Understanding neutron yield from neutrino interactions with ANNIE

EMRAH TIRAS & MATTHEW WETSTEIN

ON BEHALF OF ANNIE COLLABORATION

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IOWA STATE UNIVERSITY

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Outline

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- Physics objectives
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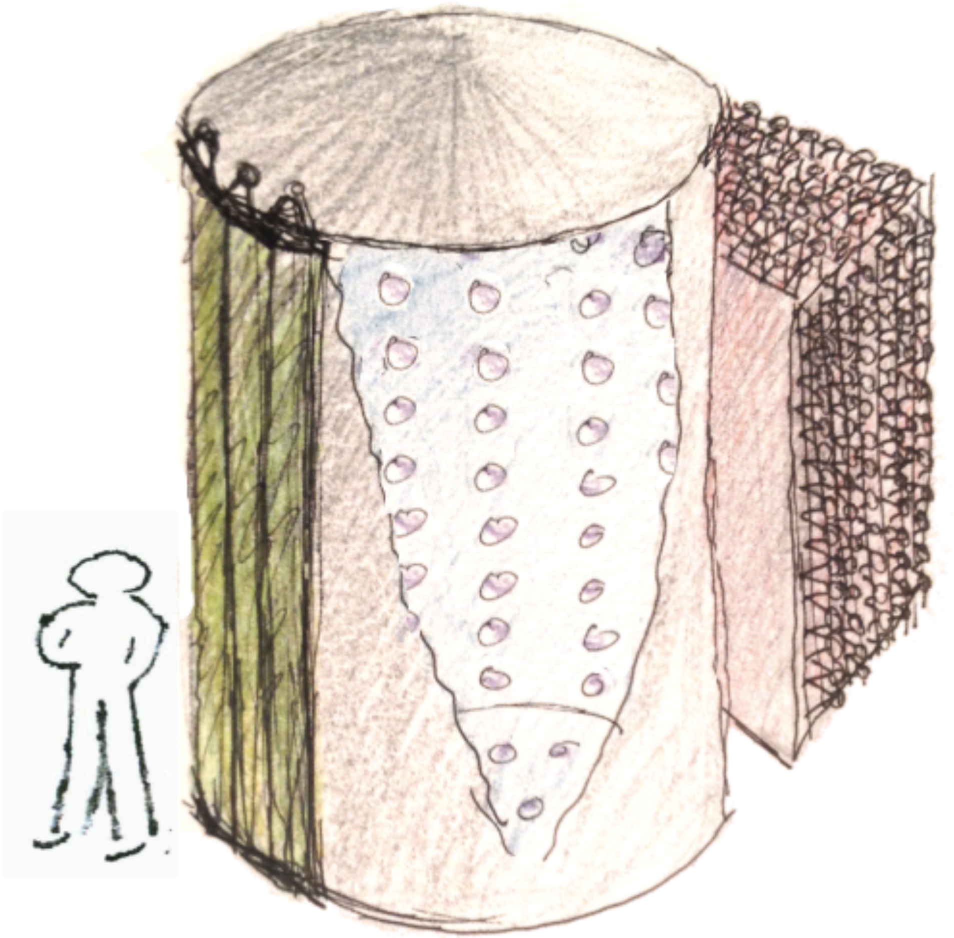
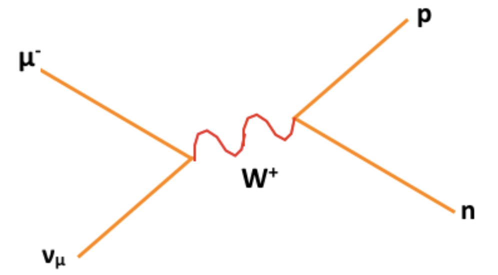


Motivation

Primary physics objectives: Measuring the abundance of final state neutrons (neutron yield) from neutrino interactions in water as a function of energy.

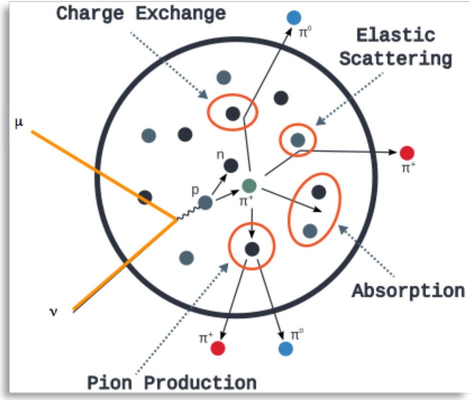


It is relevant to studies of:

① Neutrino oscillation experiments:

- help understand critical systematics on energy reconstruction in long-baseline measurements.
- could help in explaining short baseline anomalies.
- possible handle for neutrino/antineutrino separation.

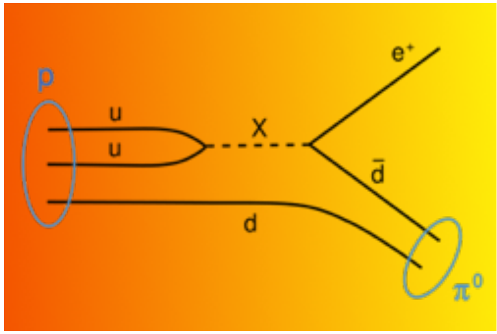
② Signal/background separation for proton decay measurements and supernova neutrino observations.



Technical goals:

① First major application of Large Area Picosecond Photo-Detectors (LAPPDs) in a neutrino experiment.

② First Gd-loaded water Cherenkov detector to run in a neutrino beam.



ANNIE Overview

ANNIE is located at SciBooNE Hall along the Booster Neutrino Beam (BNB) at Fermilab.

