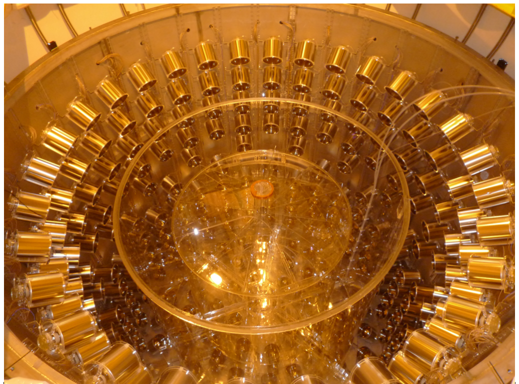
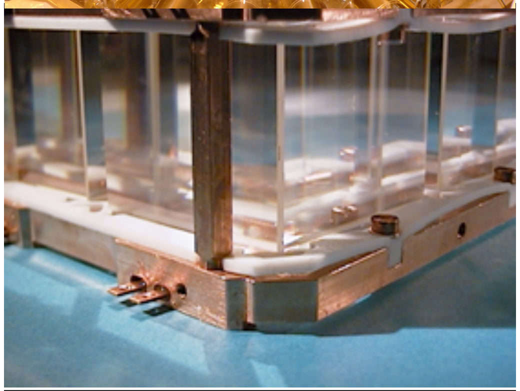
reVolution





Neutrinos and Nanotechnology

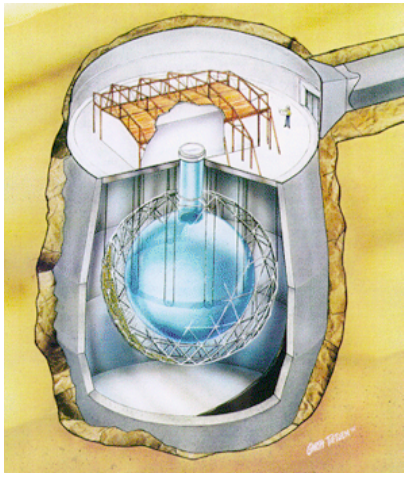
Lindley Winslow
Massachusetts Institute of Technology

Neutrino Detectors

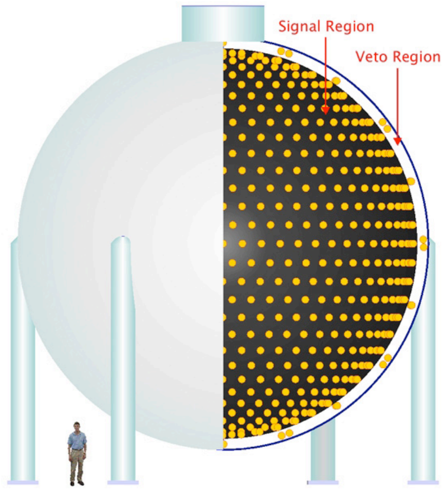
Why neutrino physics needs metal doped scintillator

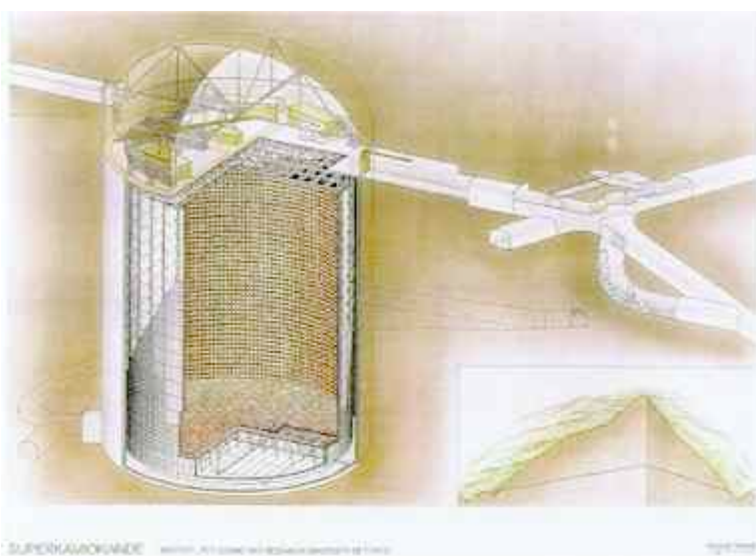
Quantum-Dot-Doped Scintillator

Cerenkov Light

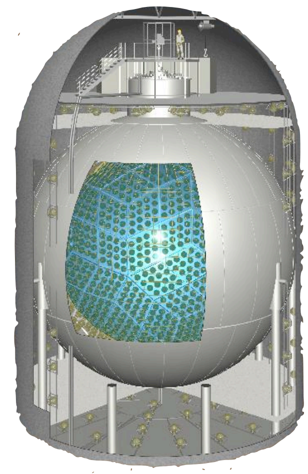


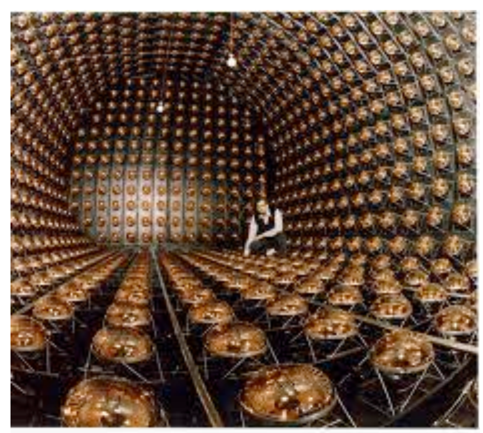
MiniBooNE Detector

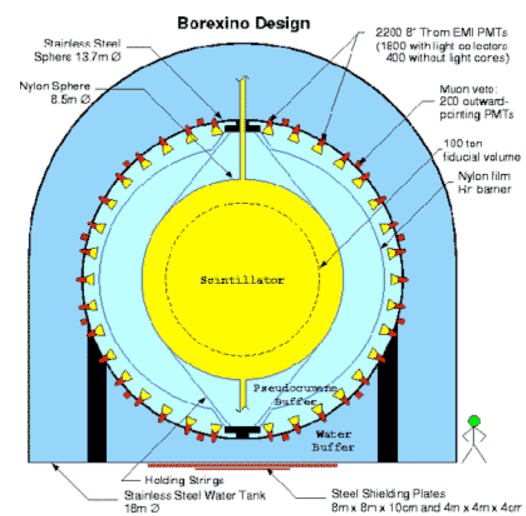




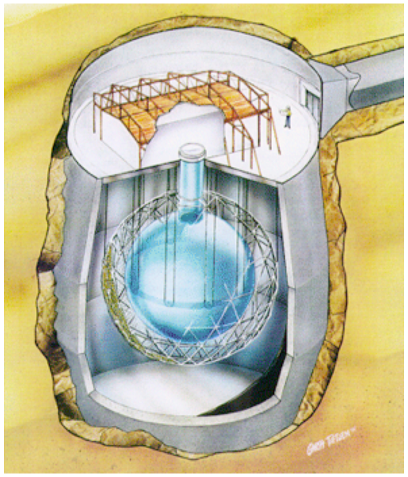
Scintillation Light



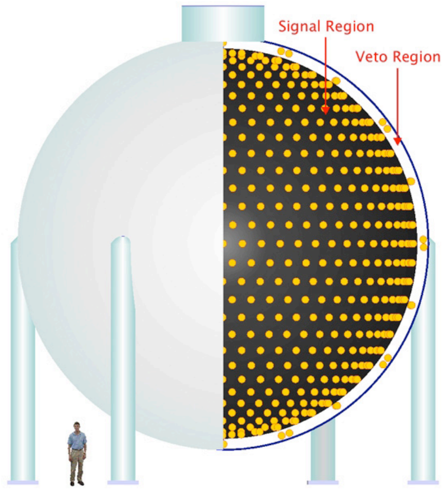


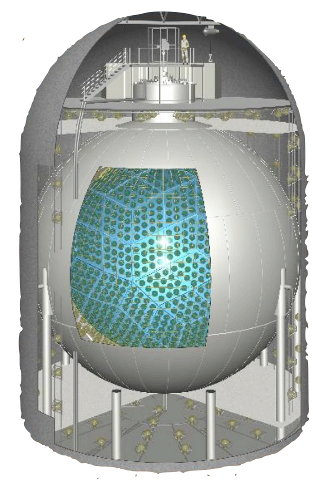


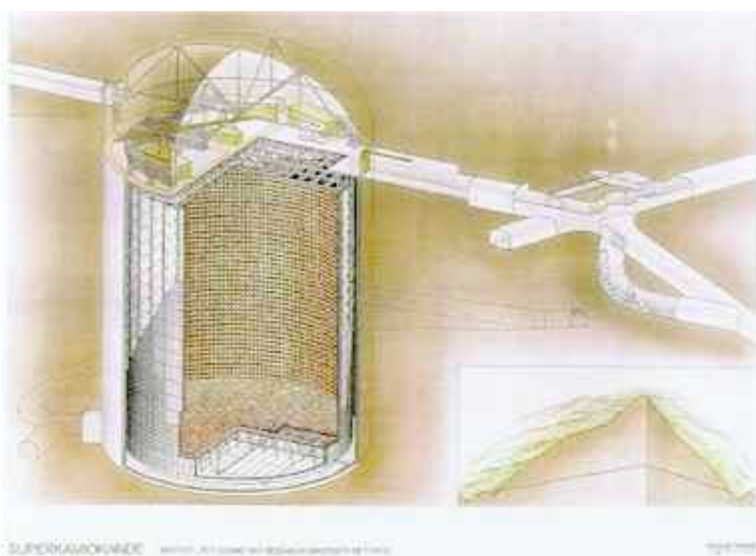
Directionality



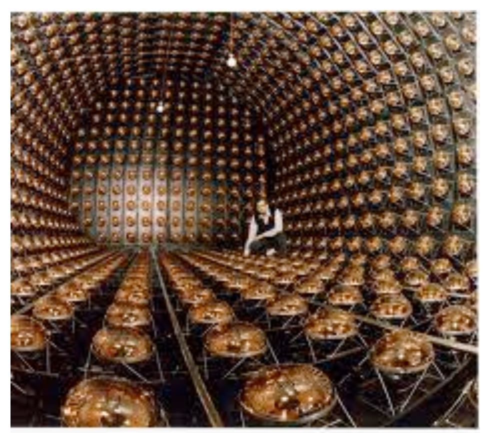
MiniBooNE Detector

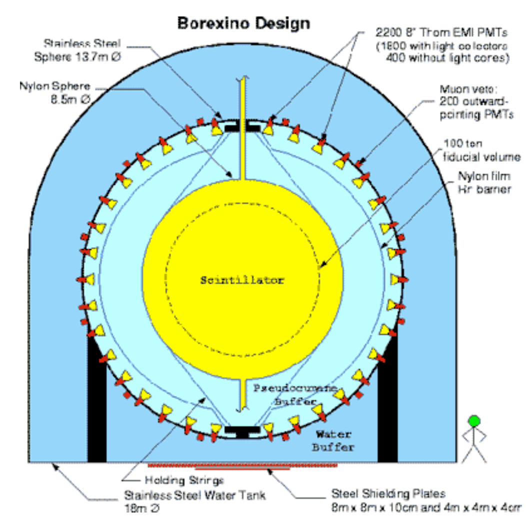


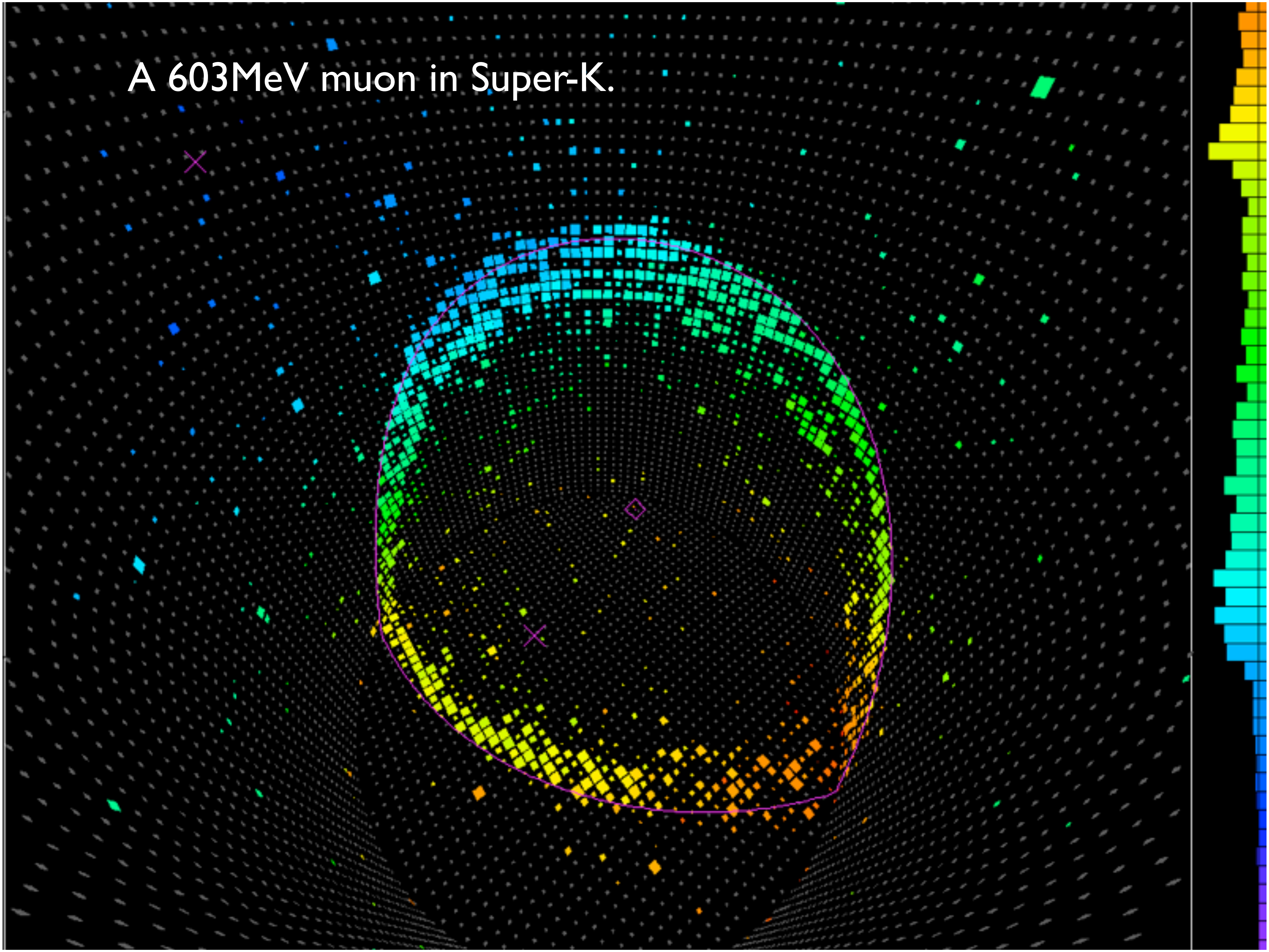


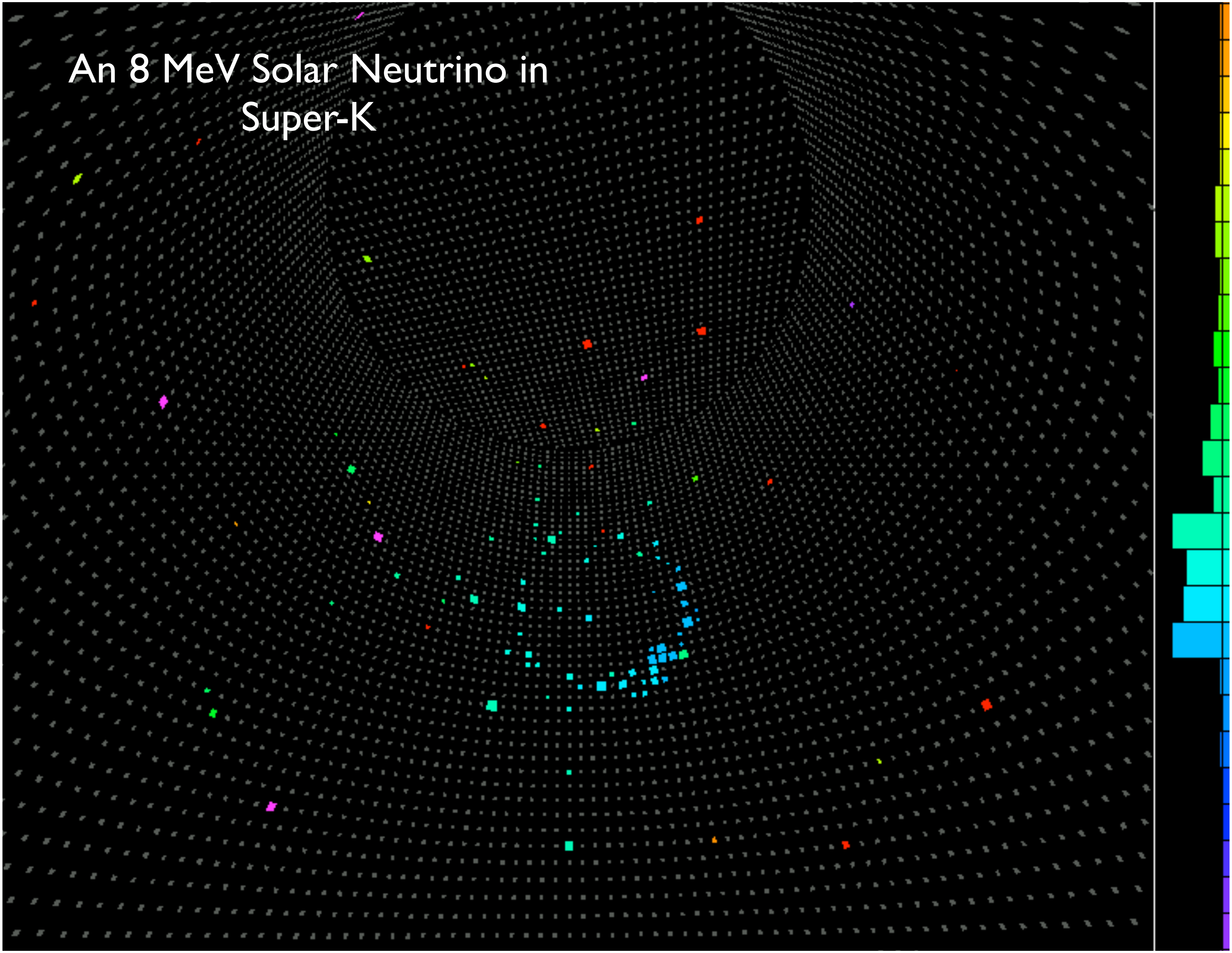


Energy Resolution

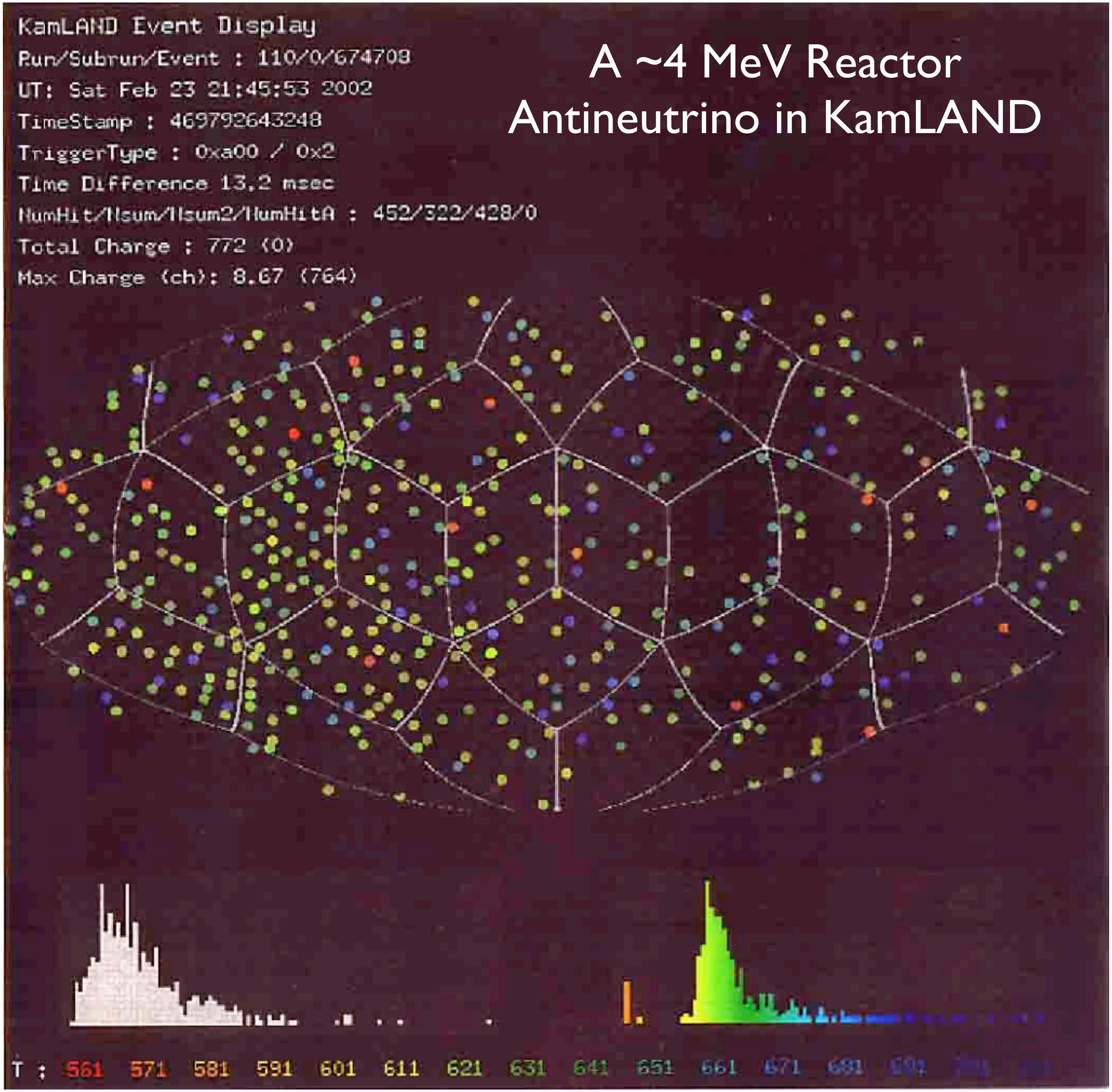





A 603MeV muon in Super-K.

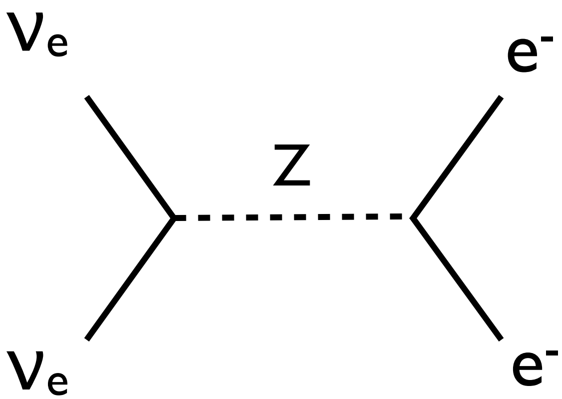

An 8 MeV Solar Neutrino in
Super-K

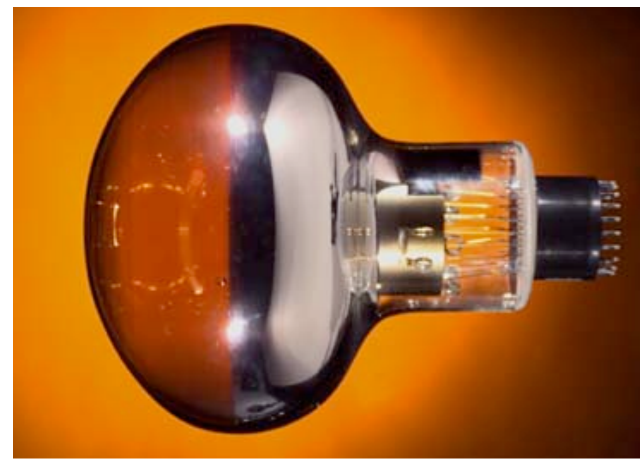
A ~4 MeV Reactor Antineutrino in KamLAND



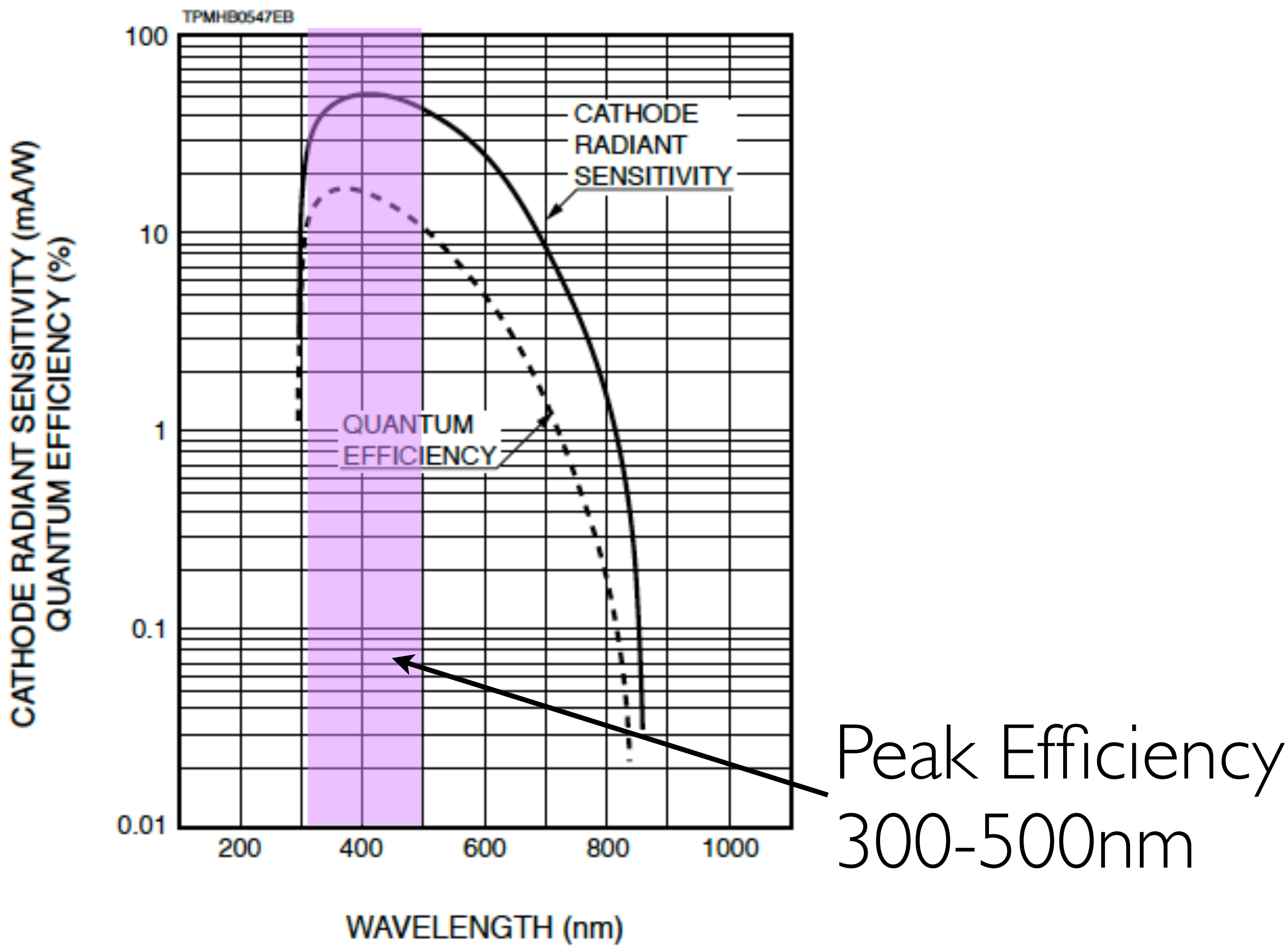
Basic Principle of Neutrino Detectors

Physics → Light → PMTs





Typical PMT Detection Efficiency:



Tune Scintillator Emmission:

