# Reducing Irreducible Background and Revealing the Unique Nature of Neutrino Mass Using Fast Timing

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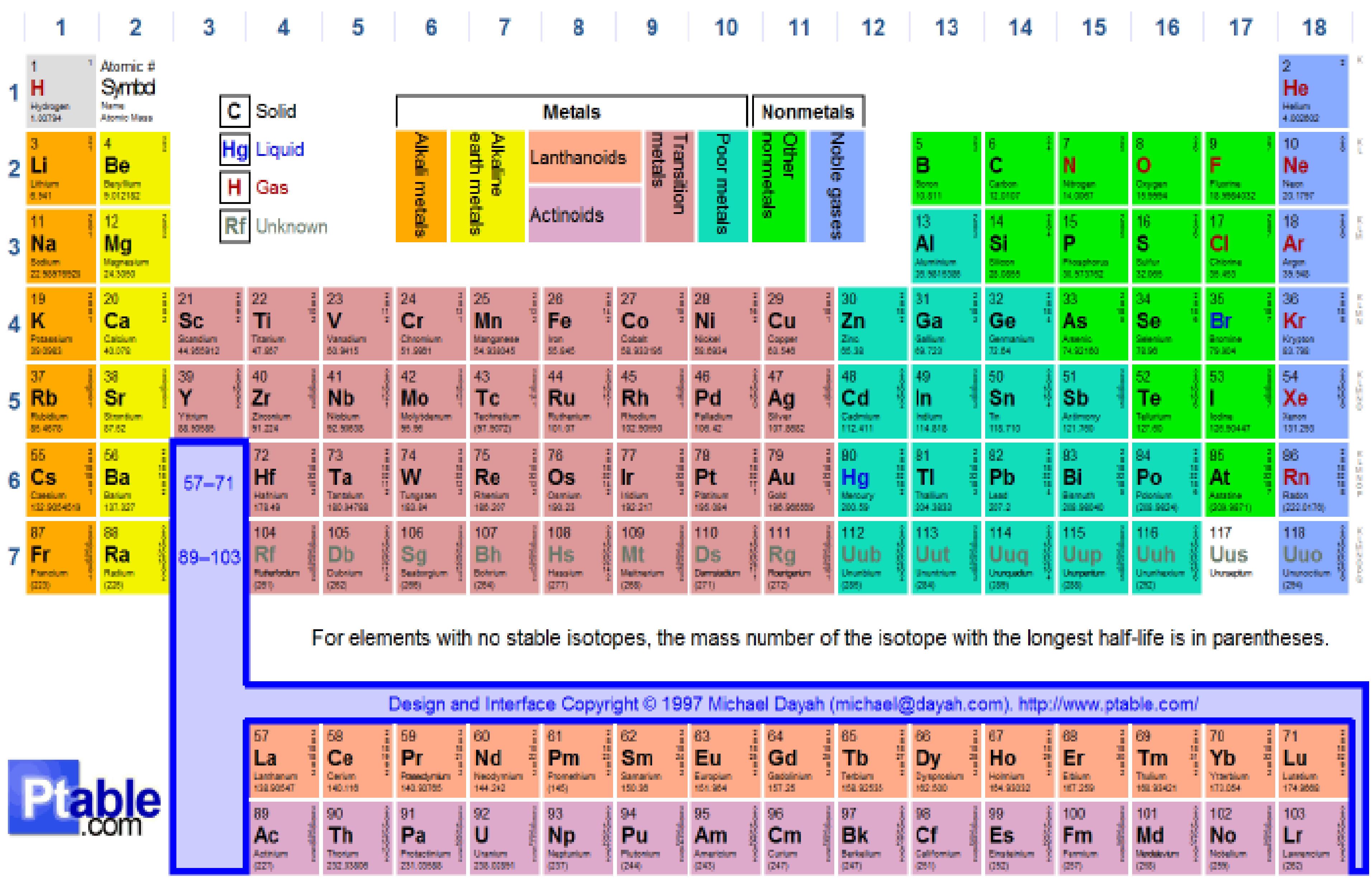
University of Chicago

University of Hawaii Physics Colloquium , March 13, 2017

# Outline

- What can we learn about neutrinos by looking for neutrinoless double beta decay ($0\nu\beta\beta$-decay)?
- What instrumentation and experimental techniques are needed to find $0\nu\beta\beta$-decay?
  - Cherenkov/scintillation light separation
  - development of the Large-Area Picosecond Photo-Detectors (LAPPD™)

# Periodic Table of Elements



Atomic #
Symbol
Name
Atomic Mass

C Solid
Hg Liquid
H Gas
Rf Unknown

**Metals**: Alkali metals · Alkaline earth metals · Lanthanoids · Actinoids · Transition metals · Poor metals

**Nonmetals**: Other nonmetals · Noble gases

| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 1 H | | | | | | | | | | | | | | | | | 2 He |
| 2 | 3 Li | 4 Be | | | | | | | | | | | 5 B | 6 C | 7 N | 8 O | 9 F | 10 Ne |
| 3 | 11 Na | 12 Mg | | | | | | | | | | | 13 Al | 14 Si | 15 P | 16 S | 17 Cl | 18 Ar |
| 4 | 19 K | 20 Ca | 21 Sc | 22 Ti | 23 V | 24 Cr | 25 Mn | 26 Fe | 27 Co | 28 Ni | 29 Cu | 30 Zn | 31 Ga | 32 Ge | 33 As | 34 Se | 35 Br | 36 Kr |
| 5 | 37 Rb | 38 Sr | 39 Y | 40 Zr | 41 Nb | 42 Mo | 43 Tc | 44 Ru | 45 Rh | 46 Pd | 47 Ag | 48 Cd | 49 In | 50 Sn | 51 Sb | 52 Te | 53 I | 54 Xe |
| 6 | 55 Cs | 56 Ba | 57–71 | 72 Hf | 73 Ta | 74 W | 75 Re | 76 Os | 77 Ir | 78 Pt | 79 Au | 80 Hg | 81 Tl | 82 Pb | 83 Bi | 84 Po | 85 At | 86 Rn |
| 7 | 87 Fr | 88 Ra | 89–103 | 104 Rf | 105 Db | 106 Sg | 107 Bh | 108 Hs | 109 Mt | 110 Ds | 111 Rg | 112 Uub | 113 Uut | 114 Uuq | 115 Uup | 116 Uuh | 117 Uus | 118 Uuo |

For elements with no stable isotopes, the mass number of the isotope with the longest half-life is in parentheses.

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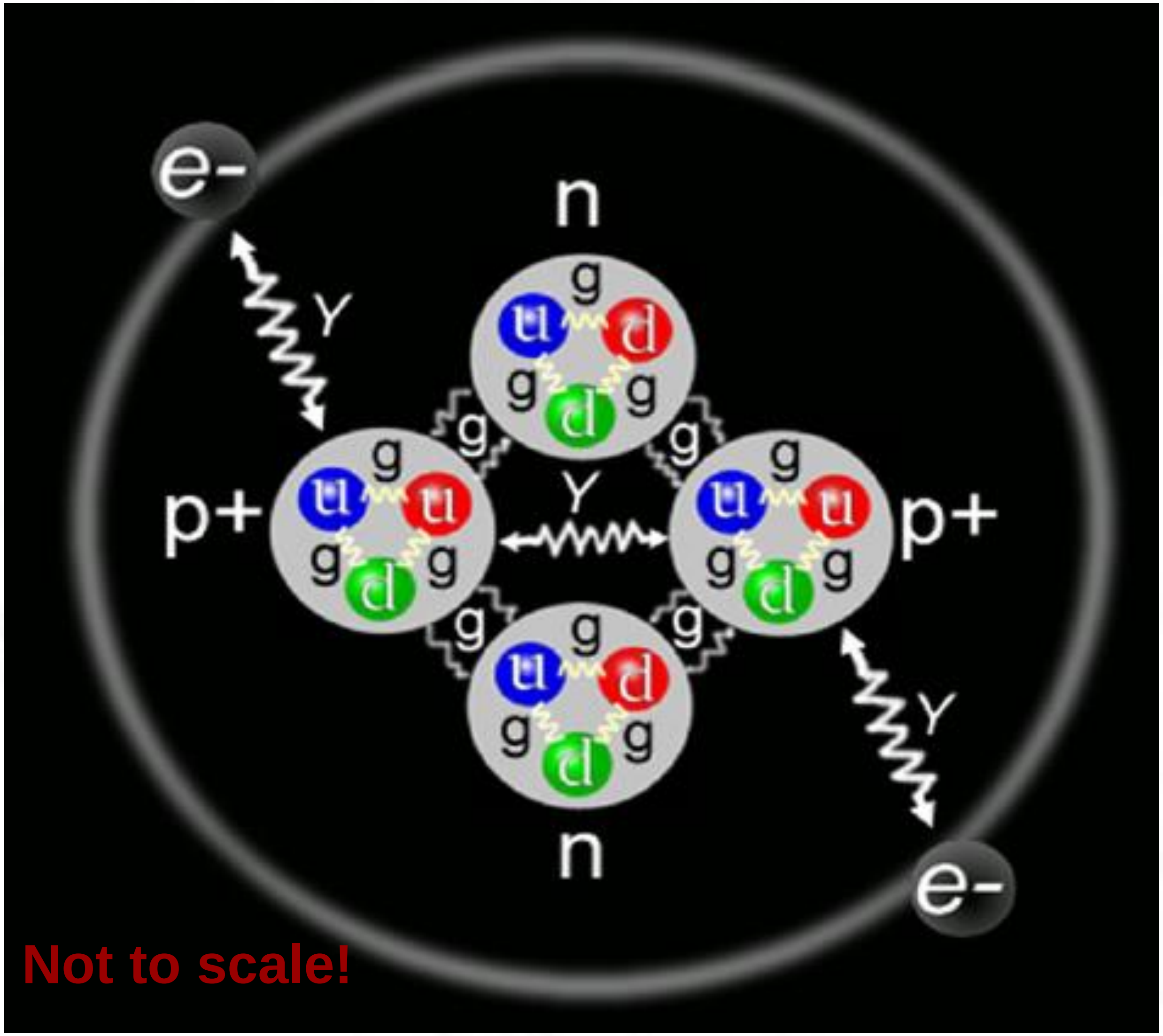
| | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 57 La | 58 Ce | 59 Pr | 60 Nd | 61 Pm | 62 Sm | 63 Eu | 64 Gd | 65 Tb | 66 Dy | 67 Ho | 68 Er | 69 Tm | 70 Yb | 71 Lu |
| 89 Ac | 90 Th | 91 Pa | 92 U | 93 Np | 94 Pu | 95 Am | 96 Cm | 97 Bk | 98 Cf | 99 Es | 100 Fm | 101 Md | 102 No | 103 Lr |

Ptable.com

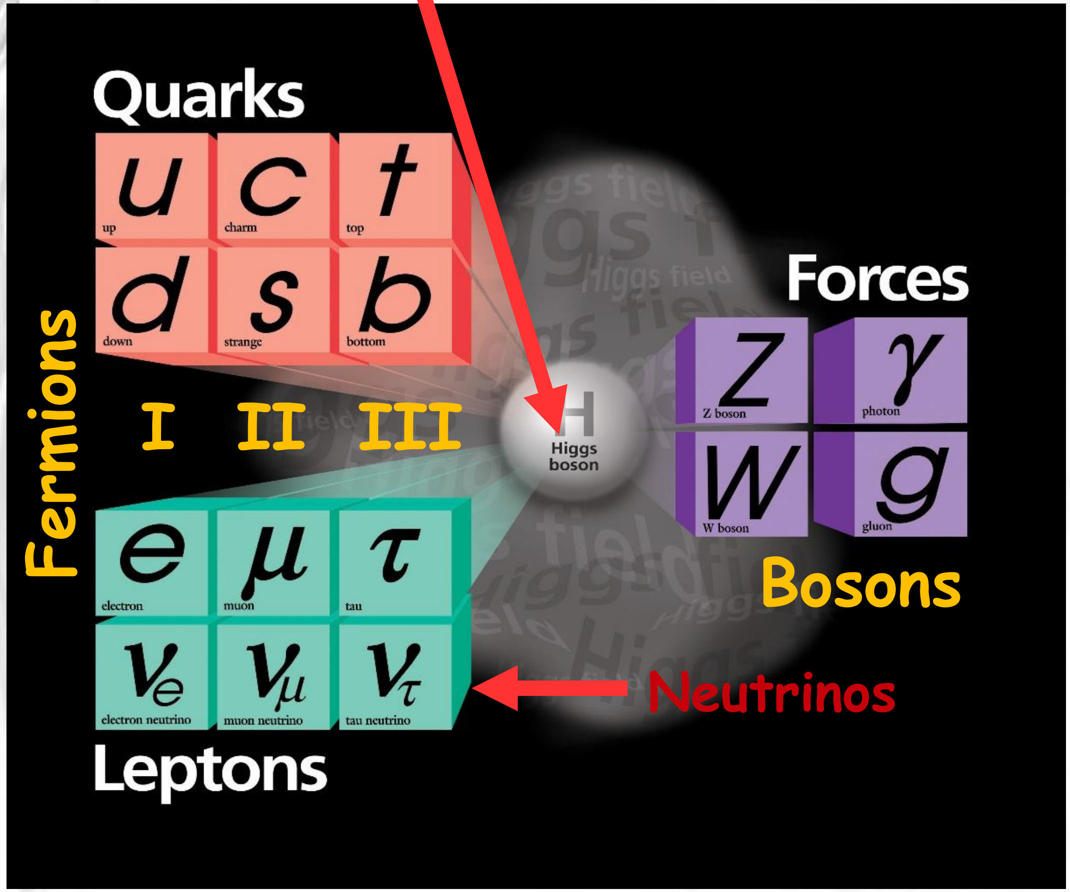
# Helium Atom



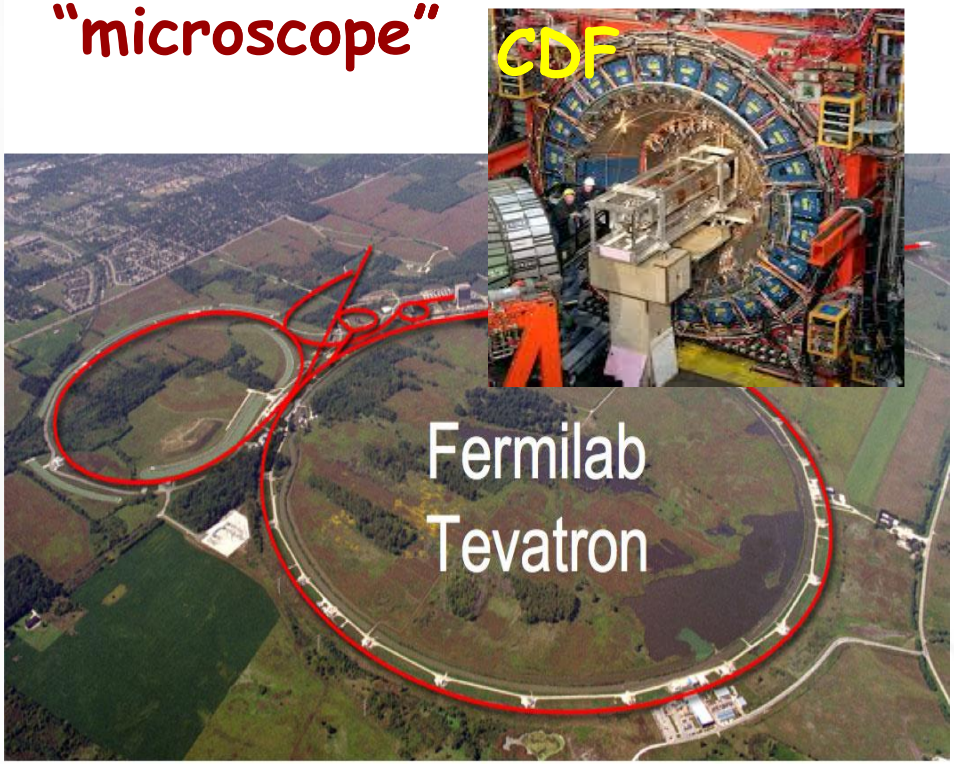
Not to scale!

# Periodic Table of Elementary Particles (the Standard Model)

The Higgs boson



Example of a particle "microscope"



As a graduate student I was searching for the Higgs

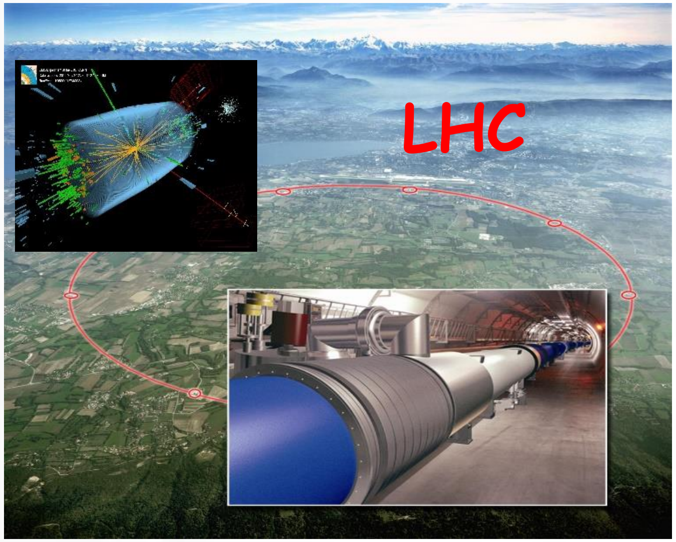
I now turned my attention to neutrinos

I'd like to build new kind of "microscopes" to study neutrinos

# Discoveries and Instrumentation

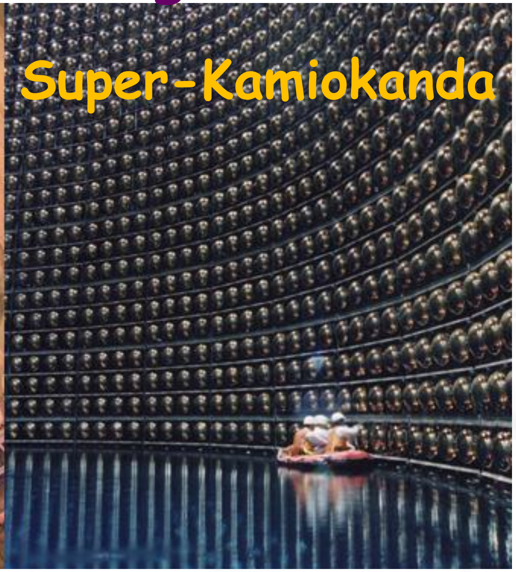
## Nobel Prize 2013: the Higgs boson is found

P.Higgs and F.Englert



## Nobel Prize 2015: neutrinos change while travel long distances

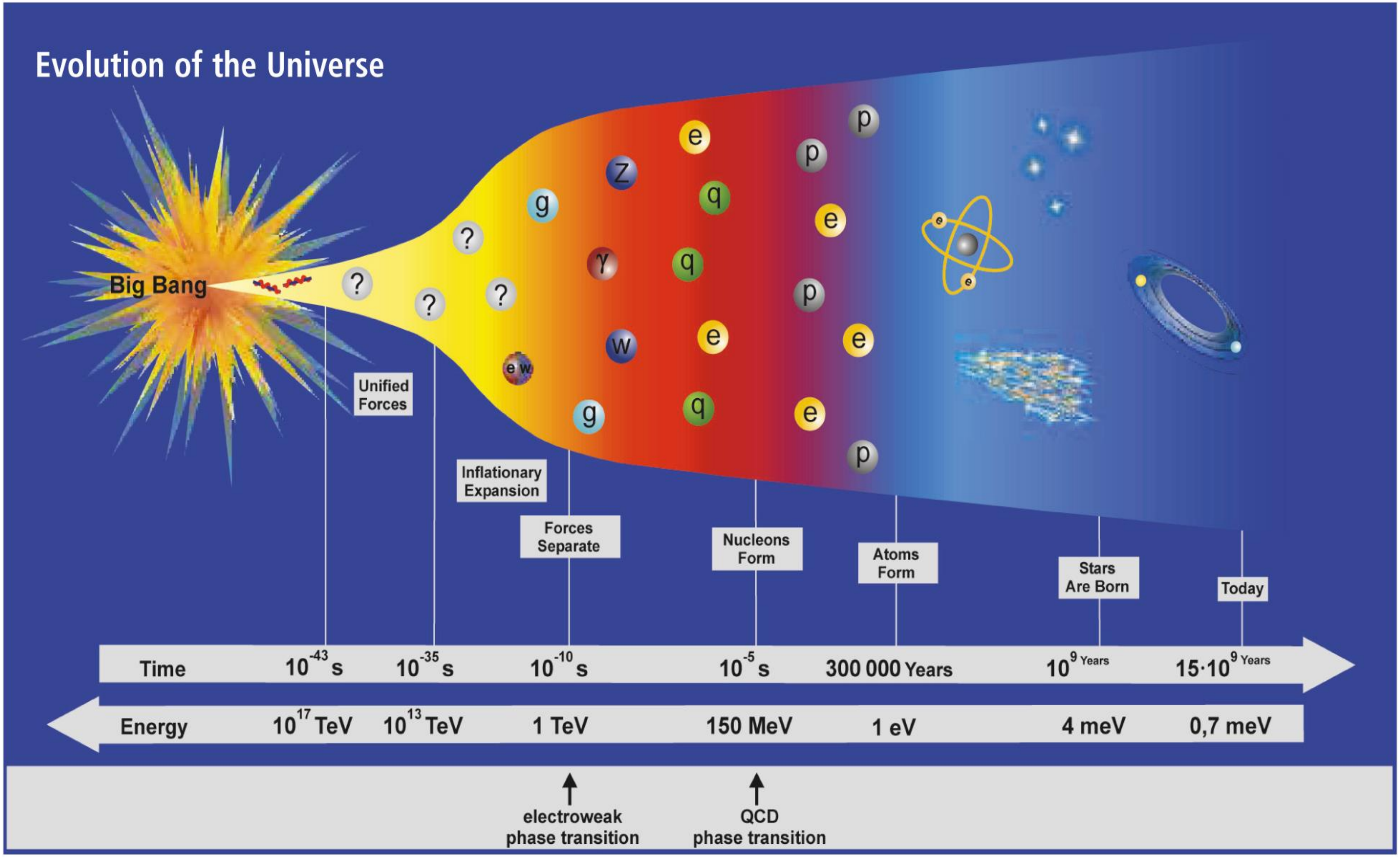
A.McDonald and T.Kojita



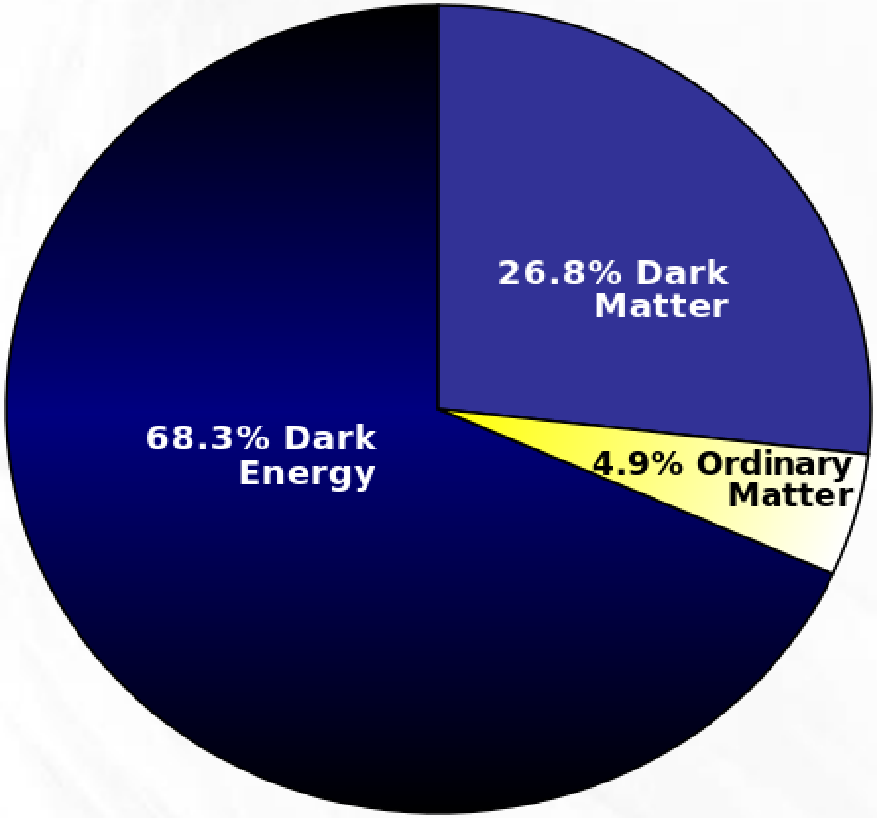
**State of the art instrumentation made these discoveries possible**

Future discoveries are waiting for new instrumentation

# This Is What We Know



# We Don't Know 95% of the Story



We have to build more instruments
More telescopes and "microscopes" are needed to find out what are those 95%

Also we are not done with the ordinary matter yet!

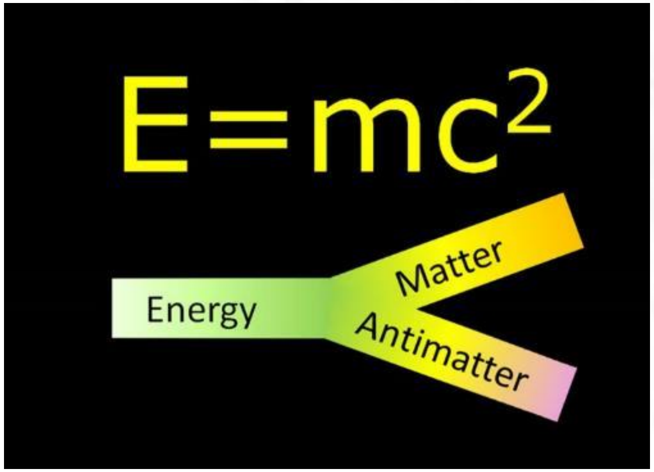
# A Question That Interests Me

## 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**

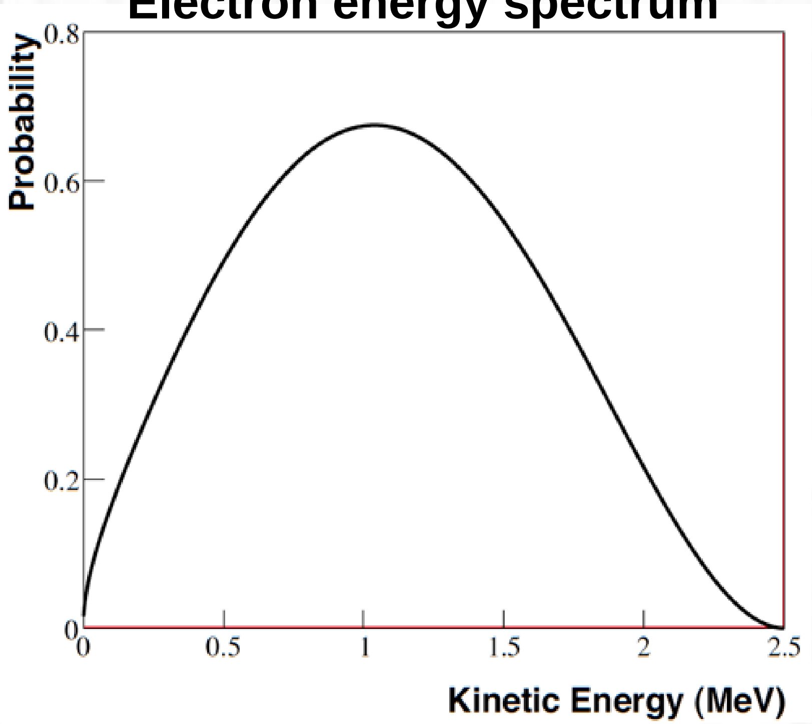
Search for neutrino-less double beta decay ($0\nu\beta\beta$-decay) is the most feasible way to answer this question

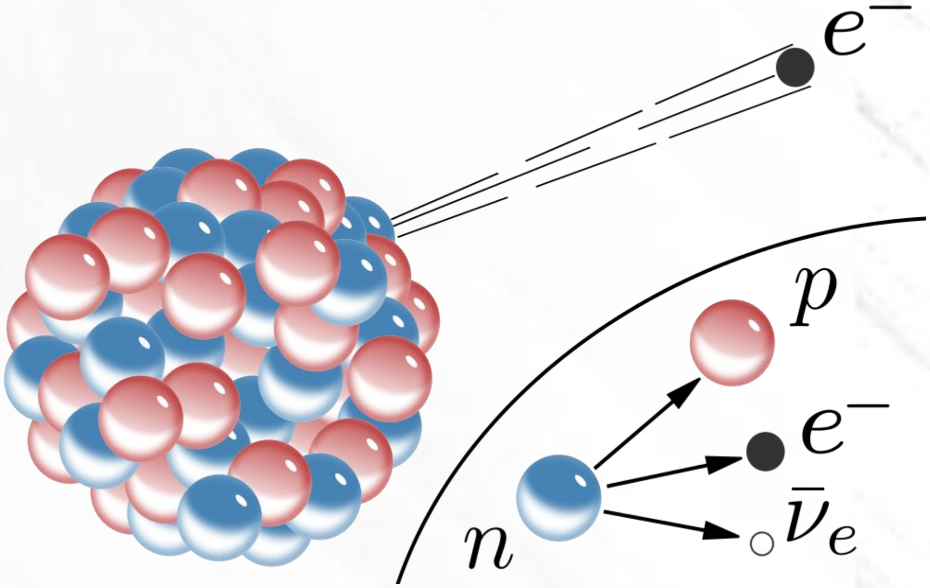
# Meet the Neutrino

Crisis in 1930
(known particles: $\gamma$, p, $e^-$ )

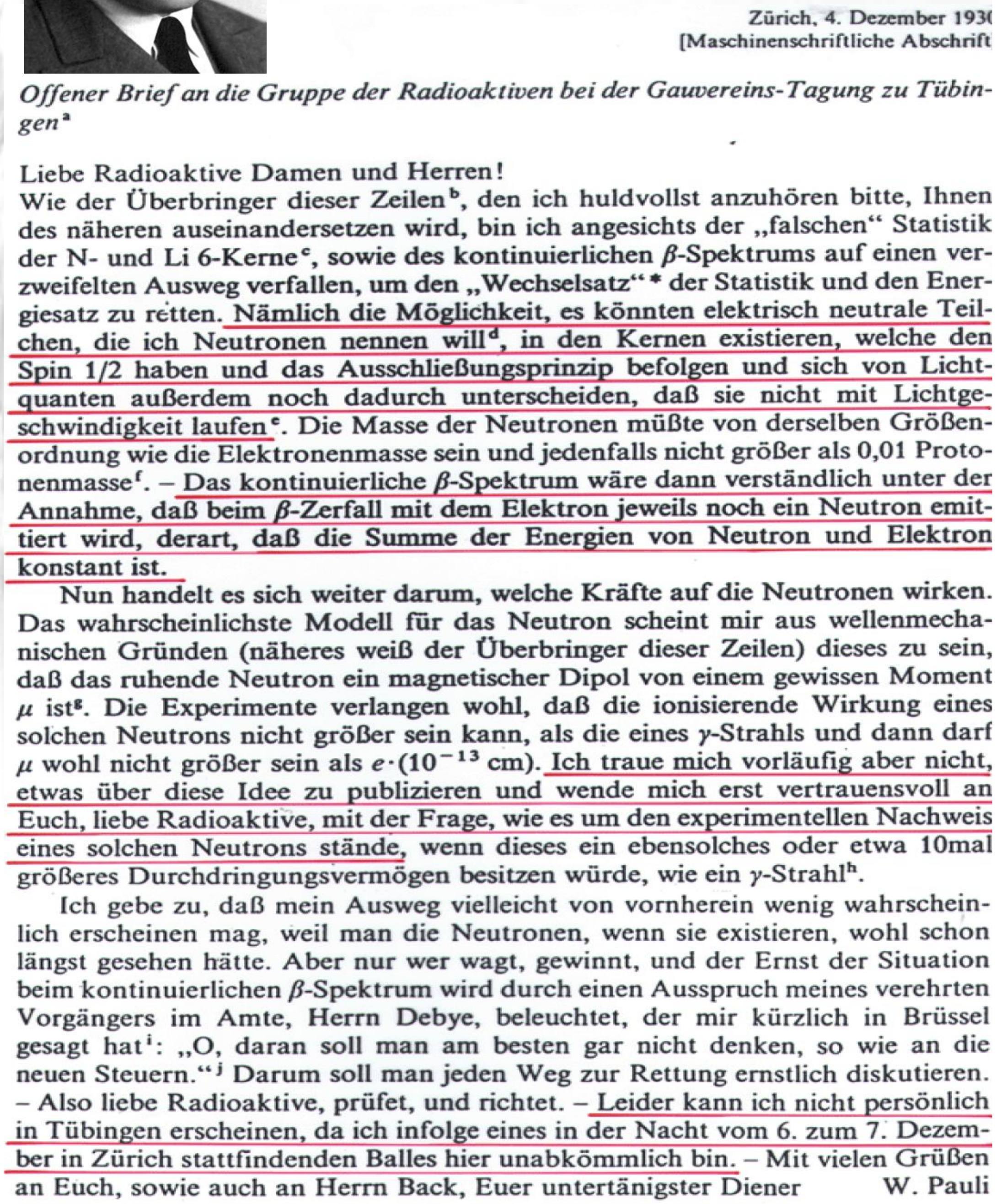
beta decay: (A,Z) → (A,Z+1) + $e^-$ + $\nu_e$

**Electron energy spectrum**





# Letter by W. Pauli



Zürich, 4. Dezember 1930
[Maschinenschriftliche Abschrift

*Offener Brief an die Gruppe der Radioaktiven bei der Gauvereins-Tagung zu Tübingen*[a]

Liebe Radioaktive Damen und Herren!
Wie der Überbringer dieser Zeilen[b], den ich huldvollst anzuhören bitte, Ihnen des näheren auseinandersetzen wird, bin ich angesichts der „falschen" Statistik der N- und Li 6-Kerne[c], sowie des kontinuierlichen $\beta$-Spektrums auf einen verzweifelten Ausweg verfallen, um den „Wechselsatz"* der Statistik und den Energiesatz zu retten. Nämlich die Möglichkeit, es könnten elektrisch neutrale Teilchen, die ich Neutronen nennen will[d], in den Kernen existieren, welche den Spin 1/2 haben und das Ausschließungsprinzip befolgen und sich von Lichtquanten außerdem noch dadurch unterscheiden, daß sie nicht mit Lichtgeschwindigkeit laufen[e]. Die Masse der Neutronen müßte von derselben Größenordnung wie die Elektronenmasse sein und jedenfalls nicht größer als 0,01 Protonenmasse[f]. – Das kontinuierliche $\beta$-Spektrum wäre dann verständlich unter der Annahme, daß beim $\beta$-Zerfall mit dem Elektron jeweils noch ein Neutron emittiert wird, derart, daß die Summe der Energien von Neutron und Elektron konstant ist.

Nun handelt es sich weiter darum, welche Kräfte auf die Neutronen wirken. Das wahrscheinlichste Modell für das Neutron scheint mir aus wellenmechanischen Gründen (näheres weiß der Überbringer dieser Zeilen) dieses zu sein, daß das ruhende Neutron ein magnetischer Dipol von einem gewissen Moment $\mu$ ist[g]. Die Experimente verlangen wohl, daß die ionisierende Wirkung eines solchen Neutrons nicht größer sein kann, als die eines $\gamma$-Strahls und dann darf $\mu$ wohl nicht größer sein als $e \cdot (10^{-13}$ cm). Ich traue mich vorläufig aber nicht, etwas über diese Idee zu publizieren und wende mich erst vertrauensvoll an Euch, liebe Radioaktive, mit der Frage, wie es um den experimentellen Nachweis eines solchen Neutrons stände, wenn dieses ein ebensolches oder etwa 10mal größeres Durchdringungsvermögen besitzen würde, wie ein $\gamma$-Strahl[h].

Ich gebe zu, daß mein Ausweg vielleicht von vornherein wenig wahrscheinlich erscheinen mag, weil man die Neutronen, wenn sie existieren, wohl schon längst gesehen hätte. Aber nur wer wagt, gewinnt, und der Ernst der Situation beim kontinuierlichen $\beta$-Spektrum wird durch einen Ausspruch meines verehrten Vorgängers im Amte, Herrn Debye, beleuchtet, der mir kürzlich in Brüssel gesagt hat[i]: „O, daran soll man am besten gar nicht denken, so wie an die neuen Steuern."[j] Darum soll man jeden Weg zur Rettung ernstlich diskutieren. – Also liebe Radioaktive, prüfet, und richtet. – Leider kann ich nicht persönlich in Tübingen erscheinen, da ich infolge eines in der Nacht vom 6. zum 7. Dezember in Zürich stattfindenden Balles hier unabkömmlich bin. – Mit vielen Grüßen an Euch, sowie auch an Herrn Back, Euer untertänigster Diener W. Pauli

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Physics Institute
of the ETH
Zürich

Zürich, Dec. 4, 1930
Gloriastrasse

Dear Radioactive Ladies and Gentlemen,

As the bearer of these lines, to whom I graciously ask you to listen, will explain to you in more detail, because of the "wrong" statistics of the N- and Li-6 nuclei and the continuous beta spectrum, I have hit upon a desperate remedy to save the "exchange theorem" (1) of statistics and the law of conservation of energy. Namely, the possibility that in the nuclei there could exist electrically neutral particles, which I will call neutrons, that have spin 1/2 and obey the exclusion principle and that further differ from light quanta in that they do not travel with the velocity of light. The mass of the neutrons should be of the same order of magnitude as the electron mass and in any event not larger than 0.01 proton mass. - The continuous beta spectrum would then make sense with the assumption that in beta decay, in addition to the electron, a neutron is emitted such that the sum of the energies of neutron and electron is constant.

Now it is also a question of which forces act upon neutrons. For me, the most likely model for the neutron seems to be, for wave-mechanical reasons (the bearer of these lines knows more), that the neutron at rest is a magnetic dipole with a certain moment µ. The experiments seem to require that the ionizing effect of such a neutron can not be bigger than the one of a gamma-ray, and then µ is probably not allowed to be larger than $e \bullet (10^{-13}$ cm).

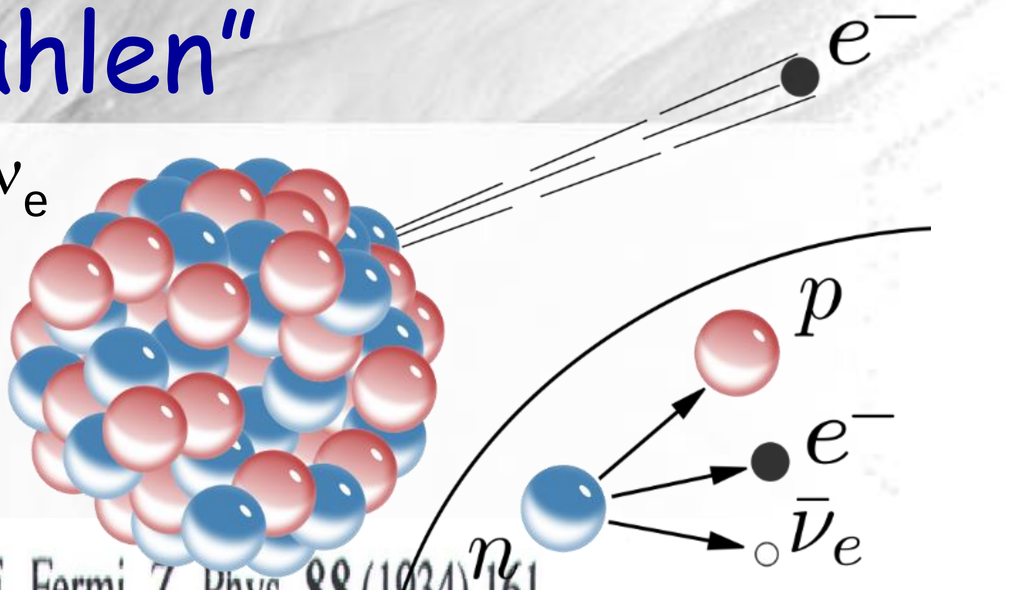
But so far I do not dare to publish anything about this idea, and trustfully turn first to you, dear radioactive people, with the question of how likely it is to find experimental evidence for such a neutron if it would have the same or perhaps a 10 times larger ability to get through [material] than a gamma-ray.

I admit that my remedy may seem almost improbable because one probably would have seen those neutrons, if they exist, for a long time. But nothing ventured, nothing gained, and the seriousness of the situation, due to the continuous structure of the beta spectrum, is illuminated by a remark of my honored predecessor, Mr Debye, who told me recently in Bruxelles: "Oh, It's better not to think about this at all, like new taxes." Therefore one should seriously discuss every way of rescue. Thus, dear radioactive people, scrutinize and judge. - Unfortunately, I cannot personally appear in Tübingen since I am indispensable here in Zürich because of a ball on the night from December 6 to 7. With my best regards to you, and also to Mr. Back, your humble servant

signed W. Pauli

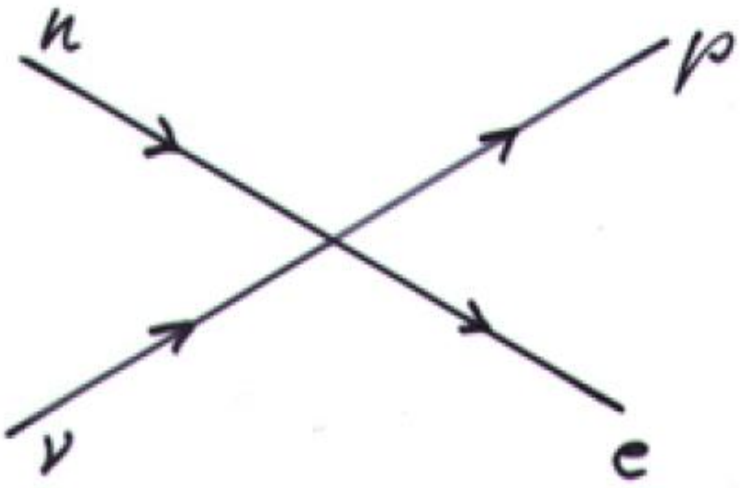
# "β-Strahlen"

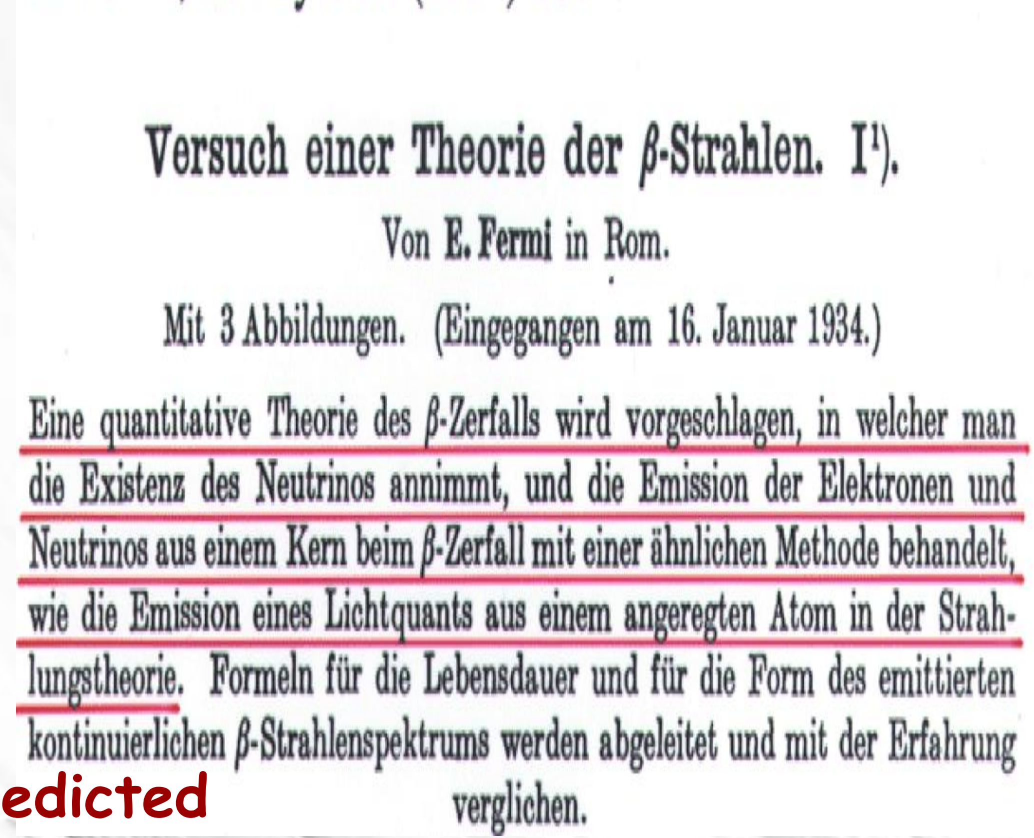
$$(A,Z) \rightarrow (A,Z+1) + e^- + \nu_e$$



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

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





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

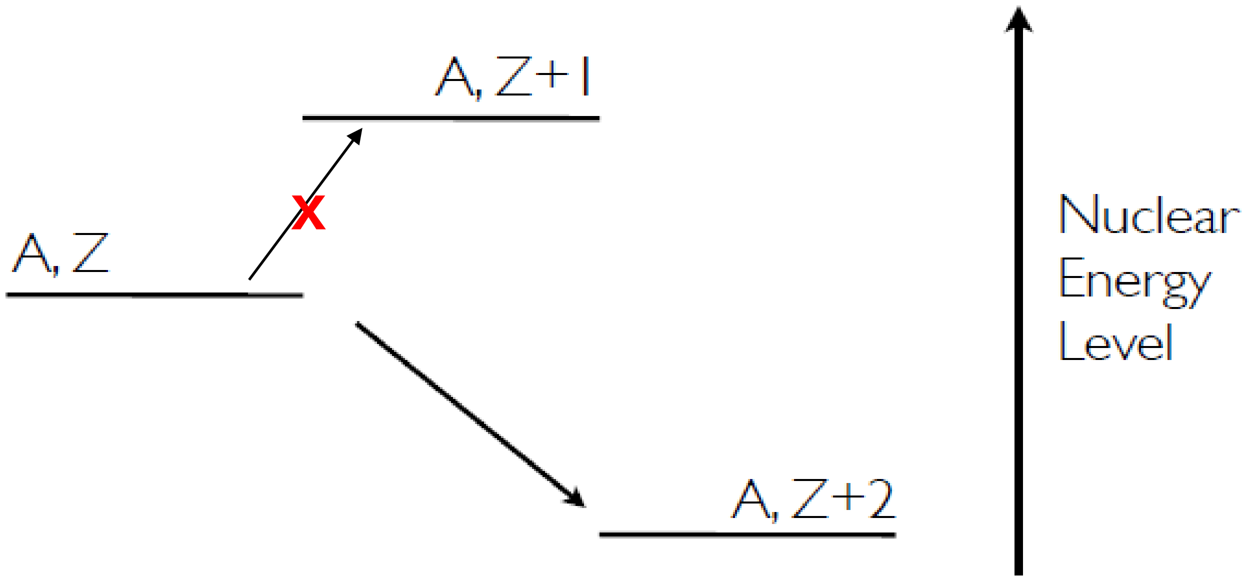
Von E. Fermi in Rom.