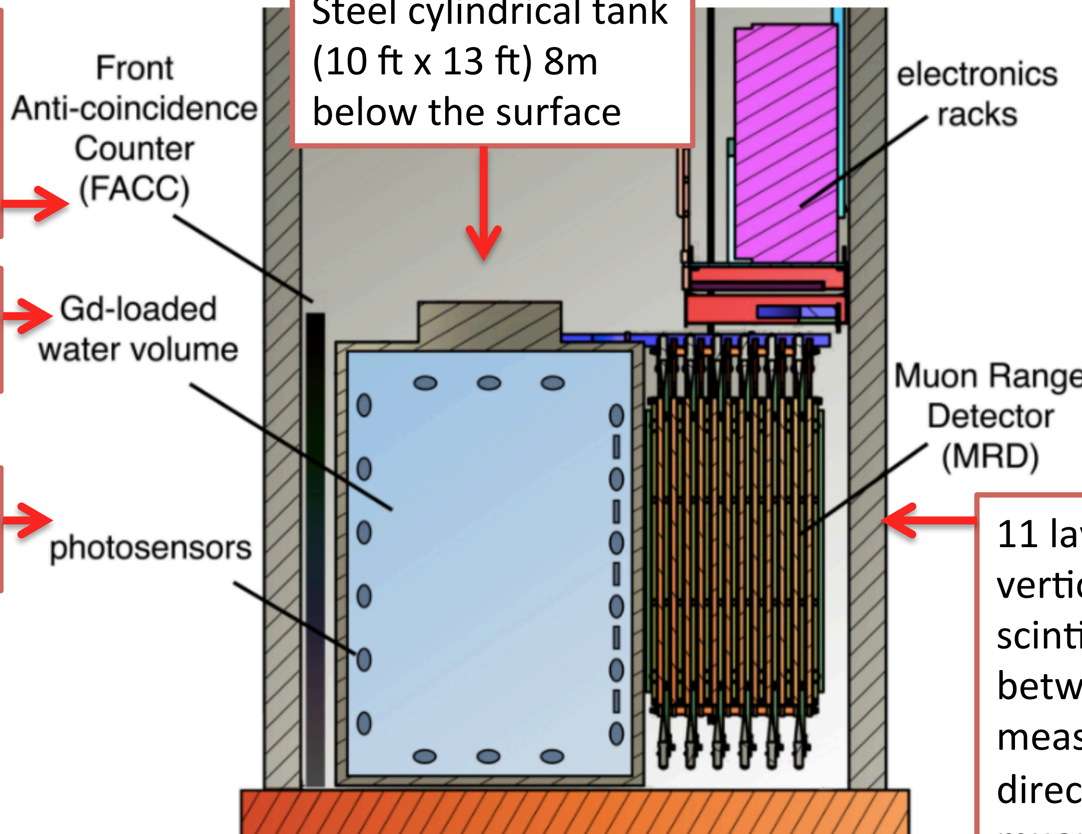
- on-axis neutrino flux
- Spectrum peaks around 0.7 GeV (range of interest for atmospheric neutrinos)
- Expect 14×10^3 ν_μ of charged-current interactions per ton of water per year.

Scintillator paddles to veto muons not originating in the tank.

26 tons of Gd-loaded water

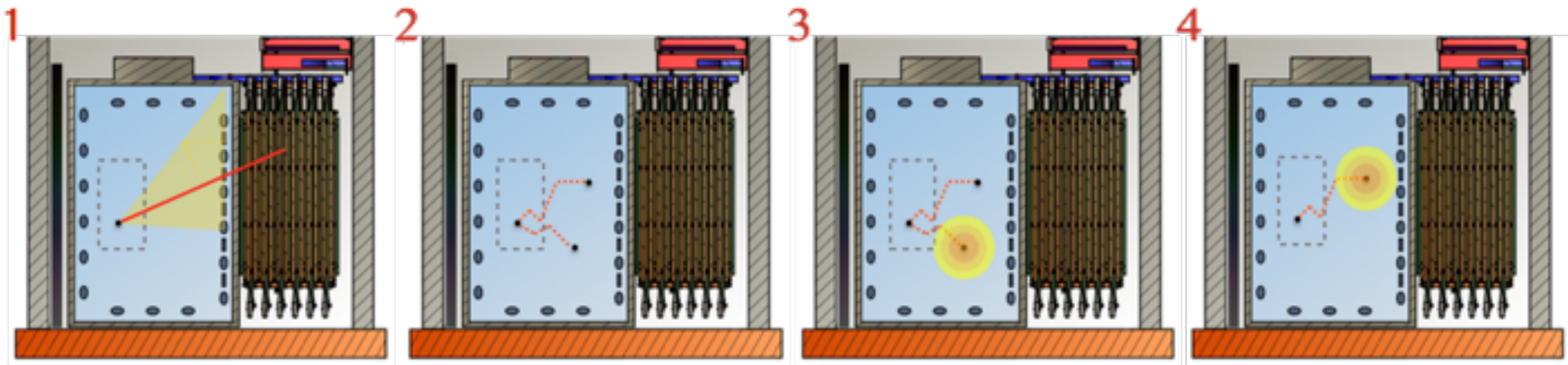
>100 PMTs + 10-20 LAPPDs

Steel cylindrical tank (10 ft x 13 ft) 8m below the surface



11 layers of alternating vertical and horizontal scintillating paddles between layers of steel to measure the energy and direction of stopped muons.

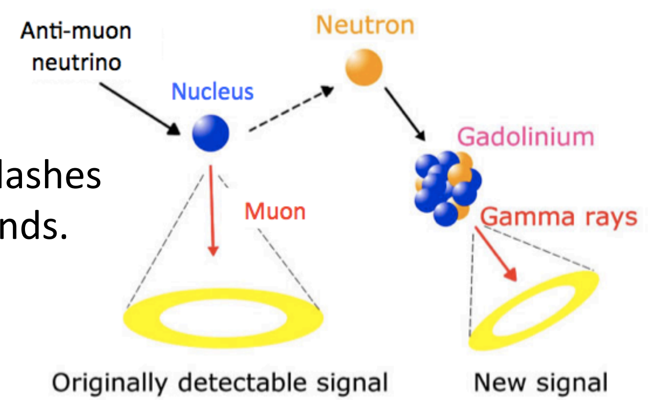
An event in ANNIE tank



1. CC interaction in the fiducial volume produces a muon, reconstructed in the water volume and MRD.

2. Neutrons scatter and thermalize

3. (3-4) Thermalized neutrons are captured on the Gd producing flashes of light, cascade of 8 MeV gammas in several tens of microseconds.