Nuclear Instruments and Methods in Physics Research A 440 (2000) 360 } 371

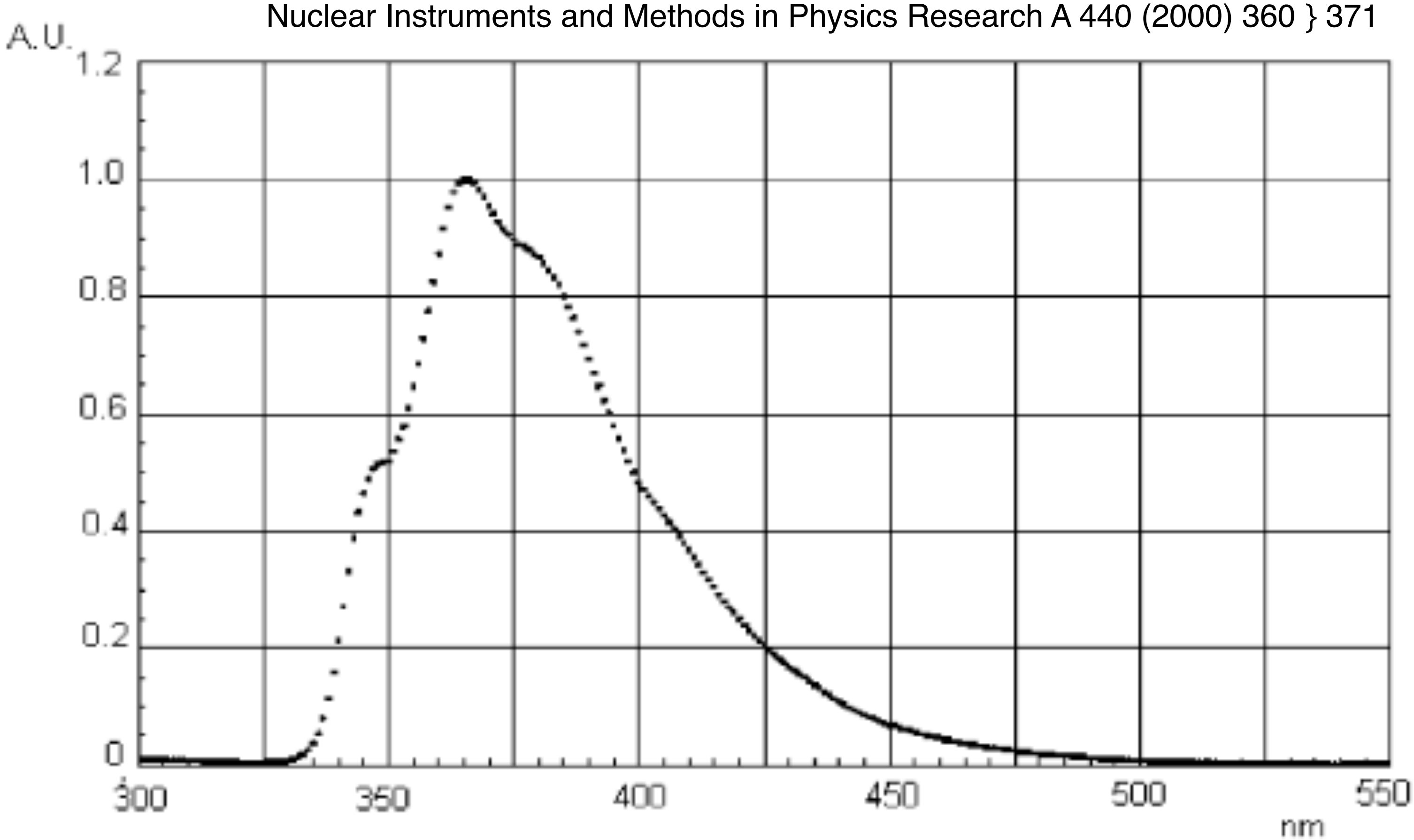
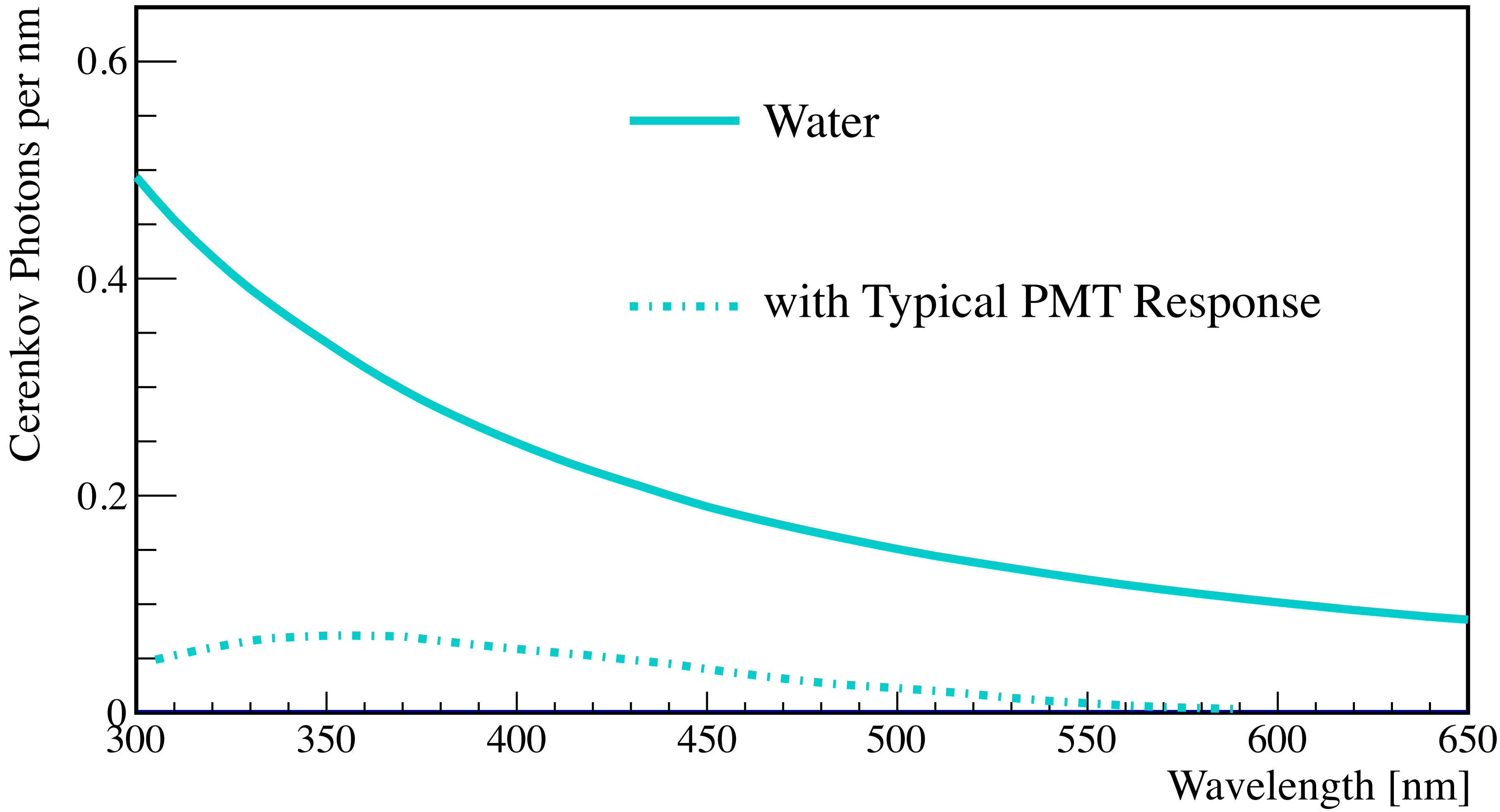


Fig. 1. PC + PPO (1.5 g/l) emission spectrum.

Example is Borexino Scintillator.

Water Cerenkov Detectors:



Or make due with higher thresholds and poorer energy resolution.

Detector = Target

Doping Detectors with Metals

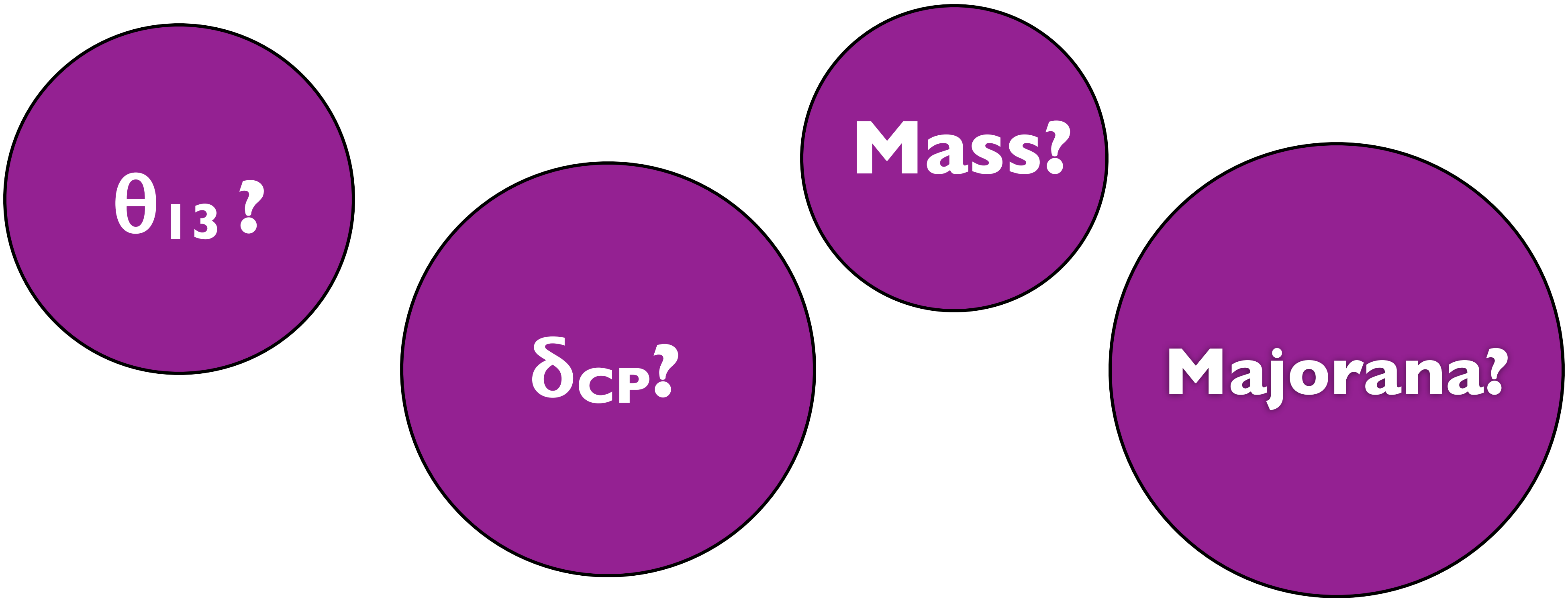
Why?

Neutron Capture Cross Sections

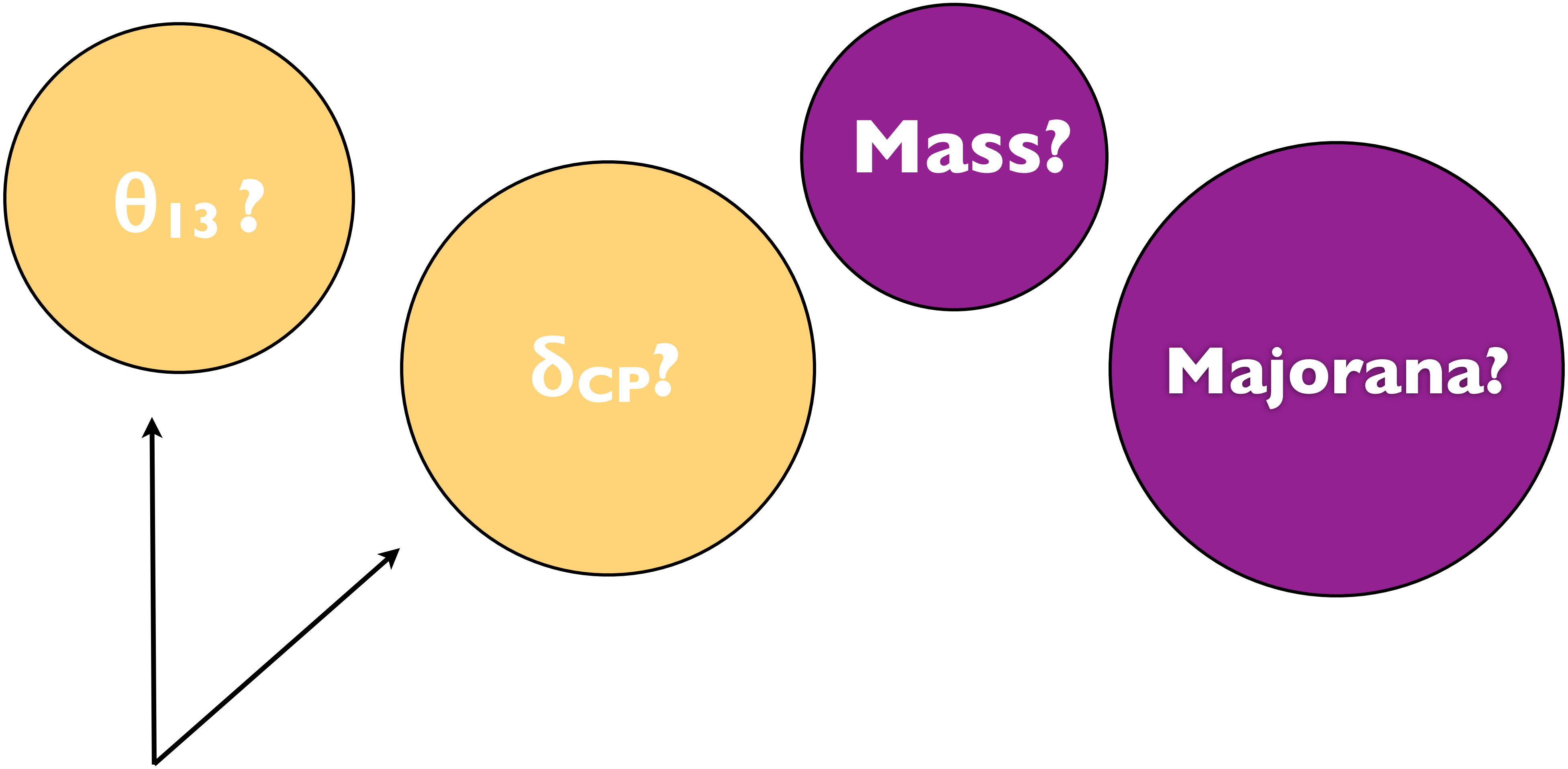
250,000b	**^{157}Gd**
60,000b	**^{155}Gd**
20,000b	**^{113}Cd**
43b	**^{35}Cl**
0.3b	**^{1}H**

Why physics leads us to metal doped scintillators...

As of a year ago these were the main questions at the forefront of **3** neutrino model:

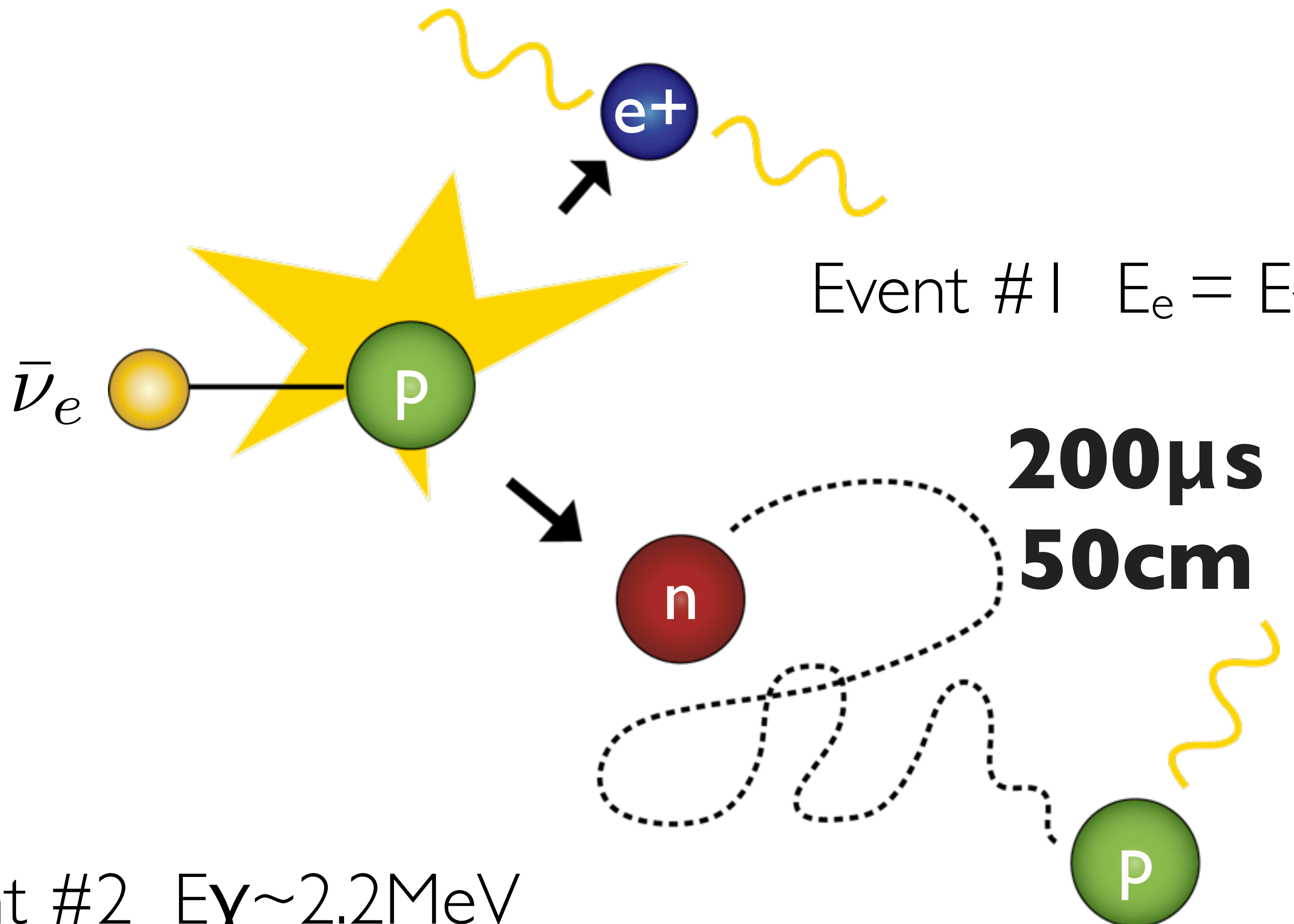


- What is the value of θ_{13}?
- Is there CP Violation in the neutrino sector?
- Absolute mass scale and hierarchy?
- Are neutrinos Majorana?



These experiments can be done with low energy antineutrinos and inverse beta decay interactions.

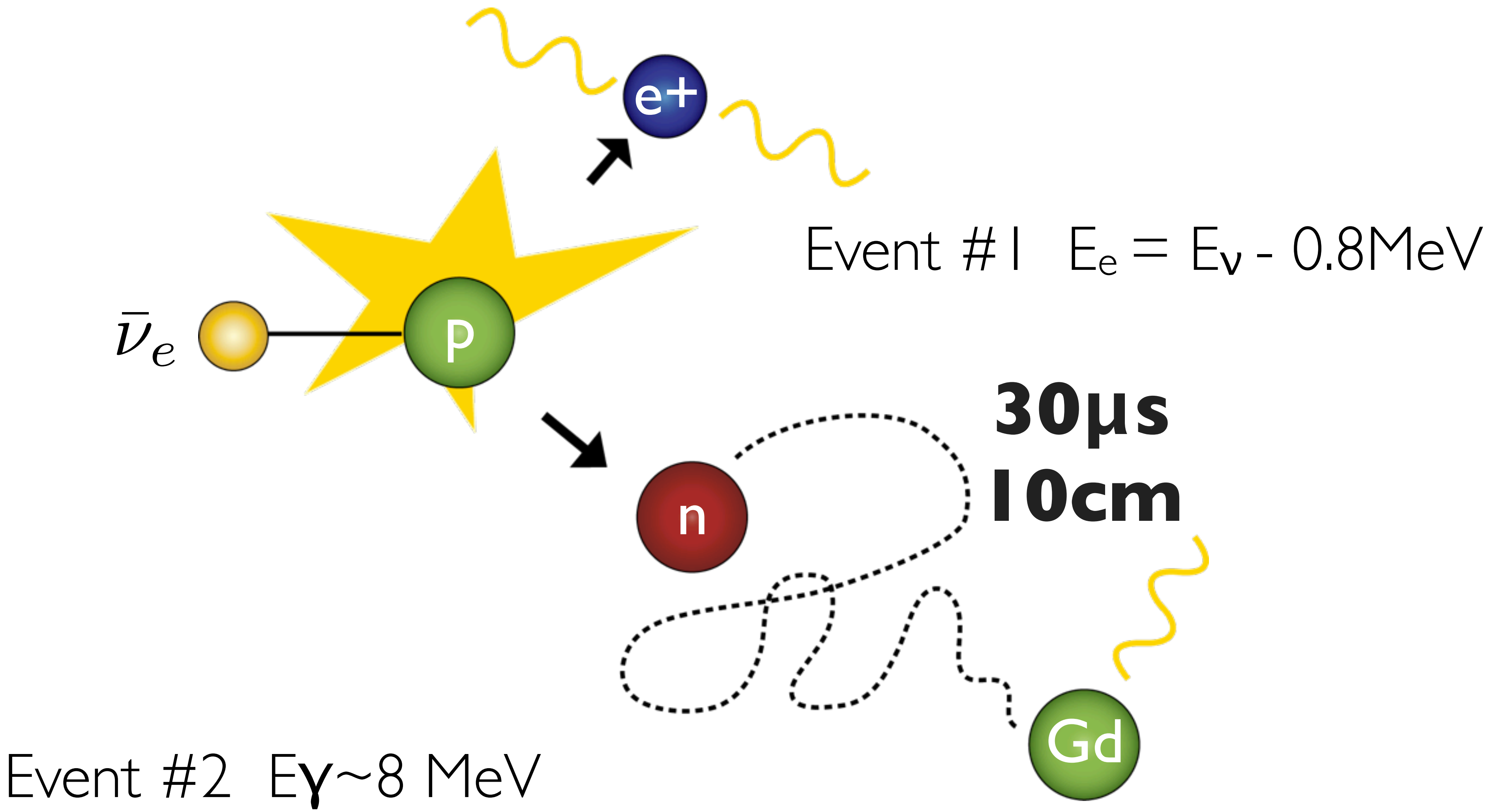
The Signal: Inverse Beta Decay



Event #1 $E_e = E_\nu$ - 0.8MeV

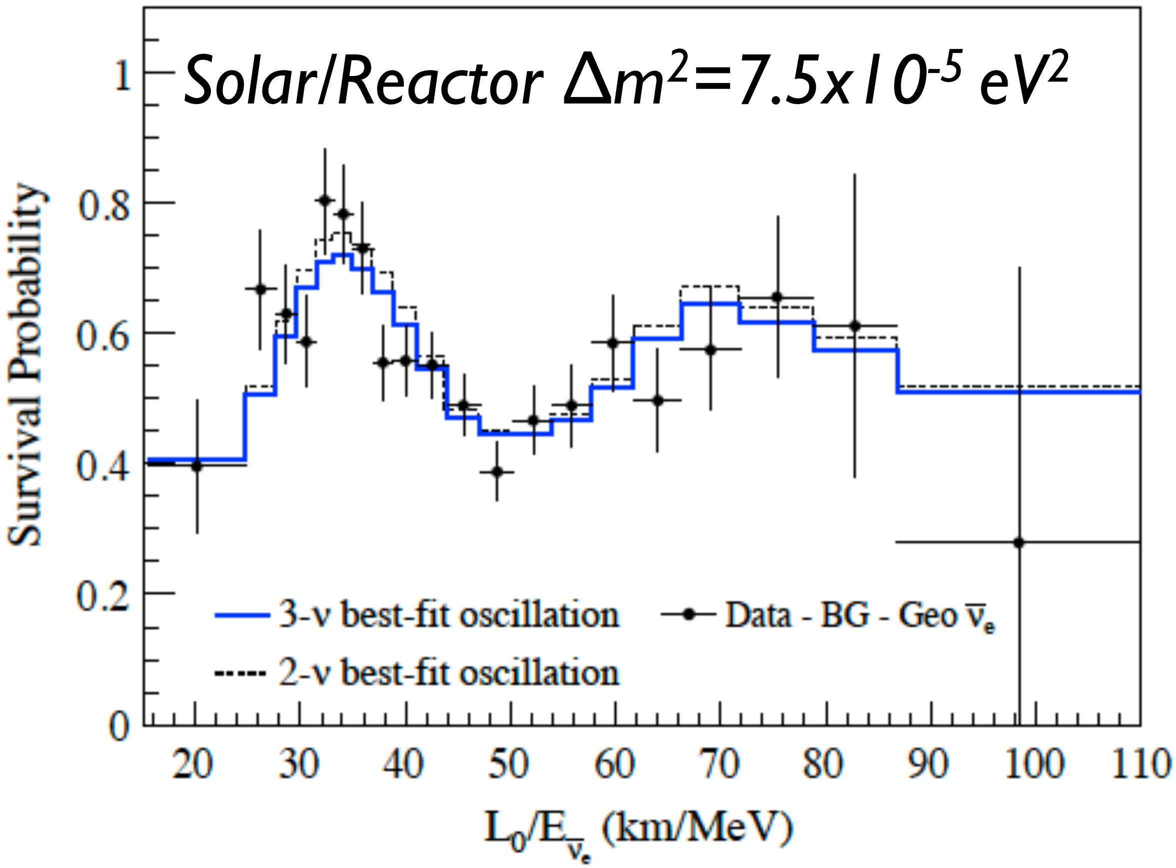
Event #2 E_γ~2.2MeV

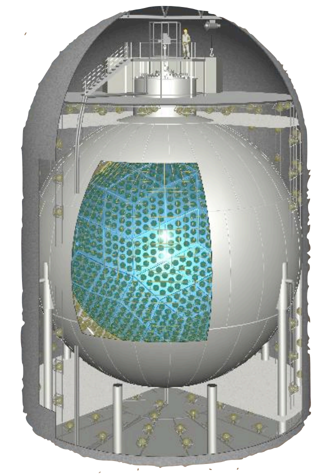
The Signal with Gd:



KamLAND Data:

$$P_{survival} = 1 - \sin^2 2\theta \sin^2\left(\frac{1.27\Delta m^2 L}{E}\right)$$





You can do oscillation physics with IBD events but...

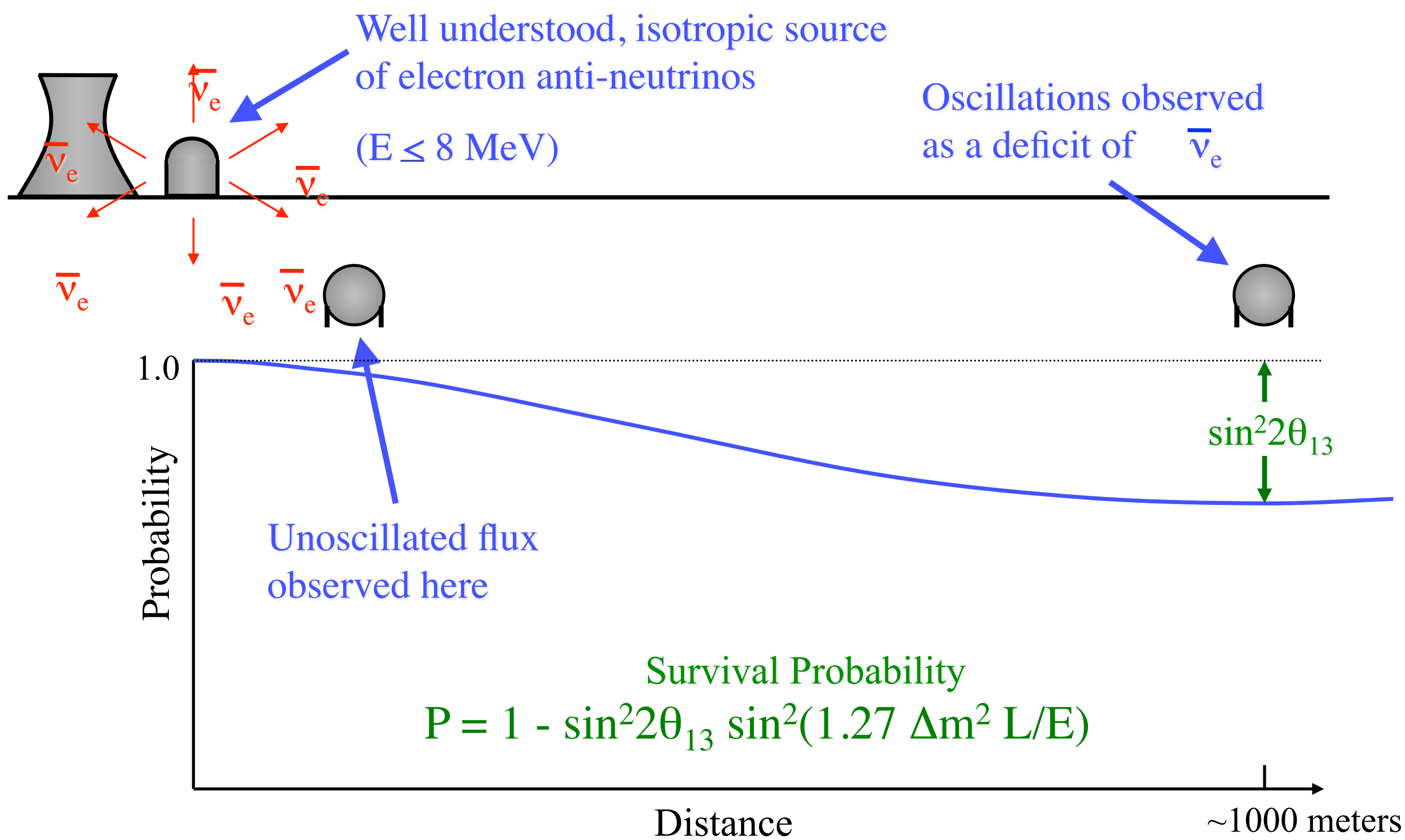
see Phys.Rev. D83 (2011) 052002

Your detector needs to be:

- Large (capture length ~50cm)
- Underground (capture energy 2.2MeV)

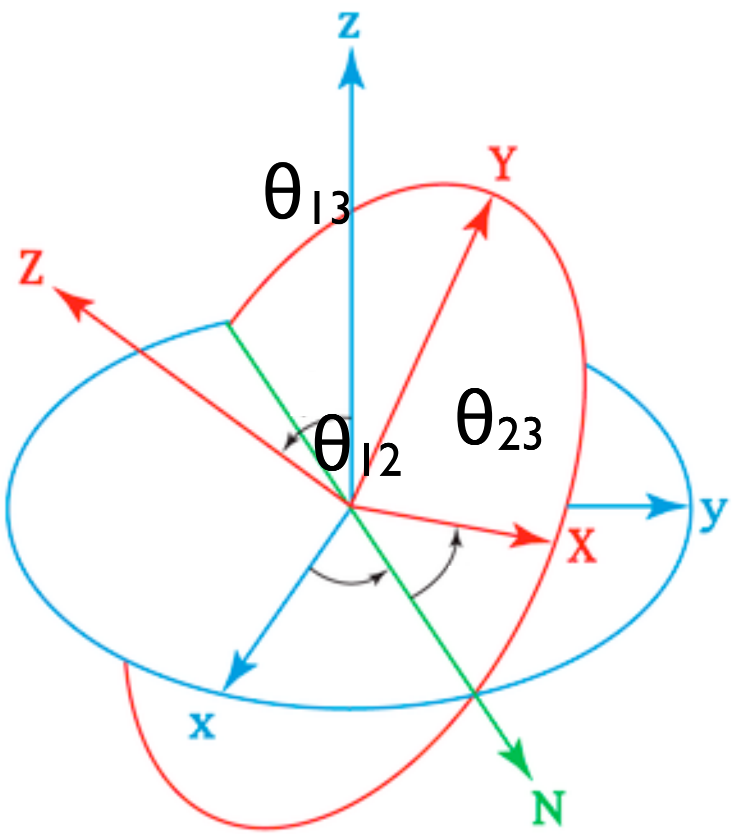
Adding a metal like Gd allows more flexibility in size and depth.

