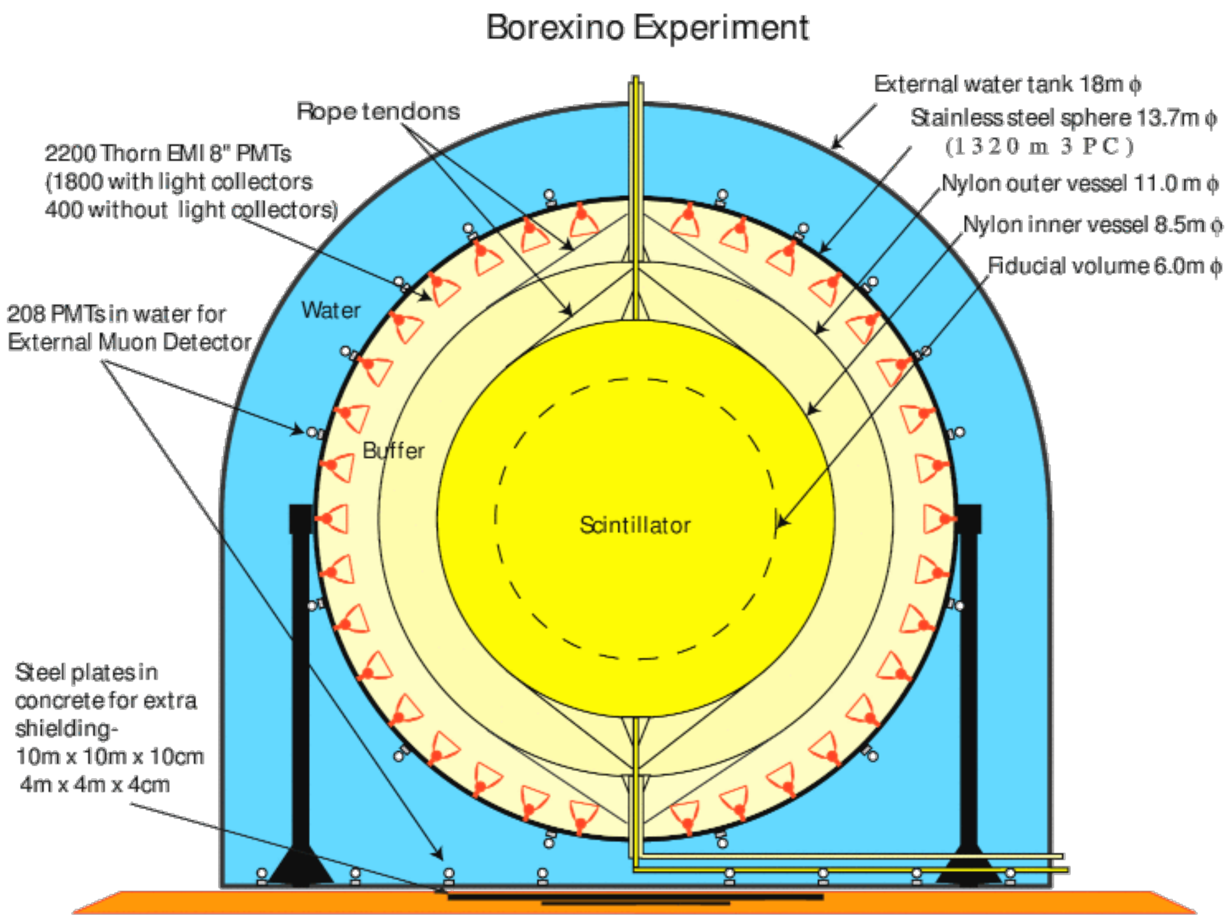
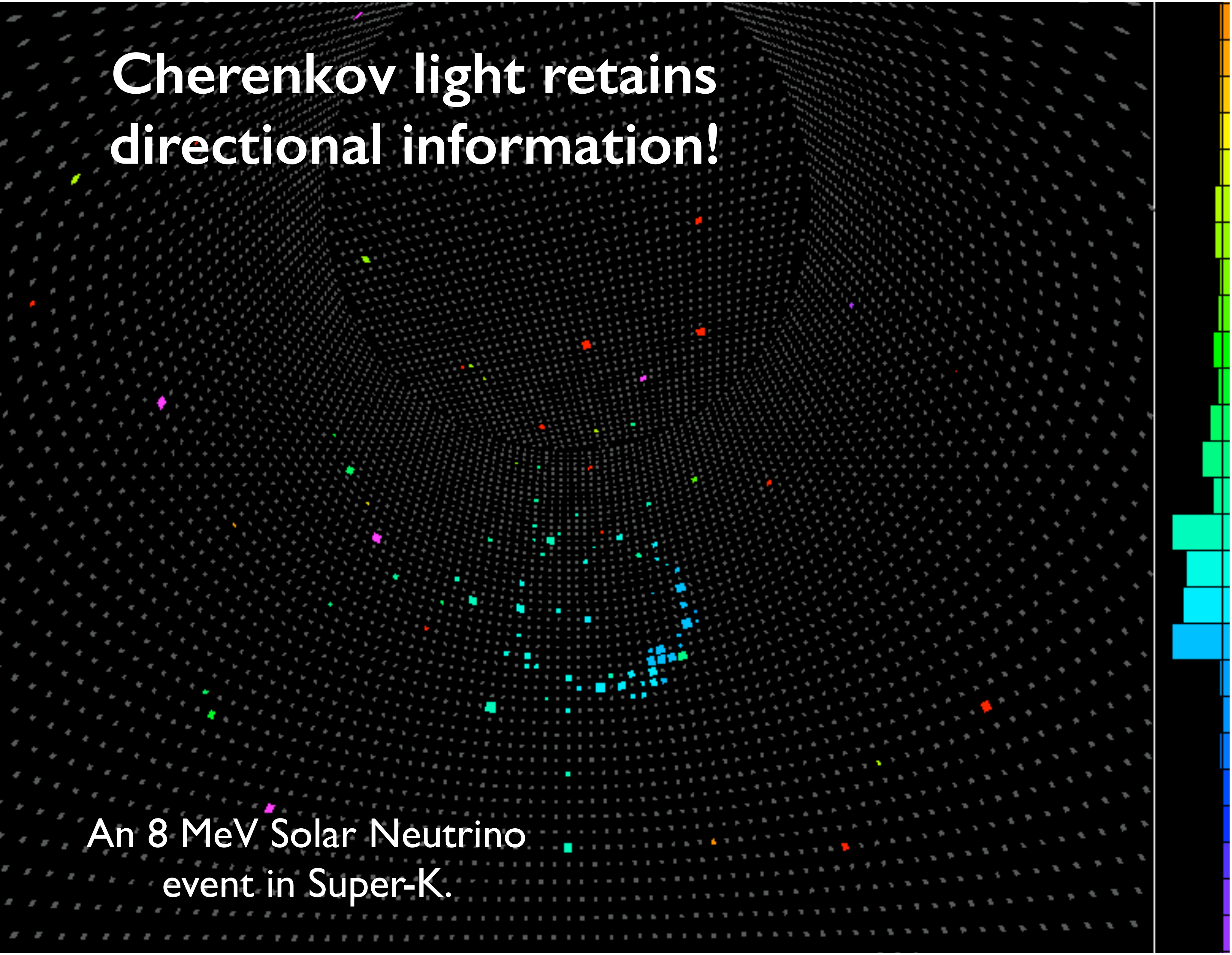
NuDot:
A Prototype Directional Liquid Scintillator

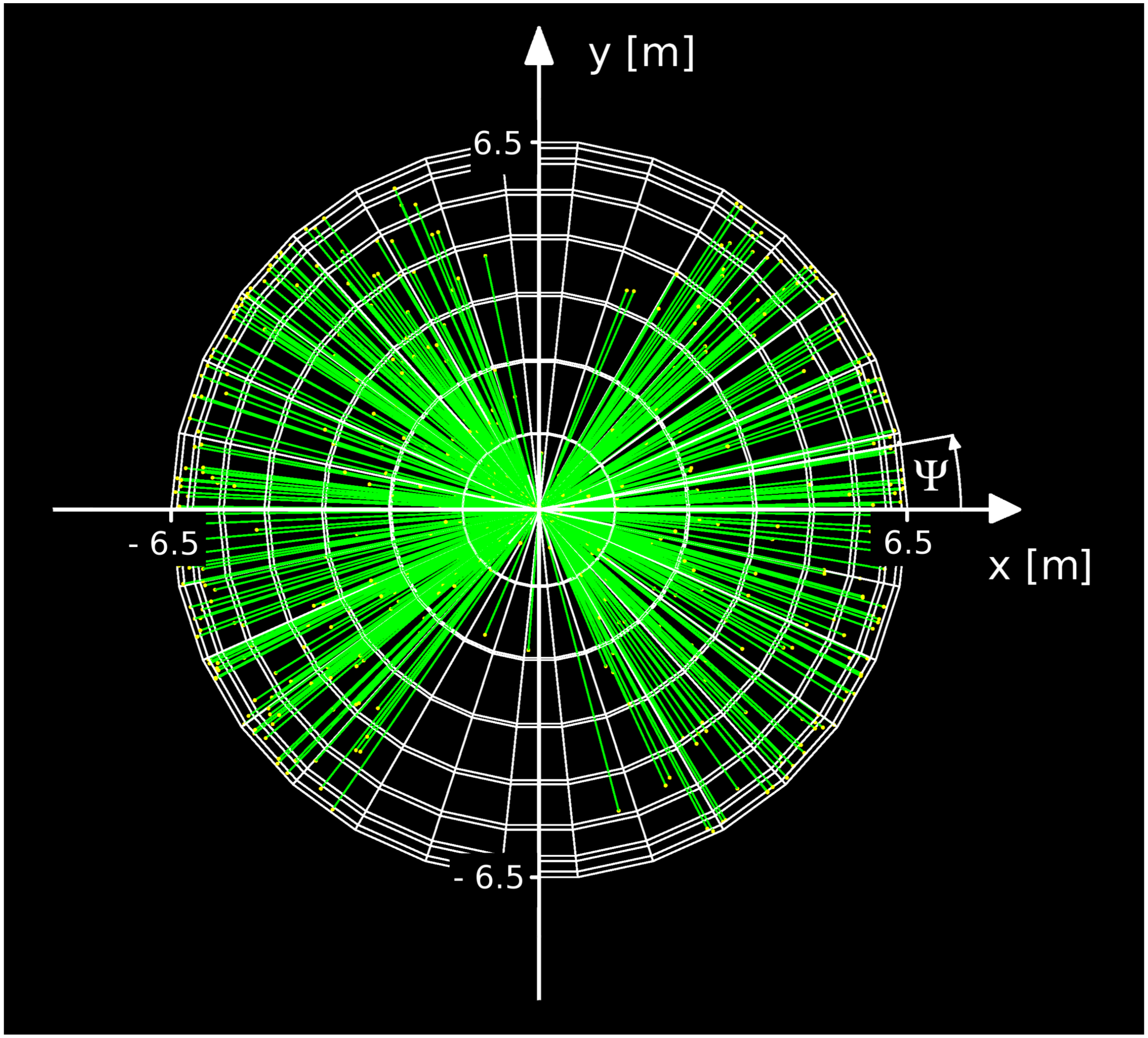
At LNGS: You do not need to prove that large liquid scintillators are powerful tools for rare event searches.



Problem: Scintillation light is isotropic.


Cherenkov light retains directional information!
An 8 MeV Solar Neutrino event in Super-K.

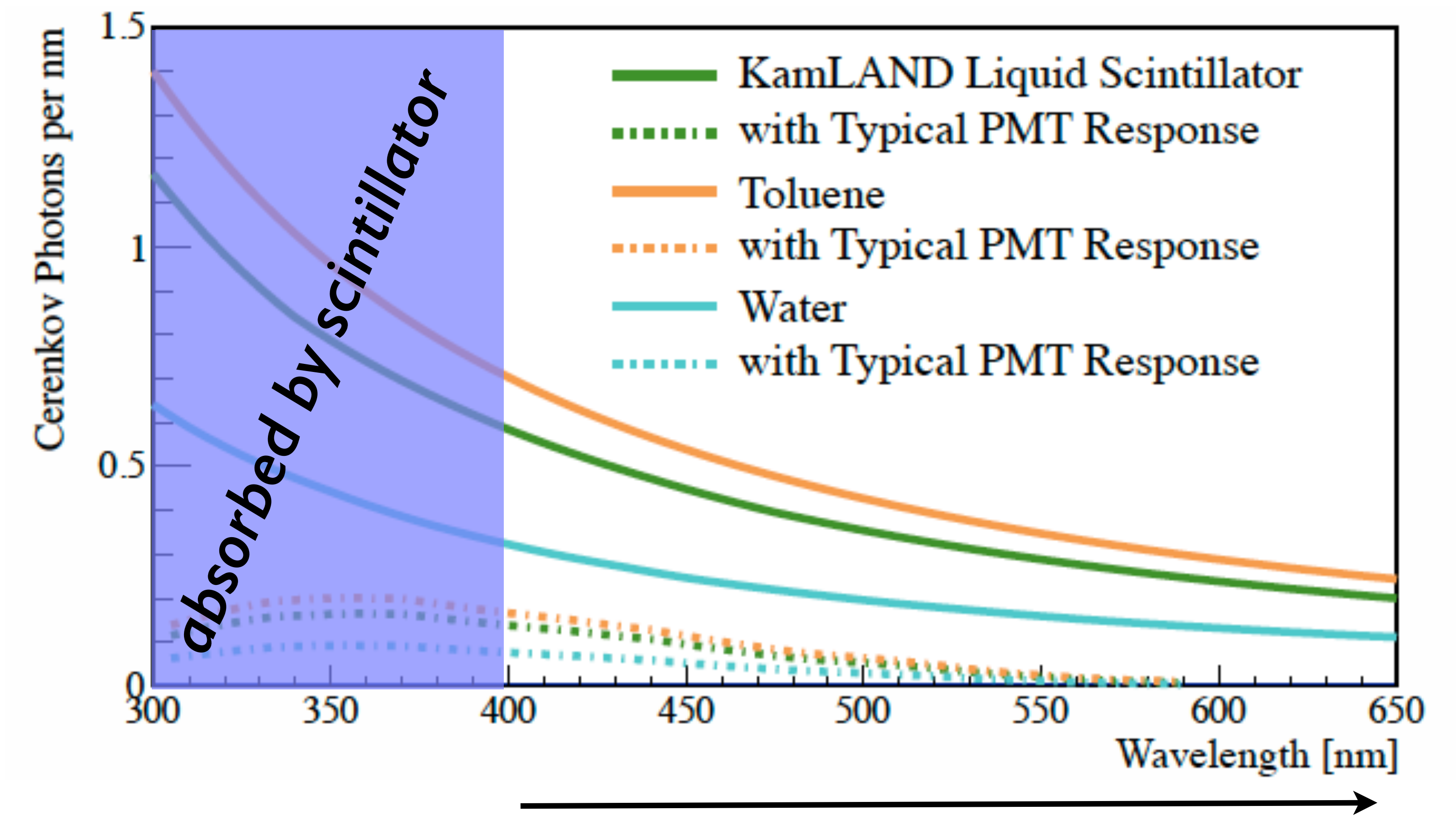
Neutrinoless Double Beta Decay



(Cherenkov Only)

How does it work?

Number of Cherenkov Photons for a 1MeV e-



Retains directional information!

Important in Big Detector.

