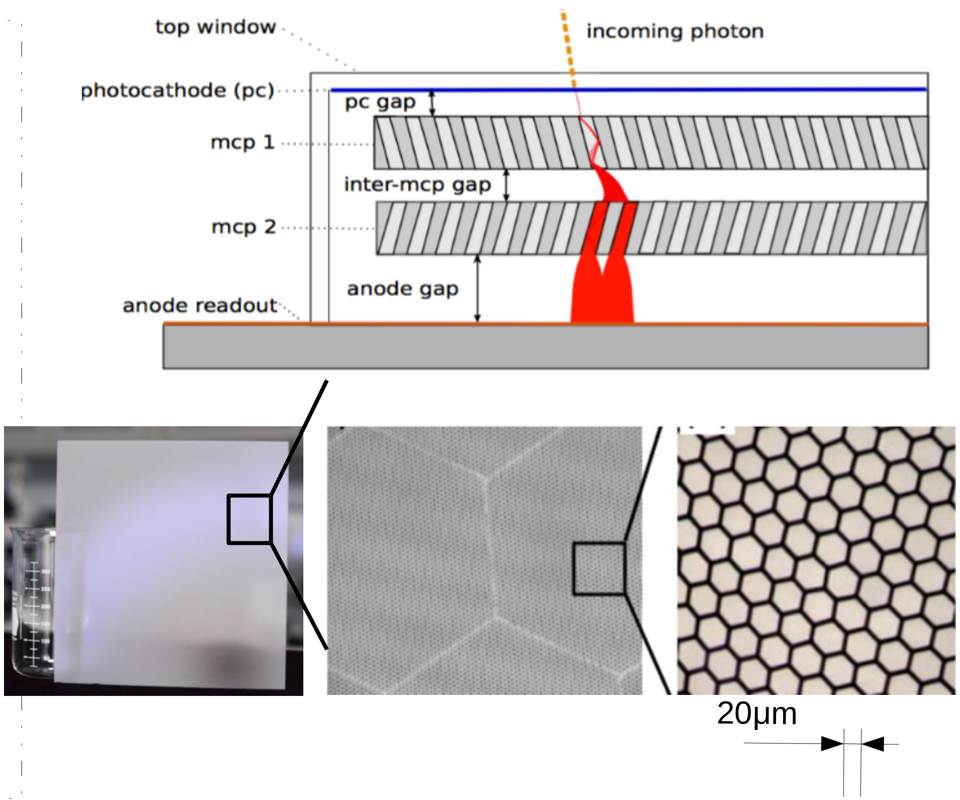
The smaller ε is, the better you need to understand the shape of P(N)

Technical Goals: I

- **First application of LAPPDs** (Large Area Picosecond Photodectors) in particle physics
  - Implementing multi-tile readout electronics
  - Integration into a hybrid DAQ framework with conventional PMTs
  - Development and demonstration of reconstruction capabilities
  - Crucial to allow ANNIE to distinguish multi-track events to reject pion production

LAPPD Technical Specifications

- 20cm x 20cm active area
- Gain of 10^7
- <60ps single pe resolution, <5ps multi-pe timing resolution
- mm-cm level spatial resolution (X-Y planes)
- 20+% QE with ~15% uniformity
- Low dark noise levels



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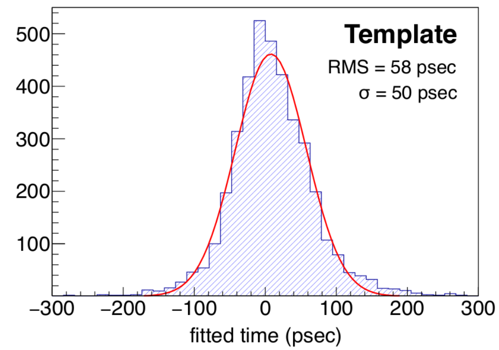