A Perfect Example the reactor experiments:



Drawing by A. Kaboth

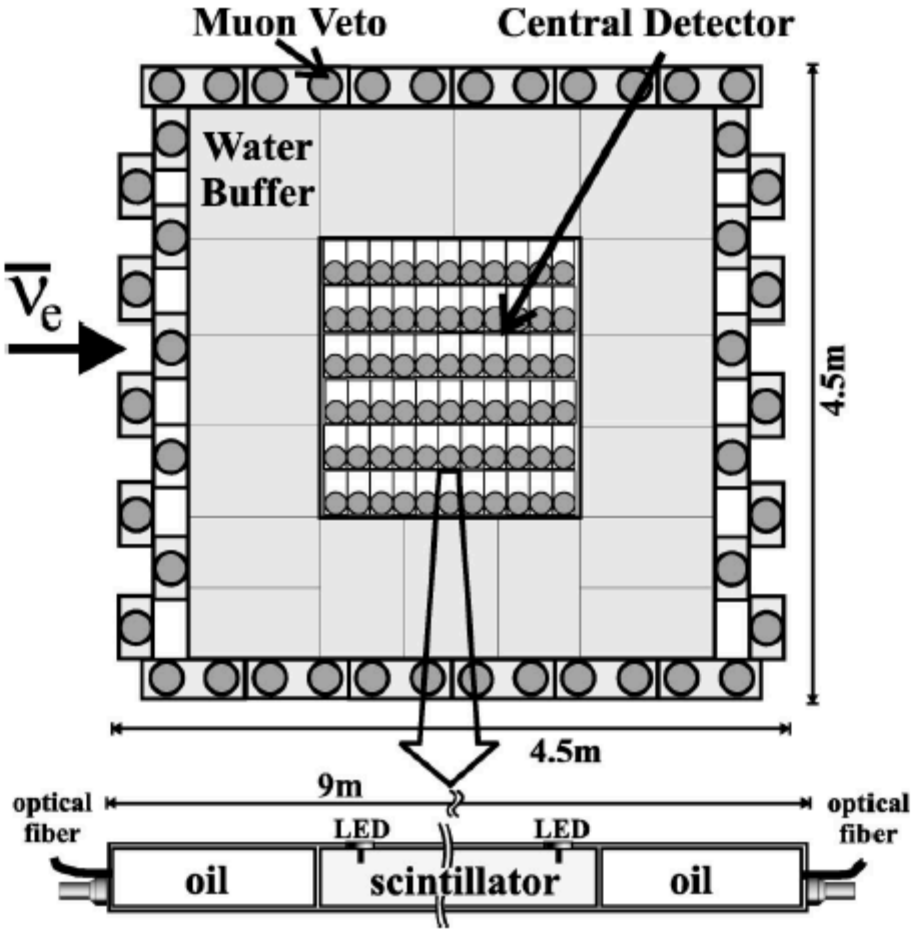
θ_{13} ?



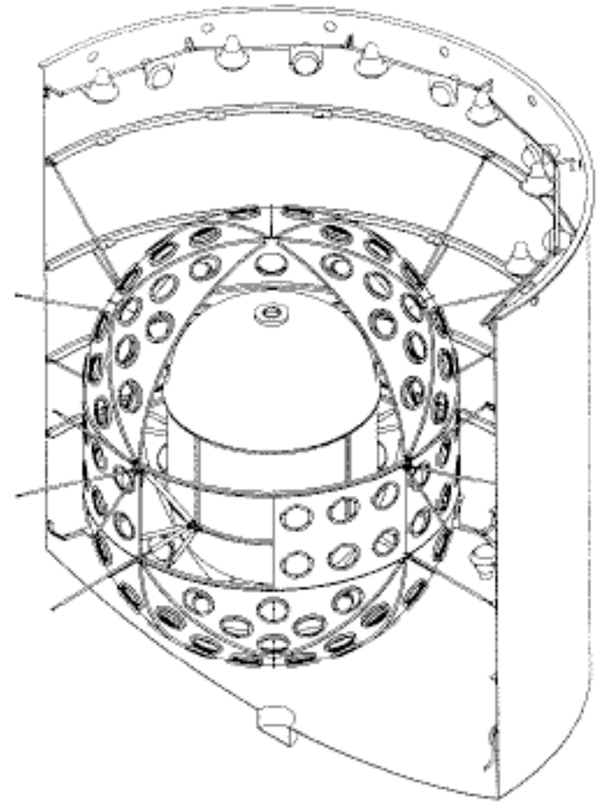
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Three neutrino mixing will be defined by three mixing angles and two independent mass differences.

Palo Verde



Chooz



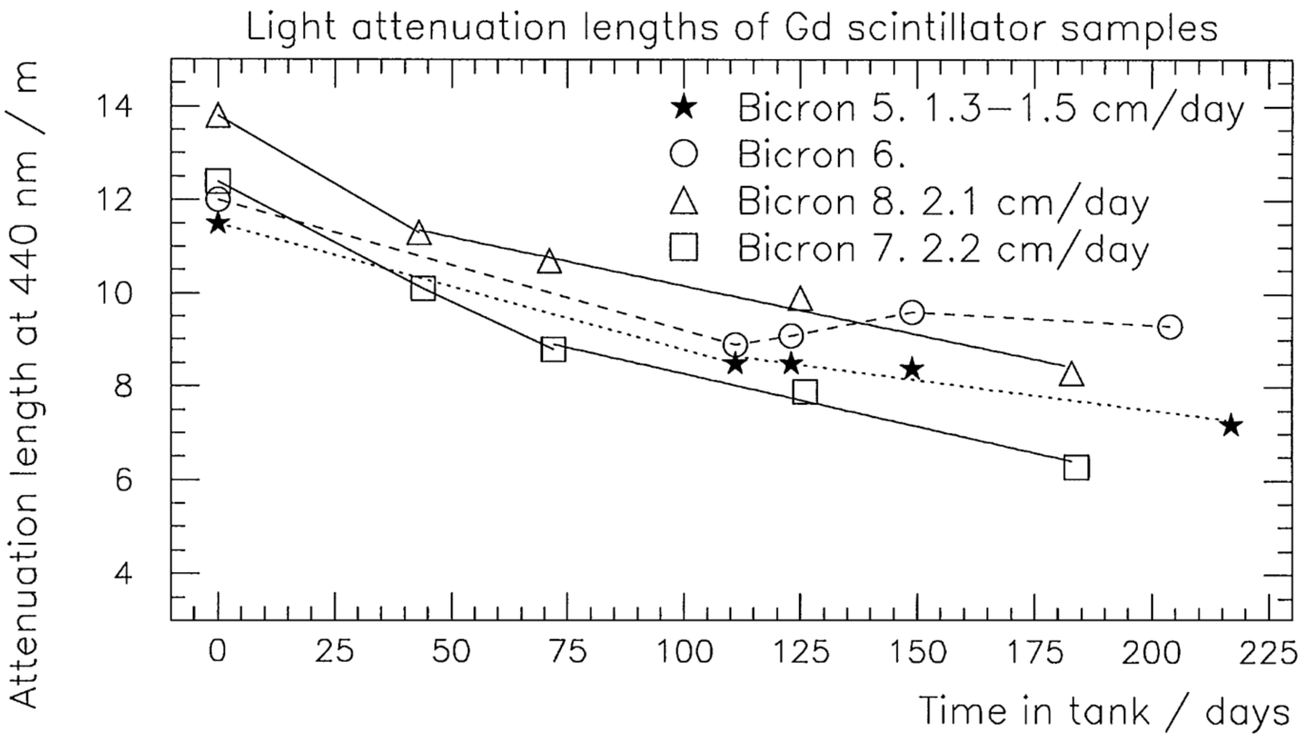
The Previous Generation

To use smaller detectors at shallow depth, they both used Gd doped scintillator:

- Palo Verde ~11 tons gadolinium 2-ethylhexanoate in PC + MO + compounds for wavelength shifting.

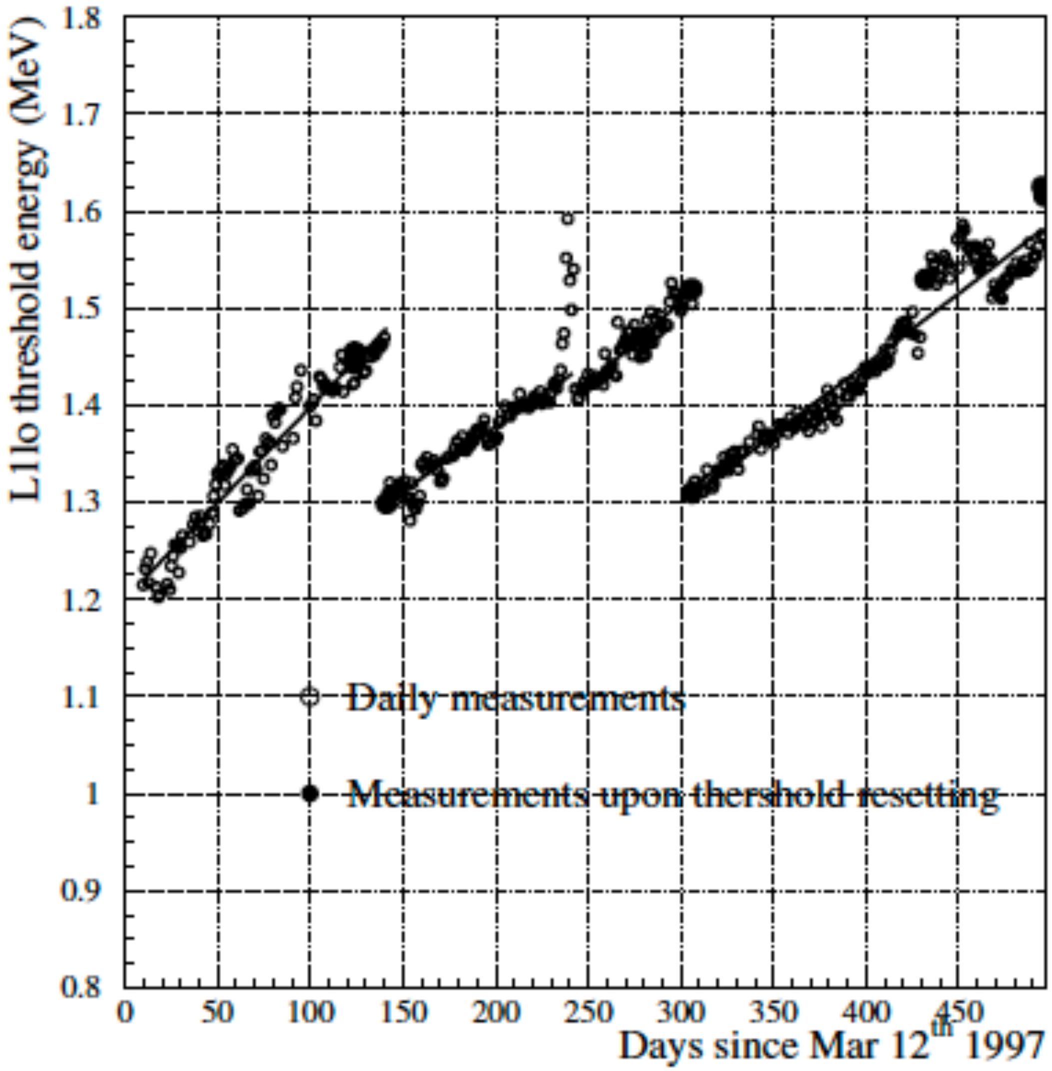
- Chooz ~5 tons gadolinium salt ($Gd(NO_3)_3$) in hexanol + MO + compounds for wavelength shifting.

Aging of the Palo Verde Scintillator:



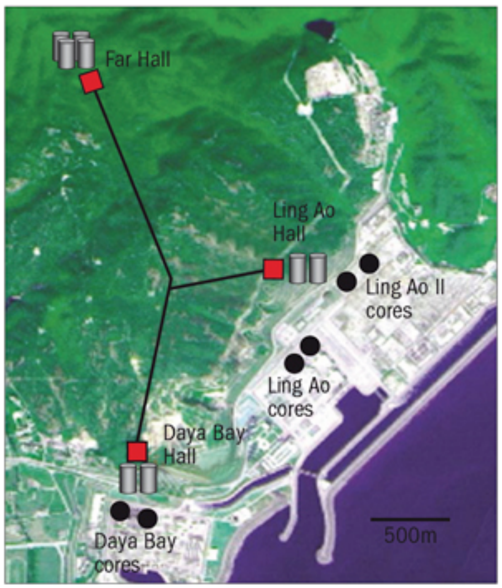
Making stable metal doped scintillator is tricky.

Chooz's rising threshold:



Instability affect quality of data and duration of data taking.

Today's experiments:



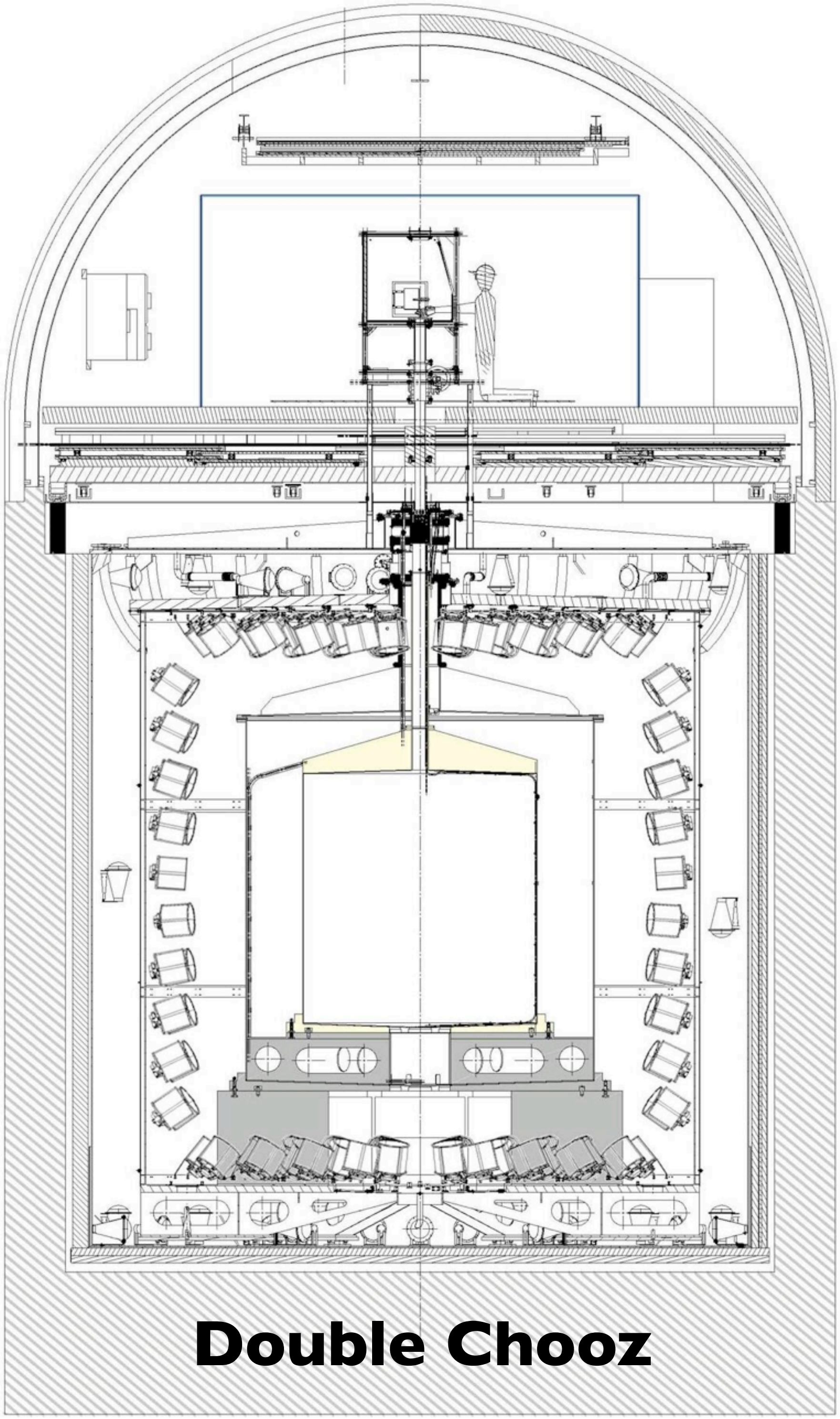
arXiv:hep-ex/0701029v1

arXiv:1003.1391v1

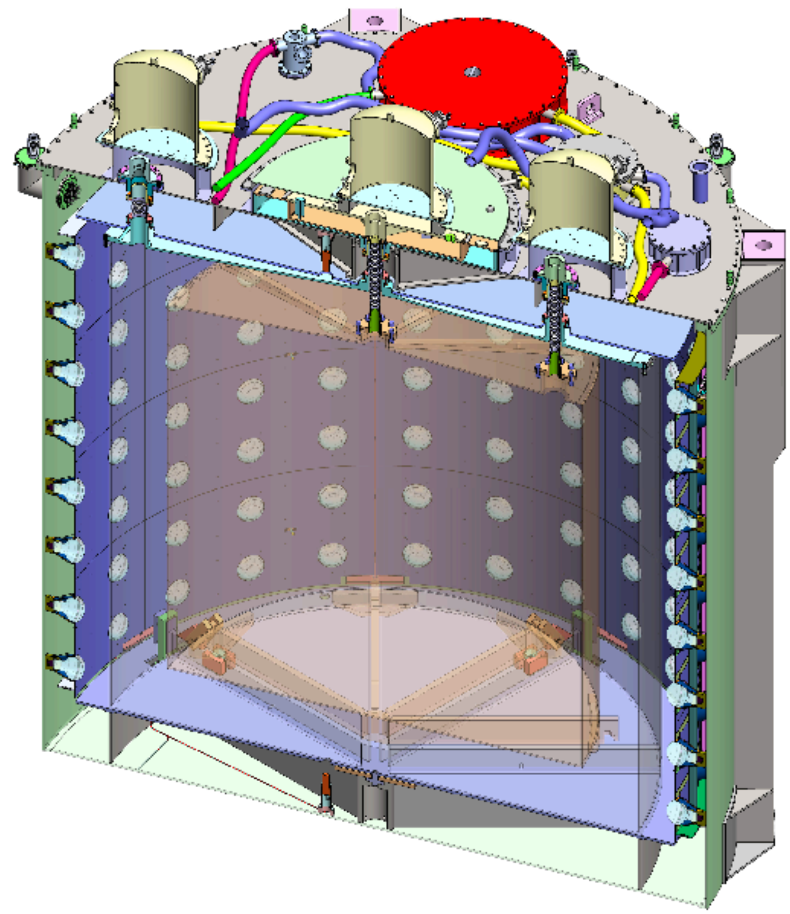
arXiv:hep-ex/0606025v4

A lot of research went into the scintillator.

Scintillation based detectors with concentric design around target of Gd doped scintillator.

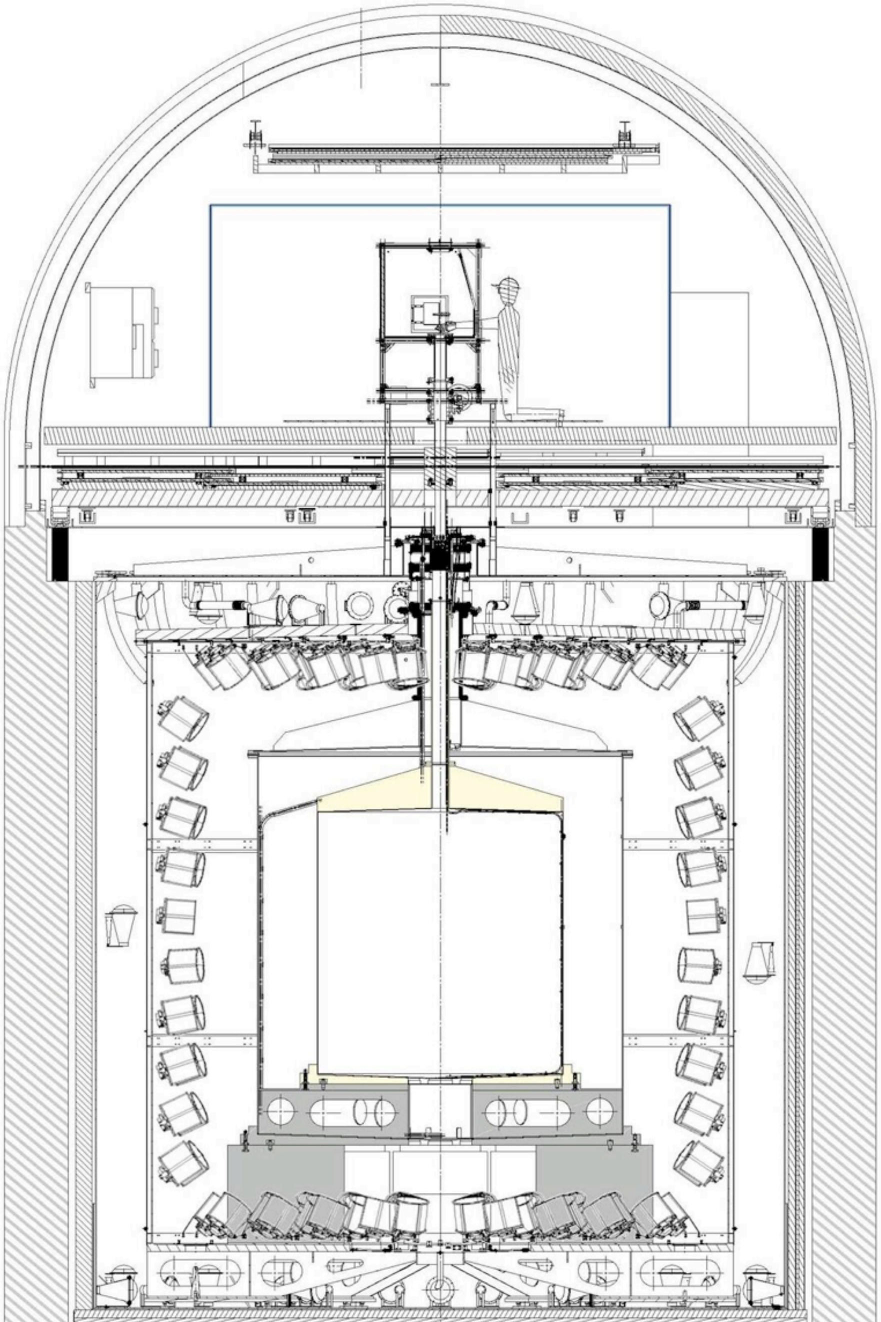


Double Chooz

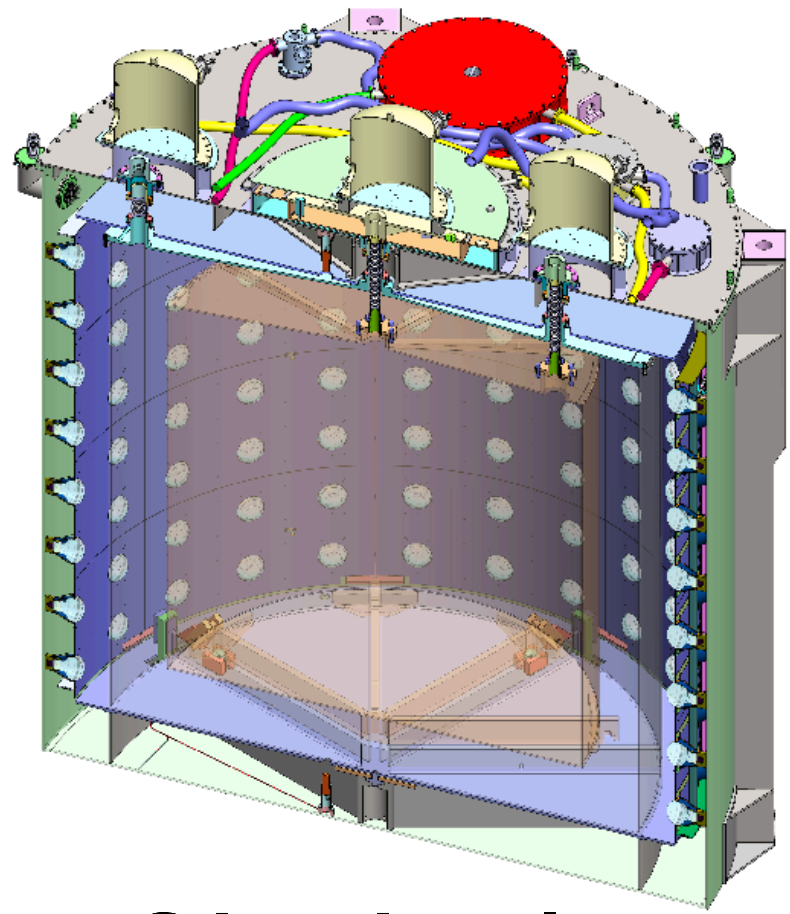


Daya Bay

Much work on the stability of Gd compounds in scintillator.