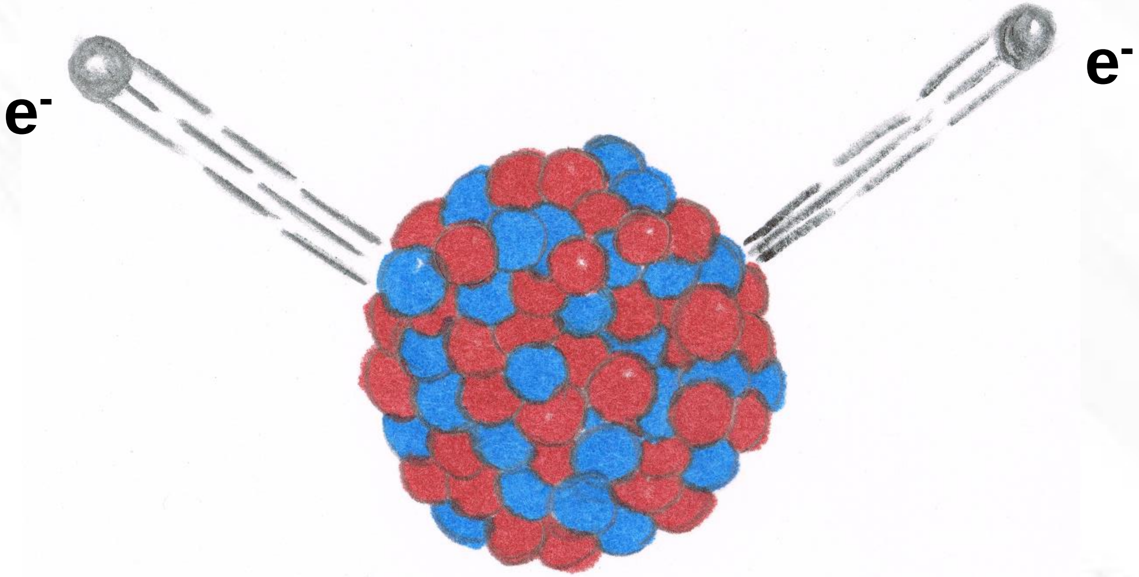
Mit 3 Abbildungen. (Eingegangen am 16. Januar 1934.)

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**

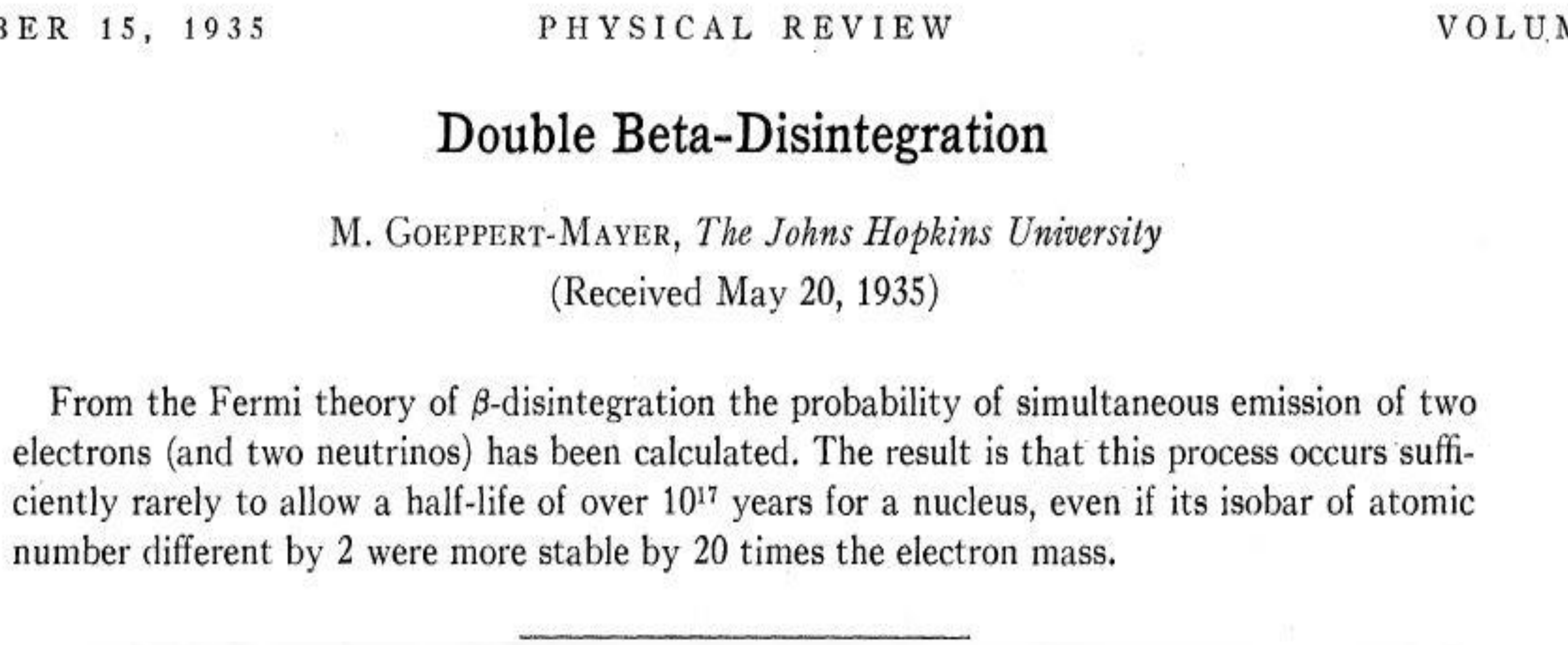
# Double Beta Decay





# Double-Beta Disintegration

## Maria Goeppert-Mayer



SEPTEMBER 15, 1935 PHYSICAL REVIEW VOLUM

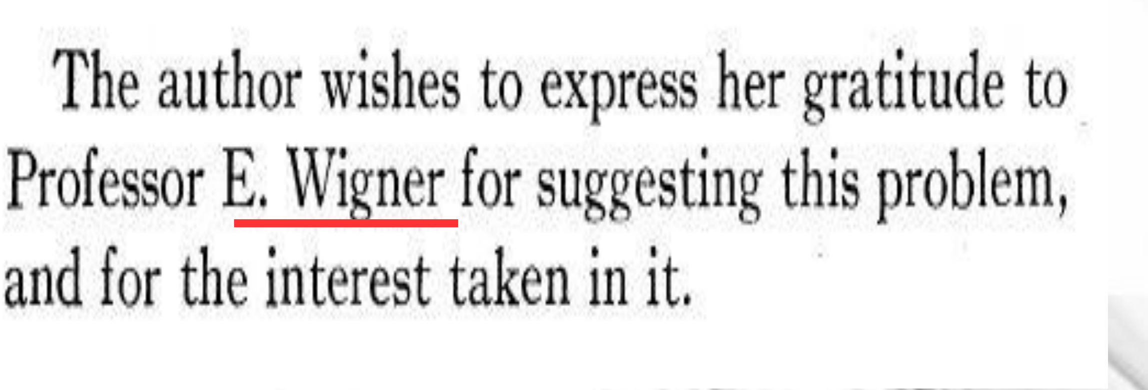
### Double Beta-Disintegration

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

(Received May 20, 1935)

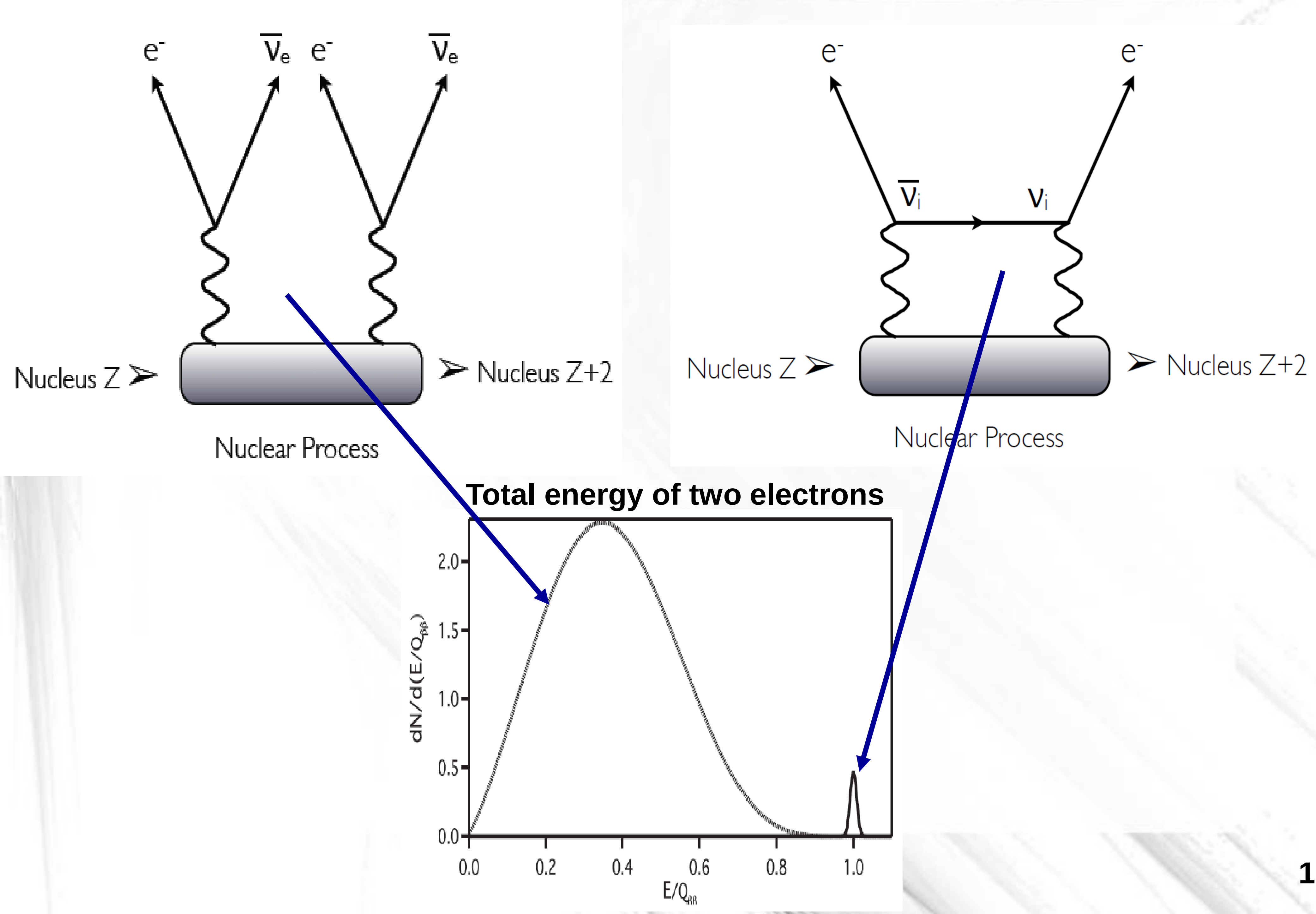
From the Fermi theory of $\beta$-disintegration the probability of simultaneous emission of two electrons (and two neutrinos) has been calculated. The result is that this process occurs sufficiently rarely to allow a half-life of over $10^{17}$ years for a nucleus, even if its isobar of atomic number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

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



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

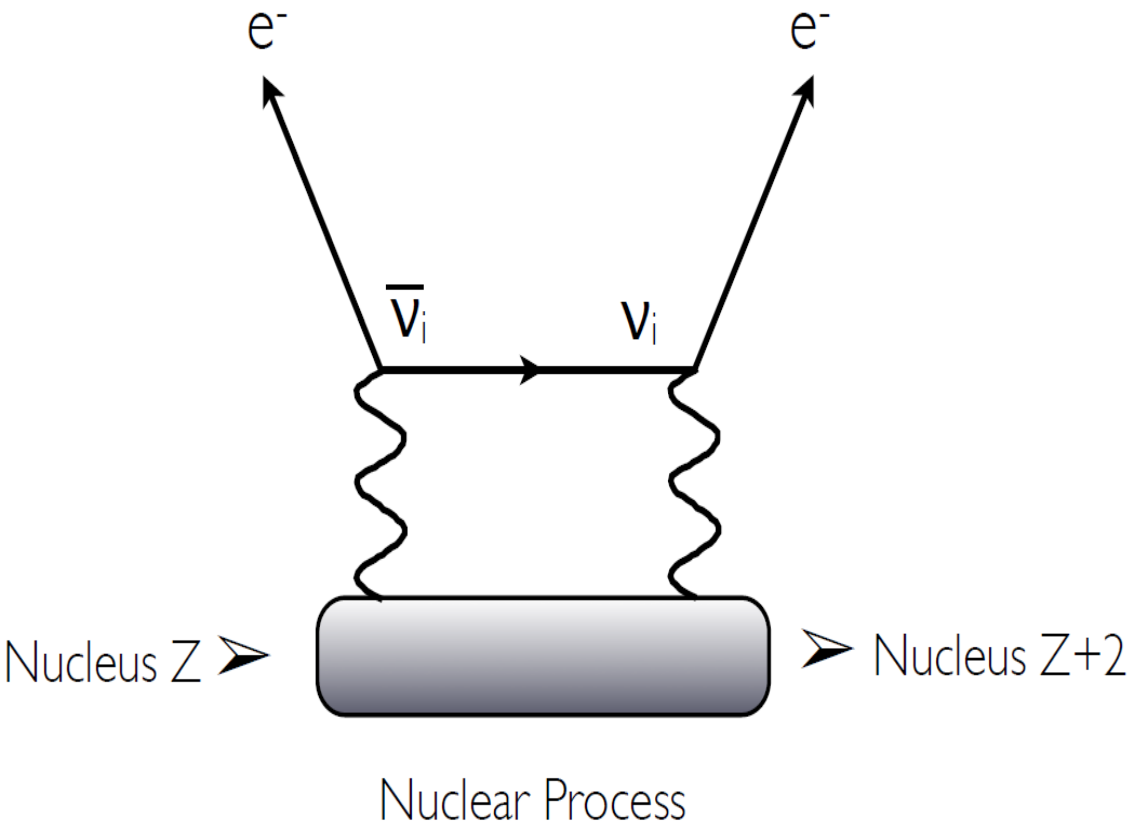
# Double Beta Decay



**Total energy of two electrons**

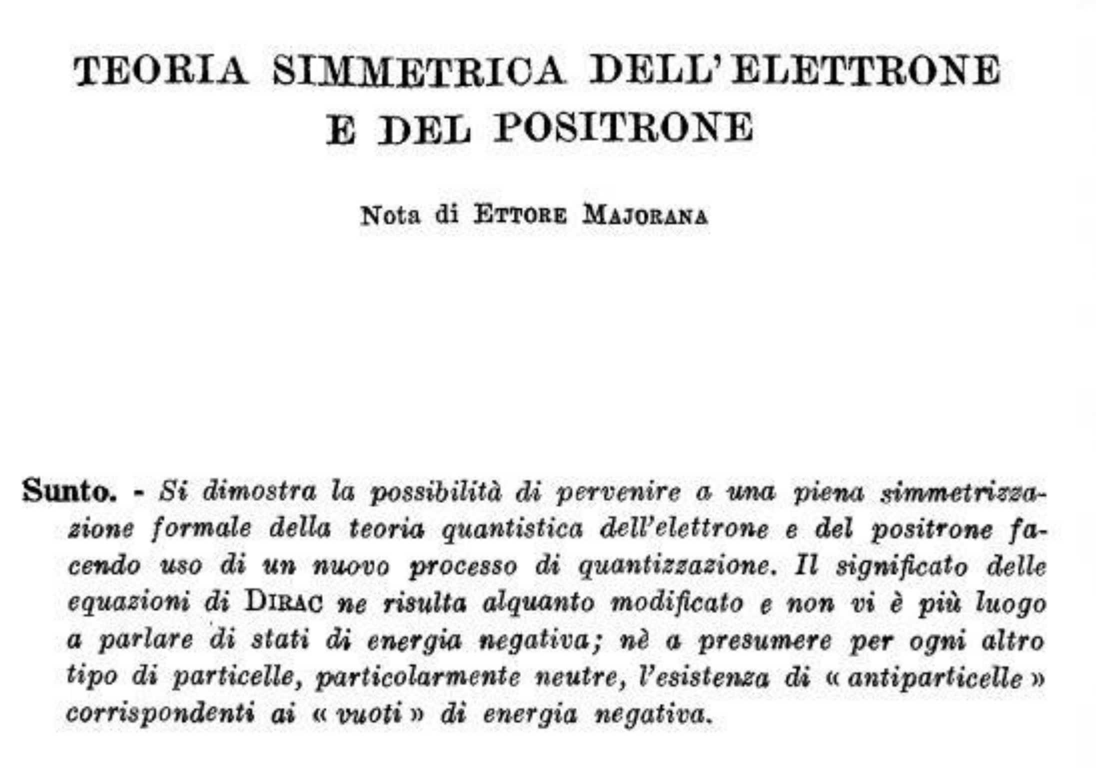
# Neutrinoless Decay

It is only possible if the neutrino is its own antiparticle



How can a particle be its own antiparticle?

# 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 ½ particles

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

# 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.

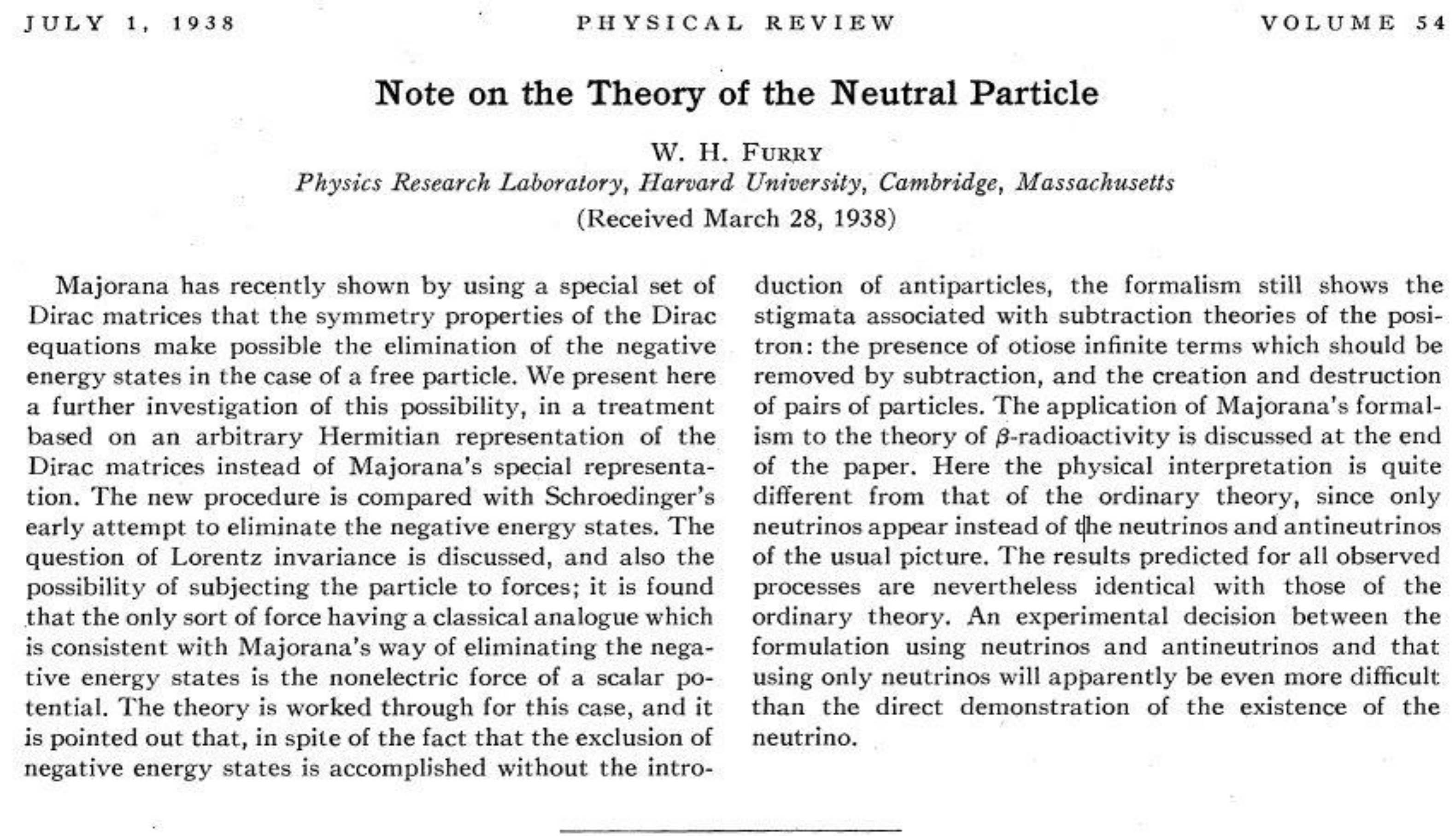
Proposed a “chain” reaction

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

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

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*

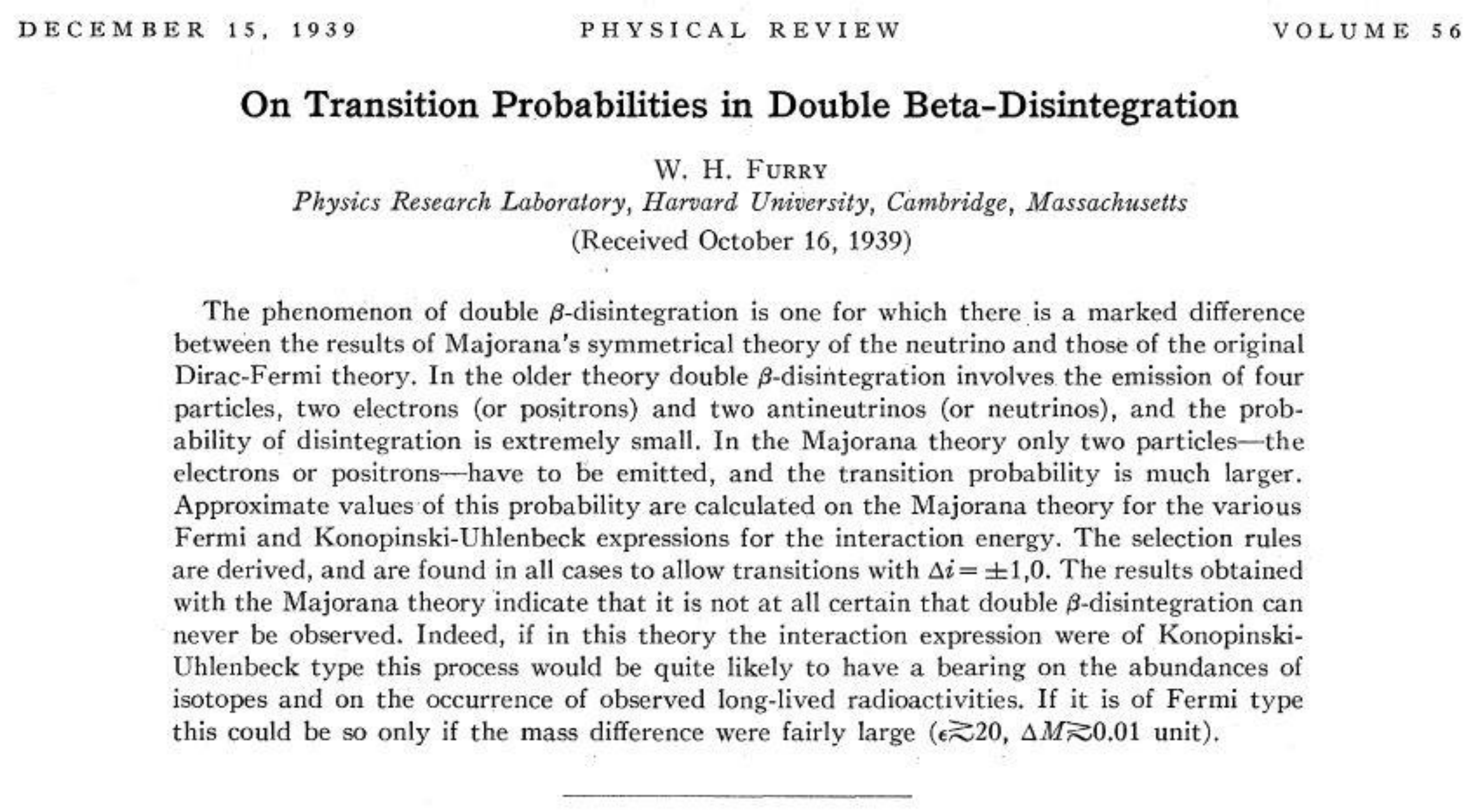
(Received March 28, 1938)

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 $\beta$-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 ~ $10^{-40}$
- 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 $\beta$-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 $\beta$-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 $\beta$-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

# Progress on Experimental Side

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 R.Davis' experiment doesn't solve Dirac/Majorana questions for neutrinos

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

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

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

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

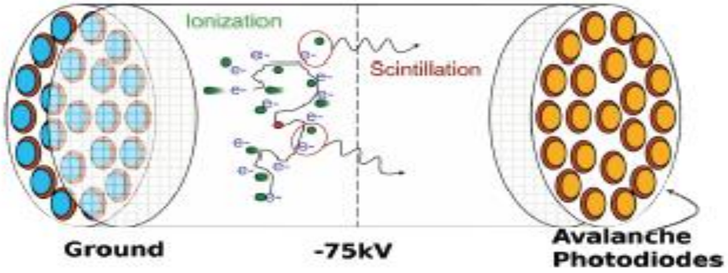
# Current Status

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

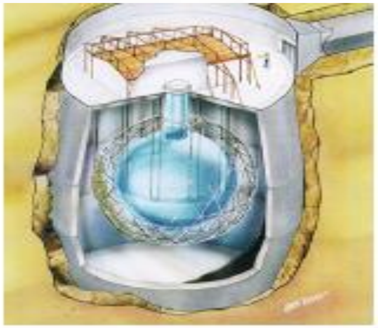
Today we have many experiments

**MAJORANA**

**EXO**

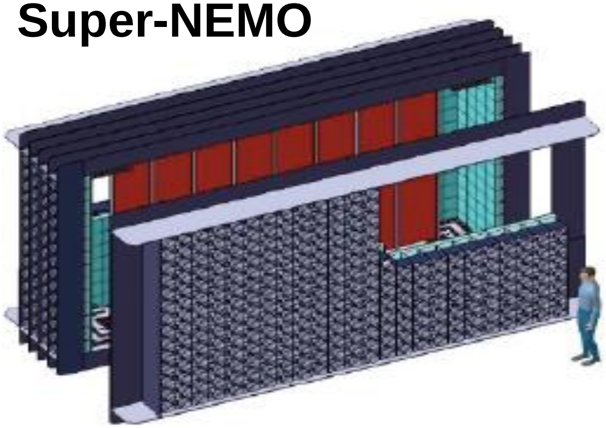


**SNO+**

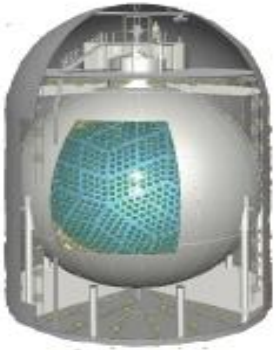


**GERDA**

**Super-NEMO**



**KamLAND**



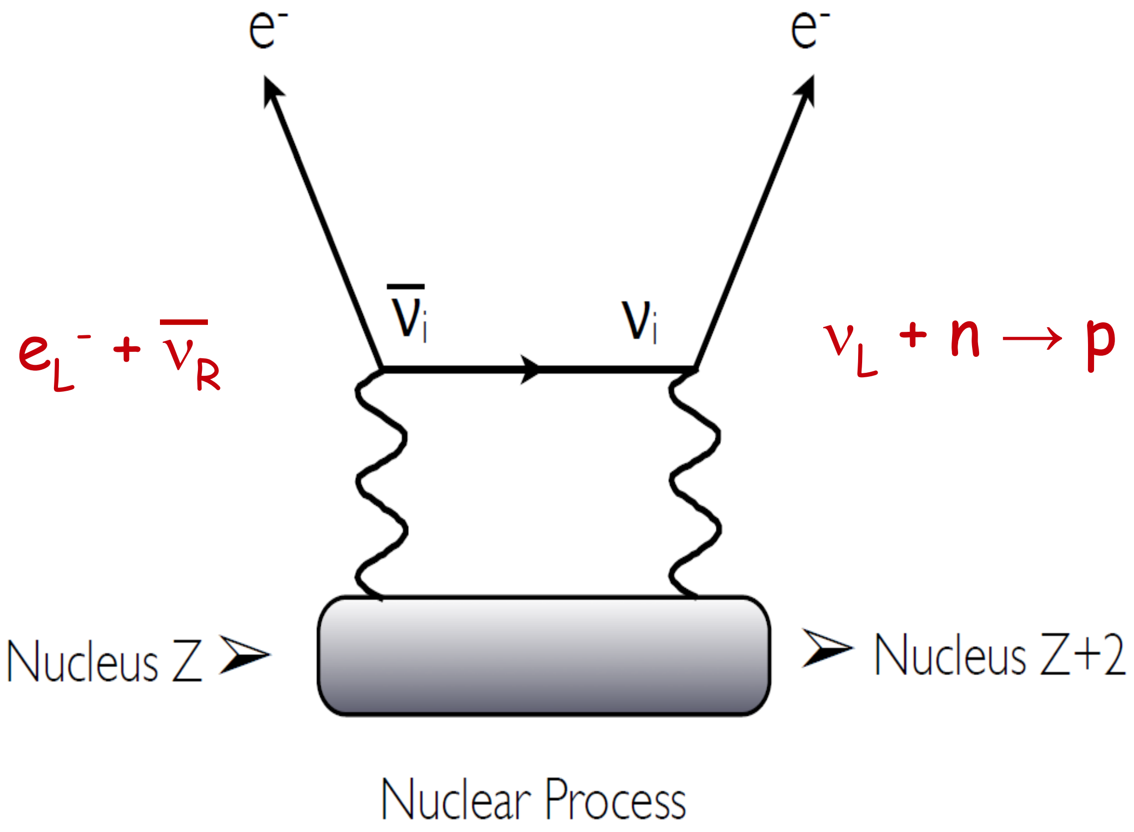
**CUORE**

In 2015 NSAC report $0\nu\beta\beta$–decay was ranked as a high priority for US nuclear physics

Why it has high priority?

# Neutrinoless Decay Is Unique

It may reveal the nature of neutrino mass



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

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

Even if neutrino is its own antiparticle $\nu_R \neq \nu_L$

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

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

Such transition is connected to a mass term in the Lagrangian

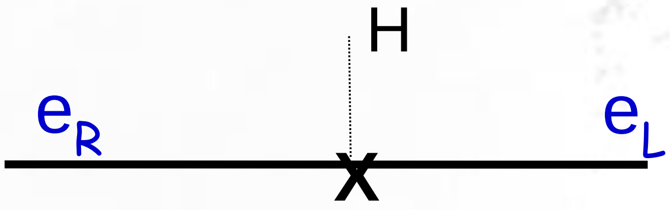
Example of a Majorana mass term: $M_N N^C N$

# See-Saw Mechanism

Electron mass term in the Standard Model Lagrangian

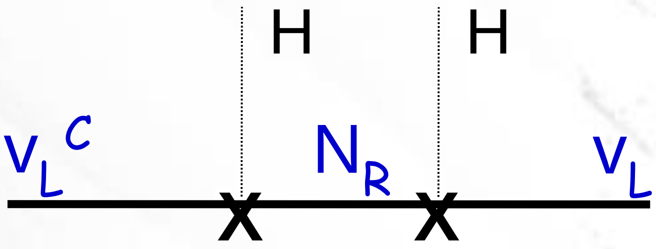
$m_e e_L e_R$

(Example of a Dirac mass term)

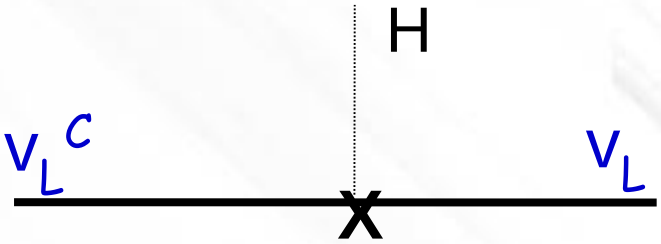


Possible extension of the SM Lagrangian to introduce neutrino mass

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



"Effectively" in the limit $M_{RR} >> m_D$



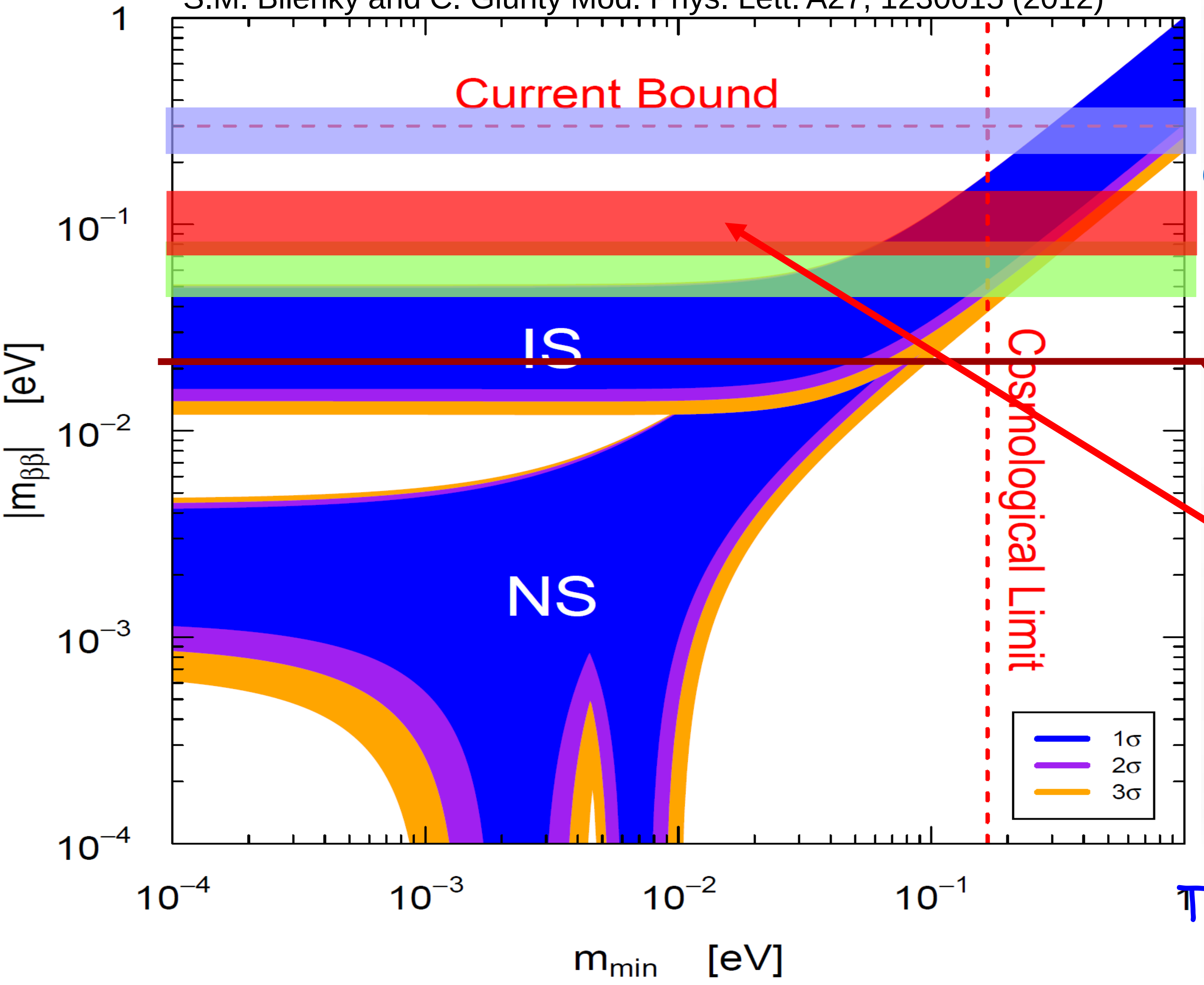
In the limit $M_{RR} >> m_D$ the eigenvalues are
$m_D^2/M_{RR}$ (light neutrino)
$M_{RR}$ (heavy neutrino)

$0\nu\beta\beta$-decay provides access to the neutrino mass mechanism

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

# Experimental Sensitivity

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



EXO (~200kg $^{136}$Xe)

KamLAND-Zen (~300 kg $^{136}$Xe,

before this Summer)

GERDA (~20 kg $^{76}$Ge)

Projections by

CUORE (~200kg $^{130}$Te)

SNO+ (0.8 ton $^{130}$Te)

SNO+ (8 ton $^{130}$Te)

Current best limit is set by KamLAND-Zen:

$T_{1/2} > 1.07\times10^{26}$ years

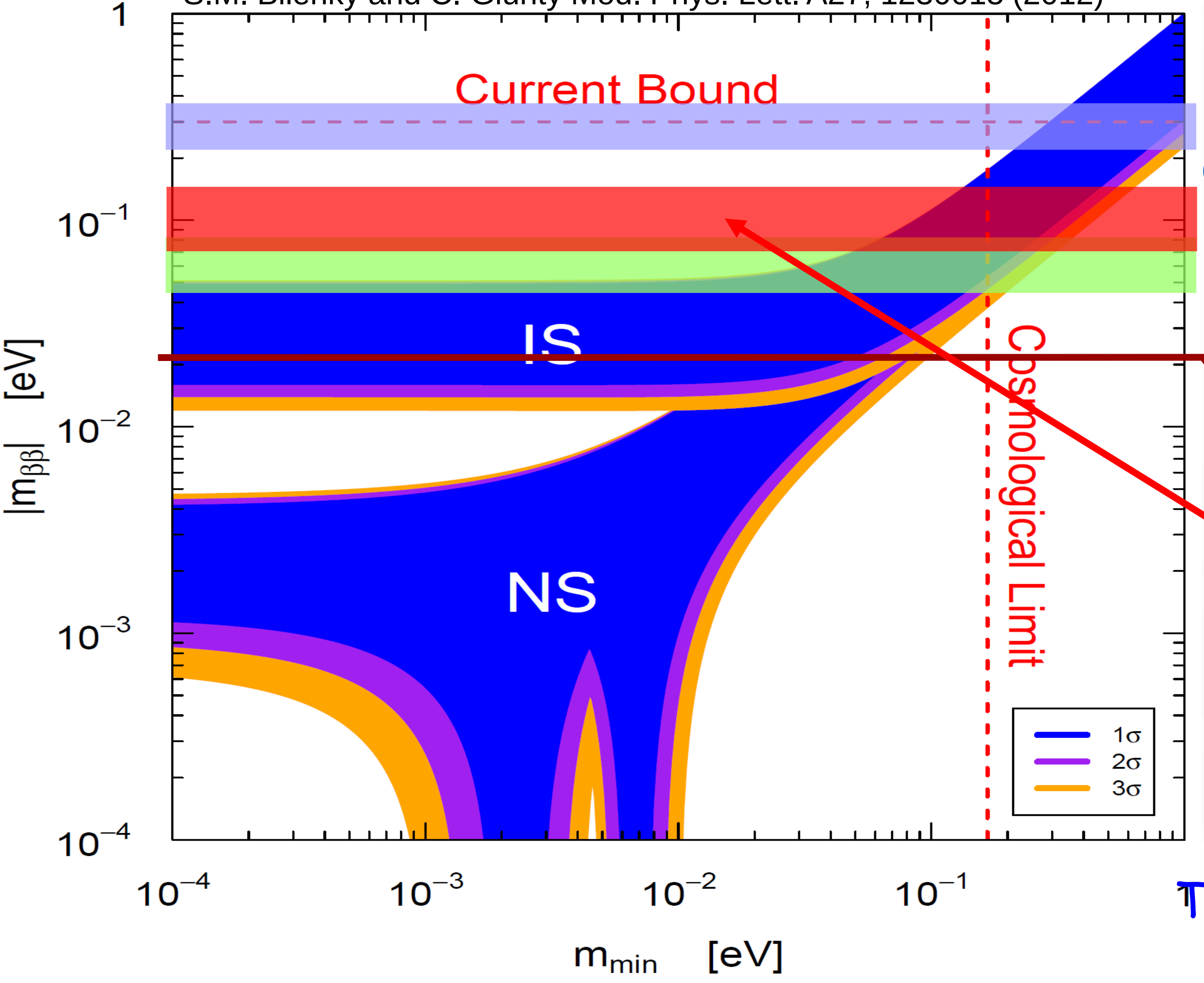
$m_{\beta\beta} < 61\text{-}165$ meV

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

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

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

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

None of currently running or planned experiments is sensitive to $m_{\beta\beta}$~1 meV