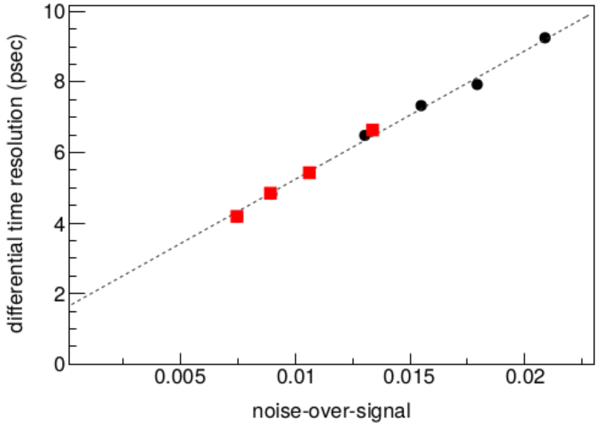

B. W. Adams et al, A Brief Technical History of the Large-Area Picosecond Photodetector (LAPPD) Collaboration

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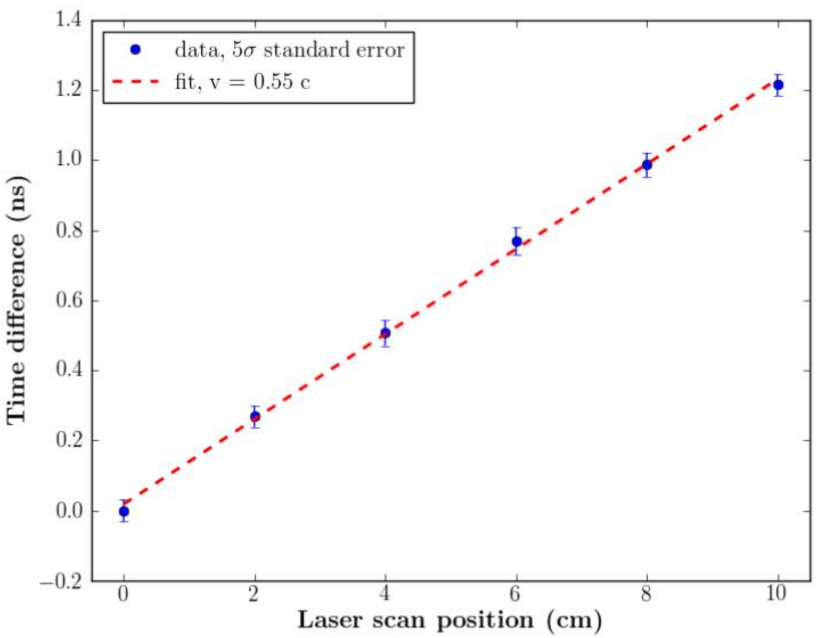

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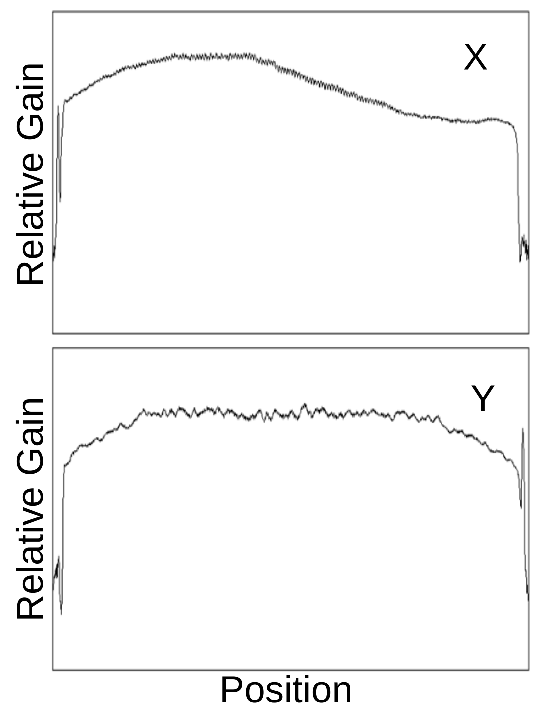

