Early Adopters of the

Large-Area Picosecond Photo-Detectors

Andrey Elagin
University of Chicago

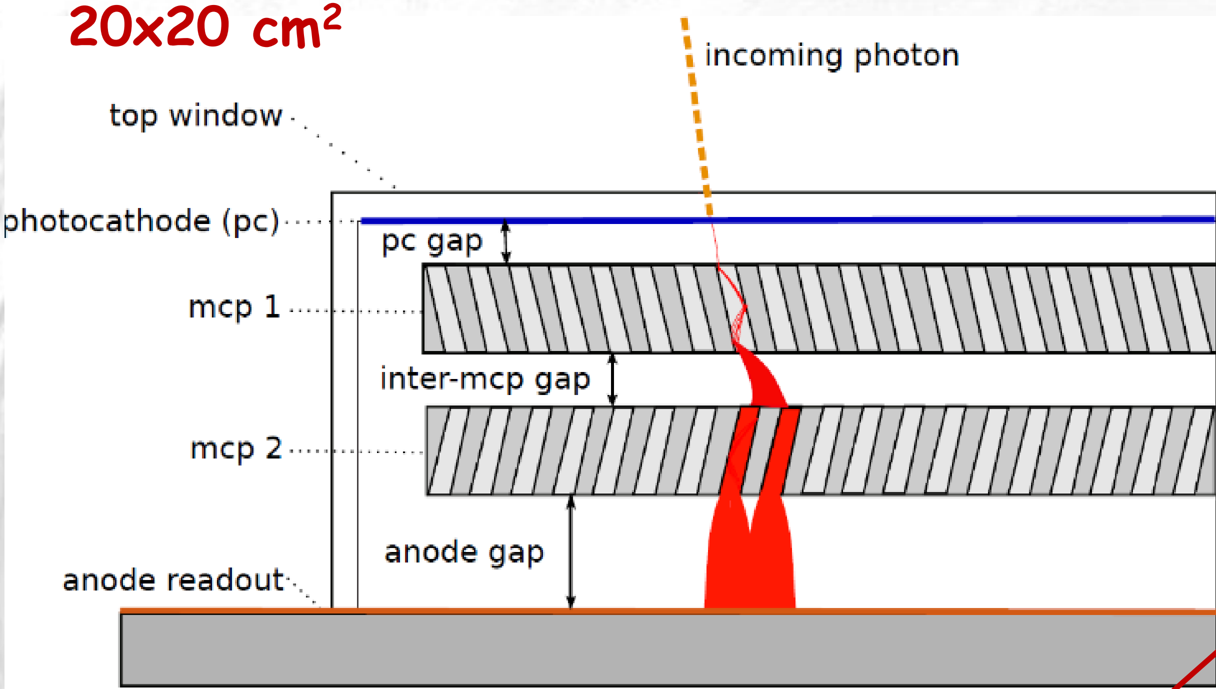
NNN 2016, IHEP, Beijing, November 2, 2016

Outline

- Large-Area Picosecond Photo-Detectors (LAPPD™)
- Some Early Adopters of LAPPD
  - ANNIE
  - NuDot/FlatDot
  - Optical TPC
- Summary

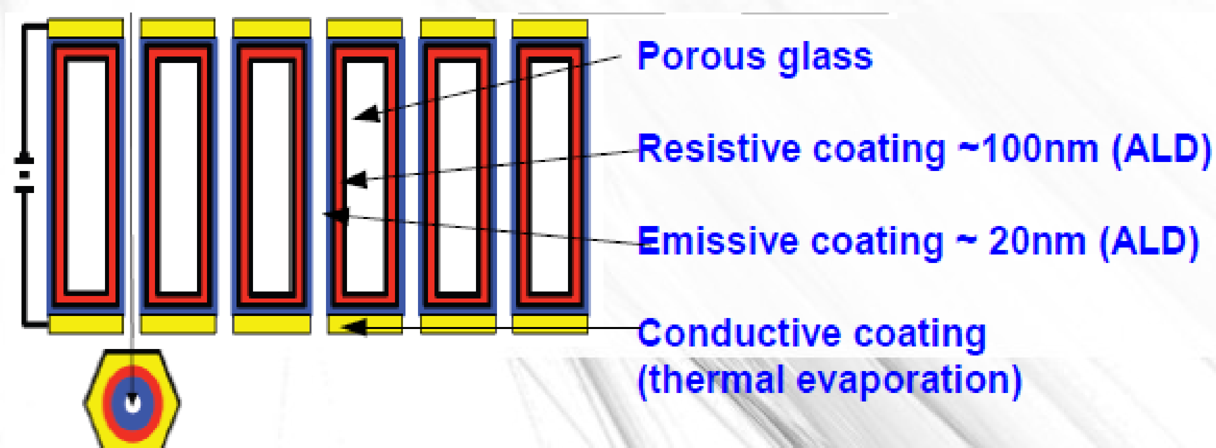
LAPPD

20×20 cm^2

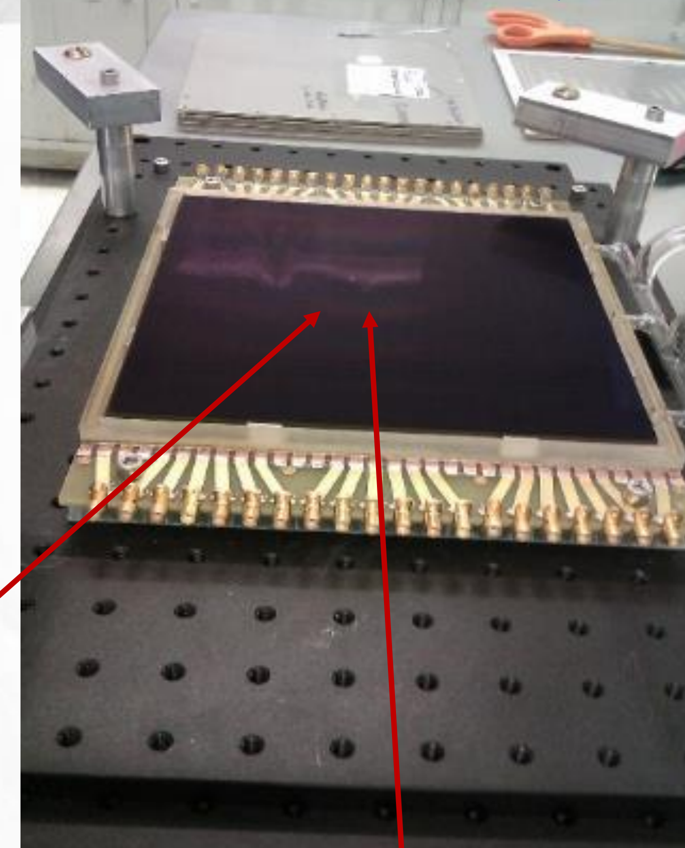


Atomic Layer Deposition (ALD)

- J.Elam and A.Mane at Argonne
(process is now licensed to Incom Inc.)
- Arradiance Inc. (independently)



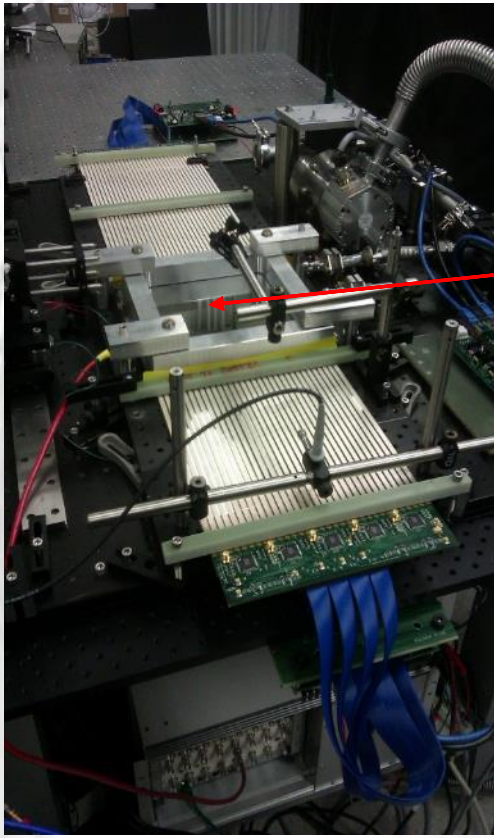
Micro-Channel Plates (MCPs)

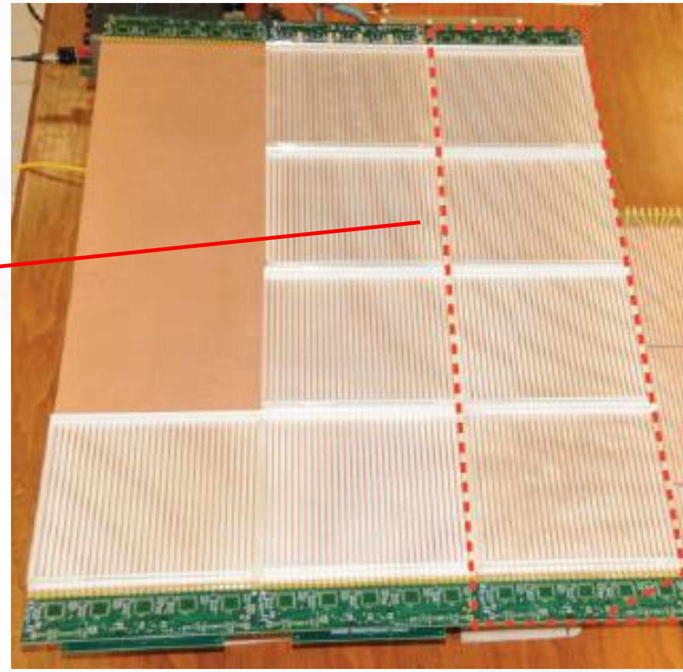


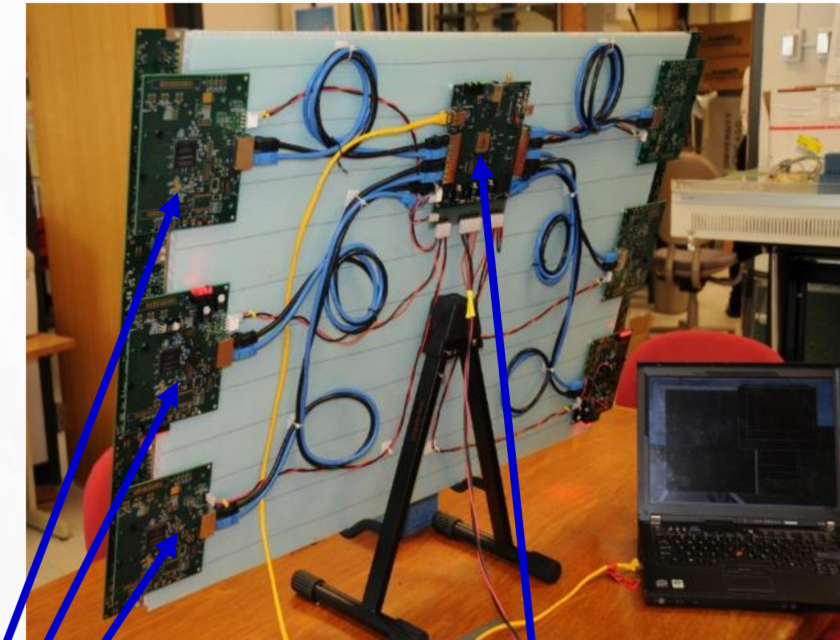
Micro-Capillary Arrays by Incom Inc.

- Material: borofloat glass
- Area: 8x8"
- Thickness: 1.2mm
- Pore size: 20 μm
- Open area: 60-80%

LAPPD Electronics @ UChicago







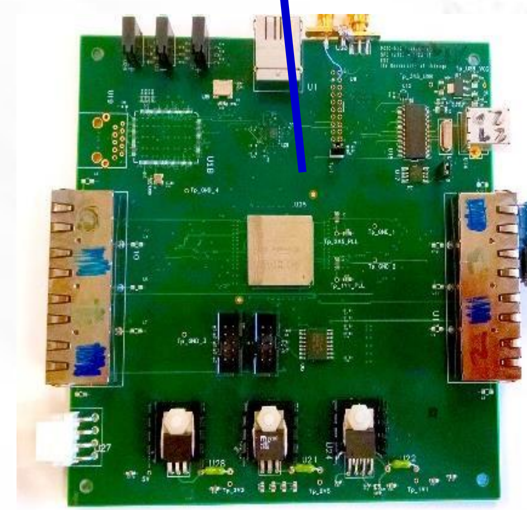
NIM 711 (2013) 124

Delay-line anode
- 1.6 GHz bandwidth
- number of channels scales linearly with area

NIM 735 (2014) 452

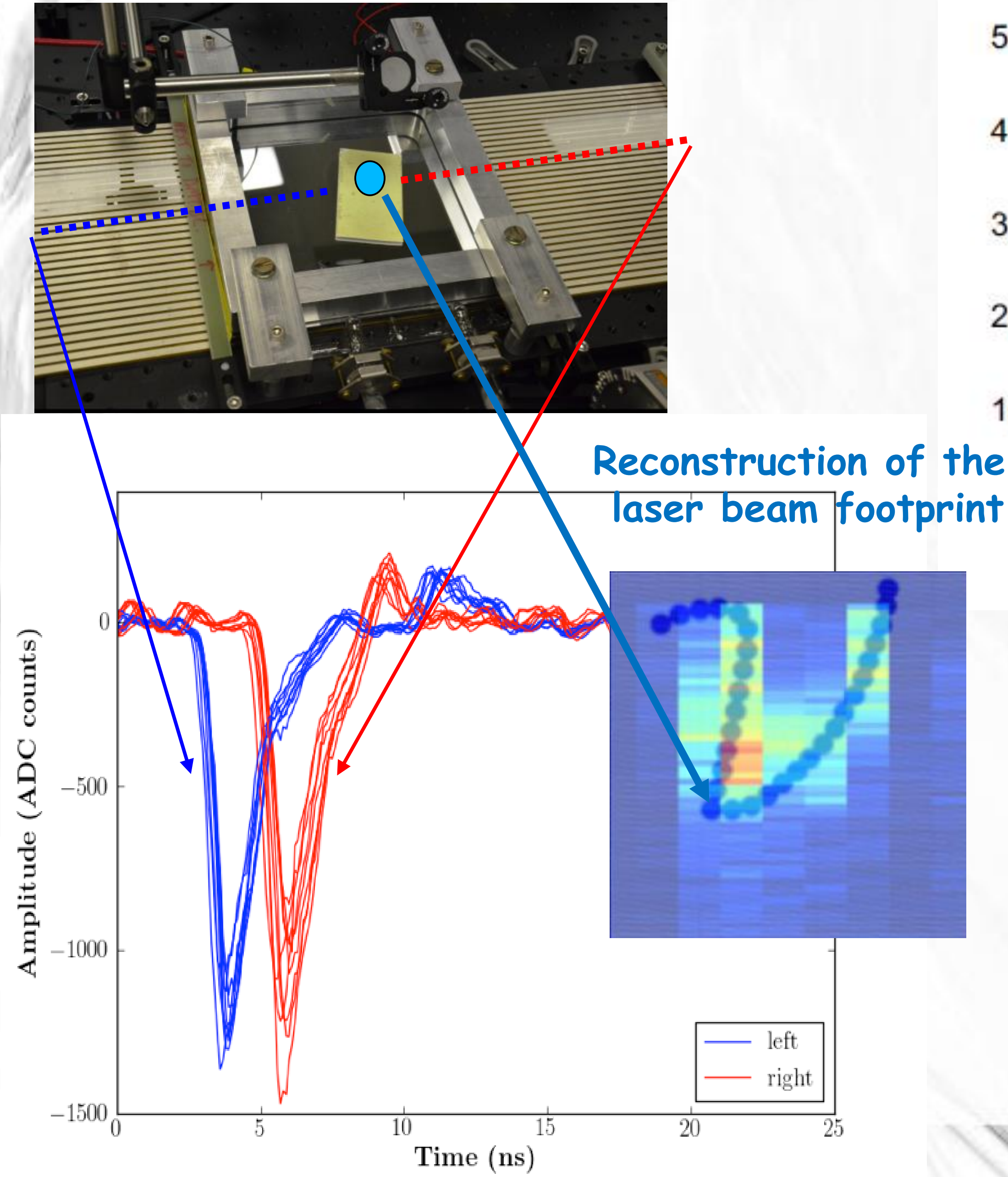
PSEC-4 ASIC chip
- 6-channel, 1.5 GHz, 10-15 GS/s

