Neutrino-less Double-Beta Decay and the Development of Large-Area Picosecond Photo-Detectors

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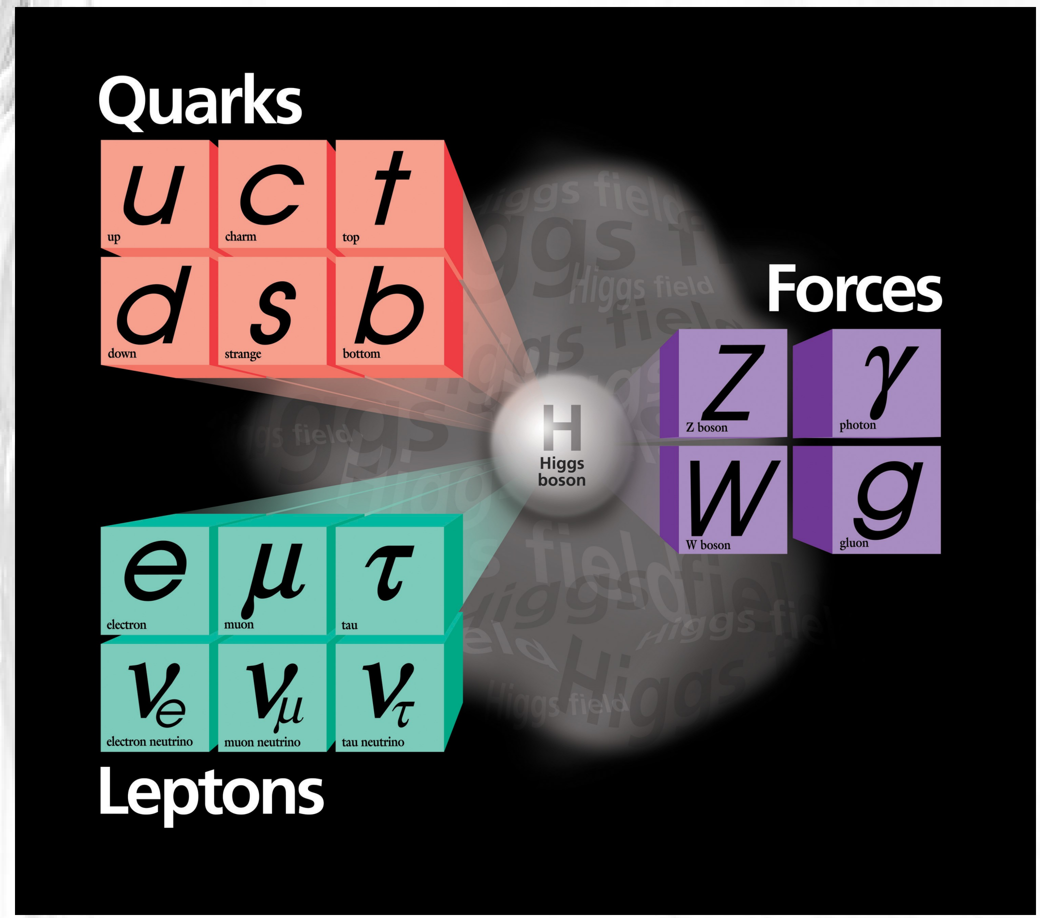
HEP Seminar, University of Chicago, February 2, 2015

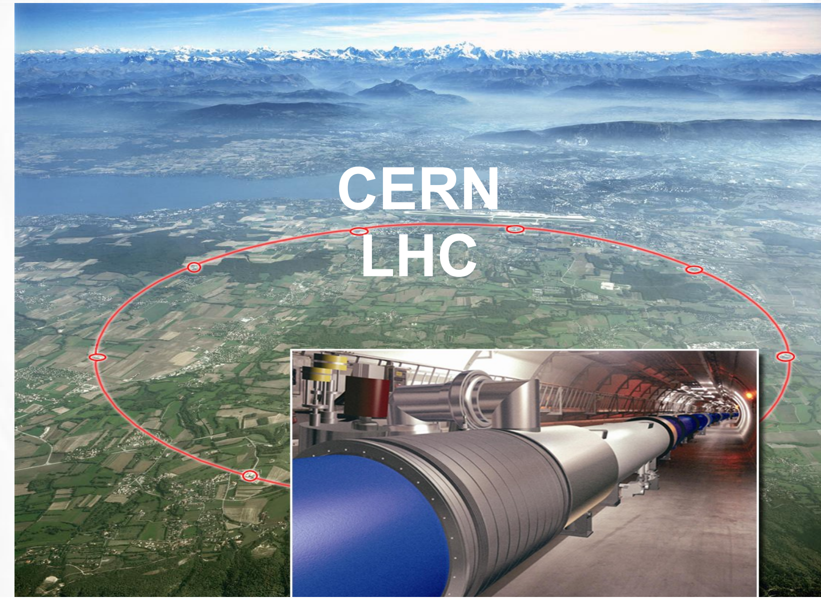
Outline

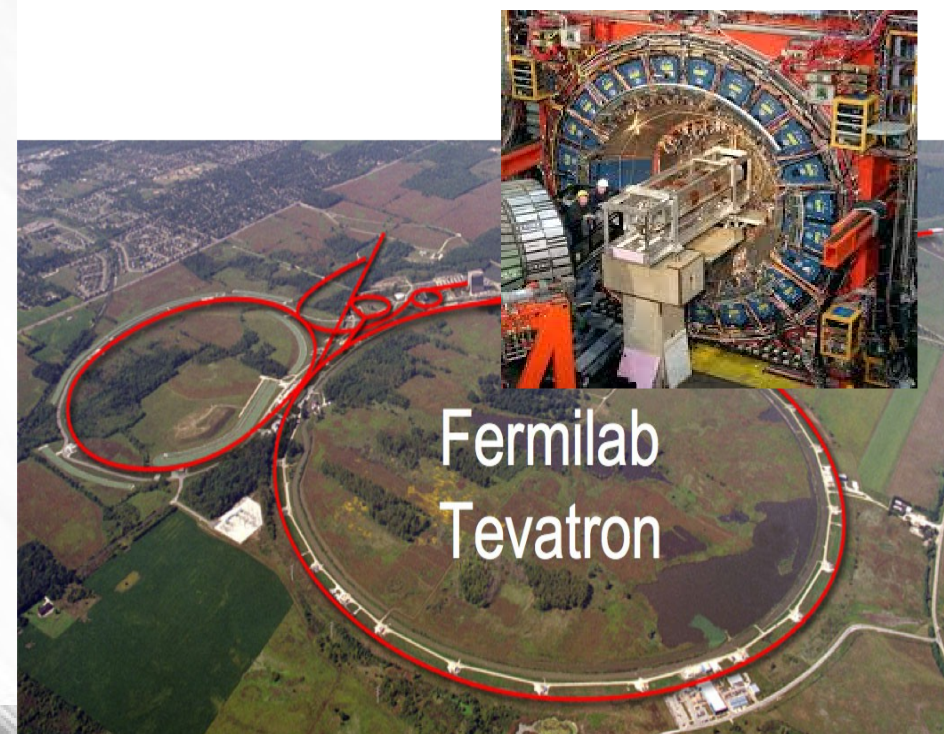
- Introduction
  - history of double beta decay (80 years)
  - brief theory overview
  - experimental status and challenges
- An idea for next generation experiments
  - separation of Cherenkov and scintillation light
- Large-Area Picosecond Photo-Detectors

The Standard Model

How did we learn about it?

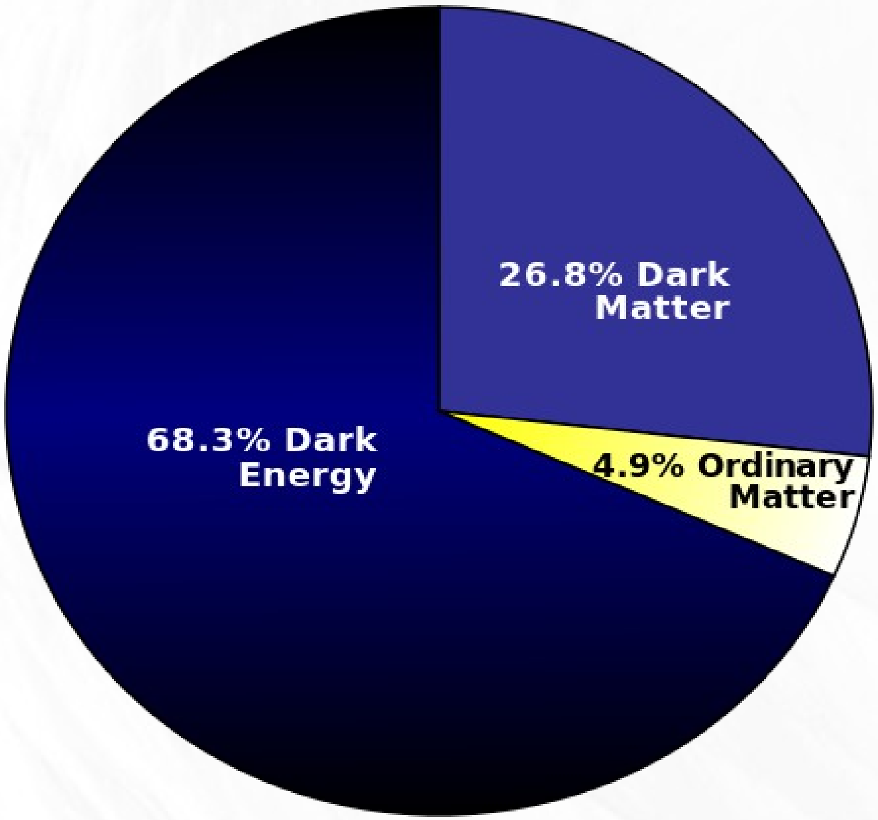






We have been building state of the art instrumentation

We don't know 95% of the story



We have to develop new instrumentation to find out what are those 95%

Also we are not done with the ordinary matter yet!

A question that interests me

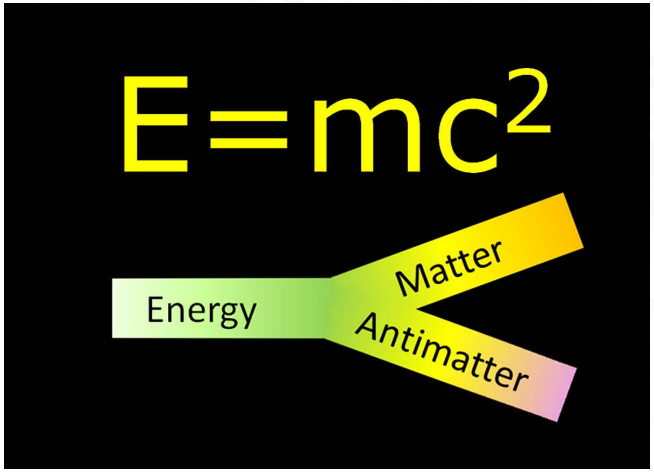
Is the neutrino its own antiparticle?

It is possible because the neutrino has no electric charge

No other fermion can be its own antiparticle

It is not only possible, but may be necessary

- origin of matter-antimatter asymmetry in the universe
- why the neutrino mass is so tiny?

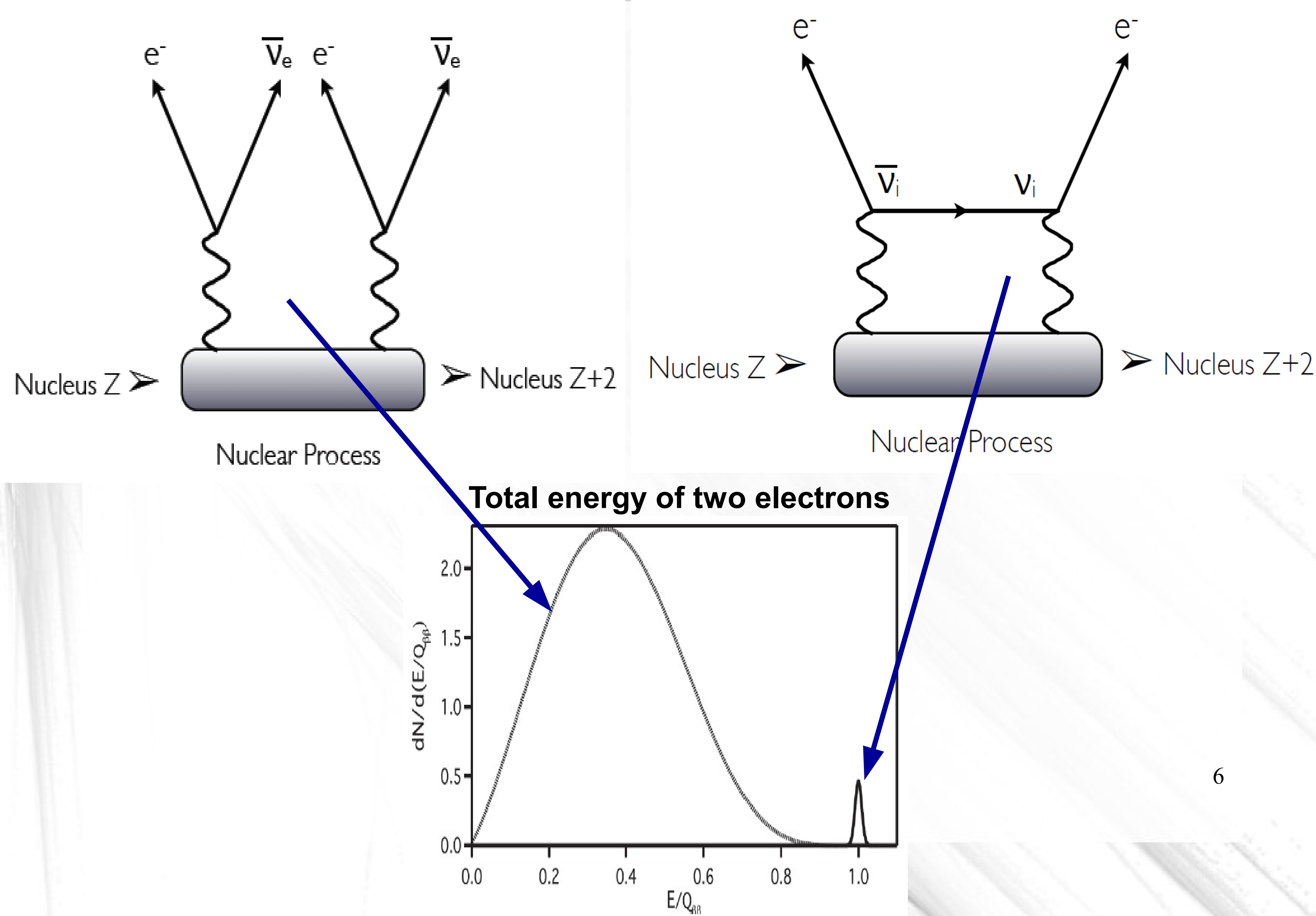


Neutrino

Any other fermion

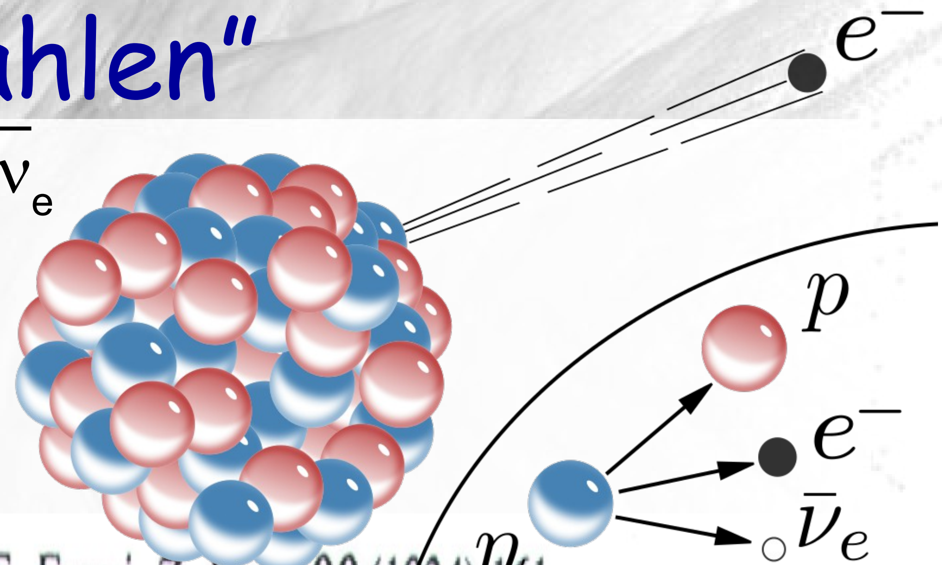
Search for neutrino-less double beta decay ($0\nu\beta\beta$-decay) is the most feasible way to answer this question

Double Beta Decay



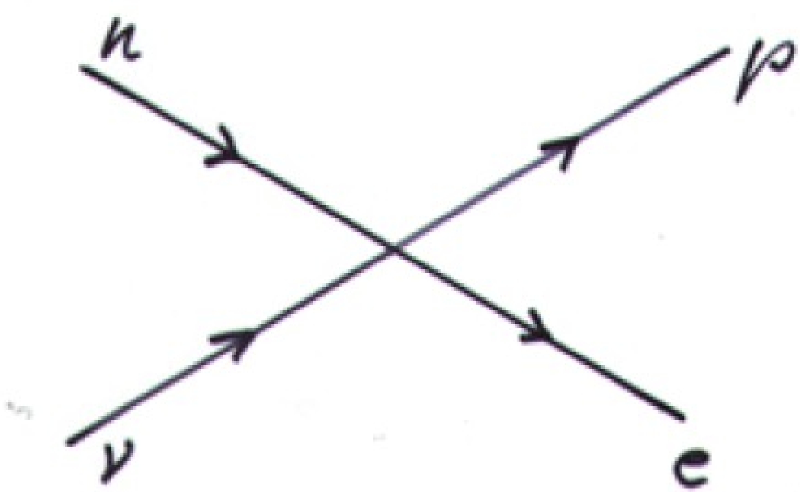
"β-Strahlen"

$(A,Z) \rightarrow (A,Z+1) + e^- + \bar{\nu}_e$



E. Fermi, Z. Phys. 88 (1934) 161

$$\mathcal{L}_{\rm weak} = G_{\rm F}(\bar{\psi}_{\rm p}\gamma_\mu\psi_{\rm n})(\bar{\psi}_{\rm e}\gamma^\mu\psi_\nu)$$



Versuch einer Theorie der β-Strahlen. I[1]).

Von E. Fermi in Rom.

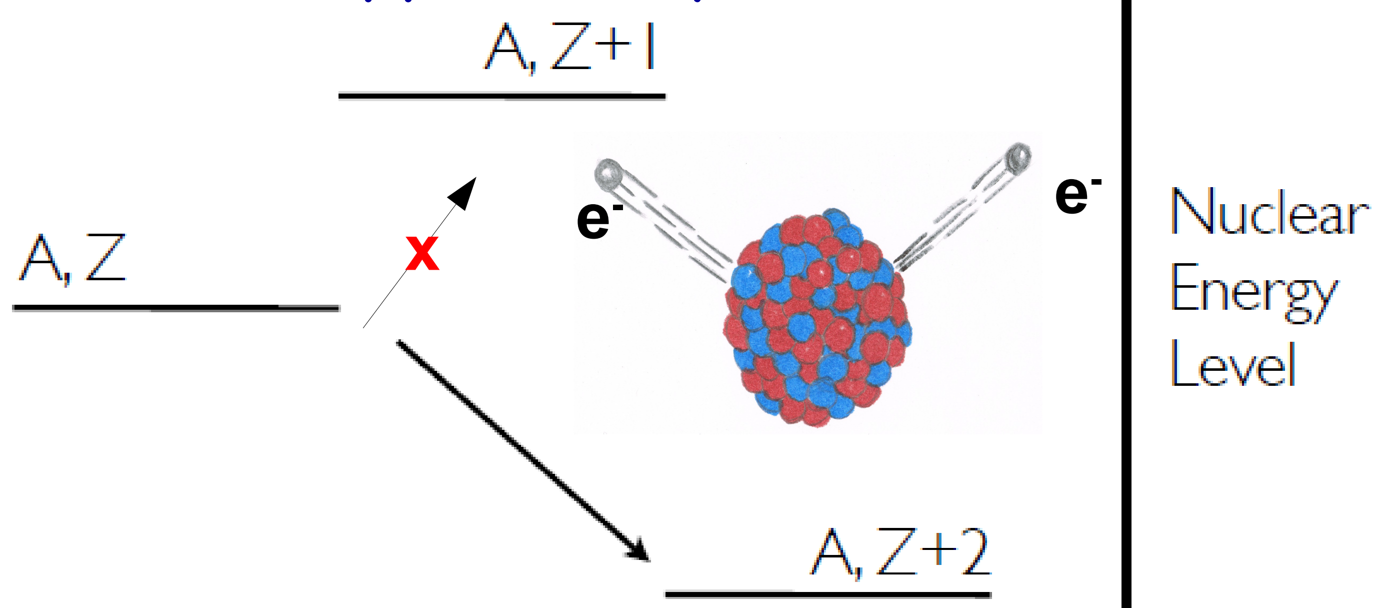
Mit 3 Abbildungen. (Eingegangen am 16. Januar 1934.)

Eine quantitative Theorie des β-Zerfalls wird vorgeschlagen, in welcher man die Existenz des Neutrinos annimmt, und die Emission der Elektronen und Neutrinos aus einem Kern beim β-Zerfall mit einer ähnlichen Methode behandelt, wie die Emission eines Lichtquants aus einem angeregten Atom in der Strahlungstheorie. Formeln für die Lebensdauer und für die Form des emittierten kontinuierlichen β-Strahlenspektrums werden abgeleitet und mit der Erfahrung verglichen.

4 particle interaction theory predicted the electron energy spectrum remarkably well

Double-Beta Disintegration

Maria Goeppert-Mayer



$$(A,Z) \rightarrow (A,Z+2) + 2e^- + 2\bar{\nu}_e$$

SEPTEMBER 15, 1935 PHYSICAL REVIEW VOLUME 48

Double Beta-Disintegration

M. GOEPPERT-MAYER, *The Johns Hopkins University*

(Received May 20, 1935) → **80 years ago**

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.

Eugene Wigner's Role

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

Ettore Majorana

TEORIA SIMMETRICA DELL'ELETTRONE E DEL POSITRONE

Nota di ETTORE MAJORANA

Sunto. - *Si dimostra la possibilità di pervenire a una piena simmetrizzazione formale della teoria quantistica dell'elettrone e del positrone facendo uso di un nuovo processo di quantizzazione. Il significato delle equazioni di* DIRAC *ne risulta alquanto modificato e non vi è più luogo a parlare di stati di energia negativa; nè a presumere per ogni altro tipo di particelle, particolarmente neutre, l'esistenza di « antiparticelle » corrispondenti ai « vuoti » di energia negativa.*

Noticed that symmetry of Dirac's theory allows to avoid solutions with negative energies (antiparticles) for neutral spin $\frac{1}{2}$ particles

Fermi's theory of beta decay is unchanged if $\nu = \bar{\nu}$

Giulio Racah

SULLA SIMMETRIA TRA PARTICELLE E ANTIPARTICELLE

Nota di GIULIO RACAH

Sunto. - *Si mostra che la simmetria tra particelle e antiparticelle porta alcune modificazioni formali nella teoria di* FERMI *sulla radioattività* β, *e che l'identità fisica tra neutrini ed antineutrini porta direttamente alla teoria di* E. MAJORANA.

Proposed a chain reaction

$$(A,Z) \rightarrow (A,Z+1) + e^- + \bar{\nu}$$

$$\bar{\nu} + (A',Z') \rightarrow (A',Z'+1) + e^-$$

to distinguish between Dirac and Majorana neutrinos

Wendell Furry

JULY 1, 1938 PHYSICAL REVIEW VOLUME 54

Note on the Theory of the Neutral Particle

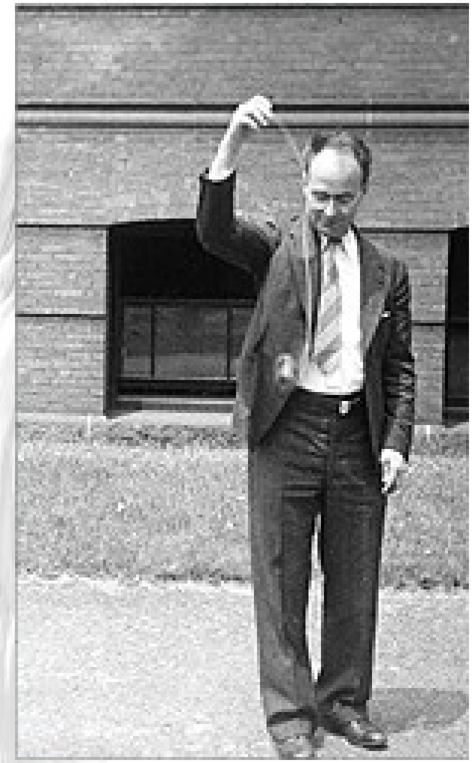
W. H. FURRY
Physics Research Laboratory, Harvard University, Cambridge, Massachusetts
(Received March 28, 1938)

Majorana has recently shown by using a special set of Dirac matrices that the symmetry properties of the Dirac equations make possible the elimination of the negative energy states in the case of a free particle. We present here a further investigation of this possibility, in a treatment based on an arbitrary Hermitian representation of the Dirac matrices instead of Majorana's special representation. The new procedure is compared with Schroedinger's early attempt to eliminate the negative energy states. The question of Lorentz invariance is discussed, and also the possibility of subjecting the particle to forces; it is found that the only sort of force having a classical analogue which is consistent with Majorana's way of eliminating the negative energy states is the nonelectric force of a scalar potential. The theory is worked through for this case, and it is pointed out that, in spite of the fact that the exclusion of negative energy states is accomplished without the introduction of antiparticles, the formalism still shows the stigmata associated with subtraction theories of the positron: the presence of otiose infinite terms which should be removed by subtraction, and the creation and destruction of pairs of particles. The application of Majorana's formalism to the theory of β-radioactivity is discussed at the end of the paper. Here the physical interpretation is quite different from that of the ordinary theory, since only neutrinos appear instead of the neutrinos and antineutrinos of the usual picture. The results predicted for all observed processes are nevertheless identical with those of the ordinary theory. An experimental decision between the formulation using neutrinos and antineutrinos and that using only neutrinos will apparently be even more difficult than the direct demonstration of the existence of the neutrino.

Pessimistic conclusion about experimental prospects to observe Racah's "chain" reaction:

- cross section is ~10^{-40-50}
- no intense source for neutrinos (no reactors yet)

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 week interactions is not known yet)

Double-Beta Decay Timeline

1935-1939 – double beta disintegration proposed,
0nbb is a tool to distinguish between Dirac and Majorana neutrino
First estimates: $T_{1/2} \sim 10^{21}$ years for $2\nu\beta\beta$ and 10^{15} years for $0\nu\beta\beta$

1950 - Experimental limits on $0\nu\beta\beta$ exceeded predictions
(a hint that neutrino is a Dirac particle???)

1955 – R. Davis sets strong limits on $\bar{\nu} + {}^{37}Cl \rightarrow {}^{37}Ar + e^-$
(interpreted as a proof that neutrino is a Dirac particle)

1957 – V-A nature of weak interactions → dramatic decrease in probability of $0\nu\beta\beta$-decay rate, also Davis's experiment doesn't solve Dirac/Majorana questions for neutrinos

From reactor: $n \rightarrow p + e^- + \bar{\nu}_R$

At the target: only $\nu_L + n \rightarrow p + e^-$ is allowed

$\bar{\nu}_R + n \rightarrow p + e^-$ is forbidden by V-A couplings

Double-Beta Decay Timeline

Because a helicity flip is required, $0\nu\beta\beta$ can't happen even for Majorana neutrino if it has no mass

The fact that $0\nu\beta\beta$-decay requires massive neutrino and lepton number violation discouraged experimental searches.