Longer wavelengths travel faster in scintillator

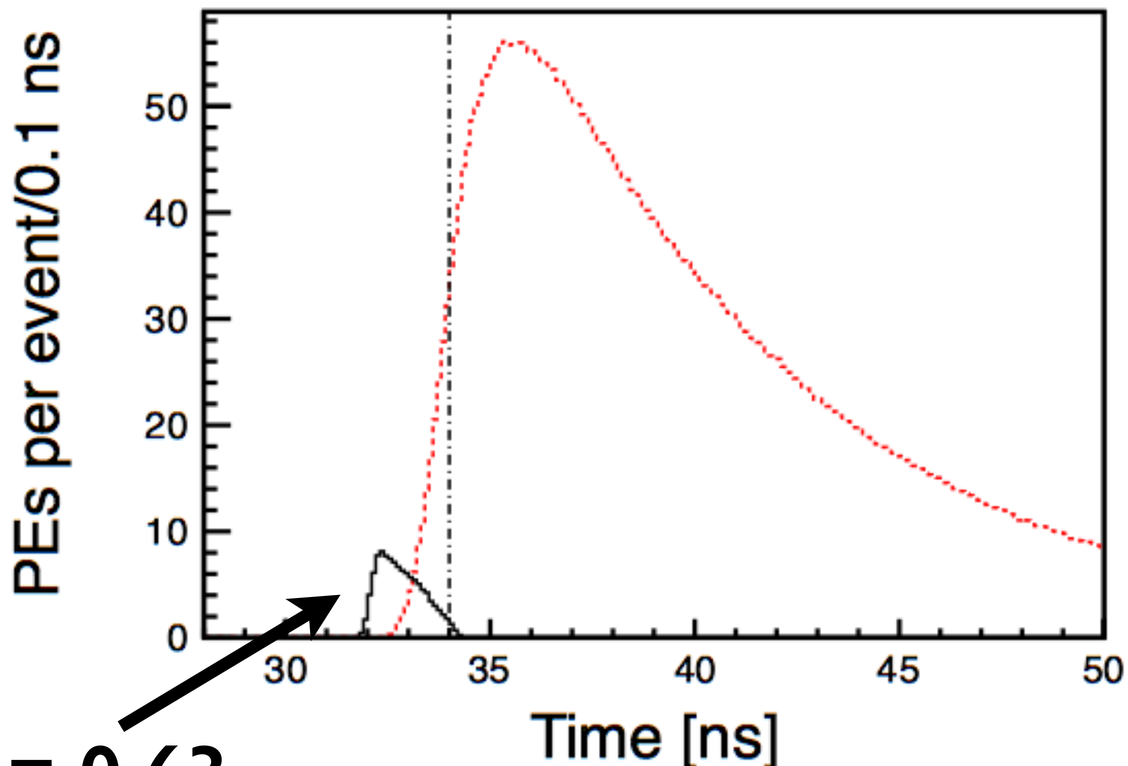
and

Scintillation processes have inherent time constants.

Always Important

JINST 9 (2014) P06012

So if you have good enough timing....

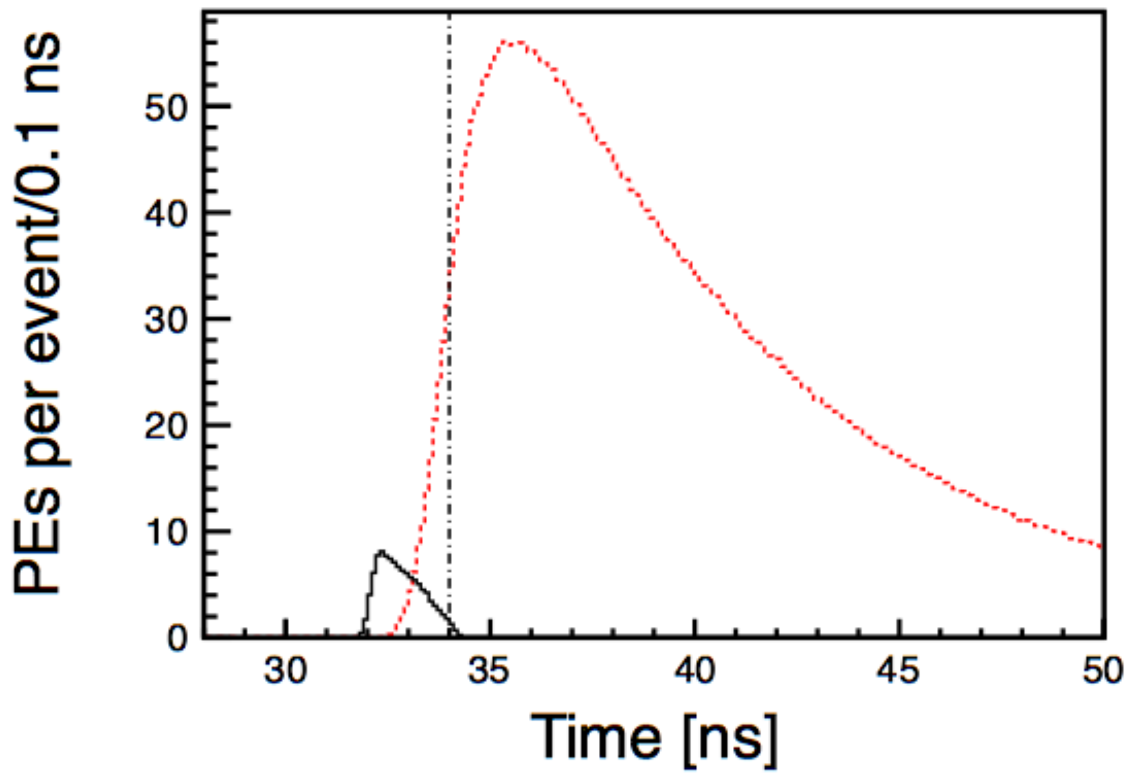


$R_{c/s} = 0.63$

…. you should be able to separate the scarce Cherenkov from the abundant scintillation light.

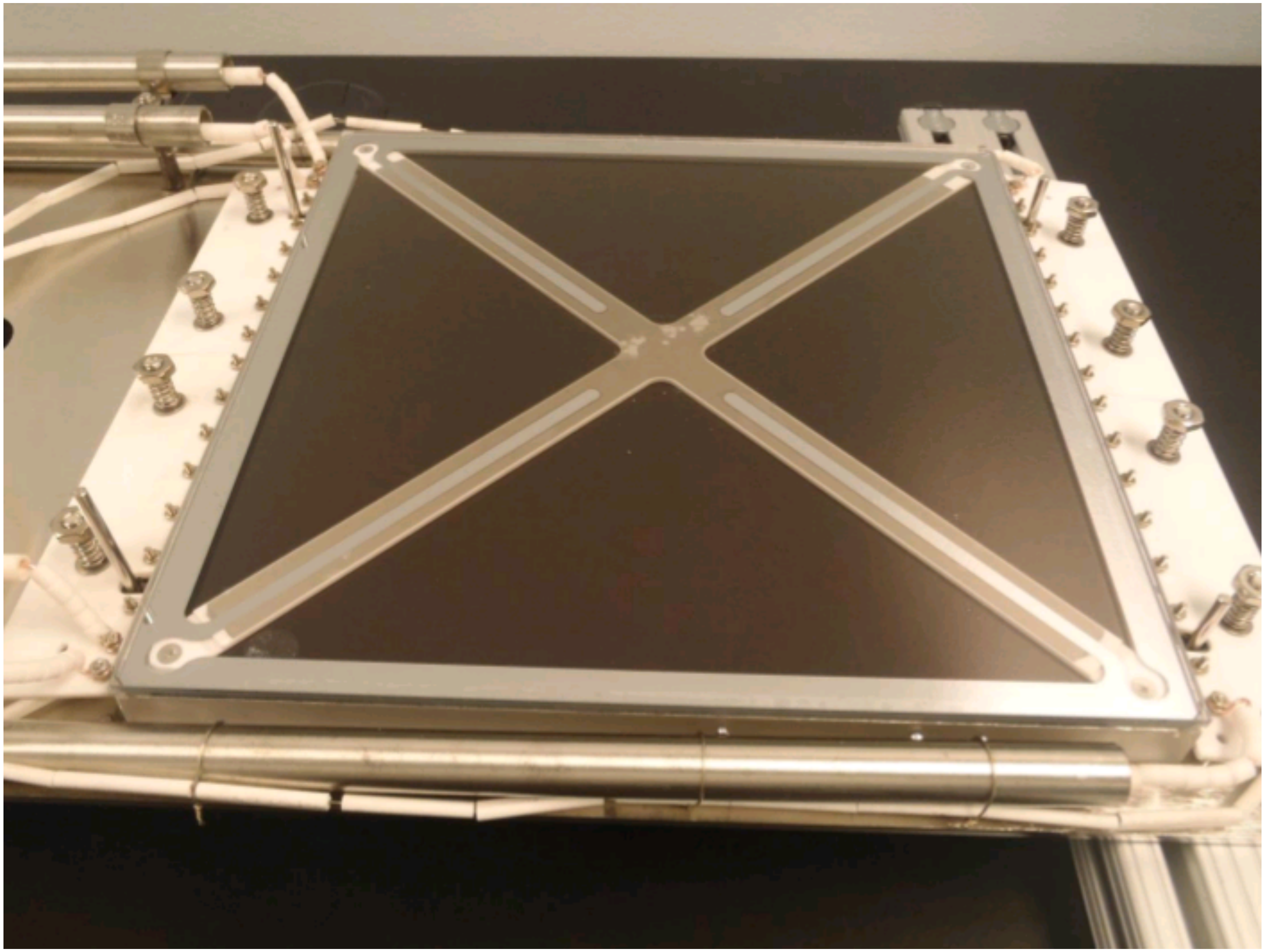
JINST 9 (2014) P06012

This corresponds to 0.1 ns.



This sort of timing is available in very tiny MCP-based PMT's/SiPMs…for now.

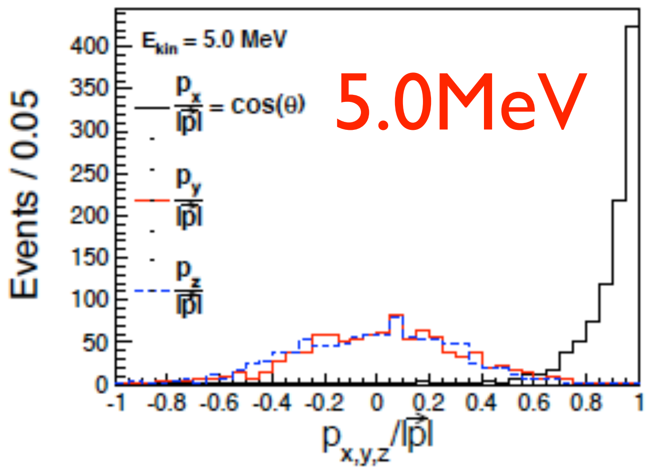
The LAPPD:

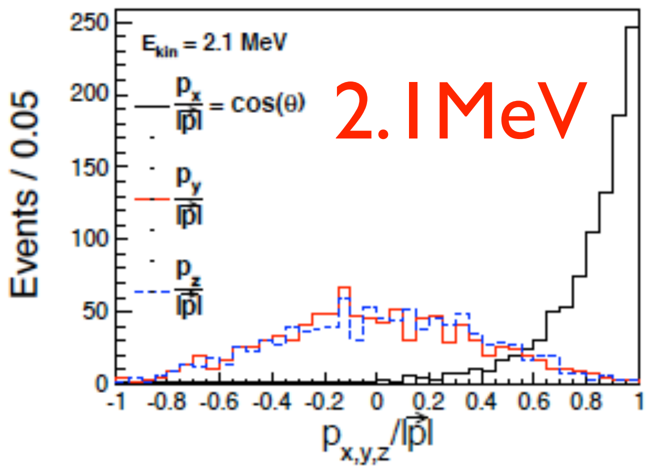


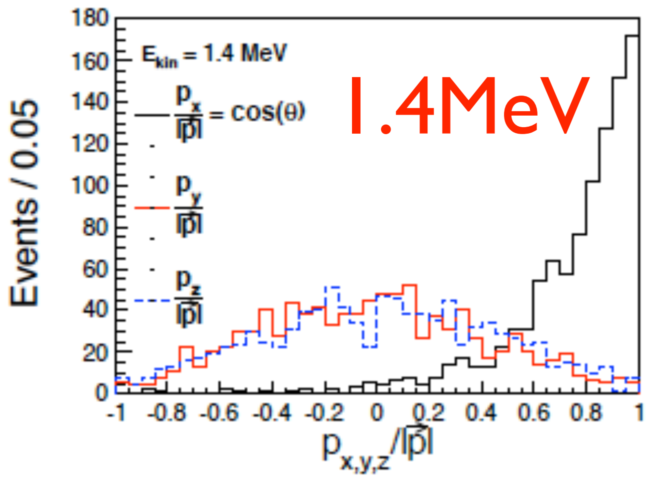
INCOM
Bright Ideas in Fiberoptics

THE UNIVERSITY OF CHICAGO

JINST 9 (2014) P06012

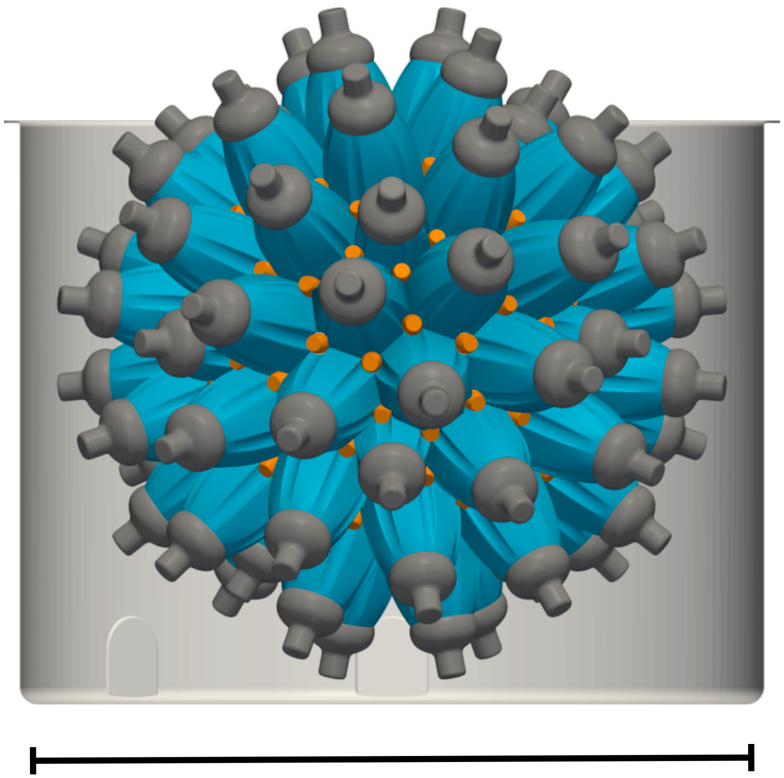






With a basic algorithm, we can reconstruct the direction of single electrons!

