Neutrino Detection : Part II

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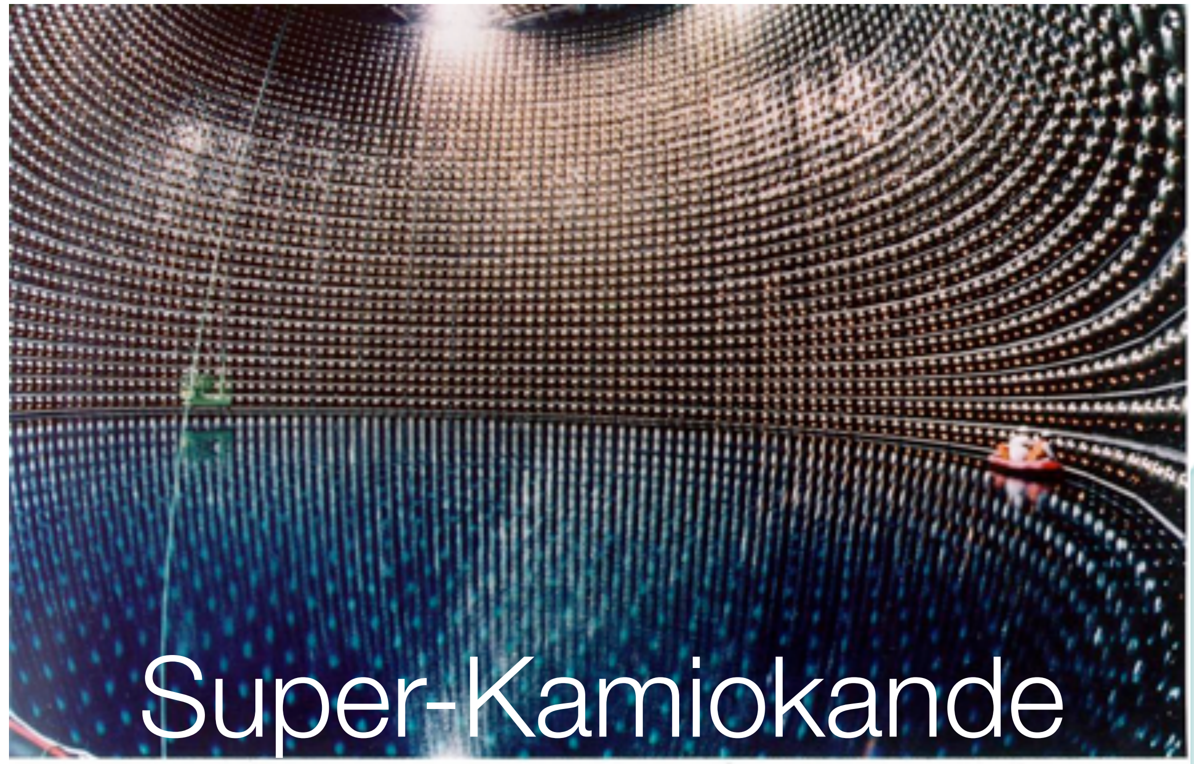
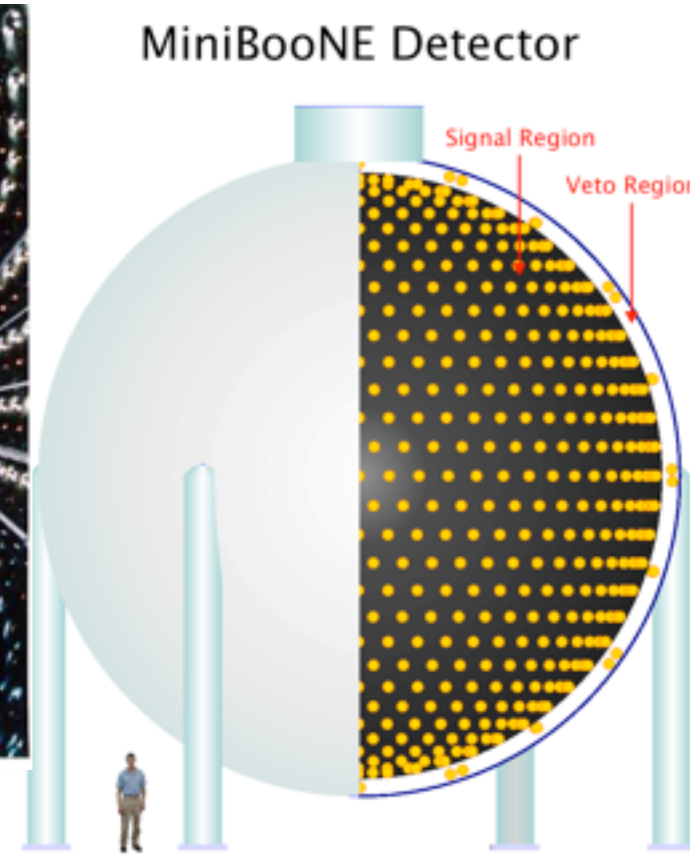
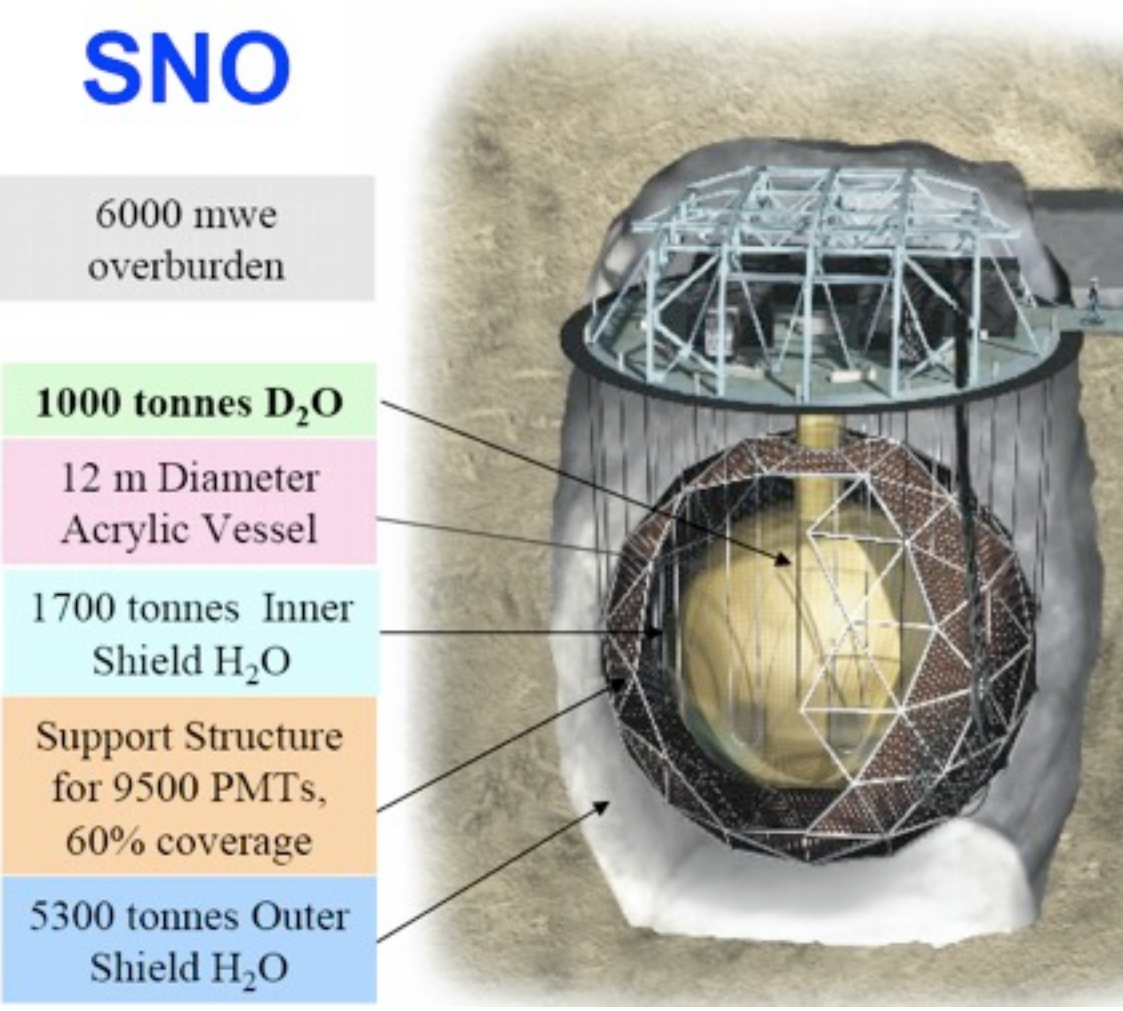
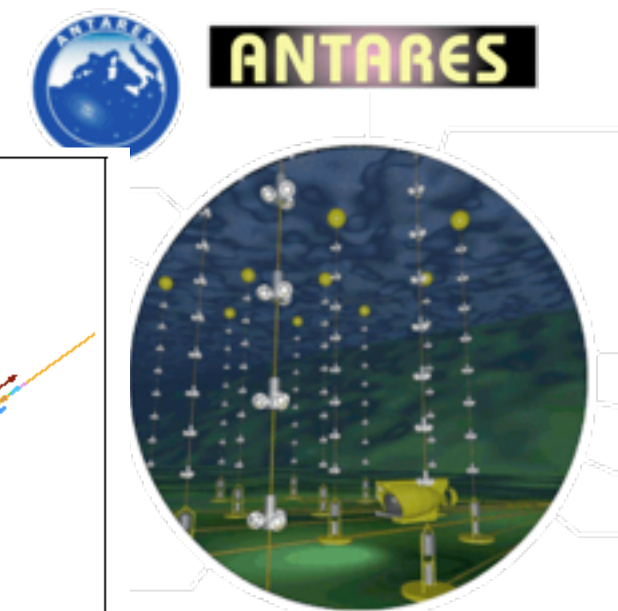
12th International Neutrino Summer School 2017
August 6, 2017
Fermilab, IL

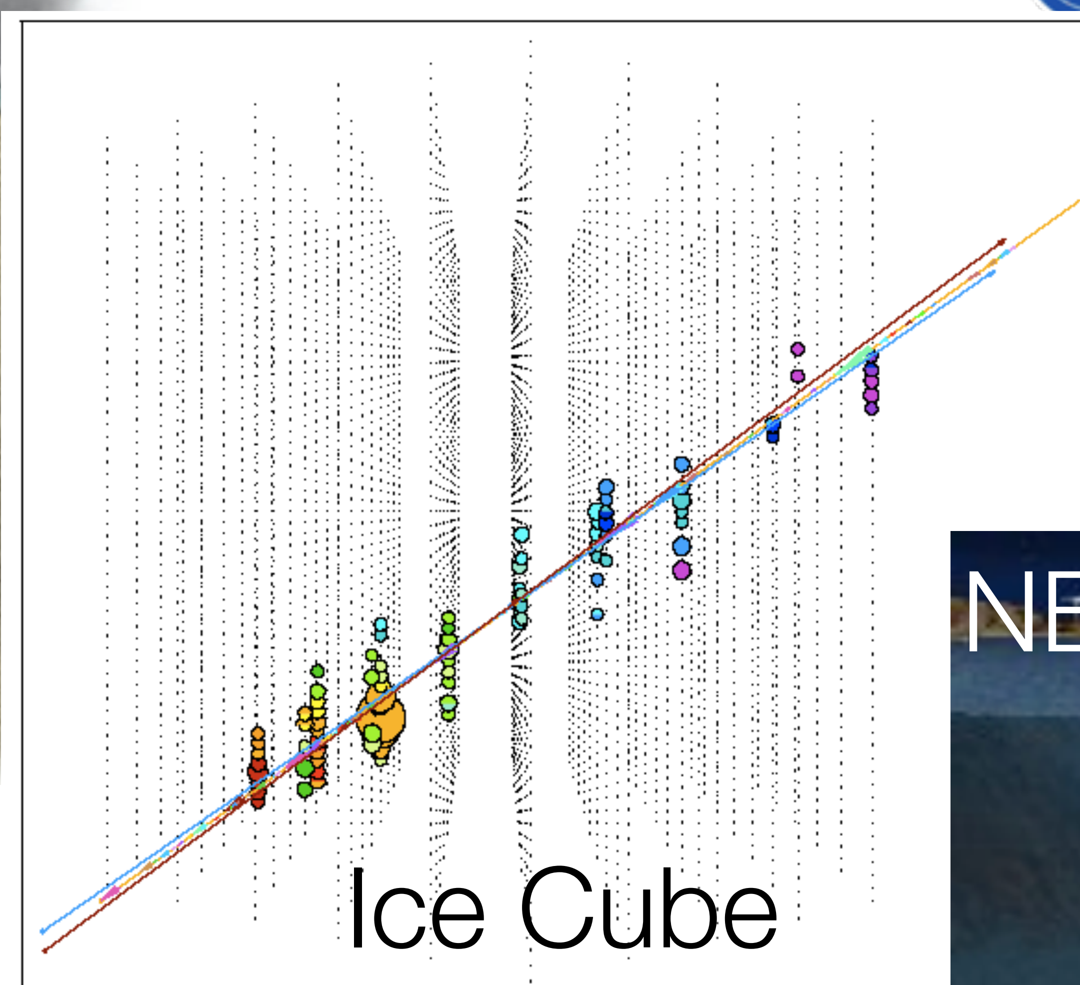
Cherenkov detectors

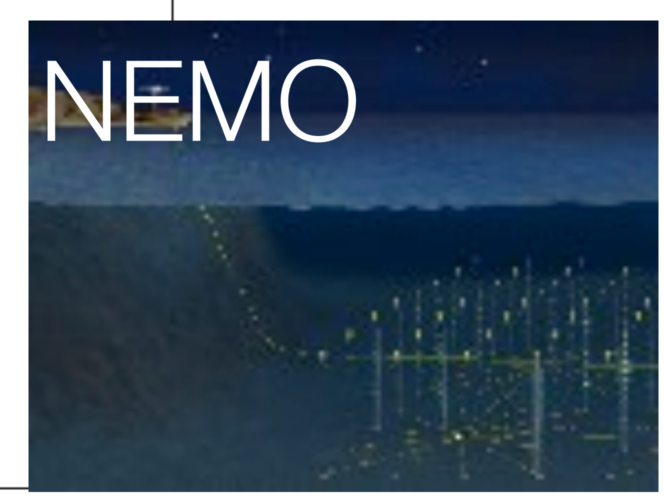






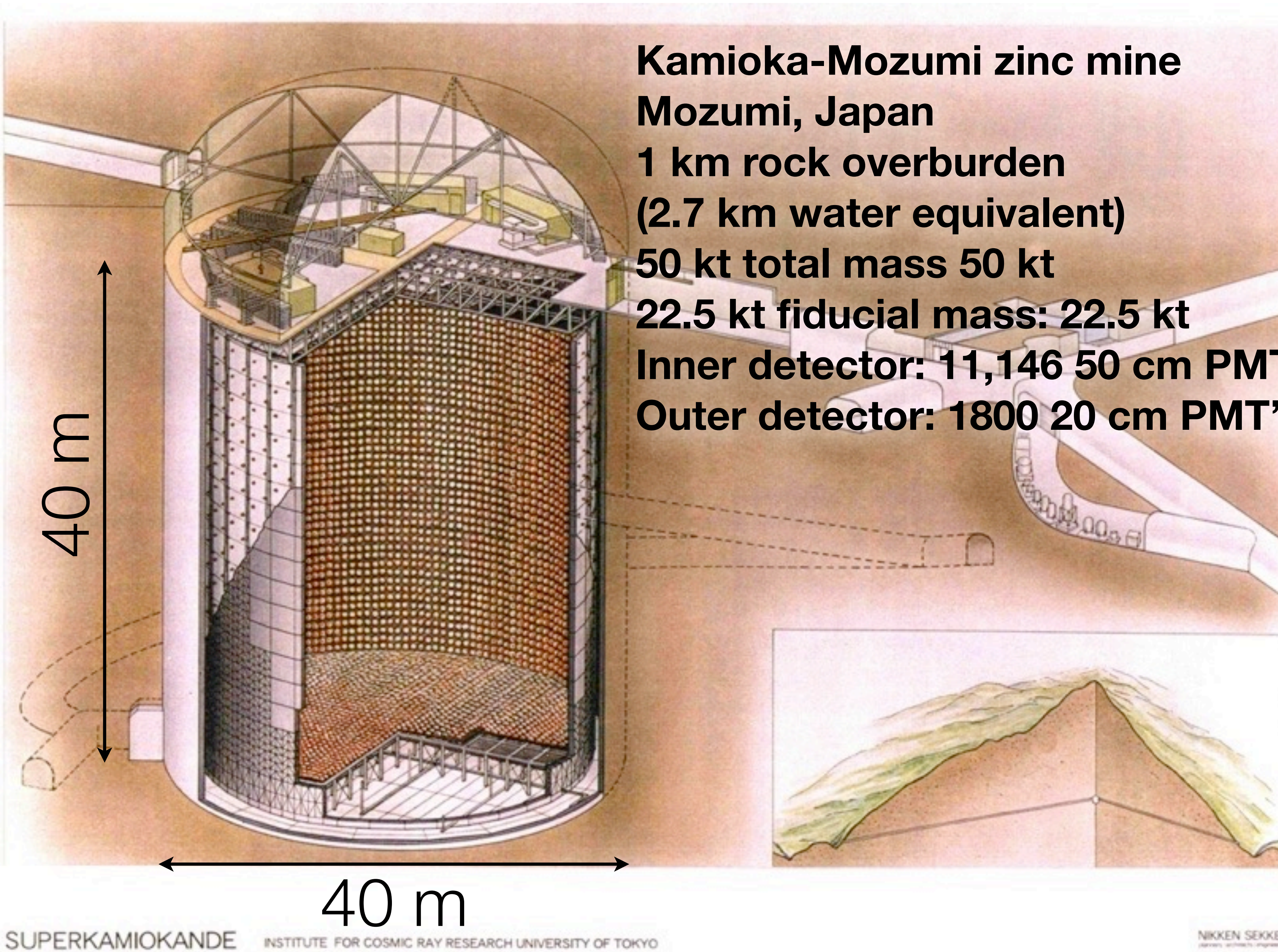






Super-Kamiokande

Kamioka-Mozumi zinc mine
Mozumi, Japan
1 km rock overburden
(2.7 km water equivalent)
50 kt total mass 50 kt
22.5 kt fiducial mass: 22.5 kt
Inner detector: 11,146 50 cm PMTs
Outer detector: 1800 20 cm PMT’s

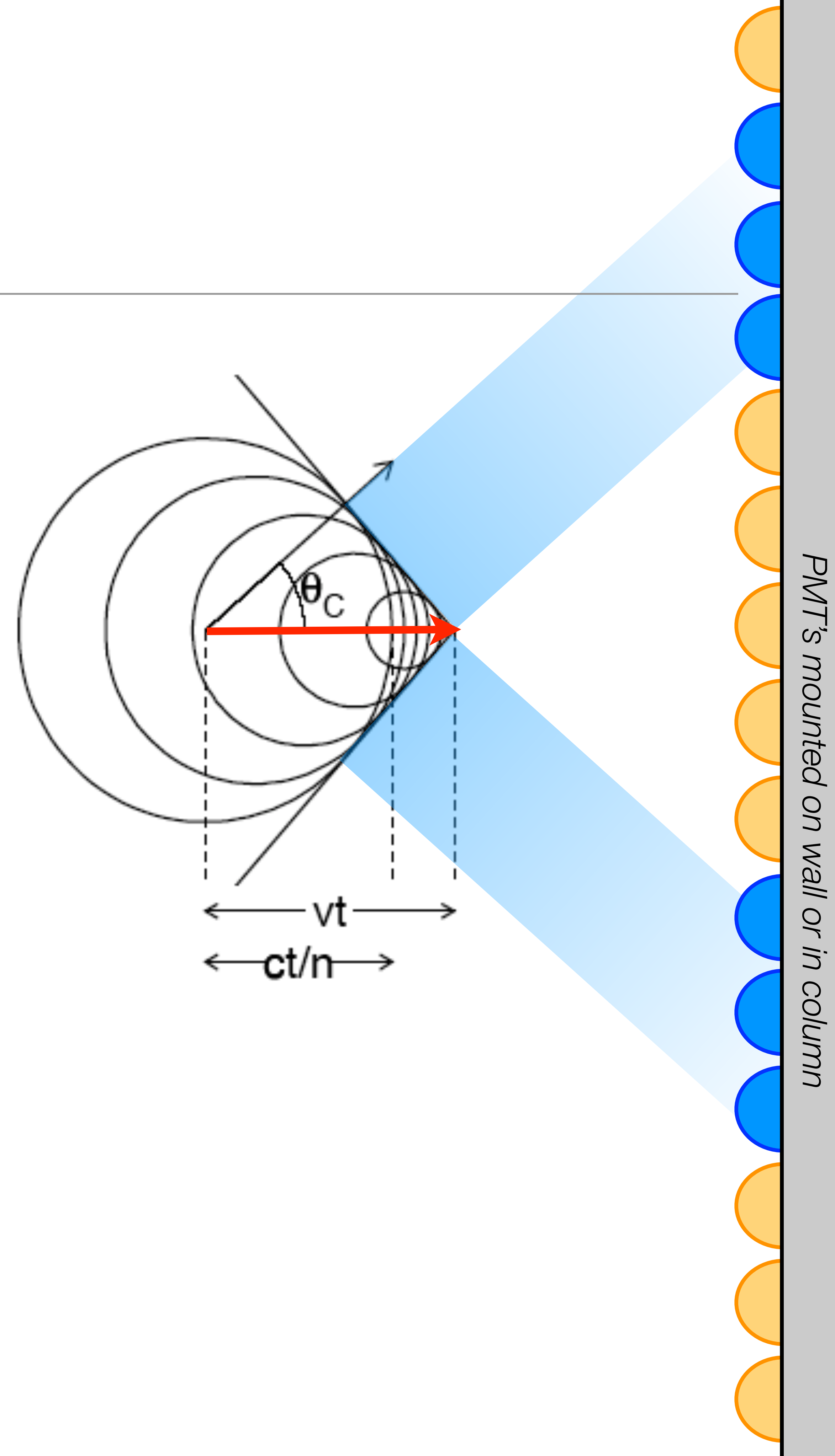


Cherenkov effect

- If speed of charged particle exceeds speed of light in a dielectric medium of index of refraction *n*, a “shock wave” of radiation develops at a critical angle:
$$\cos\theta_C = \frac{1}{\beta n}, \beta > \frac{1}{n}$$
- PMTs record time and charge which provide unique solution for track position and direction. For Nhit PMTs measuring light arrival time t, minimize:

$$\chi^2 = \sum_{i=1}^{N_{\mathrm{hit}}} \frac{(t_i - TOF_i)^2}{\sigma_t^2}$$

where TOF is the time of flight for photons to go from the track to the PMT



Cherenkov effect

- Threshold means that slow particles produce no light. As particles come to a stop their rings collapse. Useful for particle ID near threshold.

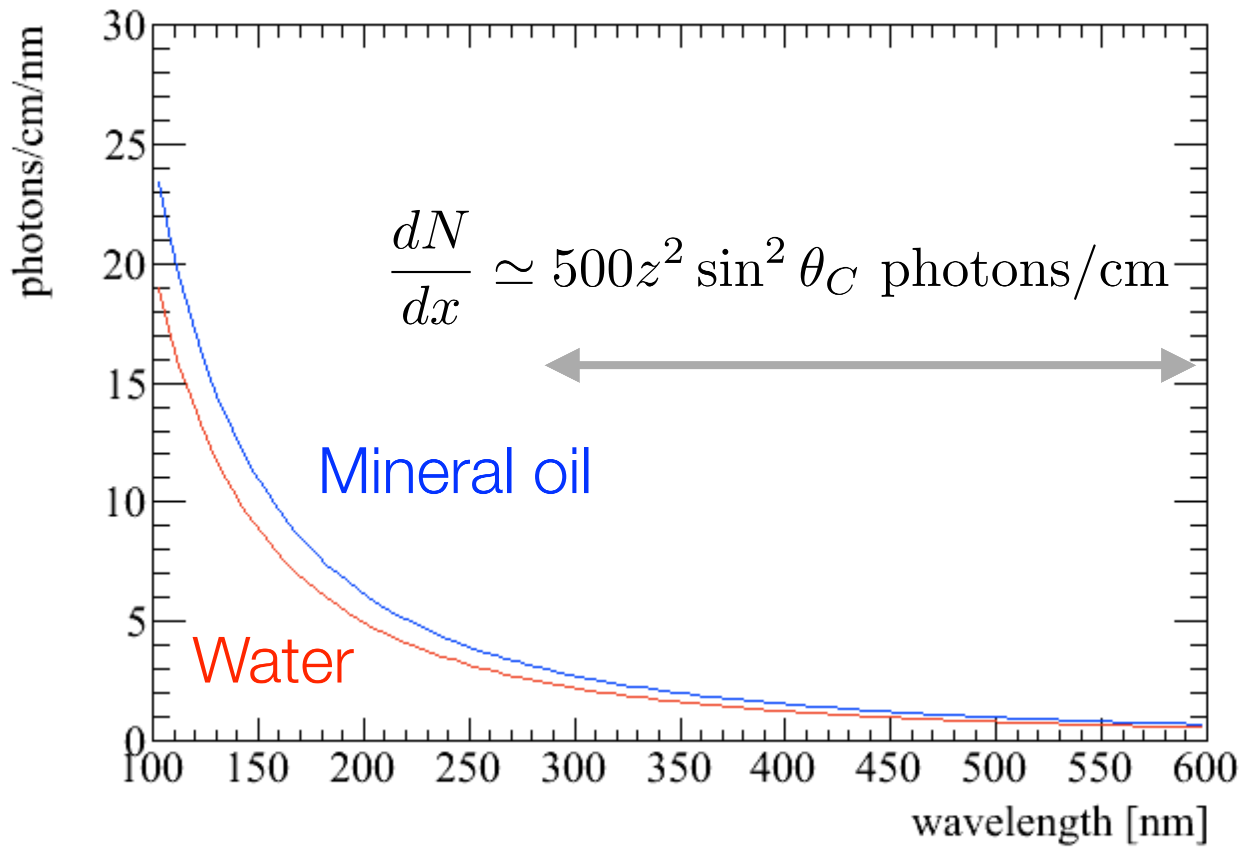
$$p_{\text{thresh}} = m\sqrt{\frac{1}{n^2-1}}$$

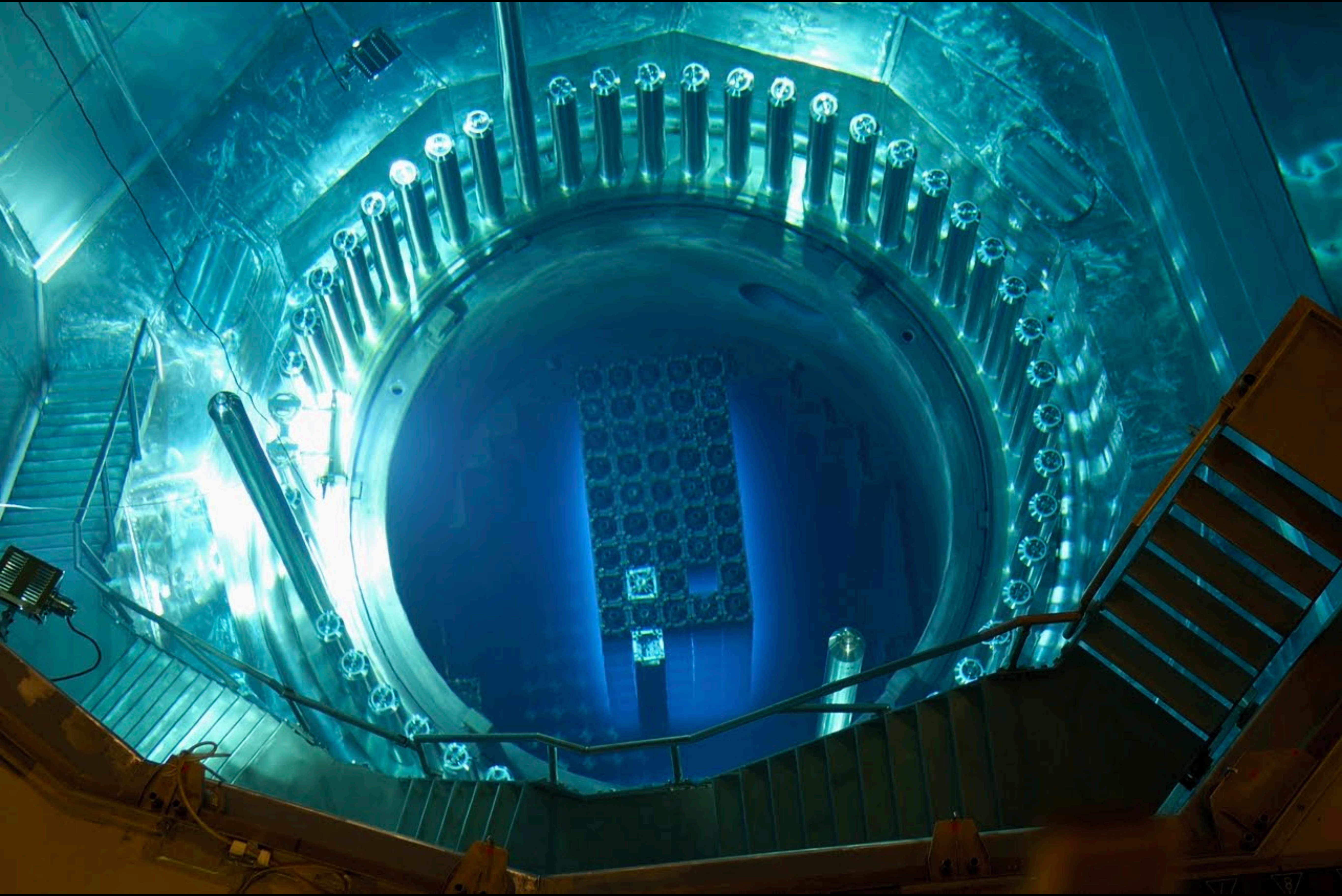
		p_{thresh} [MeV/c]					θ_C	
		e	μ	π	K	p	$\beta = 1$	$\beta = 0.9$
Water	n = 1.33	0.58	120	159	563	1070	42	33
Mineral Oil	n = 1.46	0.47	98	130	458	817	47	41

