

Next Generation Scintillation Detectors: Development of Quantum Dot Doped Scintillator

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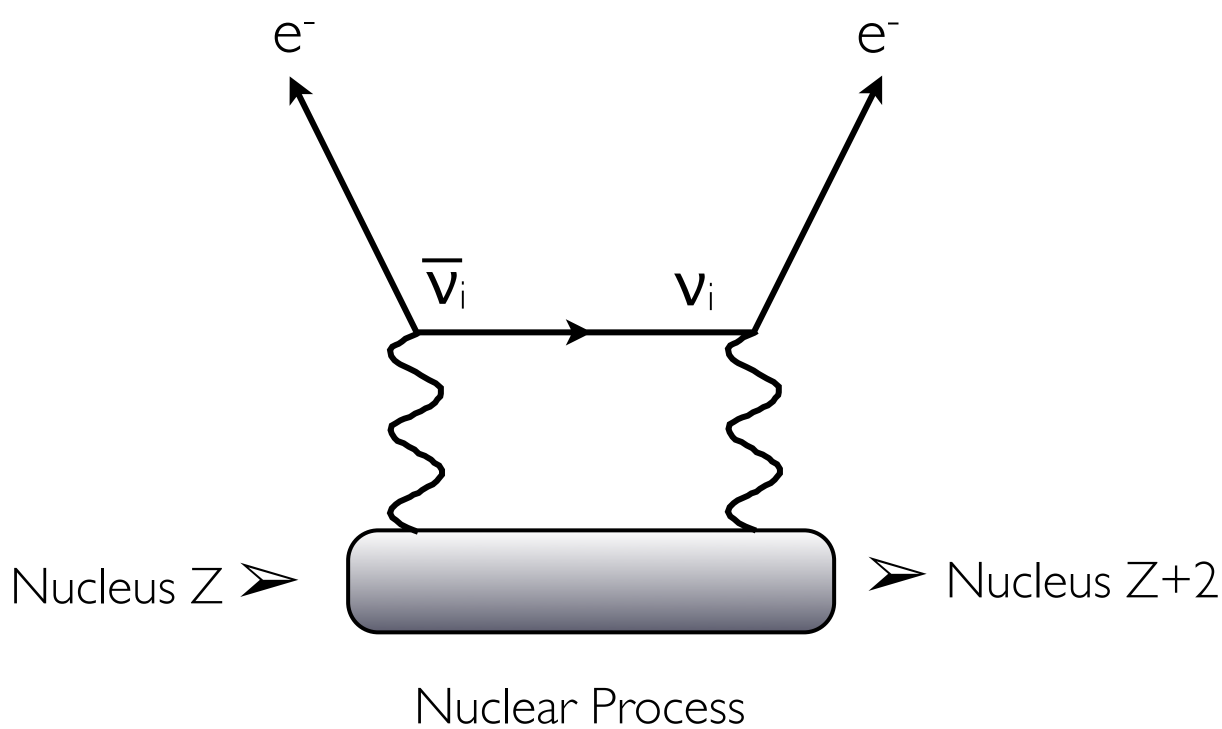
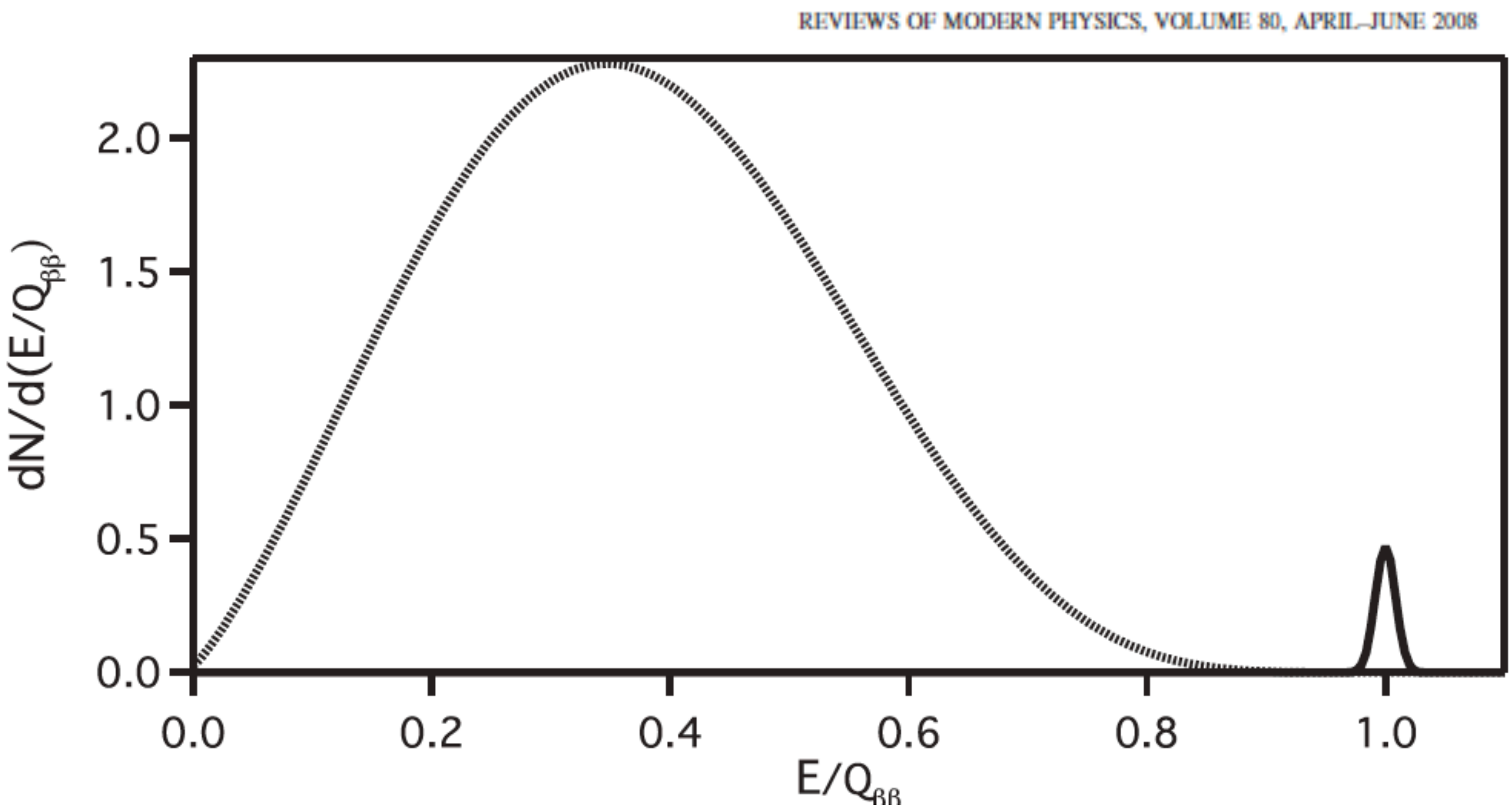
I am particularly interested in applications to ...



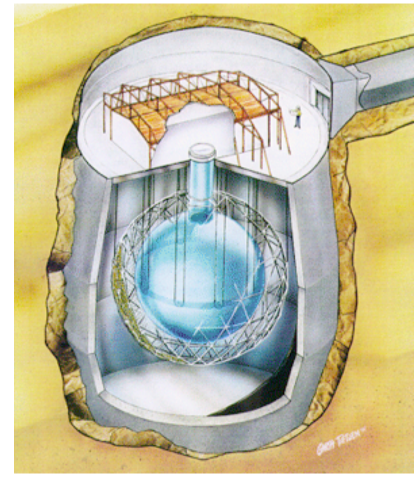
Neutrinoless Double Beta Decay

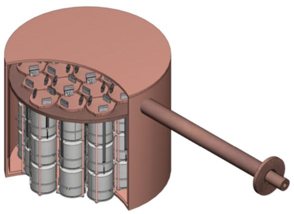
Neutrinoless Double Beta Decay

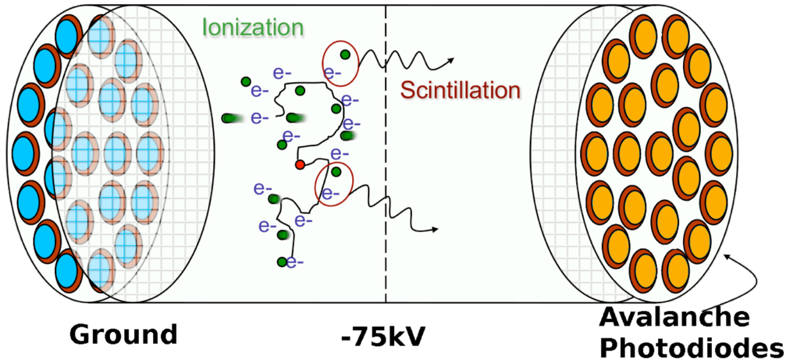
The sum of the electron energies gives a spike at the endpoint of the "neutrino-full" double beta decay.

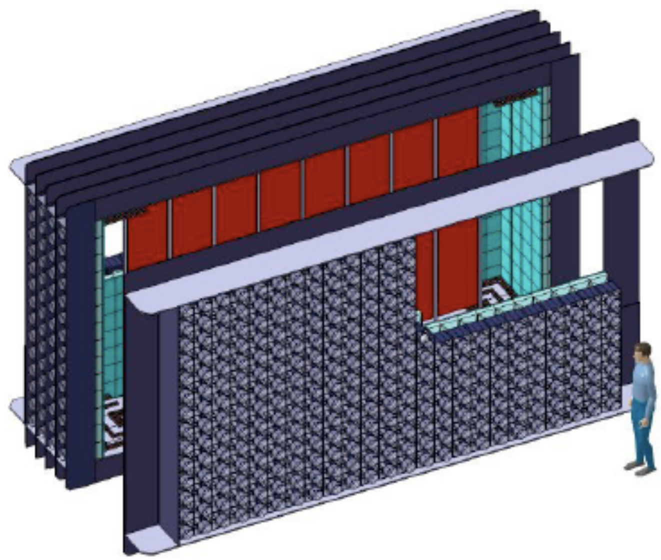


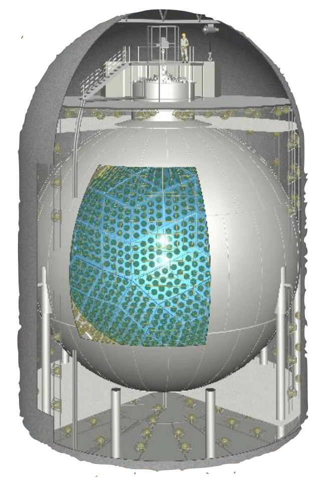
An explosion of technology!











...and even KamLAND and SNO are getting in on the action!

An analytical form for comparing experiments:

$$T_{1/2}^{0\nu}(n_\sigma) = \frac{4.16 \times 10^{26}\ \mathrm{yr}}{n_\sigma}\left(\frac{\varepsilon a}{W}\right)\sqrt{\frac{Mt}{b\Delta(E)}}$$

$$T^{0\nu}_{1/2}(n_\sigma) = \frac{4.16 \times 10^{26}\ \mathrm{yr}}{n_\sigma}\left(\frac{\varepsilon a}{W}\right)\sqrt{\frac{Mt}{b\Delta(E)}}$$

How many sigma you would like to be able to measure.

Detector Efficiency

Isotopic abundance

$$T_{1/2}^{0\nu}(n_\sigma) = \frac{4.16 \times 10^{26}\ \text{yr}}{n_\sigma}\left(\frac{\varepsilon a}{W}\right)\sqrt{\frac{Mt}{b\Delta(E)}}$$

Molecular Weight

Exposure time

$$T_{1/2}^{0\nu}(n_\sigma) = \frac{4.16 \times 10^{26}\ \mathrm{yr}}{n_\sigma}\left(\frac{\varepsilon a}{W}\right)\sqrt{\frac{Mt}{b\Delta(E)}}$$

Background rate

Total Mass

$$T^{0\nu}_{1/2}(n_\sigma) = \frac{4.16 \times 10^{26}\ \mathrm{yr}}{n_\sigma}\left(\frac{\varepsilon a}{W}\right)\sqrt{\frac{Mt}{b\Delta(E)}}$$

Being big is what kiloton-scale scintillators are good at!

Energy resolution is what they are not so good at.....

$$T^{0\nu}_{1/2}(n_\sigma) = \frac{4.16 \times 10^{26}\ \mathrm{yr}}{n_\sigma}\left(\frac{\varepsilon a}{W}\right)\sqrt{\frac{Mt}{b\Delta(E)}}$$

Energy resolution

Wrapped up in the background rate, is some method to convince yourself that you saw neutrinoless double beta decay.

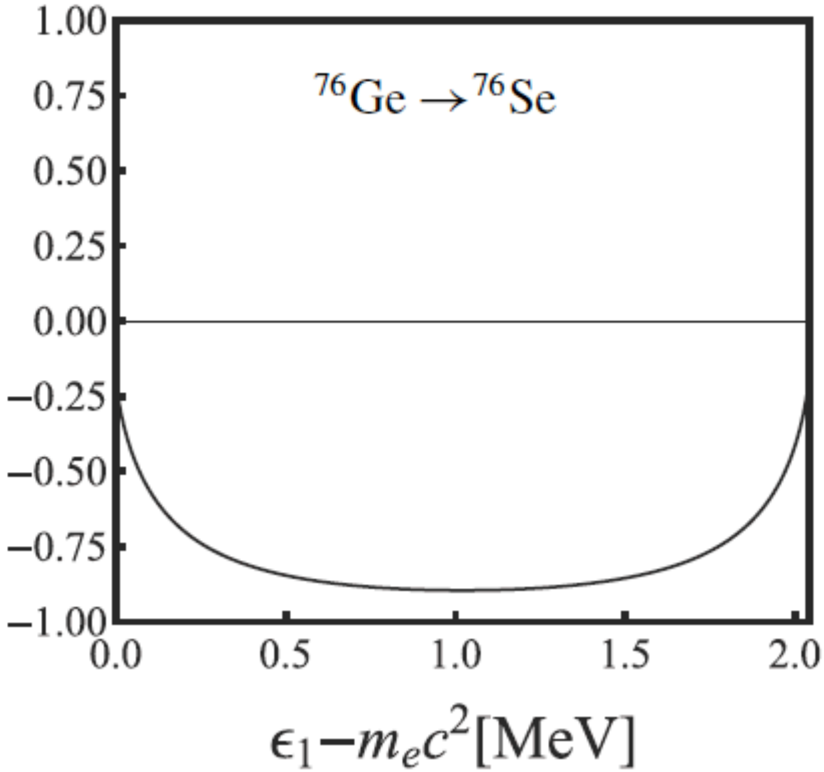
Best way would be to tag the daughter, but tracking the electrons would be nice too!

The angular correlation between outgoing electrons is fairly nucleus independent...

Kotila and Iachello

PHYSICAL REVIEW C **85**, 034316 (2012)

Angular Correlation



One electron energy

And new physics could show up in this distribution!

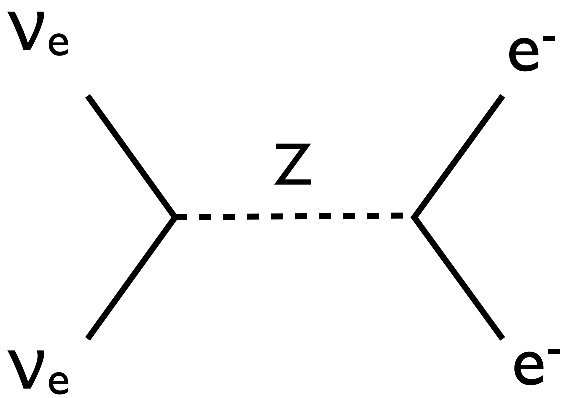
Phys.Rev.D76:093009,2007

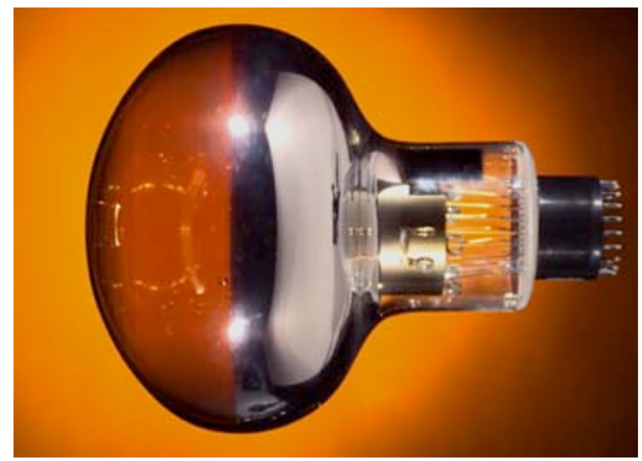
Ali, Borisov, Zhuridov

Can we do something better with Liquid Scintillator detectors?