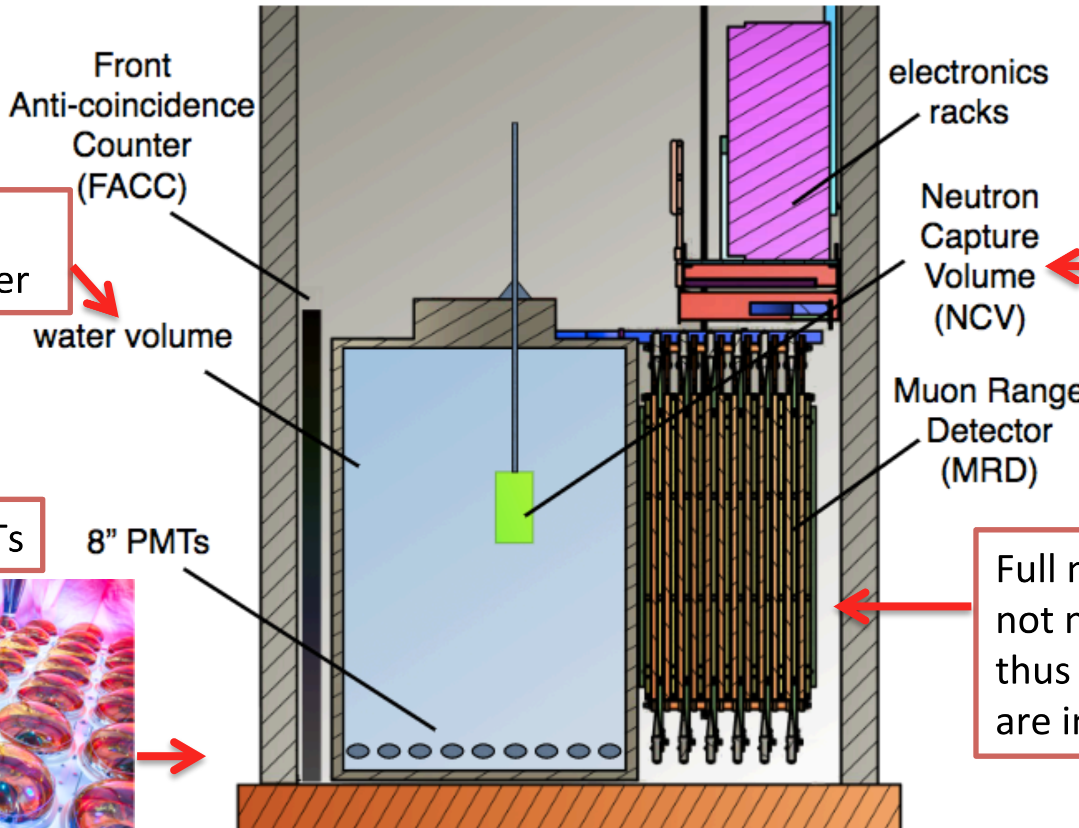


The Current State of the Detector (Phase I)

ANNIE is located at SciBooNE Hall along the Booster Neutrino Beam (BNB) at Fermilab.

- on-axis neutrino flux
- Spectrum peaks around 0.7 GeV (range of interest for atmospheric neutrinos)
- The detector was built in April 2016 and it has been taking data since then.

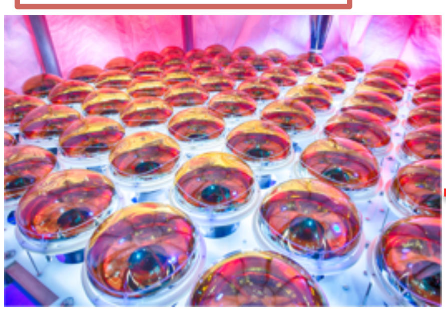
26 tons of ultra-pure (UPW) water



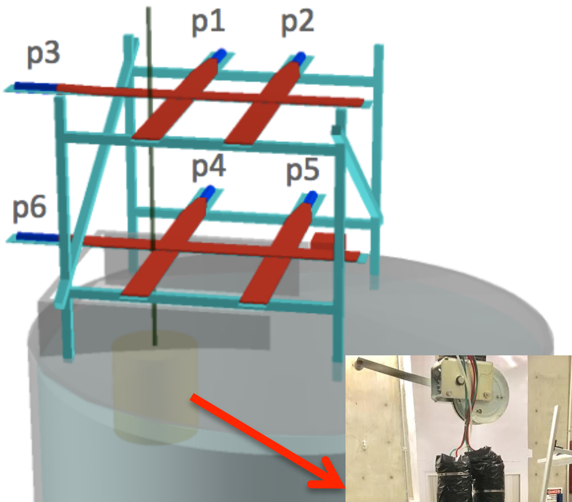
Neutron Capture Volume is a movable acrylic vessel holding 25 gallons of Gd-loaded liquid scintillator to measure position dependent neutron rates.

Full muon reconstruction is not needed for Phase I and thus only the first two layers are instrumented.

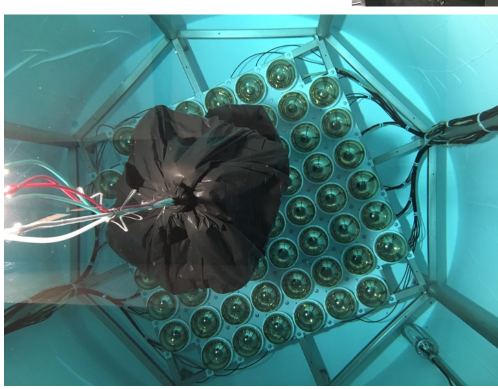
60 Super-K PMTs

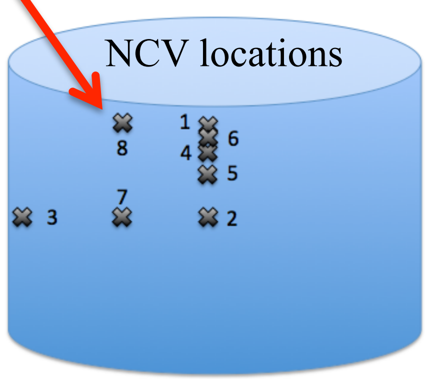


ANNIE Phase I



NCV measures position dependent neutron rates



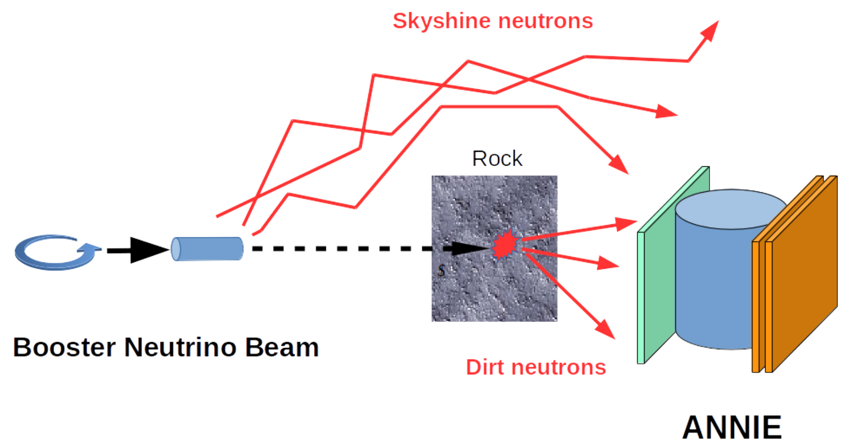


The main physics goal of Phase I is understanding neutron backgrounds. Potential background neutrons in ANNIE:

- Sky-shine neutrons from the beam dump
- Dirt neutrons from the rock

The background neutron flux was measured at different locations in the tank.