Nevertheless experiments continued:

1950 – first observation of $2\nu\beta\beta$ of ^{130}Te ($T_{1/2} = 1.4 \times 10^{21}$ yr) by Inghram and Reynolds

1960 - probability of $0\nu\beta\beta$ for massive neutrino is calculated
Realization that $0\nu\beta\beta$–decay is a good test for lepton number violation

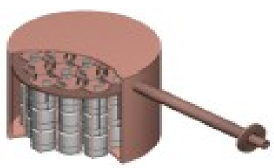
1980s-1990s – $2\nu\beta\beta$ observed in 10 isotopes
Today – $T_{1/2} \sim 10^{25}$ yrs sensitivity to $0\nu\beta\beta$

Current Status

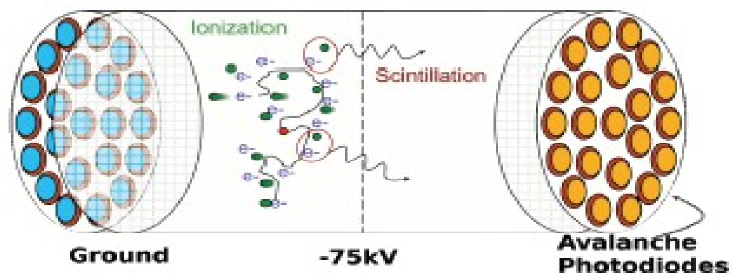
Oscillation experiments established that neutrino is massive and increased interest to $0\nu\beta\beta$ decay searches

Today we have many experiments (running or planned)

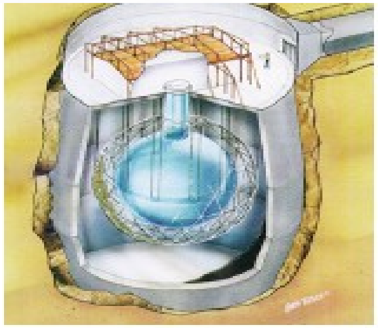
MAJORANA



EXO

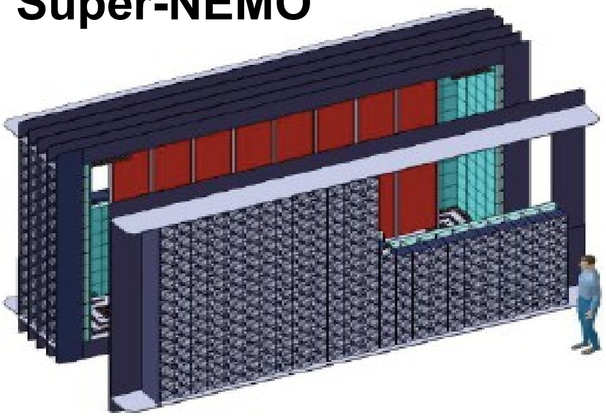


SNO+

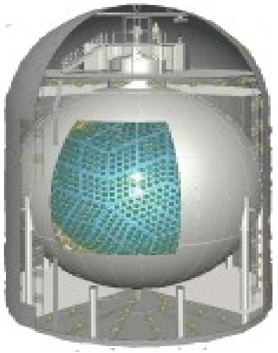


GERDA

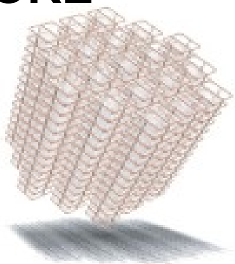
Super-NEMO



KamLAND



CUORE

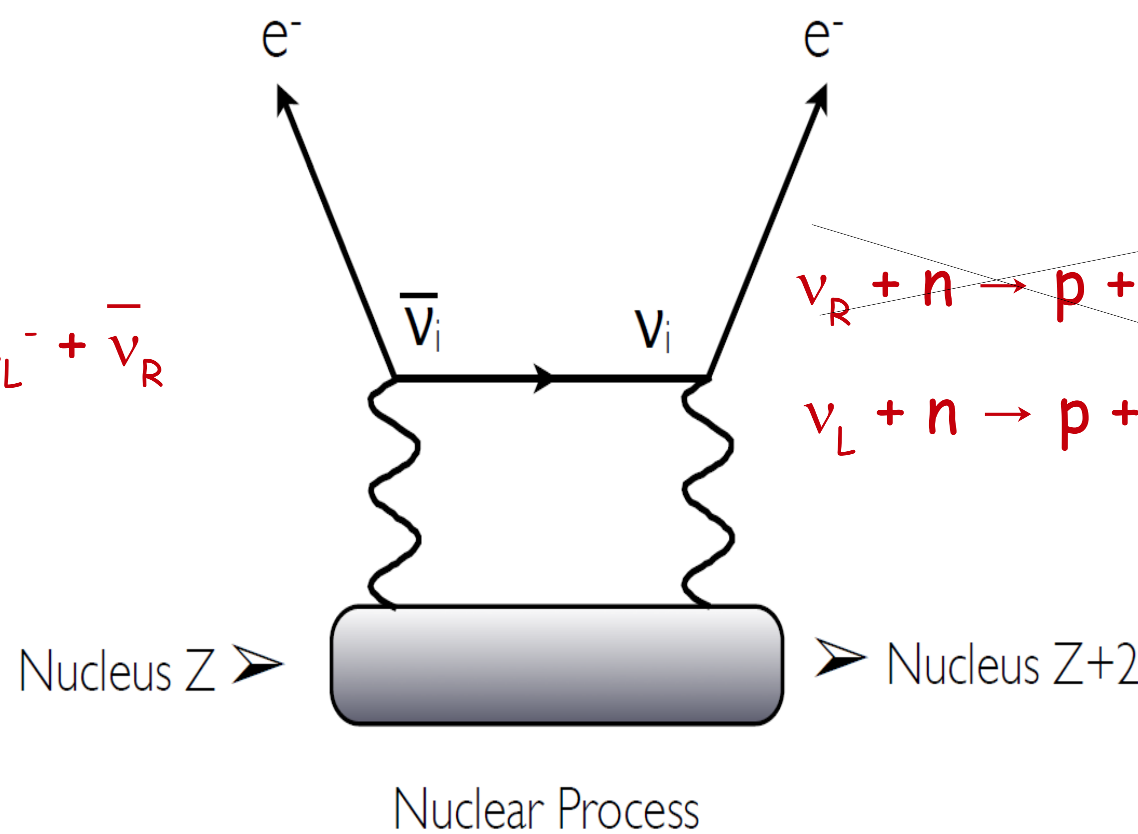


Why do we care so much?

Neutrinoless Decay is Unique

It is only possible if the neutrino is its own antiparticle and have non-zero mass

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



~~$\nu_R + n \rightarrow p + e_L^-$~~

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

Even if neutrino it's own antiparticle $\nu_R \neq \nu_L$

Neutrino has to have mass to flip helicity (~m/E)

0νββ-decay may provide access to the neutrino mass mechanism

See-saw Mechanism

If we assume Majorana neutrino, the notation '$\bar{\nu}$' should be avoided for anti-neutrinos

Neutrino participating in scattering is ν_L

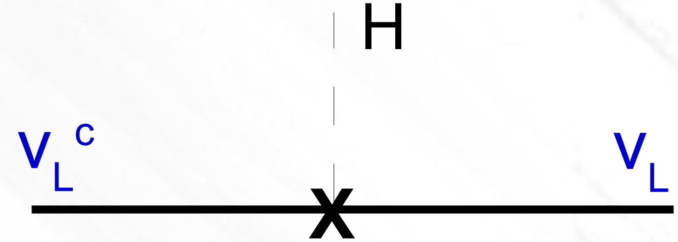
$$\nu_L + n \rightarrow p + e_L^-$$

Neutrino produced in beta-decay is CP conjugate of ν_L

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

Simplest way to introduce a neutrino mass term into the Lagrangian would be $m_{LL}\bar{\nu}_L\nu_L^c$

This is exactly what's needed for 0νββ-decay



However the Higgs is a doublet and this Majorana mass term can't directly appear in the SM Lagrangian

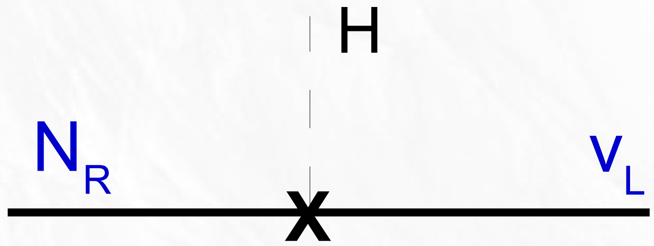
See-saw mechanism introduces this term “effectively”

See-saw Mechanism

By introducing a right-handed neutrino N_R we can write

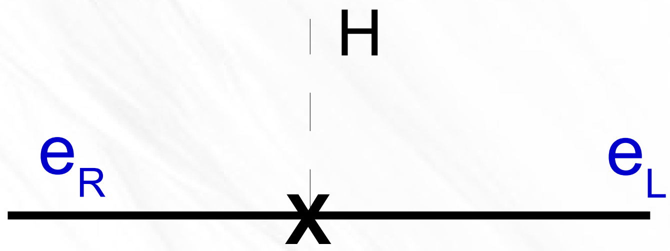
a usual Dirac mass term

$$m_D \bar{\nu}_L N_R$$



This is similar to charged leptons mass term

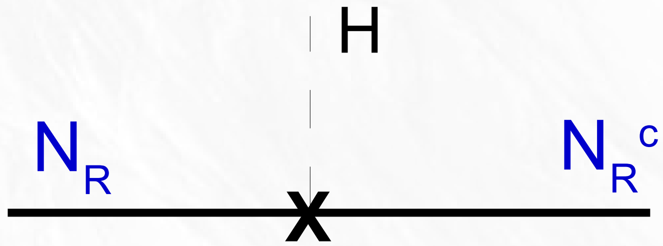
$$m_e \bar{e}_L e_R$$



See-saw Mechanism

N_R doesn't participate in weak interactions
so Majorana mass can appear in the SM Lagrangian

$$M_{RR}\overline{N}_R N_R^c$$



Note that $M\overline{e}_R e_R^c$ would violate charge conservation, so the zero charge is the key for a Majorana particle

See-saw Mechanism

Neutrino mass term in the Lagrangian

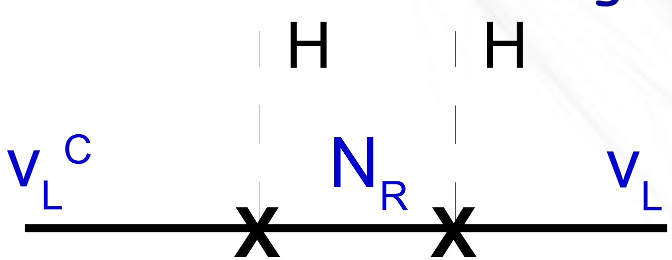
$$\left(\overline{\nu}_l, \overline{N^c_R}\right)\begin{pmatrix} 0 & m_D \\ m_D^T & M_{RR} \end{pmatrix}\begin{pmatrix} \nu_L^c \\ N_R \end{pmatrix}$$

The masses of the mass eigenstates are then the eigenvalues of this matrix

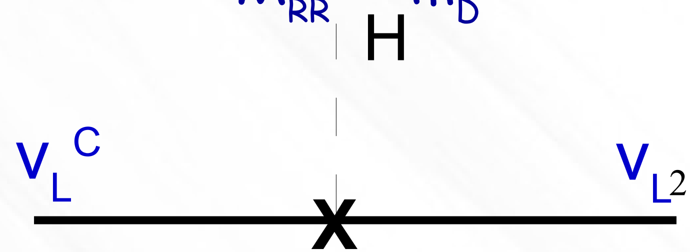
In the limit $M_{RR} \gg m_D$ the eigenvalues are

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

According to the see-saw extension of the SM Lagrangian



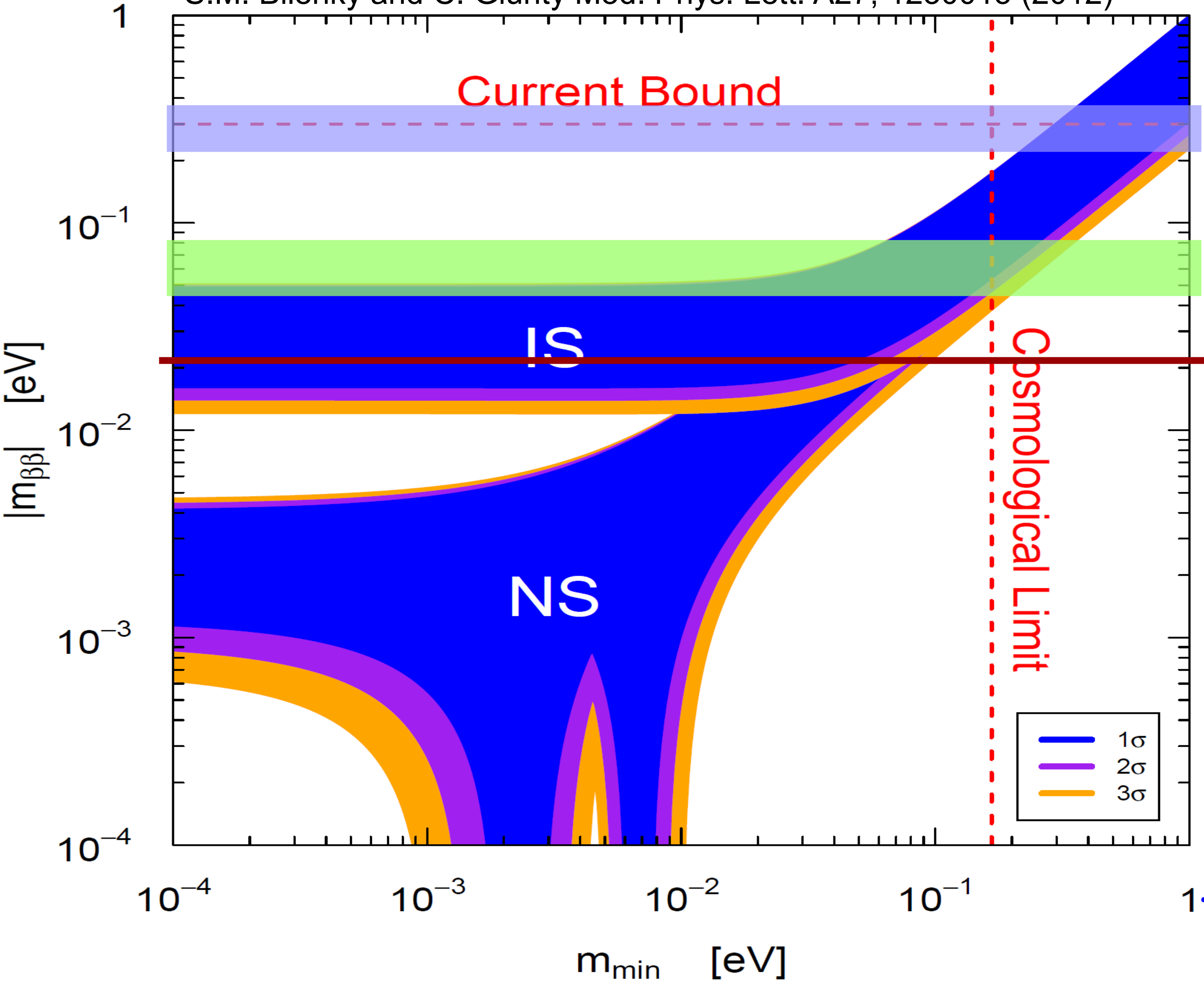
"Effectively" in the limit $M_{RR} \gg m_D$



This is exactly what's needed for 0νββ-decay

Experimental Sensitivity

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



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

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

SNO+ (8 ton ^{130}Te)

$$T_{1/2} \sim \sqrt{\frac{M \cdot t_{meas}}{bkg \cdot \Delta E}}$$

Assuming that light neutrino exchange is the dominant 0νββ-decay mechanism

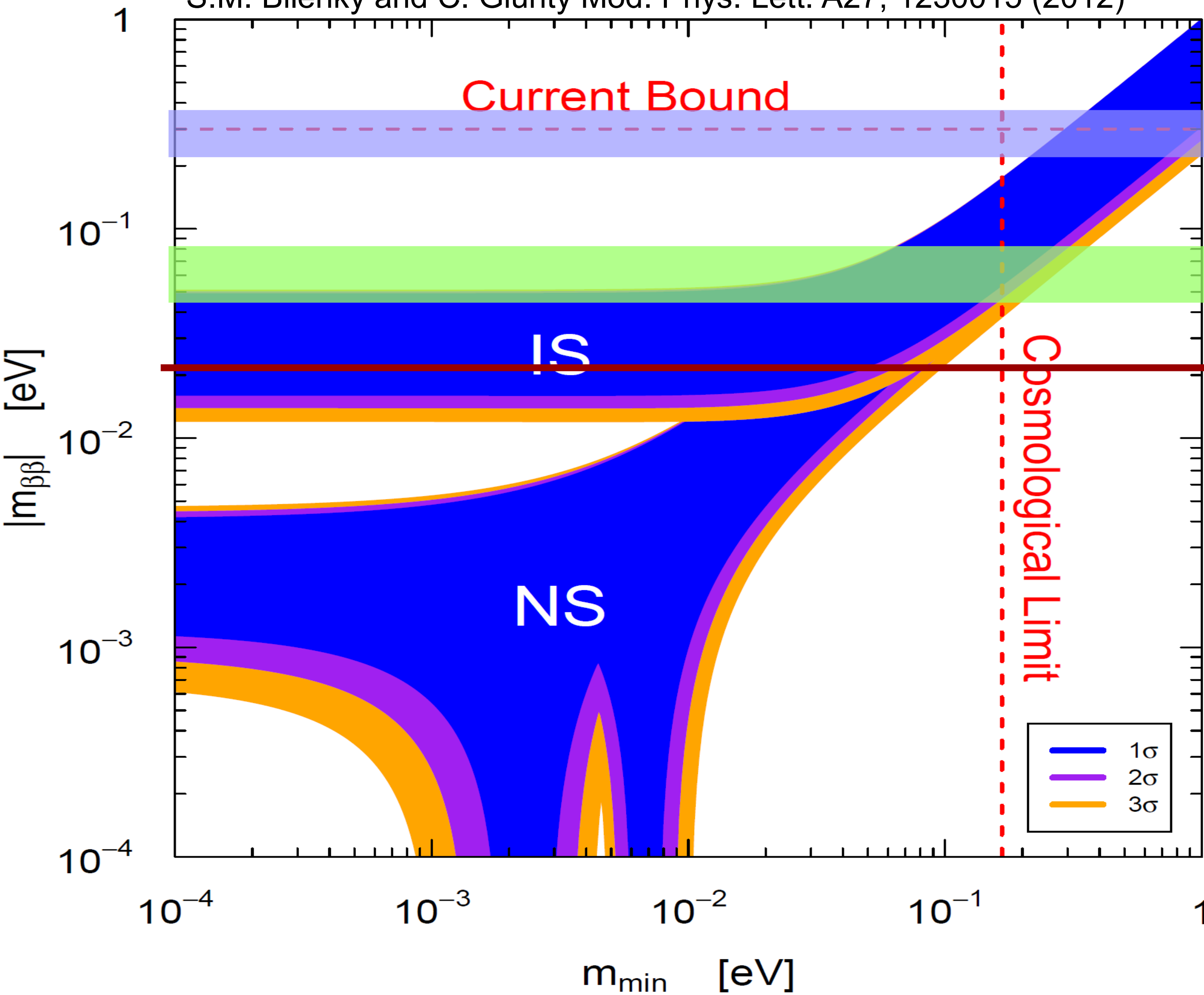
$$T_{1/2}^{-1} = G^{0\nu} \times |M^{0\nu}|^2 \times m_{\beta\beta}^2$$

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

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

Experimental Sensitivity

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



Limits by
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SNO+ (8 ton ^{130}Te)

$$T_{1/2} \sim \sqrt{\frac{M \cdot t_{meas}}{bkg \cdot \Delta E}}$$

Assuming that light neutrino exchange is the dominant $0\nu\beta\beta$-decay mechanism

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

None of the currently running or planned experiments is sensitive to $m_{\beta\beta} \sim 10^{-3}$ eV

How to Find 0νββ-decay?

1) Choose isotope where 0νββ-decay is allowed

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

Isotopes	Q-value (Total energy of 2 electrons), MeV	Natural 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

Challenge 1: Decay Probability

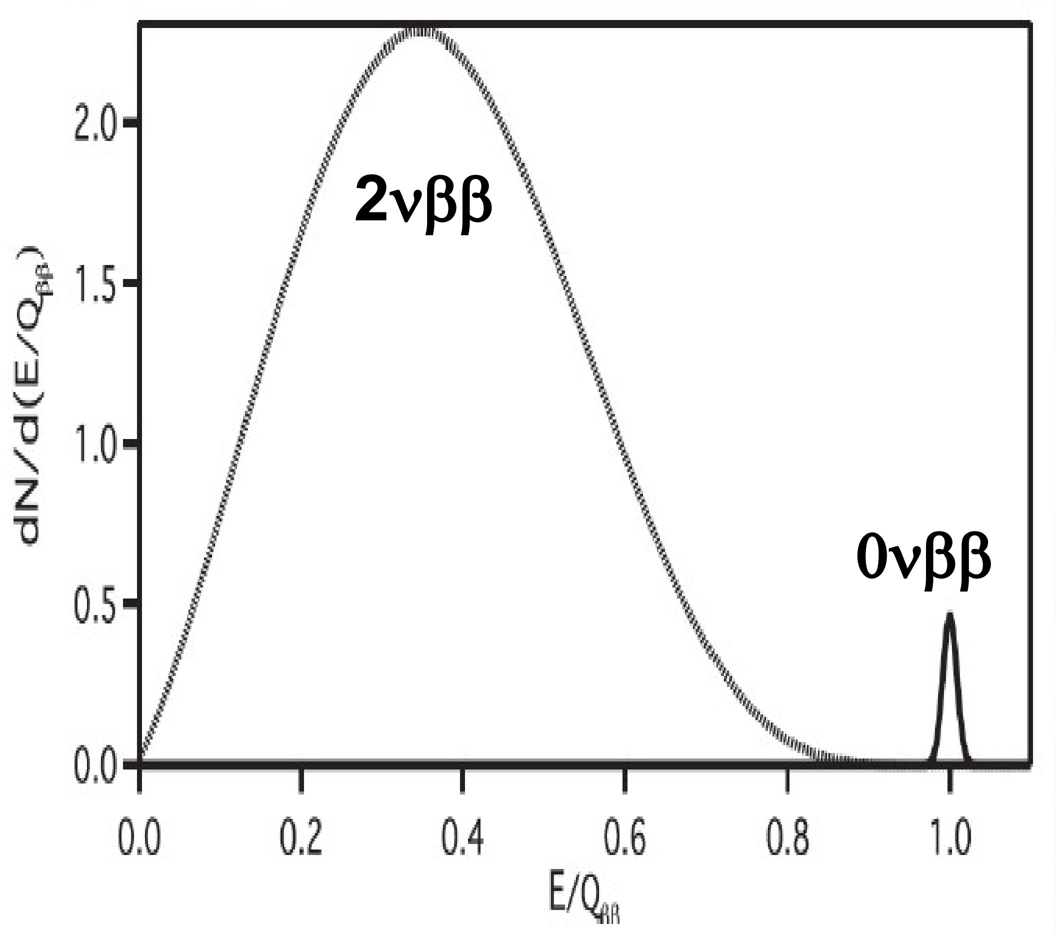
Life-time for $0\nu\beta\beta$-decay is more than ~ 10^{26} years

This is much longer than the age of the universe

Solution: look at many atoms at the same time

- Avogadro number is large $N_A = 6 \times 10^{23}$
- one ton of material can have $>10^{27}$ atoms
- even with one ton we are talking about ~10 events per year

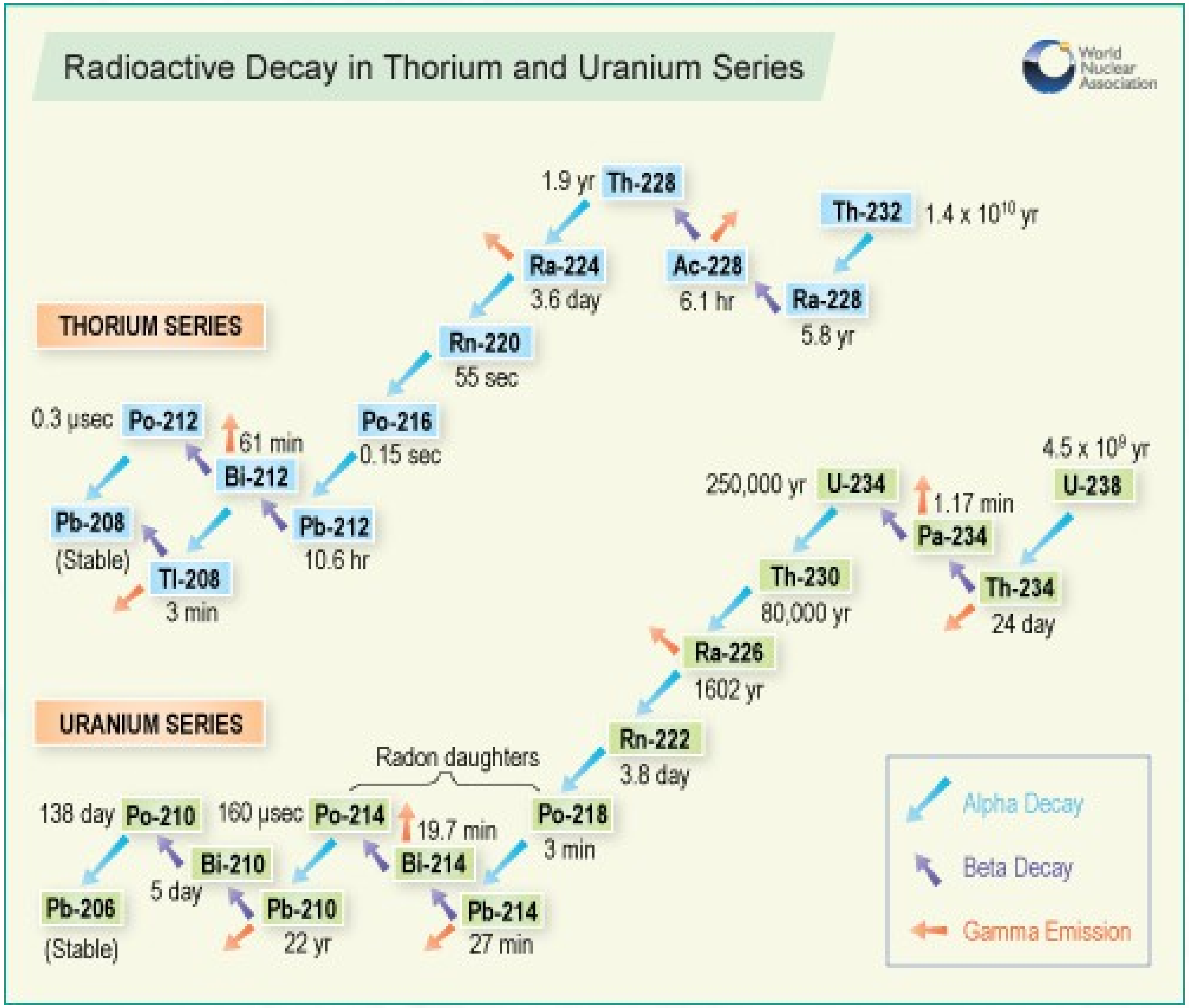
Challenge 2: Background from $2\nu\beta\beta$



Solution: good energy resolution

Challenge 3: Natural Radioactivity

There are 3g U-238 and 9g of Th-232 per ton of rock



These decays are a factor of ~10^{16} more likely than 0νββ-decay

Solution: good event selection using proper instruments

Ideal Experiment

$$T_{1/2} \sim \sqrt{\frac{M \cdot t_{meas}}{bkg \cdot \Delta E}}$$

1) Large mass (more nuclei at the same time)

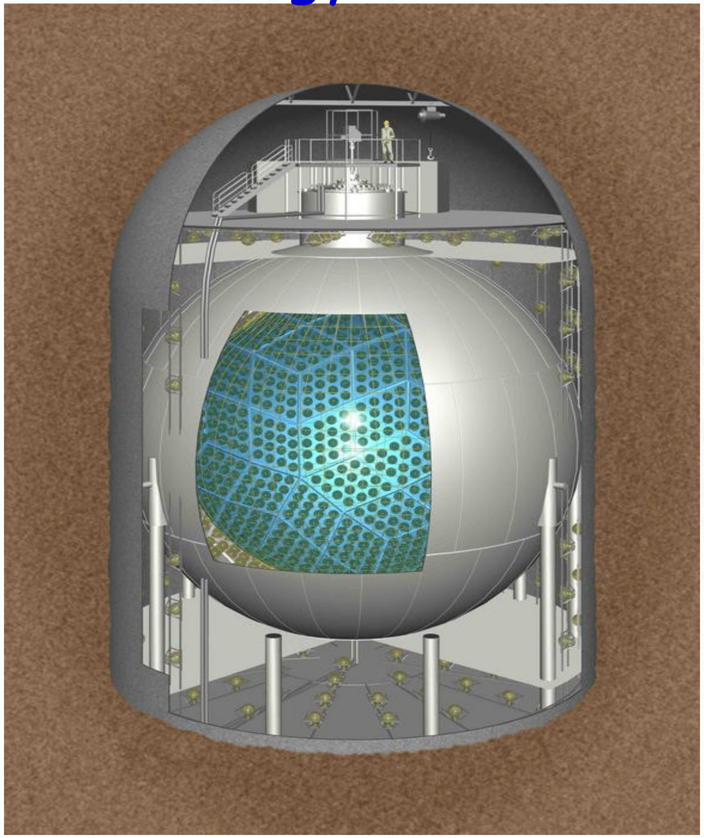
2) Good energy resolution (discriminate from 2νββ-decay)

3) Good event selection (natural radioactivity)

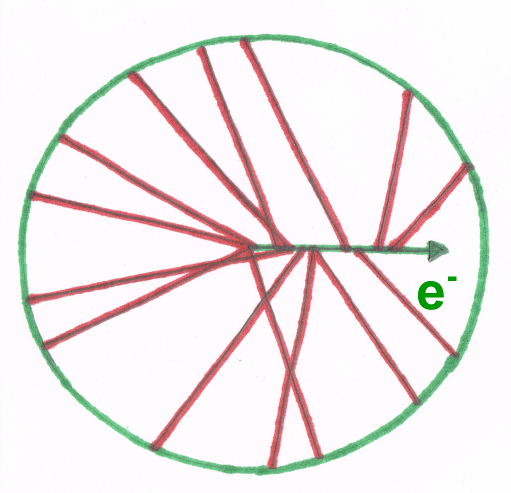
How to Make a Better Experiment?