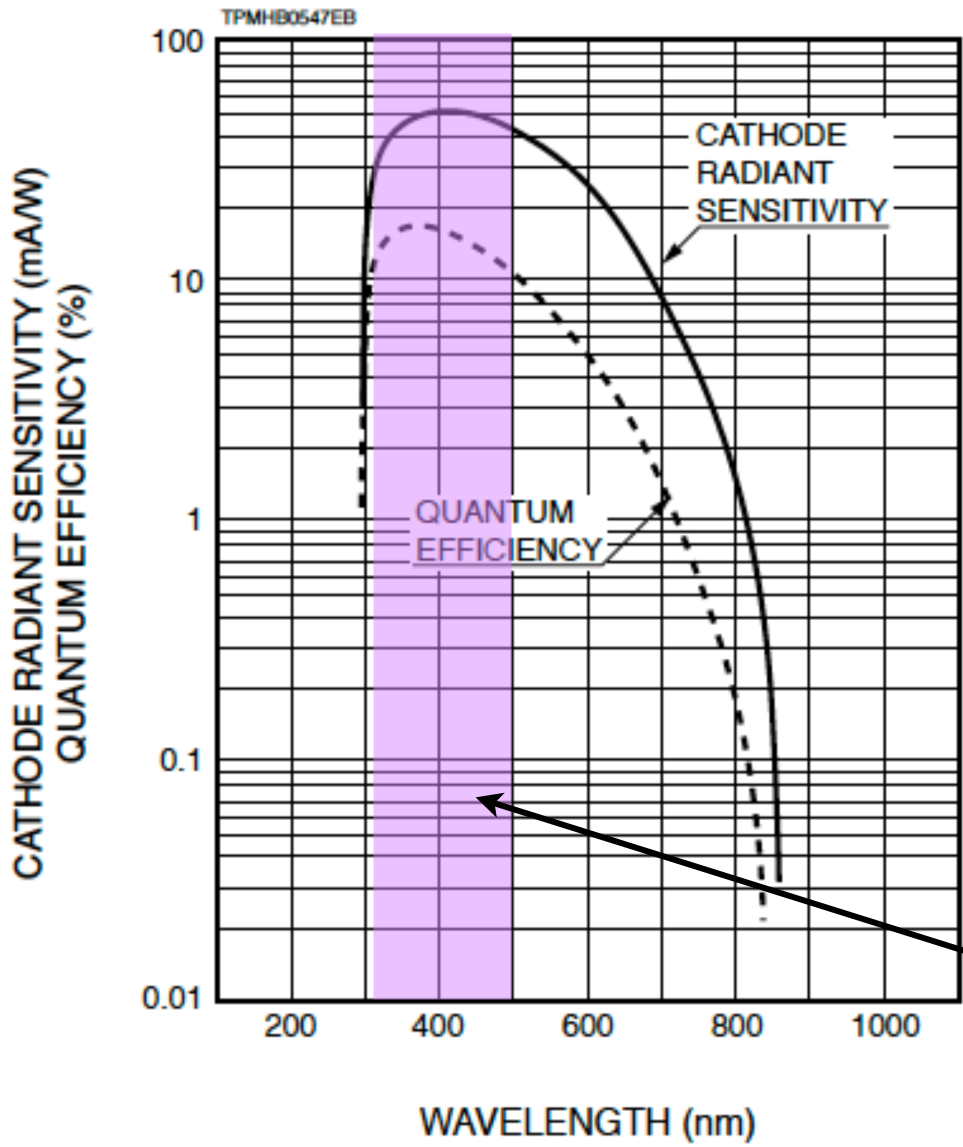
Basic Principle of Neutrino Detectors

Physics ⟶ **Light** ⟶ **PMTs**





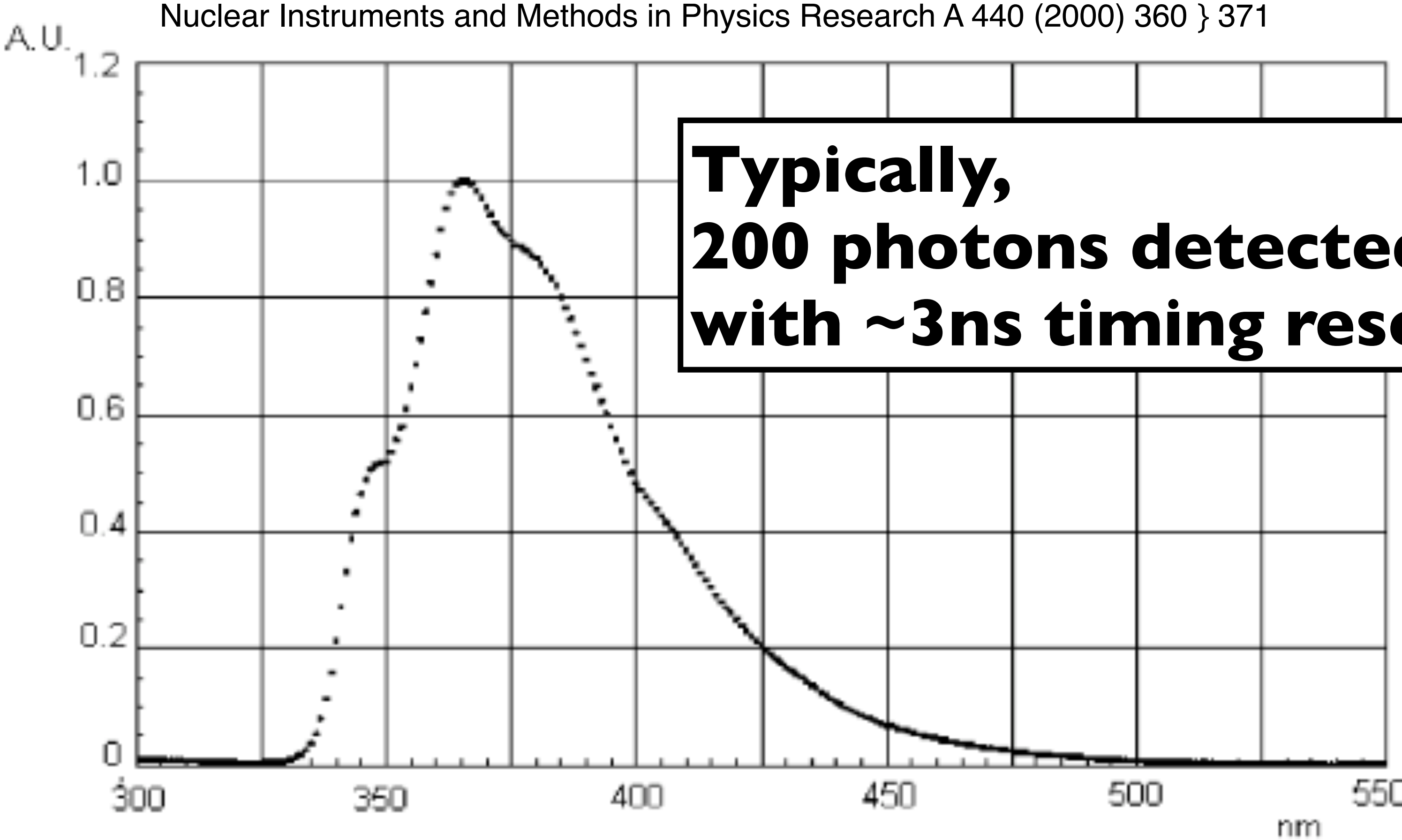
Typical PMT Detection Efficiency:



Peak Efficiency
300-500nm

Tune Scintillator Emmission:

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



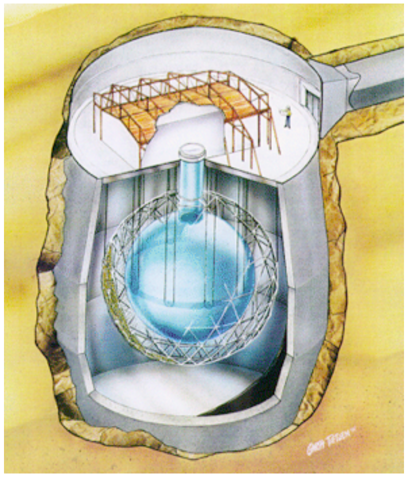
Typically,
200 photons detected per MeV
with ~3ns timing resolution.

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

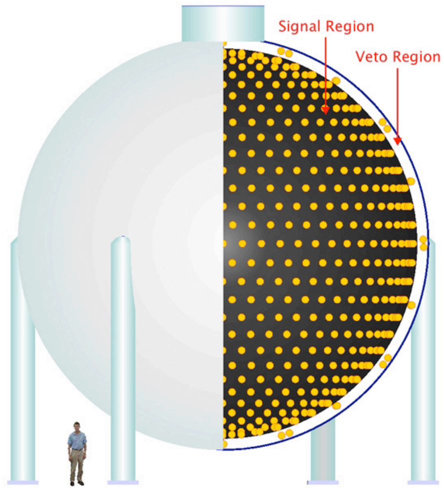
Example is Borexino Scintillator.

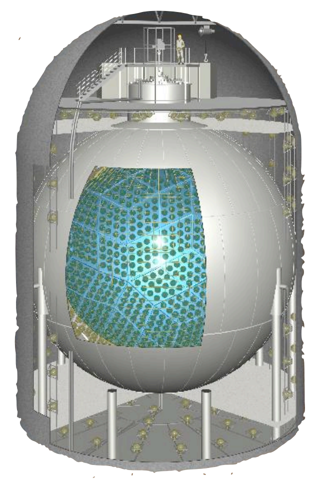
Cerenkov Light

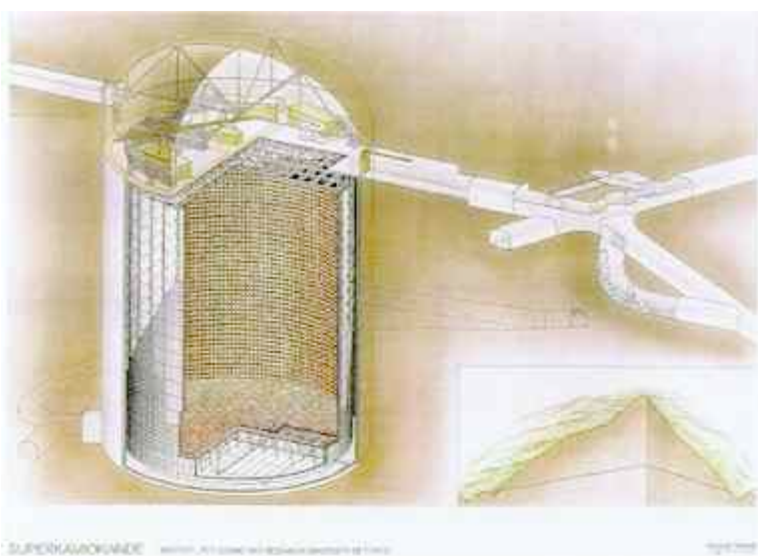
Scintillation Light

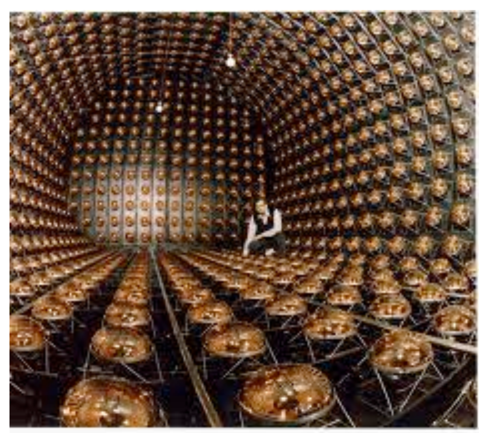


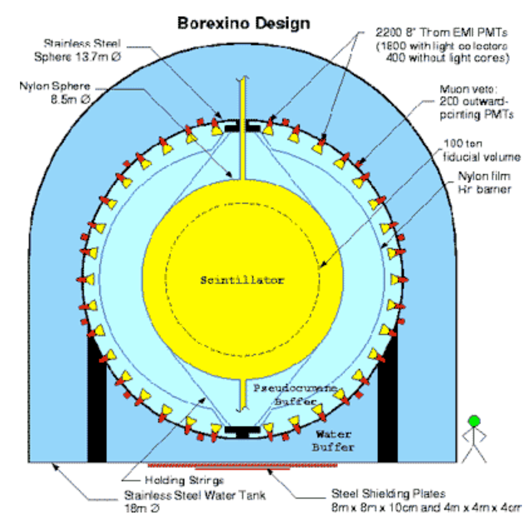
MiniBooNE Detector



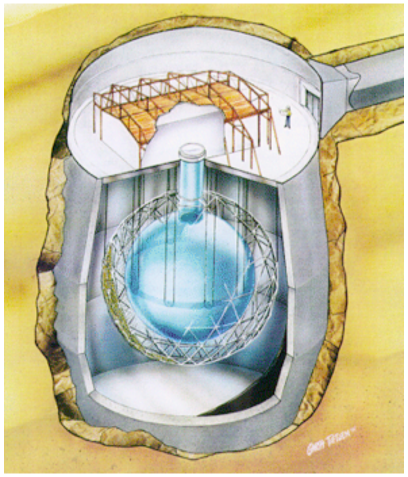


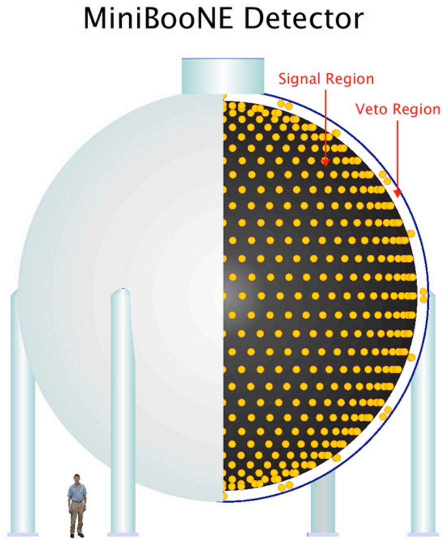


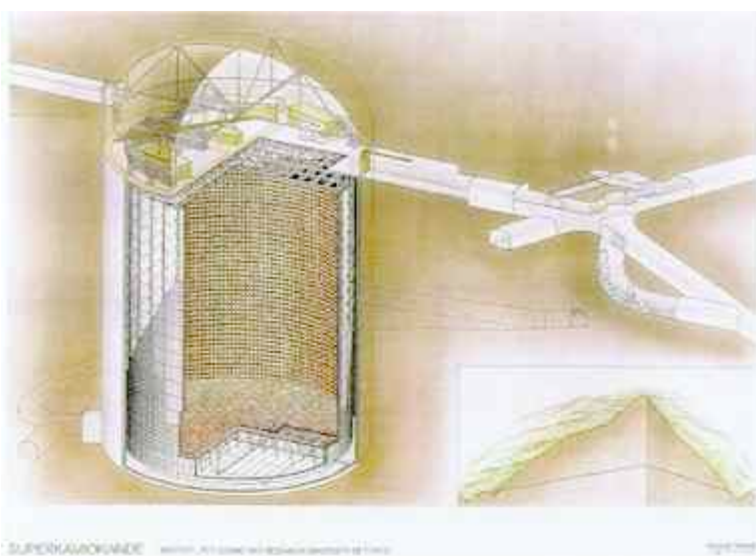




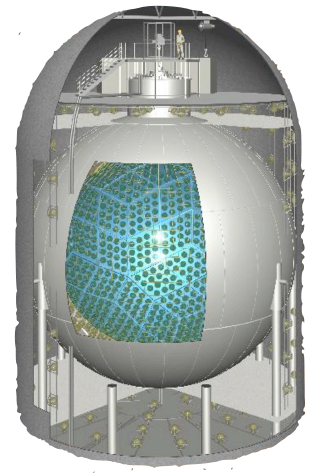
Directionality

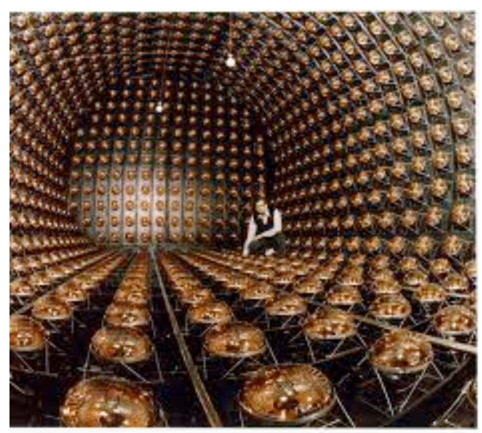


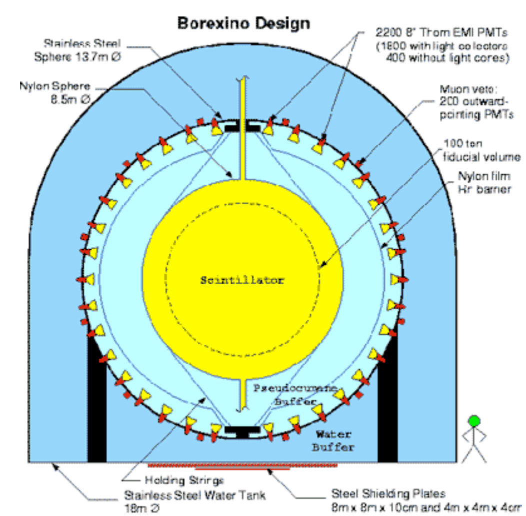




Energy Resolution

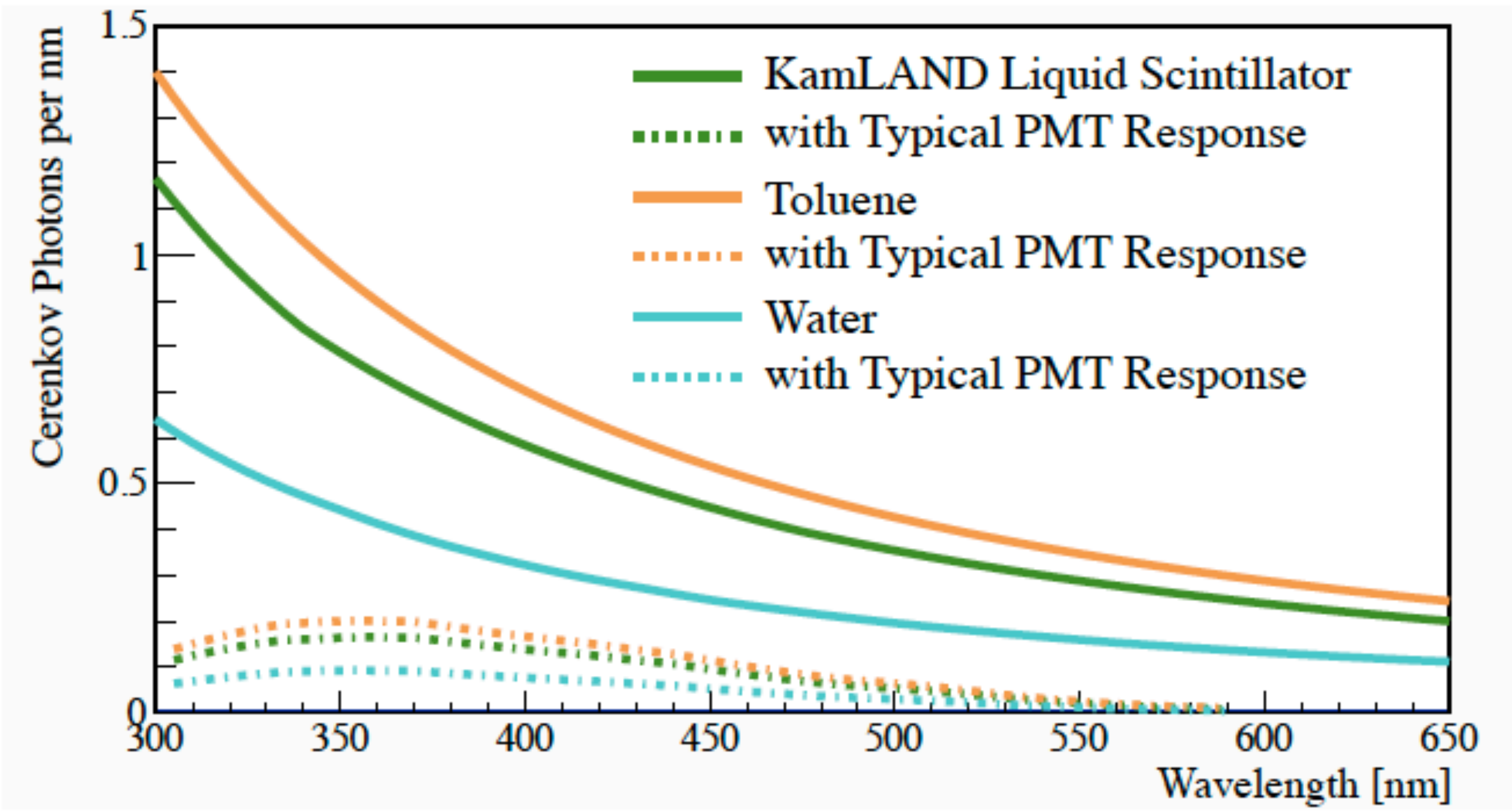






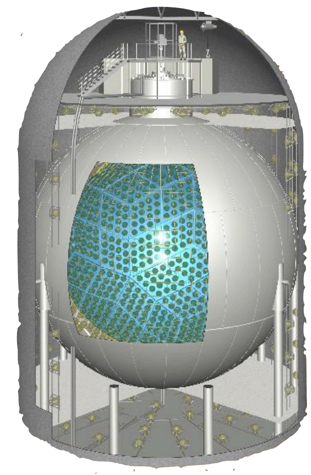
The Cerenkov light is still there...