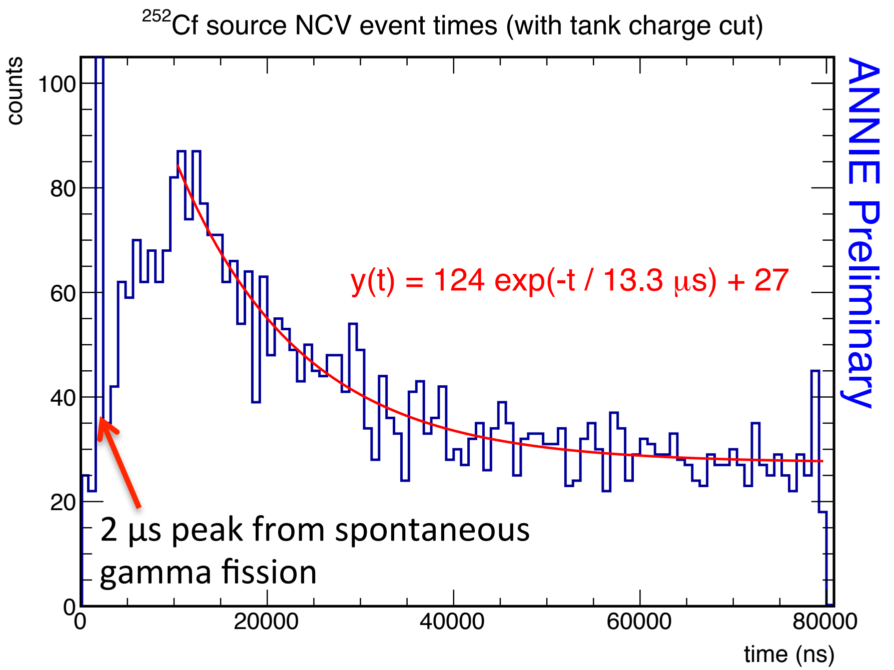
- ^{252}Cf neutron source is used for calibration.

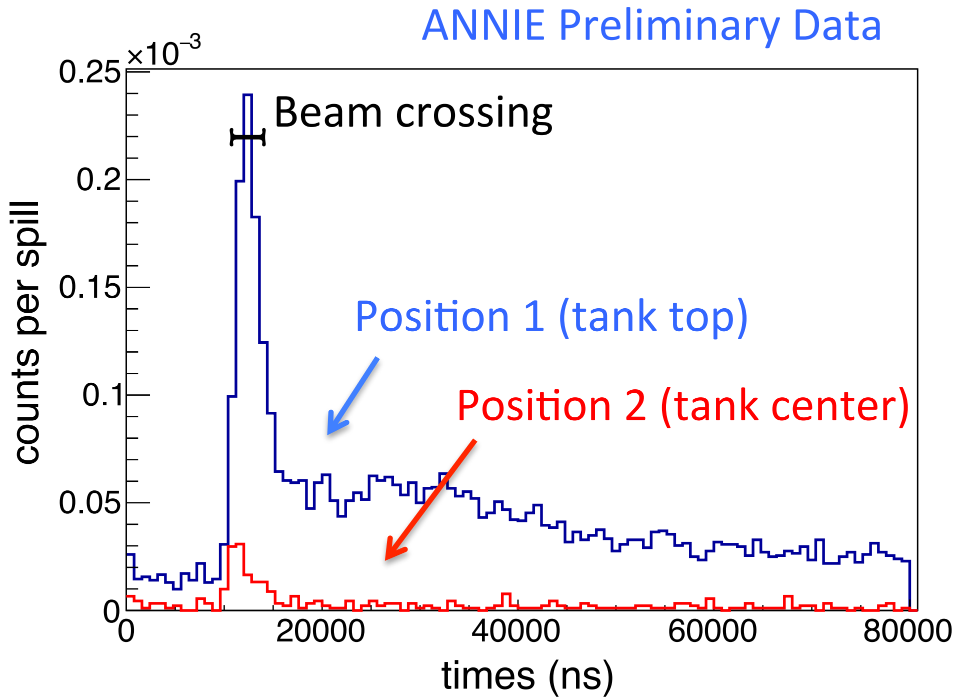


Preliminary Phase I Results

Plots from S. Gardiner (UCD)

- We have detected neutron captures from both a calibration source and the beam.
- Preliminary estimates based on measurements below the surface indicate neutron backgrounds in less than 2% of spills.
- Backgrounds are acceptable and can be mitigated with <2 ft of buffer.
- Final luminosity normalized estimates of beam induced background neutrons are coming soon.





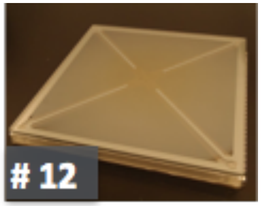
ANNIE Moving Towards Phase II

LAPPDs (20 cm x 20 cm) are:

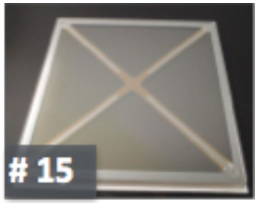
- novel technology for photodetection with gain of $>10^6$
- based on microchannel plates
- with excellent timing (~ 50 psec for SPE) and sub-centimeter spatial resolution→ this will give us a significant improvement for vertex reconstruction.

ANNIE will host the first live test of this novel technology during Phase II.

Incom has now produced multiple LAPPD prototypes, quickly approaching the specifications needed by ANNIE:

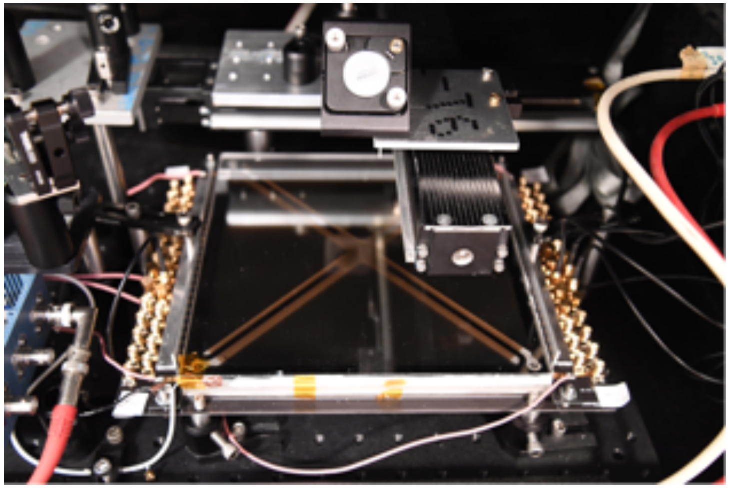


Tile #9: fully sealed detector with an aluminum photocathode
Tile #10: sealed detector with multi-alkali photocathode (~5 % QE)
Tile #12: ~10% QE
Tile #15: uniform photocathode >25% QE
Tile #18, 19: recently produced by Incom.