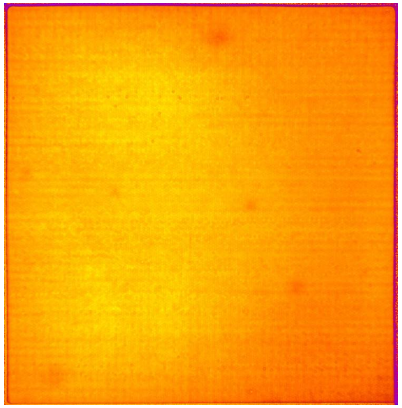

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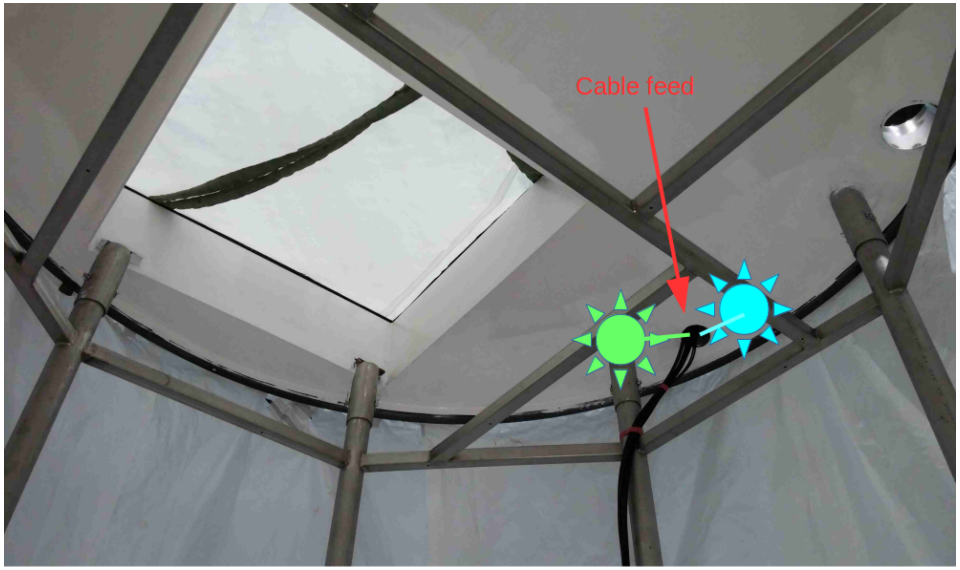
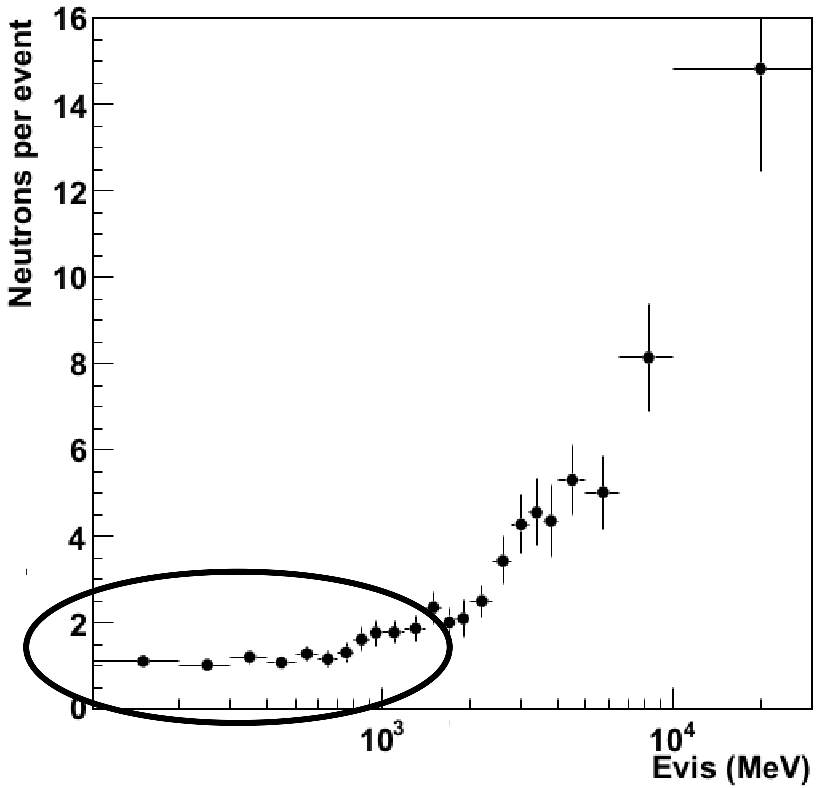
Cosmic Veto + LEDs