30-Channel ACDC Card
(5 PSEC-4)

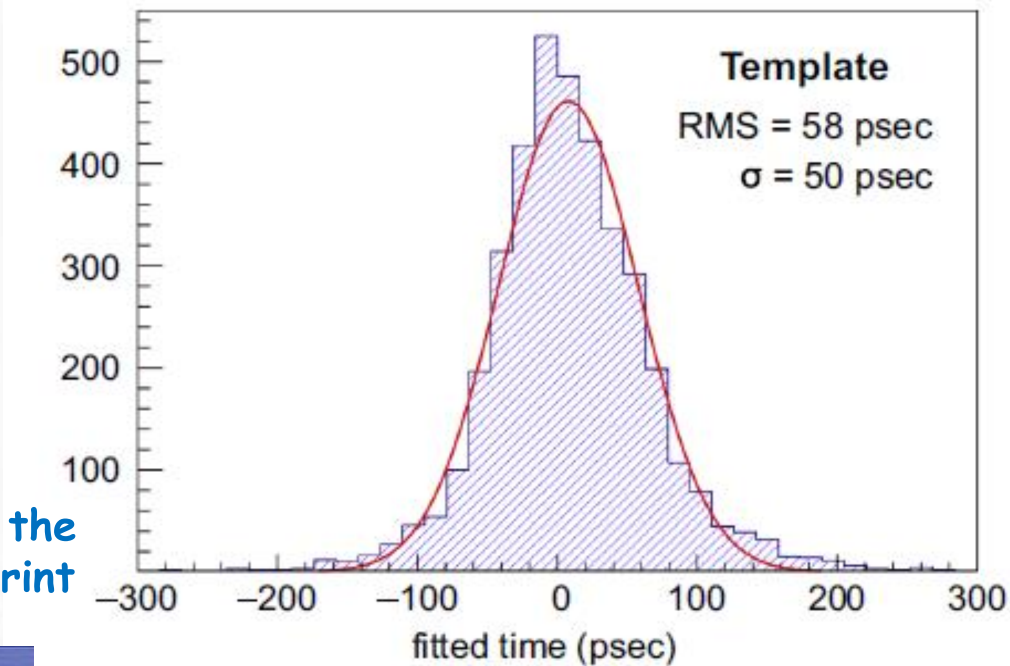


Central Card
(4-ACDC;120ch)

LAPPD Prototype Testing Results



Single PE resolution

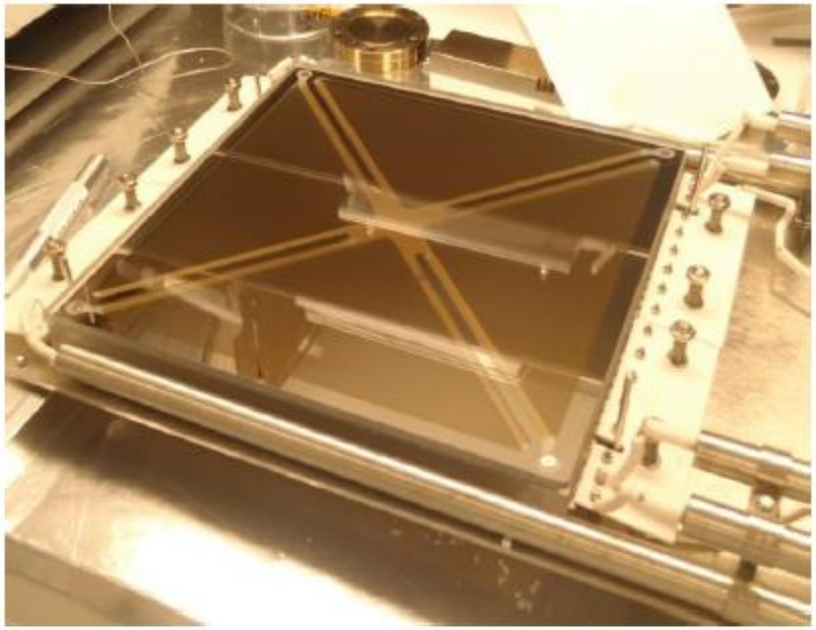


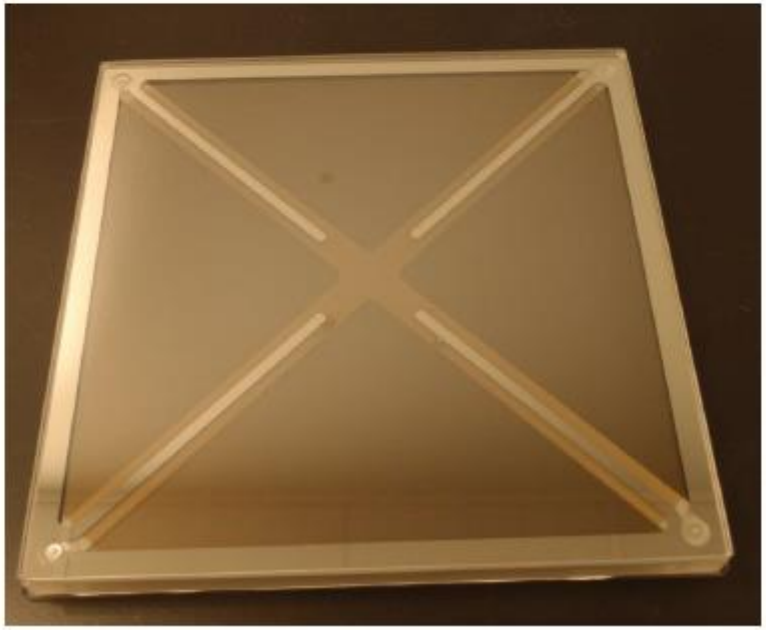
Demonstrated characteristics:
single PE timing ~50ps
multi PE timing ~35 ps
differential timing ~5 ps
position resolution < 1 mm
gain >10^7

RSI 84, 061301 (2013),
NIMA 732, (2013) 392
NIMA 795, (2015) 1
See arXiv:1603.01843 for a complete LAPPD bibliography

Commercialization Status at Incom Inc.

LAPPD #10 @STP





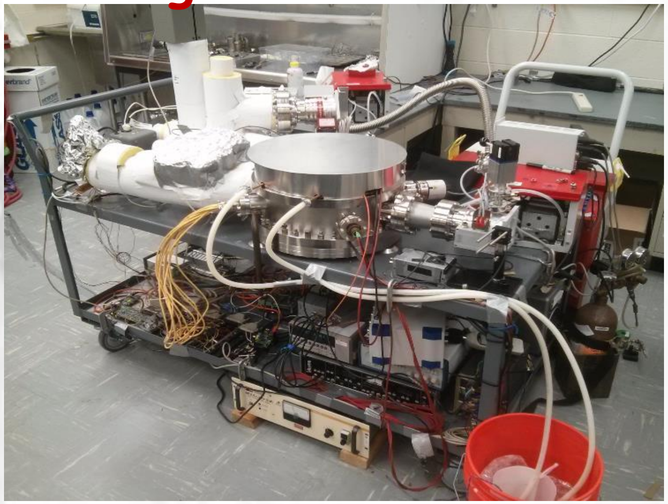
- LAPPD #10 Sealed, October 11, 2016
- No color change in PC upon venting UHV tank to STP
- Window deflection, characteristic of tile under vacuum.

See LAPPD plenary talk on Saturday for details

Slide courtesy of Incom Inc.

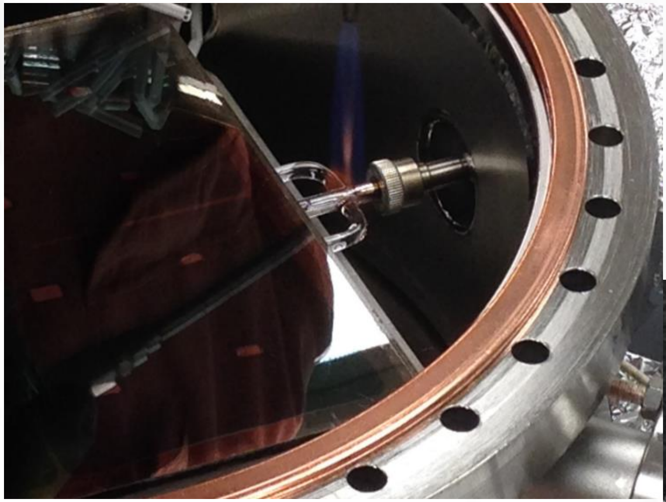
Development of a PMT-like Batch Production Process

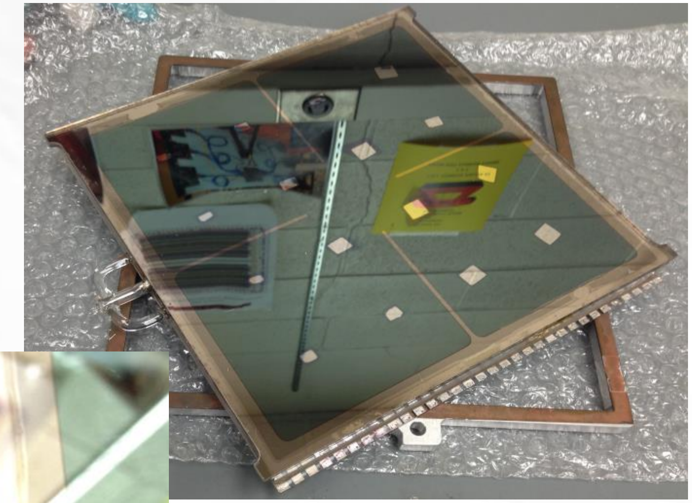
UChicago PSEC Lab



UChicago PSEC group is developing a non-vacuum transfer assembly process for high volume production of LAPPDs

The goal is tech transfer to industry

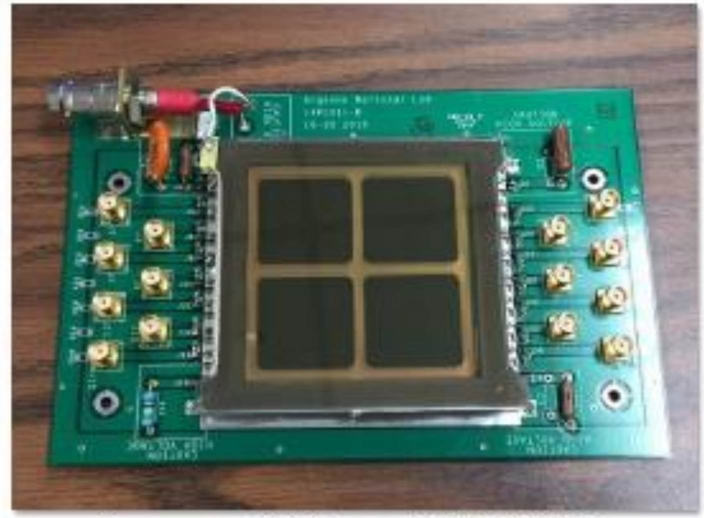




See LAPPD plenary talk on Saturday for details

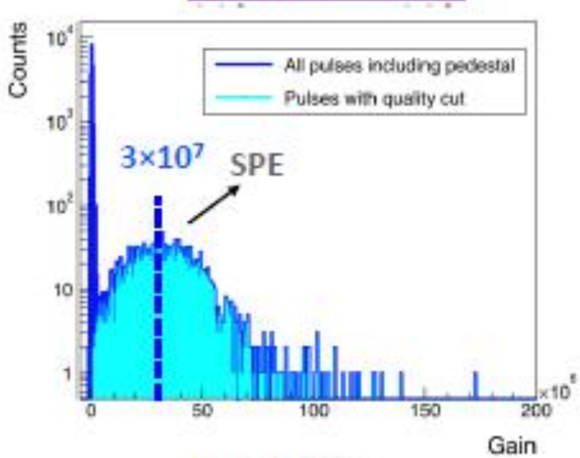
Argonne 6x6 cm^2 Photo-Detectors

- Argonne routinely producing 6X6 cm^2 functional detectors with K_2CsSb photocathode
- New IBD-1 design allows HV optimization, as biasing individual components possible
- In addition to assembly of photo-detectors, laser testing facility available and photocathode research ongoing.
- Performance:
  - Gain > 10^7
  - Quantum efficiency ~ 15%
  - Time resolution including the laser jitter: σ ~ 35 ps
  - Position resolution along anode strip: < 1 mm
  - Rate capability > 1 MHz/cm^2 for single photoelectrons



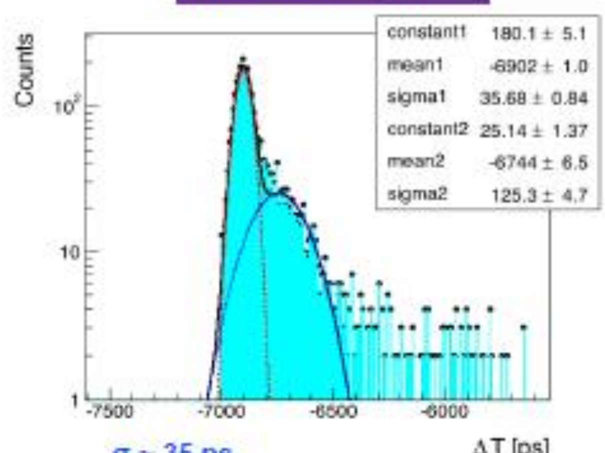
Argonne 6X6 cm MCP-PMT on custom readout board

Gain distribution



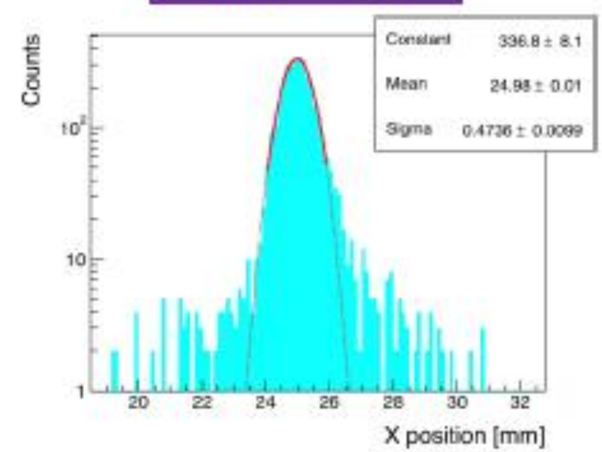
Gain > 10^7

Timing distribution

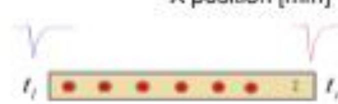


σ ~ 35 ps for SPE, including Laser jitter

Position resolution



σ < 1 mm for SPE



Slide courtesy of R. Darmapalan and R. Wagner

Early Adopters of LAPPD

Putting first LAPPD tiles into real experimental settings for testing is the highest priority

Some examples of early adopters:

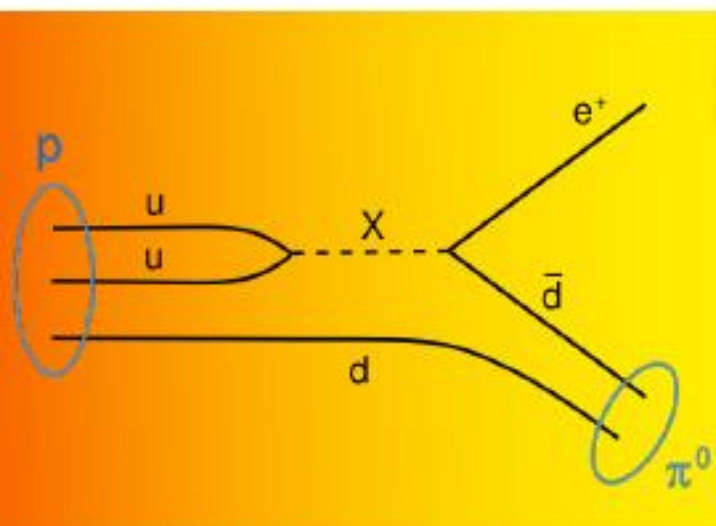
- ANNIE – Accelerator Neutrino Neutron Interactions Experiment
- Cherenkov/Scintillation light separation for particle ID
- Optical Time Projection Chamber
- TOF measurements at Fermilab Test Beam
- There are many more (lots of interest shown at the "Early Adopters Meeting" hosted by Incom Inc. in 2013)

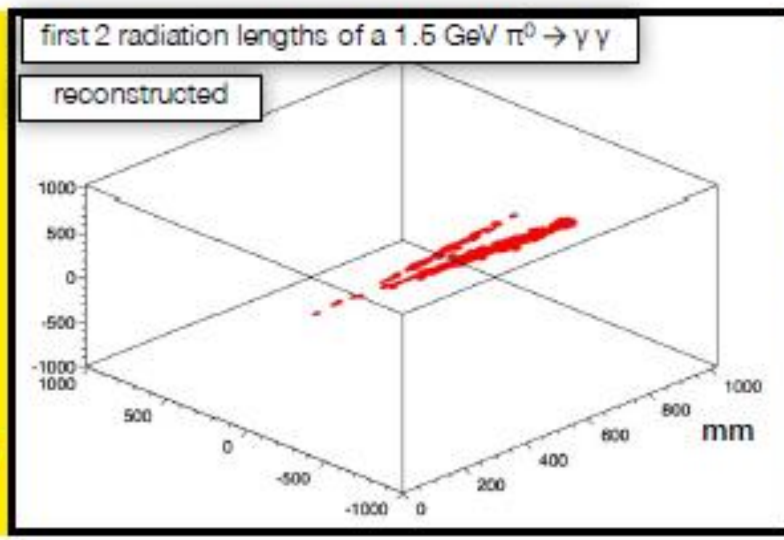
ANNIE

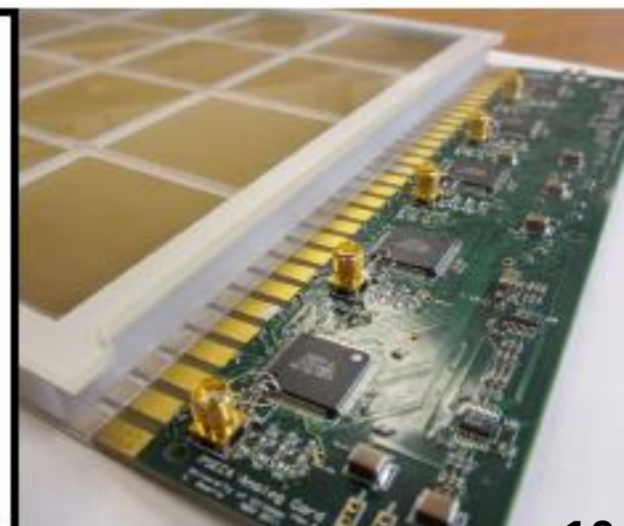
What is ANNIE?

The Accelerator Neutrino Neutron Interaction Experiment

- A measurement of the abundance of final state neutrons from neutrino interactions to aid in understanding neutrino-nucleus interactions.
- An R&D effort to further water-based neutrino detection technology.





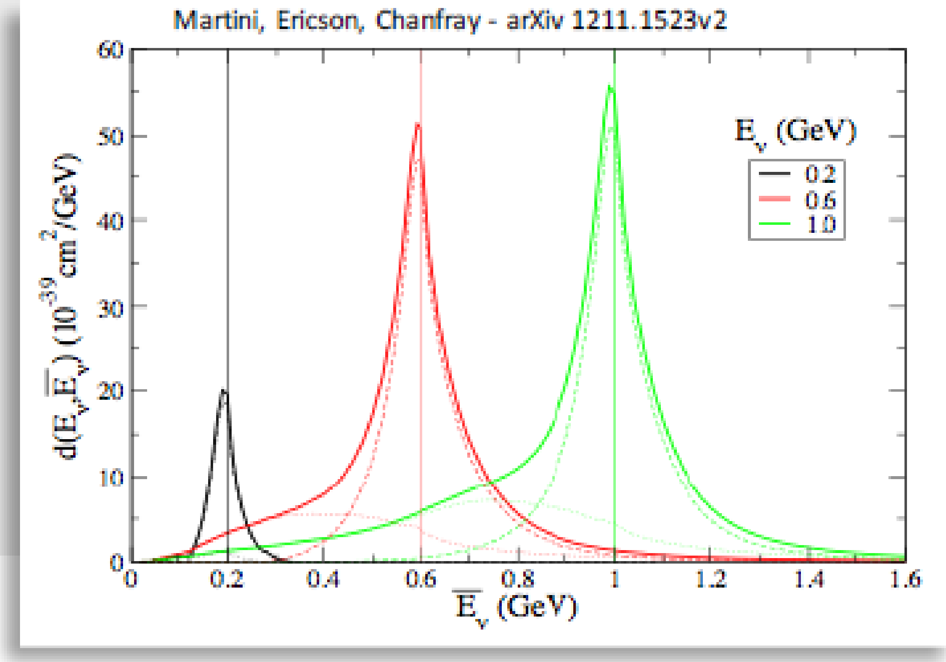


Slide courtesy of M.Wetstein

ANNIE Physics

To turn neutrino physics into a precision science we need to understand the complex multi-scale physics of neutrino-nucleus interactions.

- Dominant source of systematics on future long baseline oscillation physics
- Source of uncertainty and controversy in short baseline anomalies
- We need comprehensive and precise measurement for a variety of targets/E_ν



ANNIE is a final-state X + Nn program to complement X + Np measurements in LAr

The presence, multiplicity and absence of neutrons is a strong handle for signal-background separation in a number of physics analyses!

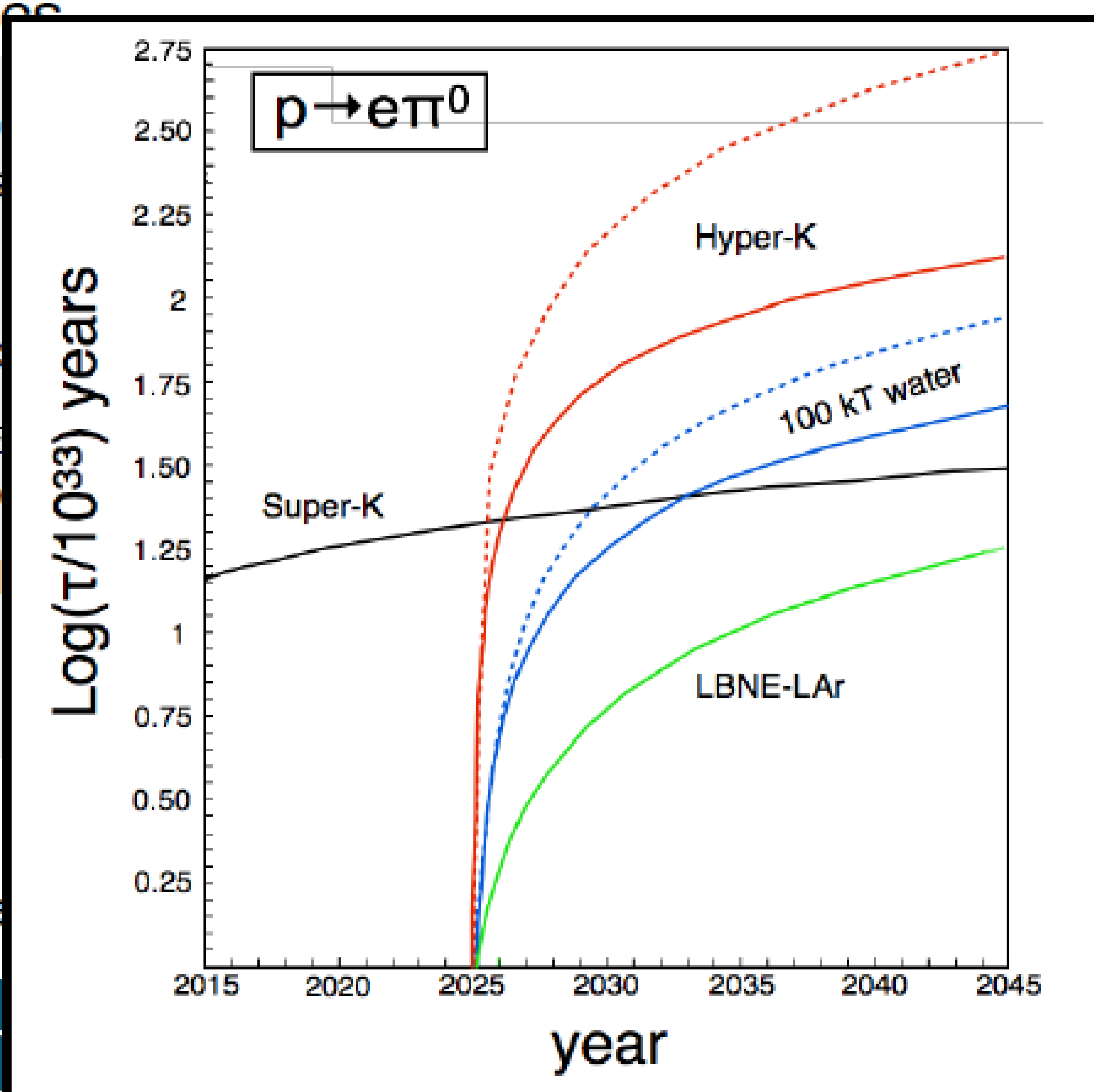
Slide courtesy of M.Wetstein

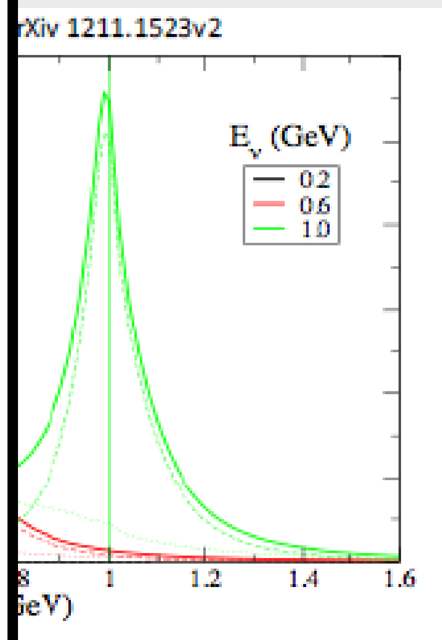
ANNIE

ANNIE Physic

To turn neutrino p ... he complex multi-scale physics

- Dominant source ... long baseline osc
- Source of uncerta ... short baseline an
- We need compre ... measurement for





ANNIE is a final-s ... urements in LAr

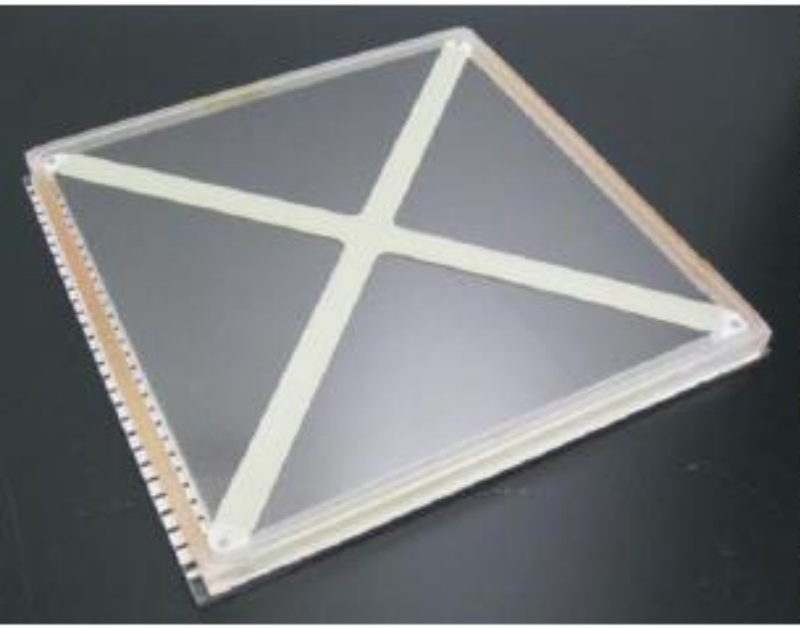
The presence, r ... dle for signal-background separation in a number of physics analyses!

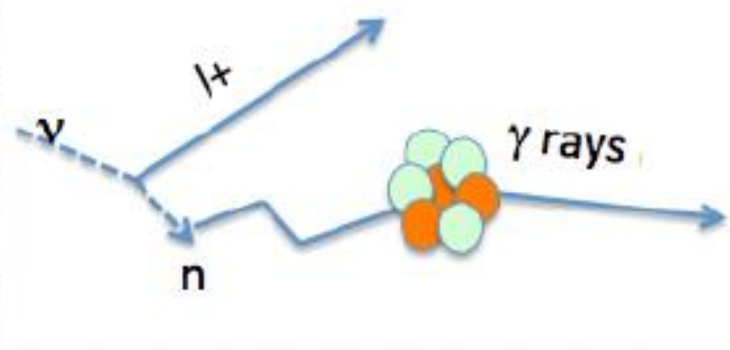
Slide courtesy of M.Wetstein

ANNIE and LAPPDs

ANNIE R&D

- Demonstration of LAPPDs in a neutrino experiment
- Application of fast, waveform sampling (PSEC) electronics
- First use of Gd on a neutrino beam