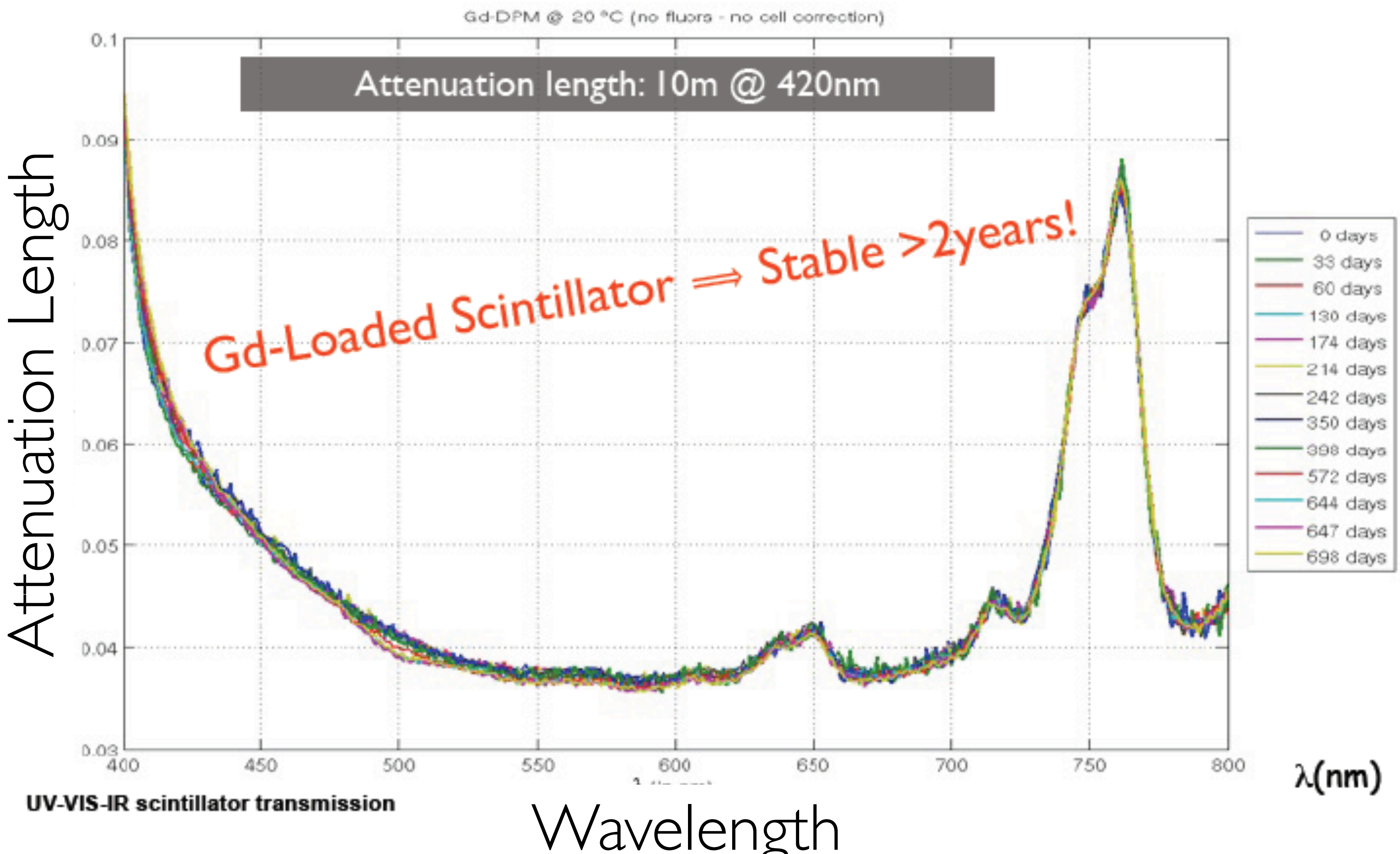


Gd-β-diketonate +PXE+MO

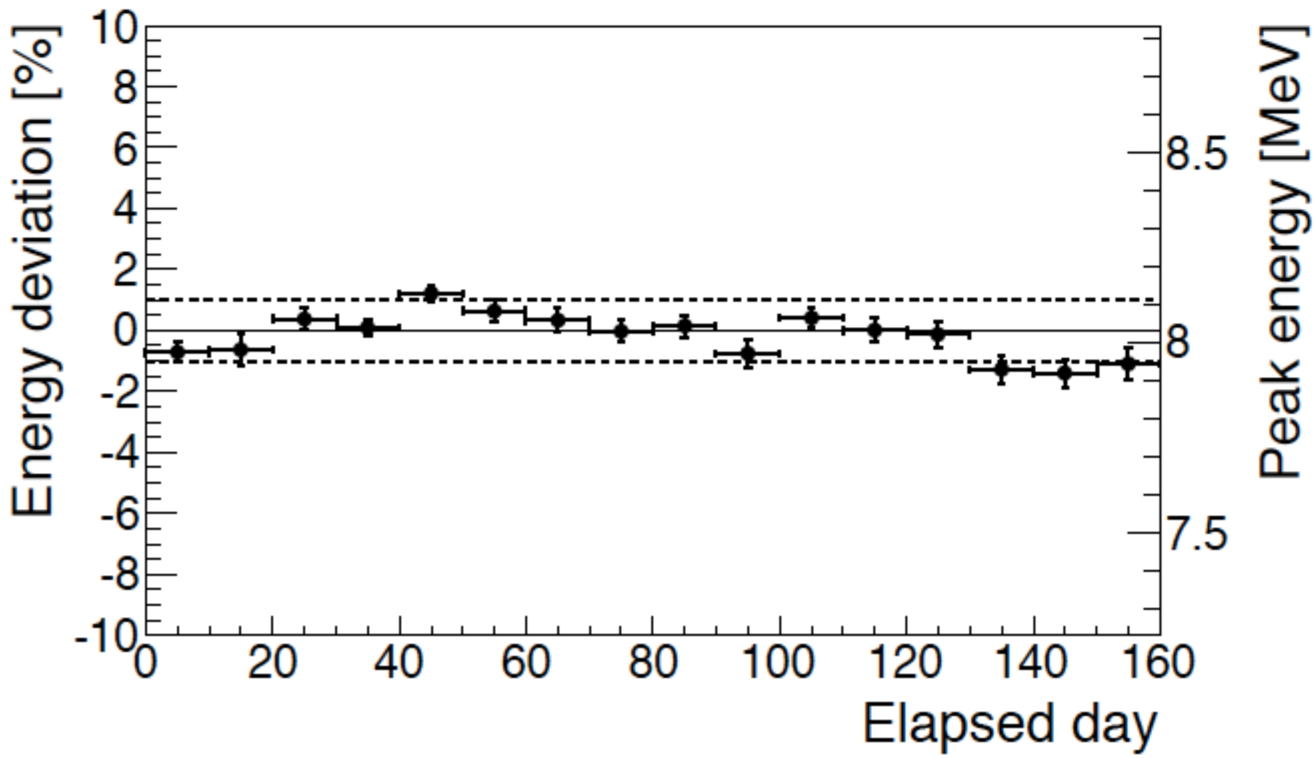


Gd-carboxylate +LAB

An older plot:



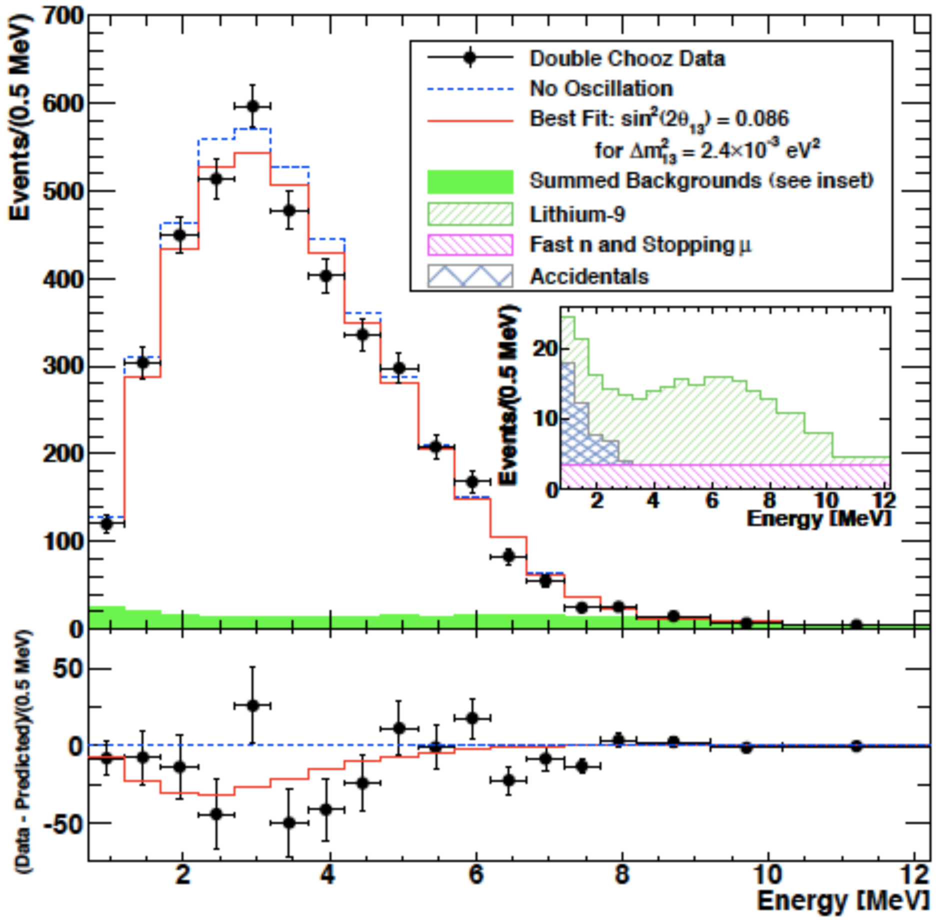
Stability of Gd Capture Peak:



And the scintillator has yielded results!

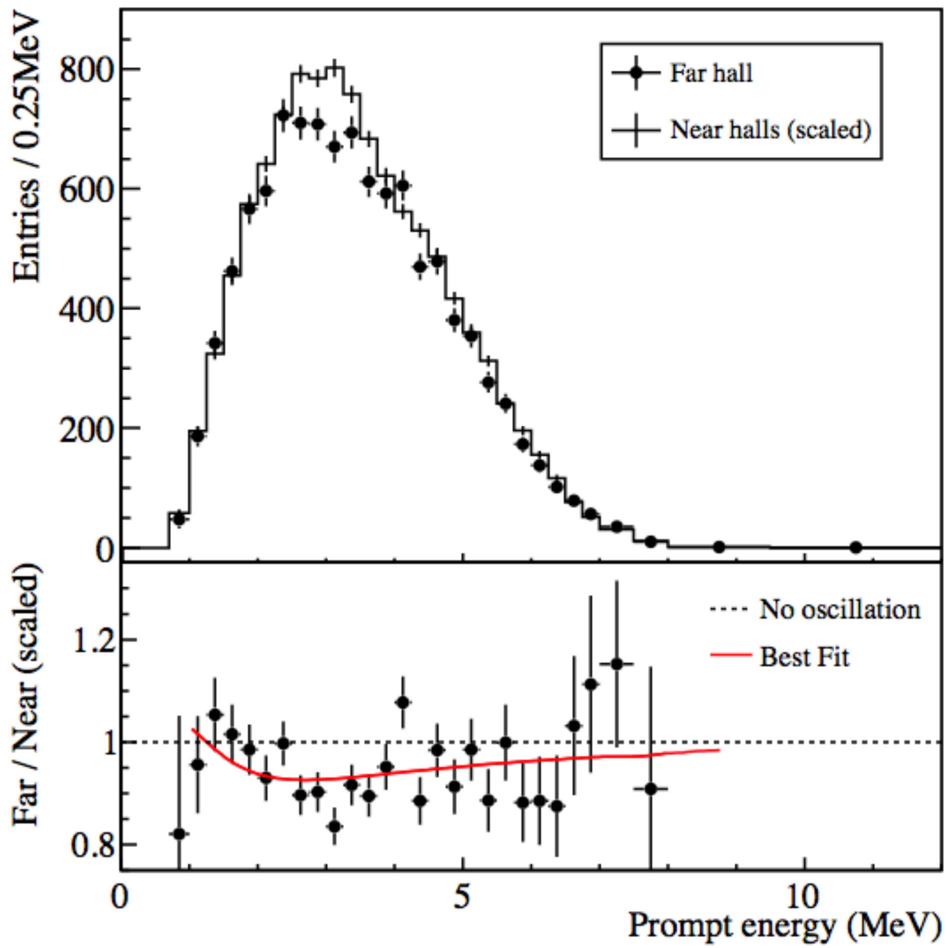
November:

See Y. Abe et al PRL 108, 131801, (2012)



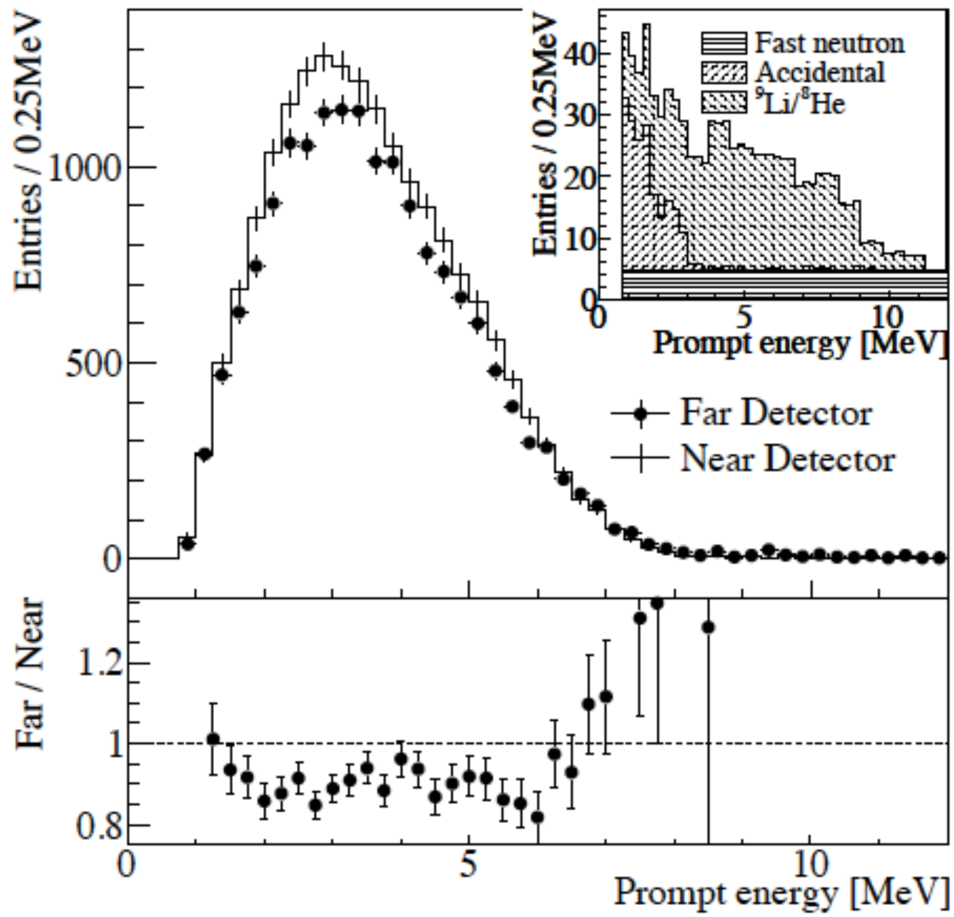
$\sin^2 2\theta_{13}$ = 0.086±0.041(stat)±0.030(sys)

March:

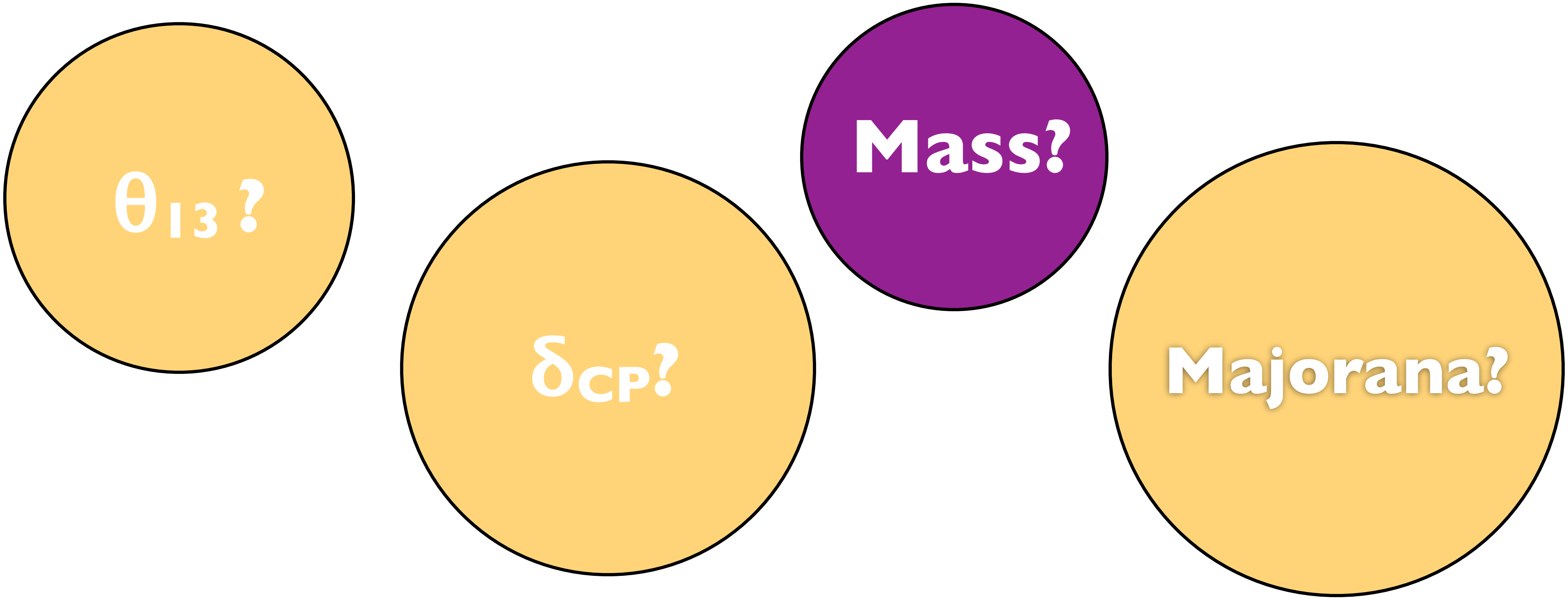


$$\sin^2 2\theta_{13} = 0.092 \pm 0.016(\mathrm{stat}) \pm 0.005(\mathrm{sys})$$

April:



$$\sin^2 2\theta_{13} = 0.113 \pm 0.013(\text{stat}) \pm 0.019(\text{sys})$$



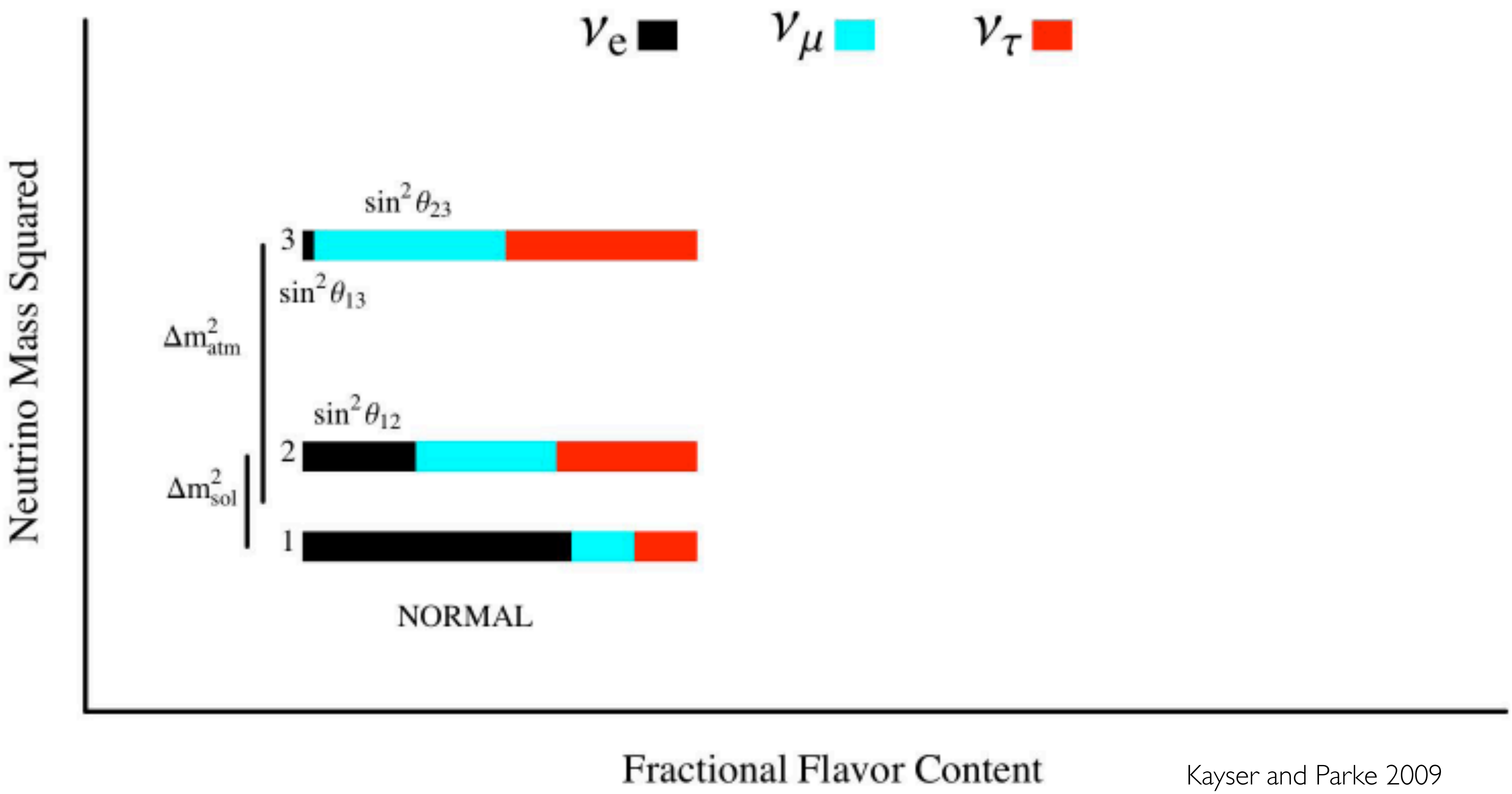
I have my own reason to want to dope scintillator with metals (very specific metals).

WARNING: Brief tangent ahead!

To motivate my interest in metal doped scintillator, I need to review double beta decay...

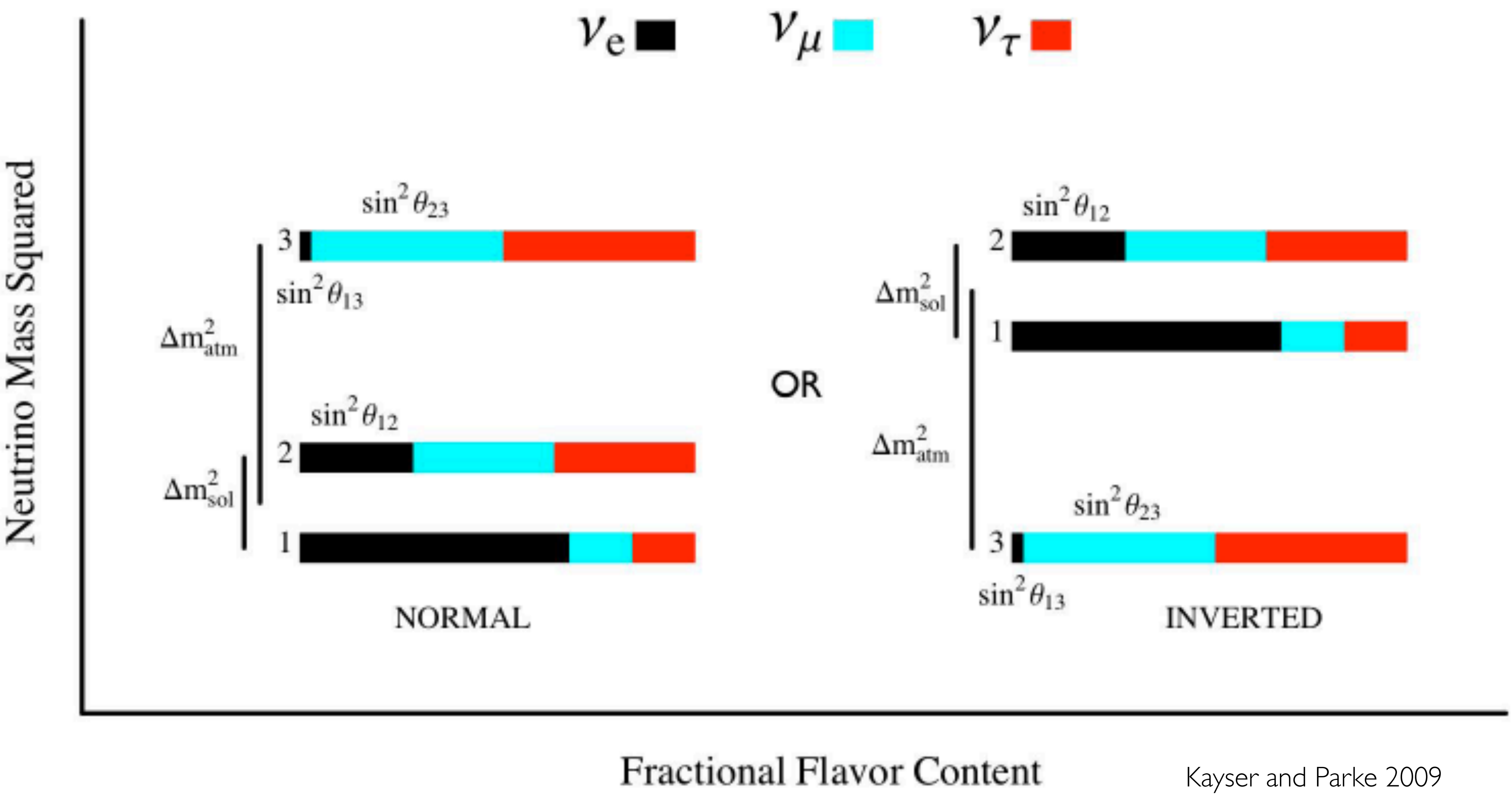
...and I need to start with neutrino masses.

This is how we ordinarily think of neutrino masses:

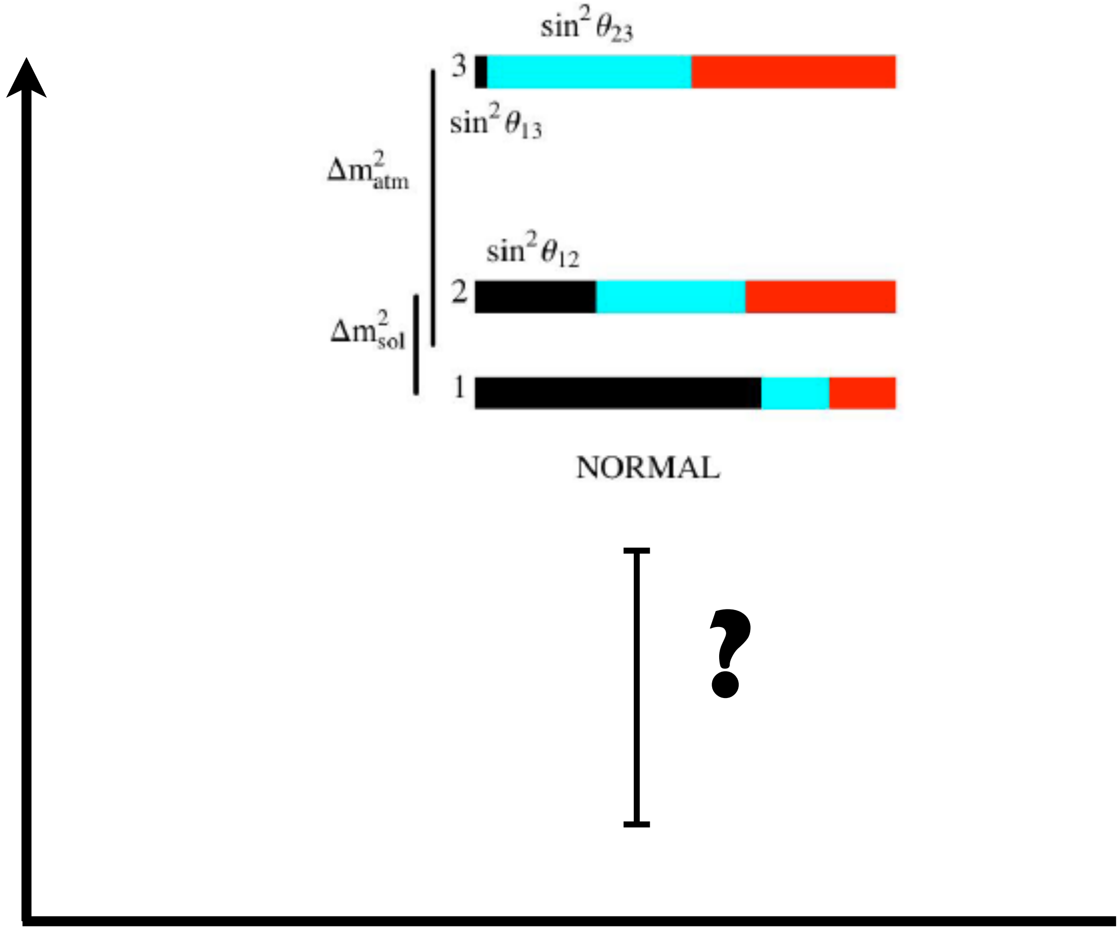


Kayser and Parke 2009

This is a valid option too:

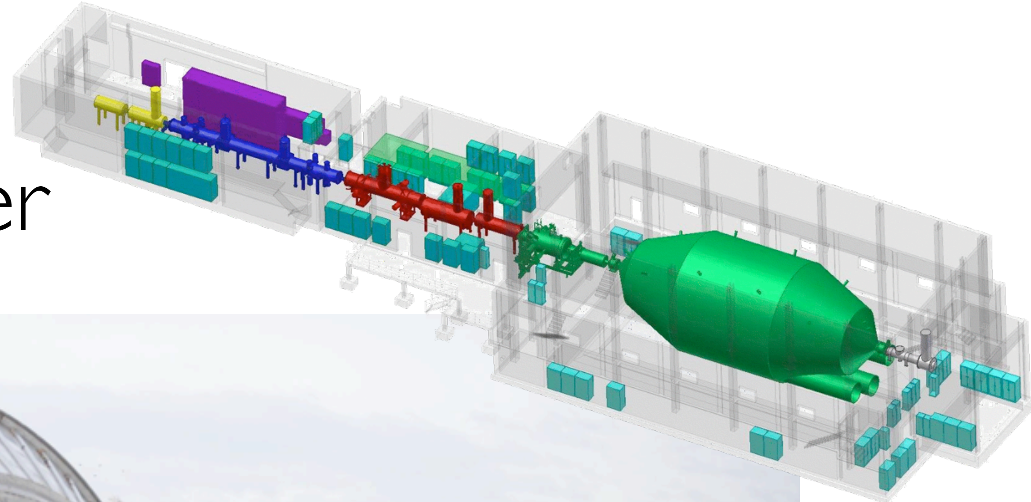


Kayser and Parke 2009

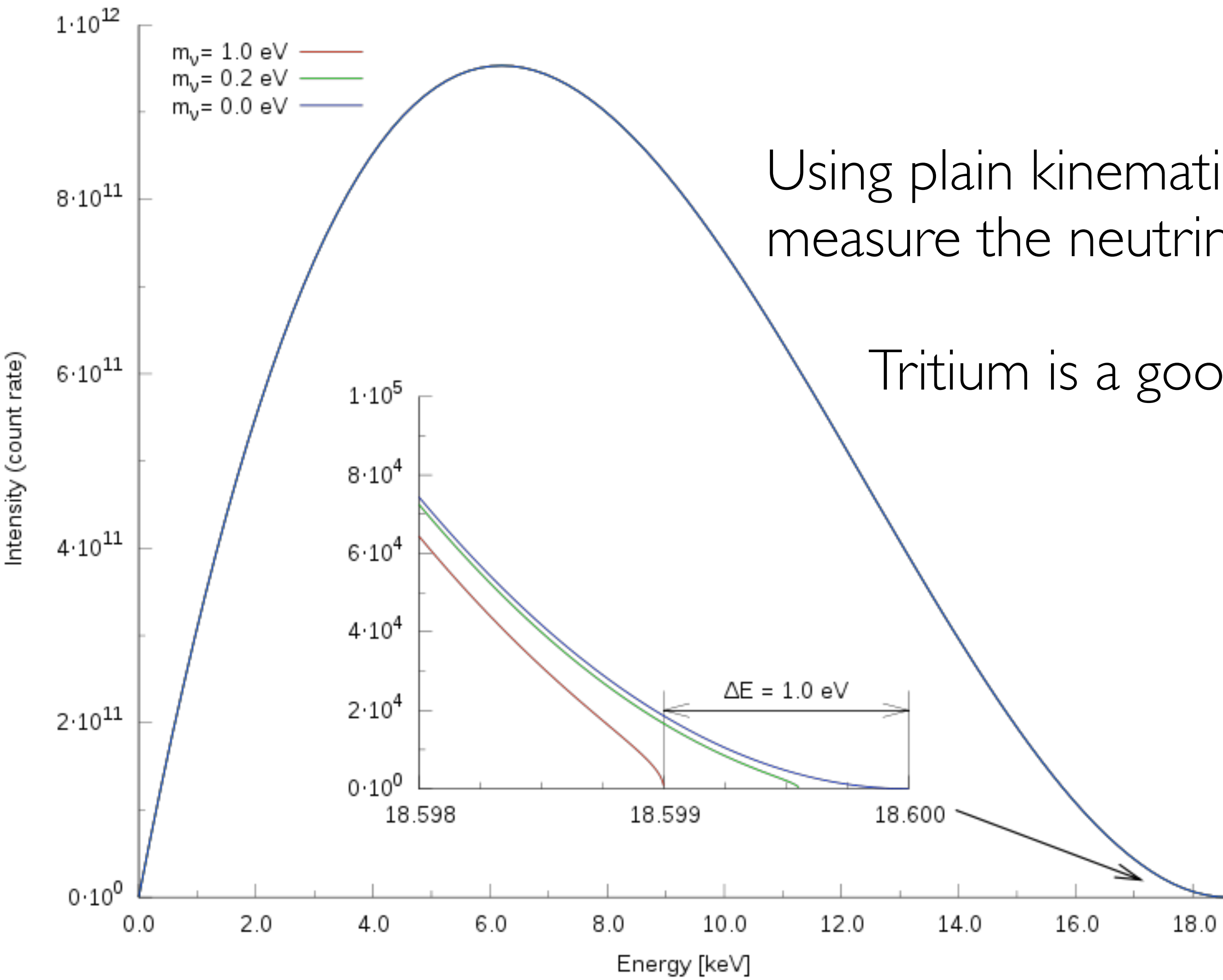


....and we still need to measure the absolute mass.