Learn what other people have done already

KamLAND experiment:
- liquid scintillator
  ("easy" to build big)
- scintillation light is used
  for energy measurement



Scintillation light



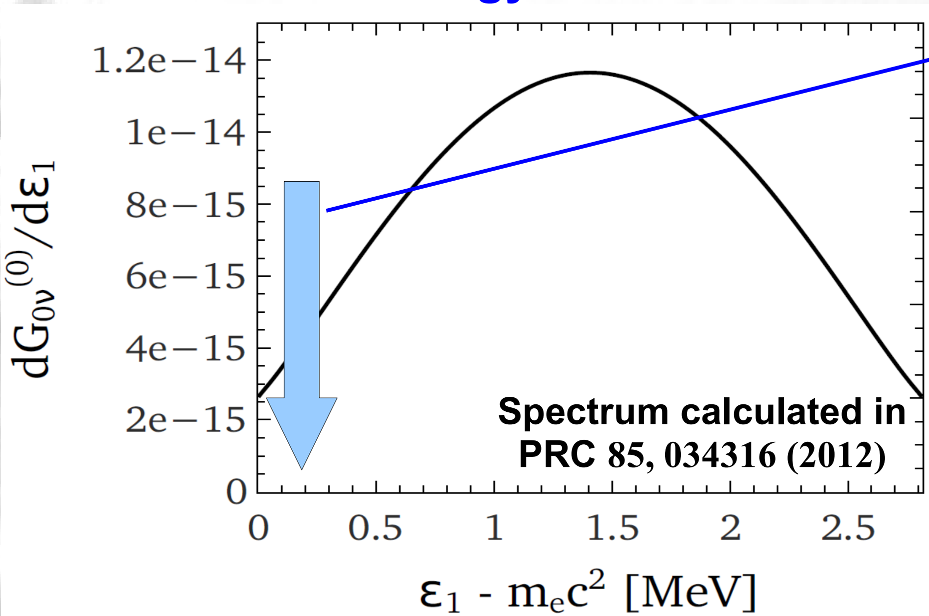
- Produced by a charged particle in a scintillation media
- Delayed
- Isotropic

How to Make a Better Experiment?

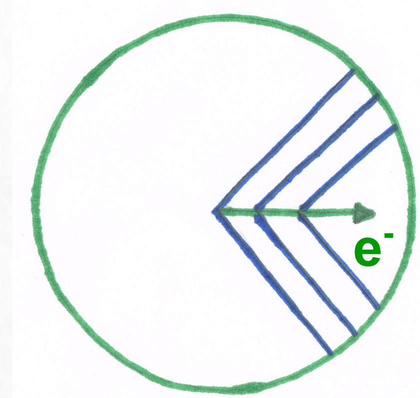
Bring new ideas

Kinetic energy of one electron

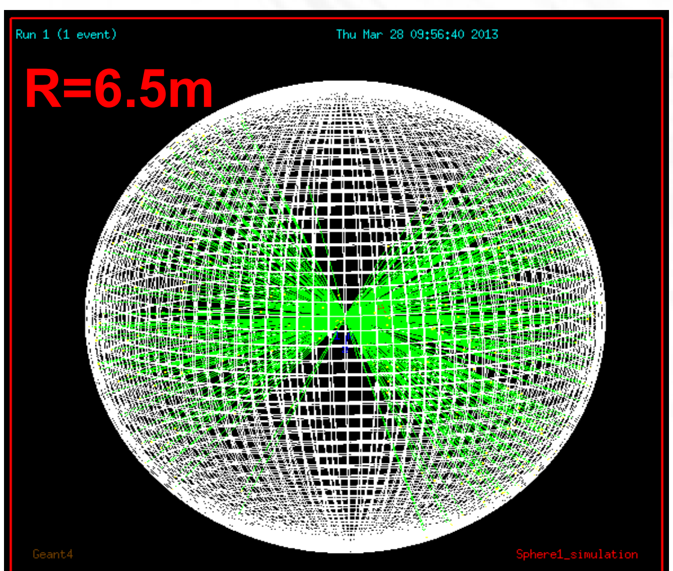
Cherenkov threshold for n=1.47



Cherenkov light



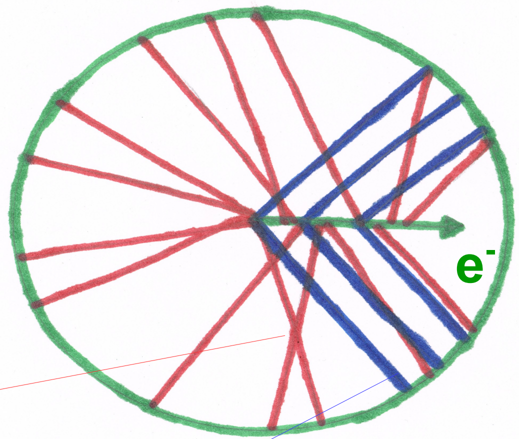
Simulation of ^{116}Cd 0νββ event

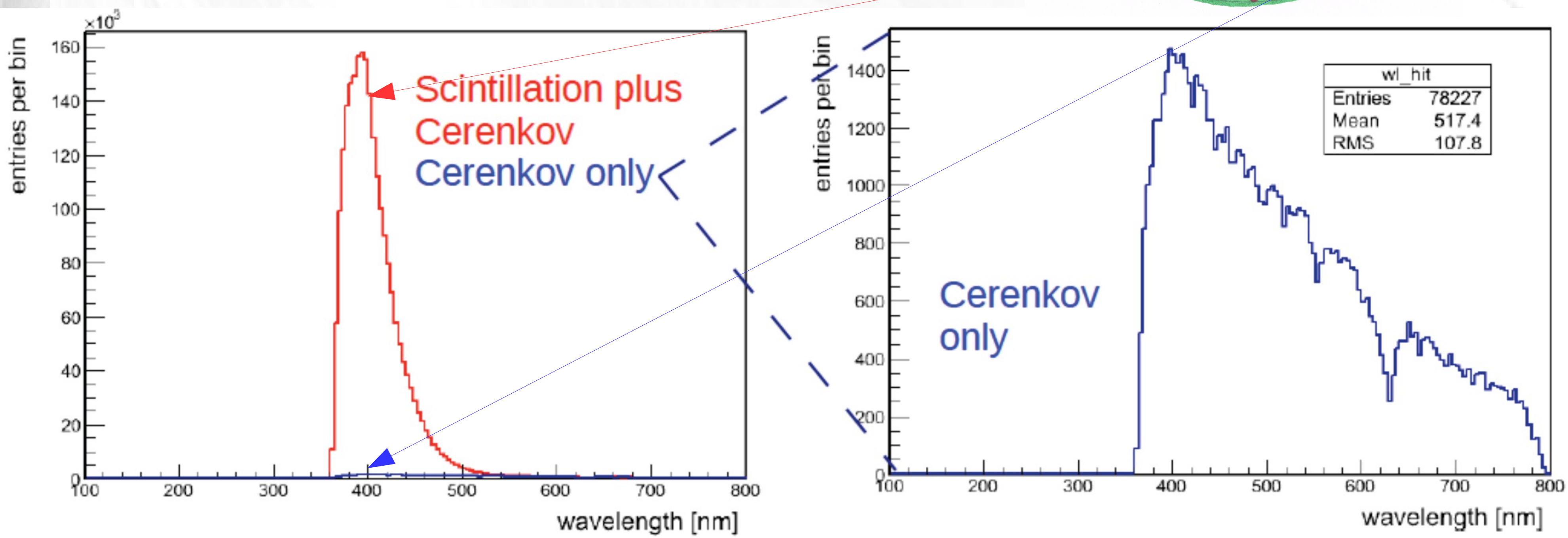


- Produced by a charged particle in a media whenever particle's speed exceeds the speed of light in that media
- Prompt
- Directional (e.g. ~42° for cosmic muons in water)

Can We Detect Cherenkov Light?

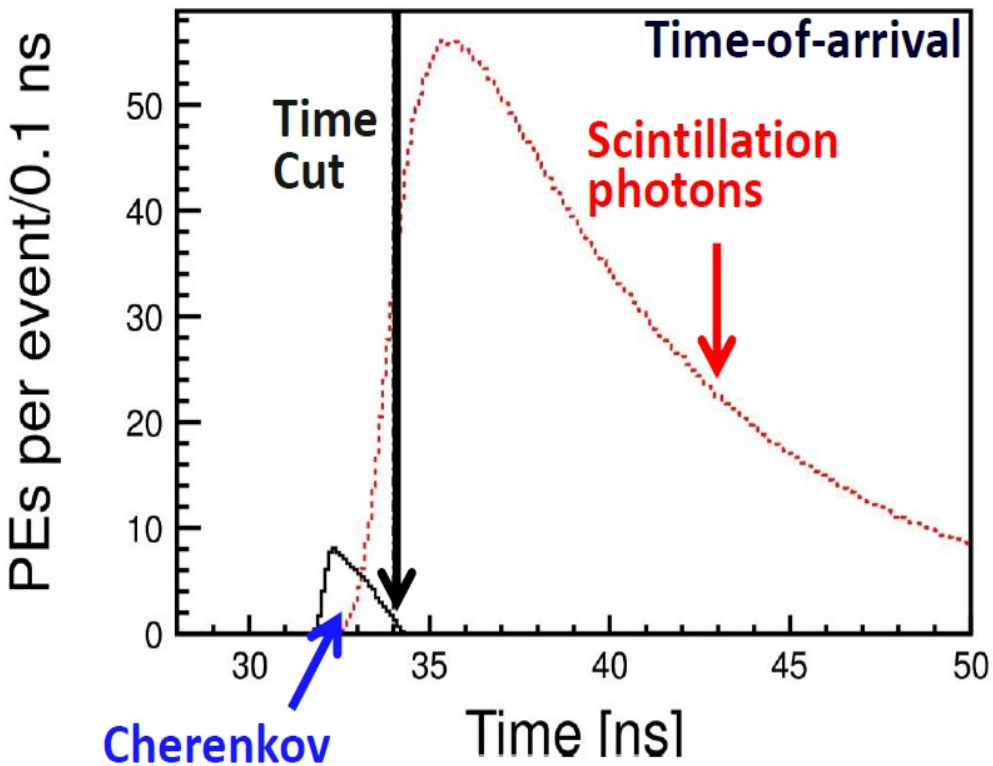
Scintillation light is more intense
Cherenkov is usually lost in liquid scintillator detectors



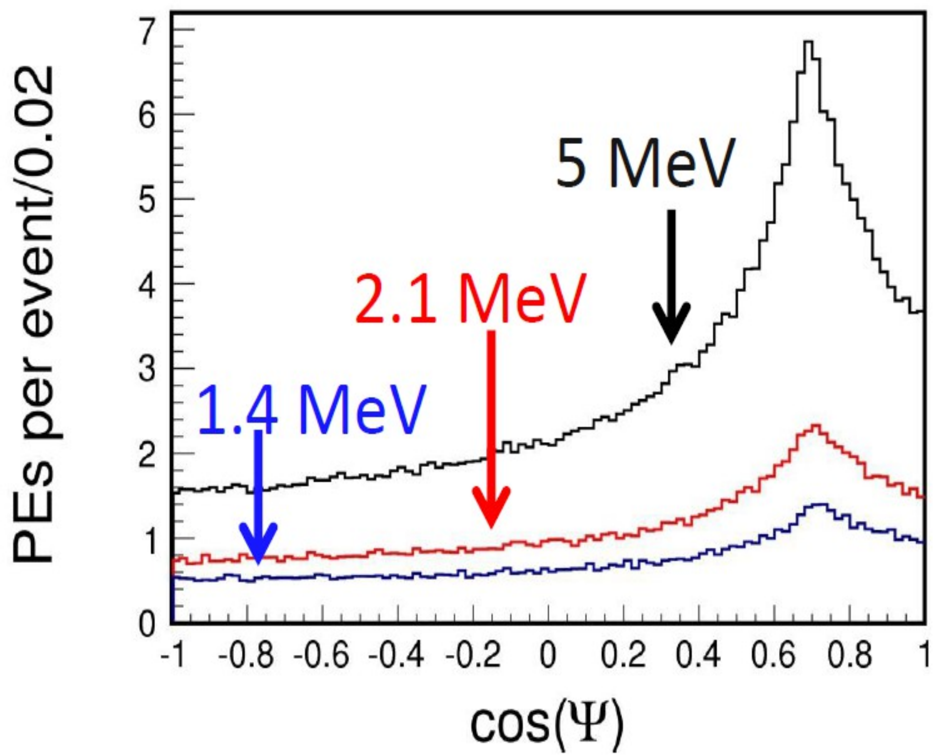


- Longer wavelengths travel faster
- Cherenkov light arrives earlier

Directionality of the Early Photons



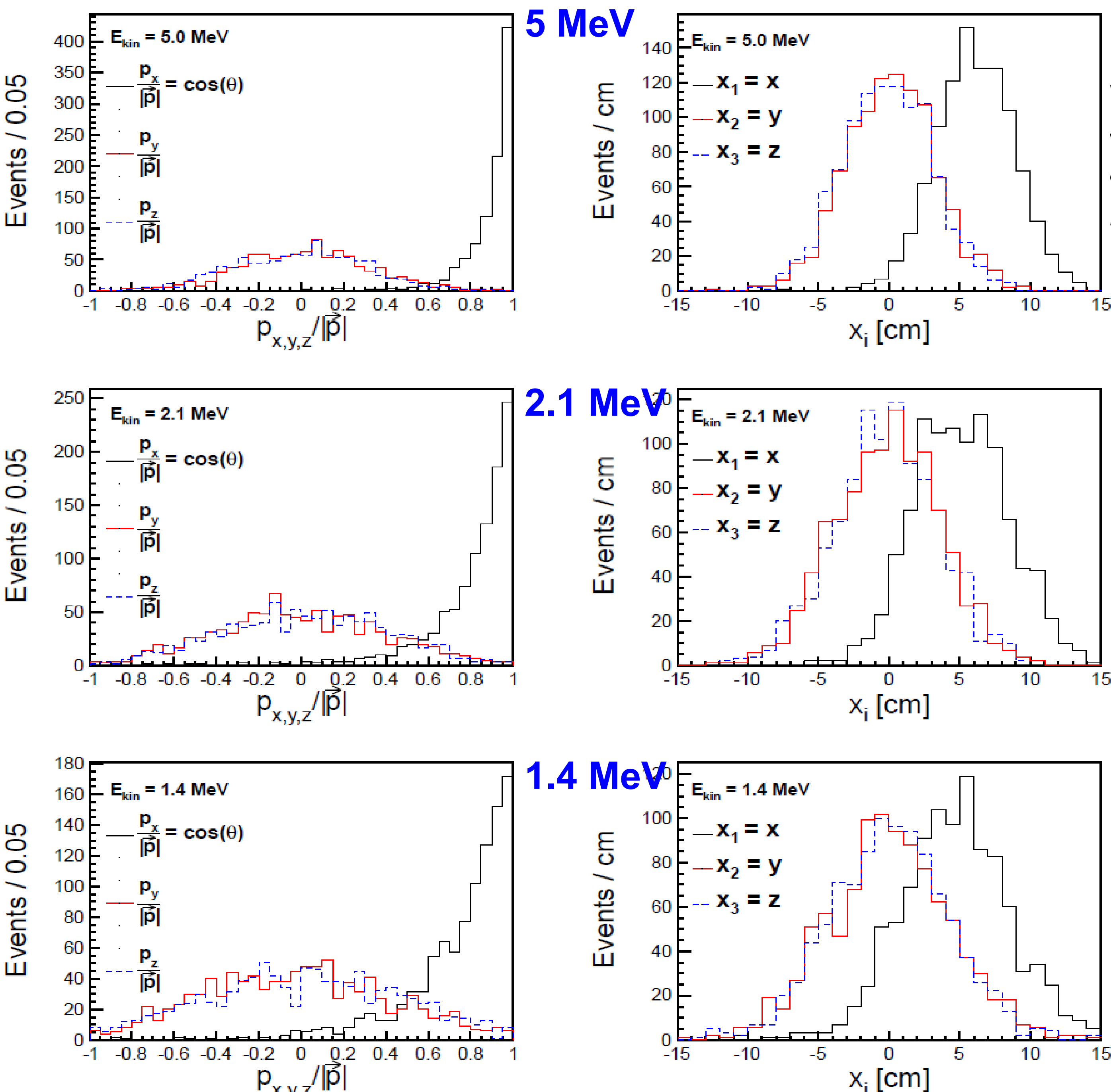
Cherenkov photons from center of 6.5m-radius sphere: TTS=100 psec



Cosine of angle between the photoelectron hit and the original electron direction after the 34 ns cut. Both Cherenkov and scintillation light are included. Note the peak at the Cherenkov angle.

Directionality and Vertex Reconstruction

Directionality | **Vertex**



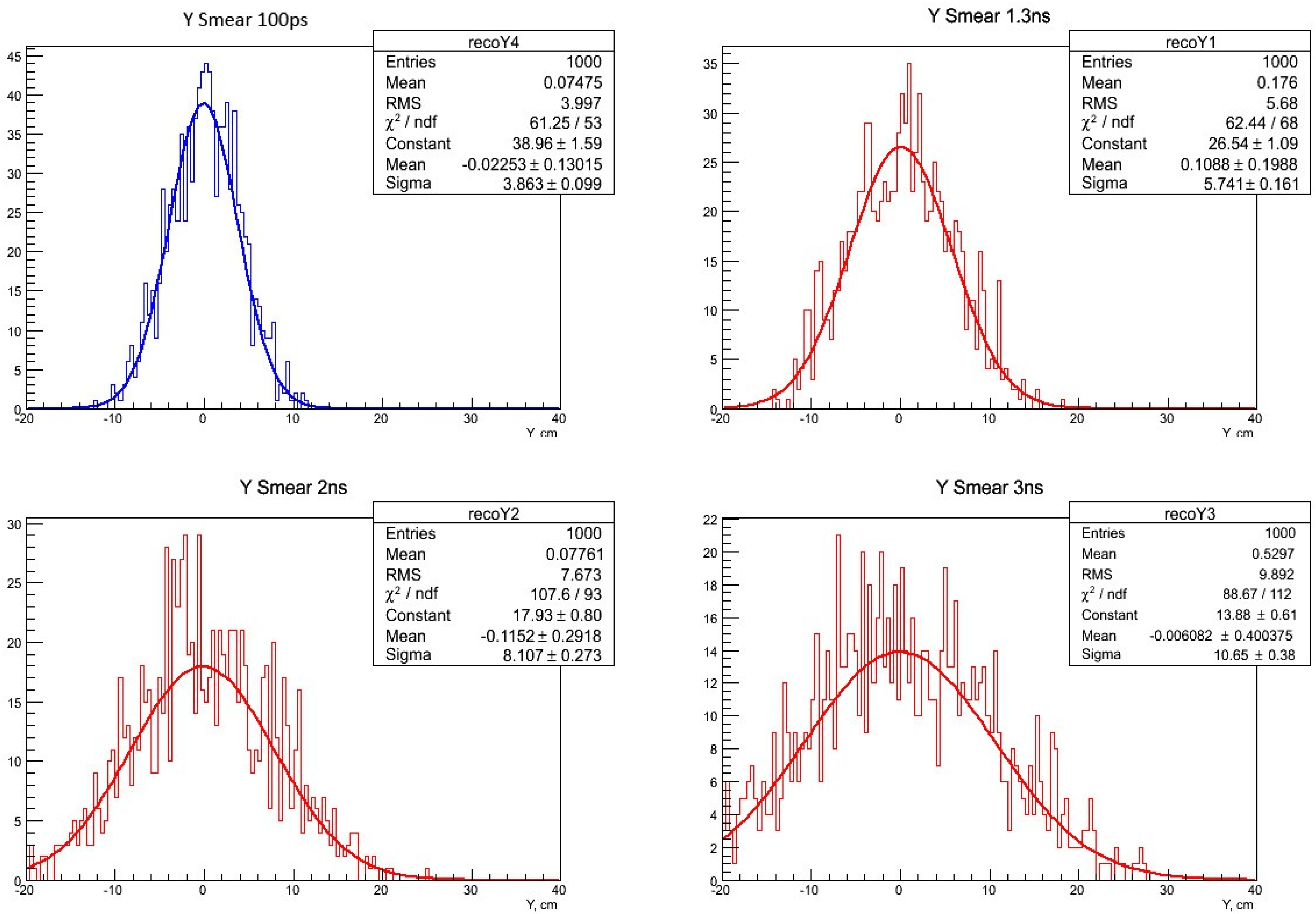
Simulation:
single electrons along X-axis at the center of 6.5m sphere KamLAND scintirllator

Reconstruction:
WCSim adapted for low energy

C.Aberle, A.E.,H.Frisch, M.Wetstein, L.Winslow

2014 JINST 9 P06012

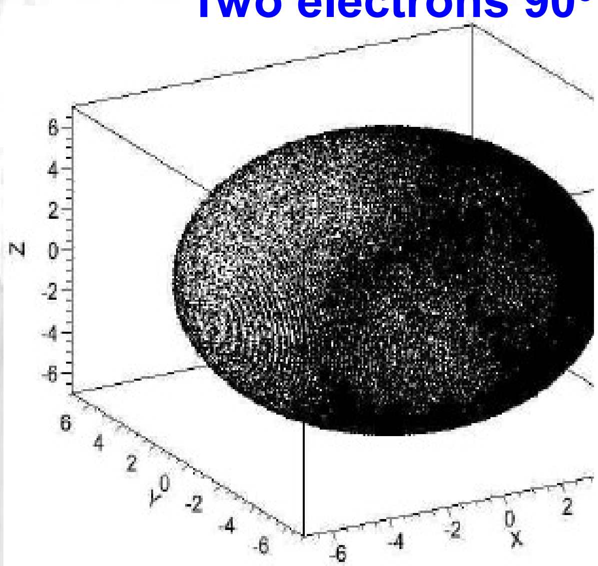
Timing and Vtx Reconstruction



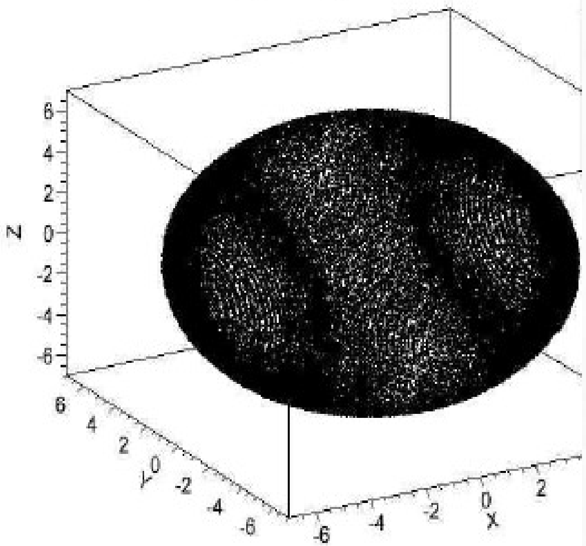
Plots from Evan Angelico, UC Davis undergraduate

Directionality or Topology?

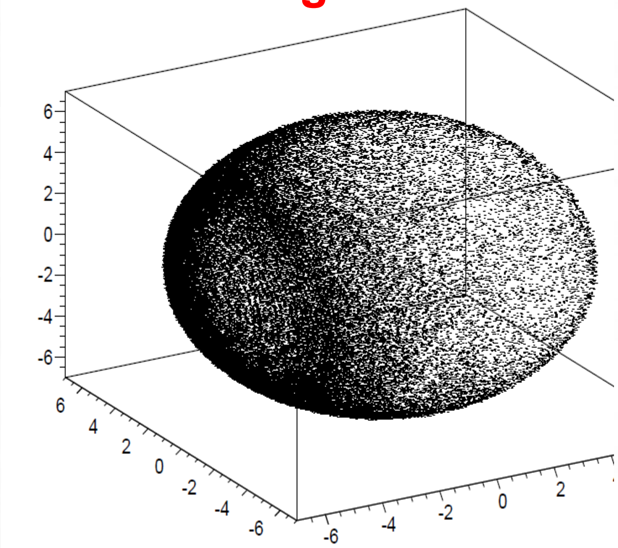
Two electrons 90°



Two electrons 180°



Single electron



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

$$N_{(\ell,m)} \equiv \sqrt{\frac{(2\ell+1)}{4\pi}\frac{(\ell-m)!}{(\ell+m)!}}.$$

$$f_\ell^m = \int_\Omega f(\theta,\varphi) Y_\ell^{m*}(\theta,\varphi)\, d\Omega = \int_0^{2\pi} d\varphi \int_0^{\pi} d\theta \, \sin\theta f(\theta,\varphi) Y_\ell^{m*}(\theta,\varphi).$$

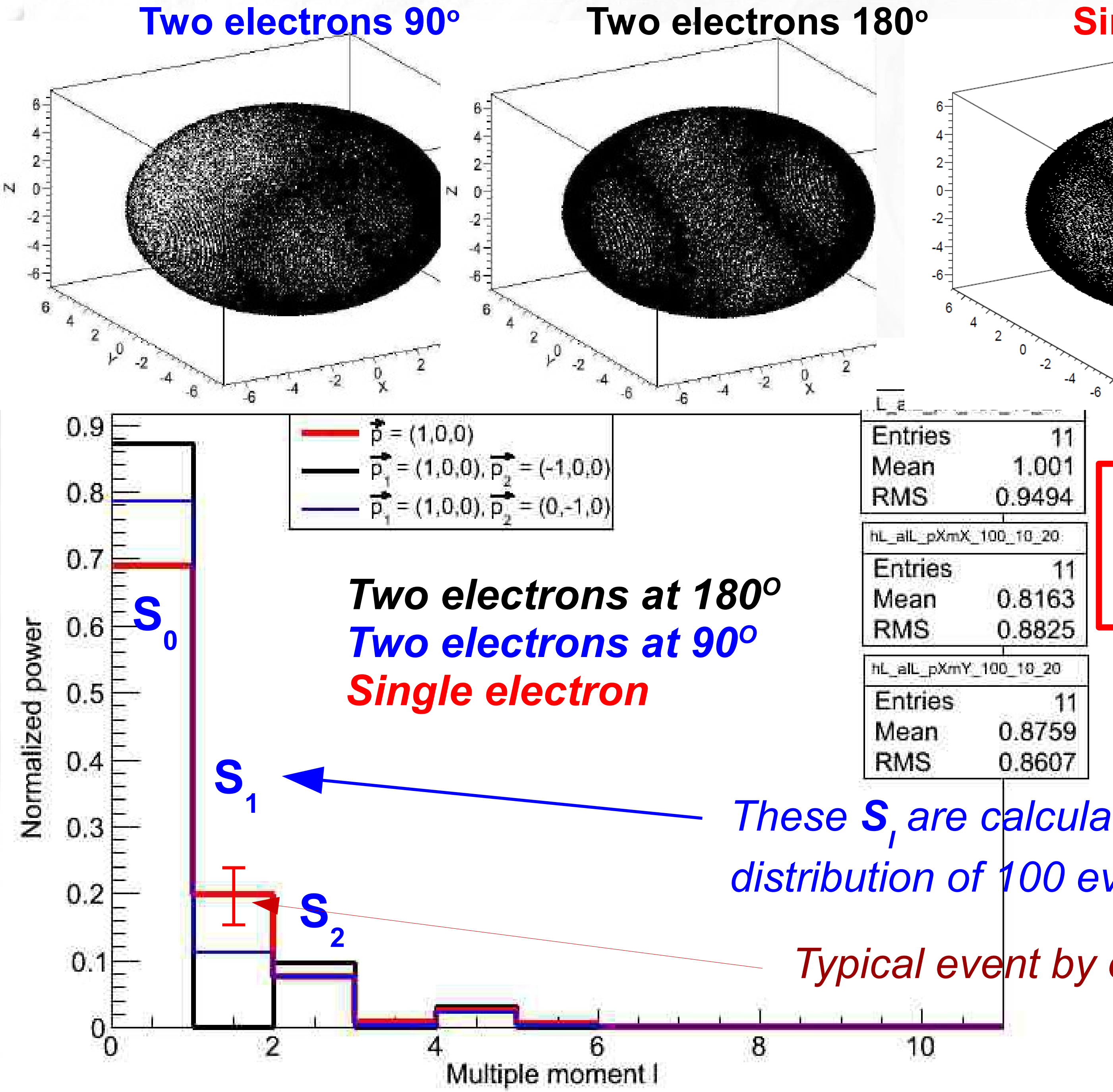
L2 norm

$$\int_\Omega |f(\Omega)|^2 d\Omega = \sum_{\ell=0}^{\infty} S_{ff}(\ell)$$

„Power“ (rotation invariant)

