Towards Revealing the Unique Nature of Neutrino Mass Using Precision Detection of Photons

Andrey Elagin
University of Chicago

Fermilab Wine & Cheese Seminar, August 21, 2020

~~Outline~~

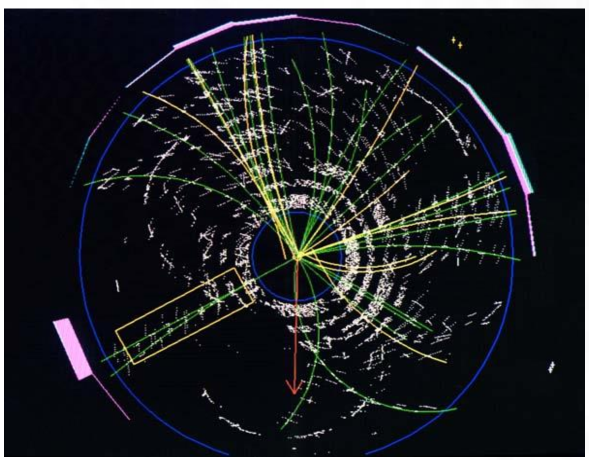
Purpose of This Talk

Discuss the importance of fast timing and suggest the next steps in the development of affordable Large-Area Picosecond Photodetectors (LAPPD)

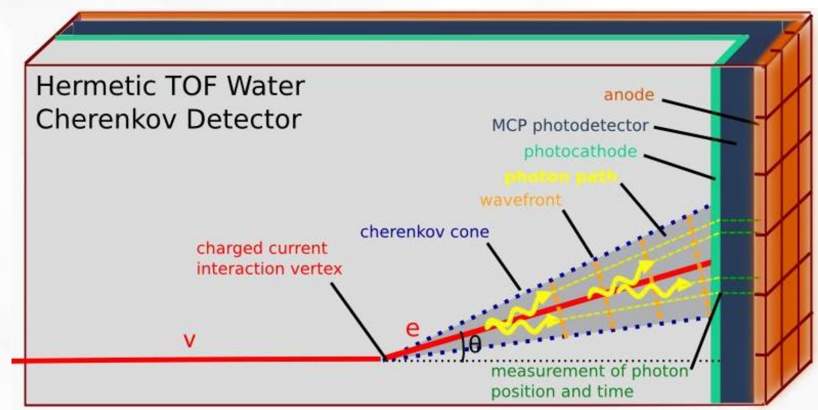
Important remarks:

- There are other fast timing technologies
- A lot of what I will be talking about applies there (e.g. SiPMs)

Fast timing is needed at colliders, fixed target, and neutrino experiments



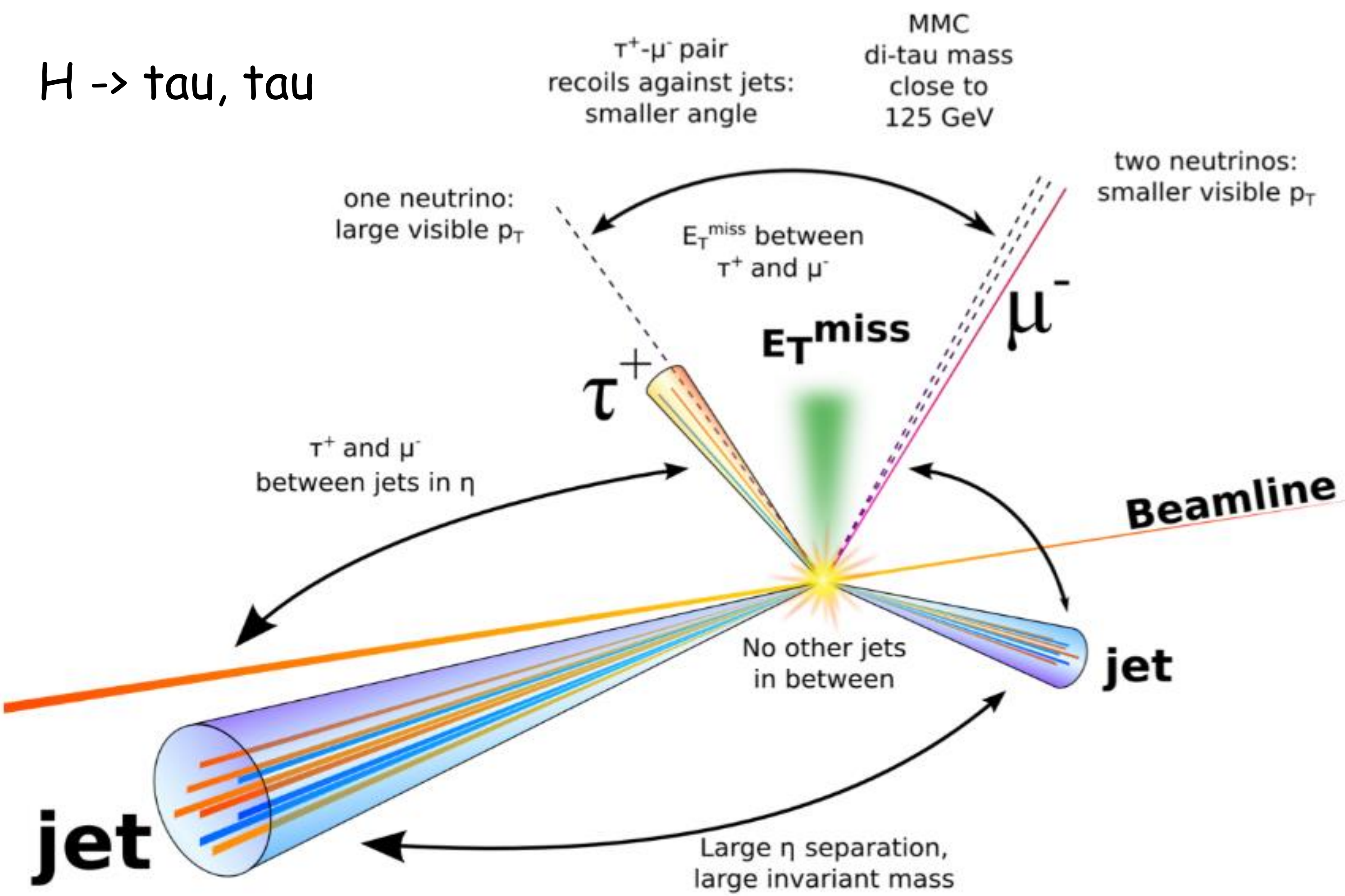
- Assign tracks to vertices
- Separate overlapping tracks
- Particle ID by TOF
- Heavy particles, displaced vertices



- Vertex reconstruction
- 3D tracking

Higgs Properties

H -> tau, tau



Missing Mass Calculator
NIMA 654 (2011) 481
A. Elagin, P. Murat,
A. Pronko, A. Safonov

Probabilistic Particle Flow
NIMA 705 (2013) 93
A. Elagin, P. Murat,
A. Pronko, A. Safonov

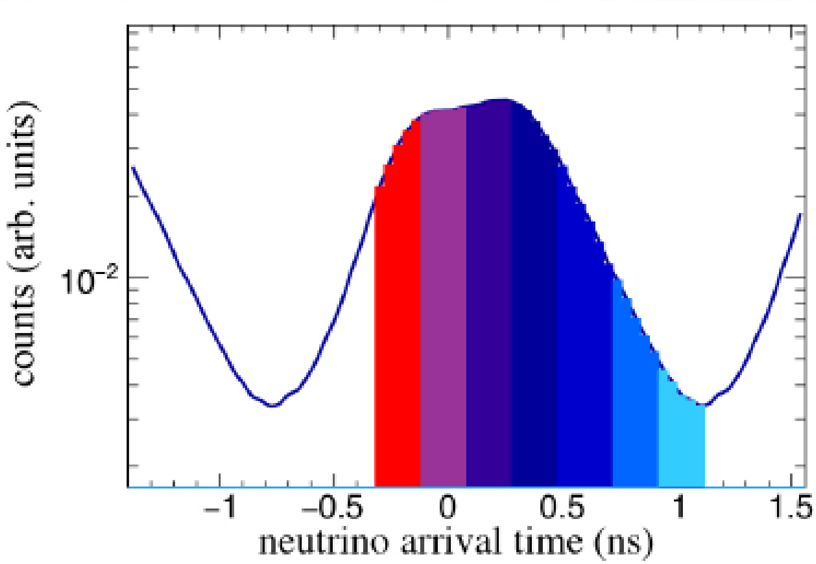
Diagram credit:
http://licollider.wordpress.com

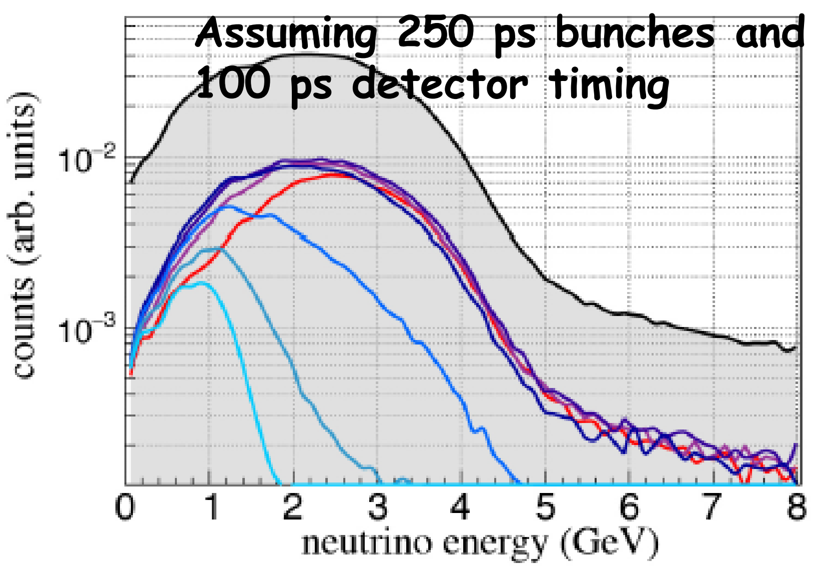
These techniques have been developed at CDF without using fast timing, but Kaon identification by TOF could have further improved energy resolution of hadronic taus

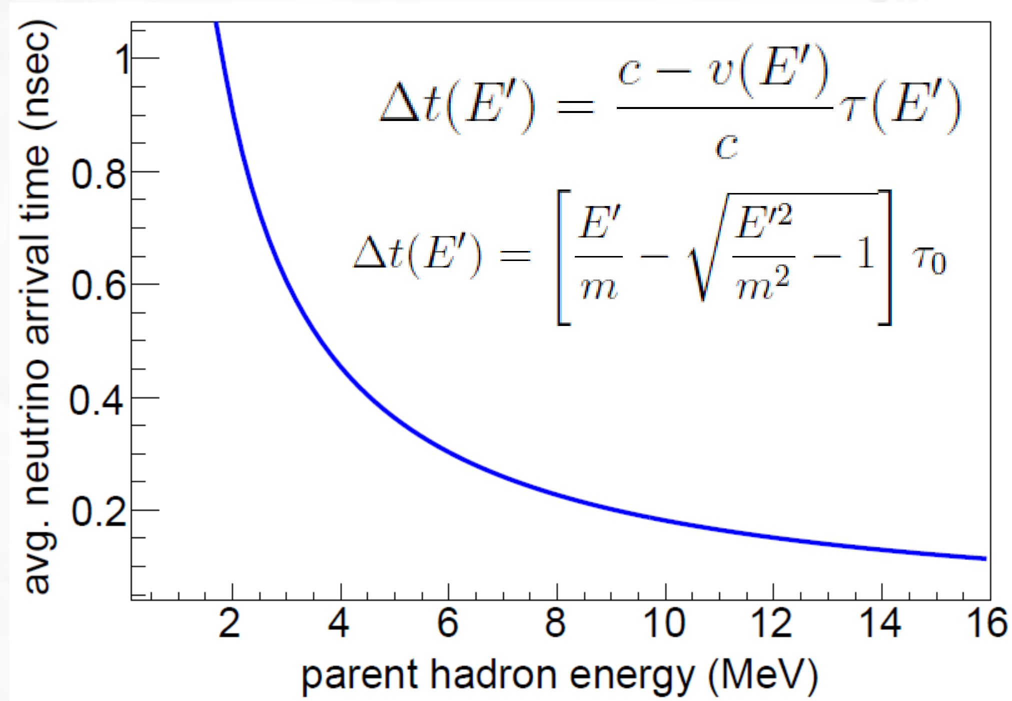
Neutrino Properties

Stroboscopic approach

PRD 100 (2019) 3, 032008
E.Angelico, J.Eisch, A.Elagin, H.Frisch, S.Nagaitsev, M.Wetstein





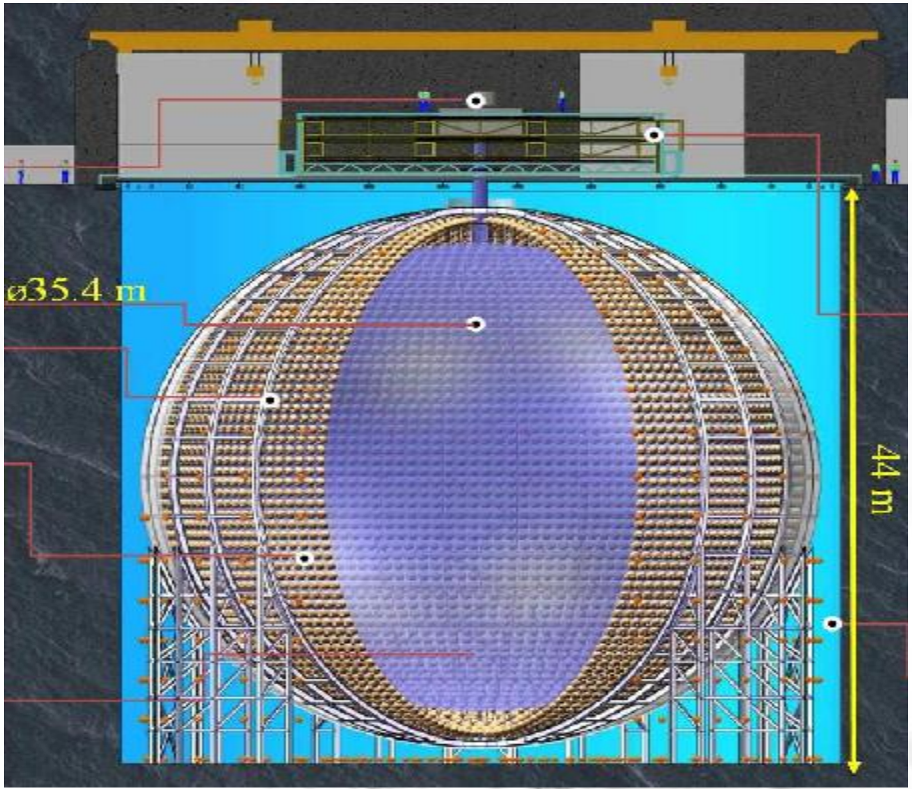


- Lower energy neutrinos arrive later
- Time slicing of neutrino events relative to the time of their parent bunch time allows for selecting different neutrino energy spectra and flavor content
- Could be complementary to NuPrism

Outline

- How precision photon measurements can be used to discover neutrino-less double-beta decay
- How LAPPD can become affordable for large-scale experiments

An example of a large-scale experiment
Surface area of the JUNO detector sphere is ~980 m^2



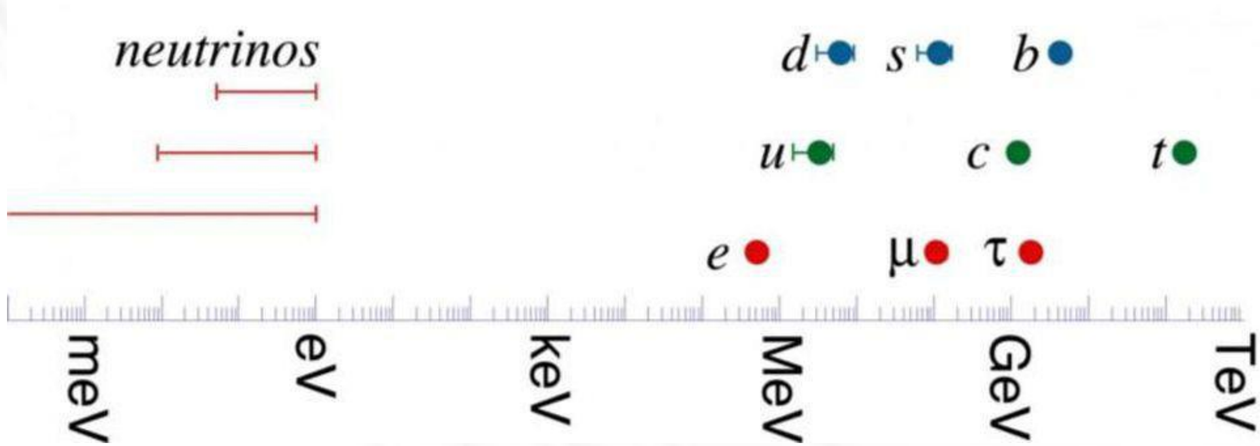
picture credit: the JUNO collaboration

Is the Neutrino Its Own Antiparticle?

- It is possible because the neutrino has no electric charge
- It is intriguing question because no other fermion can be its own antiparticle

It is not only possible, but may be necessary to explain
- the origin of matter-antimatter asymmetry in the universe
- why the neutrino mass is so tiny?

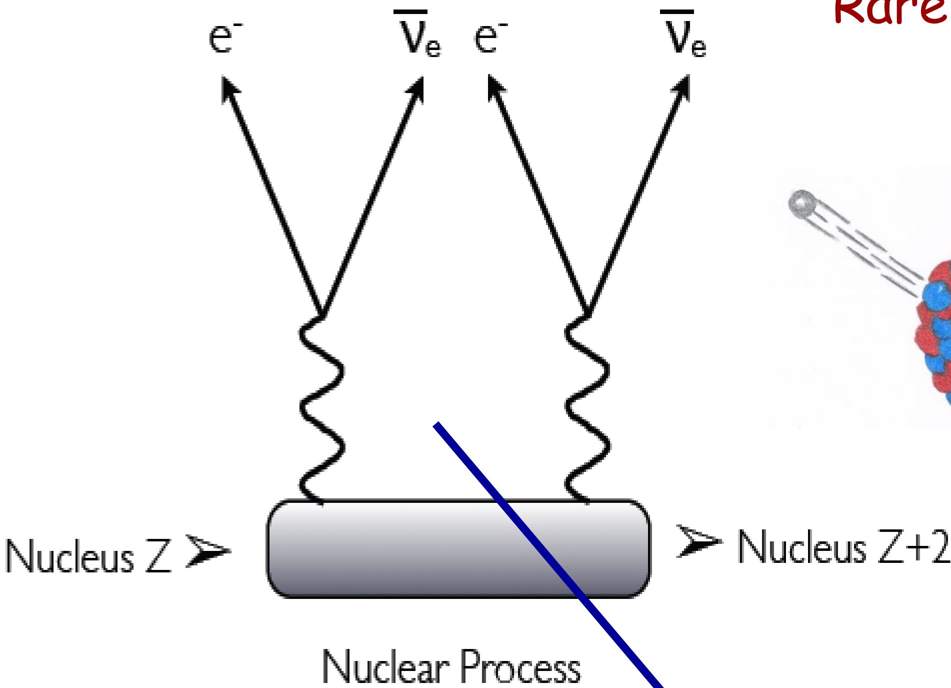
plot credit: Hitoshi Murayama
(taken from Forbes 07/14/2020)

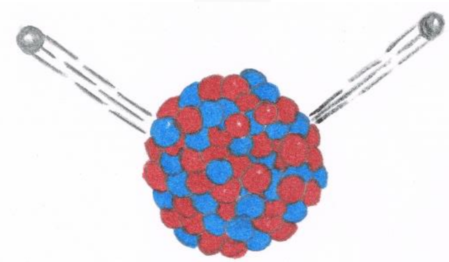


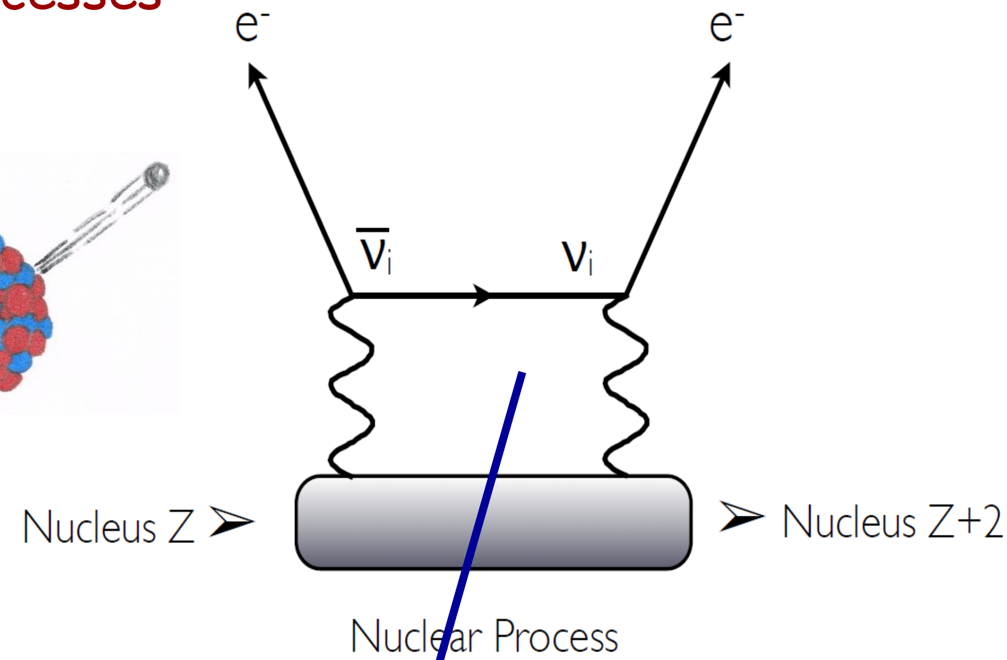
Search for neutrino-less double beta decay ($0\nu\beta\beta$-decay) is the most feasible way to answer this question

Double Beta Decay

Rare processes

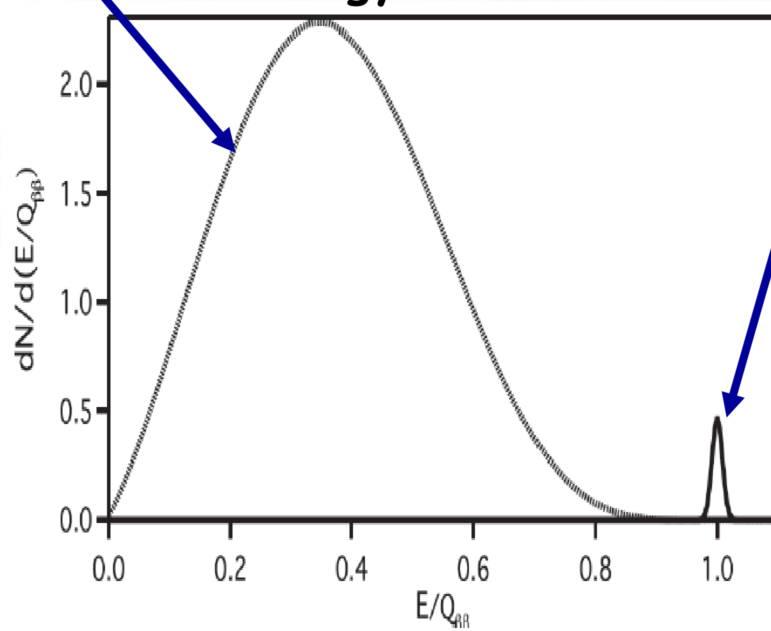




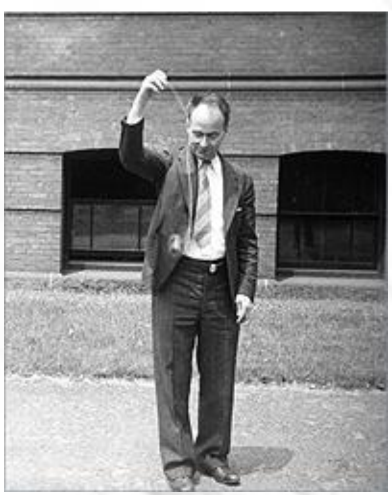


Maria Goeppert-Mayer

Total energy of two electrons



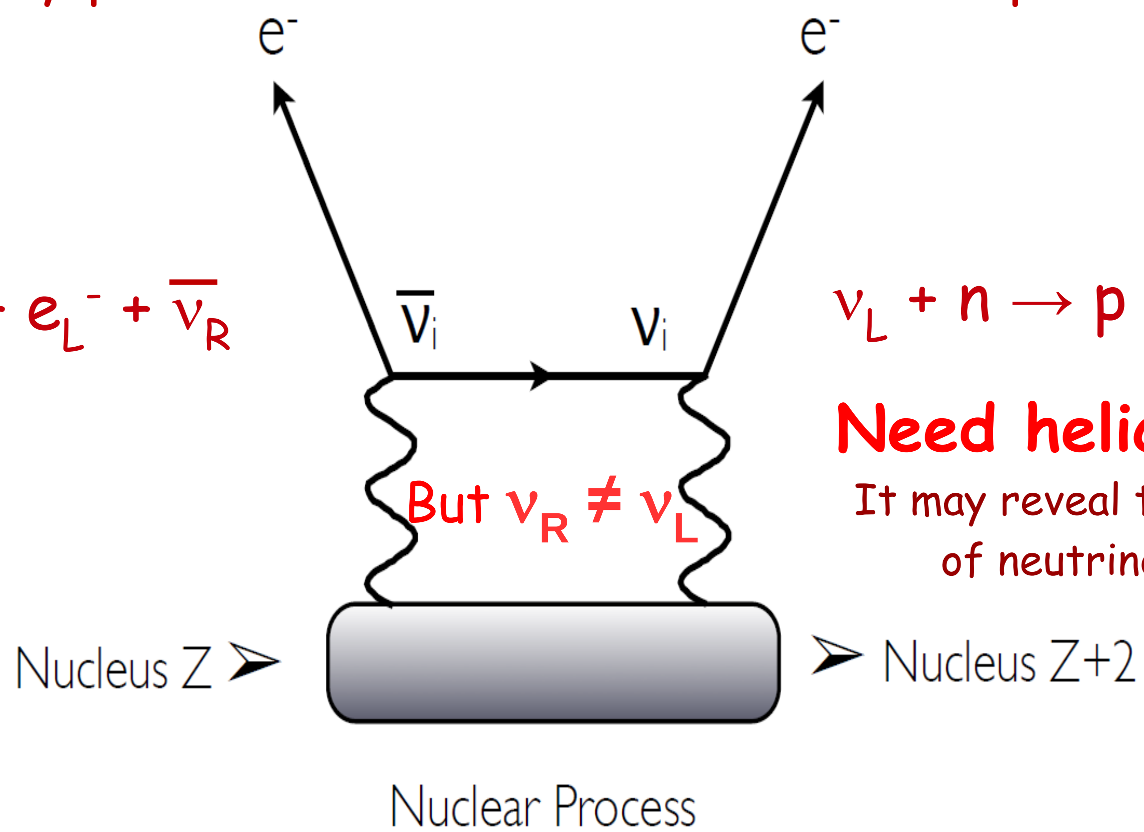
Wendell Furry



Neutrinoless Decay Is Unique

Only possible if neutrino is its own antiparticle

$n \rightarrow p + e_L^- + \overline{\nu}_R$



$\nu_L + n \rightarrow p + e_L^-$

Need helicity flip!

It may reveal the nature of neutrino mass

If neutrino is Majorana then ν_R is just a CP-conjugate of ν_L , i.e. $\nu_L^C = \nu_R$

Therefore 0νββ-decay requires a mechanism for $\nu_L^C \leftrightarrow \nu_L$ transition

Need coupling between ν_L and ν_L^C

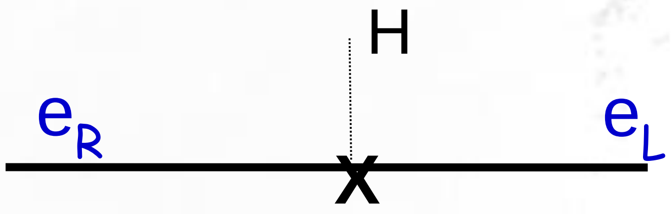
Such coupling can be effectively introduced into SM Lagrangian via "See-Saw" mechanism

Mass Terms in the SM Lagrangian

Electron mass term in the Standard Model Lagrangian

$m_e e_L e_R$

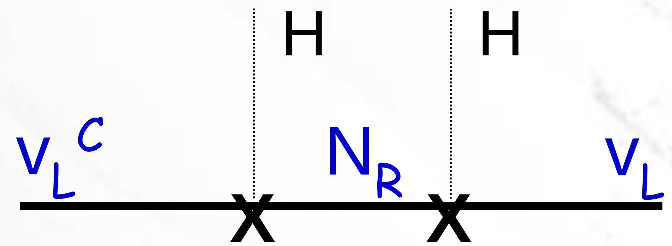
(Example of a Dirac mass term)



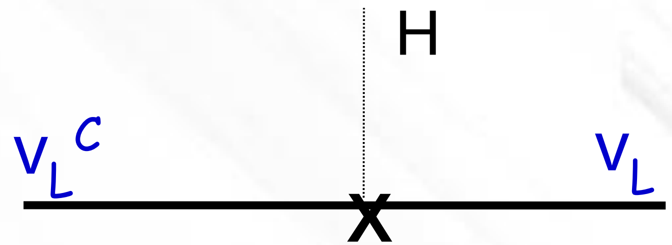
See-Saw Mechanism

Possible extension of the SM Lagrangian to introduce neutrino mass

$$\left(\overline{\nu}_l, \overline{N}_R^c\right)\begin{pmatrix} 0 & m_D \\ m_D^T & M_{RR} \end{pmatrix}\begin{pmatrix} \nu_L^c \\ N_R \end{pmatrix}$$



"Effectively" in the limit $M_{RR} \gg m_D$



In the limit $M_{RR} \gg m_D$ the eigenvalues are

$m_D{}^2/M_{RR}$ (light neutrino)

M_{RR} (heavy neutrino)

This is not the only option

There are other mechanisms leading to $0\nu\beta\beta$-decay

This is exactly what's needed for $0\nu\beta\beta$-decay

How to Find 0νββ-decay?