KATRIN
A Gigantic Spectrometer



Beta Decay Endpoint Measurement:

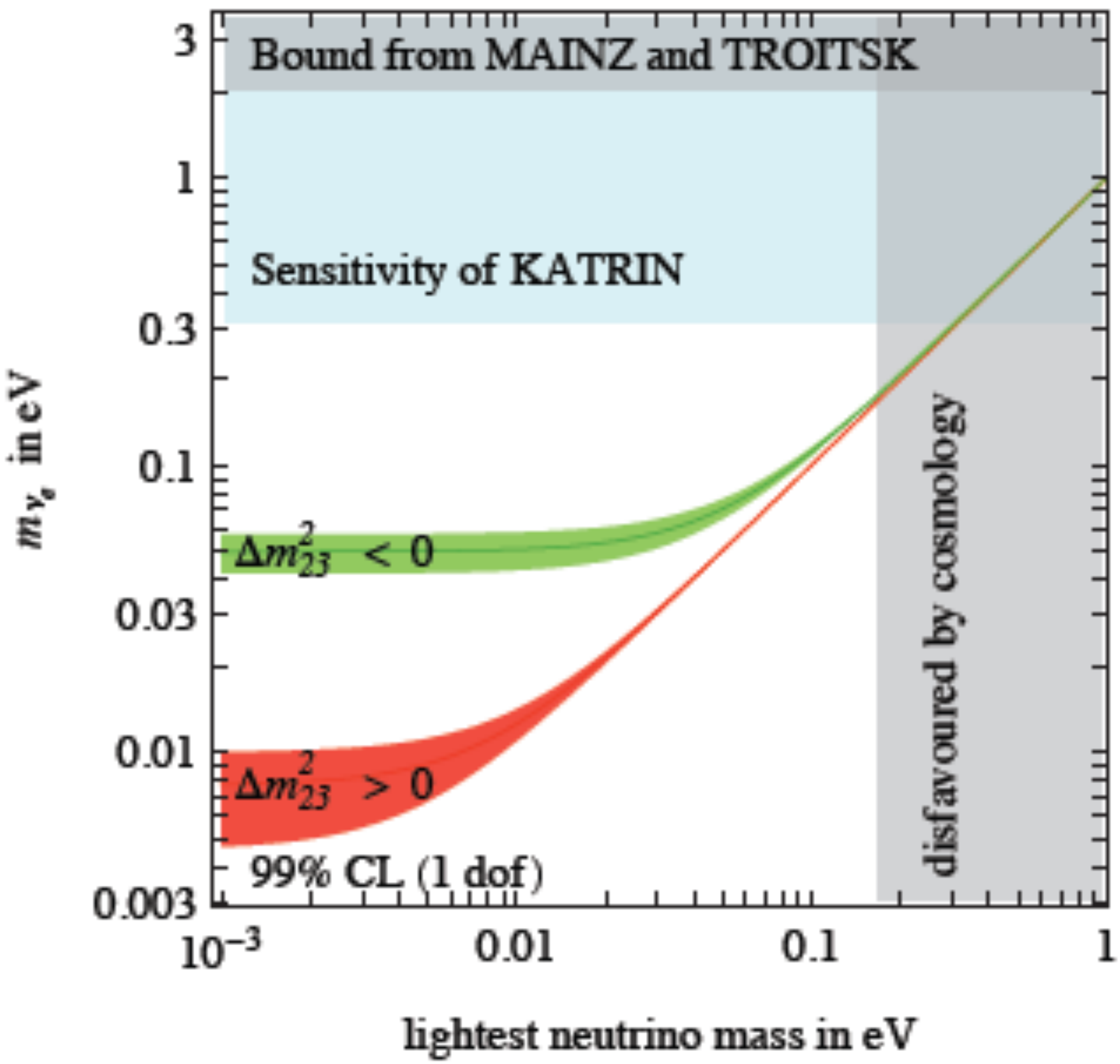


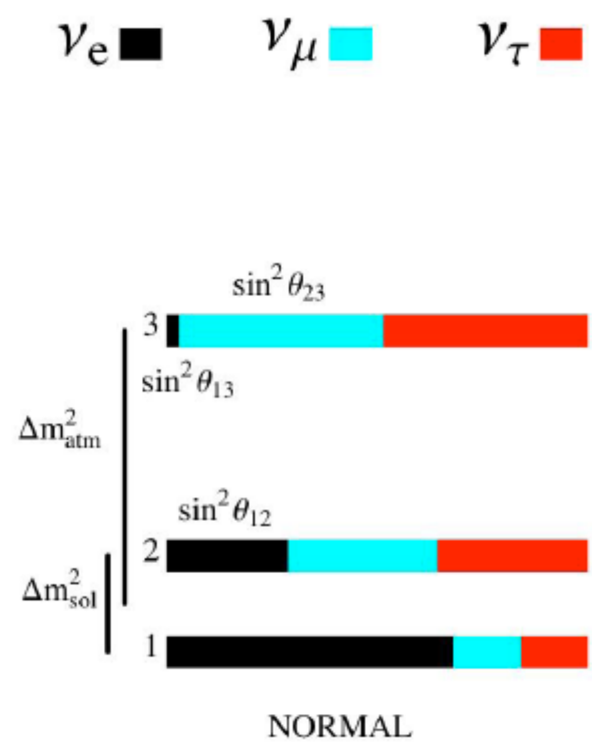
Using plain kinematics, you can measure the neutrino mass.

Tritium is a good choice.

What does KATRIN actually measure?

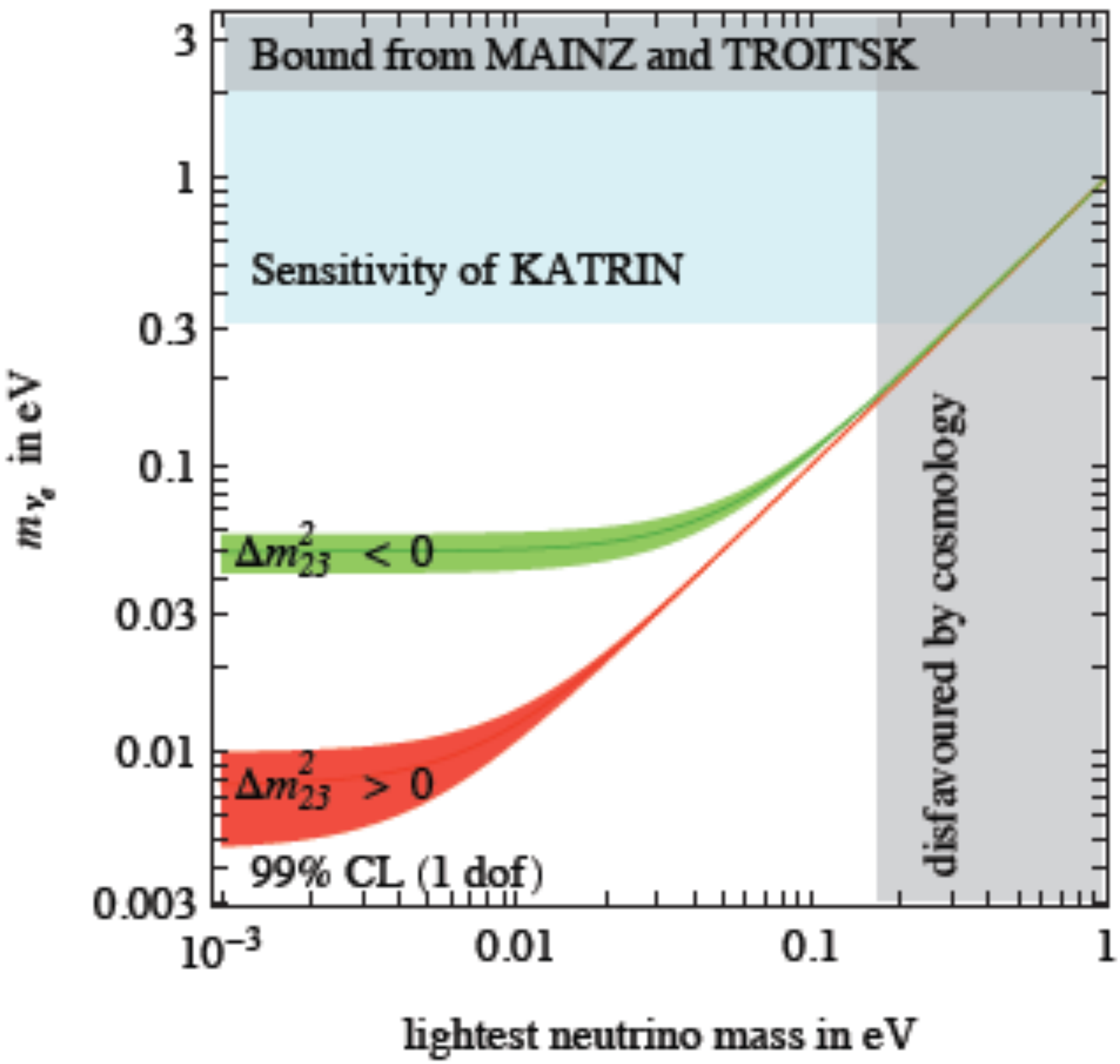
$$m_{\nu_e}^2 \equiv \sum_i |V_{ei}^2| m_i^2 = \cos^2\theta_{13}(m_1^2\cos^2\theta_{12} + m_2^2\sin^2\theta_{12}) + m_3^2\sin^2\theta_{13}$$

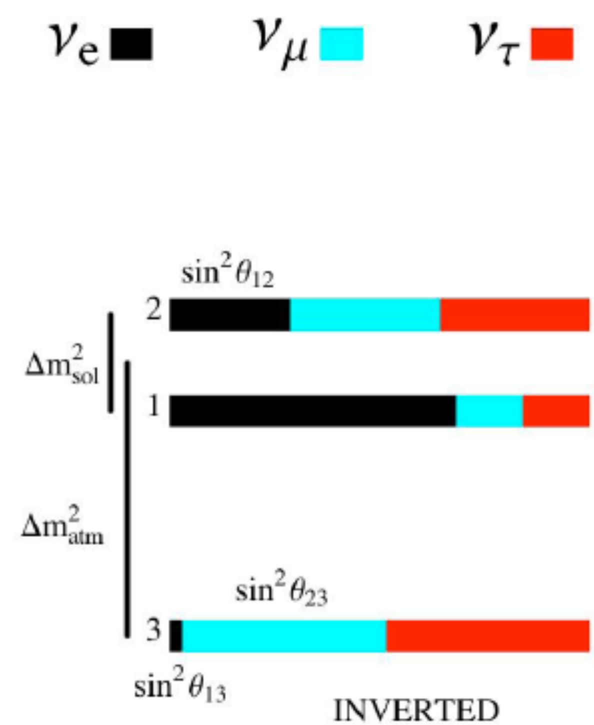




What does KATRIN actually measure?

$$m_{\nu_e}^2 \equiv \sum_i |V_{ei}^2| m_i^2 = \cos^2\theta_{13}(m_1^2\cos^2\theta_{12} + m_2^2\sin^2\theta_{12}) + m_3^2\sin^2\theta_{13}$$





Another way to talk about neutrino mass.

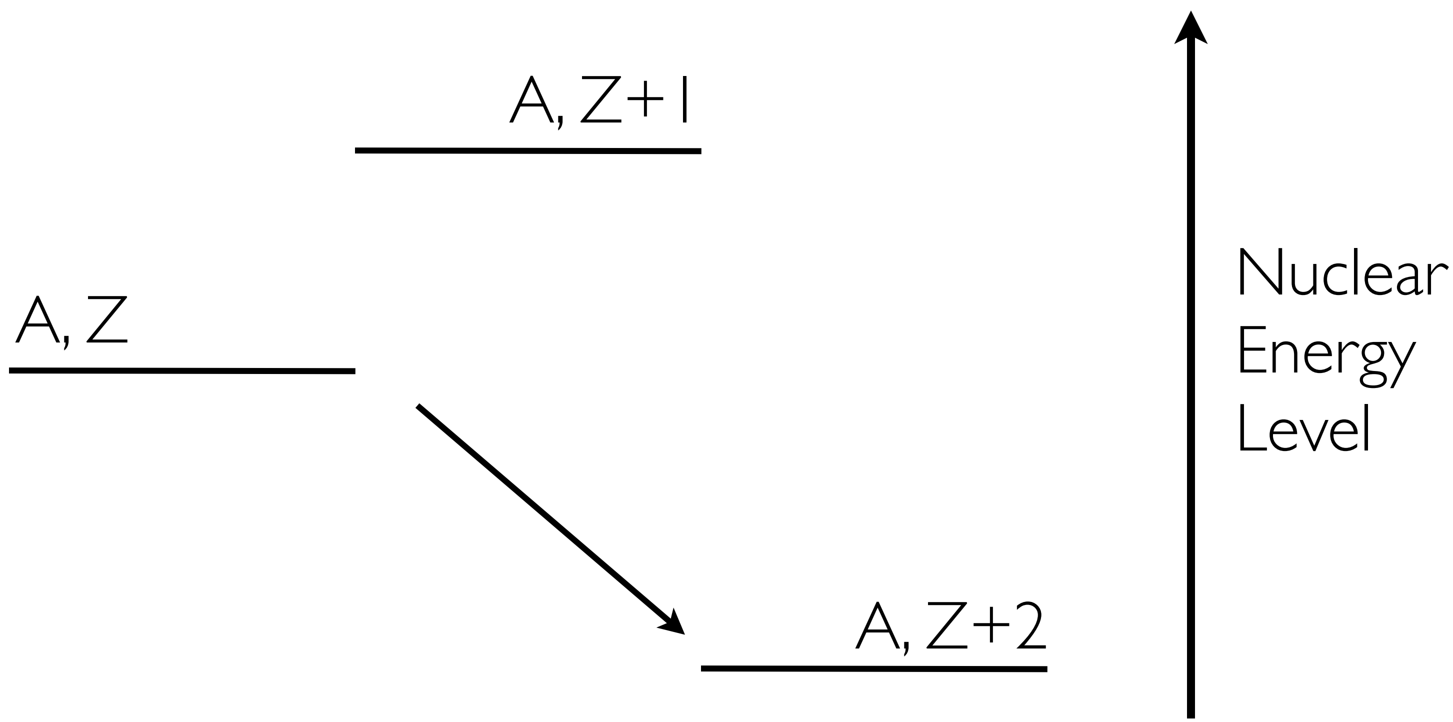
This discussion requires a Majorana nature for the neutrino.

Neutrinoless Double Beta Decay

Two amazing pieces of information for the price of one!

Double Beta Decay

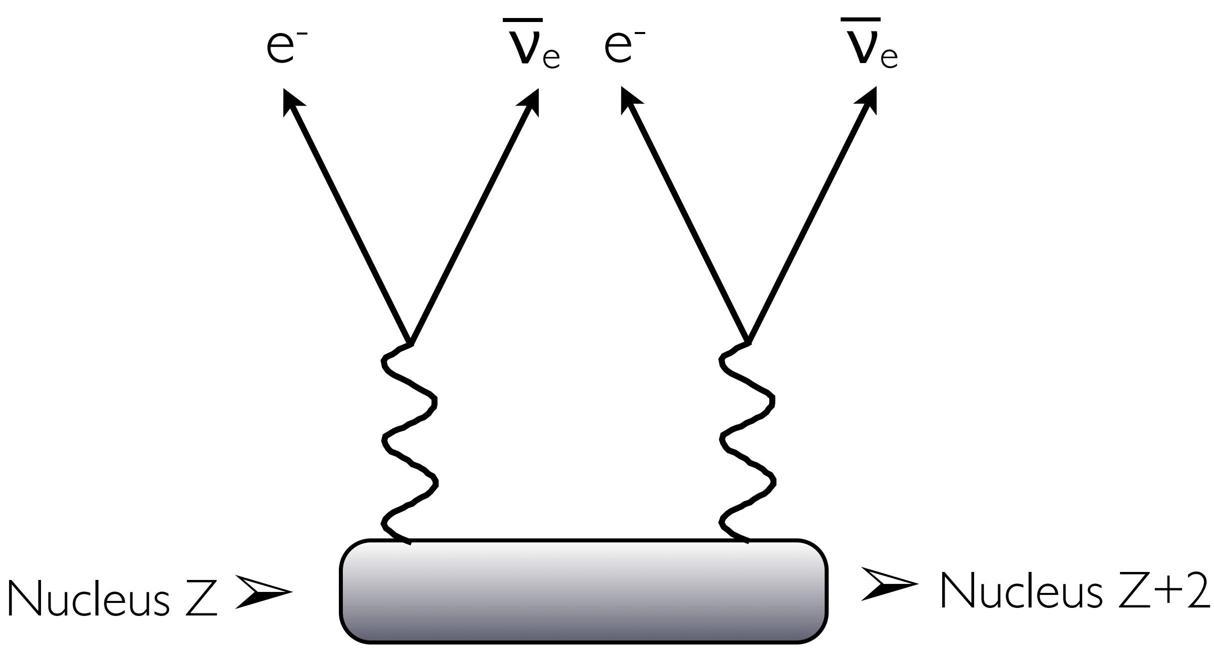
Due to energy conservation some nuclei can't decay to their daughter nucleus, but can skip to their granddaughter nucleus.



Just a few isotopes!

The Standard Model Process

This process is completely allowed and the rate was first calculated by Maria Goeppert-Mayer in 1935.

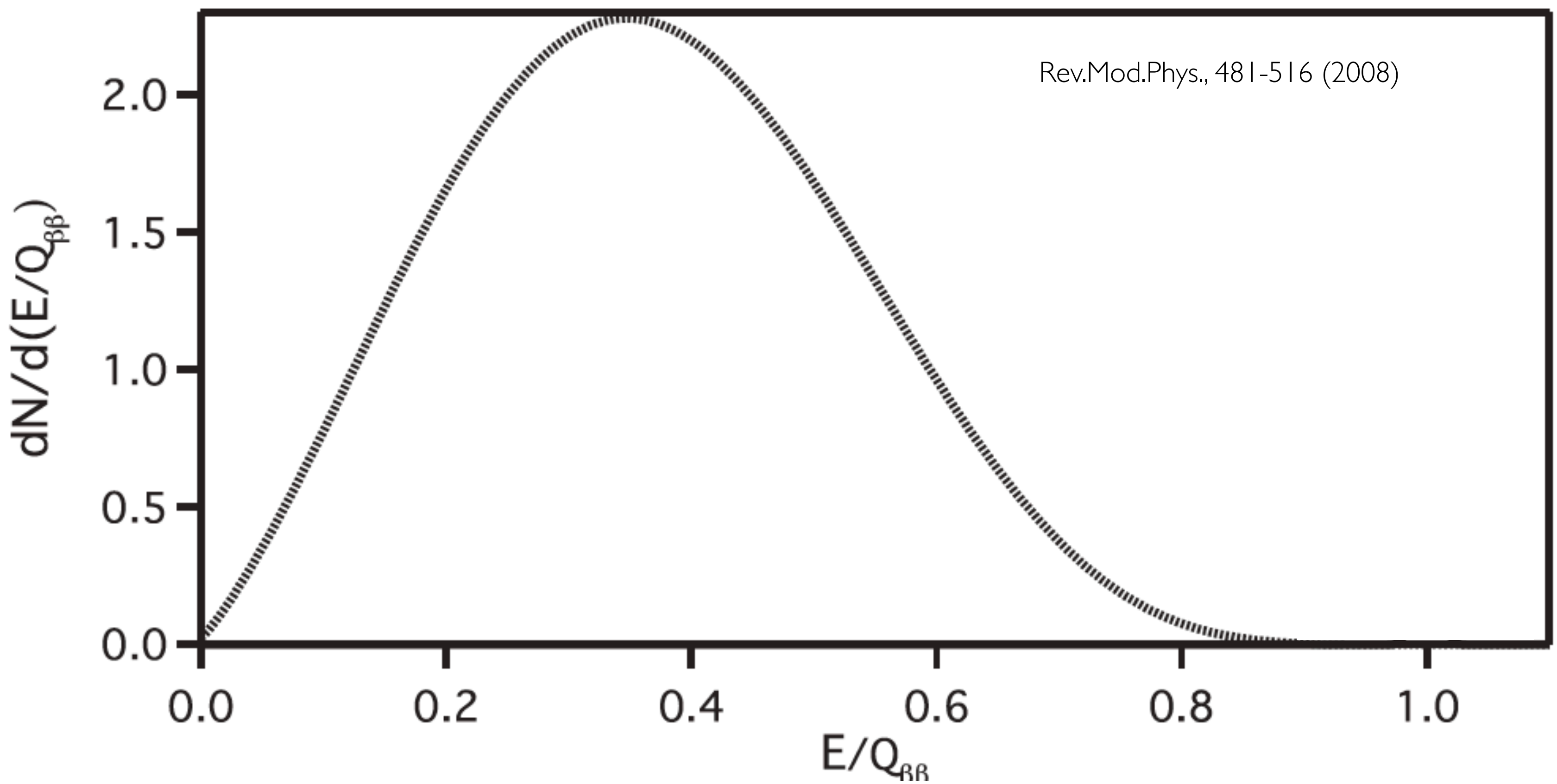


Nuclear Process

Phys. Rev. 48, 512-516 (1935)

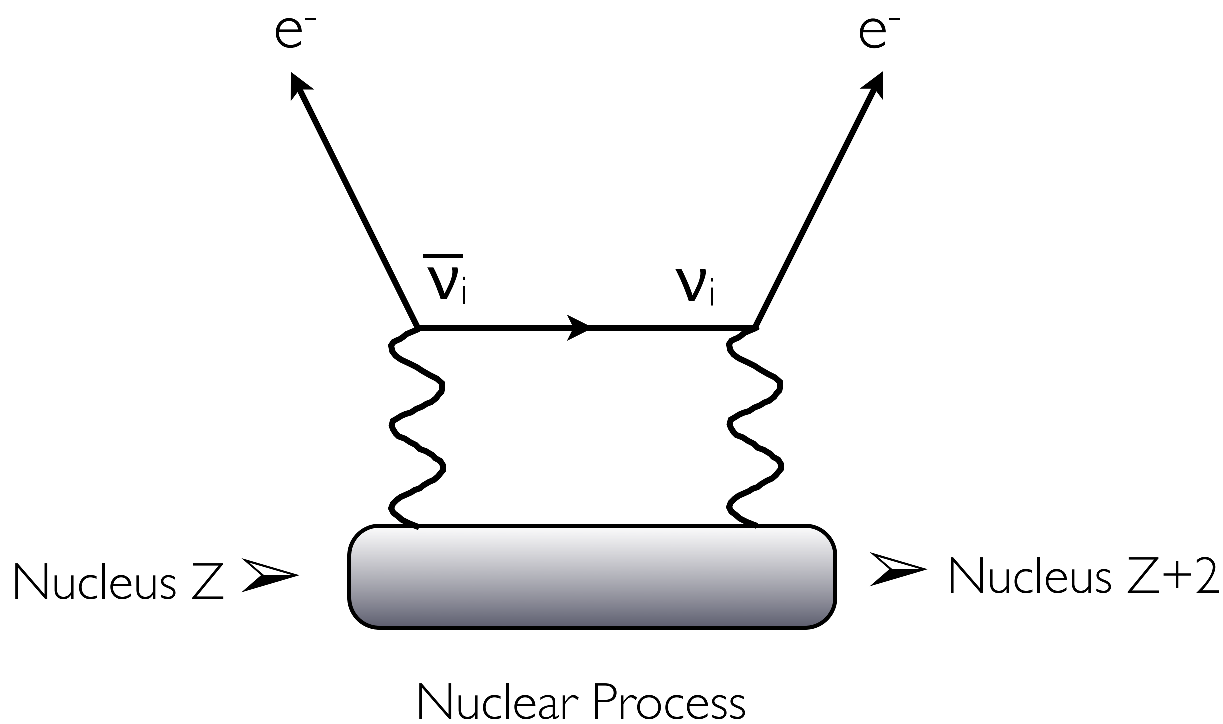
Double Beta Decay

The sum of the electron energies gives a spectrum similar to the standard beta decay spectrum.



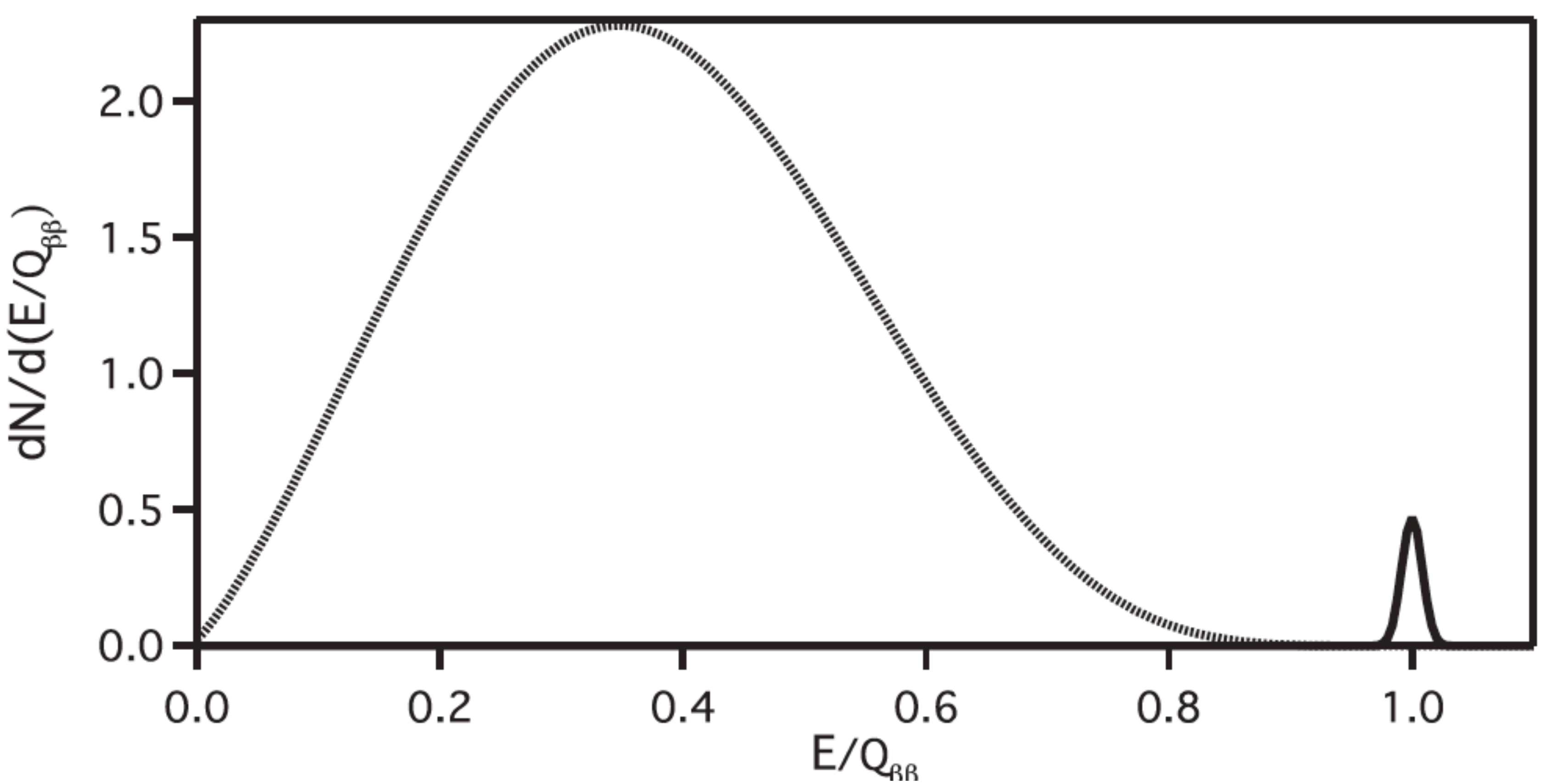
This has been observed in isotopes such as ^{130}Te and ^{116}Cd.