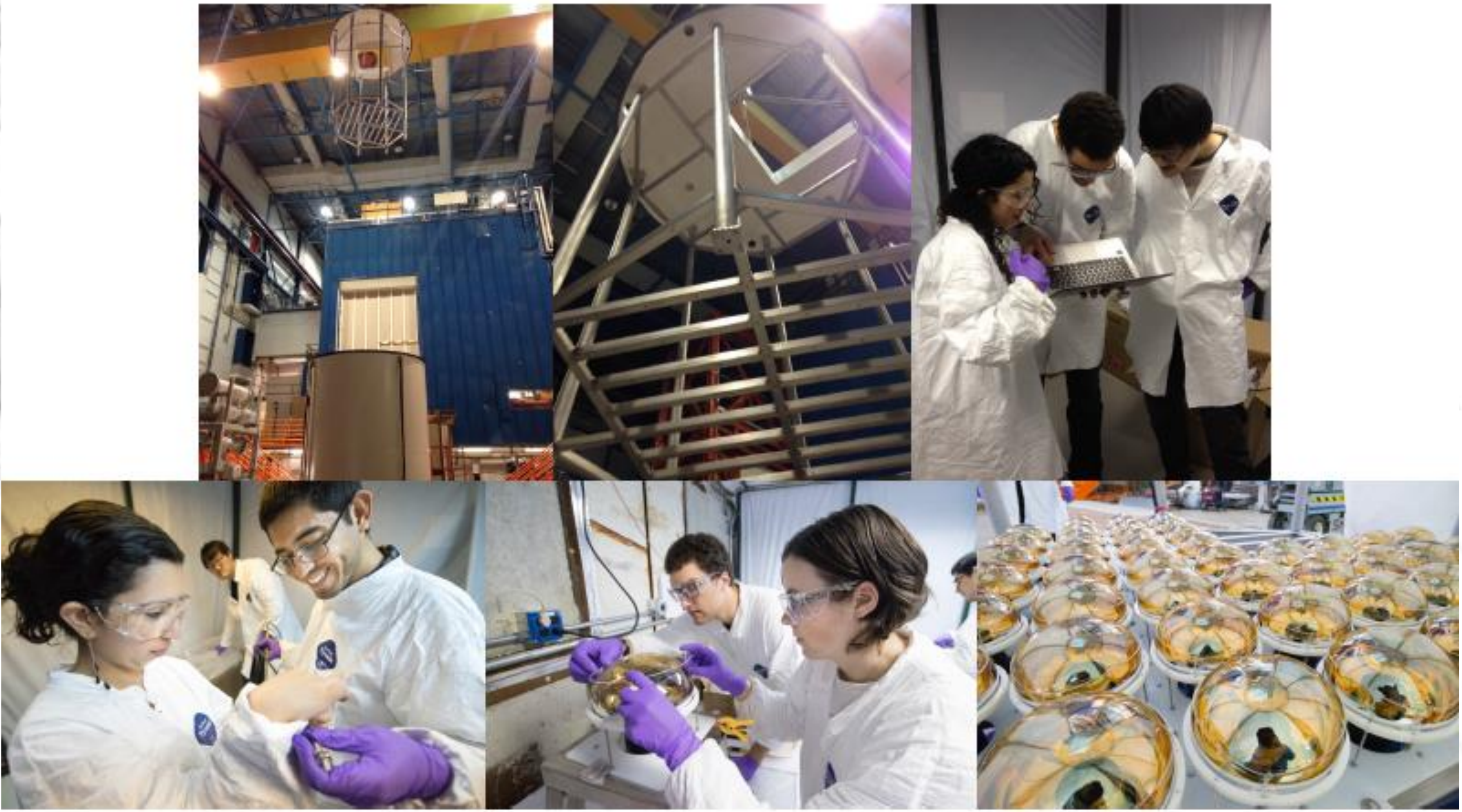




- A test bed for other novel photosensors
- Possible later addition of water-based liquid scintillator

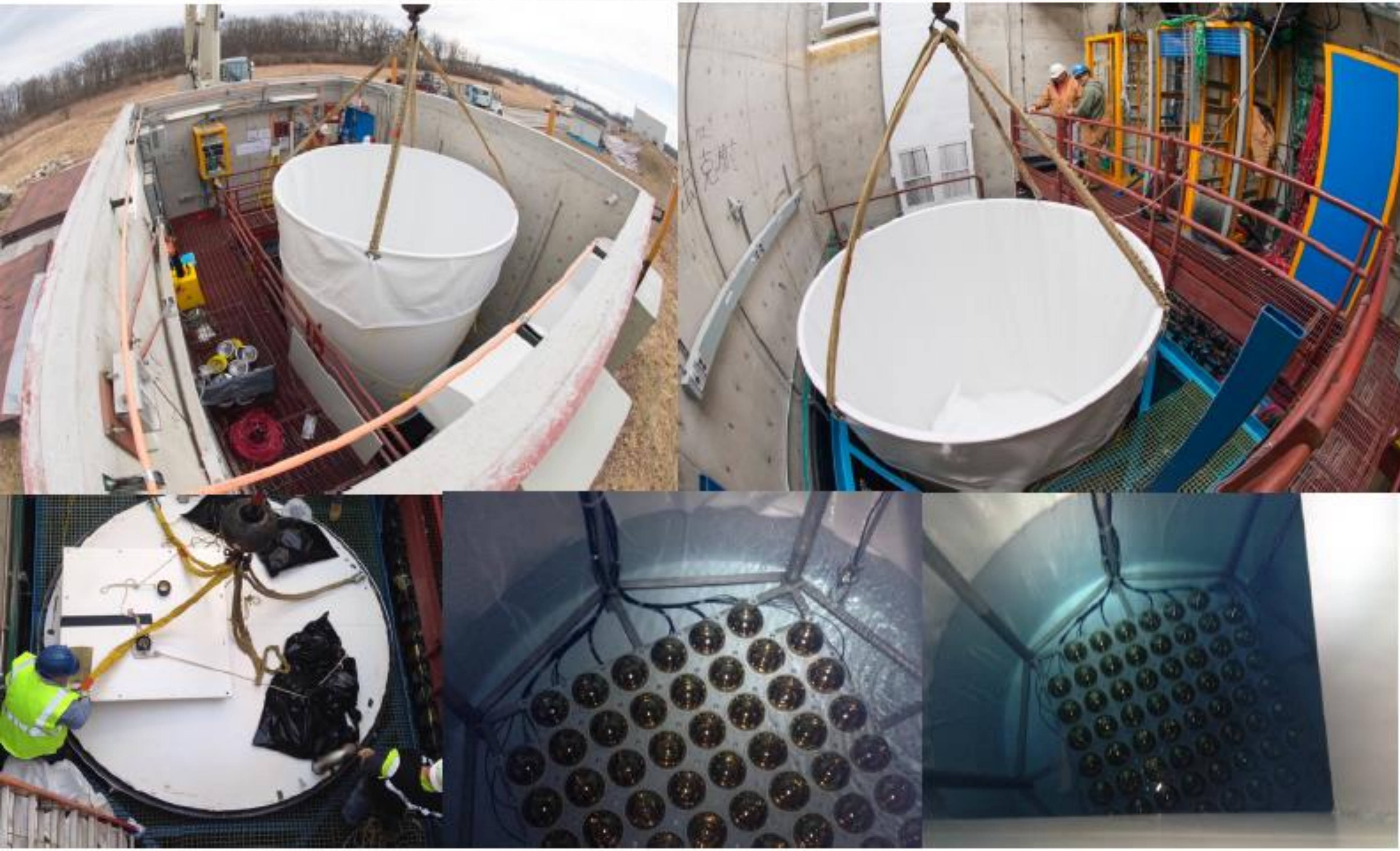
ANNIE Phase I Was Executed

ANNIE Phase I: A neutron background measurement using conventional 8” PMTs



Slide courtesy of M.Wetstein

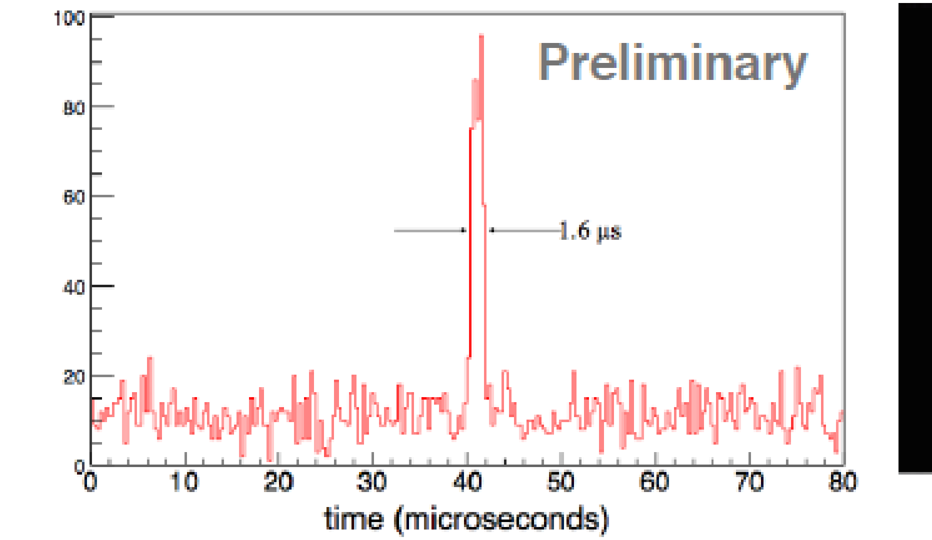
ANNIE Phase I Was Executed

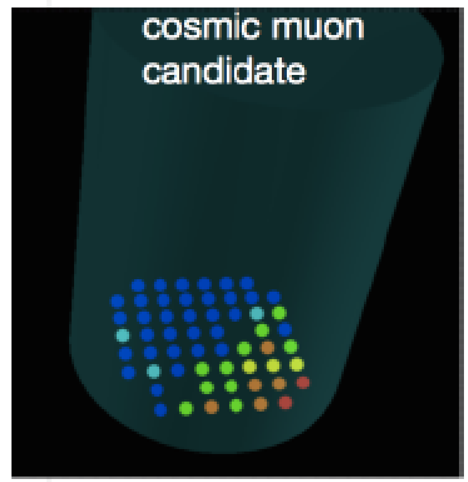


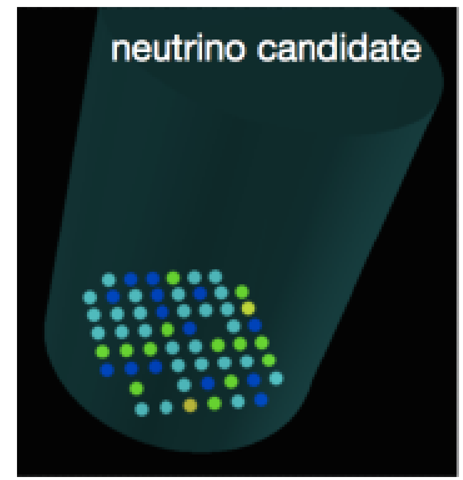
Slide courtesy of M.Wetstein

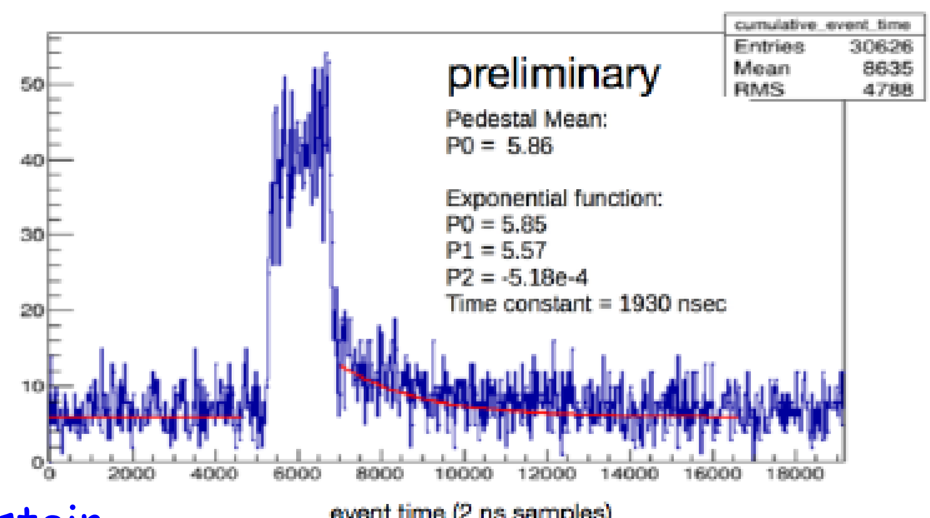
ANNIE Phase I

The Phase I Data Looks Good - Results Coming Soon





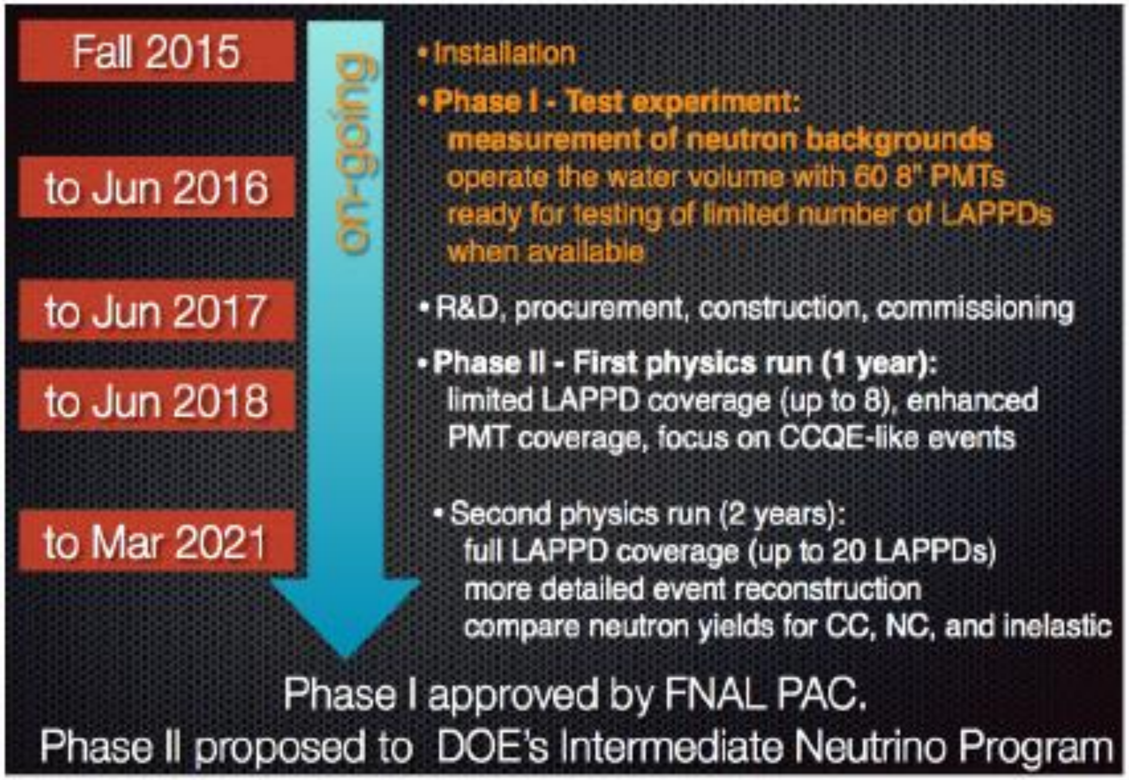




Slide courtesy of M.Wetstein

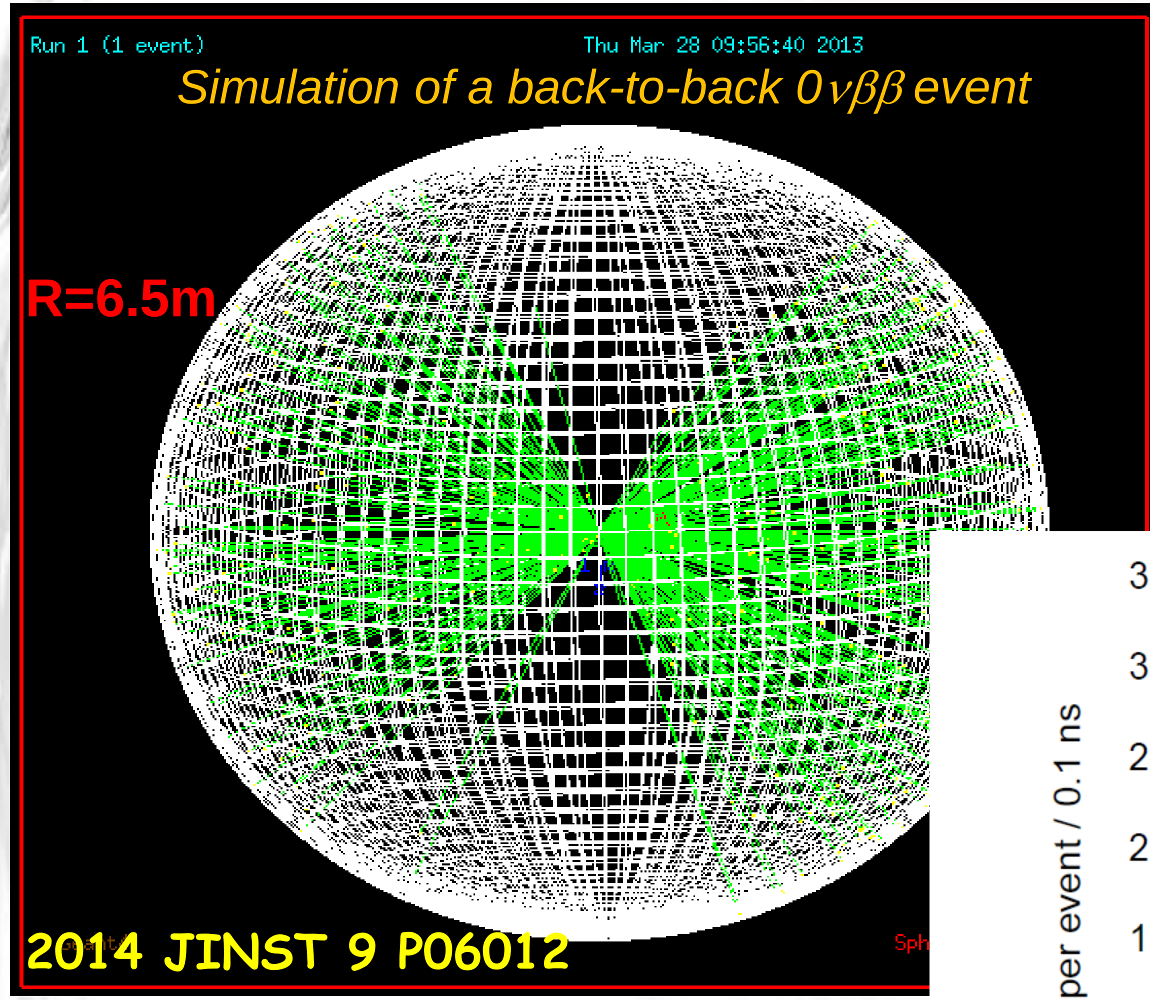
ANNIE Status and Plans

- The ANNIE Phase I is still collecting good data
- The DOE Approved 1 year of R&D/prep for ANNIE Phase II
  - Through the Intermediate Neutrino Program
  - We've termed this year "Phase IB"
  - Phase IB has been granted FNAL PAC approval
  - If we succeed, we will still be on schedule for Phase II
- This winter, with an LAPPD in hand we will submit our full Phase II proposal to FNAL and the DOE