# How to Find 0νββ-decay?

1) Choose an 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

## Very Small Decay Probability

Life-time for 0νββ-decay is more than > $10^{26}$ years

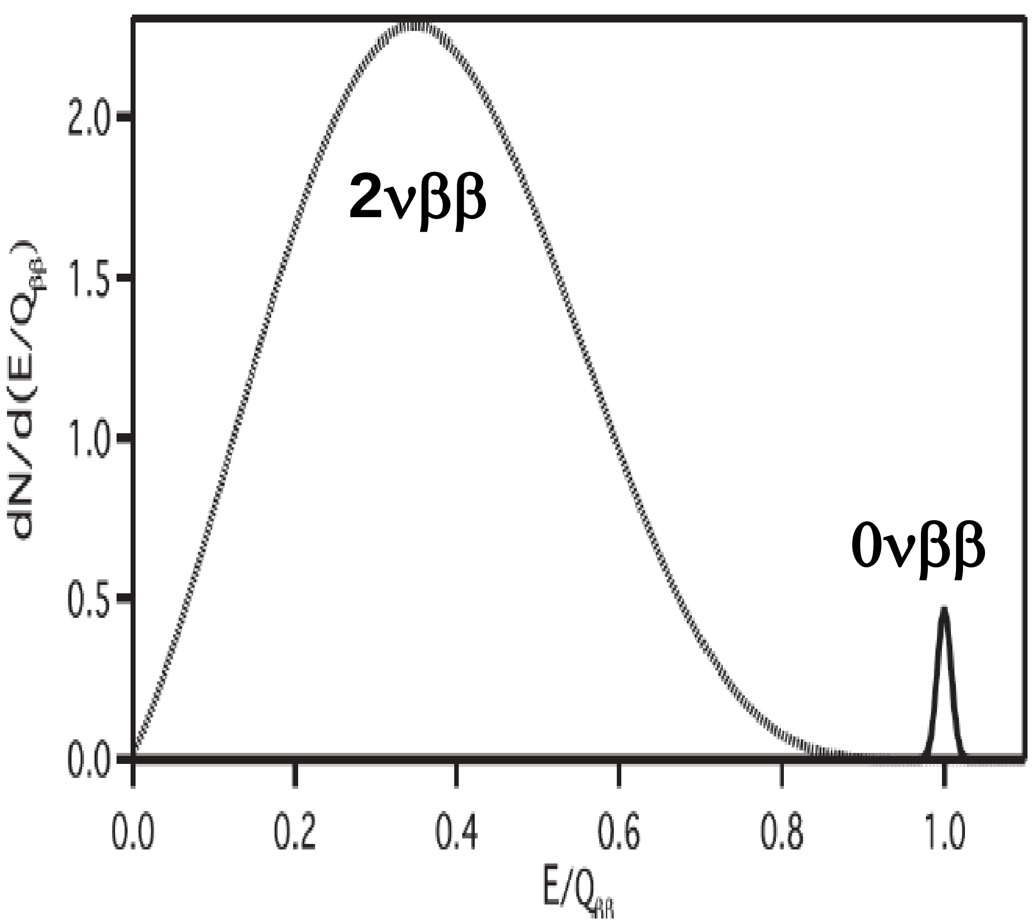
This is much longer than the age of the universe

Solution: look at many atoms at the same time

- Avogadro number is large $N_A = 6x10^{23}$
- 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 $2\nu\beta\beta$–decay

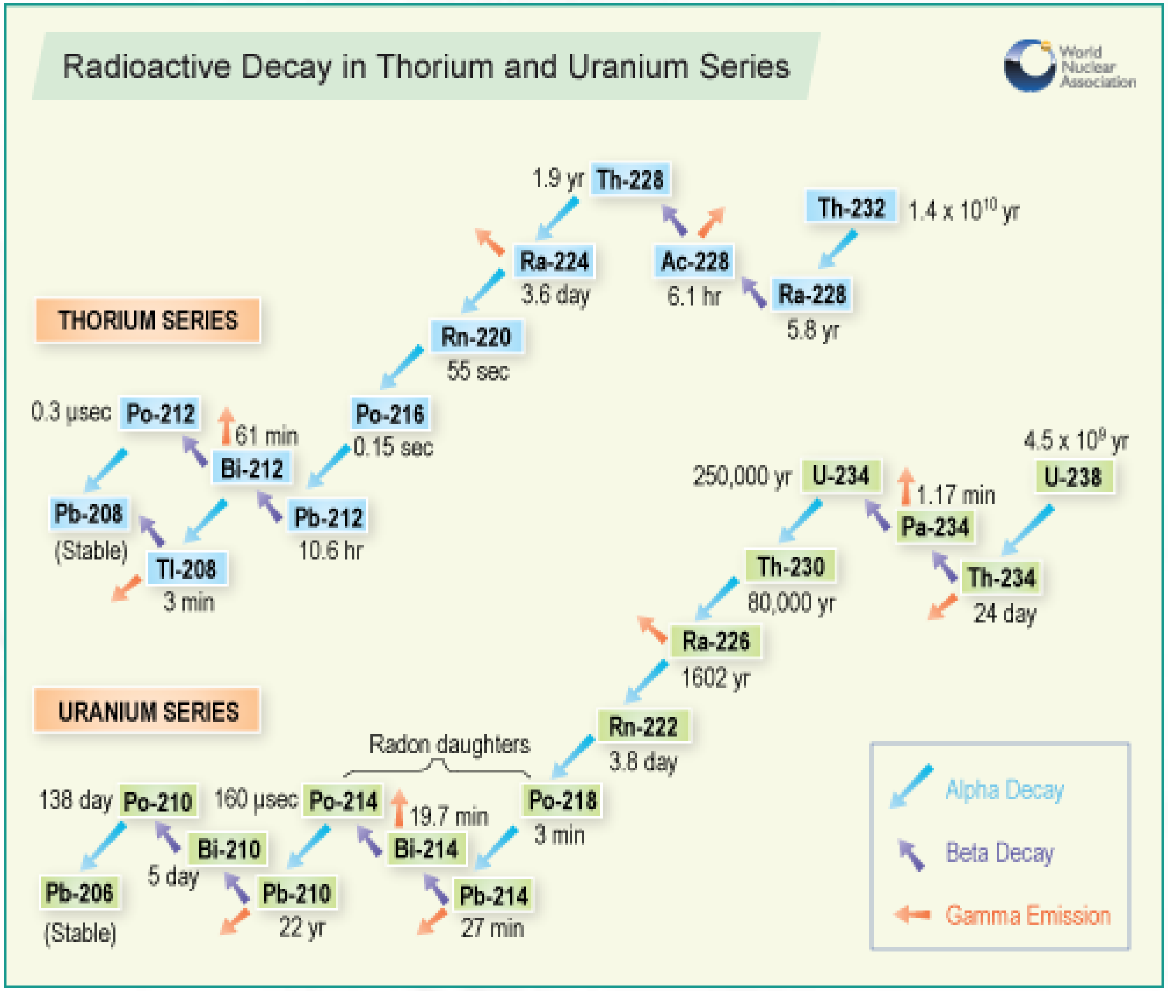


Solution: good energy resolution

# 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 $0\nu\beta\beta$-decay

**Solution: purification and shielding**

# Ideal 0νββ-decay Experiment

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

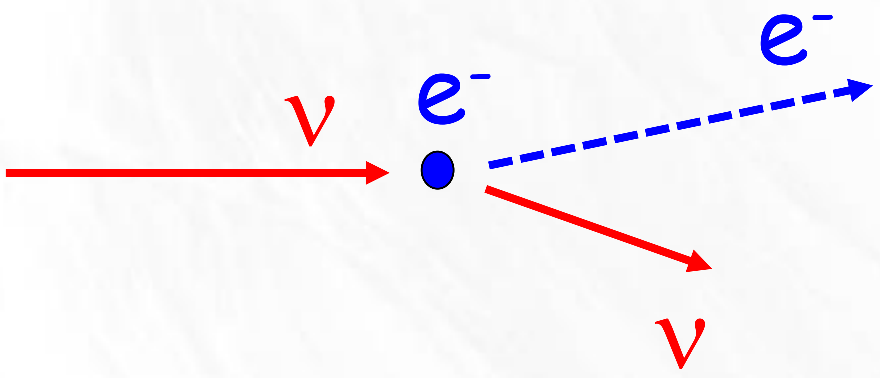
2) Good energy resolution (discriminate from 2νββ-decay)

3) Purification and shielding (natural radioactivity)

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

# New Challenge for a Large Detector

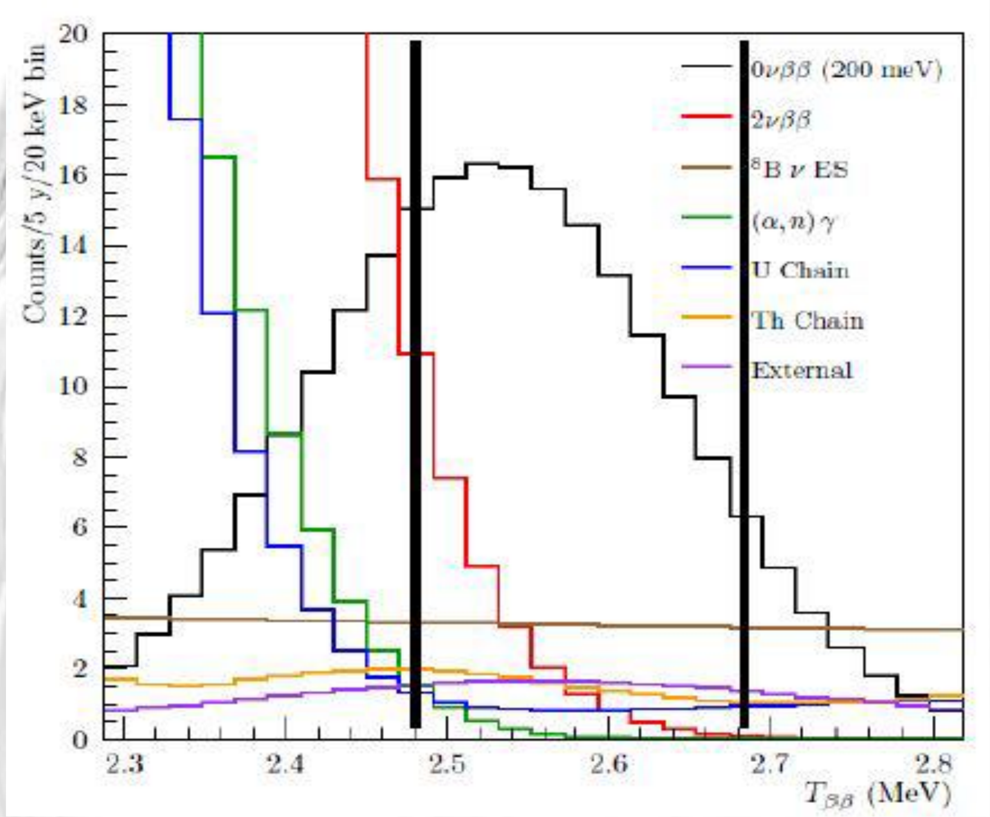
Electron scattering of neutrinos coming from $^{8}$B-decays in the sun

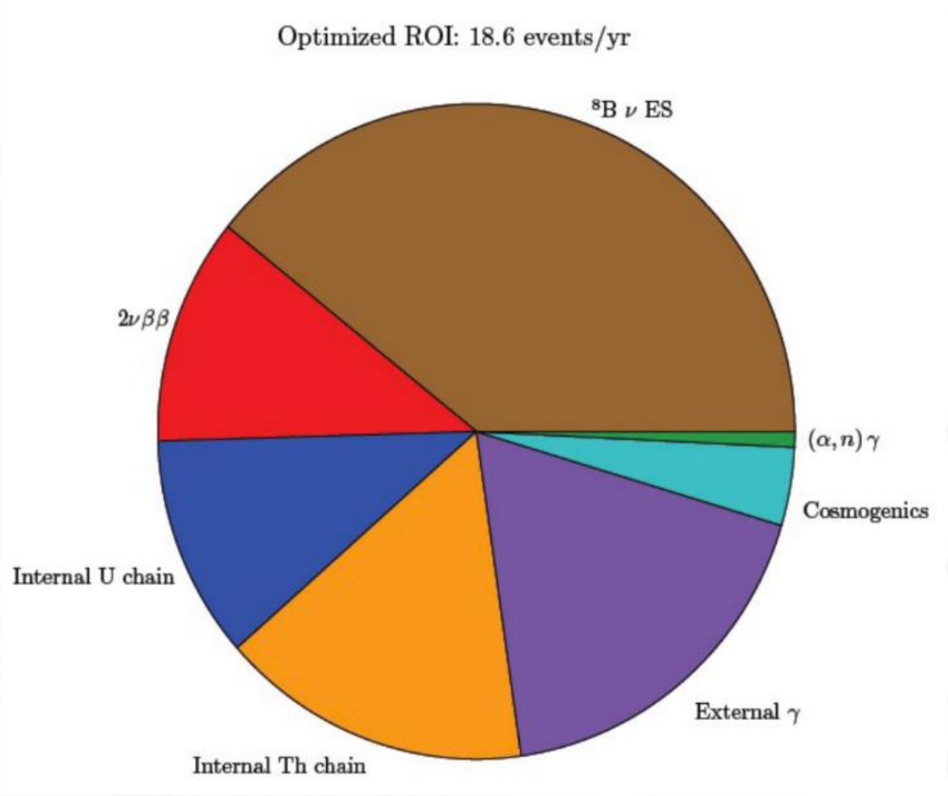


$^{8}$B solar neutrino interactions become dominant background

**This is irreducible background without event topology reconstruction**

# Background Budget at SNO+



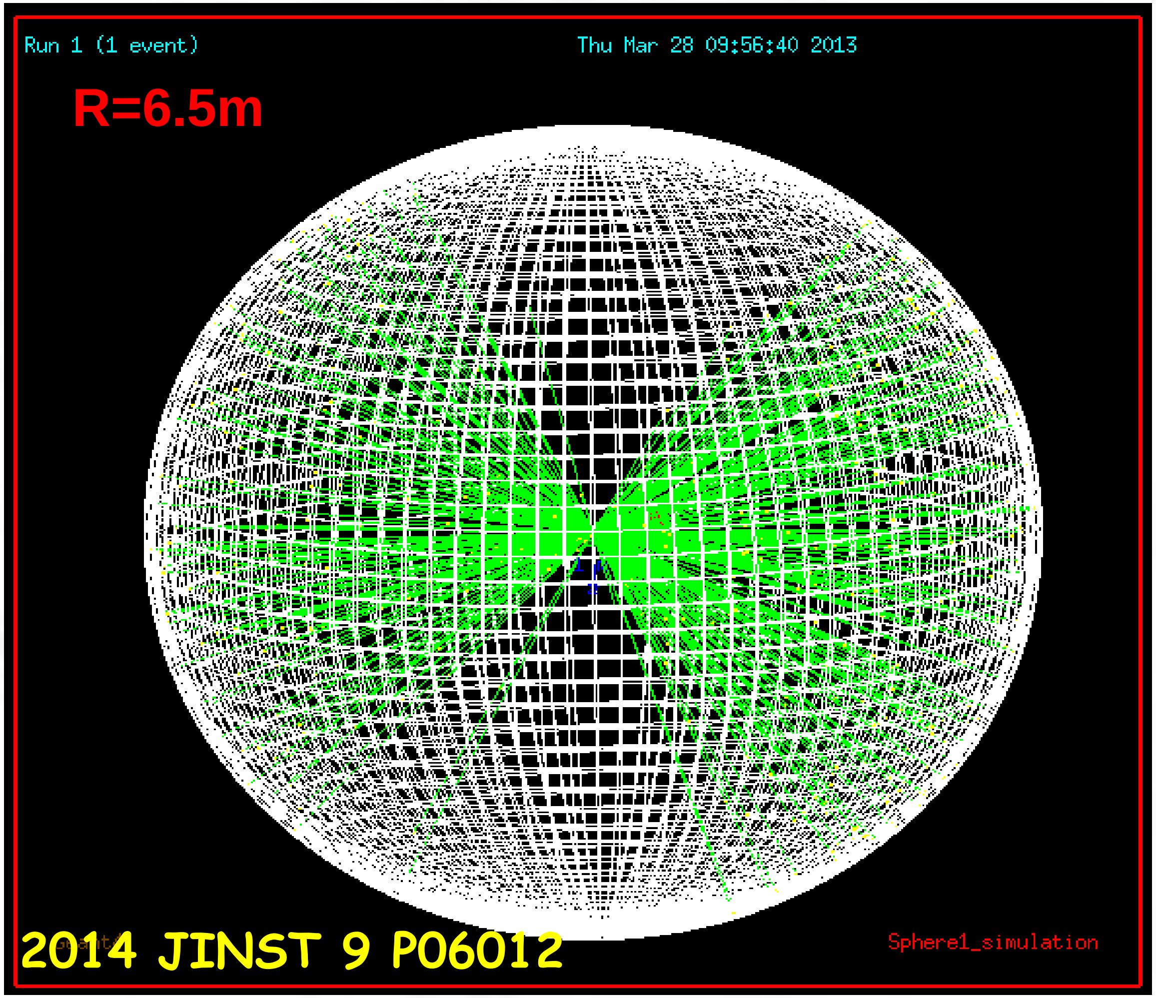


The largest background is coming from $^8$B solar neutrinos
It has only 1 electron, while νββ-decay has 2 electrons

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

# Can We See This?

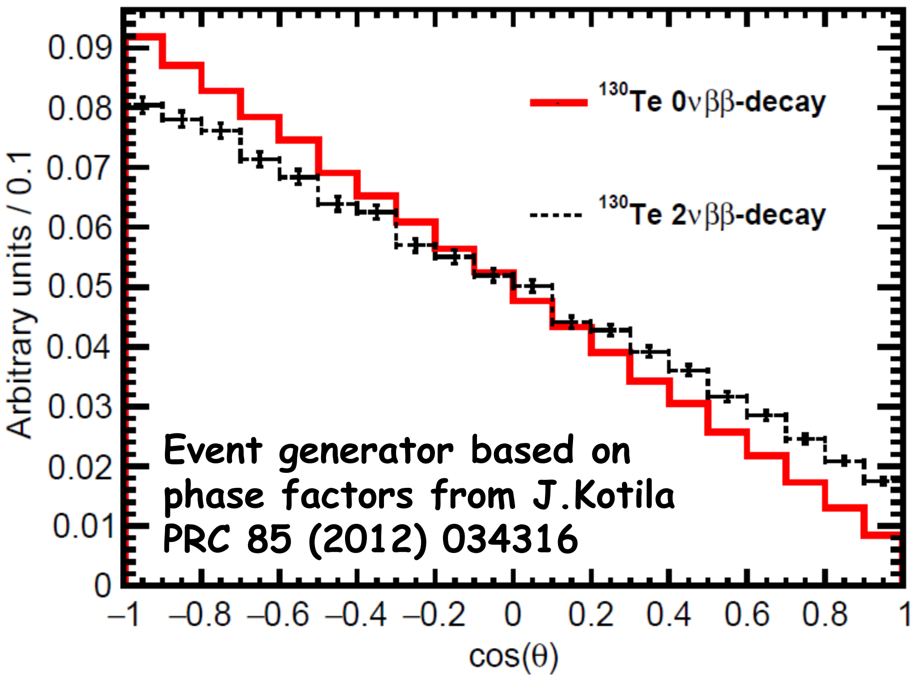
*Simulation of a back-to-back $0\nu\beta\beta$ event*



# Double-Beta Decay Kinematics

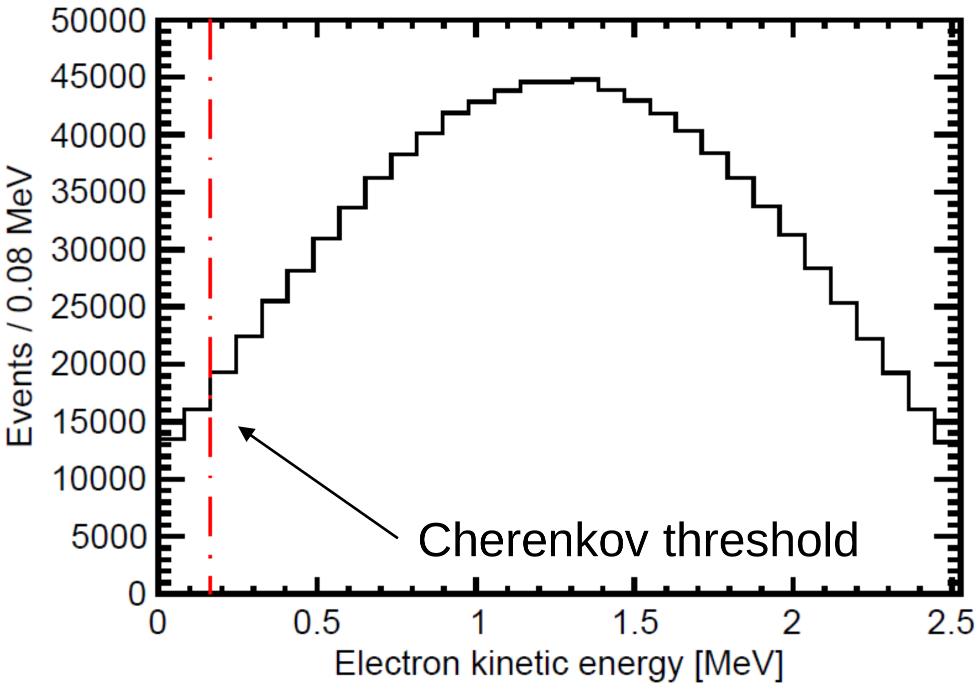
- Distinct two-track topology with preference to be “back-to-back”
- Electrons are above Cherenkov threshold

**Angle (cosΘ) between two electrons**



Event generator based on
phase factors from J.Kotila
PRC 85 (2012) 034316

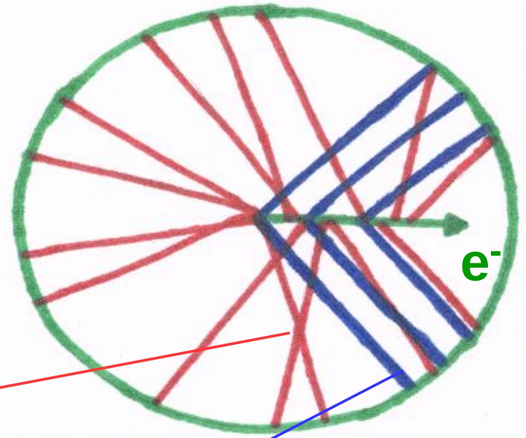
**Kinetic energy of each electron**



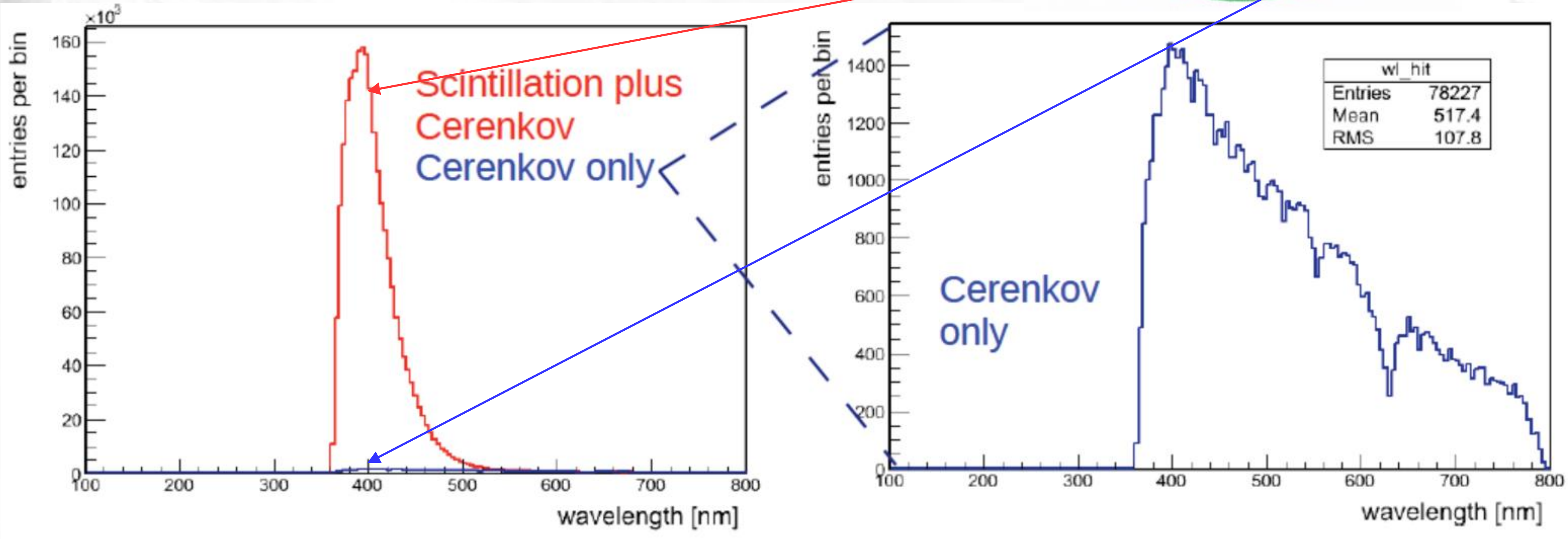
Cherenkov threshold

# Can We Detect Cherenkov Light?

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



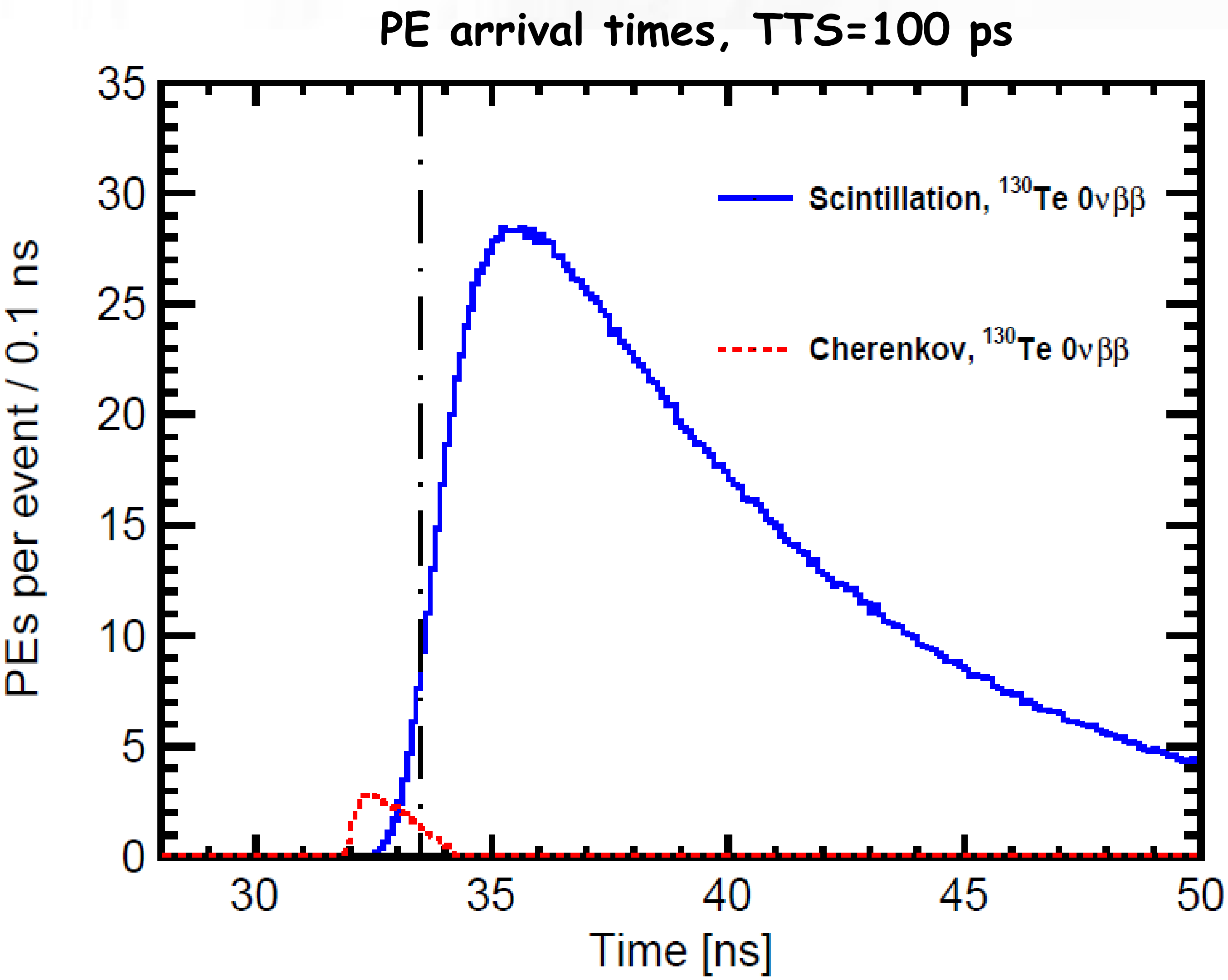
Scintillation model based on KamLAND-Zen simulation

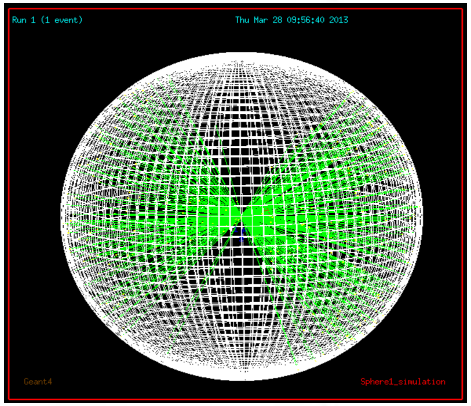


- Scintillation emission is slower
- Longer wavelengths travel faster
- Cherenkov light arrives earlier

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

# Can We Detect Cherenkov Light?

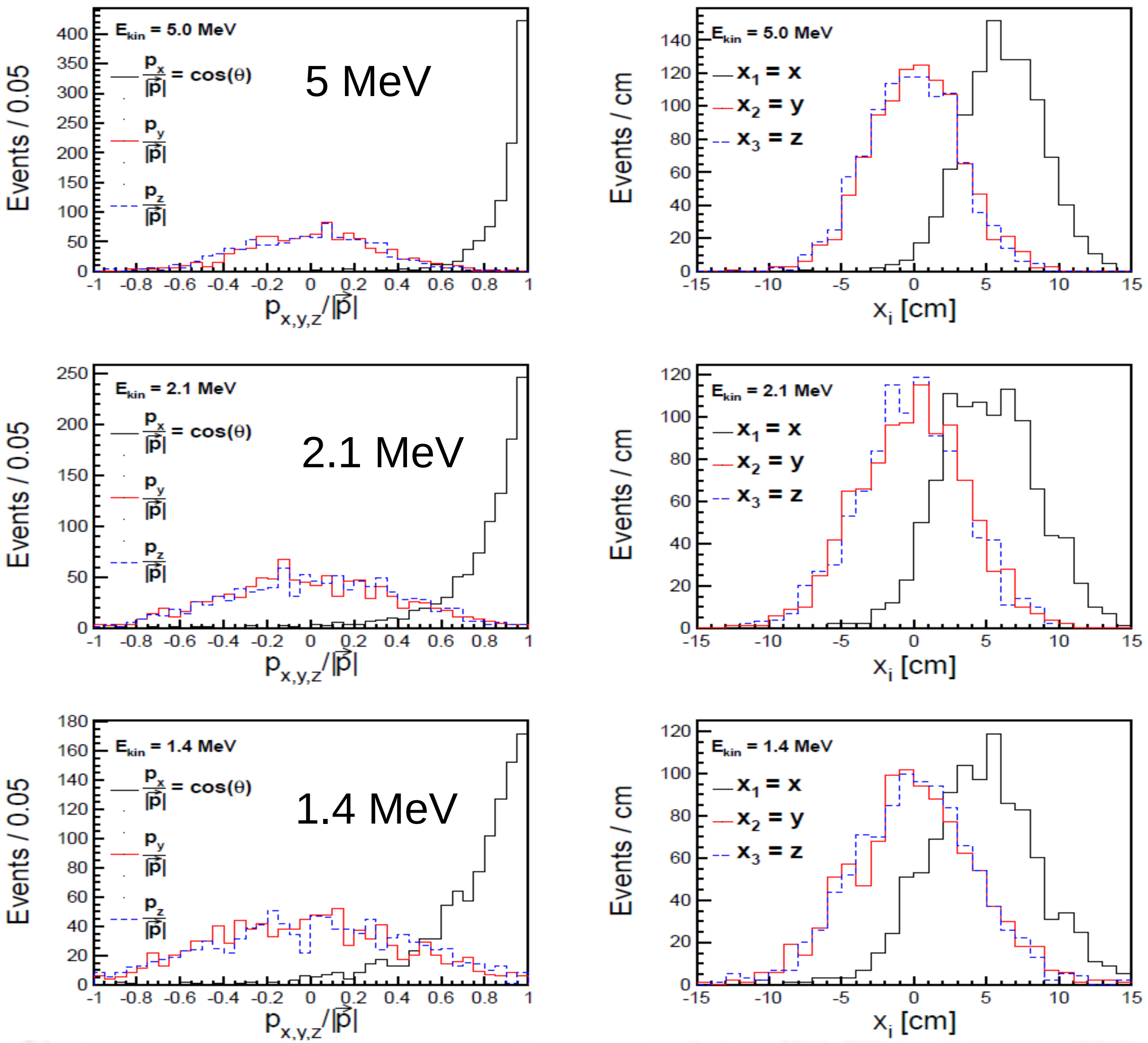




- Cherenkov light arrives earlier
- Need good timing to see the effect

# Directionality and Vertex Reconstruction

Directionality Vertex



Simulation:

- single electrons along X-axis at the center of 6.5m sphere
- KamLAND scintillator

Reconstruction:

WCSim adapted for low energy

2014 JINST 9 P06012

Directionality “survives” some detector effects

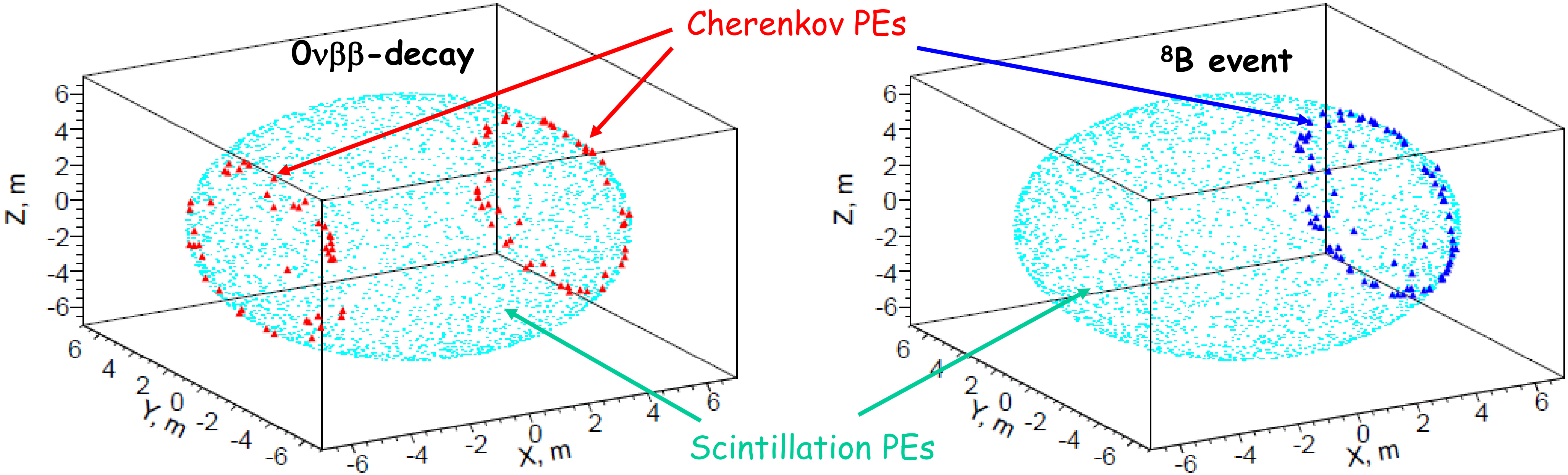
Vertex resolution is promising

Directionality is already a handle on $^8$B events

Solar neutrinos come from the sun and outgoing electrons “remember” that

# Directionality or Topology?

Idealized event displays: no multiple scattering of electrons, all PEs, QE=30%



Cherenkov PEs

Scintillation PEs

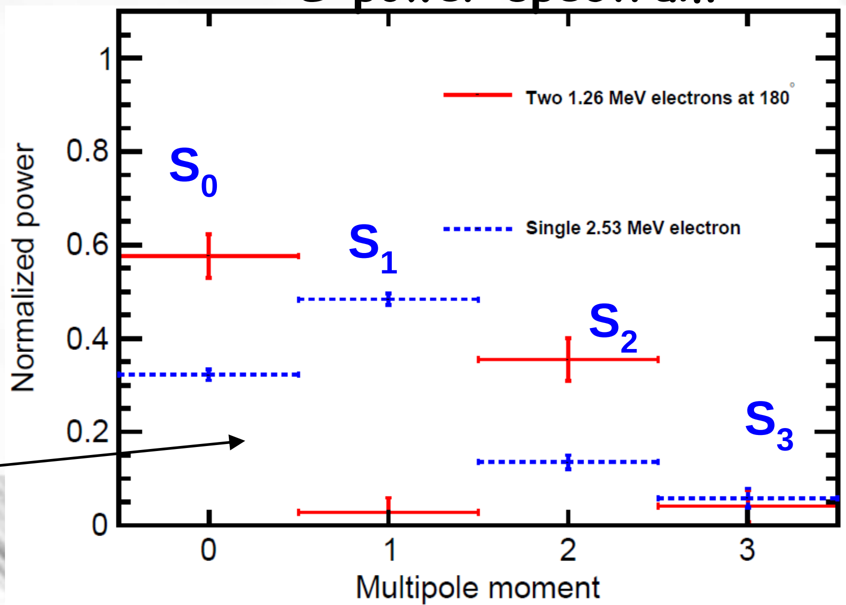
Spherical harmonics analysis

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

Rotation invariant power spectrum

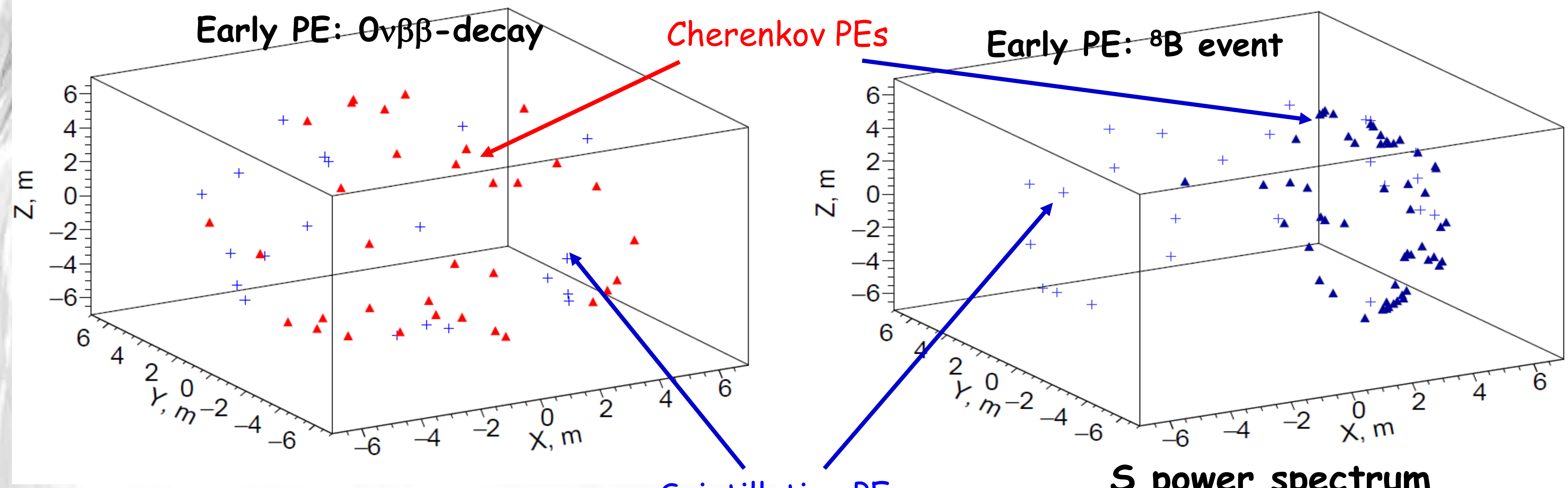
$$S_{ff}(\ell)=\sum_{m=-\ell}^{\ell}|f_{\ell m}|^2$$

**S power spectrum**



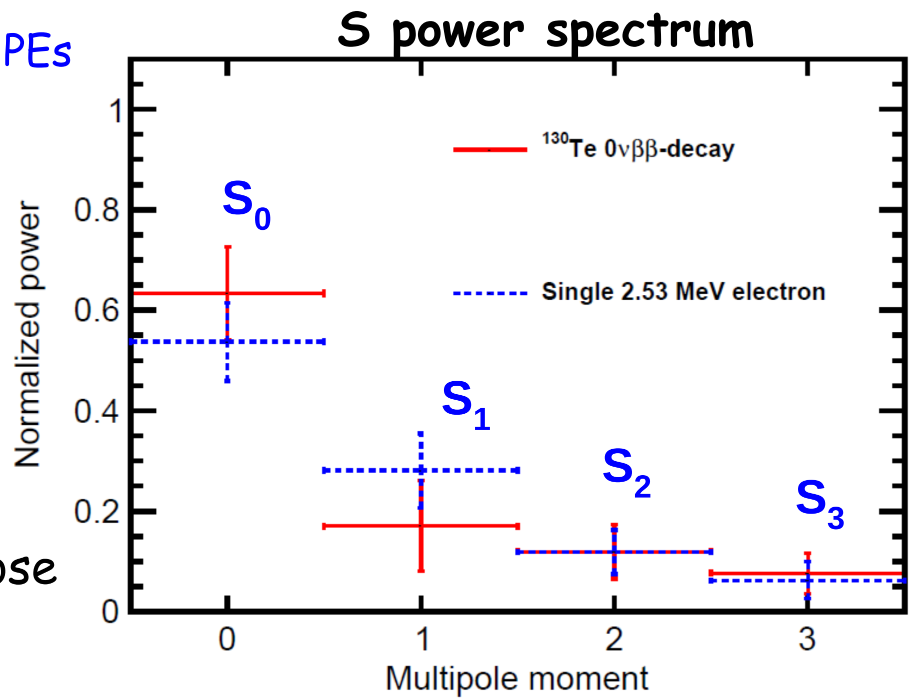
# Early Light Topology

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



Cherenkov PEs

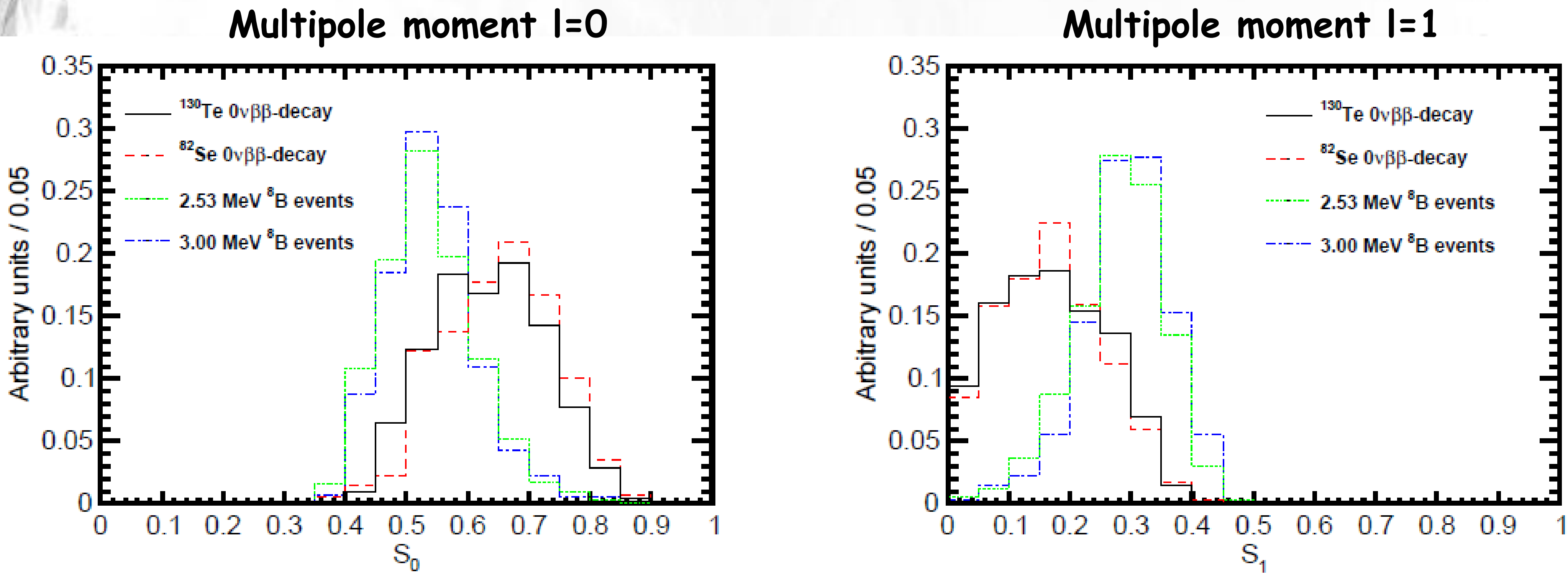
Scintillation PEs



## Why spherical harmonics?

- Spherical harmonics analysis is a natural and "easy" choice for a spherical detector
- Advanced machine learning techniques will do even better
- Understanding of requirements on hardware components is now a much higher priority – those are hard to change once the detector is built