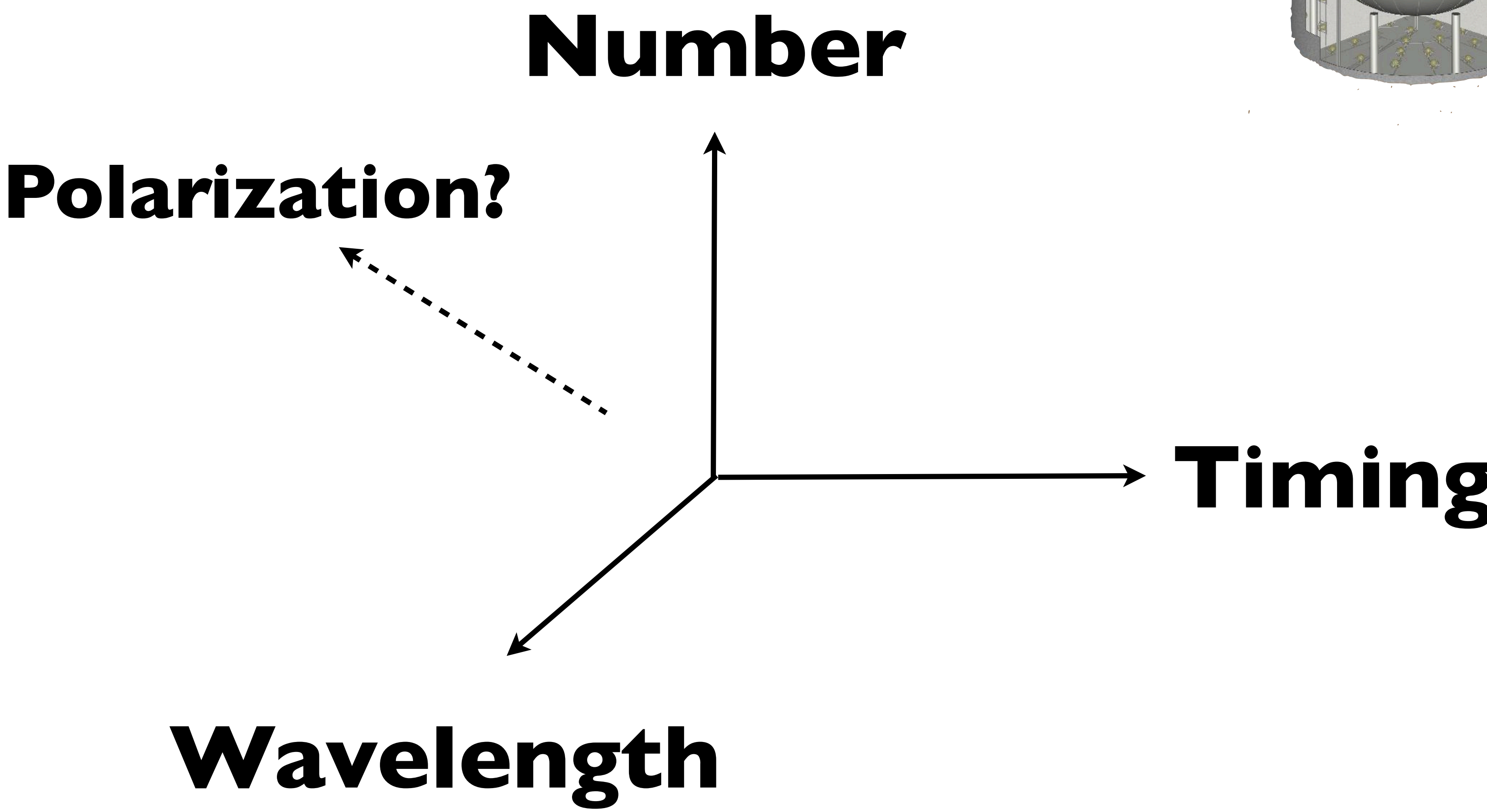
Number of Cerenkov Photons for a 1MeV e-



For KamLAND scintillator, this is 60 (10) photons per MeV above 400nm below 400nm the light is absorbed and reemitted as scintillation light.

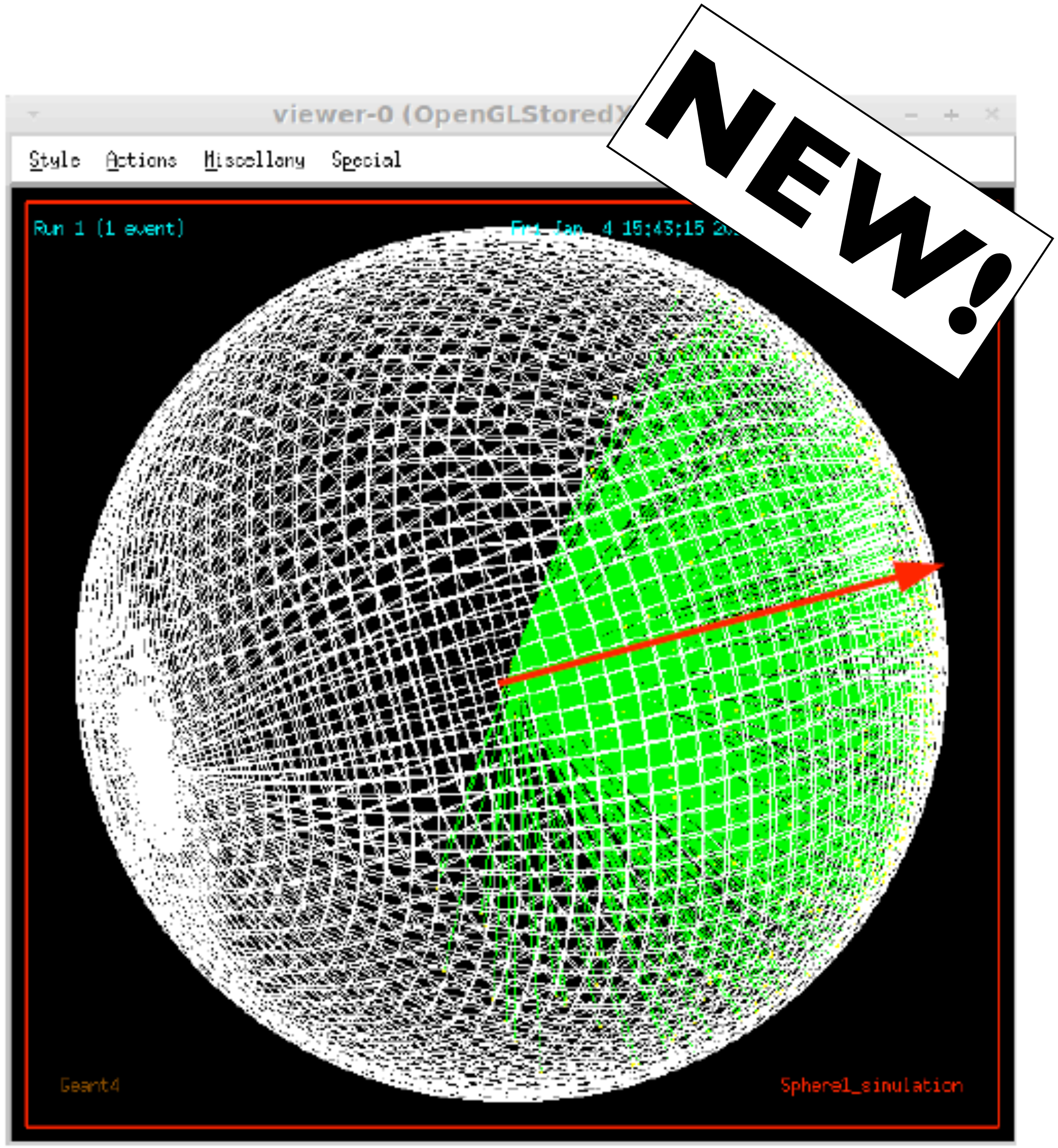
What are the handles in a scintillator detector?





Geant4 simulation

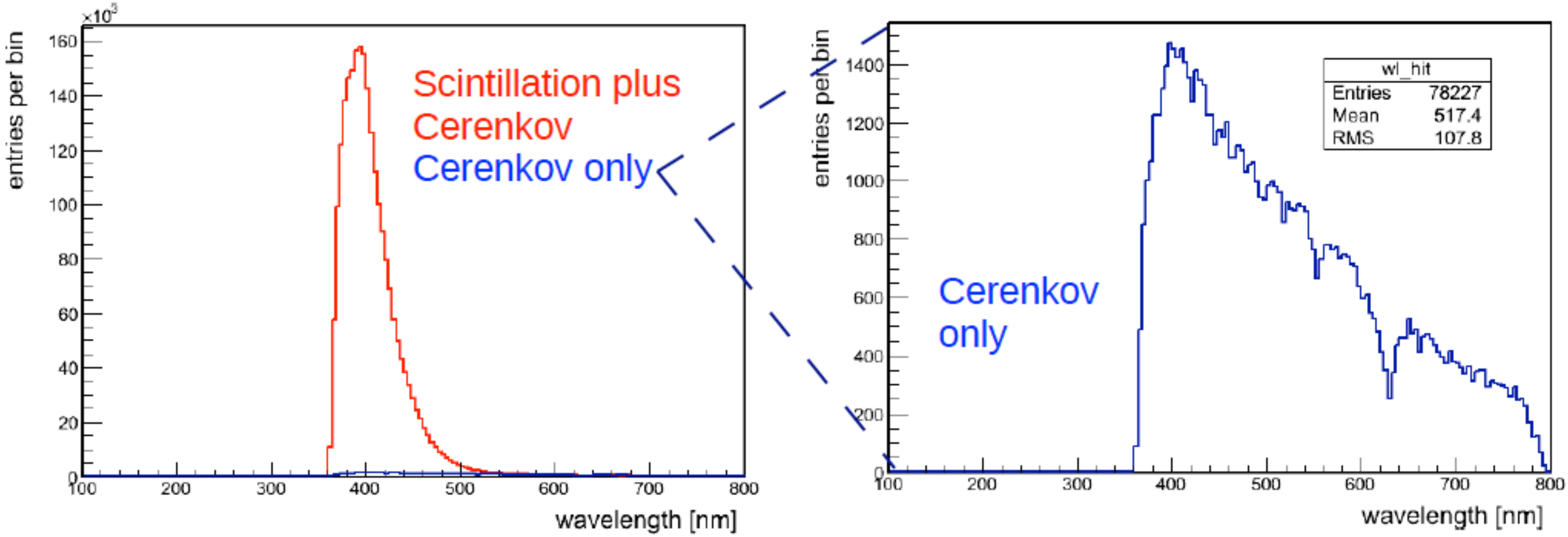
- Simplified R=6.5m spherical geometry.
- Simulating single 5MeV electrons.
- Current KamLAND scintillator and PMTs.
- Can we pick out the Cerenkov signal?



Green: optical photon tracks
Red arrow: z-axis

From: Christoph Aberle

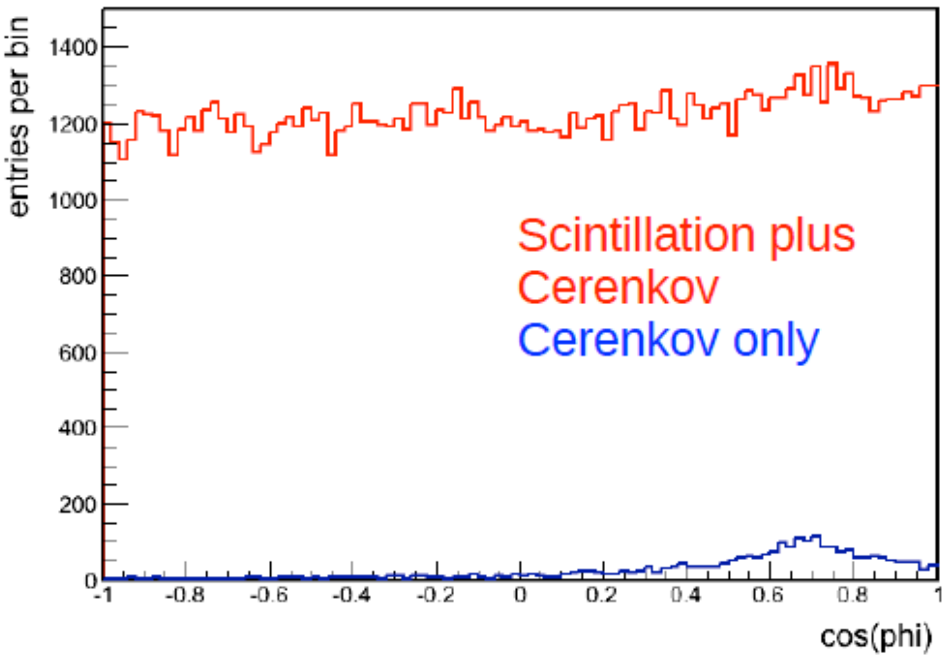
Results for 100 e- events:

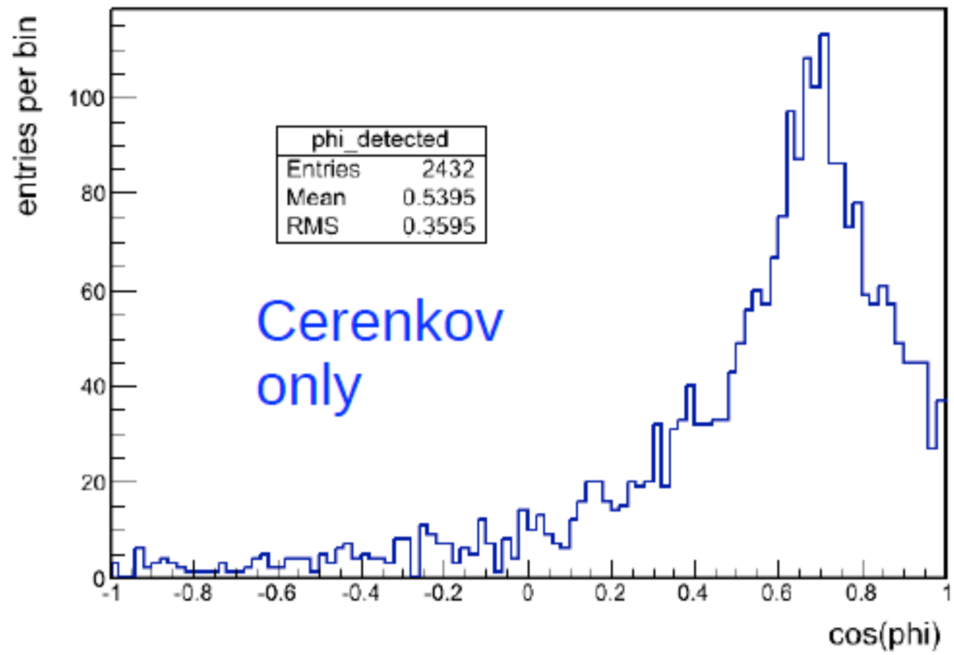


Absorption of all photons below 360 nm.