NuDot: A Prototype Directional Liquid Scintillator Detector

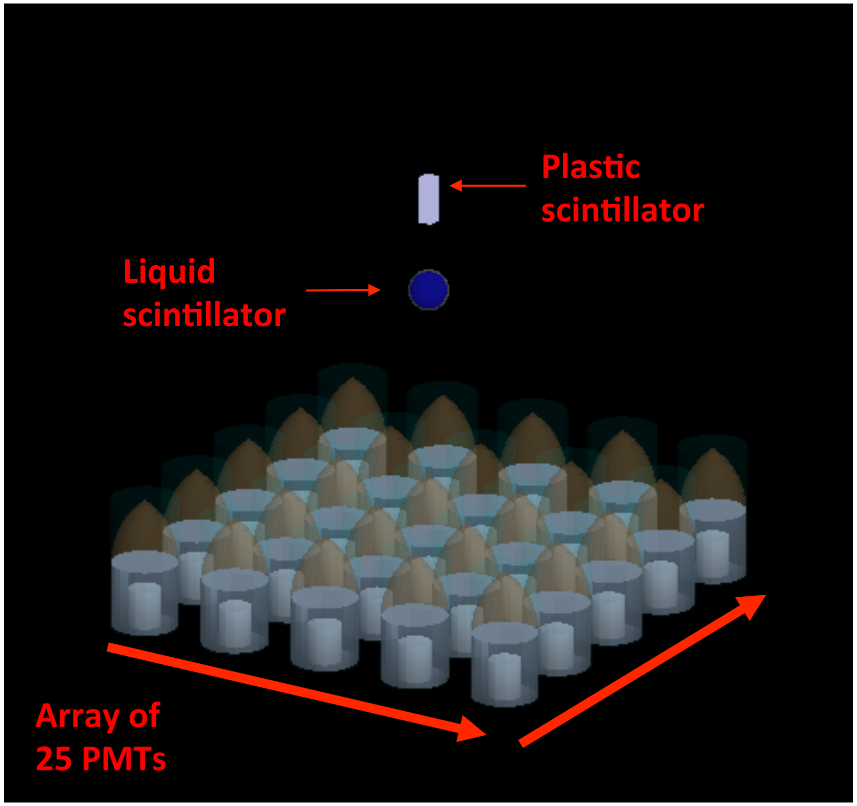


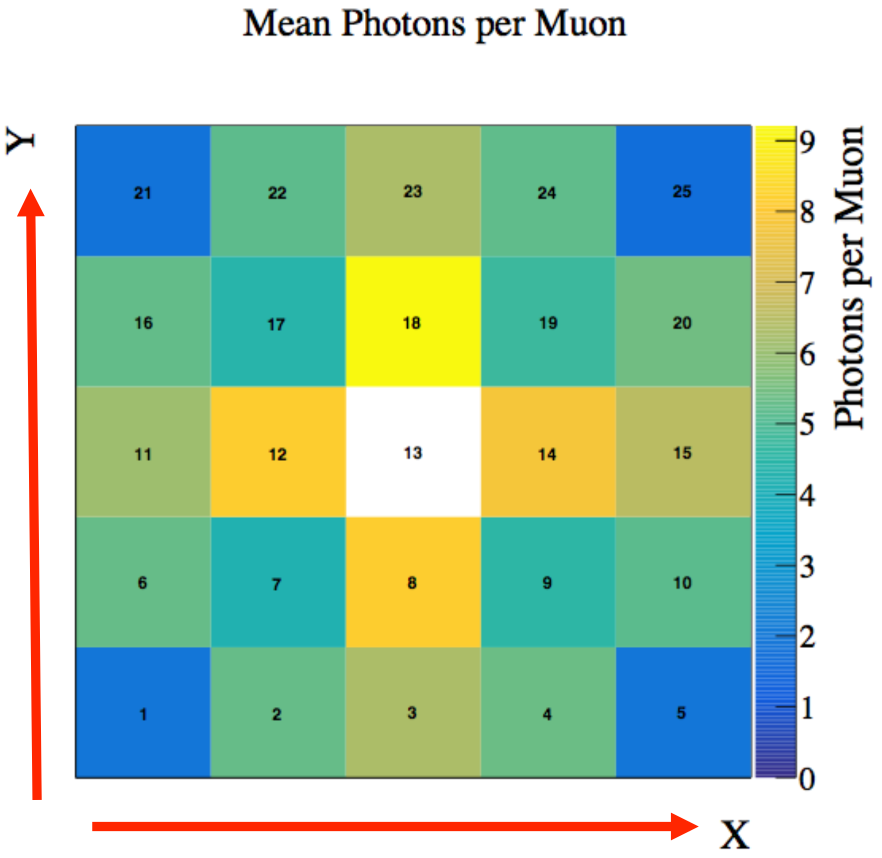
2.17 m

TDR in preparation:

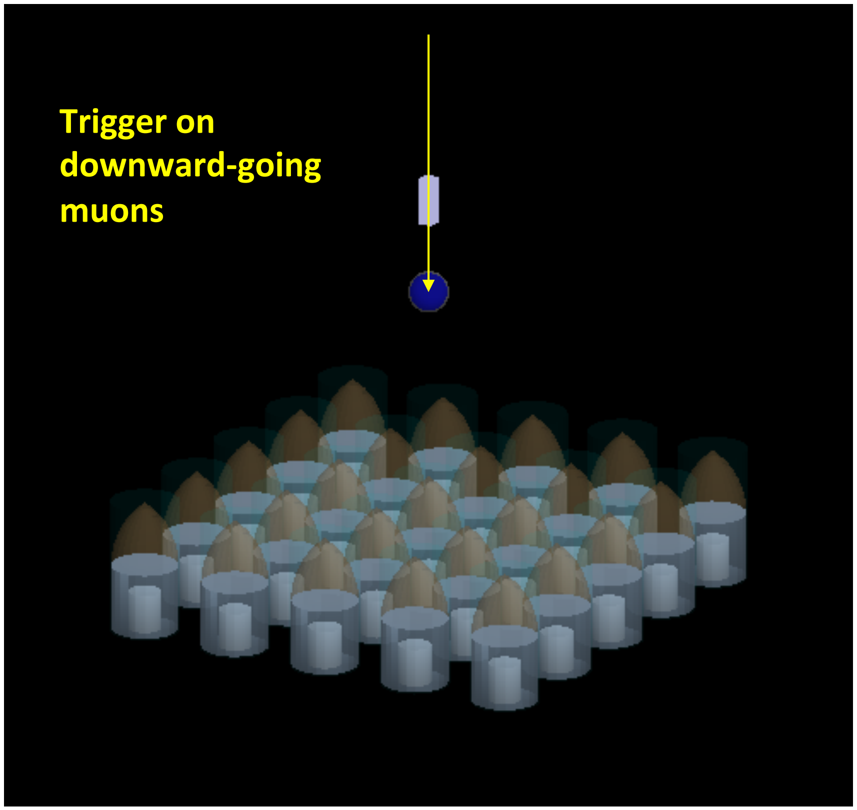
- 140 2" PMTs (300 ps timing, shown in orange).
- 72 8" PMTs for energy reconstruction.
- Smaller 25 PMT setup being used to understand DAQ and chemistry.