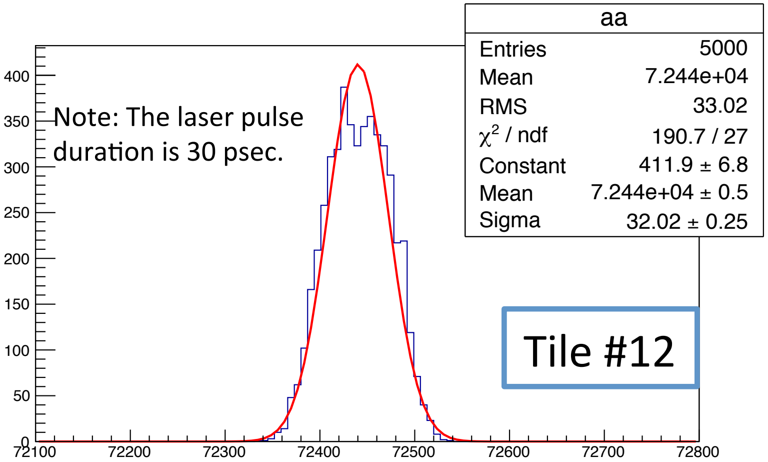


LAPPD Characterization Tests at ISU

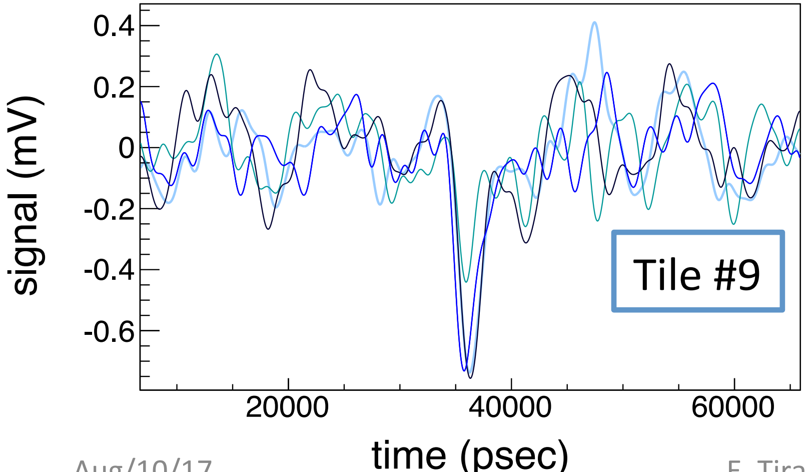
LAPPDs #9 and #12 were tested at ISU
w/ PSEC electronics provided by UChicago