# 0νββ vs $^8$B

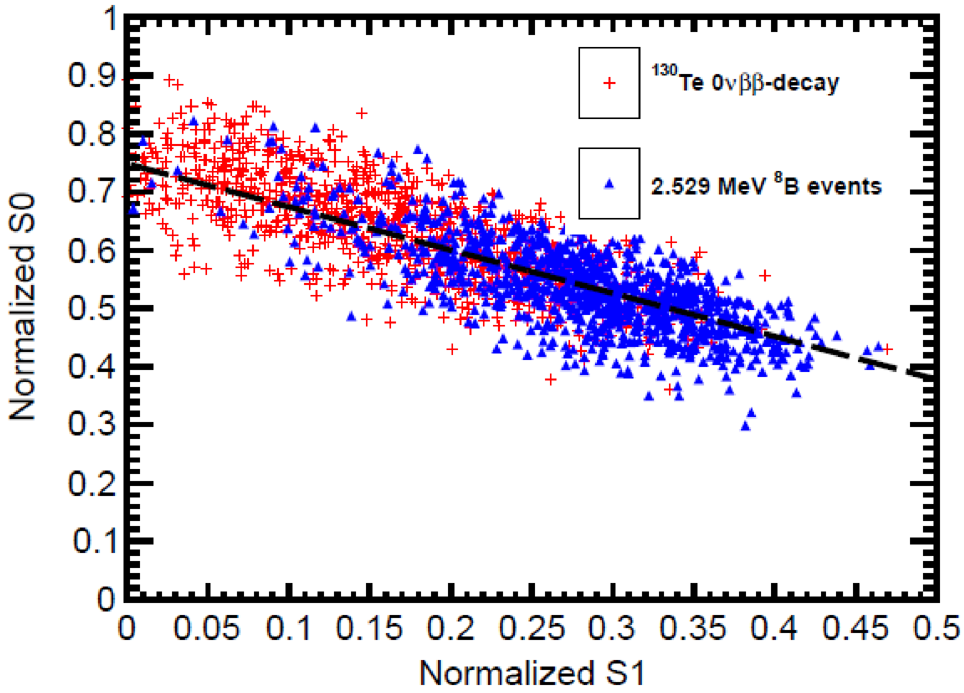


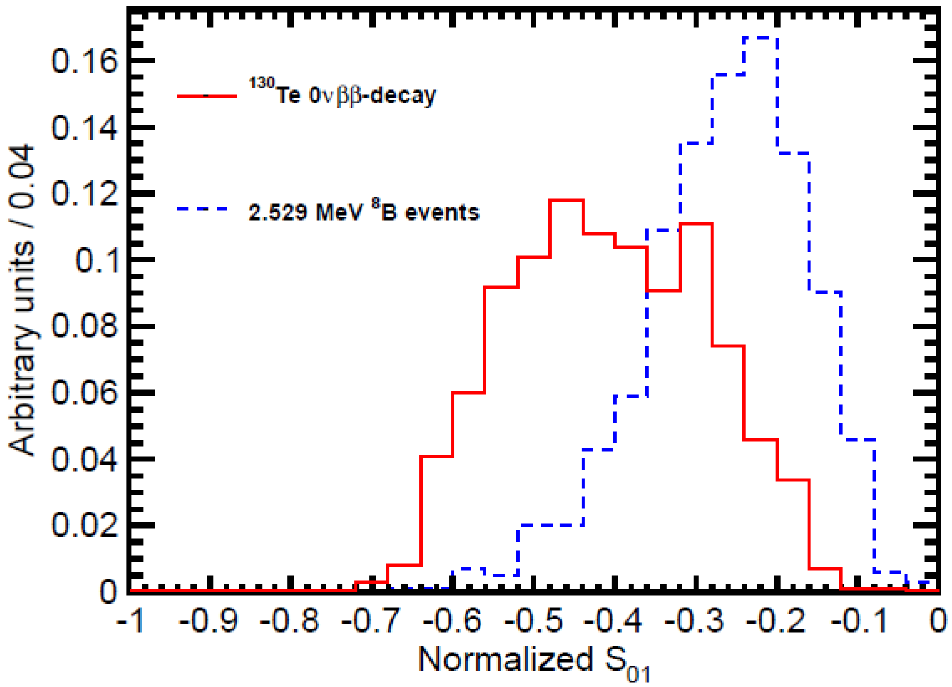
## Simulation details:

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

# 0νββ vs $^8$B

Ideal vertex, **central events** only
Scintillation rise time **1 ns**





## Key parameters determining separation of 0νββ-decay from $^8$B

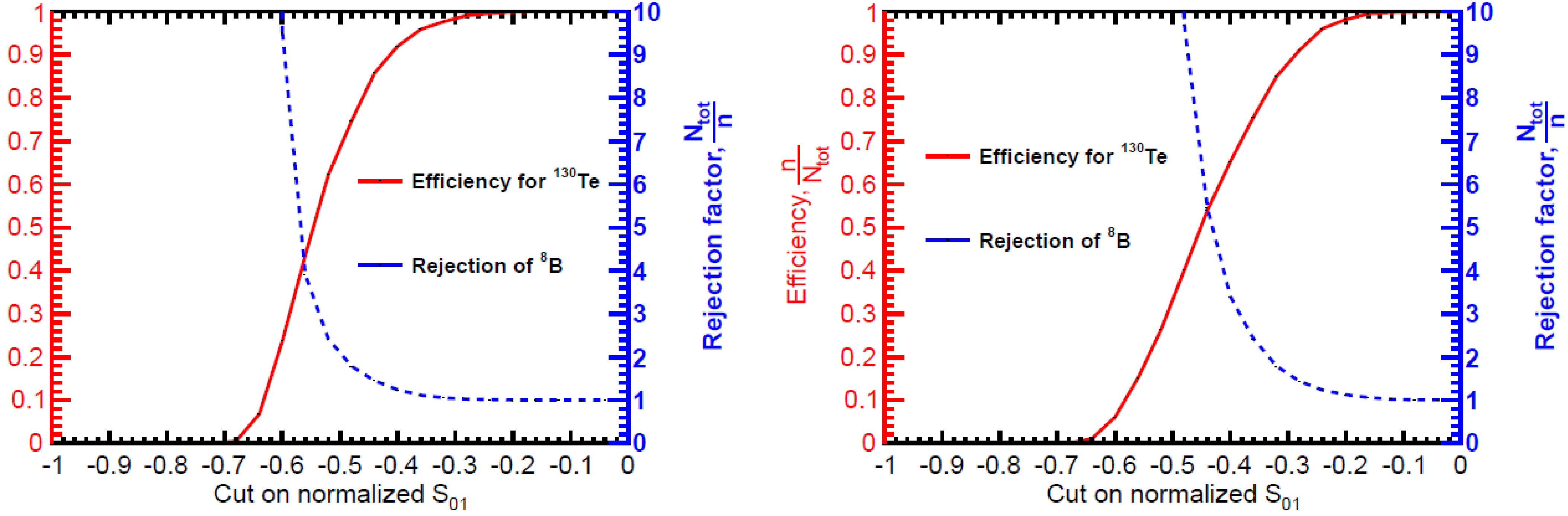
- Scintillator properties (narrow spectrum, slow rise time)
- Photo-detector properties (fast, large-area, high QE, red-sensitive)

# $0\nu\beta\beta$ vs $^8B$

For details see NIM A849 (2017) 102

Vertex res **5cm**, events within **R<3m**
Scintillation rise time **1 ns**

Vertex res **5cm**, events within **R<3m**
Scintillation rise time **5 ns**



Background rejection factor = 2
@ 70% signal efficiency

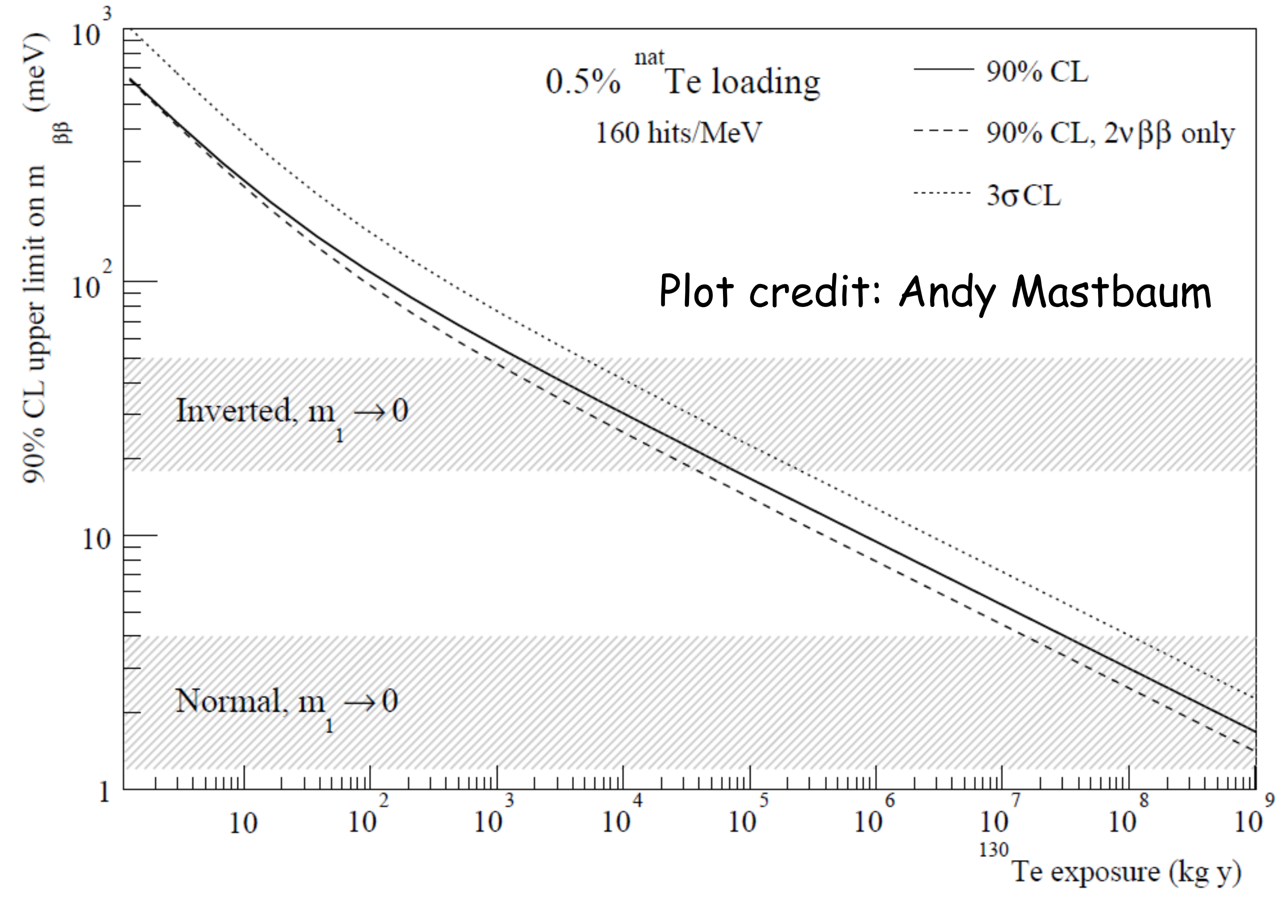
Background rejection factor = 3
@ 70% signal efficiency

Other backgrounds (gammas, alphas, $^{10}C$, etc) also have distinct topologies
Event reconstruction in liquid scintillator would enable new opportunities

# THEIA

Potential for 0νββ-decay search

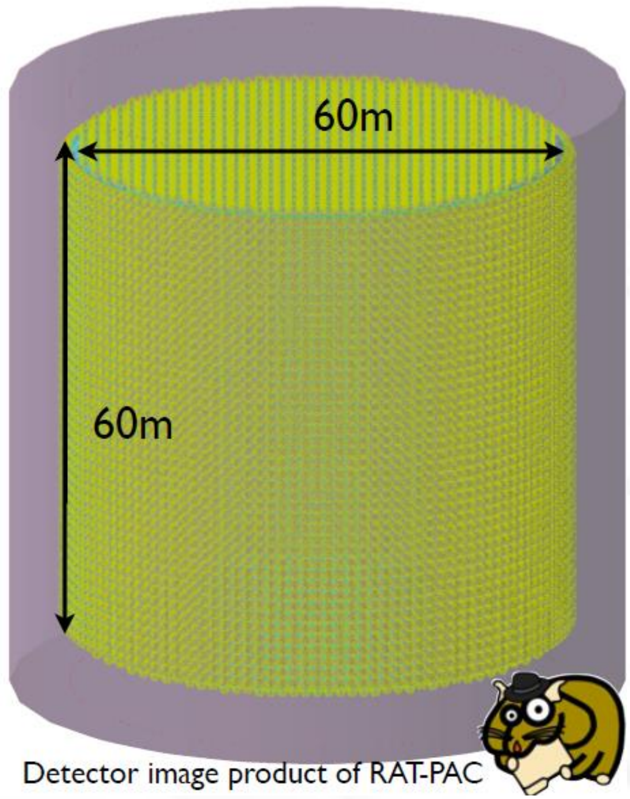
- 50kt detector
- 50% reduction of $^{8}$B
- 0.5% $^{nat}$Te loading
- 50t $^{130}$Te after fiducial cuts
- 15 meV after 10 years



Plot credit: Andy Mastbaum

Multipurpose detector
(including neutrino oscillation physics)

Concept paper - arXiv:1409.5864



Detector image product of RAT-PAC

Illustration from a presentation by Gabriel Orebi Gann

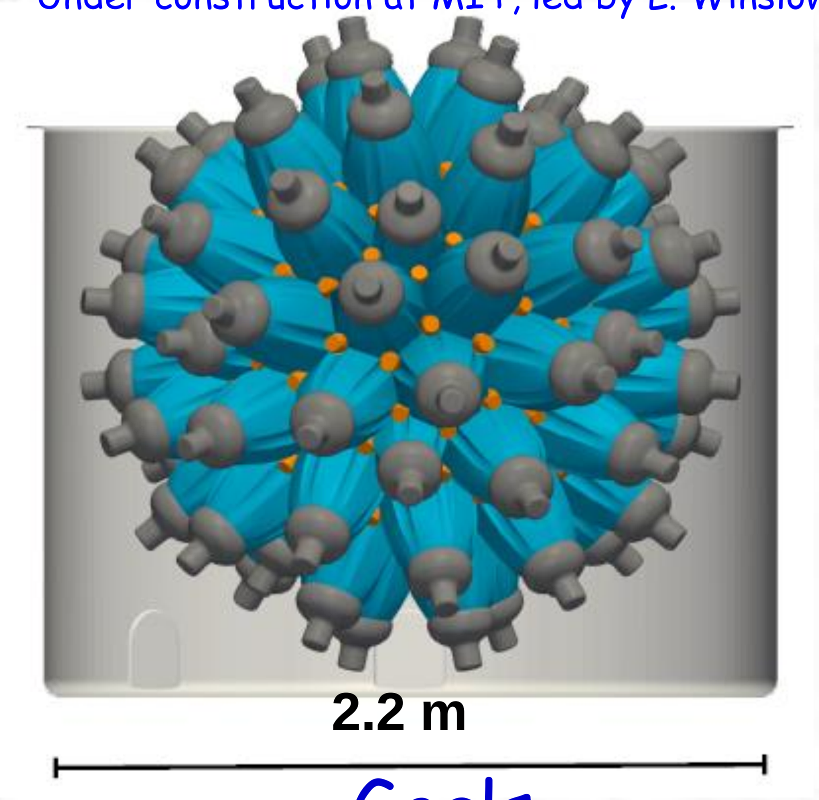
Broad detector R&D program to realize THEIA

# NuDot - Directional Liquid Scintillator

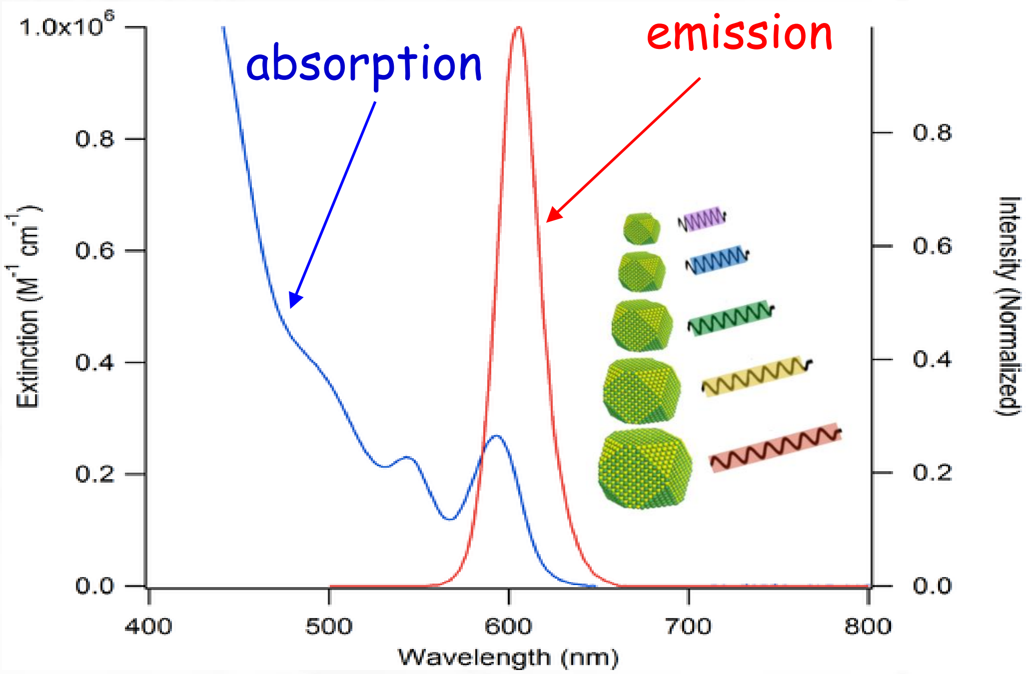
## R&D Towards Large Scale Detector

- 140 2" fast PMTs for timing
- 72 10" regular PMTs for energy resolution

Under construction at MIT, led by L. Winslow



## Q-dots



## Goals

- Demonstrate directionality and event topology reconstruction using che/sci separation by fast timing
  - ideally by measuring 2νββ-decay
- Study scintillators, including quantum dots

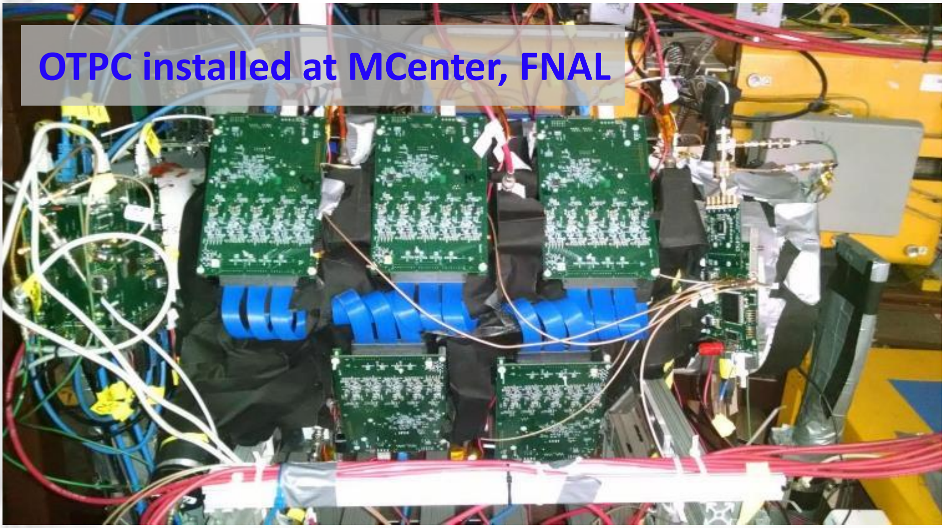
- Nanocrystals of CdS, CdSe, CdTe
- Interesting optical properties
- νββ-decay candidates
- Q-dots can be suspended in organic solvents and water
- In-depth R&D is needed to evaluate Q-dots potential

# Optical Tracking Demonstration

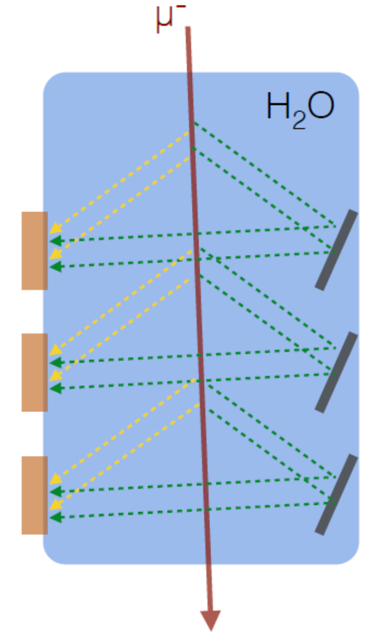
Eric Oberla PhD thesis

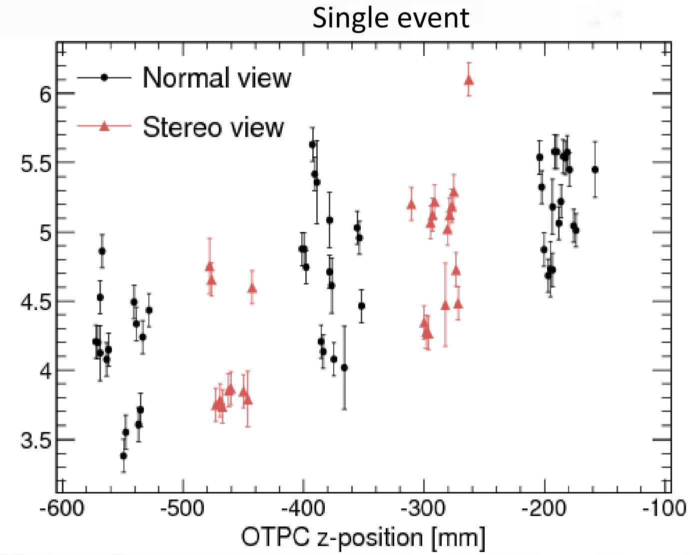
NIM A814 (2016) 19

## 180-channel PSEC4 system



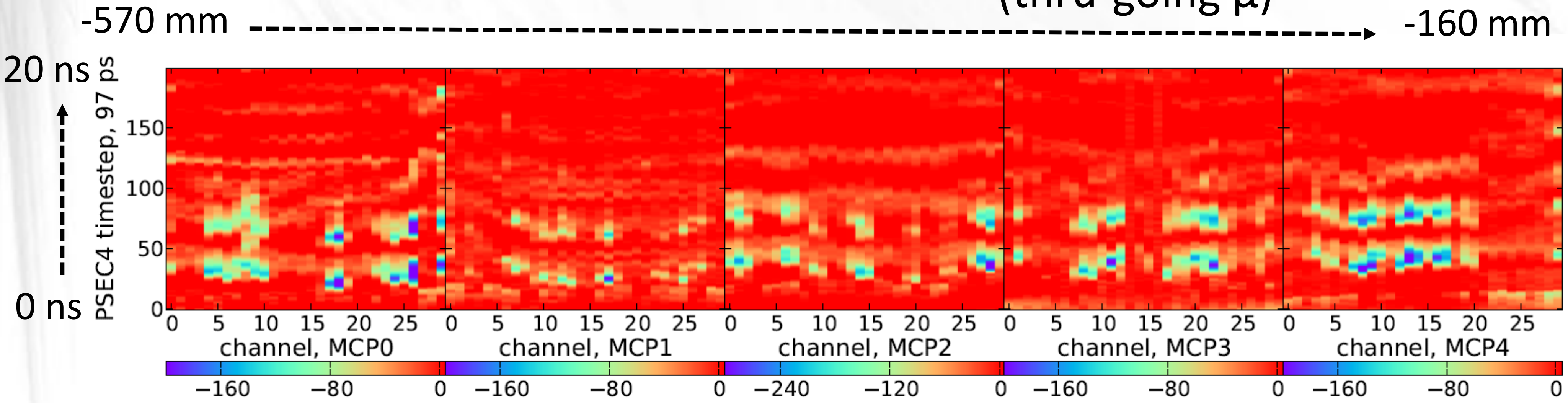
OTPC installed at MCenter, FNAL





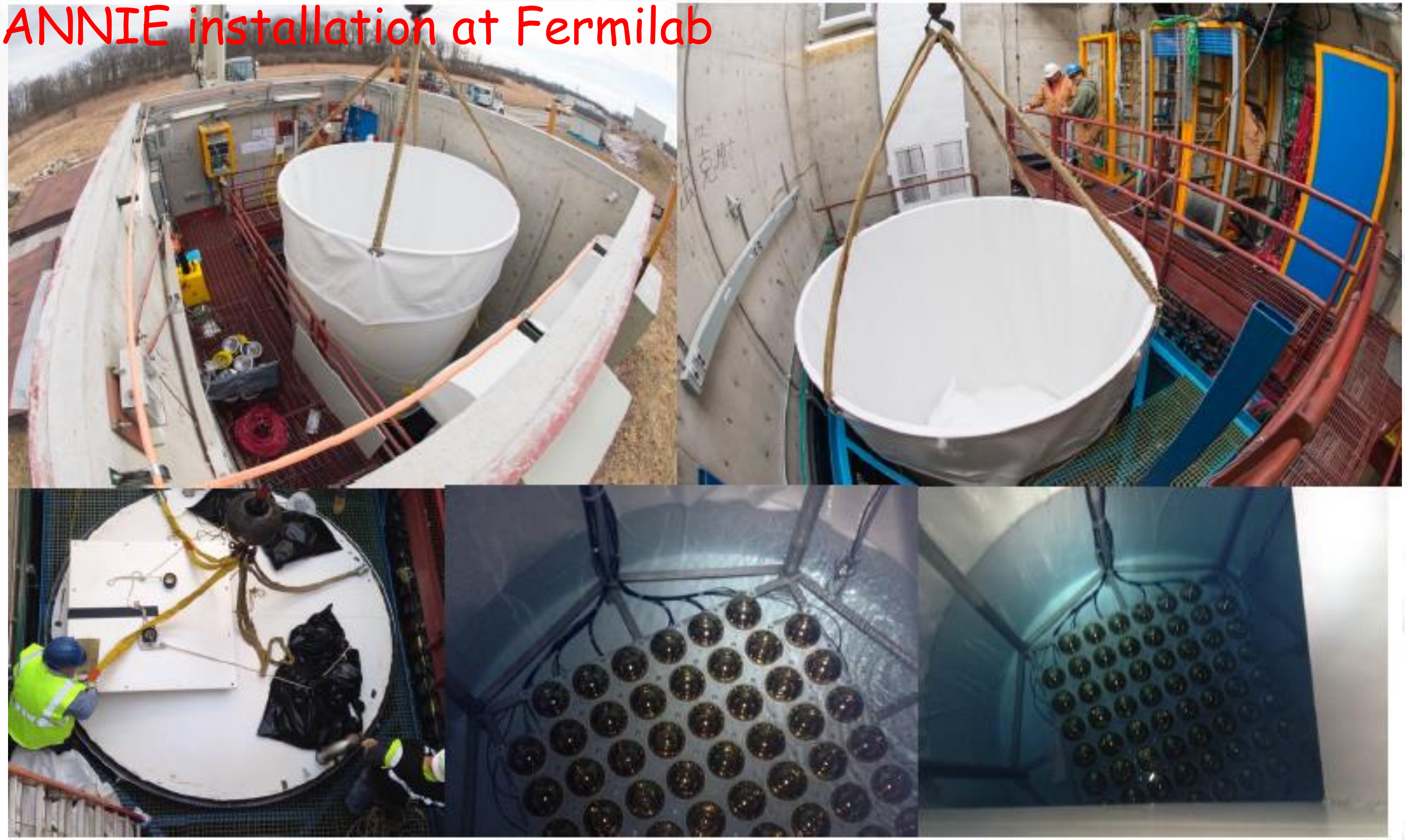
Example event

Typical event (thru-going μ)



# The ANNIE Experiment

- Measure neutron multiplicity in neutrino-nucleus interactions
- R&D towards water-based neutrino detection technology
- Explore optical tracking using novel photo-detectors



ANNIE installation at Fermilab

Data taking is ongoing

# Photo-Detector Options

MCP-PMT by Photonis:
Fast, but small…

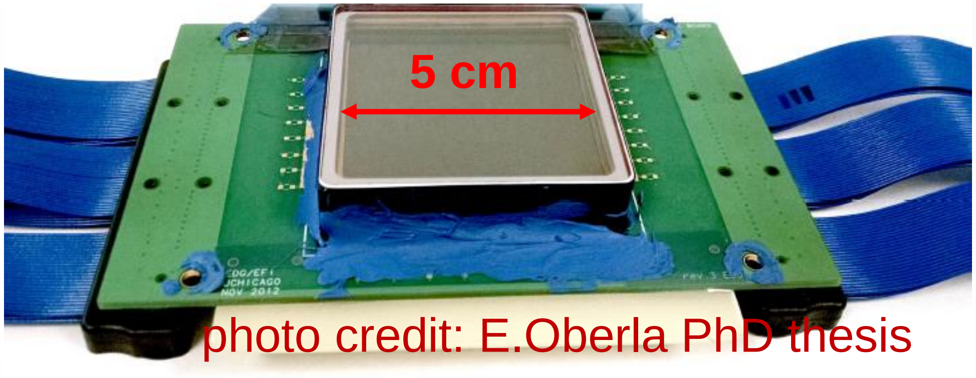


photo credit: E.Oberla PhD thesis

PMT by Hamamatsu
Large area, but slow…

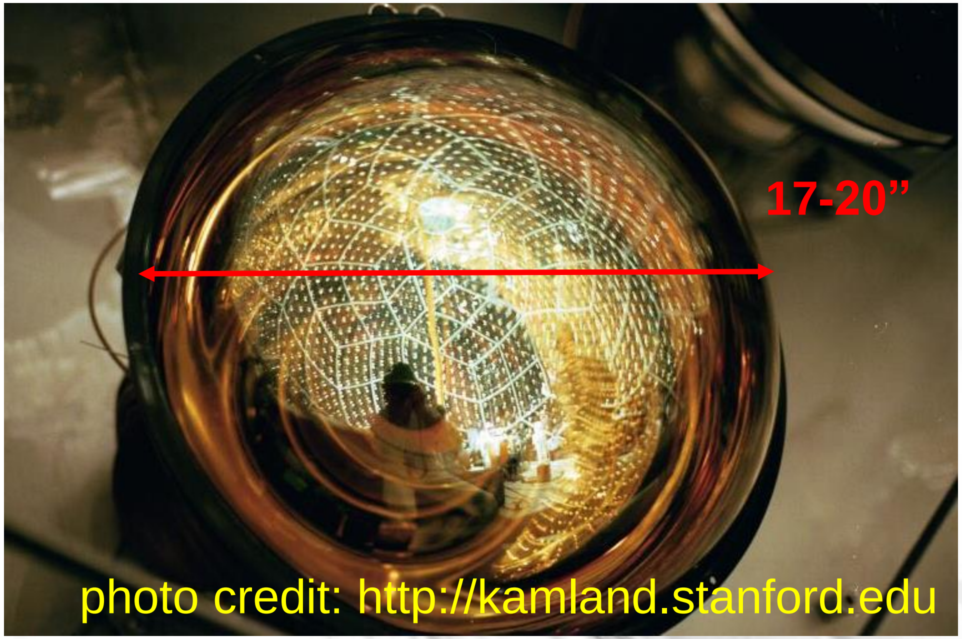
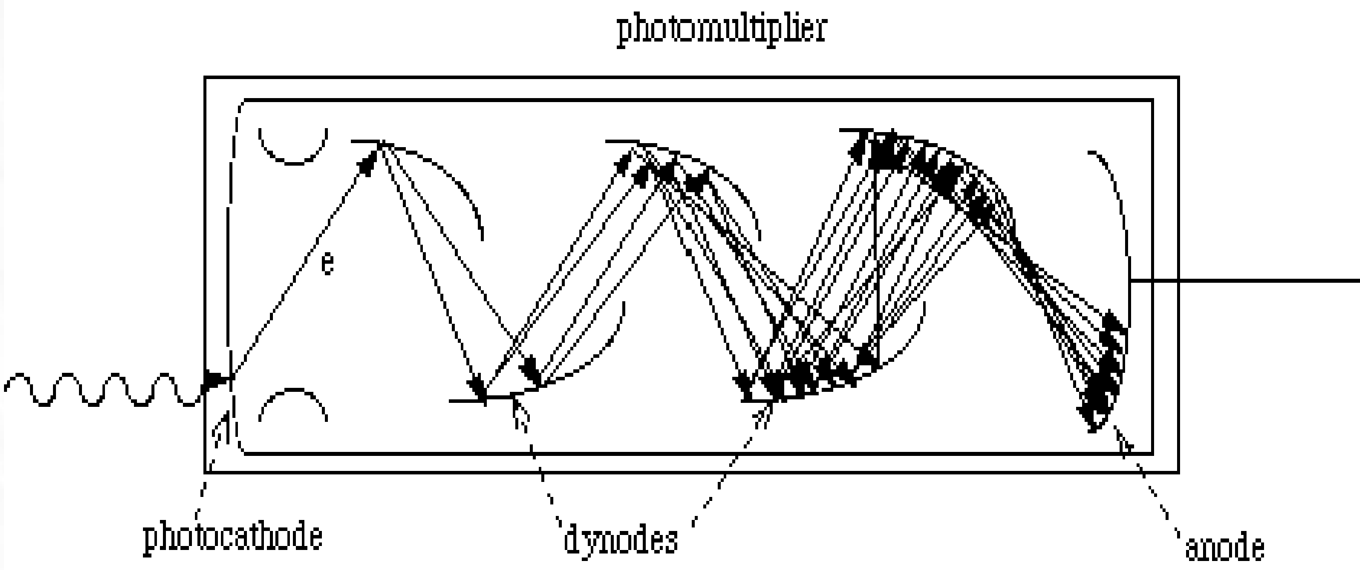


photo credit: http://kamland.stanford.edu

# 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



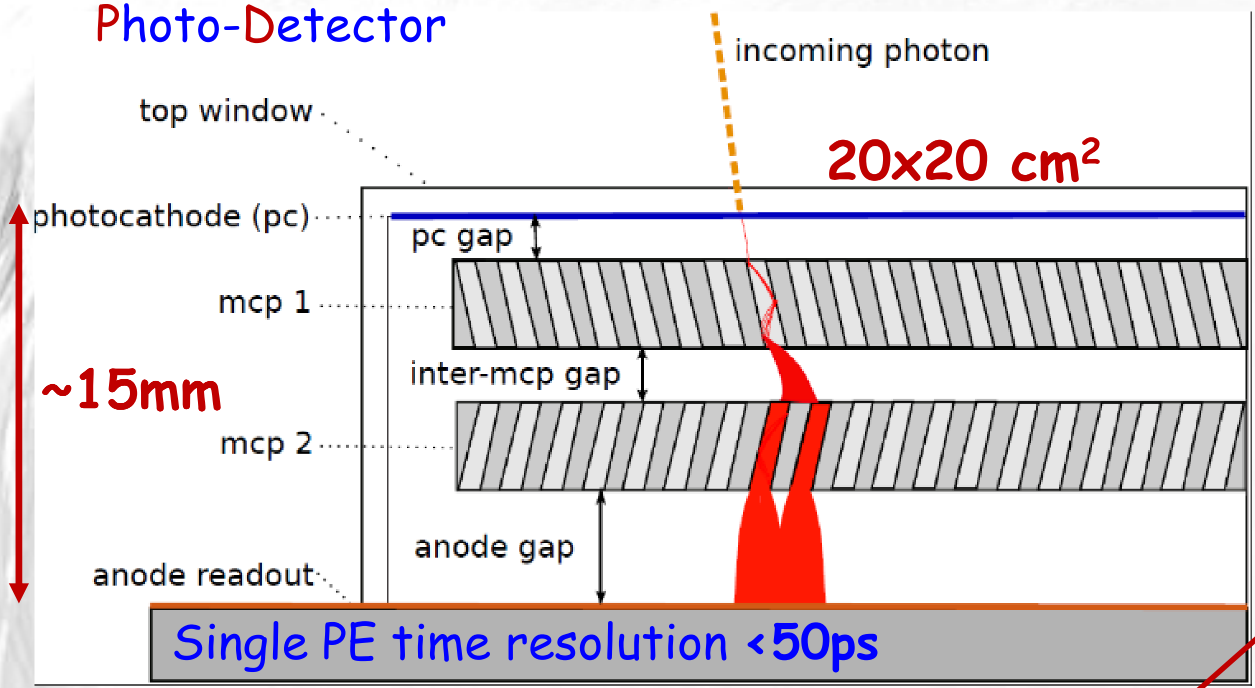
Uncertainty on the electron path causes uncertainty on the signal timing

The shorter the electron path the better the time resolution

No existing fast photo-detectors can cover large area at a reasonable cost

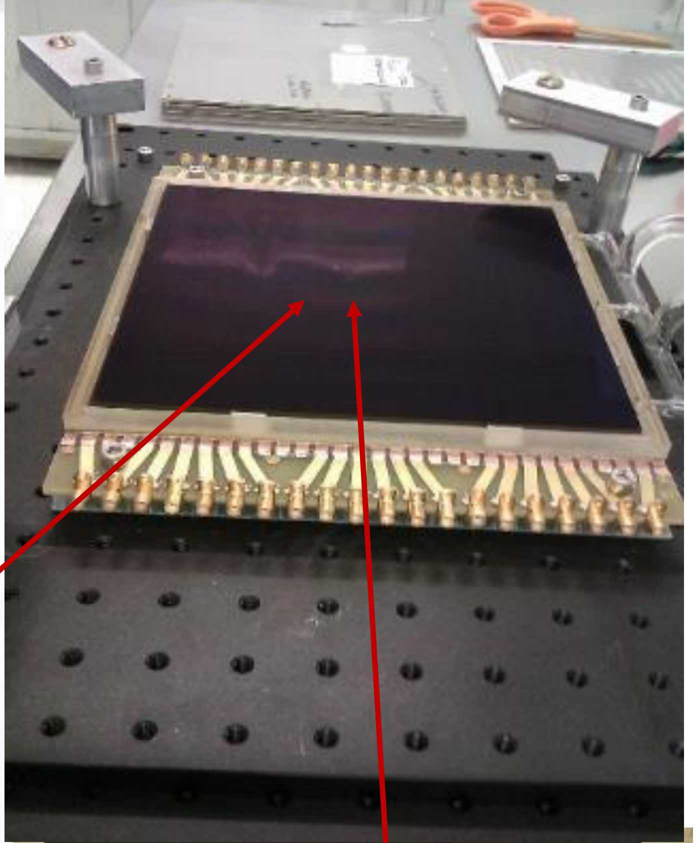
# LAPPD™

## Large-Area Picosecond Photo-Detector



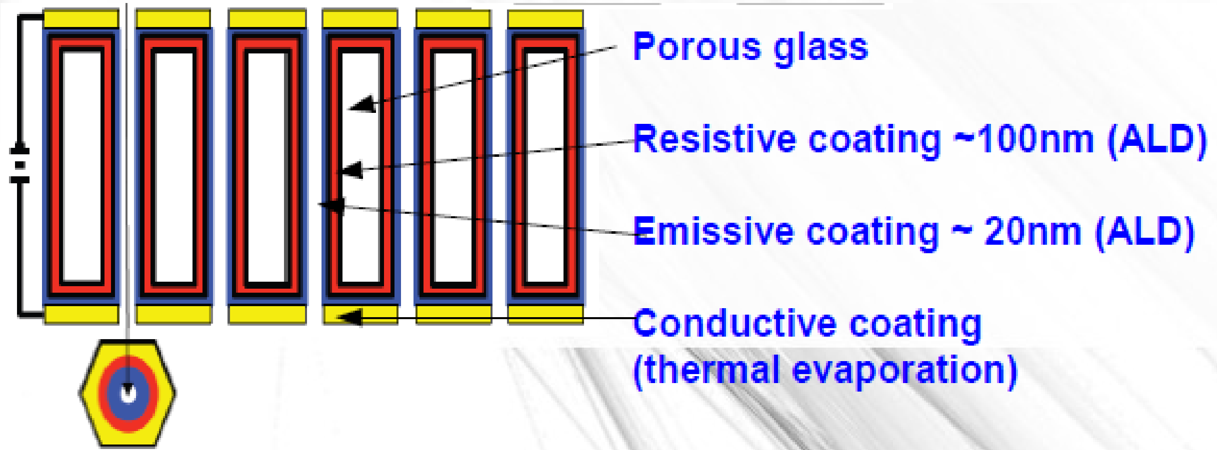
Single PE time resolution <**50ps**

## 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)



**Porous glass**

**Resistive coating ~100nm (ALD)**

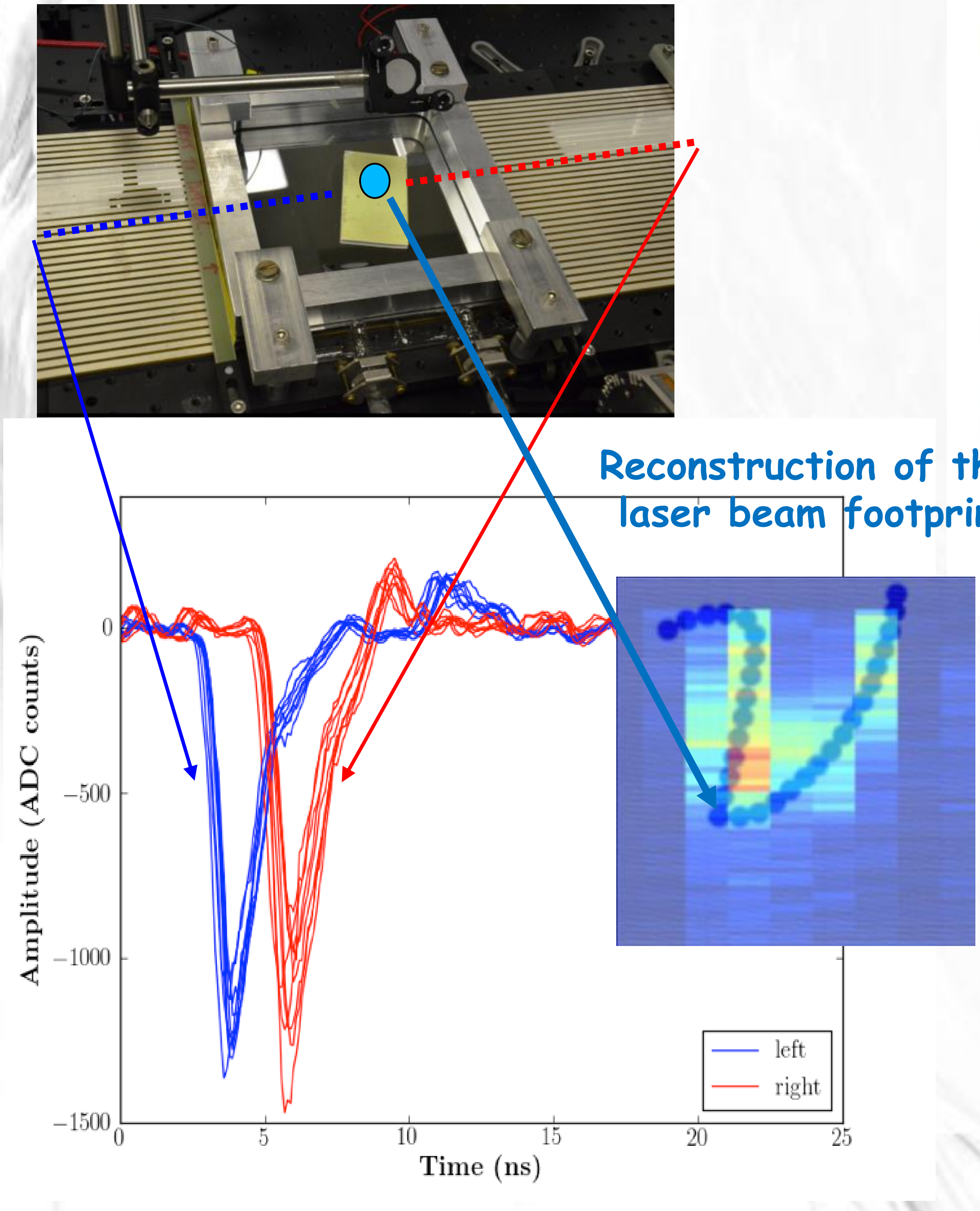
**Emissive coating ~ 20nm (ALD)**

**Conductive coating (thermal evaporation)**

## Micro-Capillary Arrays by Incom Inc.

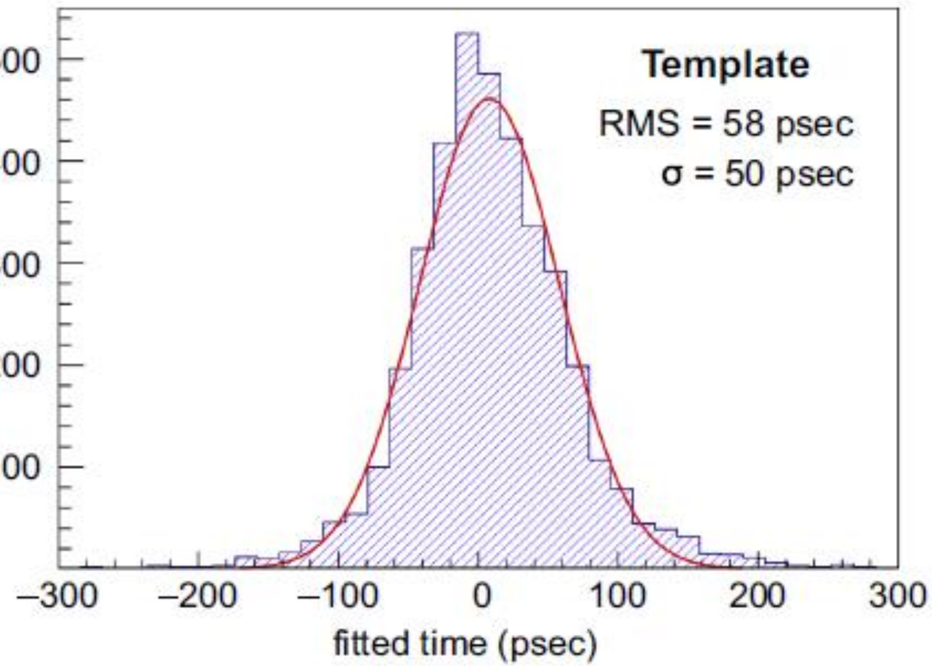
- Material: borofloat glass
- Area: 8x8″
- Thickness: 1.2mm
- Pore size: 20 μm
- Open area: 60-80%