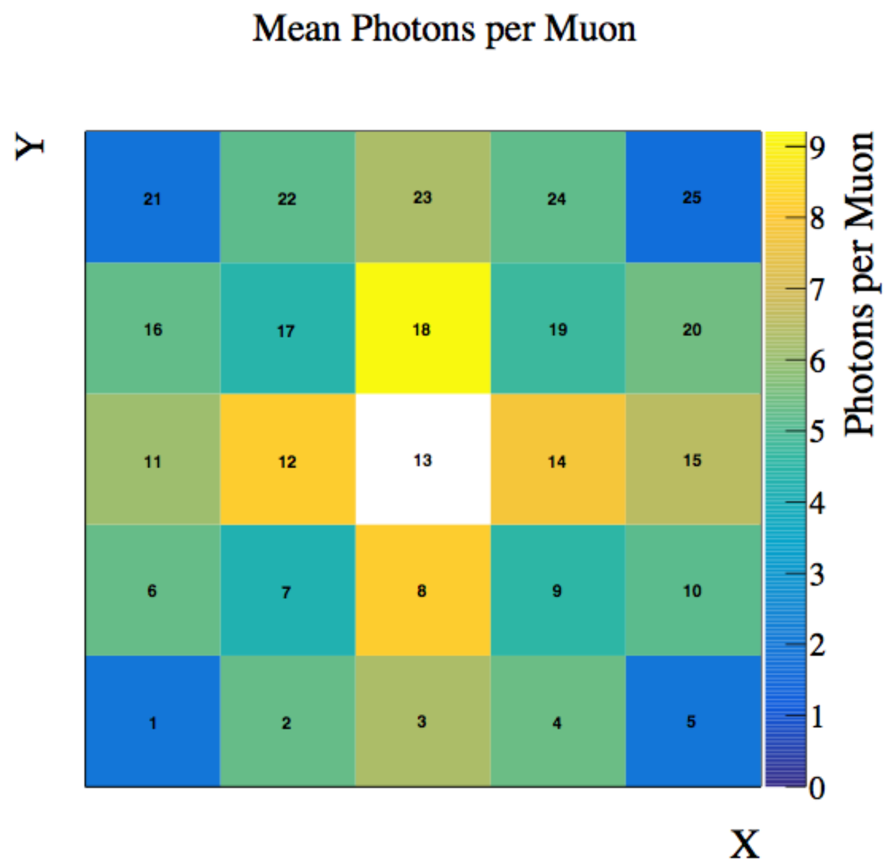
FlatDot: A prototype prototype



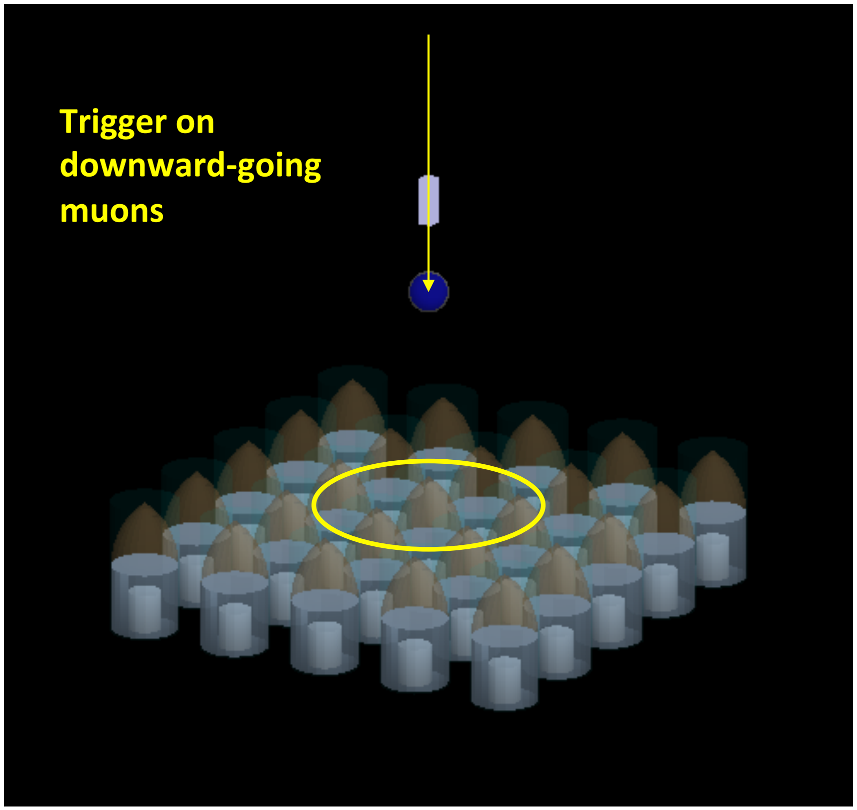


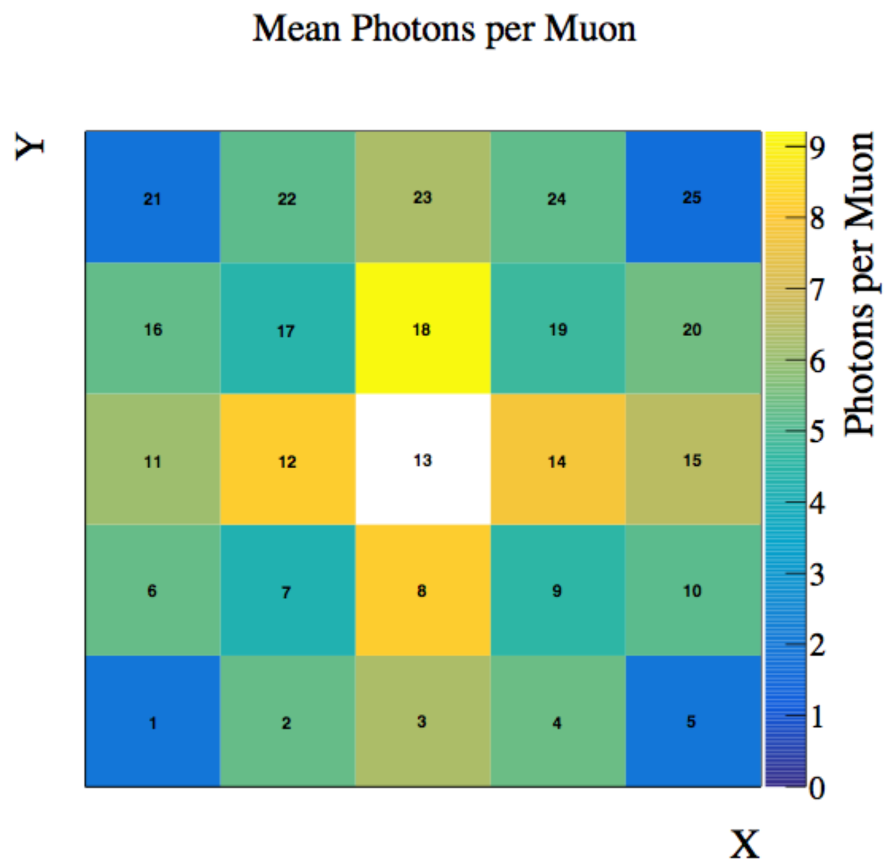
FlatDot: A prototype prototype



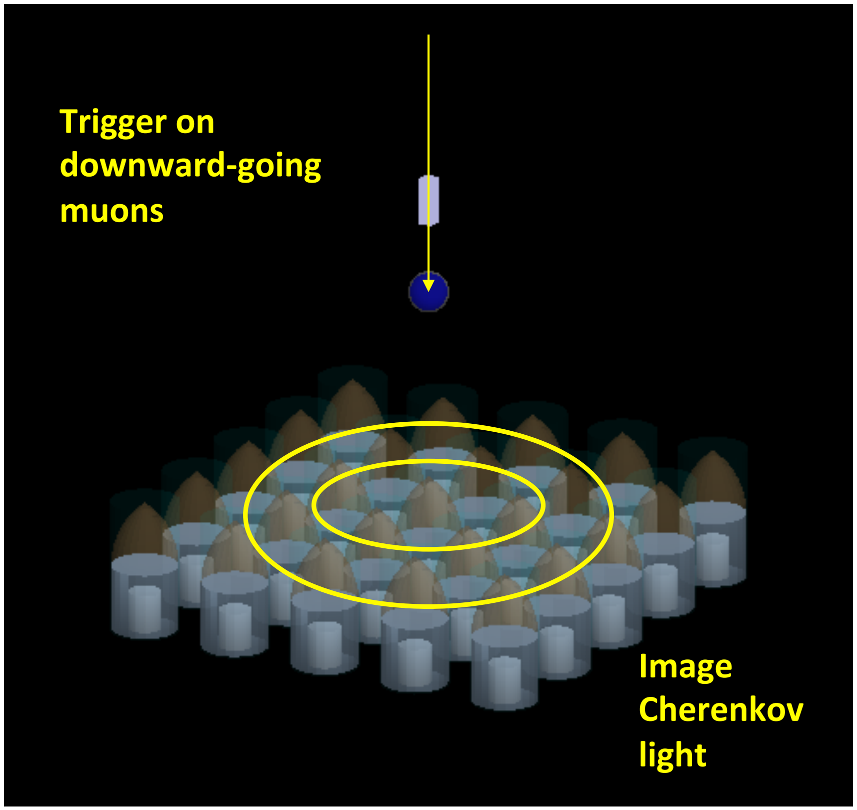


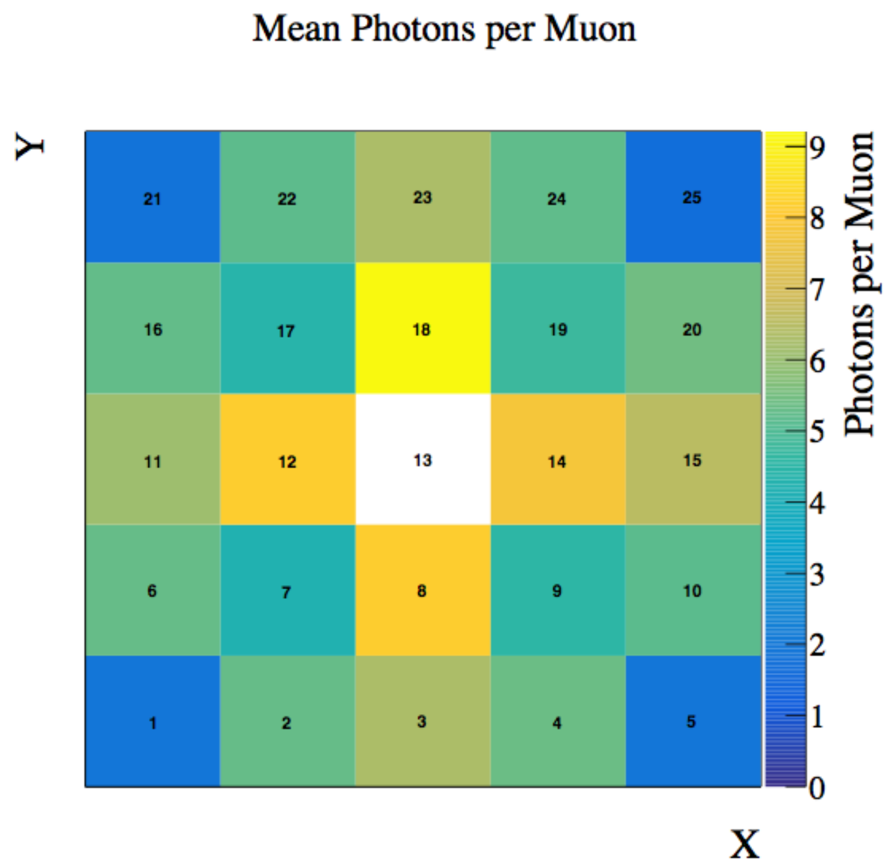
FlatDot: A prototype prototype



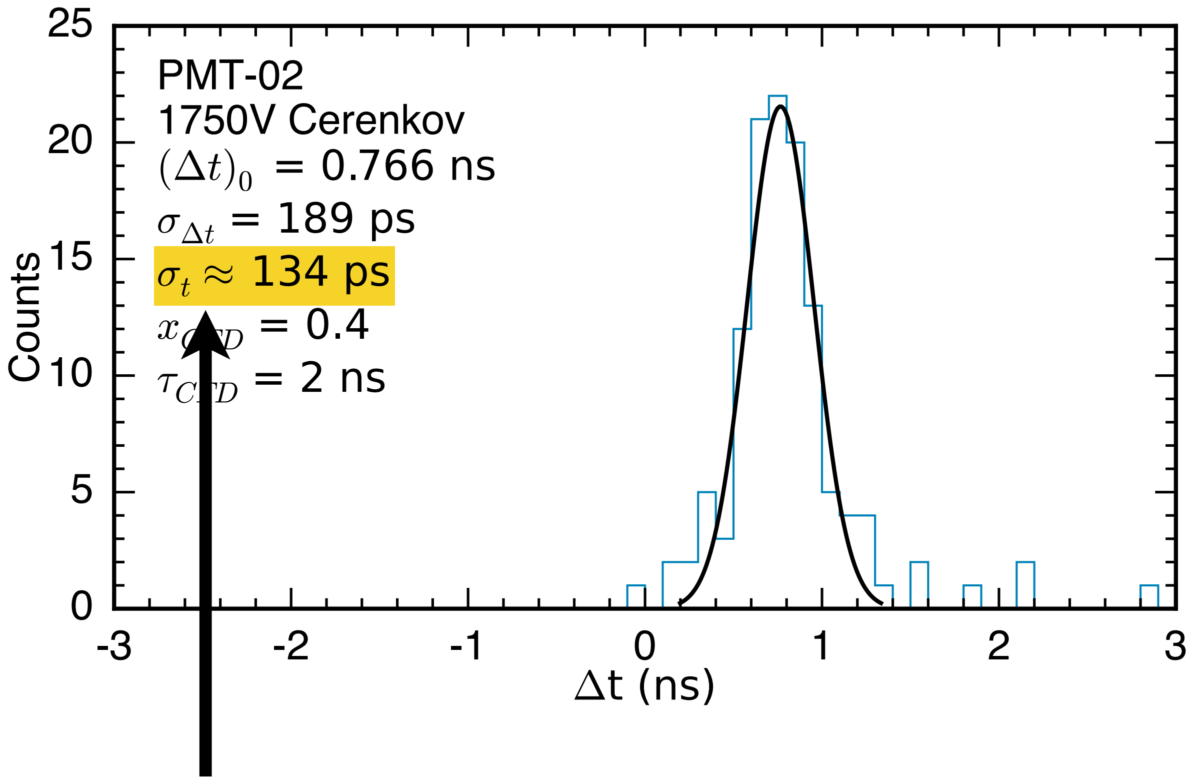


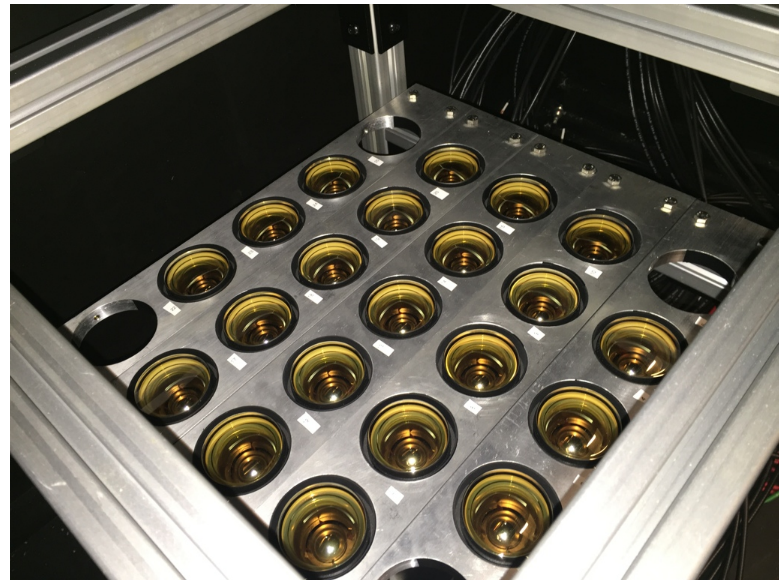
FlatDot: A prototype prototype

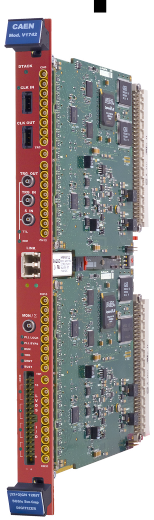




FlatDot: A prototype prototype



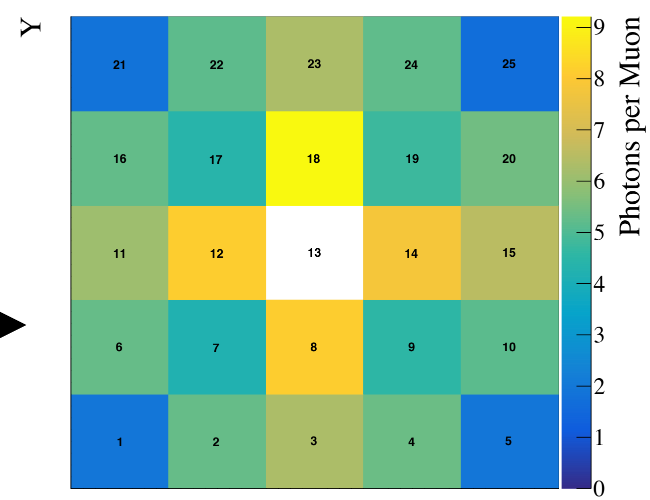




Timing Achieved!

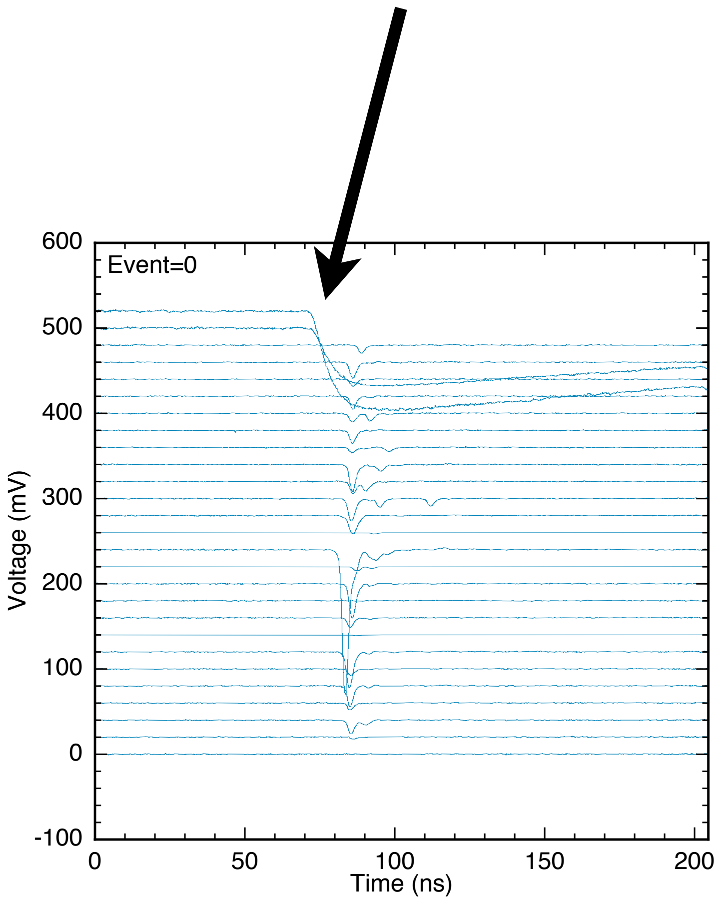
v1742 - CAEN

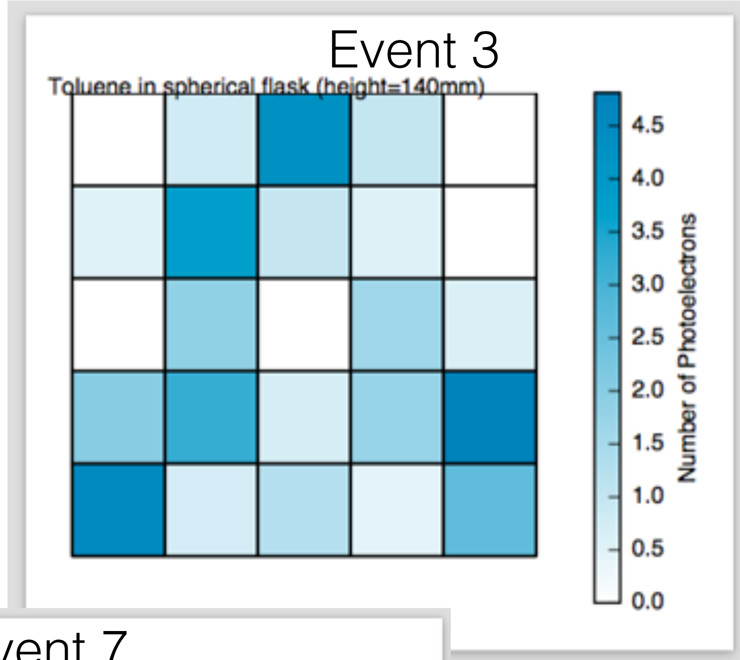
Simulation working!

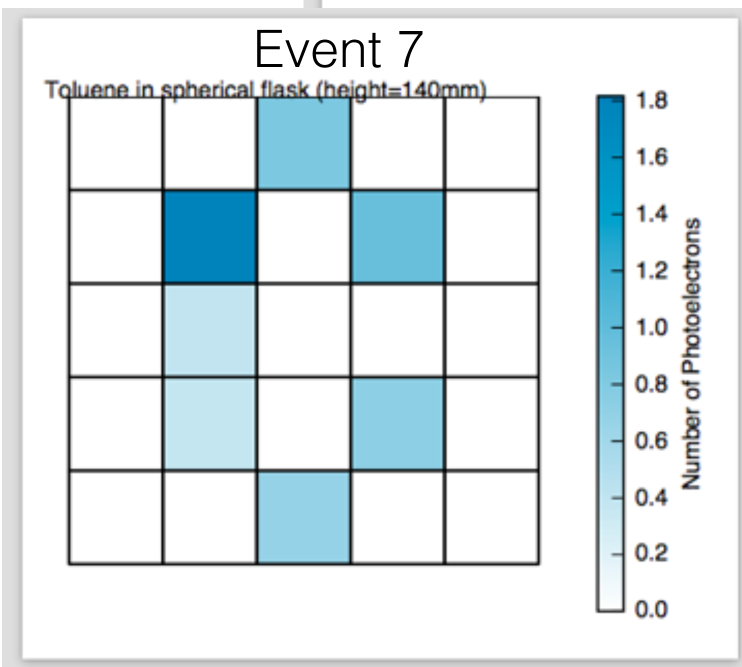


Got Rings?

SiPM trigger

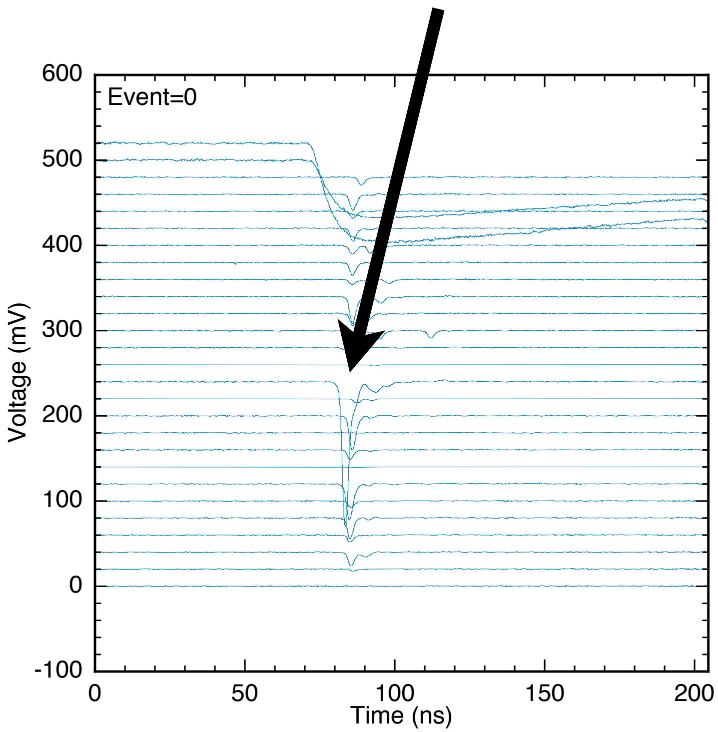


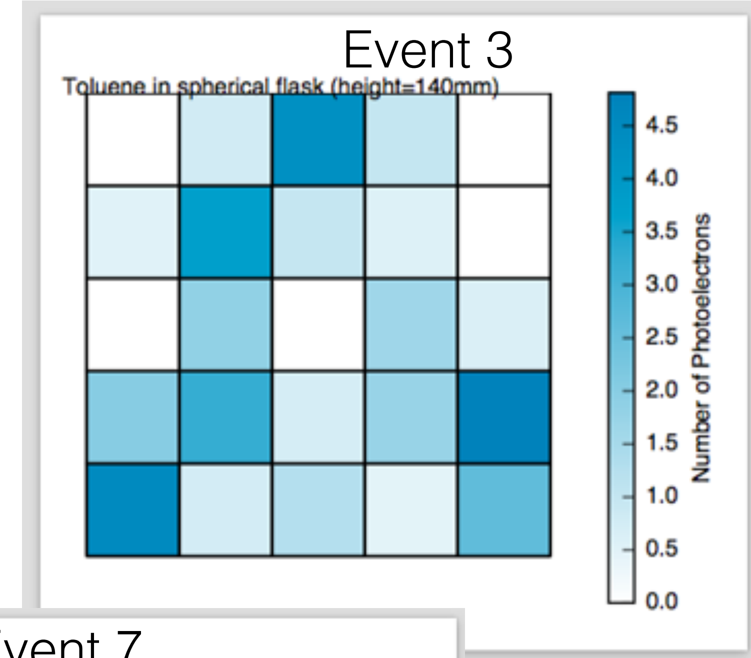


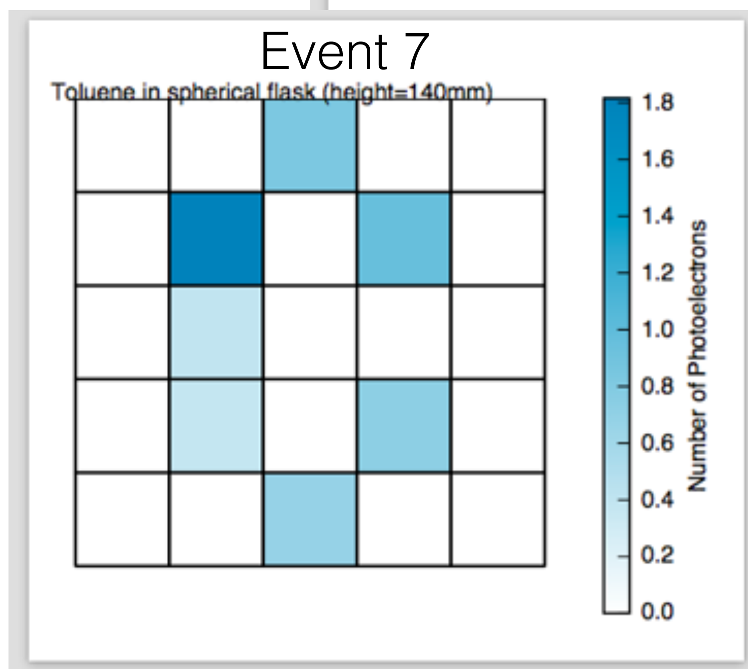


Got Rings?