Neutrinoless Double Beta Decay



Neutrinoless Double Beta Decay

The sum of the electron energies gives a spike at the endpoint of the "neutrino-full" double beta decay.



What is measured is a half-life...

The half-life of the neutrinoless decay:

$$(T^{0\nu}_{1/2})^{-1} = G_{0\nu}(Q_{\beta\beta}, Z)|M_{0\nu}|^2\langle m_{\beta\beta}\rangle^2$$

Phase space factor
Notice higher endpoint means faster rate.

What is measured is a half-life:

$$(T^{0\nu}_{1/2})^{-1} = G_{0\nu}(Q_{\beta\beta}, Z)|M_{0\nu}|^2\langle m_{\beta\beta}\rangle^2$$

↑

Nuclear Matrix Element

This is a difficult calculation with large errors and substantial variation between isotopes...motivates searches with multiple isotopes.

What is measured is a half-life:

$$(T_{1/2}^{0\nu})^{-1} = G_{0\nu}(Q_{\beta\beta}, Z)|M_{0\nu}|^2\langle m_{\beta\beta}\rangle^2$$

Effective Majorana Mass of the neutrino

Effective Majorana Mass:

$$m_{ee} = \sum_i V_{ei}^2 \, m_i = \cos^2\theta_{13}(m_1 e^{2i\beta}\cos^2\theta_{12} + m_2 e^{2i\alpha}\sin^2\theta_{12}) + m_3\sin^2\theta_{13}$$

This is not what we discussed with KATRIN.

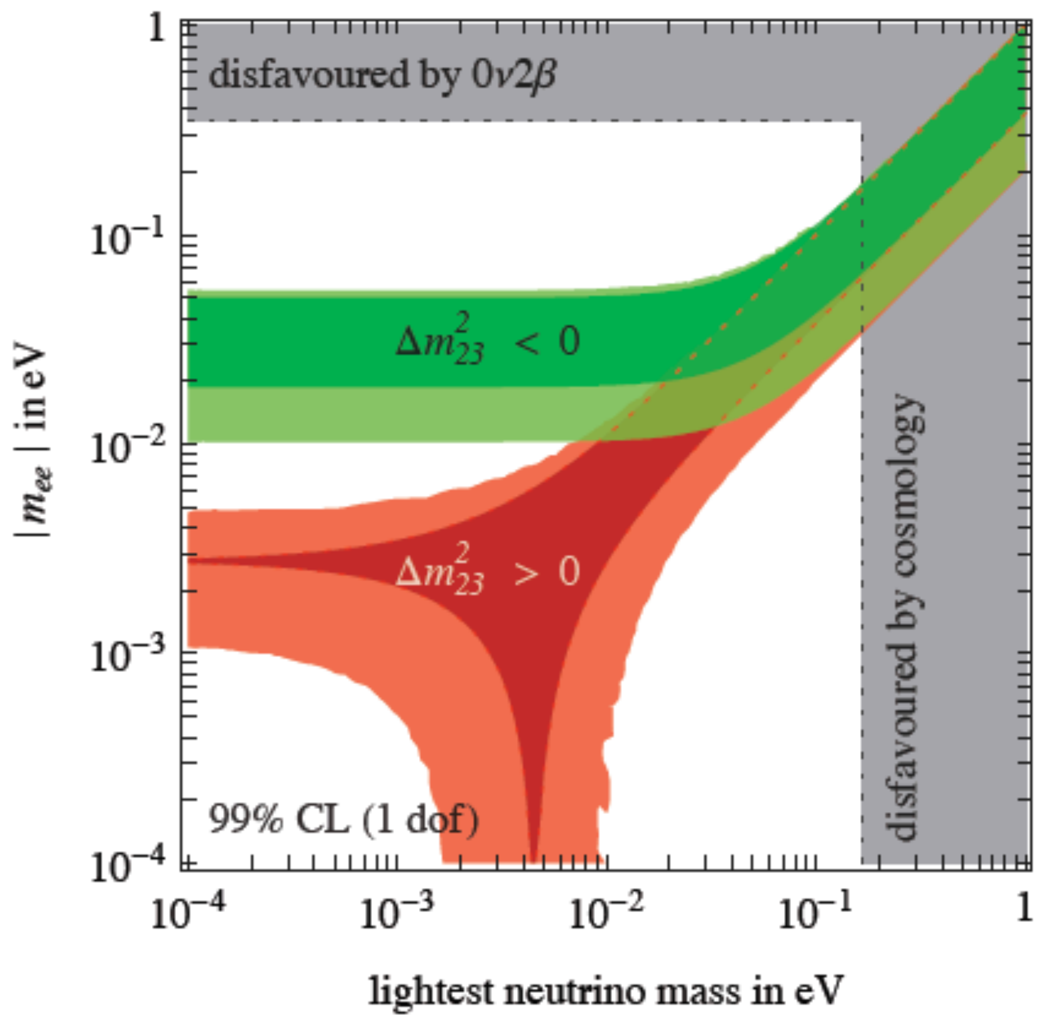
Electron Neutrino Mass:

$$m_{\nu_e}^2 \equiv \sum_i |V_{ei}^2| m_i^2 = \cos^2\theta_{13}(m_1^2\cos^2\theta_{12} + m_2^2\sin^2\theta_{12}) + m_3^2\sin^2\theta_{13}$$

Double Beta Decay Visualizing the Equations:

$$m_{ee} = \sum V_{ei}^2\, m_i = \cos^2\theta_{13}(m_1 e^{2i\beta}\cos^2\theta_{12} + m_2 e^{2i\alpha}\sin^2\theta_{12}) + m_3\sin^2\theta_{13}$$

arXiv:hep-ph/0606054v3



For θ_{13}:

Detector = Target

For Neutrinoless Double Beta Decay:

Detector = Source

Detector Design Issues:

Size

- Natural Abundance
- Detector technology

Backgrounds

(2.6 MeV is the highest energy U/Th gamma ray)

- Energy of endpoint
- Cleanliness
- Particle/Event identification

Energy resolution

Pick your favorite candidate isotope......

Isotope	Endpoint	Abundance
^{48}Ca	4.271 MeV	0.0035%
^{150}Nd	3.367 MeV	5.6%
^{96}Zr	3.350 MeV	2.8%
^{100}Mo	3.034 MeV	9.6%
^{82}Se	2.995 MeV	9.2%
^{116}Cd	2.802 MeV	7.5%
^{130}Te	2.533 MeV	34.5%
^{136}Xe	2.479 MeV	8.9%
^{76}Ge	2.039 MeV	7.8%
^{128}Te	0.868 MeV	31.7%

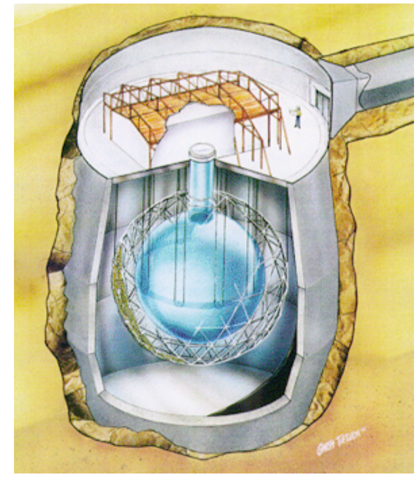
Many of these are metals.....

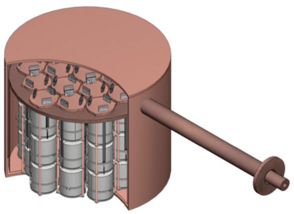
Pick your favorite candidate isotope......

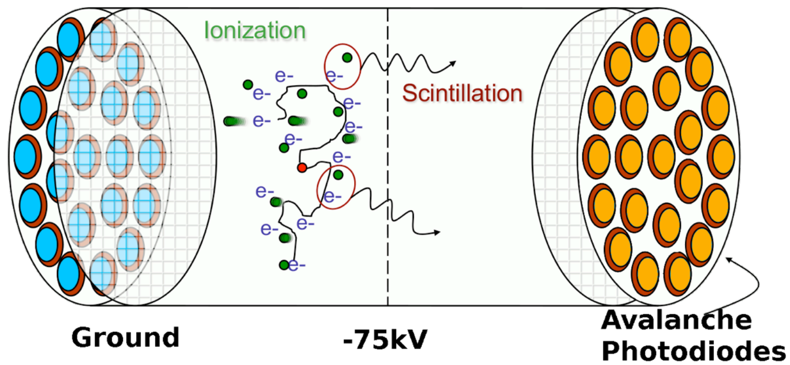
Isotope	Endpoint	Abundance
^{48}Ca	4.271 MeV	0.0035%
^{150}Nd	3.367 MeV	5.6%
^{96}Zr	3.350 MeV	2.8%
^{100}Mo	3.034 MeV	9.6%
^{82}Se	2.995 MeV	9.2%
^{116}Cd	2.802 MeV	7.5%
^{130}Te	2.533 MeV	34.5%
^{136}Xe	2.479 MeV	8.9%
^{76}Ge	2.039 MeV	7.8%
^{128}Te	0.868 MeV	31.7%

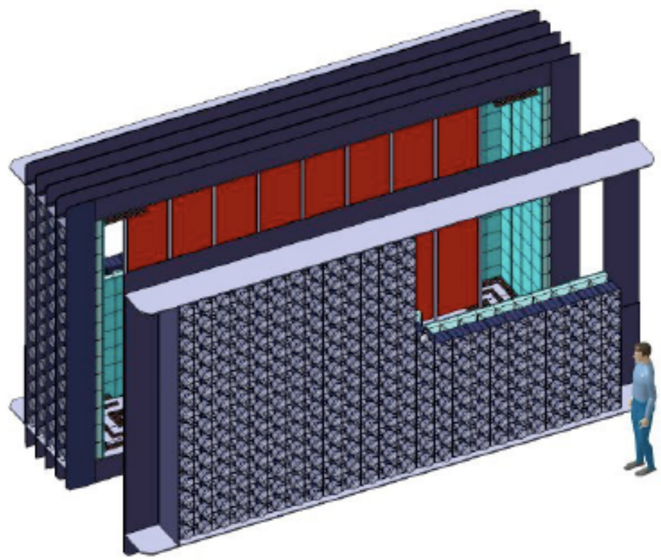
Lower Background! ↑

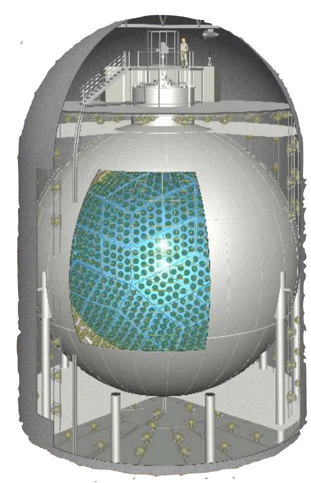
An explosion of technology!







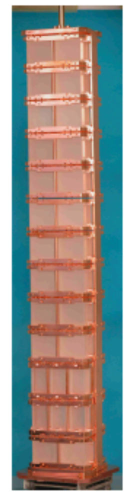




Because of the sensitivity needed almost all experiments have the source = detector.

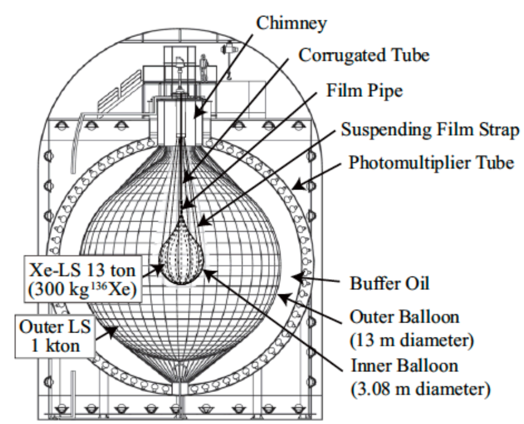
Current best limits:

$^{76}Ge \Rightarrow T_{1/2} = 2.23^{+0.44}_{-0.31} \times 10^{25}$ years



Cuoricino
2003–2008
11 kg ^{130}Te

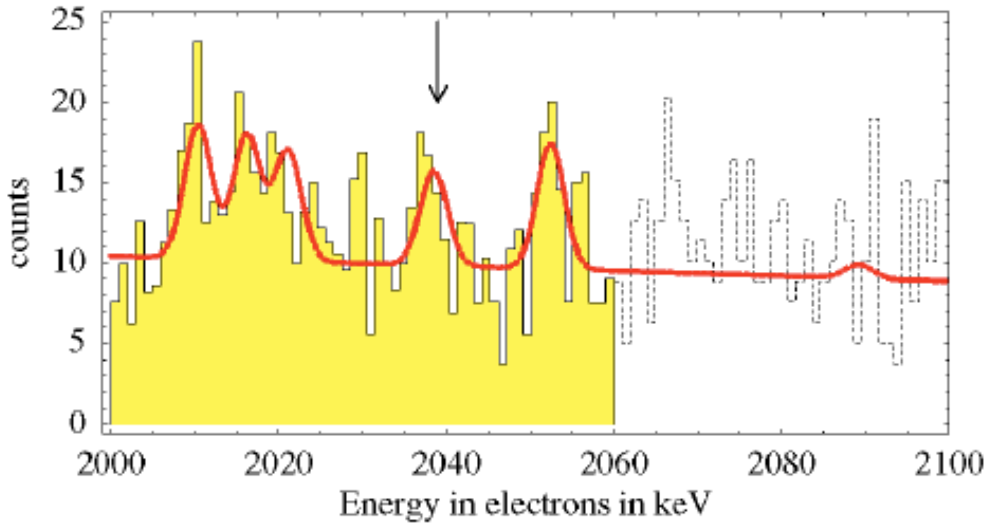
$^{130}Te \Rightarrow T_{1/2} = 3.0 \times 10^{24}$ years



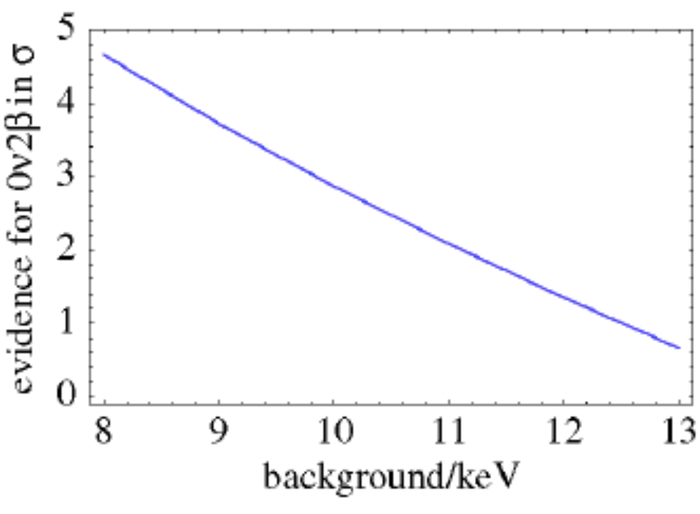
$^{136}Xe \Rightarrow T_{1/2} = 5.7 \times 10^{24}$ years

The Controversial Signal

Heidelberg-Moscow Experiment using ^{76}Ge......

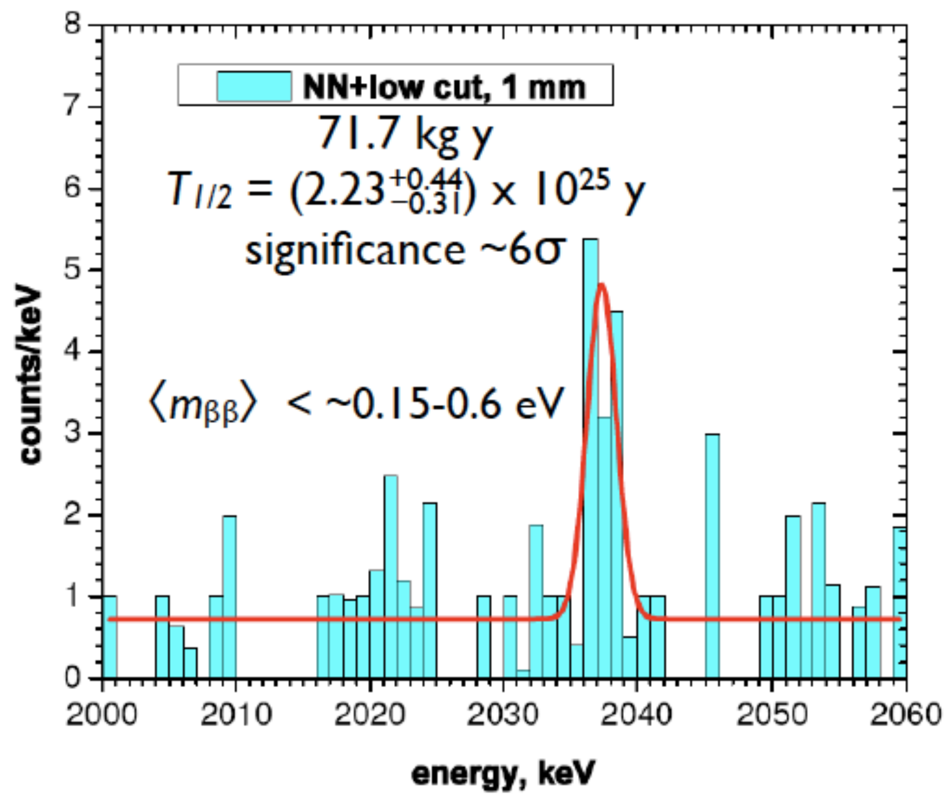


From: Nuclear Physics B 726 (2005) 294–316

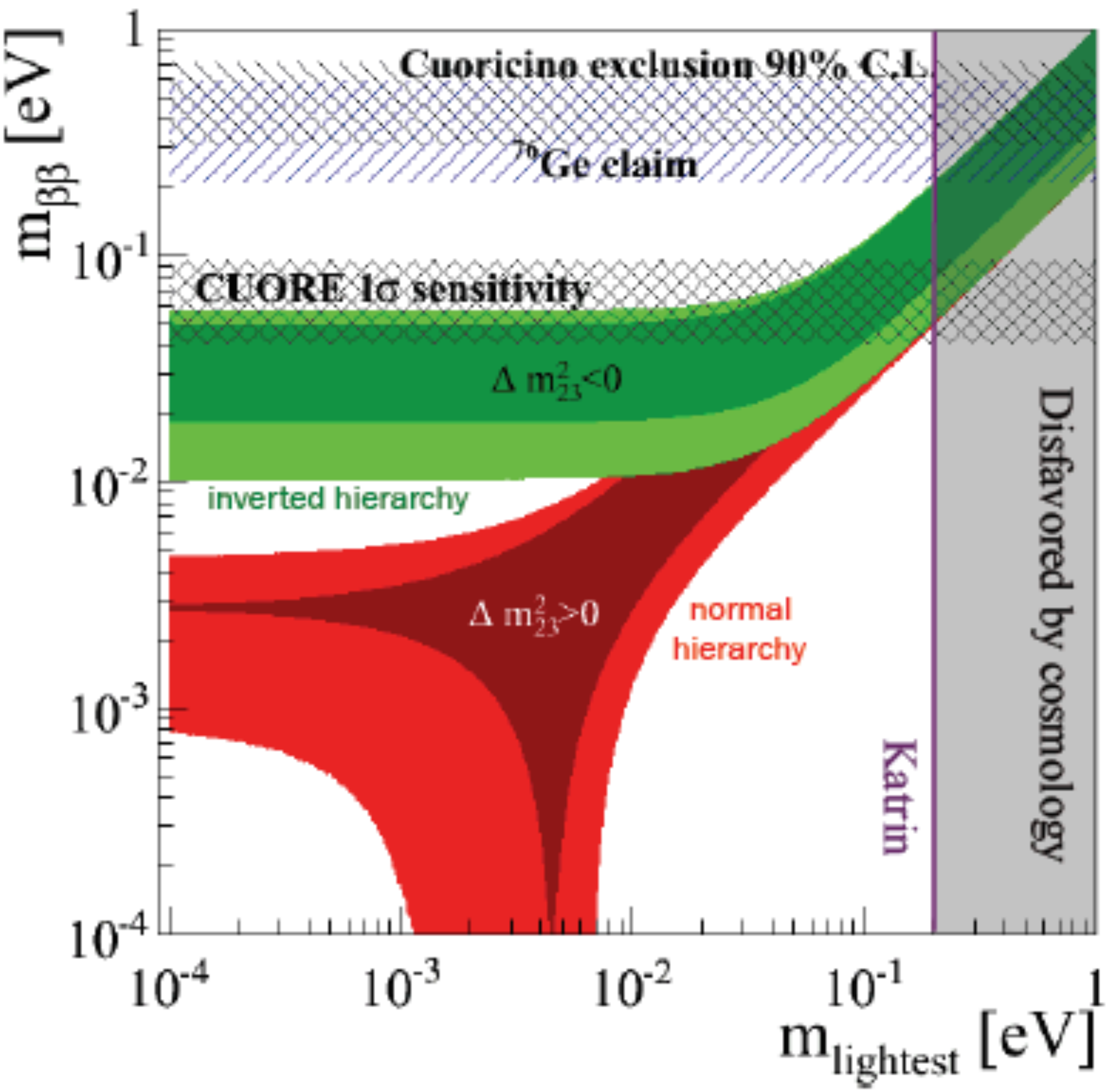


Final Analysis of the data using more advanced techniques makes the measurement almost background free.

Klapdor Kleingrothaus *et al.*, Mod. Phys. Lett. A **21** (2006) p 1547.



The current generation of experiments will clip the top of the inverse hierarchy.



If current generation sees something.

Go after more rare processes to determine whether its the "vanilla" standard model or new physics.

If one experiment sees something and others do not.

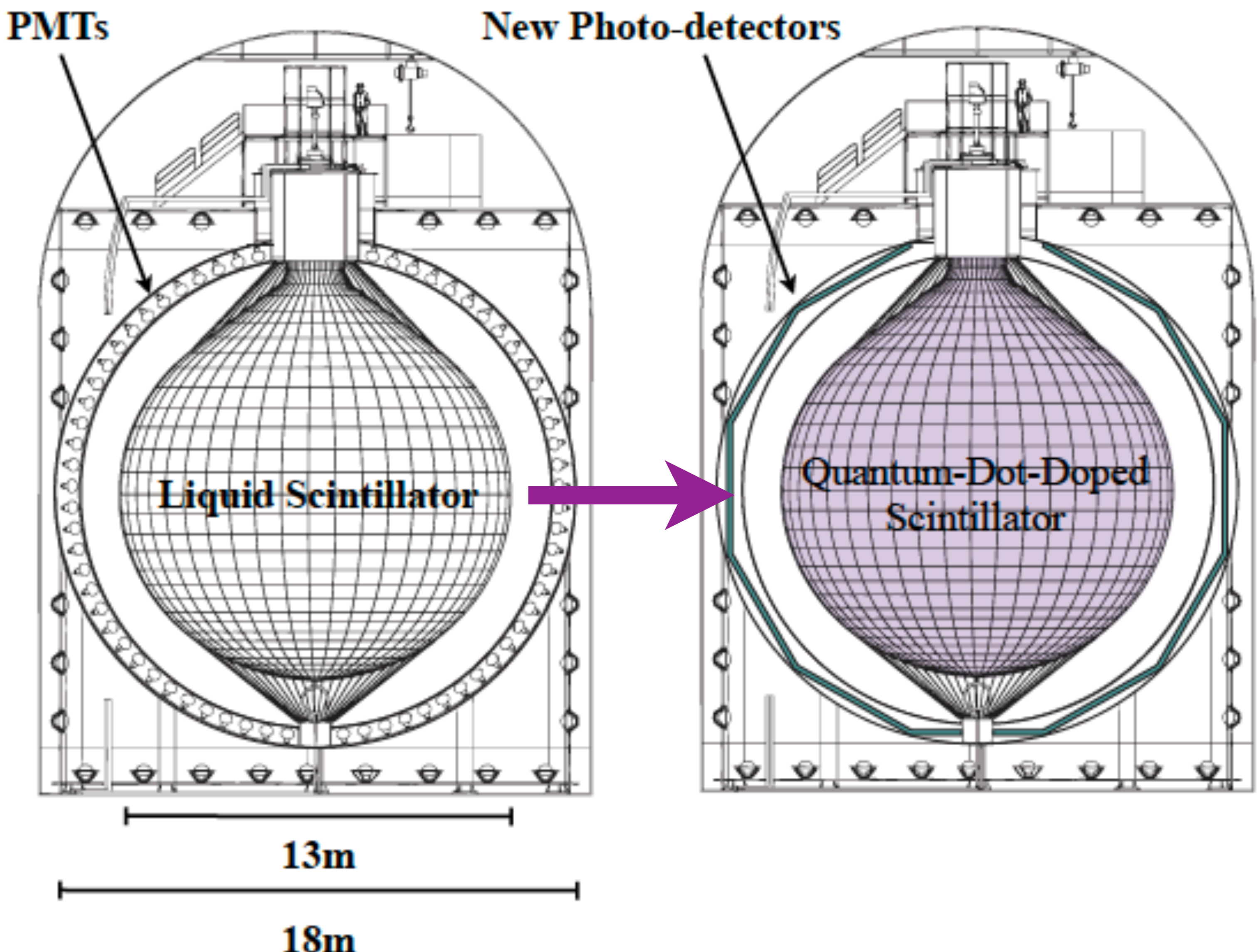
If no experiments see a signal.

Bigger
Cleaner
Better
Detector

Connecting Back:

Can we imagine a giant clean scintillator detector doped with a double beta decay candidate metal?

I can....



1ton = 1g/L → Test IH
10 ton = 10 g/L → Test NH

First Results from ν•

FOR WOMEN IN SCIENCE

UNESCO
United Nations
Educational, Scientific and
Cultural Organization

L'ORÉAL
USA

AAAS

Because ν's are worth it.

Preprint typeset in JINST style - HYPER VERSION

Characterizing Quantum-Dot-Doped Liquid Scintillator for Applications to Neutrino Detectors

Lindley Winslow[a*] **and Raspberry Simpson**[a]

[a]*Massachusetts Institute of Technology,*
77 Massachusetts Ave Cambridge, MA 02139, USA
E-mail: `lwinslow@mit.edu`

ABSTRACT: Liquid scintillator detectors are widely used in modern neutrino studies. The unique optical properties of semiconducting nanocrystals, known as quantum dots, offer intriguing possibilities for improving standard liquid scintillator, especially when combined with new photodetection technology. Quantum dots also provide a means to dope scintillator with candidate isotopes for neutrinoless double beta decay searches. In this work, the first studies of the scintillation properties of quantum-dot-doped liquid scintillator using both UV light and radioactive sources are presented.

KEYWORDS: Scintillators; Large detector systems for particle and astroparticle physics; Particle identification methods.

*Corresponding author.

Available at arXiv:1202.4733

What are Quantum Dots?

Quantum Dots are semiconducting nanocrystals.

A shell of organic molecules is used to suspend them in an organic solvent (toluene) or water.

Why are they so popular?

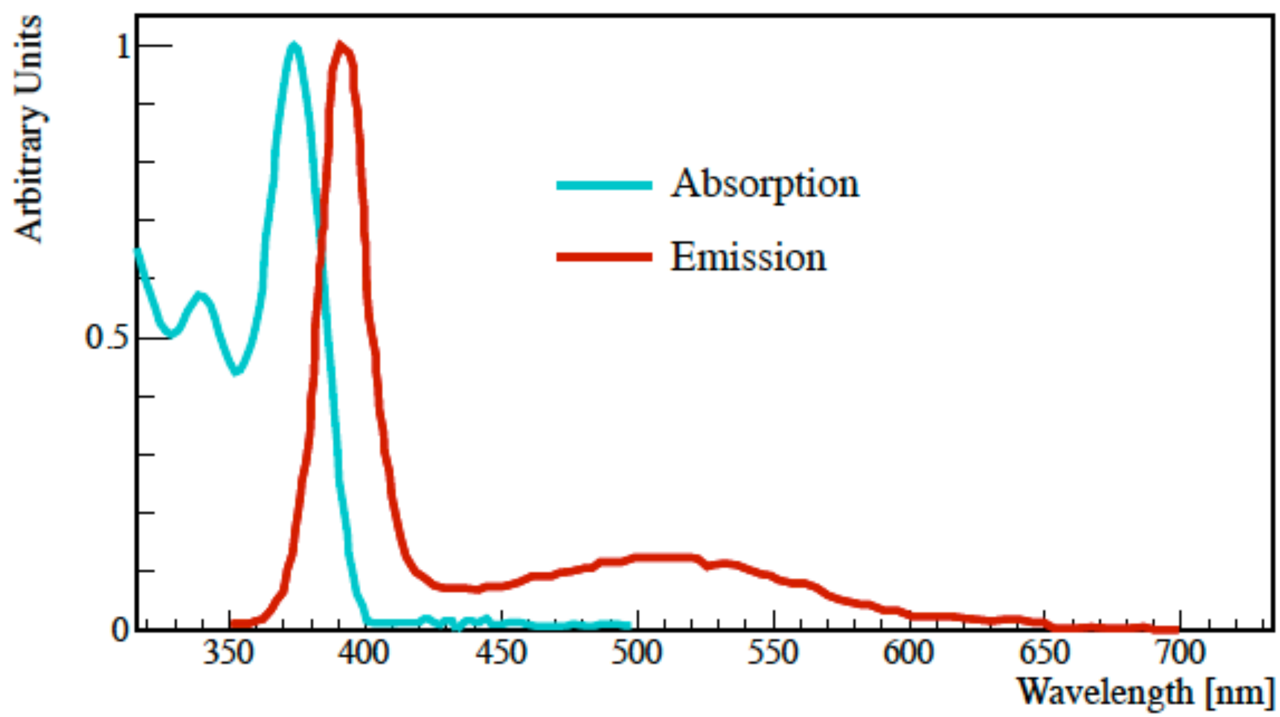
Because of their small size, their electrical and optical properties are more similar to atoms than bulk semiconductors.