- LED flashers to calibrate PMT response
- Generated by trigger system for parasitic data taking
- Sparse array of scintillator paddles to select cosmic tracks passing through a tank diagonal, and/or through NCV
- Useful for water transparency measurements



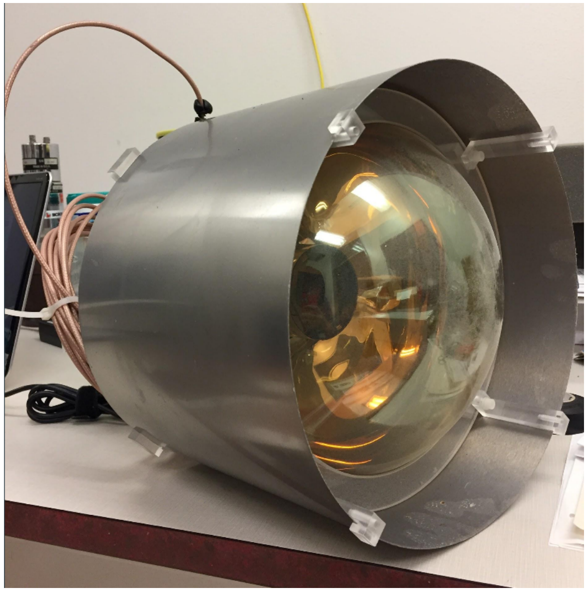
SK neutron yield

- SuperK measured **energy integrated** neutron yield as function of **visible energy** using atmospherics
- Extended trigger & offline processing to identify 2.2MeV capture event on H_2O
- 45% efficiency is with 19% uncertainty
- Since direction is unknown, only have E_{vis} available
- Combined statistics for ν_e, ν_μ for both ν & $\bar{\nu}$
- Results are of limited in modelling atmospheric neutrino interactions
- ANNIE provides more precise and detailed kinematics, flavour and type discrimination



“Borrowed” Photosensors

- ~120 PMTs covering all tank faces
  - 45x 10”Watchbooy R7081
  - 20x 10”LUX R7081
  - 22x 11”HQE ETEL prototypes
  - 40x 8”HQE R5912 – purchased new