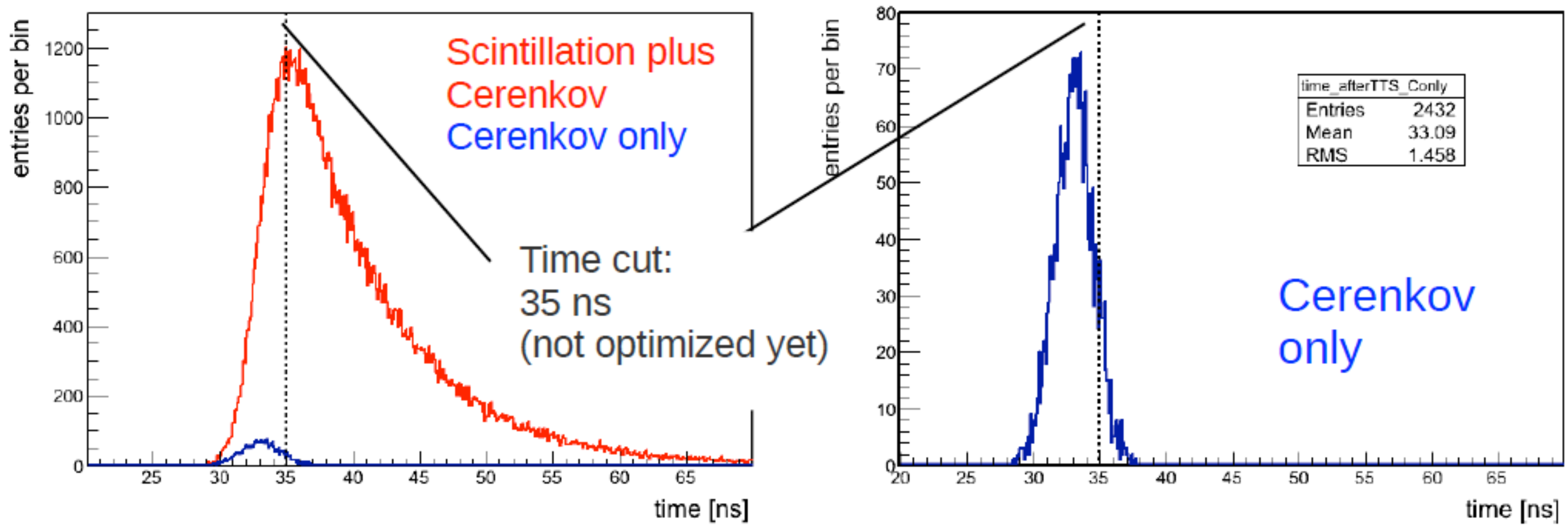
Cerenkov light more important at longer wavelengths.

As expected Cerenkov light is directed forward...



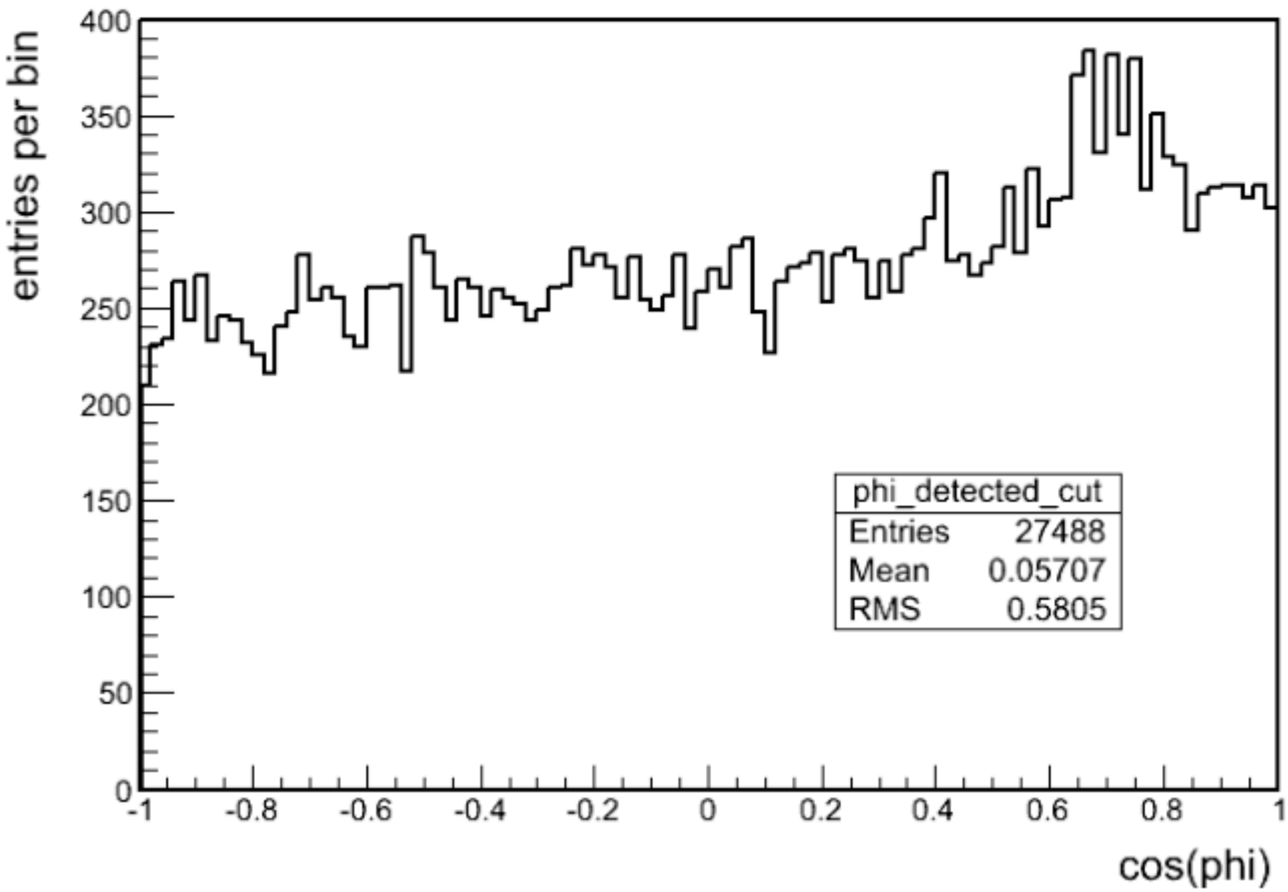


and the Cerenkov light arrives earlier...



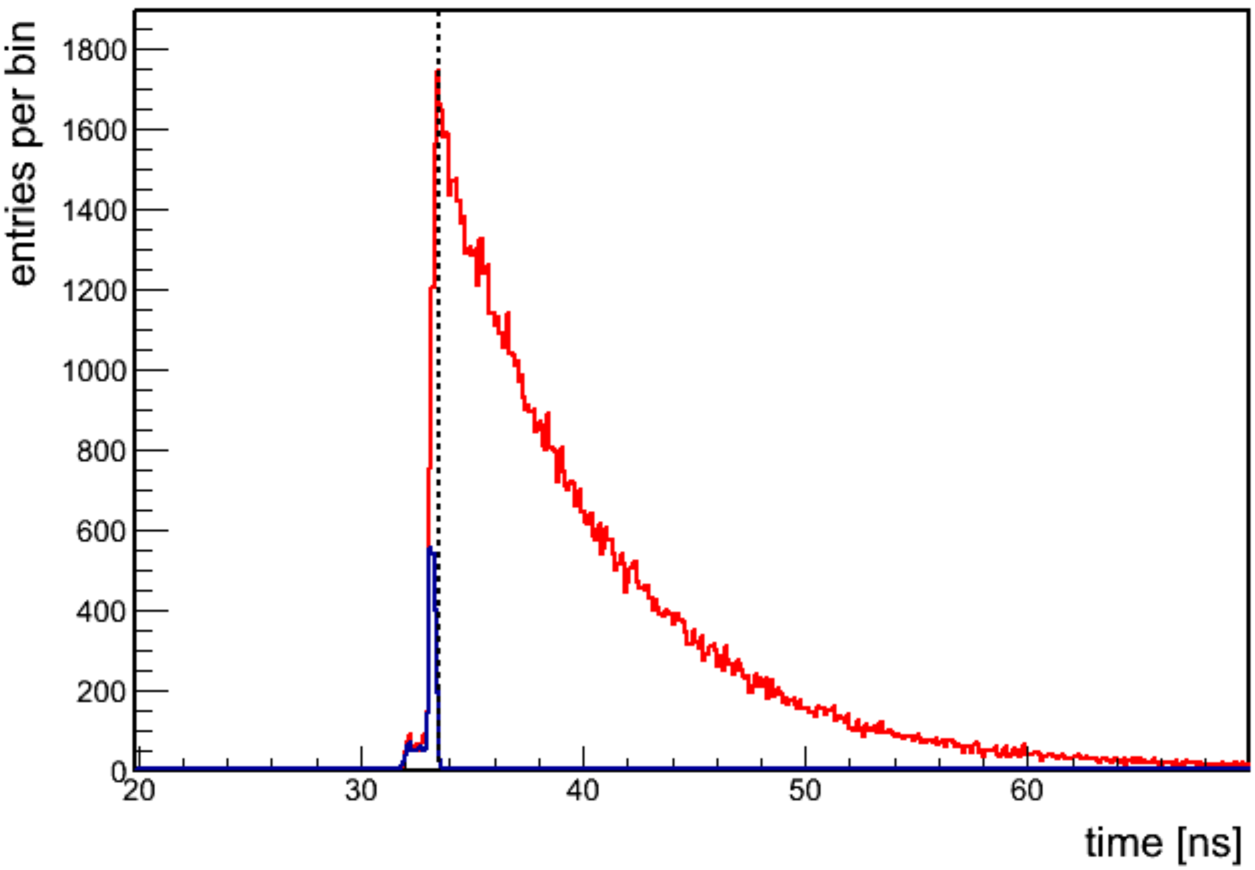
Note: 3ns transit time spread of KamLAND PMTs is not great.

Now with a 35ns cut we can pull out a directional signal...

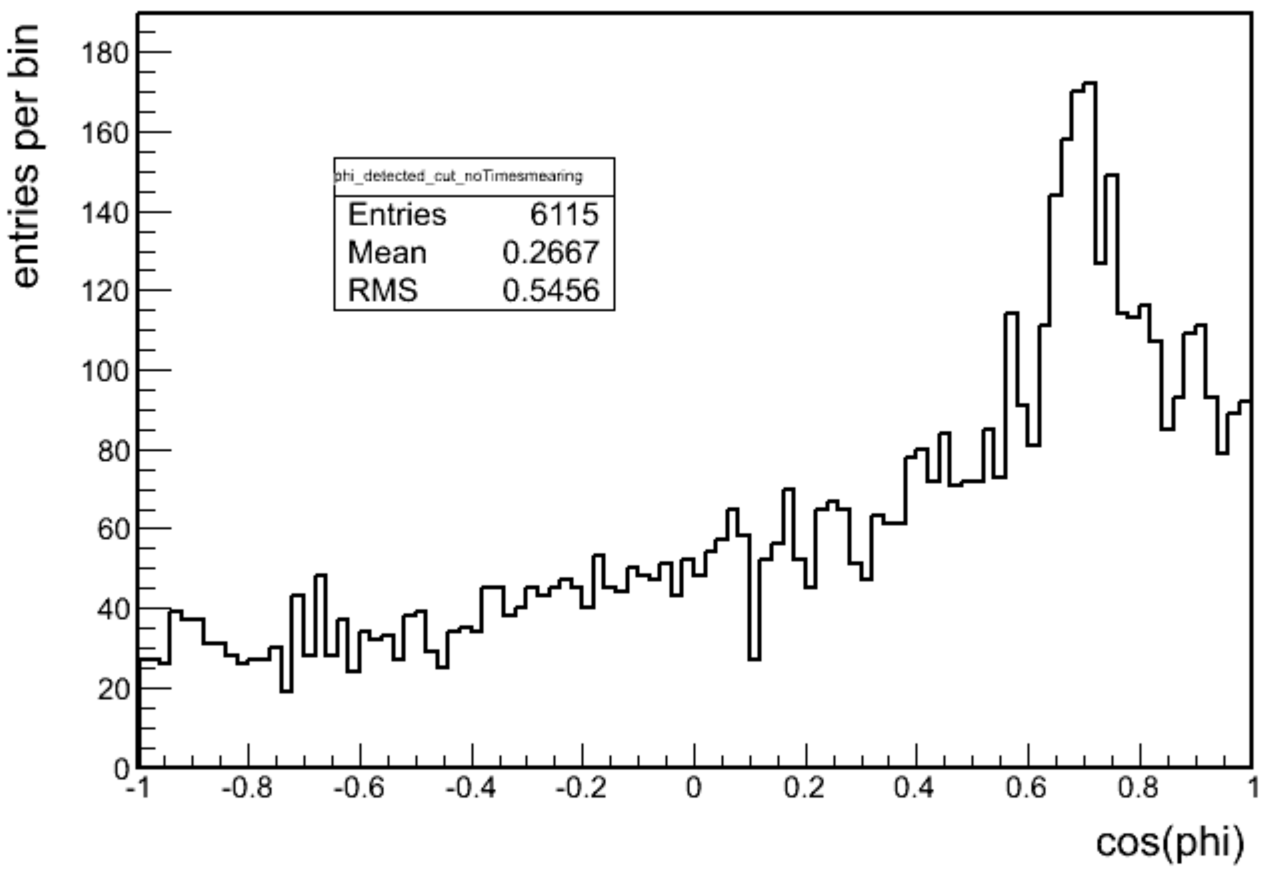


Event by event is going to be difficult, unless...

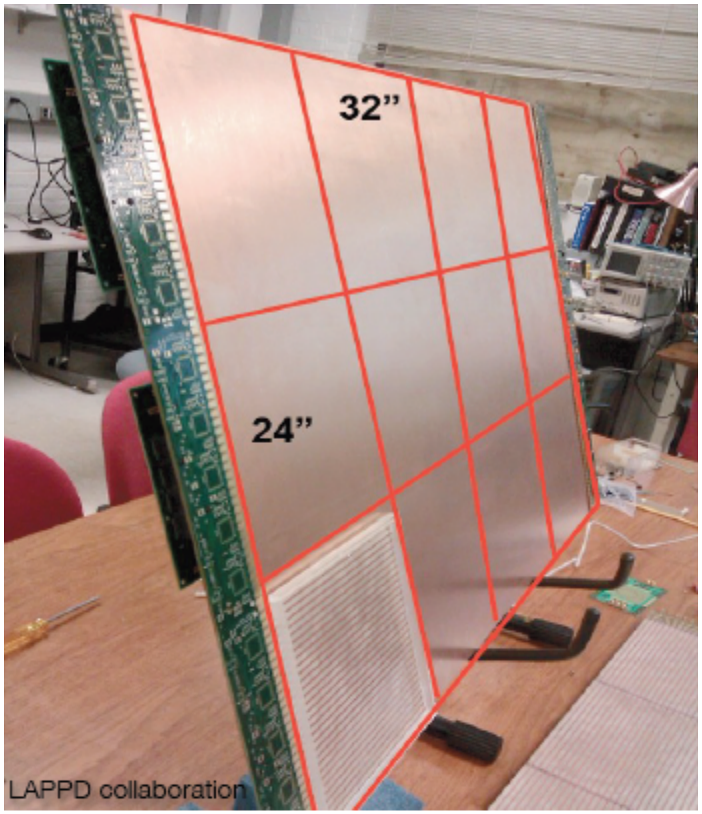
With perfect timing...



Much better directional distribution...

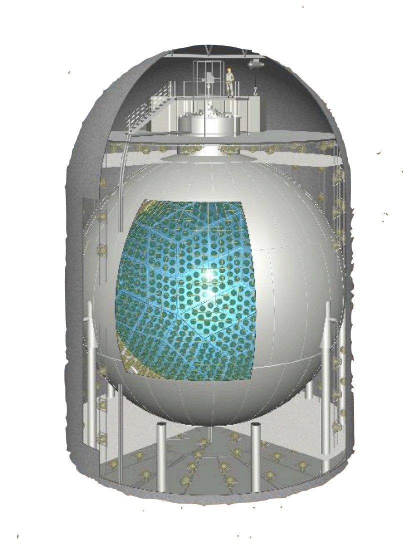


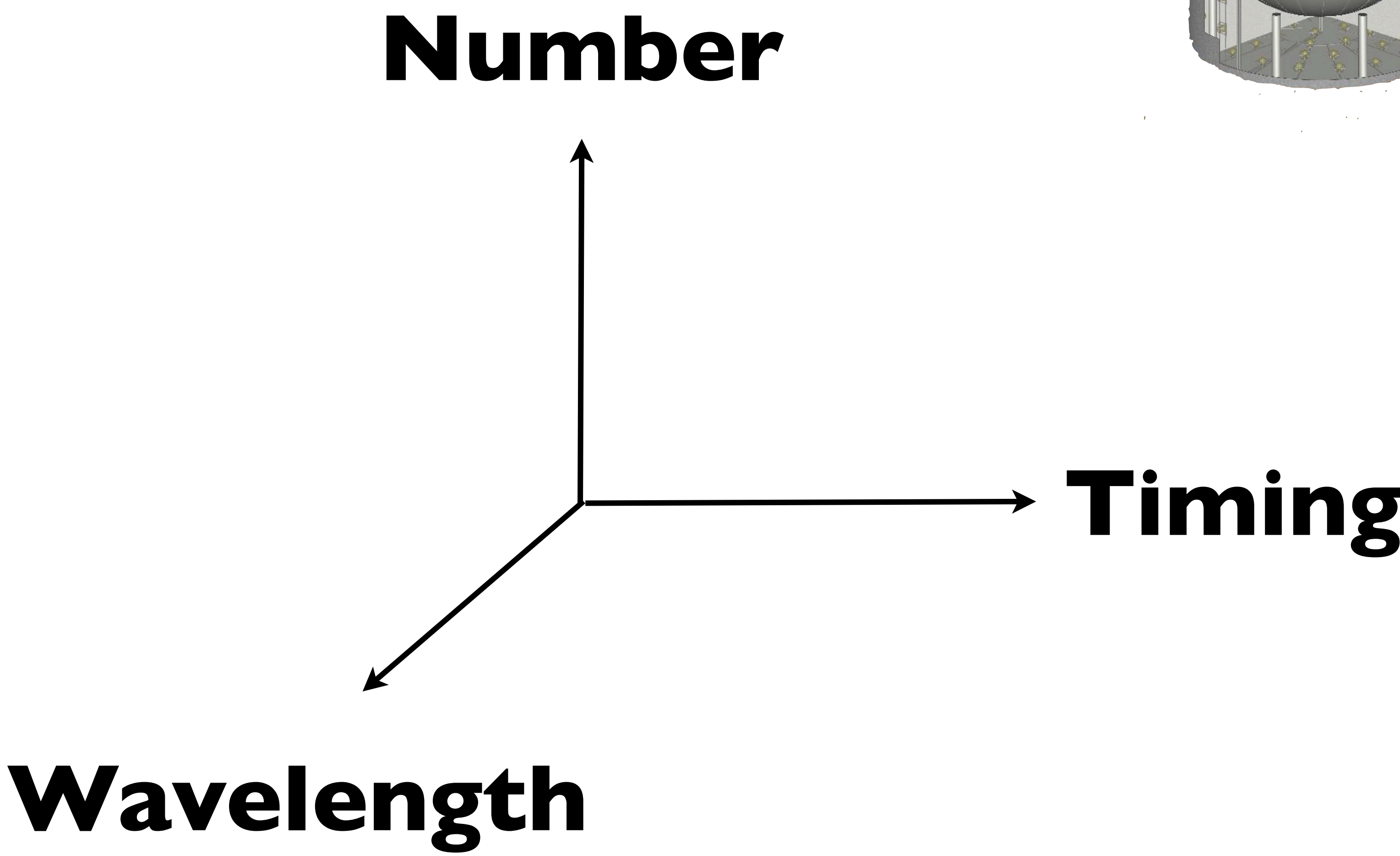
and even event by event looks possible.