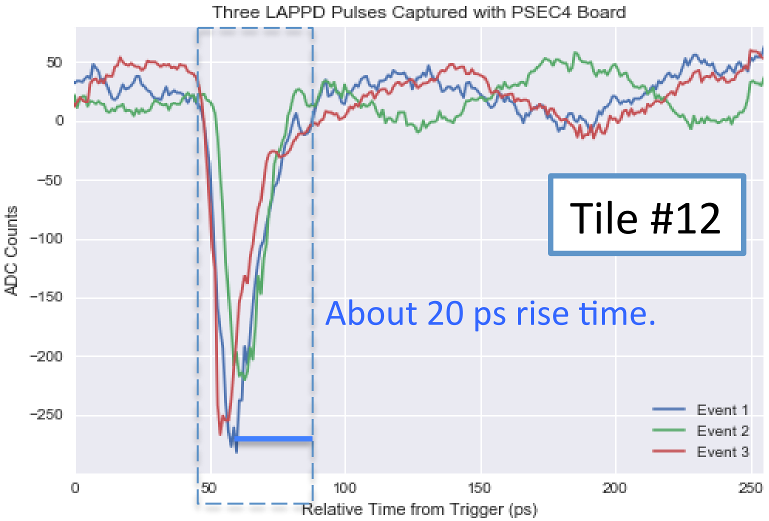
Multi-PE transit time spread



example single PE-pulses



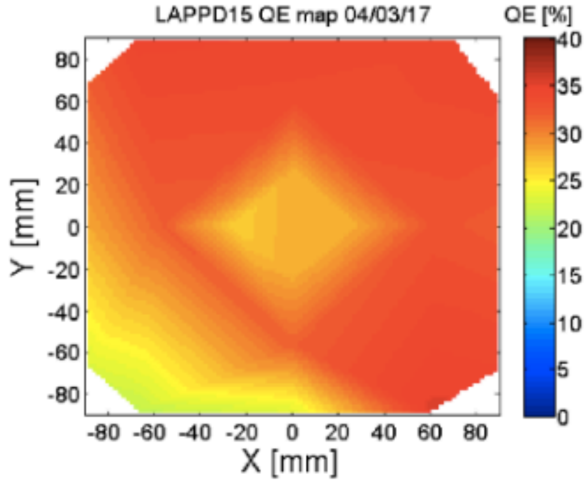
Multi-PE pulses with PSEC electronics



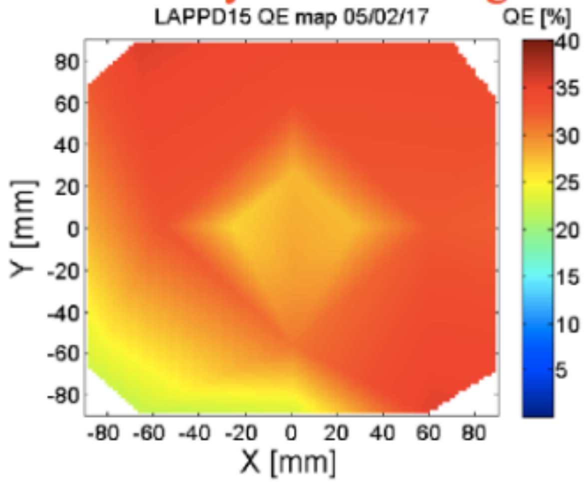
Quantum Efficiency Tests at Incom

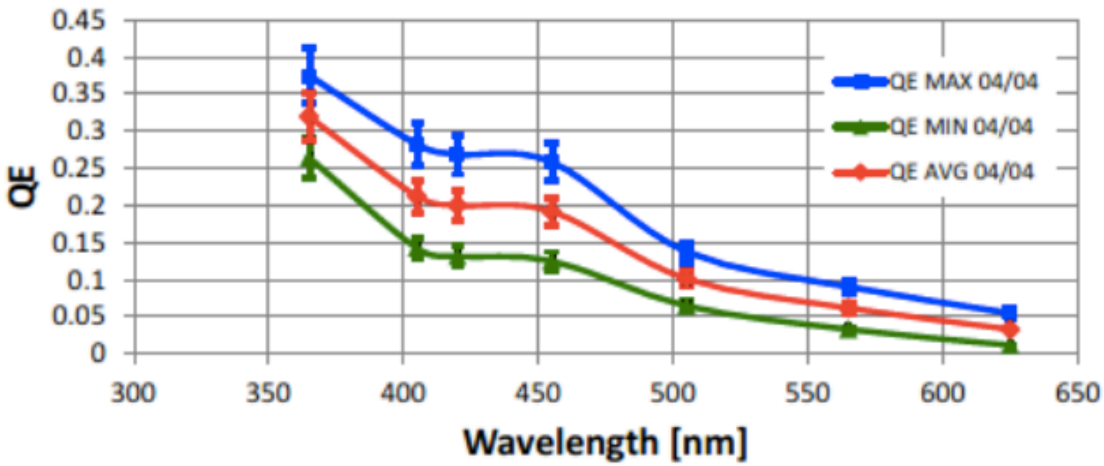
LAPPD Tile # 15

3 Days after Sealing



32 Days after Sealing

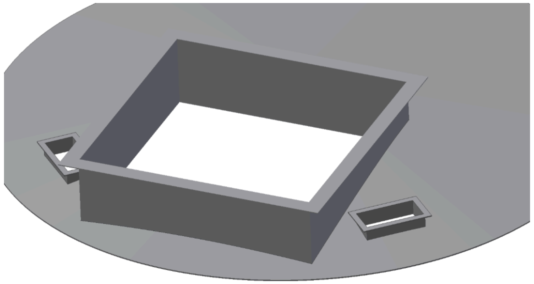


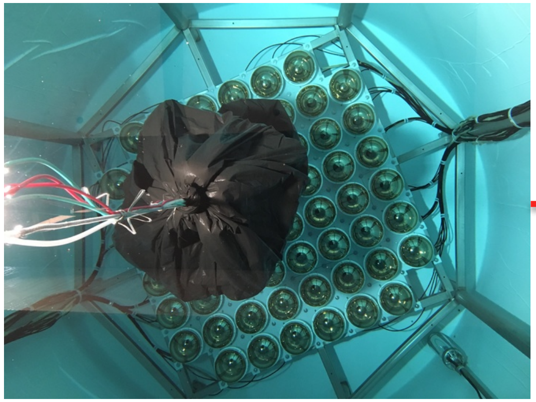


The average QE at 375 nm remains at 30%, with a maximum 35% and minimum of 22%

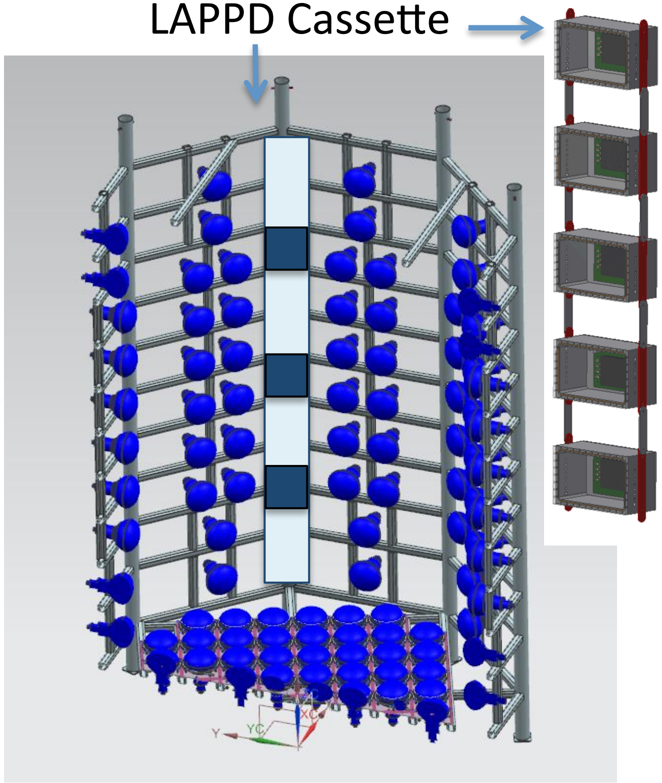
Phase I → Phase II

- Complete the tank inner structure
- Add the LAPPD System
- Add Gadolinium (0.2% Gd-sulfate concentration)
- Finish refurbishing the muon range detector (reinstall paddles)
- Expand standard photocathode coverage w/ more PMTs
- Expand electronics channel count



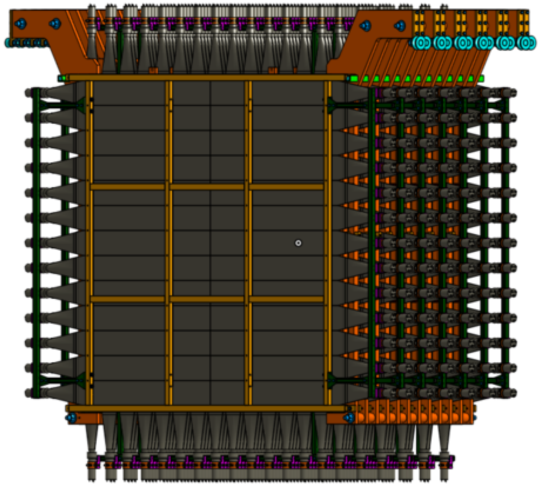


LAPPD Cassette



Small slots to insert the LAPPDs through guides.