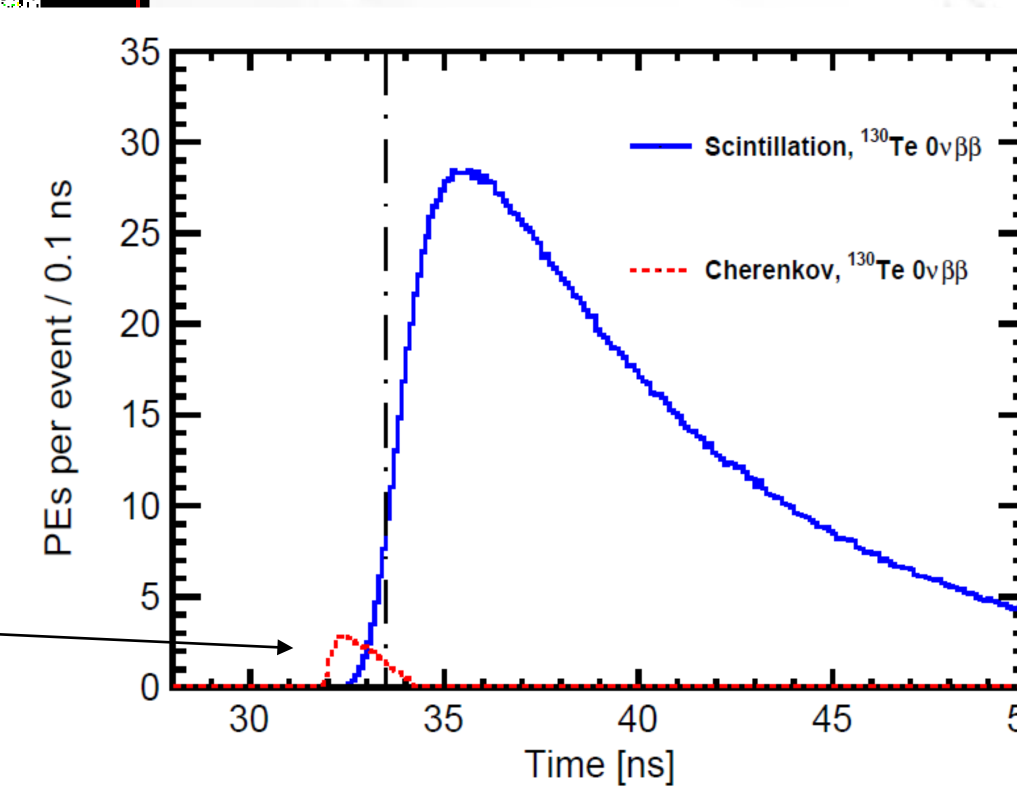
Can We See Event Topology in a LS Detector?

It's important for separating $0\nu\beta\beta$-decays from ^{8}B in a large scintillator detector



- Scintillation emission is slower
- Cherenkov spectrum from a ~1 MeV electron in liquid scintillator is redder
- Longer (red) wavelengths travel faster

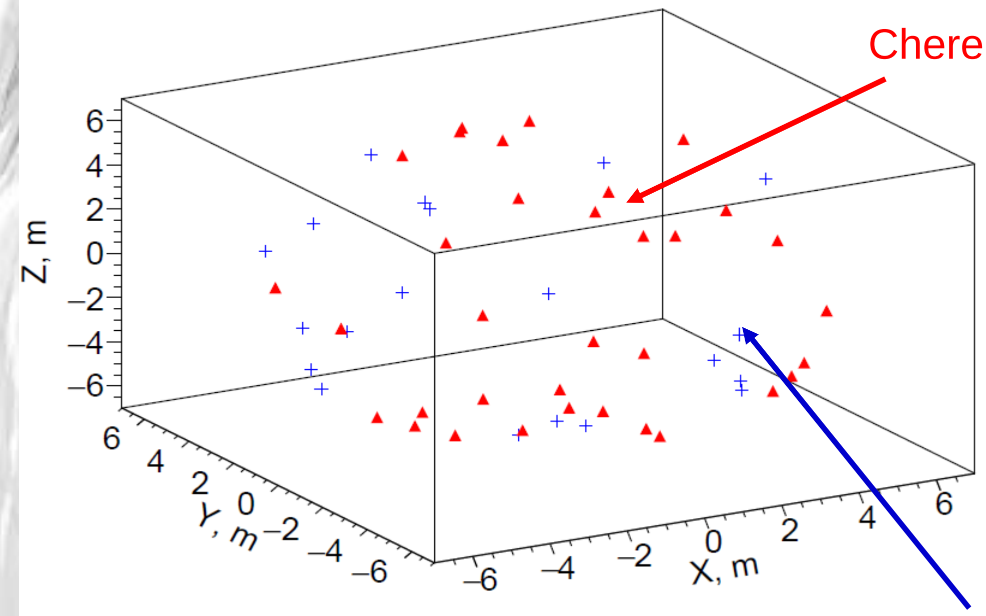
PE arrival times, TTS=100 ps



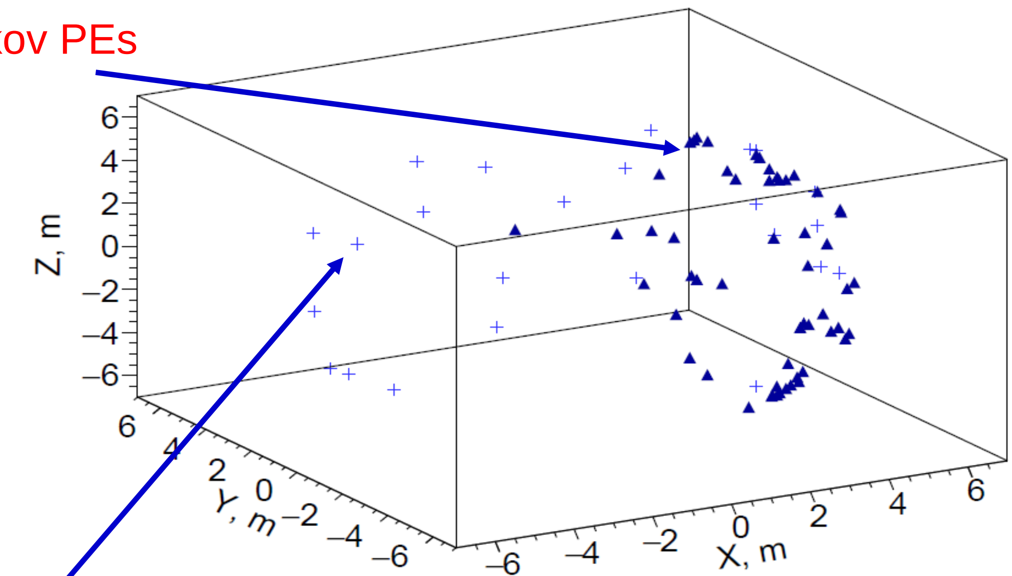
- Cherenkov light arrives earlier
- Need good timing to see the effect

Event Topology Using Early Light

Early PE: 0νββ-decay



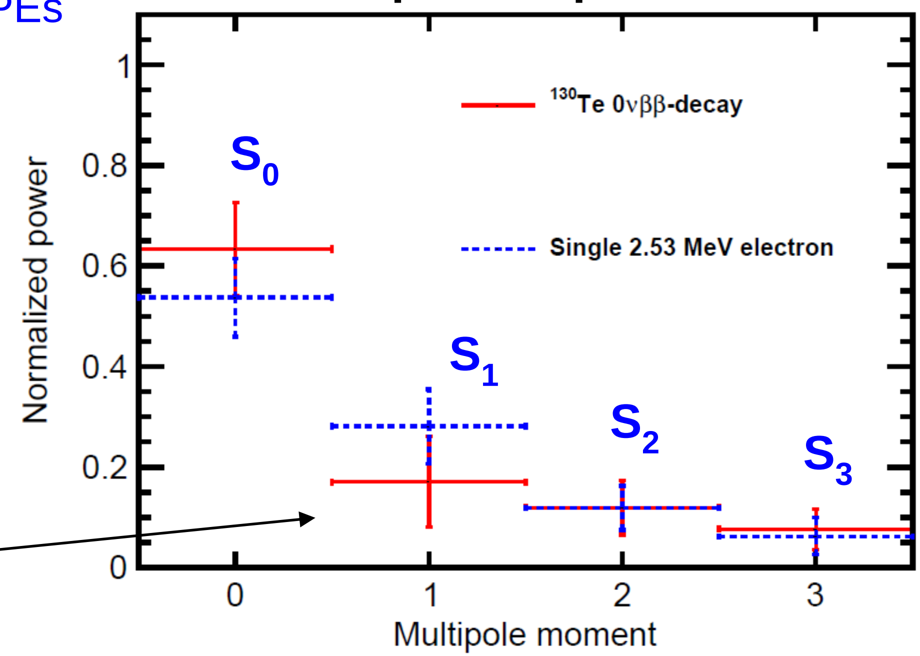
Early PE: ^{8}B event



Cherenkov PEs

Scintillation PEs

S power spectrum



Spherical harmonics analysis

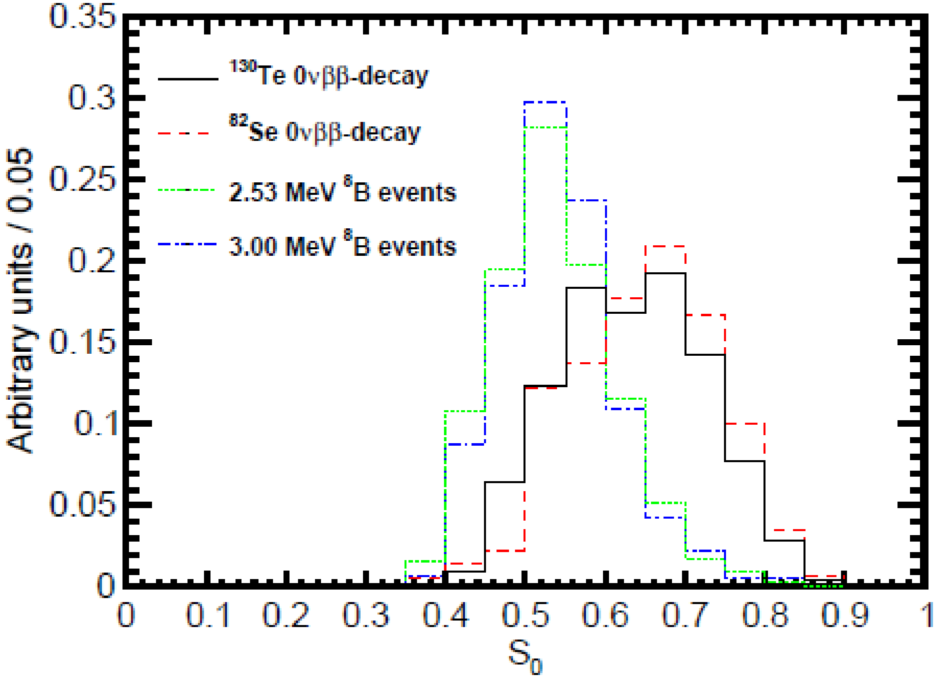
$$f(\theta,\varphi)=\sum_{\ell=0}^{\infty}\sum_{m=-\ell}^{\ell} f_{\ell m} Y_{\ell m}(\theta,\varphi).$$

Rotation invariant power spectrum

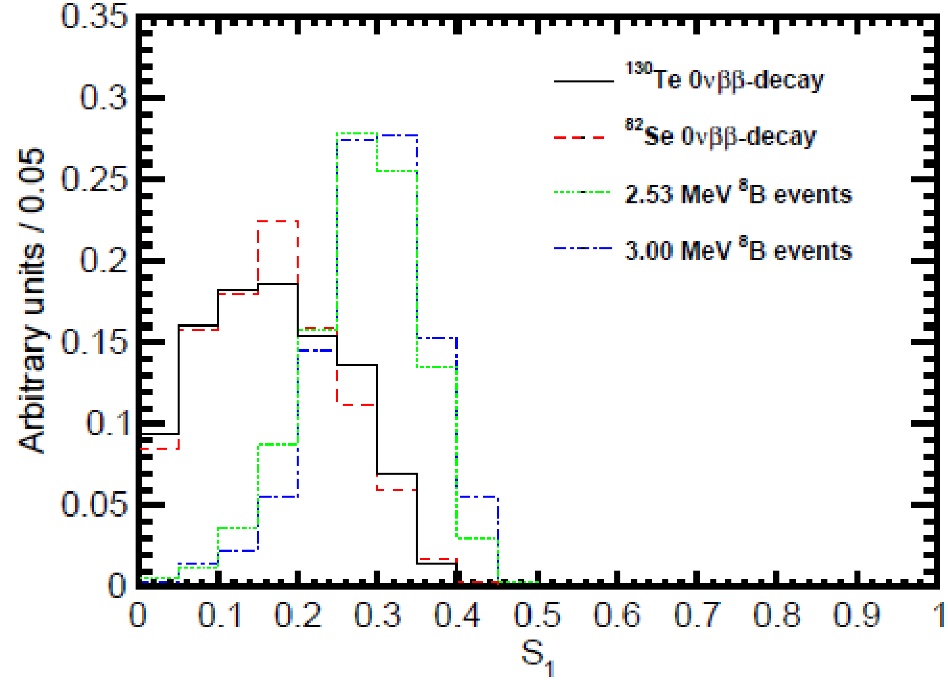
$$S_{ff}(\ell)=\sum_{m=-\ell}^{\ell}|f_{\ell m}|^2$$