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

Early Light Spherical Harmonics

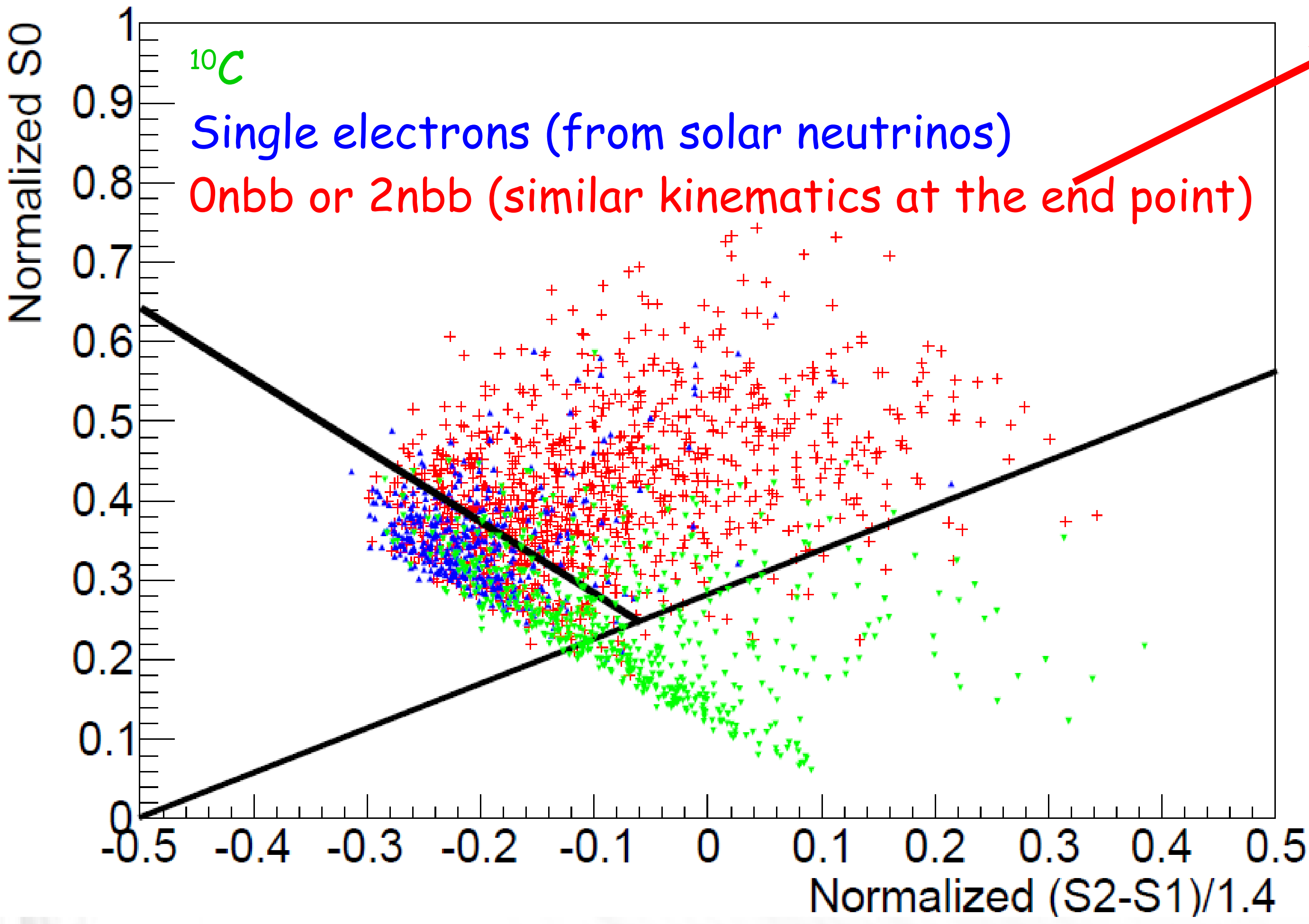


$$S_{ff}(\ell) = \sum_{m=-\ell}^{\ell} |f_{\ell m}|^2$$

These S_l are calculated for a combined hit distribution of 100 events

Typical event by event spread

Early Light Spherical Harmonics



Good energy resolution is essential to separate 0νββ and 2νββ decays

Topology helps against other backgrounds

Stay tuned for a complete analysis to quantify sensitivity improvements due to fast timing

Credits:

- the idea to try spherical harmonics to test event topology by Henry Frisch
- many productive discussions on the implementation with Eric Spieglan

Planned Demonstrations

Table by Gabriel Orebi Gann

Eric Oberla PhD thesis → UChicago

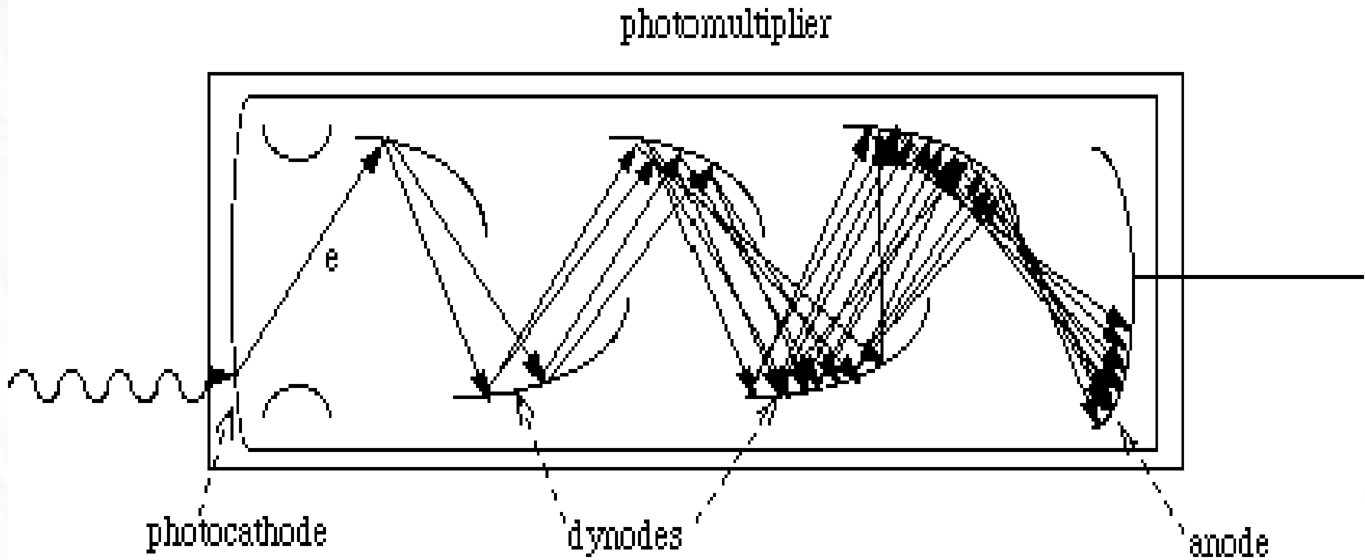
L. Winslow NuDot Project → UCLA/MIT

Site	Scale	Target	Measurements	Timescale
UChicago	bench top	H2O	fast photodetectors	Exists
EGADS	200 ton	H2O+Gd	isotope loading, fast photodetectors	Exists
ANNIE	1 ton			2016
WATCHMAN	1 kton			2018
UCLA/MIT	1 ton	LS	fast photodetectors	2015
Penn	30 L	(Wb)LS	light yield, timing, loading	Exists
SNO+	780 ton			2016
LBNL	bench top	WbLS	light yield, timing, cocktail optimization, loading, attenuation, reconstruction	Early 2015
BNL	1 ton			Summer 2015
WATCHMAN-II	1 kton			2019

Do we have fast photo-detectors?
(large coverage, good timing, cheap)

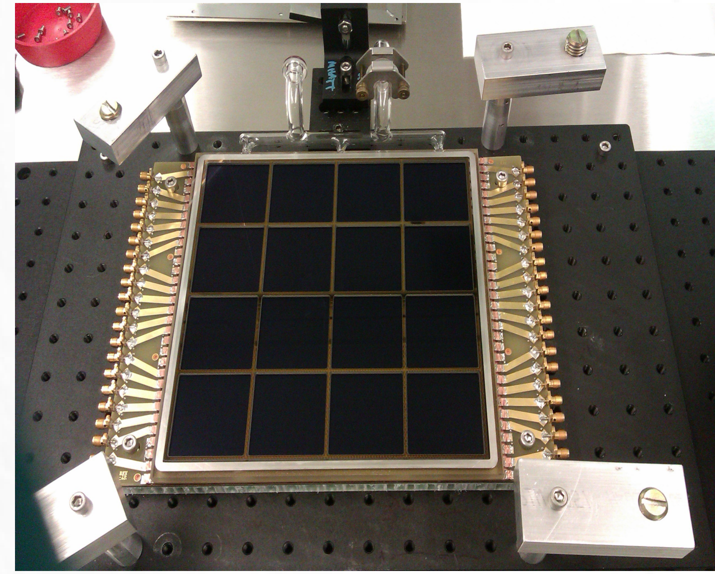
Photo-Detectors

Photo-Multiplier Tube (PMT) is a classical example of a photo-detector
- use photo-electric effect to convert a photon to an electron
- use secondary electron emission (SEE) to amplify the signal



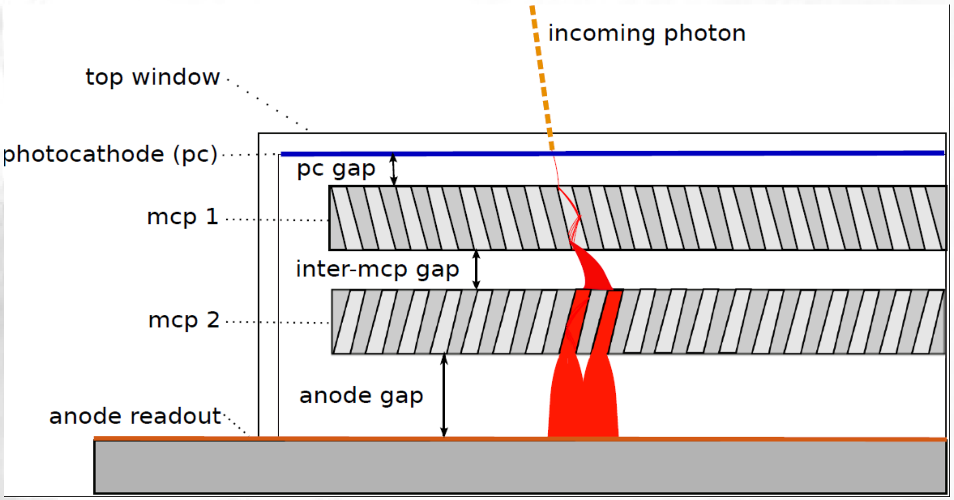
Uncertainty on the electron path causes uncertainty on the signal timing
The shorter the electron path the better the time resolution

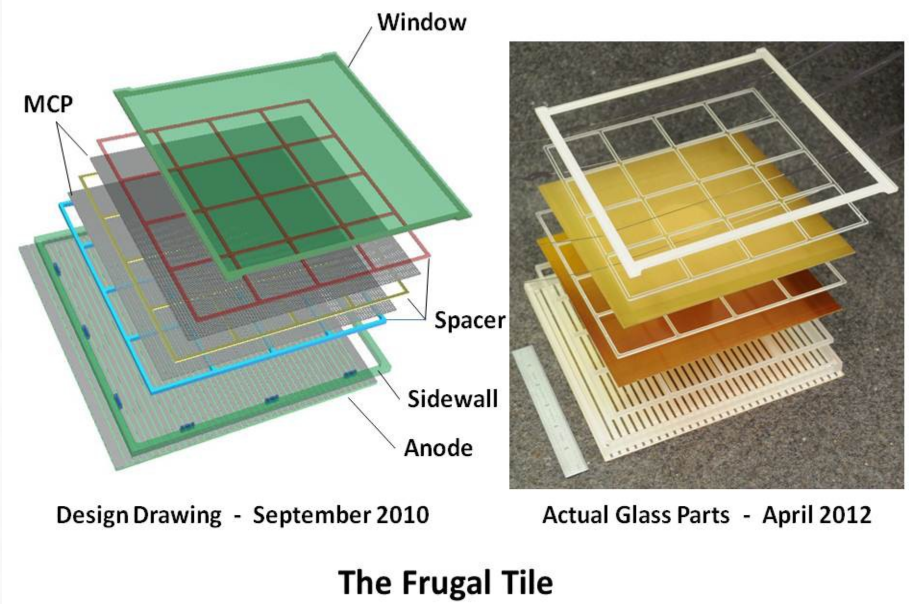
Large-Area Picosecond Photo-Detectors (LAPPD)

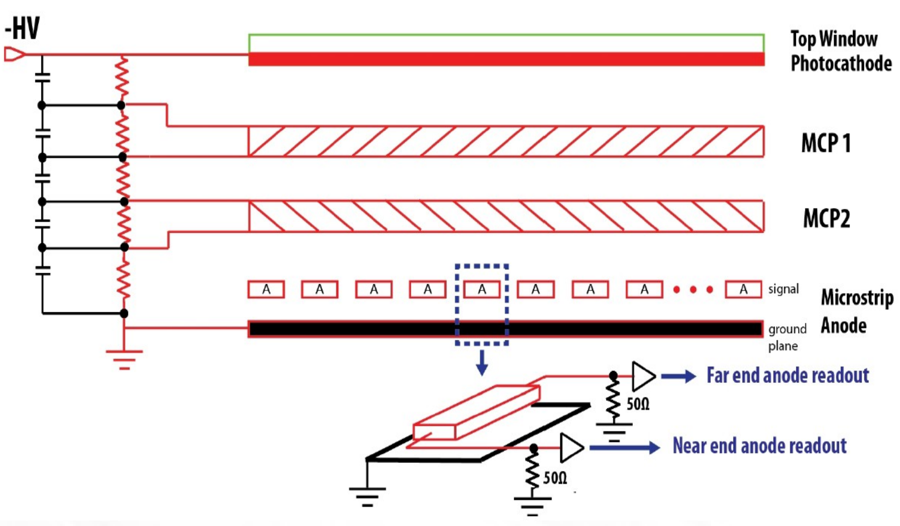


Transformational change

Glass Package (20x20 cm^2)





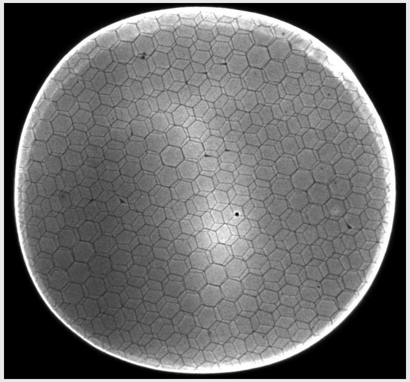


- Widely available float glass
- Anode is made by silk-screening
- Flat panel
- No pins, single HV cable
- Modular design
- High bandwidth 50 Ω object
  - designed for fast timing

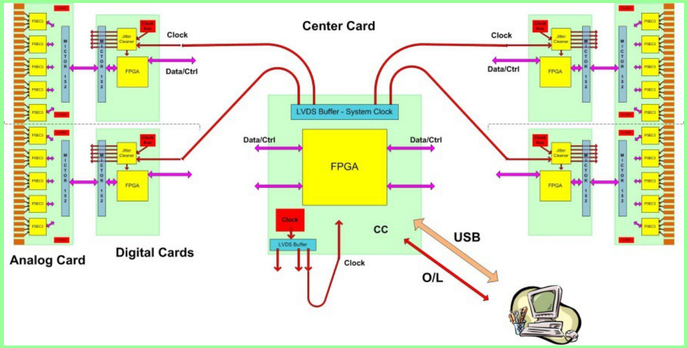
Ceramic body packaging is a parallel (and collaborative) effort at Berkeley SSL

LAPPD Components

MicroChannel Plates

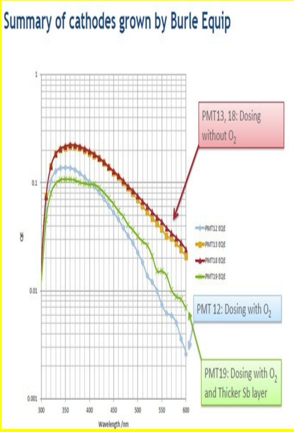


Electronics/Integration



Hermetic Packaging

Photocathodes

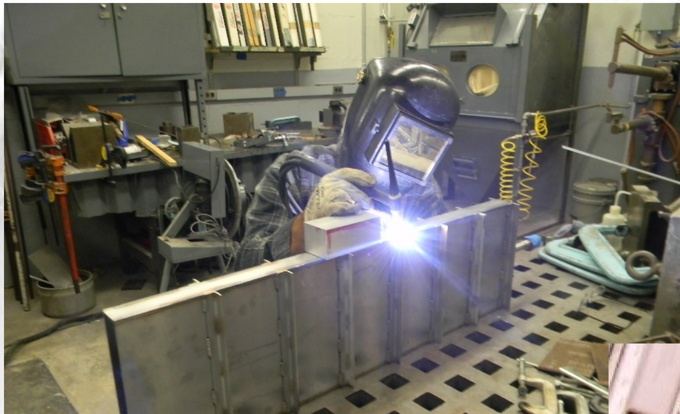


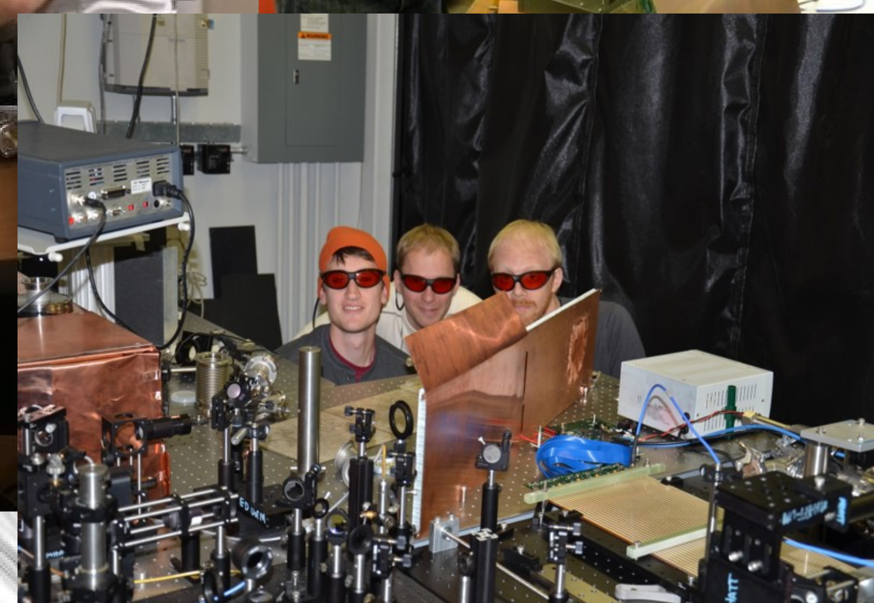
Multidisciplinary Effort

Lots of Hands On Experience

We need lots of stuff and we often build what we need

This is fun!

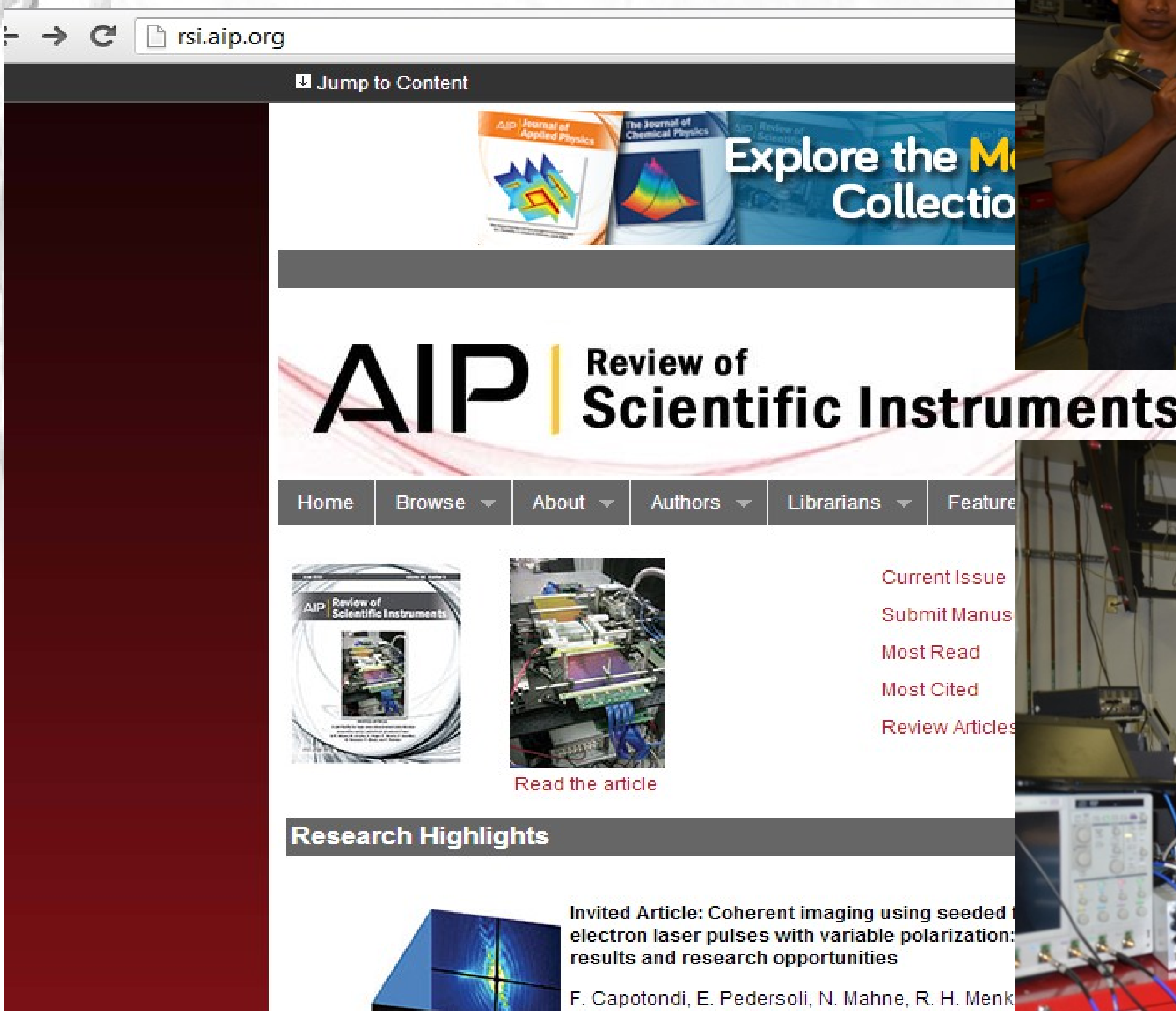


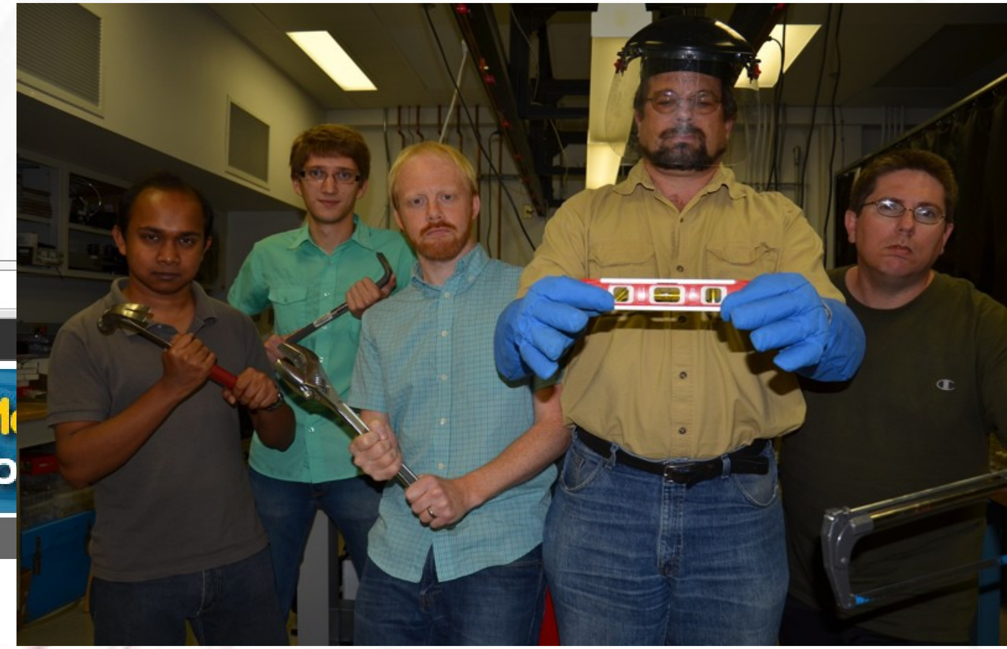


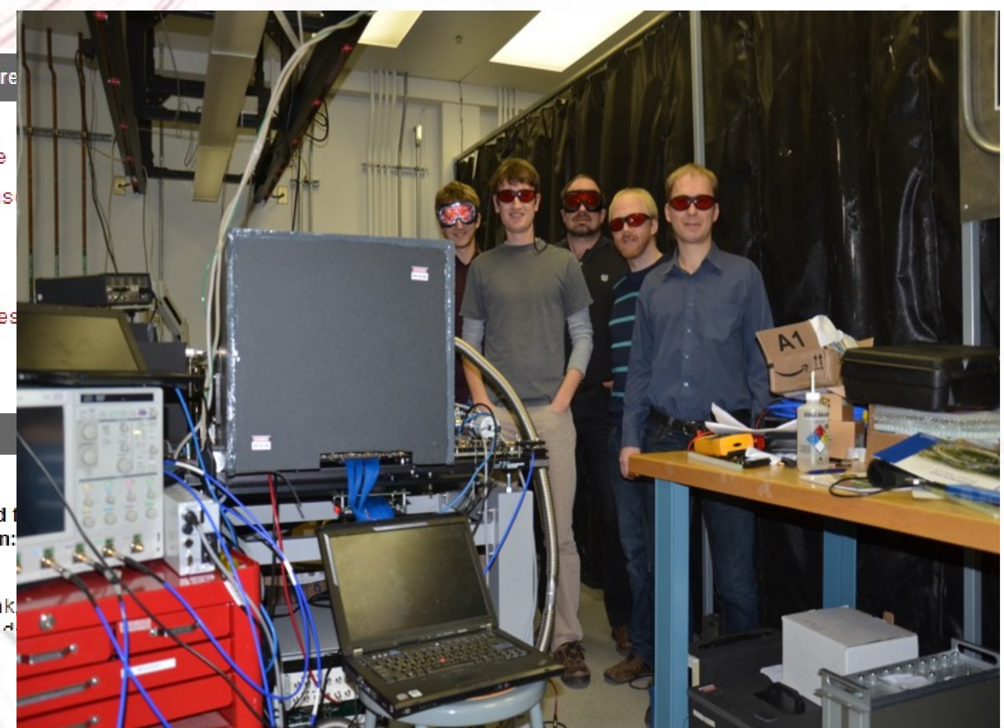
It's Hard but Rewarding

Invited article

Rev. Sci. Instrum. 84, 061301 (2013)

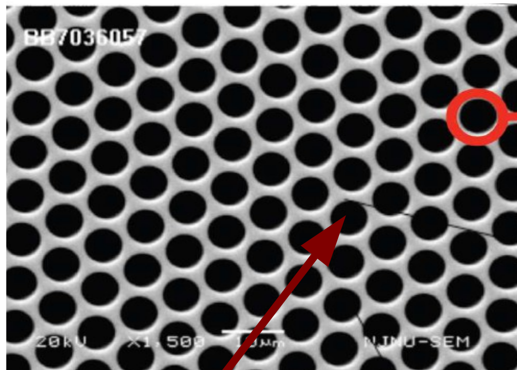


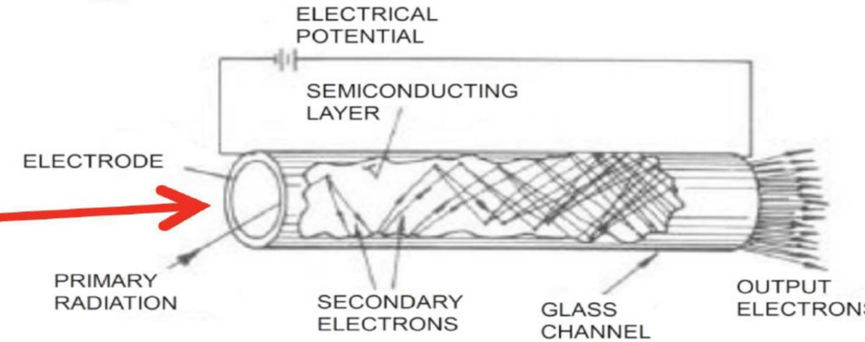


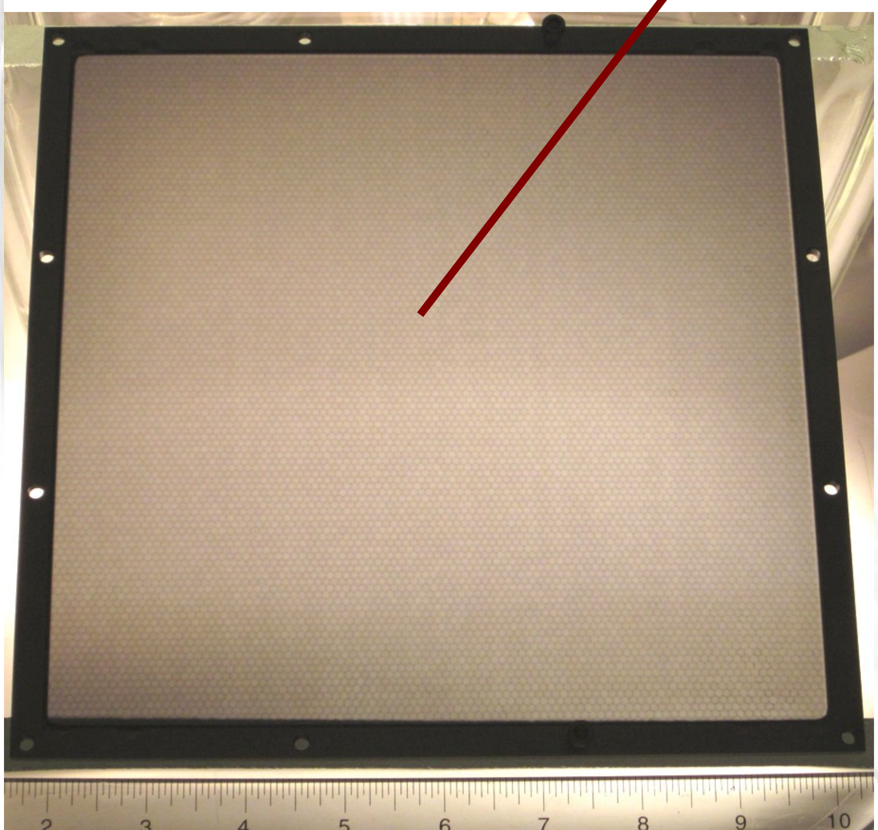


Micro-channel Plates

~1kV





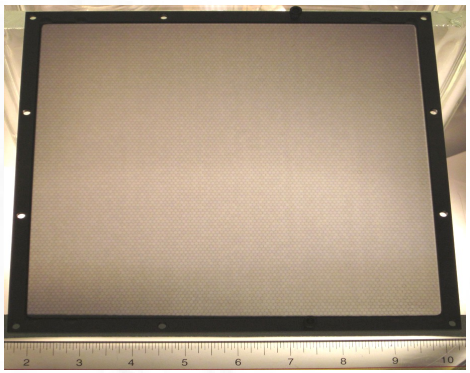


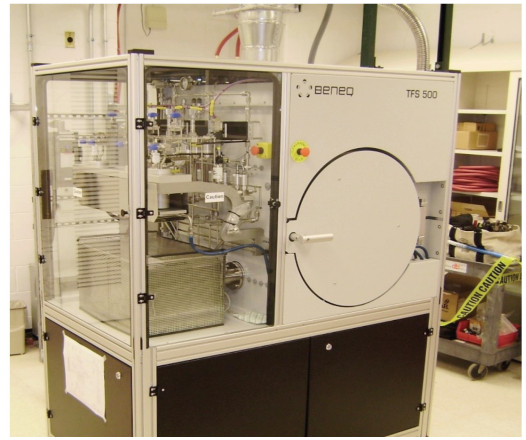
Micro-Capillary Arrays by Incom Inc.