In fact, the optical properties of quantum dots with diameter <10nm is completely determined by their size.

Example CdS Quantum Dot Spectra:

They absorb all light shorter than 400nm and re-emit it in a narrow resonance around this wavelength.

Very Useful for Biology, Solar Cells, and LEDs!



Other types of quantum dots include CdSe, CdTe, and ZnS....

Quantum Dot Materials Overlap with Candidate Isotopes!

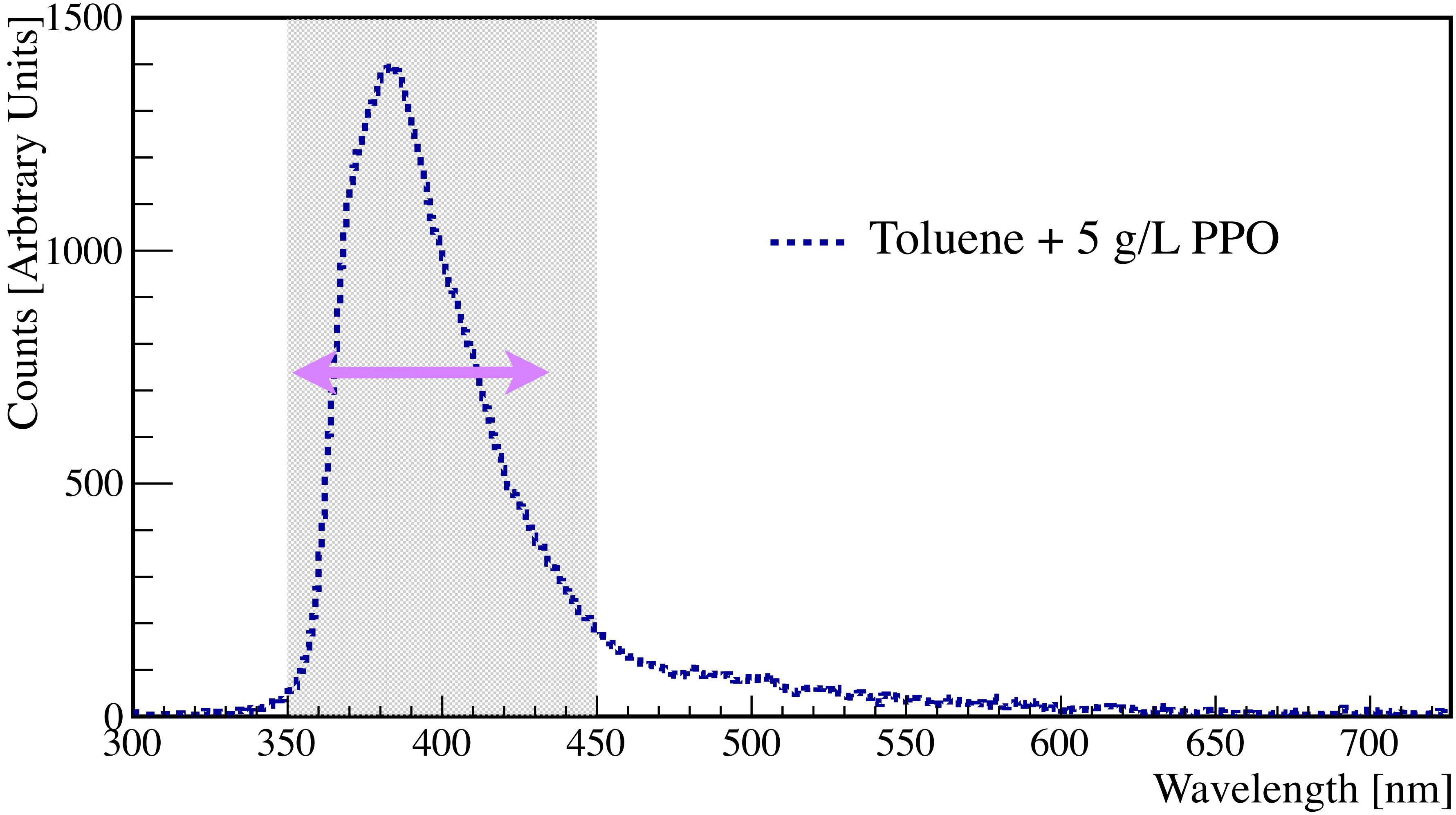
Isotope	Endpoint	Abundance
^{48}Ca	4.271 MeV	0.0035%
^{150}Nd	3.367 MeV	5.6%
^{96}Zr	3.350 MeV	2.8%
^{100}Mo	3.034 MeV	9.6%
^{82}Se	2.995 MeV	9.2%
^{116}Cd	2.802 MeV	7.5%
^{130}Te	2.533 MeV	34.5%
^{136}Xe	2.479 MeV	8.9%
^{76}Ge	2.039 MeV	7.8%
^{128}Te	0.868 MeV	31.7%

Their synthesis allows precise control of the size of the quantum dots.

Can use them to select any wavelength of light that you want!

They are delivered in water or toluene.
(so they come suspended in scintillator!)

My scintillator is toluene with PPO



Adding quantum dots will tune the peak of this curve.

How could we use the wavelength tuning?

Perfectly tune the wavelength of your scintillator's emission

- Increases total light collected by photomultiplier tubes.
- Match photo-cathode efficiency of new devices.

An example of a new devices being design by the LAPPD collaboration (Large Area Picosecond Photodetectors). Such a device could be made cheaper than a PMT, covers more area, and improves timing resolution by an order of magnitude.

One idea of what you might be able to do....

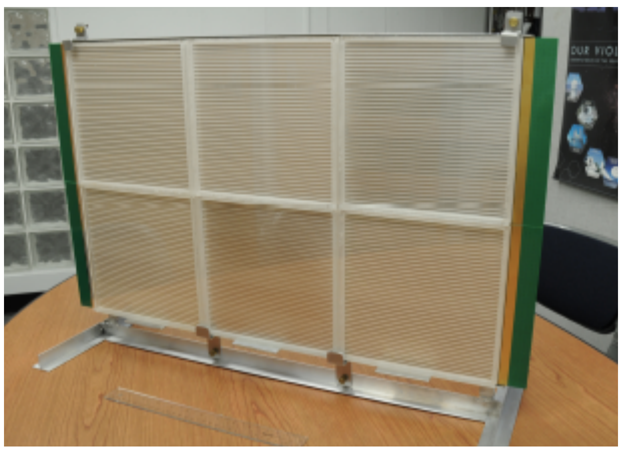
Recall I drew a distinction between Cerenkov and Scintillation detectors.

Tuning absorption and reemission using the right choice of quantum dot may be a way to use both types of light in the detector.

We will need to be able to distinguish prompt Cerenkov light from scintillation light.

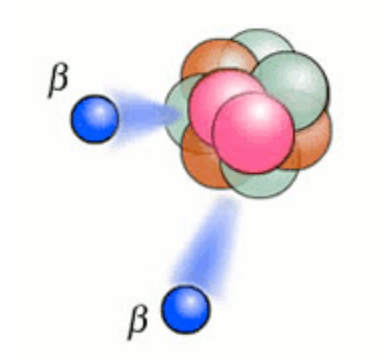
I will need ~100 picosecond timing.

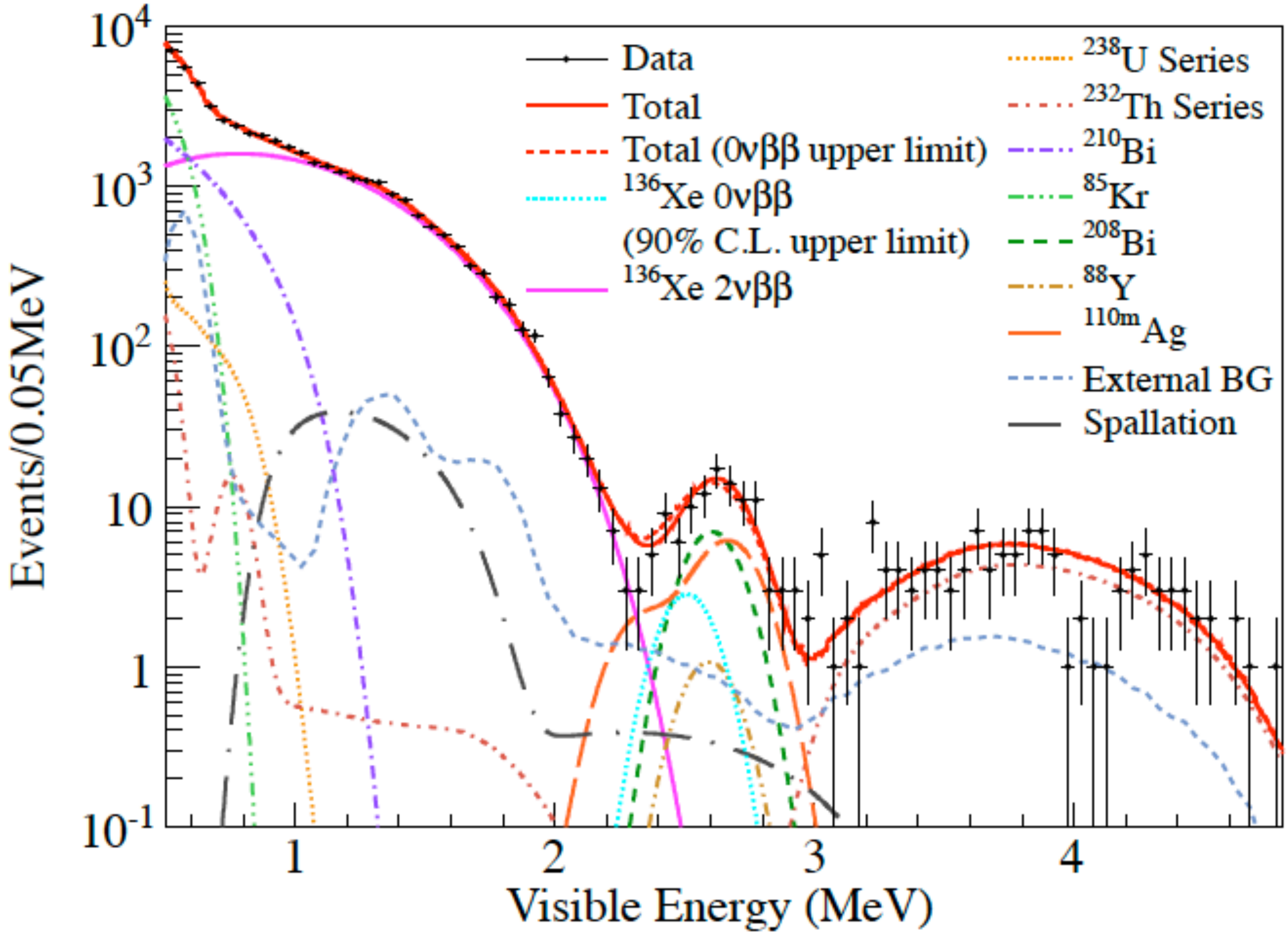
This application is perfect for the LAPPD's.



First **P** is for picosecond.

Why do I want to image the electrons with Cerenkov light?

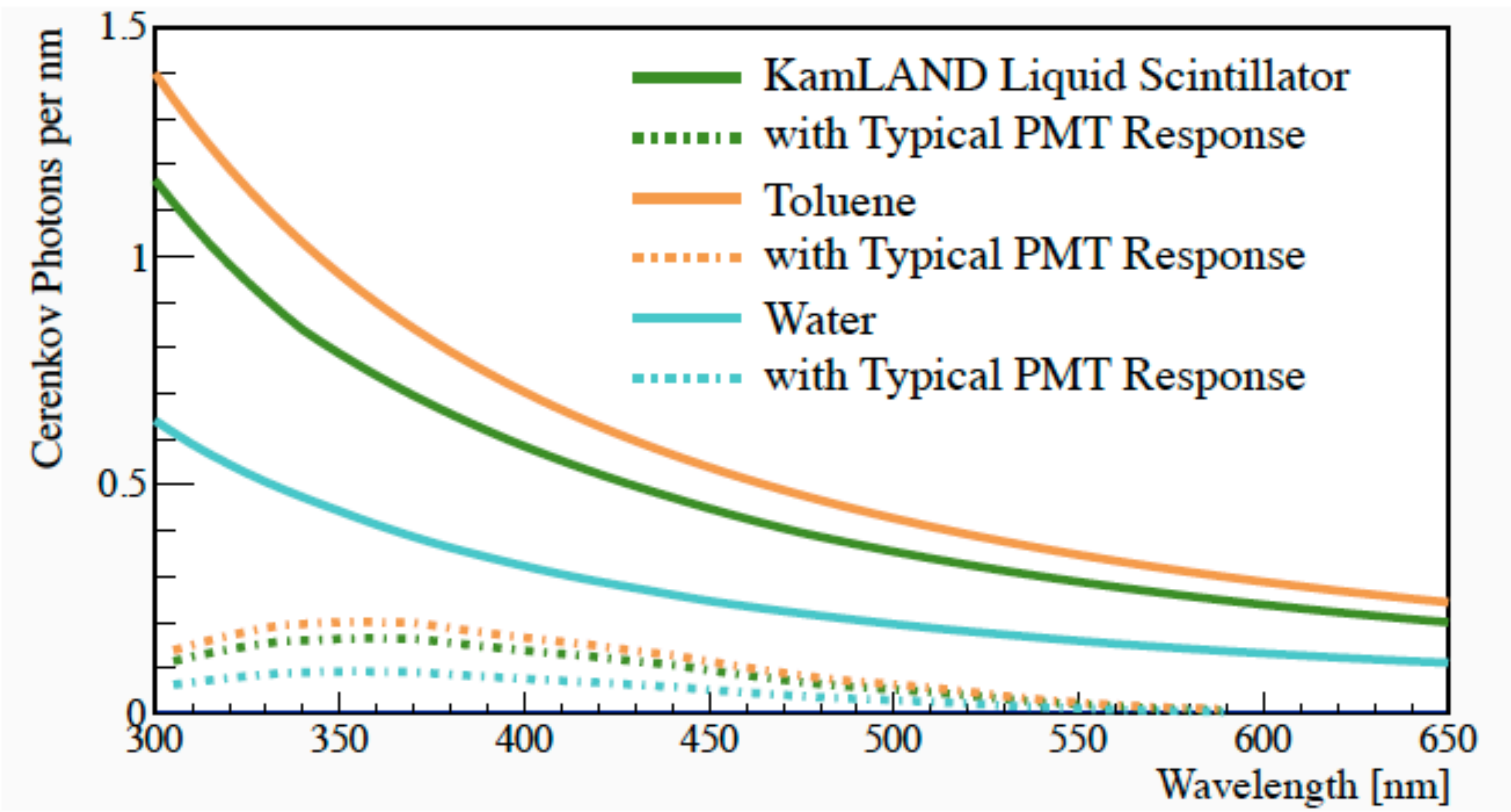


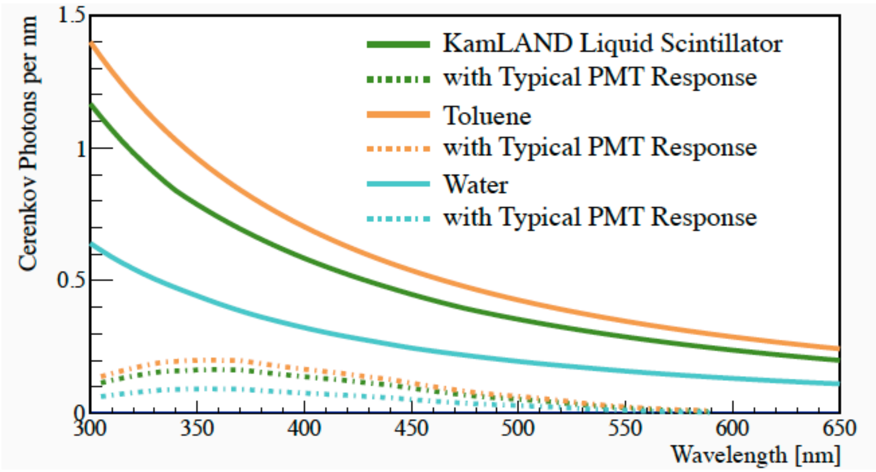


Reduce backgrounds and look for new physics in electron angular correlations!

How many photons do we get?

Calculation of Cerenkov Photons vs. Wavelength



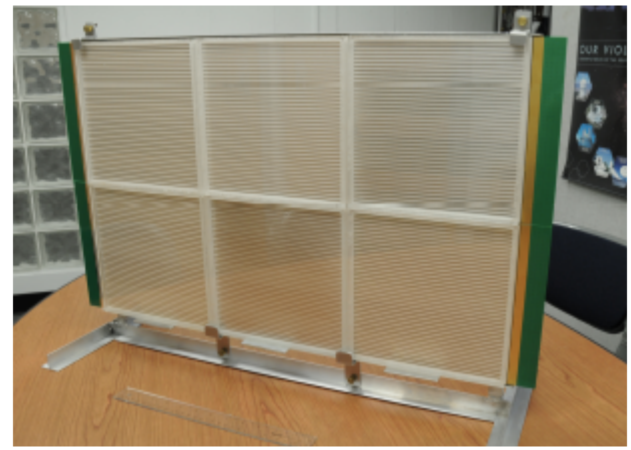


Pushing to shorter wavelengths increases the number of detected Cerenkov photons...

	Number of Photons		with PMT Efficiency	
	400 nm	360 nm	400 nm	360 nm
Toluene	65.8	94.0	12.0	18.5
KamLAND Scintillator	61.5	87.7	11.1	17.3
Water	26.0	37.0	4.7	7.3

....but this is not going to be easy.

So happy together?



Just one idea, but I think there may be many more out there...

This is a neat idea…but we are a long way from knowing if this will work.

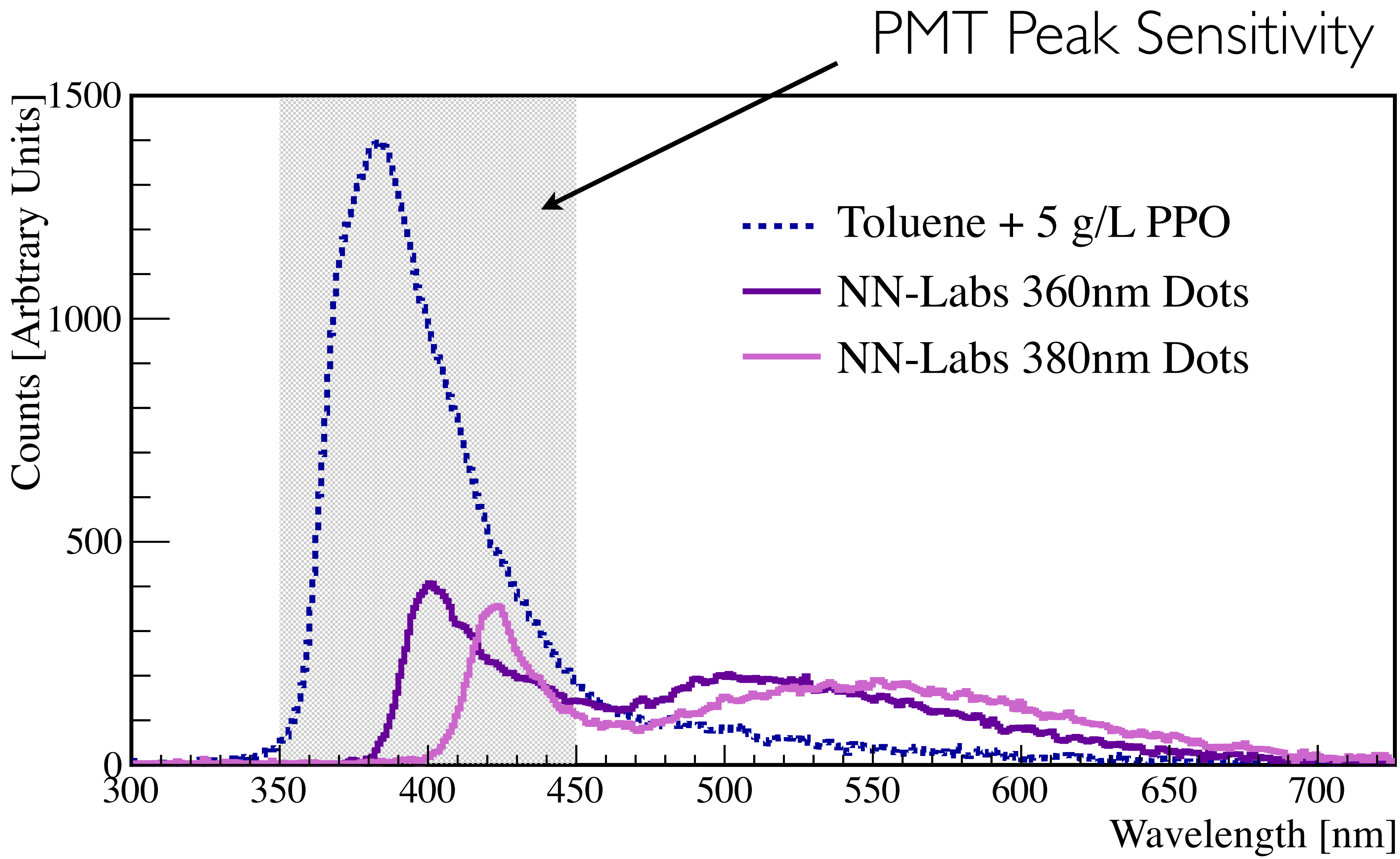
Let’s start with some basic measurements!

First spectrometer data with excitation with 280nm LED.

Samples are:
20mL toluene + 5 g/L PPO + 1.25 g/L quantum dots.

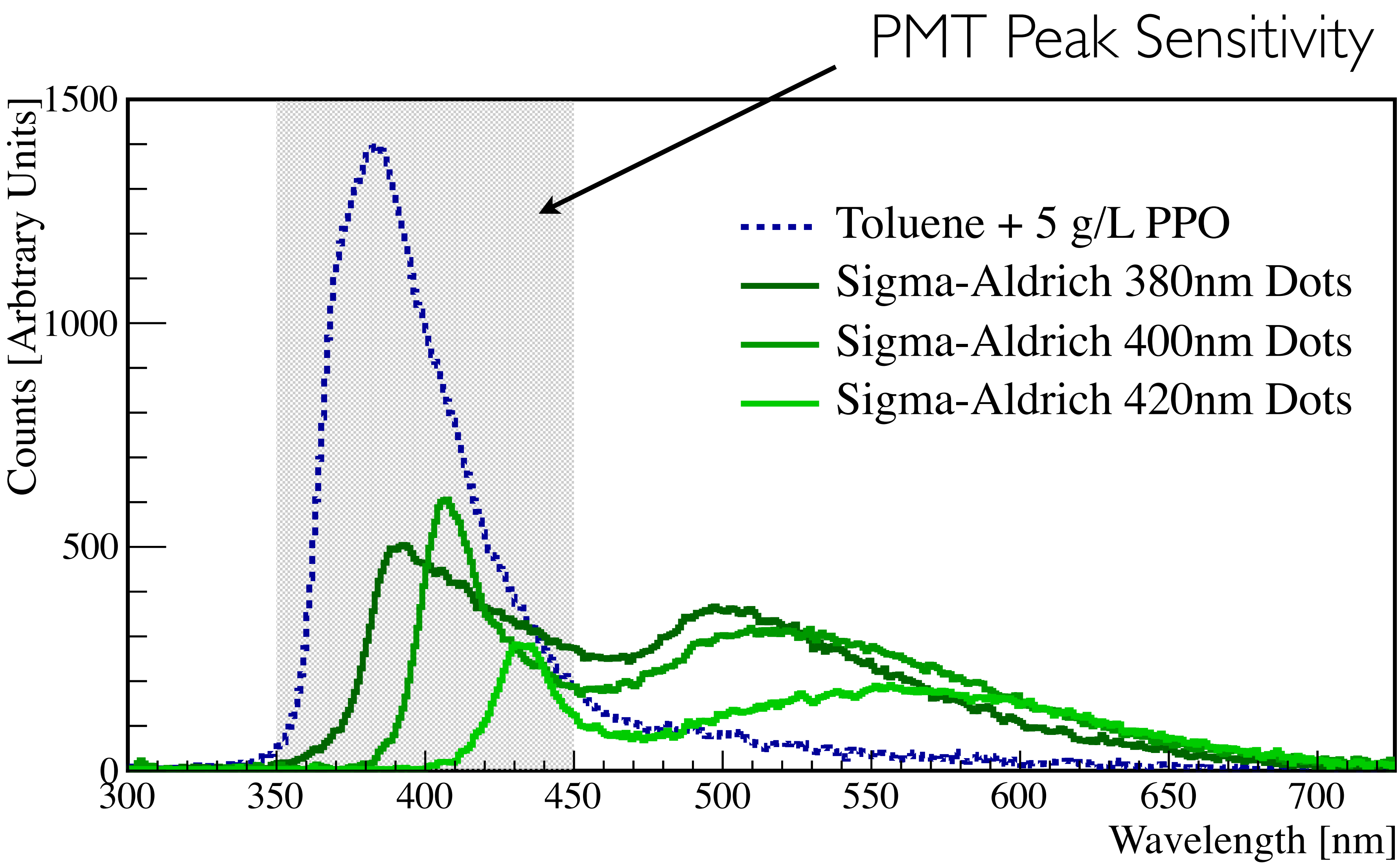
How much light?

Excite the scintillator with a 280nm LED.



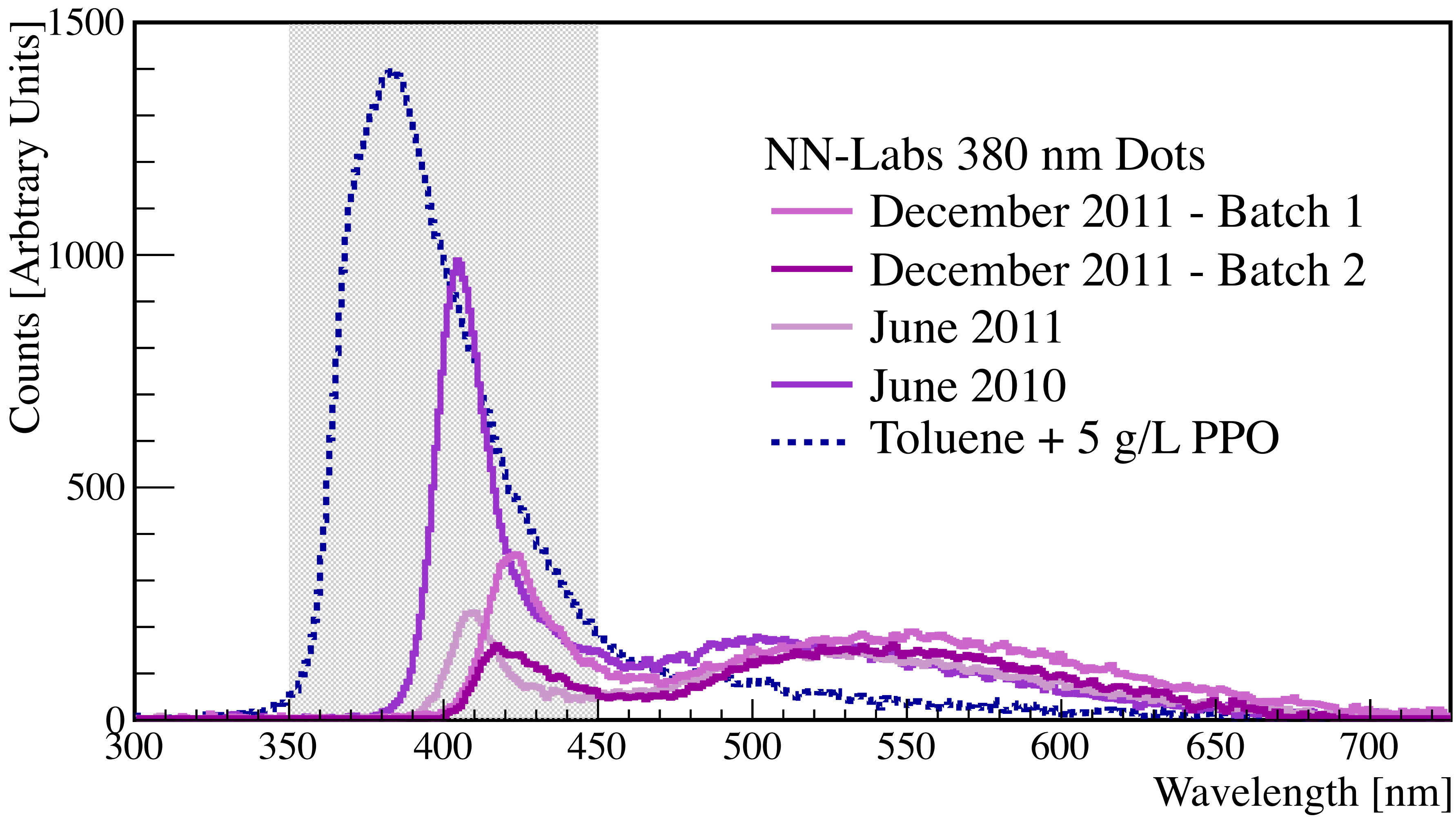
How much light?