So the timing and photocathode coverage requirements point to something like the LAPPD (higher quantum efficiency would be nice too).

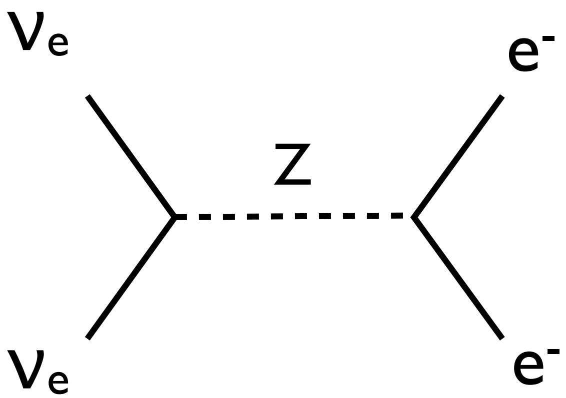
So new photodetectors can be used to tune all 3.

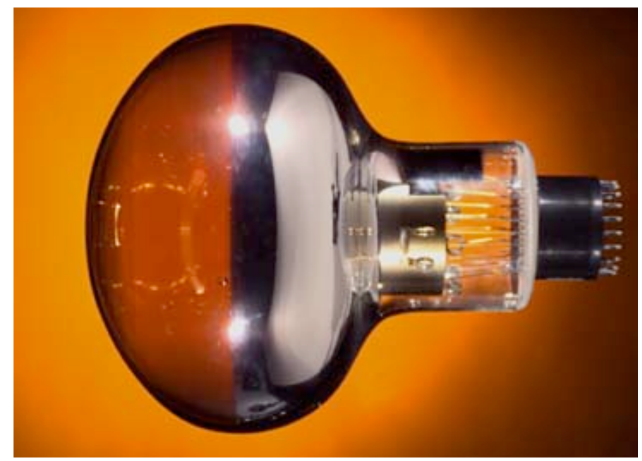




But can we do anything to the step before?

Physics ⟶ Light ⟶ PMTs





Quantum Dot Doped Scintillator

What are quantum dots?

What are Quantum Dots?

Quantum Dots are semiconducting nanocrystals.

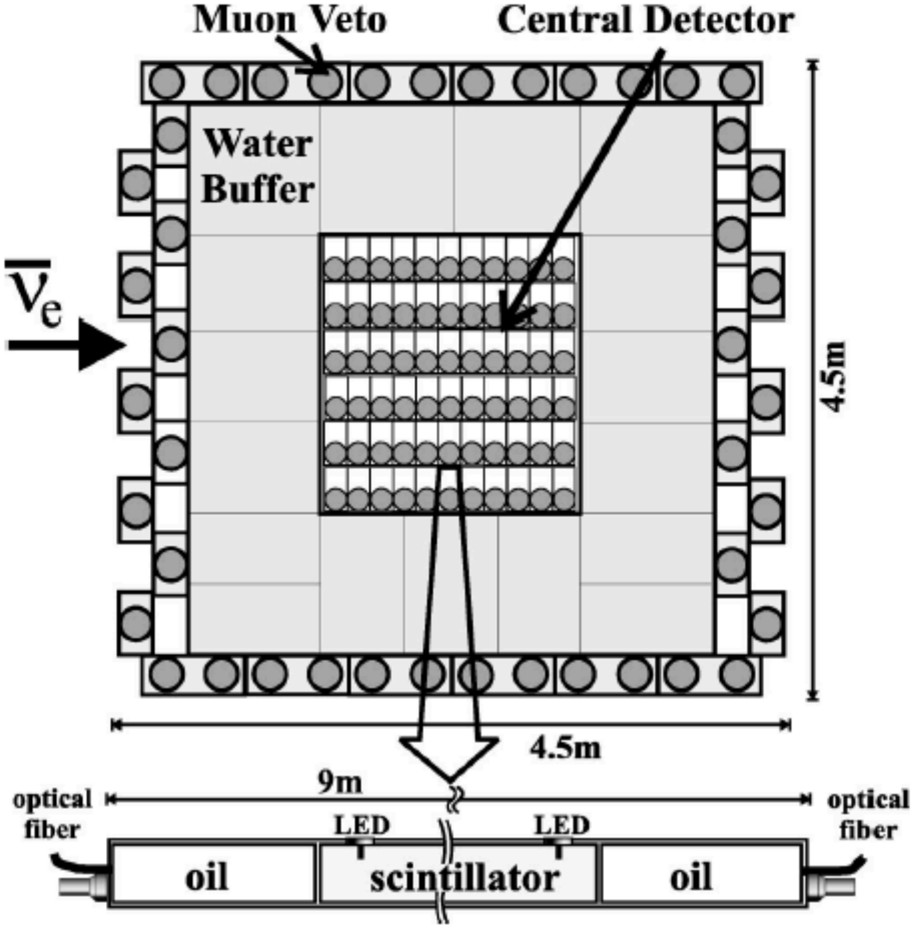
A shell of organic molecules is used to suspend them in an organic solvent (toluene) or water.

Common materials are CdS, CdSe, CdTe...

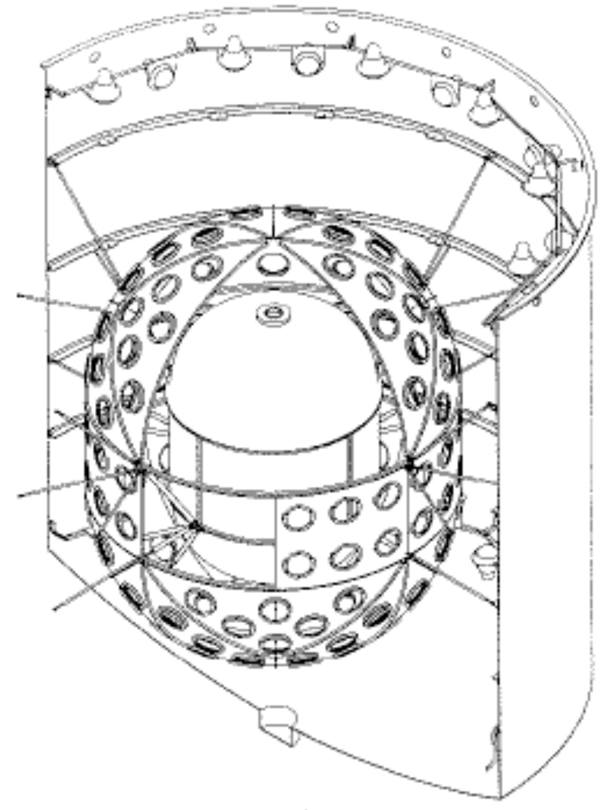
Quantum Dot Materials Overlap with Candidate Isotopes!

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%

Palo Verde

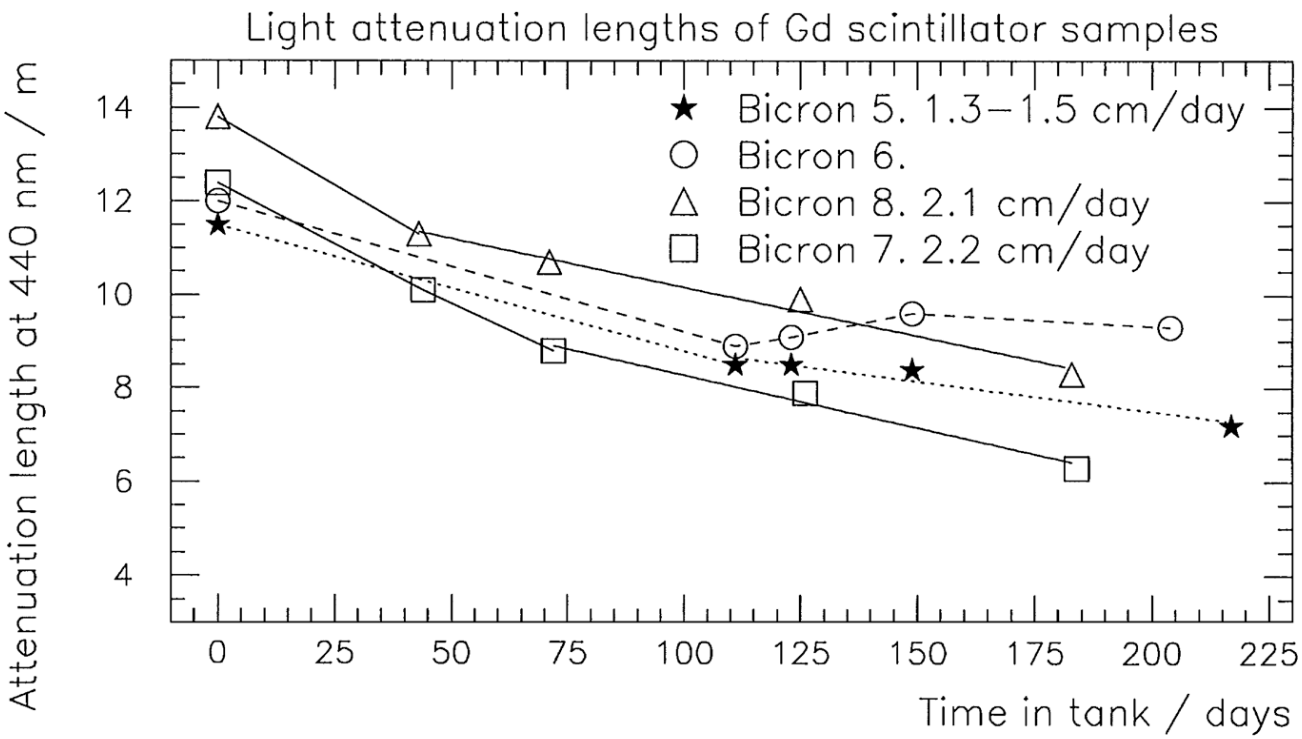


Chooz



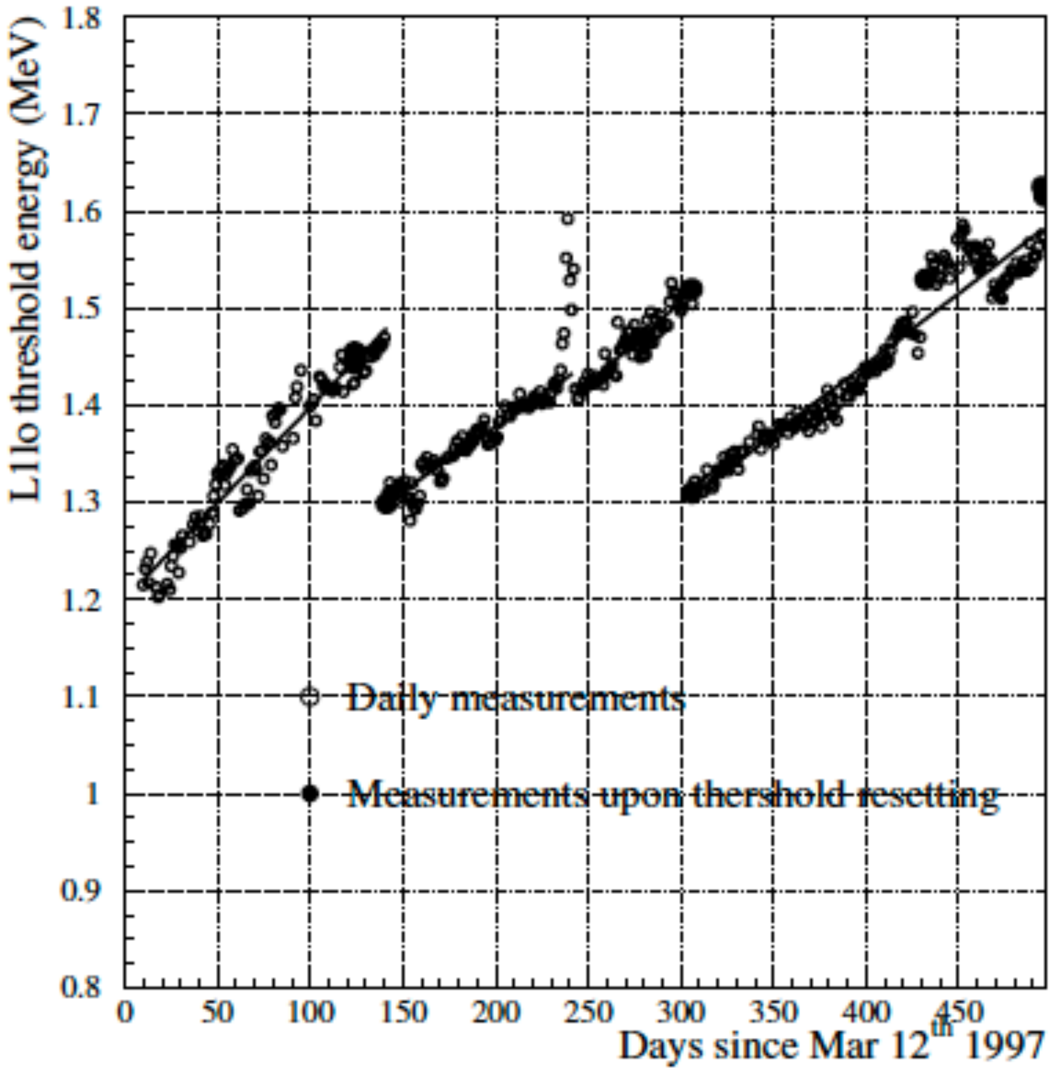
The Previous Generation of Short Baseline Reactor Experiments

Aging of the Palo Verde Scintillator:



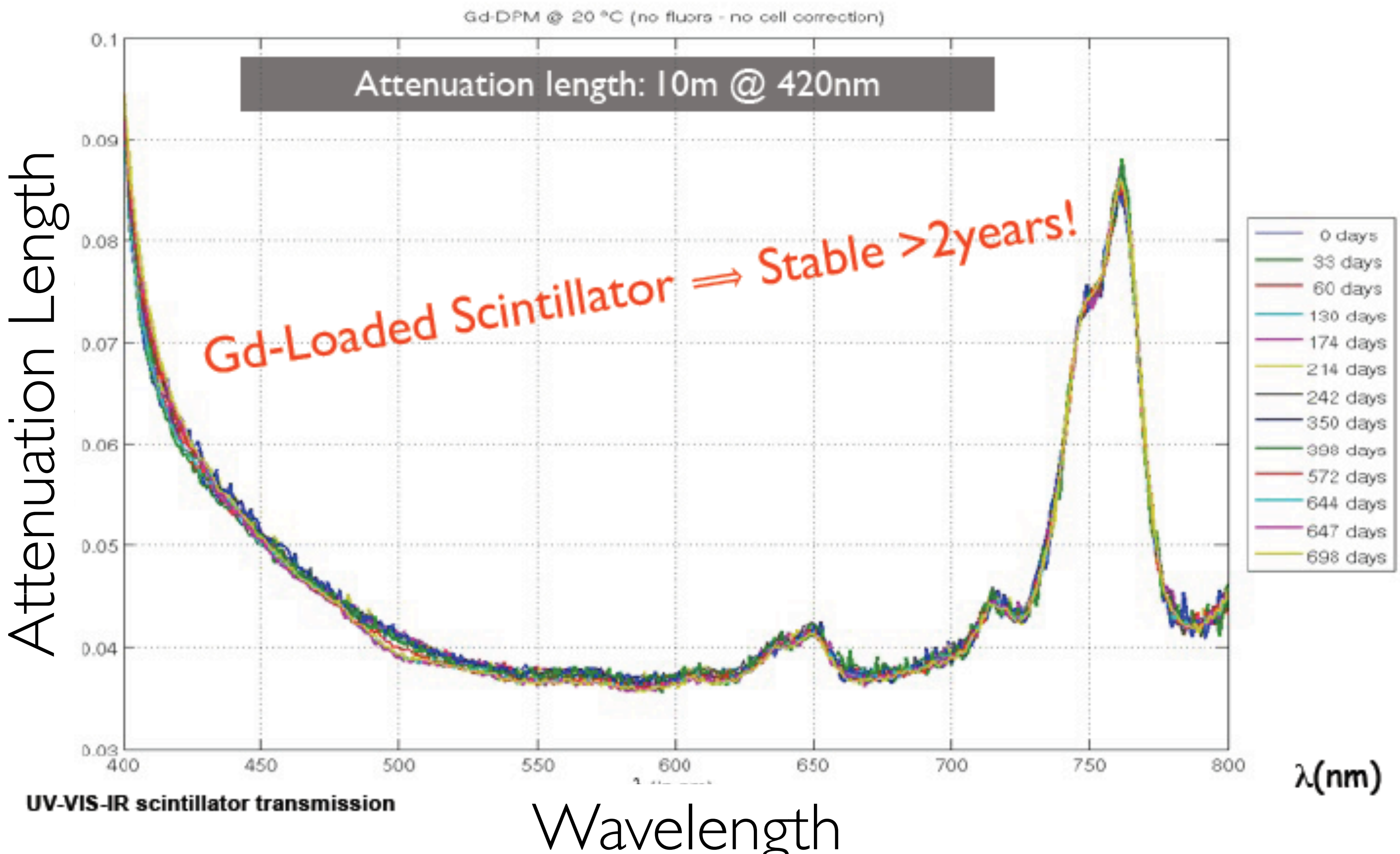
Making stable metal doped scintillator is tricky.