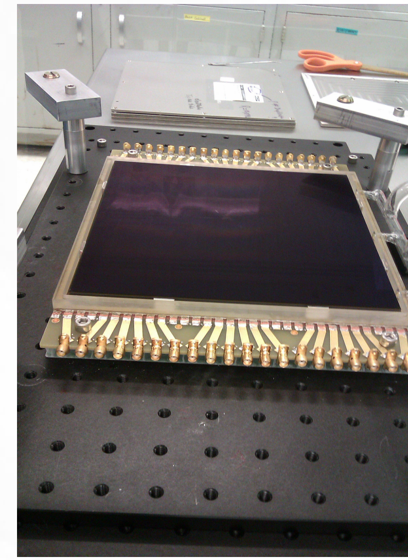
- ***Material:*** ***ordinary glass***
- ***Area:*** ***20x20cm² → 8x8"***
- ***Thickness:*** ***1.2mm***
- ***Pore size:*** ***20 μm***
- ***Open area:*** ***60-80%***

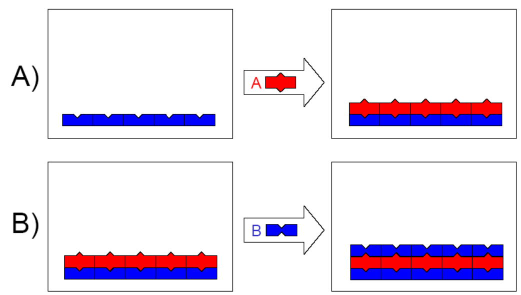
Atomic Layer Deposition

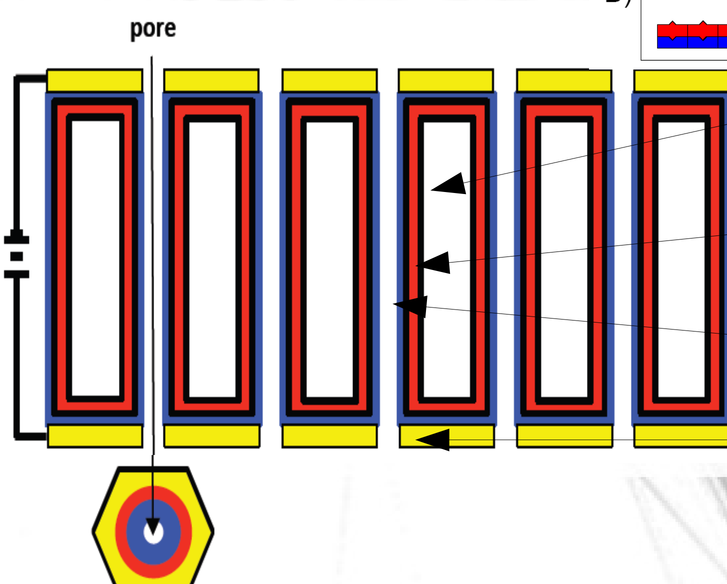
ALD Process for MCP Coating
by A.Mane, J.Elam
and independently by Arradiance Inc.











Porous glass

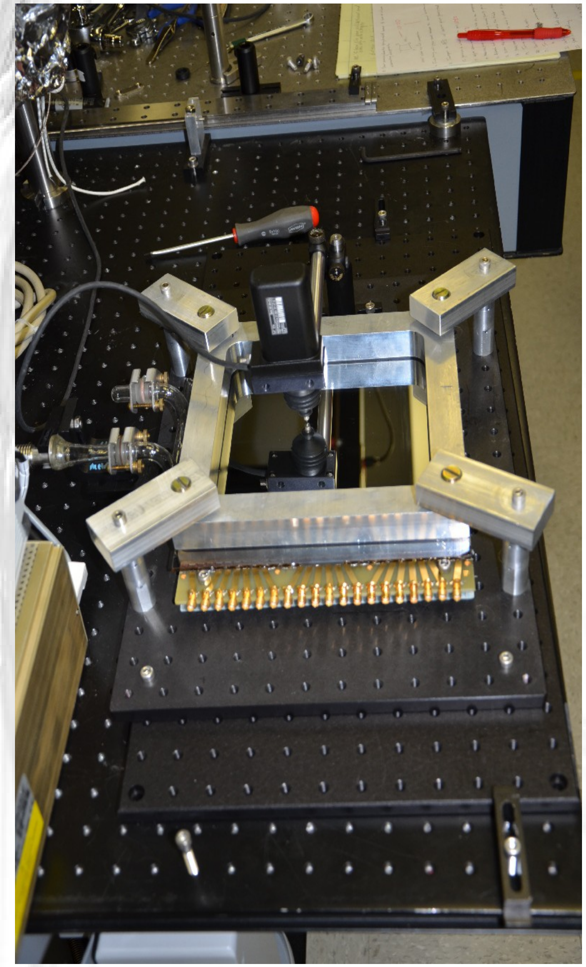
Resistive coating ~100nm (ALD)

Emissive coating ~ 20nm (ALD)

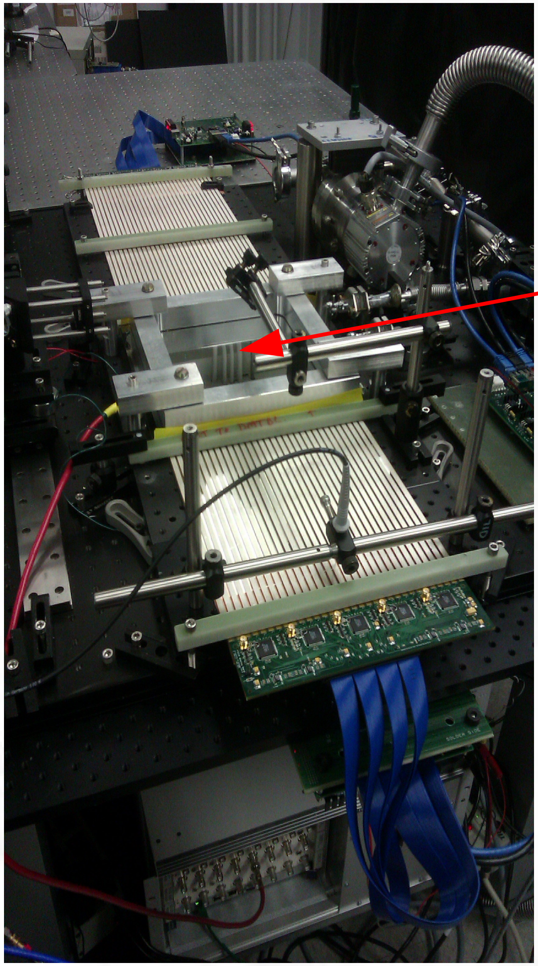
Conductive coating
(thermal evaporation or sputtering)

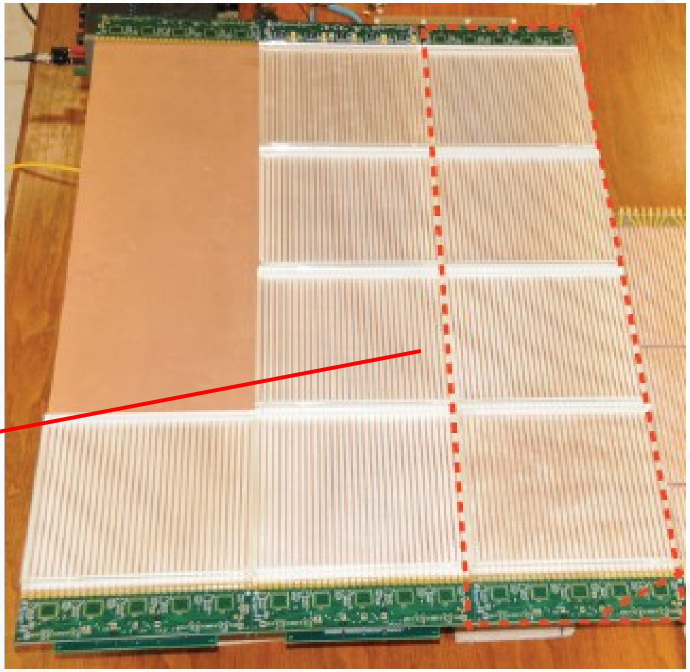
Detector Prototype

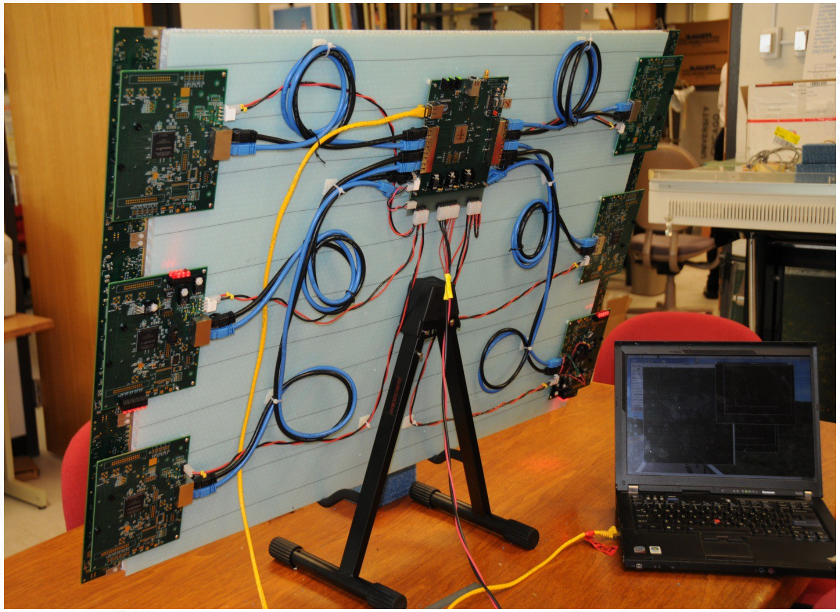
Demountable 1.0
(May 2012)



Demountable 3.0
(Sep-Dec 2012)

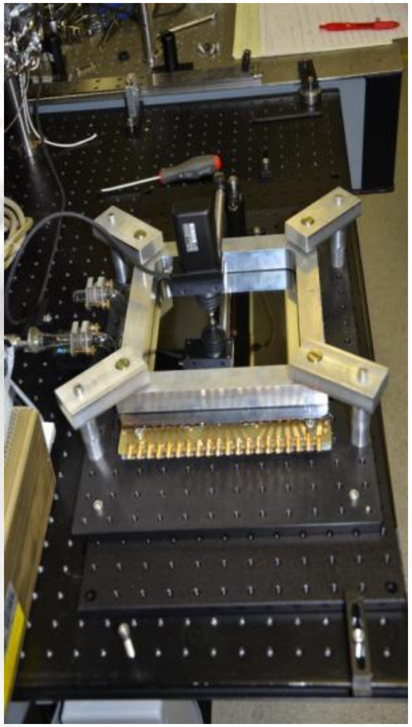


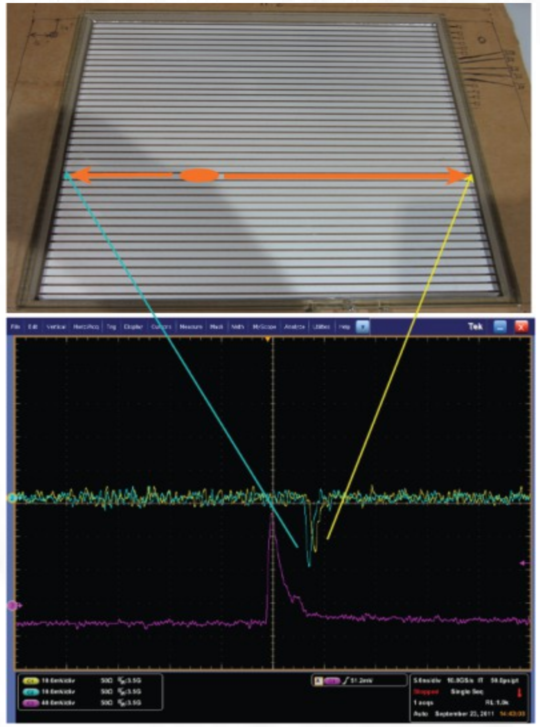




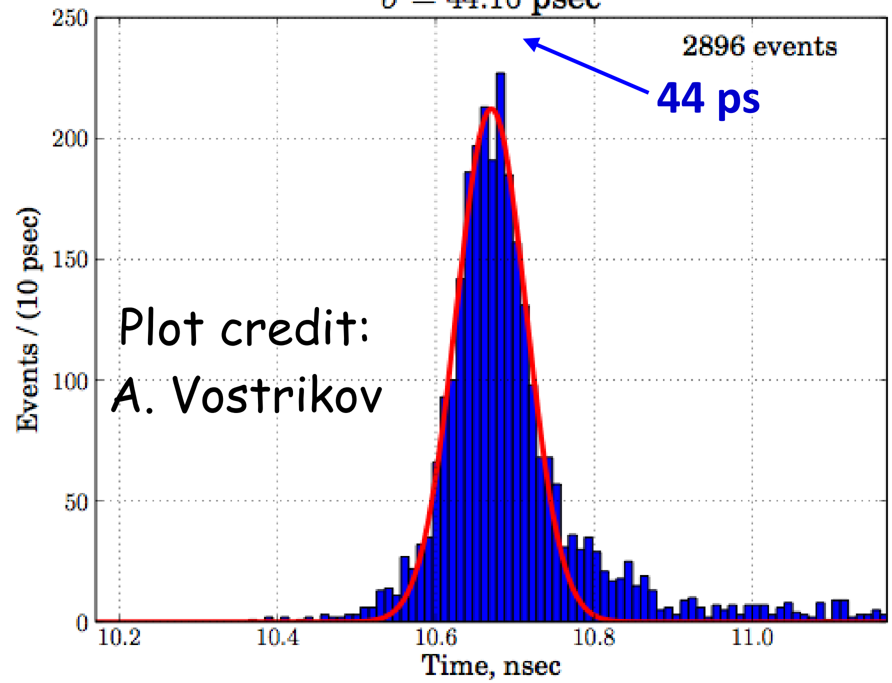
B.Adams, A.E., E.Oberla, R.Obaid,
A.Vostrikov, M.Wetstein

Testing Results

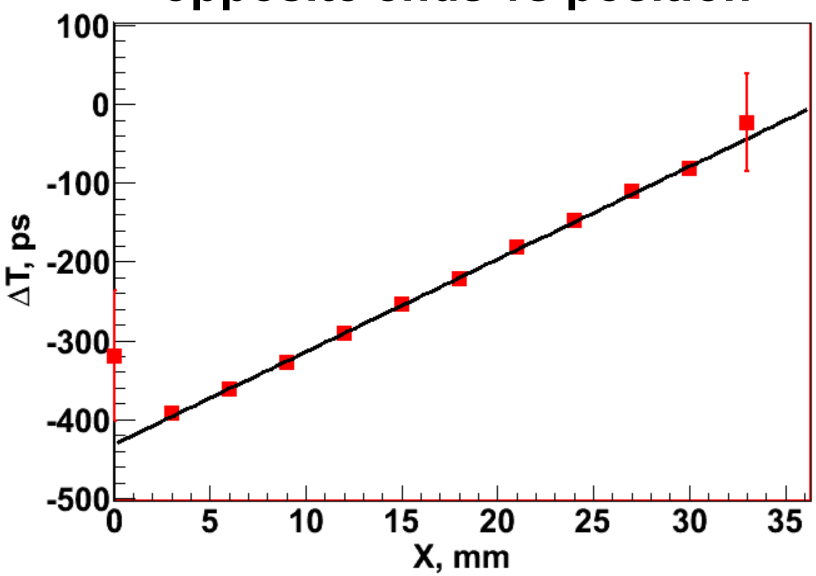


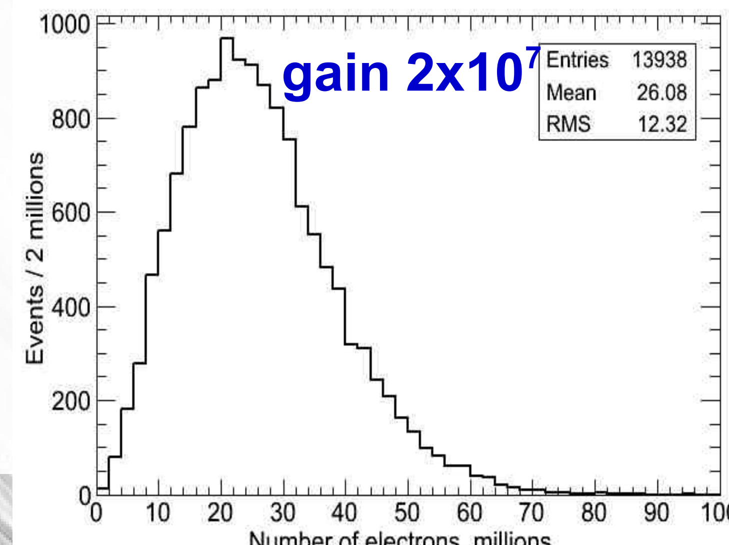


Single PE time resulution

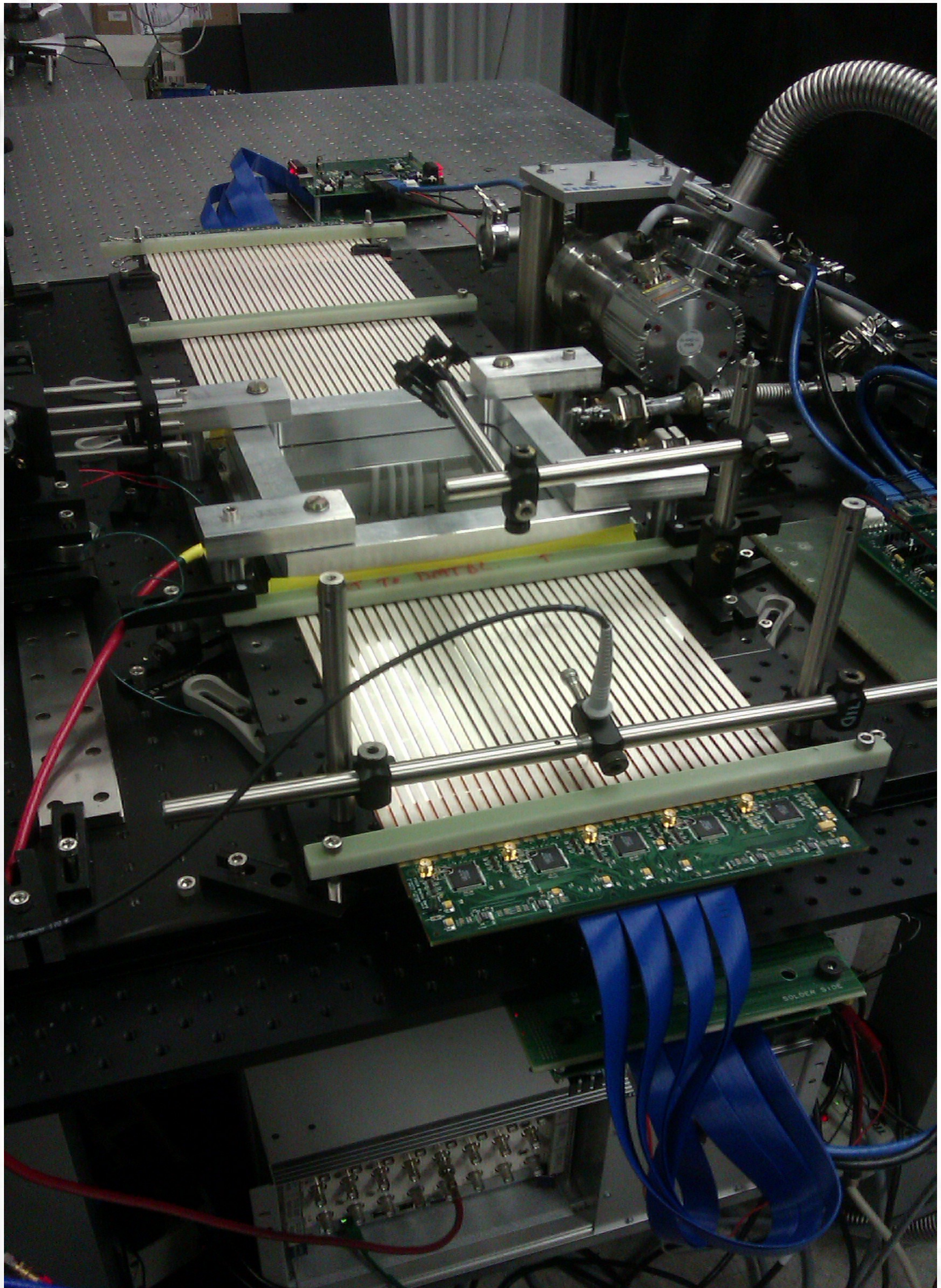


Time delay between two opposite ends vs position



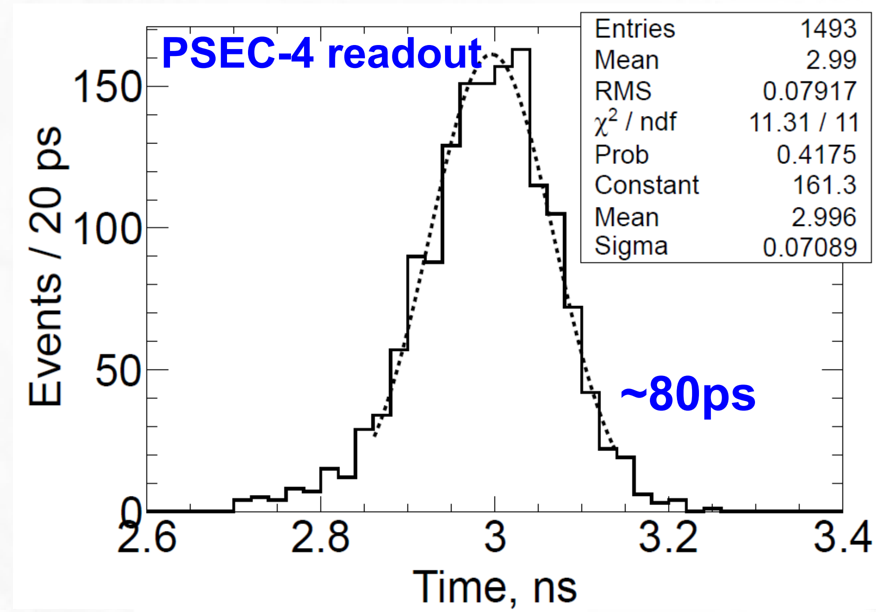


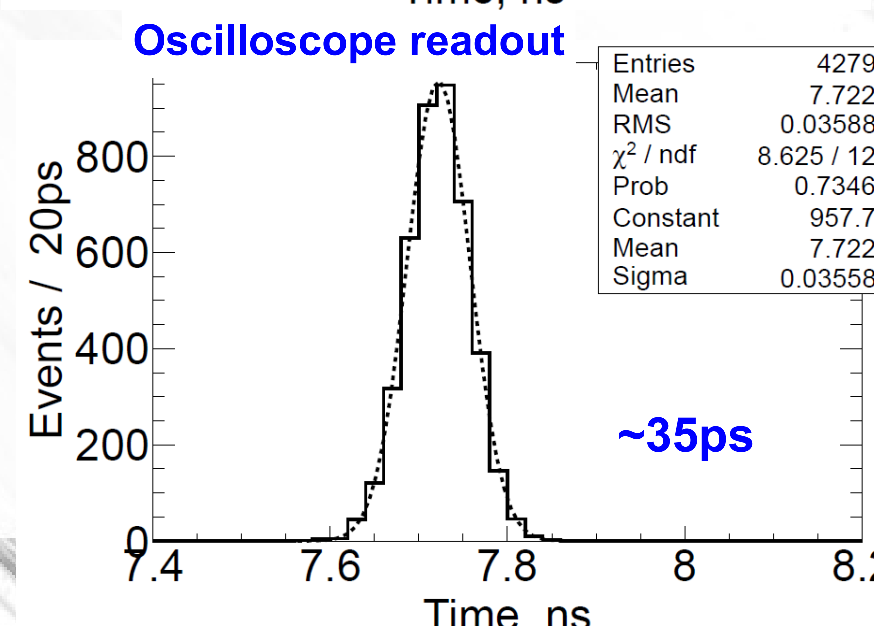
Testing Results



Multi PE Time resolution

90-cm long anode!