- Number of photons produced per unit path length:

$$\frac{d^2N}{d\lambda dx} = \frac{2\pi z^2\alpha}{\lambda^2}\left(1 - \frac{1}{\beta^2 n^2(\lambda)}\right)$$

- In both oil and water the useful part of this spectrum is between 300 and 600 nm bracketed by Rayleigh scattering on the low end and absorption on the high end

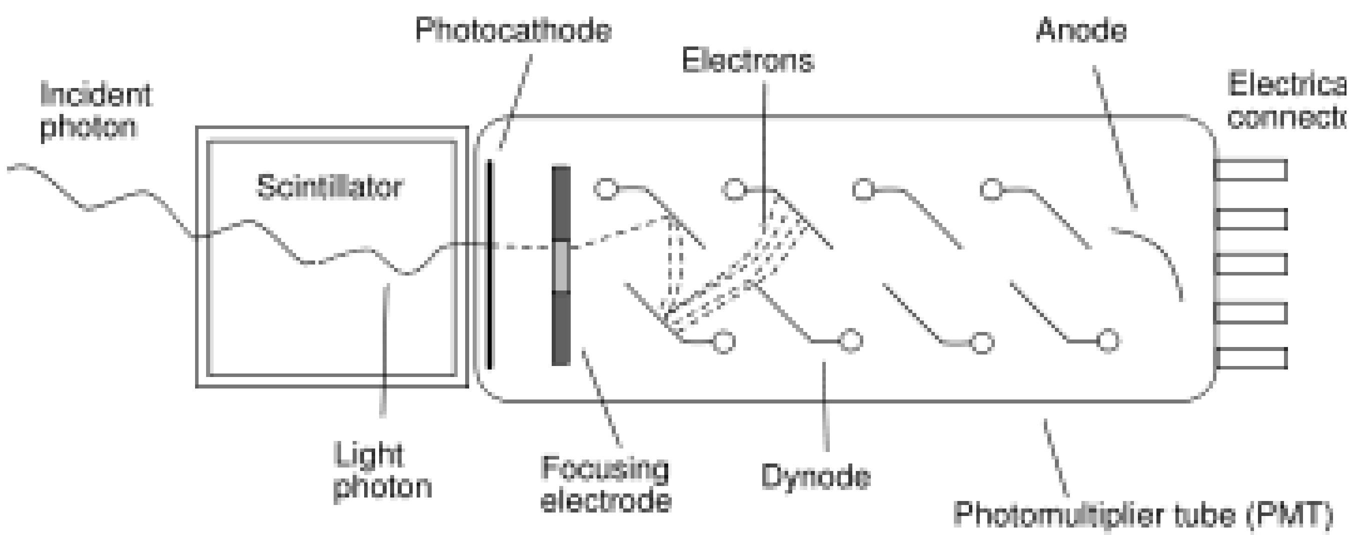




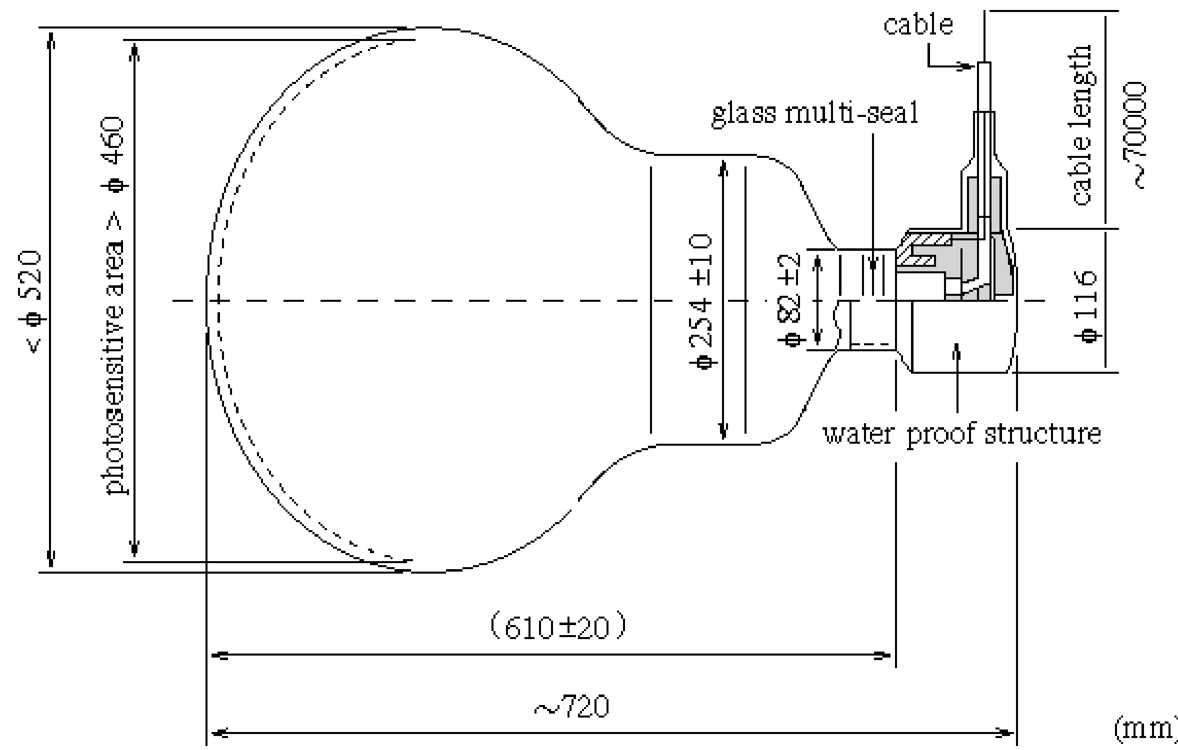
Photomultiplier tubes

Photon incident on the ***photocathode*** produces a ***photo-electron*** via the photoelectric effect. Probability to produce a photoelectron is called the ***quantum efficiency*** of the PMT.

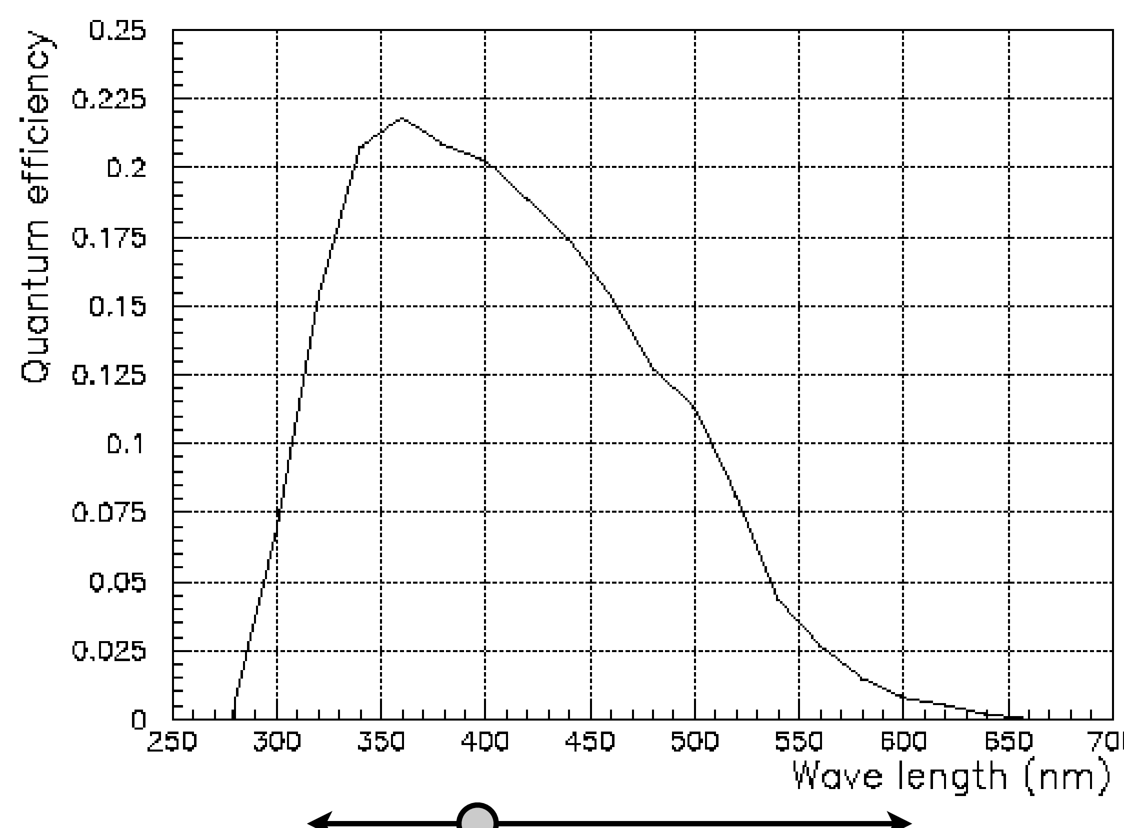
Output signal is seen as a current delivered to the ***anode***. Typical ***gains*** are 10^6 yielding pC-scale currents



A series of plates called ***dynodes*** are held at high voltage by the *base* such that electrons are accelerated from one dynode to the next. At each stage the number of electrons increases. Probability to get first electron from the photocathode to the first dynode is called the ***collection efficiency***.

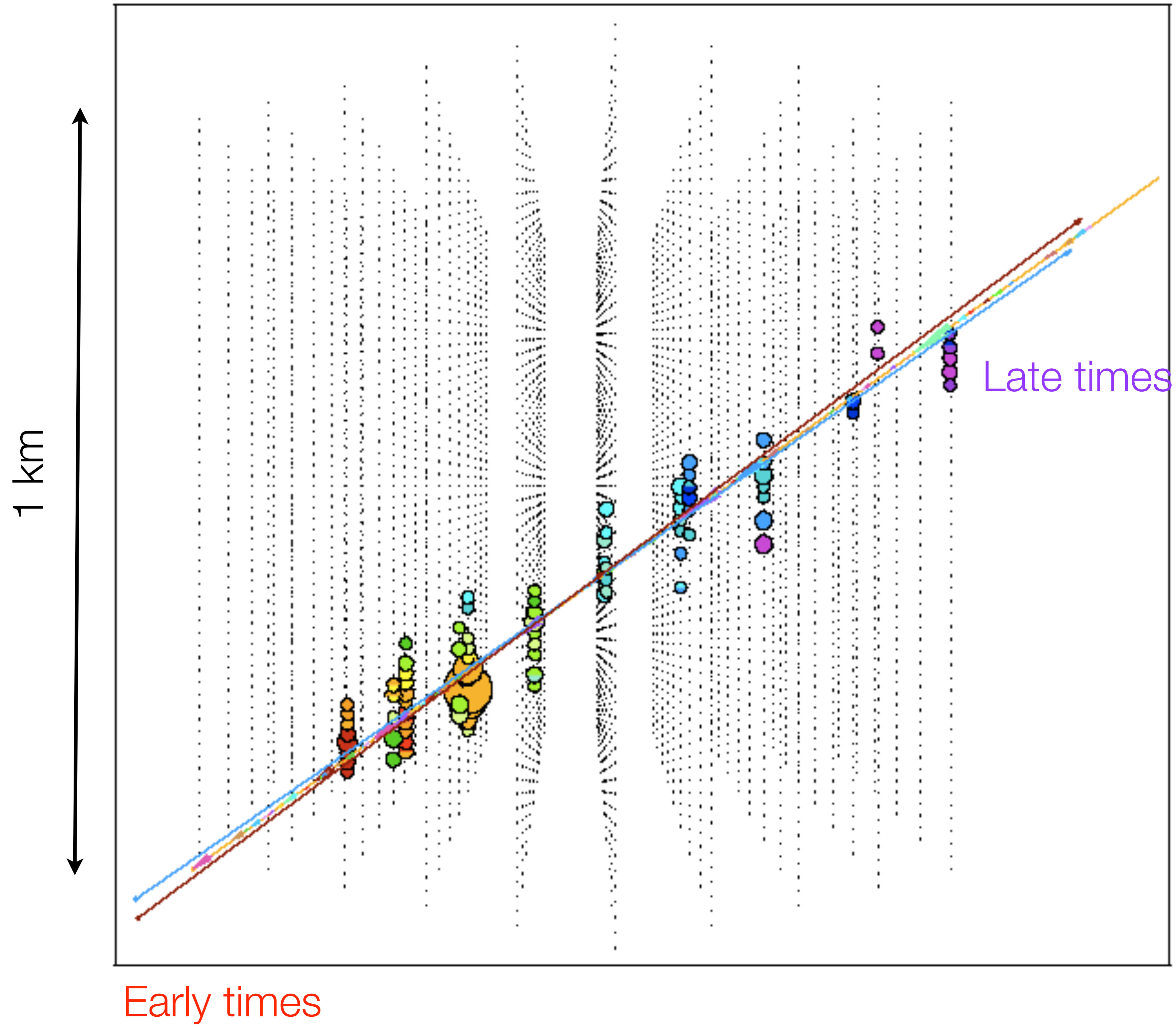


100 ns transit time, 2.2 ns time resolution



wavelength of Cherenkov photons in water

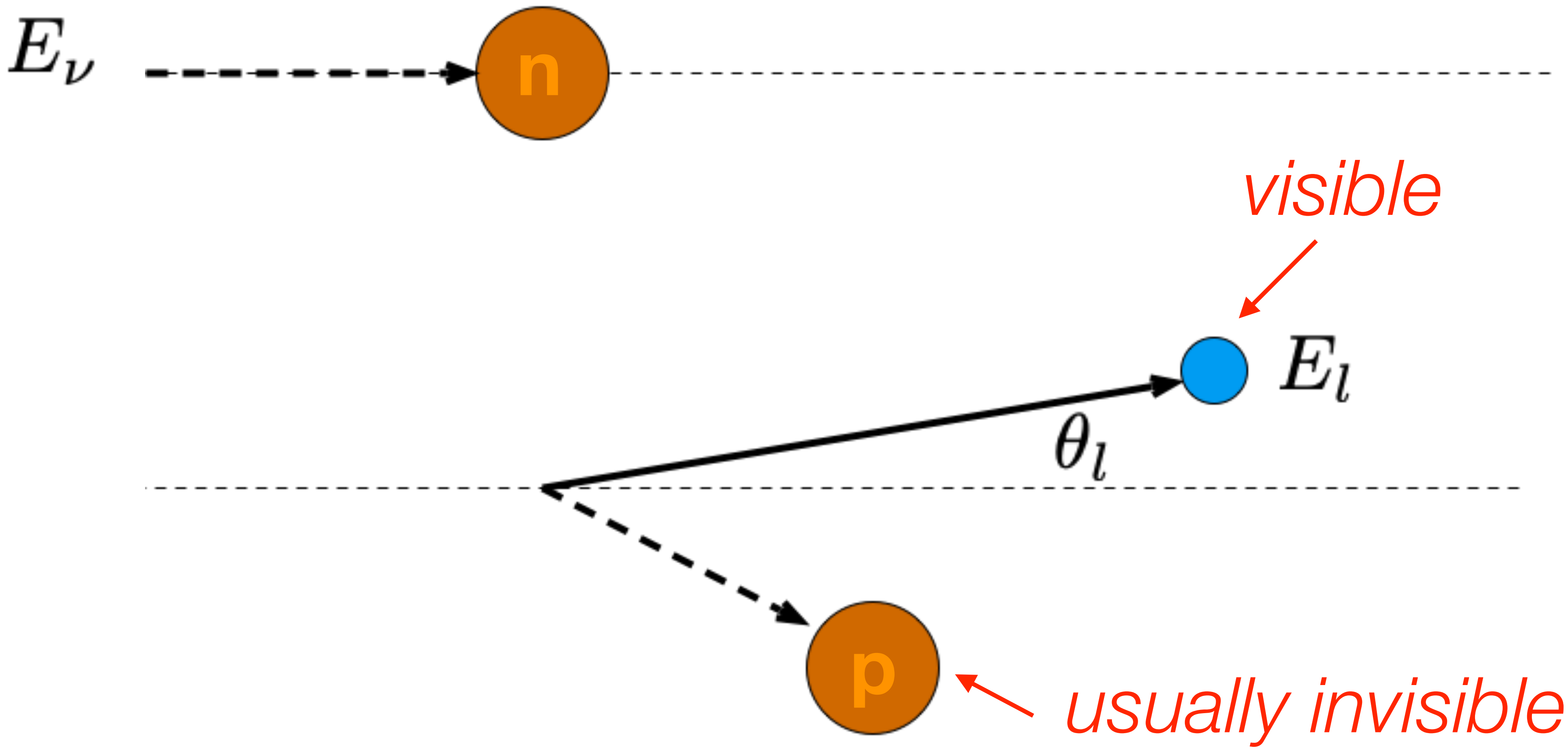
10 TeV neutrino induced muon neutrino in Ice Cube



Times differ by roughly 2.5 usec. For PMT with ~10 ns time resolution this gives an up vs. down discrimination of > 250 sigma !

Quasi-elastic reconstruction

$$\nu_\mu + n \rightarrow \mu^- + p \quad / \quad \nu_e + n \rightarrow e^- + p$$



$$E_\nu = \frac{m_N E_l - m_l^2/2}{m_N - E_l + p_l cos\theta_l}$$

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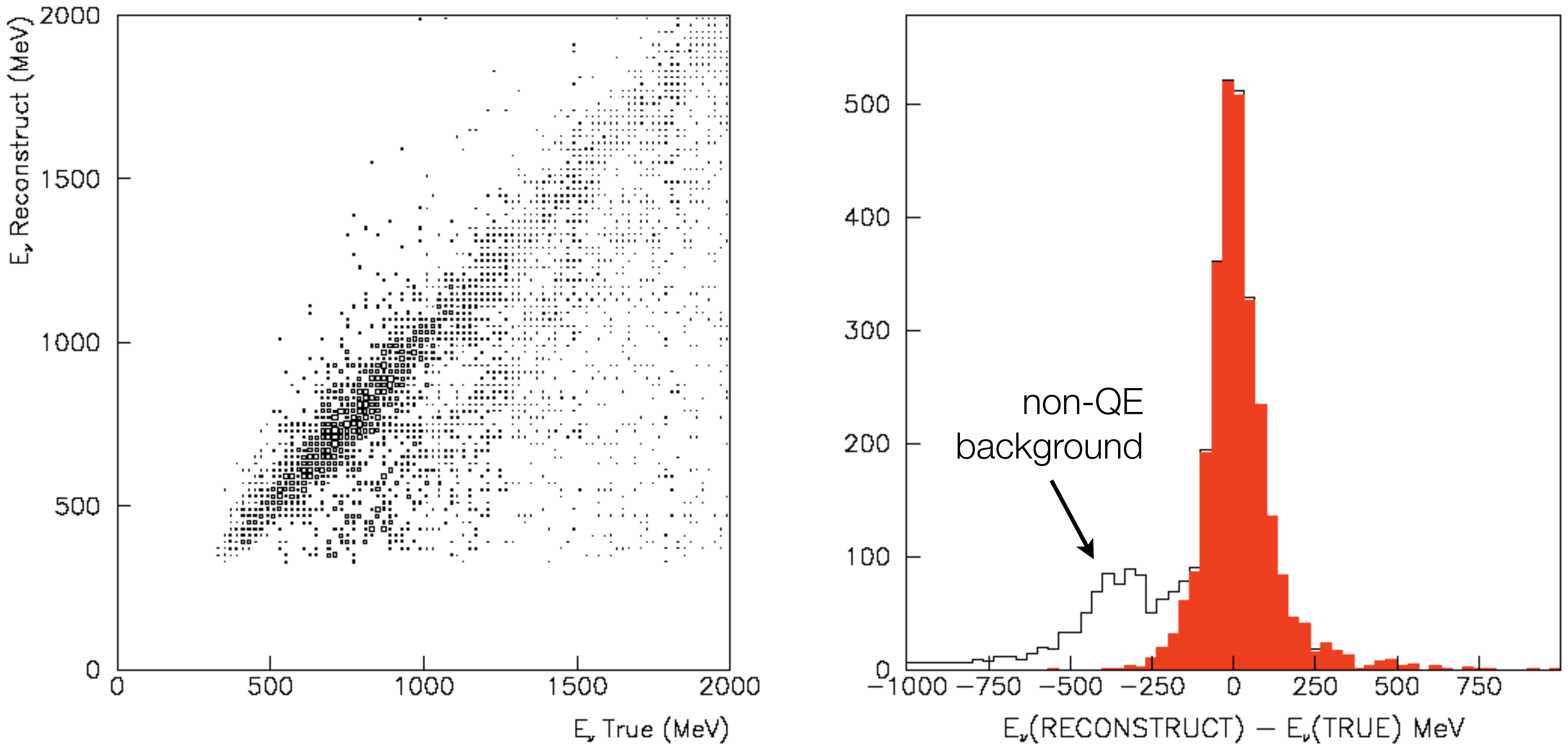
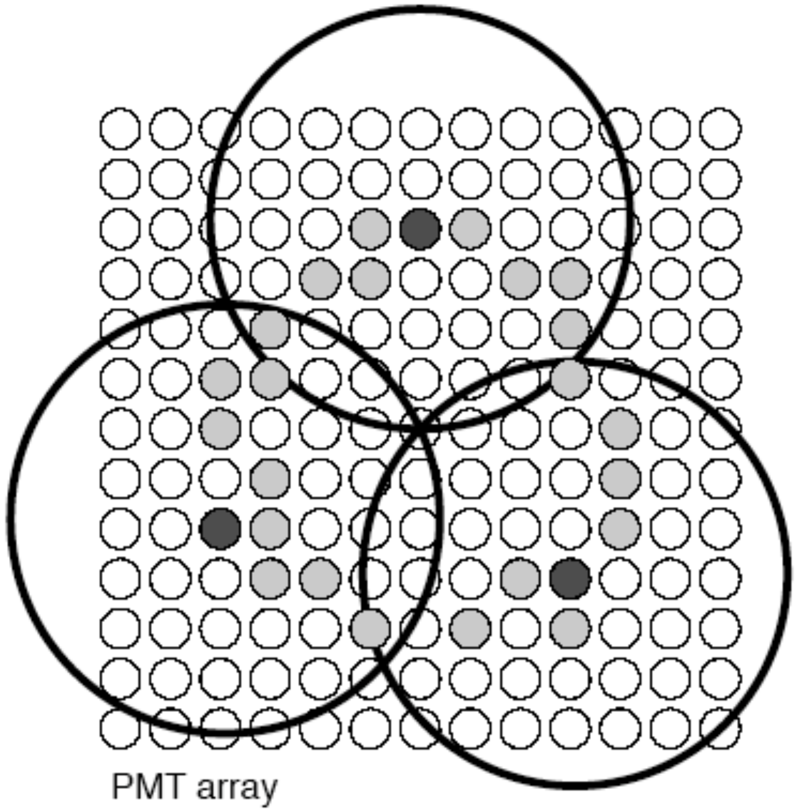


Figure 2: (left) The scatter plots of the reconstructed neutrino energy versus the true one for ν_μ events. The method of the energy reconstruction is expressed in Equation 14. (right) The energy resolution of ν_μ events for 2 degree off-axis beam. The shaded (red) histogram is for the true QE events.