Chooz's rising threshold:



Instability affect quality of data and duration of data taking.

An older Double Chooz plot:



Quantum dots provide the chemistry for suspending isotope in scintillator.

Why are they so popular?

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

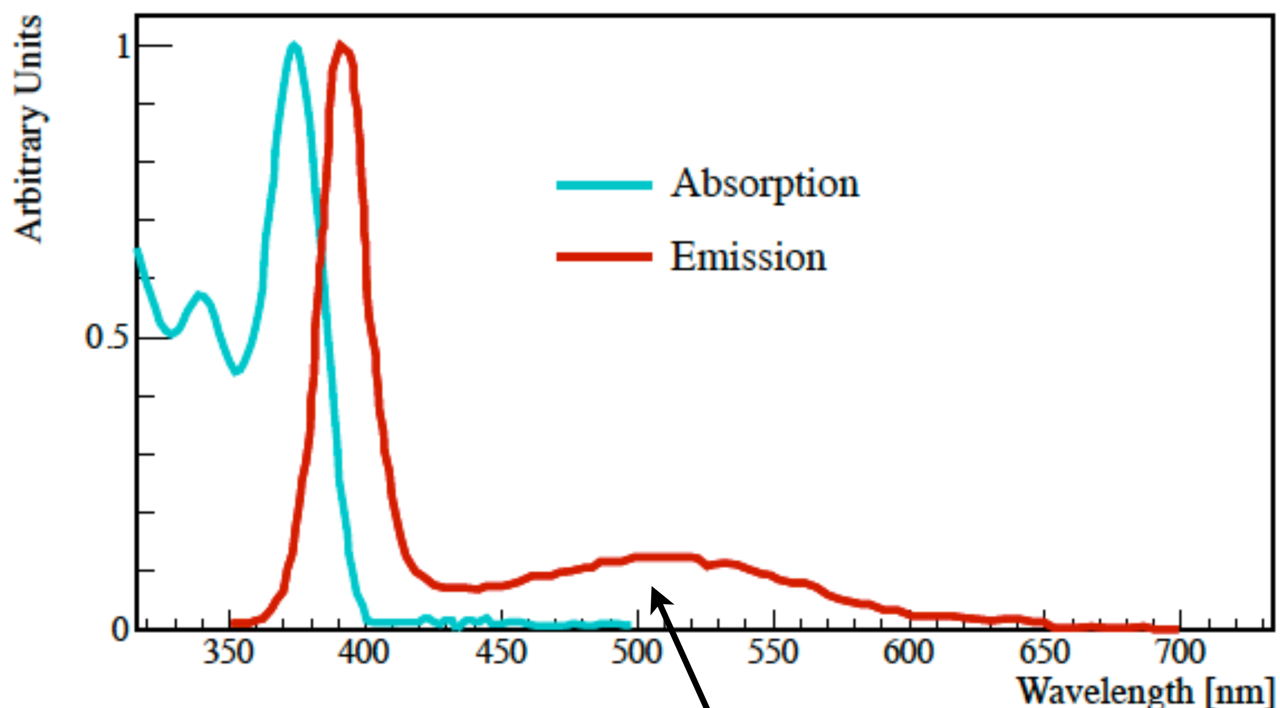
In fact, the optical properties of quantum dots with diameter <10nm is completely determined by their size.

Their size is easily regulated during their synthesis.

Example CdS Quantum Dot Spectra:

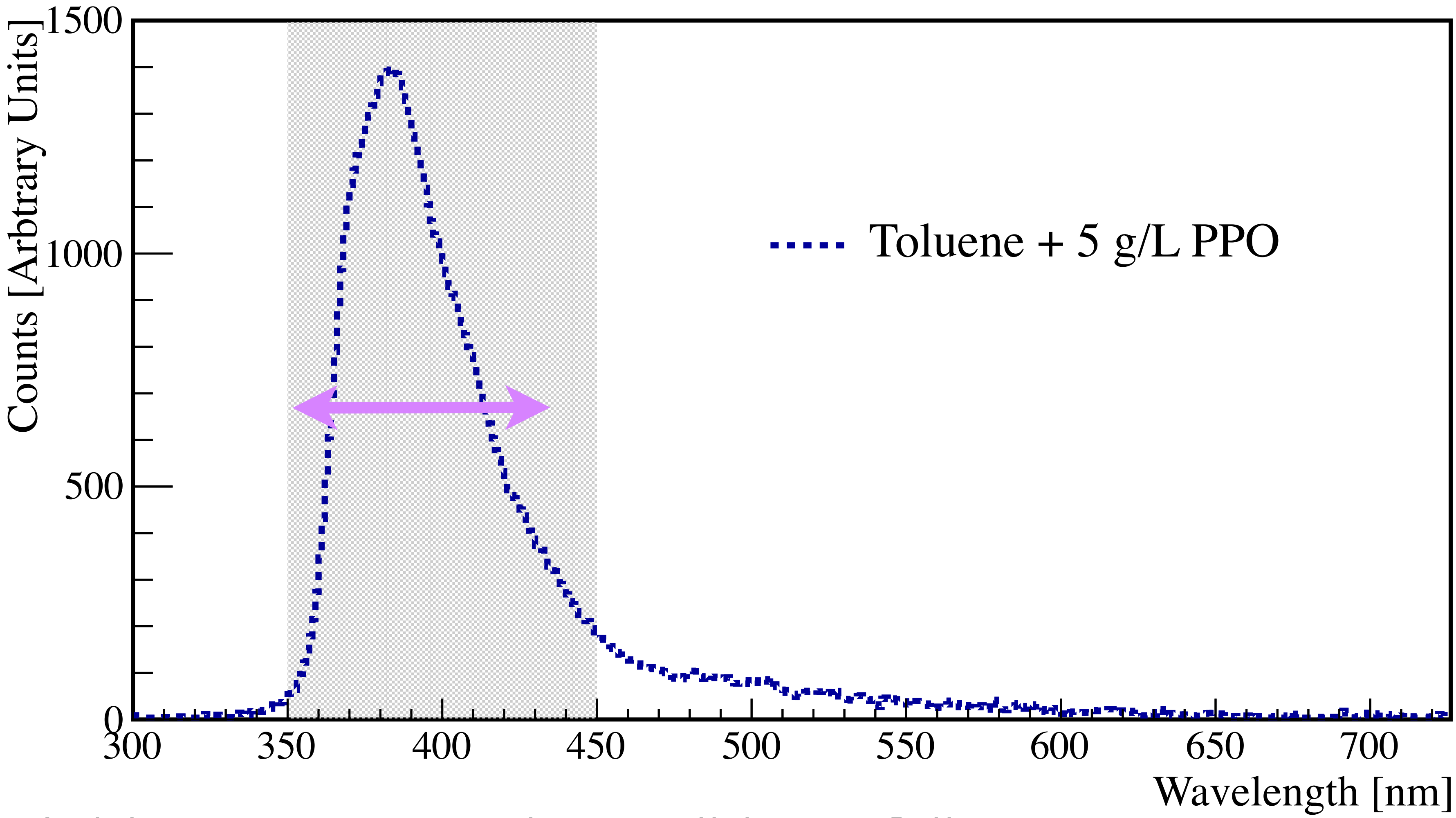
They absorb all light shorter than 400nm and re-emit it in a narrow resonance around this wavelength.

Very Useful for Biology, Solar Cells, and LEDs!



surface states which can be eliminated with a second shell.

My scintillator is toluene with PPO



Adding quantum dots will hopefully tune and narrow the peak of this curve.

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.

arXiv:1202.4733v1 [physics.ins-det] 21 Feb 2012

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

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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:
JINST 7 (2012) P07010
arXiv:1202.4733

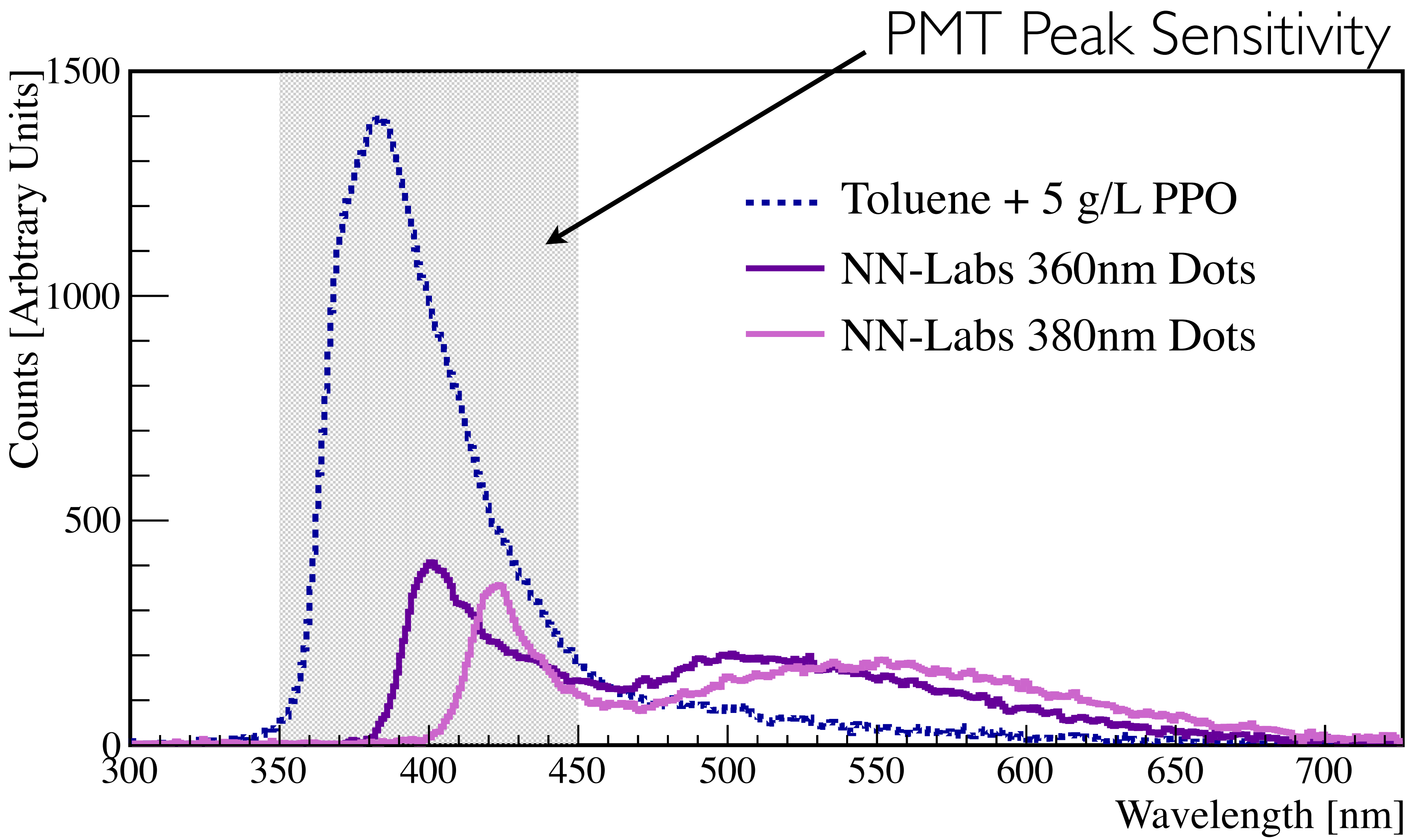
Let’s start with some basic measurements!

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?

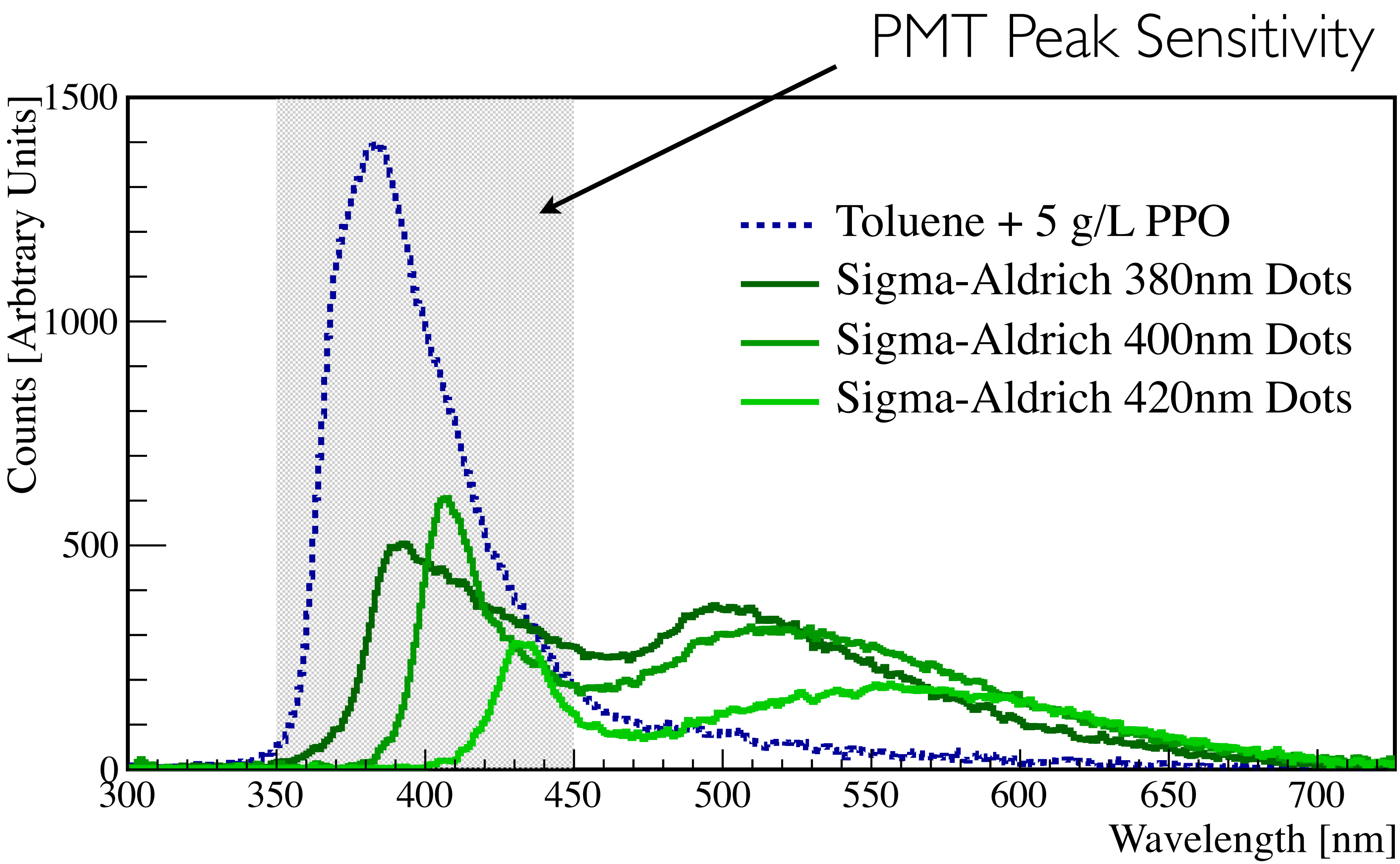
Excite the scintillator with a 280nm LED.



These dot have a 20% quantum efficiency, state of the art is > 80%.

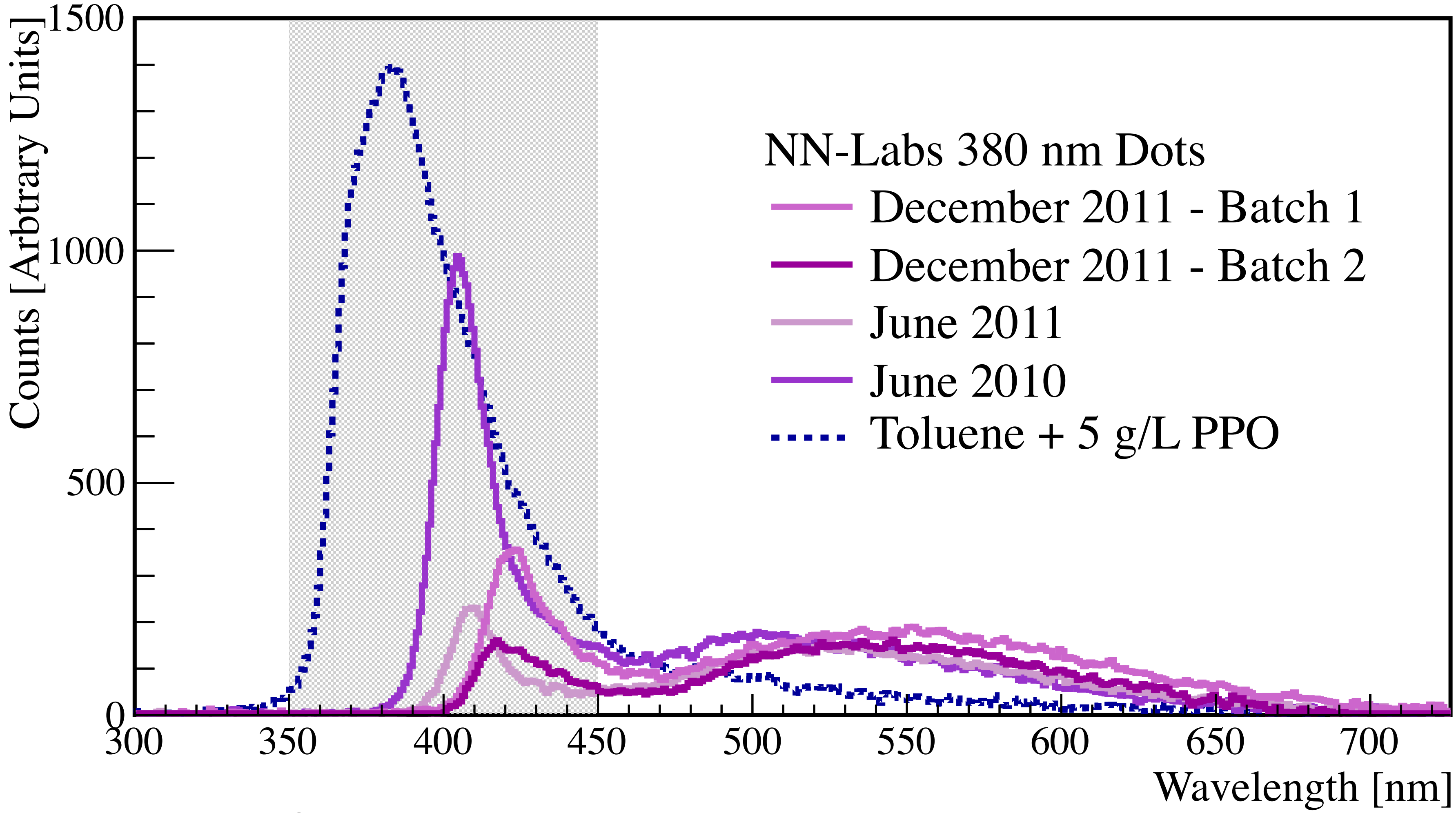
How much light?