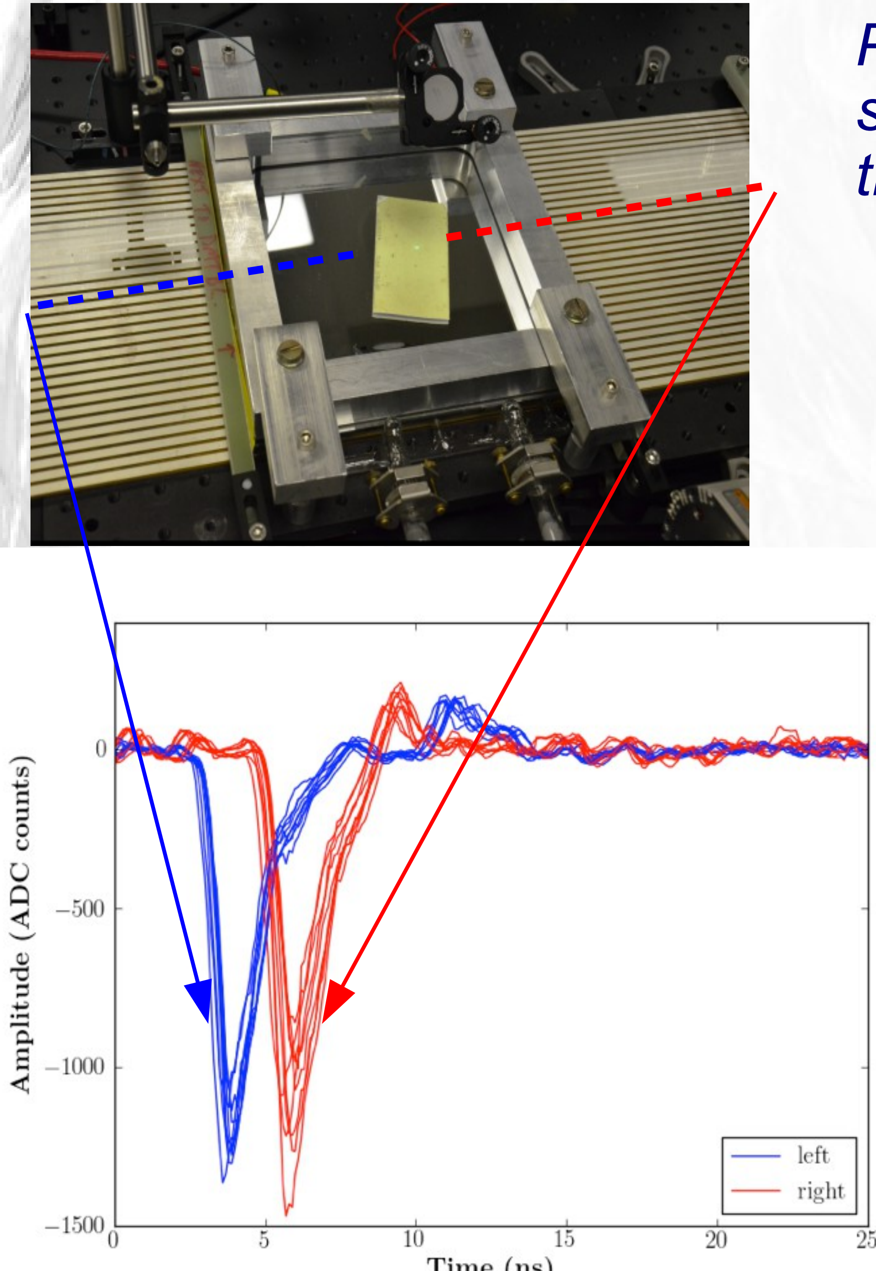


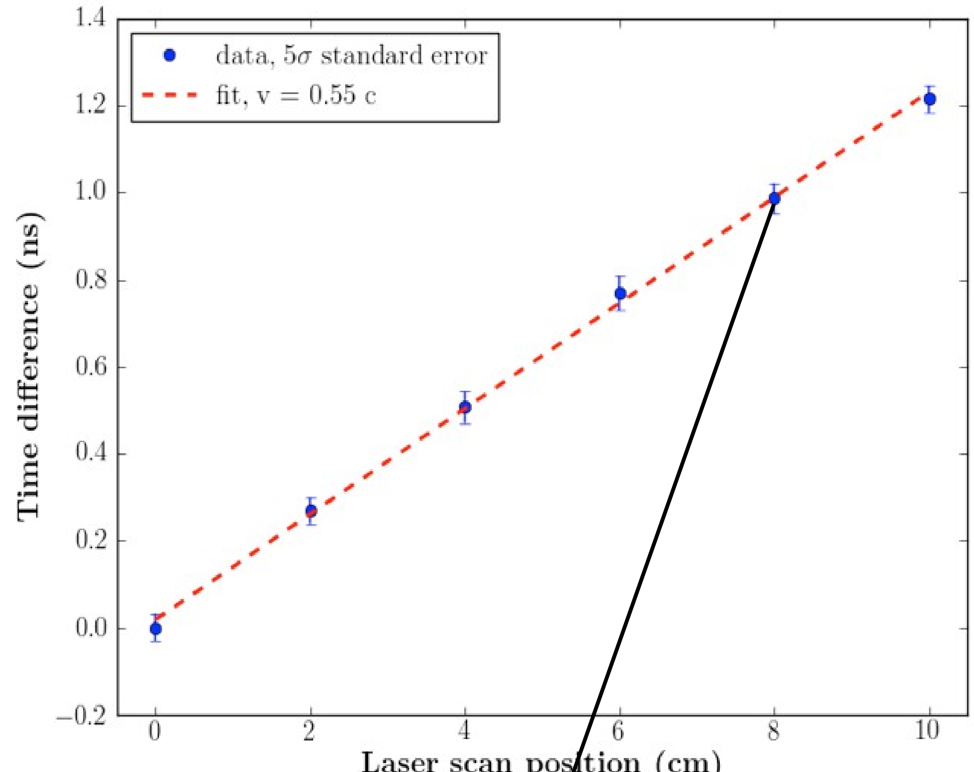


NIMA 732, (2013) 392

Spatial Resolution (longitudinal)

Position in the direction parallel to the striplines is determined by differential transit time to the opposite ends of the anode





4 tiles (90-cm anode): ΔT=~18ps → **ΔX=~1.8mm**

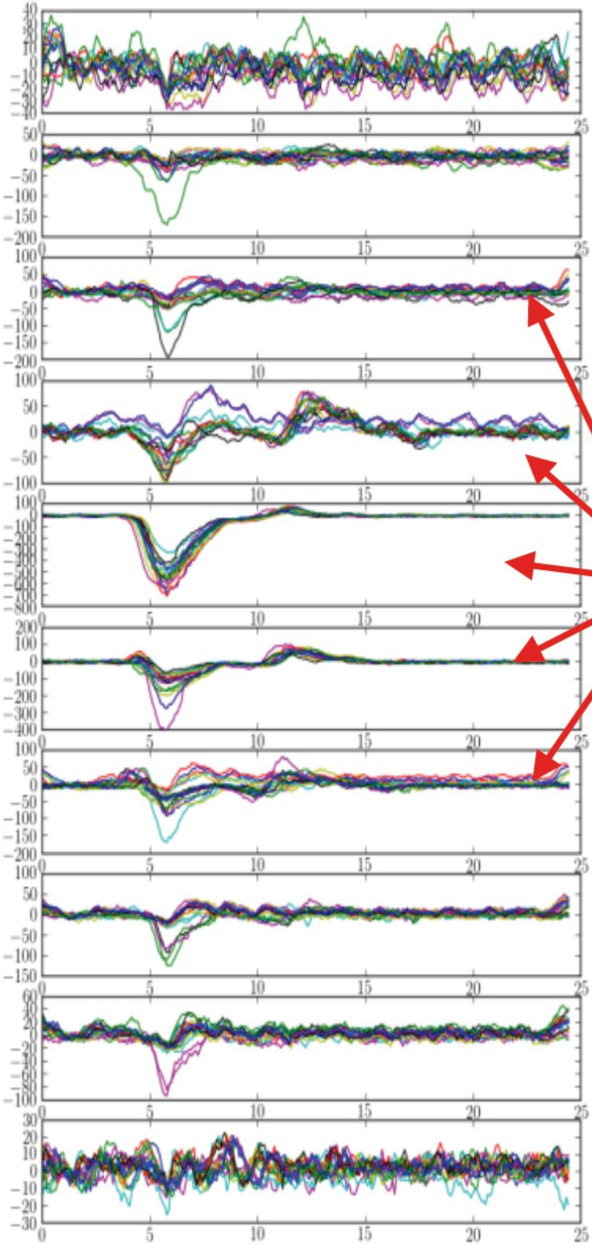
1 tile (20-cm anode): ΔT=~5ps → **ΔX=~0.5mm**

Plots credit: Eric Oberla

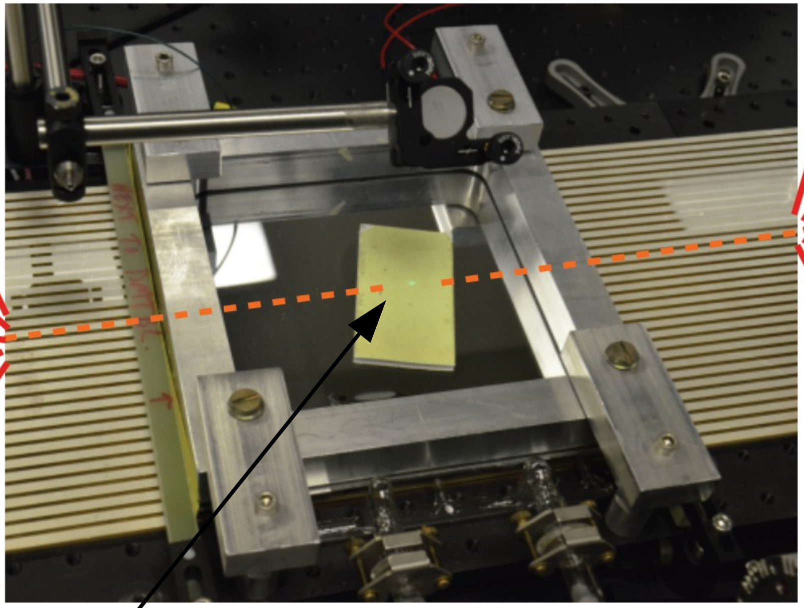
Spatial Resolution (transverse)

Pulses on 10 striplines

Left Side

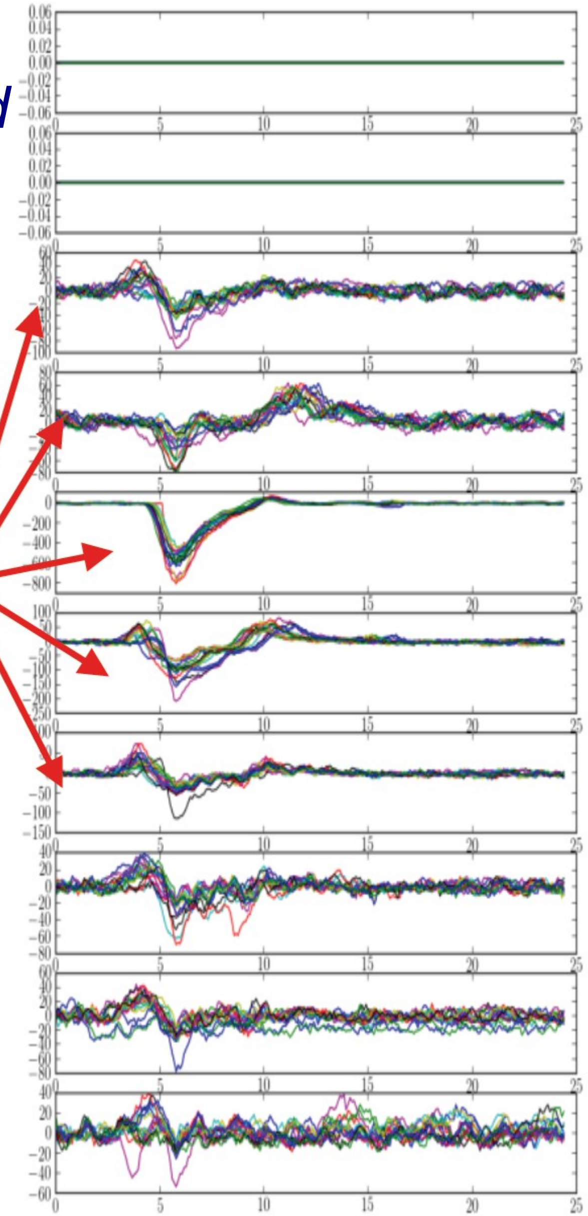


Transverse position is determined by centroid of integrated signal on a cluster of striplines



Laser beam spot

Spatial resolution across the striplines **~0.7mm**



Right Side

Pulses on 10 striplines

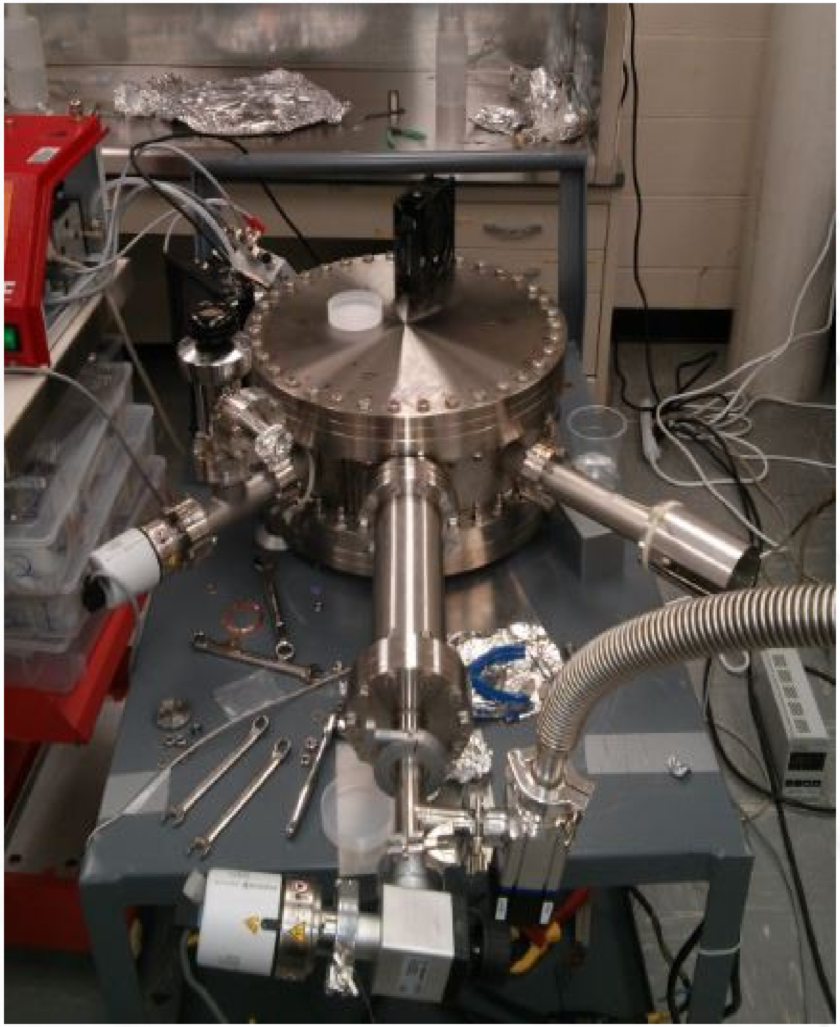
Plots credit: Eric Oberla

How to Cook a Tile

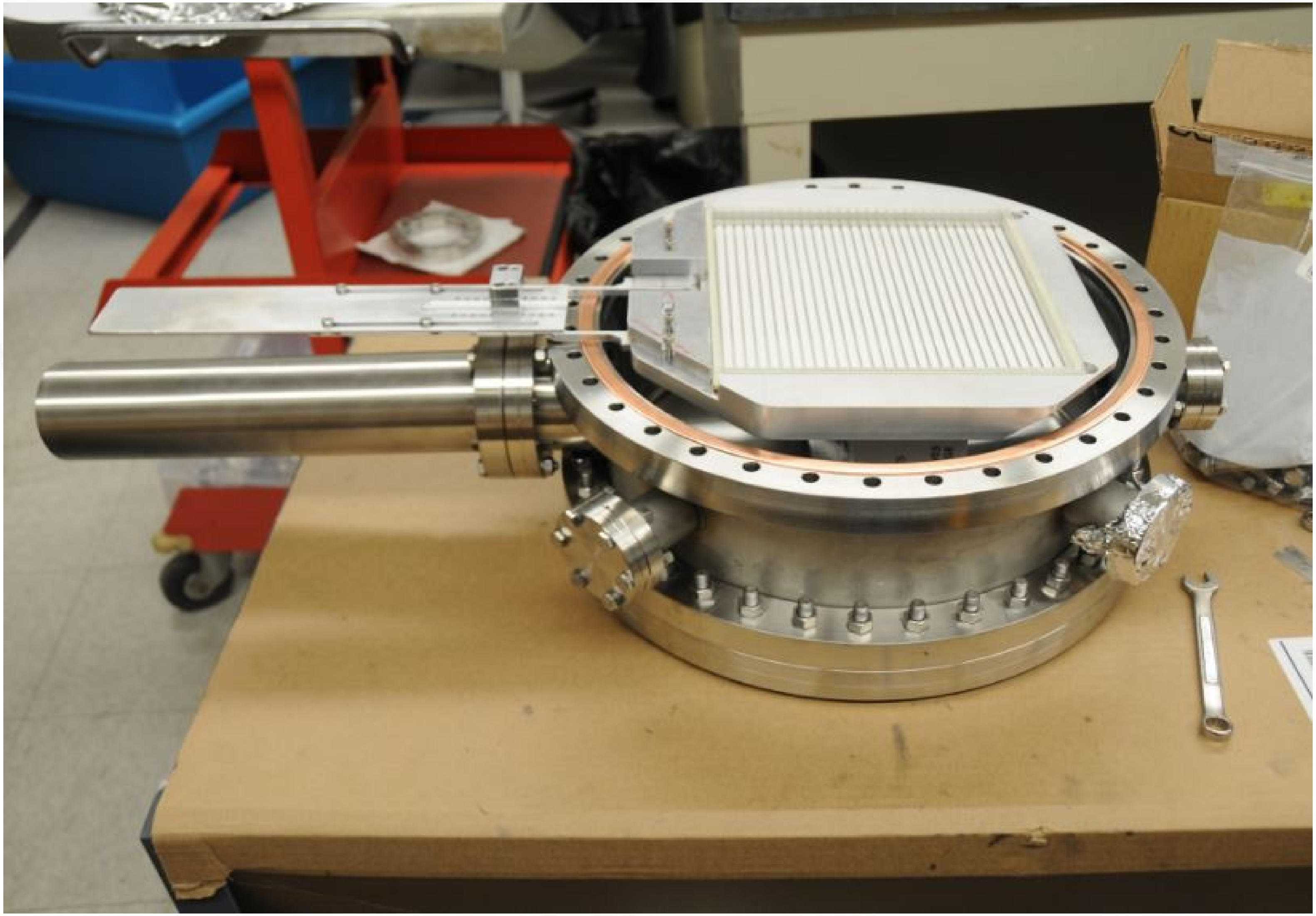
In parallel to commercialization through Incom Inc.

SSL vacuum transfer assembly

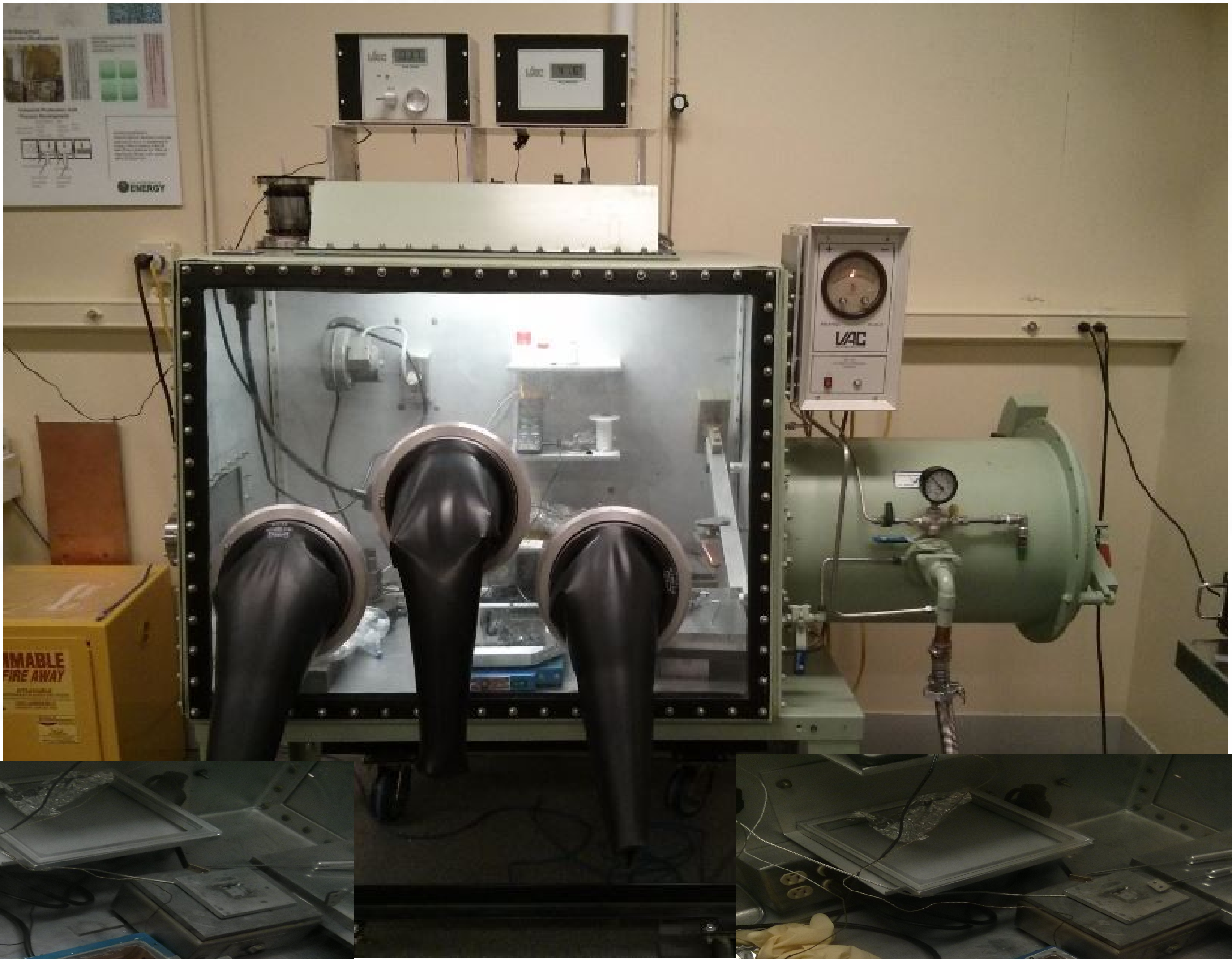
UChicago ultra-lightweight "in-situ" assembly