$0\nu\beta\beta$ vs ^{8}B

Multipole moment l=0



Multipole moment l=1



Simulation details:

- 6.5m radius detector, KamLAND scintillator model
- TTS=100 ps, 100% area coverage, QE(che) ~12, QE(sci) ~23%

Key parameters determining separation of $0\nu\beta\beta$-decay from ^{8}B:

- Scintillator properties (narrow spectrum, slow rise time)
- Photo-detector properties (fast, large-area, high QE)
- Measuring photon color and timing with high precision would be even better…

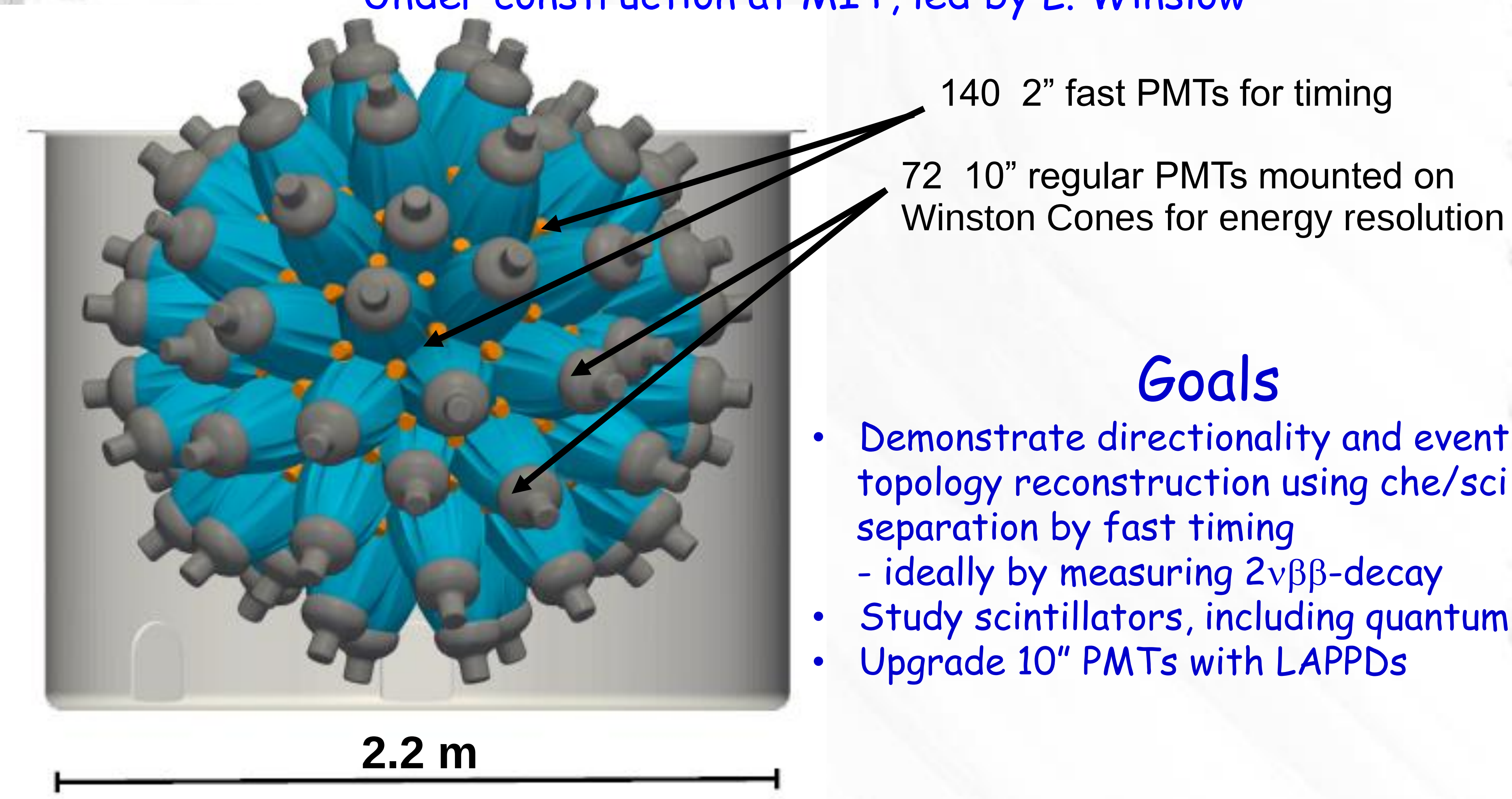
For details see arXiv:1609.09865
(submitted to NIM)

NuDot - Directional Liquid Scintillator

Following up on the ideas discussed in JINST 7 P07010 and JINST 9 06012

R&D Towards Large Scale Detector for $0\nu\beta\beta$-decay

Under construction at MIT, led by L. Winslow

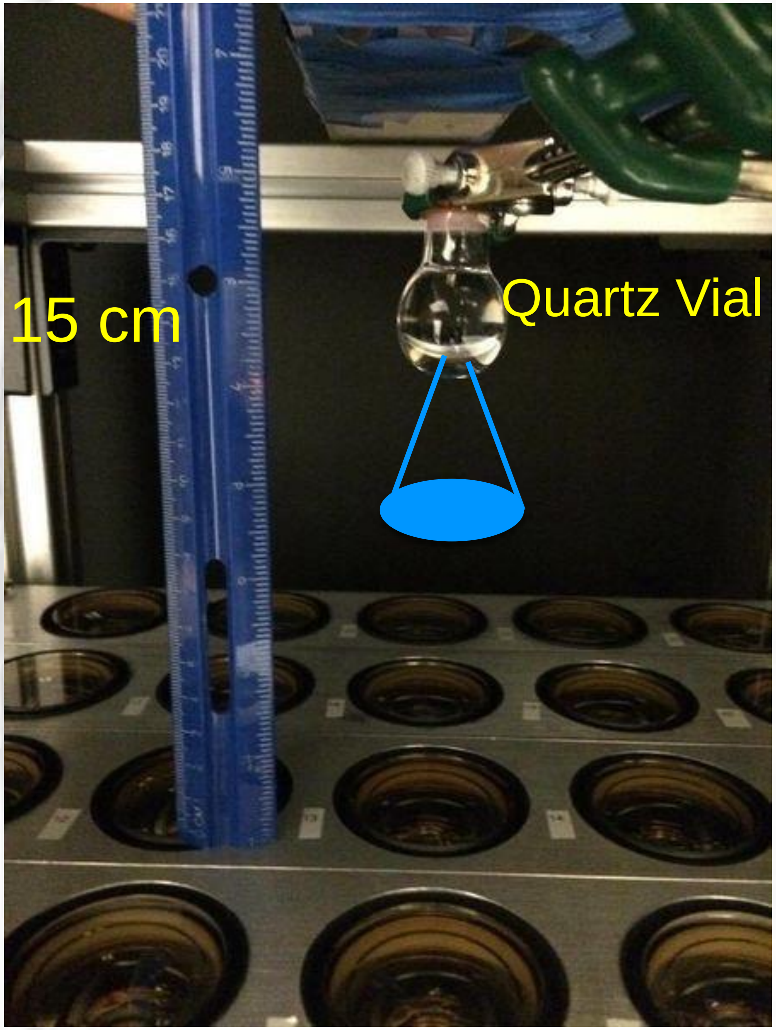


Goals

- Demonstrate directionality and event topology reconstruction using che/sci separation by fast timing
  - ideally by measuring $2\nu\beta\beta$-decay
- Study scintillators, including quantum dots
- Upgrade 10" PMTs with LAPPDs

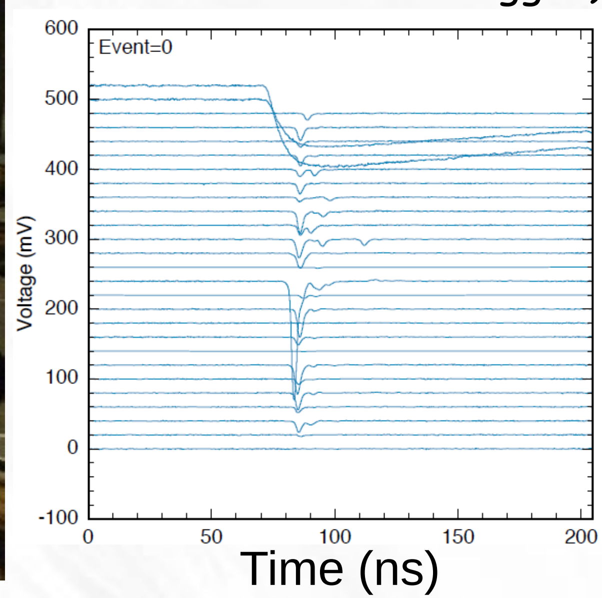
FlatDot Demonstration

2" PMTs with TTS=300ps

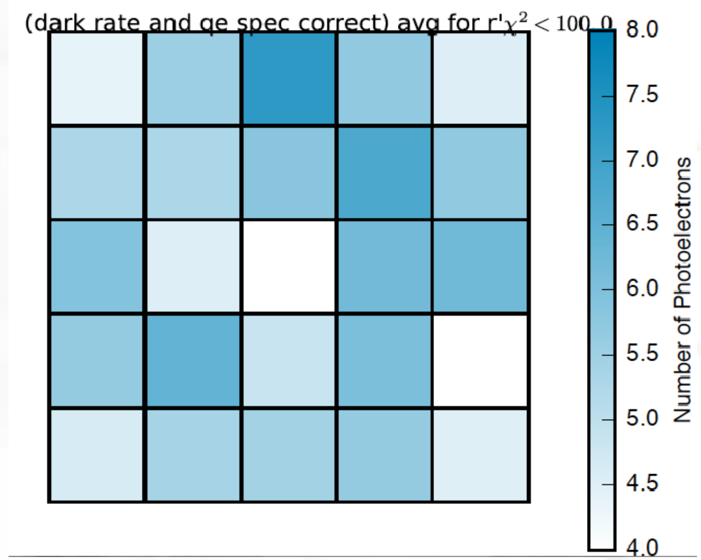


- Intermediate step towards 1m^3 spherical NuDot
  - e.g. detection of Cherenkov "rings" from low energy electrons using a tagged Compton source
- Testing different scintillator cocktails
- Readout testing

Raw pulses (the top two channels are the trigger)



Event display after corrections



Note: there is an independent effort on Che/Sci light separation - the CHESS experiment at Berkeley by G. Orebi Gann et al., aXiv:1610.02011 and 1610.02029

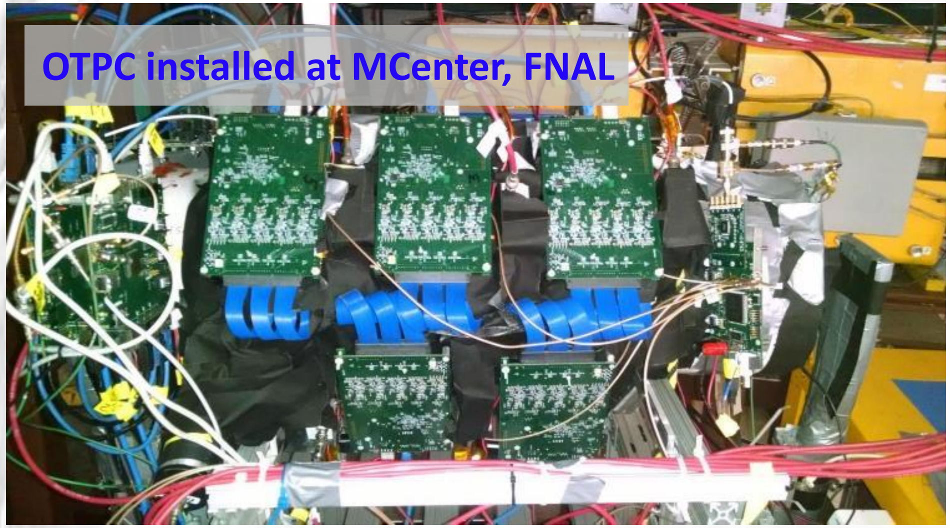
See talk by M.Yeh (given by R.Svoboda)

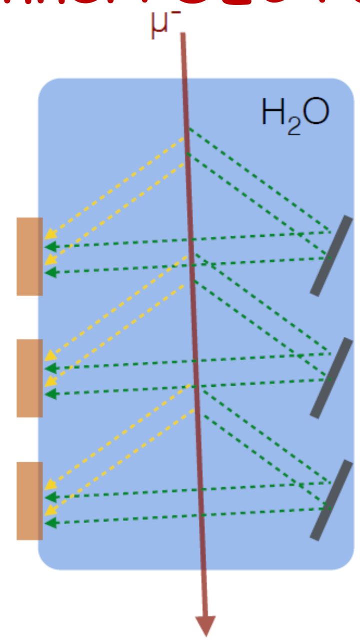
OTPC Demonstration

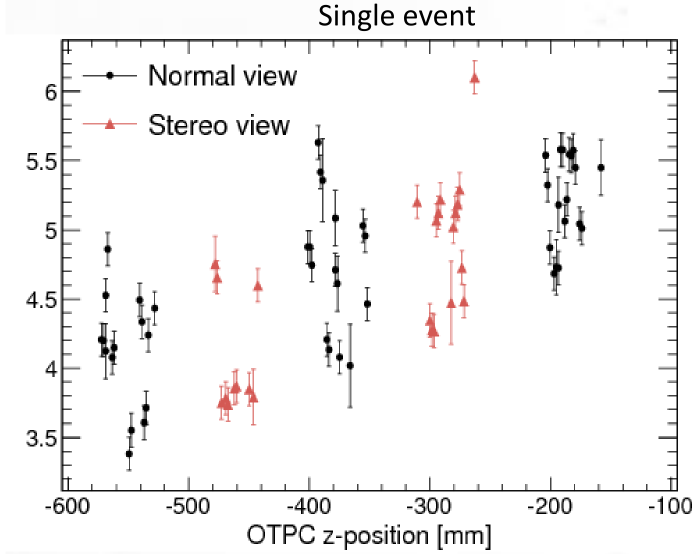
Eric Oberla

NIM 814 (2016) 19

180-channel PSEC4 system

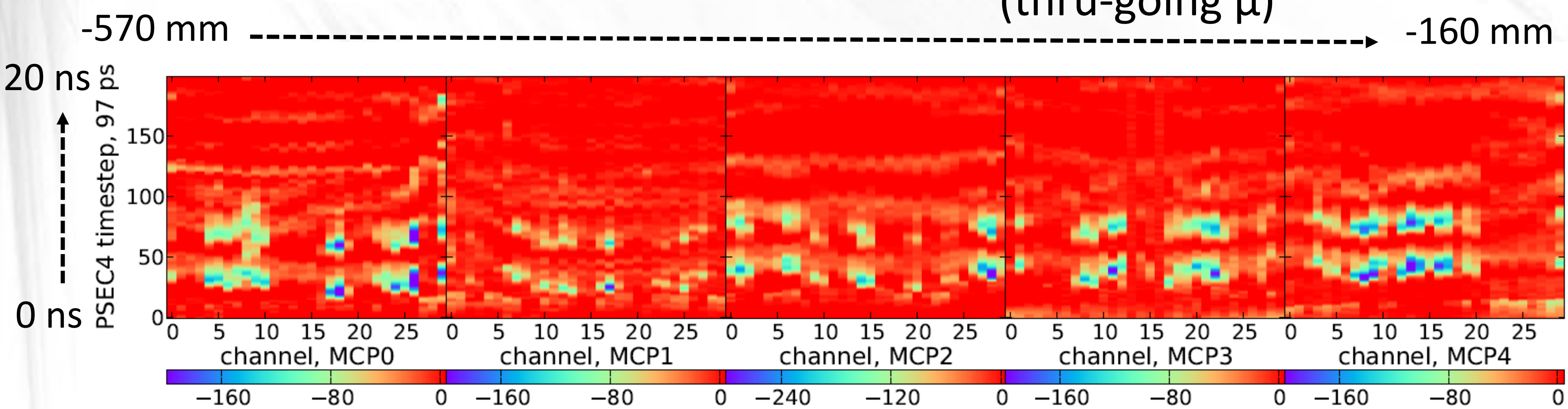






Example event

Typical event (thru-going μ)