Excite the scintillator with a 280nm LED.



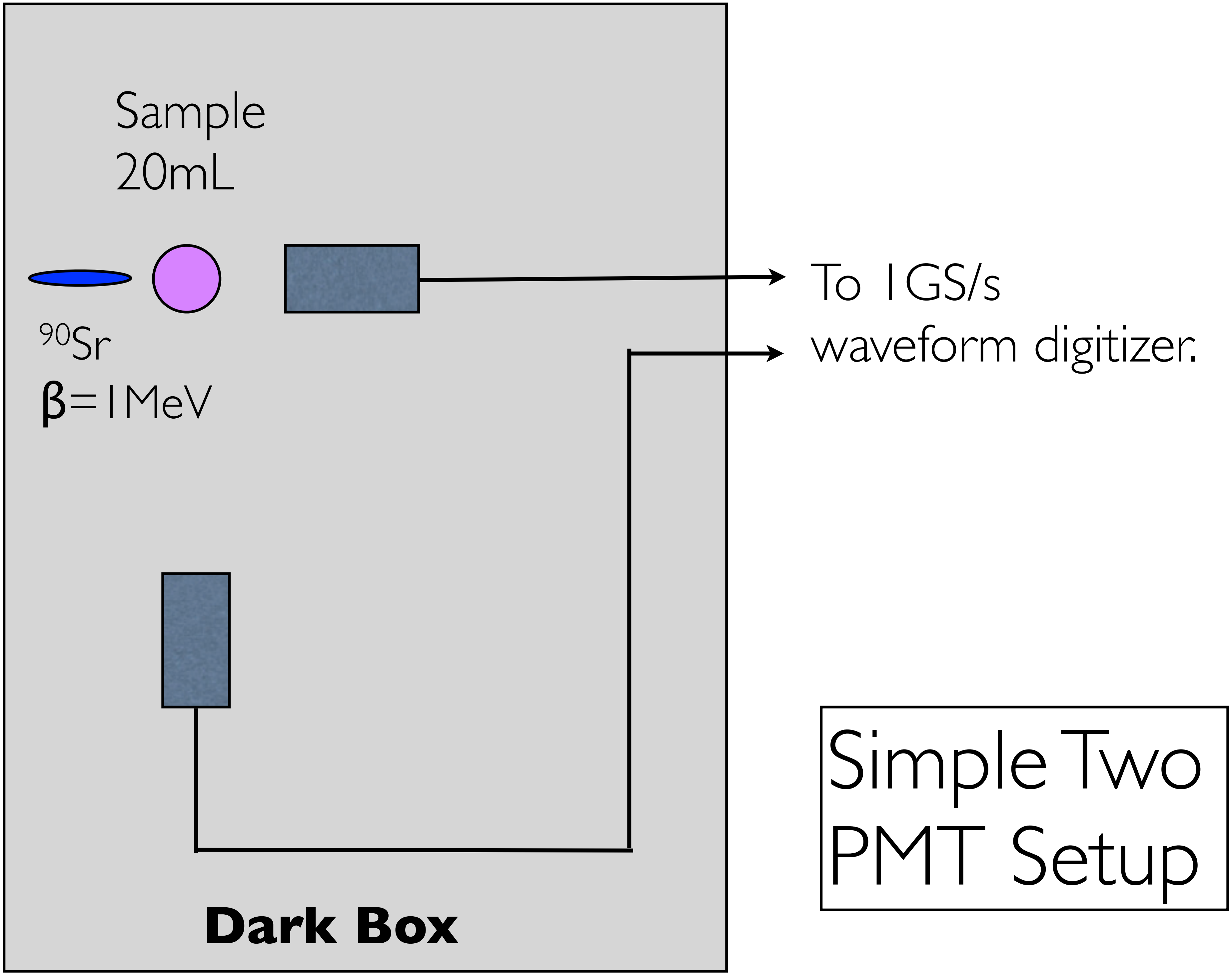
Do Quantum Dots Age?

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



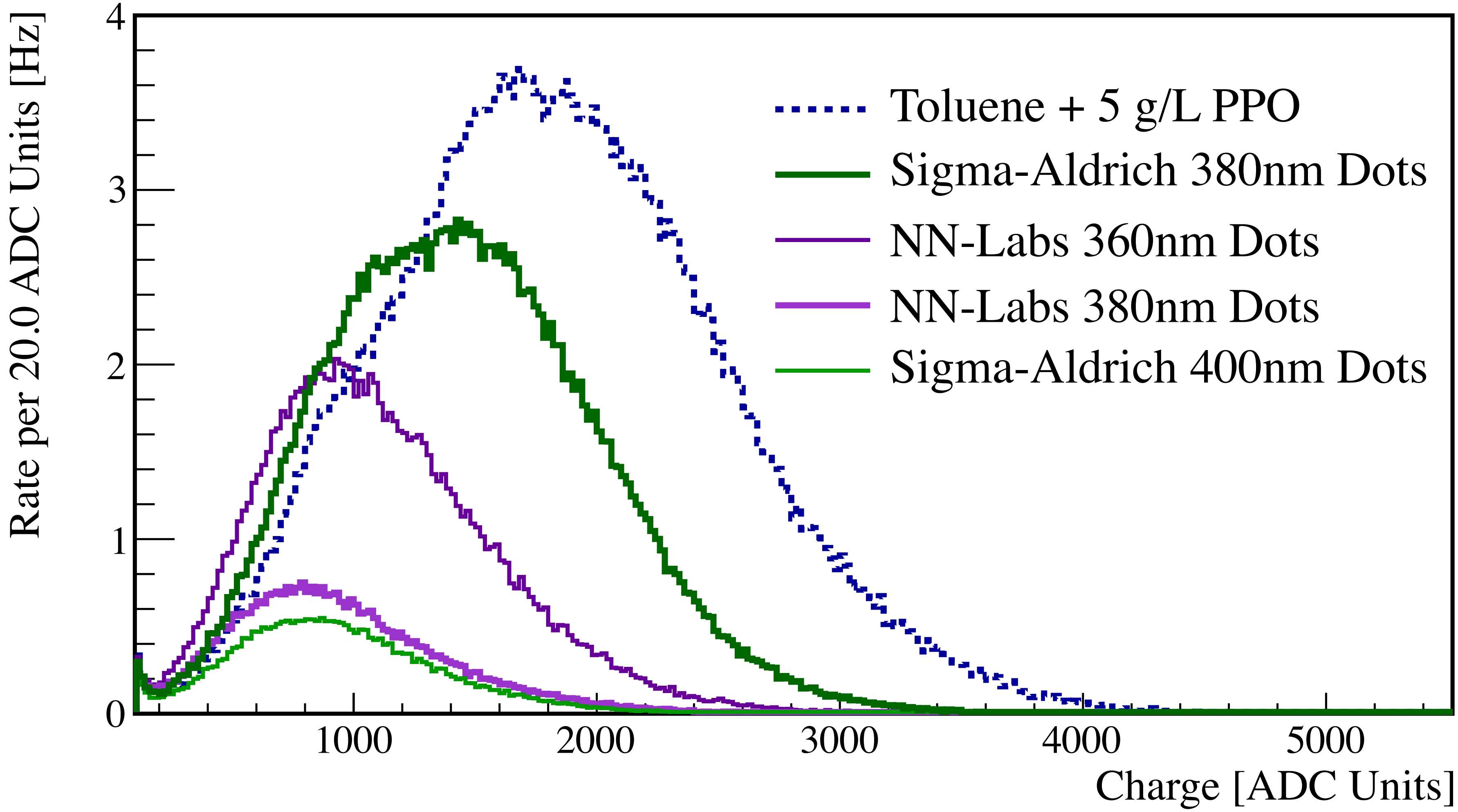
No evidence for aging.

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


Sample
20mL
^{90}Sr
β=1MeV
To 1GS/s
waveform digitizer.
Dark Box
Simple Two
PMT Setup

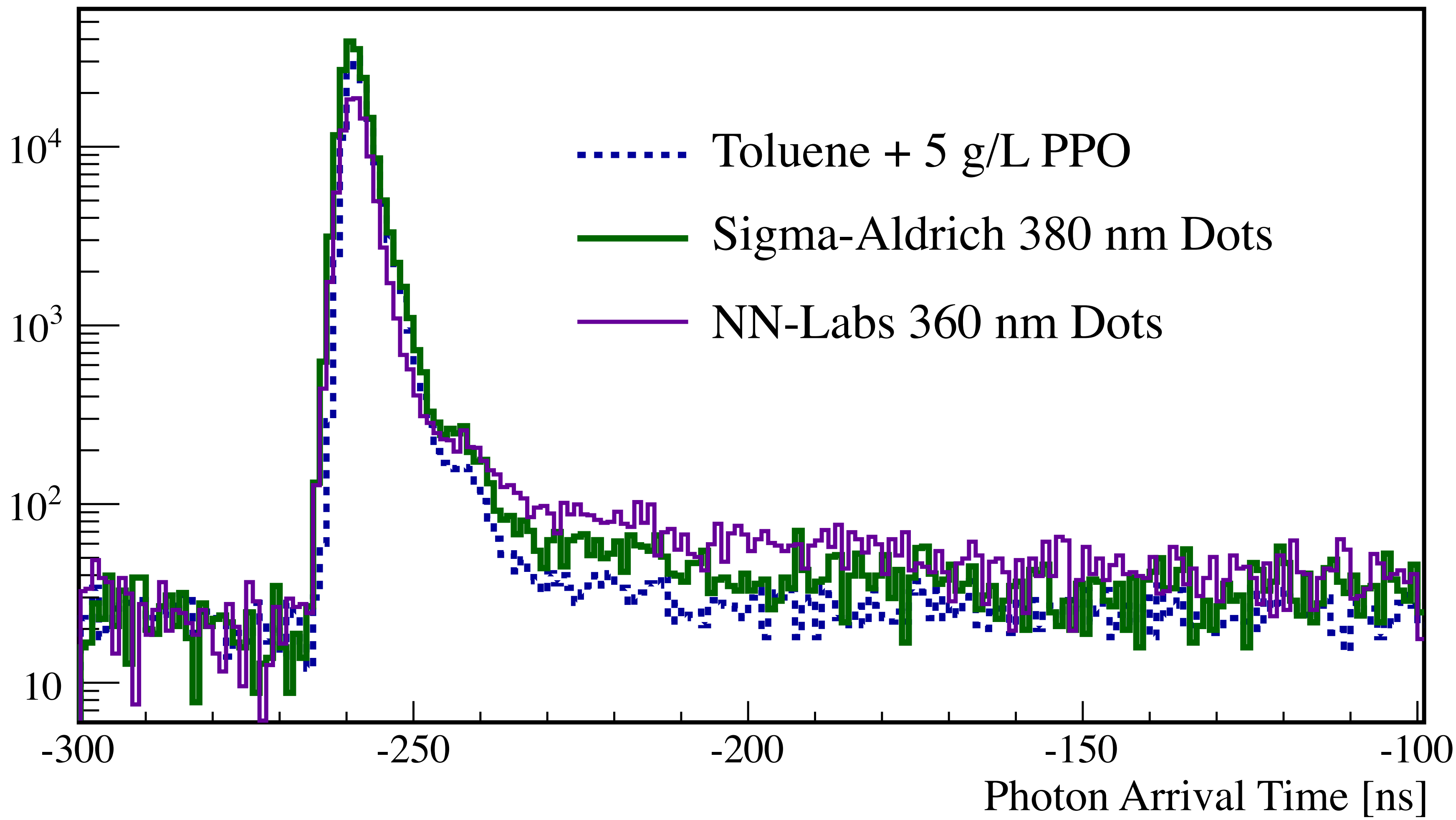
Does the scintillator still scintillate?

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



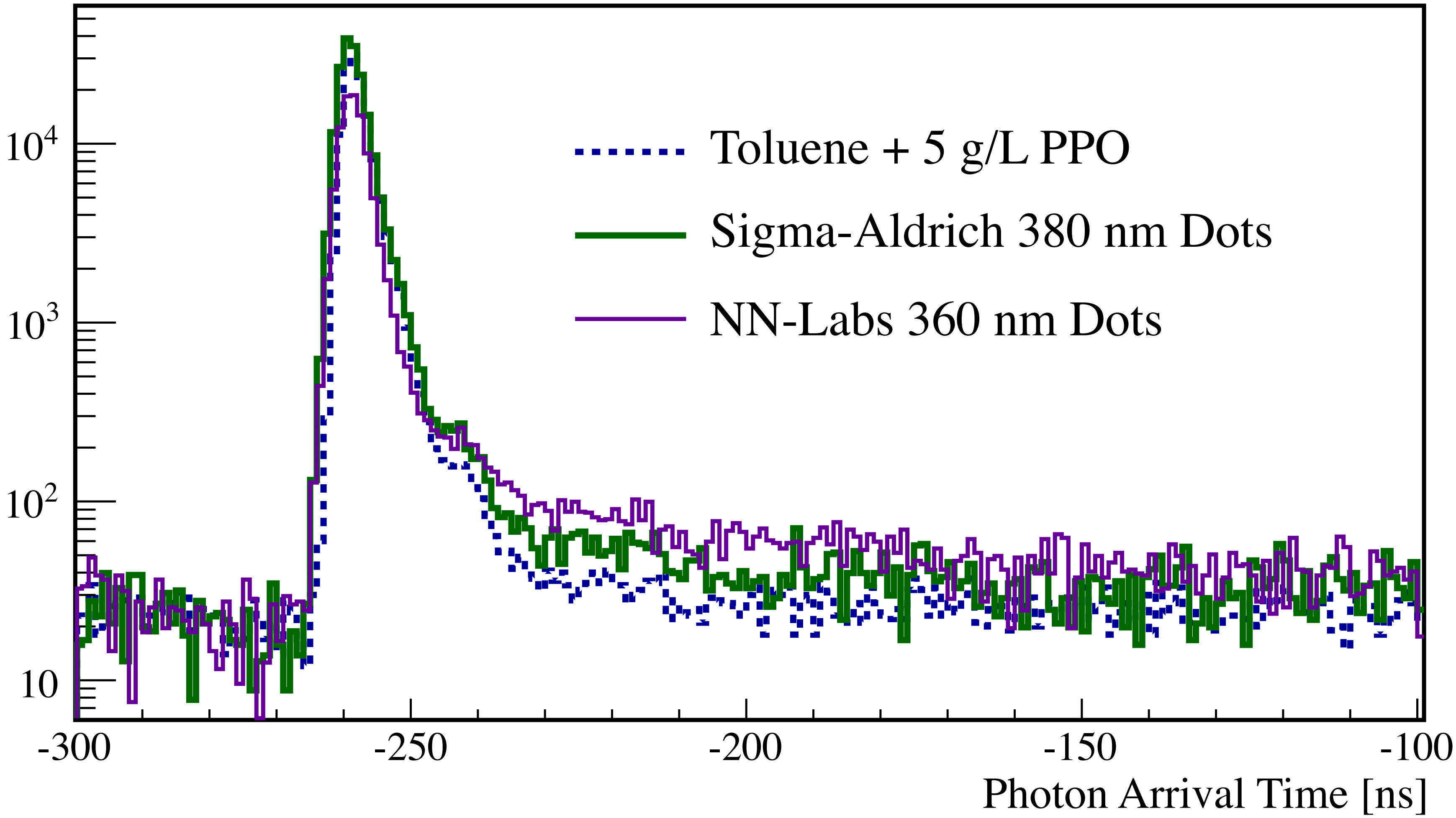
The light yield is reduced compared to the standard scintillator

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:

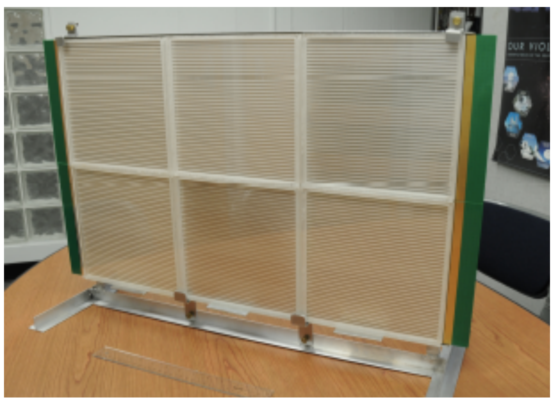


Sample	q_1	τ_1 [ns]	q_2	τ_2 [ns]	q_3	τ_3 [ns]
Tol + PPO	0.94±0.01	1.73±0.03	0.08±0.01	5.7±0.5	0.004±0.001	45.9±23.4
SA 380 nm	1.10±0.01	1.84±0.02	0.09±0.01	6.5±0.4	0.022±0.001	96.5±10.7
NN 360 nm	0.80±0.01	1.55±0.03	0.06±0.01	10.9±0.7	0.092±0.003	174.5±14.9

Quantum dots allow you unprecedented control over the wavelength response of your metal-doped scintillator.