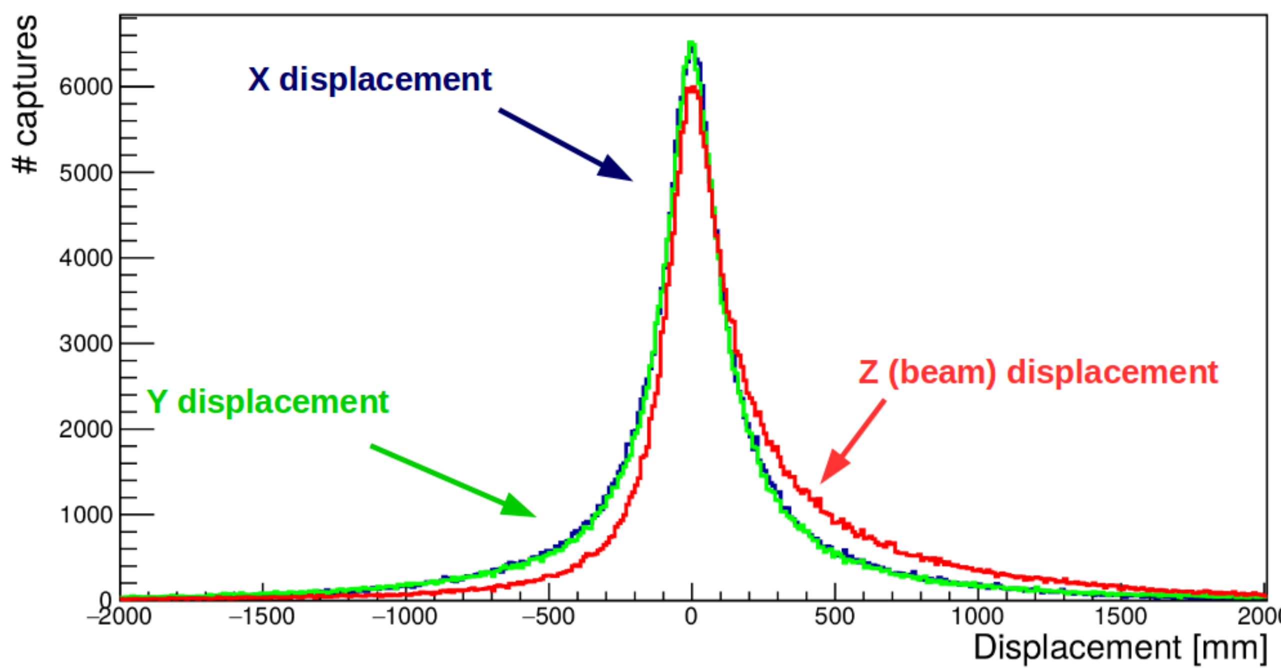
Watchboy R7081

LUX R7081

ETEL D784KFBL

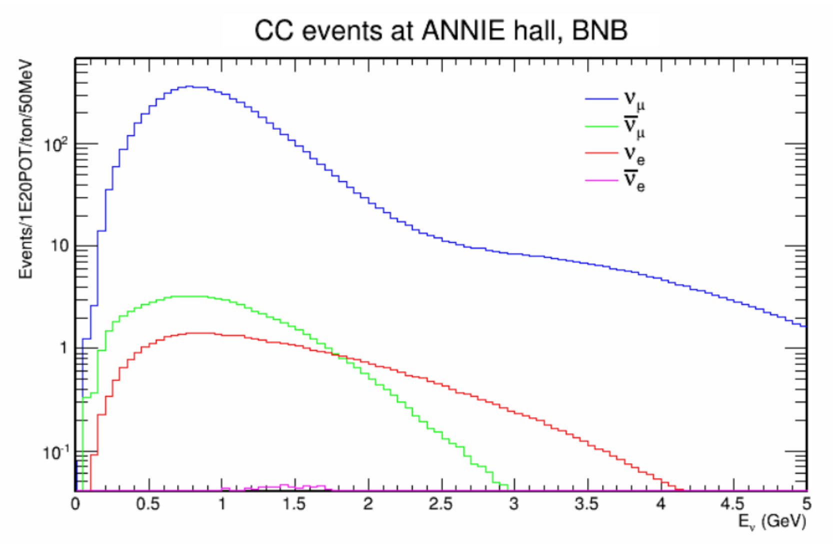
Neutron Drift in ANNIE

- Primary multiplicity from GENIE v2.8 estimates ~2% of events with >2 neutrons
- Neutrons diffuse ~200cm from their vertex before capture
- Offset in the beam direction by ~18cm due to imparted momentum from neutrino
- Fiducial volume defined in offline analysis to maximise combination of containment and detection efficiency



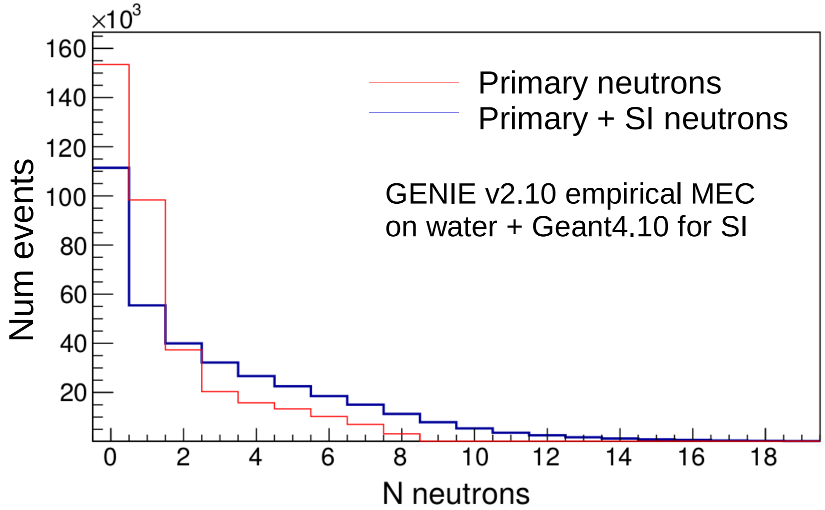
Flux at ANNIE

- BNB delivers 4×10^{12} POT per 1.6 µS spill at 5Hz
- Mean energy 0.7GeV
- 93% pure ν_μ, 6.4% $\bar{\nu}_\mu$, 0.6% ν_e and $\bar{\nu}_e$