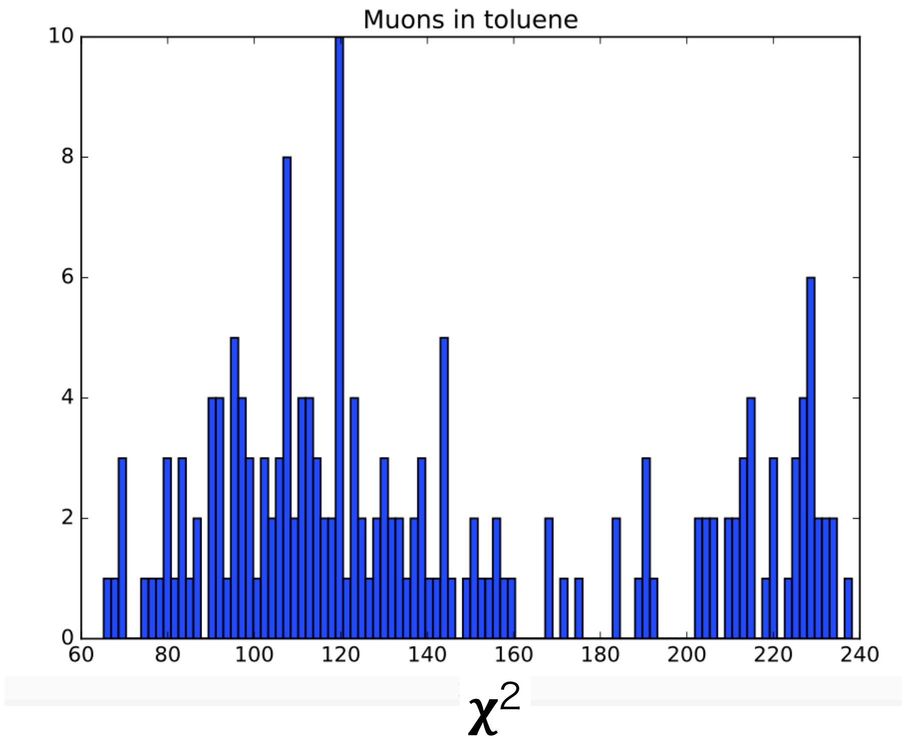
Muon through central PMT.

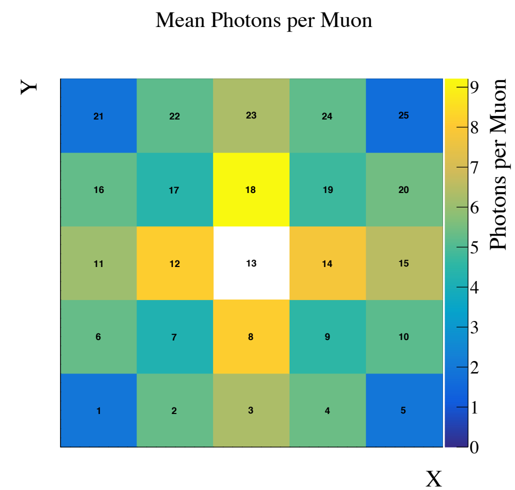






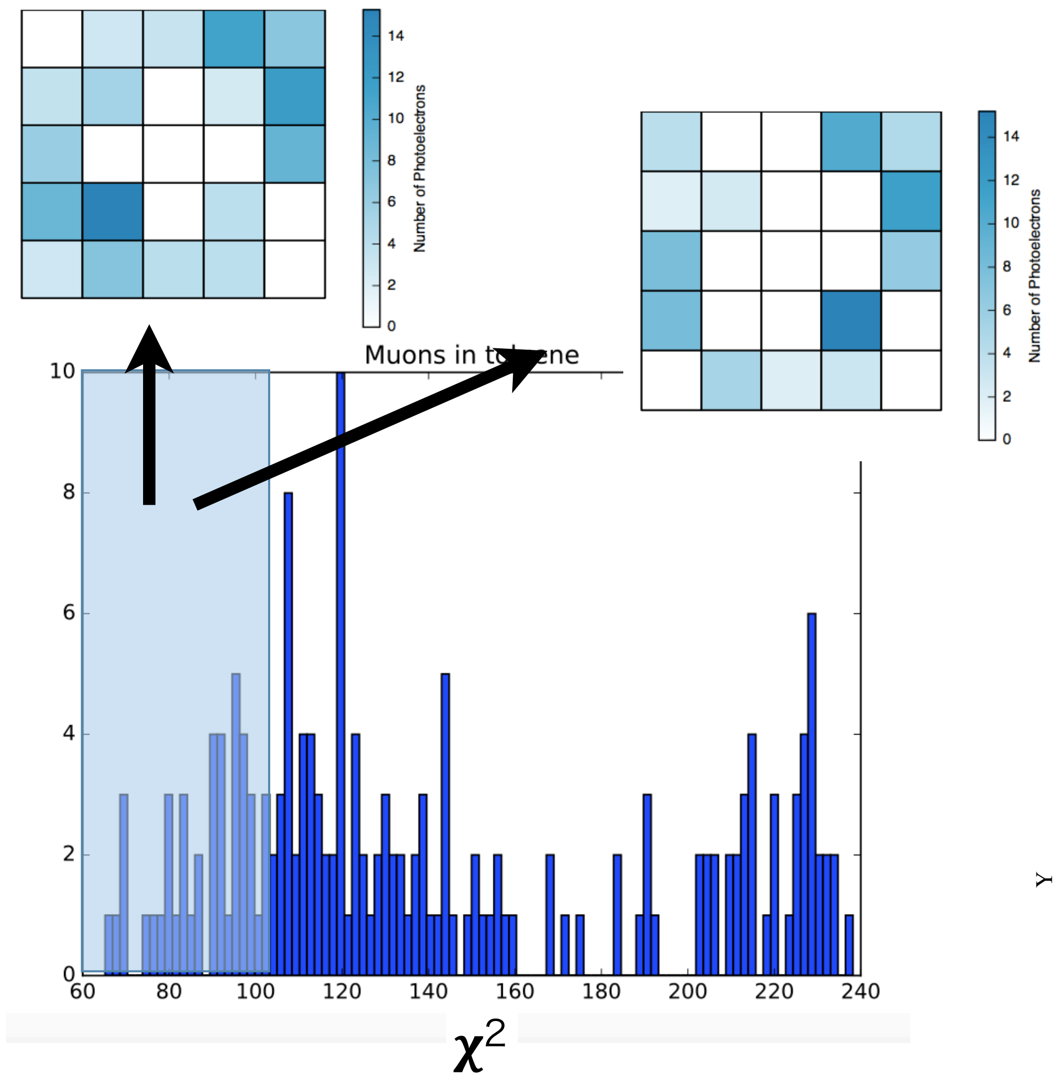
Got Rings?



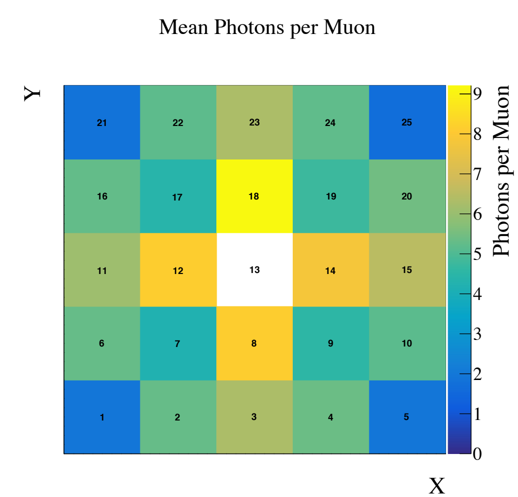


Understand χ2 relative to Monte Carlo…

Got Rings?

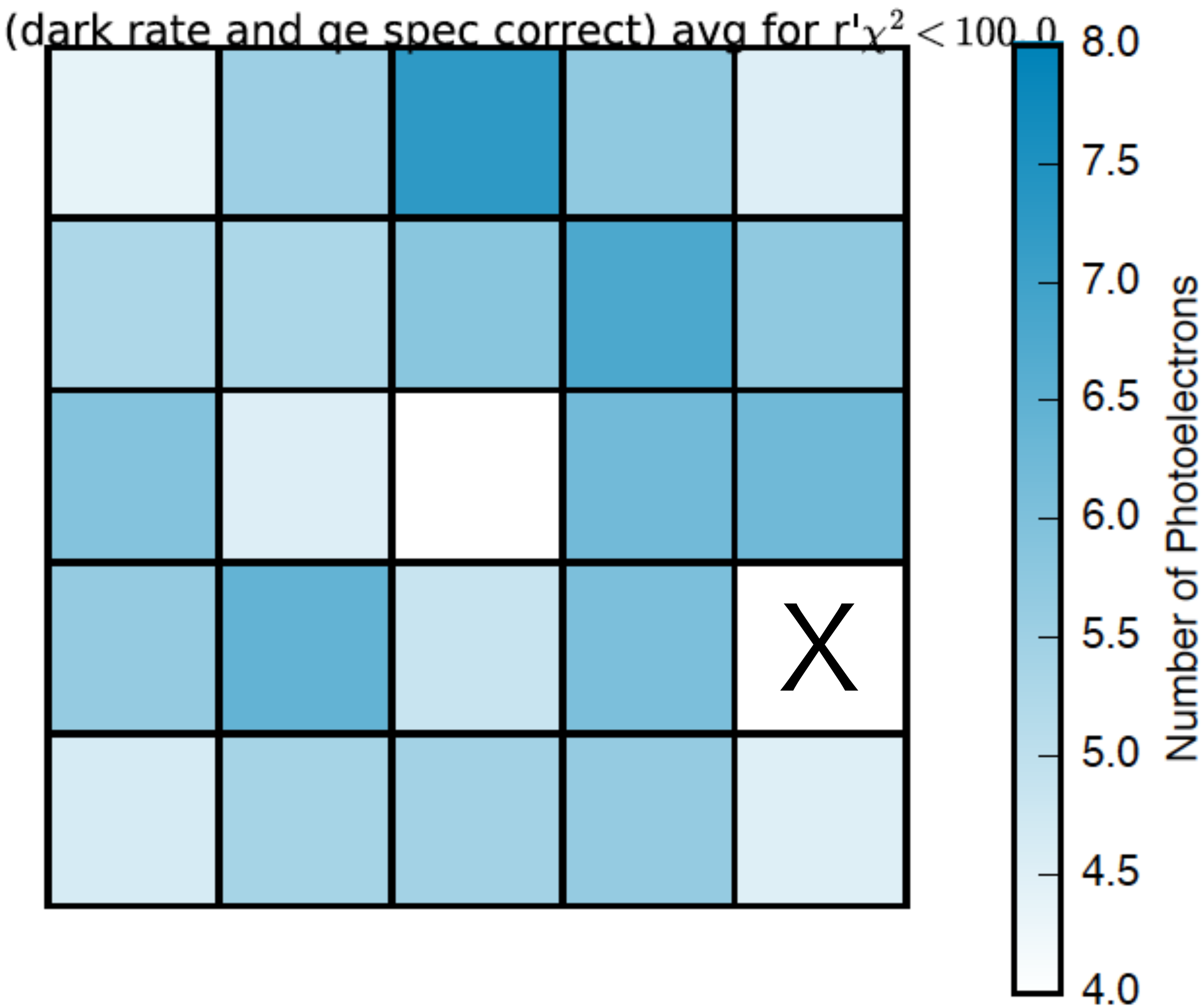


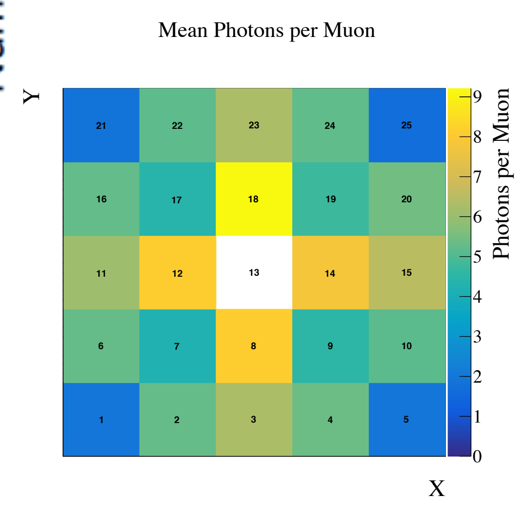
Number of Photoelectrons
Number of Photoelectrons
χ^2