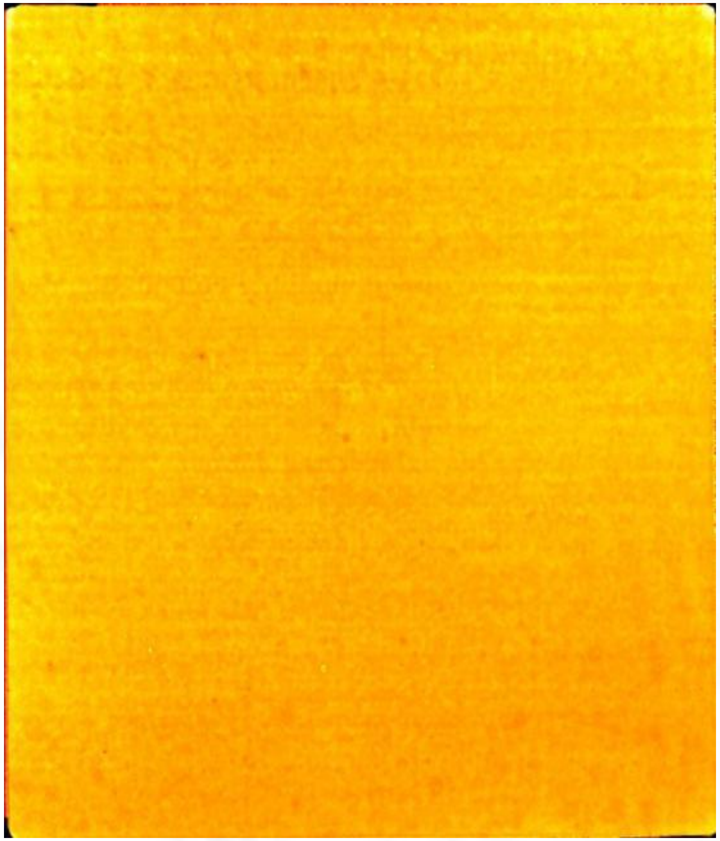


Summary

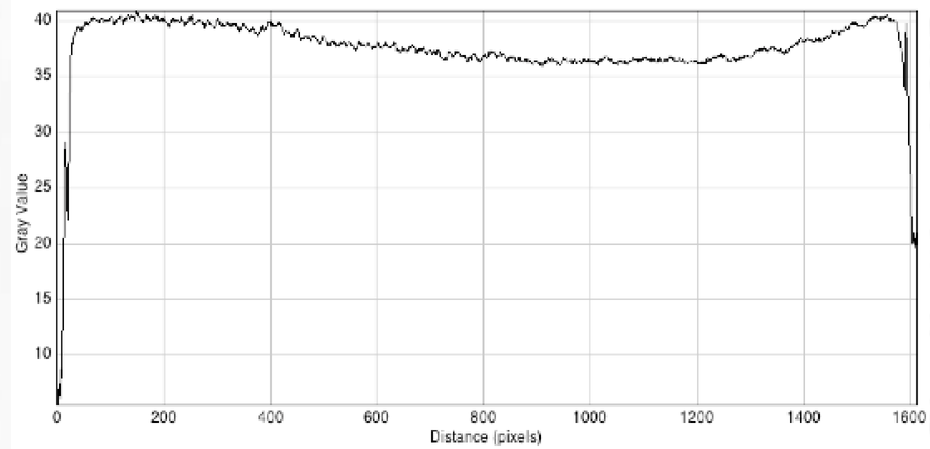
- Commercialization of LAPPD™ is ongoing
- Many interesting applications to test first LAPPD tiles
  - ANNIE collaboration is finishing Phase I and getting ready to use LAPPDs in Phase II
  - Cherenkov/Scintillation light separation is a hot topic (potentially very interesting for $0\nu\beta\beta$-decay search using a large scintillator-based detector)
  - Optical Tracking using LAPPDs is very attractive

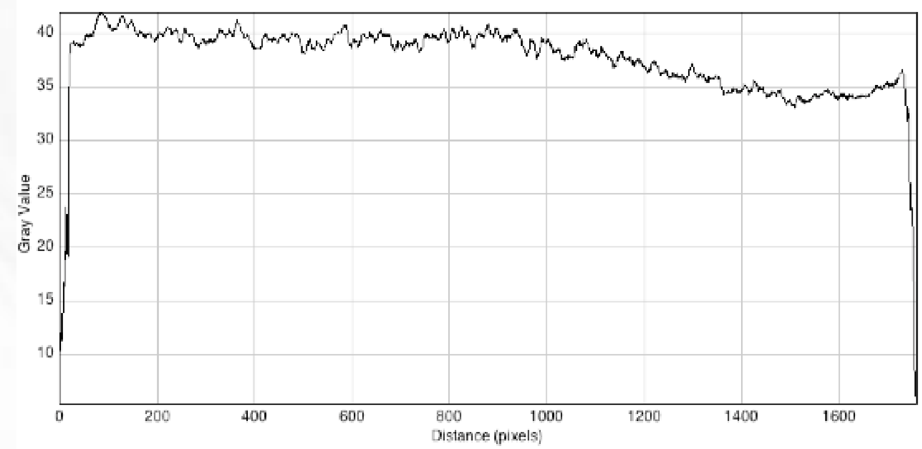
Back-Up

Gain Uniformity



Gain map image for a pair of 20 µm pore, 60:1 L/D, ALD borosilicate MCPs, 950 V per MCP, 184 nm UV



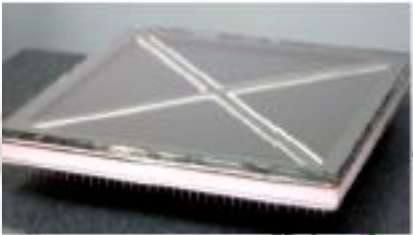


Gain is uniform within ~15% across full 20 x 20 cm^2 area

O.H.W. Siegmund, N. Richner, G. Gunjala, J.B. McPhate, A.S. Tremsin, H.J. Frisch, J. Elam, A. Mane, R. Wagner, C.A. Craven, M.J. Minot, “Performance Characteristics of Atomic Layer Functionalized Microchannel Plates” Proc. SPIE 8859-34, in press (2013).

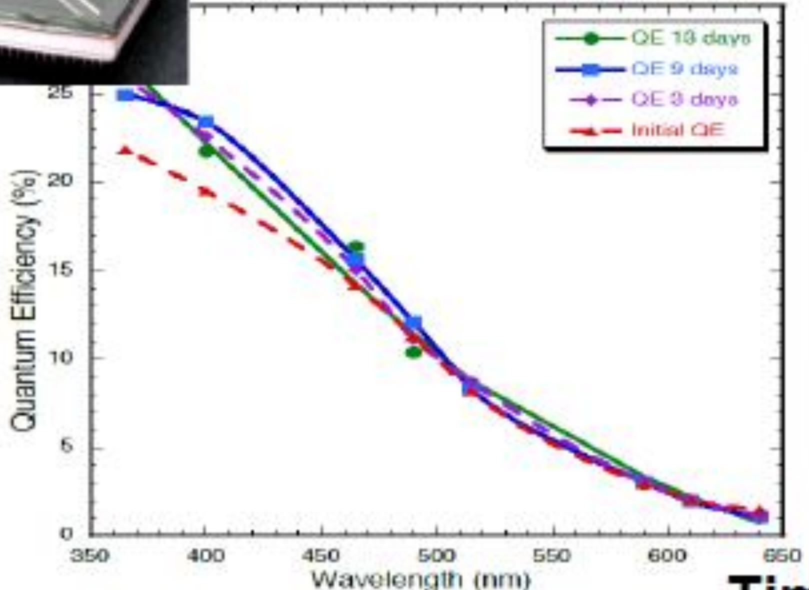
Noise <0.1 counts cm^{-2} s^{-1}

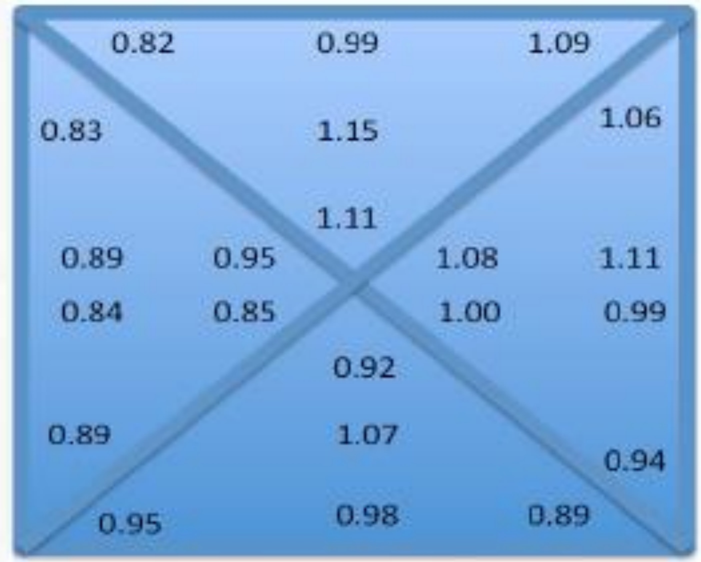
SSL Ceramic LAPPD Tile Results



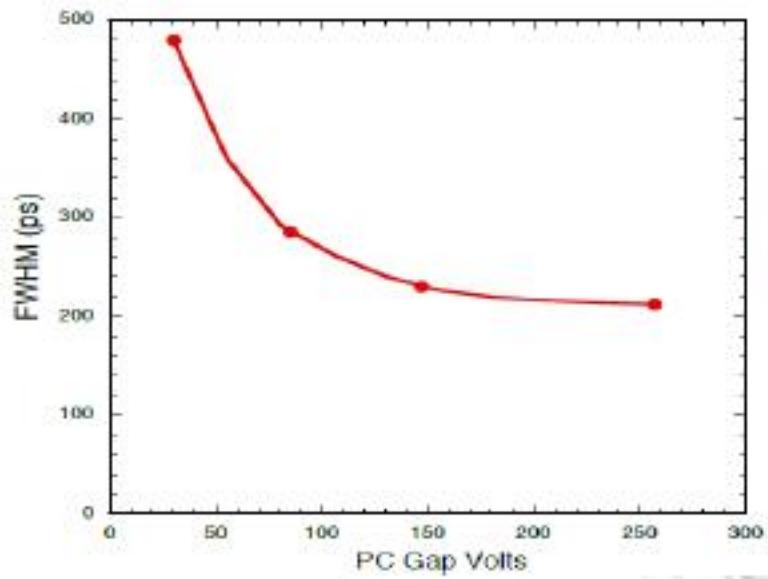
Measurements after full processing cycle inside the vacuum chamber