# LAPPD Prototype Testing Results



Reconstruction of the laser beam footprint

Single PE resolution



Demonstrated characteristics:

single PE timing ~50ps

multi PE timing ~35 ps

differential timing ~5 ps

position resolution < 1 mm

gain >$10^7$

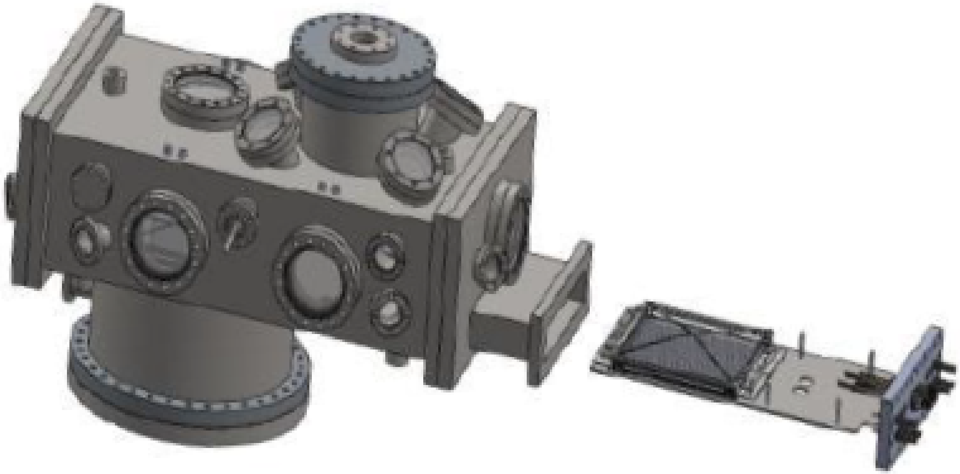
RSI 84, 061301 (2013),
NIMA 732, (2013) 392
NIMA 795, (2015) 1

**See arXiv:1603.01843 for a complete LAPPD bibliography**

# LAPPD™ Commercialization

## Incom V2.0 LAPPD Integration & Sealing

### Process & Hardware



**Process:**

- UHV - with Conflat seals, scroll, turbo and ion pump.
- Tile kit components pre-assembled & locked in place .
- Baked to low $10^{-10}$ torr range
- In-tank operation of tile / scrubbing
- Window Transfer Process
- Multi-alkali Photocathode deposited on underside of window.
- Hot Indium Seal - with grooved sidewalls

**Hardware:**

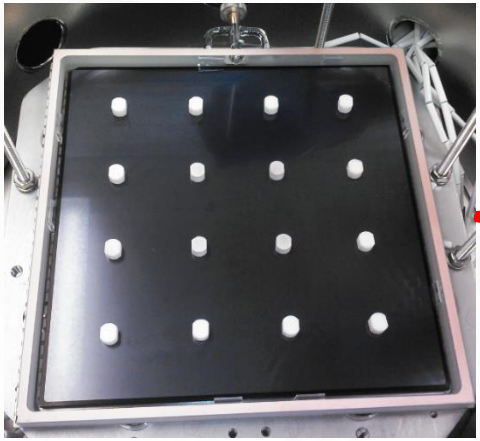
- Single "Fully Bakeable" Chamber: 30"L X 16"W X 8"H
- Simple window transfer between photocathode deposition & sealing.
- Electrical interconnects for in-process monitoring
- Readily expandable for volume production

Slide courtesy of Incom Inc.

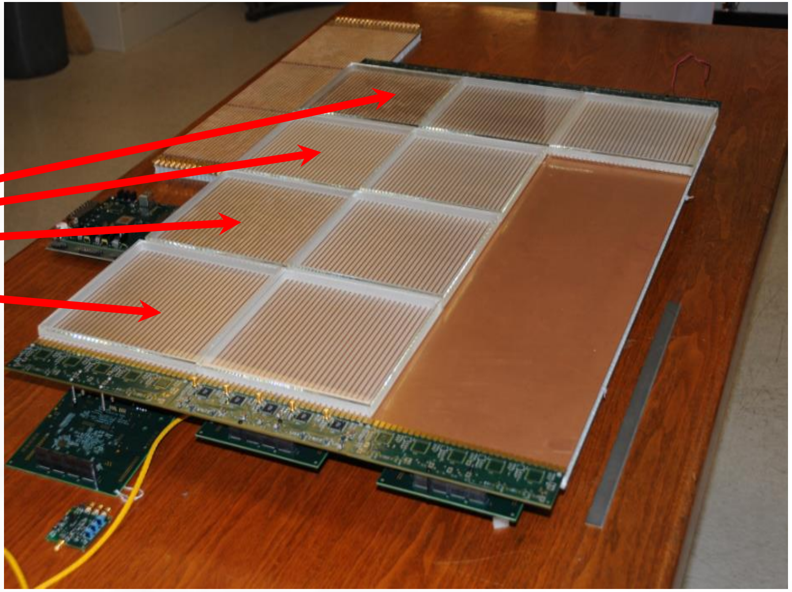
# Goal of the R&D Effort at UChicago

<u>Affordable</u> large-area many-pixel photo-detector systems with picosecond time resolution

LAPPD module 20x20 cm$^2$



Example of a Super Module



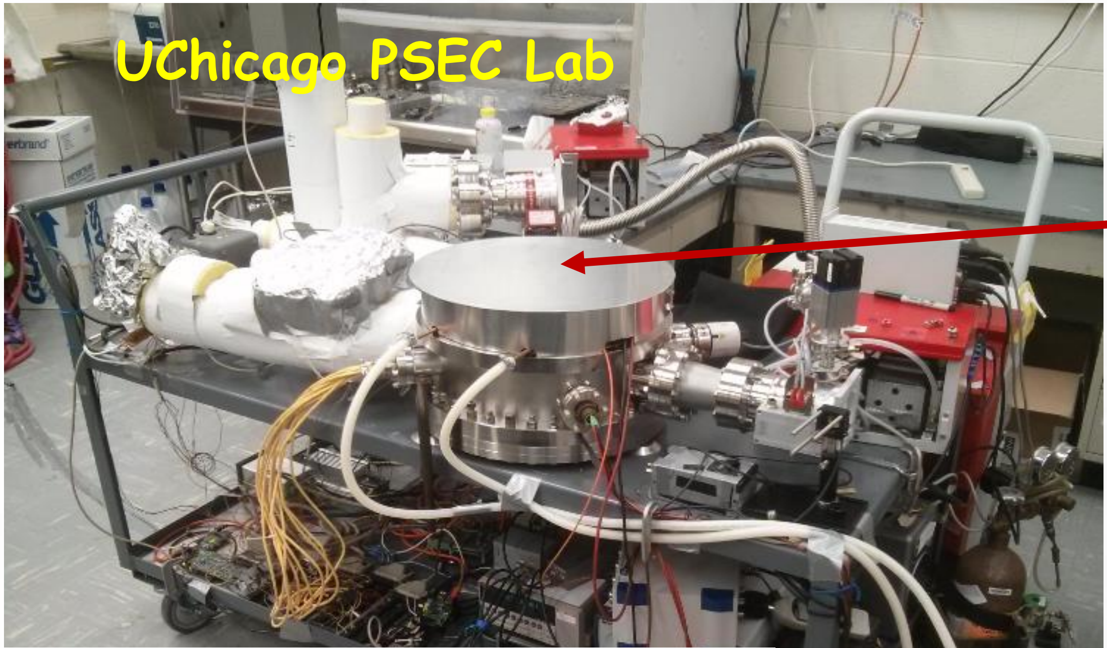
- High volume production can be challenging for vacuum transfer process
- We are exploring if a *<u>non-vacuum transfer</u>* process can be inexpensive and easier to scale for a very high volume production

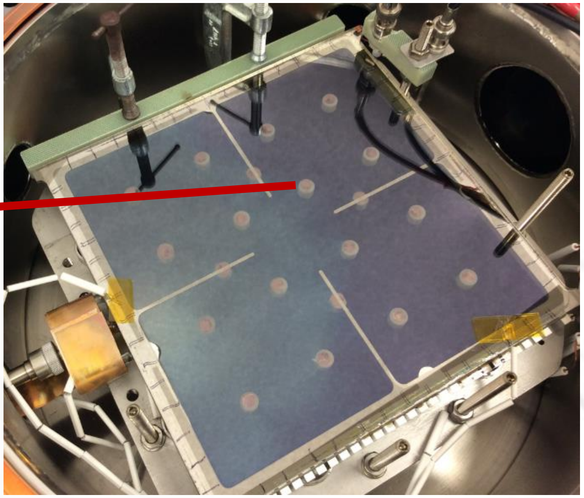
UChicago goal is to enable high volume production at Incom so that LAPPD$^{TM}$ become available for HEP community

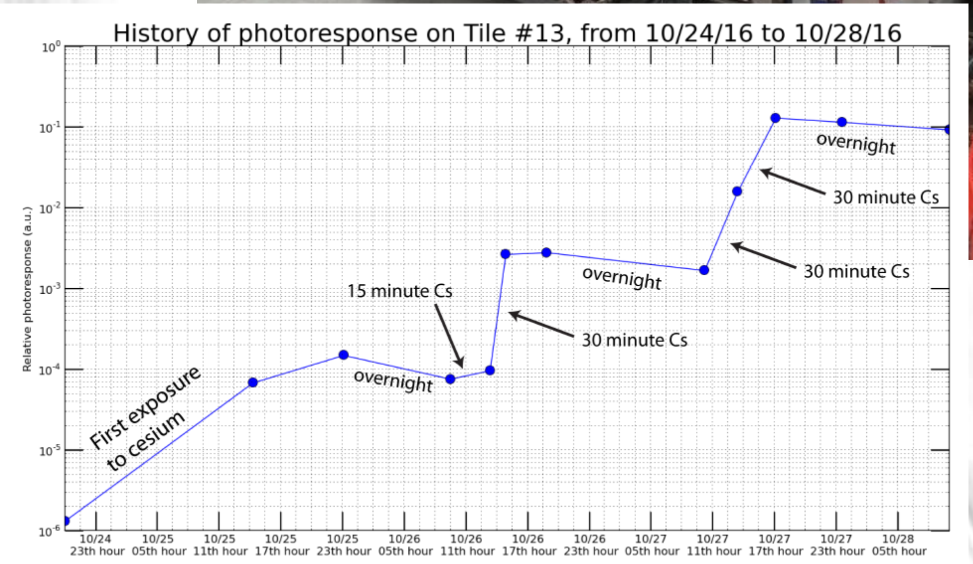
Production rate of 50 LAPPDs/week would cover 100 m$^2$ in one year

# In-Situ LAPPD Fabrication

Simplify the assembly process by avoiding vacuum transfer:
make photo-cathode after the top seal
(PMT-like batch production)







**Heat only the tile
not the vacuum vessel**

***Intended for
parallelization***

# In-Situ Assembly Facility UChicago

The idea is to achieve volume production by operating many small-size vacuum processing chambers at the same time

UChicago PSEC Lab

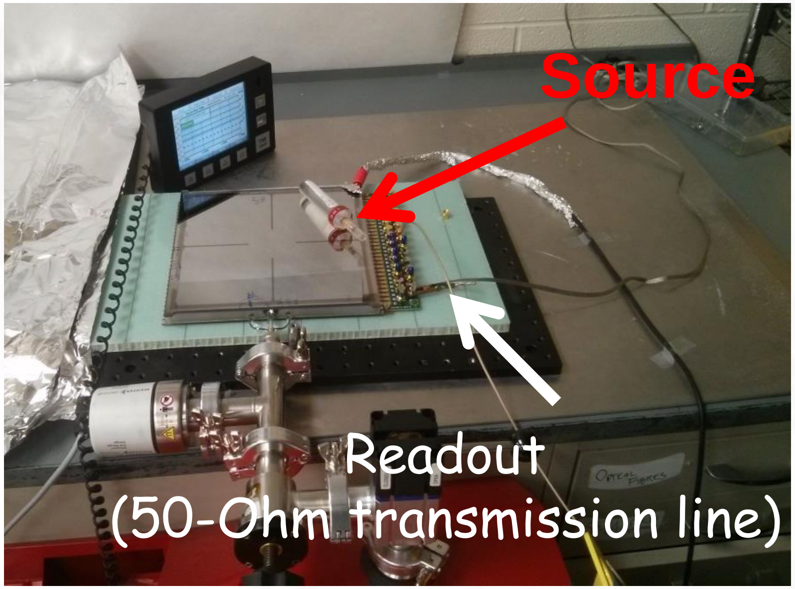
Looking forward towards transferring the in-situ process to industry

# First Signals from an In-Situ LAPPD

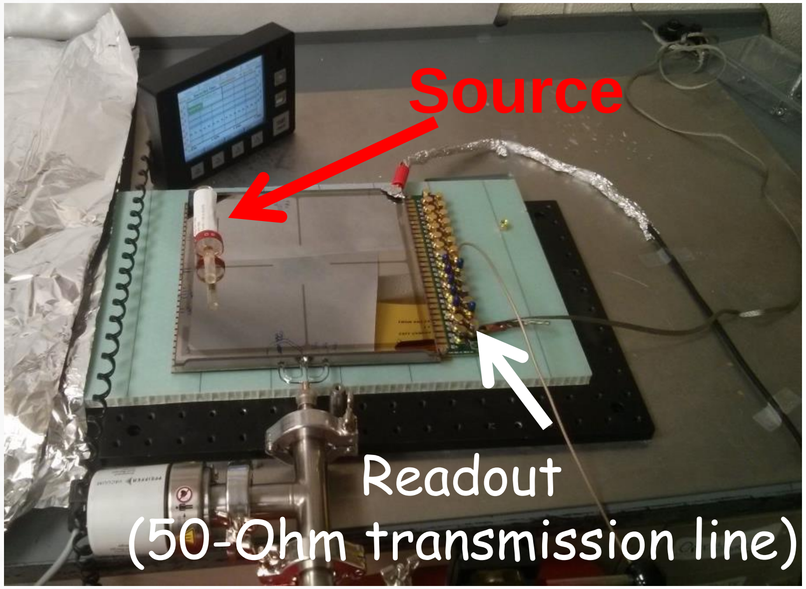
April, 2016

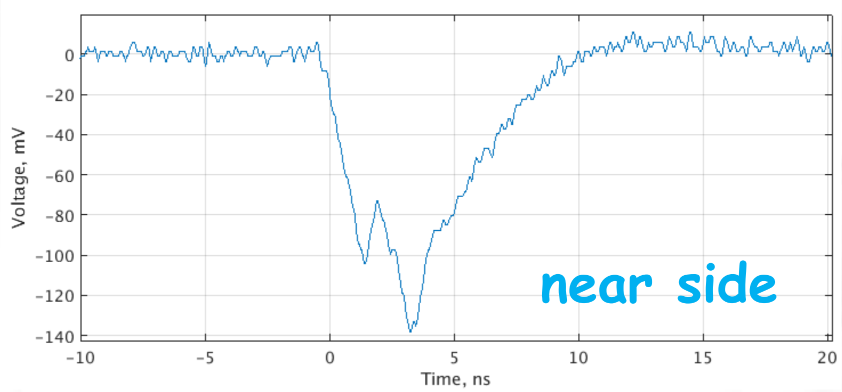
(Sb cathode)

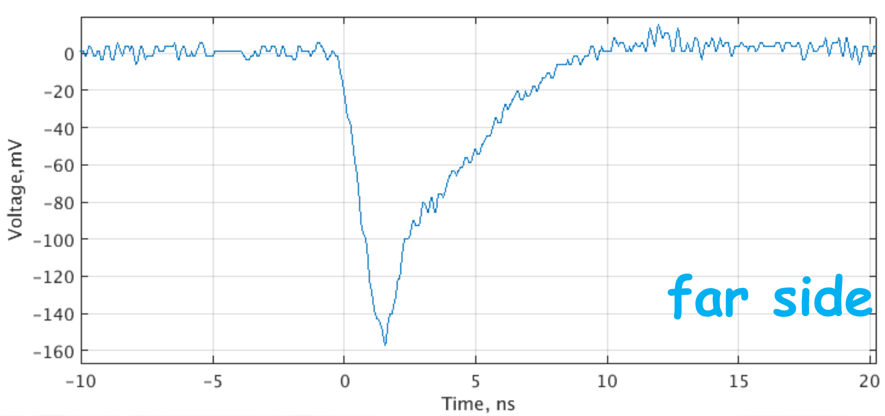
Near side: reflection from unterminated far end



Far side: reflection is superimposed on prompt





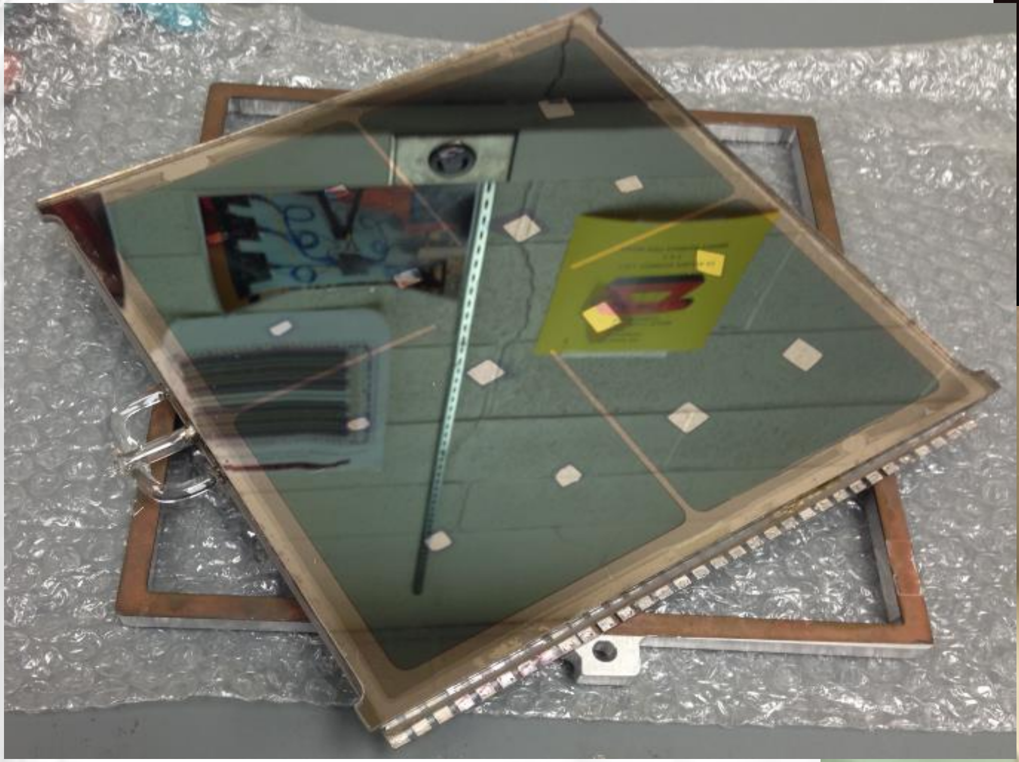


The tile is accessible for QC before photo-cathode shot
This is helpful for the production yield

# First Sealed In-Situ LAPPD

August 18, 2016

($Cs_3Sb$ photo-cathode)

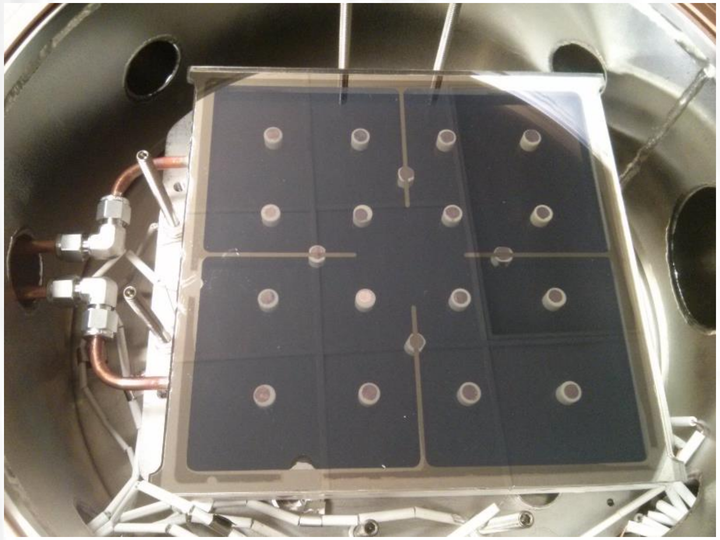


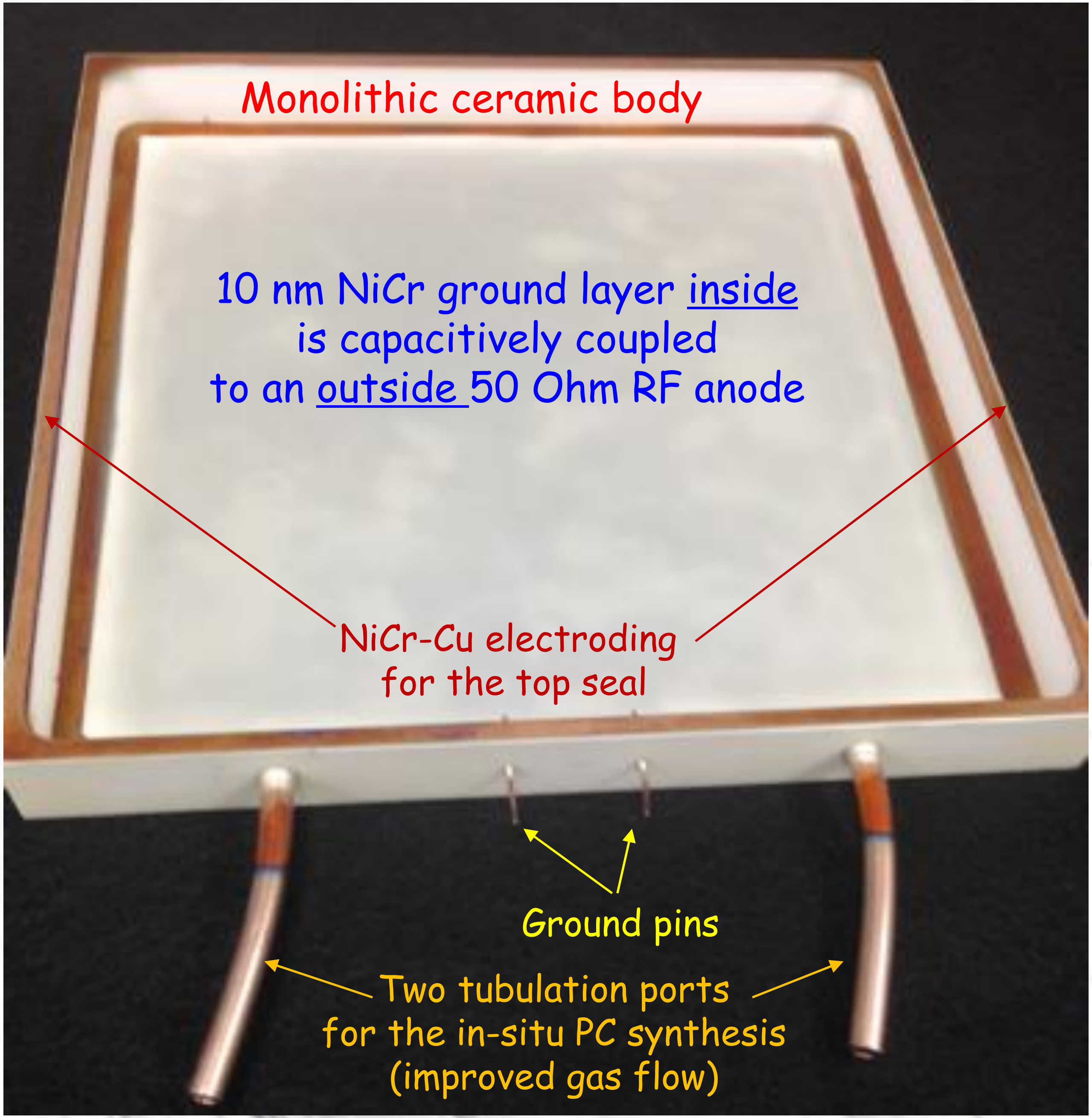
Flame seal by
J.Gregar, Argonne

# Gen-II LAPPD

- Robust ceramic body
- Anode is not a part of the vacuum package
- Enables fabrication of a generic tile for different applications
- Compatible with in-situ and vacuum transfer assembly processes

January, 2017





Monolithic ceramic body

10 nm NiCr ground layer inside is capacitively coupled to an outside 50 Ohm RF anode

NiCr-Cu electroding for the top seal

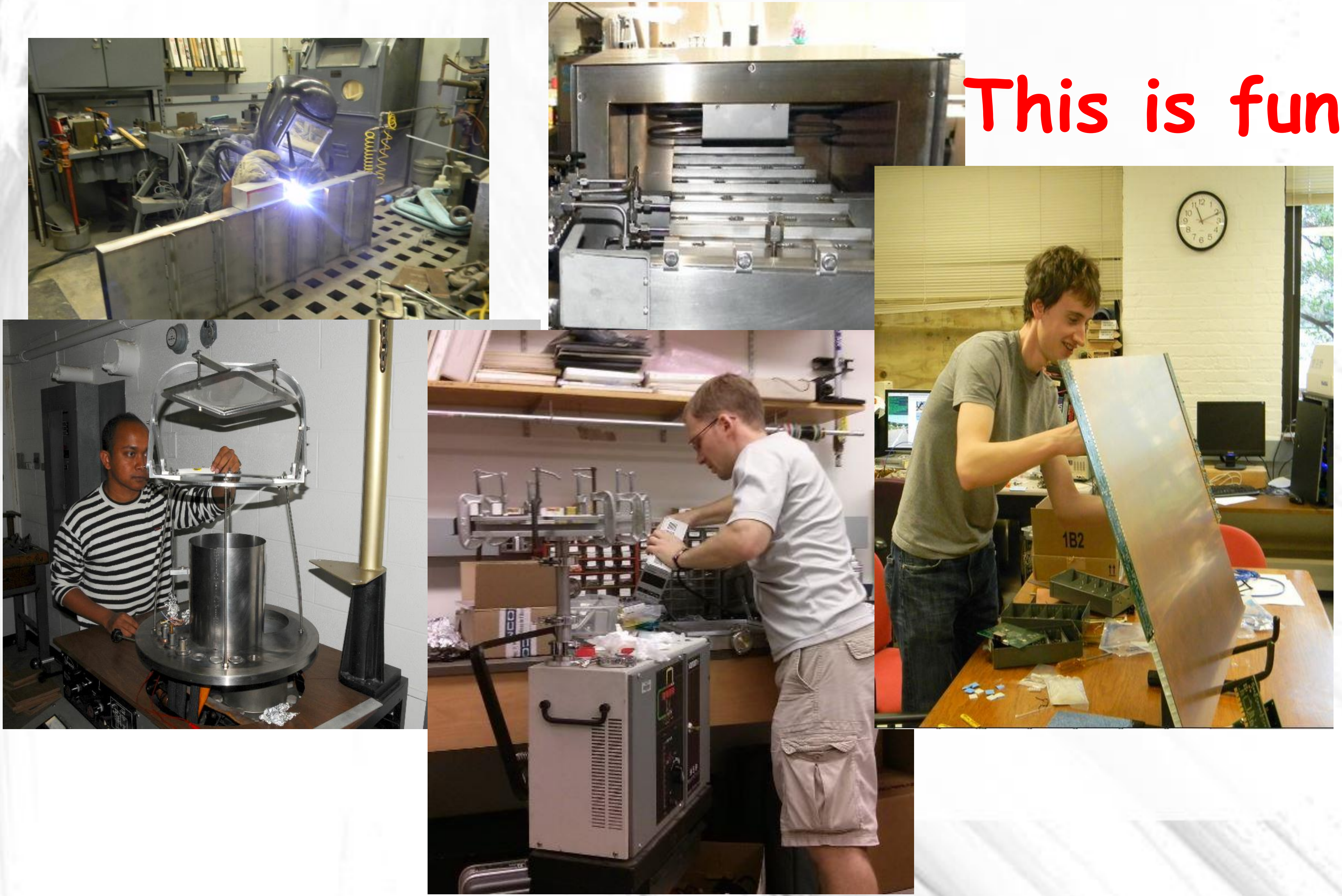
Ground pins

Two tubulation ports for the in-situ PC synthesis (improved gas flow)

Joint effort with Incom Inc. via DOE SBIR

# Lots of Hands On Experience

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



This is fun!

# Take Away Messages

Dirac/Majorana nature of the neutrino is a fundamental question

Search for $0\nu\beta\beta$-decay is the most feasible approach to answer this question

Very large detector mass (kilo-ton) is required to probe small $m_{\beta\beta}$

$^{8}$B solar neutrinos become dominant background - traditionally viewed as irreducible

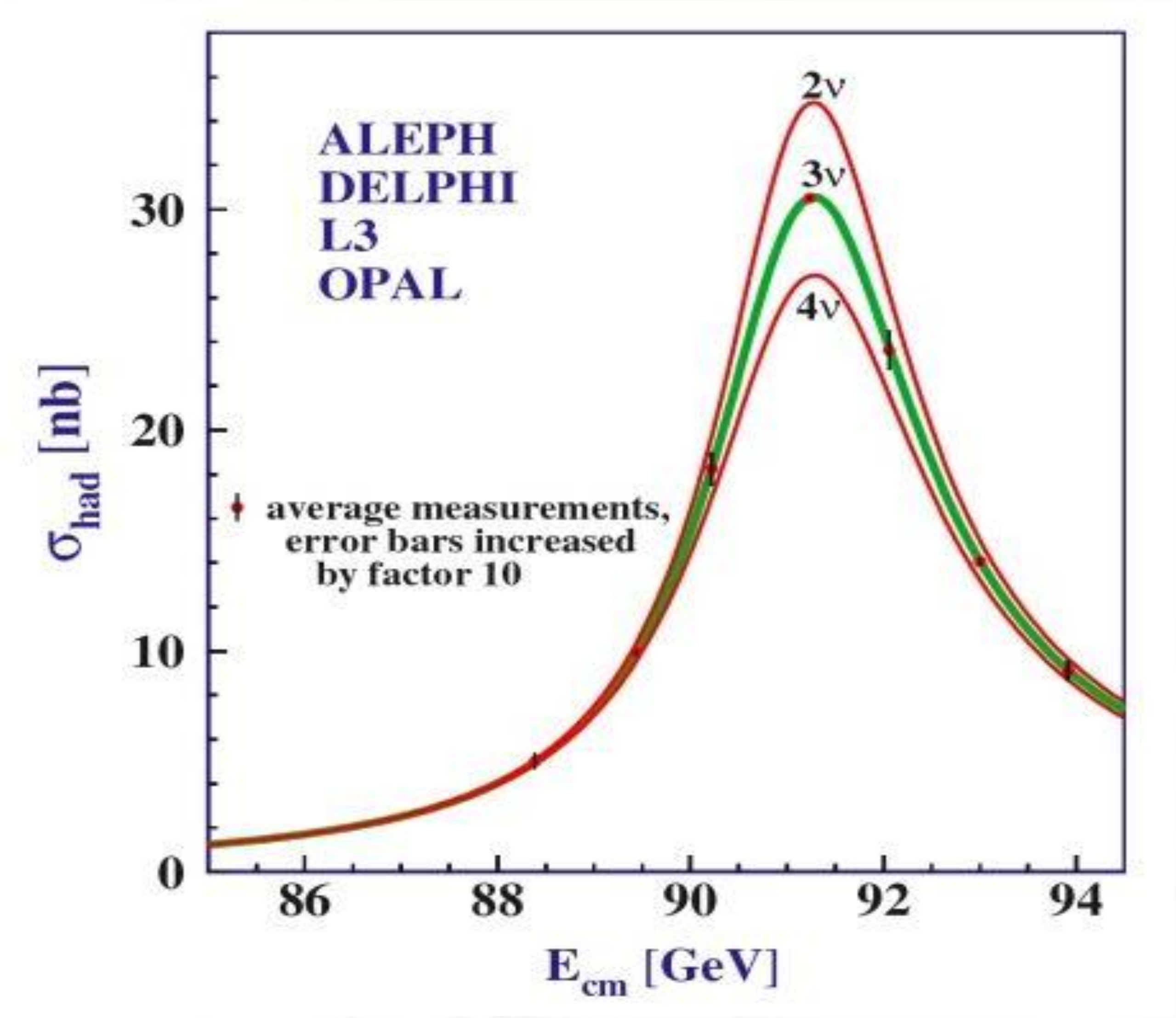
Directionality and event topology provide handles on $^{8}$B background

Detector R&D is ongoing to demonstrate event topology reconstruction using Cherenkov/scintillation light separation

Fast timing is critical and there has been lots of progress in the development of LAPPD™

# Thank You

# Only Three Flavors*



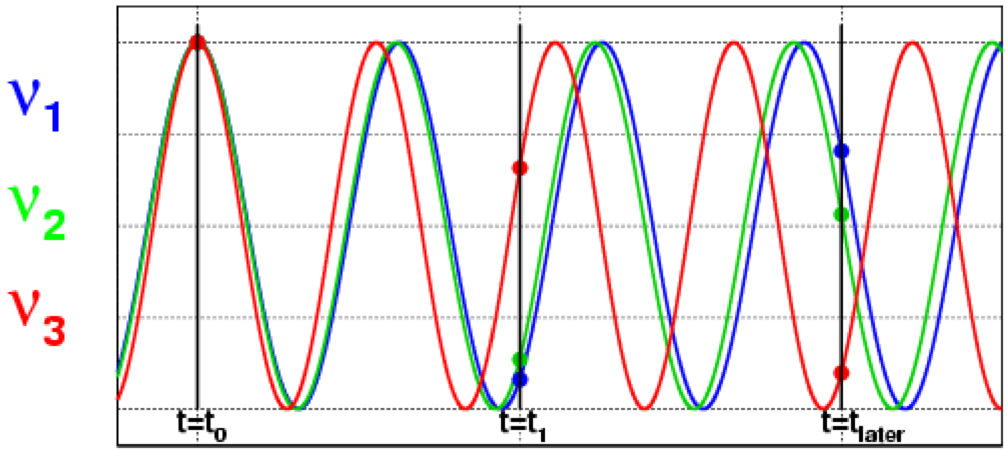
$N_\nu$ = 2.9840+- 0.0082

# Neutrino Mixing

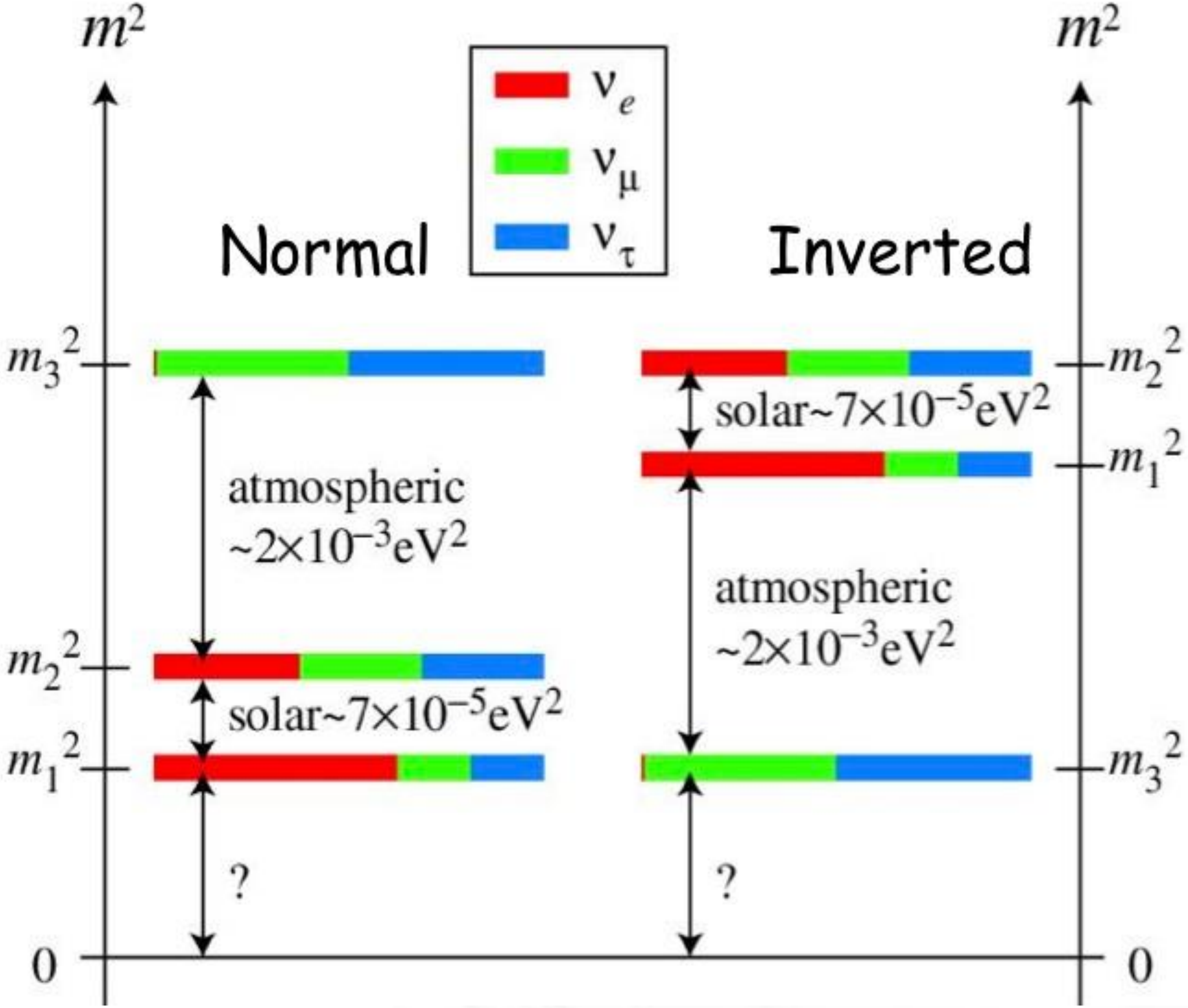
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

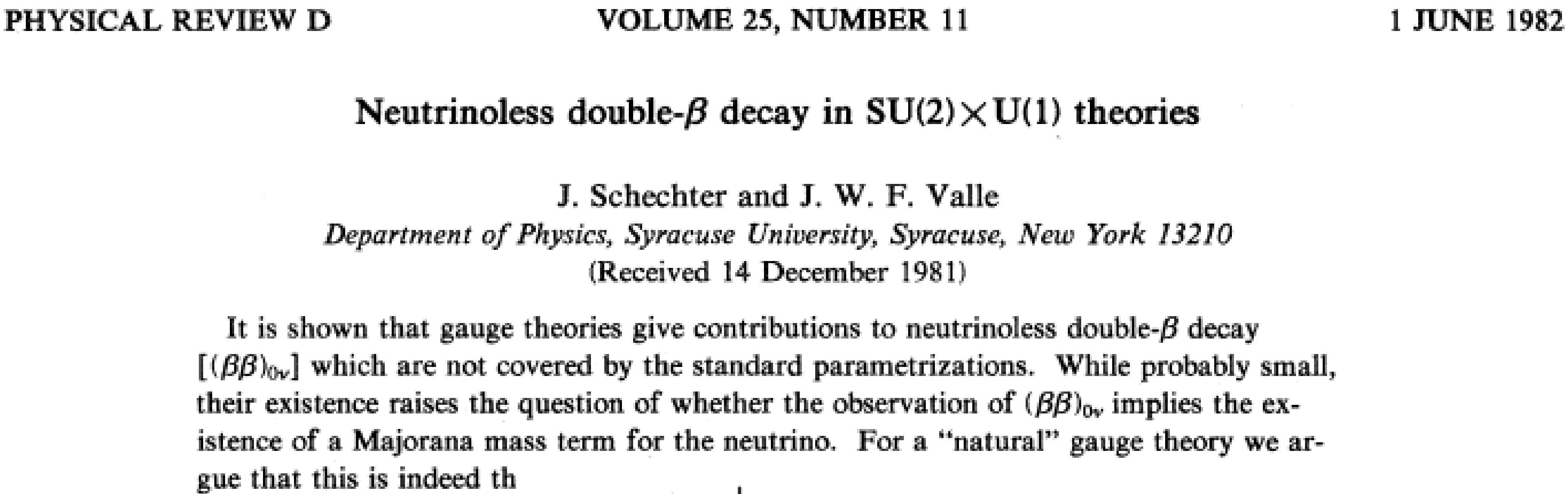
Flavor eigen states
(interaction)

Mass eigen states
(propagation)



# Neutrino Mass Hierarchy





PHYSICAL REVIEW D VOLUME 25, NUMBER 11 1 JUNE 1982

# Neutrinoless double-$\beta$ 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-$\beta$ 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

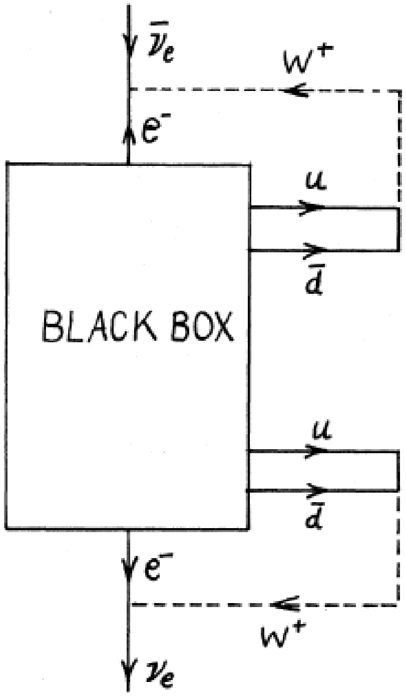
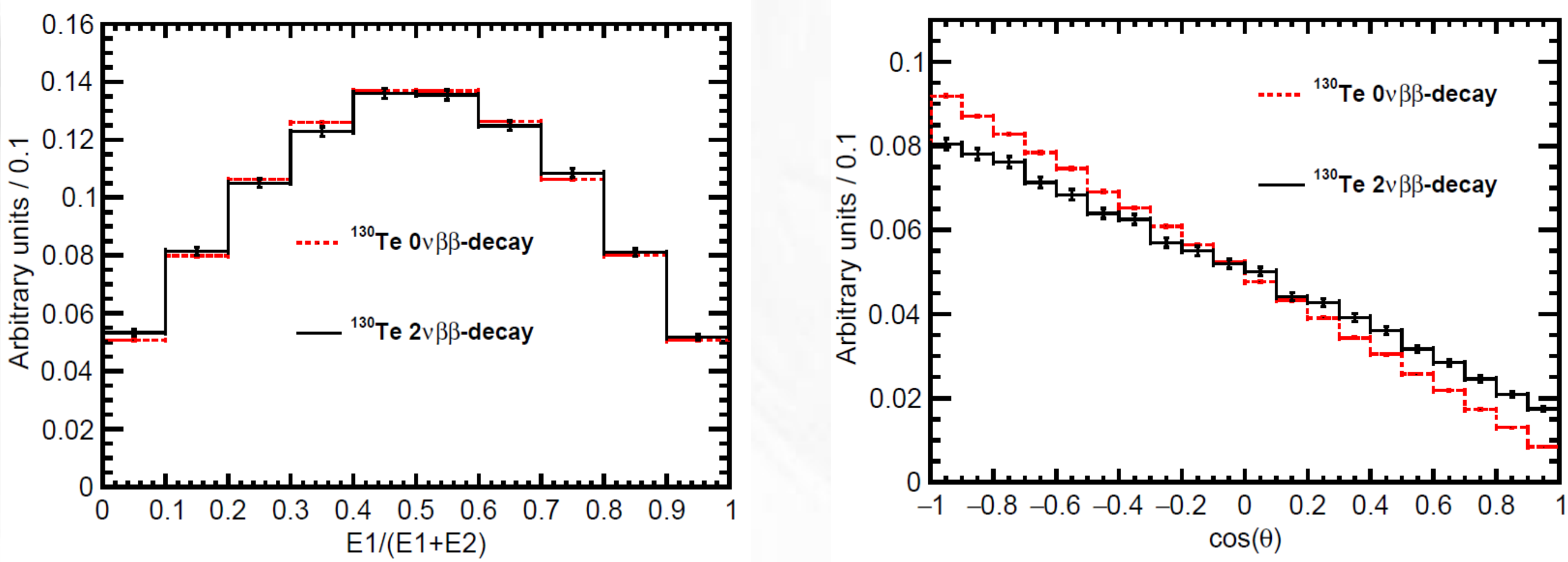


FIG. 2. Diagram showing how any neutrinoless double-$\beta$ decay process induces a $\bar{\nu}_e$-to-$\nu_e$ transition, that is, an effective Majorana mass term.