Water Cherenkov: Ring Counting

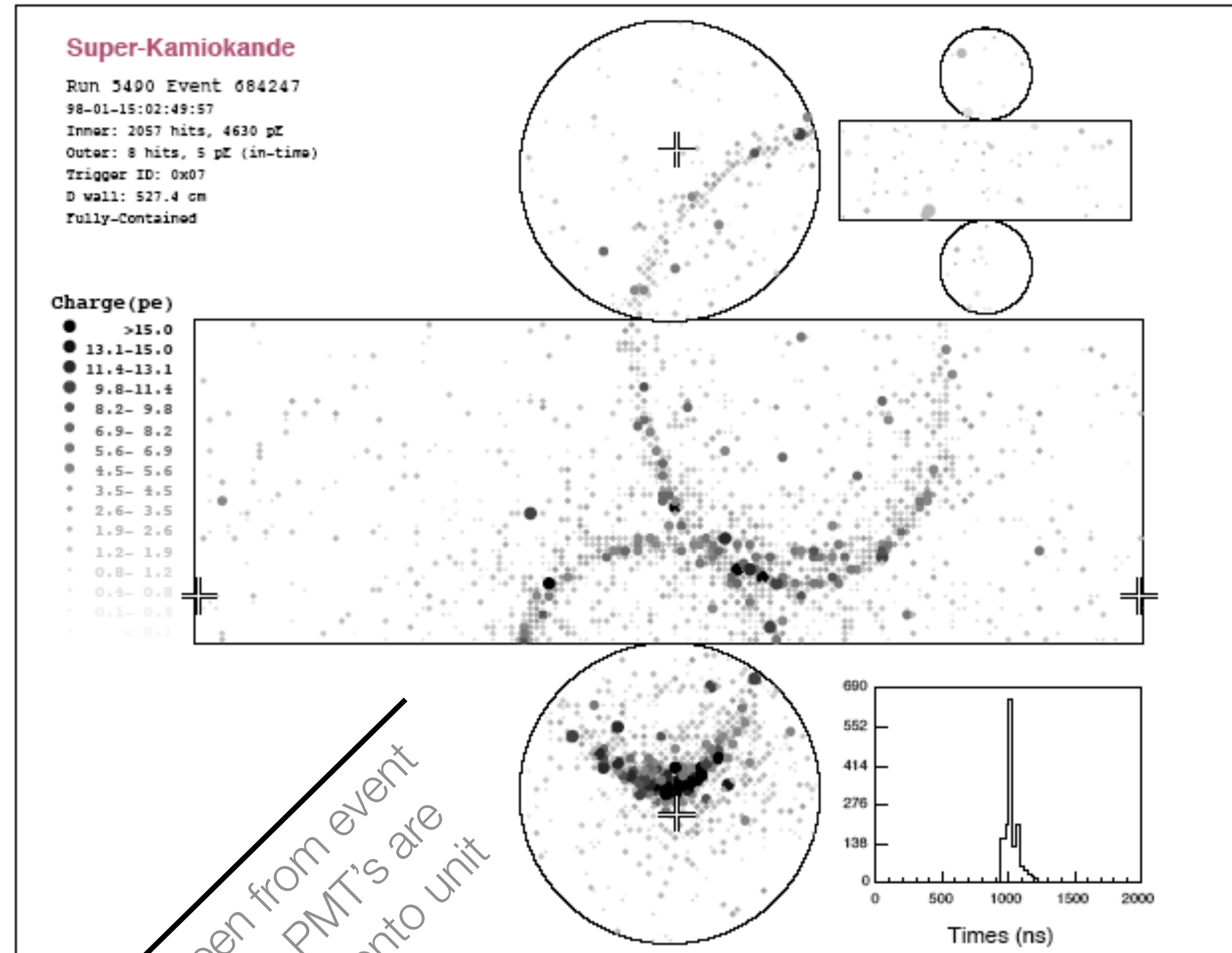


Not-hit PMT

Hit PMT

PMT corresponding to circle

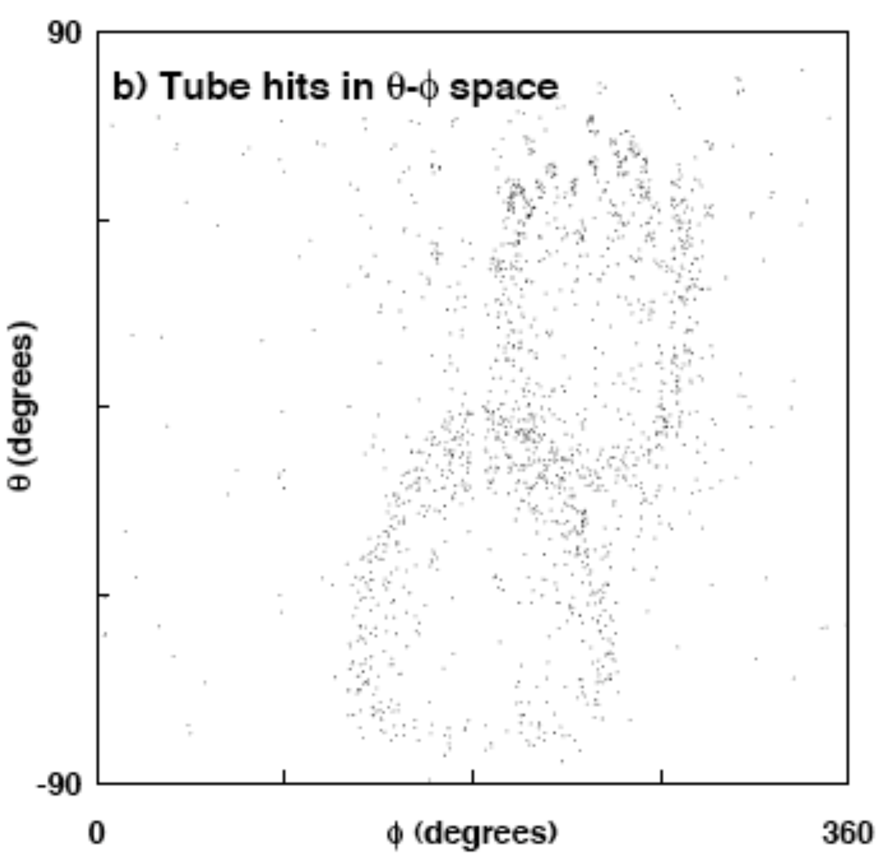
Circles overlap in center of ring corresponding to direction of particle

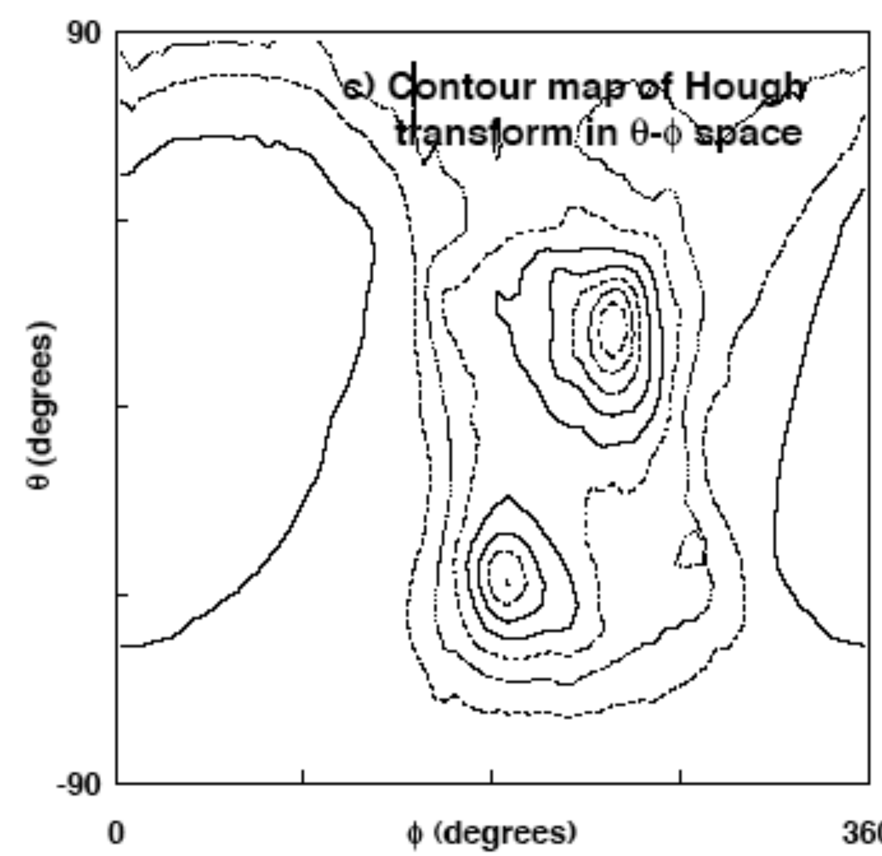


Figures from M. Earl's PhD Thesis

As seen from event vertex, PMT's are mapped onto unit sphere

If you know the pattern you are looking for (line, circle, oval, etc.) the Hough transform is a method for converting a pattern recognition problem to a peak finding problem

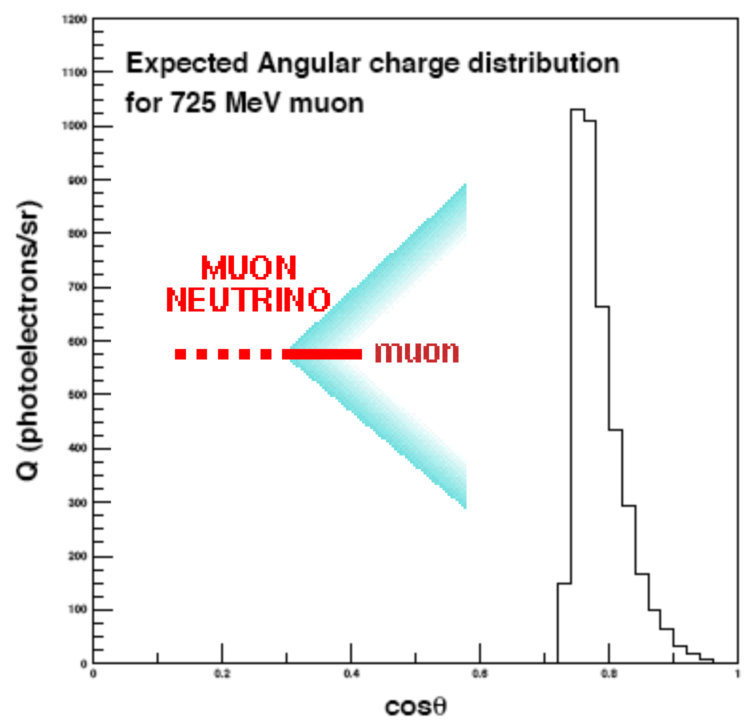


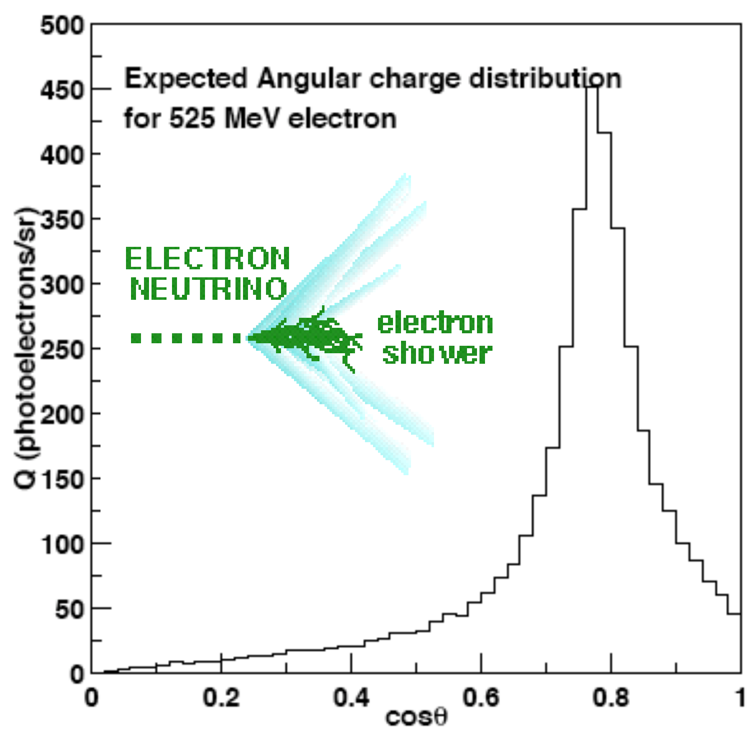


Water Cherenkov: e/μ identification

- At low momenta one can correlate the particle visible energy with the Cherenkov angle. Muons will have “collapsed” rings while electrons are ~always at 42°.

- At higher momenta, look at the distribution of light around Cherenkov angle. Muons are “crisp”, electron showers are “fuzzy”. See plots and figures at the right.





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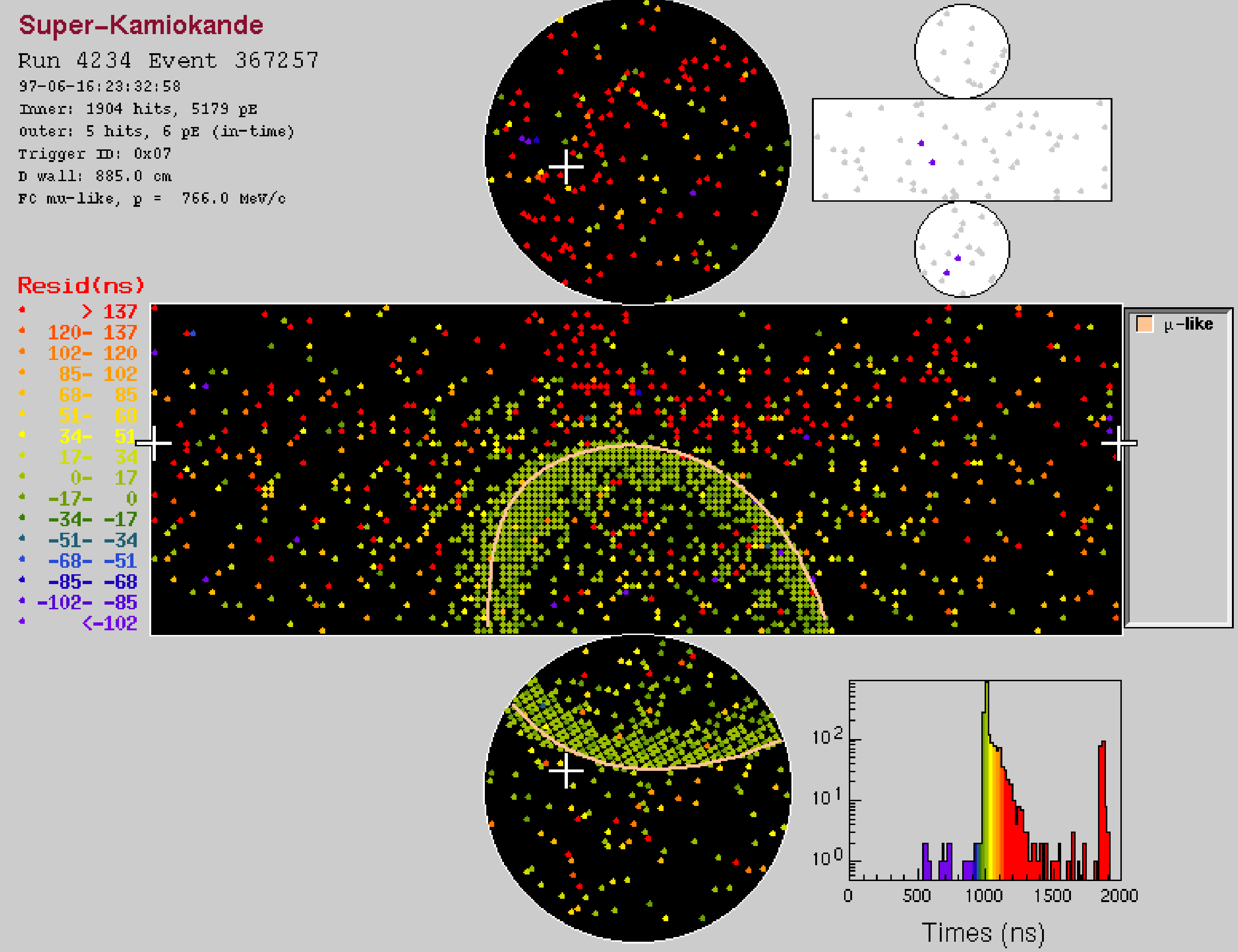

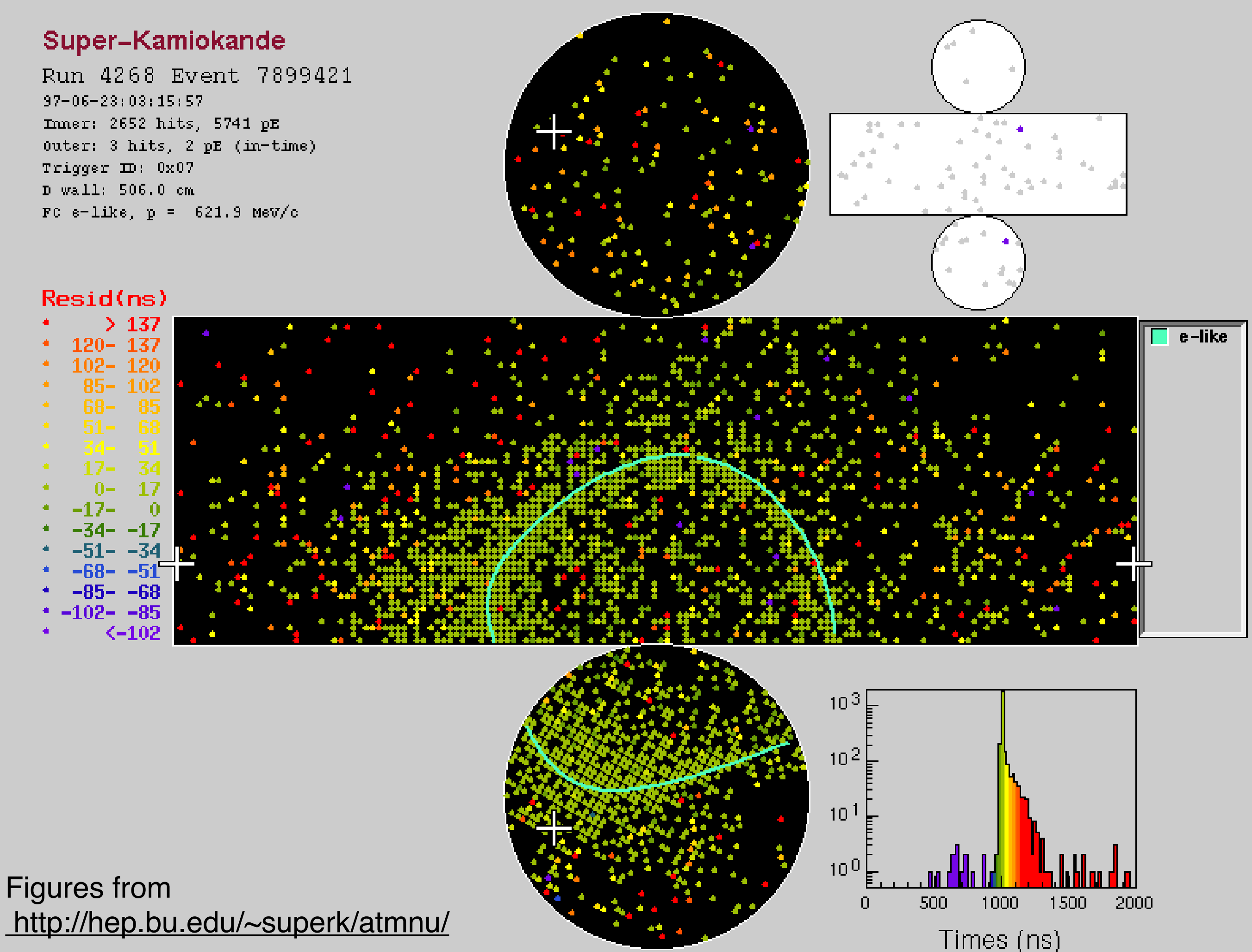

Figures from
http://hep.bu.edu/~superk/atmnu/

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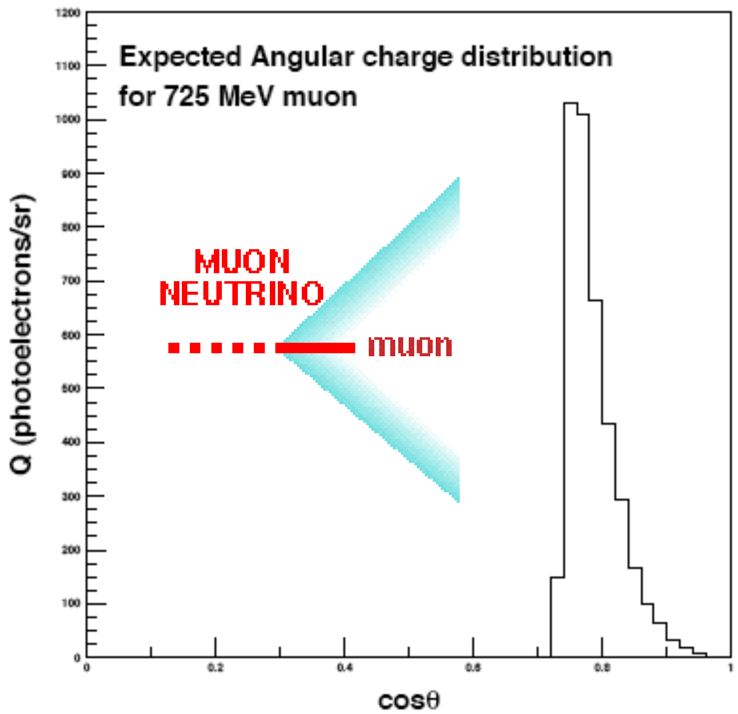

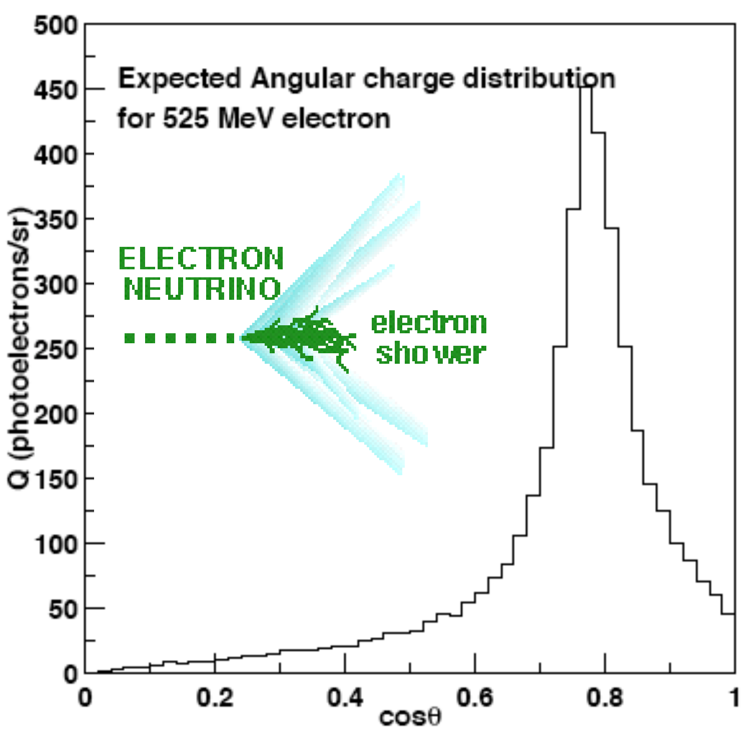

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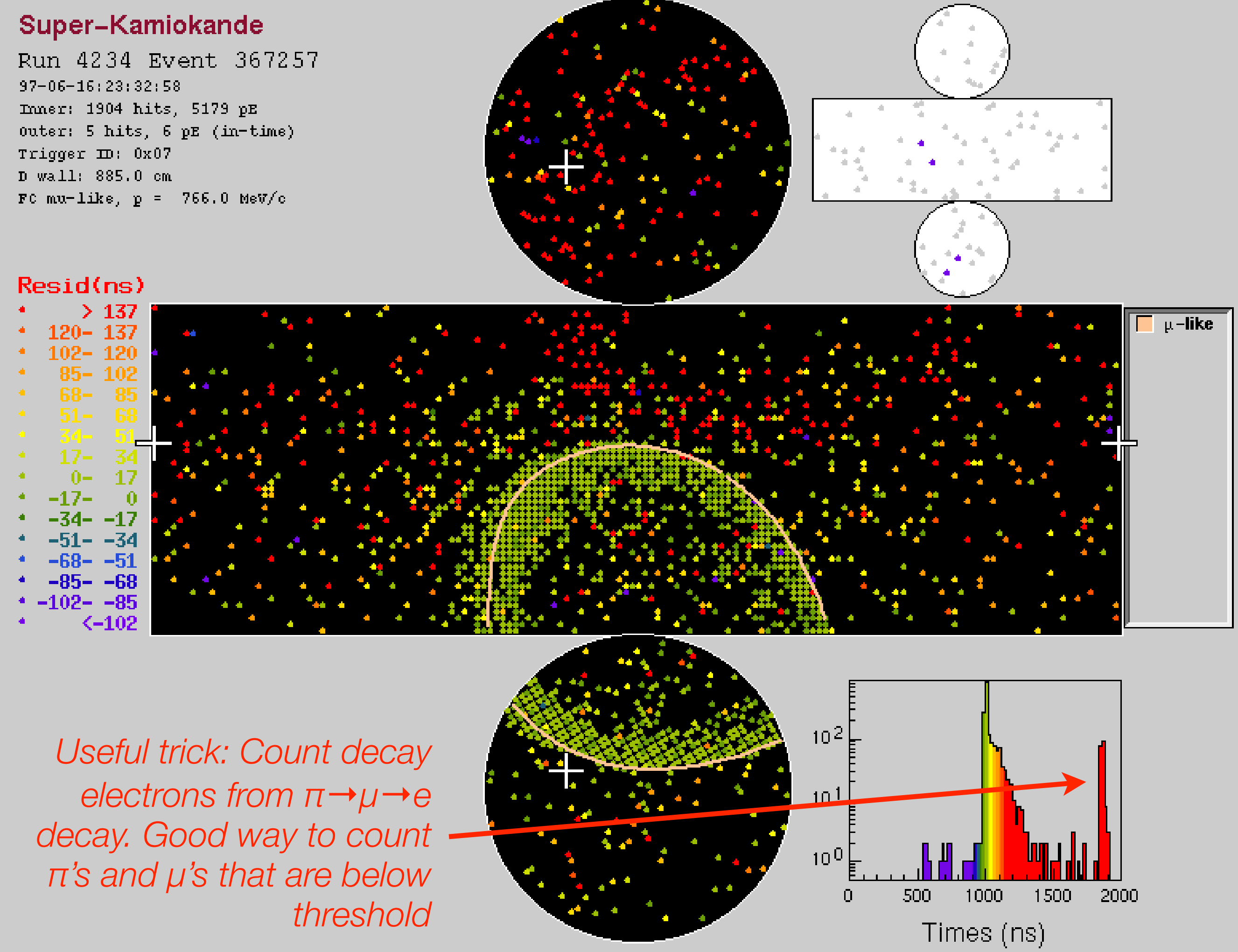
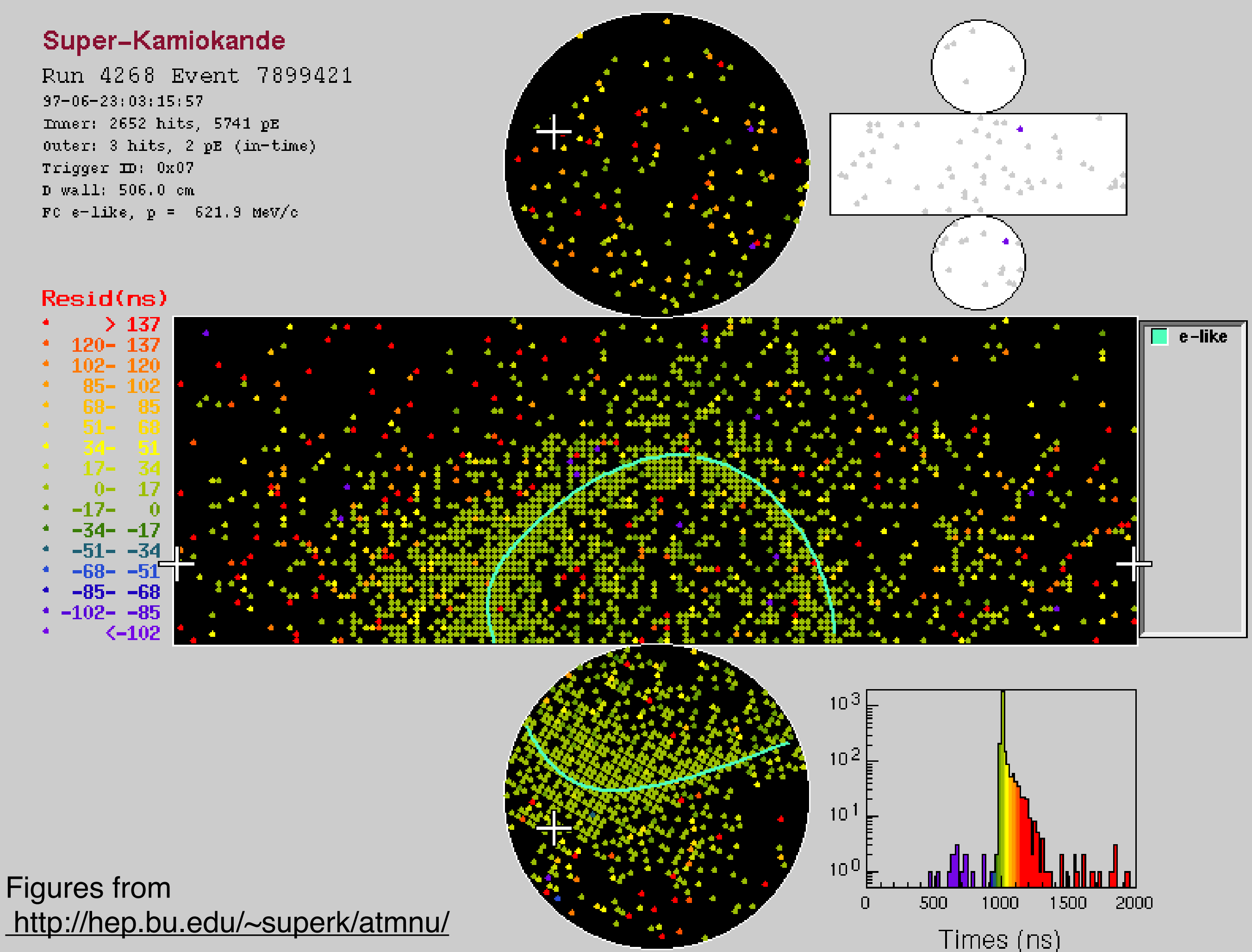


Useful trick: Count decay electrons from π→μ→e decay. Good way to count π’s and μ’s that are below threshold



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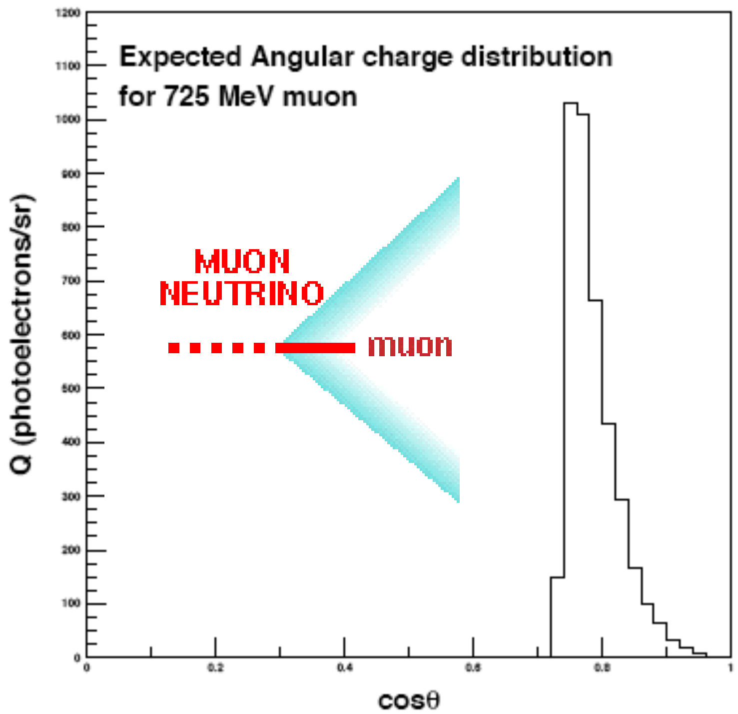