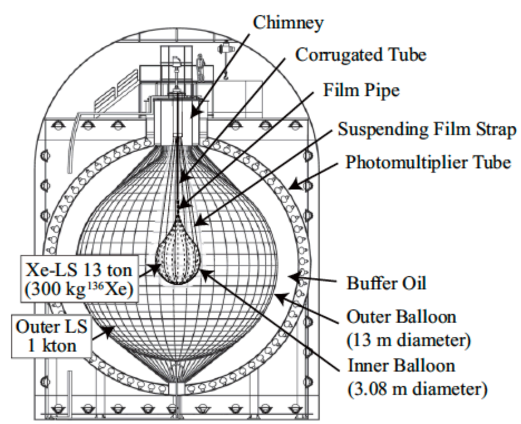
So this is the idea...

Better Scintillator

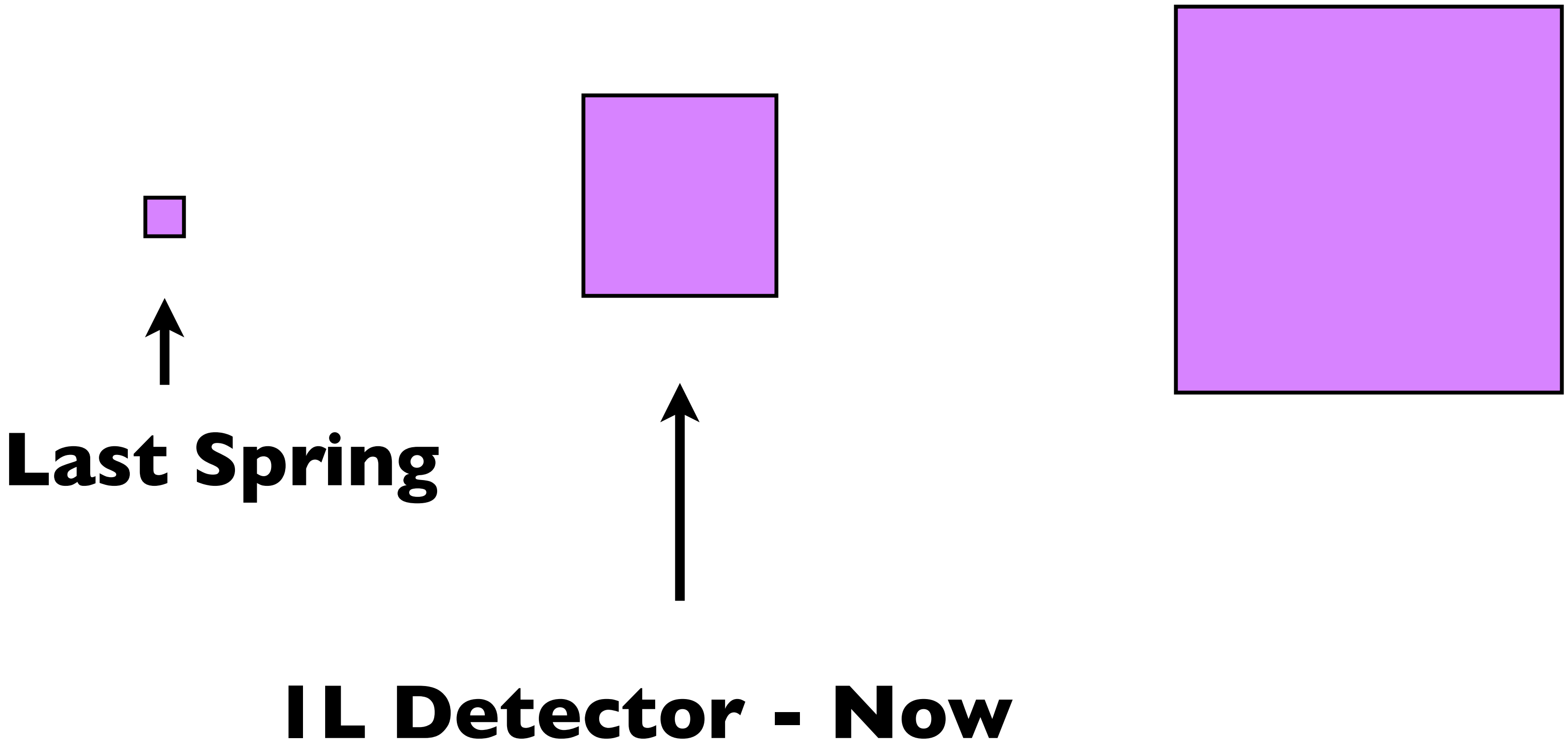


Better Photo-Detectors

= Better

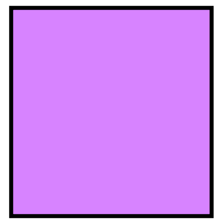


Next Steps:

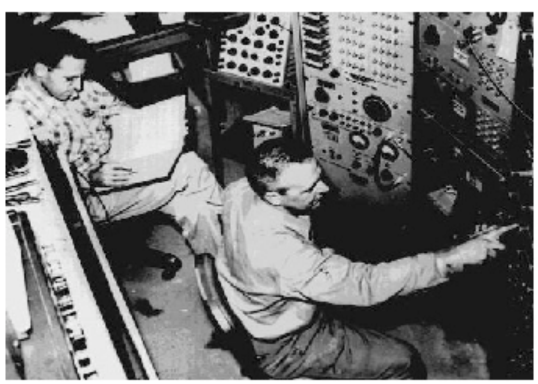


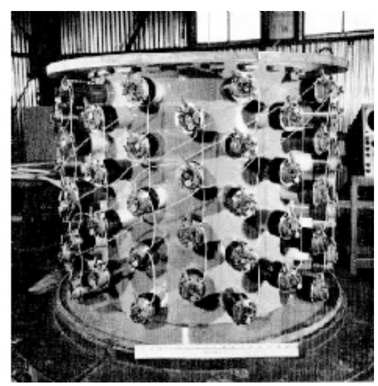
- More quality control of the dots before using.
- Nitrogen purging for better light yield
- Larger quantum quantities
- Attenuation length measurements

The 1 L detector can be a neutron detector!



Cadmium is a good alternative to Gadolinium.





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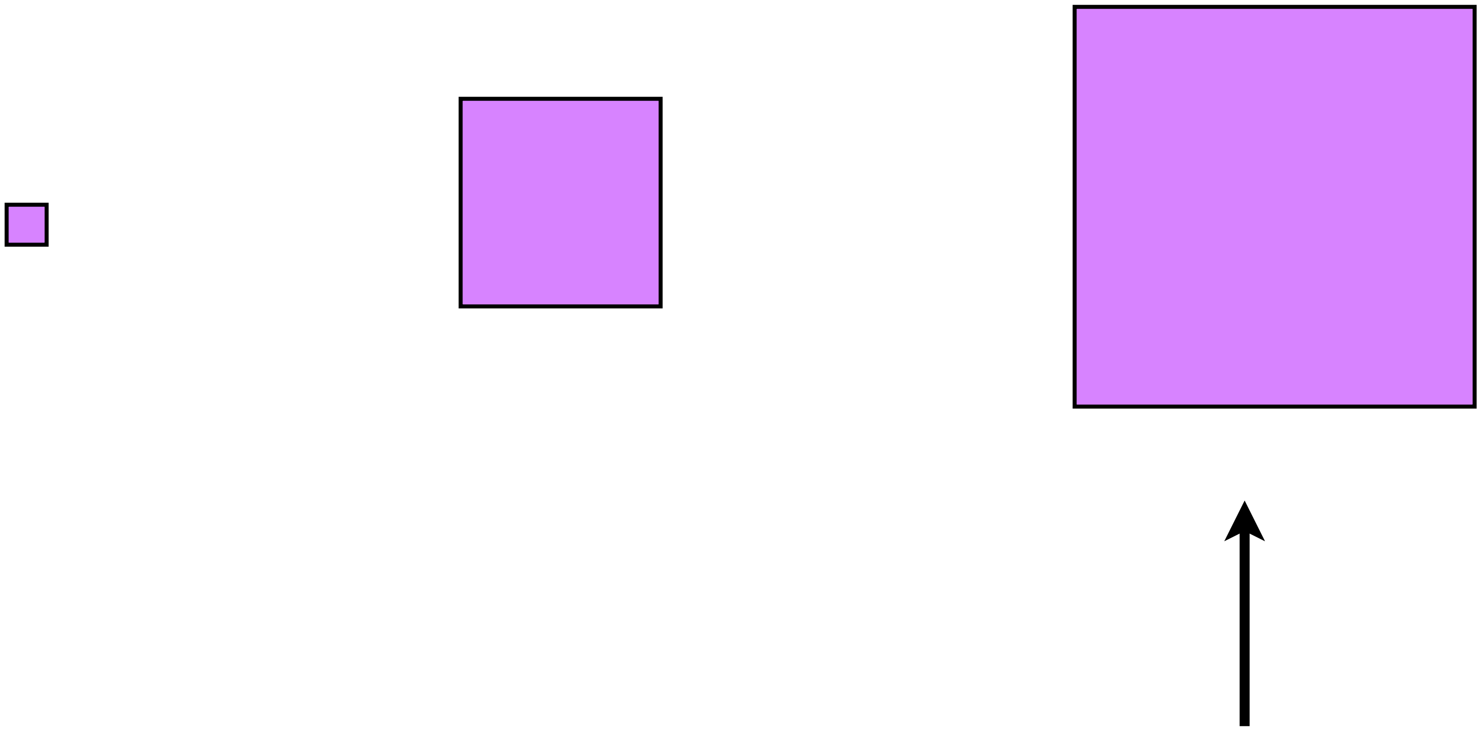
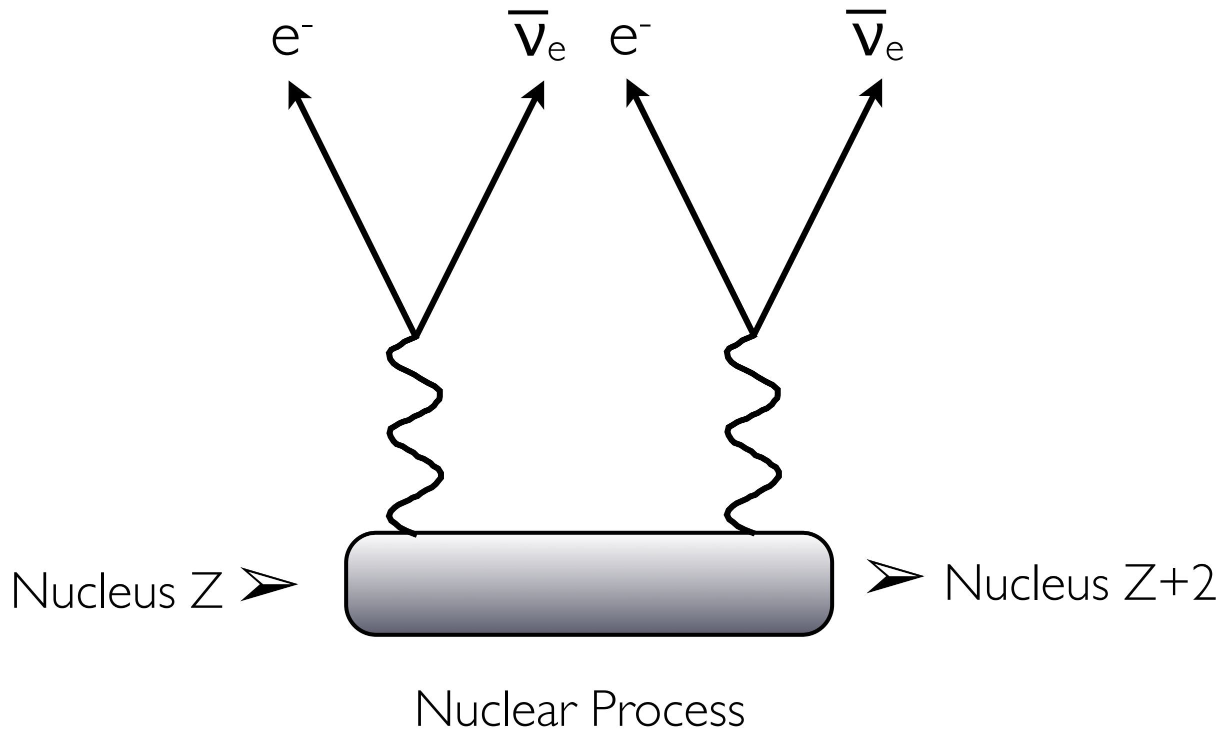


1m^3 Detector

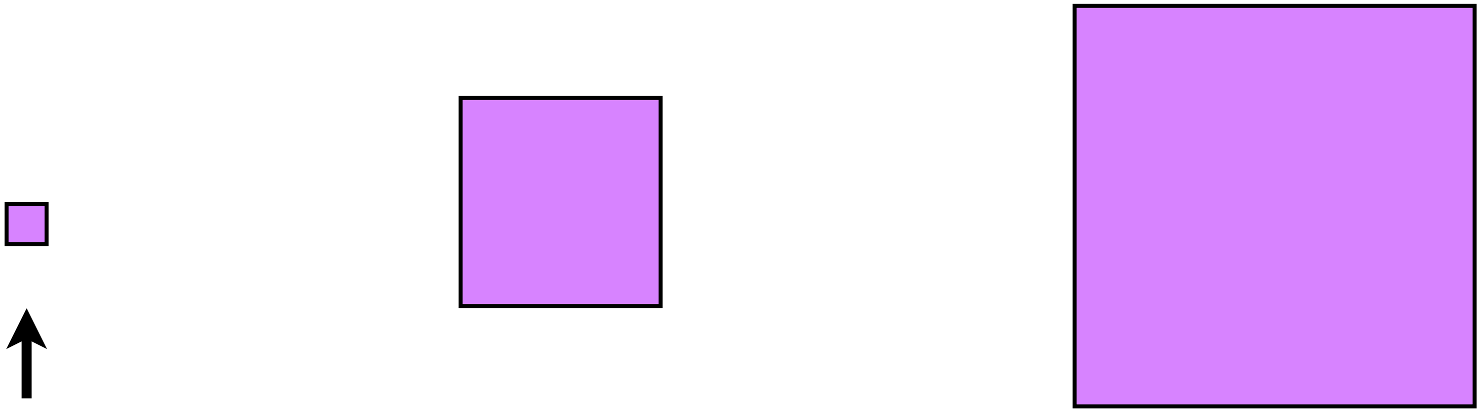
- Make use of knowledge from 1L detector
- Hopefully, experiment with new photodetectors.
- Make measurement of two neutrino double beta decay in ^{116}Cd.

Recall you can have Two Neutrino Double Beta Decay:

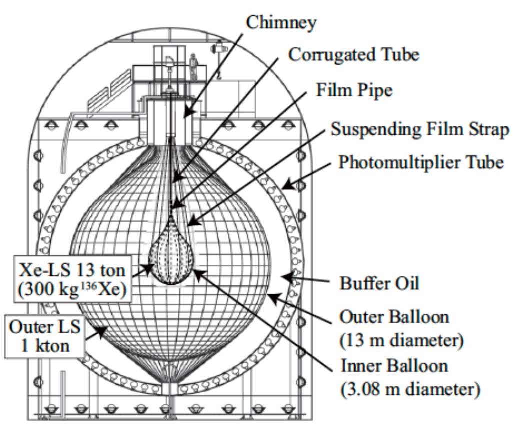


With 10g of ^{116}Cd, I expect 1000 events in 6 months.

Next Steps:

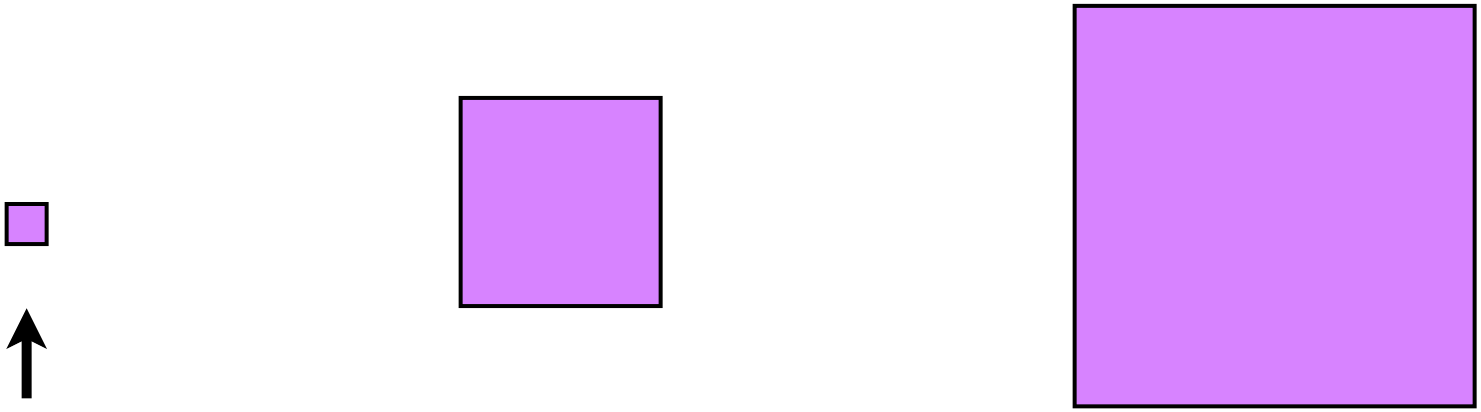


We are here

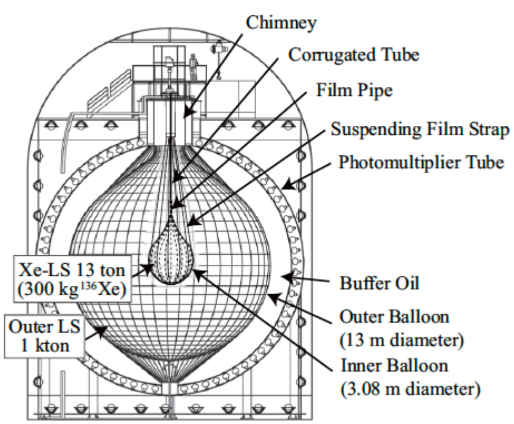


Staged refurbishment of KamLAND between 2015-2020.

Next Steps:



We are here



Exciting work ahead!

The End