Step 1: Choose an isotope where 0νββ-decay is allowed

Step 2: Wait for emission of two electrons with the right total energy

Isotope	Q-Value	Abundance (%)
Ca 48	4.271	0.187
Ge 76	2. 039	7.8
Se 82	2.995	9.2
Zr 96	3.350	2.8
Mo 100	3.034	9.6
Pd 110	2.013	11.8
Cd 116	2.802	7.5
Sn 124	2.288	5.64
Te 130	2.529	34.5
Xe 136	2.479	8.9
Nd 150	3.367	5.6

Challenges:

1. Rare process
2. 2νββ-background
3. Natural radioactivity

Solutions:

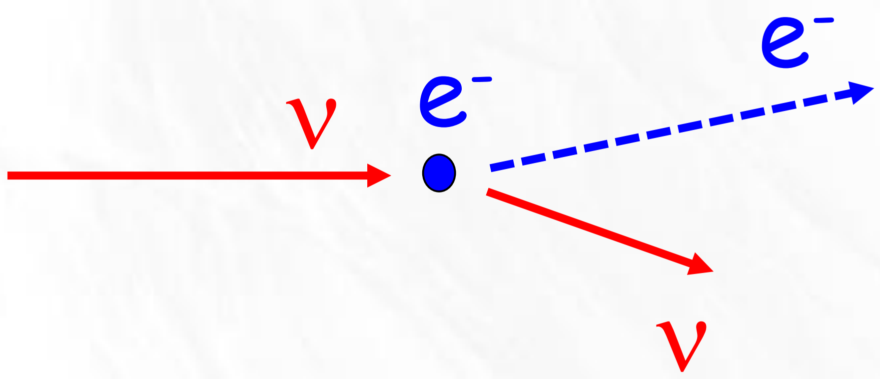
1. Very large detector mass
2. Good energy resolution
3. Purification and shielding

^{130}Te-loaded multi-kiloton liquid scintillator detector may become the only viable option for discovery

[See S.Biller, PRD87 (2013) 071301]

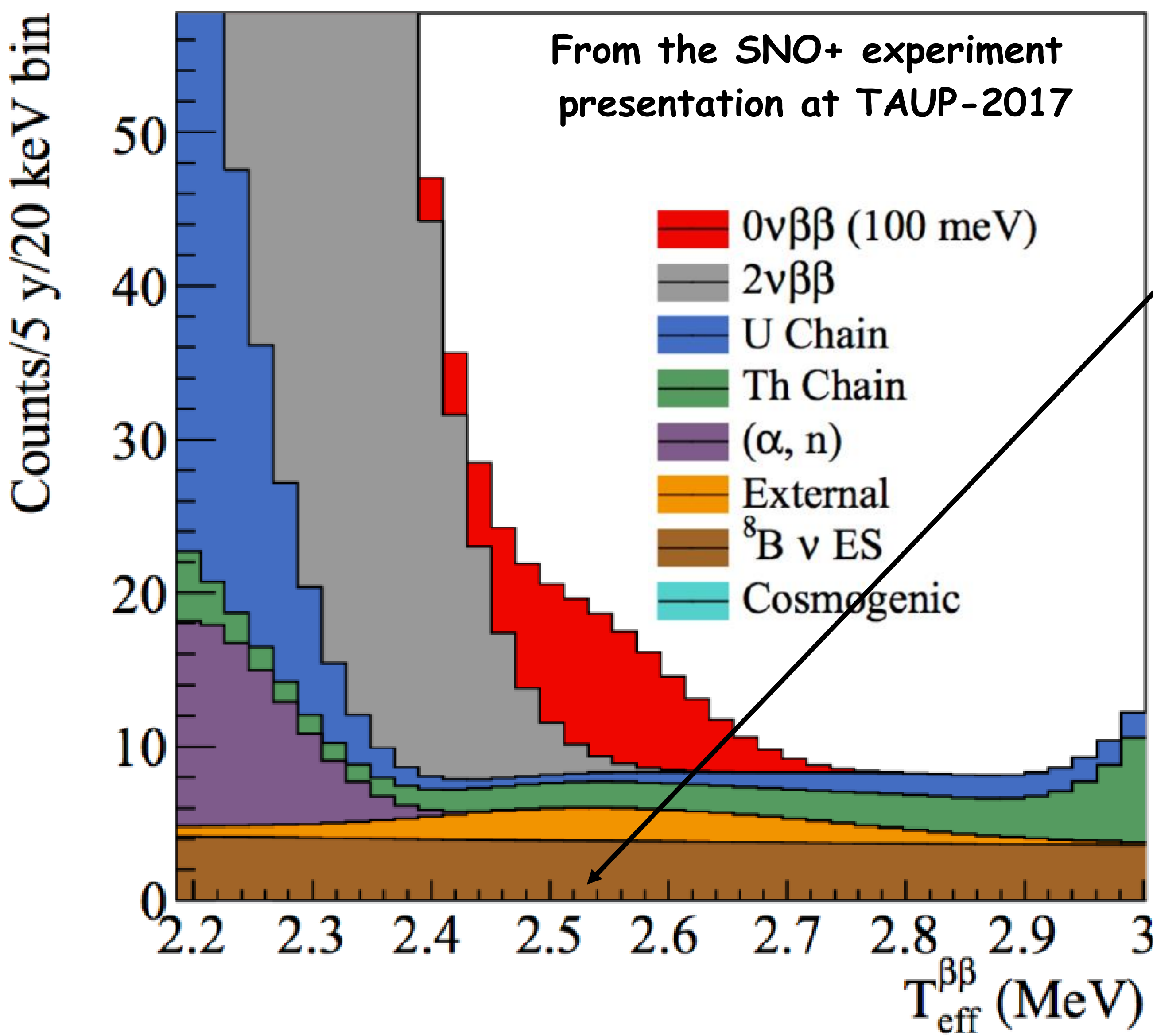
New Challenge for a Large Detector

Electron scattering of neutrinos coming from ^8B-decays in the sun



^8B can become dominant "irreducible" background without event topology reconstruction

Example of Background Budget



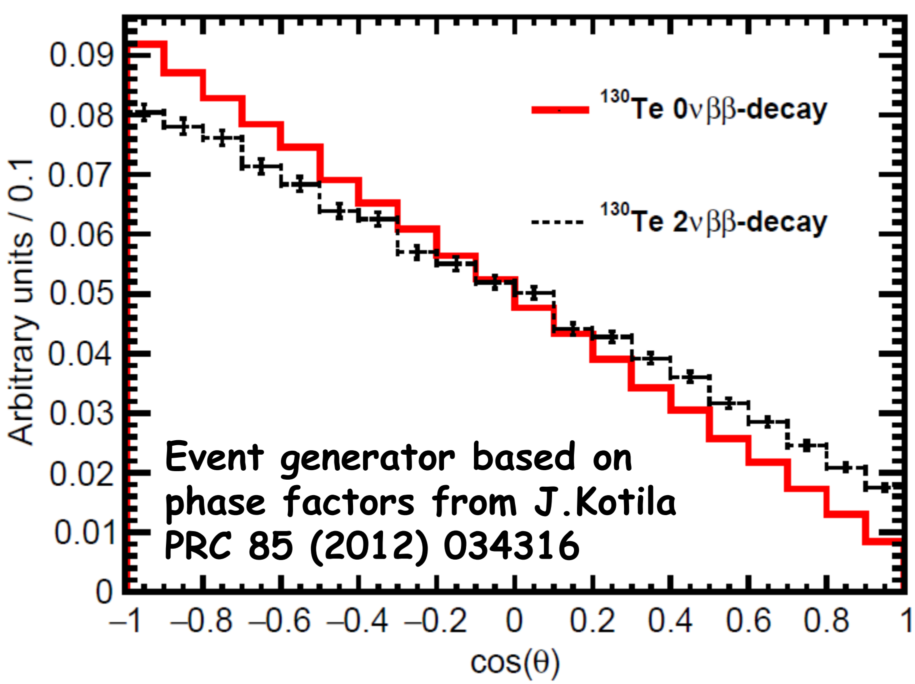
Q(^{130}Te) = 2.53 MeV
The largest background in the ROI is coming from ^{8}B solar neutrinos

It has only 1 electron, while 0νββ-decay has 2 electrons

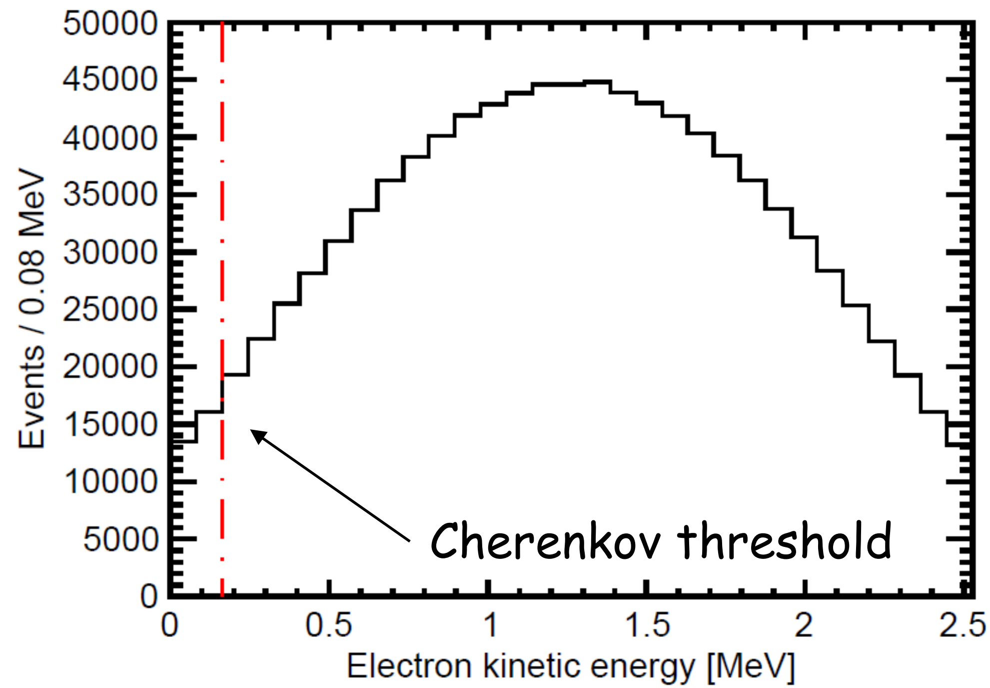
Is it possible to separate two-track and one-track events?

Double-Beta Decay Kinematics

Angle (cosΘ) between two electrons



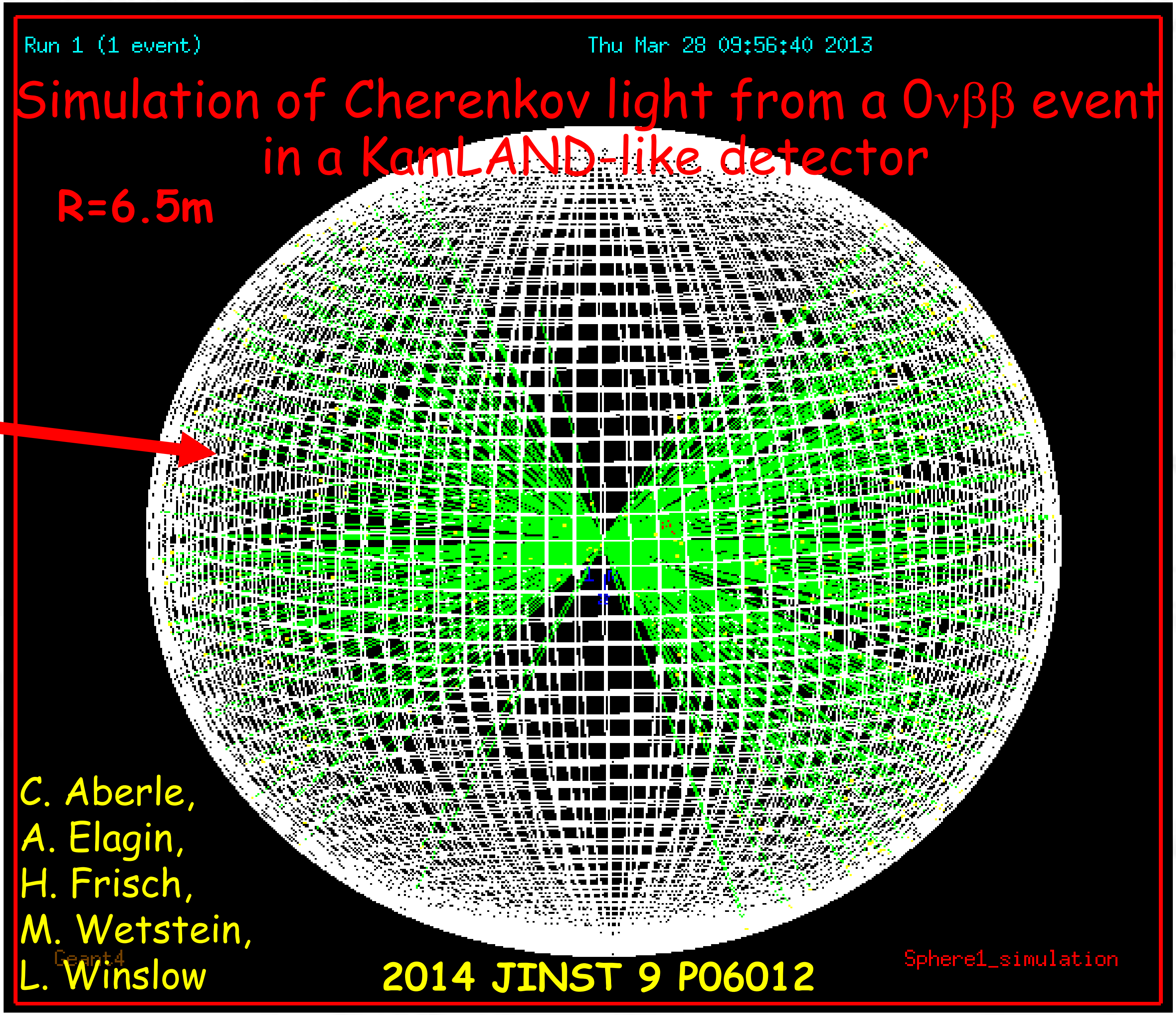
Kinetic energy of each electron



- Lots of "back-to-back" (large angle) events
- Most of electrons are above Cherenkov threshold

Can We See This?

One selected event with large angle between electrons



A detailed Geant4 simulation was built to study how to separate directional Cherenkov light from abundant isotropic scintillation

Normalized Che/Sci Spectra

Spectral threshold sorting for che/sci separation is also being investigated.
See T.Kaptanoglu et al PRD 101 (2020) 7, 072002

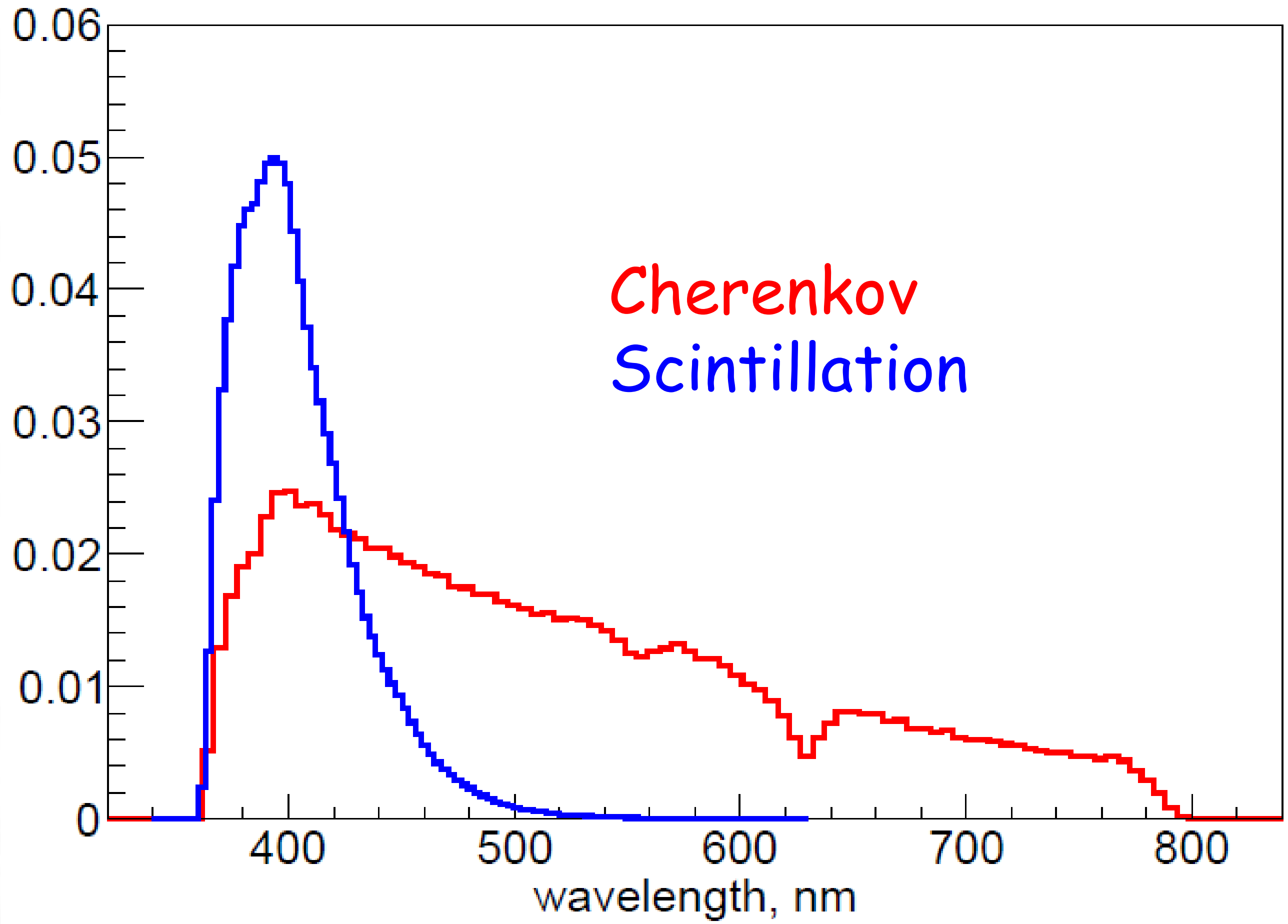
The focus of this talk is on timing

Many groups are exploring various aspects of che/sci separation

E.g. see also
PRC95 (2017) 055801
Eur.Phys.J. C77 (2017) no.12, 811
NIMA 830 (2016) 303

There is more
It's a hot field!

An example of a scintillator model similar to KamLAND



Scintillation emission is slower

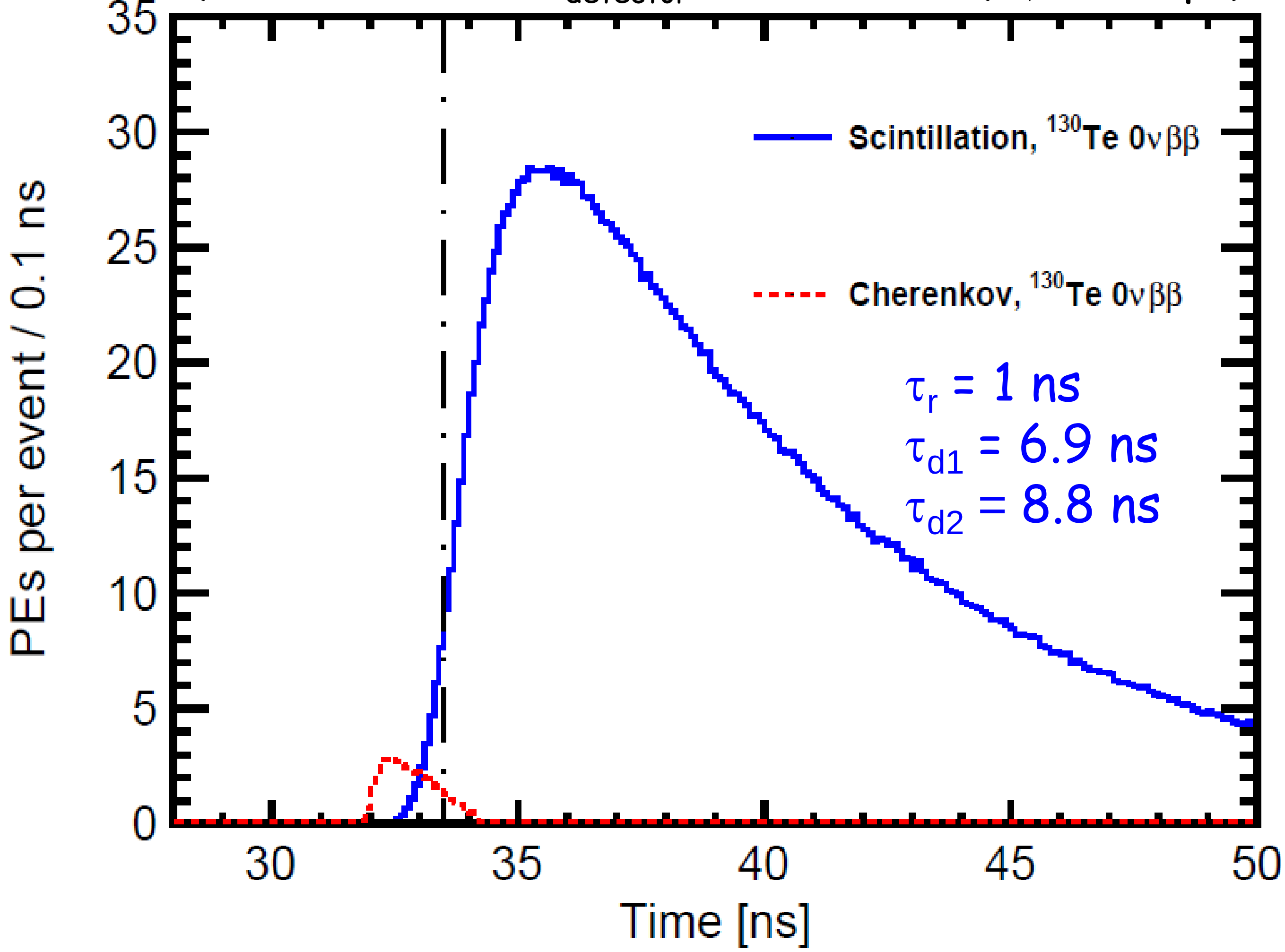
Longer (red) wavelengths travel faster

370 nm → 0.191 m/ns
600 nm → 0.203 m/ns
~2 ns difference over 6.5m distance

Cherenkov Light Comes First

Distribution of photon arrival times

(central events, $R_{detector}$ = 6.5 m, TTS(σ) = 100 ps)



Cherenkov light arrives earlier

Nuclear Instruments and Methods in Physics Research A 334 (1993) 353–366
North-Holland

NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH
Section A

LSND did separation of Cherenkov and scintillation light in a diluted scintillator

Dilute scintillators for large-volume tracking detectors

R.A. Reeder, B.D. Dieterle, C. Gregory, F. Schaefer [1] and K. Schum
University of New Mexico, Albuquerque, NM 87131, USA
W. Strossman
University of California, Riverside, CA 92521, USA
D. Smith
Embry-Riddle Aeronautical University, Prescott, AZ 86301, USA
L. Christofek, K. Johnston [2], W.C. Louis, M. Schillaci, M. Volta [3], D.H. White and D. Whitehouse
Los Alamos National Laboratory, Los Alamos, NM 87545, USA
M. Albert and K. Yaman
University of Pennsylvania, Philadelphia, PA 19104, USA
C. Athanassopoulos, L.B. Auerbach, P. Hermida and D. Works
Temple University, Philadelphia, PA 19122, USA

Received 2 April 1993

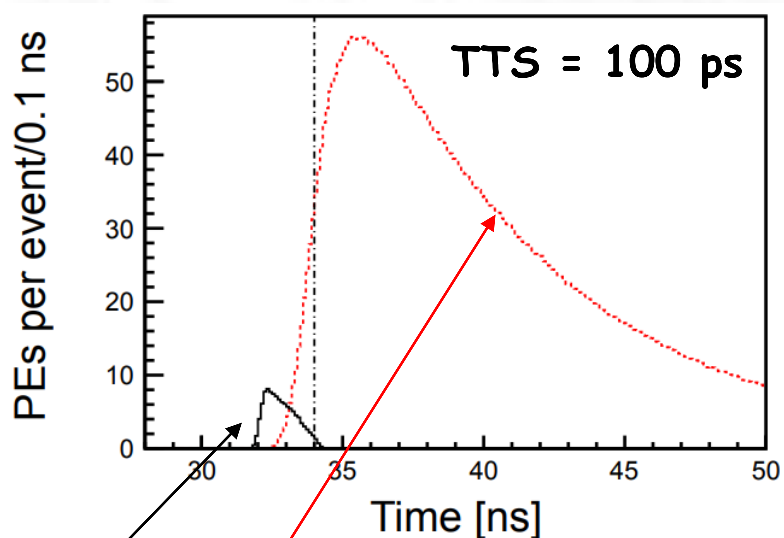
Che:Sci = 2.4:1

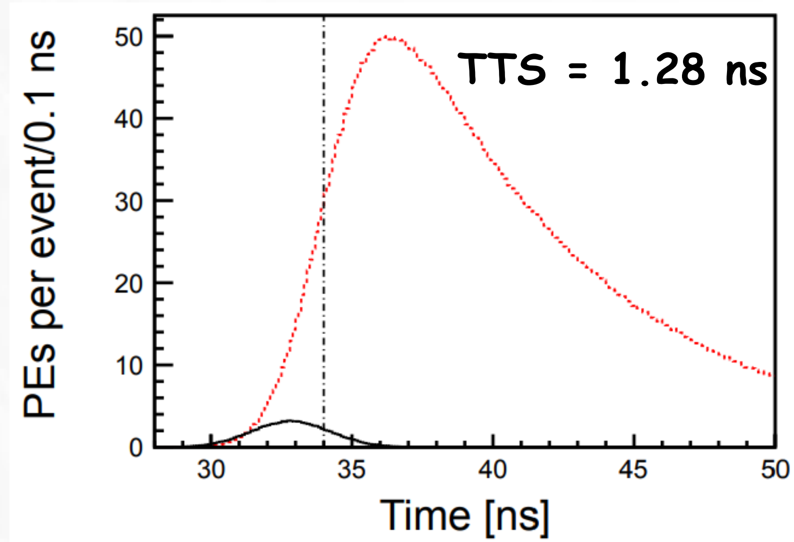
Dilute scintillation mixtures emit isotropic light for both fast and slow particles, but retain the Cherenkov light cone from fast particles. Large volume detectors using photomultipliers to reconstruct relativistic tracks will also be sensitive to slow particles if they are filled with these mixtures. Our data show that 0.03 g/l of b-PBD in mineral oil has a 2.4:1 ratio (in the first 12 ns) of isotropic light to Cherenkov light for positron tracks. The light attenuation length is greater than 15 m for wavelength above 400 nm, and the scintillation decay time is about 2 ns for the fast component. There is also a slow isotropic light component that is larger (relative to the fast component) for protons than for electrons. This effect allows particle identification by a technique similar to pulse shape discrimination. These features will be utilized in LSND, a neutrino detector at LAMPF.