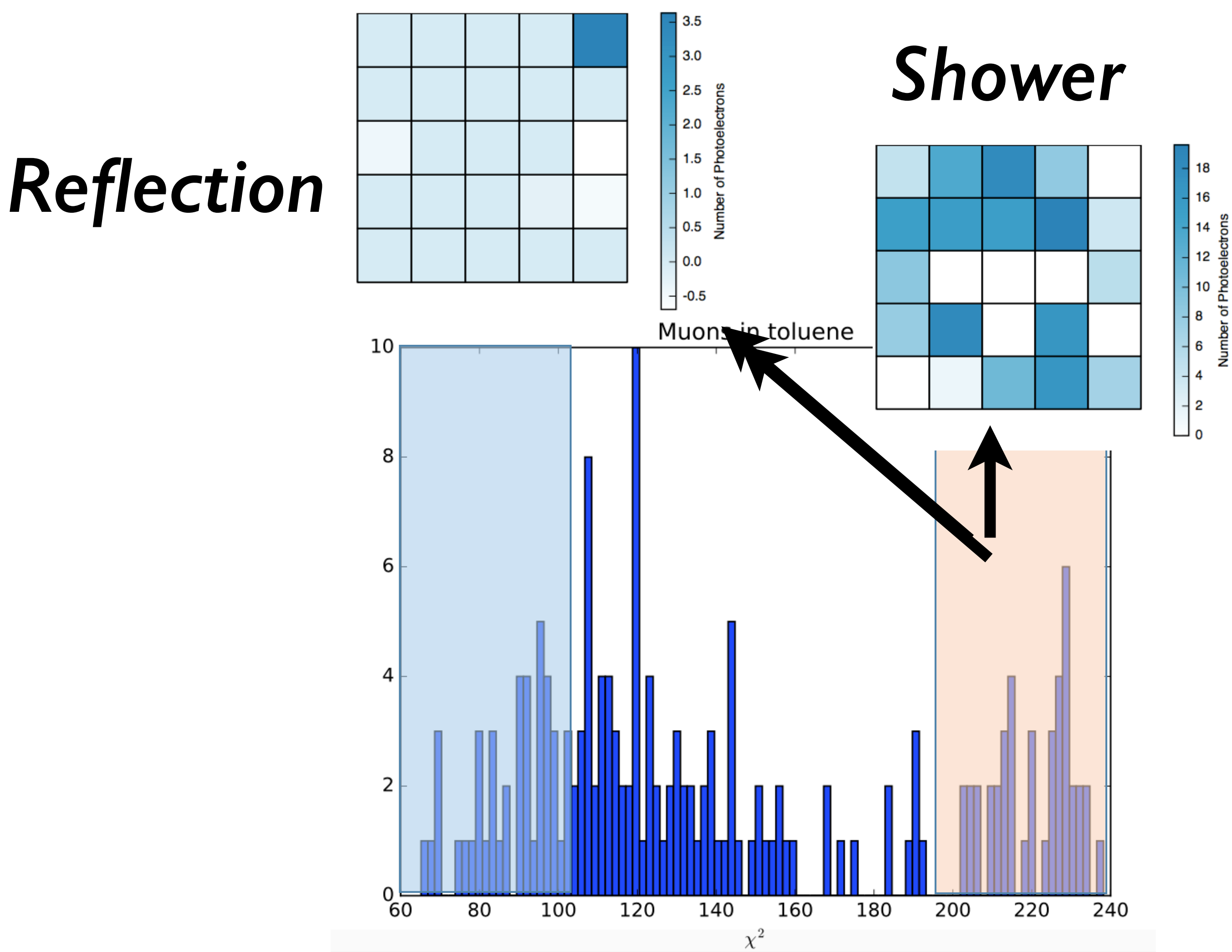
Mean Photons per Muon
Photons per Muon
X
Y

Got Rings?

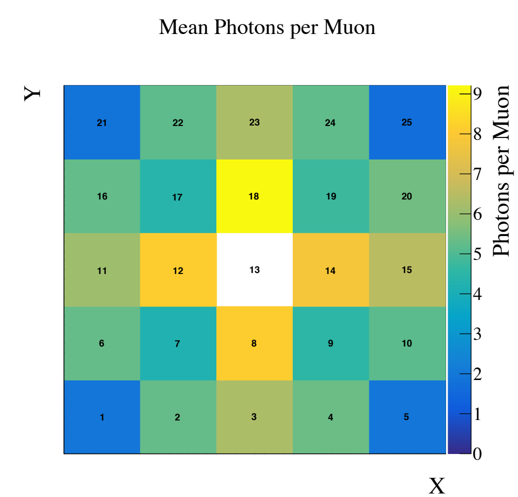

(dark rate and qe spec correct) avg for r'$\chi^2 < 100.0$
8.0
7.5
7.0
6.5
6.0
5.5
5.0
4.5
4.0
Number of Photoelectrons
X


Mean Photons per Muon
Y
X
Photons per Muon
21 22 23 24 25
16 17 18 19 20
11 12 13 14 15
6 7 8 9 10
1 2 3 4 5
0 1 2 3 4 5 6 7 8 9

Got Rings?



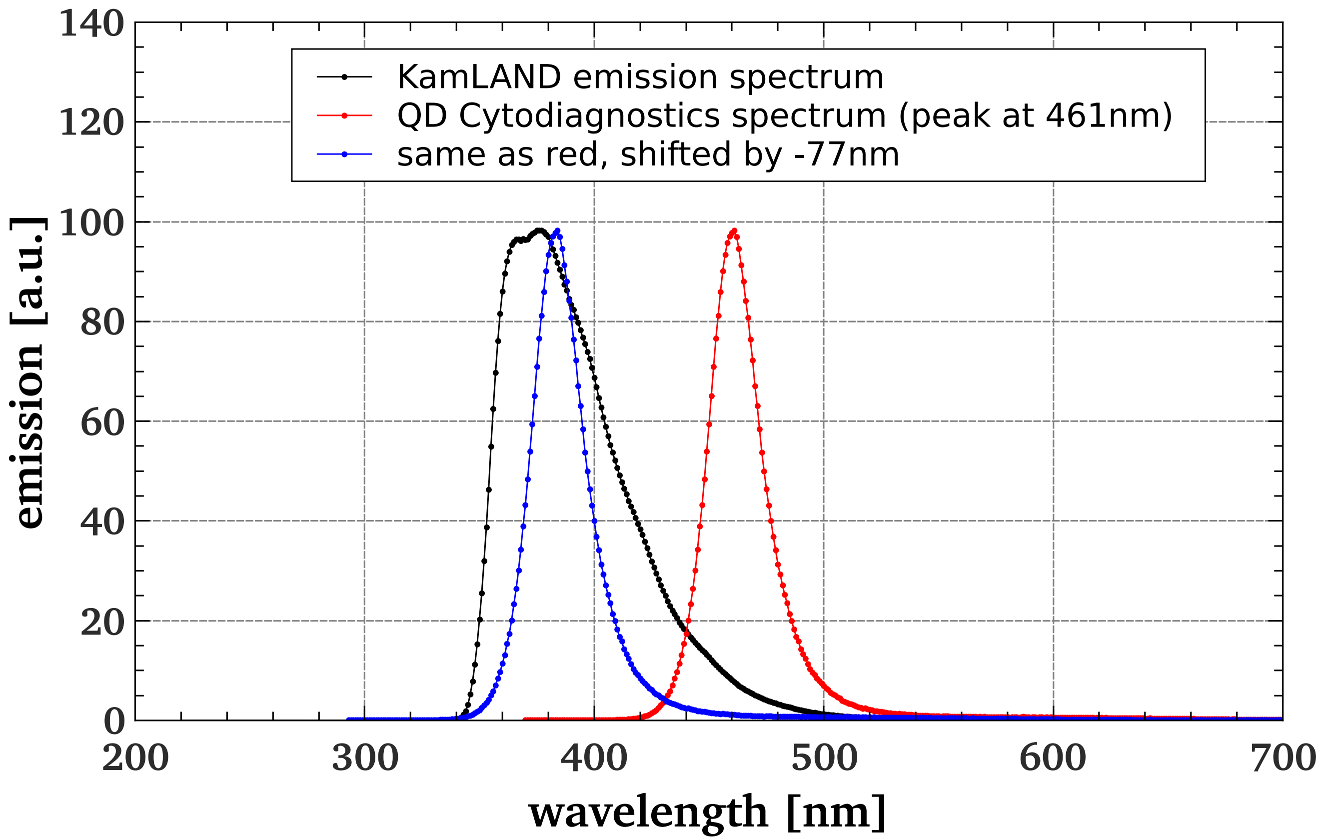
Reflection
Shower
Number of Photoelectrons
Number of Photoelectrons
Muons in toluene
χ^2



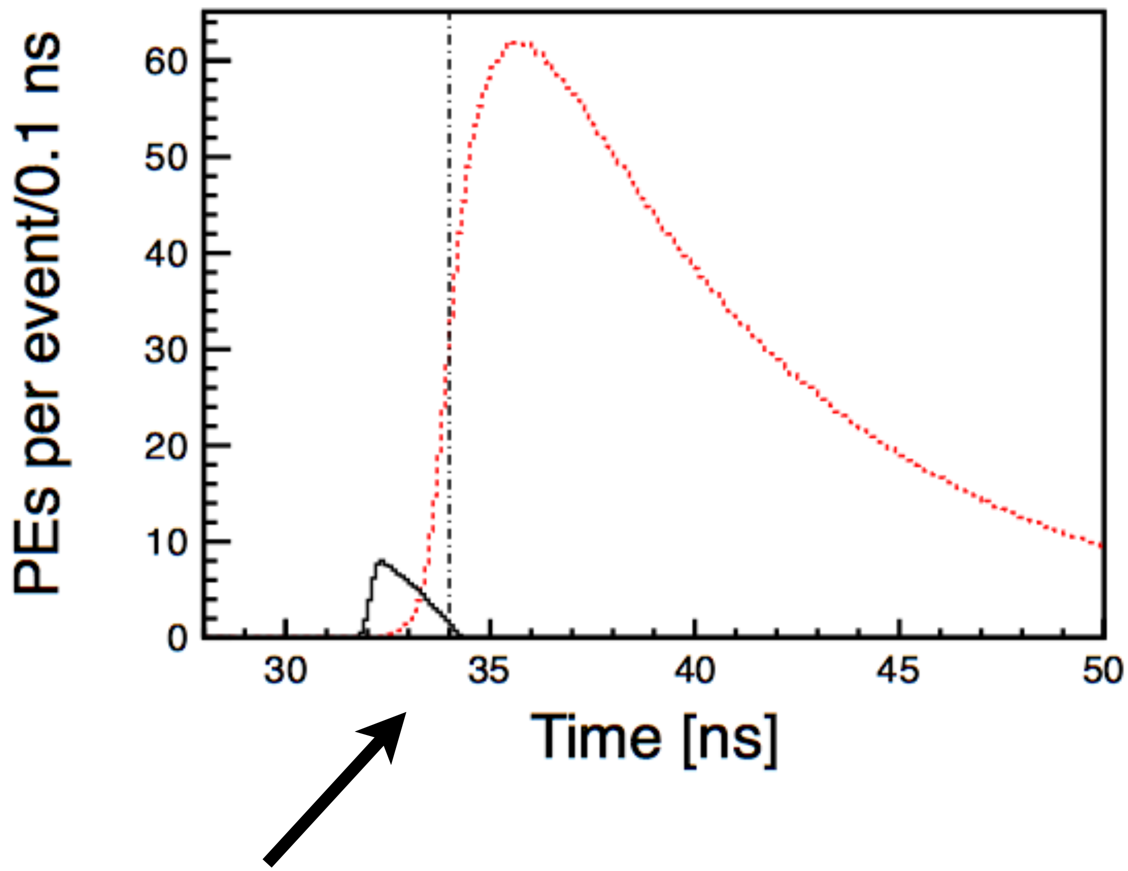
Mean Photons per Muon
Photons per Muon
Y
X

Did you say something about quantum dots?

What if I could narrow the emission spectrum?



Narrowed emission spectrum with traditional PMTs and 0.1ns timing.



$R_{c/s}$ = 0.86

What are Quantum Dots?

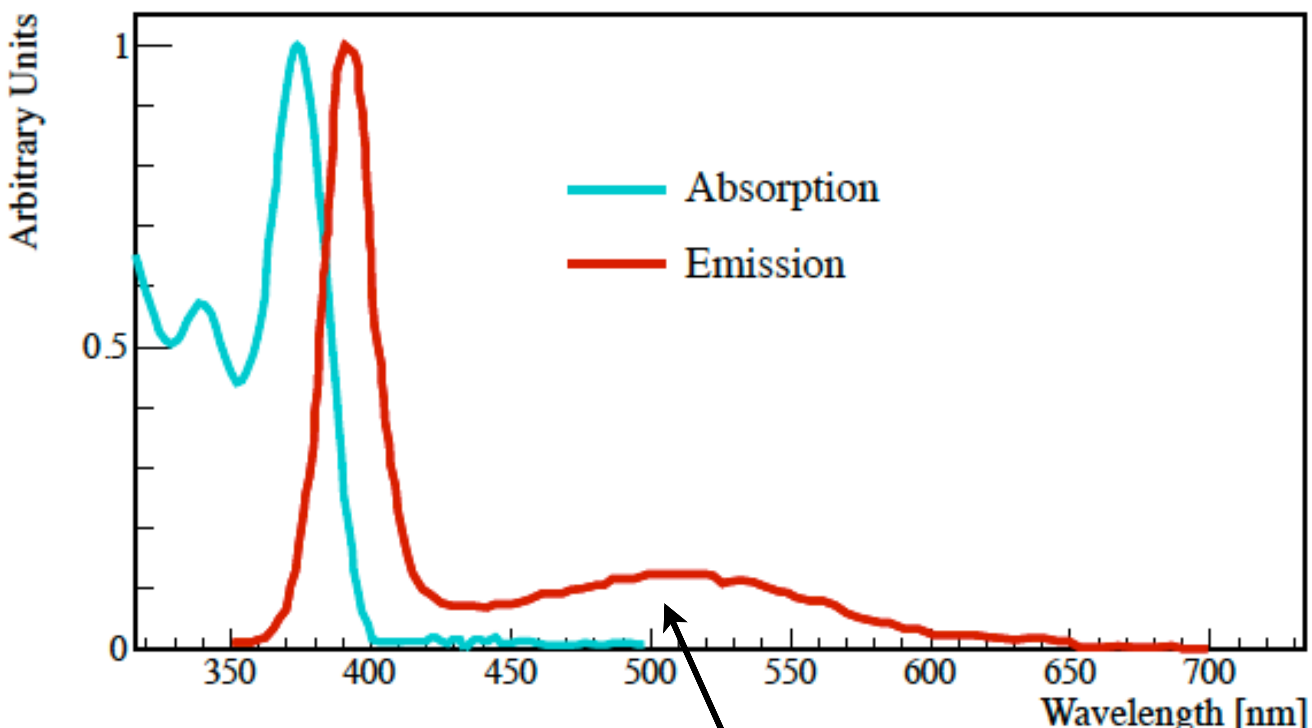
Quantum Dots are semiconducting nanocrystals.

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

Common materials are CdS, CdSe, CdTe...