MRD

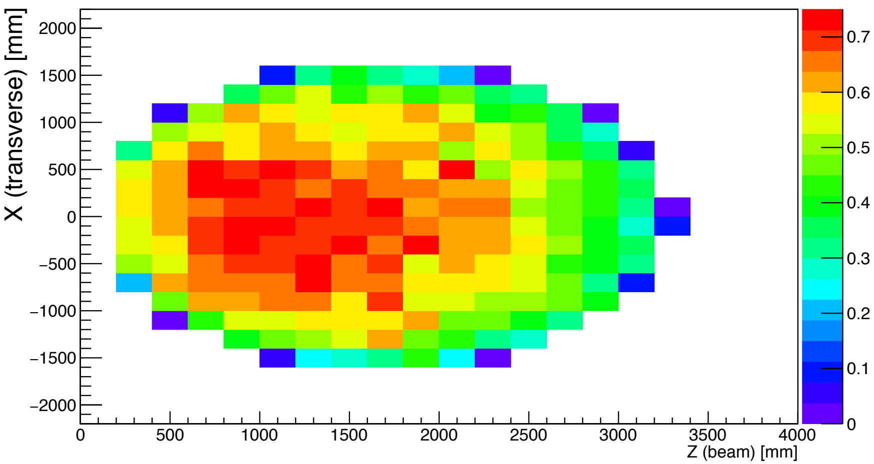


Neutron Detection Efficiency

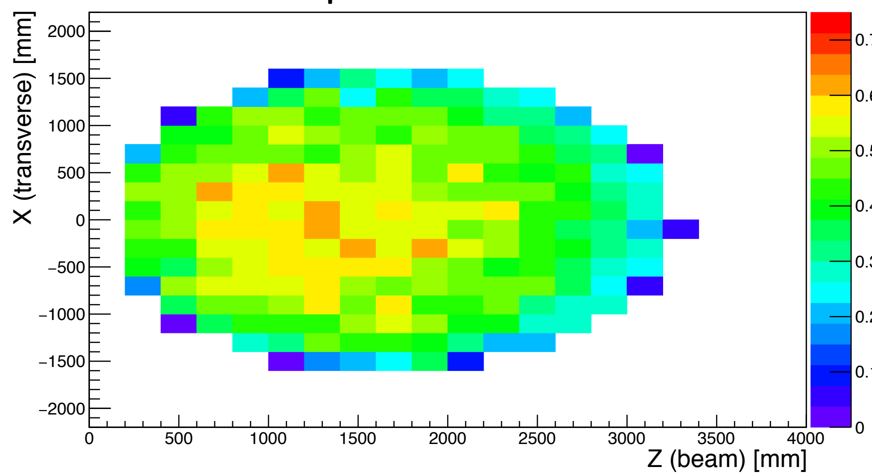
Plots from V. Fischer (UCD)

- Neutron detection efficiency as a function of the interaction position in X (the transverse direction) and Z (the beam direction)
- The plots are integrated between -1 and +1 meters in the vertical direction, Y.

5 p.e. threshold



10 p.e. threshold

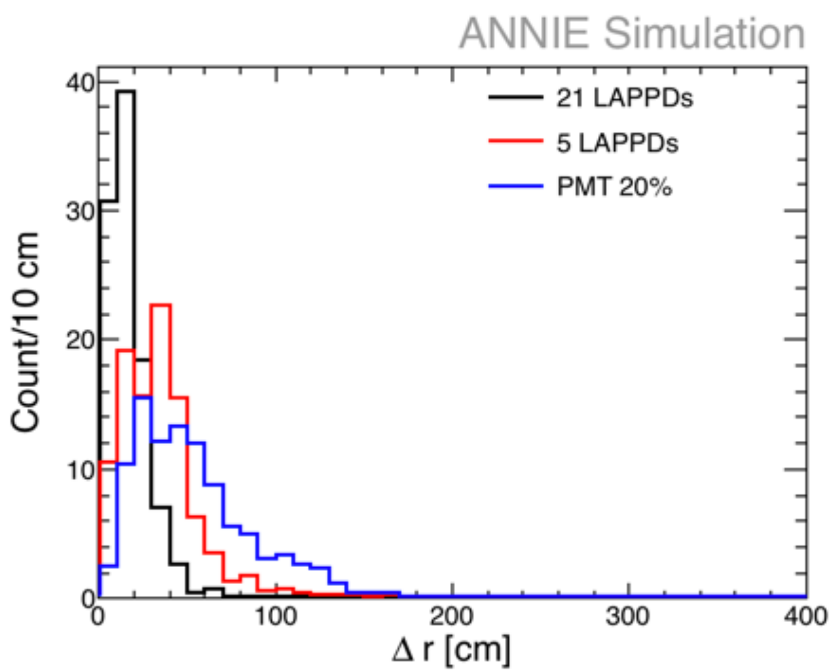


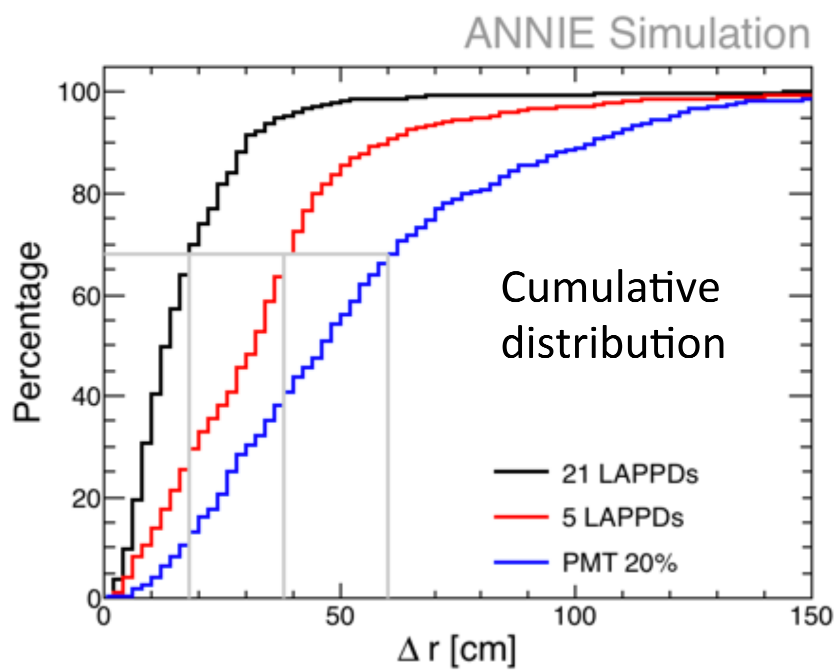
- The detector is large enough to fully contain neutrons
- Requested PMT coverage is sufficient to efficiently detect neutrons.

Vertex Reconstruction and Fiducialisation

Plots from J. Wang (UCD) and A. Back (ISU)

- LAPPDs show substantial improvement in precision for vertex reconstruction.
- LAPPDs help to understand the topology of the events.