Cherenkov/Scintillation Separation

Simulation of a KamLAND-like detector non-diluted high light-yield scintillator

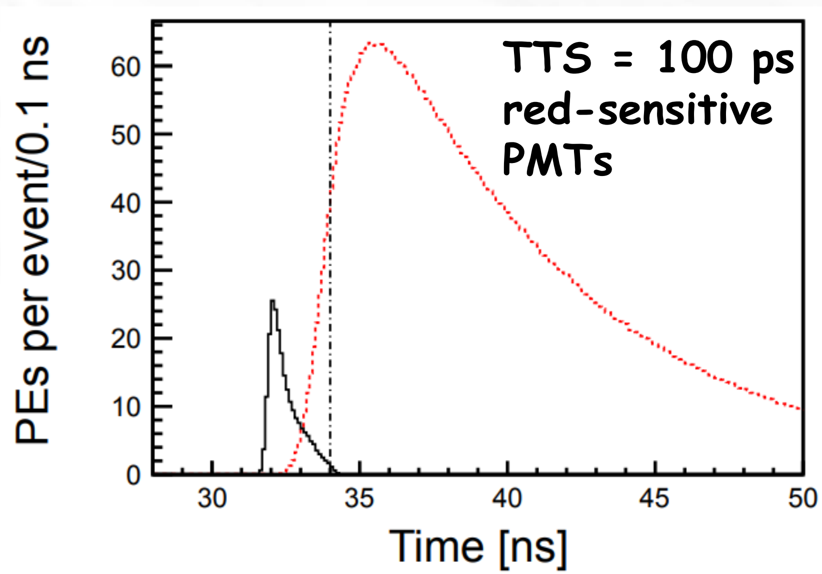
Photon arrival times for events originated at the center of the detector





Cherenkov

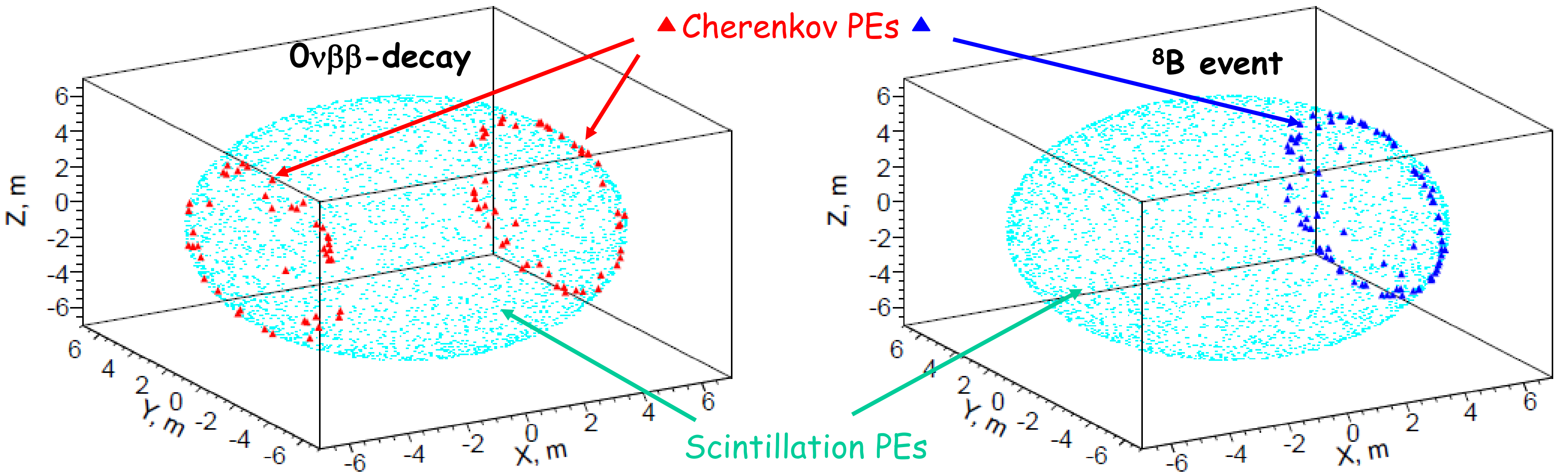
Scintillation



2014 JINST 9 P06012

Event Topology

Idealized event displays
- no multiple scattering of electrons
- QE=30%
- no time cut on PE arrival time



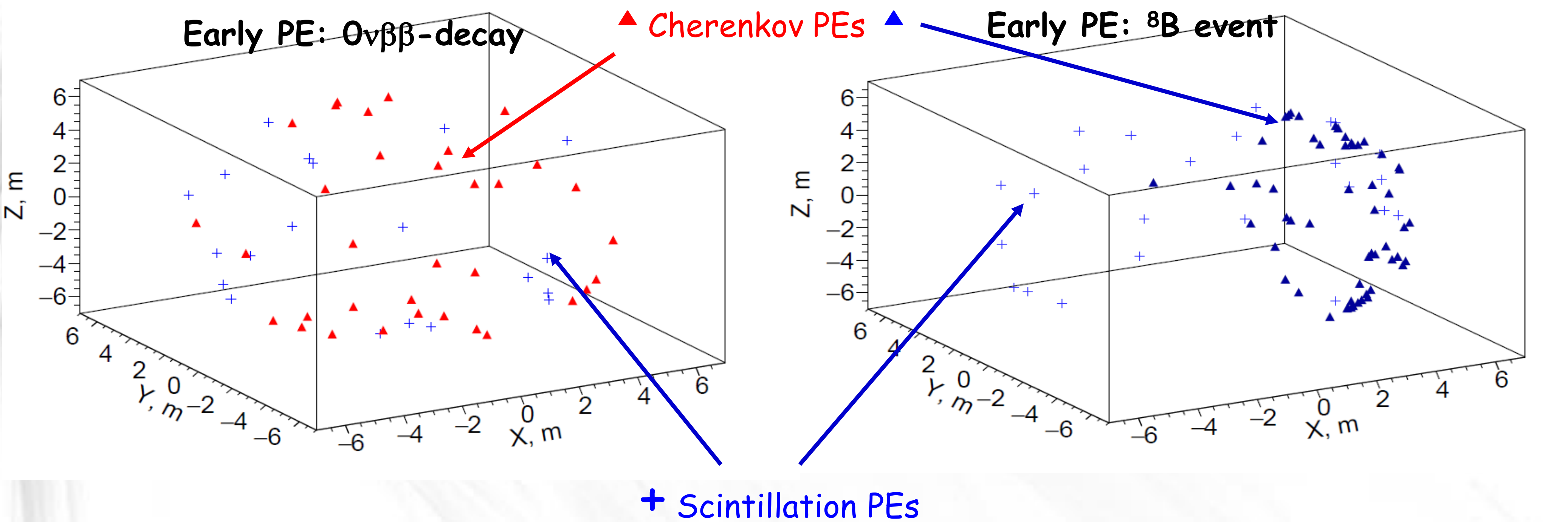
Tagging Cherenkov photons would clearly separate signal and background

Potential markers to tag Cherenkov photons
1) Timing
2) Spectral sorting
3) Polarization

Early Light Topology

Realistic event displays

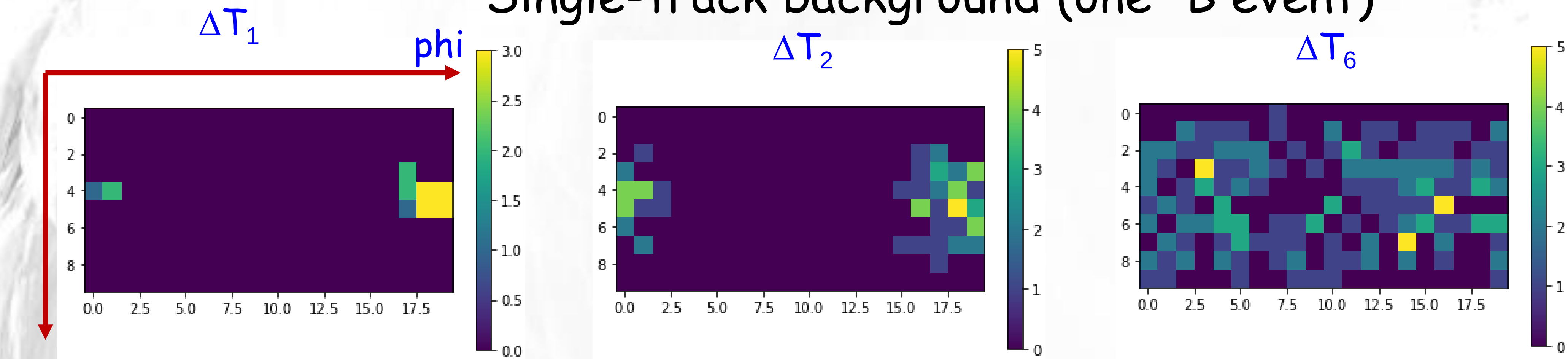
- full Geant4 simulation
- QE: **Che~12%**, Sci~23% (modeled after KamLAND PMTs)
- early PEs only (first 2.5ns)



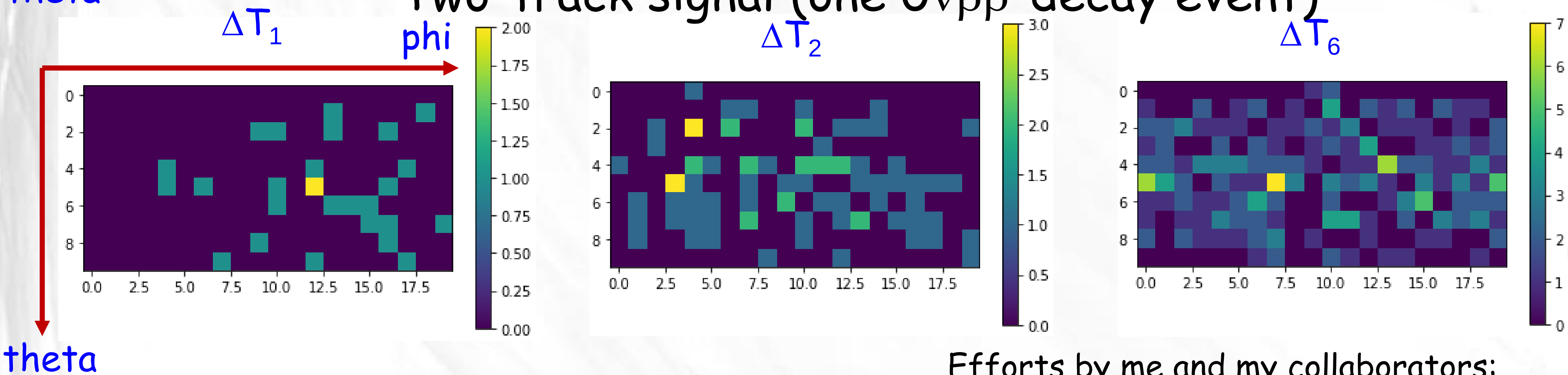
Timing alone allows for getting a sample of PEs with high enough fraction of Cherenkov light to apply various pattern recognition algorithms to separate signal from background

Pattern Recognition Problem

Single-track background (one ^{8}B event)



Two-track signal (one 0νββ-decay event)



There are plenty ideas on how to "see" 0νββ-decay in liquid scintillator via prompt directional Cherenkov light

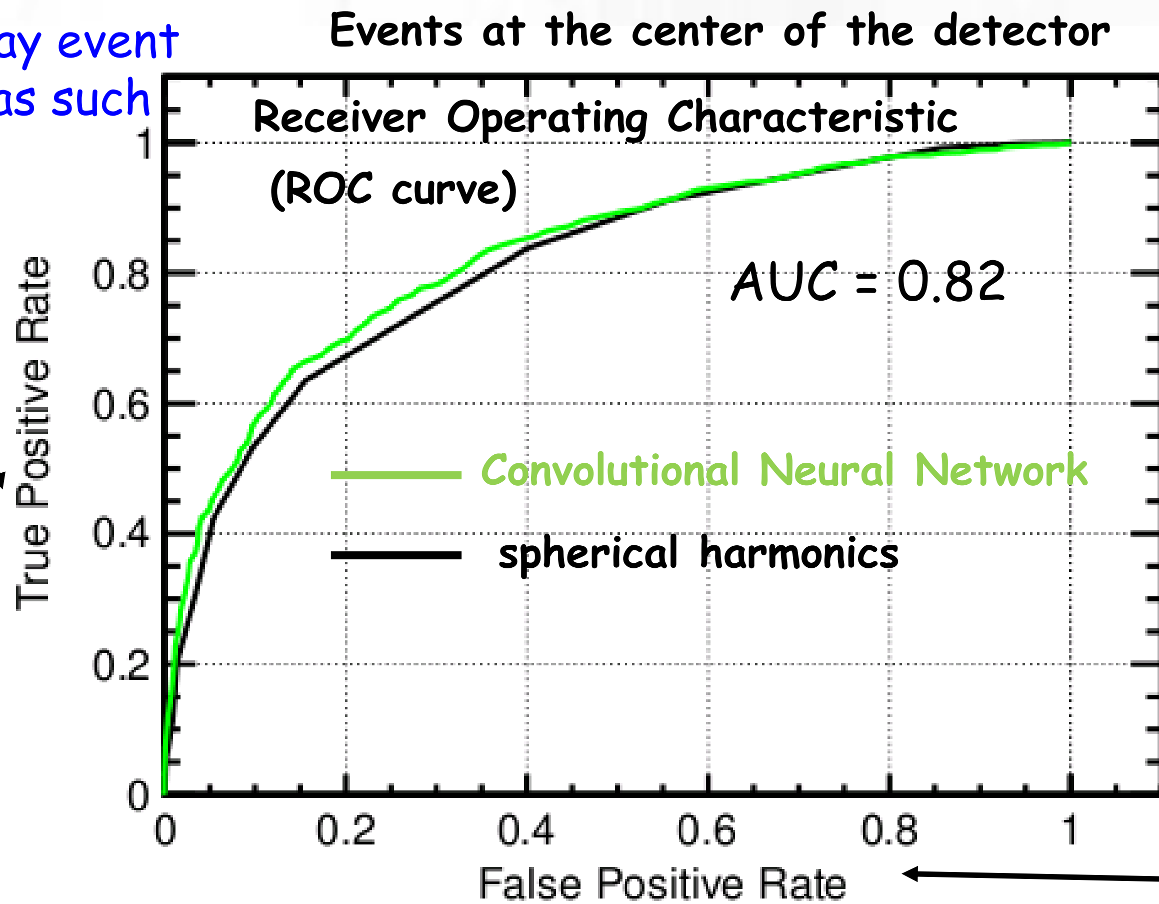
Efforts by me and my collaborators:
JINST 9 (2014) P06012
NIMA 849 (2017) 102-111
JINST 14 (2019) 02, P02005
NIMA 947 (2019), 162604
arXiv:1902.06912 (submitted to NIMA)
Eur.Phys.J.C 80 (2020) 5, 416

See Eur.Phys.J.C 80 (2020) 5, 416 for a complete overview of all recent efforts

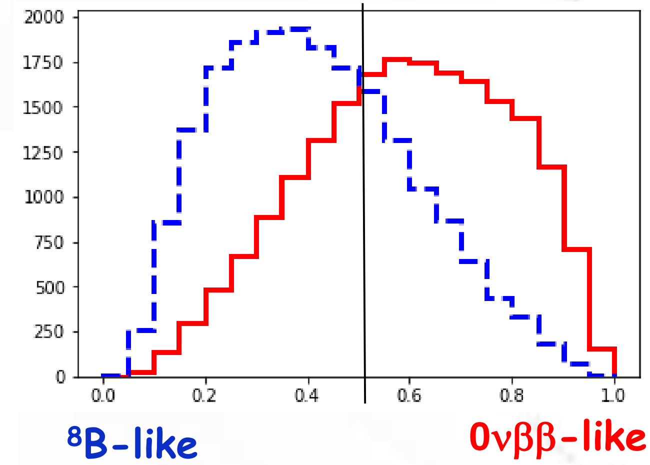
Which Pattern Recognition Works Best?

$0\nu\beta\beta$-decay vs ^{8}B classification

$0\nu\beta\beta$-decay event labeled as such



^{8}B event mislabeled as $0\nu\beta\beta$-decay



- AUC of 1.0 means perfect reconstruction/classification
- AUC of 0.5 means a random guess
- Note: some fraction of 0nbb-decays have only one track above Che threshold or there is very small angle between two electrons

When the vertex location is explicitly reconstructed separately, all neural networks (CNNs, PCA, Fully Connected, Locally Connected, and LSTM) have similar performance. Actual AUC depends on photo-coverage, QE, and vertex resolution.

LSTMs work well without vertex reconstruction

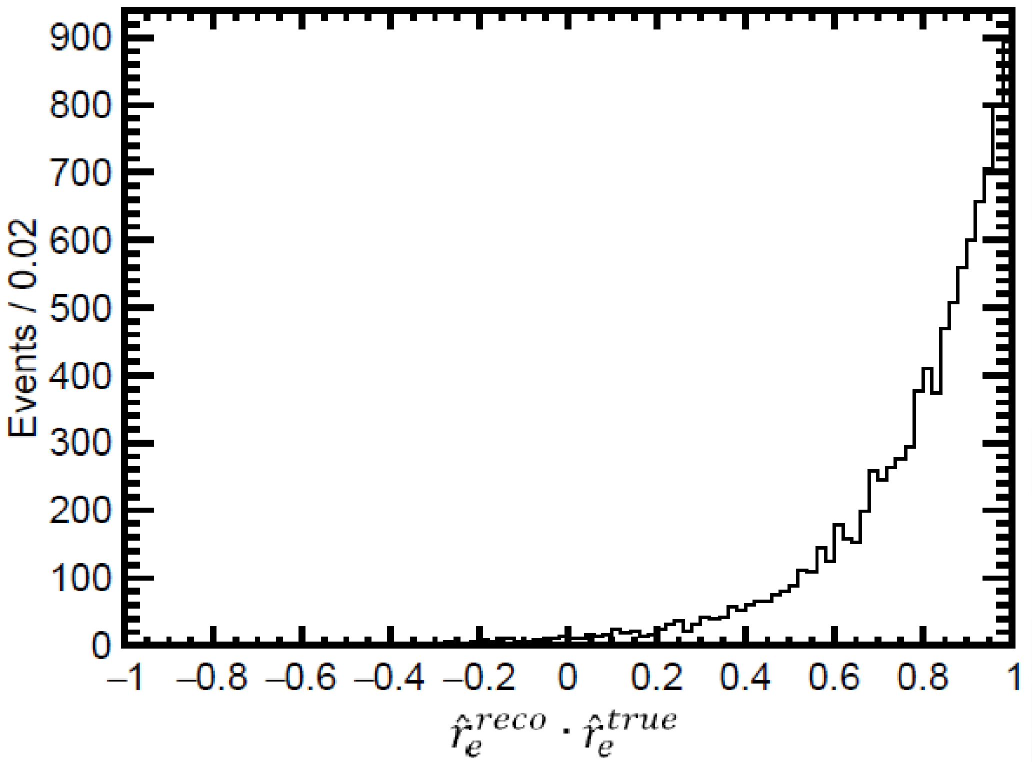
Thank you to I. Vukotic and E. Toropov for introducing me to all these ML acronyms

Don't Forget Directionality

^{8}B neutrinos are coming from the Sun

Dot product of reconstructed and true direction of an electron

A. Elagin, R. Jiang
arXiv:1902.06912

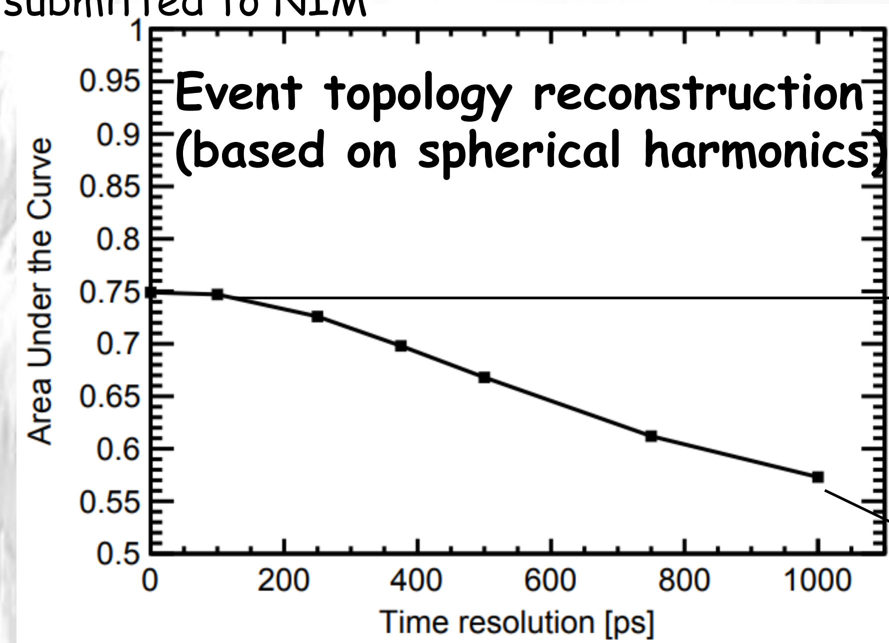


- Combined signal-background separation based on both topological and directionality reconstruction is subject of ongoing studies
- A lot depends on actual detector parameters (scintillator properties, quantum efficiency, photo-coverage, total fiducial volume, etc)

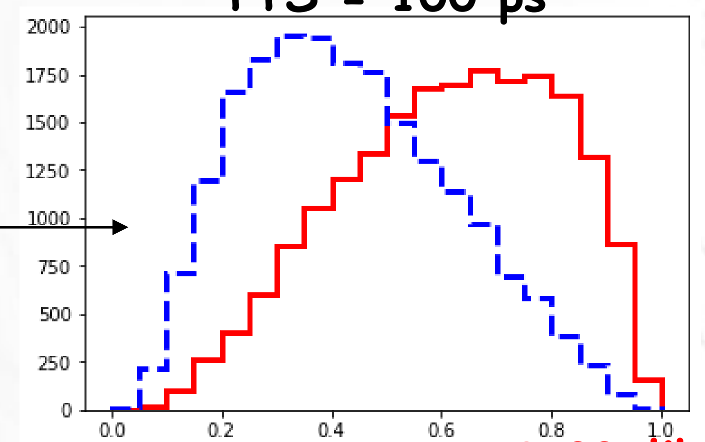
The goal of suppressing 50% of ^{8}B background at 75% signal efficiency is within the reach

How Good the Timing Should Be?

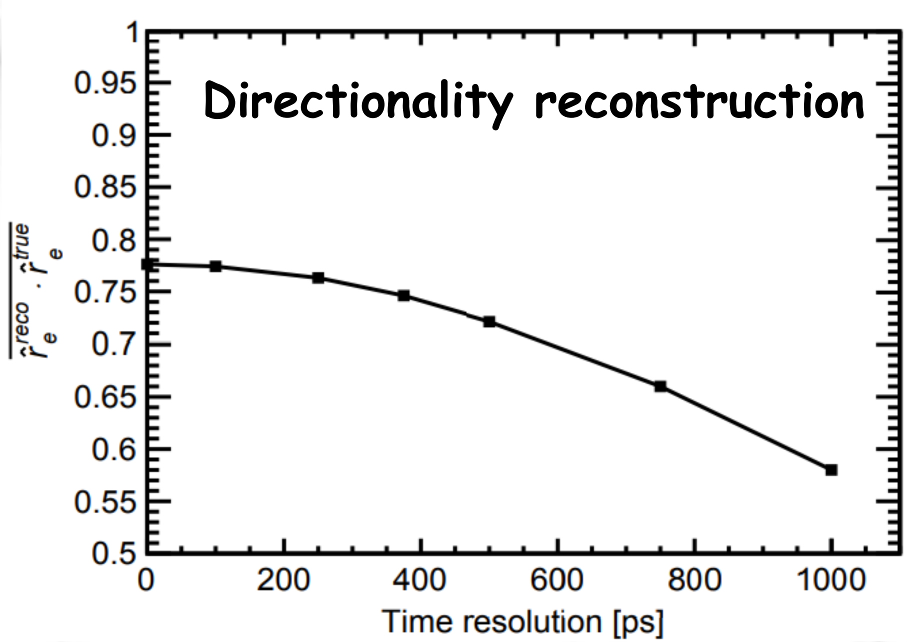
A. Elagin, R. Jiang
submitted to NIM



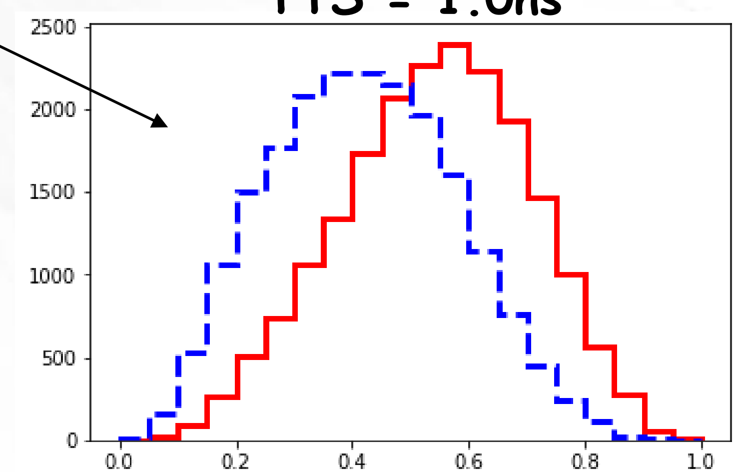
Classifier output for
TTS = 100 ps



^{8}B-like <- -> $0\nu\beta\beta$-like



Classifier output for
TTS = 1.0ns

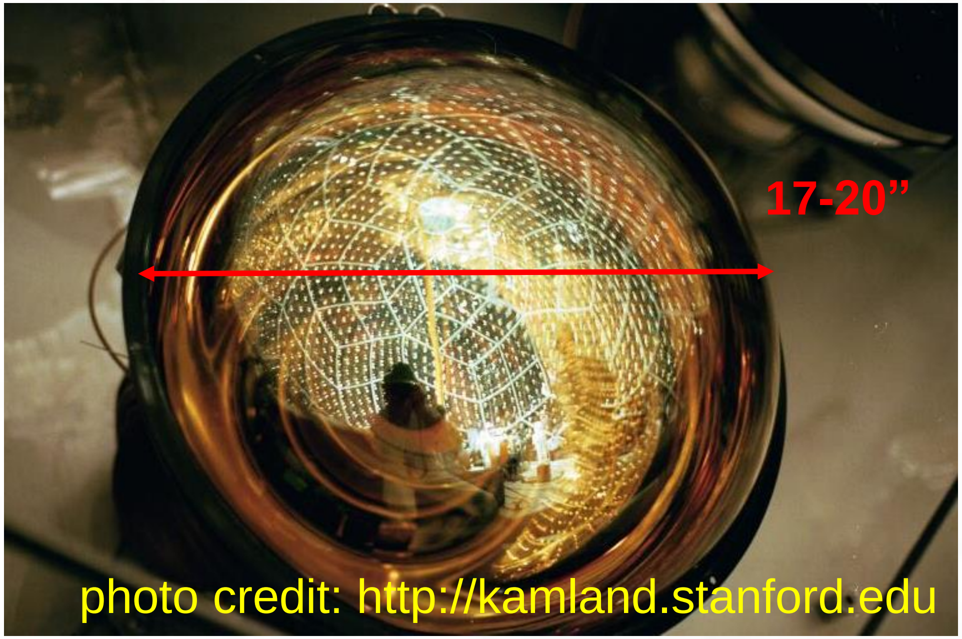


^{8}B-like <- -> $0\nu\beta\beta$-like

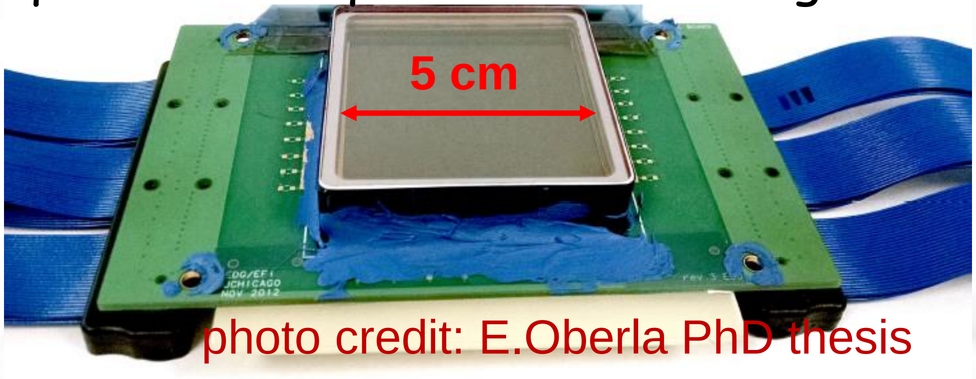
100 ps is close to optimal for a KamLAND-like detector

Photo-Detector Candidates

1) Regular PMTs
Large area, but slow…

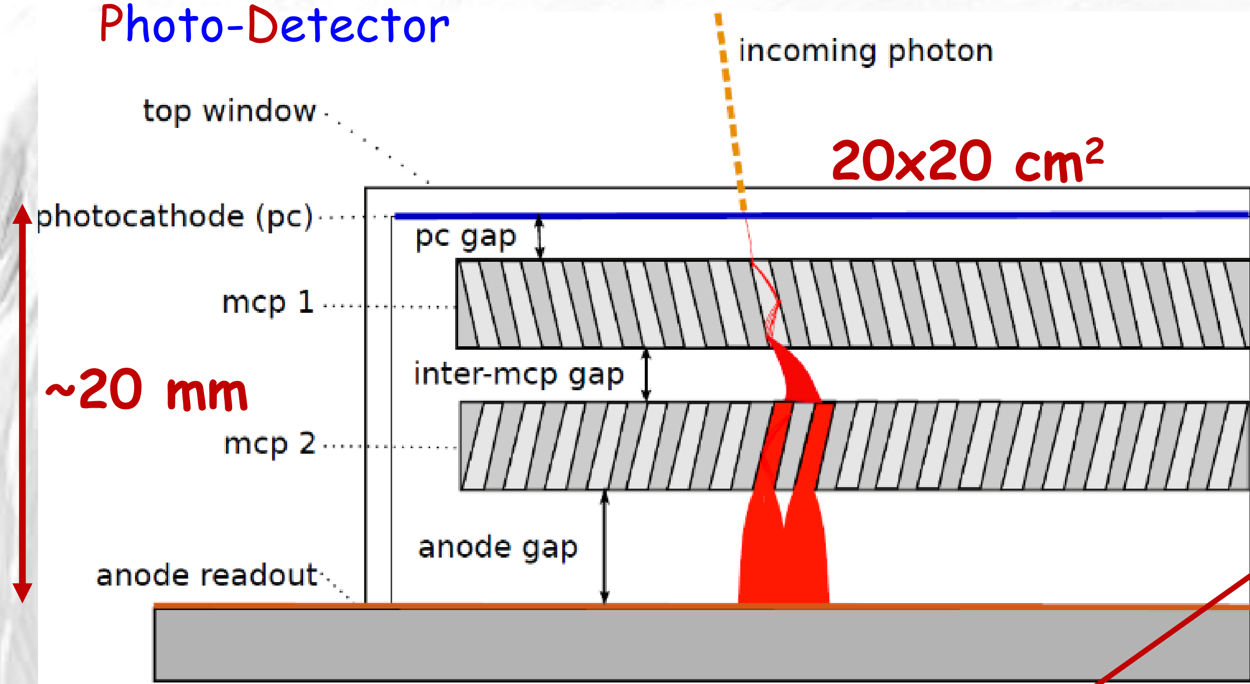


2) MCP-PMTs
Fast, but small…and not really available
in quantities required to cover large areas

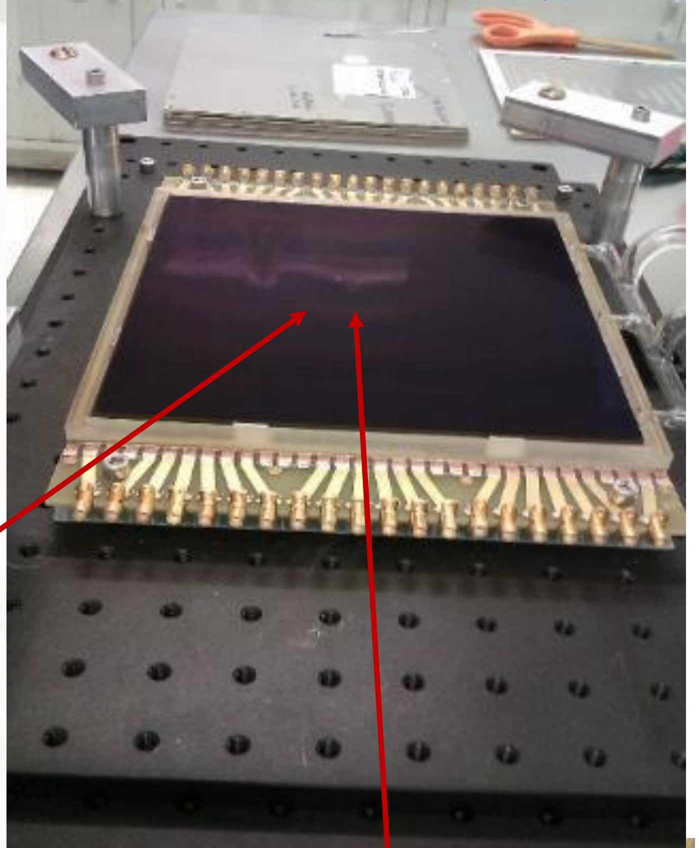


LAPPD™

Large-Area Picosecond Photo-Detector

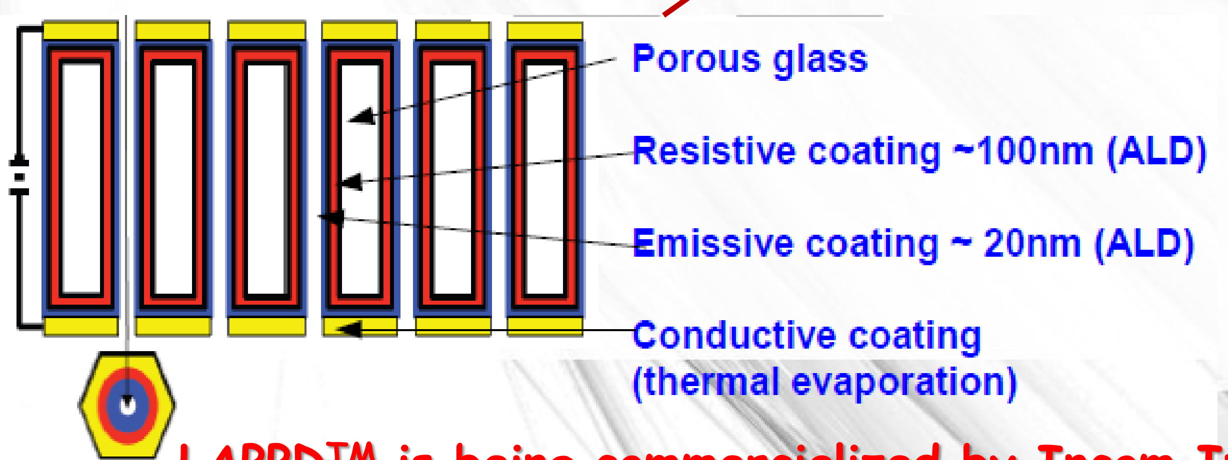


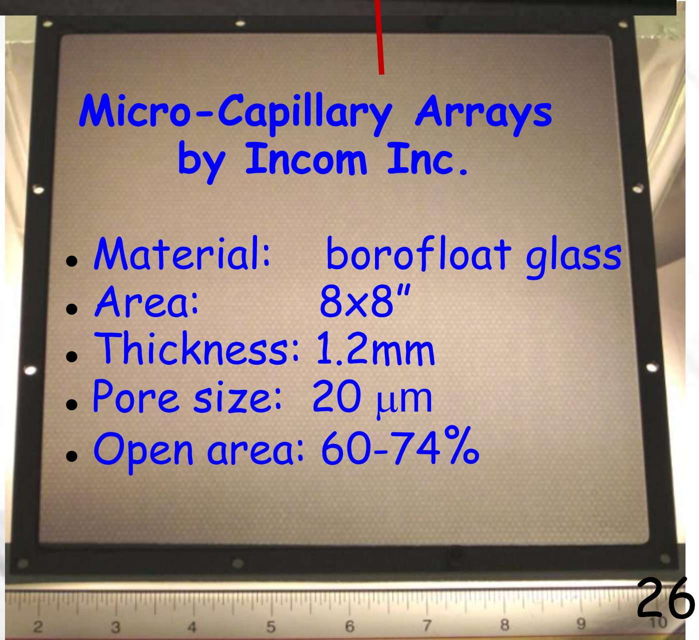
Micro-Channel Plates (MCPs)



Atomic Layer Deposition (ALD)

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





Micro-Capillary Arrays by Incom Inc.