# 0νββ vs 2νββ

## Events within 5% of the end point

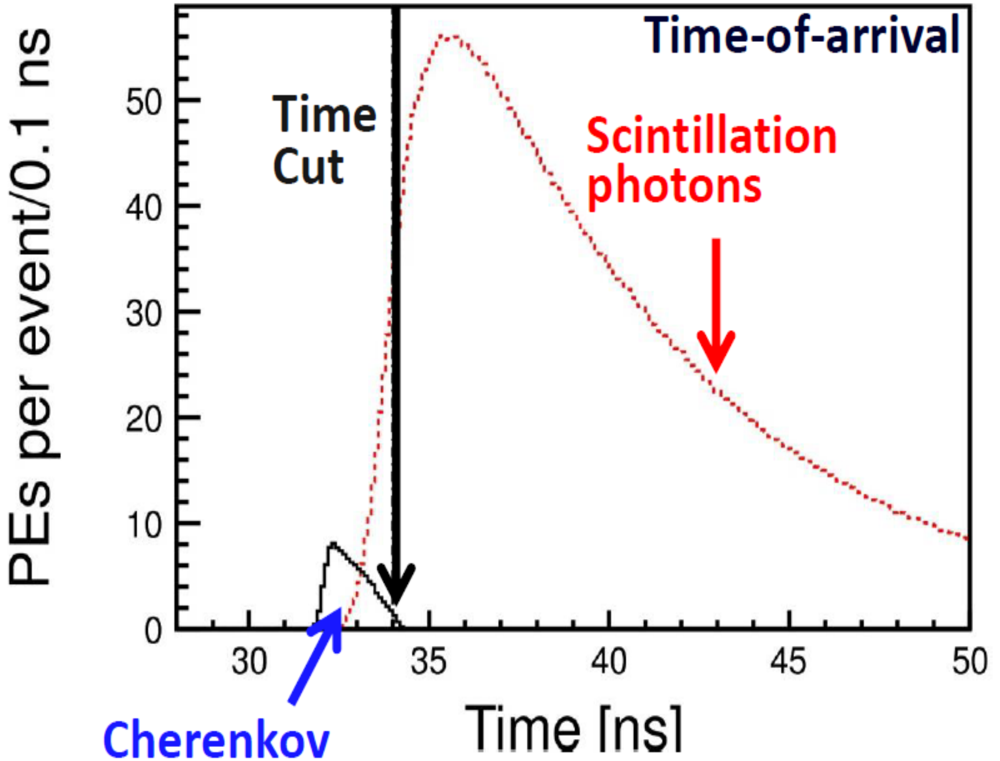
Event generator from L.Winslow based on phase factors from PRC 85, 034316 (2012)
by J. Kotila and F. Iachello



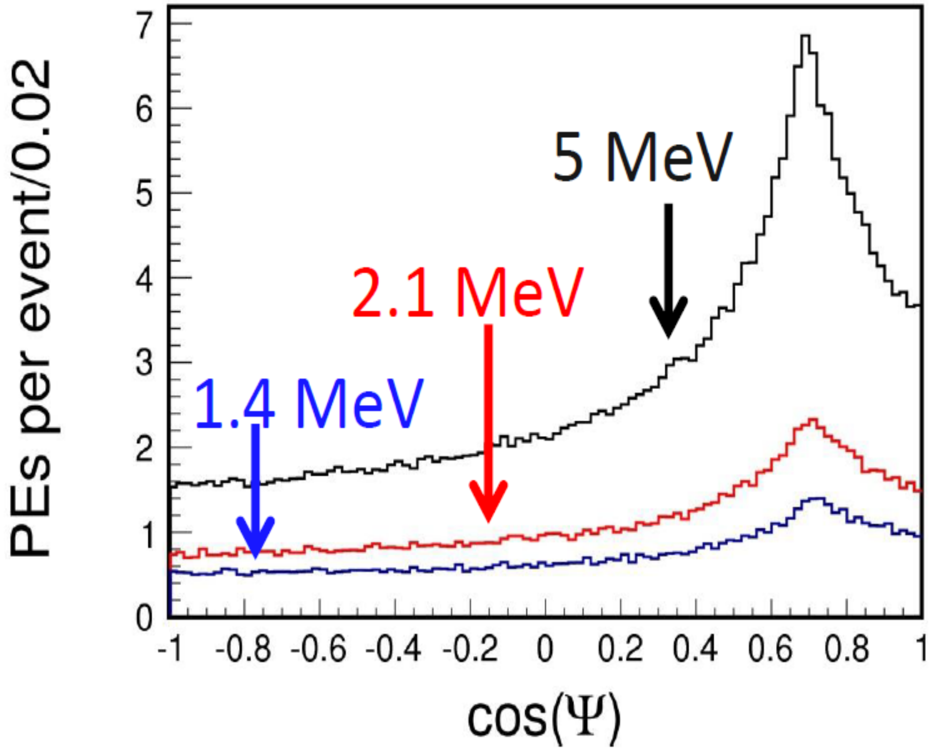
My e-mail exchange with Jenni Kotila:

"...The angular correlation is basically the a^(1)/a^(0), where a^(i) are defined in Eq. (24) for 2nbb and in Eq. (51) for 0nbb. In case of 0nbb only thing that matters are the electron wavefunctions but in case of 2nbb there are these additional factors that are a combination of <K_N> and <L_N>, that are defined in Eq. (23) and include the electron energies, the neutrino energies and the closure energy. So even with small neutrino energies, for example e_1=0.749Q, e_2=0.249Q, w_1=0.002Q, w_2=0 a factor of 0.4329 is obtained. Regarding the question about the situation for different isotopes, the closure energy entering the equations is different for each isotope and can be approximated by 1.12A^(1/2) MeV..."

# Directionality of Early Photons



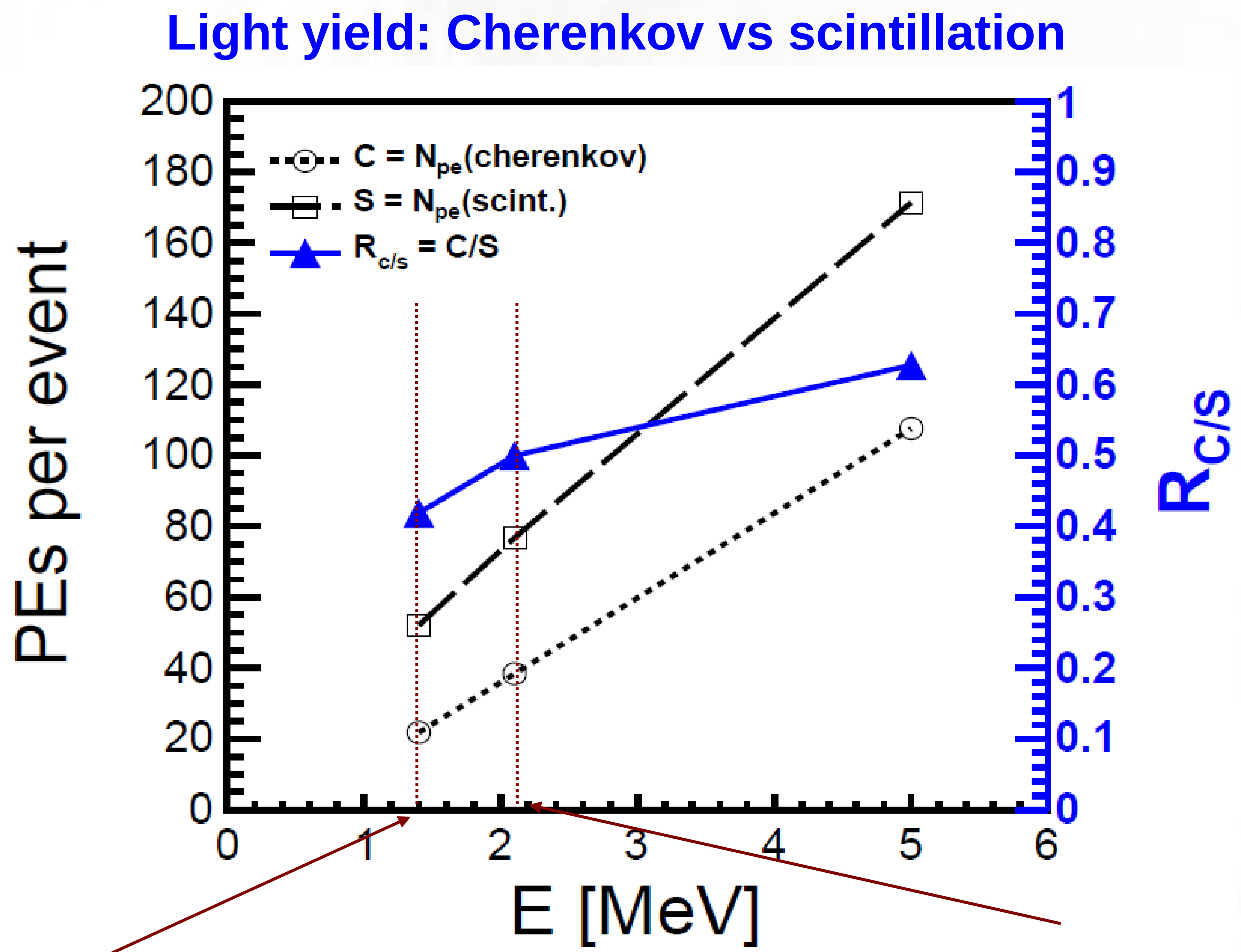
**Cherenkov photons from center of 6.5m-radius sphere: TTS=100 psec**



**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.**

C.Aberle, A.Elagin, H.Frisch,
M.Wetstein, L.Winslow
2014 JINST 9 P06012

# What About Lower Energies?

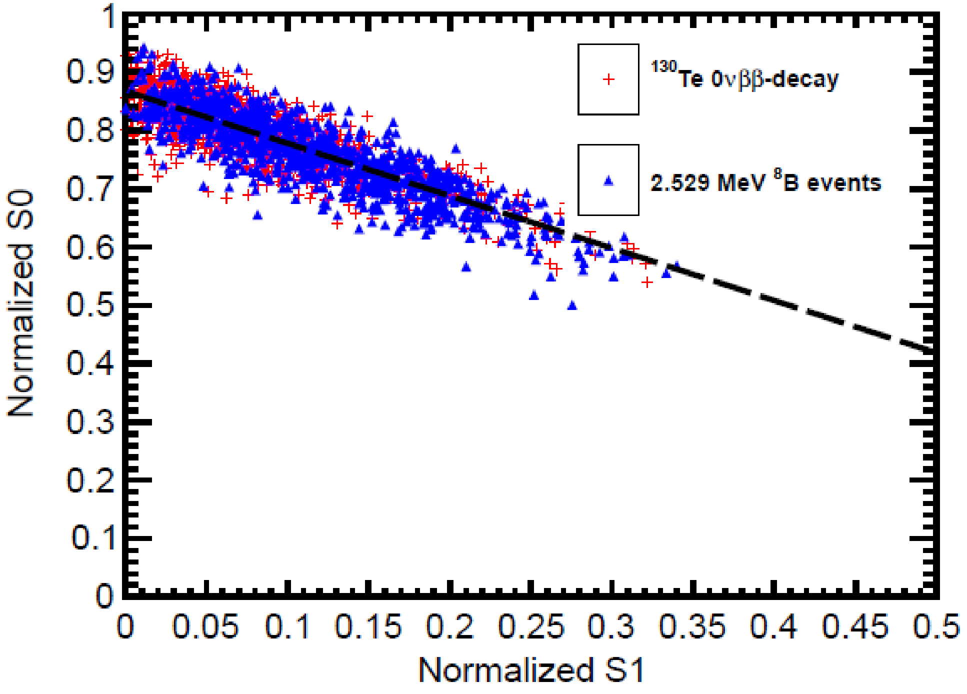

Light yield: Cherenkov vs scintillation

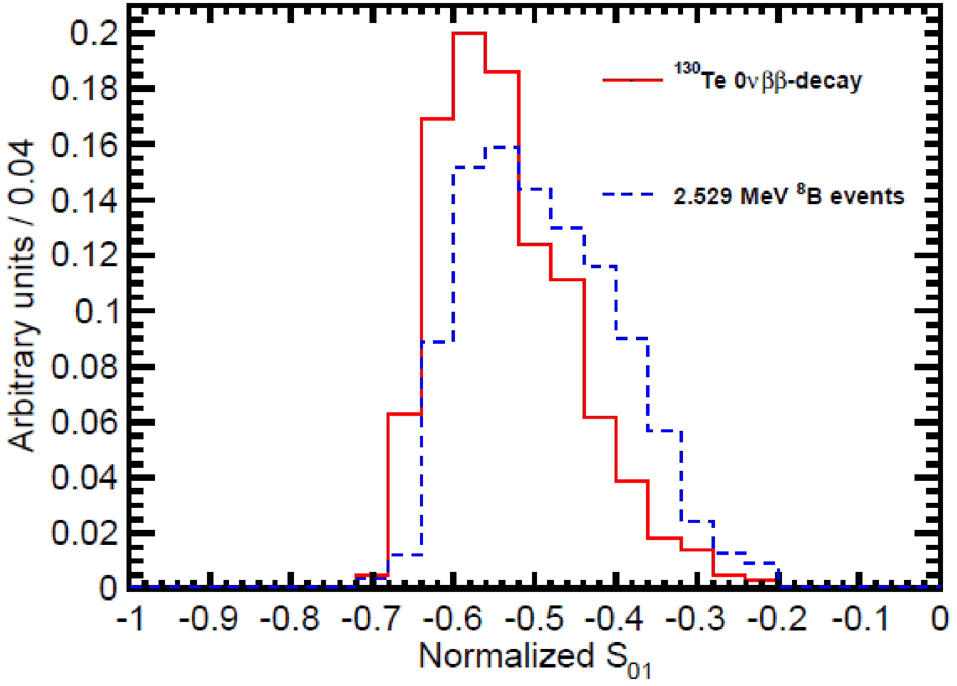
**½ Q ($^{116}$Cd) =1.4 MeV**

**½ Q ($^{48}$Ca) =2.1 MeV**

# $0\nu\beta\beta$ vs $^8$B

Vertex res **5cm**, events within **R<3m**
Sci rise time **1 ns**

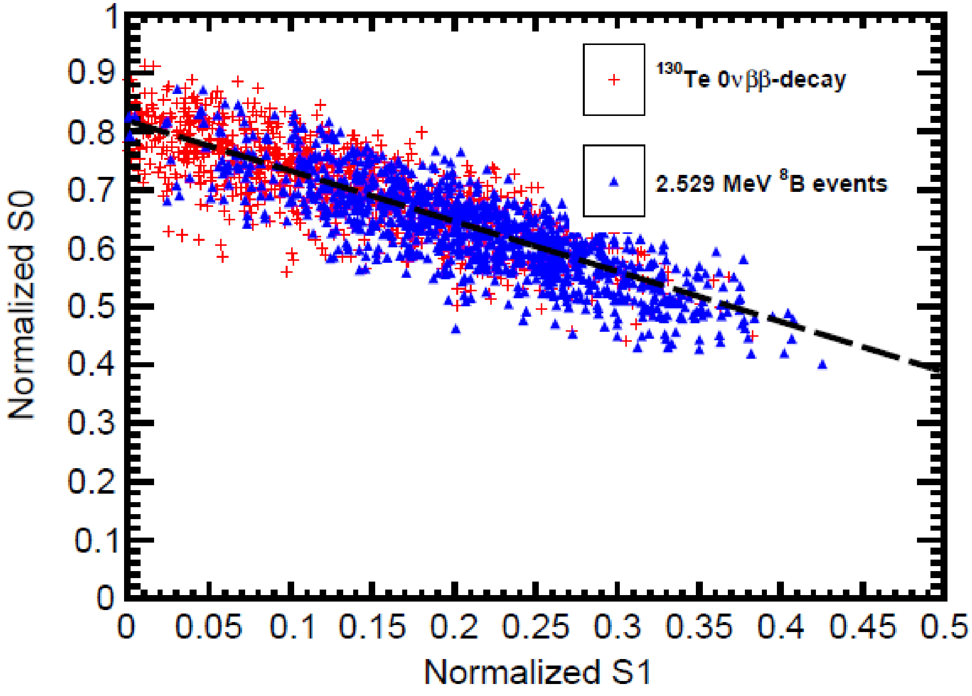


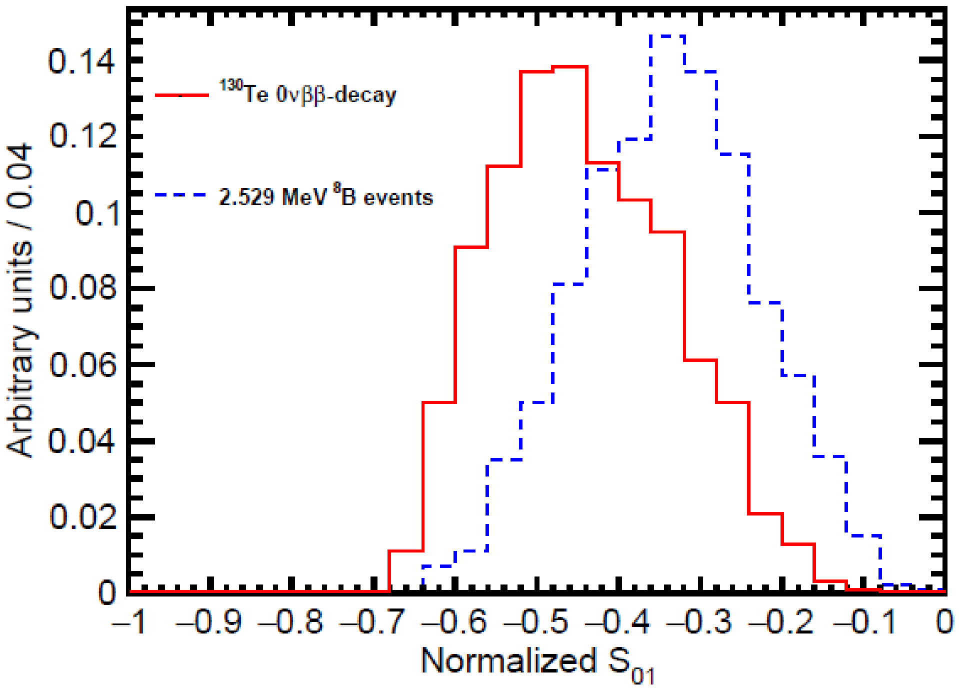


$I_{overlap} = 0.79$

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

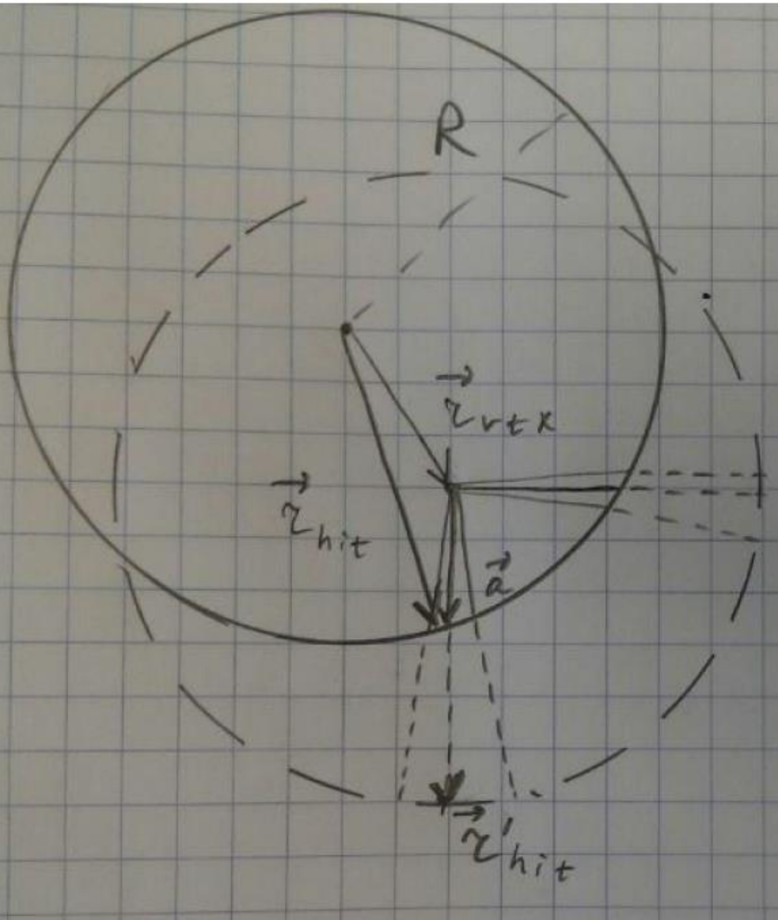
Vertex res **5cm**, events within **R<3m**
Sci rise time **5 ns**





$I_{overlap} = 0.64$

# Off-Center Events



$$\vec{r}\,'_{hit} = \frac{\vec{a}}{|\vec{a}|} \cdot R$$

$$\vec{a} = \vec{r}_{hit} - \vec{r}_{vtx}$$

$$\vec{r}\,'_{hit} = \frac{\vec{r}_{hit} - \vec{r}_{vtx}}{|\vec{r}_{hit} - \vec{r}_{vtx}|} \cdot R$$

$$x' = \frac{a_x}{\sqrt{a_x^2 + a_y^2 + a_z^2}} \cdot R$$

$$y' = \frac{a_y}{\sqrt{\ }} \cdot R$$

$$z' = \frac{a_z}{\sqrt{\ }} R$$

$a_x = x_{hit} - x_{vtx}$, $a_y = y_{hit} - y_{vtx}$, $a_z = z_{hit} - z_{vtx}$

# $0\nu\beta\beta$-decay vs $^{10}$C

*two-track vs a "complicated" topology*

## $^{10}$C decay chain:

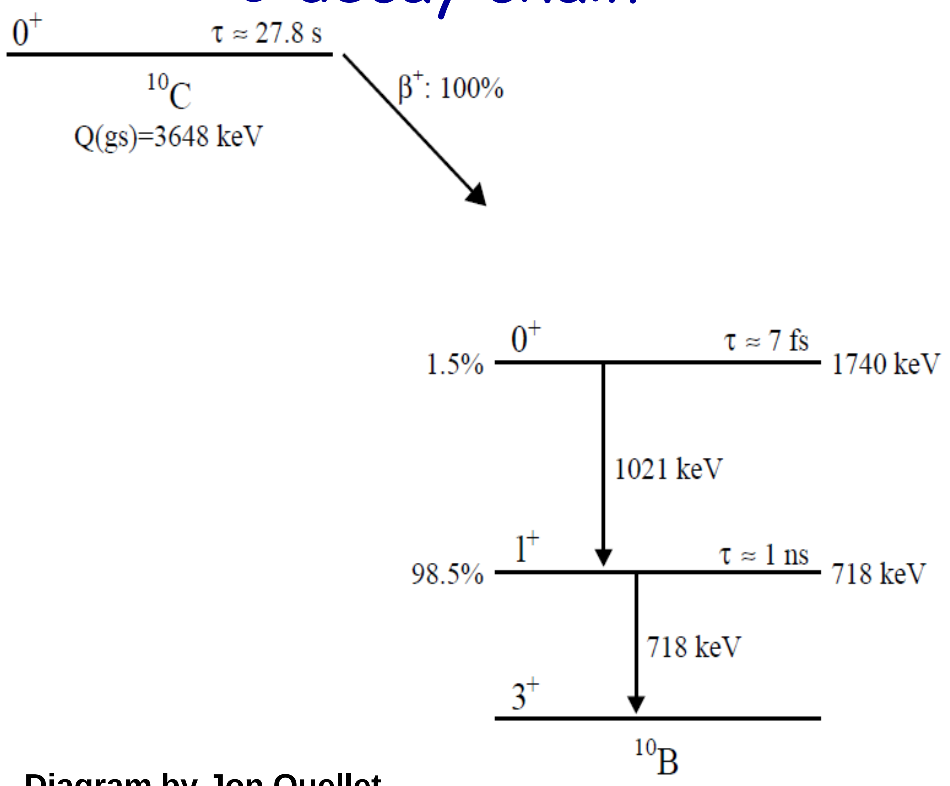
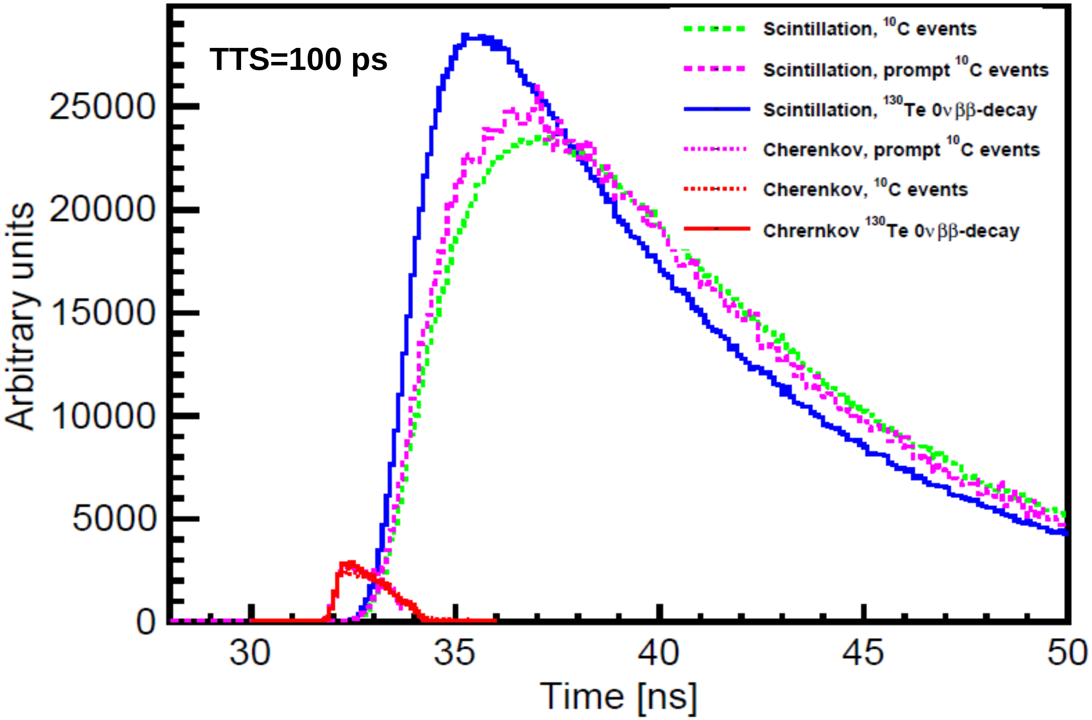


**Diagram by Jon Ouellet**

$^{10}$C vs $0\nu\beta\beta$-decay: photons arrival time profile

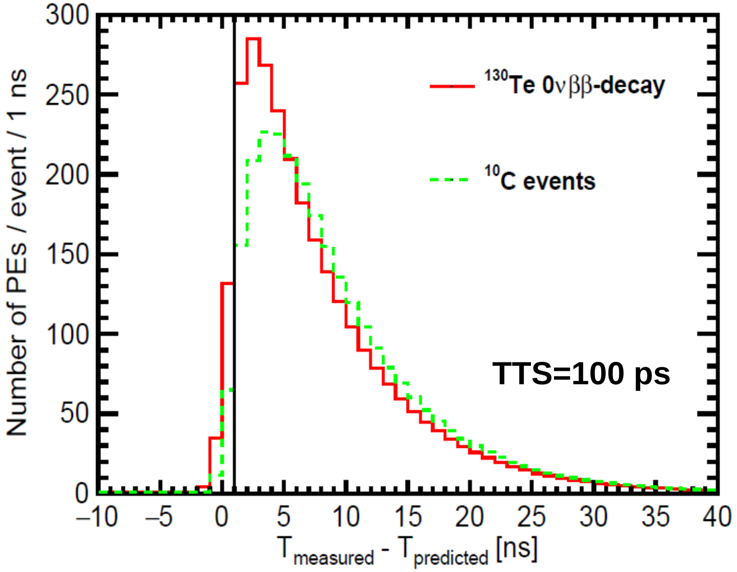


- $^{10}$C final state consist of a positron and gamma (e+ also gives 2x0.511MeV gammas after loosing energy to scintillation)
- Positron has lower kinetic energy than $0\nu\beta\beta$ electrons
- Positron scintillates over shorter distance from primary vertex
- Gammas can travel far from the primary vertex

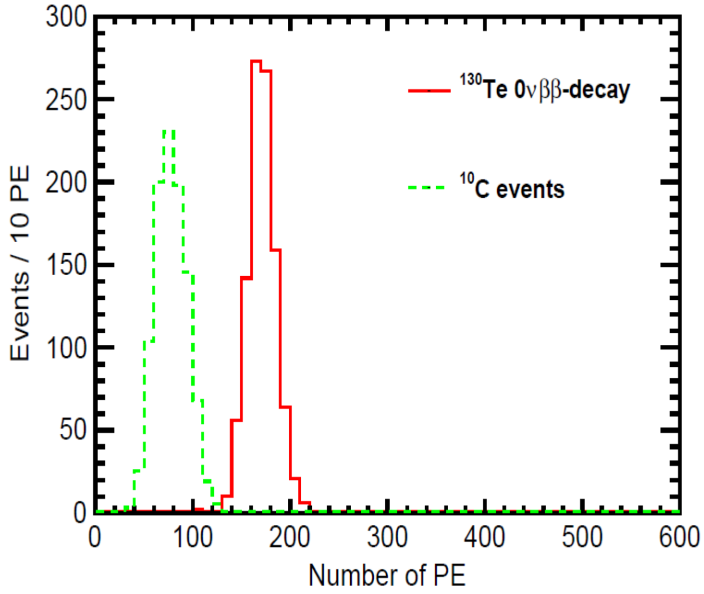
$^{10}$C background can be large at a shallow detector depth

# 0νββ-decay vs $^{10}$C

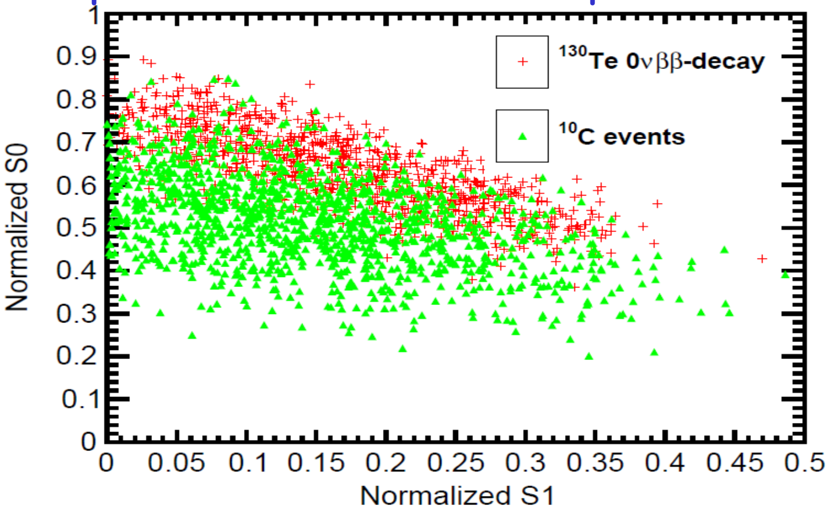
Time profile for events uniformly distributed within the fiducial volume, R<3m
Vertex resolution of 3cm is assumed



Photons count in early light sample

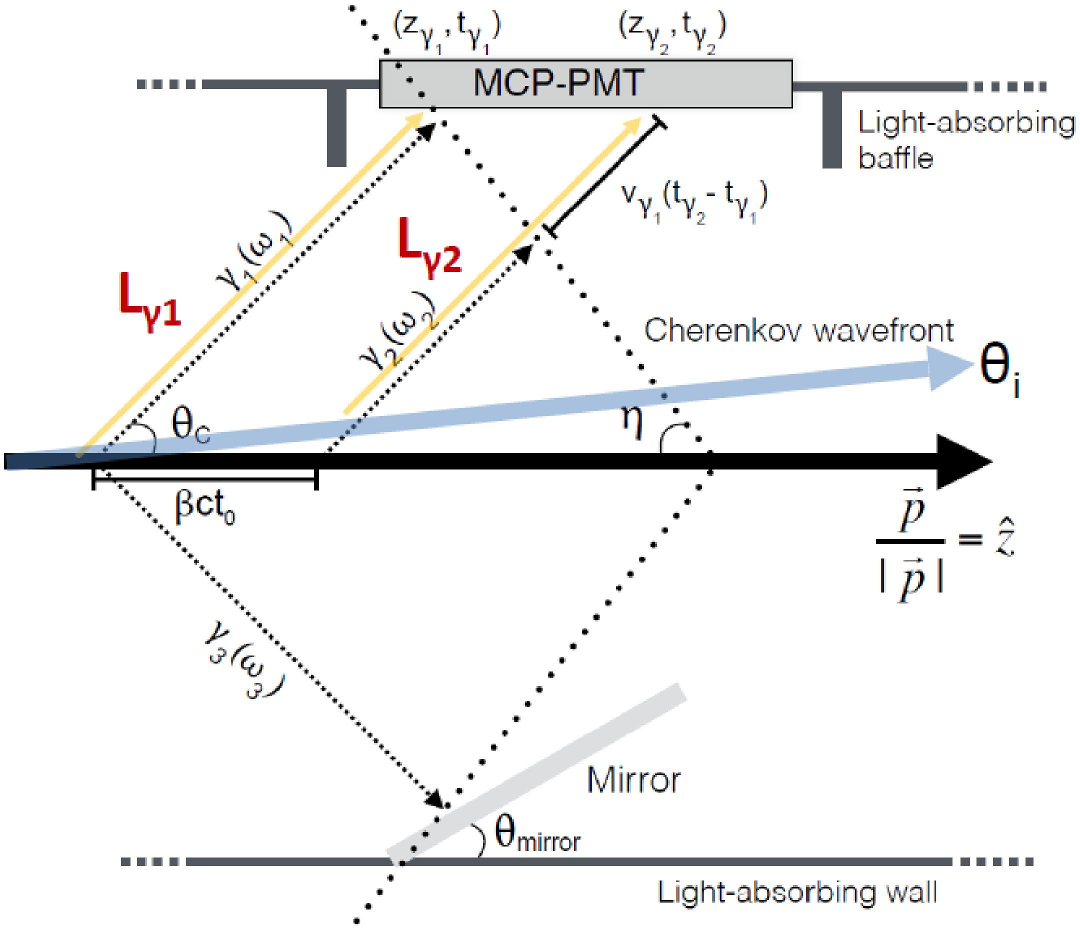


Spherical harmonics help here too



**Disclaimer:** there are other handles on $^{10}$C that are already in use (e.g., muon tag, secondary vertices). Actual improvement in separation power may vary.