Excite the scintillator with a 280nm LED.



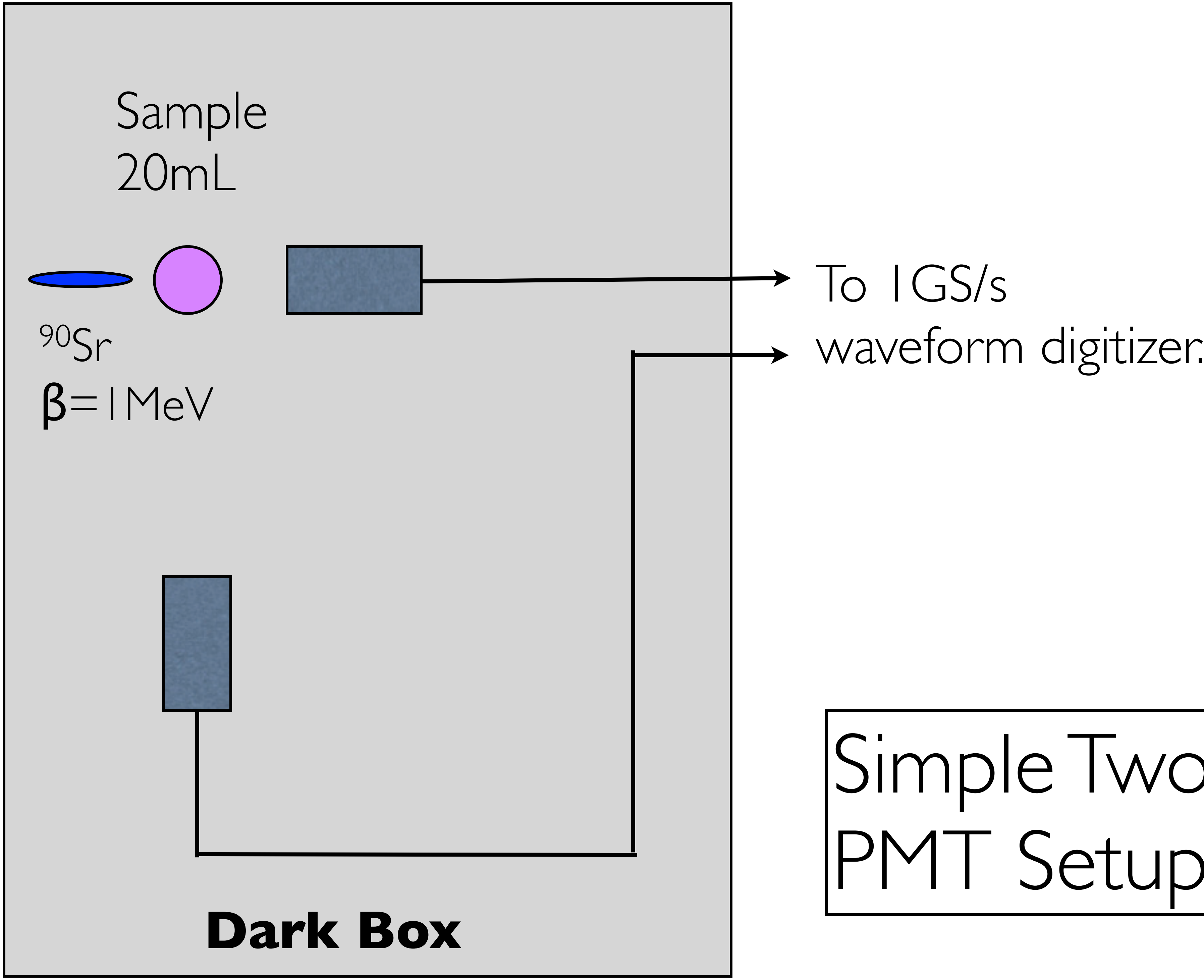
Do Quantum Dots Age?

One of the NSF reviewers asked if this was an issue.



No evidence for aging.

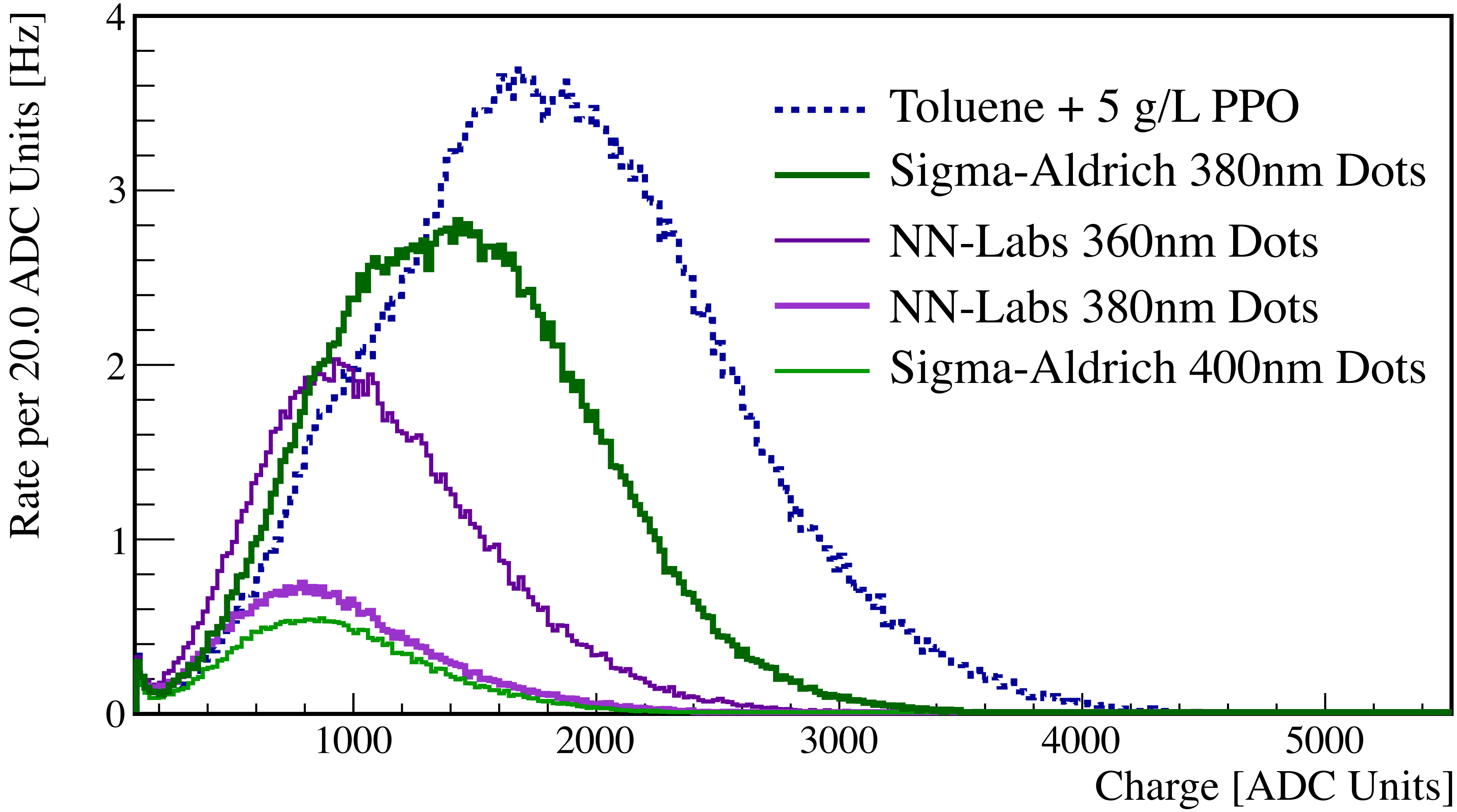
The bigger issue for us seems to be batch to batch variations.



Simple Two
PMT Setup

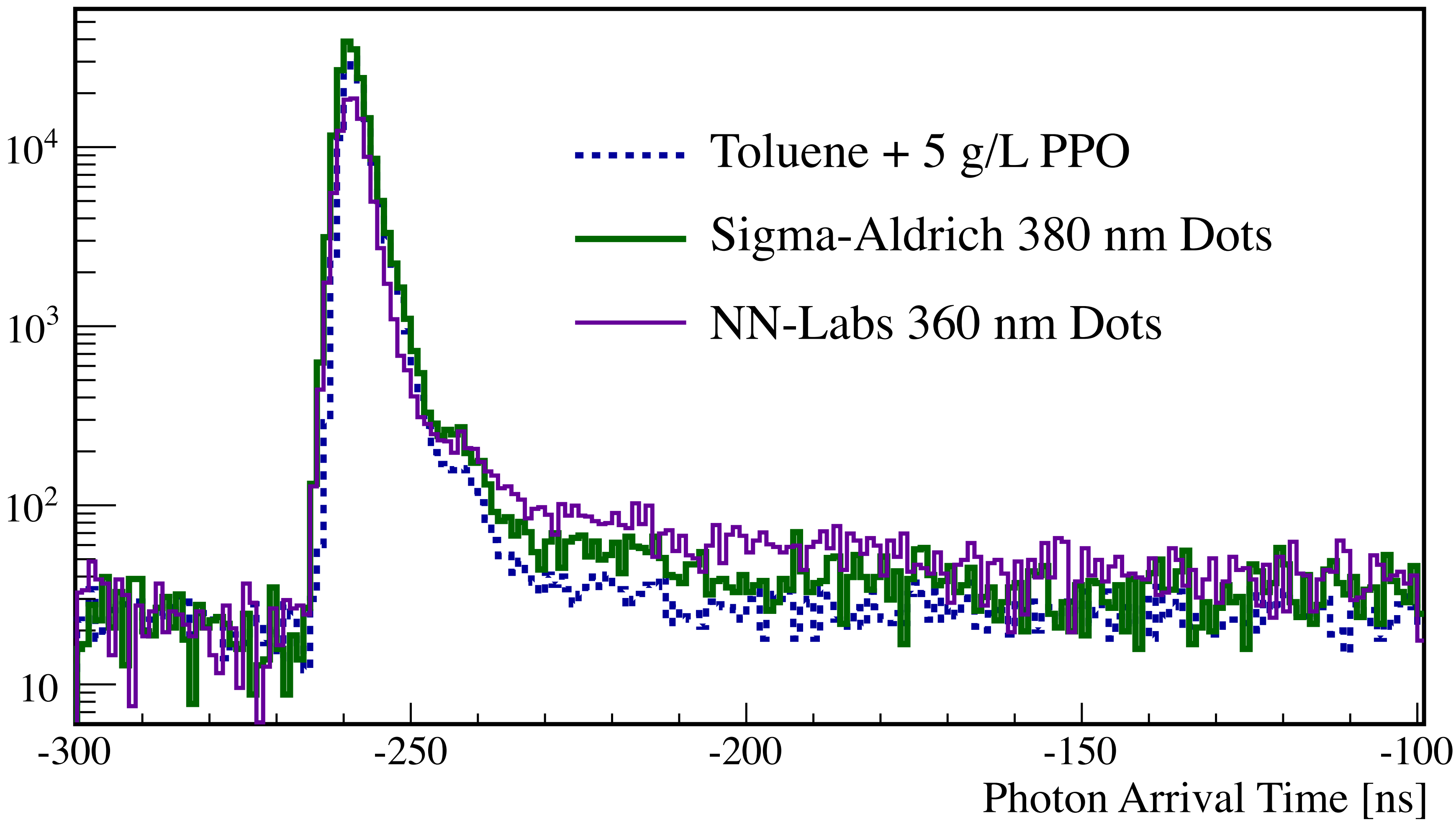
Does the scintillator still scintillate?

Study the scintillator with a ^{90}Sr beta source.



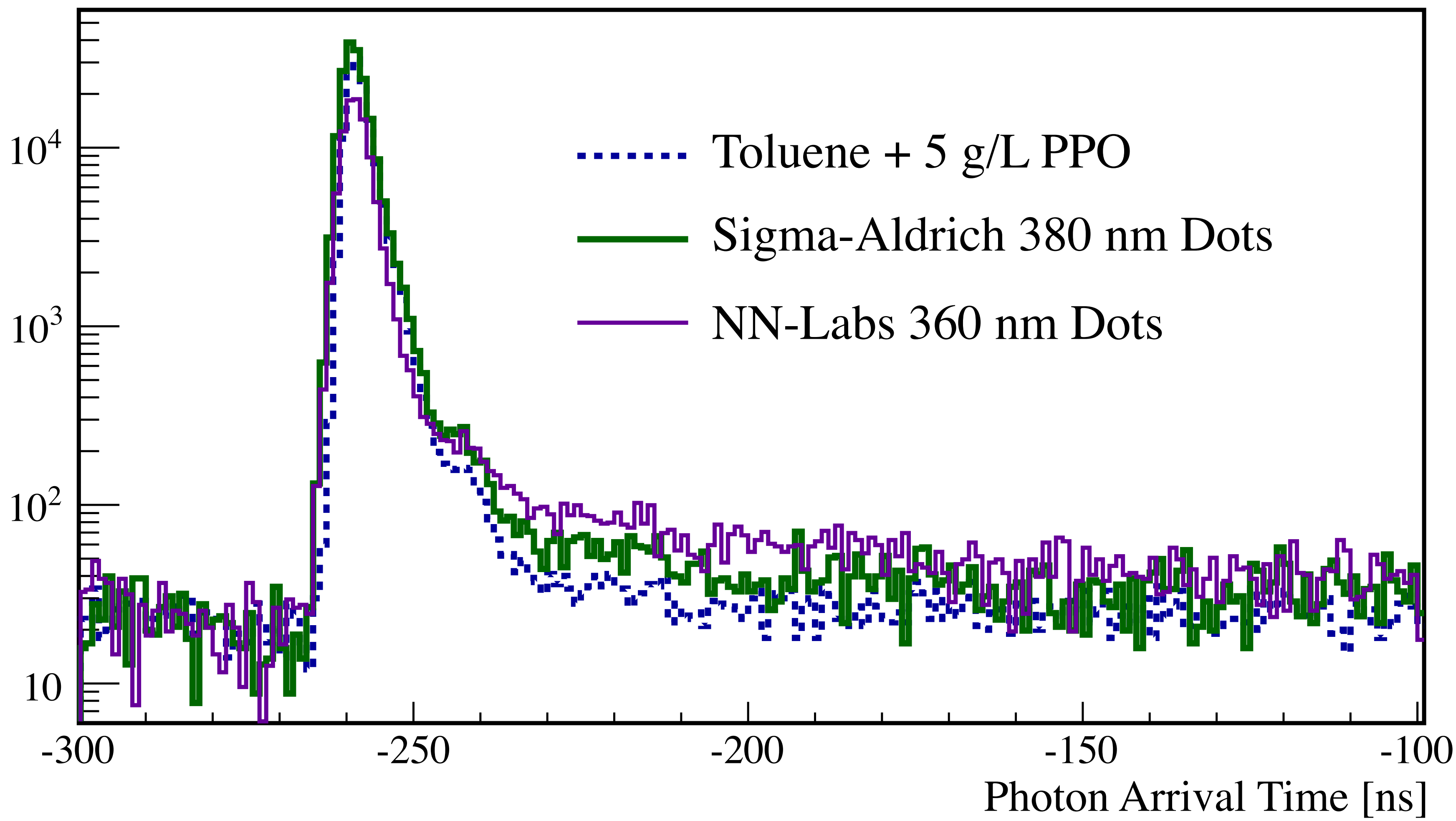
The light yield is reduced compared to the standard scintillator

Do quantum dots change the timing characteristics of the scintillator?



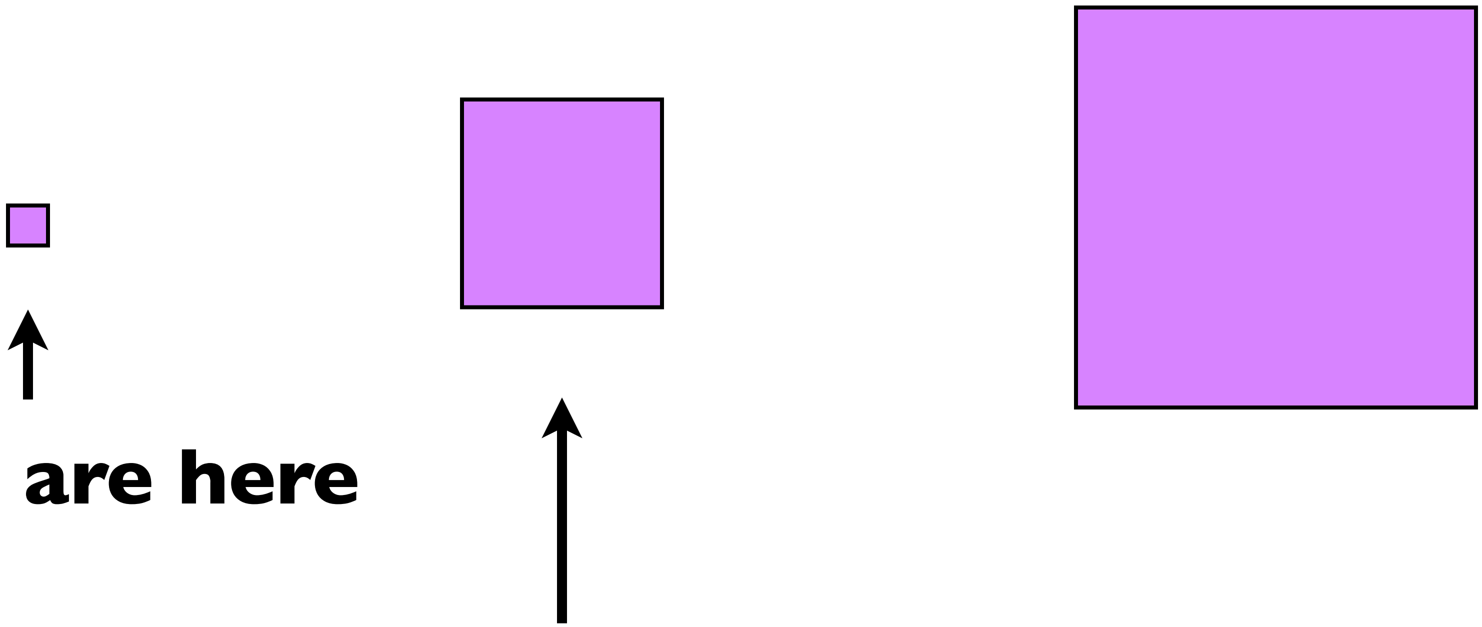
The answer is no, though the quantum dot scintillator seems to have a slightly larger late light component.

Fitting to a three exponential model + PMT response:



Sample	q_1	τ_1 [ns]	q_2	τ_2 [ns]	q_3	τ_3 [ns]
Tol + PPO	0.94±0.01	1.73±0.03	0.08±0.01	5.7±0.5	0.004±0.001	45.9±23.4
SA 380 nm	1.10±0.01	1.84±0.02	0.09±0.01	6.5±0.4	0.022±0.001	96.5±10.7
NN 360 nm	0.80±0.01	1.55±0.03	0.06±0.01	10.9±0.7	0.092±0.003	174.5±14.9

Next Steps:

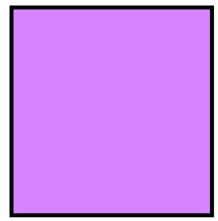


We are here

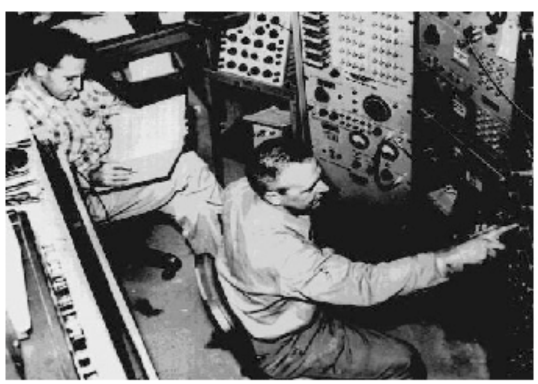
1L Detector - This Fall

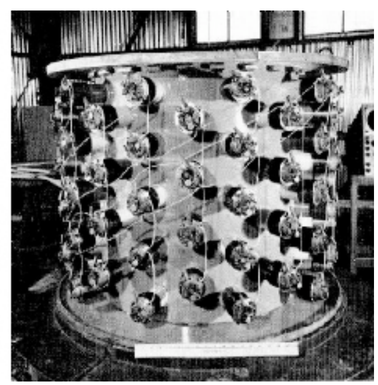
- More quality control of the dots before using.
- Nitrogen purging for better light yield
- Larger quantum quantities
- Attenuation length measurements

The 1 L detector can be a neutron detector!

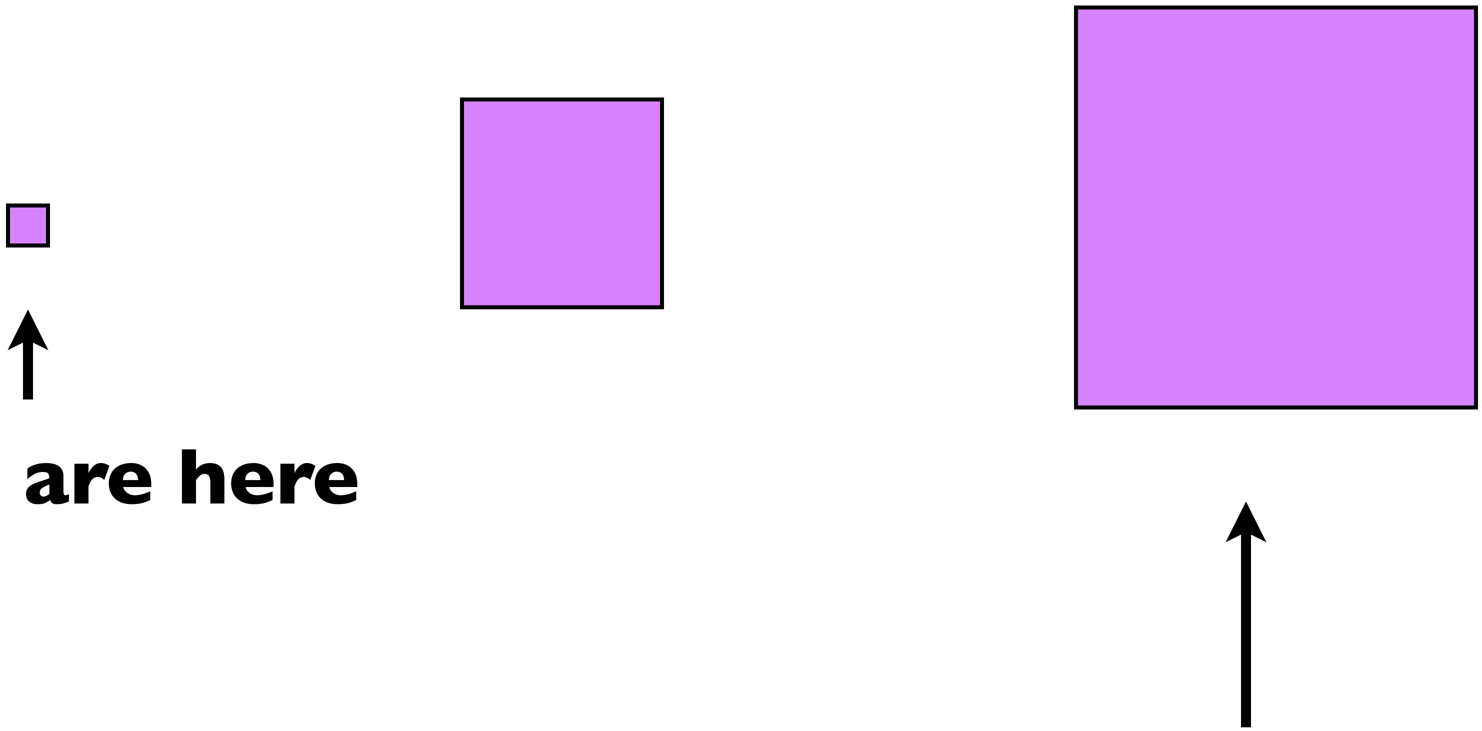


Cadmium is a good alternative to Gadolinium.





Next Steps:

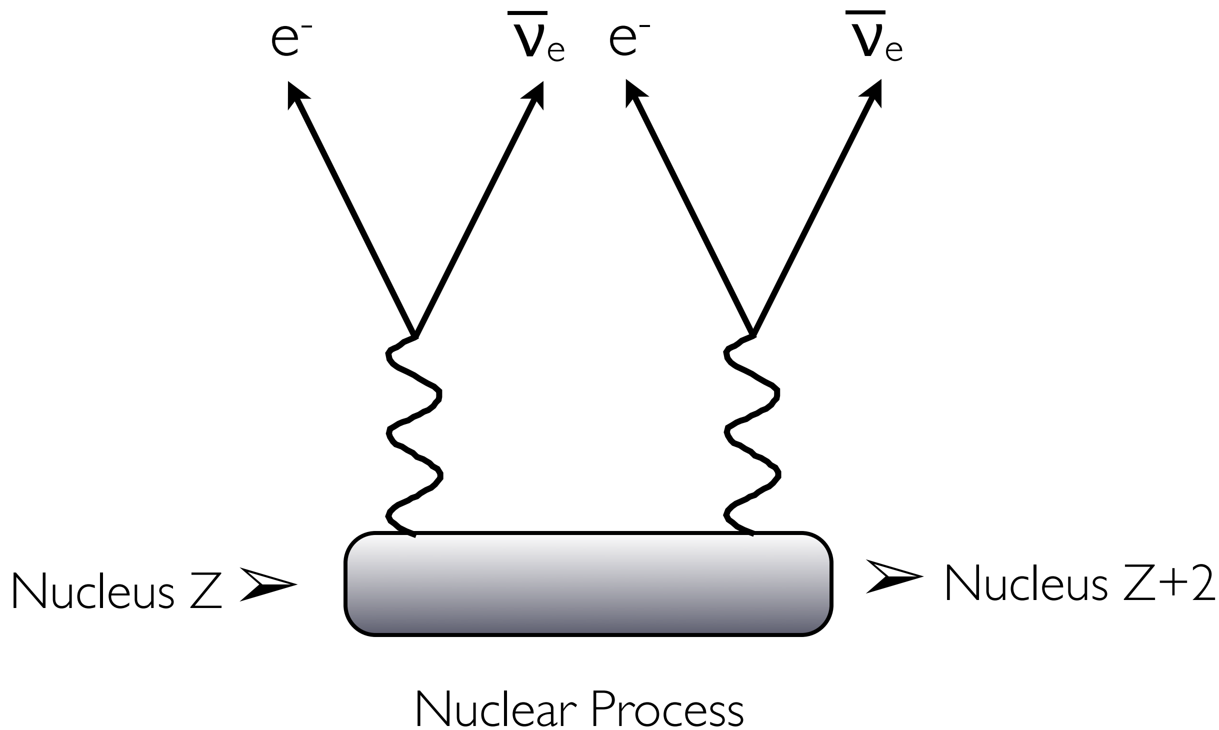


We are here

1m³ Detector

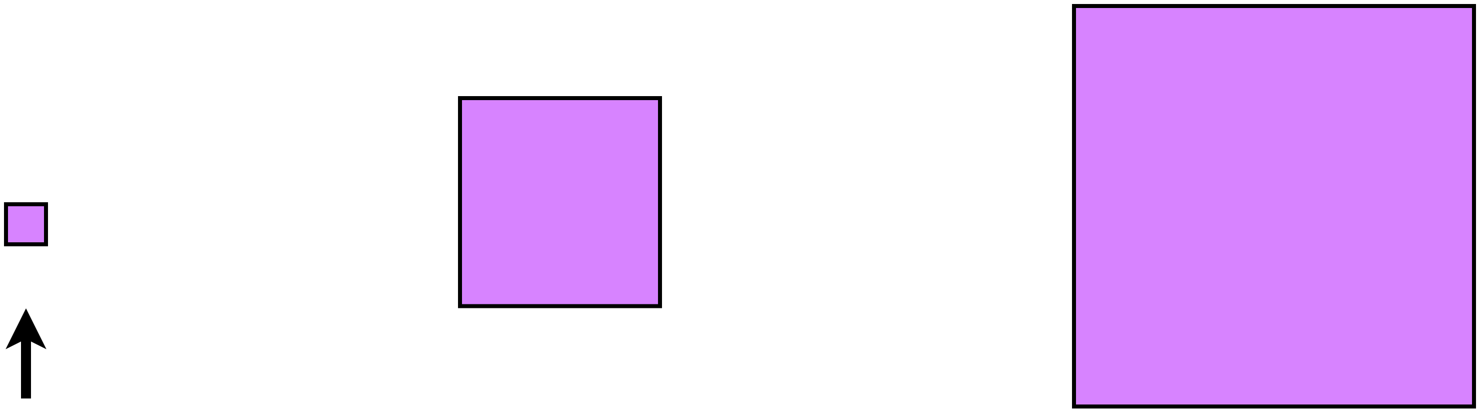
- Make use of knowledge from 1L detector
- Perhaps experiment with new photodetectors.
- Make measurement of two neutrino double beta decay in ^{116}Cd.

Recall you can have Two Neutrino Double Beta Decay:



With 10g of ^{116}Cd, I expect 1000 events in 6 months.

Next Steps:



We are here

Exciting work ahead!

The End