- Material: borofloat glass
- Area: 8x8"
- Thickness: 1.2mm
- Pore size: 20 μm
- Open area: 60-74%

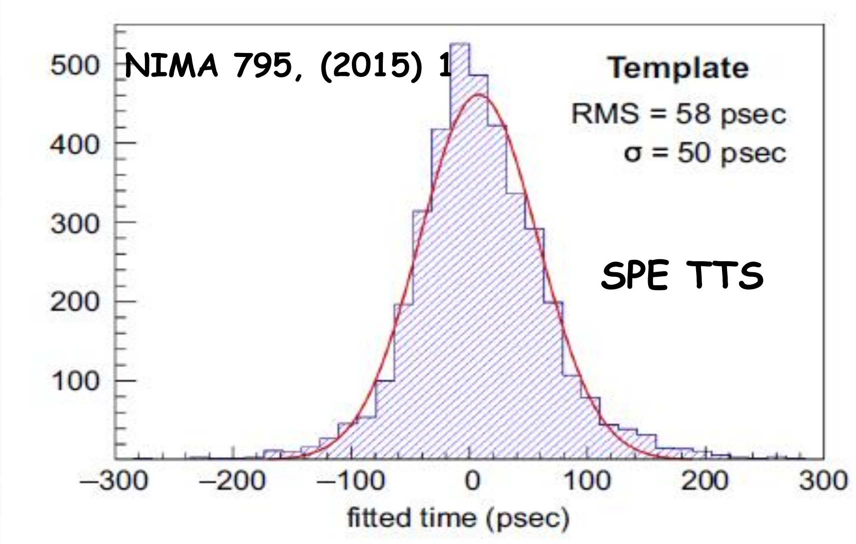
LAPPD™ is being commercialized by Incom Inc.

LAPPD Timing Capabilities

There are two very distinct scenarios
to define Transit Time Spread (TTS):

1) Single Photo-Electron (SPE TTS)

- applications with a low number of photons per surface area (e.g. neutrino experiments)
- 50 ps has been demonstrated
- can be improved with smaller pores size



2) Multi Photo-Electrons (MPE TTS)

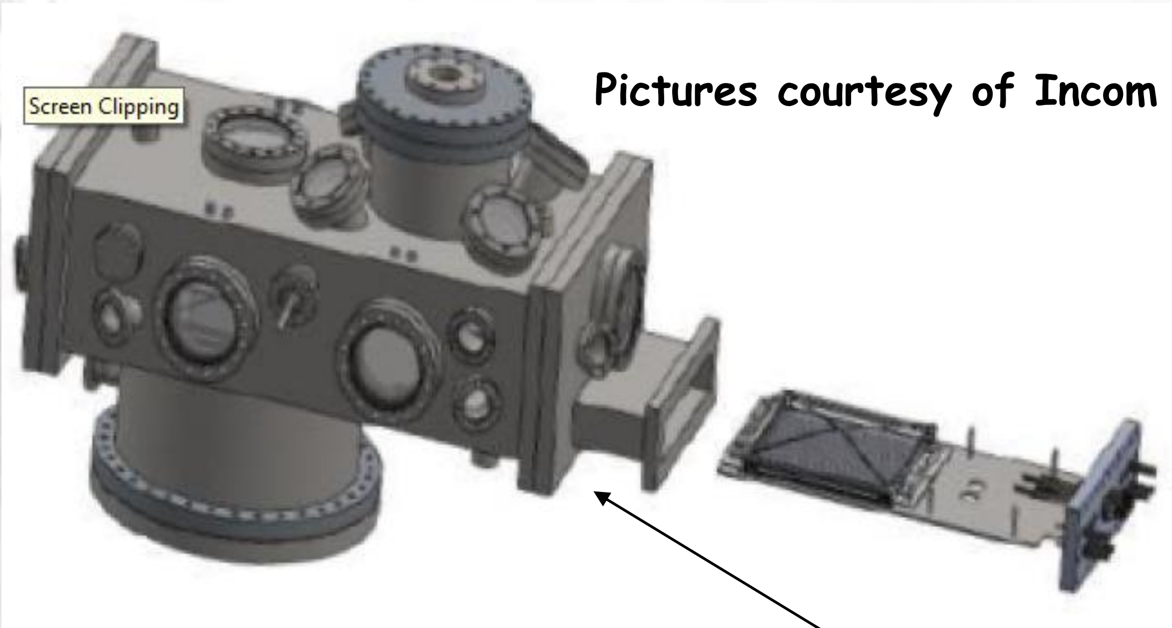
- applications with lots of light (e.g. Cherenkov light from charged particle on the front window)
- effort is ongoing to measure MPE TTS

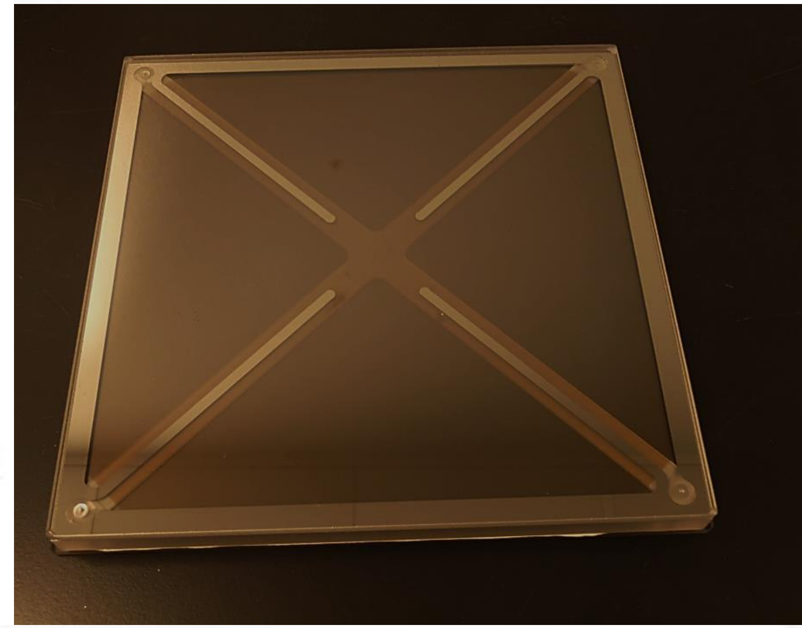
Oshima et al demonstrated ~5 ps MPE TTS for MCP-PMTs

Anatoly Ronzhin and Caltech team got ~7 ps at the Testbeam at Fermilab

Vacuum Transfer

LAPPDs are now routinely produced
using this process at Incom Inc

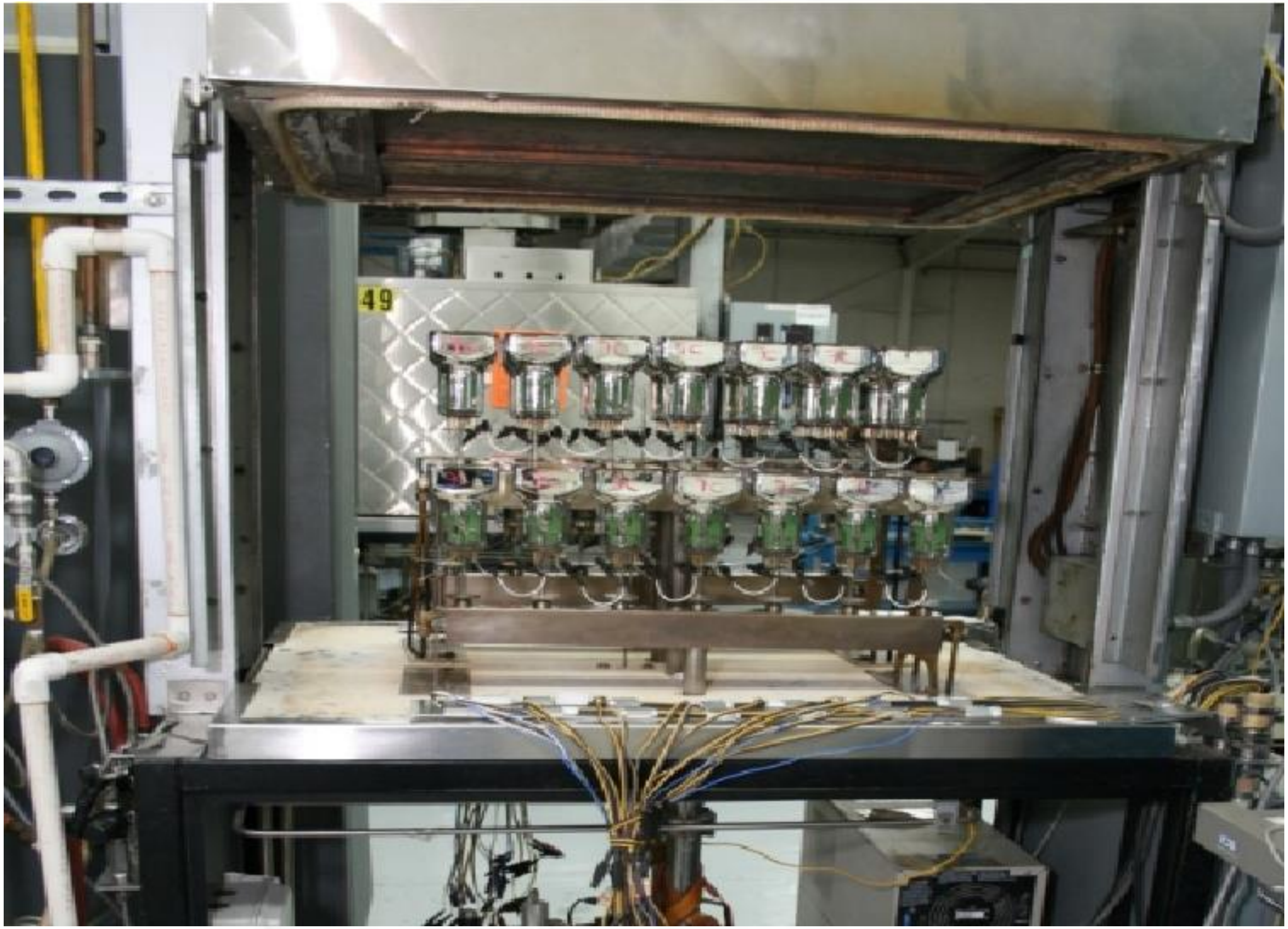




Industry standard vacuum transfer process

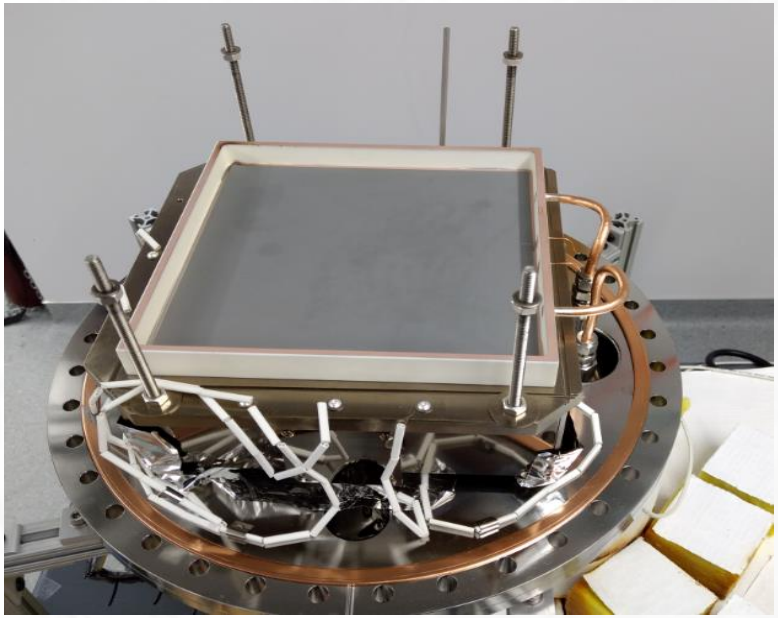
- Photocathode is synthesized in a separate volume of the assembly chamber
- The window is transferred in ultra-high vacuum to be hermetically sealed over the pre-assembled MCP-Anode stack-up ("tile")

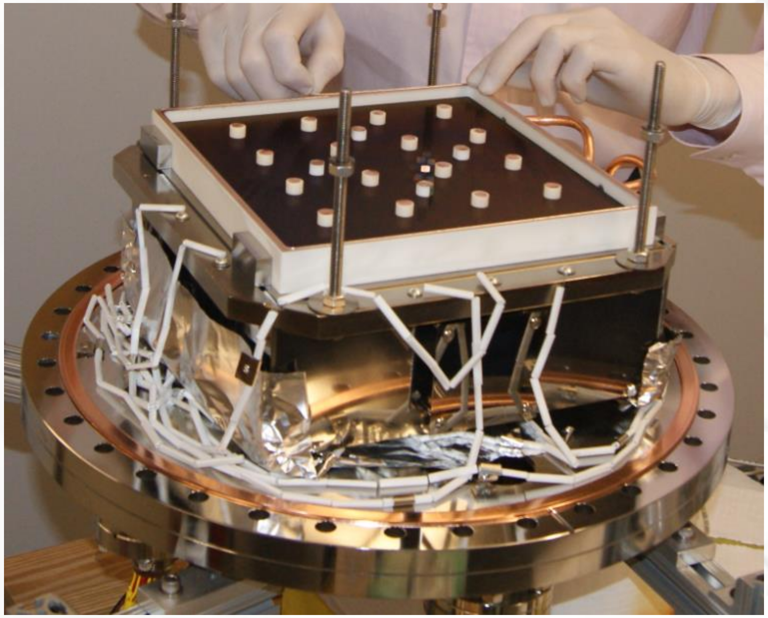
Can We Make LAPPDs in Batches Like PMTs?



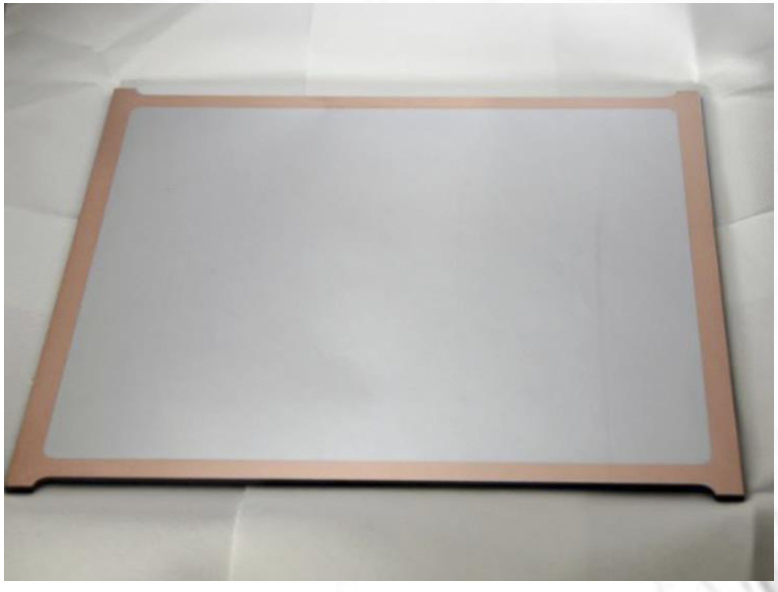
Chicago group has been exploring if a process without vacuum transfer can be inexpensive and easier to scale for a very high volume production

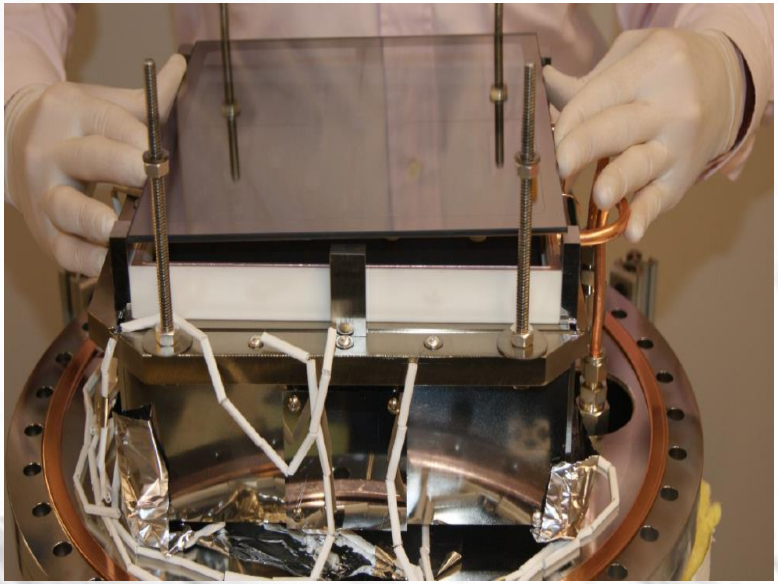
Air-Transfer



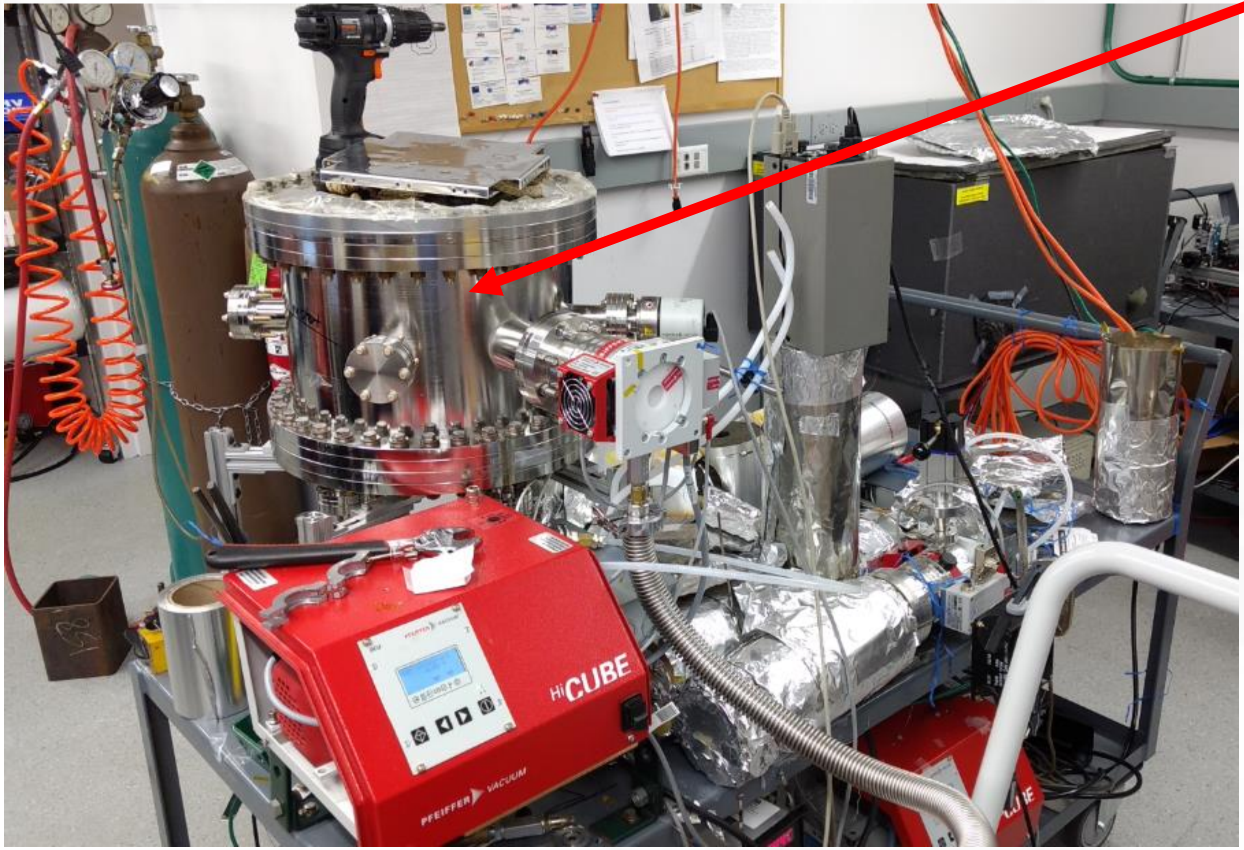


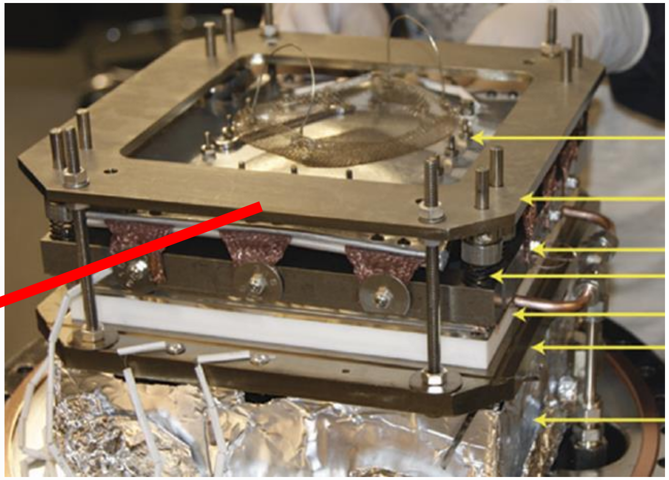
Transfer the window with a pre-deposited Sb precursor in air to synthesize photocahode after hermetic package is formed





Air-Transfer Processing Chamber

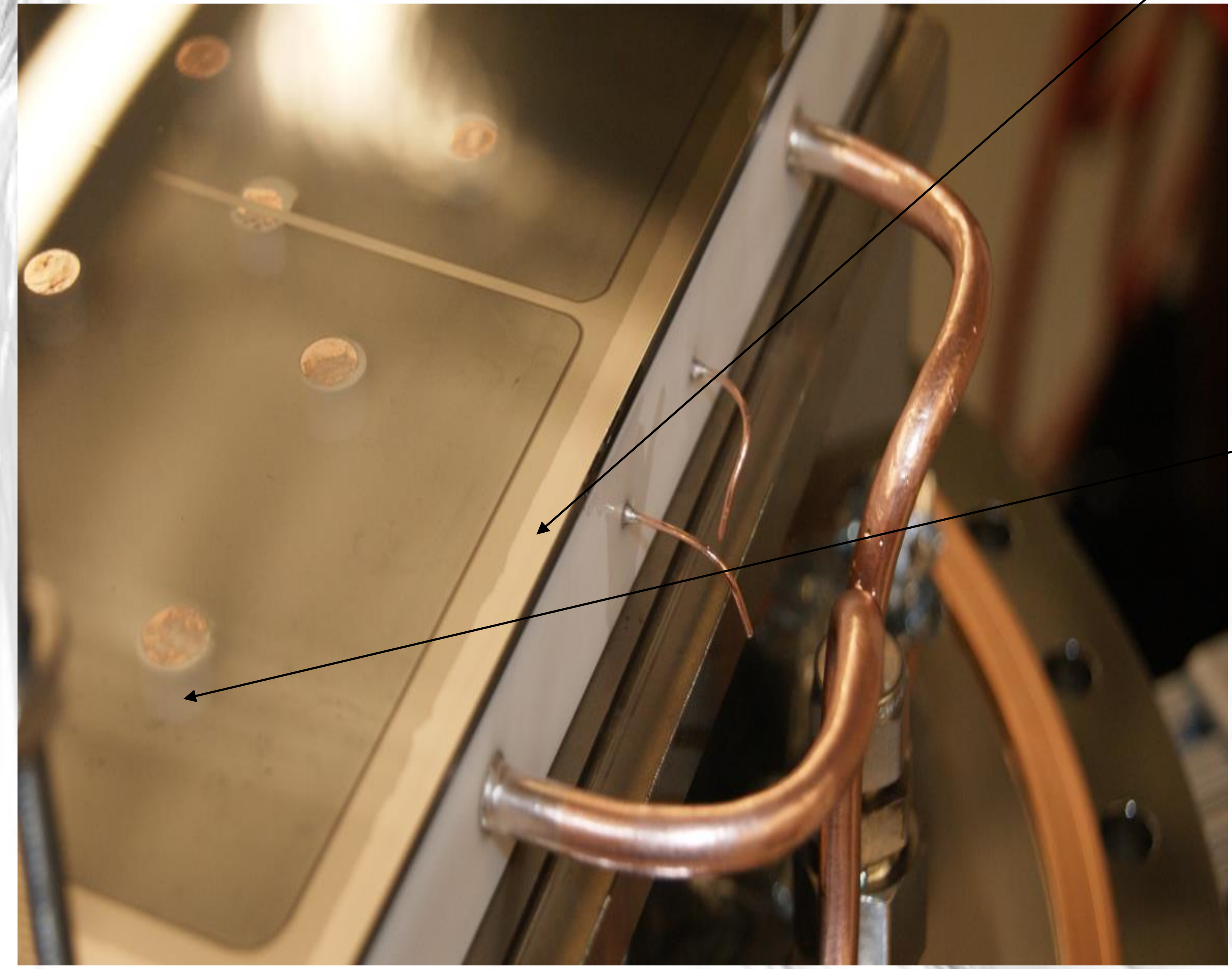




Dual vacuum system
Heaters are around the tile, not around the vacuum vessel

After Bakeout and Hermetic Seal

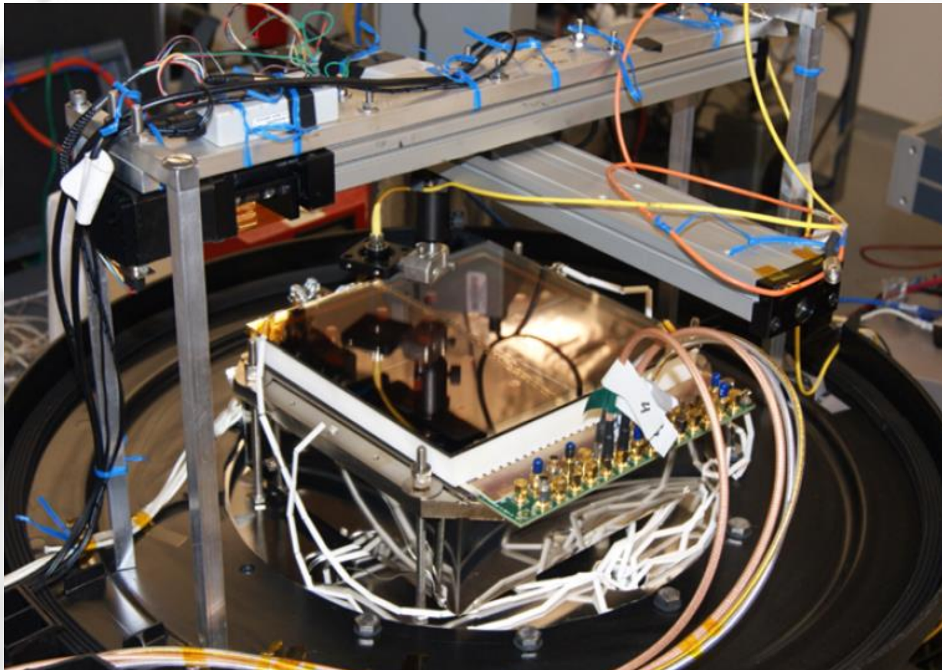
Ultra-sensitive (~10^{-12} cc/s of He) check for leaks can be done at this step



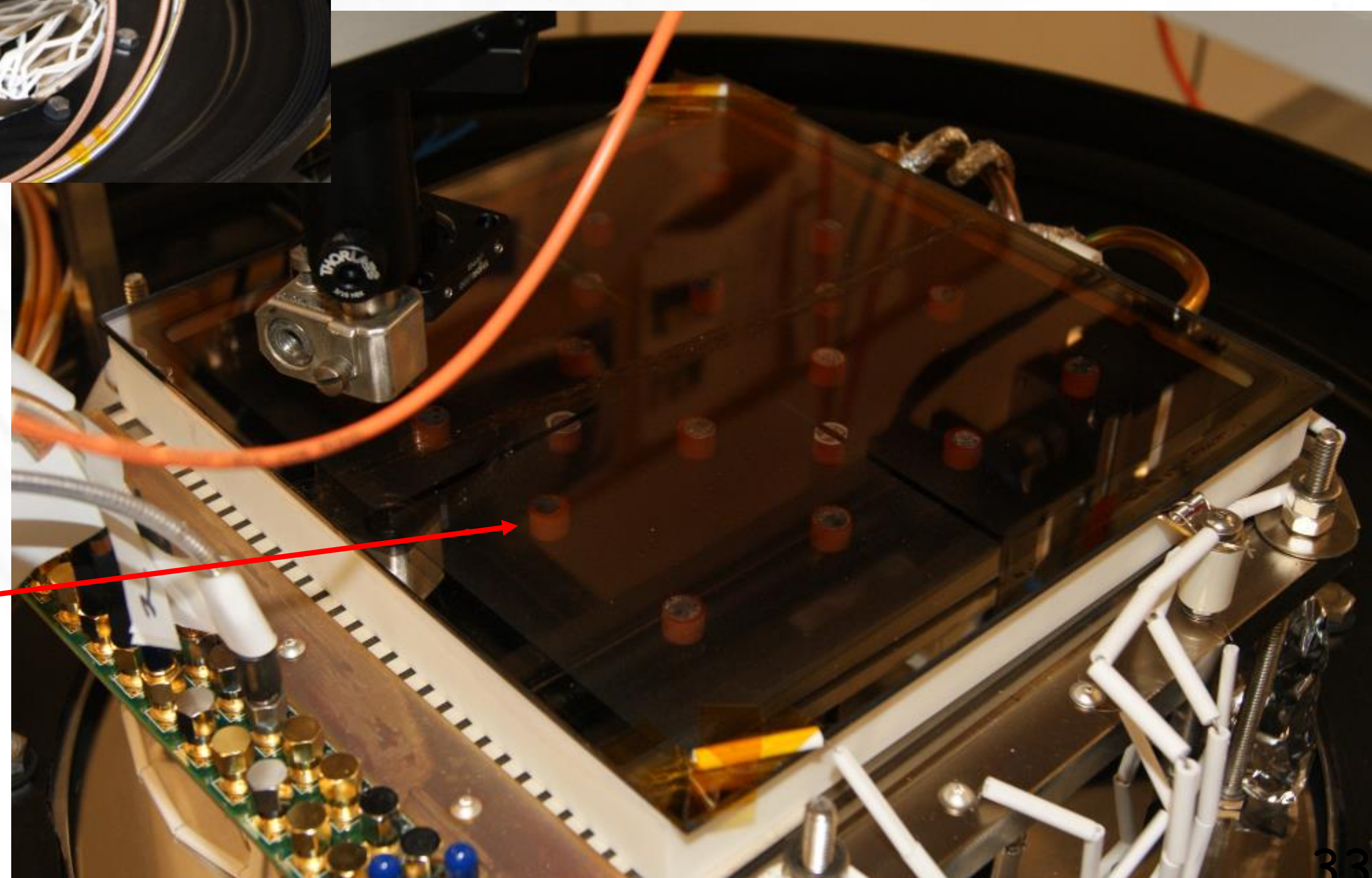
Indium seal line
(The most tricky part. A lot of effort has gone into development of a robust hermetic packaging.)