20% conventional PMTs : 60 cm resolution
5 LAPPDs (only) : 38 cm resolution
21 LAPPDs (only) : 16 cm resolution

Conclusion

Phase I:

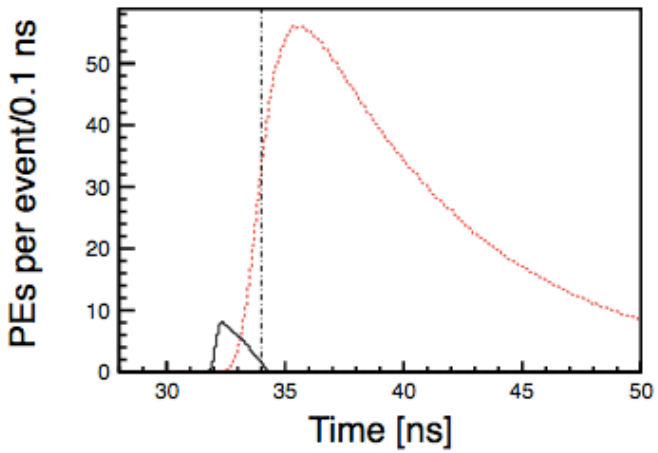
- The detector was built in April 2016 and it has been taking data since then.
- We have detected neutron captures from both a calibration source and the beam.
- Preliminary results of neutron backgrounds show they are acceptable.
- LAPPDs are ready and we are testing them at ISU.

Phase II:

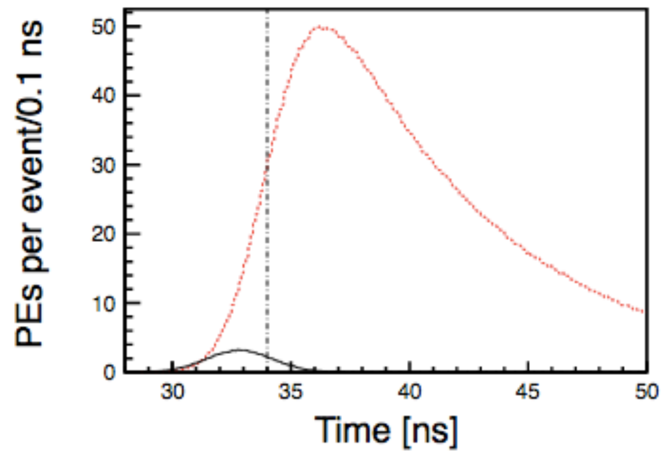
- It was recently approved by Fermilab Physics Advisory Committee (PAC).
- ANNIE will measure the neutron yield from neutrino-nucleus interactions in the energy range of atmospheric neutrinos.
- Also, it will be the first experiment testing LAPPDs in Gd-loaded water.

Backup Slides

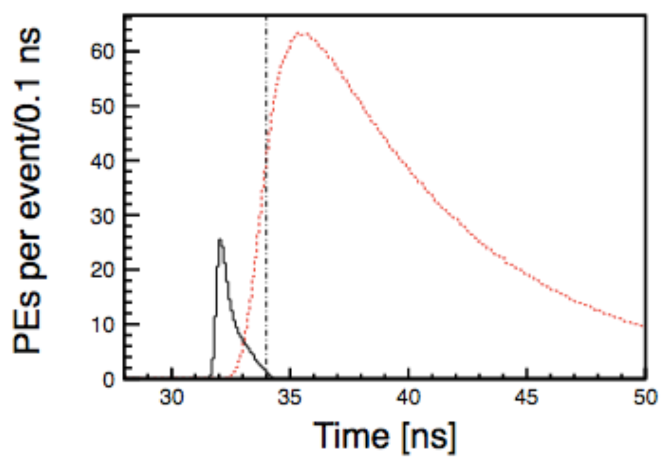
Timing to separate between Cherenkov and scintillation light



(a) Default simulation.



(b) Increased TTS (1.28 ns).



(c) Red-sensitive photocathode.

Black – PEs from Cherenkov light

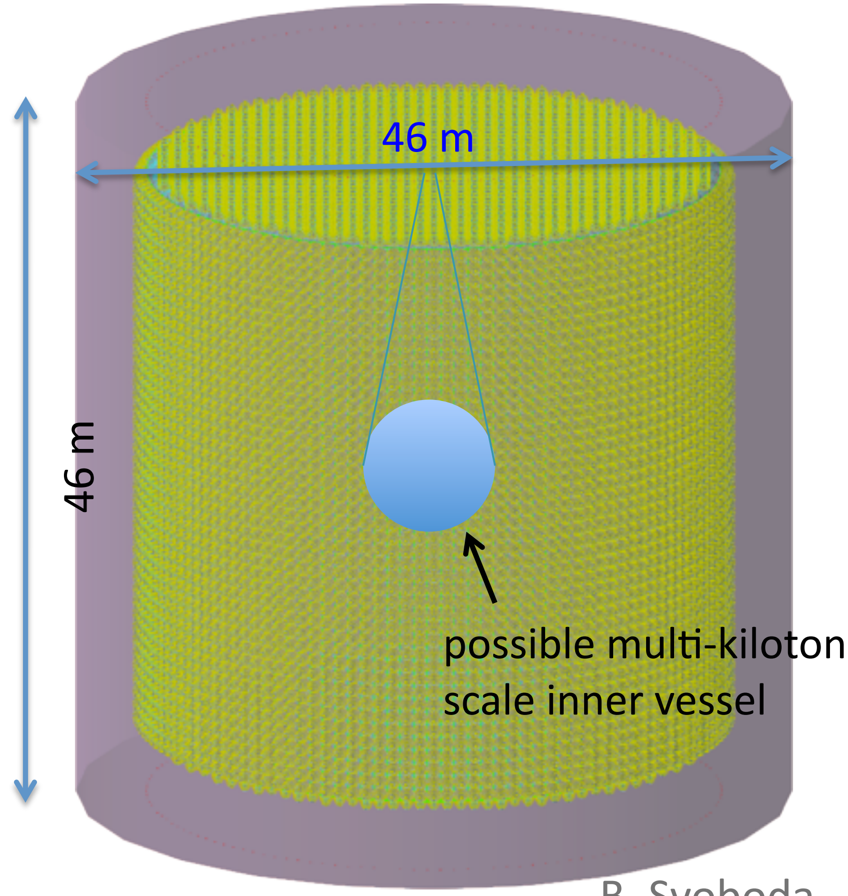
Red – PEs from Scintillation light

arXiv:1307.5813

THEIA Concept

arXiv:1409.5864

- **50 kilotons** fiducial
- **Deep depth** (>4000 mwe)
- **Fast timing**, high efficiency photosensors, high coverage
- **Isotopic loading**, possibly with a balloon to avoid "wasting" isotope and to achieve long attenuation lengths
- **Reconfigurable**, capable of economically for long periods to have a broad program



B. Svoboda