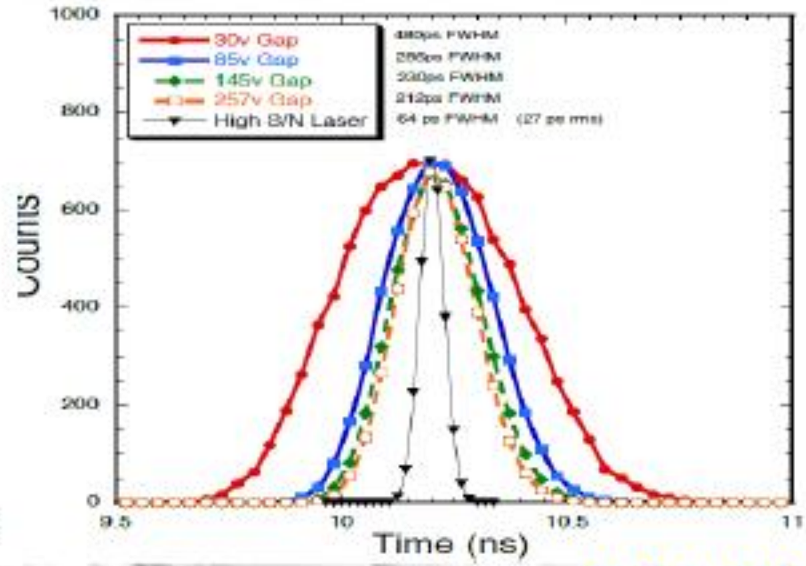
QE





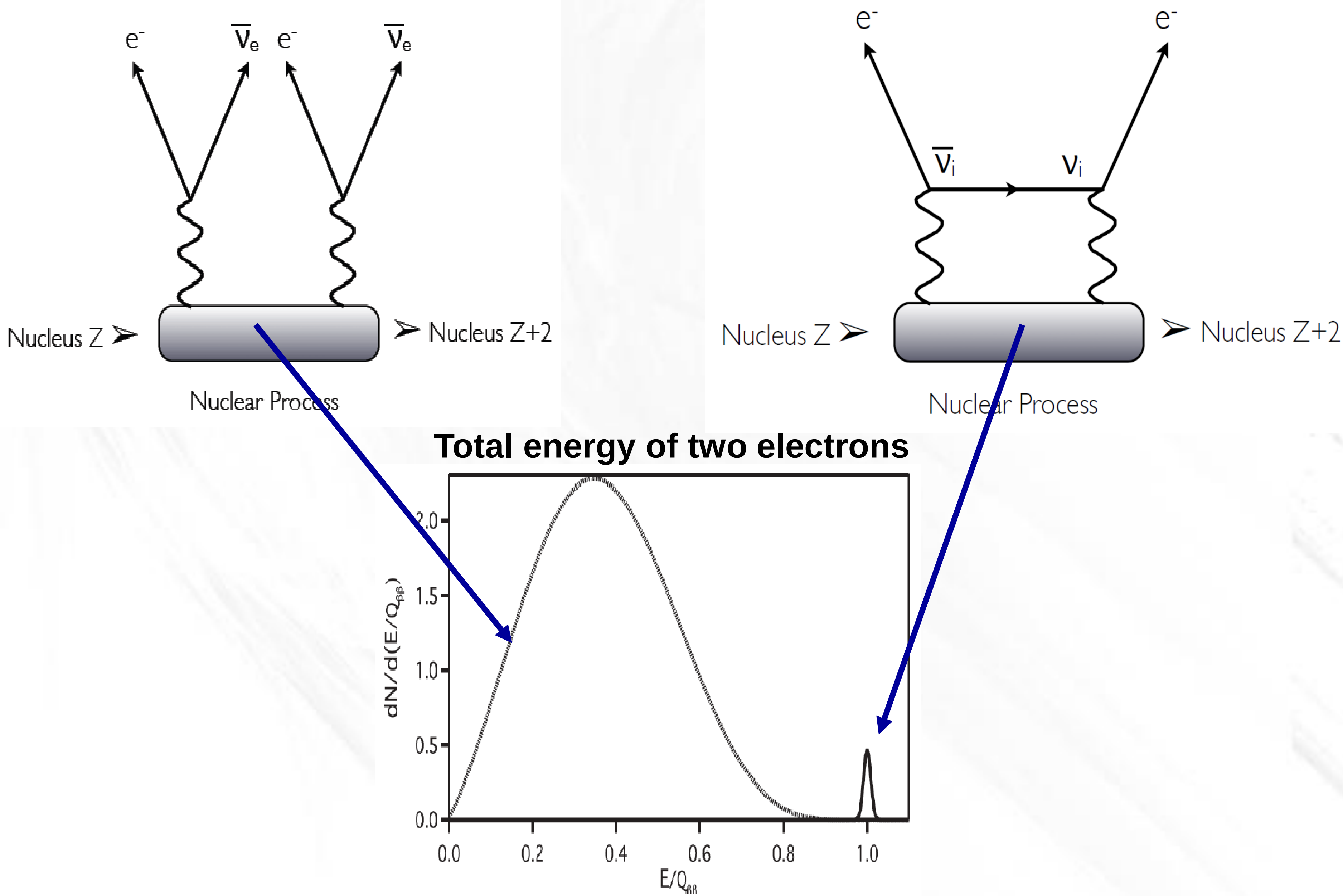
Timing





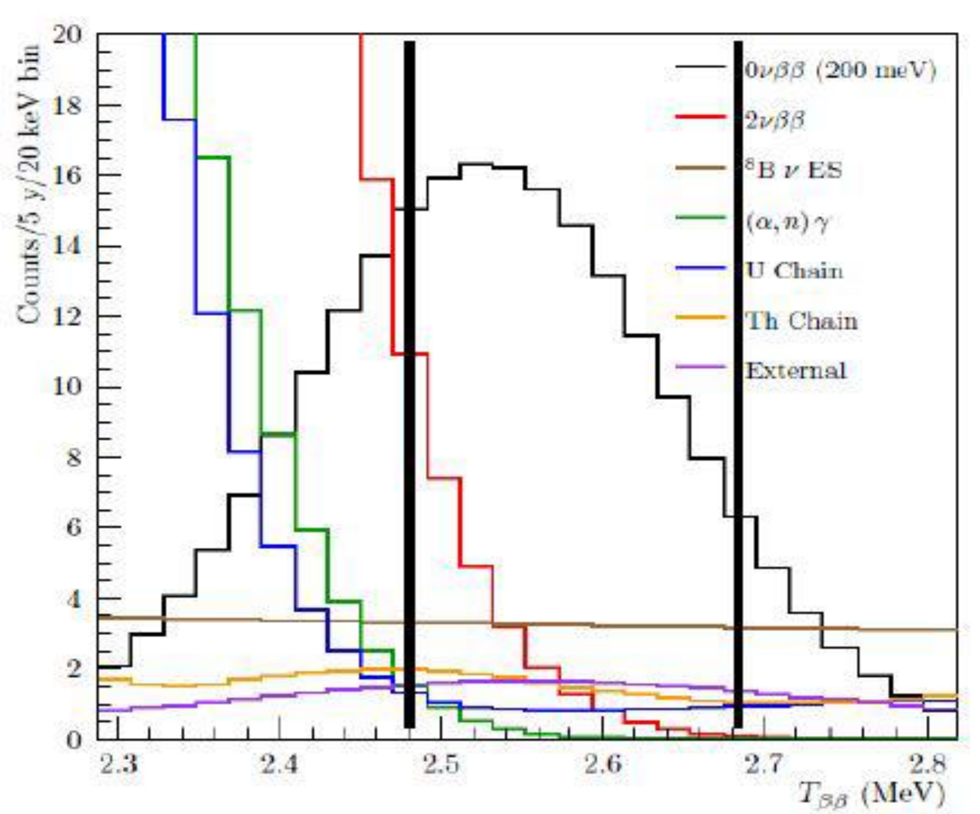
2014 JINST 9 C04002

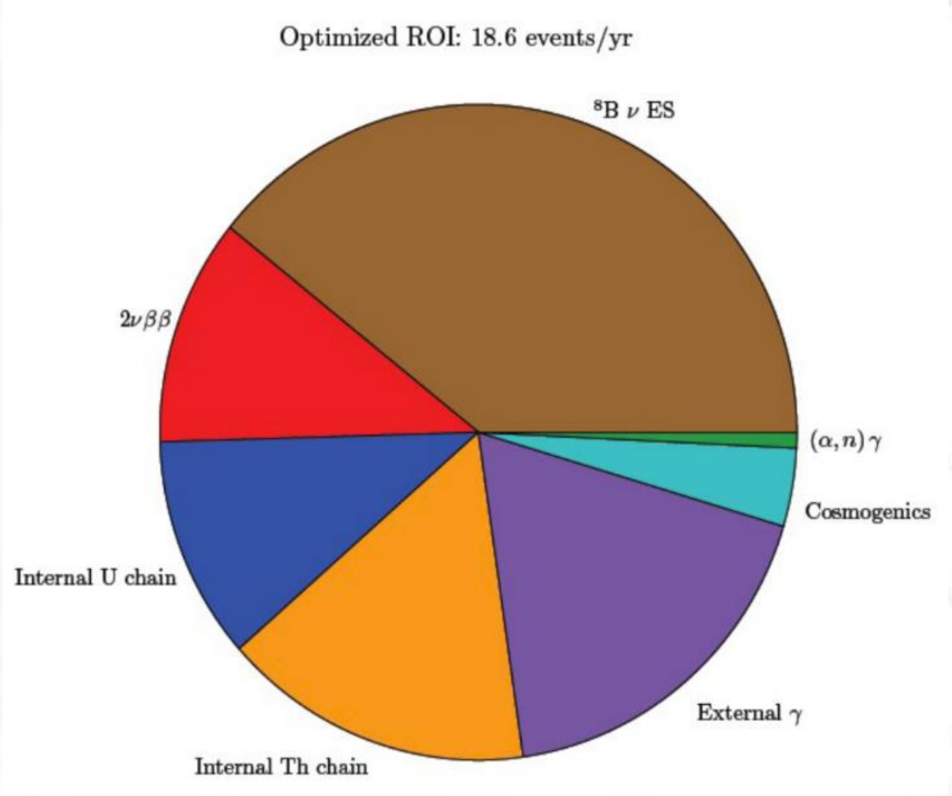
Double Beta Decay



Search for neutrino-less double beta decay (0νββ-decay) is the most feasible way to determine if the neutrino is its own antiparticle

Background Budget at SNO+



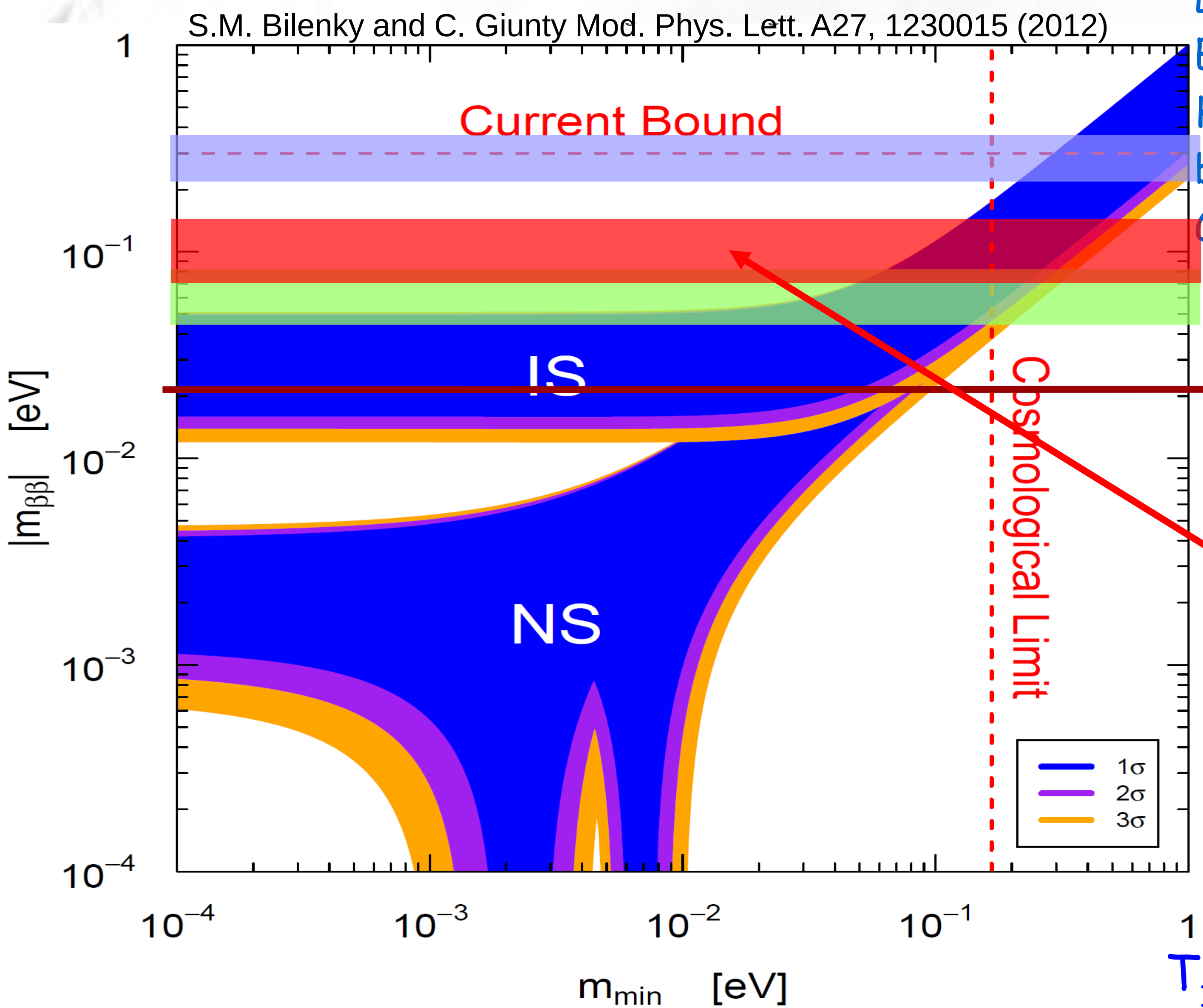


The largest background is coming from ^{8}B solar neutrinos
It has only 1 electron, while νββ-decay has 2 electrons

Is it possible to separate two-track and one-track events using Cherenkov light in a liquid scintillator detector?

Figures are borrowed from SNO+ presentations

Experimental Sensitivity



Limits by
EXO (~200kg ^{136}Xe)
KamLAND-Zen (~300 kg ^{136}Xe, before this Summer)
GERDA (~20 kg ^{76}Ge)

Projections by
CUORE (~200kg ^{130}Te)
SNO+ (0.8 ton ^{130}Te)

SNO+ (8 ton ^{130}Te)

Current best limit is set by KamLAND-Zen:
$T_{1/2} > 1.07 \times 10^{26}$ years
$m_{\beta\beta} < 61\text{-}165$ meV

$$T_{1/2}^{-1} = G^{0\nu} \times |M^{0\nu}|^2 \times m_{\beta\beta}^2$$

Getting down to $m_{\beta\beta}$~1 meV is very difficult

Why search for 0nbb-decay is difficult?

- Need very large mass
  - could be a few events per year even in a kilo-ton scale detector

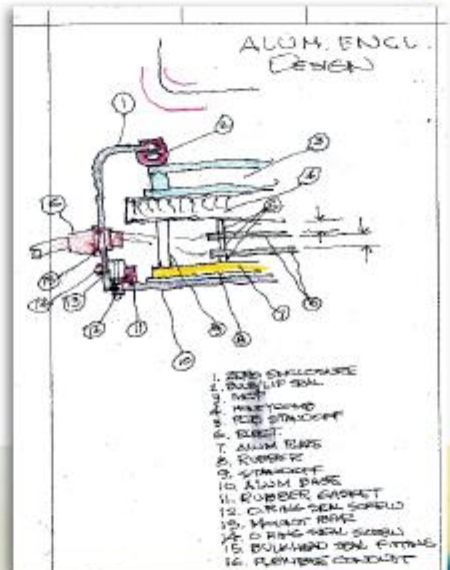
- Need "zero" background
  - high purity
  - good energy resolution
  - good particle ID and event topology reconstruction at ~1 MeV

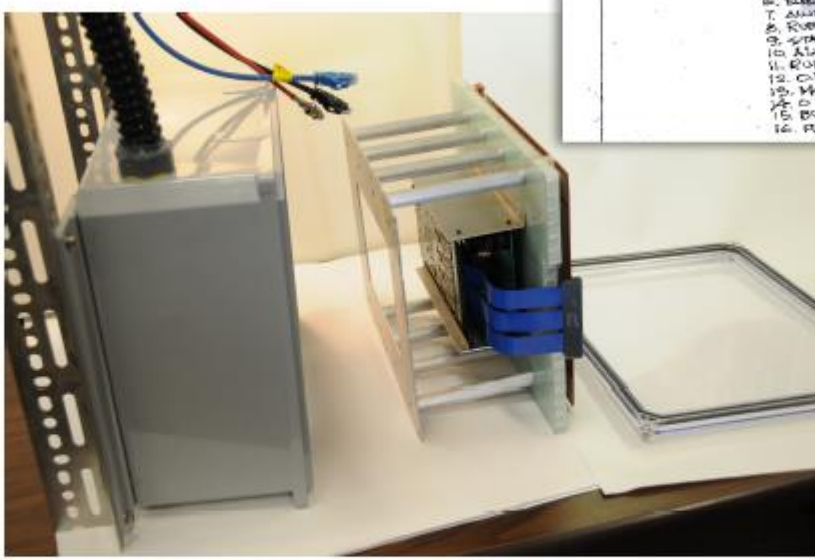
- Liquid scintillator detectors scale well to very large masses
  - purification and self-shielding may allow for "zero" reducible background
  - high light yield and collection efficiency may allow for low $2\nu\beta\beta$ background
  - ^{8}B solar neutrino becomes dominant background
    - nearly flat energy spectrum around Q-value
    - this is irreducible background without event topology reconstruction

Phase IB Goals

- Install LAPPD (PSEC4) electronics, integrated with full DAQ.
- Submerge 4-6 ANL 6cm tiles and test them in water.
- Demonstrate track reconstruction capabilities with the fast photosensor system.
- Borrow and characterize an LAPPD at the ISU test bench.
- Possibly test a small concentration of Gd in the main water volume.

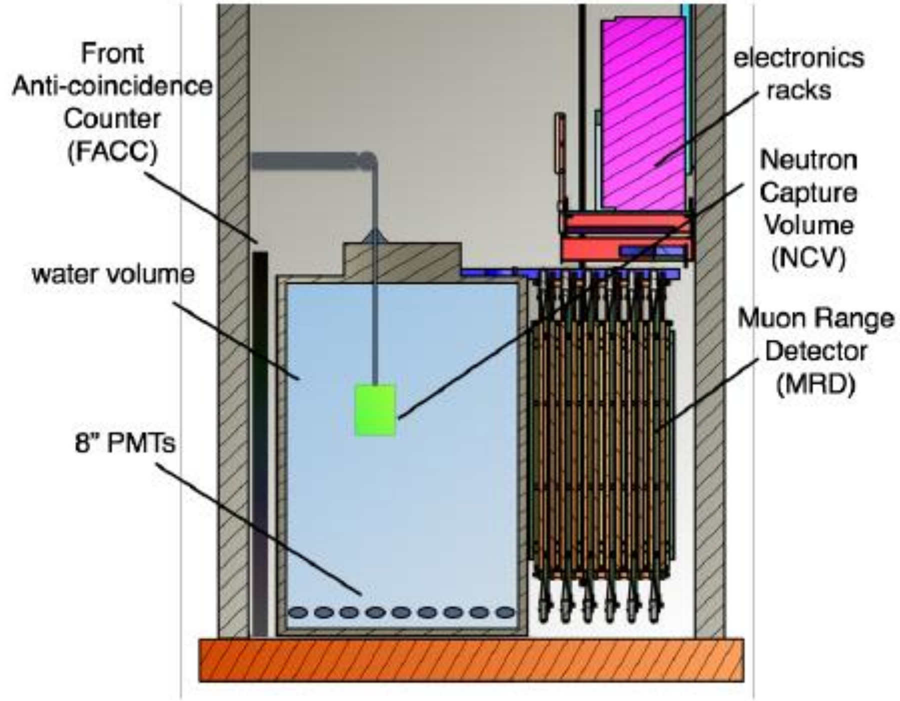
Water-proof housing





Evolution of the detector

Phase I



Evolution of the detector

Phase II