Buttons appear gray/white color (view through a window with a thin Sb layer)

Photocathode Synthesis

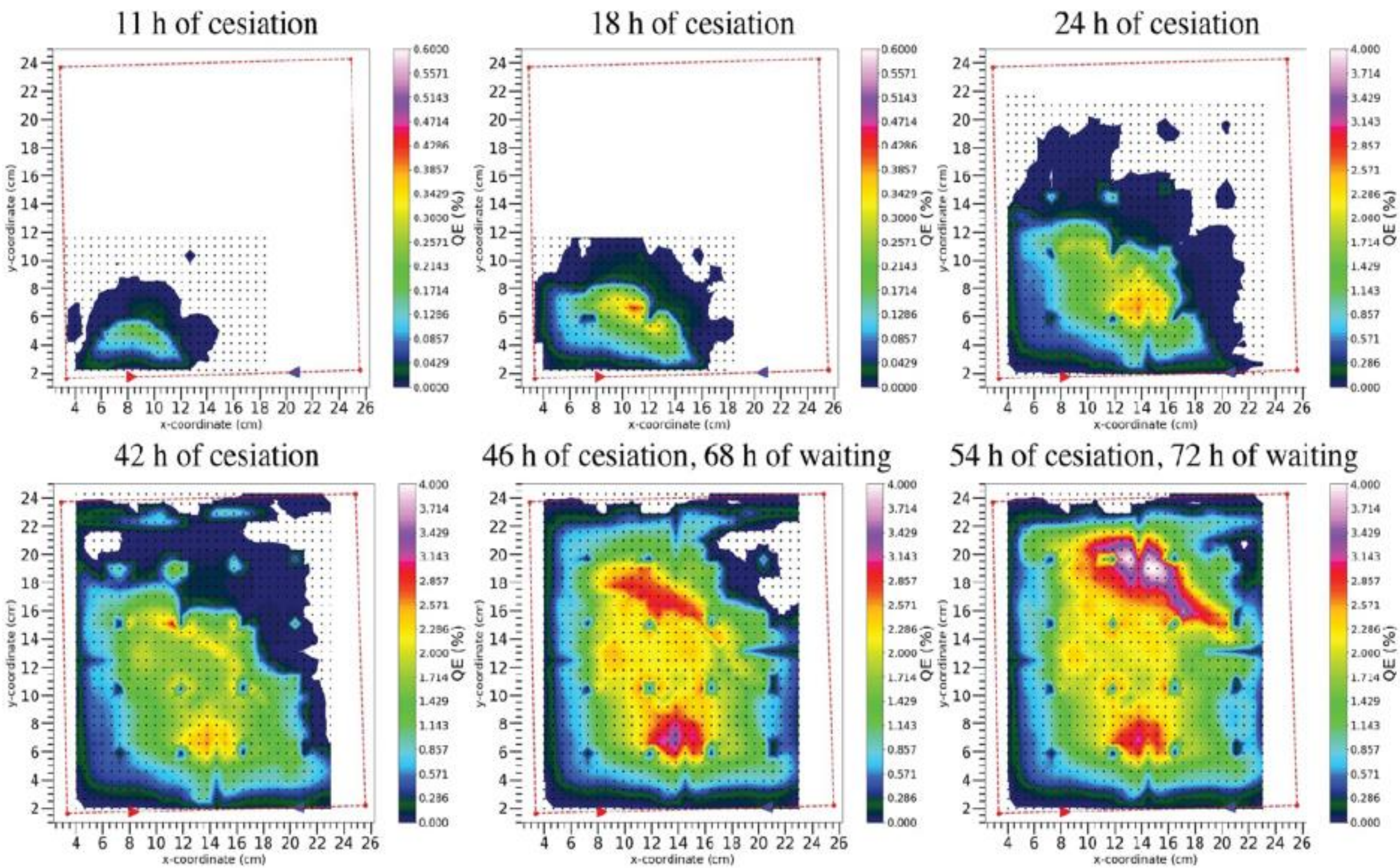


In-situ photocathode synthesis with full access to the detector



Note reddish color of the buttons appearance (view through a window with Cs-Sb layer)

Air-Transfer Photocathode



Chemistry of photocathode synthesis using Sb in equilibrium with Cs is well known

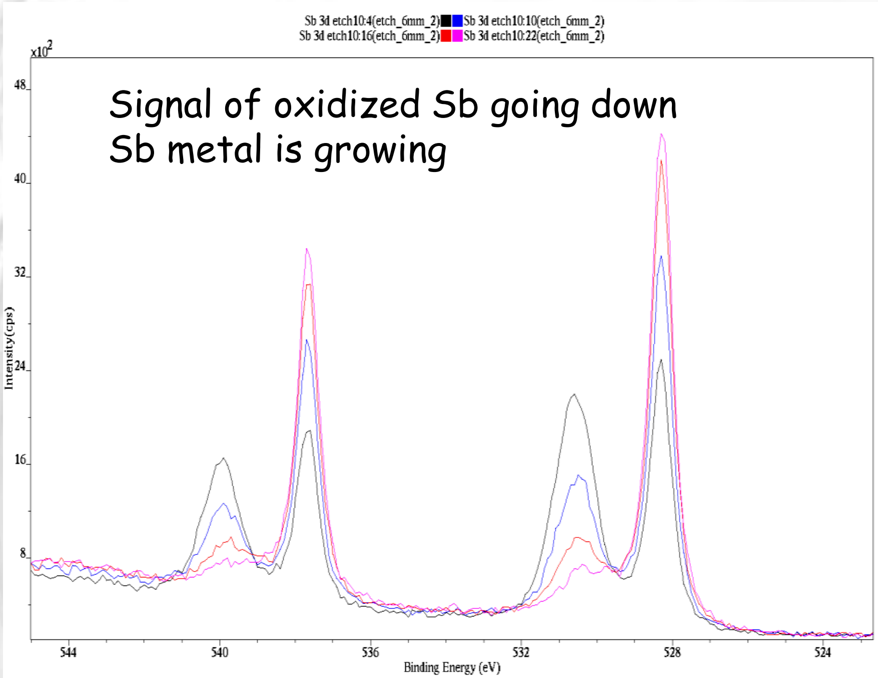
- J.M. Barois et al, Mater. Chem. Phys. **24** (1989) 189, Mater. Chem. Phys. **30** (1991) 7

Making photocathode after Sb exposure to air is a well established industry process

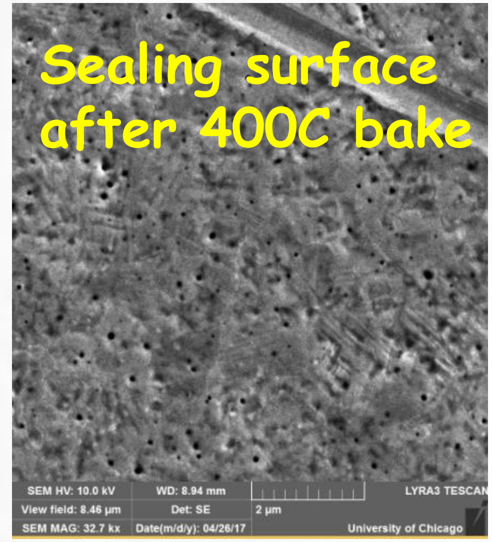
- MELZ-FEU Ltd., Zelenograd, Russia, catalog item FEU-527
- Hamamatsu [NIMA **970** (2020) 163373]

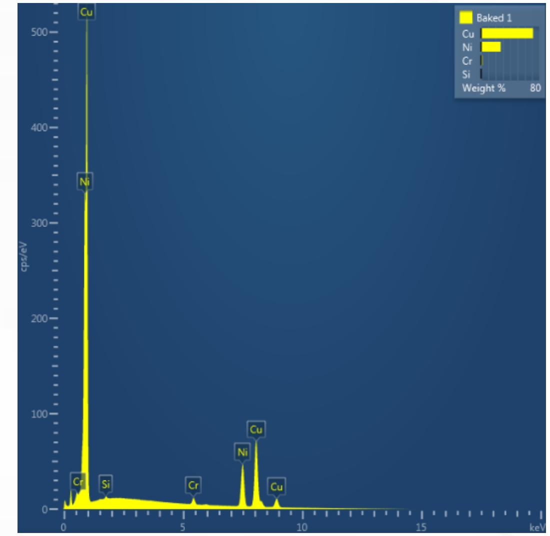
Material Characterization

XPS



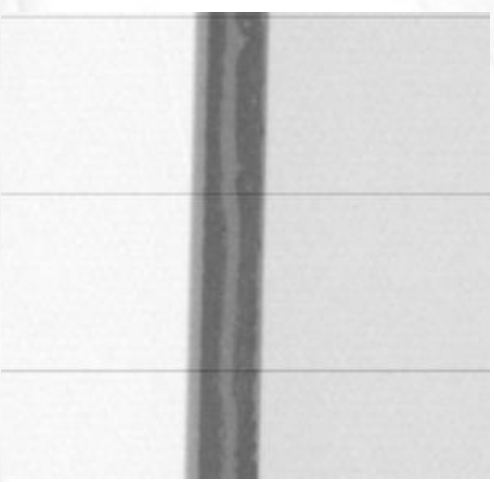
SEM and EDS





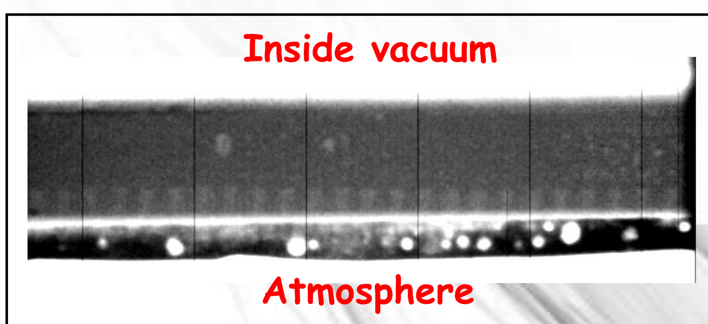
(Very Good) Optical Microscope

X-ray

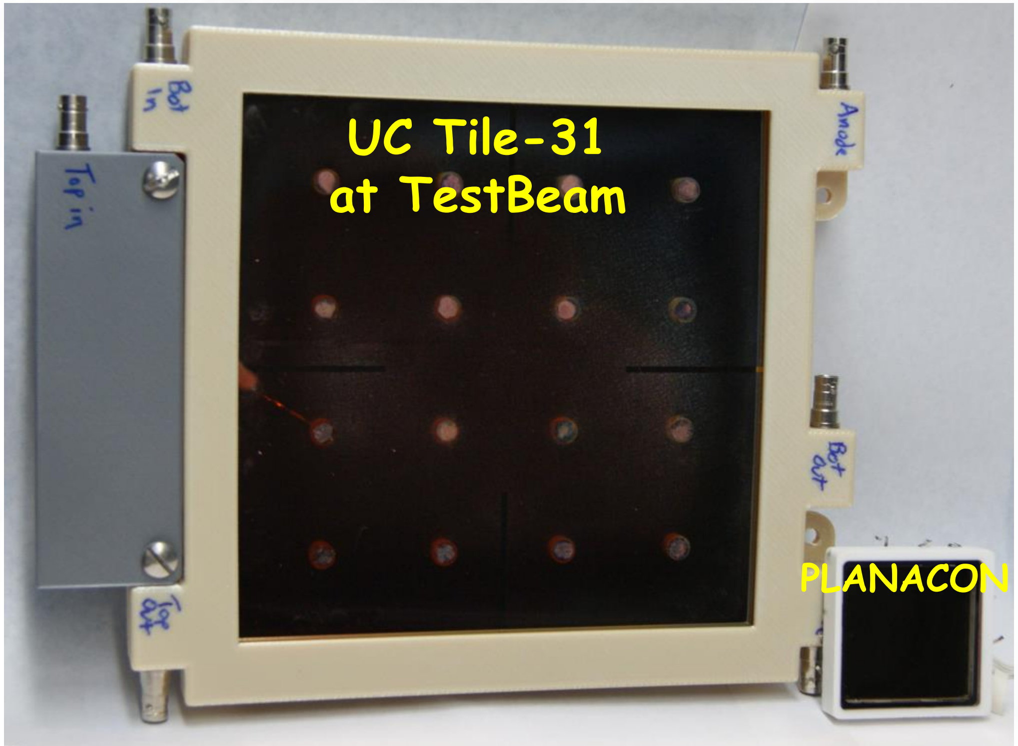


Turning (very) good recipes into well understood processes

X-ray showing continuity and quality of indium in capillary seal



Tile-31



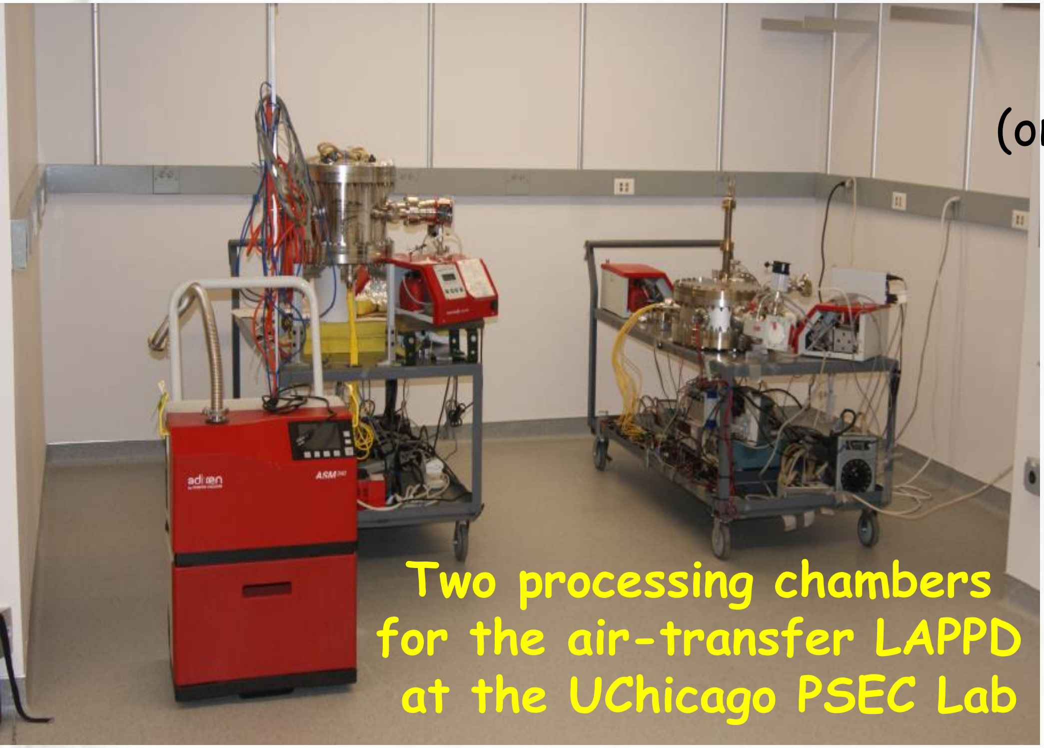
E. Angelico, A. Elagin, H.J. Frisch, E. Spieglan, B.W. Adams, M.R. Foley, M.J. Minot, "Air-Transfer Production Method for Large-Area Picosecond Photodetectors", Rev.Sci.Instrum. **91** (2020) 5, 053105

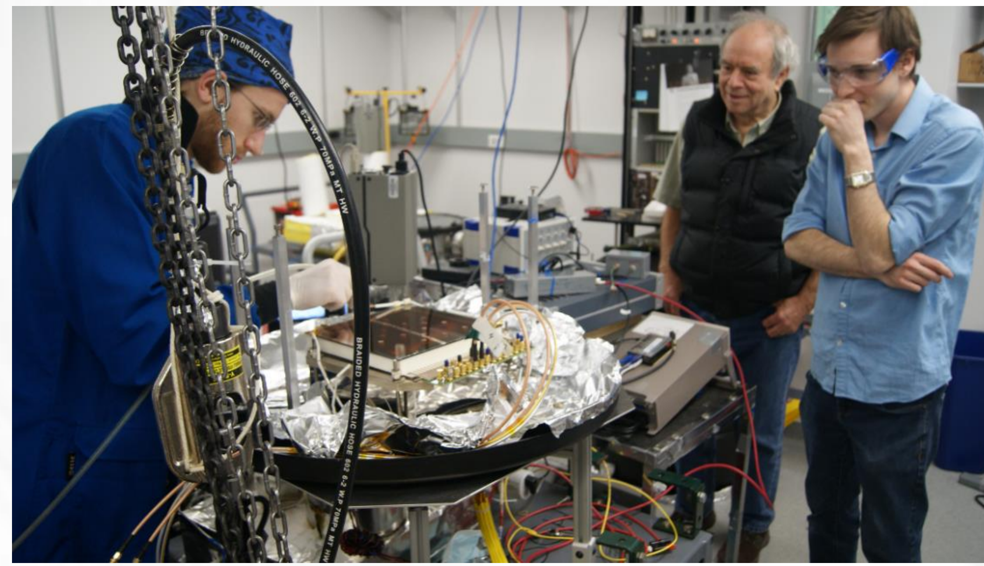
This was not a competition with industry

- The entire time we worked closely with our industry partners from Incom Inc
- We took a risky R&D path while Incom were focusing on another difficult and very important task - making LAPPDs available by scaling up the vacuum-transfer process to an unprecedented 8x8" format

Towards Batch Production

UC Team:
Evan Angelico, Henry Frisch, Eric Spieglan,
and AE behind the camera
(only 75% of the group can be on the same photo)





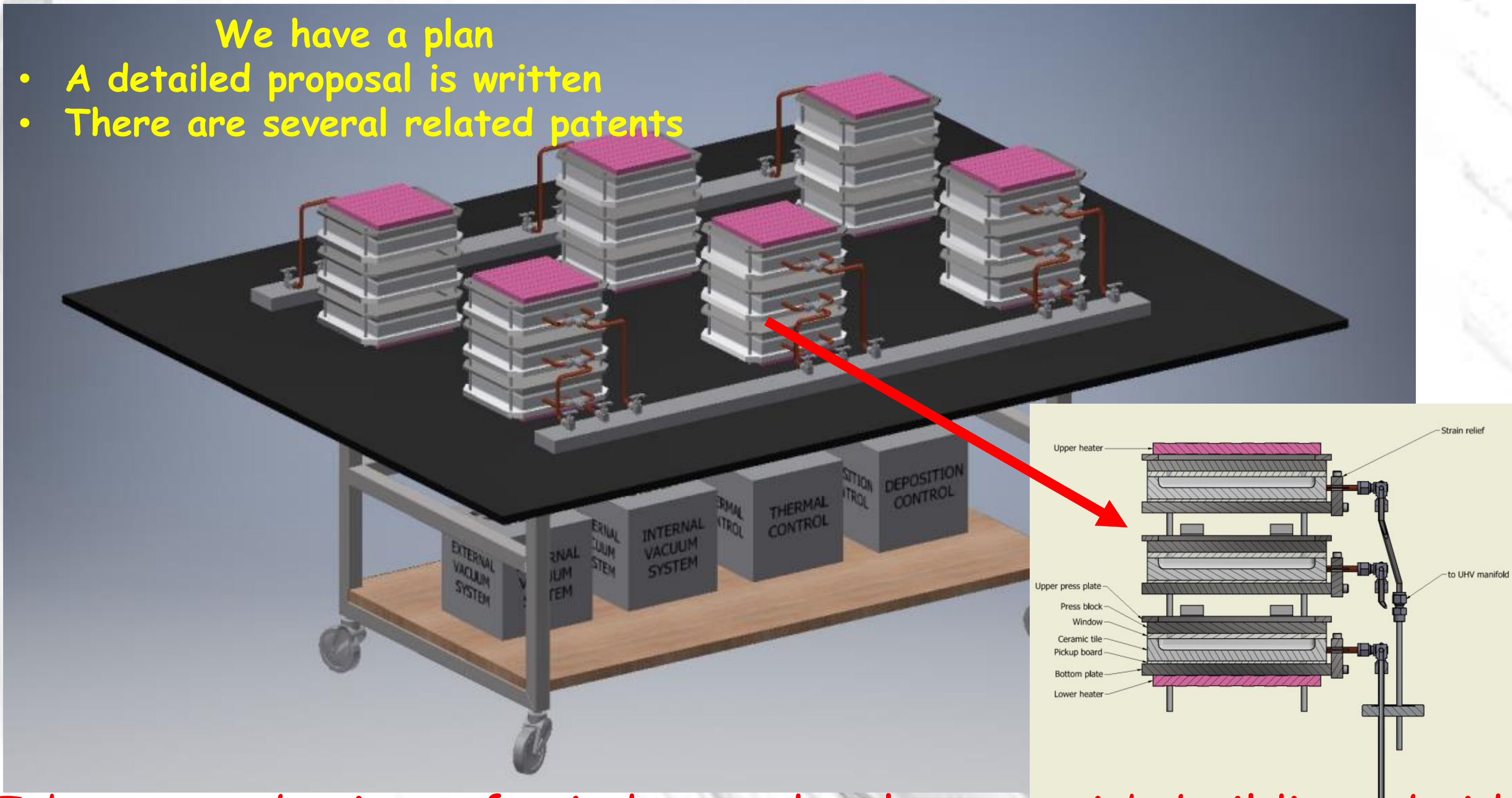
- I believe that as a small team at a university settings we have gone as far as we could
- Feasibility of using air-transfer for LAPPD production has been demonstrated
- Optimization is still to be done, but
- There are no showstoppers

Proposal

- I would like to bring the UC processing chamber to Fermilab
- Optimize process for single tile production
- Build an 18-tiles production table
- Transfer the technology to industry so that we can focus on how to use LAPPDs for new discoveries

We have a plan

- **A detailed proposal is written**
- **There are several related patents**



It's not a substitute for industry development, it's building a bridge

How Large the Effort Would Be?

A relatively small-size operation is required

People

- 1 Engineer (~75% FTE)
- 2 Experienced Techs (full time)
- 1 Postdoc (mostly TestBeam and LAPPD applications)
- 1 Junior Tech (part time, mostly to help with Testbeam)

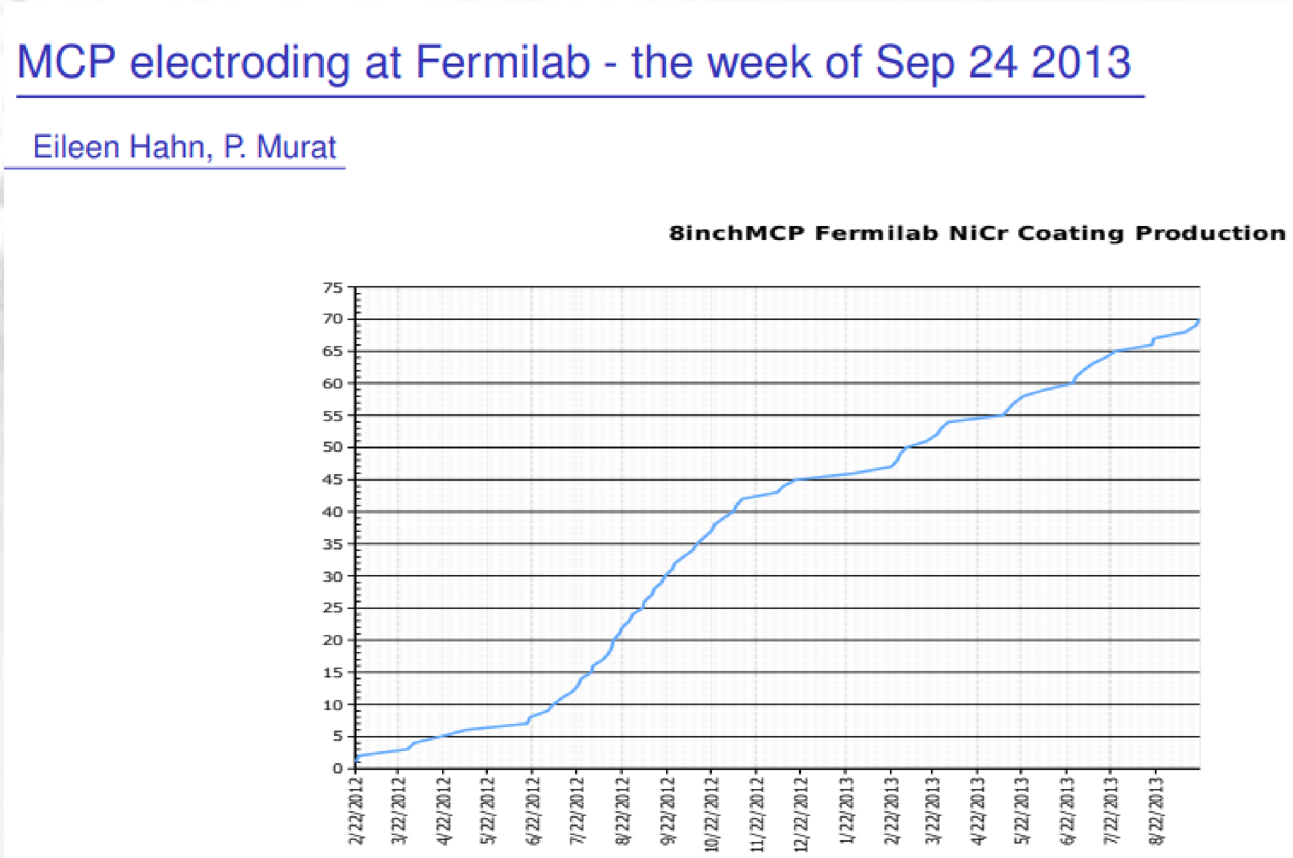
Equipment

- For a 3-year period, MCPs would be about half of the total price tag for the hardware
- The other half is a typical cost of building a mid-size vacuum system

Important clarifications

- It's a project with an end day in about 3 years
- That's the time for the bridge
- The 18-tile production table is just a prototype for industry to pick up and scale-up further
- The goal is to enable an industrial yield of up to 100 LAPPDs/week
- The goal is NOT to turn Fermilab into an LAPPD factory

Why at Fermilab?



Over 70 large-size 8x8" MCP were electroded by Eileen Hahn, thank you!

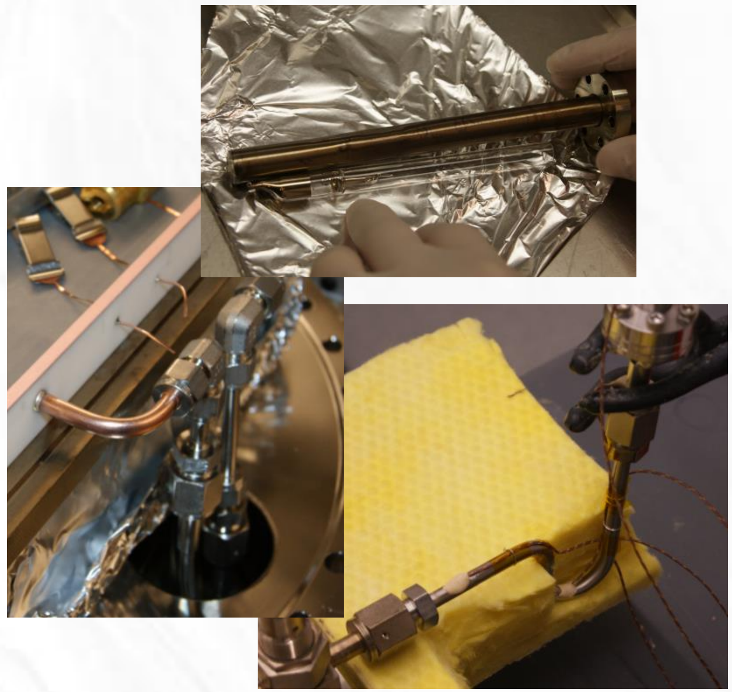
Fermilab has already played a major role in LAPPD development

(many thanks to Pasha Murat and Erik Ramberg)

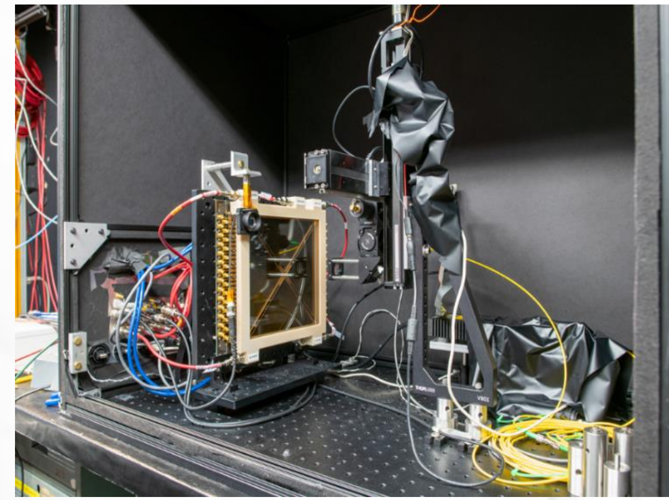
Why at Fermilab?