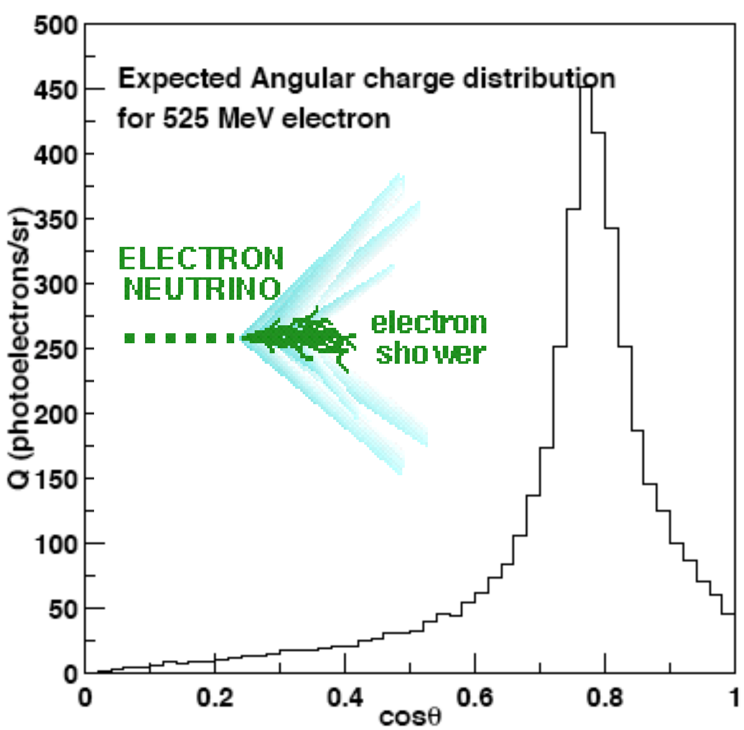

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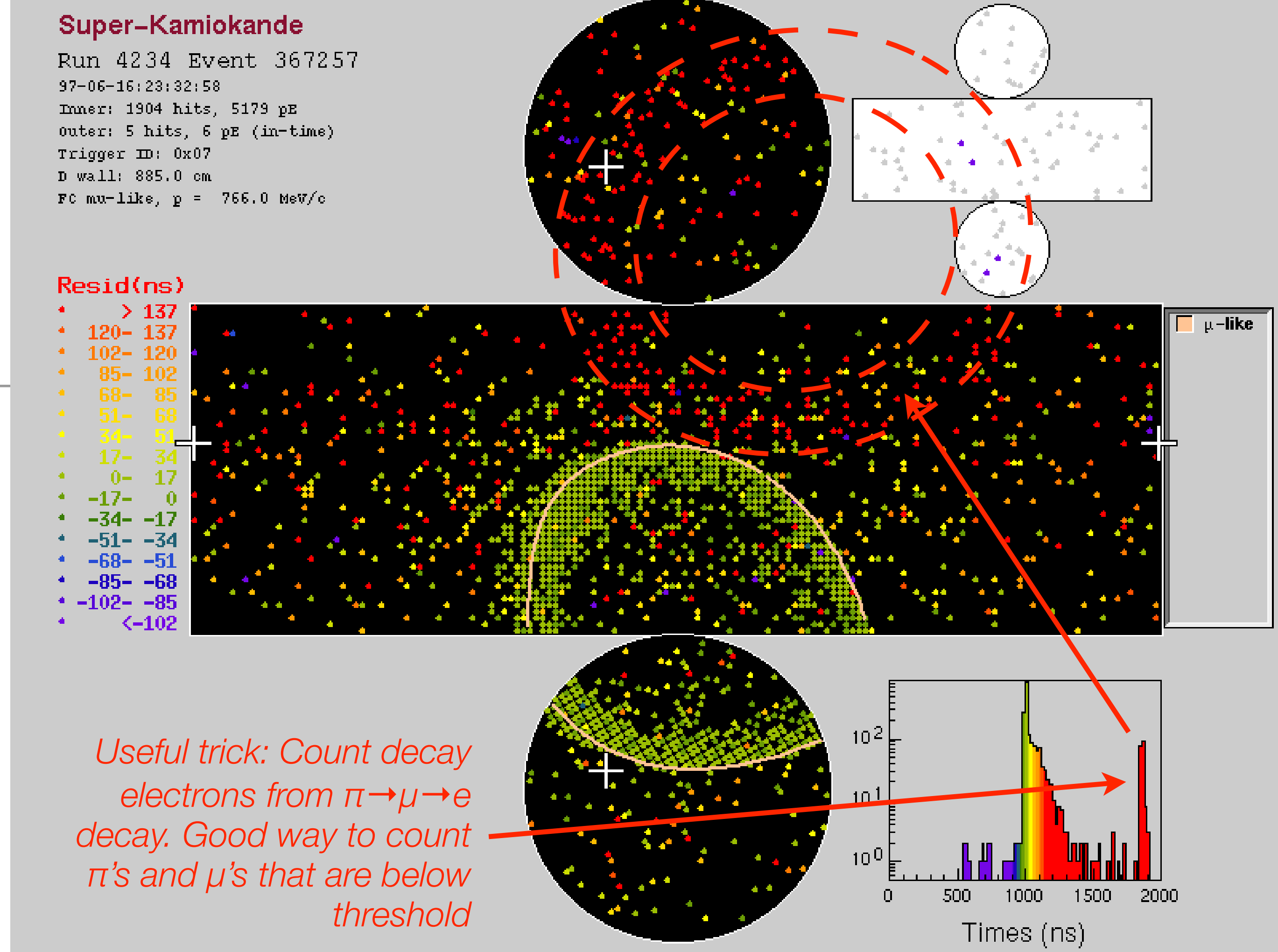

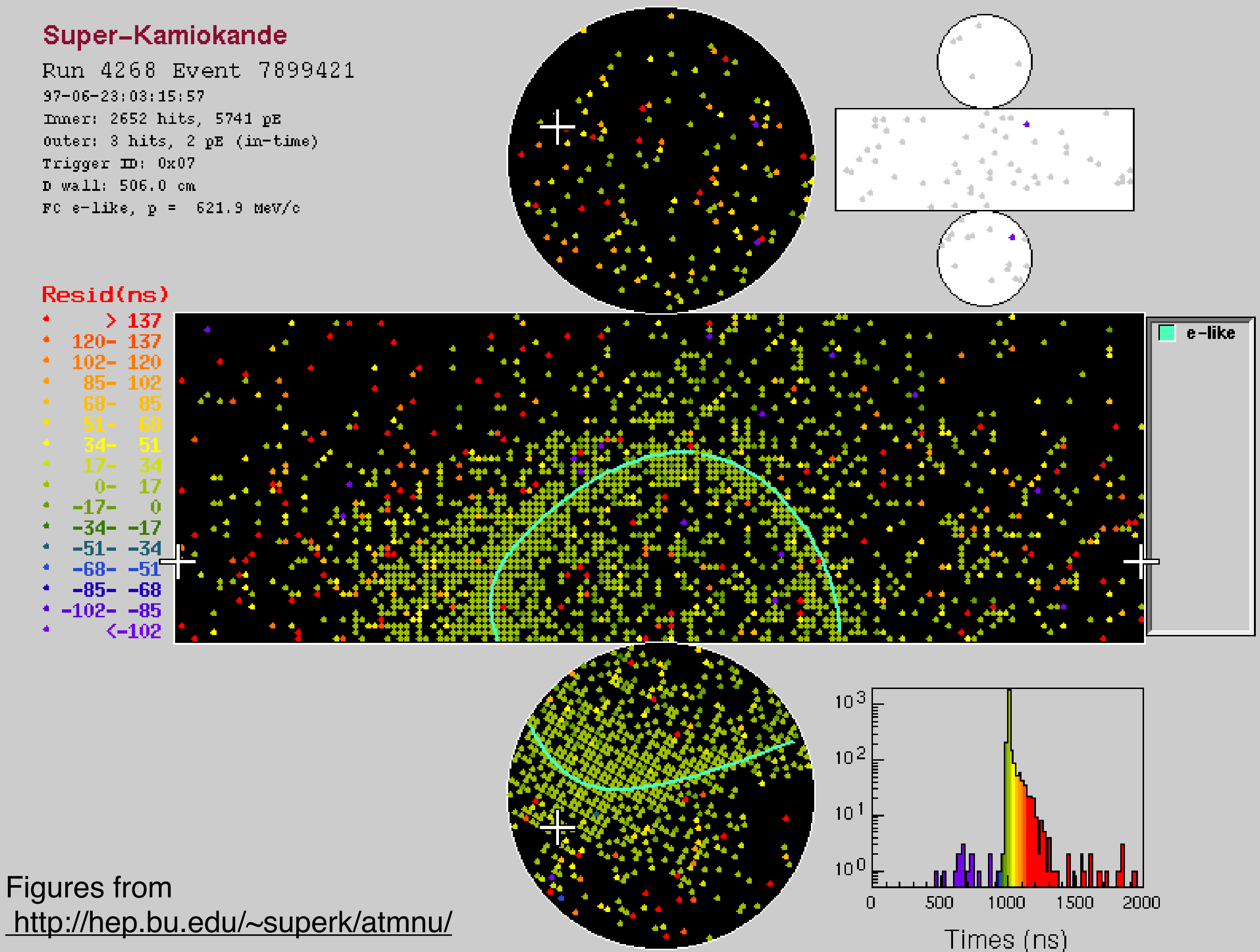

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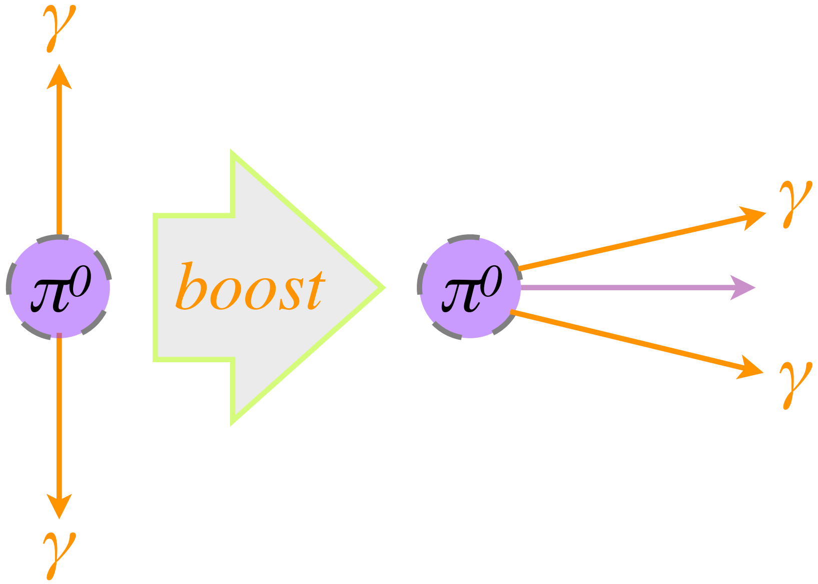
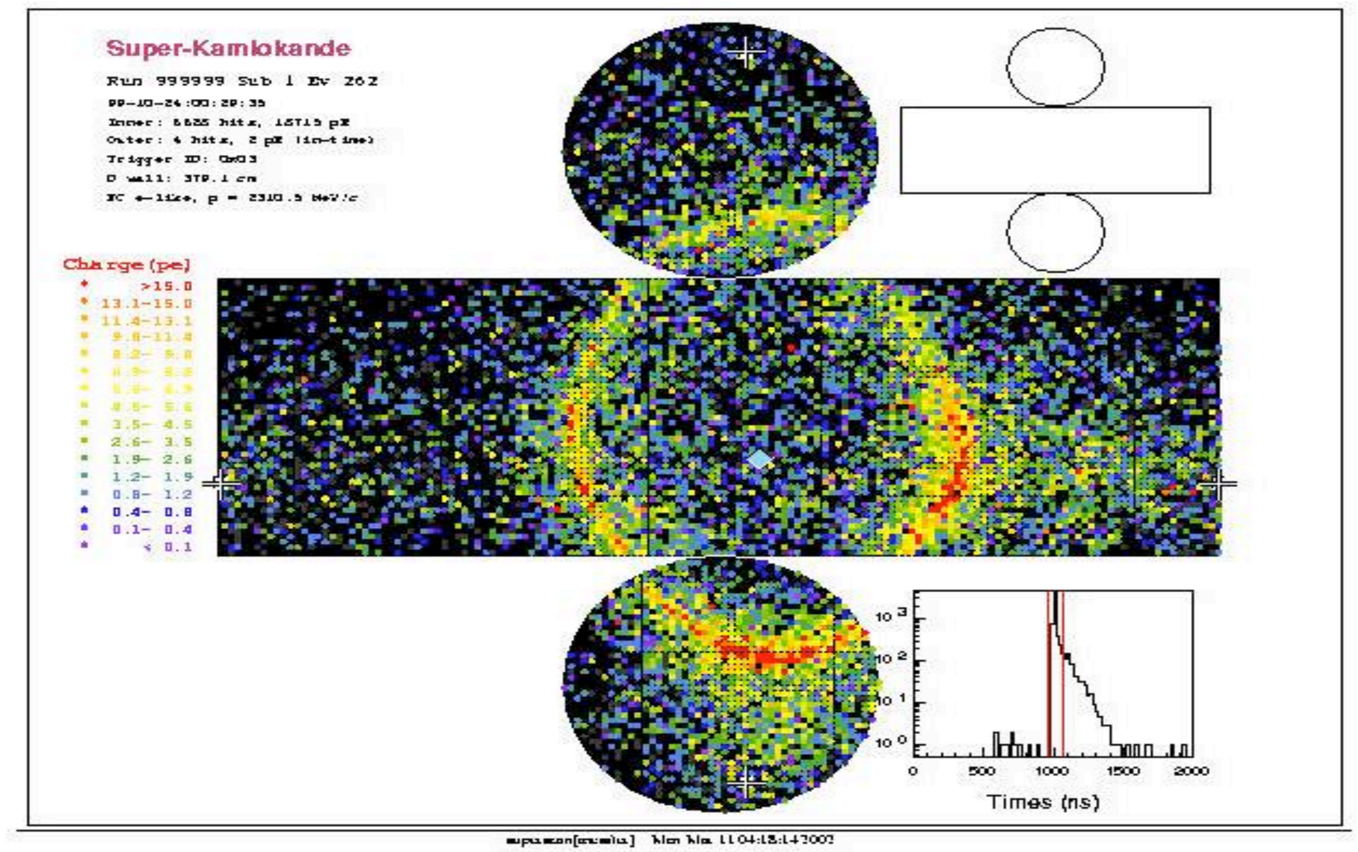
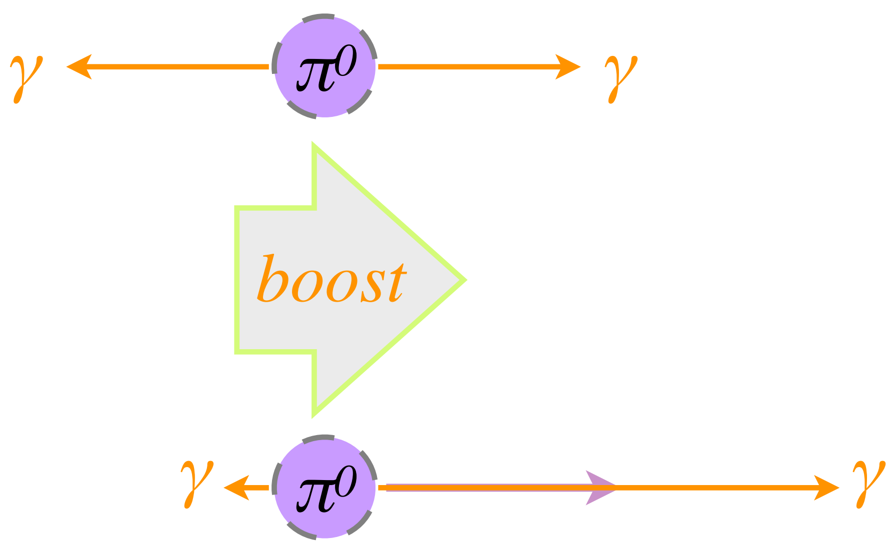
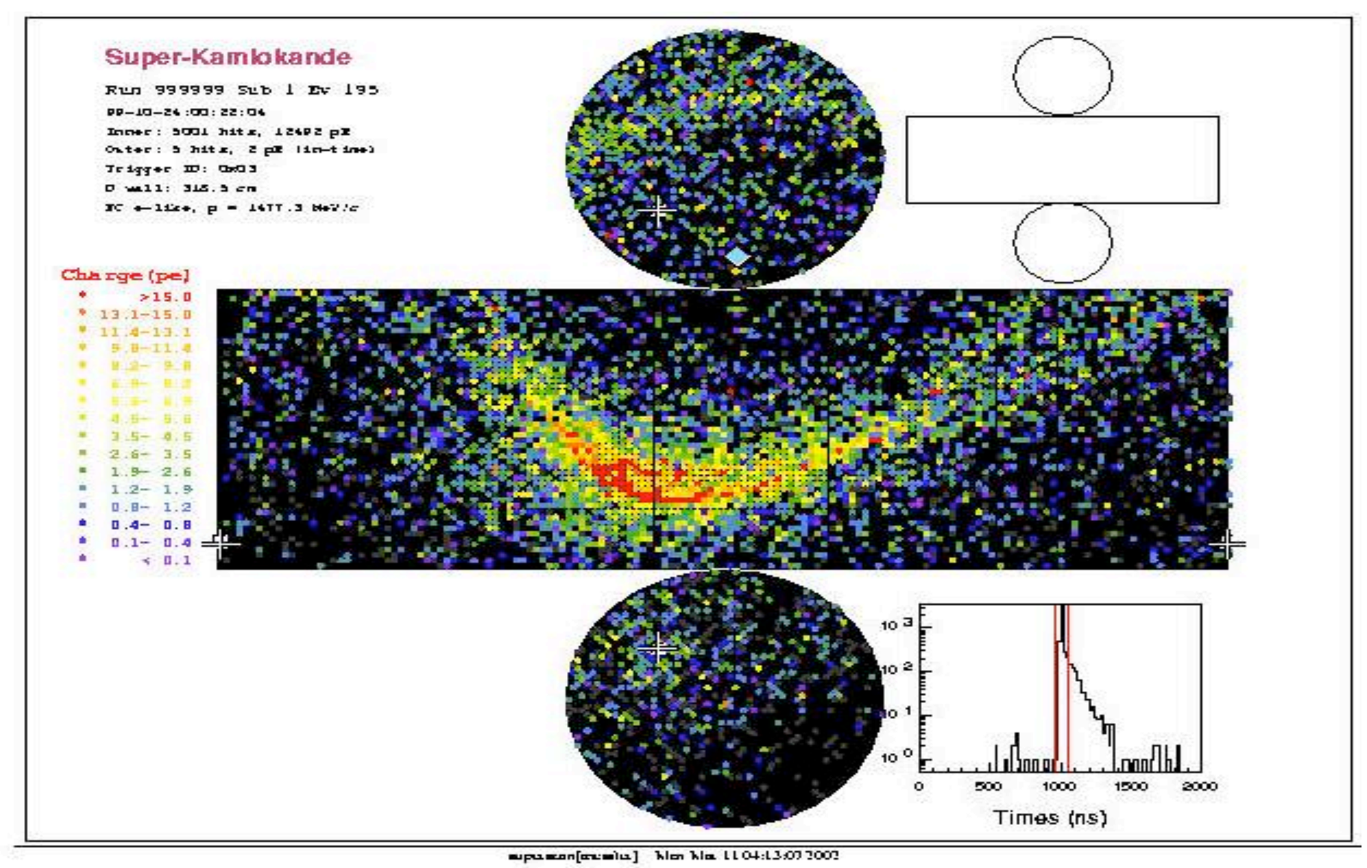
2 GeV visible energy
One is signal, the other background

π^0 decay at high energy









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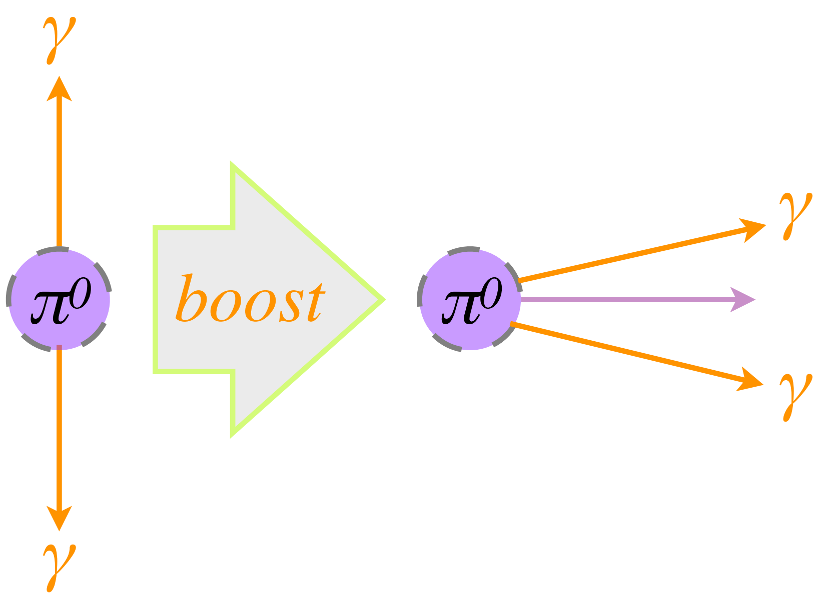
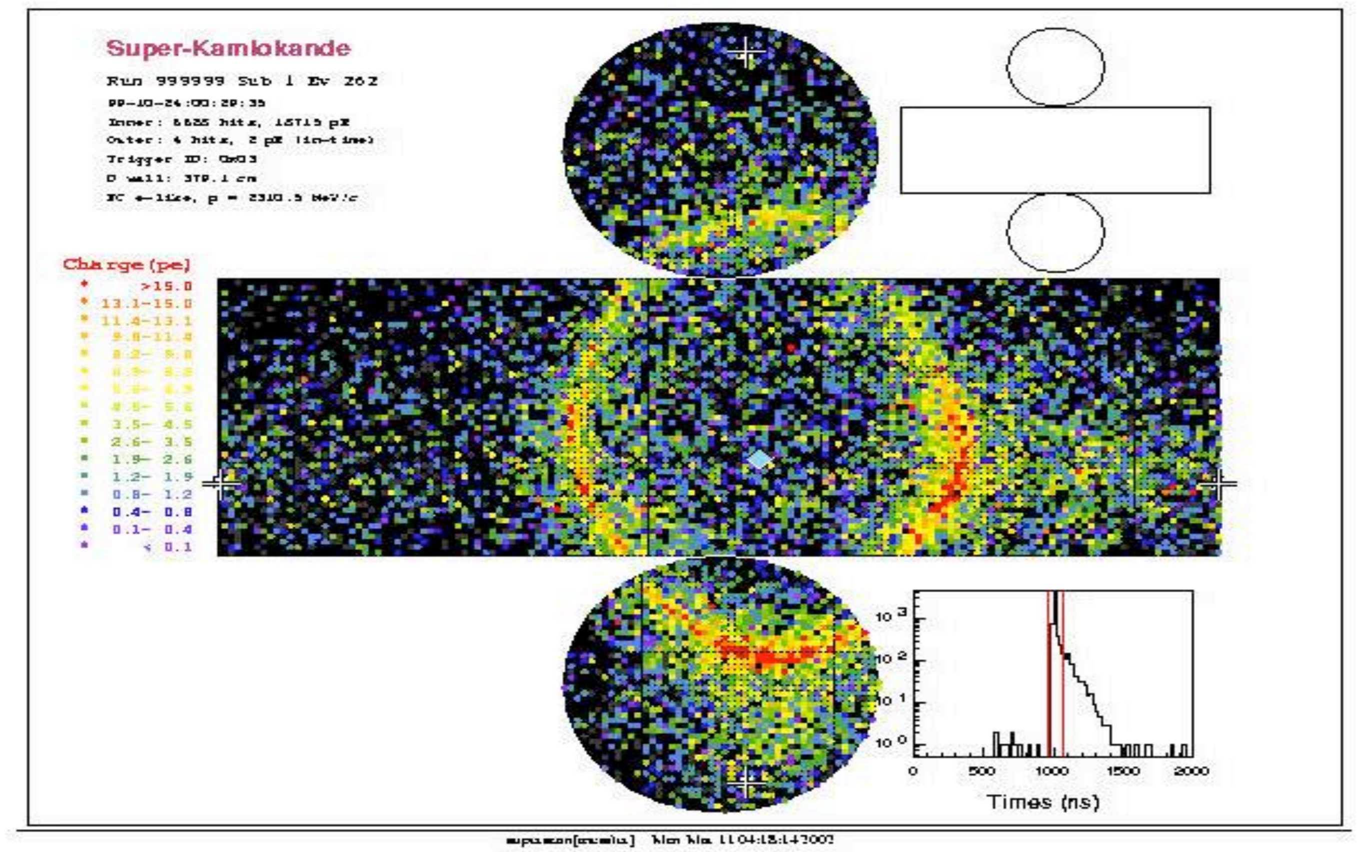
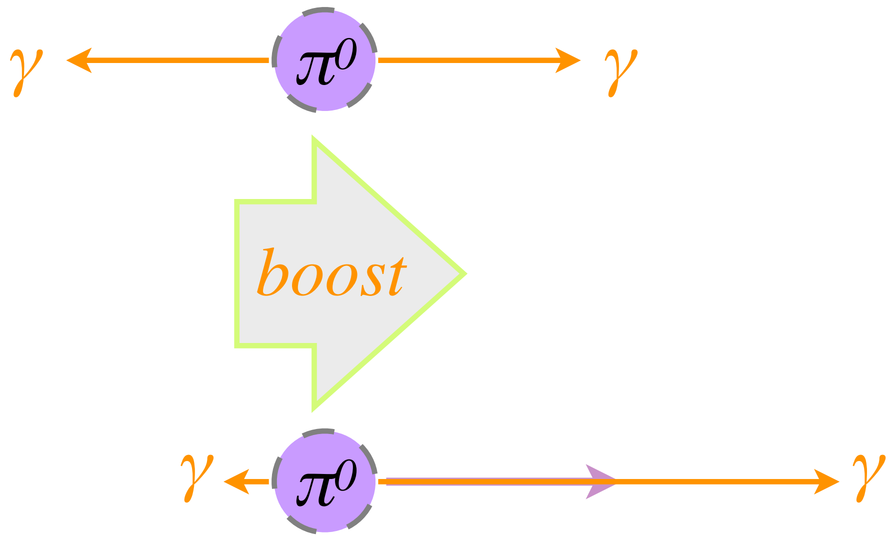
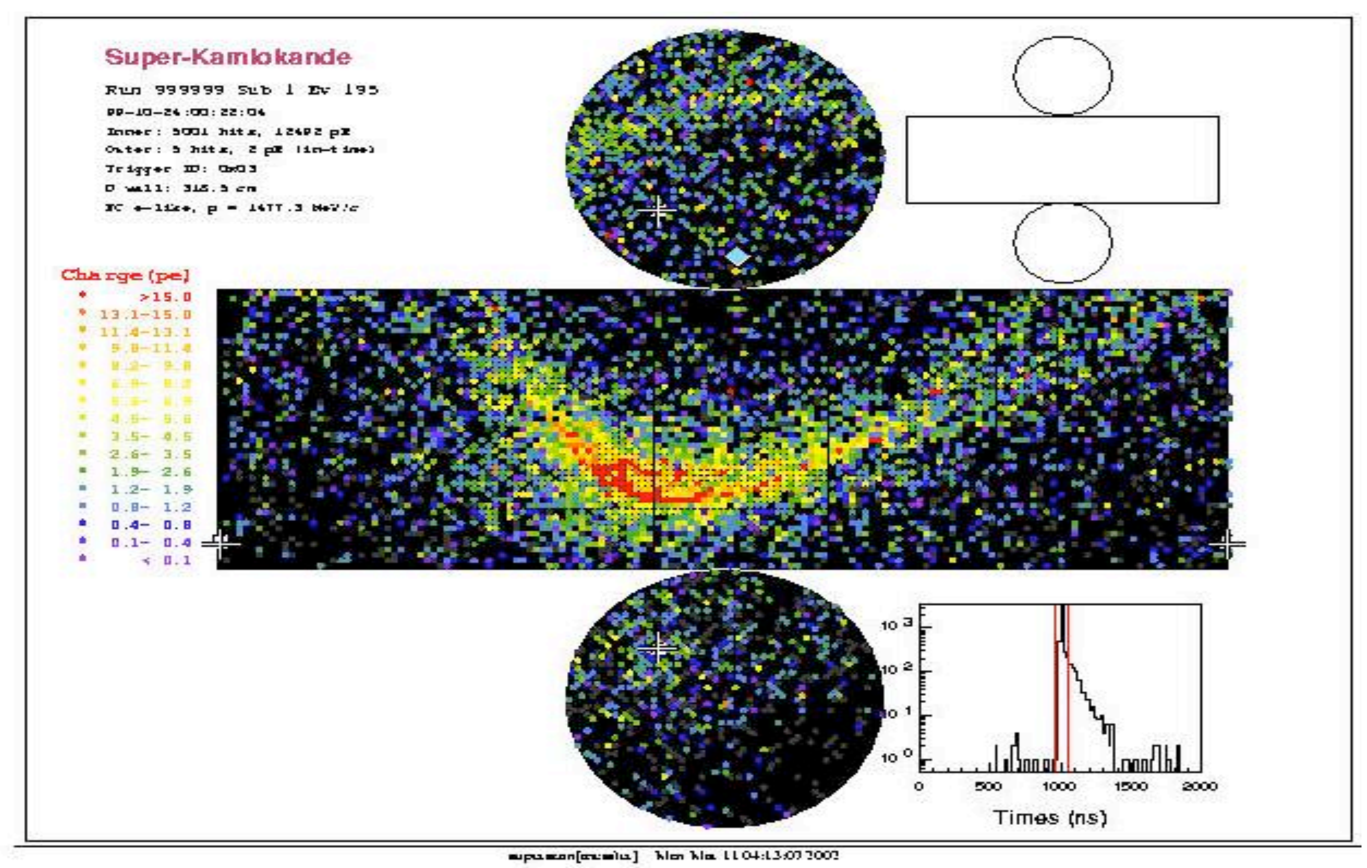