Event counts in a 2.5-ton fiducial volume over $2\mathrm{x}10^{20}$ POTs, or 1 year of running

	NC	CC	CCQE	CC-Other
All	11323	26239	13674	12565
Entering MRD	2	7466	4279	3187
Stopping in MRD	2	4830	2792	2038

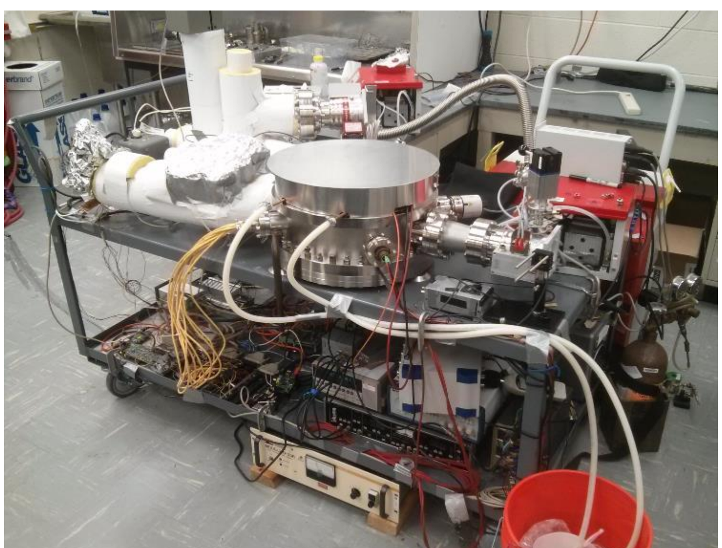


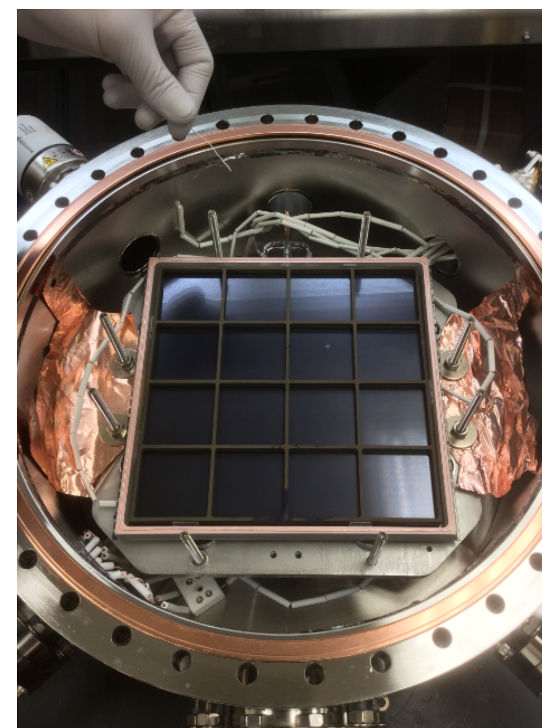
LAPPDs: Getting Your Own

- LAPPDs are moving from 'commissioning' to 'pilot production' phase of commercialisation
- As a new technology manufacturing process is not yet optimised for cost
- **But are already** competitive with alternative MCP-based multi-pixel detectors from Photonis and Hamamatsu, for equivalent areas of coverage
- Costs expected to drop as experience and production volumes grow
  - LAPPDs may see market interest outside HEP from private sector areas such as medical imaging, homeland security etc
- 'Gen II' design could help substantially drop manufacturing costs also

LAPPDs Gen II

- Process improvement by Uchicago
- New approaches to photocathode production, eliminate need for vacuum transfer by making photo-cathode after top-seal
- First sealed, in-situ LAPPD produced August '16
- Potentially incorporate more robust ceramic body, readout by capacitive coupling to external anode
- Compatible with current fabrication facilities





Cross-Section Analysis