Example CdS Quantum Dot Spectra:

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



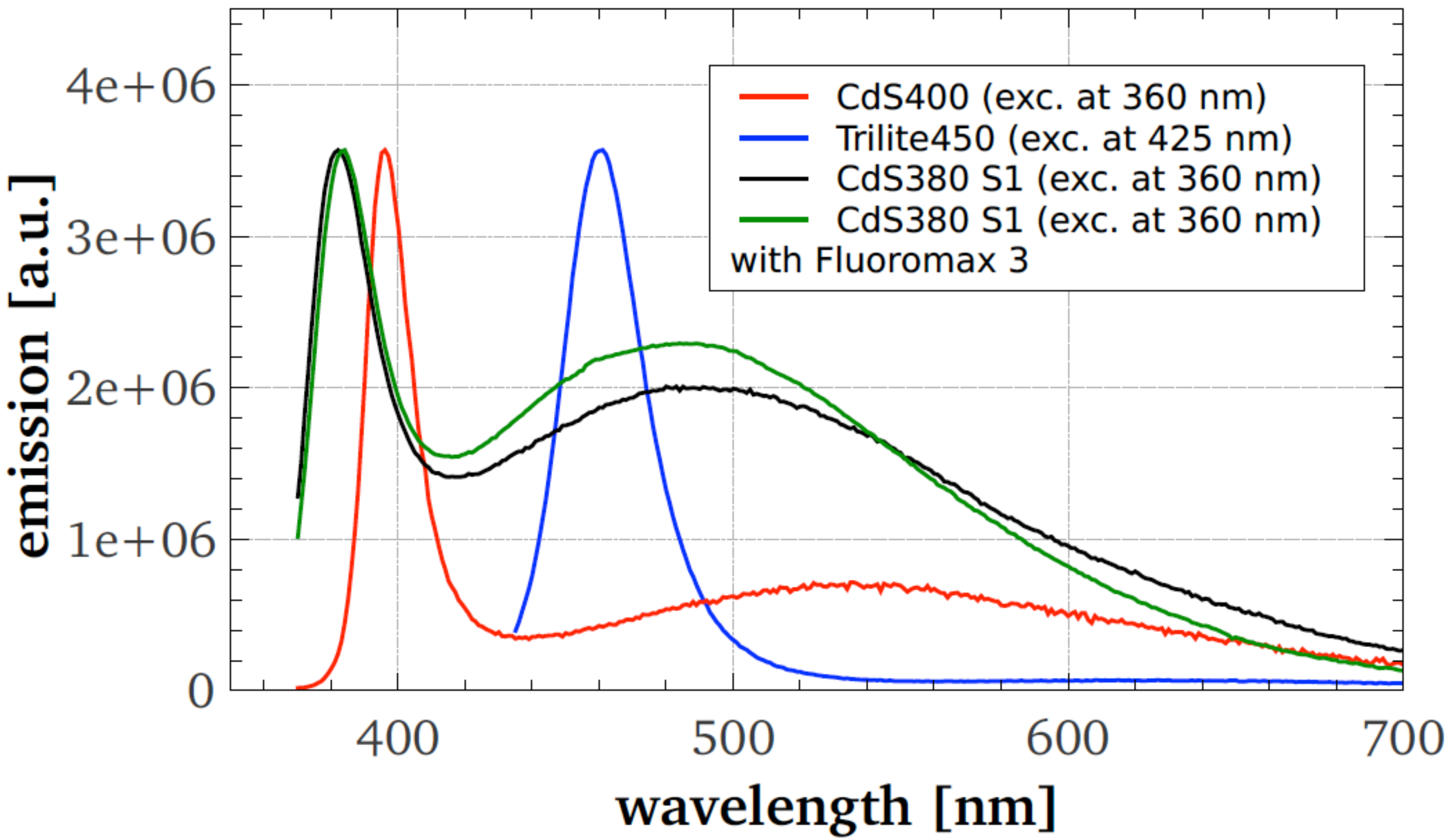
Very Useful for Biology, Solar Cells, and LEDs!

surface states=not good for us

Quantum Dot Materials Overlap with Candidate Isotopes!

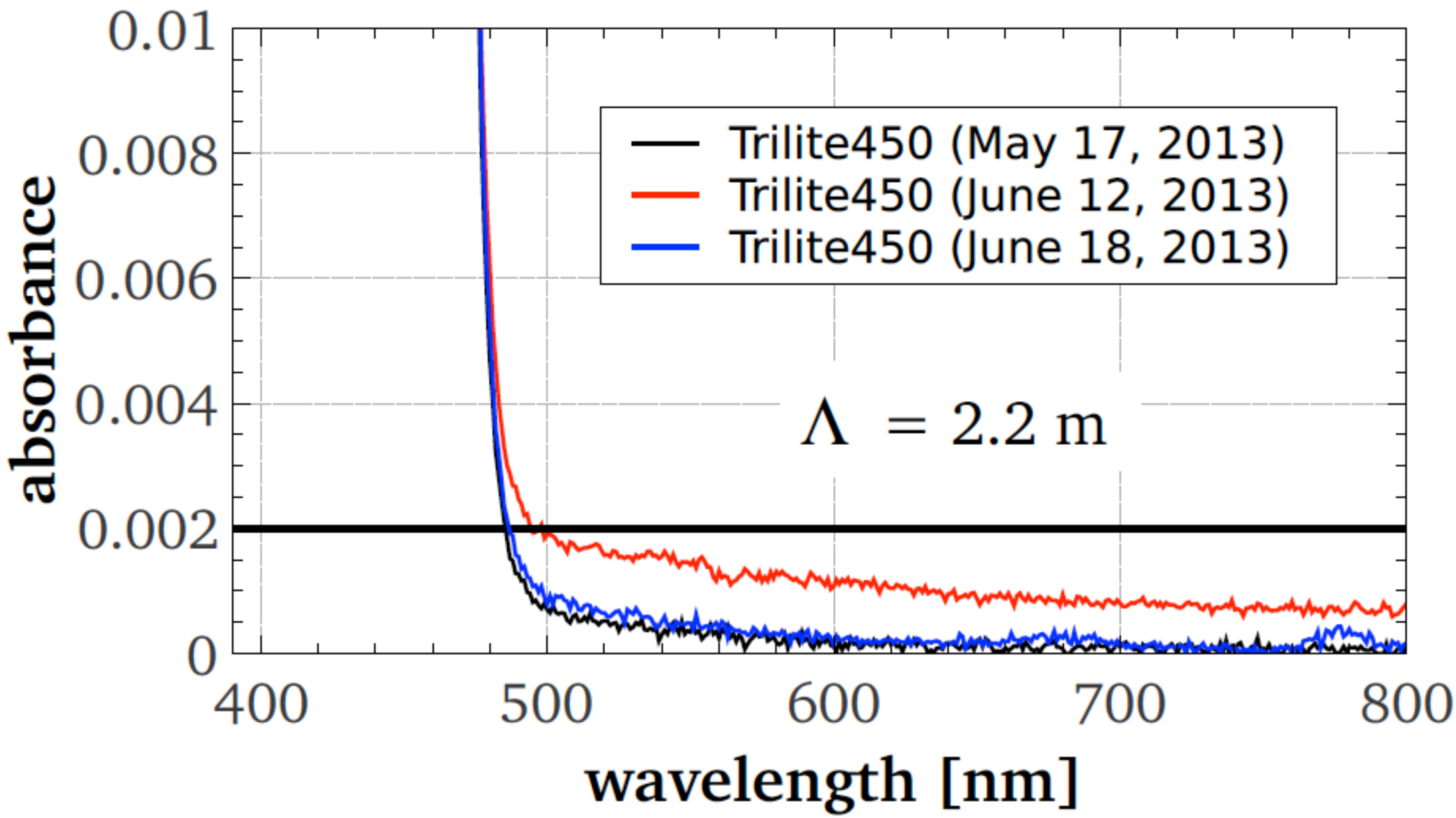
Isotope	Endpoint	Abundance
^{48}Ca	4.271 MeV	0.187%
^{150}Nd	3.367 MeV	5.6%
^{96}Zr	3.350 MeV	2.8%
^{100}Mo	3.034 MeV	9.6%
^{82}Se	2.995 MeV	9.2%
^{116}Cd	2.802 MeV	7.5%
^{130}Te	2.533 MeV	34.5%
^{136}Xe	2.479 MeV	8.9%
^{76}Ge	2.039 MeV	7.8%
^{128}Te	0.868 MeV	31.7%

We have found better quantum dots!



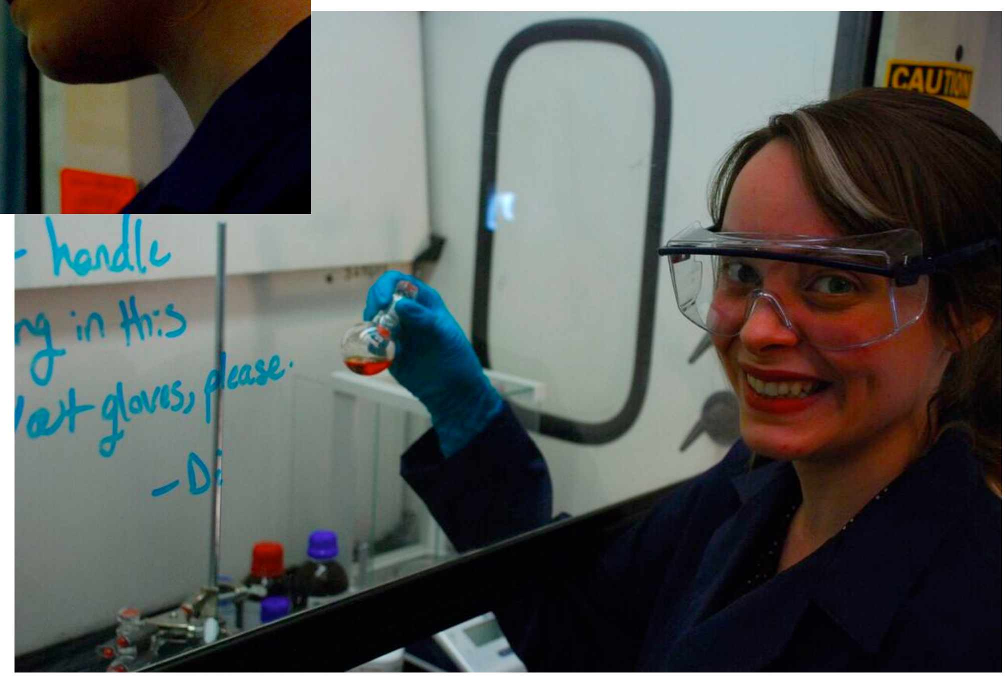
JINST 8 (2013) P10015

The Trilite450 quantum dots are looking good!



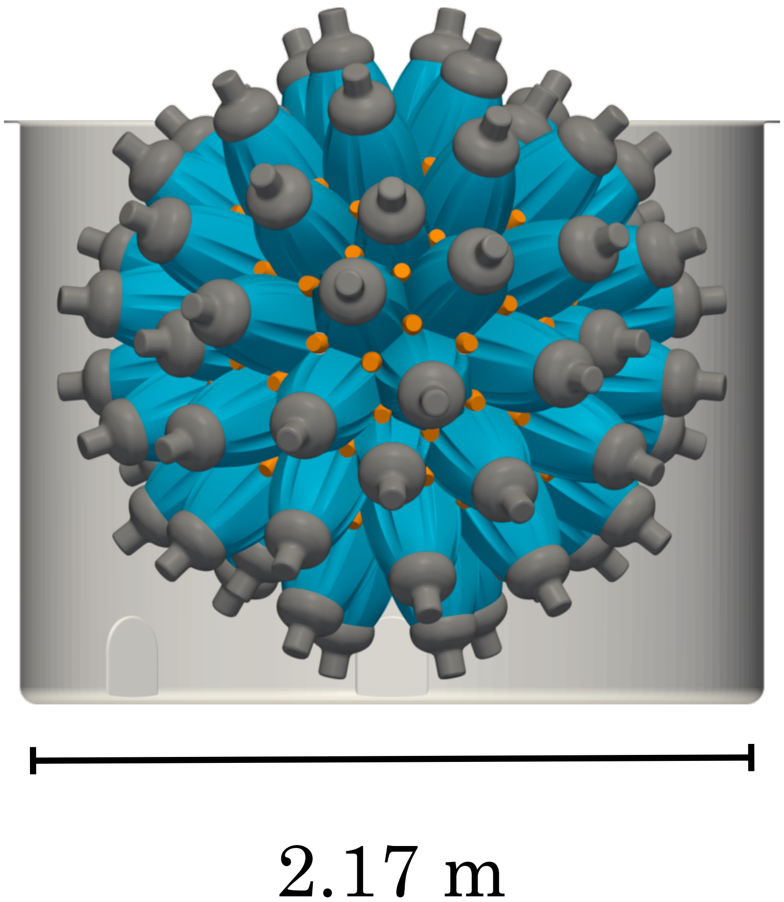
JINST 8 (2013) P10015

So we are learning by trying the synthesis ourselves!



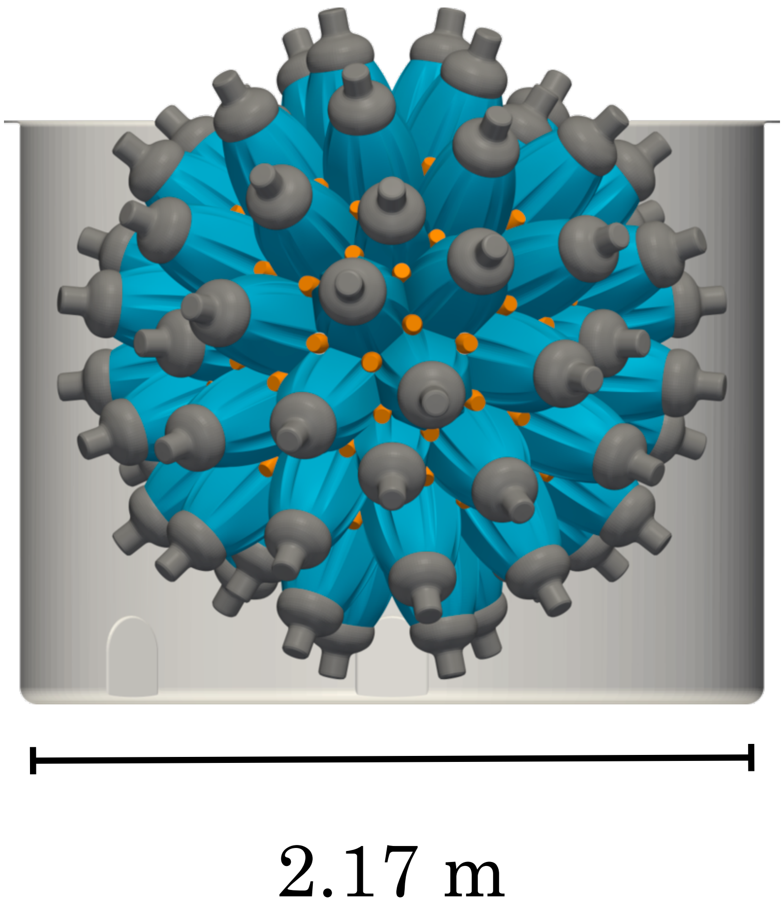
Working towards finding a company that would like to collaborate on a larger-scale endeavor.

NuDot:
A Prototype Directional Liquid Scintillator Detector



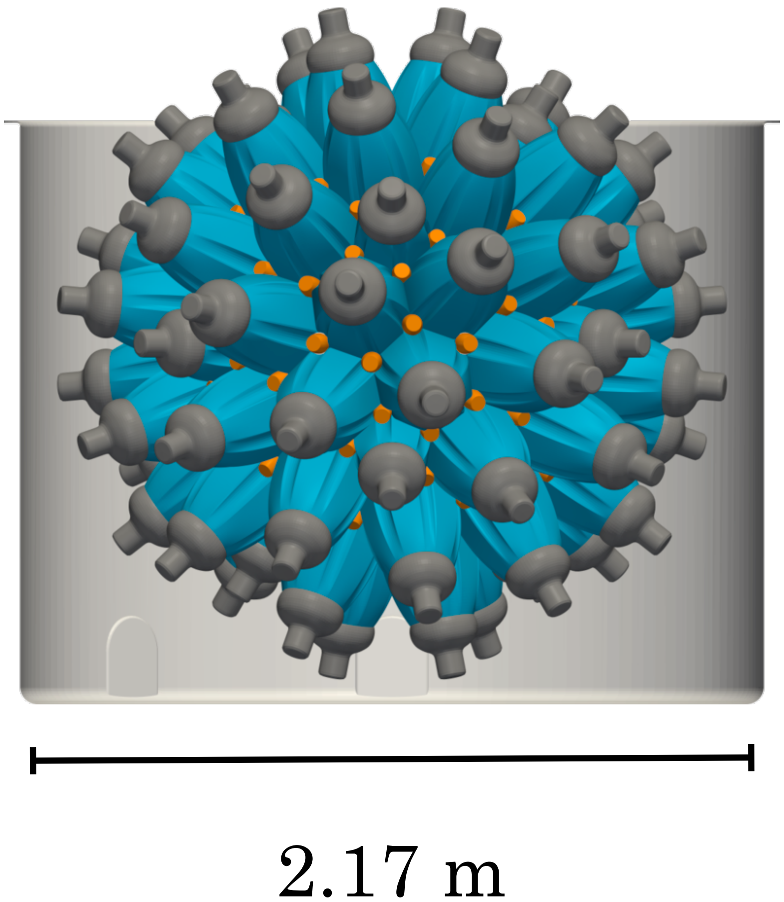
- Construction at MIT 2017
- Calibration tests 2018
- Move underground 2019
- Measure two neutrino double-beta decay with direction!