LAPPD coating chamber at Lab 7

Precision welding of vacuum components for Cs source



Dark box test setup at Lab 6



Fermilab has the necessary infrastructure that we are already using

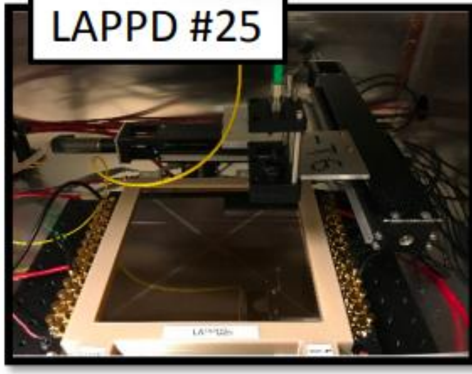
(many thanks to Petra Merkel, Luciano Ristori, Rick Ford)

Why at Fermilab?

ANNIE

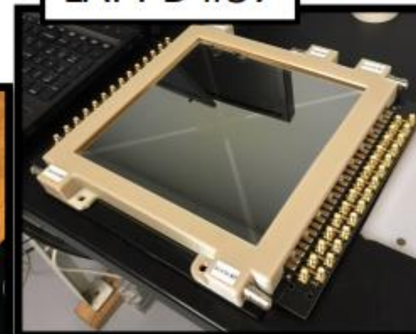
Currently can use up to 32 LAPPDs, Phase III ANNIE can use up to 200 LAPPDs

LAPPD #25

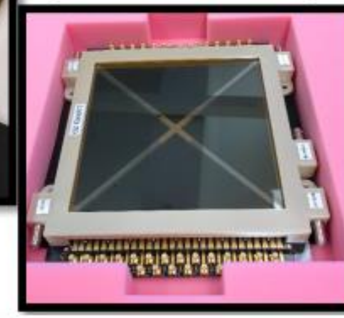


LAPPD #31

LAPPD #37



LAPPD #39



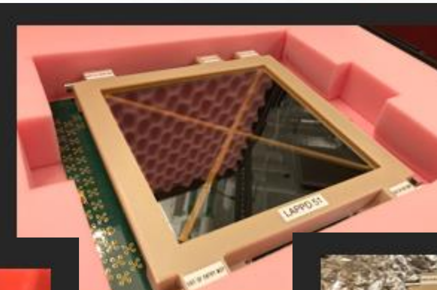
LAPPD #40

Commercial LAPPDs by Incom Inc.

Testbeam

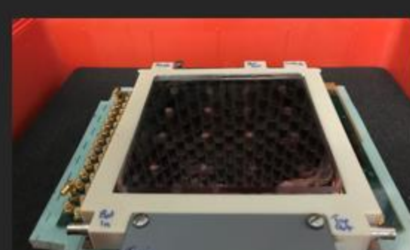
LAPPD 43

LAPPD 51



Potential candidate for IOTA run at 150 MeV

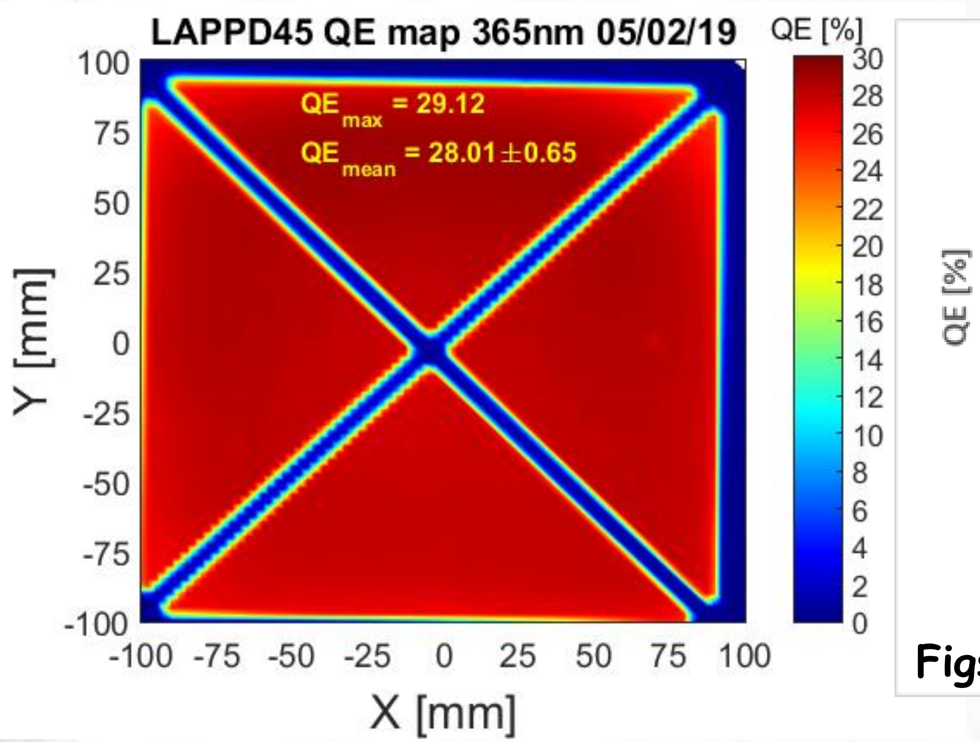
UChicago Tile 31

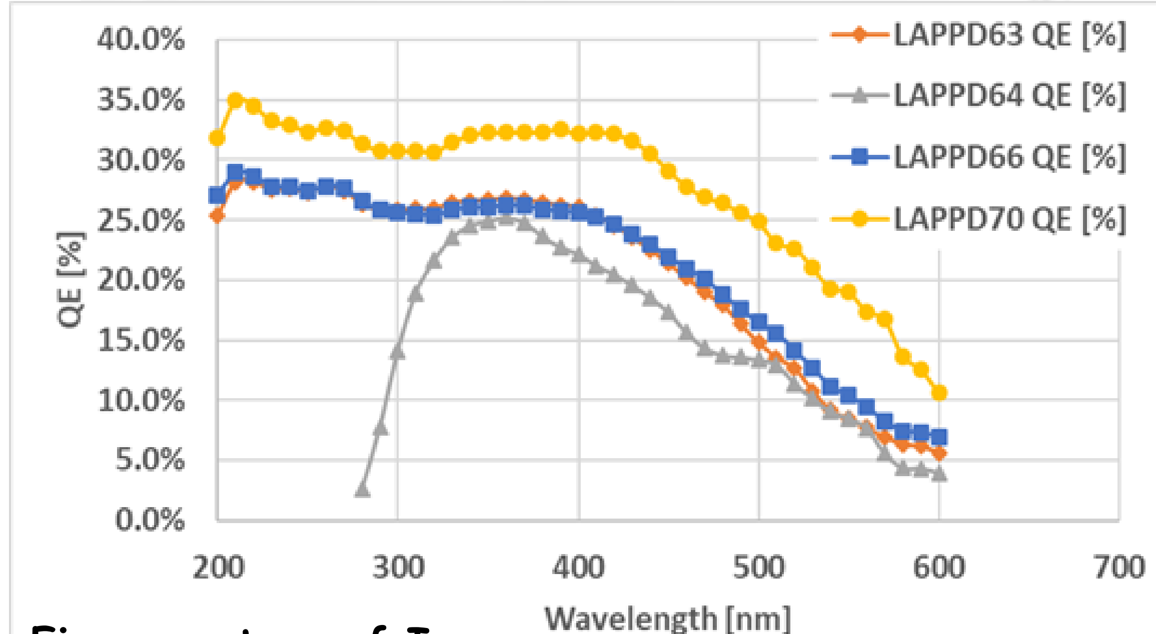


LAPPD 42

Fermilab already has the largest number of LAPPDs on site

Incom LAPPDs





Figs. courtesy of Incom

Performance summary

- Gain: mid-10^6 and above
- Dark rate: $10^3/cm^2$
  (in the mid-10^6 gain range)
- TTS: ~55 ps or better
- QE: 20-30% @ 365 nm

Availability status

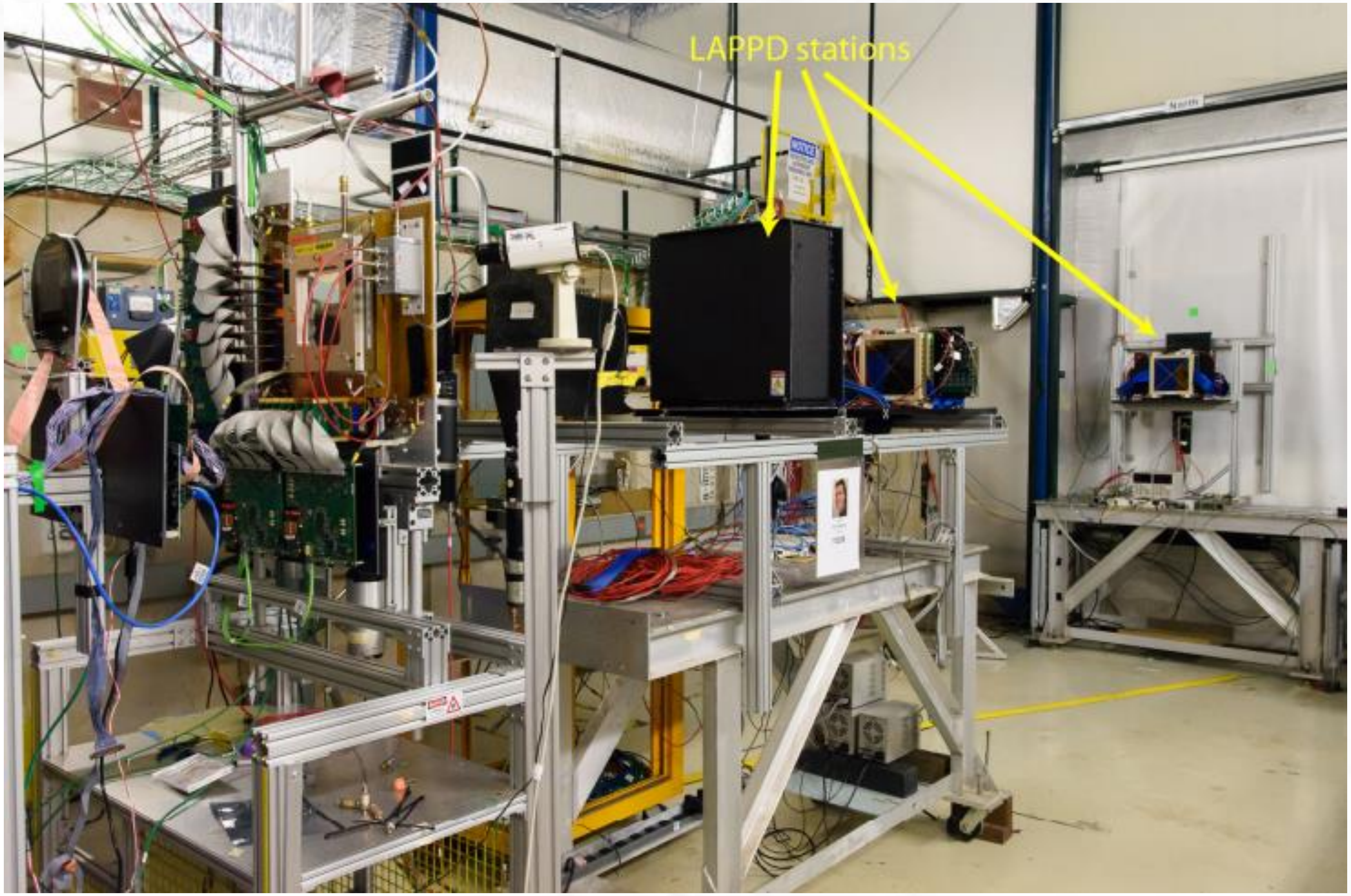
- Established reproducible process
- Present capacity 4 LAPPDs/month
- Plan 6 LAPPDs/month by late 2020
- LAPPDs are available for rent or purchase
- Qualified prospects that don't presently have a budget or the ability to either rent or purchase an LAPPD may qualify for special negotiated terms.

Particle physics community needs high production yield of LAPPDs (50+/week)
Working closely with Incom on batch production is important

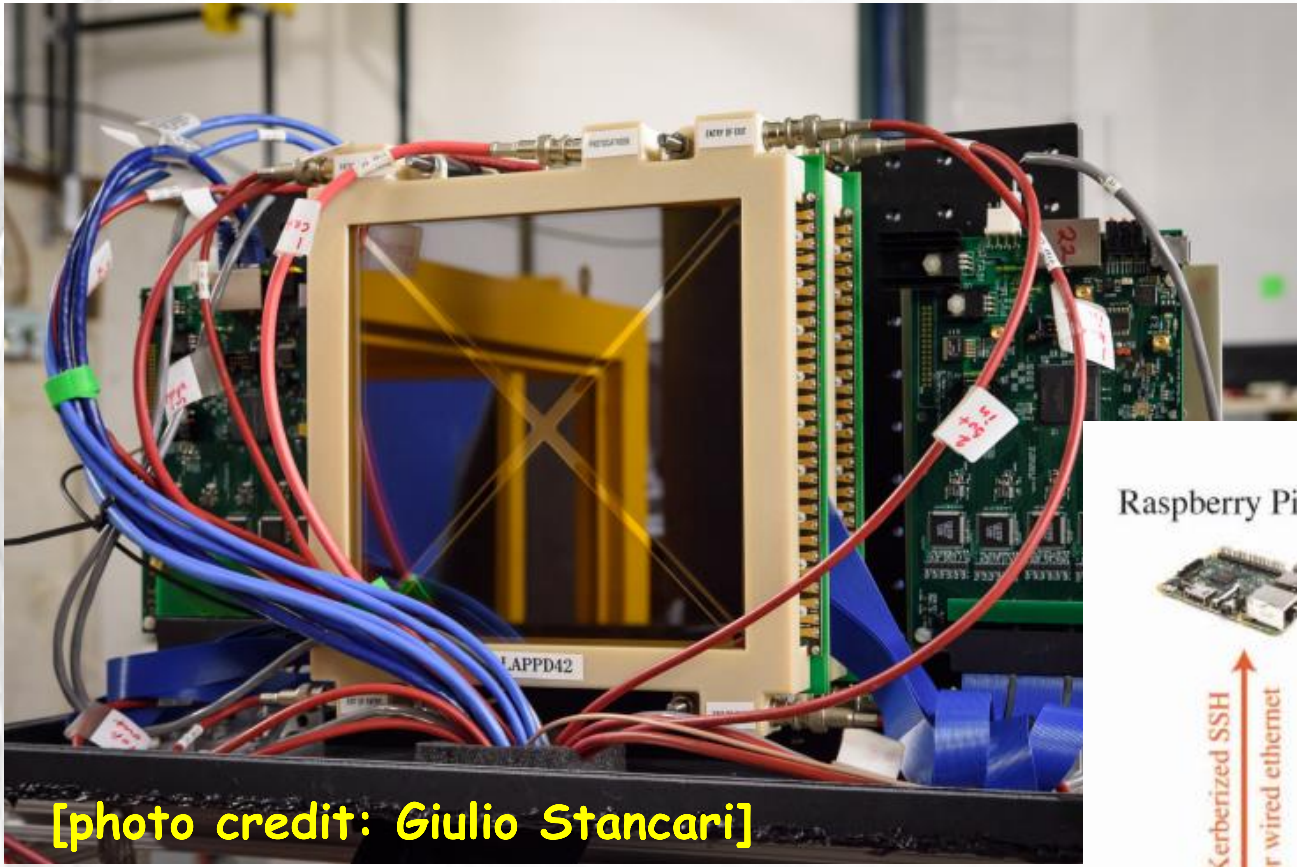
TOF Particle ID at FTBF

Enable users to:

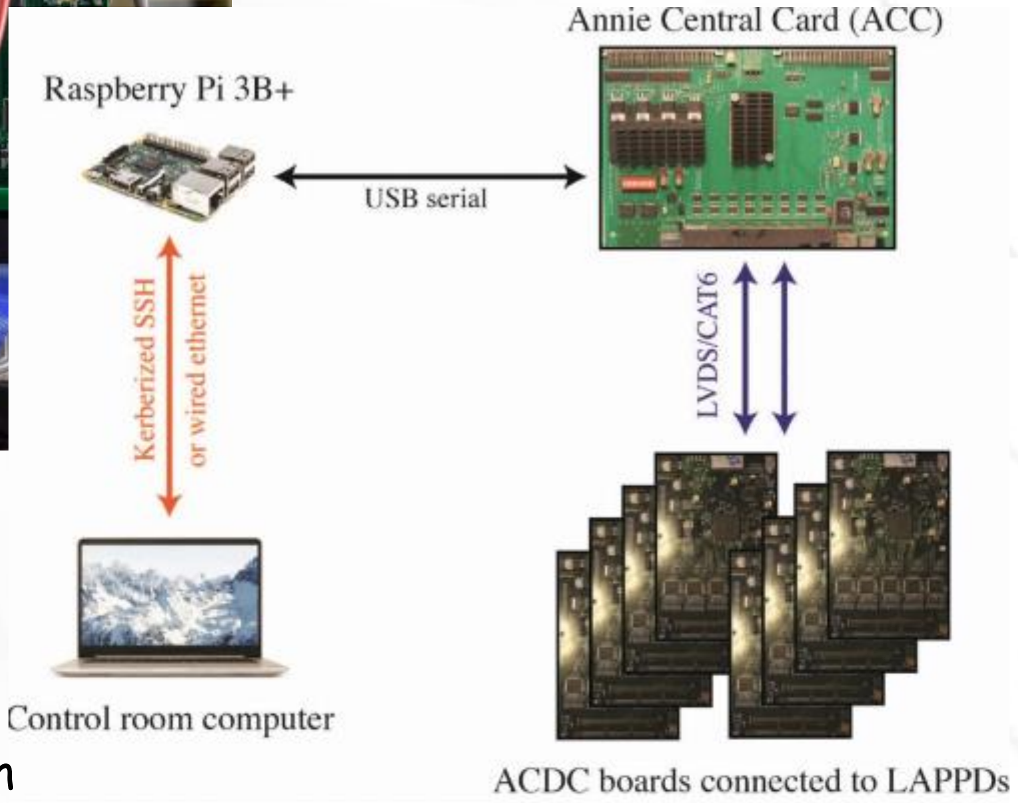
- Identify particles in the beam
- Measure how their detector respond to different flavors (e.g. calorimeter response to K and pi)
- Reject unwanted particles from their data analysis sample



TOF Particle ID at FTBF

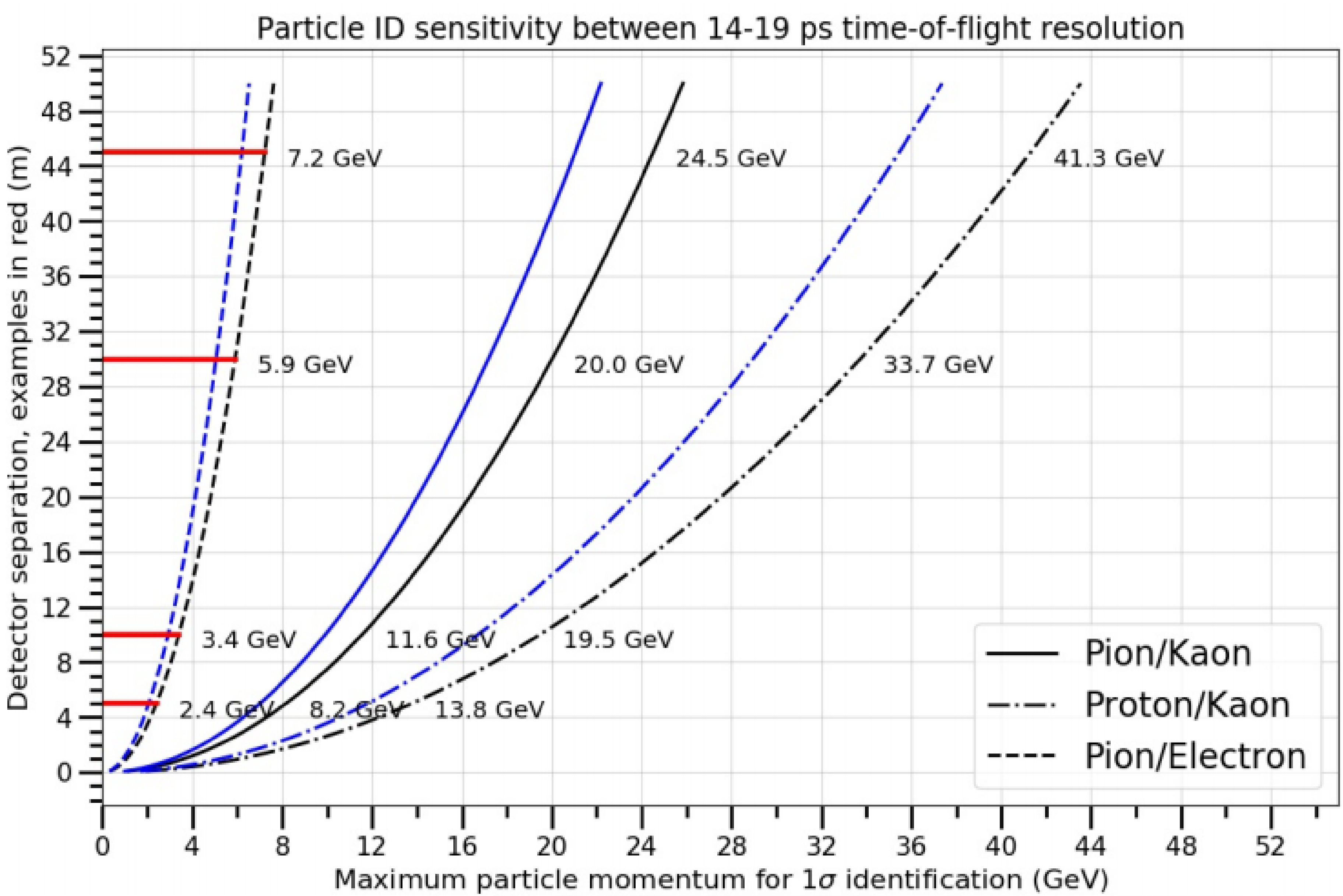


Multi-channel PSEC4 electronics has been developed



A commercially available clock synchronization system (White Rabbit) has been identified and is being implemented at FTBF

TOF Particle ID at FTBF



Evan Angelico PhD thesis, June 2020

A 3 Year Plan for FTBF

Single PE TTS

Readout electronics

White Rabbit
Clock synchronization

	$\sigma_L/\sqrt{N_{pe}}$	σ_{pulse}	σ_{WR}	σ_{tof}	Maximum π/K momentum at 5 m / 45 m
Present installation	55 ps / $\sqrt{30}$	7 ps	5 ps	19 ps	7.0 / 21 GeV/c
Use of fused silica window	55 ps / $\sqrt{200}$	7 ps	5 ps	14 ps	8.2 / 25 GeV/c
Low-jitter WR-ZEN	55 ps / $\sqrt{200}$	7 ps	< 0.5 ps	13 ps	8.5 / 25 GeV/c
10 μm pores and higher cathode voltages	10 ps / $\sqrt{200}$	7 ps	< 0.5 ps	11 ps	9.2 / 28 GeV/c
PSEC4 chip development	10 ps / $\sqrt{200}$	1 ps	< 0.5 ps	1.7 ps	24 / 70 GeV/c

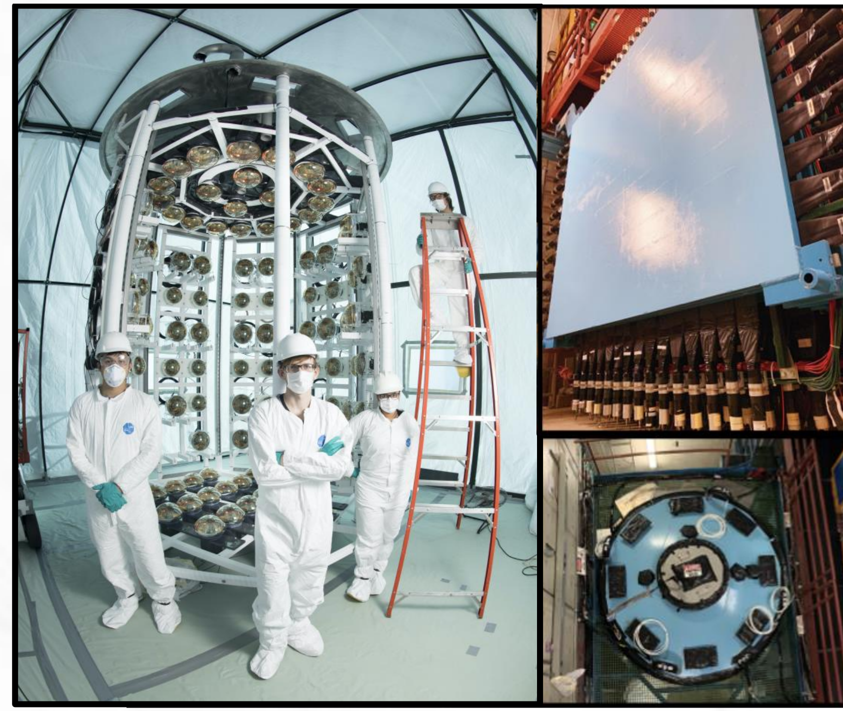
Evan Angelico PhD thesis, June 2020

ANNIE

Accelerator Neutrino Neutron Interaction Experiment

- Fermilab is already leading the field in the development of the next-generation water-based neutrino detector as the home of the ANNIE experiment
- International collaboration with 12 institutions from 3 countries:

- Fermilab approved and deployed on the Booster Neutrino Beam (former SciBooNE Hall)



New technologies

- First application of LAPPDs in a neutrino detector
- First Gd-loaded water on a neutrino beam and *only* Gd-loaded near detector.
- Likely first deployment of WbLS

New reconstruction capabilities

- Demonstration of Ch/Sc separation using LAPPDs in a neutrino detector
- Able to efficiently count final-state neutrons
- Able to resolve energy from sub-Cherenkov particles

New physics opportunities

- Ability to measure neutrino-Oxygen cross-sections with unprecedented statistics and detail
- Particular attention to neutron yields of neutrino-Oxygen scatters

The material for this slide is courtesy of Matt Wetstein

Built, commissioned, and ready for beam data in November

Longer Time Scale Plan for the Field

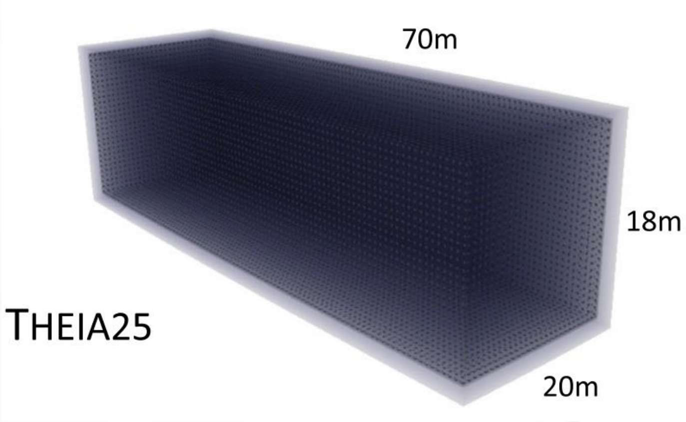
Large Directional Liquid Scintillator

- Large scintillator detectors and large water-Cherenkov detectors have been very effective in measuring neutrino properties

- Combining the two technologies may allow expanded physics reach of the next generation large neutrino experiments:
  - Cherenkov light provides directionality
  - Scintillation light provides good energy measurements

- Physics Program of THEIA:
  - Neutrinoless double beta decay
  - Solar neutrinos
  - Geo-neutrinos
  - Supernova burst neutrinos & DSNB
  - Nucleon decay
  - Long-baseline physics (mass hierarchy, CP-violation)
  - Unexpected surprises

A concept drawing of the THEIA detector



Several design options exist (e.g. 25kT, 50kT, and 100kT)

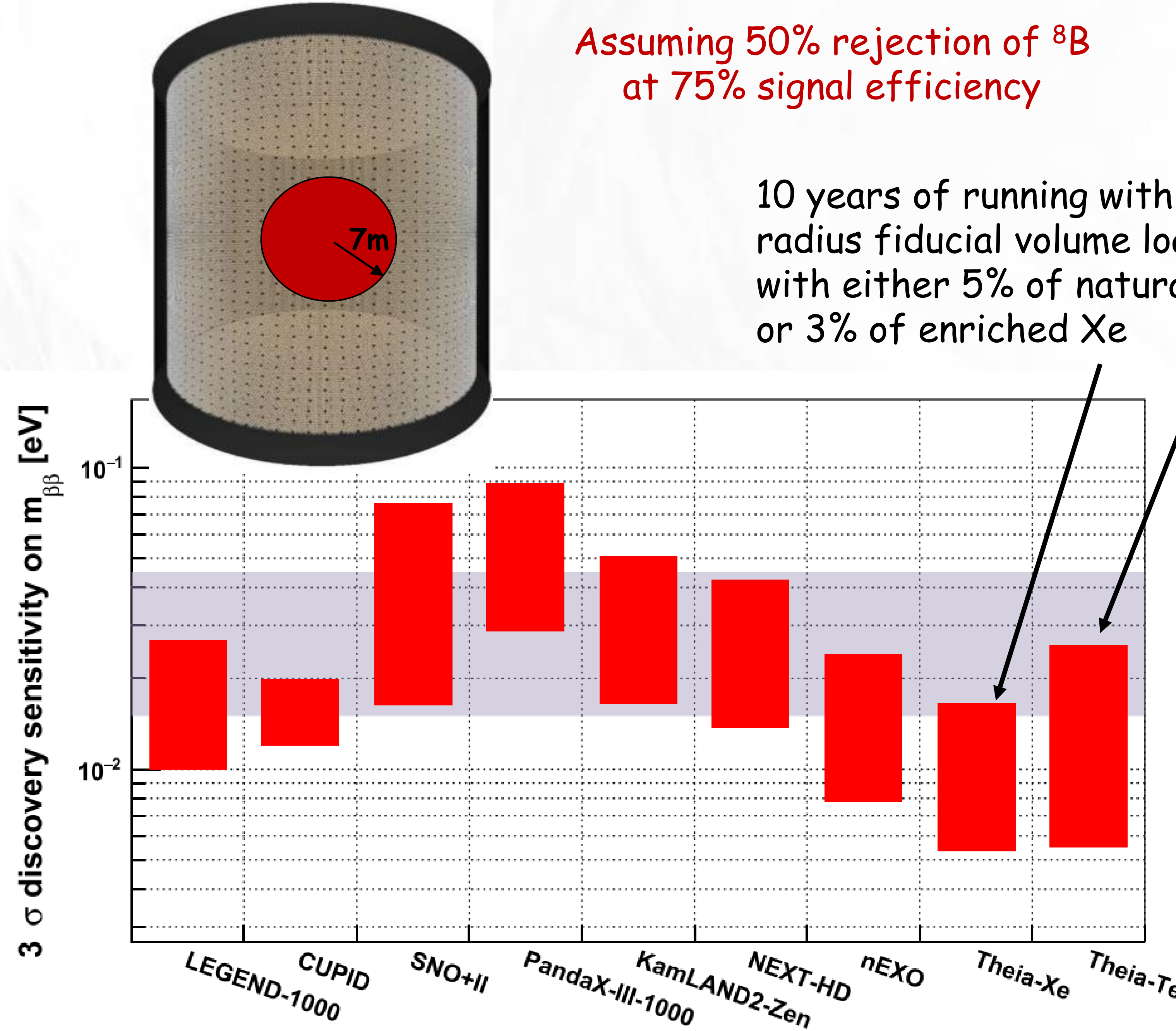
Currently there are several smaller scale experiments that can develop components and test ideas for such hybrid detector