# OTPC Optics – direct light



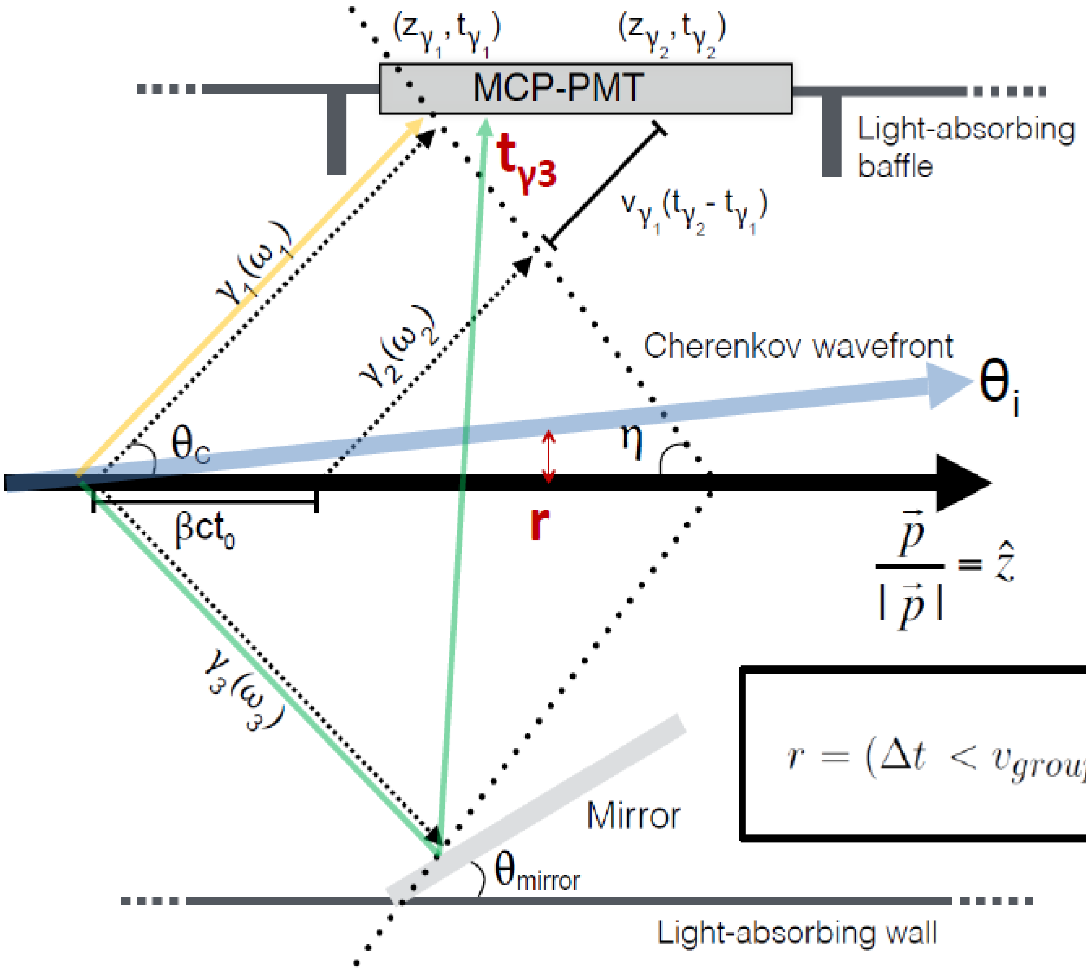
The time projection of the direct Cherenkov photons on the OTPC z-axis is a measure of the Cherenkov angle (β) and the particle angle with respect to the OTPC longitudinal axis

$$\Delta t_{\gamma_{21}} = t_o\,(1 - \frac{\beta\, c}{< v_{group} >}\,\tan\theta_i)$$

$$\Delta z_{\gamma_{21}} = \beta\, c\, t_o\, \cos\theta_i$$

$$\boxed{\frac{dt}{dz} \approx \frac{1}{\beta\, c} - \frac{\tan\theta_i}{< v_{group} >}}$$

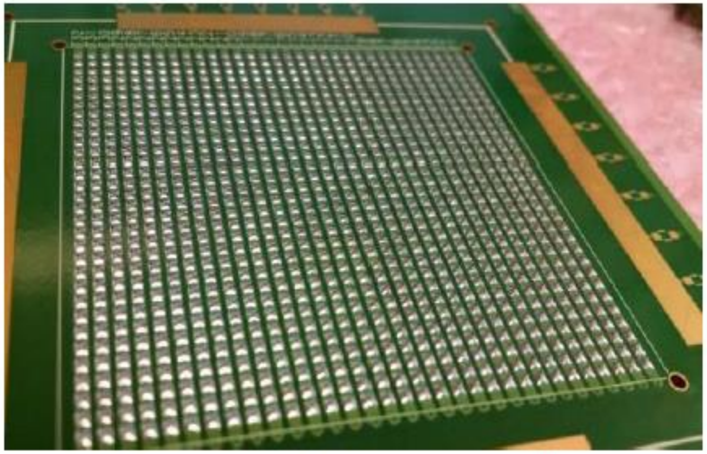
# OTPC Optics – direct + reflected light



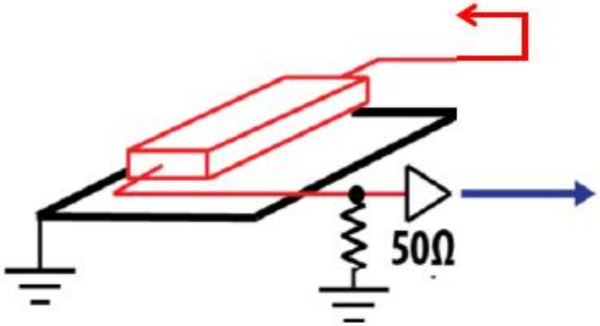
Time-resolving the direct and reflected photons provides the lateral particle displacement from the OTPC center-line as a function of z- and ϕ-position

$$\boxed{r = (\Delta t \ < v_{group} > - D)\, \frac{1}{2} \left( \frac{1}{\sin \theta_c} - \frac{< v_{group} >}{\beta c \tan(\theta_c)} \right)^{-1}}$$

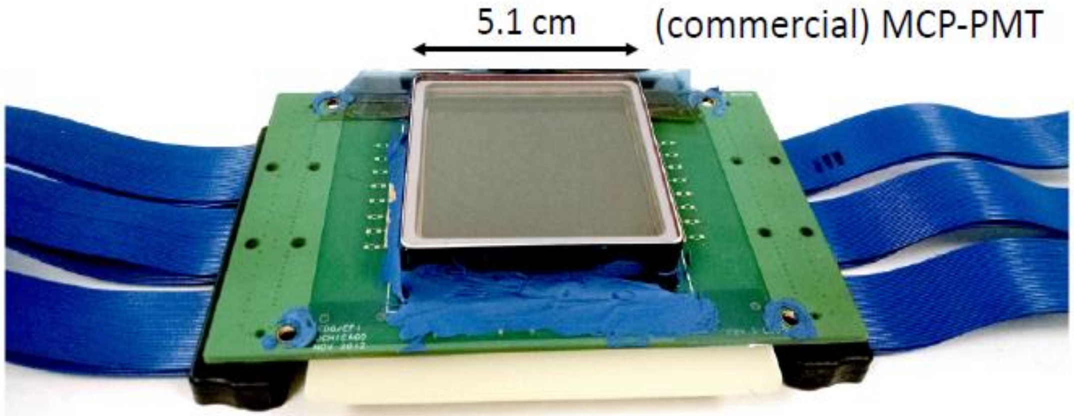
# OTPC Photodetector Module (PM)

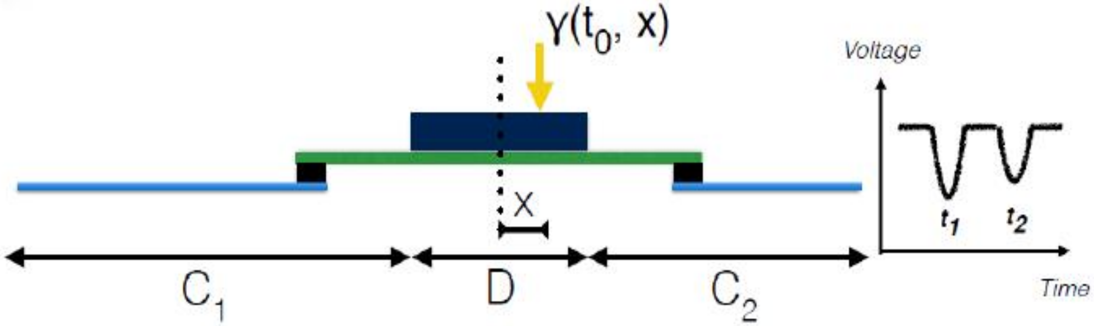


- 1024 anode pad mapped to thirty-two 50Ω micro-strips with custom anode card
- MCP-PMT mounted to anode card with low-temperature Ag epoxy
- Terminate one end of micro-strip, other end open (high-impedance):



PHOTONIS XP85022 (commercial) MCP-PMT





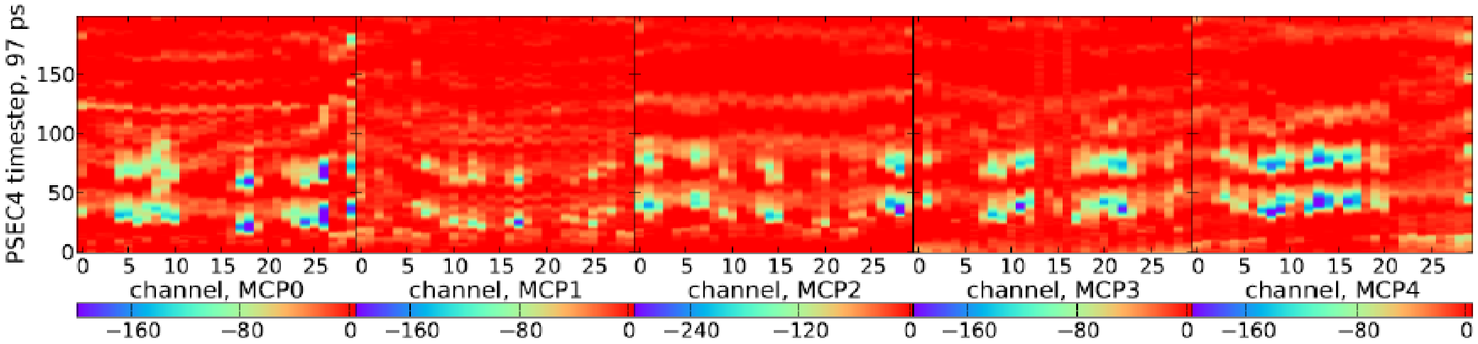
Expressions for the position and time-of-arrival of the detected photon

$$x = v_{prop}\frac{t_2 - t_1}{2} - \frac{D + 2\,C_1}{2}$$

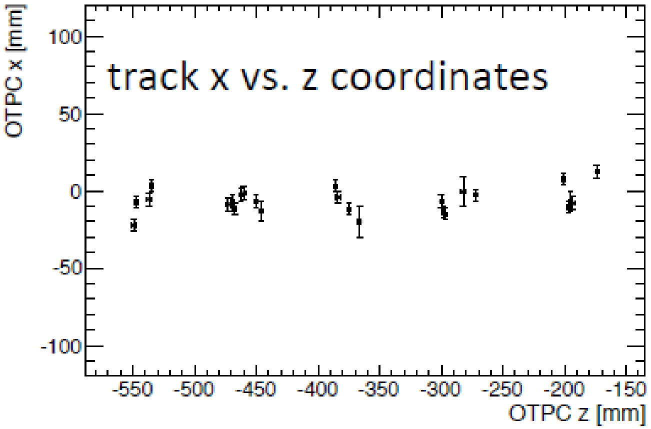
$$t_0 = \frac{t_2 + t_1}{2} - \frac{1}{v_{prop}}(D + C_2 + C_1)$$

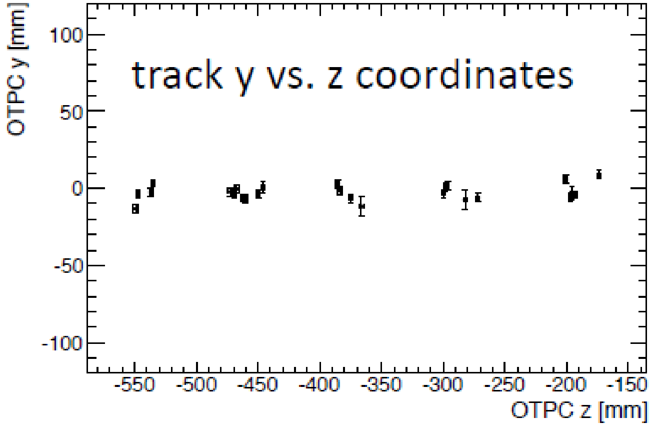
# OTPC spatial reconstruction (3)

Example event

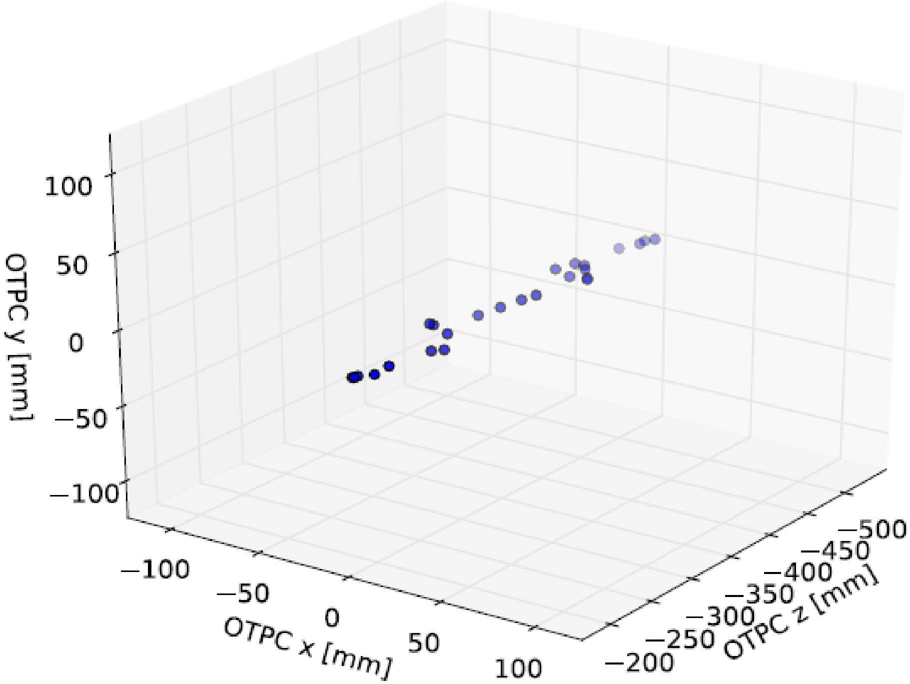


Typical event
(thru-going μ)





Projecting the direct photons onto the reconstructed r-coordinate at each PM



# Need for High Volume Production

## Key applications

- Cherenkov/scintillation light separation to reconstruct $0\nu\beta\beta$-decay event topology
- Optical tracking
- Particle identification by time-of-flight (colliders and fixed-target experiments)
- Medical imaging, proton therapy, nonproliferation, quantum imaging

## How many LAPPDs are needed?

- NuDot needs up to 72 LAPPDs (small-scale prototype with a path to a very large directional liquid scintillator detector for $0\nu\beta\beta$-decay)
- ANNIE needs 20-100 LAPPDs (water Cherenkov detector at Fermilab)
- KamLAND-Zen and SNO+ may benefit from LAPPDs but would need thousands of LAPPDs
- THEIA would need over 20,000 LAPPDs for just a 10% photo-coverage

Production rate of 50 LAPPDs/week
would substitute all PMTs at SNO+
in 3-4 years

# Early Adopters of LAPPD

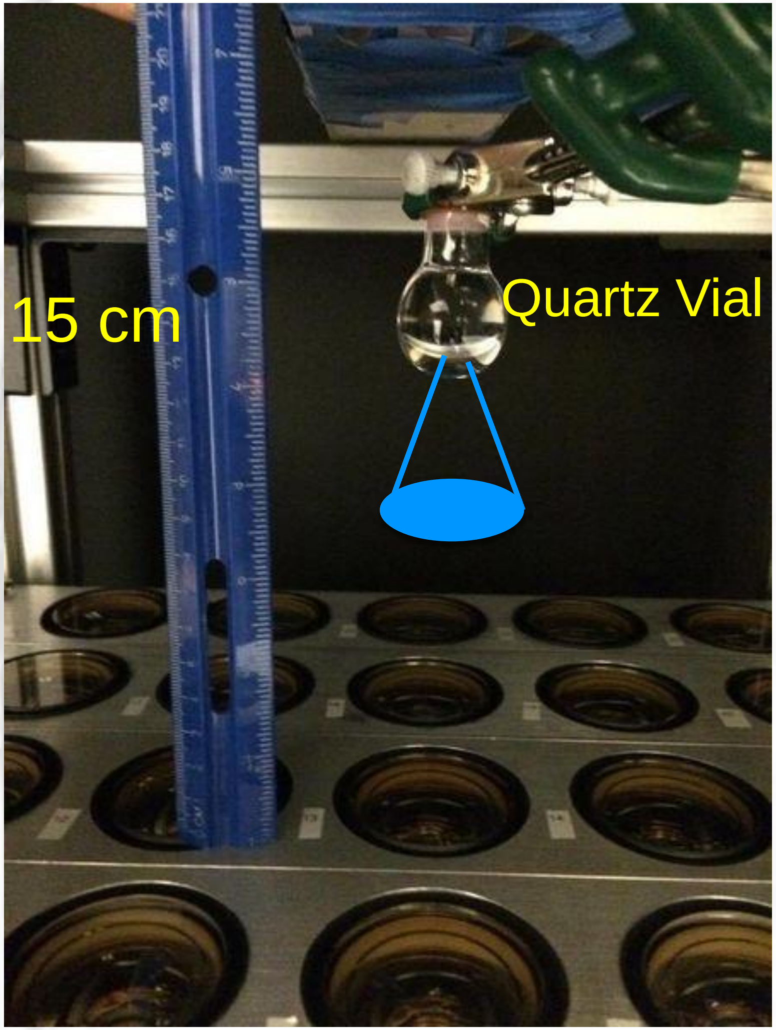
Putting first LAPPD tiles into real experimental settings for testing is the highest priority

Some examples of early adopters:

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

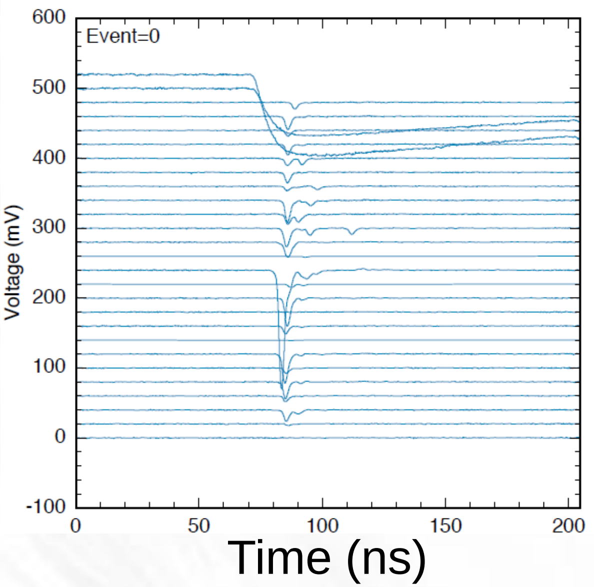
# FlatDot Demonstration

2" PMTs with TTS=300ps

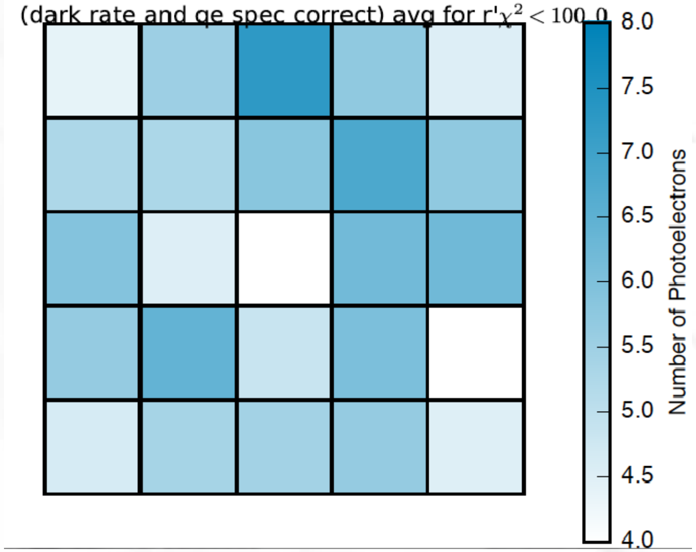


- Intermediate step towards 1m$^3$ spherical NuDot
  - e.g. detection of Cherenkov "rings" from low energy electrons using a tagged Compton source
- Testing different scintillator cocktails
- Readout testing

Raw pulses (the top two channels are the trigger)



Event display after corrections



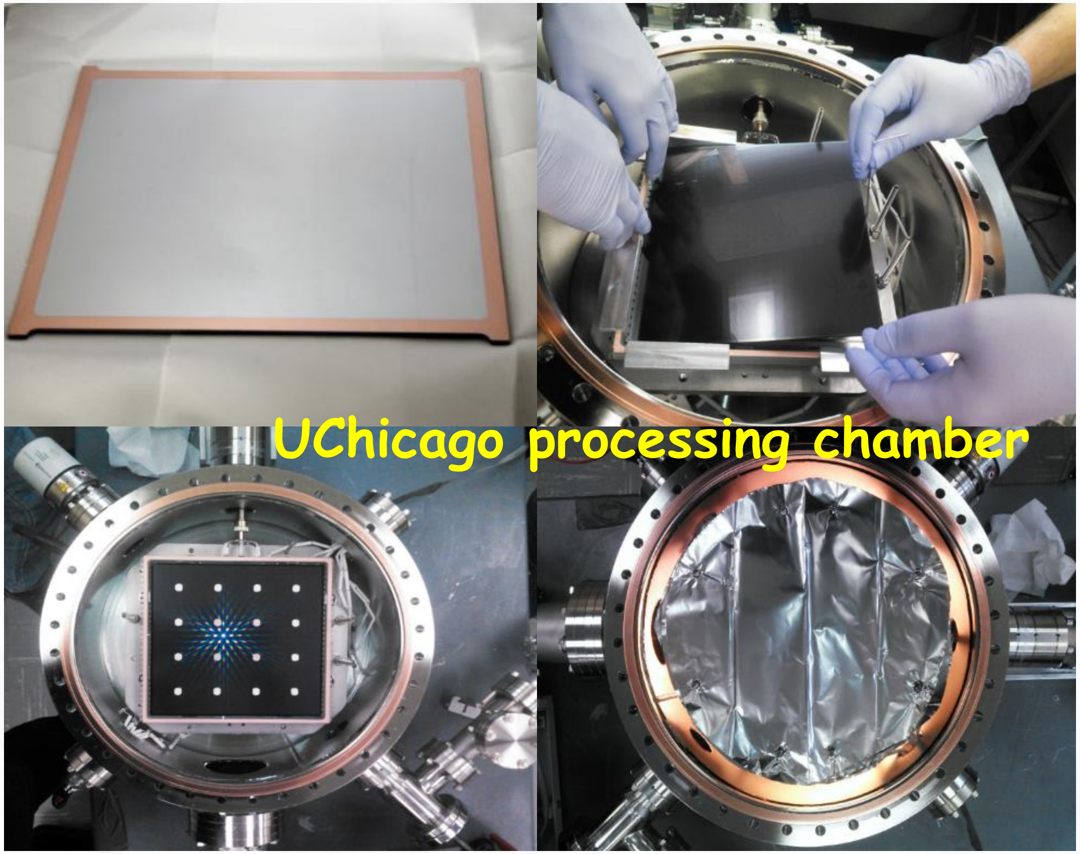
Note: there is an independent effort on Che/Sci light separation - the CHESS experiment at Berkeley by G. Orebi Gann et al., aXiv:1610.02011 and 1610.02029

# In-Situ Assembly Strategy

Simplify the assembly process by avoiding vacuum transfer:
make photo-cathode after the top seal
(PMT-like batch production)

**Heat only the tile not the vacuum vessel**

**Intended for parallelization**

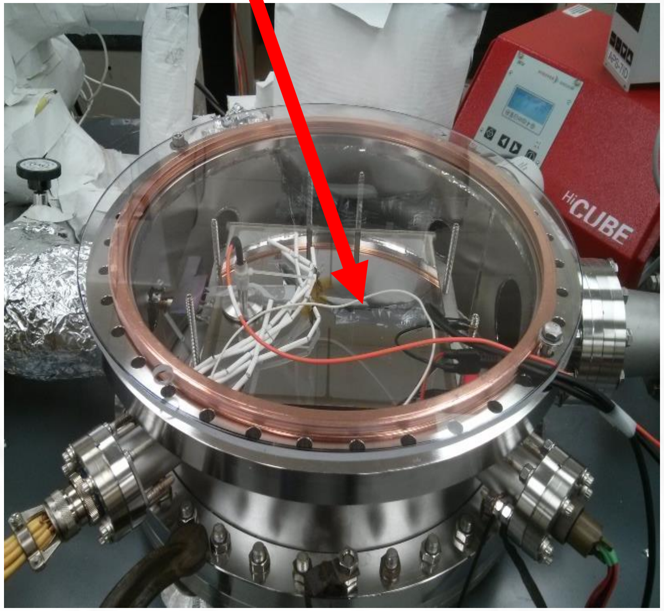


**Step 1:** pre-deposit Sb on the top window prior to assembly
**Step 2:** pre-assemble MCP stack in the tile-base
**Step 3:** **do top seal and bake in the same heat cycle using dual vacuum system**
**Step 4:** bring alkali vapors inside the tile to make photo-cathode
**Step 5:** flame seal the glass tube or crimp the copper tube

# In-Situ Photo-Cathode

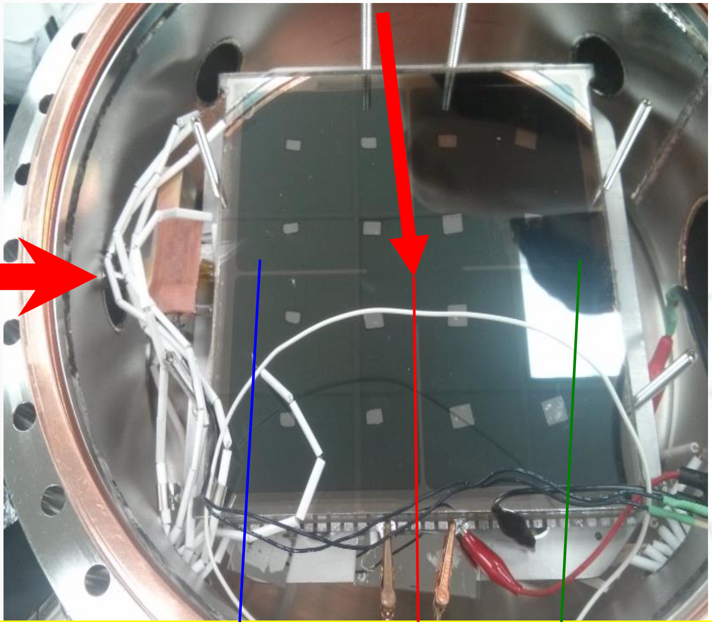
July, 2016

Sb layer only

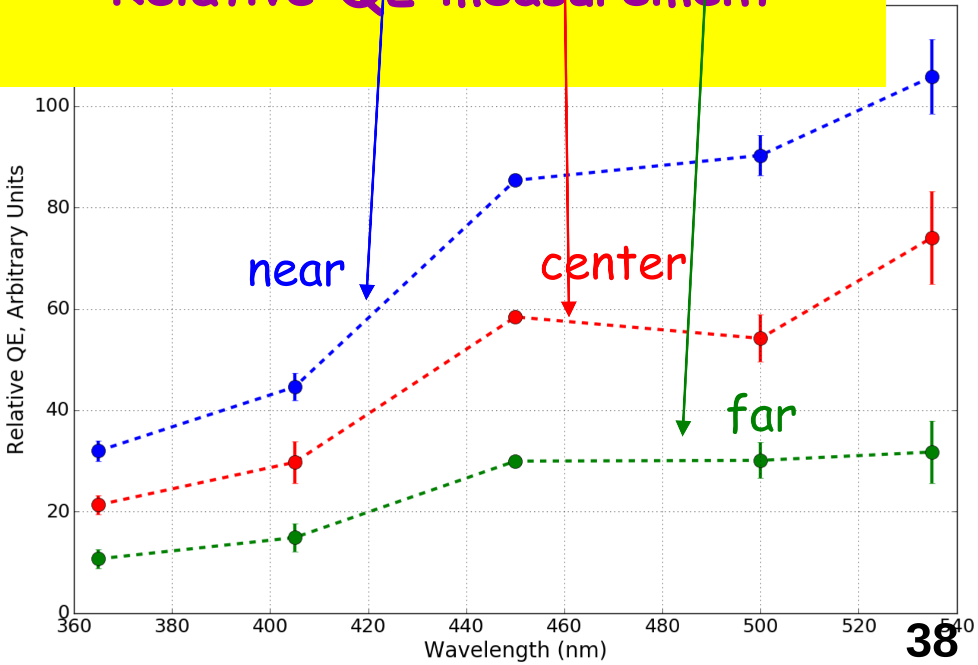


Cs

Cs-Sb photo-cathode



Relative QE measurement



First in-situ commissioning run (Summer 2016)

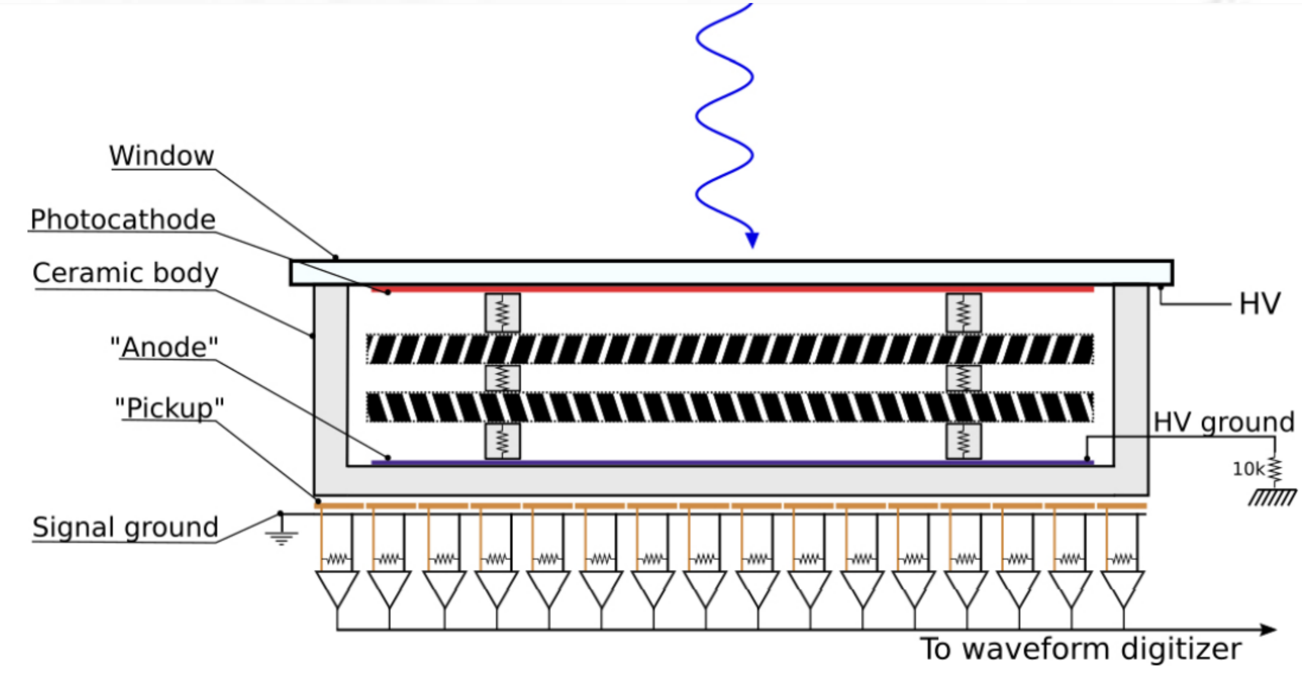
- saw the first photo-current response from in-situ photo-cathode
- measured relative QE (absolute QE is tricky due to DC current through the whole stack)
- demonstrated a <u>sealed tile</u> configuration
  - no QE drop for 2 weeks after the valve to the pump was closed
  - no QE drop for 3 weeks after flame seal

Note on this commissioning run:
PC is very thick for transmission mode operation
(initial 20nm of Sb translates into ~80nm of Cs-Sb)

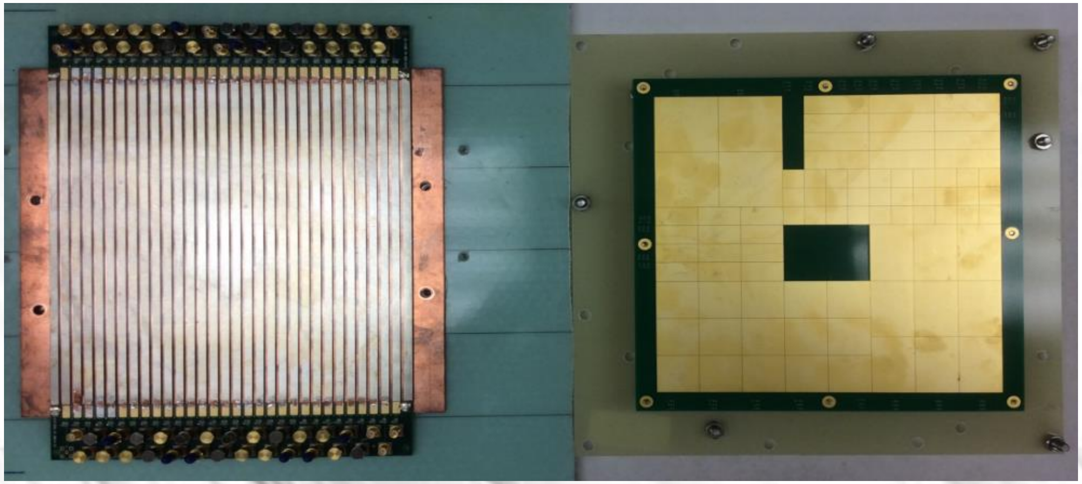
# Gen-II LAPPD: "inside-out" anode

Custom anode is outside

Compatible with high rate applications



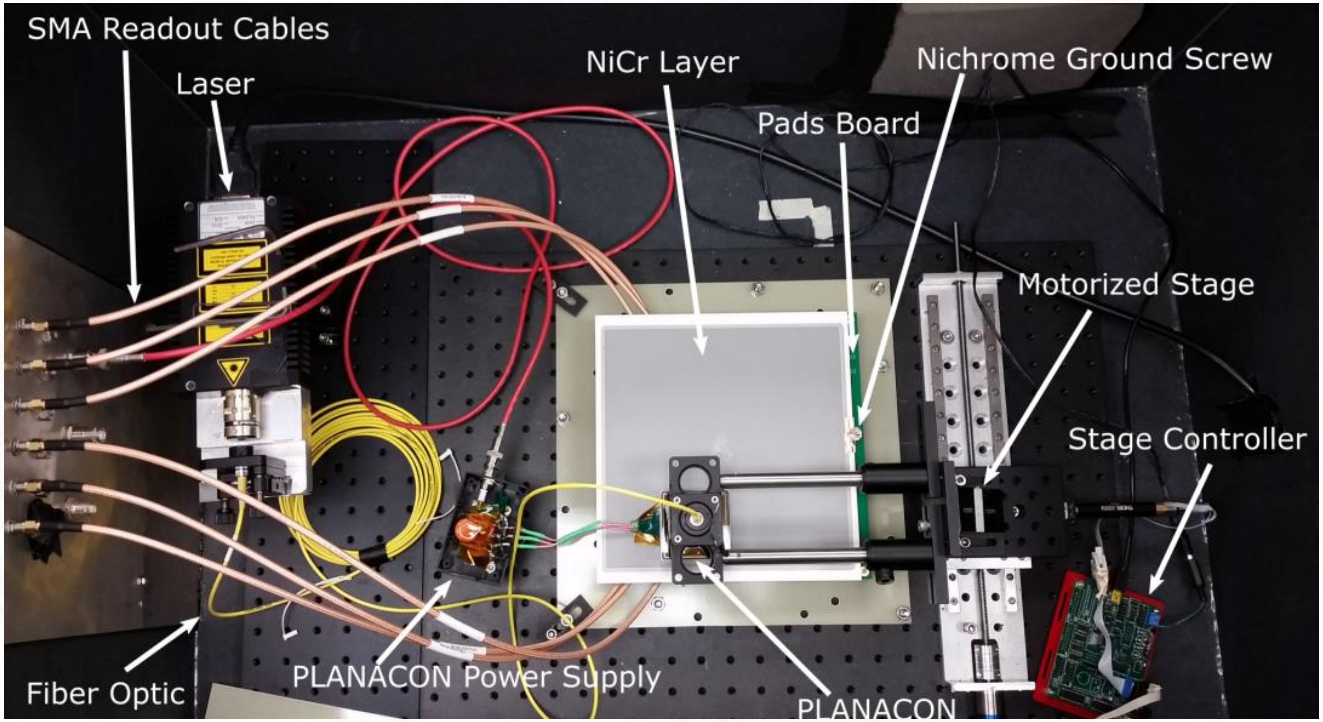
Choose your own readout pattern



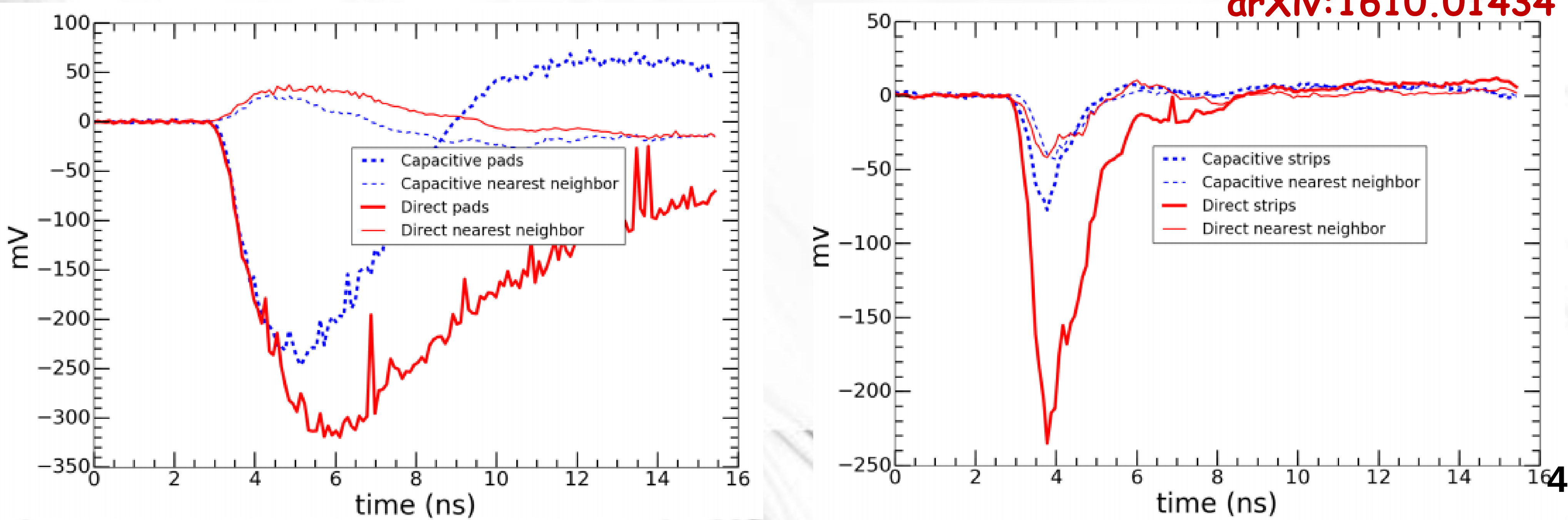
**For details see arXiv:1610.01434 (submitted to NIM)**

# Inside-out Anode Testing

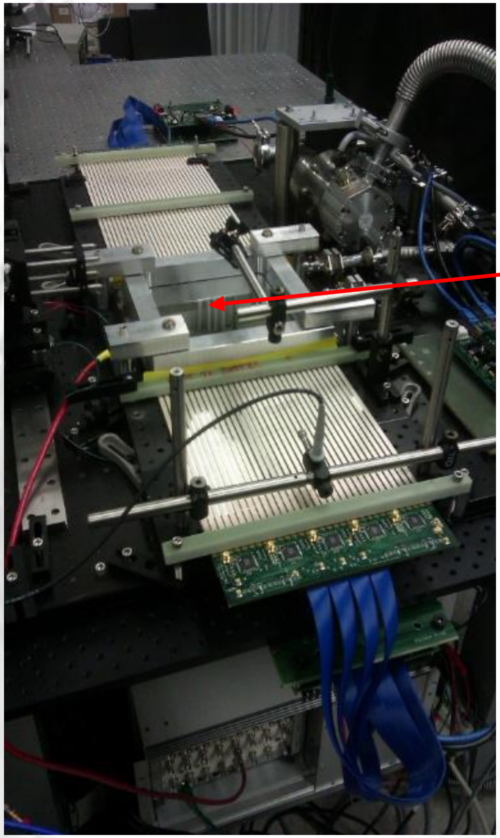
Evan Angelico
and
Todd Seiss

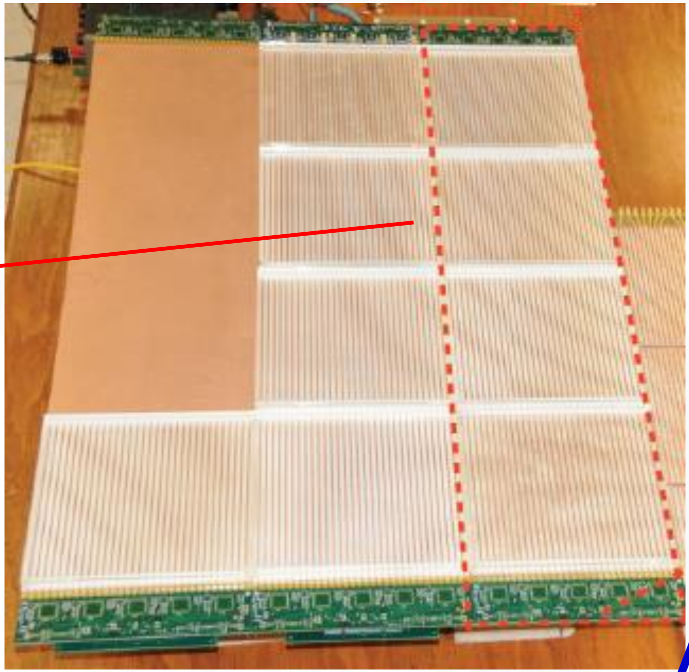


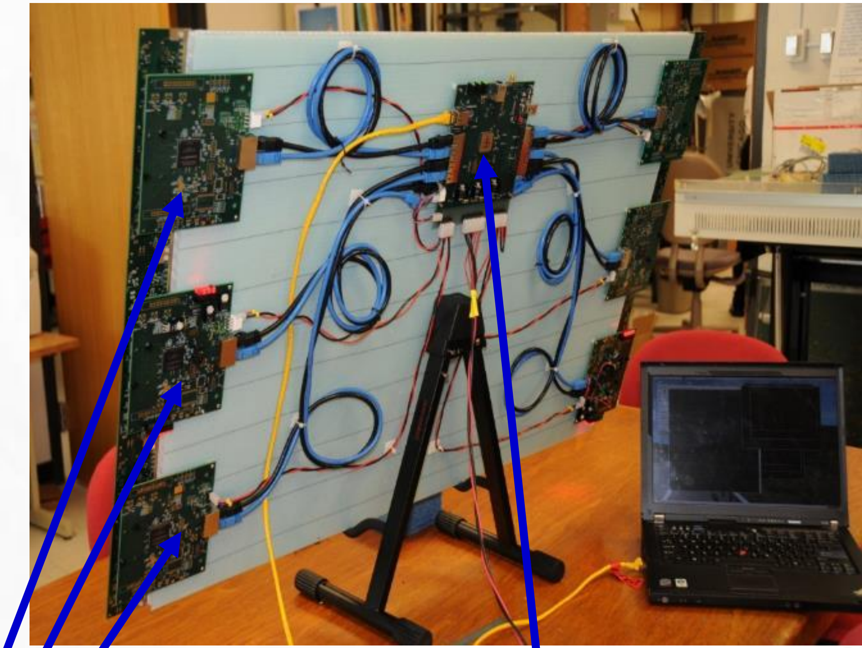
arXiv:1610.01434

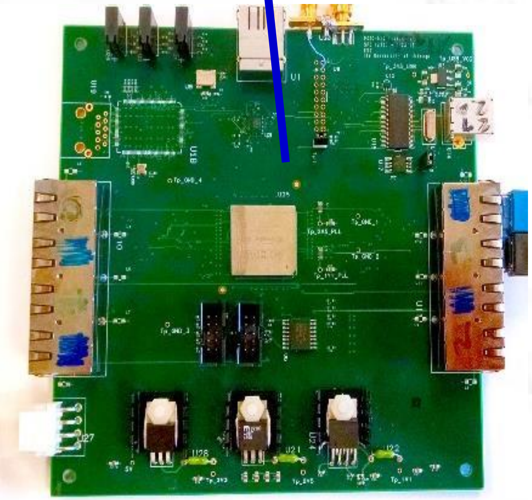


# LAPPD Electronics @ UChicago









NIM 711 (2013) 124

**Delay-line anode**

- 1.6 GHz bandwidth
- number of channels scales linearly with area

NIM 735 (2014) 452

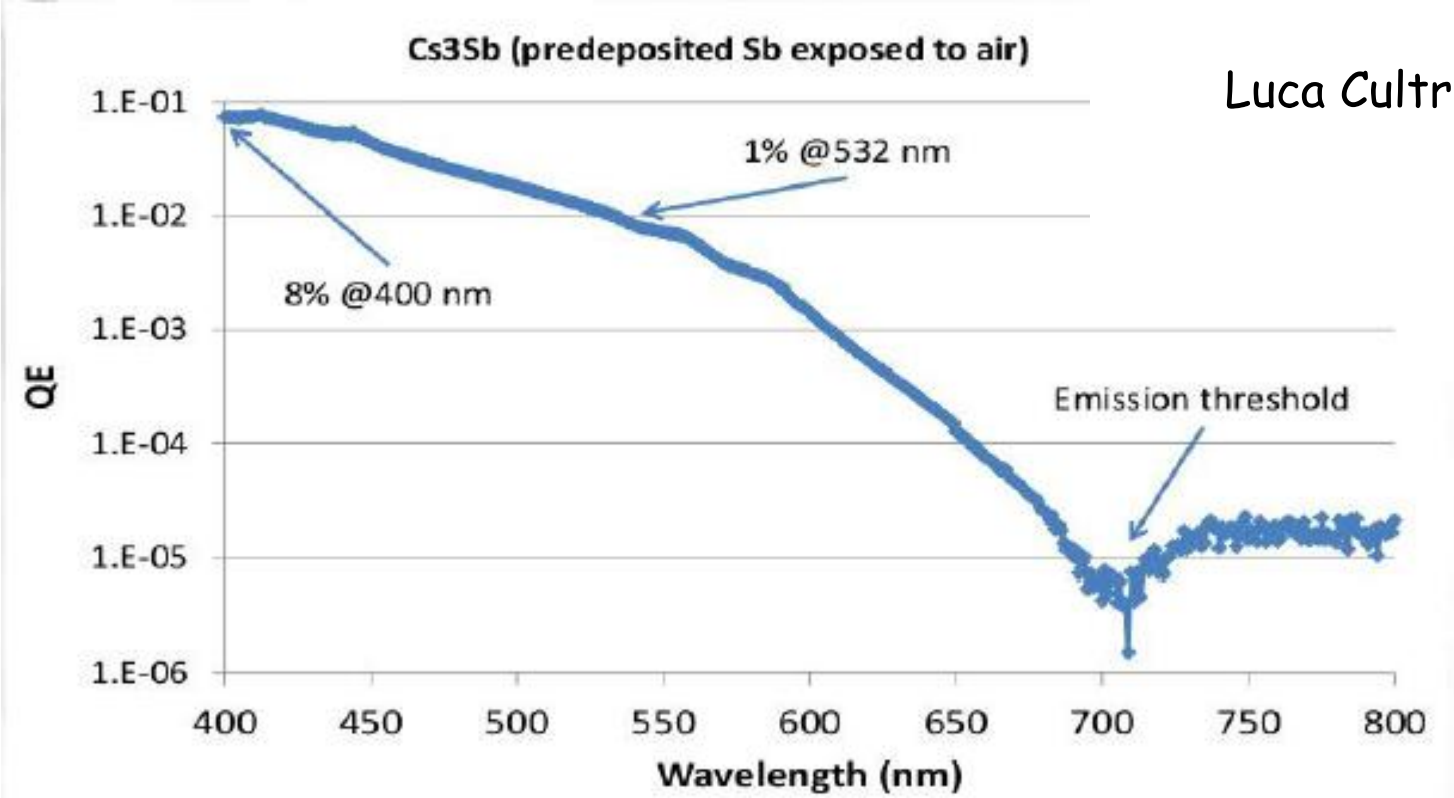
**PSEC-4 ASIC chip**

- 6-channel, 1.5 GHz, 10-15 GS/s

**30-Channel ACDC Card (5 PSEC-4)**

**Central Card (4-ACDC;120ch)**

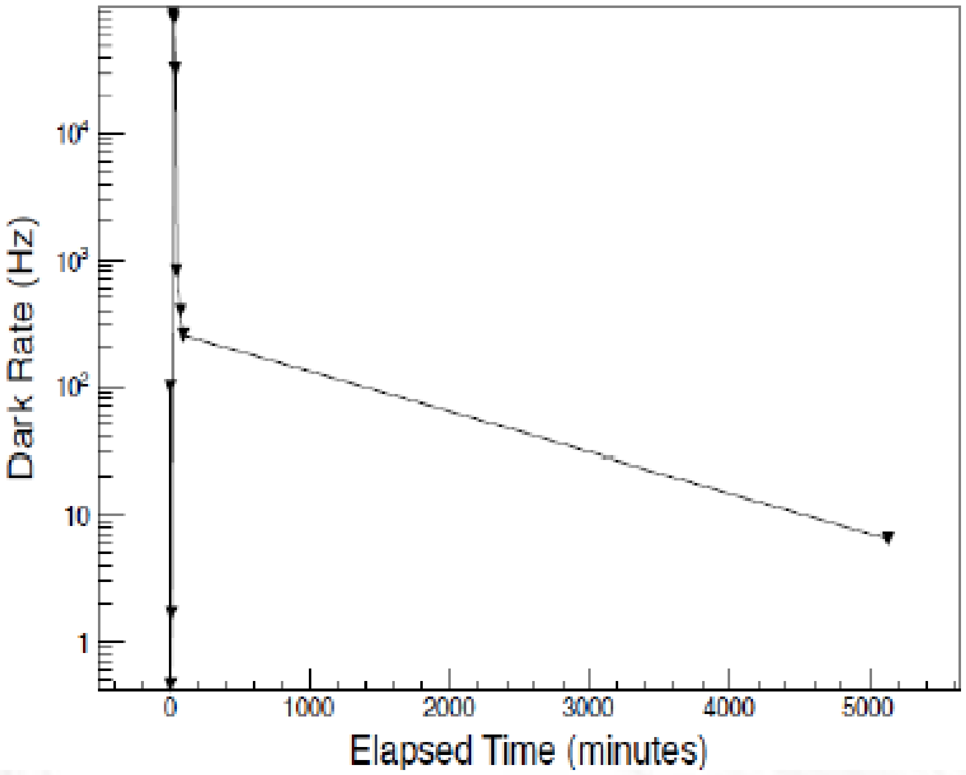
# Can you make PC after Sb was exposed to air?