NuDot:
A Prototype Directional Liquid Scintillator Detector



- Self-contained
- Need power, network
- LAB scintillator (easy handling)

NuDot:
A Prototype Directional Liquid Scintillator Detector

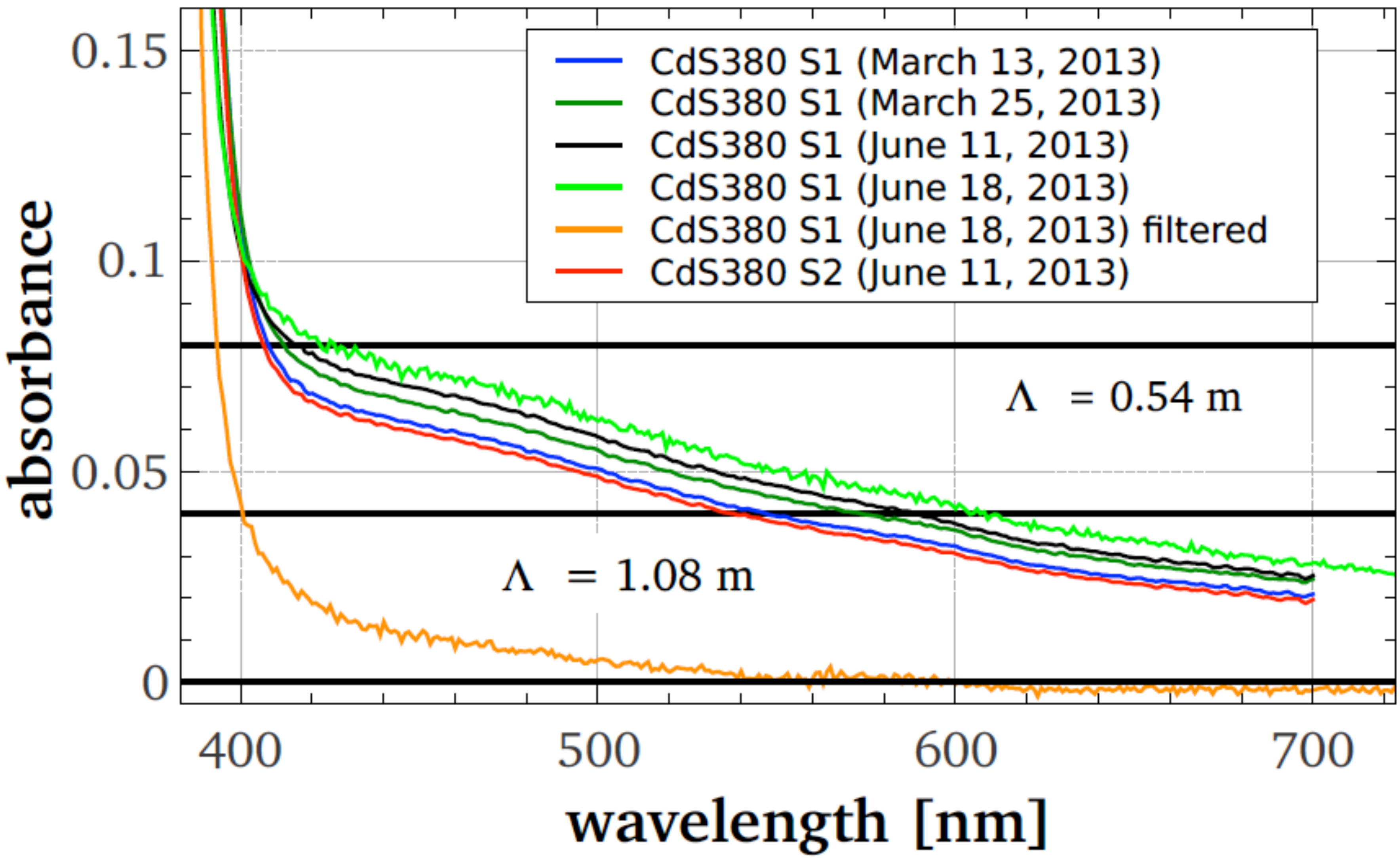


Why LNGS?

- Scintillator expertise (collaborators?)
- SiPM expertise (red sensitive SiPM are on the market)
- Ease of access
- Condense CUORE + NuDot parts of MIT group.
- Borexino upgrade 2025?

Thank you!

We have made attenuation length measurements!

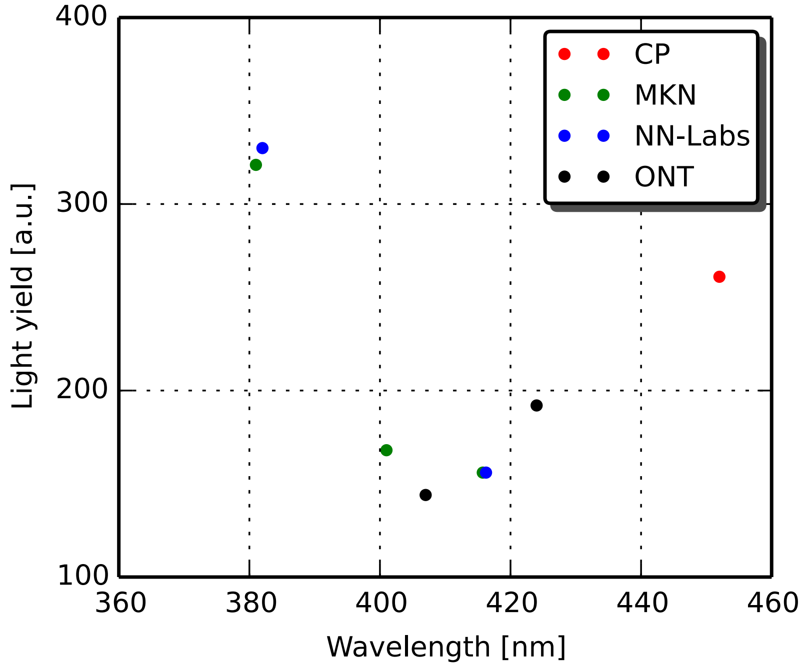


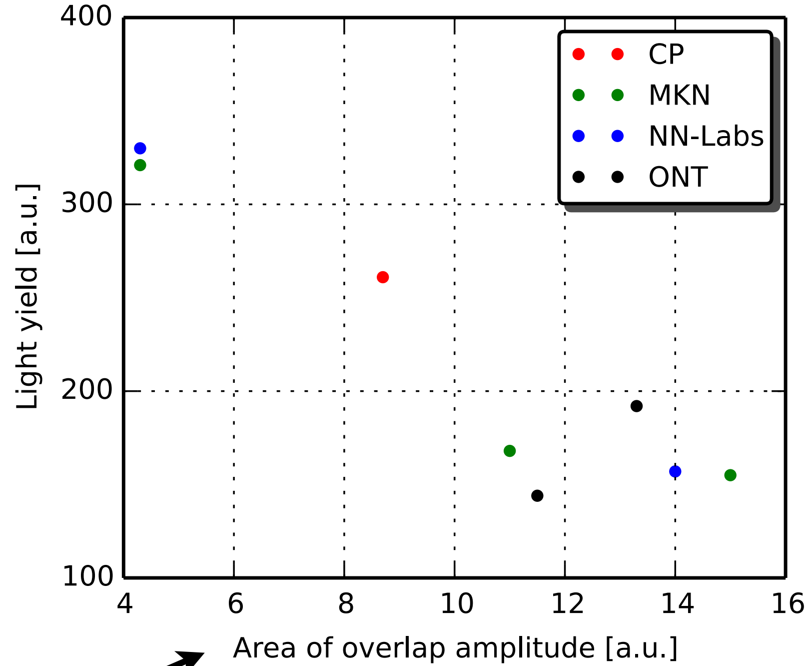
We believe filtering is removing aggregated quantum dots.

JINST 8 (2013) P10015

Latest Light Yield Measurements

Measure the total light output of 25mL samples when exposed to gamma-ray source.

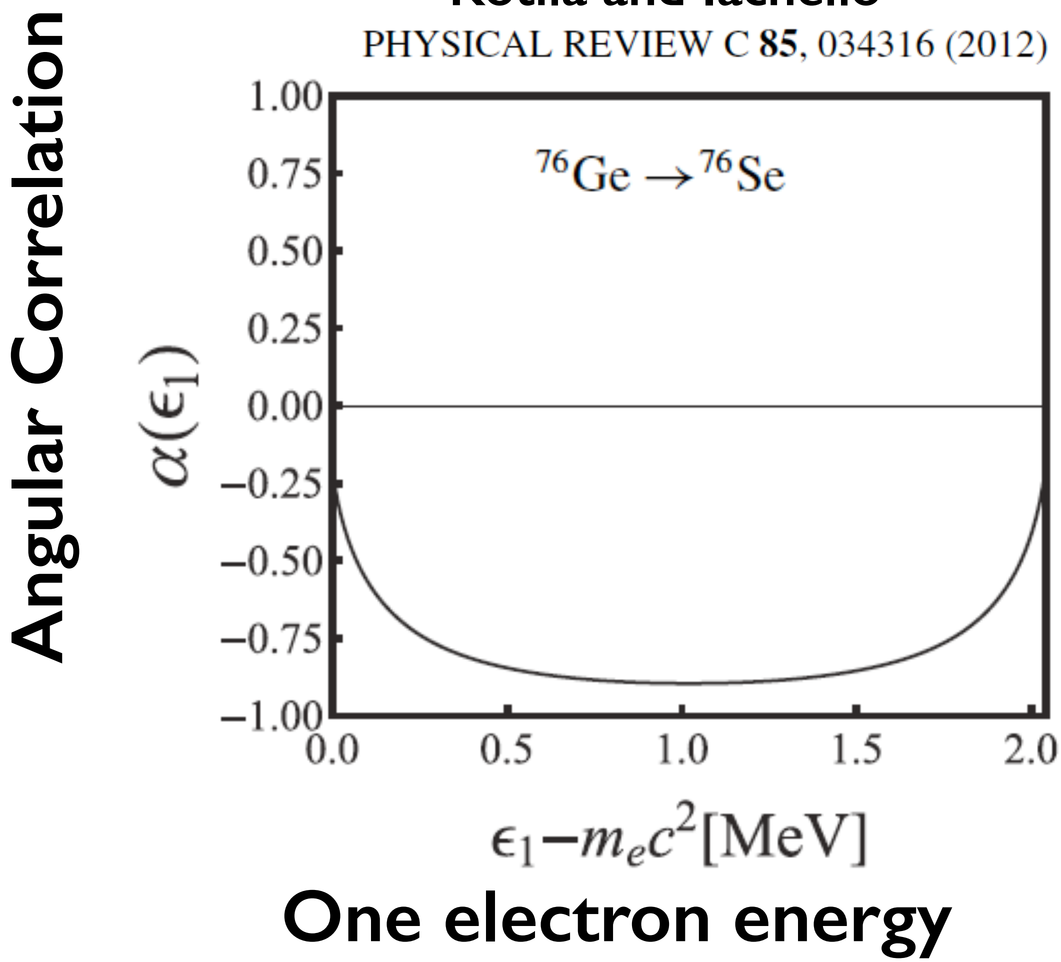




Light yield dominated by self-absorption of the quantum dots.

➠ ***Need High Quantum Efficiency Dots (And Cheaper)!***

Kotila and Iachello
PHYSICAL REVIEW C **85**, 034316 (2012)

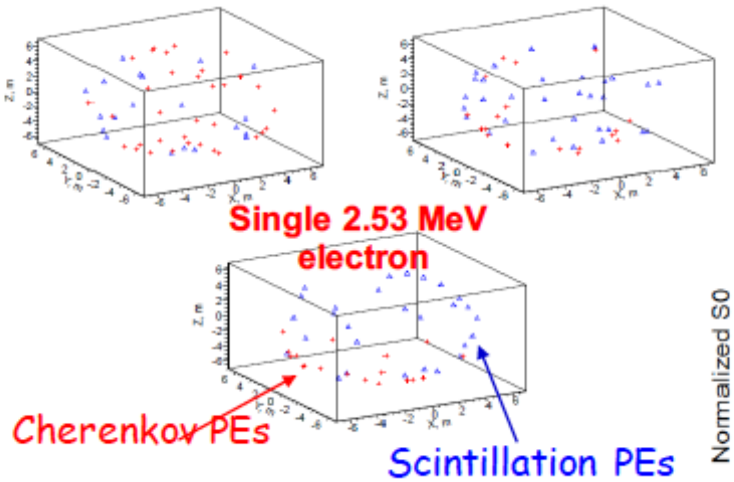


New physics could show up in this distribution!

Phys.Rev.D76:093009,2007
Ali, Borisov, Zhuridov

BG Rejection using Topology of Cherenkov/Scintillation Photons

A. Elagin
arXiv:1609.09865



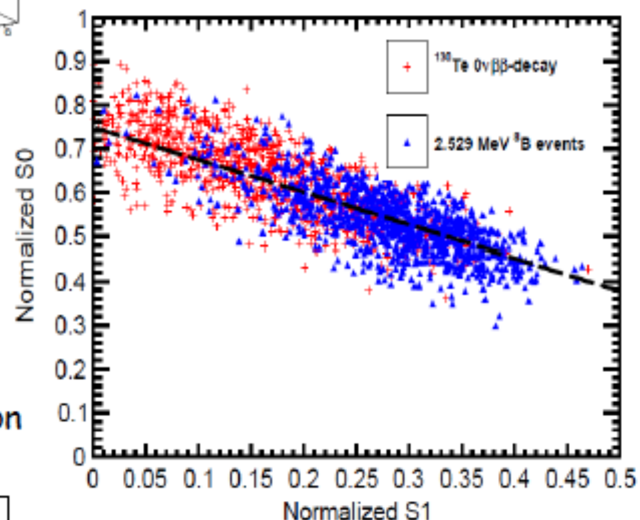
Differences that are hardly seen by eye can be reconstructed by pattern recognition e.g. spherical harmonics analysis

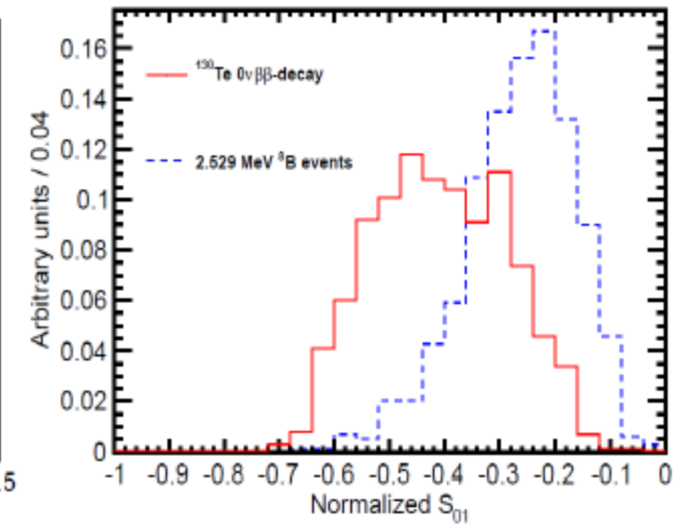
$$f(\theta,\varphi)=\sum_{\ell=0}^{\infty}\sum_{m=-\ell}^{\ell} f_{\ell m} Y_{\ell m}(\theta,\varphi).$$

Power spectrum
(rotation invariant: works well in spherical geometry e.g., SNO+, KamLAND)

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

two-tracks (double-beta decay signal)
vs
single-track (8B solar neutrino background)





Simulation details

- 6.5m radius detector, scintillator model from KamLAND simulation
- TTS=100 ps, 100% area coverage, QE 12-23%
- Light within a pre-defined time window to capture early light

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)

(Publication in preparation)