Besides ANNIE there is CHESS, NuDot, Watchman, and more

0νββ-decay Sensitivity

Assuming 50% rejection of ^8B
at 75% signal efficiency

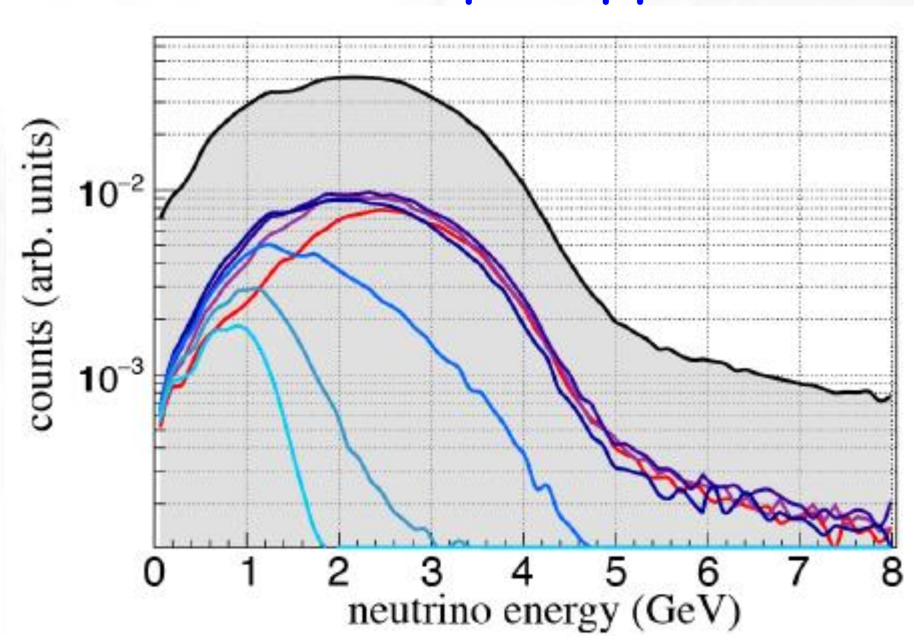
10 years of running with a 7 m radius fiducial volume loaded with either 5% of natural Te or 3% of enriched Xe



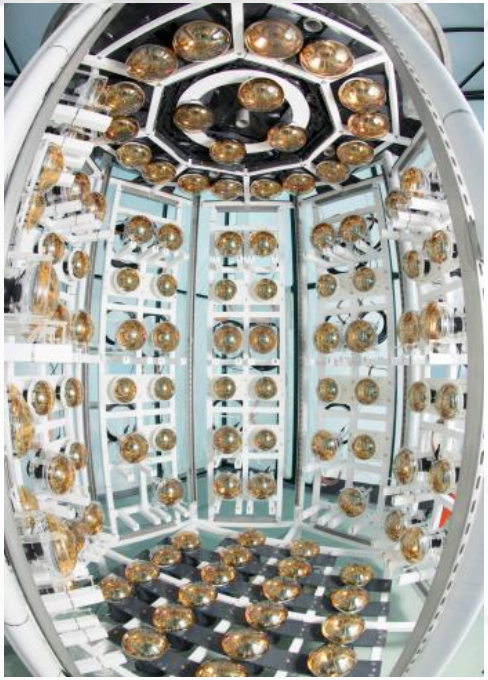
Eur.Phys.J.C 80 (2020) 5, 416

Mid-Term Opportunities at Fermilab

Stroboscopic approach

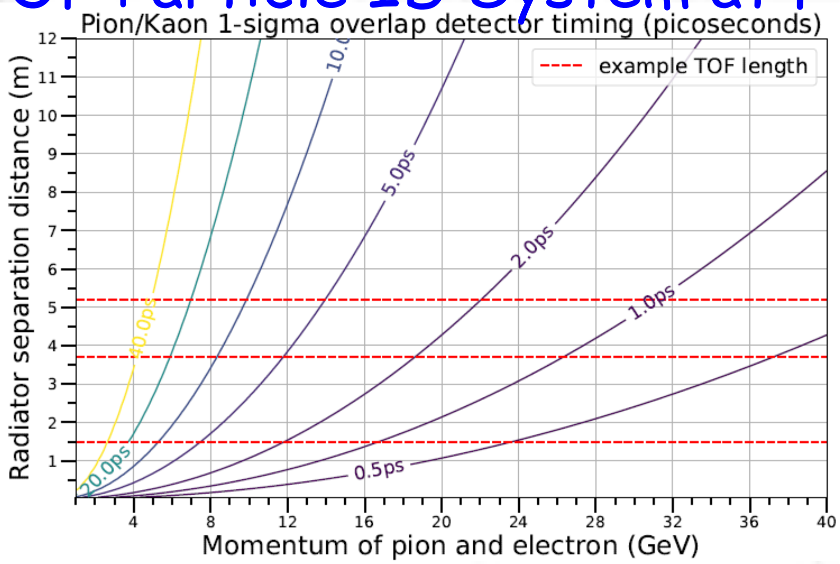


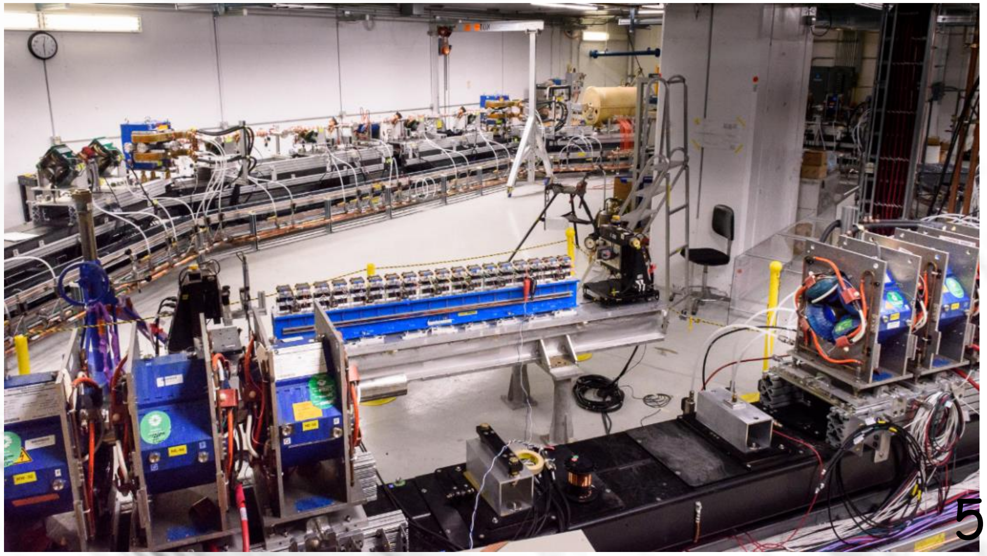
ANNIE



Single photon detection experiments at IOTA

TOF Particle ID System at FTBF





Take Away Messages

Dirac/Majorana nature of the neutrino is a fundamental question

A very large liquid scintillator surrounded by LAPPDs
has a good chance of answering that question

High volume production of LAPPDs requires a bridge between industry's yield at the present and the future demand of particle physics

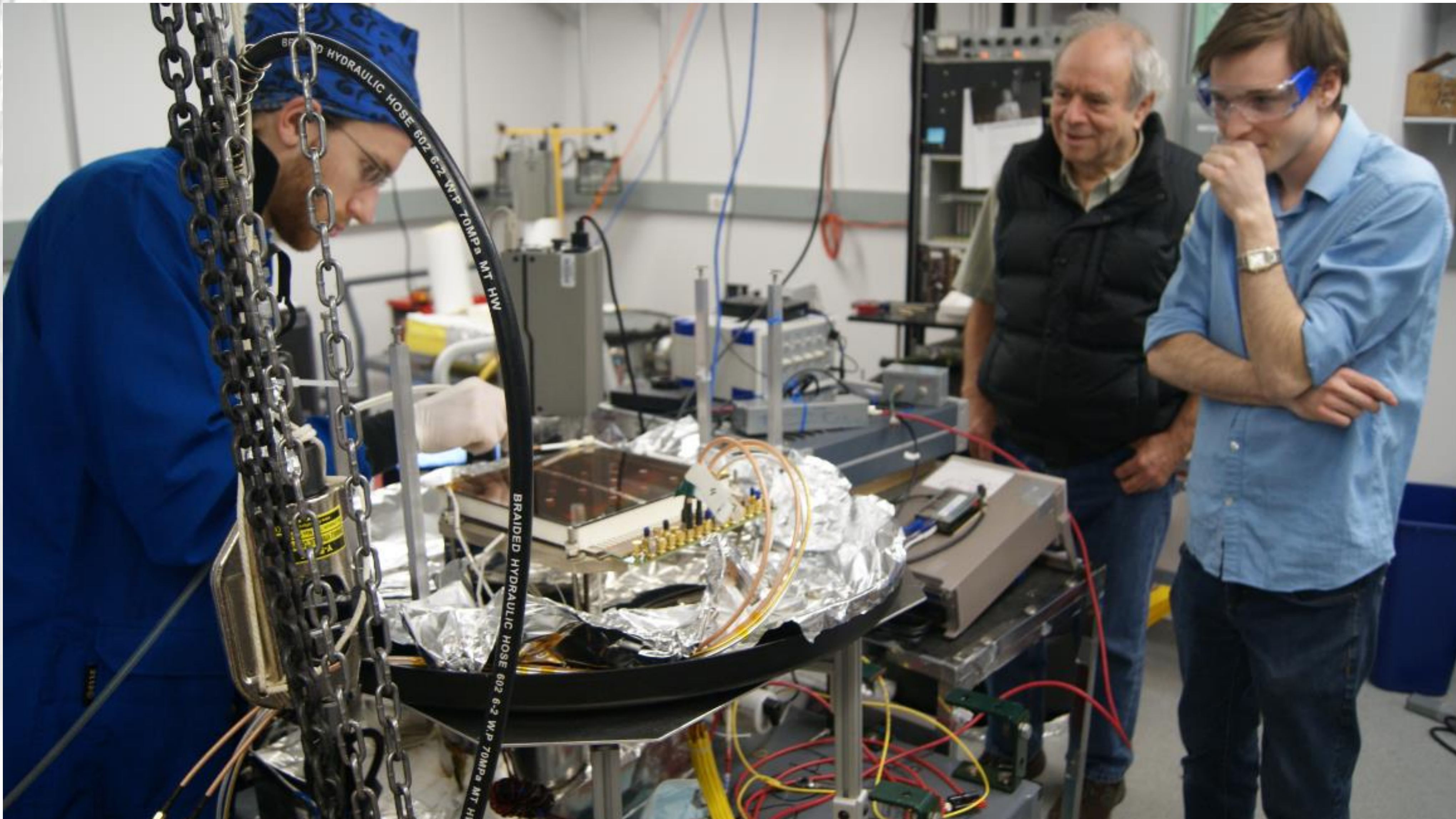
There are many other opportunities for fast timing at Fermilab
These opportunities are not limited to LAPPDs

Acknowledgments

- We are thankful for the support from the DOE Office of Science (Helmut Marsiske, Michelle Shinn)
- We also acknowledge support from the Physical Sciences Division at the University of Chicago
- We are grateful for the help from our staff at UC
- Many thanks to the team at Incom Inc
- We value crucial contributions from SSL Berkeley, Argonne , and Fermilab

A very large number of people contributed to the work presented today. I thank them all.

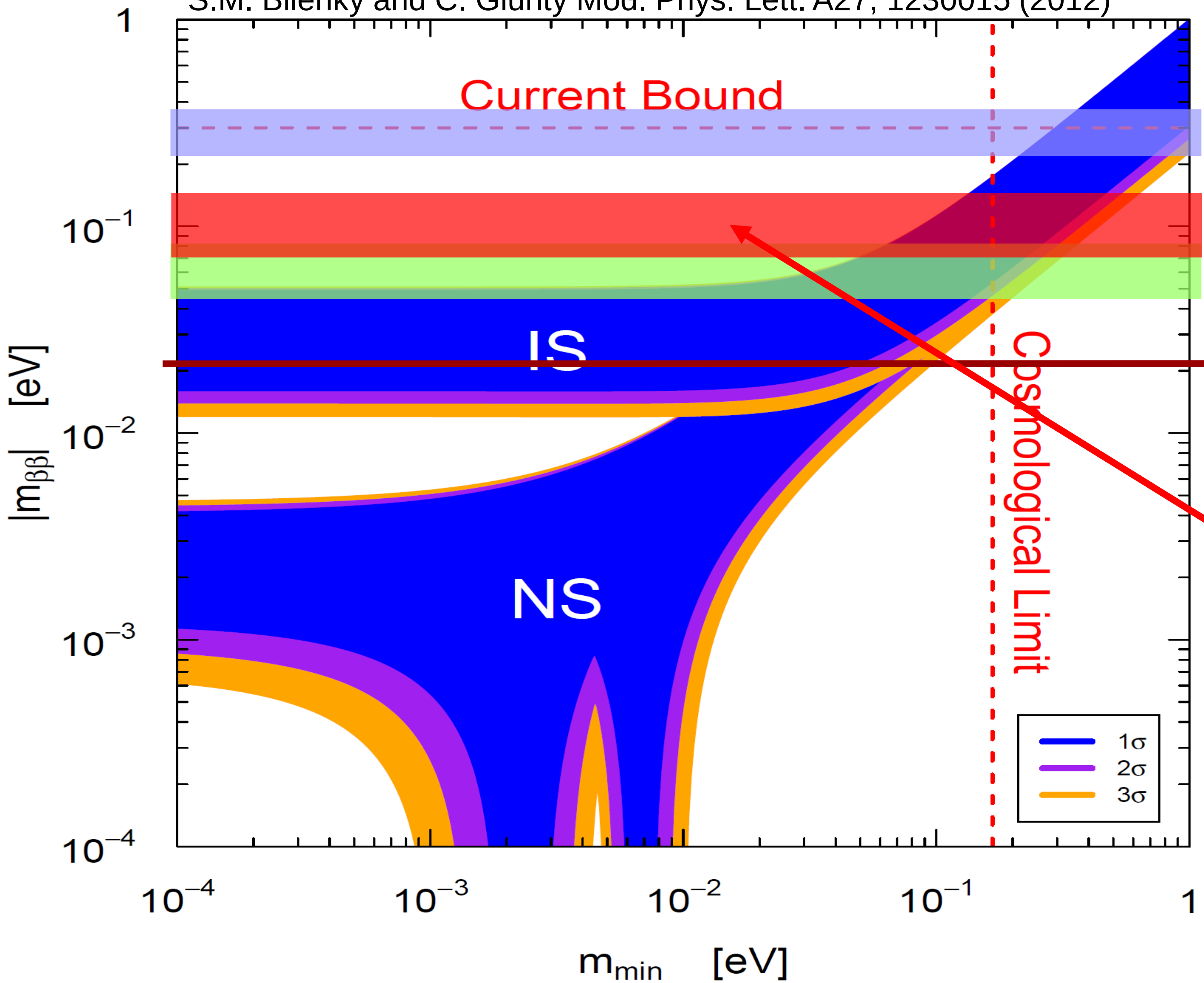
Thank You



Back-ups

Experimental Status of 0νββ-decay

S.M. Bilenky and C. Giunty Mod. Phys. Lett. A27, 1230015 (2012)



EXO (~200kg ^{136}Xe)
KamLAND-Zen (~300 kg ^{136}Xe, before Summer 2016)
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:
$T_{1/2} > 1.07\times10^{26}$ years
$m_{\beta\beta} < 61\text{-}165$ meV

$$|m_{\beta\beta}| = |\cos^2\vartheta_{12}\cos^2\vartheta_{13}m_1 + e^{2i\alpha_{12}}\sin^2\vartheta_{12}\cos^2\vartheta_{13}m_2 + e^{2i\alpha_{12}}\sin^2\vartheta_{13}m_3|$$

$$m_\beta = \sqrt{\sum_i |U_{ei}|^2 m_i^2}$$

Double-Beta Disintegration

Maria Goeppert-Mayer

$$(A,Z) \rightarrow (A,Z+2) + 2e^- + 2\nu_e$$

ER 15, 1935 PHYSICAL REVIEW VOLU

Double Beta-Disintegration

M. Goeppert-Mayer, *The Johns Hopkins University*

(Received May 20, 1935)

From the Fermi theory of β-disintegration the probability of simultaneous emission of two electrons (and two neutrinos) has been calculated. The result is that this process occurs sufficiently rarely to allow a half-life of over 10^{17} years for a nucleus, even if its isobar of atomic number different by 2 were more stable by 20 times the electron mass.

Rare process

The author wishes to express her gratitude to Professor E. Wigner for suggesting this problem, and for the interest taken in it.

Wendell Furry

DECEMBER 15, 1939 PHYSICAL REVIEW VOLUME 56

On Transition Probabilities in Double Beta-Disintegration

W. H. FURRY
Physics Research Laboratory, Harvard University, Cambridge, Massachusetts

(Received October 16, 1939)

The phenomenon of double β-disintegration is one for which there is a marked difference between the results of Majorana's symmetrical theory of the neutrino and those of the original Dirac-Fermi theory. In the older theory double β-disintegration involves the emission of four particles, two electrons (or positrons) and two antineutrinos (or neutrinos), and the probability of disintegration is extremely small. In the Majorana theory only two particles—the electrons or positrons—have to be emitted, and the transition probability is much larger. Approximate values of this probability are calculated on the Majorana theory for the various Fermi and Konopinski-Uhlenbeck expressions for the interaction energy. The selection rules are derived, and are found in all cases to allow transitions with $\Delta i = \pm 1, 0$. The results obtained with the Majorana theory indicate that it is not at all certain that double β-disintegration can never be observed. Indeed, if in this theory the interaction expression were of Konopinski-Uhlenbeck type this process would be quite likely to have a bearing on the abundances of isotopes and on the occurrence of observed long-lived radioactivities. If it is of Fermi type this could be so only if the mass difference were fairly large ($\epsilon \gtrsim 20$, $\Delta M \gtrsim 0.01$ unit).

Proposed $(A,Z) \rightarrow (A,Z+2) + 2e^-$ via virtual neutrino exchange

Quite optimistic experimentally:

- $0\nu\beta\beta$-decay is a factor of 10^6 more favorable than $2\nu\beta\beta$-decay due to the phase factor advantage
- V-A structure of weak interactions is not known yet

PHYSICAL REVIEW D VOLUME 25, NUMBER 11 1 JUNE 1982

Neutrinoless double-β decay in SU(2)$\times$U(1) theories

J. Schechter and J. W. F. Valle
Department of Physics, Syracuse University, Syracuse, New York 13210
(Received 14 December 1981)

It is shown that gauge theories give contributions to neutrinoless double-β decay [$(\beta\beta)_{0\nu}$] which are not covered by the standard parametrizations. While probably small, their existence raises the question of whether the observation of $(\beta\beta)_{0\nu}$ implies the existence of a Majorana mass term for the neutrino. For a "natural" gauge theory we argue that this is indeed the case.

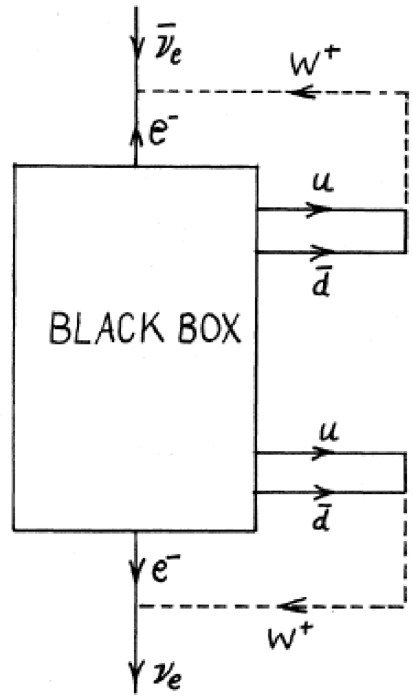
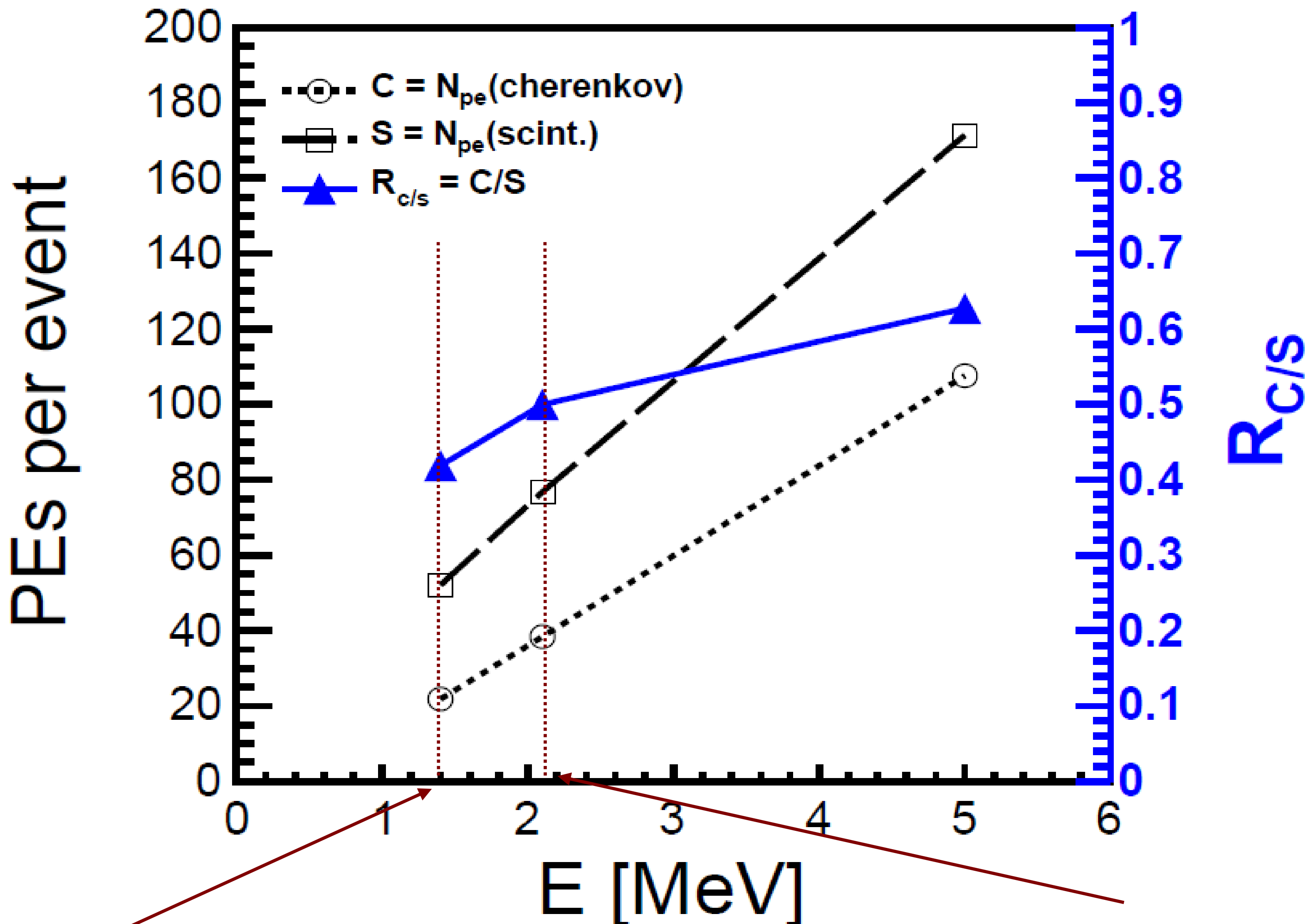


FIG. 2. Diagram showing how any neutrinoless double-β decay process induces a $\bar{\nu}_e$-to-ν_e transition, that is, an effective Majorana mass term.

Light yield: Cherenkov vs scintillation



½ Q (^{116}Cd) =1.4 MeV

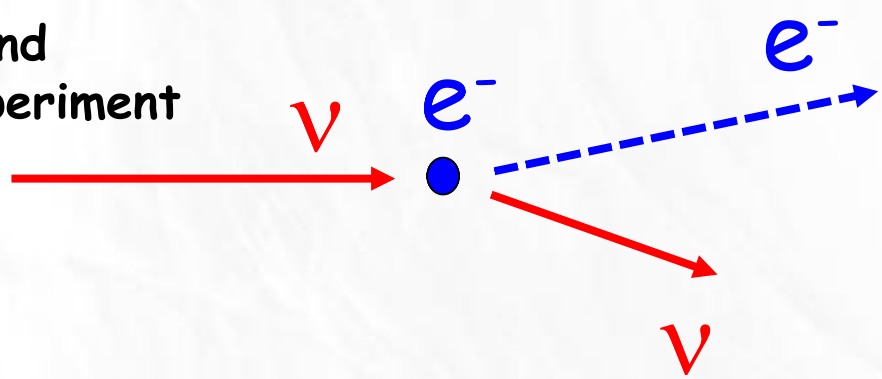
½ Q (^{48}Ca) =2.1 MeV

Backgrounds in Liquid Scintillators

Q-value of most interesting $0\nu\beta\beta$-decay isotopes is 2-3 MeV
A lot is going on in the MeV range. Let's consider two (major) backgrounds.