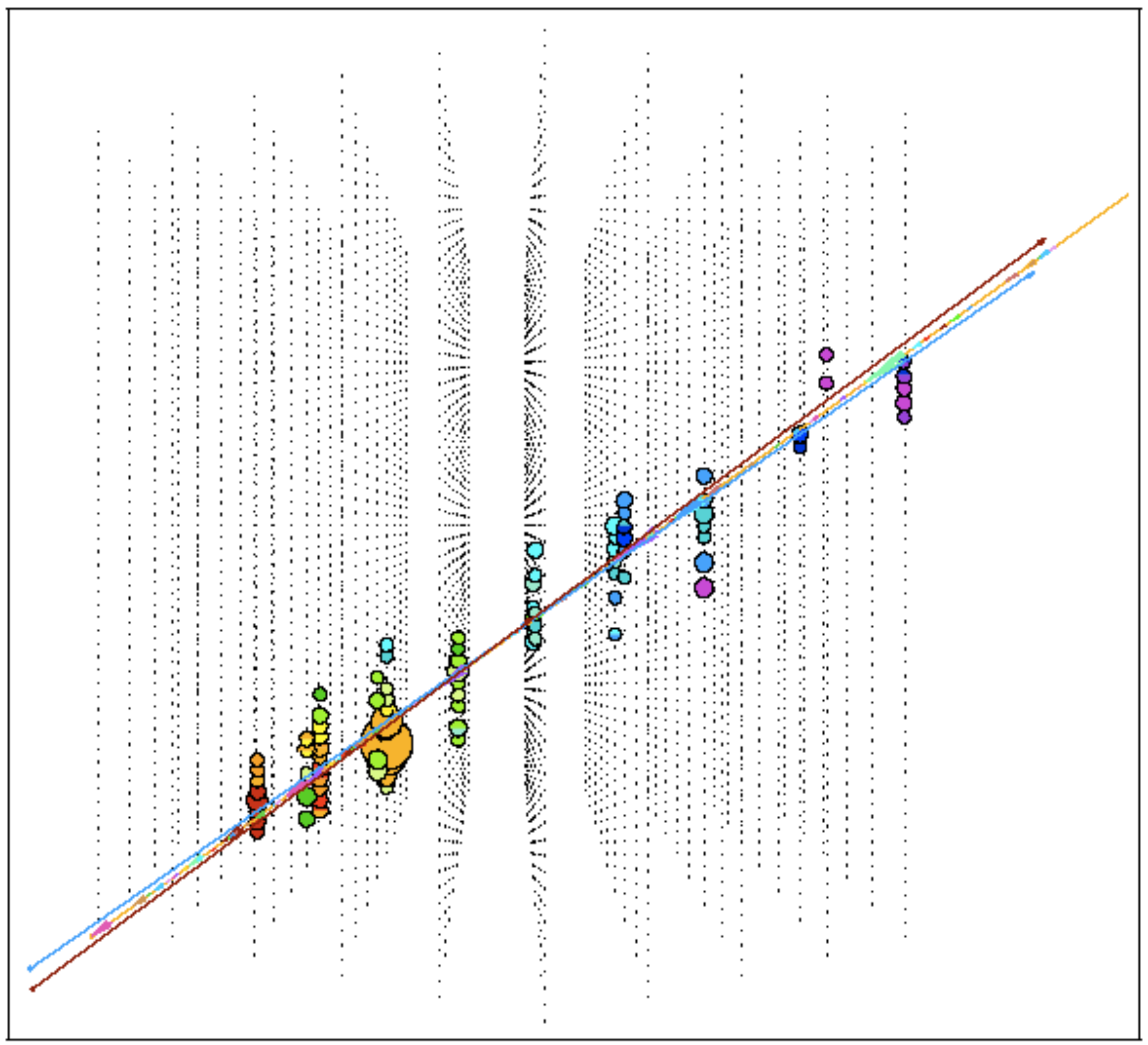
ν_e CC



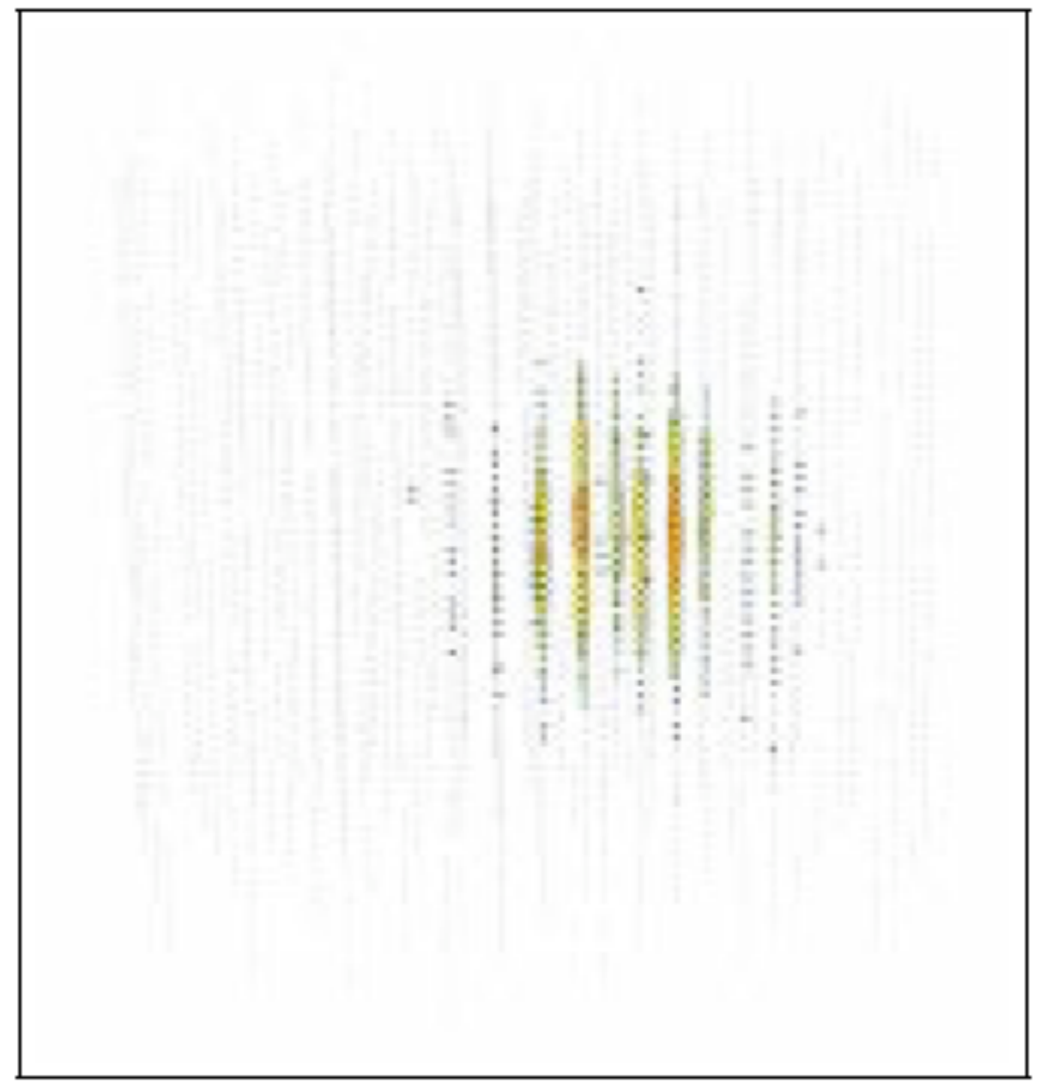


NC π^0

Particle ID in Ice Cube



10 TeV muon neutrino induced upward muon



375 TeV electron neutrino

Quiz

Q: Estimate the vertex resolution for a water Cherenkov detector for a 10 MeV electron produced by the elastic scatter of a solar neutrino. Assume that 50% of the photons make it to a wall before being absorbed, that 40% of the detector walls are covered by PMT's and that the PMT's have an average of 10% efficiency. Estimate the energy resolution at this energy.

Q: Compare the detection efficiencies for the Kamiokande (20% photocathode coverage) and IMB-1 (1% photocathode coverage) for a 15 MeV super-nova neutrino

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A: A 10 MeV electron will go about 5 cm in the tank making about N = 5*500*sin(42^{o})^{2} = 1100 photons. Of those (50%x40%x10%) = 5% will be detected. So I have ~20 detected photons each with a timing resolution of 2 ns ~= (2 ns x 30 cm/ns / 1.33) = 45 cm since the speed of light is 30/1.33 cm/ns. This gives a final resolution of about: 45 cm/sqrt(20) = *10 cm which is an best-case.* Energy resolution dominated by Poisson fluctuations on the number of photons collected. In this case ~sqrt(20)/20 = *22%*.

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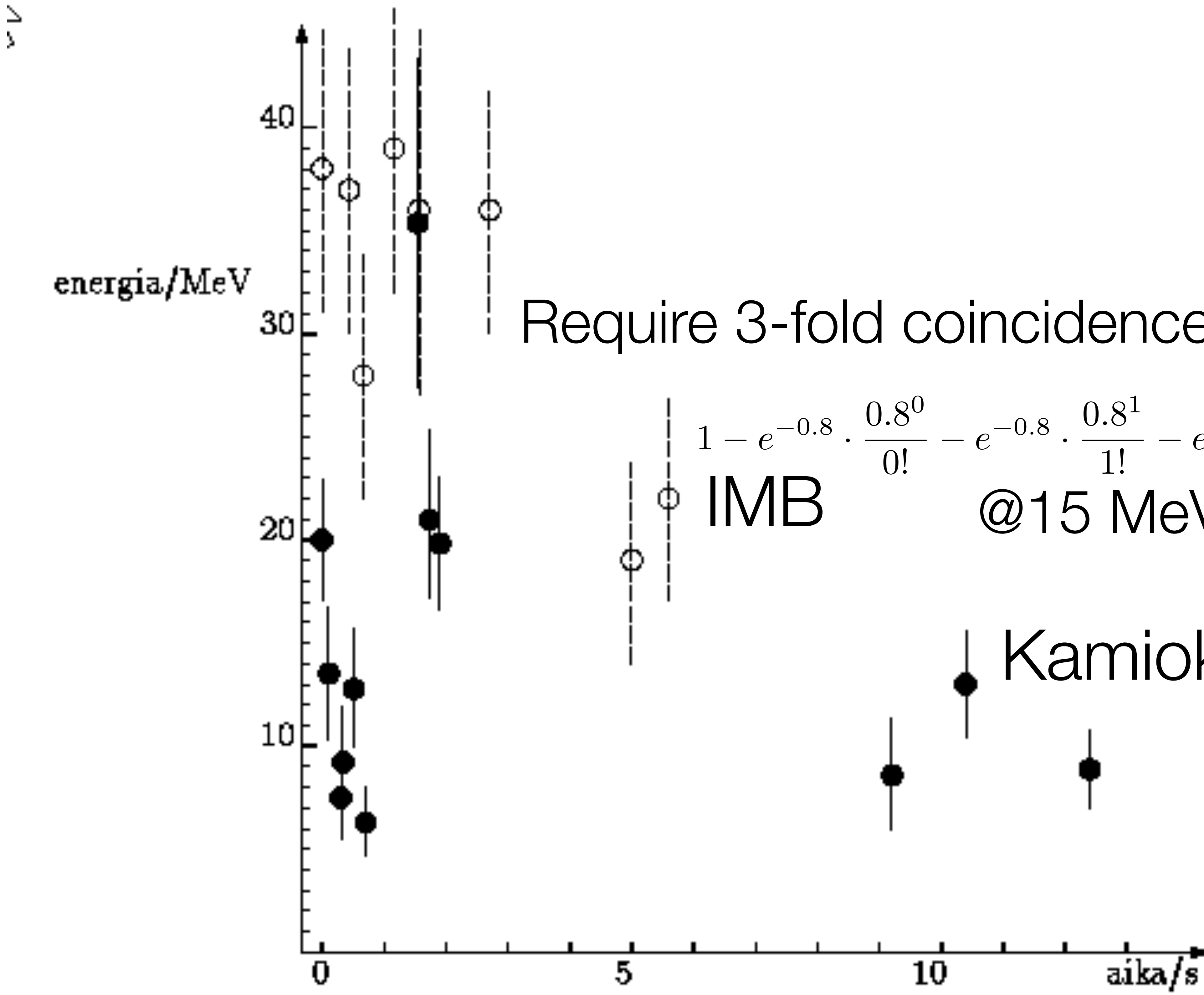
A: 15 MeV corresponds to about 1700 photons which is about 0.8 detected photons on average in IMB and 17 in Kamiokande. Efficiency for detection is roughly 1-exp(-0.8) = 55% for IMB and 1-exp(-17) ~= 100% for Kamiokande. (Overestimates since I assume 1 detected photon is enough!)



Require 3-fold coincidence for trigger

$$1 - e^{-0.8} \cdot \frac{0.8^0}{0!} - e^{-0.8} \cdot \frac{0.8^1}{1!} - e^{-0.8} \cdot \frac{0.8^2}{2!} = 5\%$$