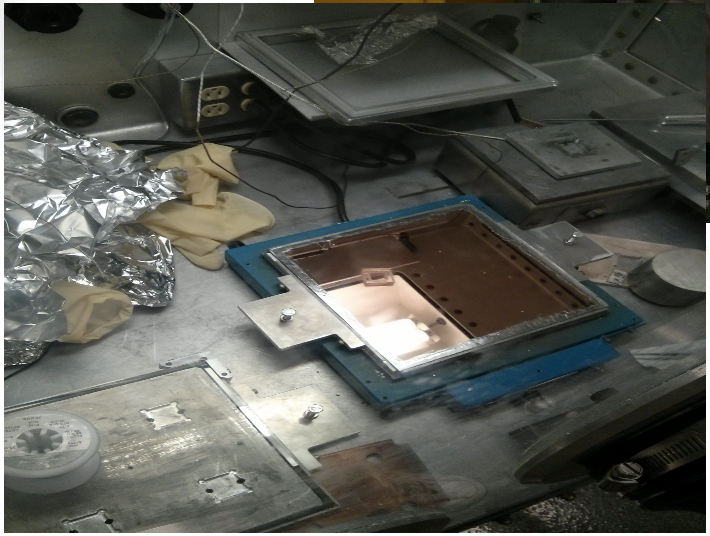


Ultra-Lightweight Facility



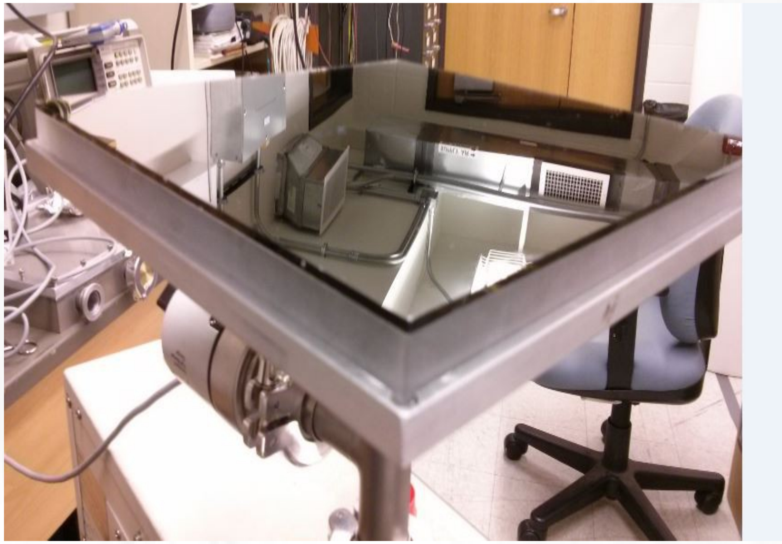
Glove Box at Argonne





8x8" Sealing Tests

Seal #1 – August 2013



Seal #2 – February 2014

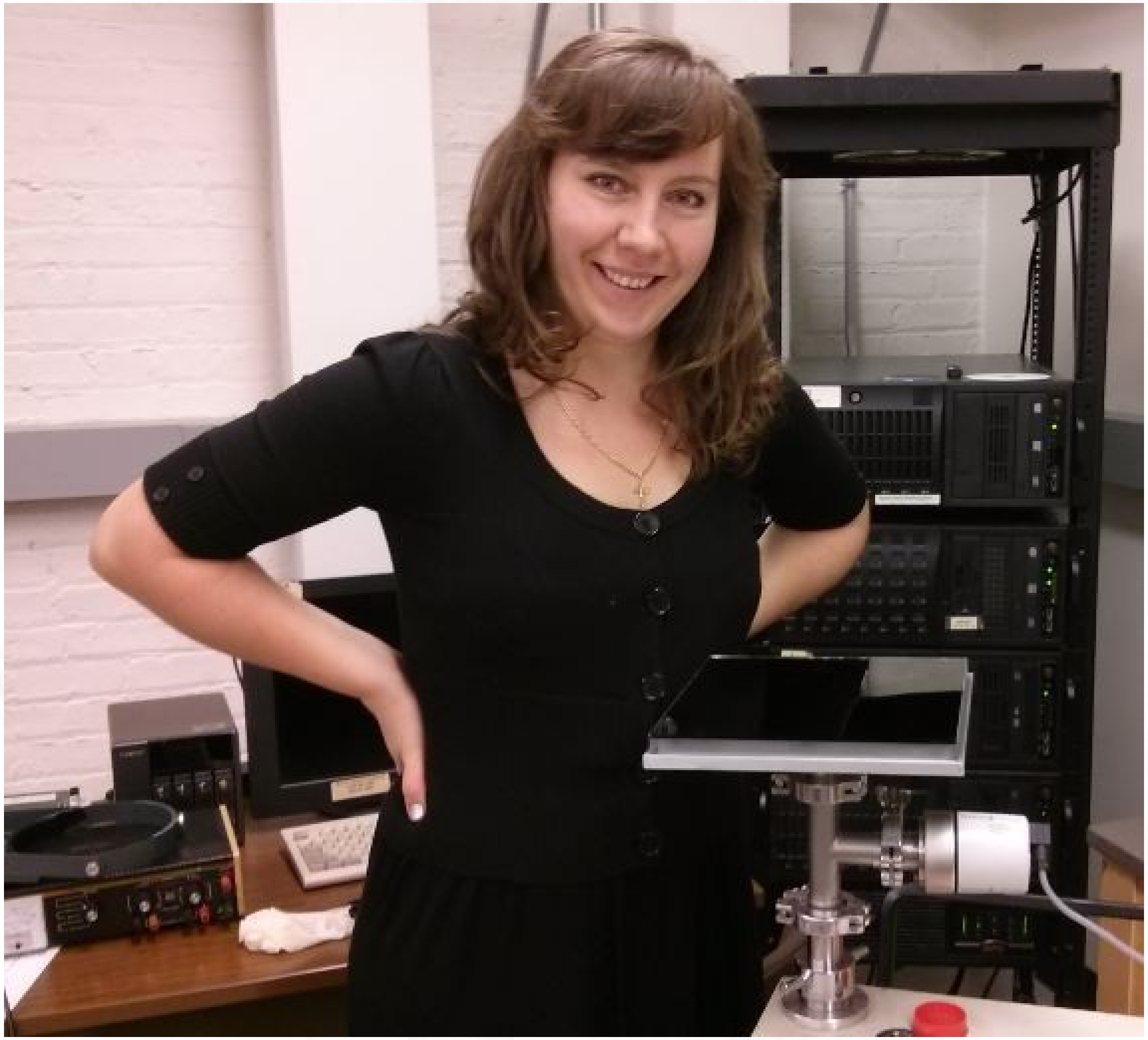
Seal #3 – February 2014

Seal #4 – March 2014

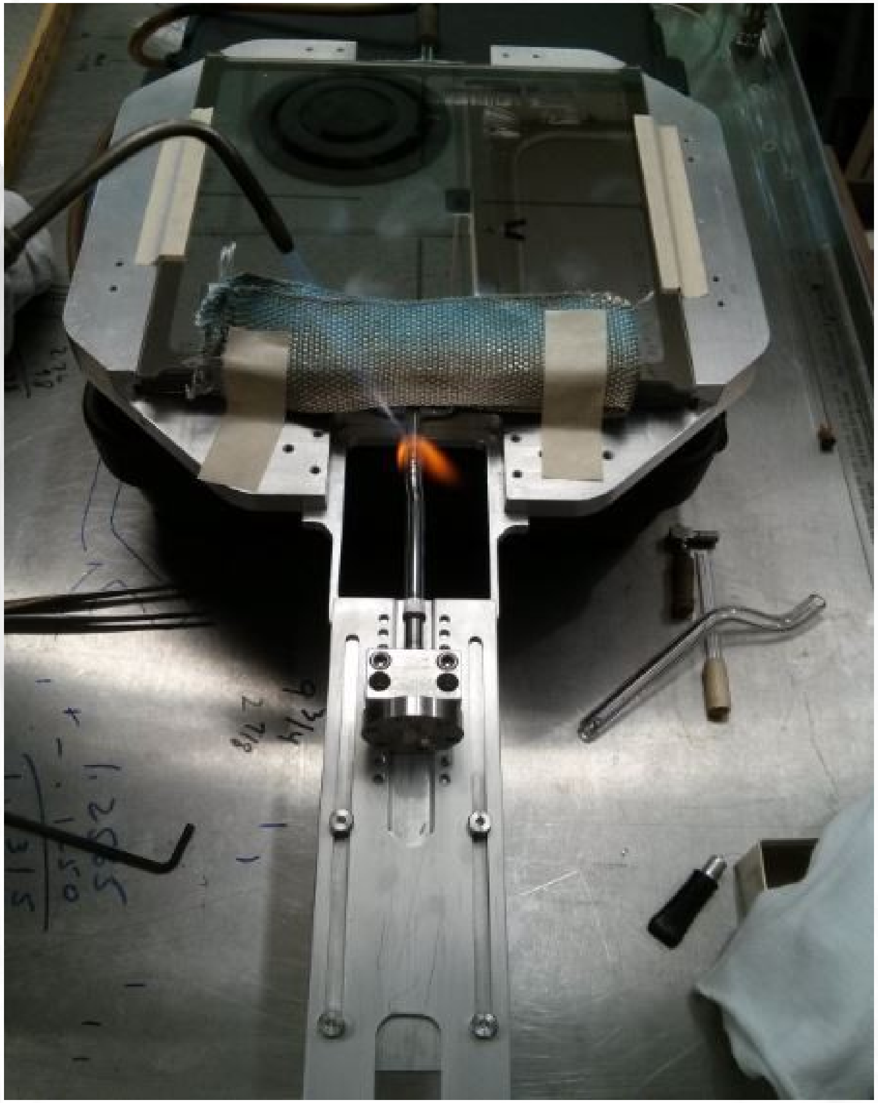
The sealing recipe is reproducible

More Credits

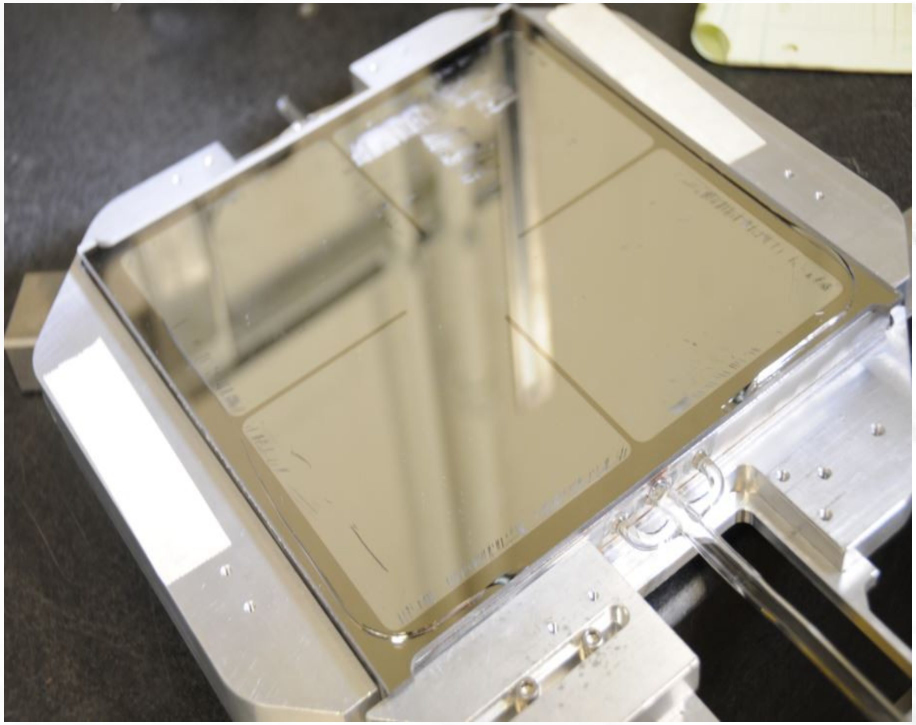
Yes, I did get help with the 1st seal



Tile Assembly: 1st Attempt



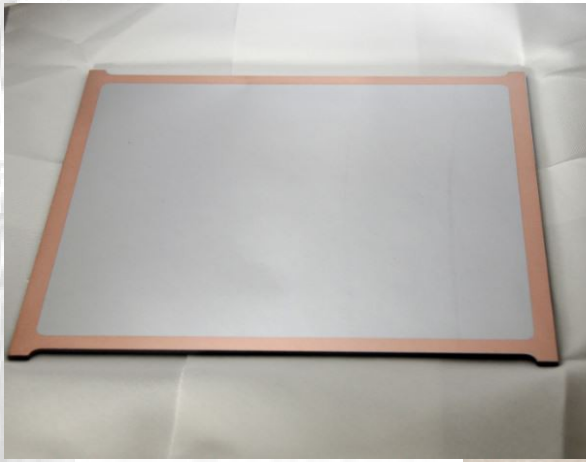
What's inside?
- Two 8x8” MCPs (no ALD)
- Set of grid spacers
- Getter glass beads
- Sb on the window

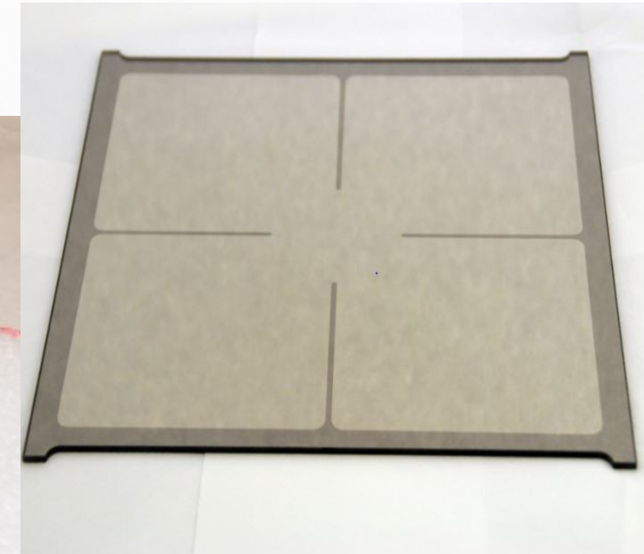


Held vacuum for ~20mins
Cracked
Found ~0.015” bow on the window

Tile Assembly: 4th Attempt

Re-sealed: the same tile with the same stack, but a flat window



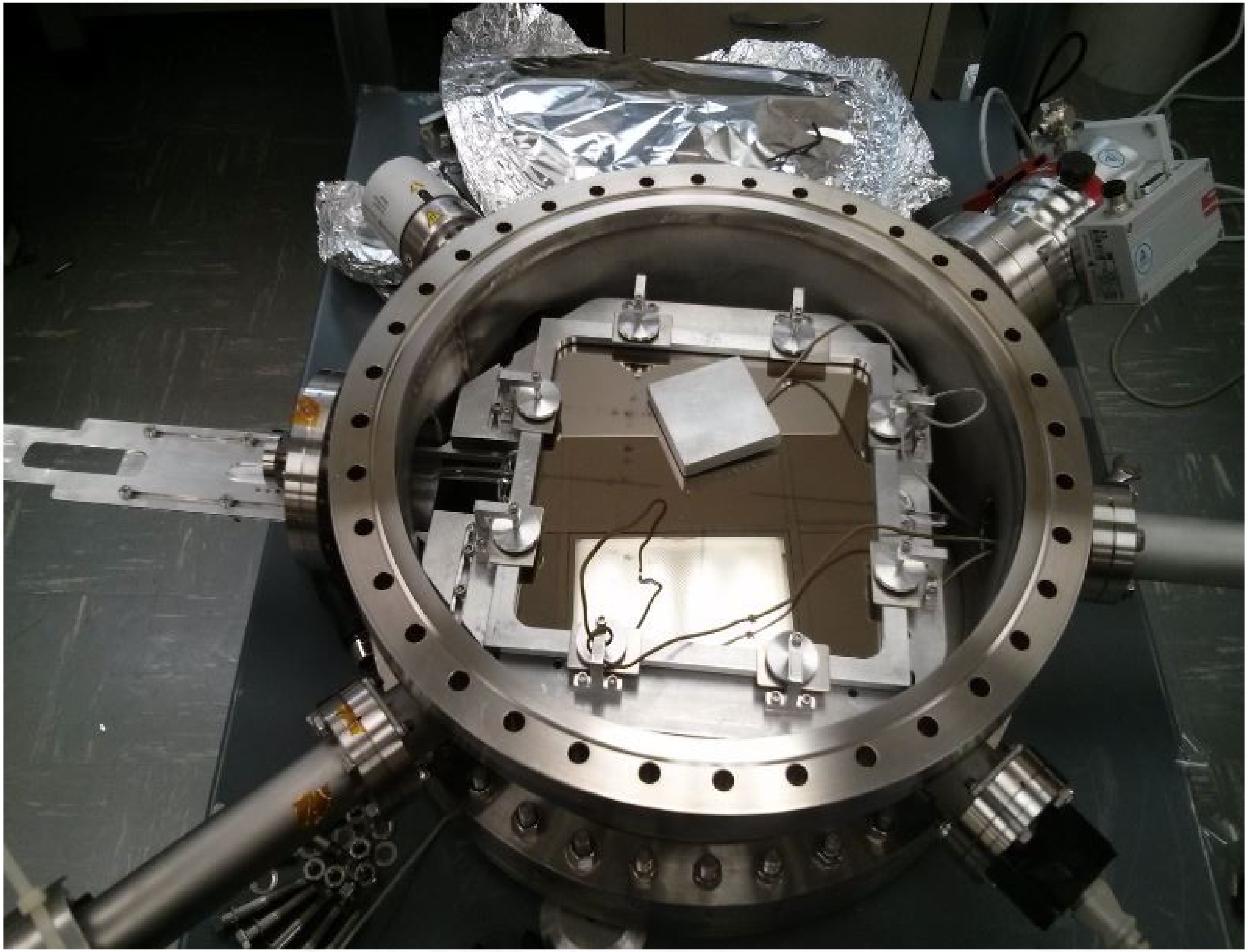


Hard work by Eric Spieglan, Richard Northrop, Bob Metz, Henry Frisch @ UChicago and Joe Gregar @ Argonne

Many thanks to H. Clausing (Clausing Inc.)
C. Liu (Argonne)
Q. Guo (Uchicago)

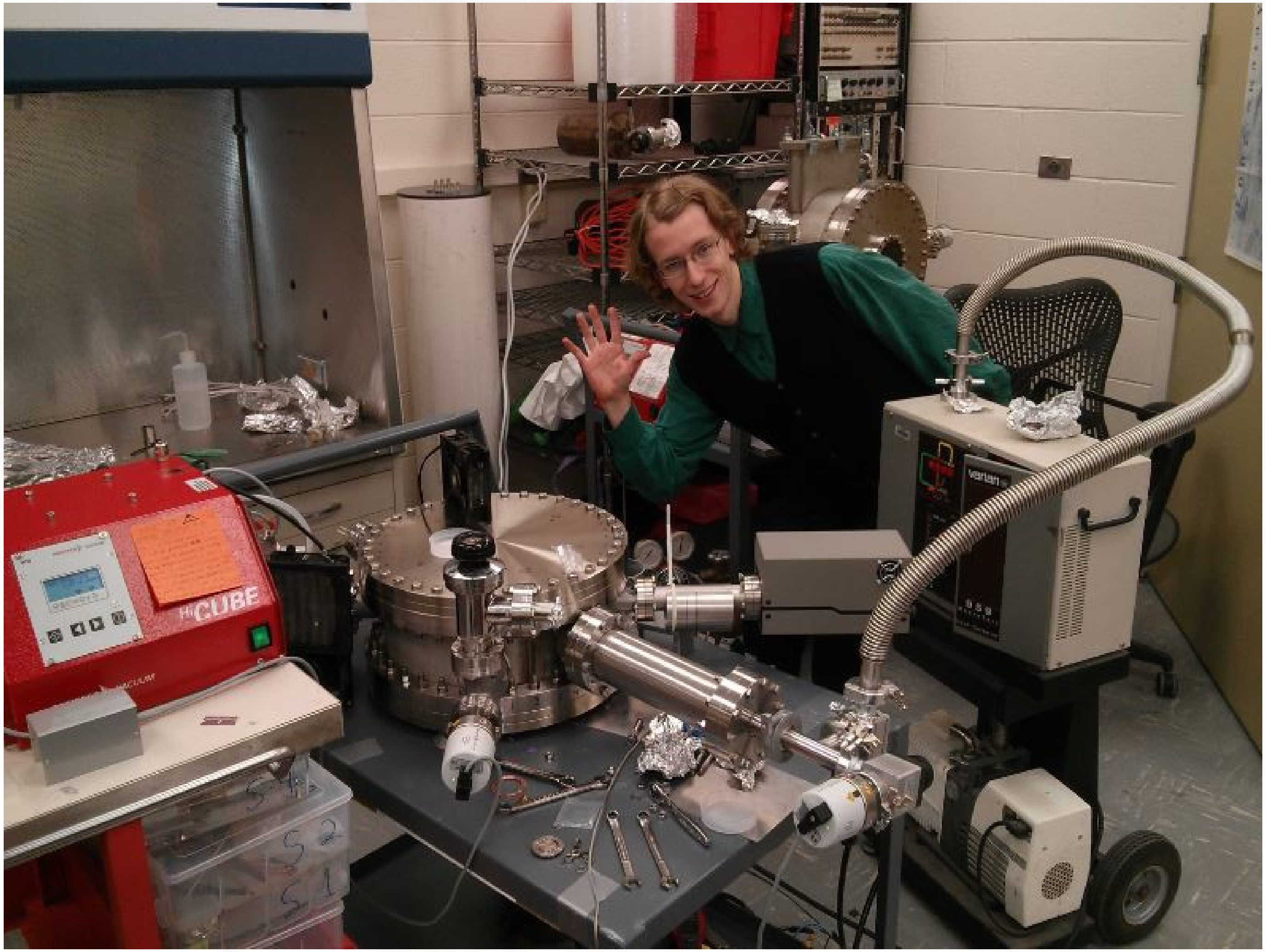
Big thanks to our summer students: E. Angelico, B. Murphy, E. Schockley, Y. Ji

Ultra-Lightweight "in-situ" Assembly

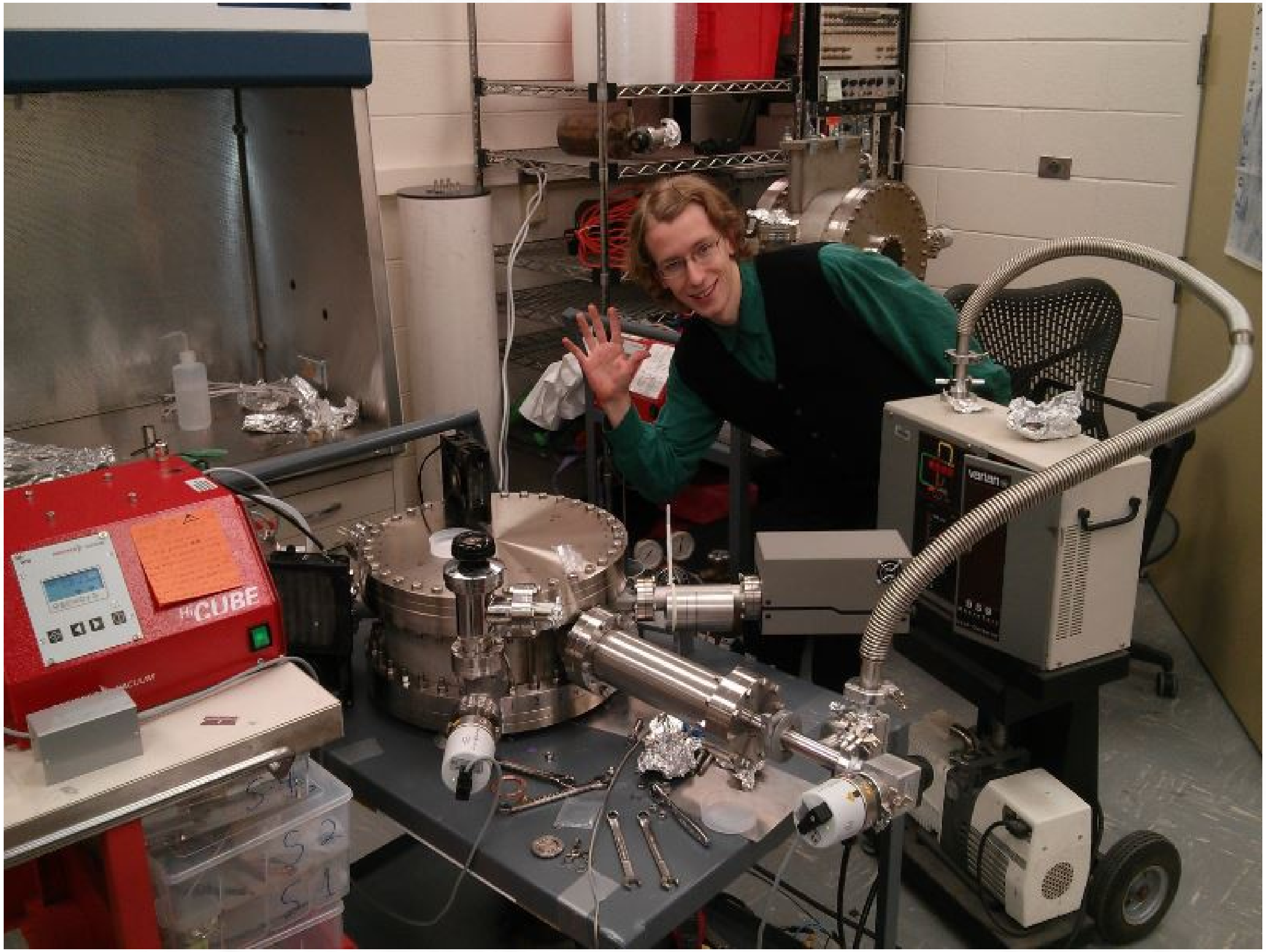


Getting ready for the photo-cathode activation

Ultra-Lightweight "in-situ" Assembly



Ultra-Lightweight "in-situ" Assembly



Breaking news (last Friday)

One more recipe for hermetic packaging

- simpler (in-situ, no glove box)
- we think we understand the metallurgy behind this recipe better

My (Personal) Conclusions

As a graduate student I was searching for the Higgs at the Tevatron

Instead of taking a standard career path and joining the LHC, I took a postdoc to work on instrumentation with the goal to build my own, completely different, detector

I believe that building a Very Large Liquid Scintillator Detector to answer Majorana question is the way to go forward

I would never guess that I would need to learn some chemistry and metallurgy along the way

Is it just the beginning?

Thank You

Back Up

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 th

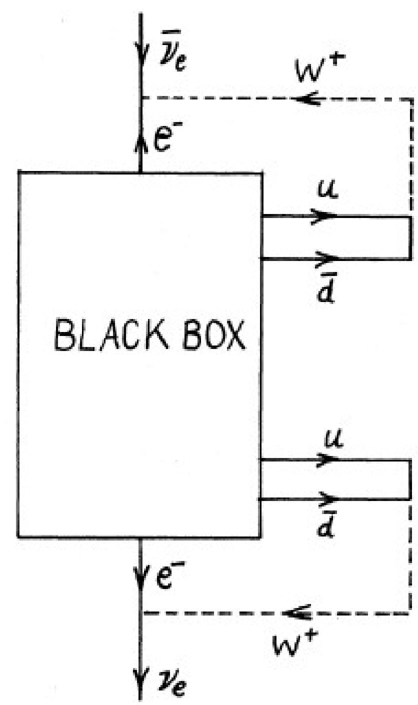
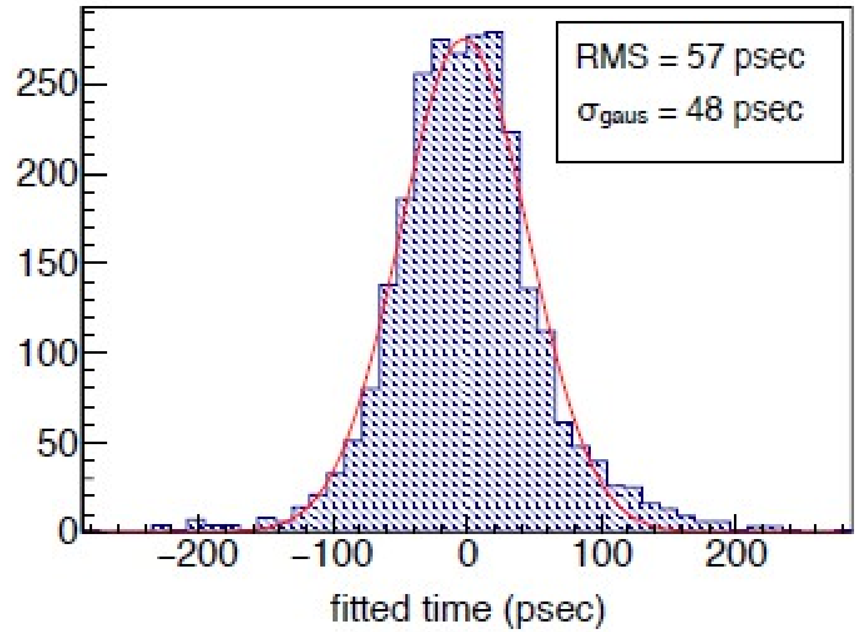


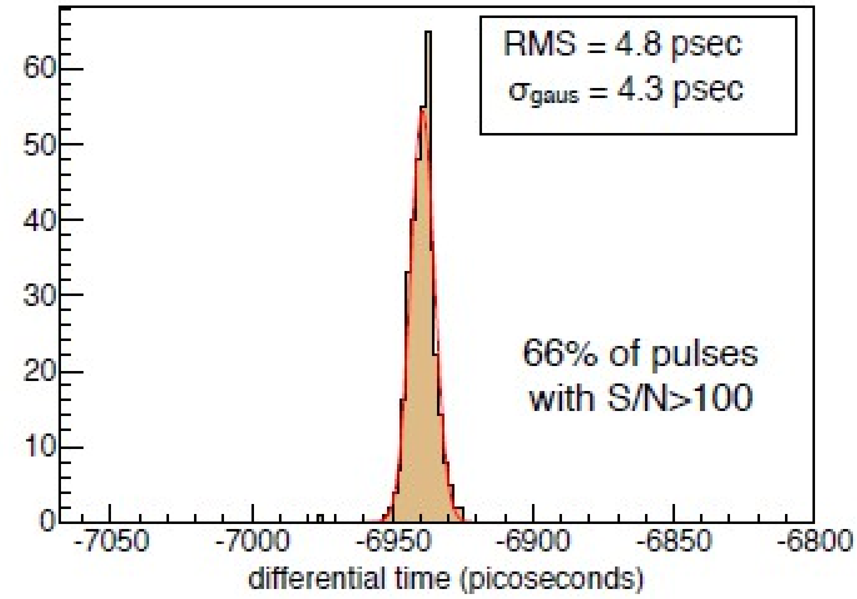
FIG. 2. Diagram showing how any neutrinoless double-β decay process induces a $\bar{\nu}_e$-to-ν_e transition, that is, an effective Majorana mass term.

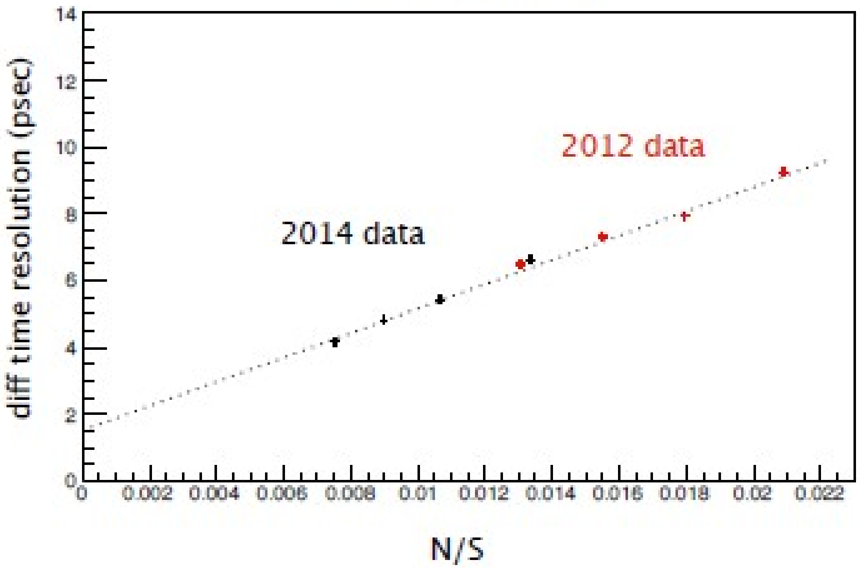
LAPPD capabilities

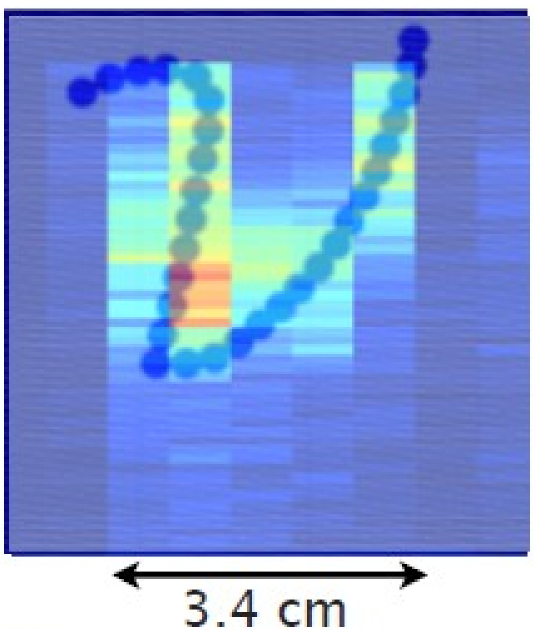
single photoelectron absolute time resolution



differential time resolution between 2 ends of stripline



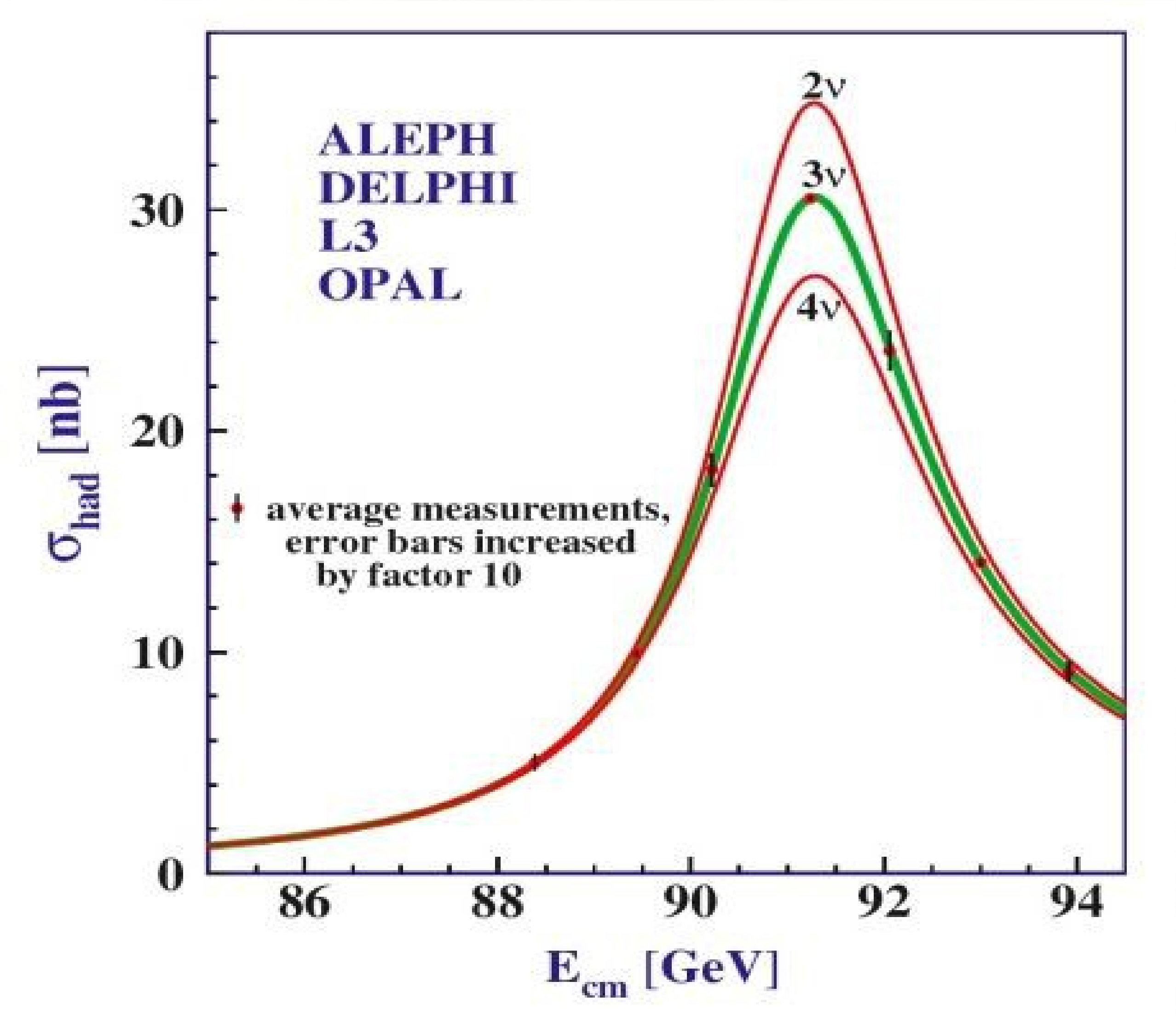




Neutrino Observation

- 1956: ν_e by Reines and Cowan
- 1962: ν_μ by Lederman, Schwartz, and Steinberger
- 2000: ν_τ by DONUT experiment