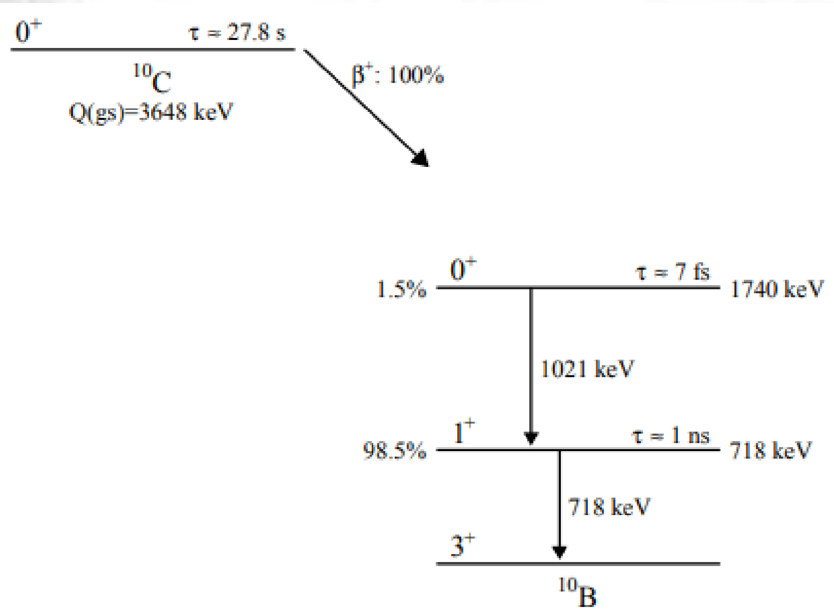
1) Electron scattering of neutrinos coming from ^{8}B-decays in the sun

Key background for the SNO+ experiment

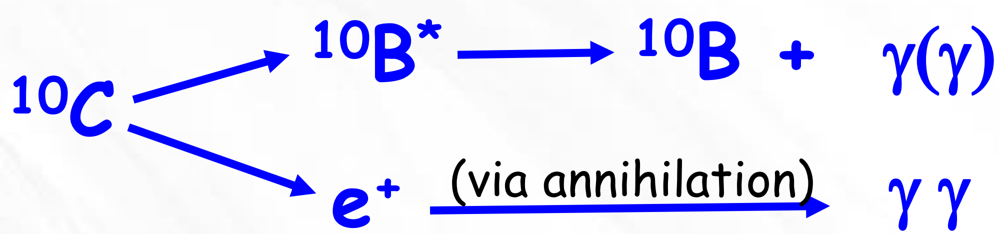


one-track event

2) ^{10}C decays produced by cosmic muon spallation



Key background for the KamLAND-Zen experiment

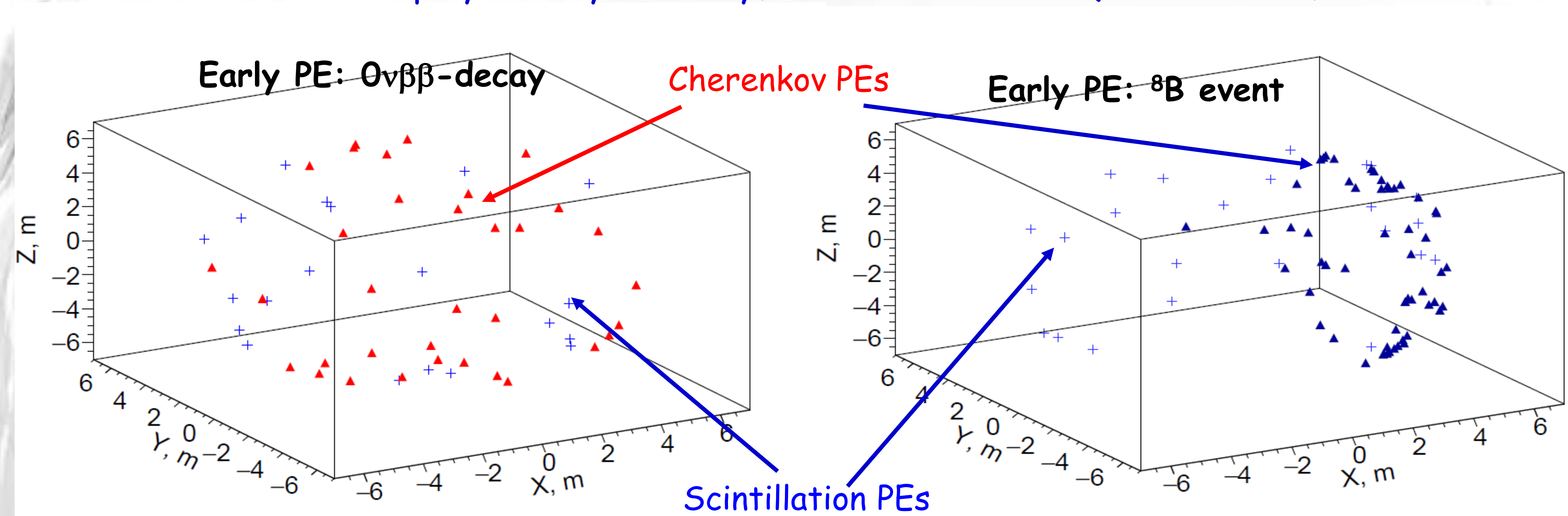


multi-track multi-vertex event

Early Light Topology

NIMA 849 (2017) 102

Realistic event displays: early PEs only, KamLAND PMTs QE: Che~12%, Sci~23%



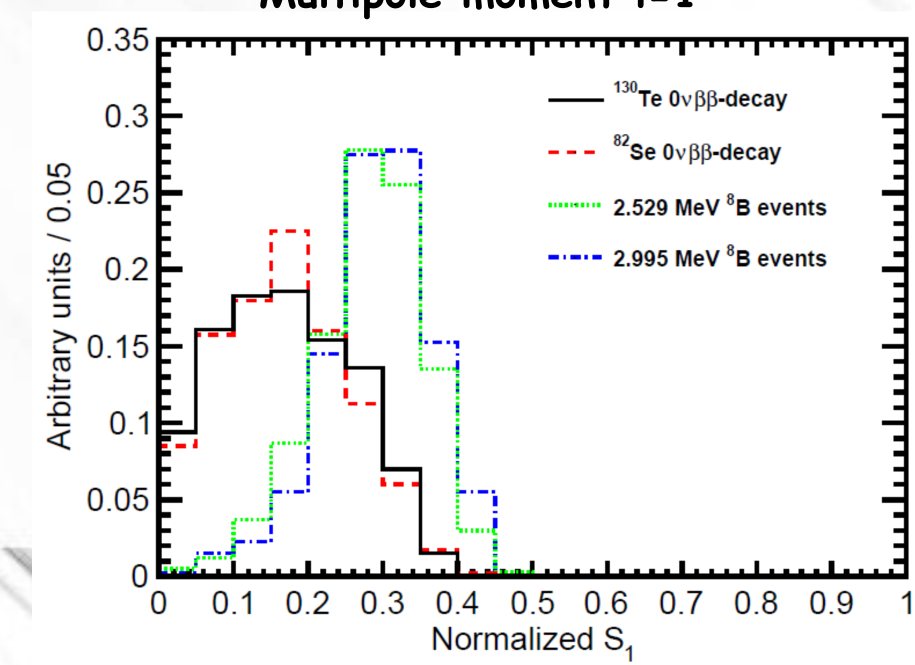
Spherical harmonics analysis

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

Rotation invariant power spectrum

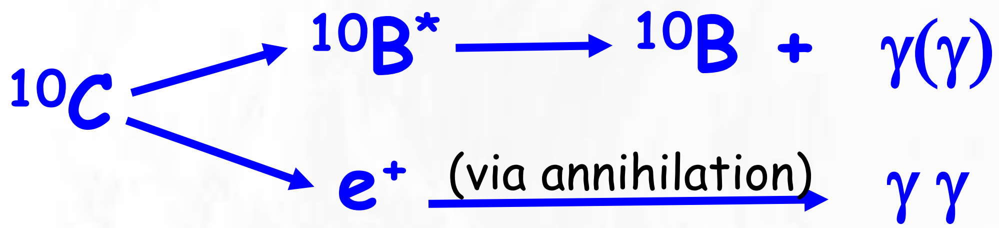
$$S_{ff}(\ell) = \sum_{m=-\ell}^{\ell} |f_{\ell m}|^2$$

Multipole moment l=1



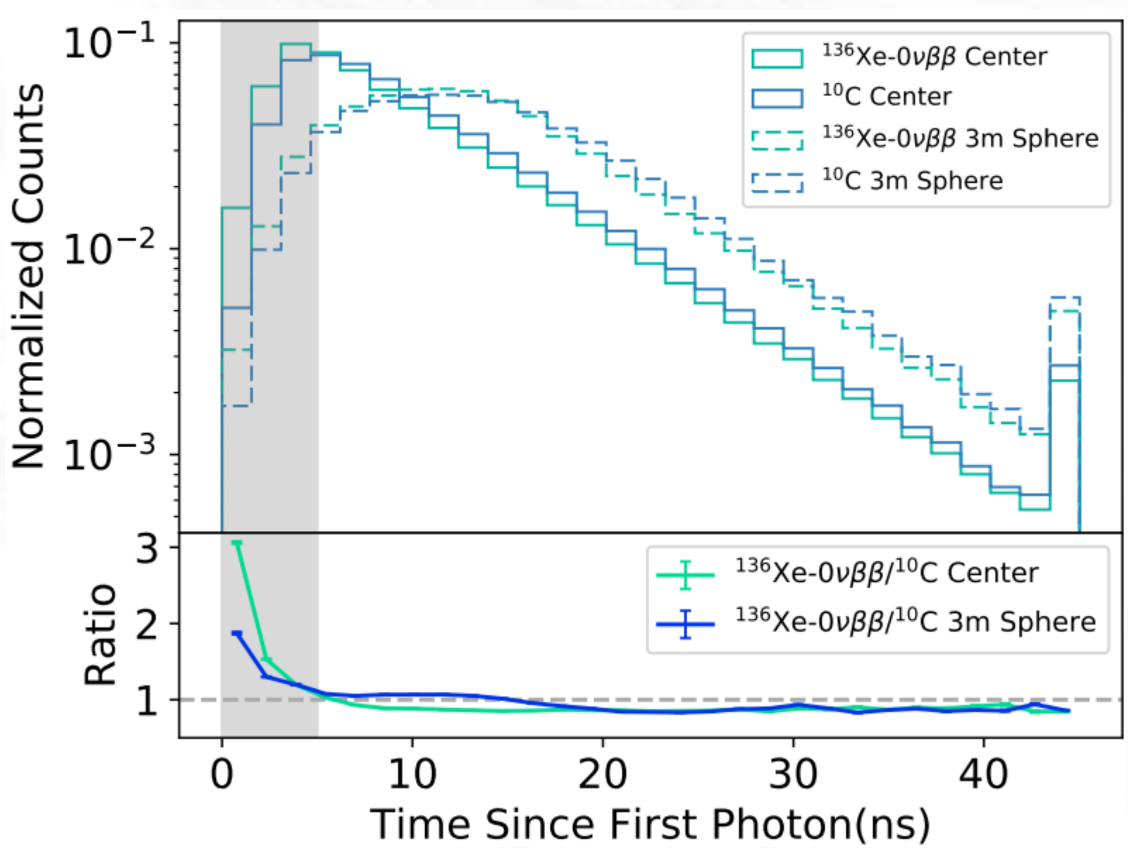
Runyu Jiang and AE have updated this technique
See **arXiv:1902.06912**

Timing of 0νββ-decay vs ^{10}C



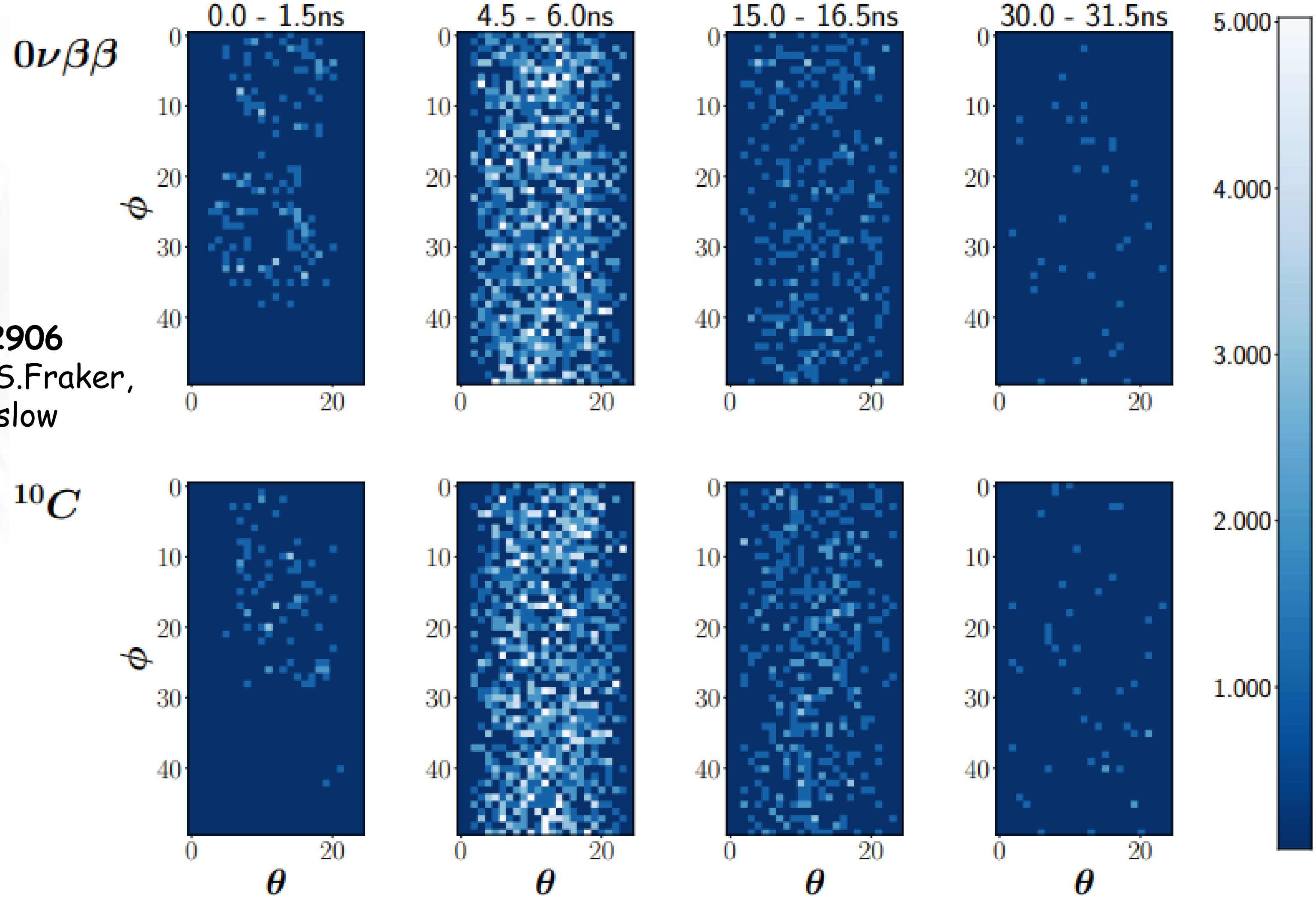
Multi-track-vertex topology leads to different timing distribution

arXiv:1812.02906
A.Li, A.Elagin, S.Fraker, C.Grant, L.Winslow



~3ns delay from ortho-positronium is not included (~50% of ^{10}C have even longer delay)

PE Spatial Distribution: ^{10}C vs $0\nu\beta\beta$

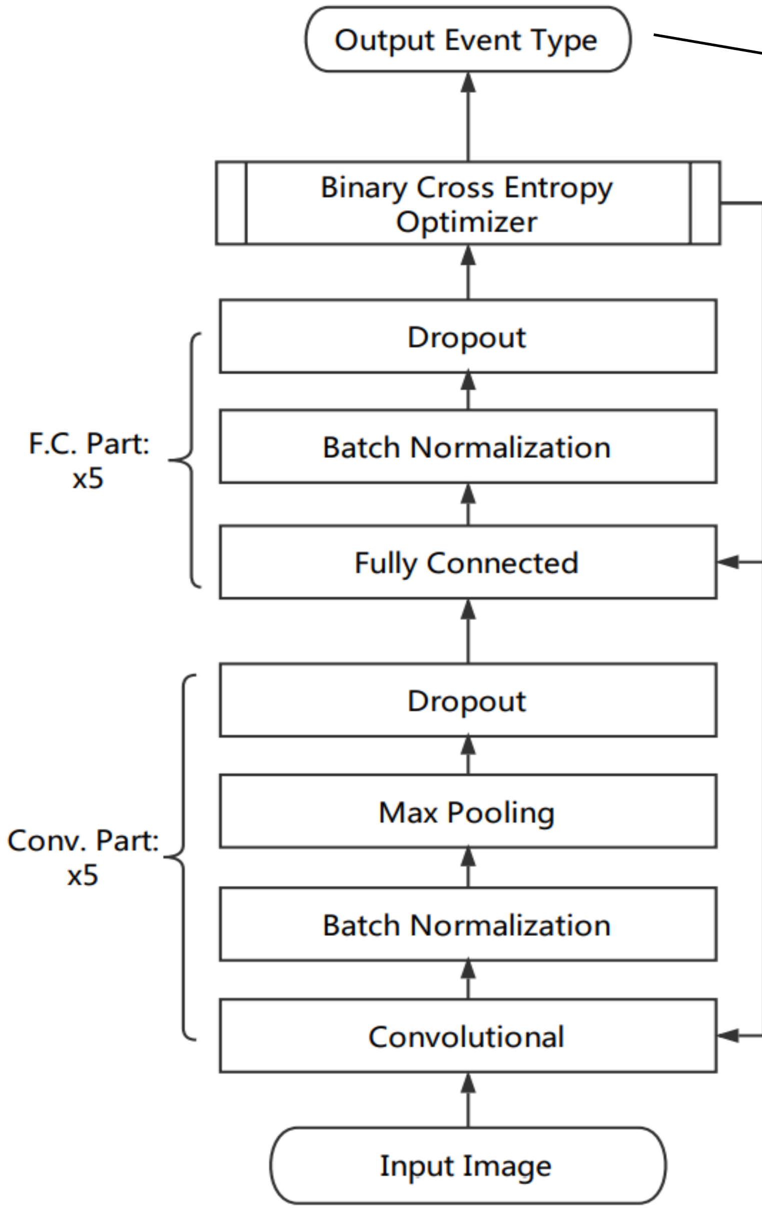


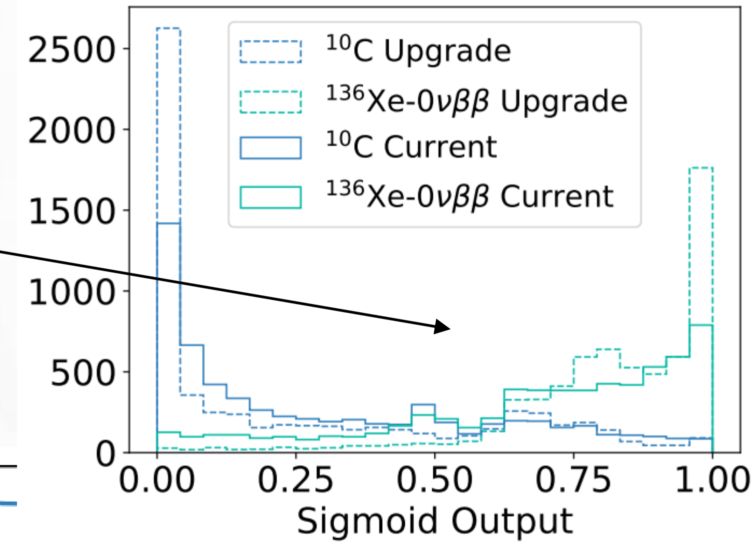
arXiv:1812.02906
A.Li, A.Elagin, S.Fraker,
C.Grant, L.Winslow

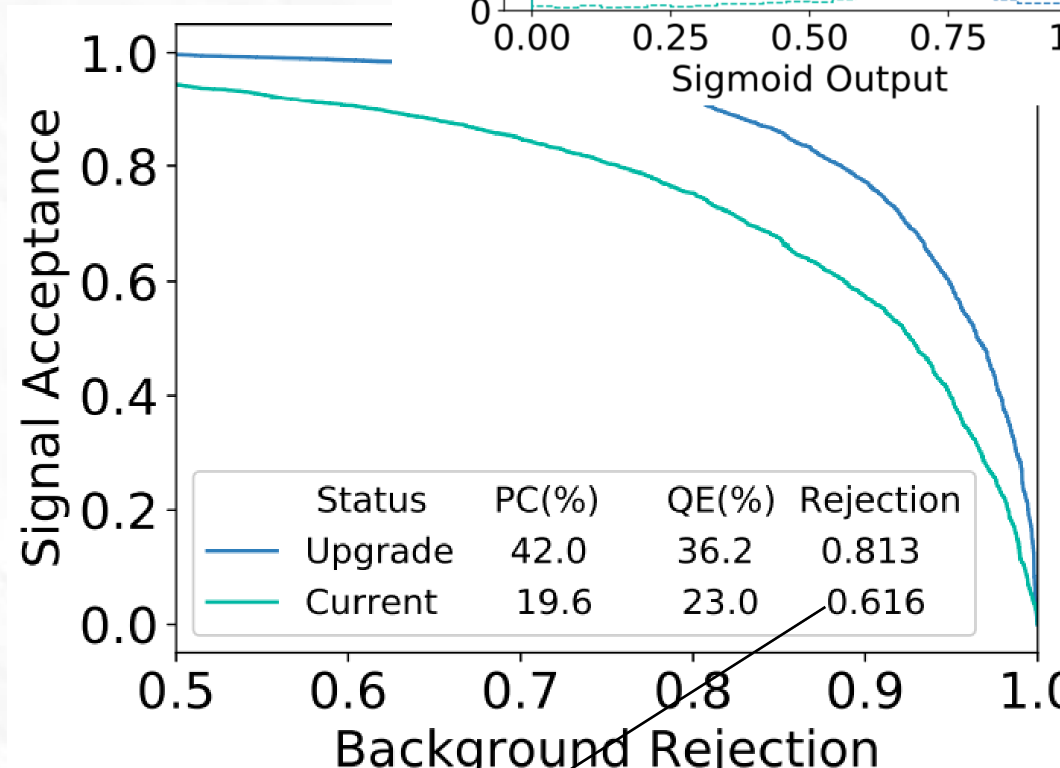
CNN input: theta x phi x time = 25 x 50 x34

CNN for ^{10}C Suppression at KamLAND-Zen

arXiv:1812.02906
A.Li, A.Elagin, S.Fraker, C.Grant, L.Winslow



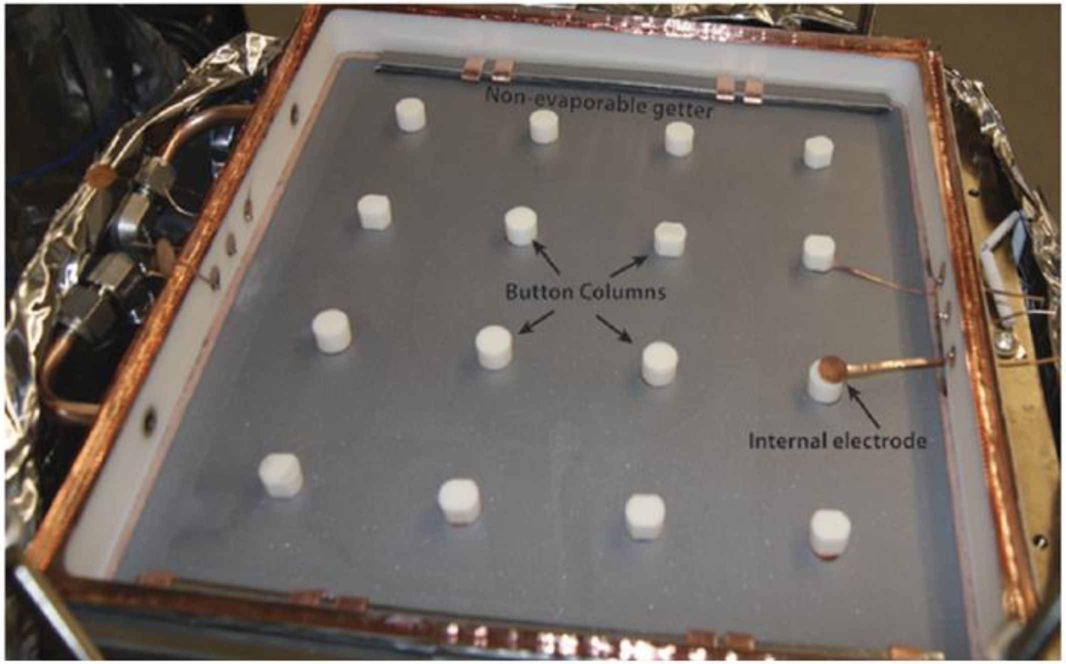


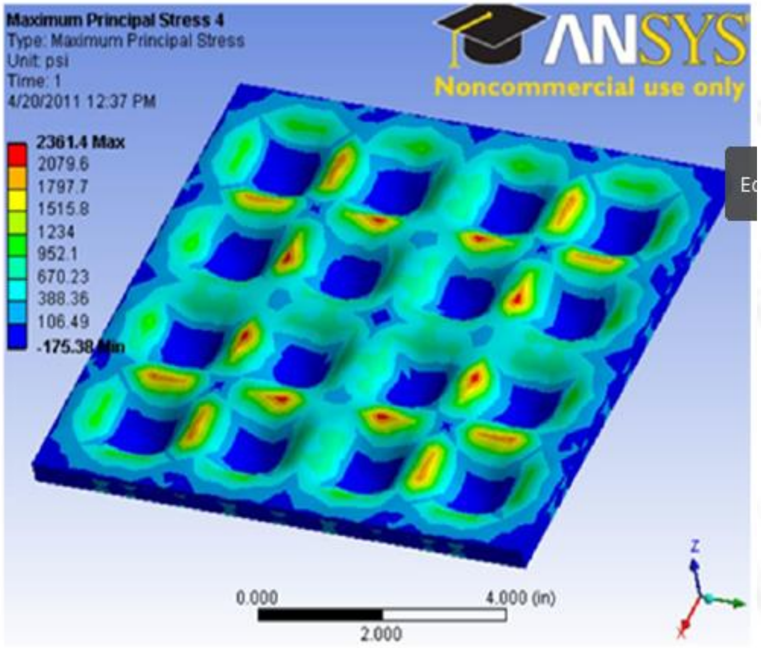


Bkg rejection is 0.55 if only timing is used

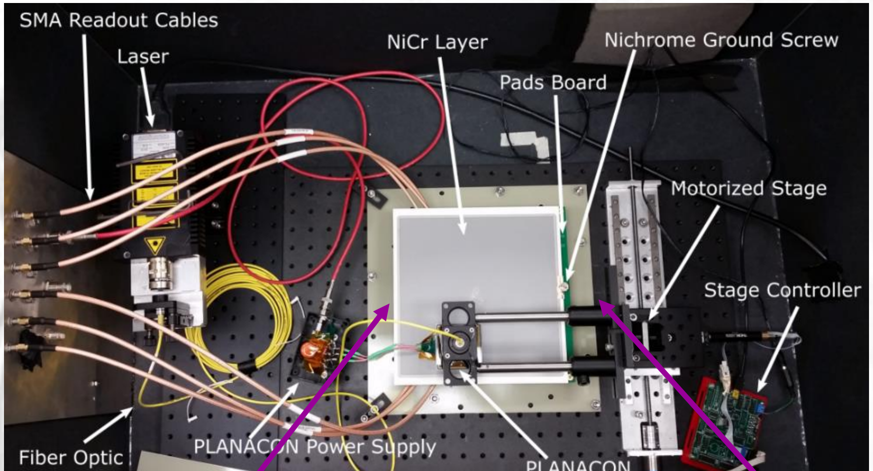
Table 1 THEIA physics reach. Exposure is listed in terms of the fiducial volume assumed for each analysis. For NLDBD the target mass assumed is the mass of the candidate isotope within the fiducial volume

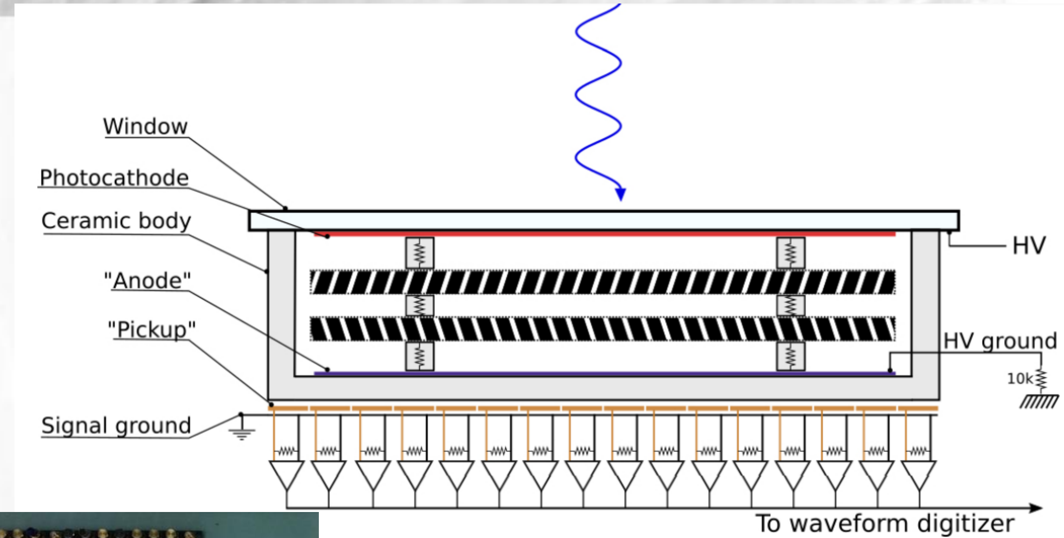
Primary physics goal	Reach	Exposure/assumptions
Long-baseline oscillations	$> 5\sigma$ for 30% of δ_{CP} values	524 kt-MW-year
Supernova burst	$< 1(2)^{\circ}$ pointing accuracy	100(25)-kt detector, 10 kpc
	20,000 (5000) events	
DSNB	5σ discovery	125 kton-year
CNO neutrino flux	< 5 (10)%	300 (62.5) kton-year
Reactor neutrino detection	2000 events	100 kton-year
Geo neutrino detection	2650 events	100 kton-year
NLDBD	$T_{1/2} > 1.1 \times 10^{28}$ year	211 ton-year ^{130}Te
Nucleon decay $p \rightarrow \overline{\nu} K^{+}$	$T > 3.80 \times 10^{34}$ year (90% CL)	800 kton-year

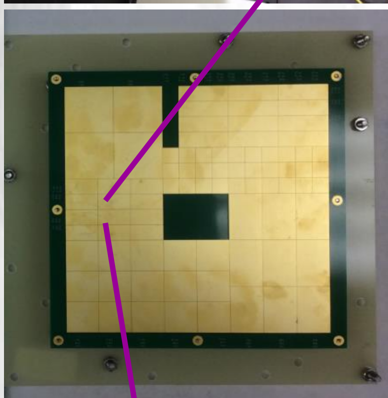

Non-evaporable getter
Button Columns
Internal electrode


Maximum Principal Stress 4
Type: Maximum Principal Stress
Unit: psi
Time: 1
4/20/2011 12:37 PM
2361.4 Max
2079.6
1797.7
1515.8
1234
952.1
670.23
388.36
106.49
-175.38 Min
ANSYS
Noncommercial use only
0.000
4.000 (in)
2.000

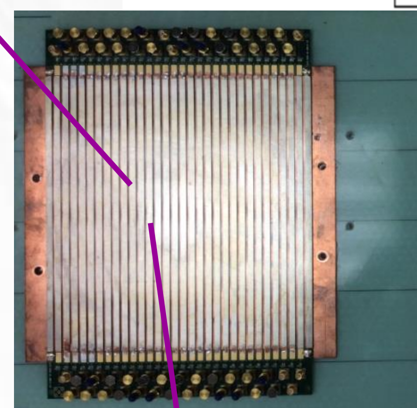
Gen-II LAPPD: "inside-out" anode



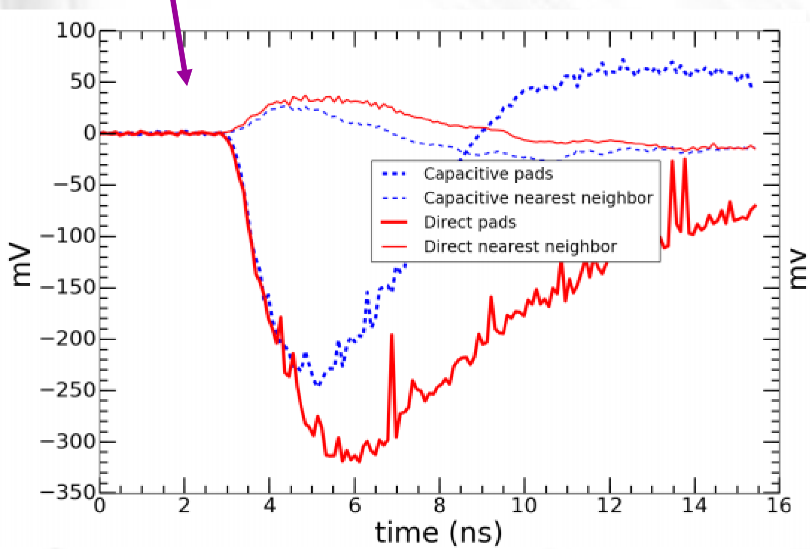


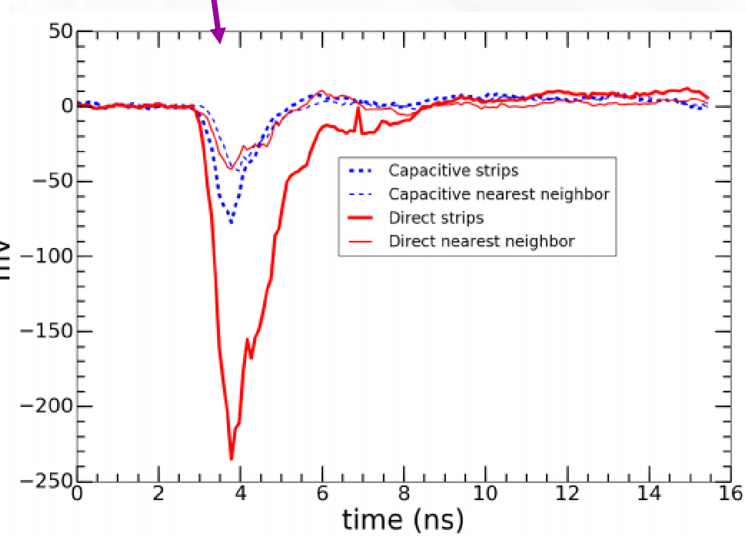


Chose your own readout pattern



- Custom anode is outside
- Capacitively coupled
- Compatible with high rate applications





For details see NIMA 846 (2016) 75