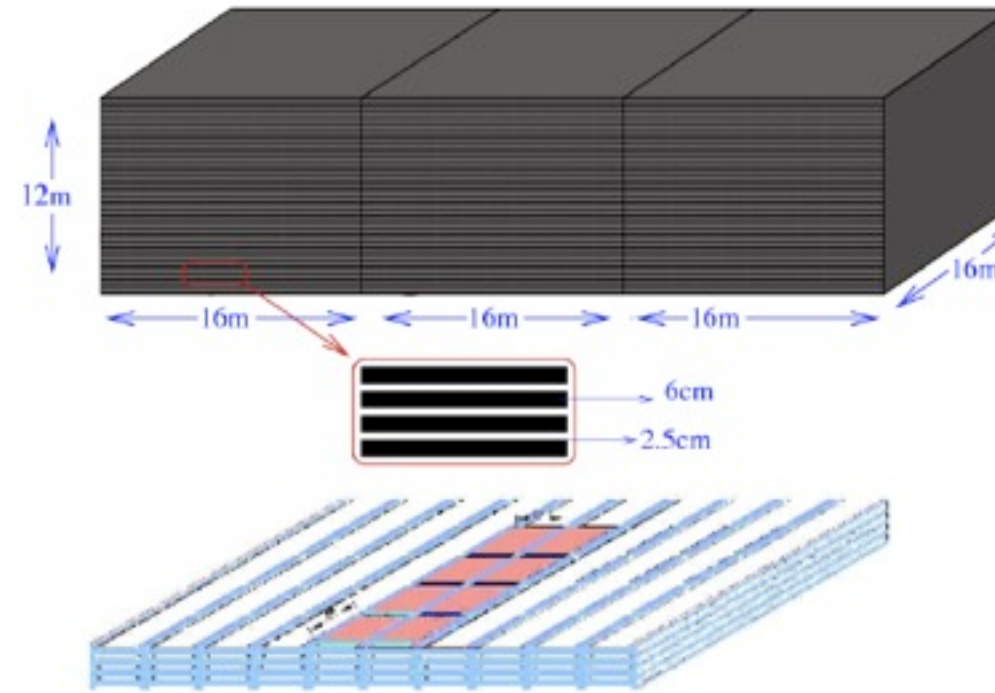
IMB

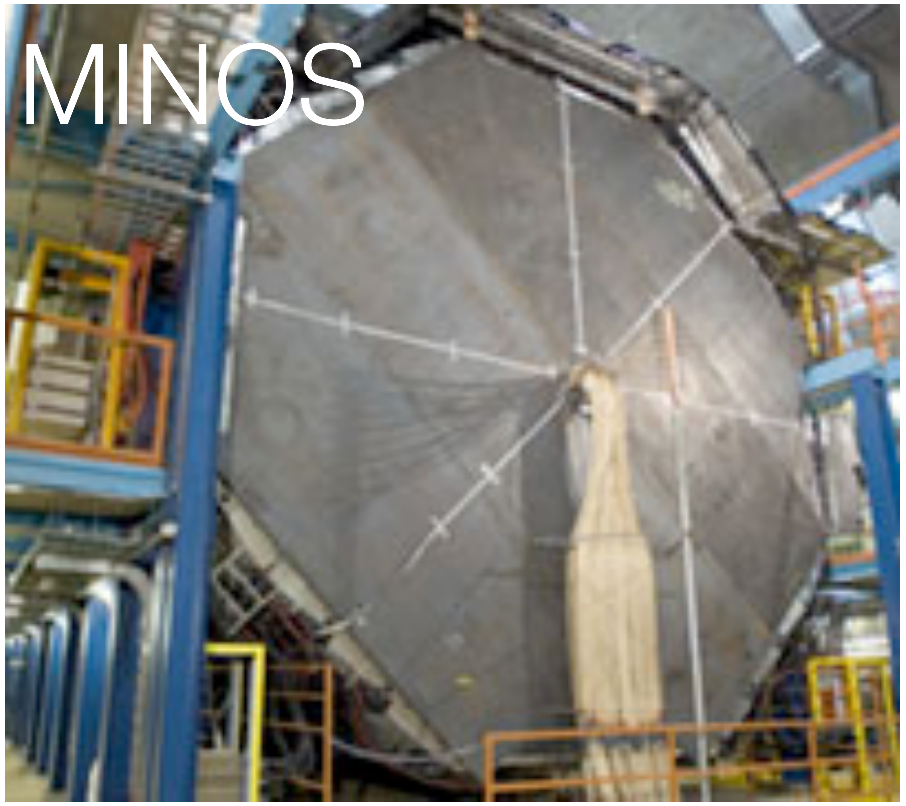
@15 MeV

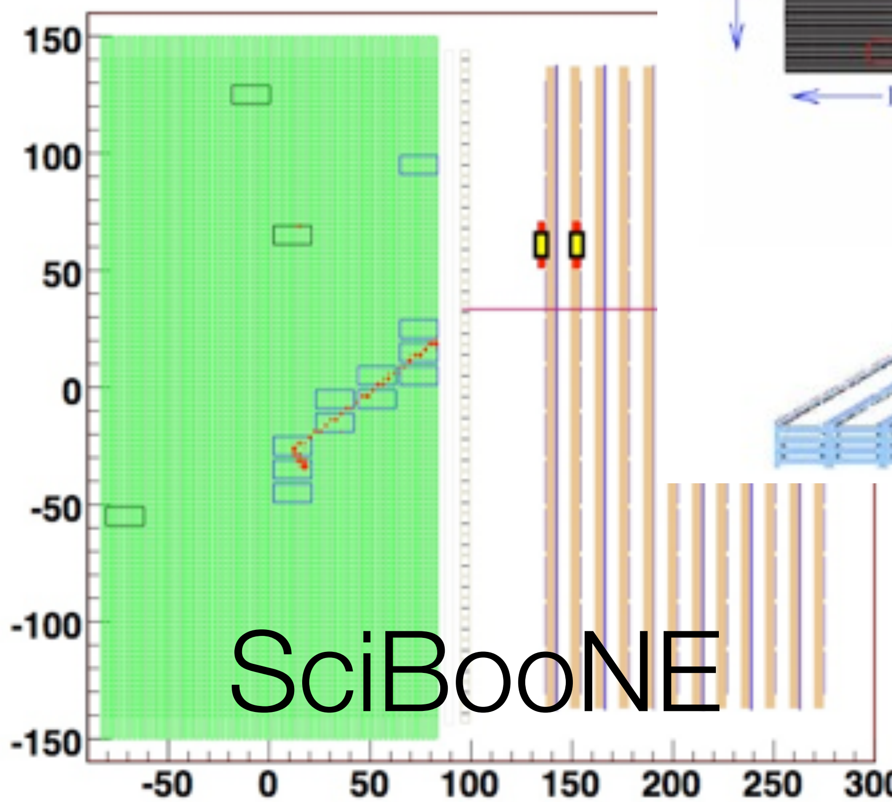
Kamiokande

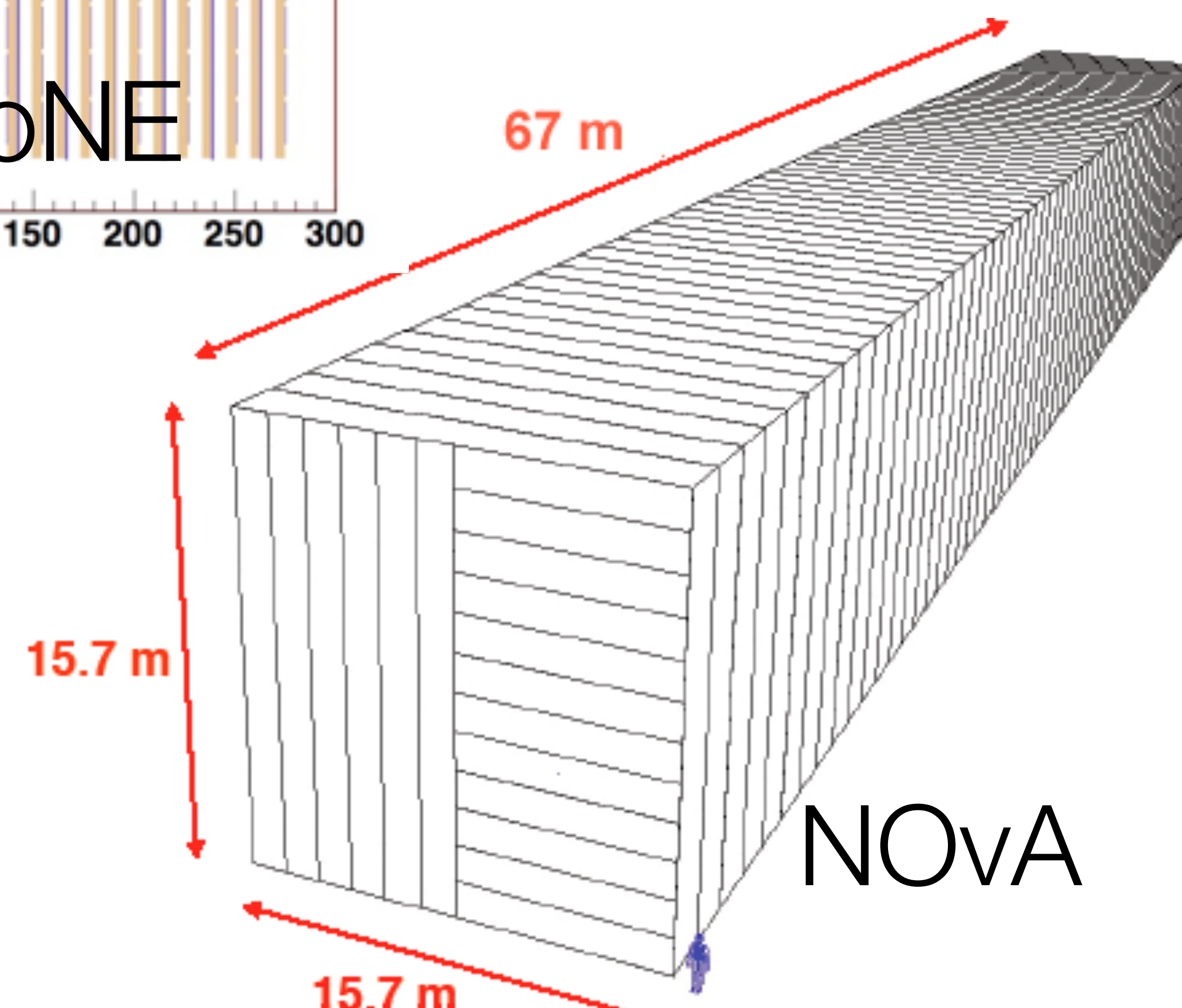
Tracking calorimeters

INO

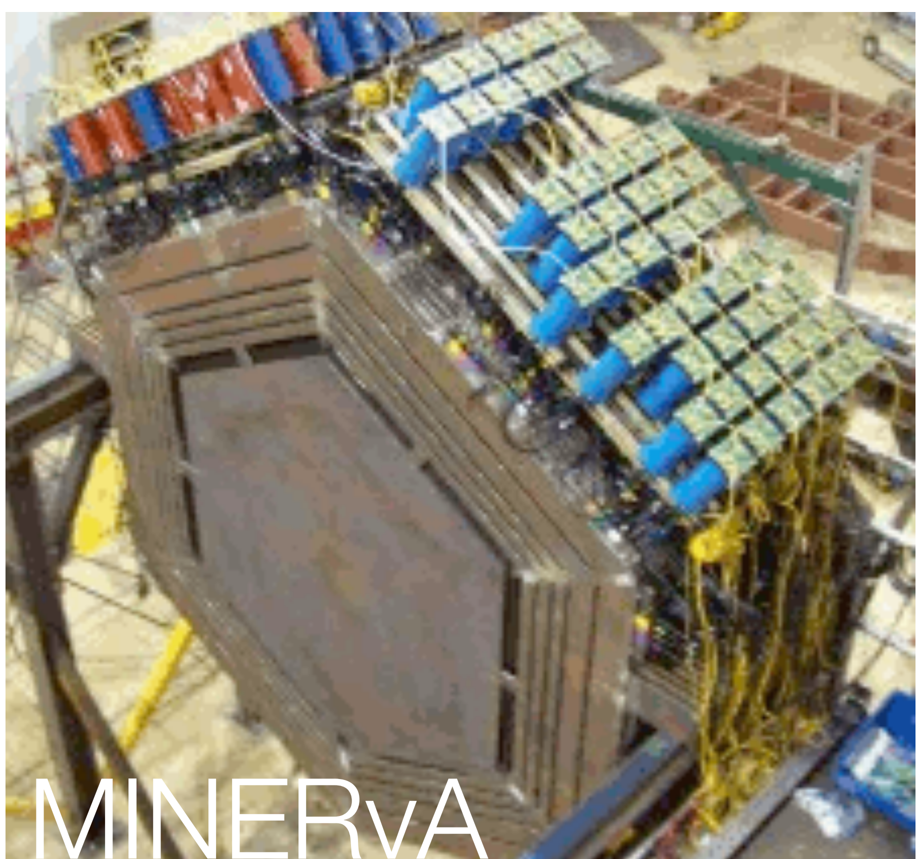








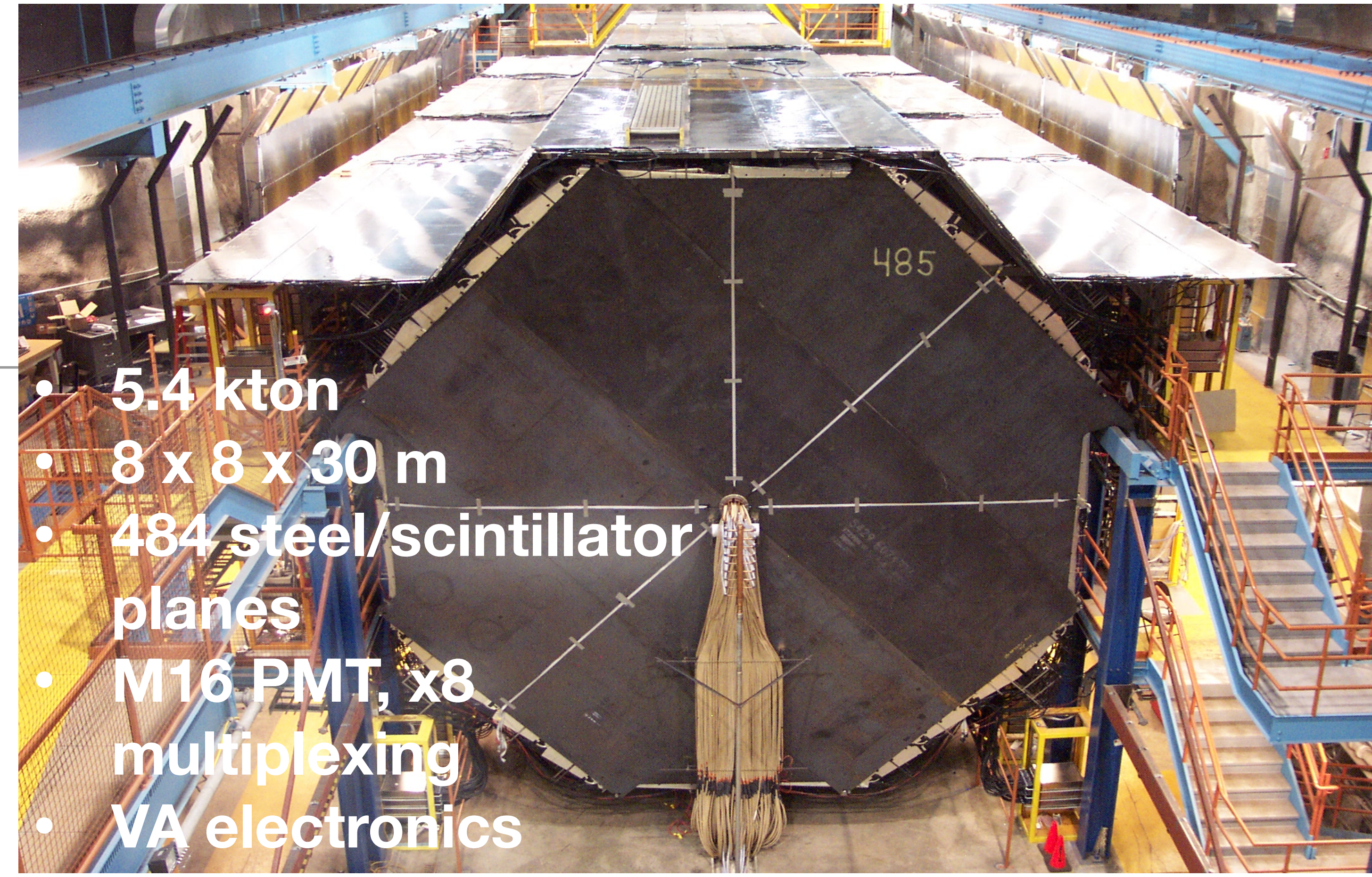
NOvA

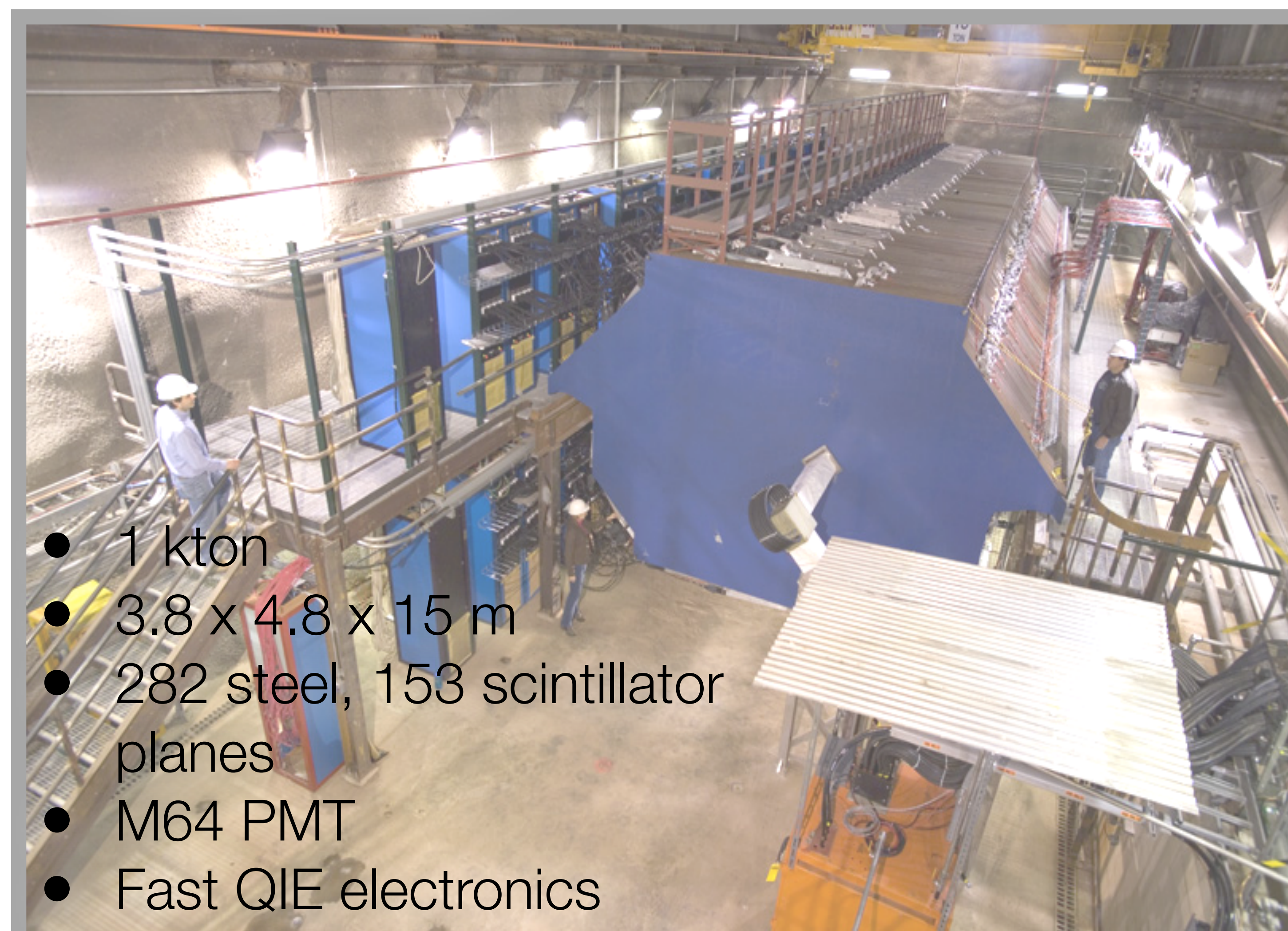


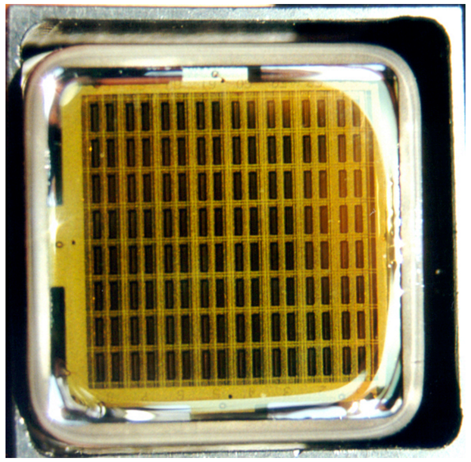
The MINOS Detectors

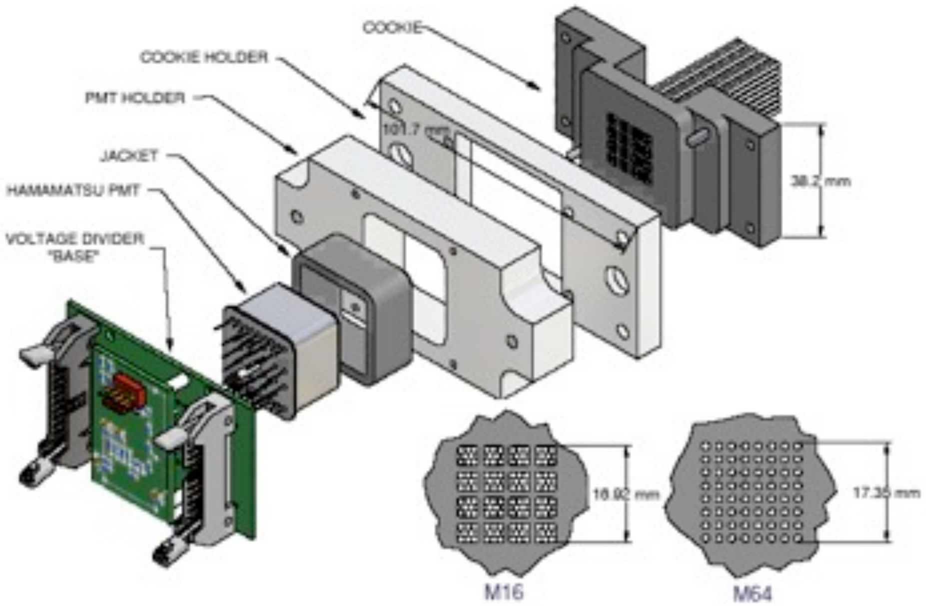
MINOS used two functionally equivalent detectors:

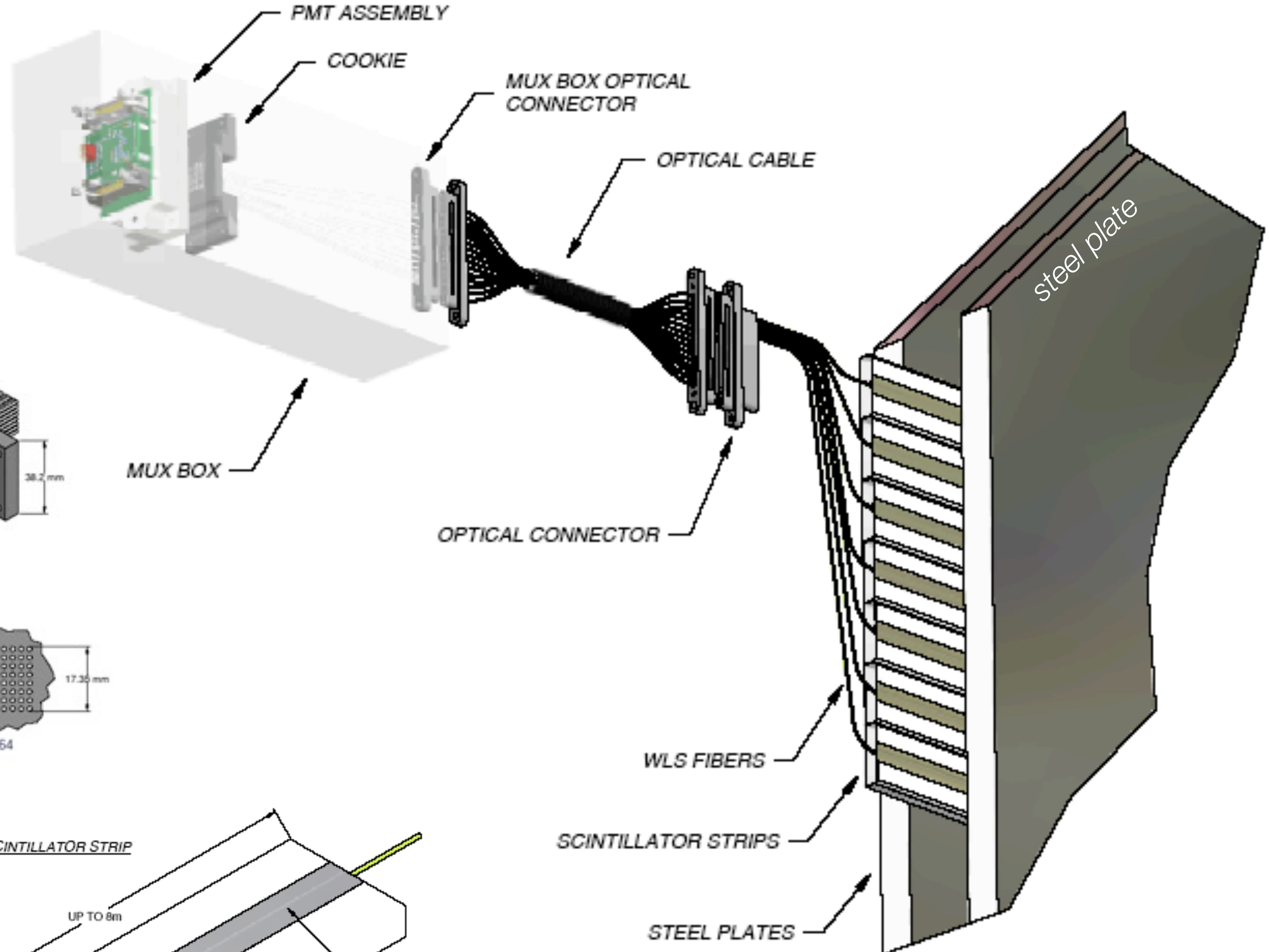
- 2.54 thick magnetized steel plates
- 4.1 x 1 cm co-extruded scintillator strips
- optical fiber readout to multi-anode PMT's

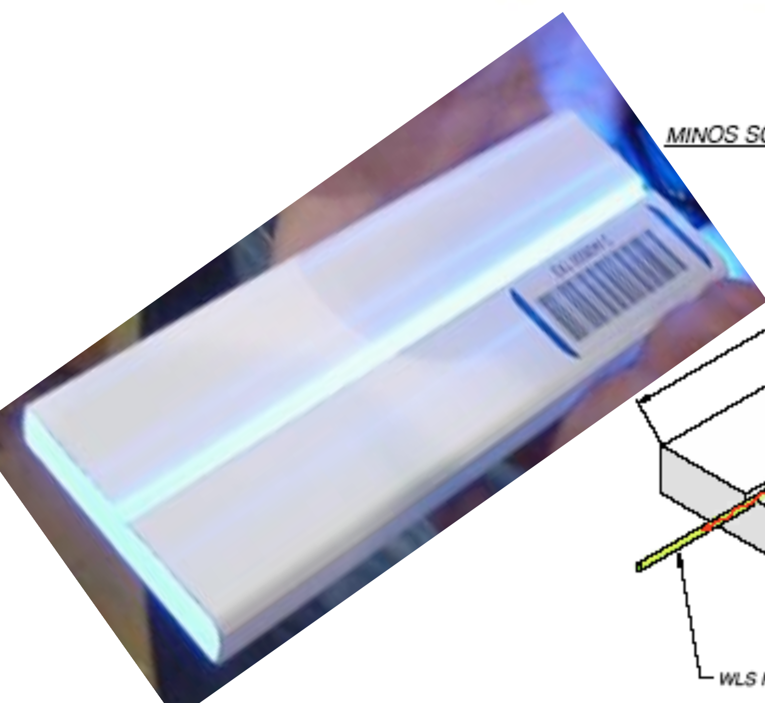


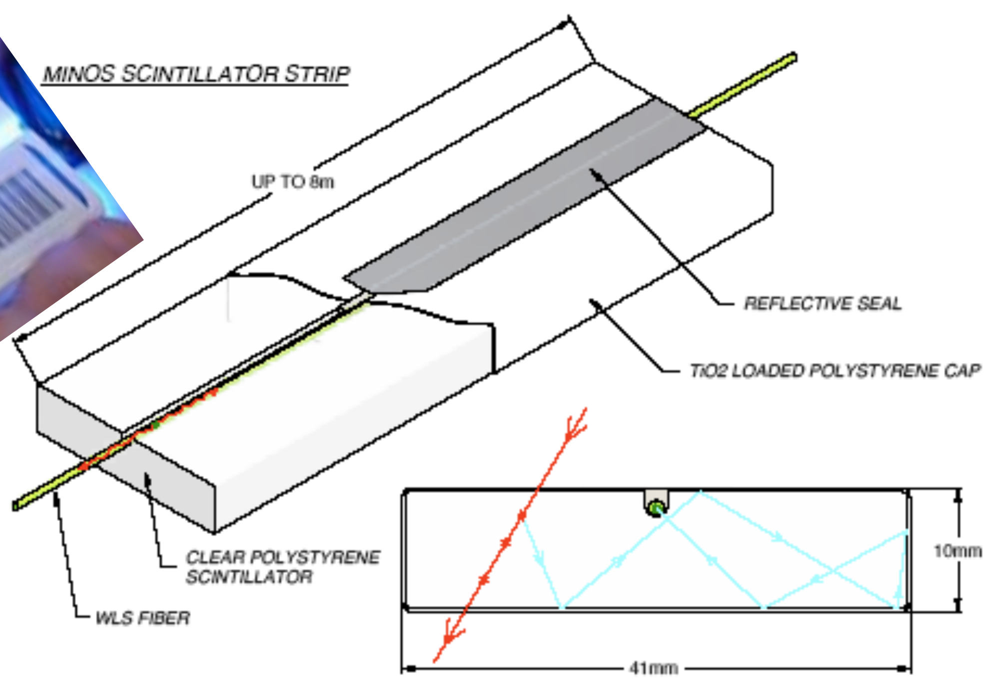












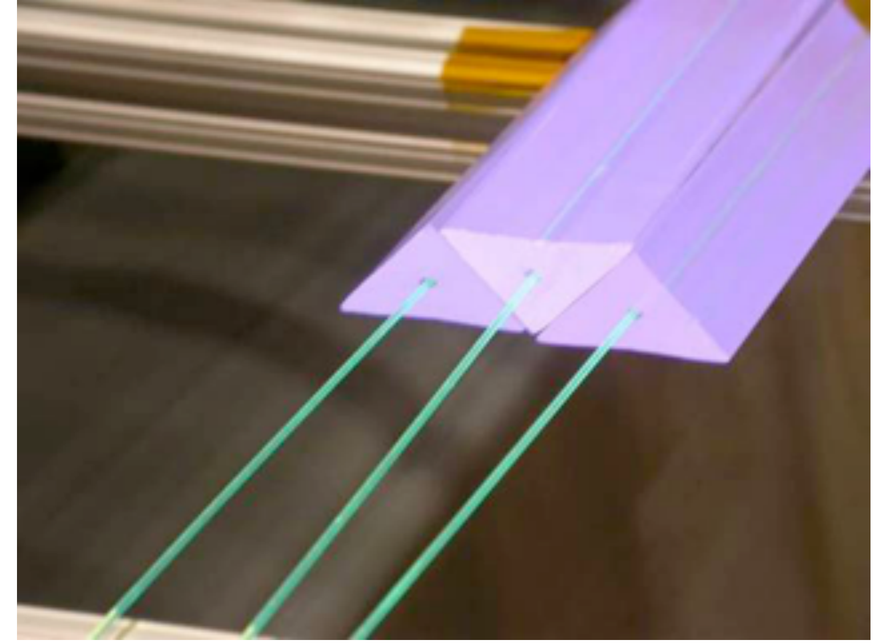
MINOS Detector

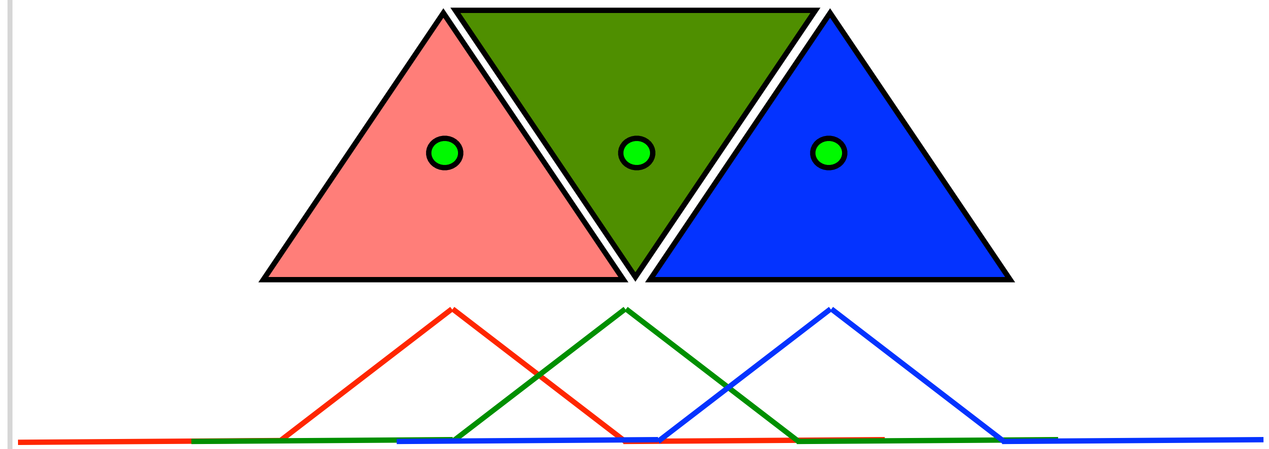
scintillator modules layered on steel plane

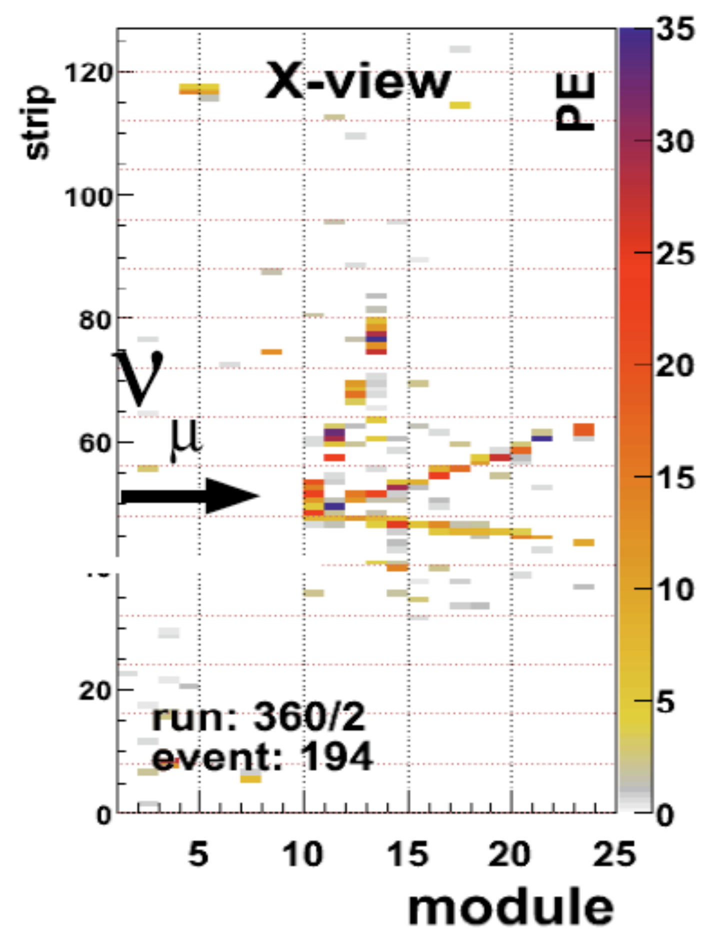
“strong back”. Removed after plane is hung in place

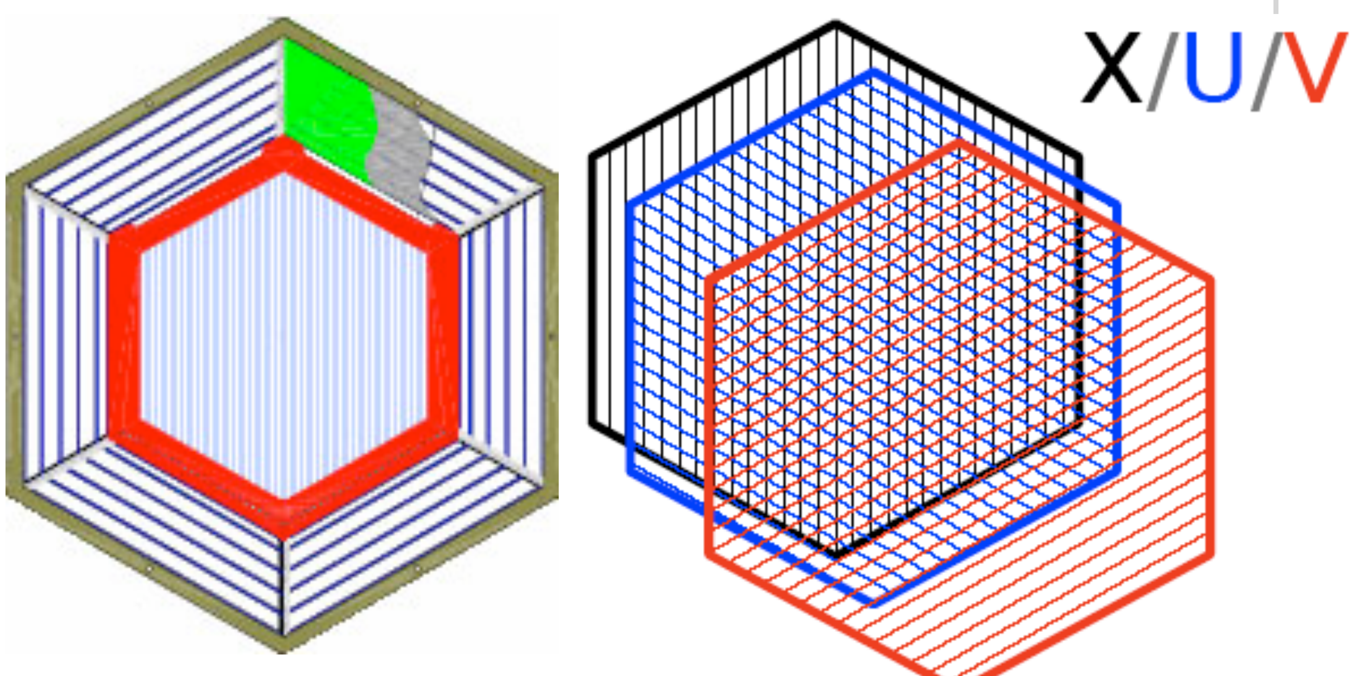
MINERvA

- MINERvA incorporates several improvements in tracking resolution
- Triangularly extruded scintillator bars allows track position to be estimated by light-sharing fractions
- Three tracking views. Resolves ambiguity when track travels along one of the strip directions or overlaps with another track in one view

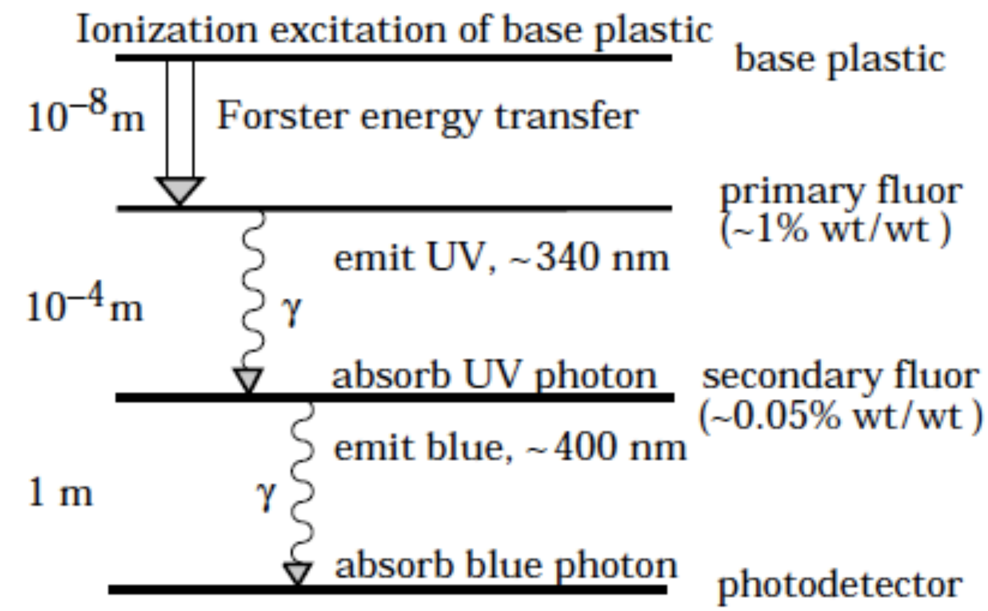








Scintillation process

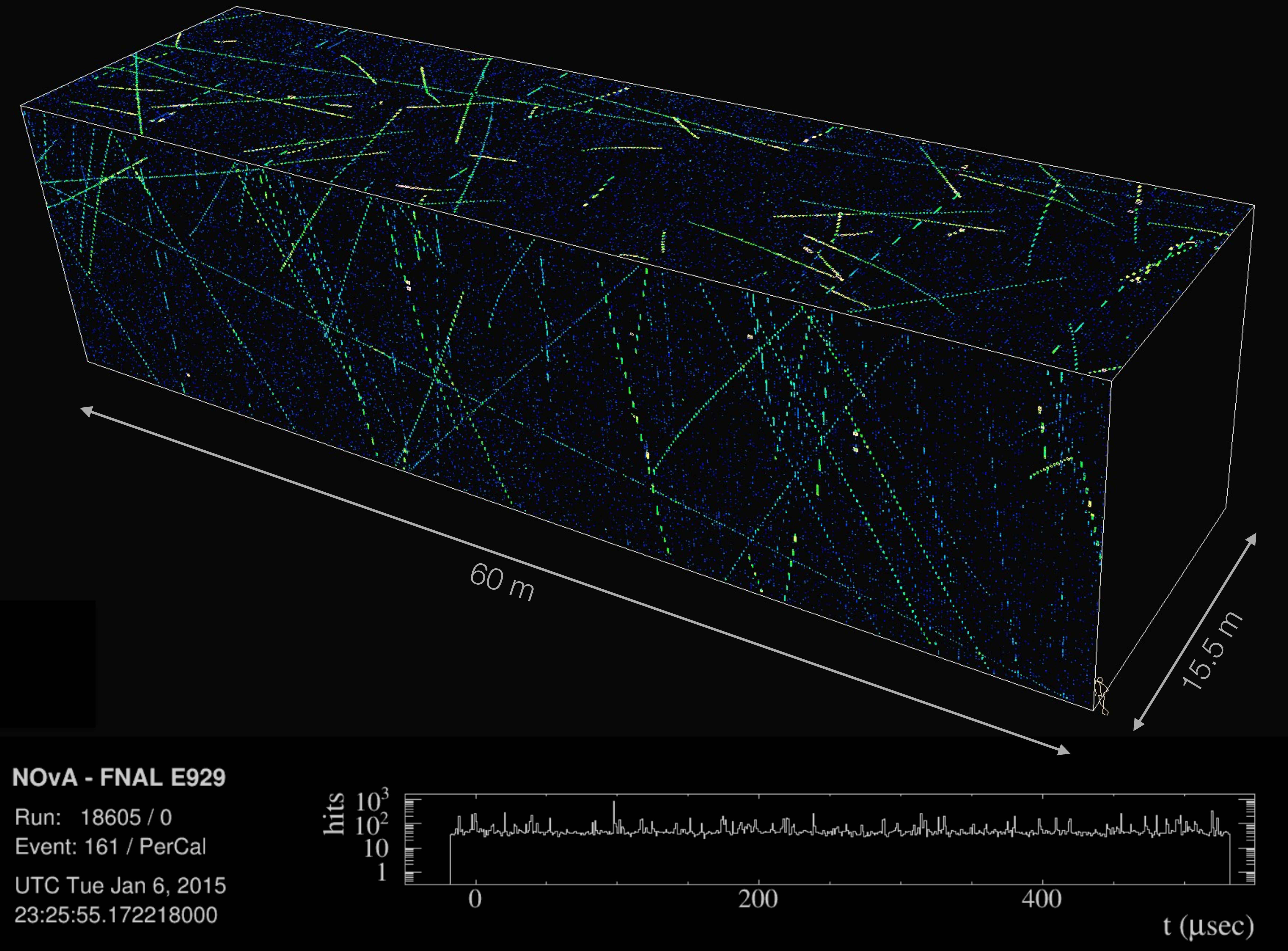


- Scintillators are solid or liquid materials that produce light shortly after absorbing energy from a passing particle
- “Shortly” here is characterized by the decay time of the scintillator with the number of photons emitted varying as
  - $n(t) = k(1 - e^{-t/\tau})$
- The scintillators with lowest dead times have tau’s at low as 5 ns. Typical values are 10-100 ns.
- The number of scintillation photons produced per unit energy deposited goes as:

$$n = n_0 \frac{dE/dx}{1 + BdE/dx}$$

  where B is “Birk’s” constant and accounts for saturation of the scintillator at high energy depositions.