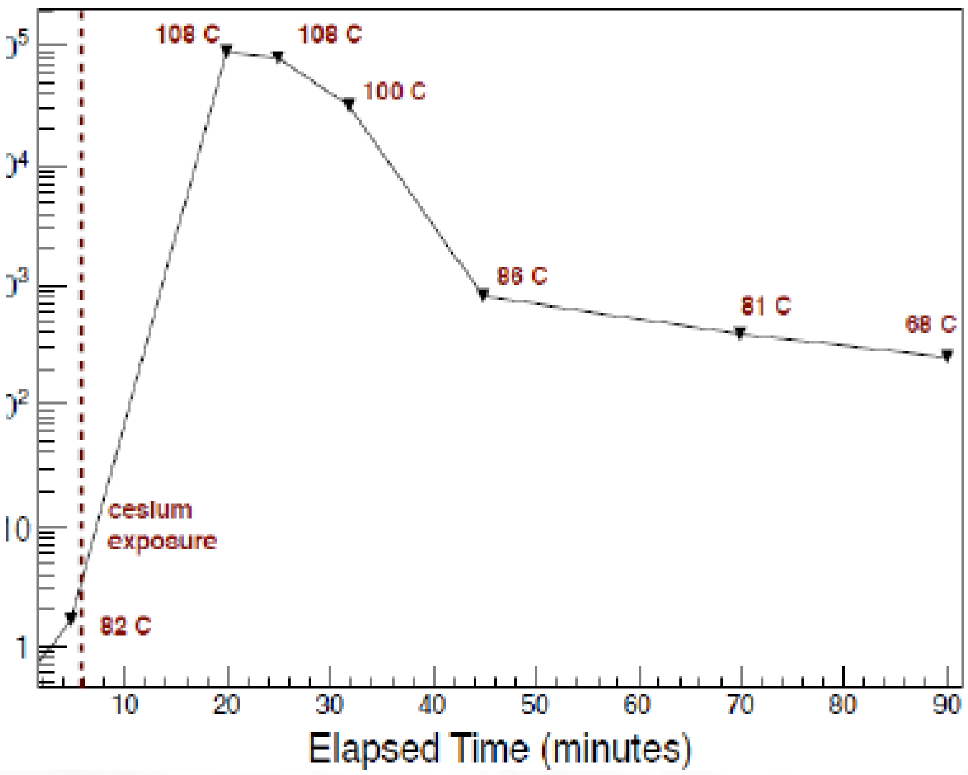


Luca Cultrera at Cornell

# What about noise in the MCPs after Cs-ation?

Matt Wetstein

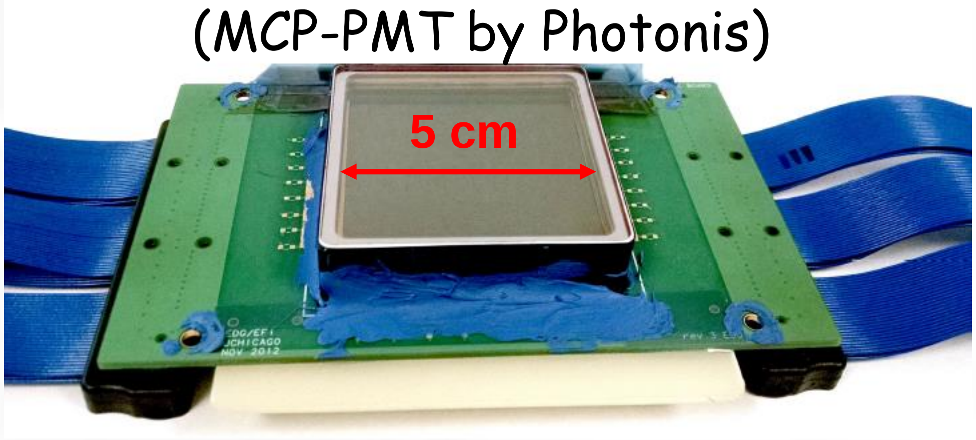




# Indium seal recipes exist for a long time

We adapted NiCr-Cu scheme
from O.Siegmund at SSL UC Berkeley

PLANACON™
(MCP-PMT by Photonis)



## Why do we need another indium seal recipe?

Make larger photo-detectors
Our recipe scales well to large perimeter

Simplify the assembly process
Our recipe is compatible with PMT-like batch production

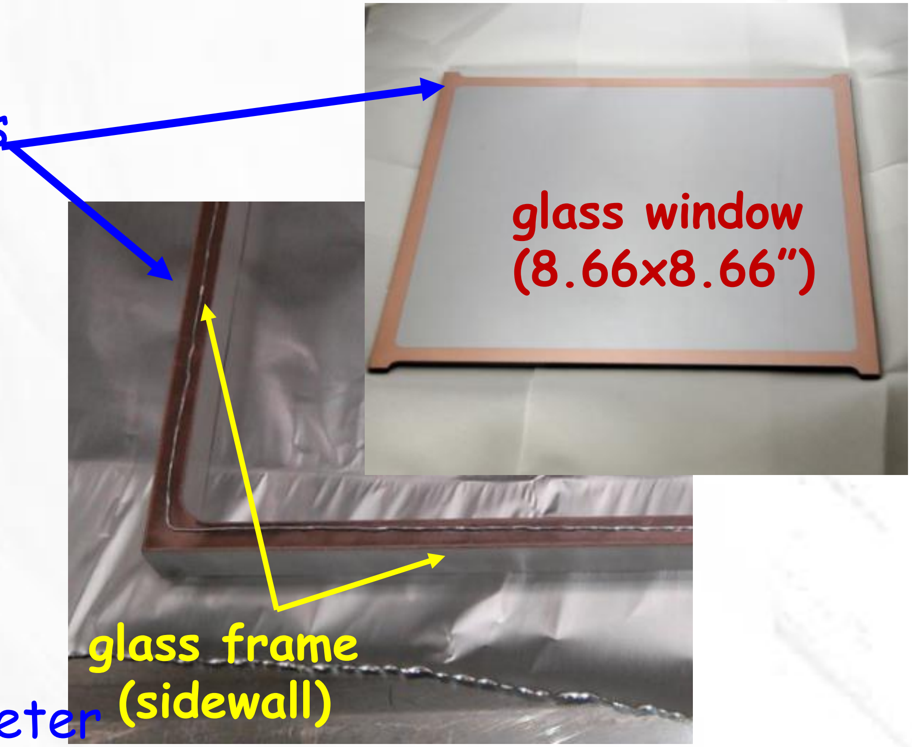
# In-Situ Process Pre-requisite

## Reliable hermetic seal over a 90-cm long perimeter

### Indium Solder Flat Seal Recipe

Input:

- Two glass parts with flat contact surfaces

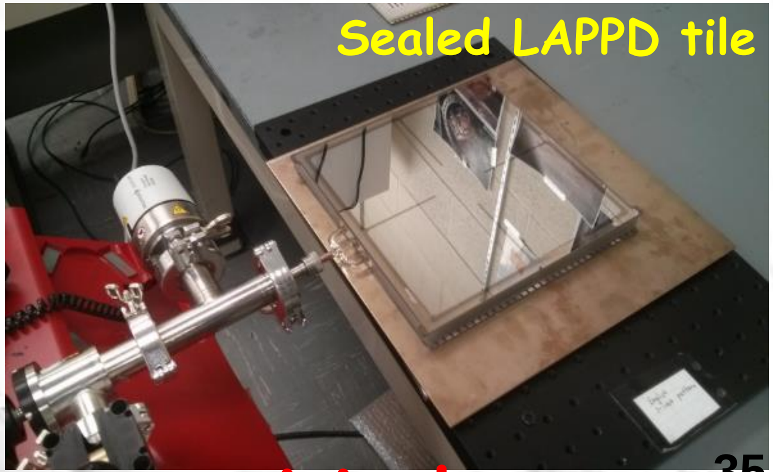


Process:

- Coat 200 nm of NiCr and 200 nm of Cu on each contact surface (adapted from seals by O.Siegmund at SSL UC Berkeley)
- Make a sandwich with indium wire
- Bake in vacuum at 250-300C for 24hrs

Key features:

- A good compression over the entire perimeter is needed to compensate for non-flatness and to ensure a good contact
- In good seals indium penetrates through entire NiCr layer (Cu always “dissolves”)



This recipe is now understood

It works well over large perimeters

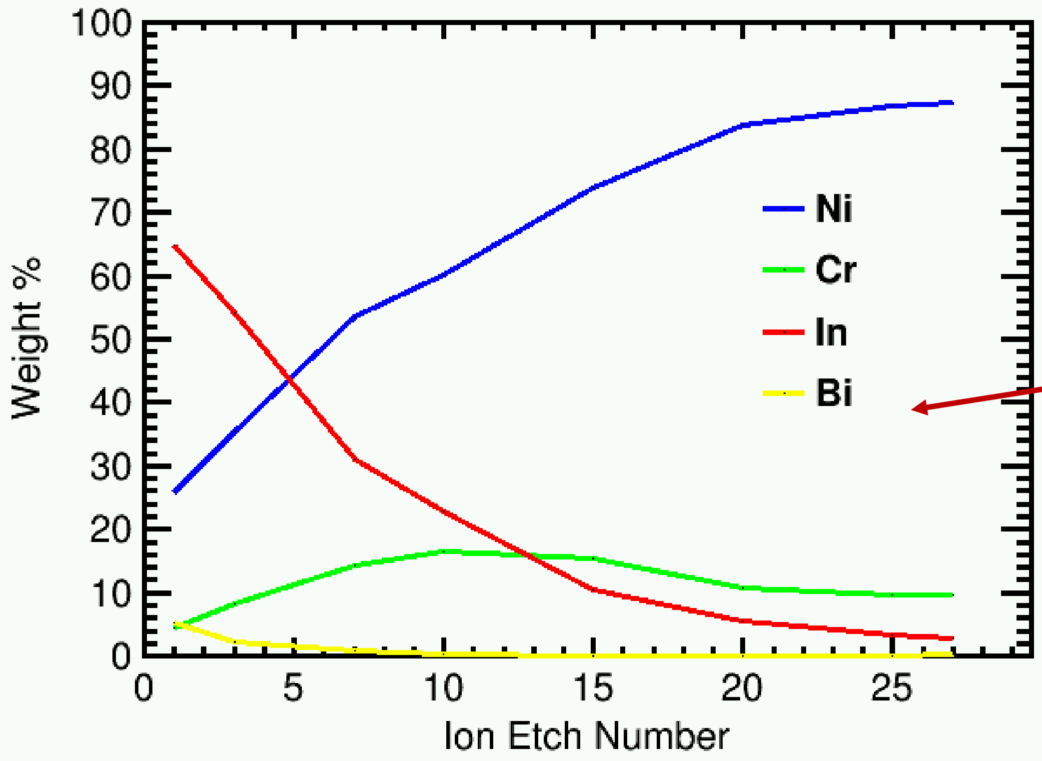
**Metallization and compression are critical**

# Metallurgy of the Seal

Moderate temperatures and short exposure time:

- A thin layer of copper quickly dissolves in molten indium
- Indium diffuses into the NiCr layer

Depth profile XPS

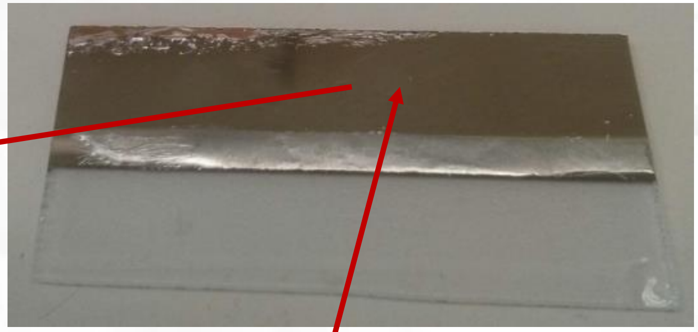


Layer depth (uncalibrated)

XPS access courtesy of
J. Kurley and A. Filatov at UChicago

Low melting InBi alloy
allows to explore temperatures
below melting of pure In (157C)

Glass with NiCr-Cu metallization
exposed to **InBi** at ~100C for <1hrs
(it seals at these conditions)



InBi was scraped when still
above melting (72C)

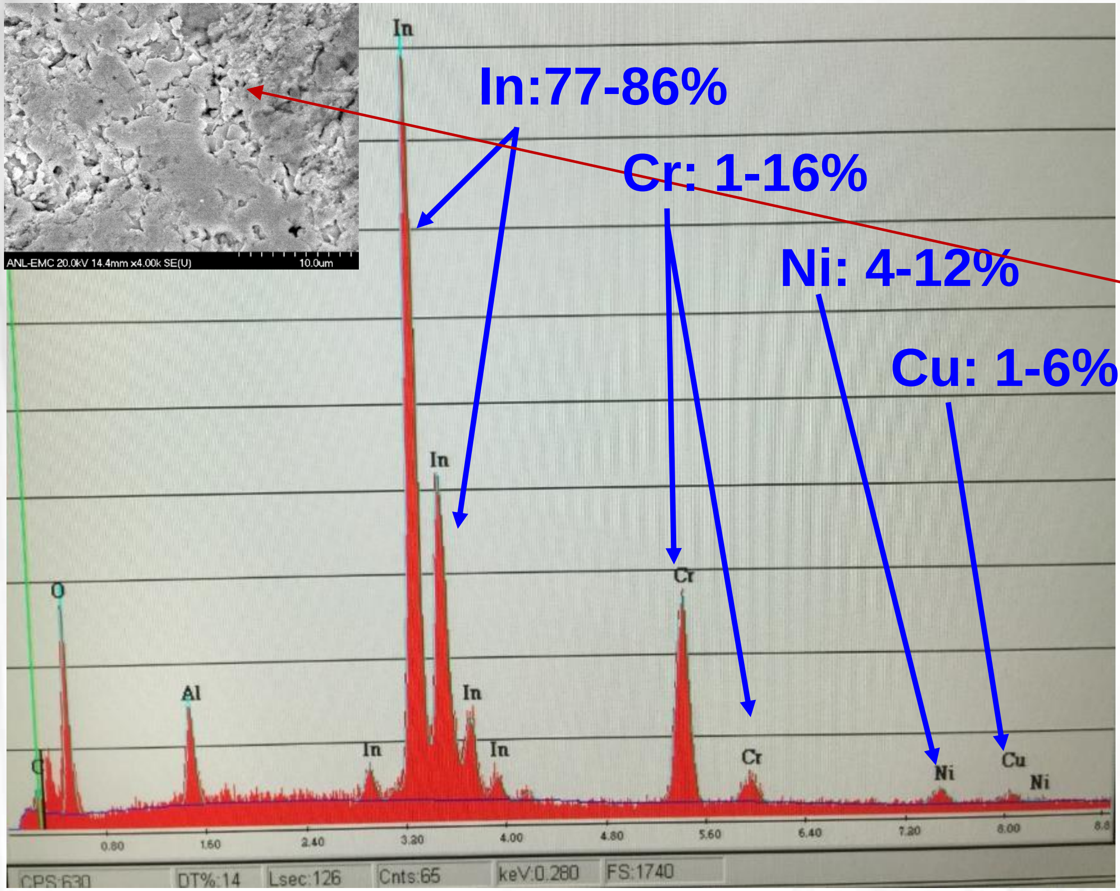
The ion etch number is a measure
for the depth of each XPS run

# Metallurgy of the Seal

High temperatures and long exposure time

- Indium penetrates through entire NiCr layer

## SEM and EDAX of the metal surface scraped at the interface



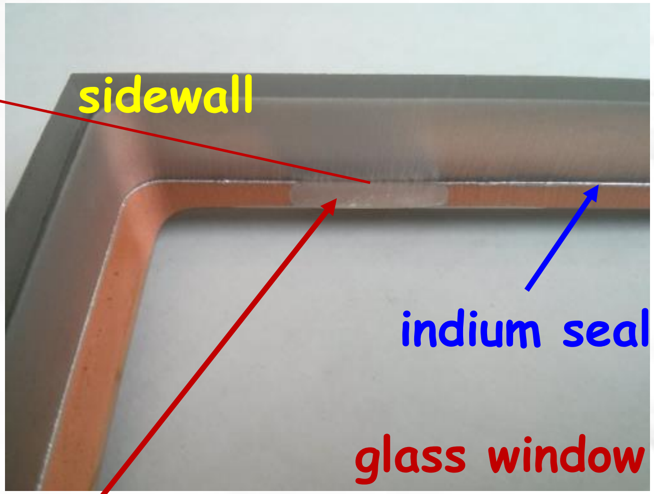
**In:77-86%**

**Cr: 1-16%**

**Ni: 4-12%**

**Cu: 1-6%**

Glass with NiCr-Cu metallization bonded by **pure In** at ~250C for 2hrs (it seals at these conditions)



Cut and scrape at the metal-glass interface

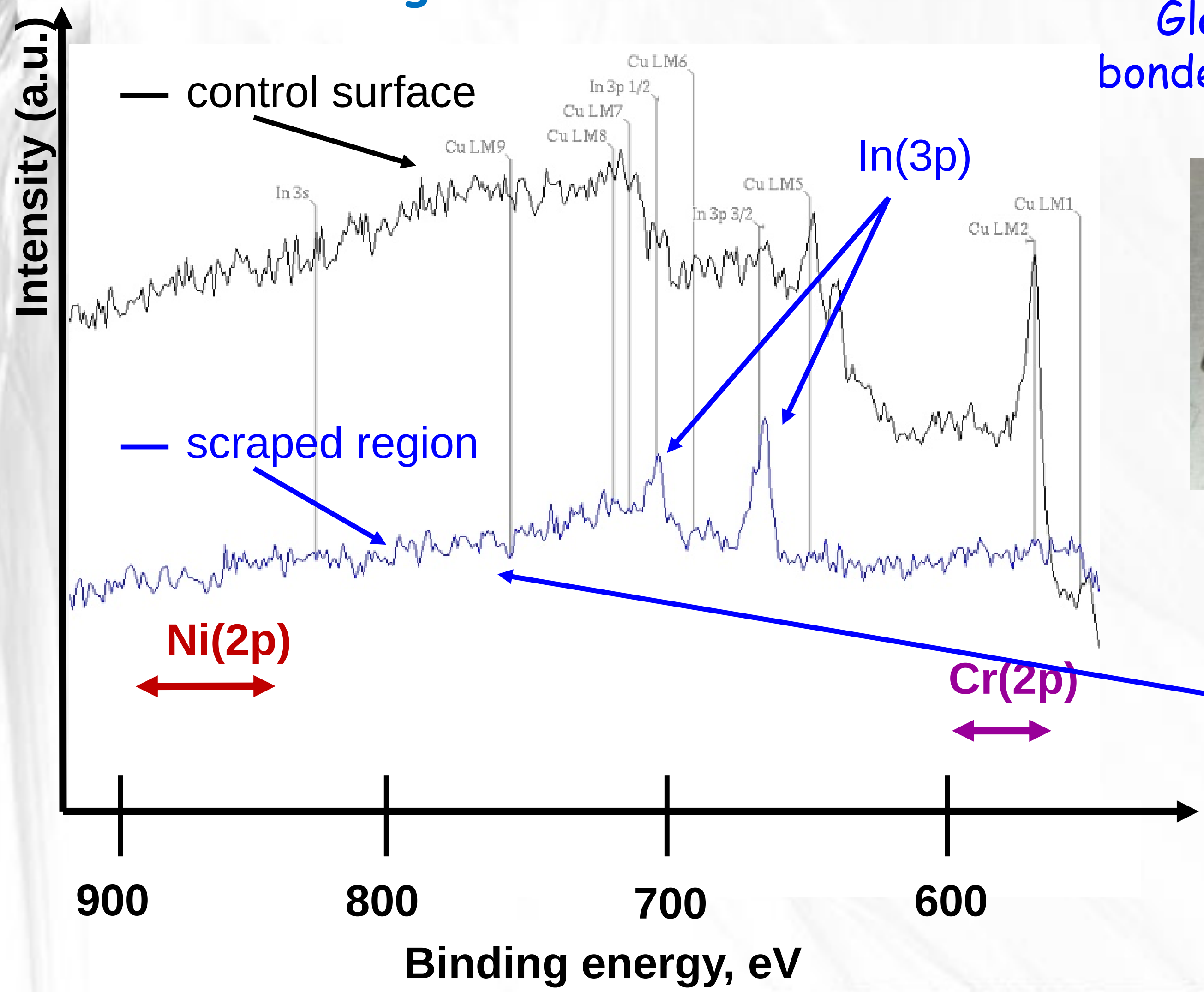
SEM/EDAX data courtesy of J. Elam at Argonne

# Metallurgy of a Good Seal

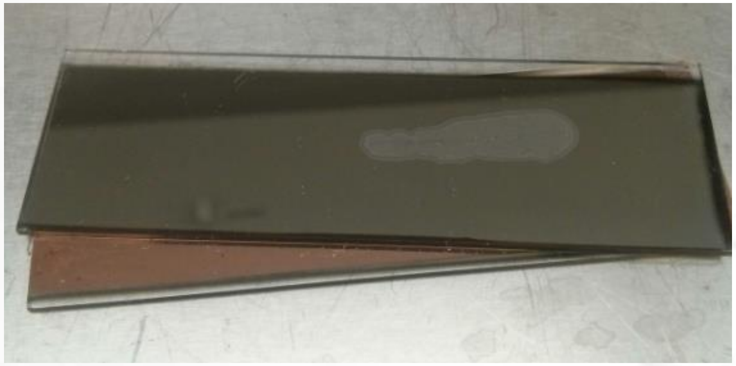
Higher temperatures and longer exposure time

- Indium penetrates through entire NiCr layer

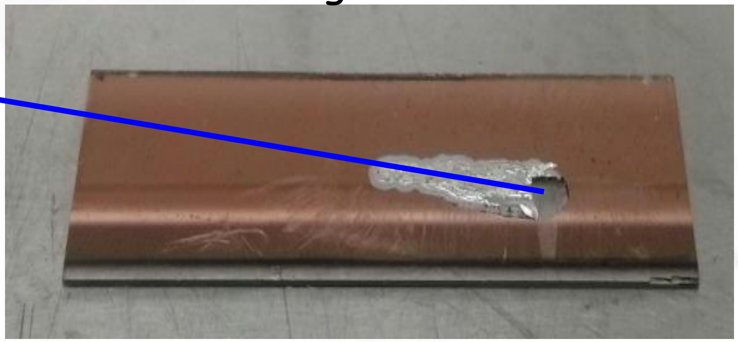
## XPS of the glass side of the interface



Glass with NiCr-Cu metallization
bonded by **pure In** at ~350C for 24hrs
(it seals at these conditions)



Cut and scrape at
the metal-glass interface



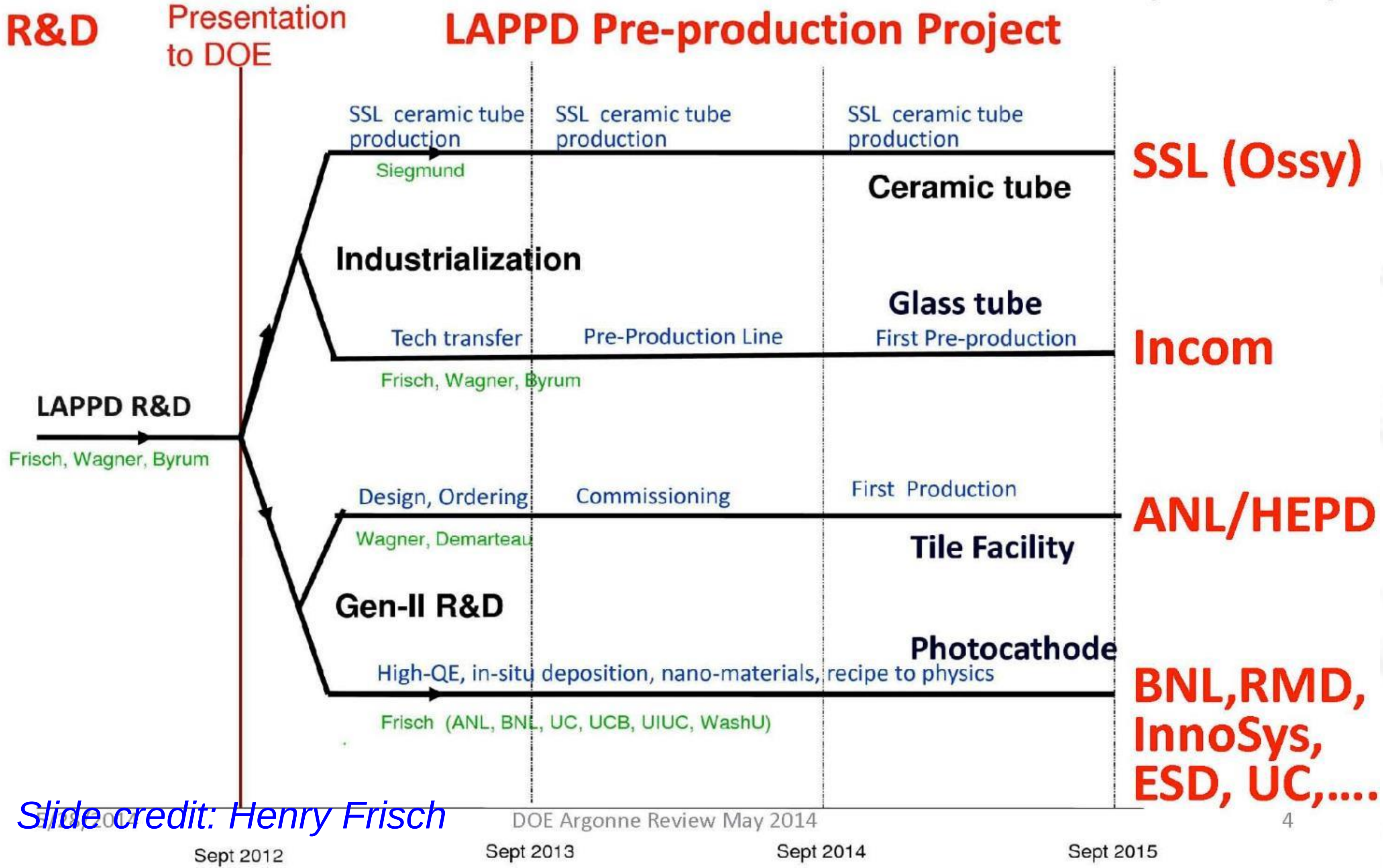
We now reliably seal
at 250-300C for 12-24hrs

XPS data courtesy of A. Filatov at UChicago

# The 2013 Transition from LAPPD to Production: The 4 Parallel Paths

**Dec 12, 2012 Presentation to DOE**

(a UC view)



**R&D**

Presentation to DOE

**LAPPD Pre-production Project**

**LAPPD R&D**

Frisch, Wagner, Byrum

**Industrialization**

SSL ceramic tube production

Siegmund

SSL ceramic tube production

SSL ceramic tube production

**Ceramic tube**

**SSL (Ossy)**

**Glass tube**

Tech transfer

Pre-Production Line

First Pre-production

Frisch, Wagner, Byrum

**Incom**

**Gen-II R&D**

Design, Ordering

Commissioning

First Production

Wagner, Demarteau

**Tile Facility**

**ANL/HEPD**

**Photocathode**

High-QE, in-situ deposition, nano-materials, recipe to physics

Frisch (ANL, BNL, UC, UCB, UIUC, WashU)

**BNL,RMD, InnoSys, ESD, UC,….**

Sept 2012

Sept 2013

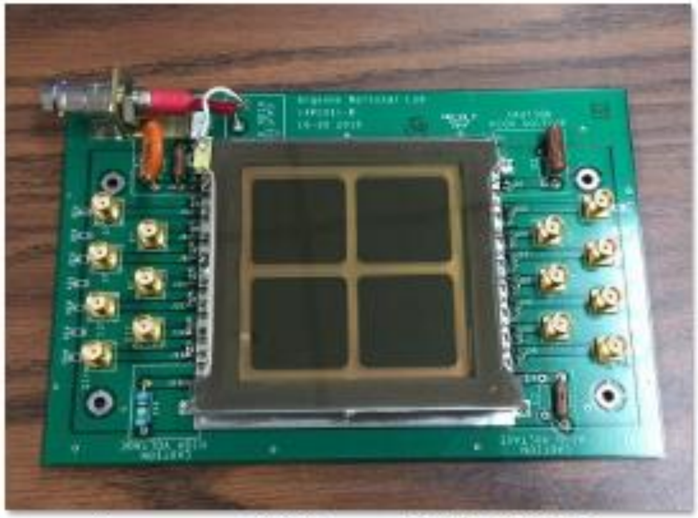
Sept 2014

Sept 2015

*Slide credit: Henry Frisch*

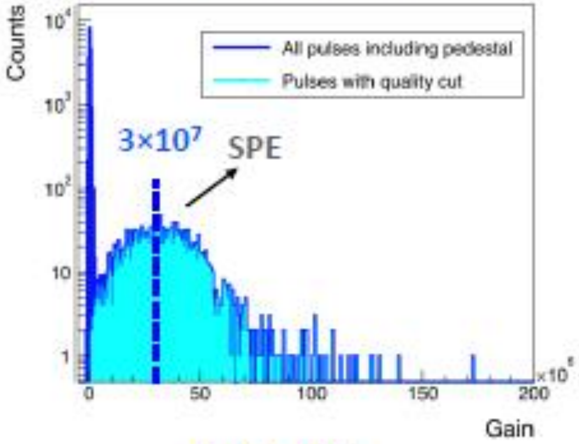
# Argonne 6x6 cm$^2$ Photo-Detectors

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



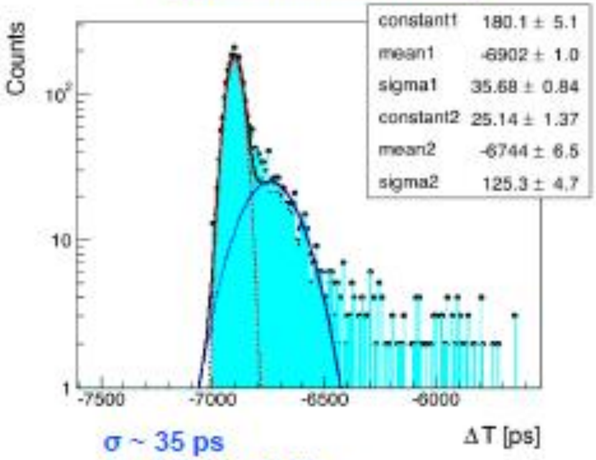
Argonne 6X6 cm MCP-PMT on custom readout board

**Gain distribution**



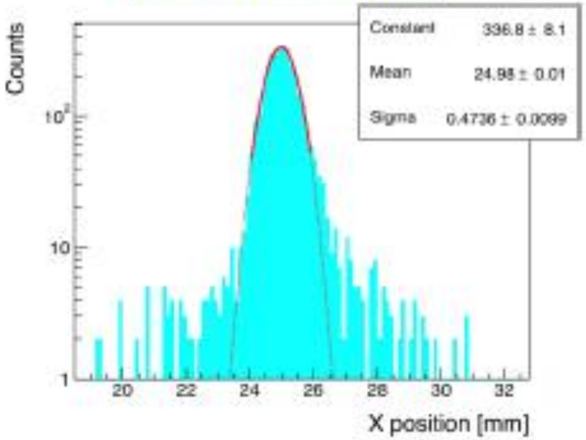
Gain > $10^7$

**Timing distribution**



σ ~ 35 ps for SPE, including Laser jitter

**Position resolution**



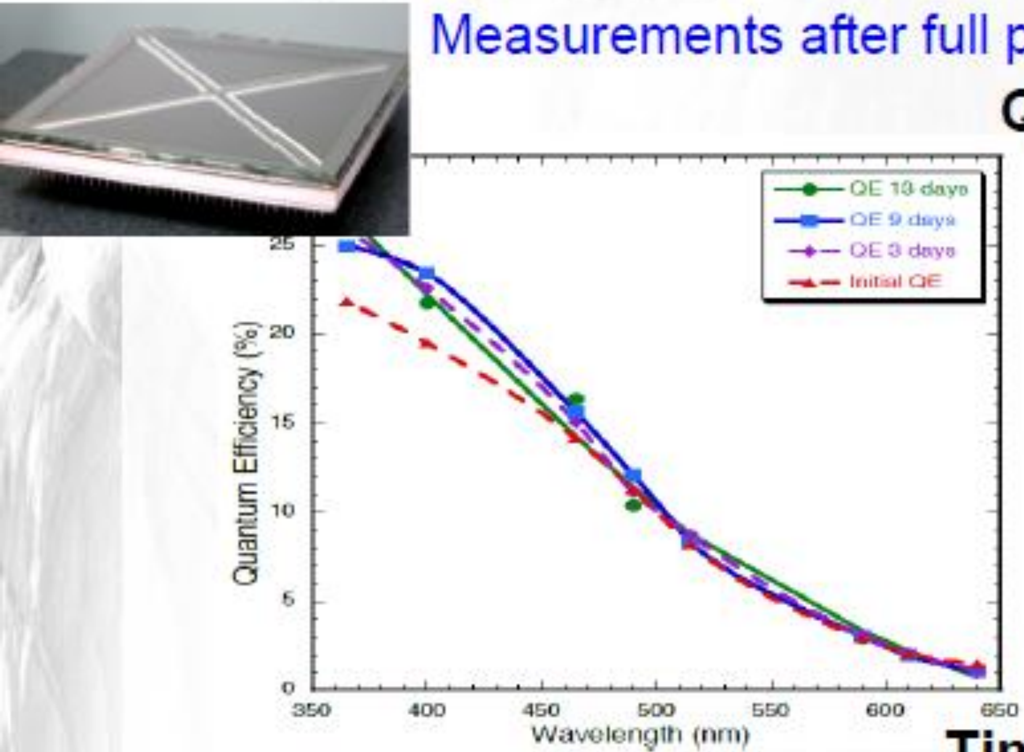
σ < 1 mm for SPE

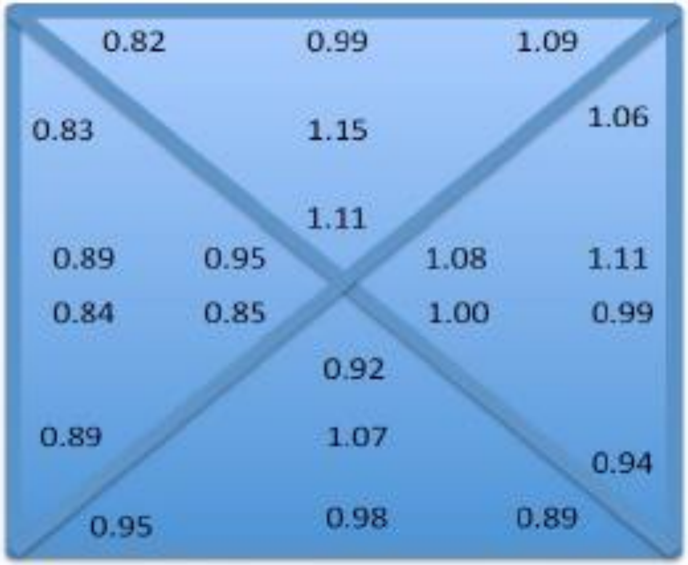
Slide courtesy of R. Darmapalan and R. Wagner

# SSL Ceramic LAPPD Tile Results

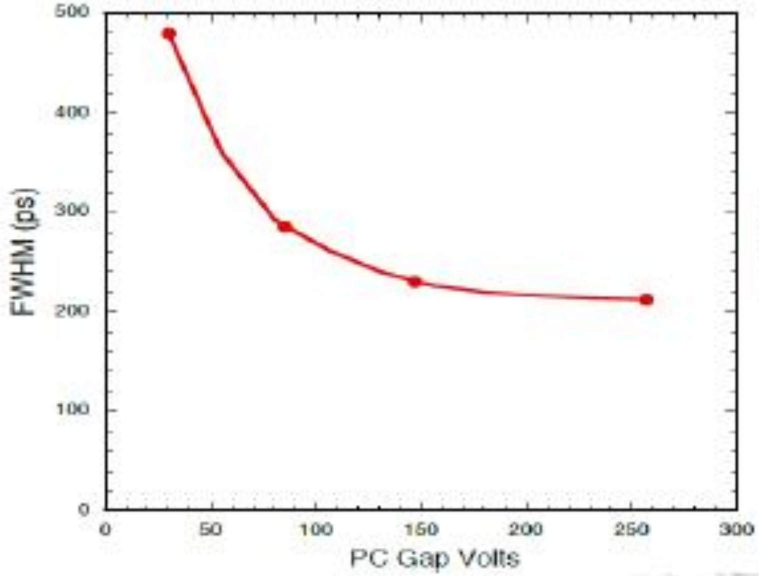
Measurements after full processing cycle inside the vacuum chamber

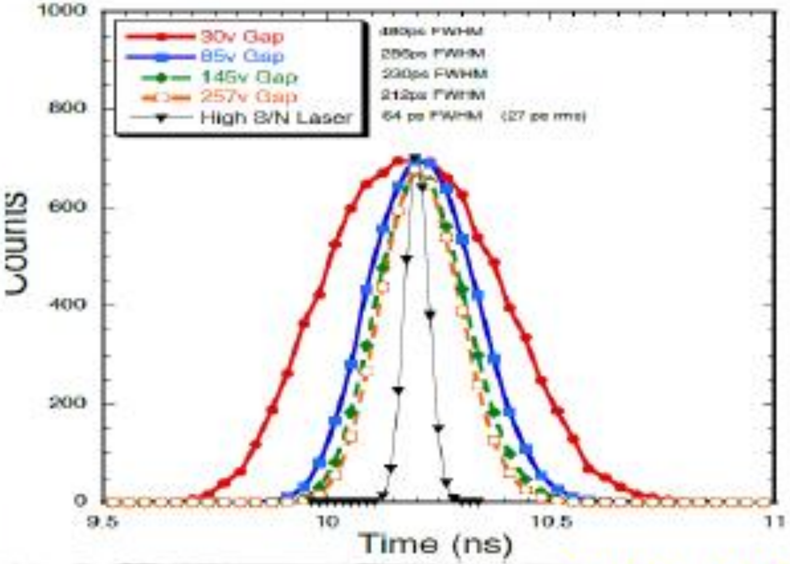
## QE





## Timing

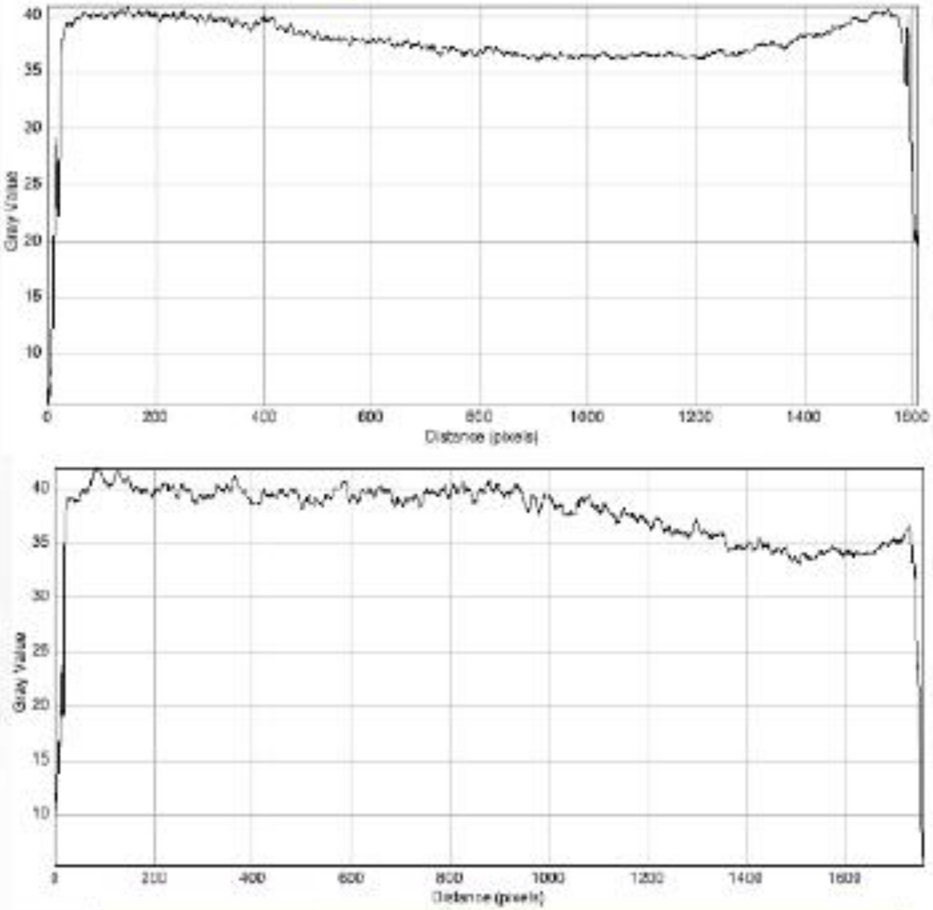




2014 JINST 9 C04002

# Gain Uniformity

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



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

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

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