Only Three Flavors*



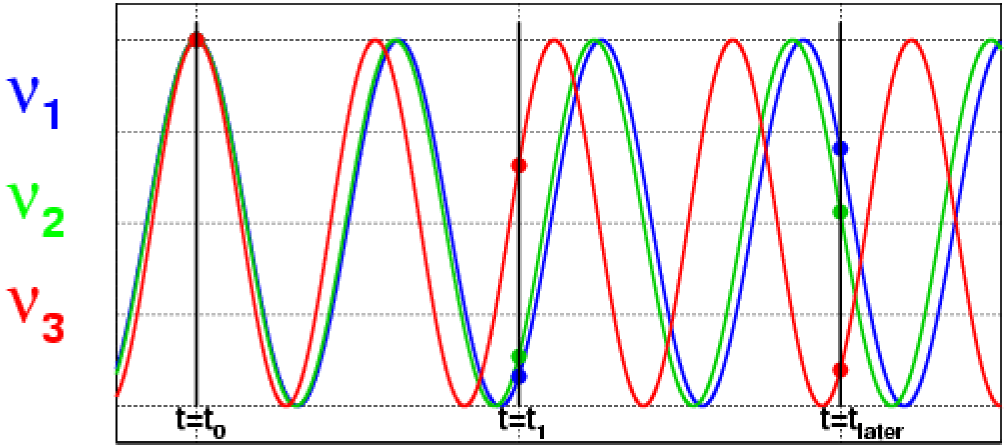
N_{ν} = 2.9840+- 0.0082

Neutrino Mixing

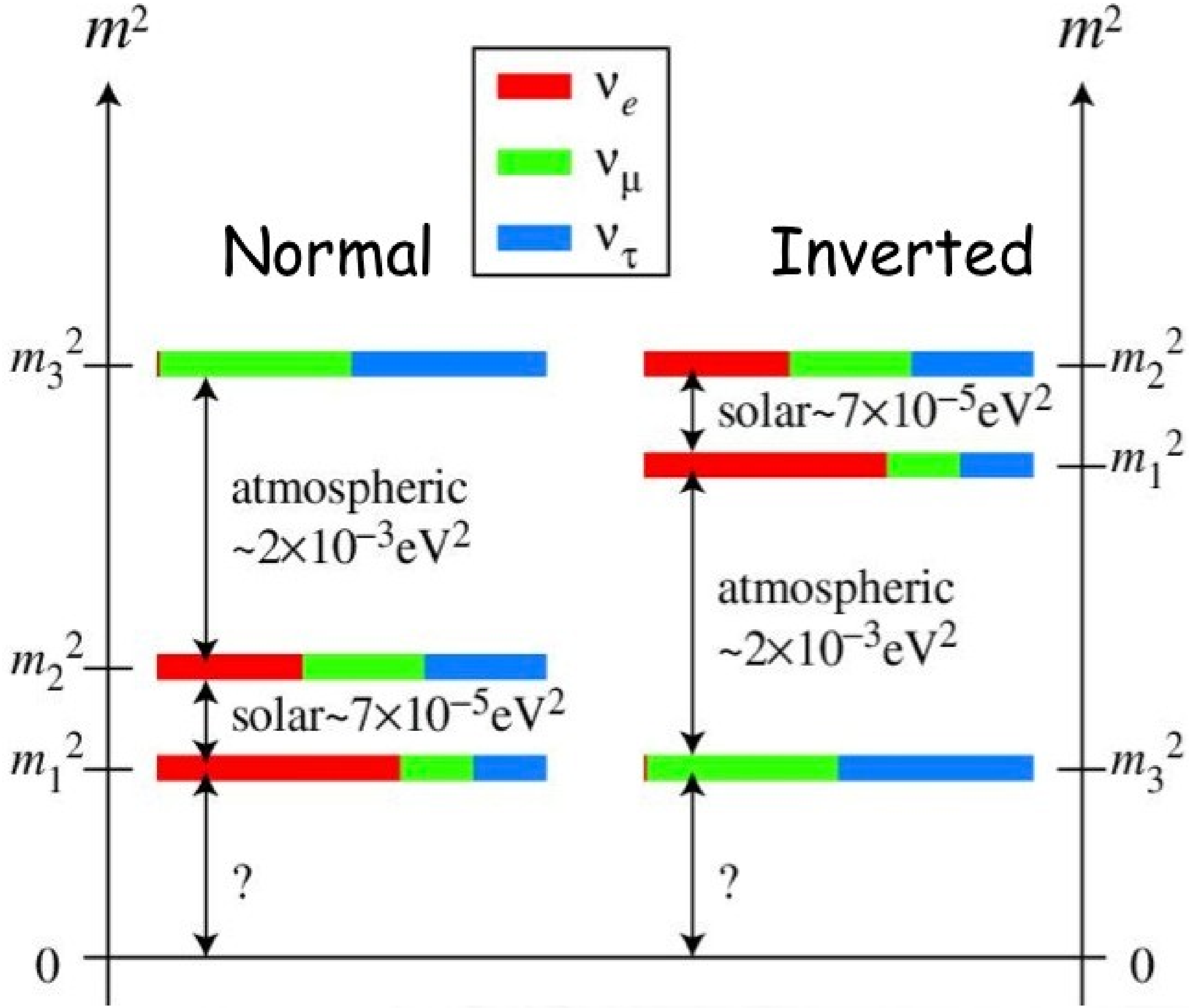
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Flavor eigen states
(interaction)

Mass eigen states
(propagation)



Neutrino Mass Hierarchy



^{10}C background timing

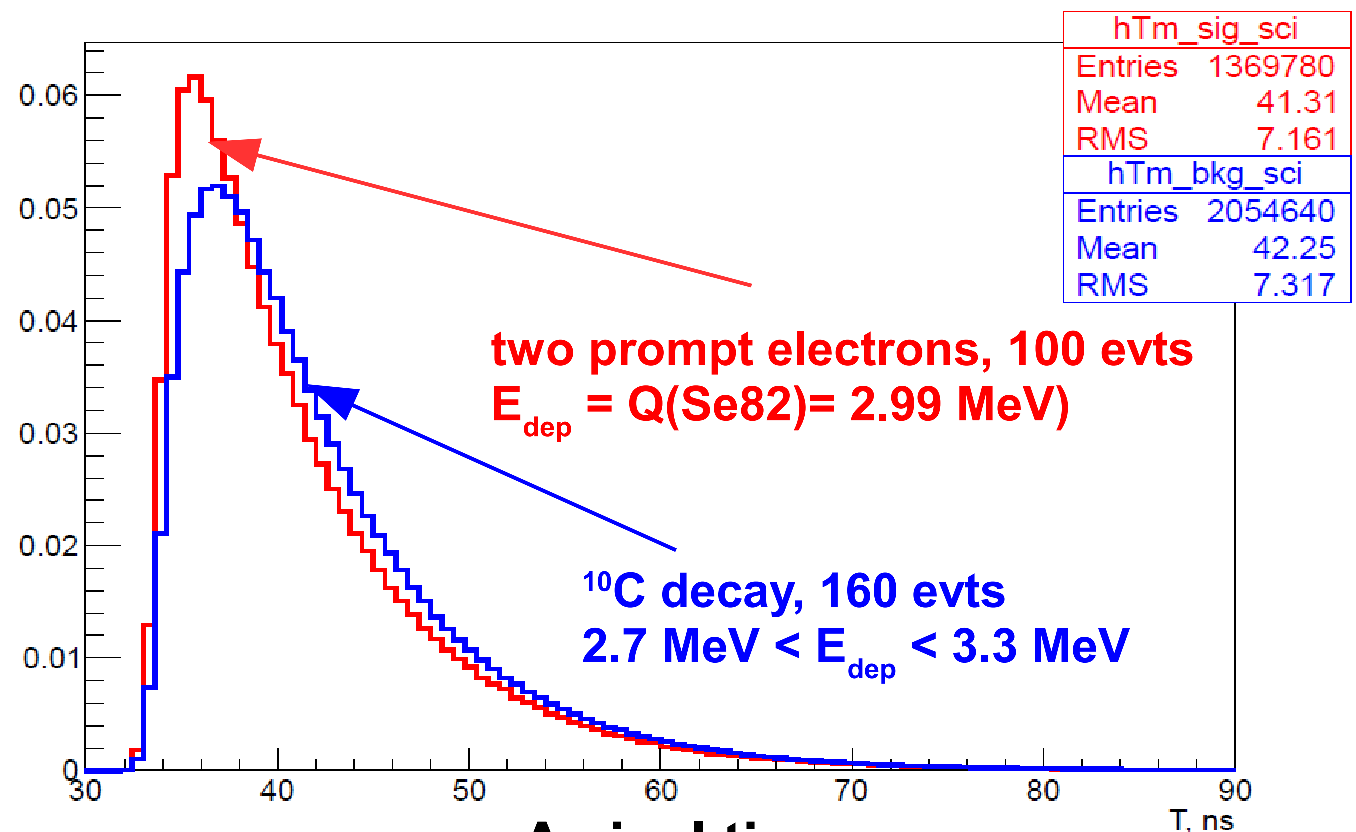
An example of what TTS<<1ns can make us think about

98.6% $^{10}C \rightarrow {}^{10}B(718) + e^{+} \rightarrow {}^{10}B(0) + \gamma$
T(1/2) ~ 1ns

1.4% $^{10}C \rightarrow {}^{10}B(1740) + e+ \rightarrow {}^{10}B(718) + \gamma$
T(1/2) → very fast (~ps)

Scintillation light: photon hits timing

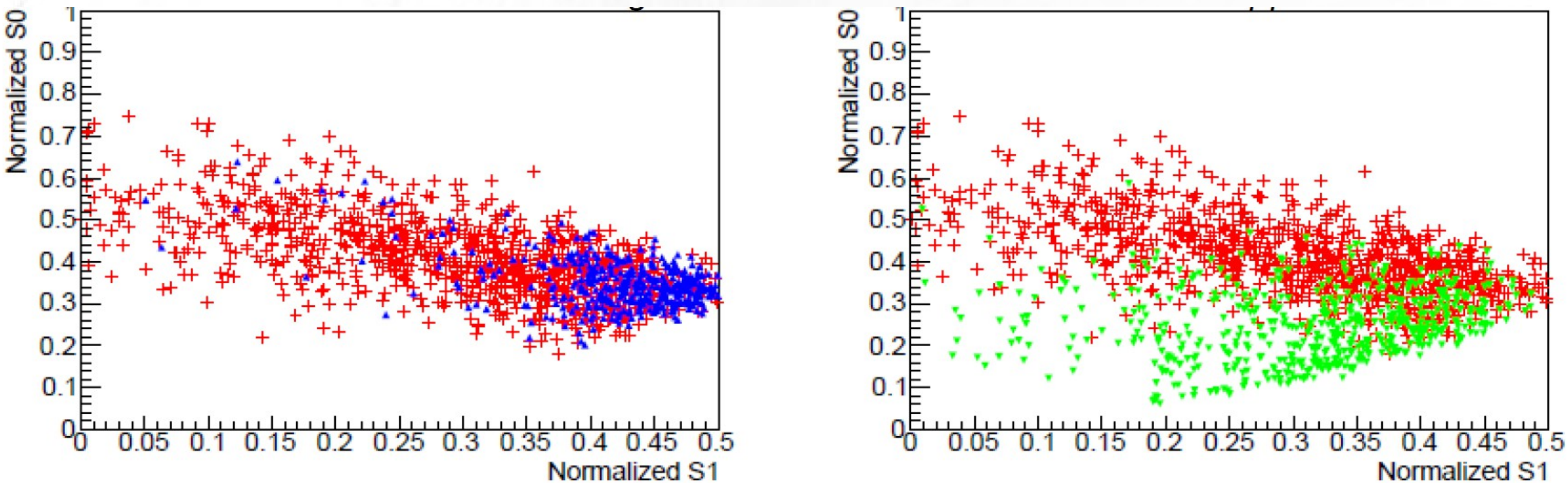
events generated at the center of 6.5 m sphere



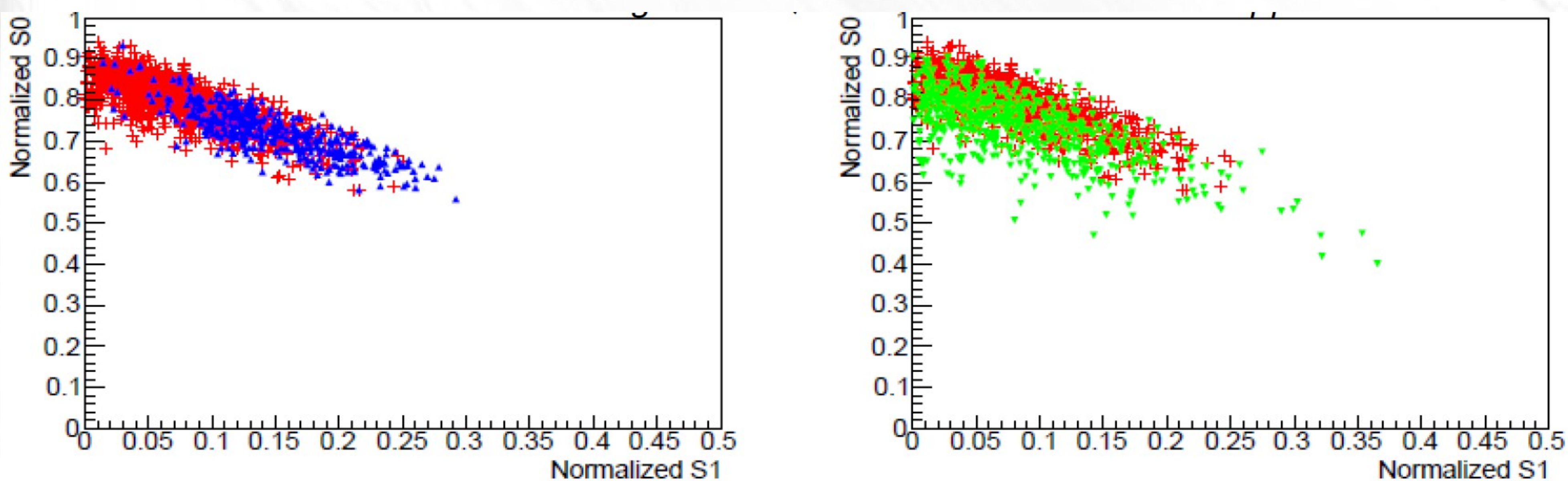
Arrival time, ns

Se82 0vbb events vs single 3 eV electron and C10

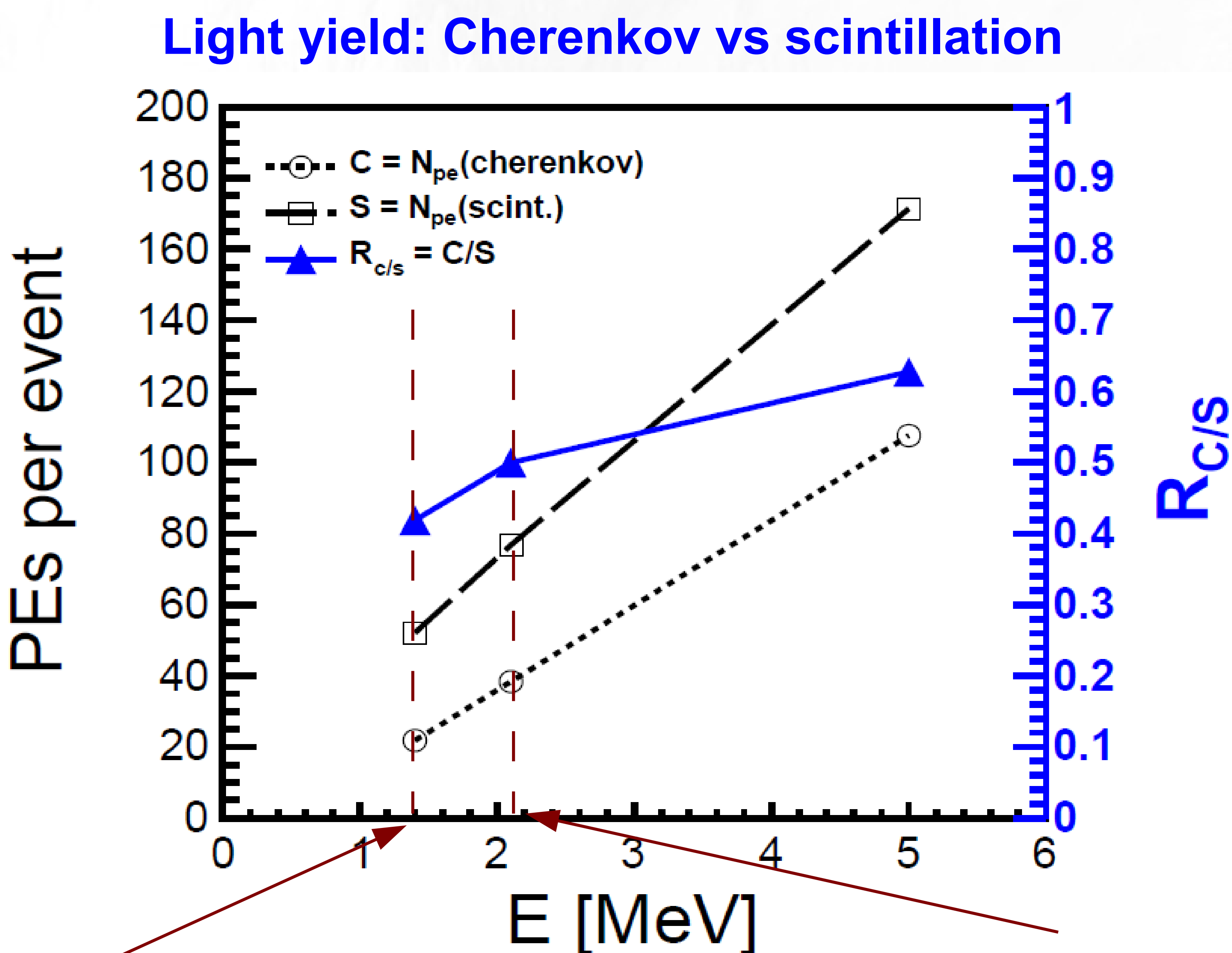
Early light (t<0.5ns)



Early light (t<1.5ns)



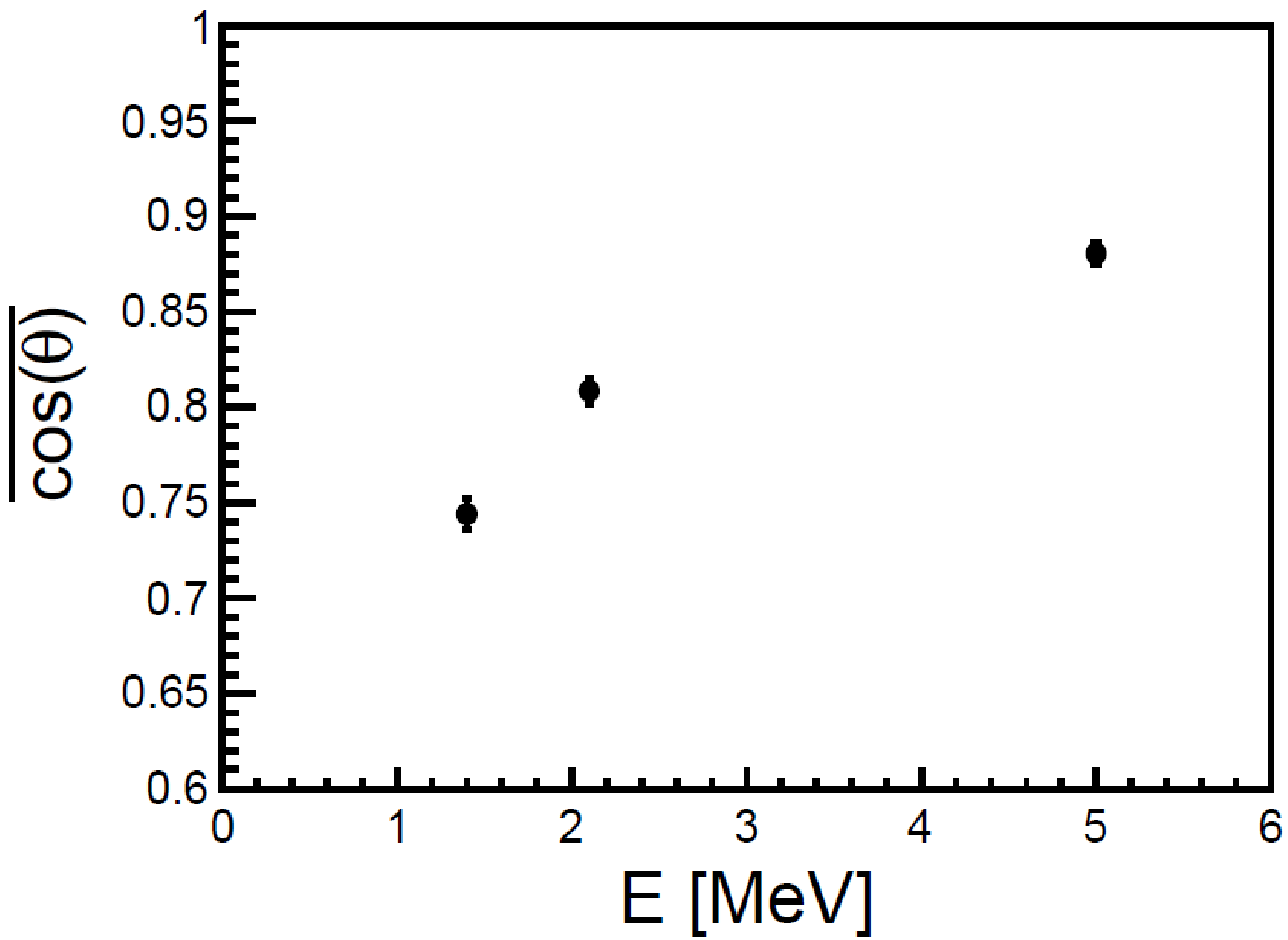
What About Lower Energies?



½ Q (^{116}Cd) =1.4 MeV

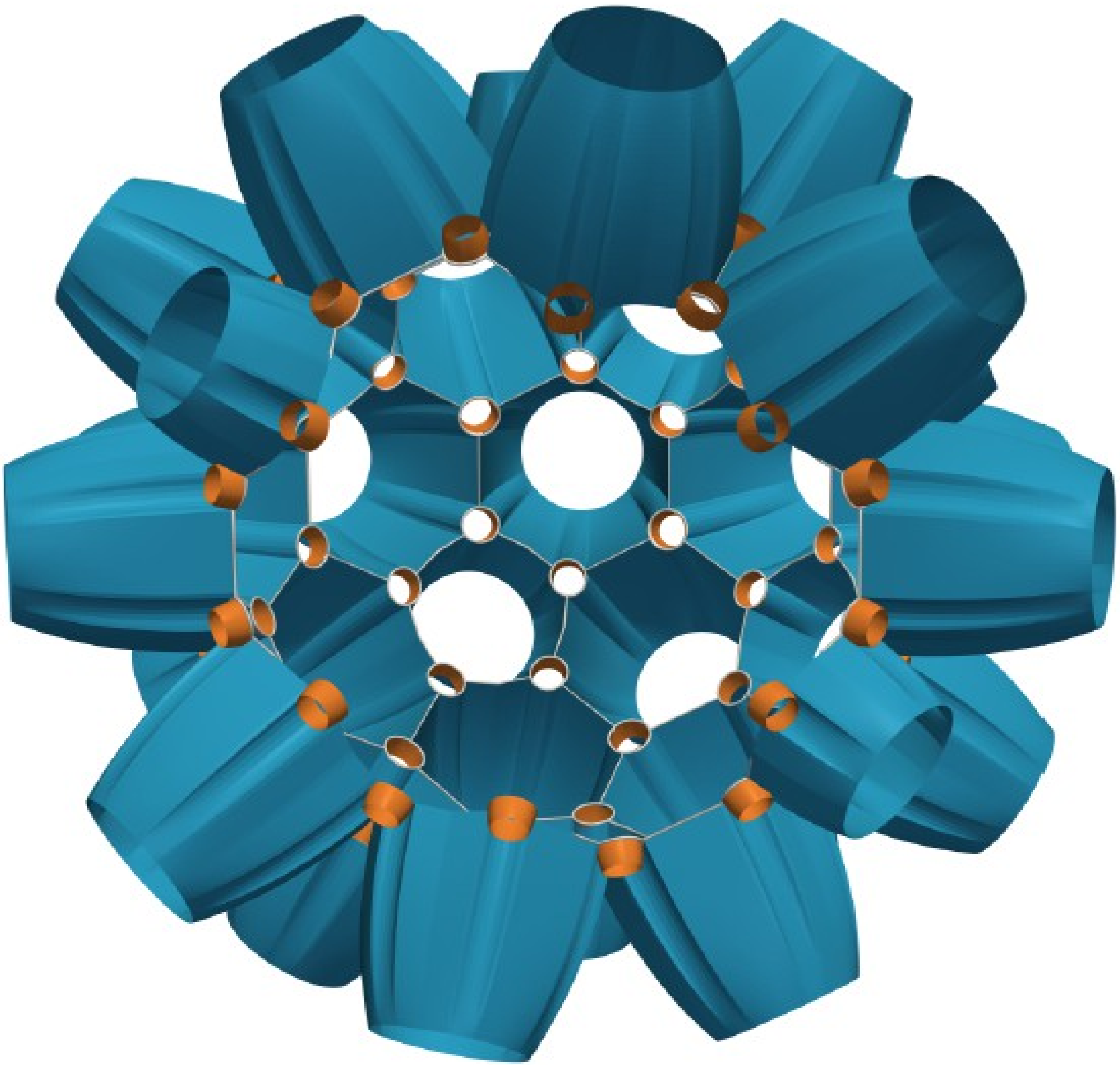
½ Q (^{48}Ca) =2.1 MeV

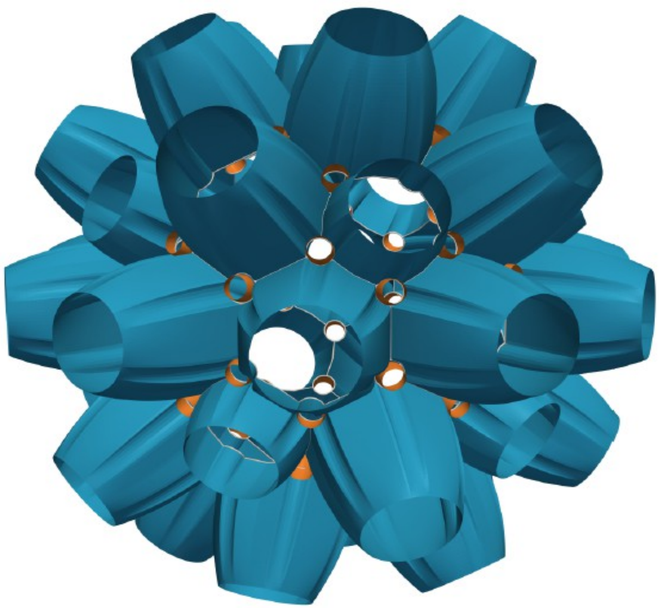
What About Lower Energies?



NuDot

Lindley Winslow, UCLA (->MIT)





- 42 8" PMTs → **(TTS = 1.2ns)**
- 80 2" PMTs → **(TTS = 250ps)**