- Scintillation light is emitted in a distribution peaked typically around 350-400 nm. It is common to use compounds (eg. PPO, POPOP) which absorb this light and re-emit it at longer wavelengths where the scintillator has less absorption and where the fiber absorbs strongly.
- Light is captured by the fiber at typically 420 nm and reemitted at around 470 nm and is carried to the ends by total internal reflection. Transport characterized by a short attenuation length (~2 m) and a long attenuation length (~8 m).

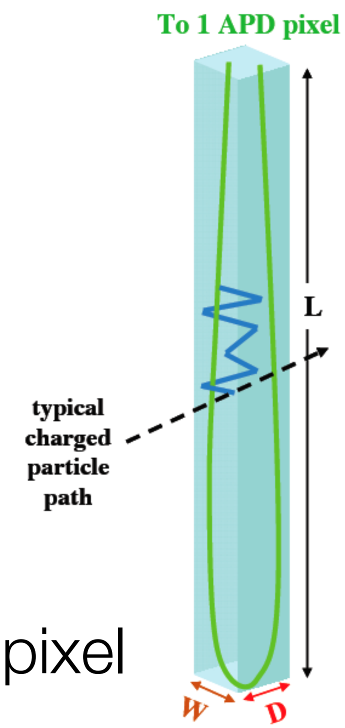

60 m
15.5 m
NOvA - FNAL E929
Run: 18605 / 0
Event: 161 / PerCal
UTC Tue Jan 6, 2015
23:25:55.172218000
hits
10^3
10^2
10
1
0
200
400
t (μsec)

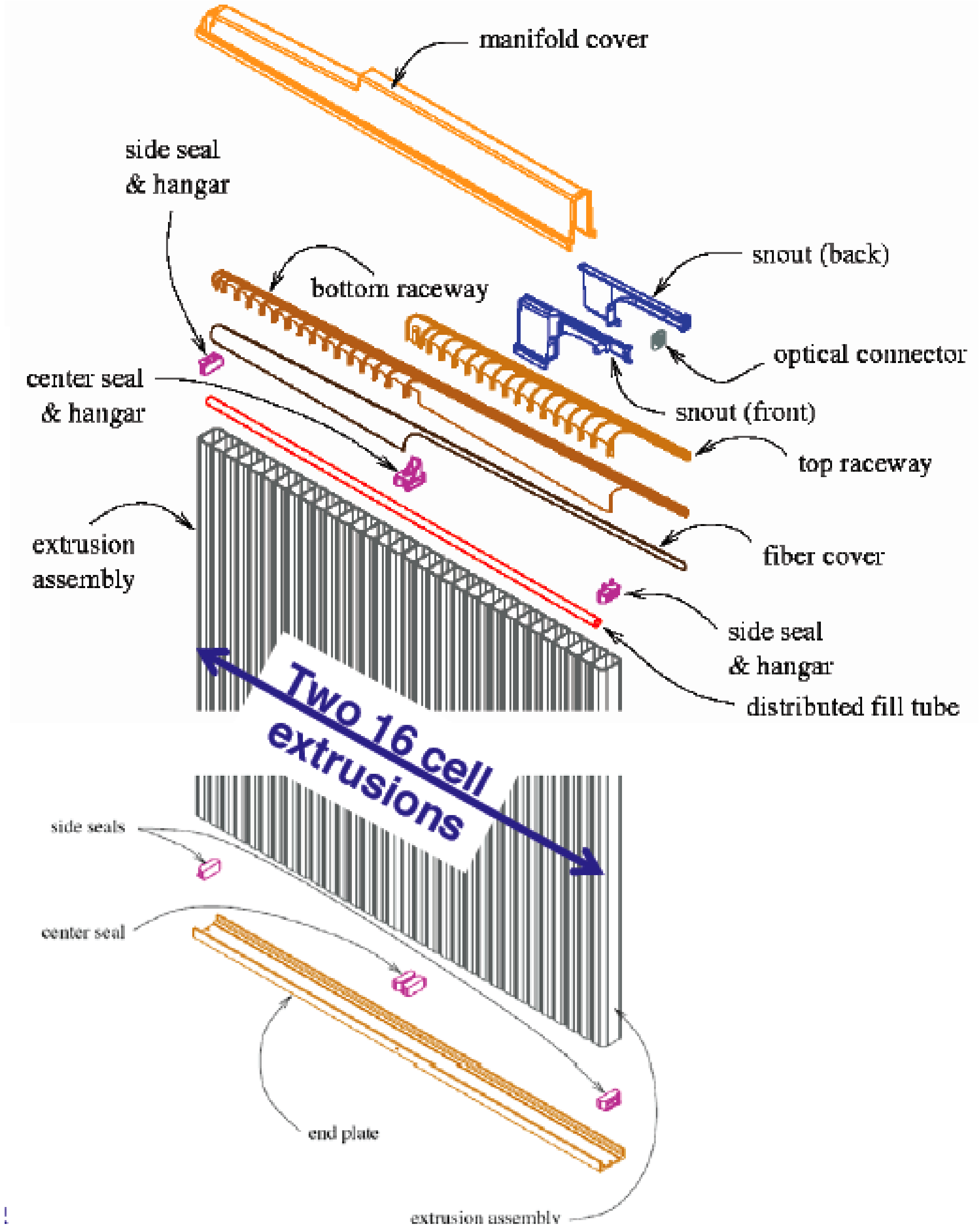
Liquid scintillator
(14.8M liters, 12.6 ktons)
Contained in 3.9 x 6.6 cell cells of length 15.7 m
-18 m attenuation length
-5.5% pseudocumene

Extruded PVC
(5.4 ktons)
15% anatase TiO_2 for high reflectivity

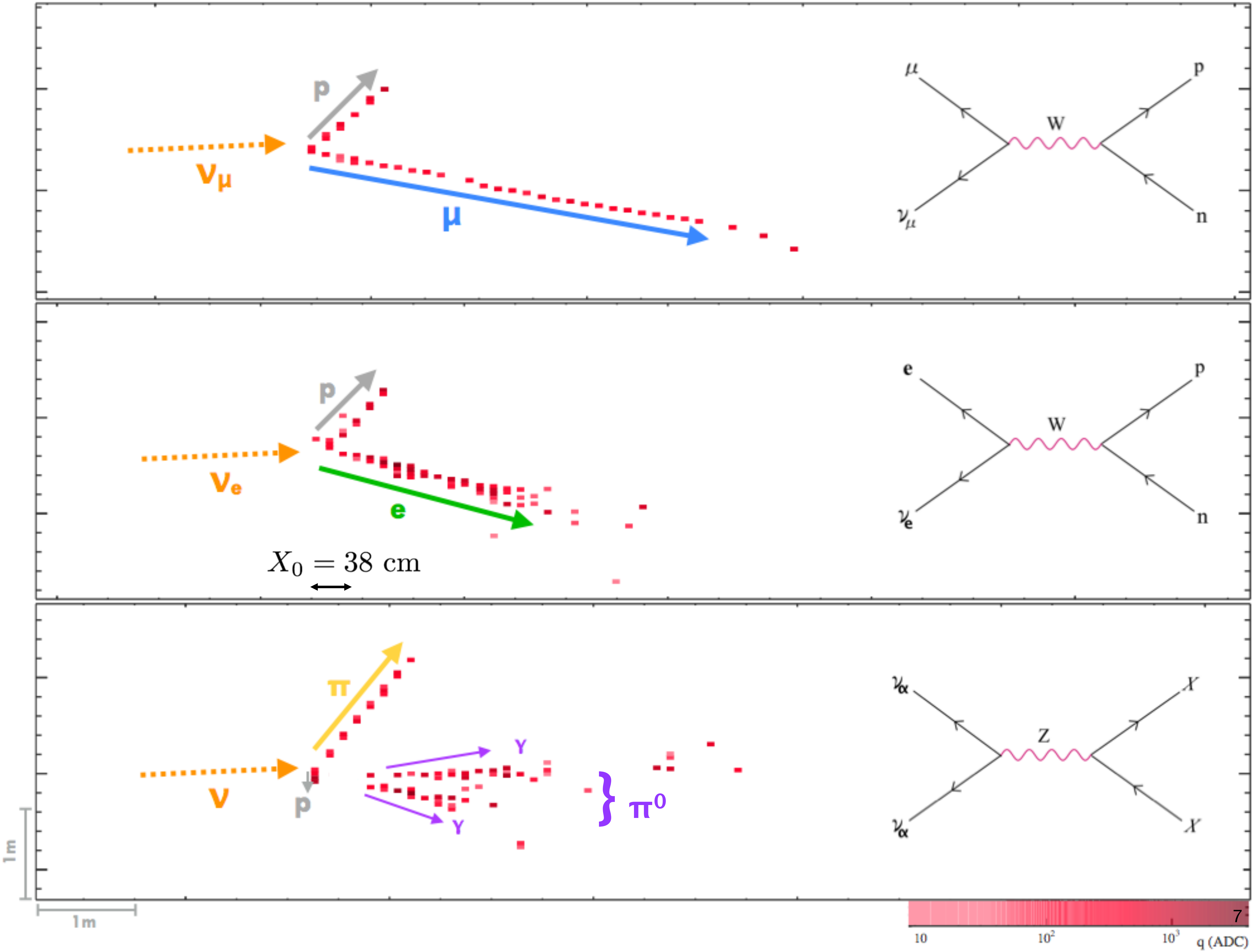
Wavelength shifting fiber
(18k km)
- 0.7 mm diameter
- Looped, both ends to same readout pixel

Avalanche photodiodes (APD)
(14k boards, 32 channels each)
- 85% quantum efficiency at long wavelengths
- Collect 30 photoelectrons per muon crossing at far end of cell

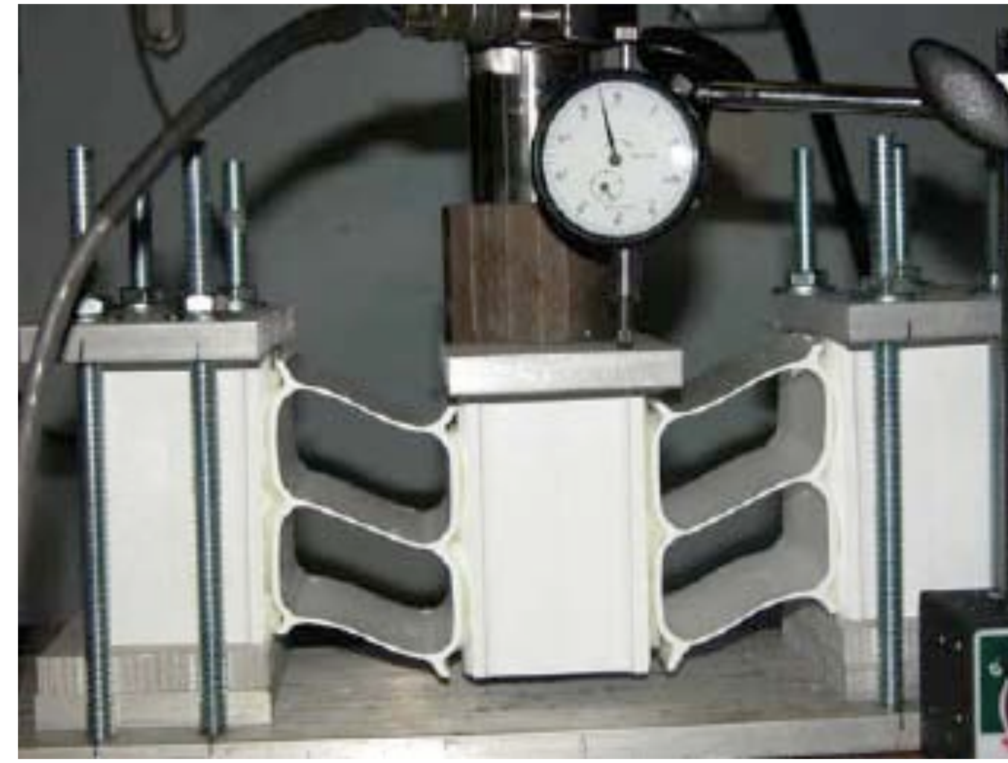




Detector design

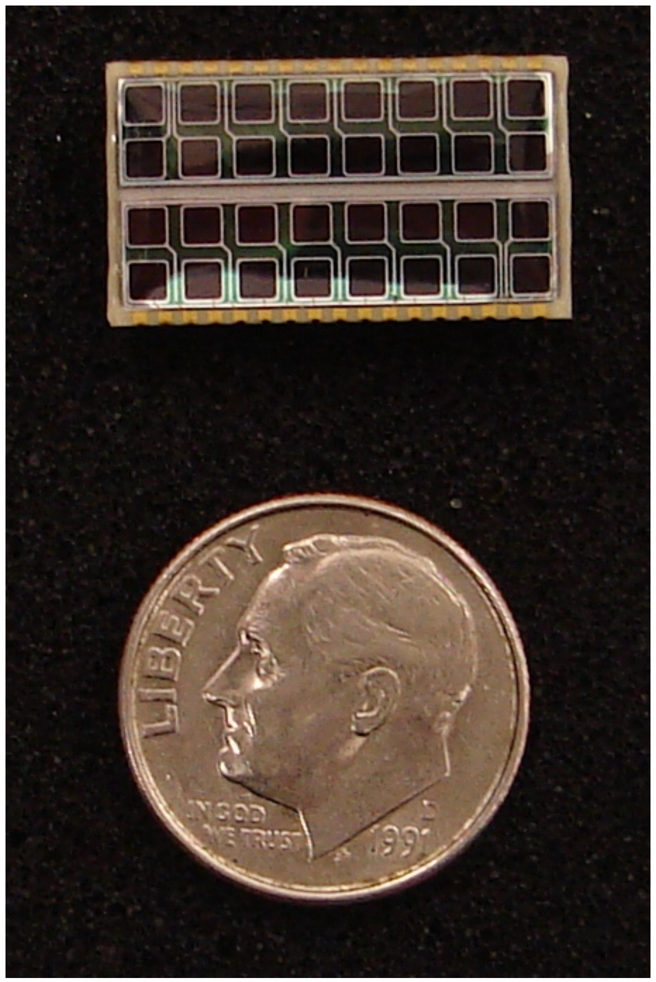


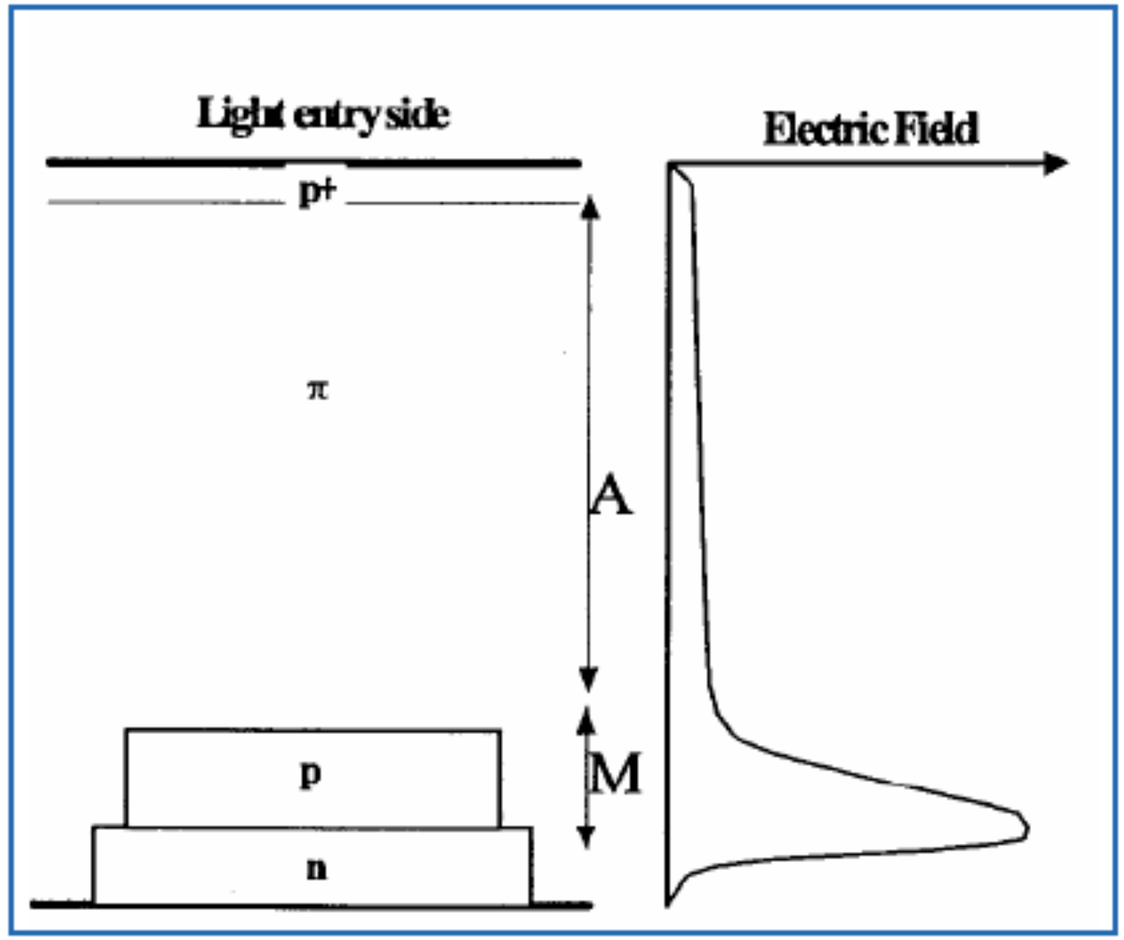
ν_μ
p
μ
μ
p
W
ν_μ
n
ν_e
p
e
e
p
W
ν_e
n
$X_0 = 38$ cm
ν
p
π
γ
γ
π^0
ν_α
X
Z
ν_α
X
1m
1m
10
10^2
10^3
q (ADC)



Can you build big structures with plastic?

Avalanche photo diodes (APD)





Absorption region

Multiplication region

High (80%) quantum efficiency even into UV

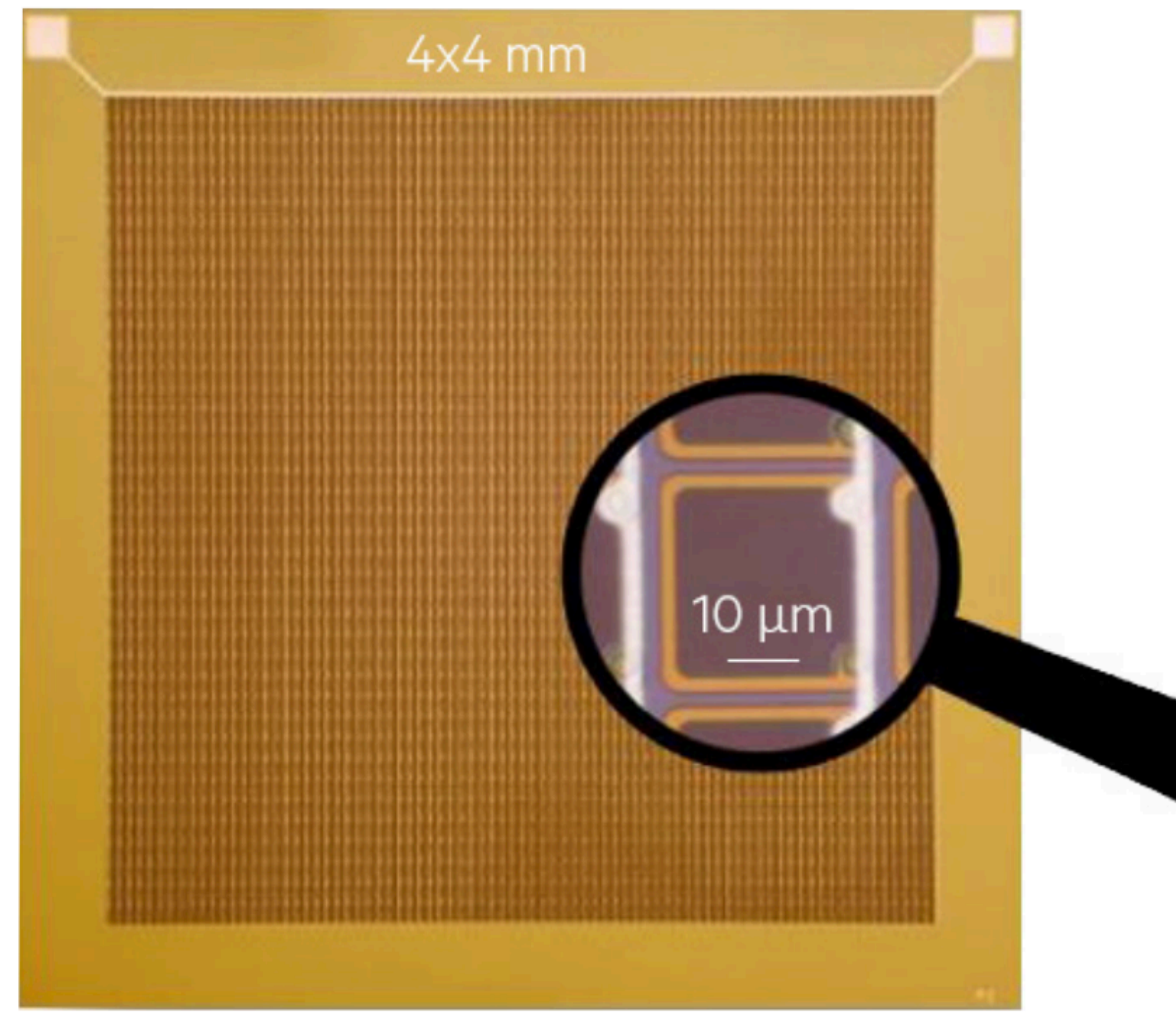
Large dark currents - must be cooled to -10^{o}C to get noise down to ~10 pe equivalent

Low gains, x100

Silicon Photomultipliers - SiPMs

- Large array of small APDs pixels.
- Each APD pixel is operated slightly above the breakdown voltage.
- When light is incident on a pixel it initiates an avalanche within the pixel, multiplying with a gain of ~10^6 up to a maximal current set by either an active of passive quenching circuit.
- The output is proportional to the number of activated pixels which gives a count of the number of photoelectrons.

Figure 1



https://www.first-sensor.com/cms/upload/appnotes/AN_SiPM_Introduction_E.pdf

Silicon Photomultipliers - SiPMs

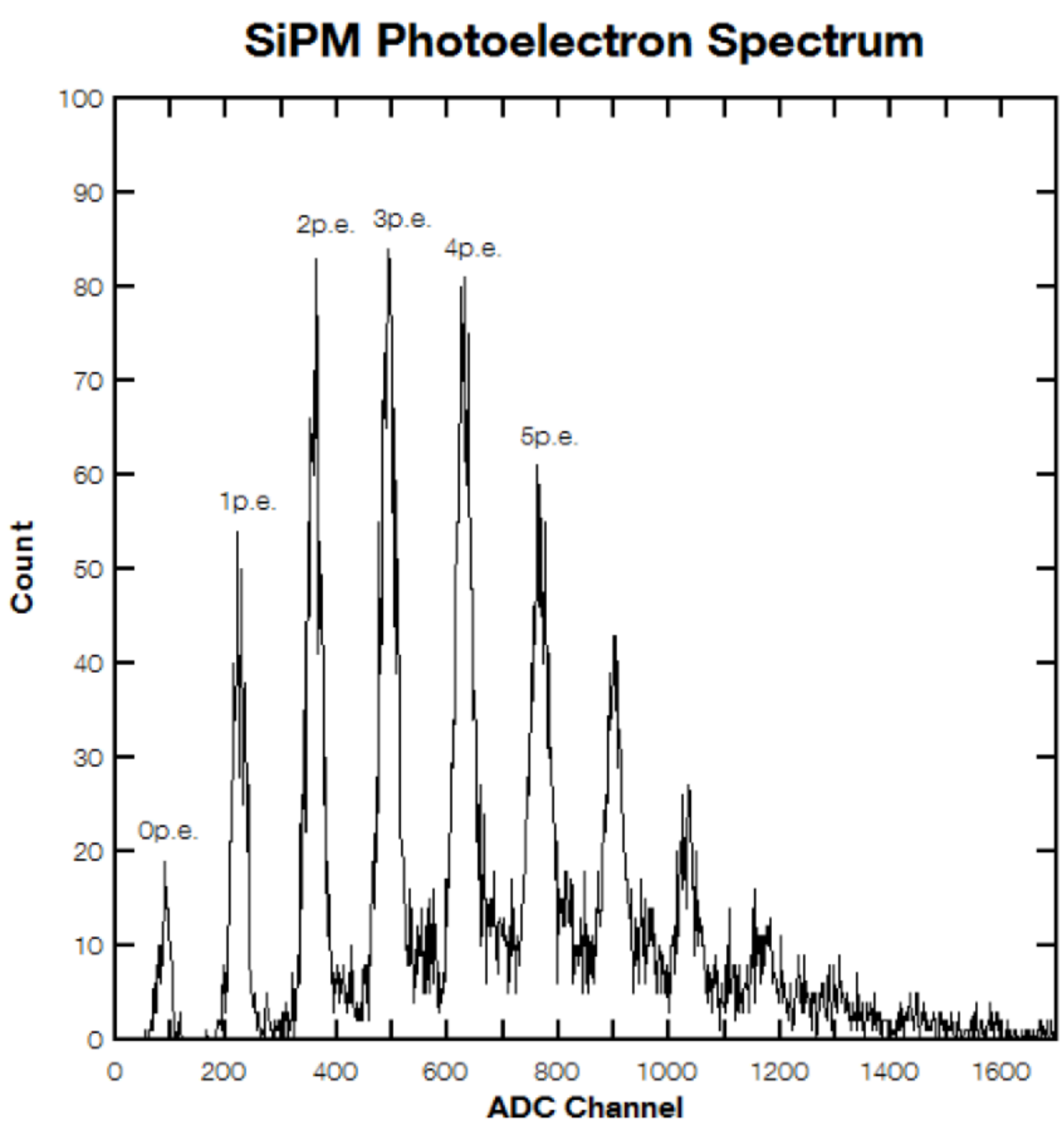


Figure 7, Photoelectron spectrum of the SiPM, achieved using brief, low-level light pulses, such as those from Fig. 6.

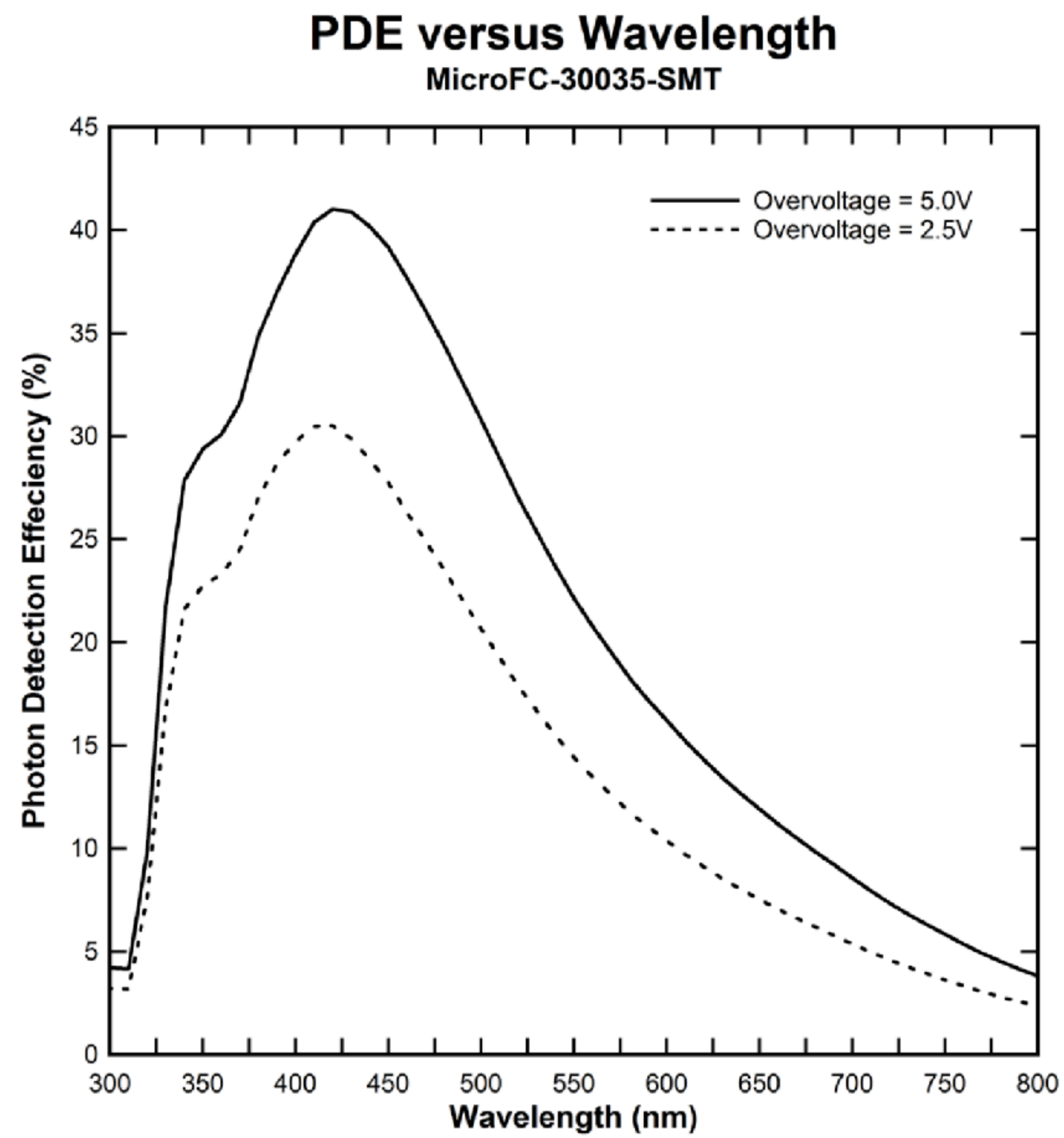
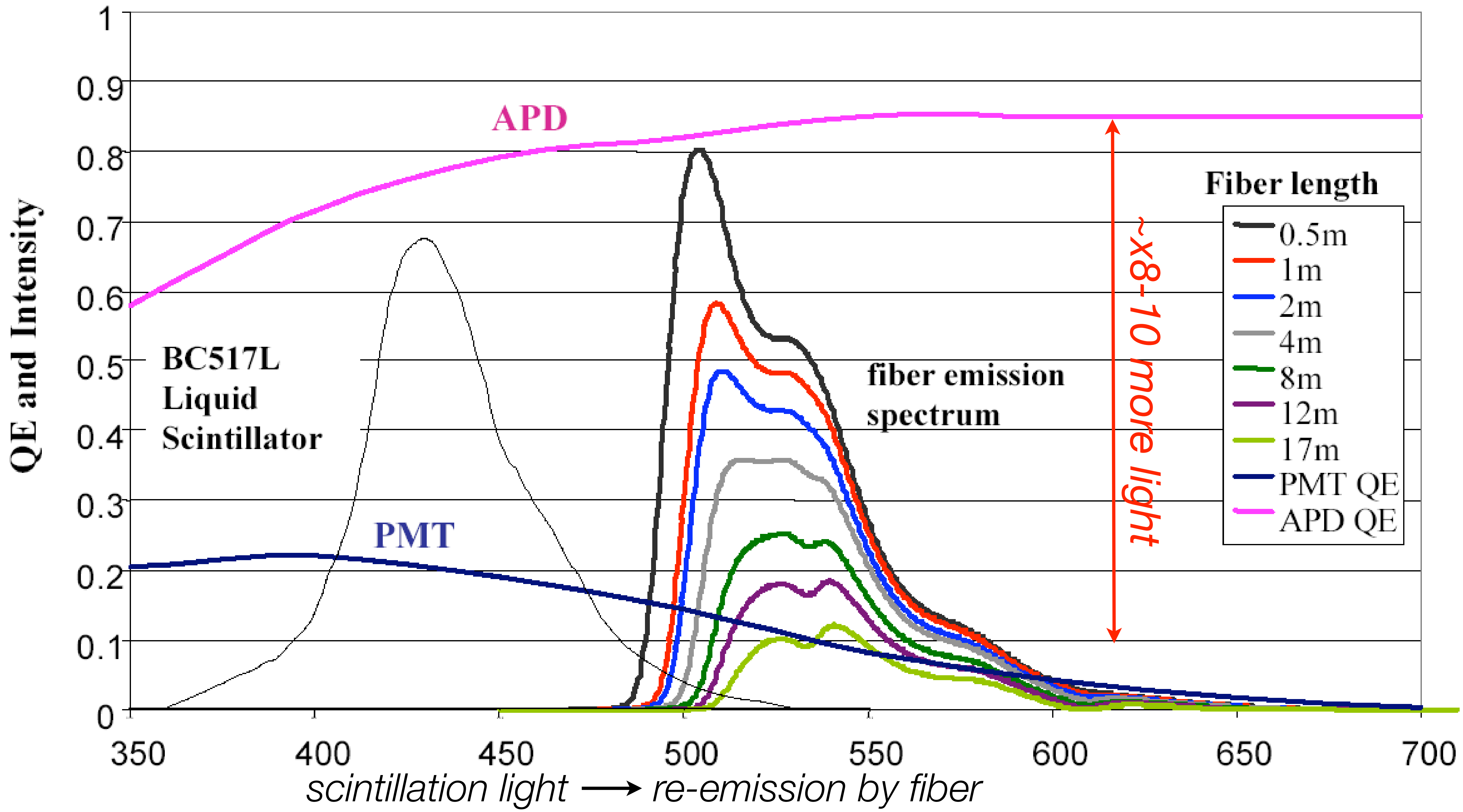


Figure 16, PDE as a function of wavelength for different overvoltages.

https://www.sensl.com/downloads/ds/TN%20-%20Intro%20to%20SPM%20Tech.pdf

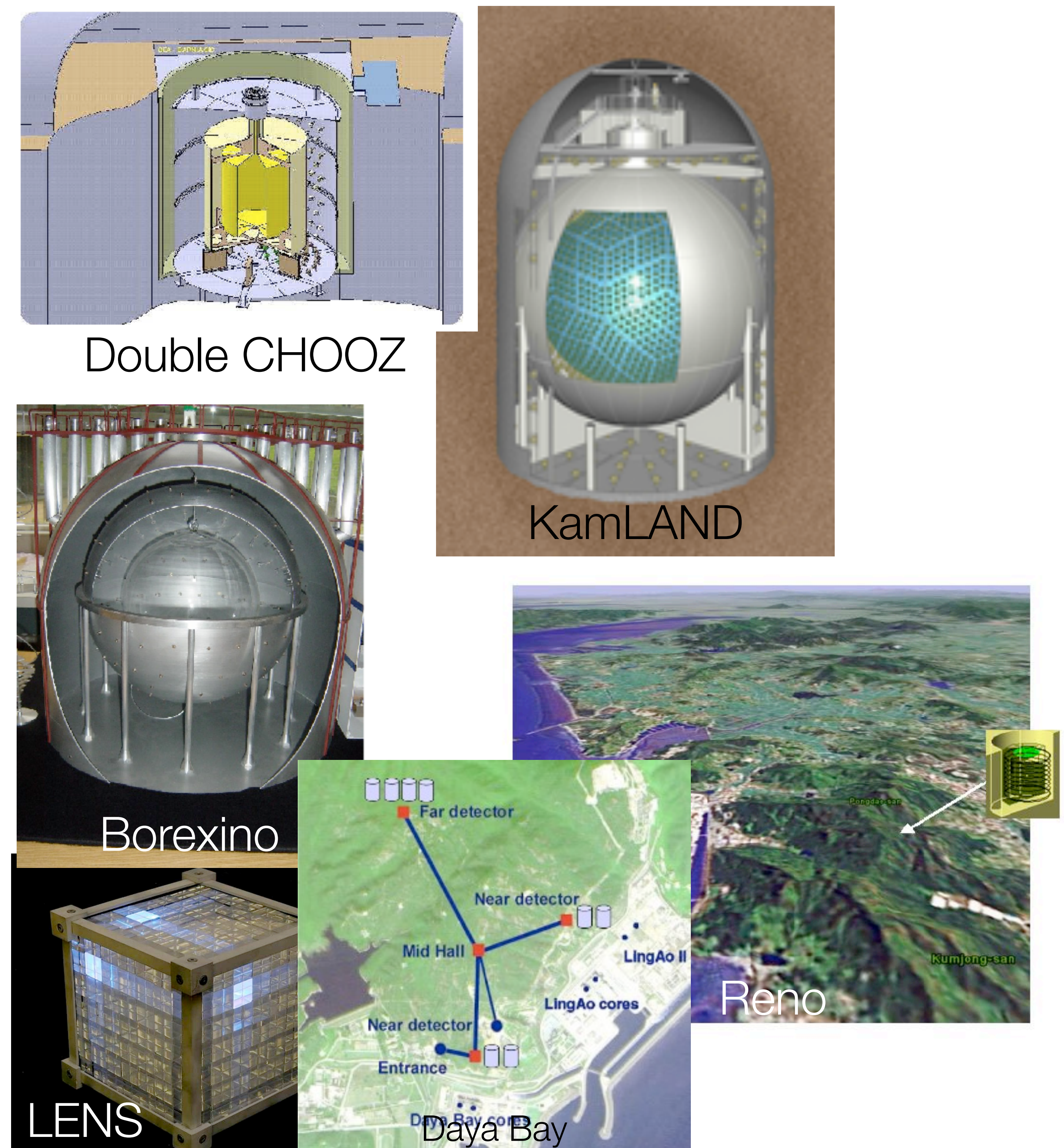
NOvA Fiber and Photodetector



The high QE of APD's, especially at long wavelength, is crucial to NOvA performance

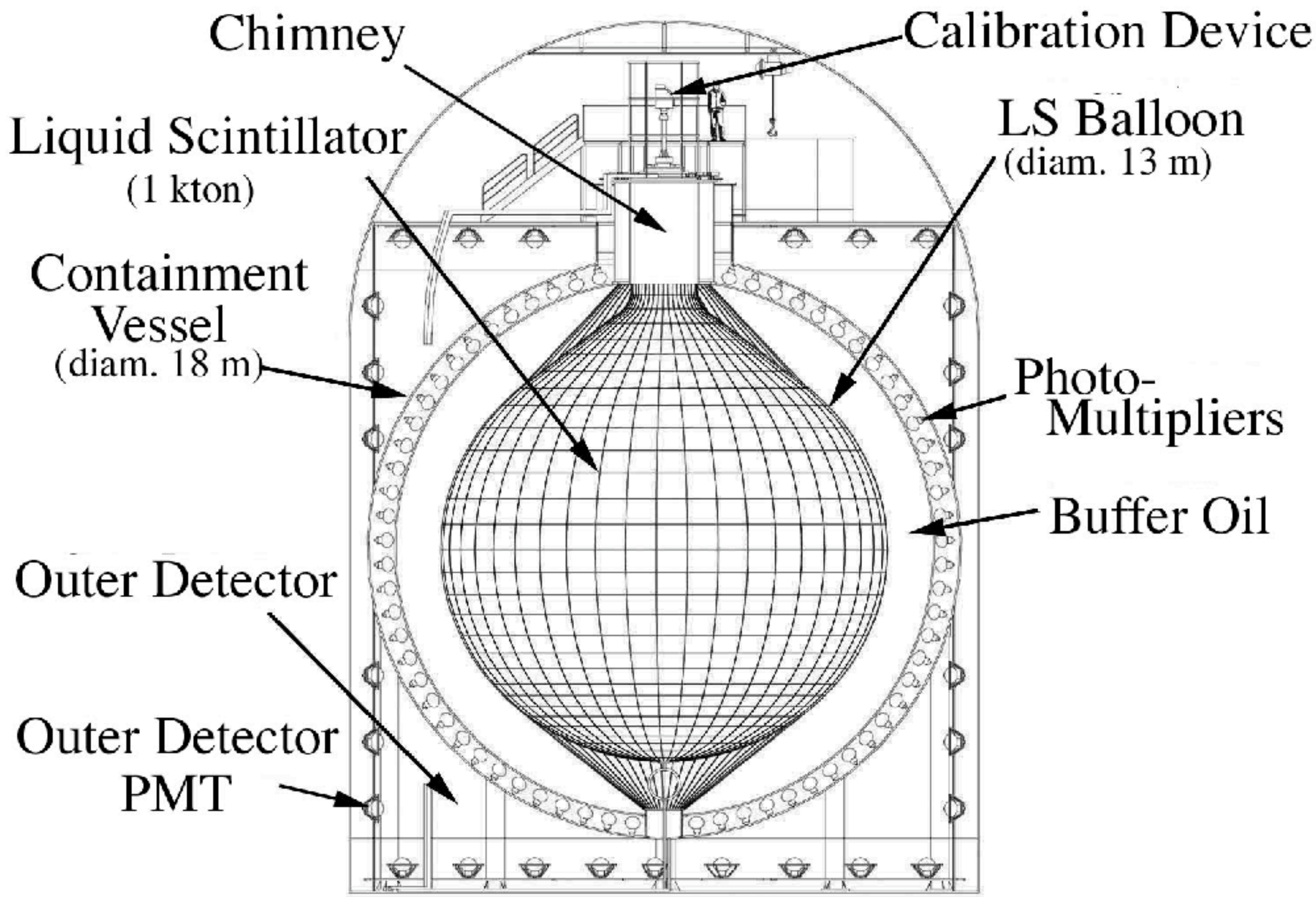
Unsegmented liquid scintillator detectors

- Large volume of liquid scintillator viewed by PMT's
- Anti-electron neutrino detection from reactors at ~3.5 MeV
- Electron neutrino detection via elastic scattering from Sun at 0.7 MeV
- Scintillator allows for larger light collection (~200 photons/MeV) than water
- Used for detection of anti-neutrinos from reactor experiments (CHOOZ/KamLAND/Double CHOOZ/Daya Bay/Reno) and neutrinos from the Sun (Borexino)
- At these low energies the name of the game is background suppression from naturally occurring radioactive sources



Building for low background: Buffer zones

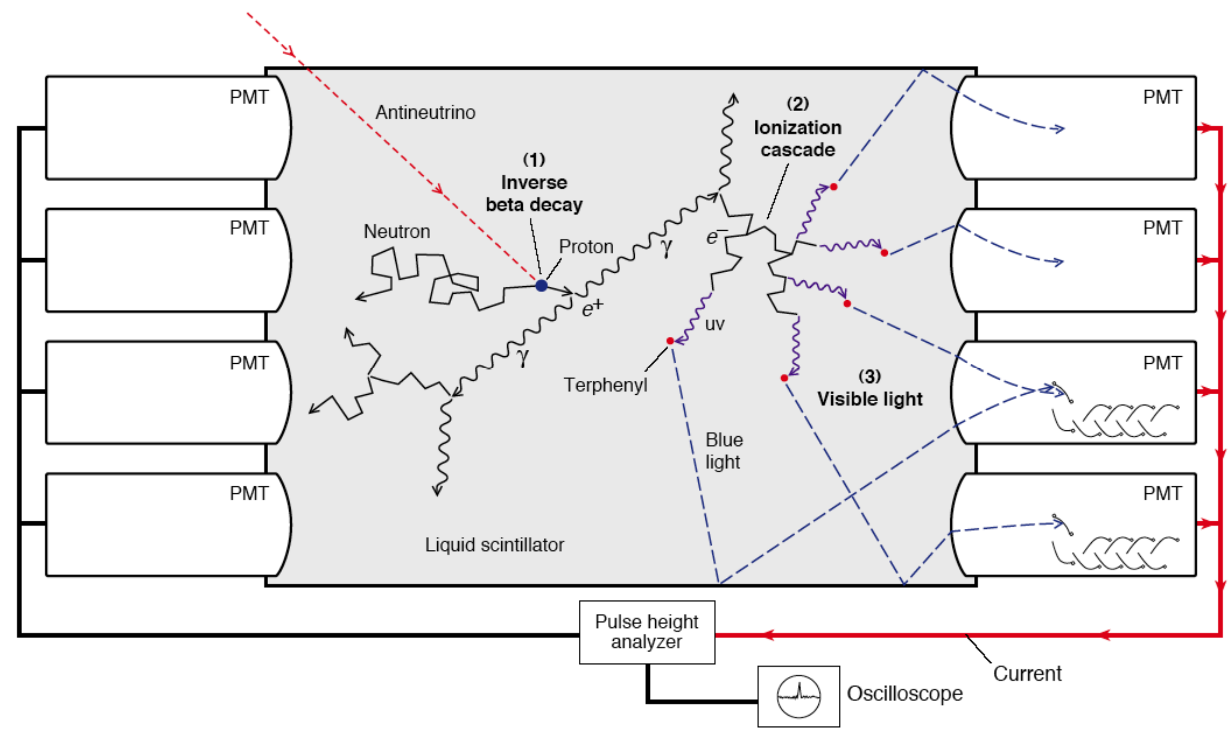
- For these low energy detectors it is common to build the detector in layers of buffer zones with careful control of components that go into the central most zones
- “Dirty” components, for example PMT glass which contains lots of U and Th, are kept away from the central regions.

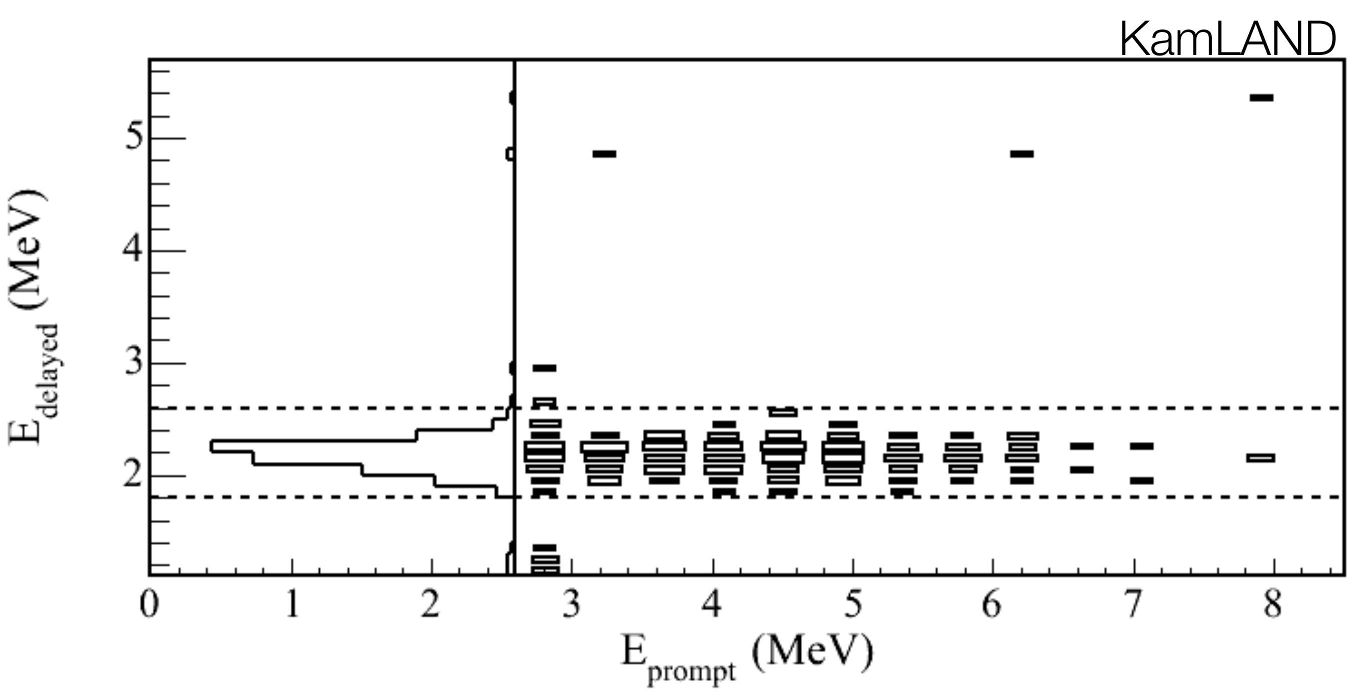


KamLAND

Background rejection: Coincidence

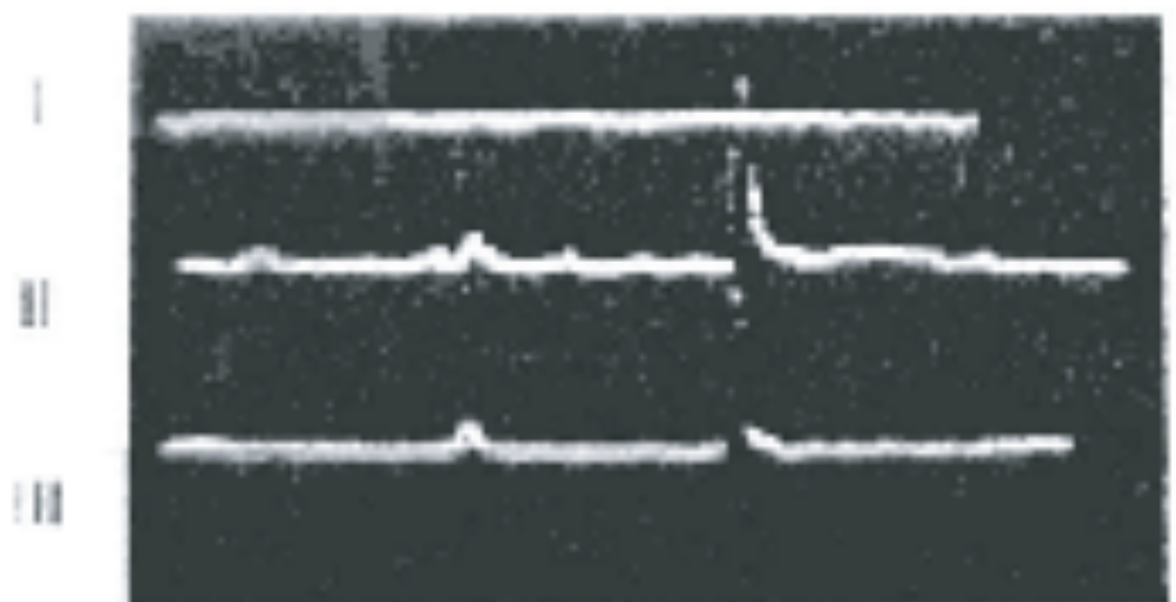
- For reactor neutrino experiment the detection channel is:
$$\bar{\nu}_e + p \rightarrow e^+ + n$$
- Positron deposits its kinetic energy and annihilates promptly
$$E_{e^+} = E_{\bar{\nu}_e} - (M_n - M_p) + m_e$$
- Neutron wanders around for ~5 ms and is captured about 5 cm away from interaction vertex (on Gd or Cd dissolved in scintillator) releasing 2.2 MeV in gamma rays (in case of KamLAND shown here)
- This energy-time double coincidence signal dramatically beats the background down



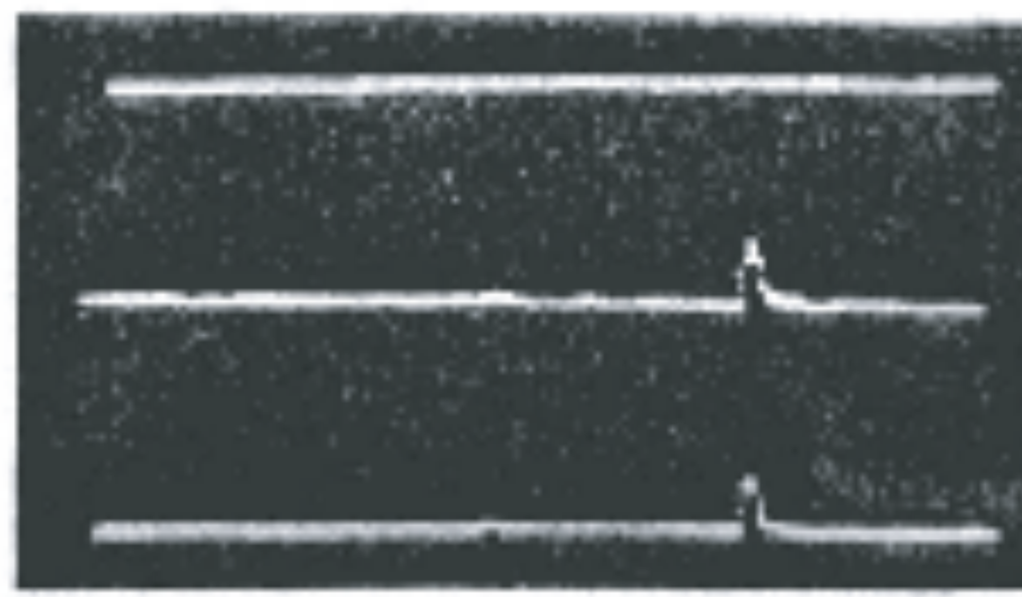


Los Alamos Science, Number 25 1997

Fred Reines and Clyde Cowan. 1995 Nobel to Reines for the detection of the neutrino



(b) Positron scope

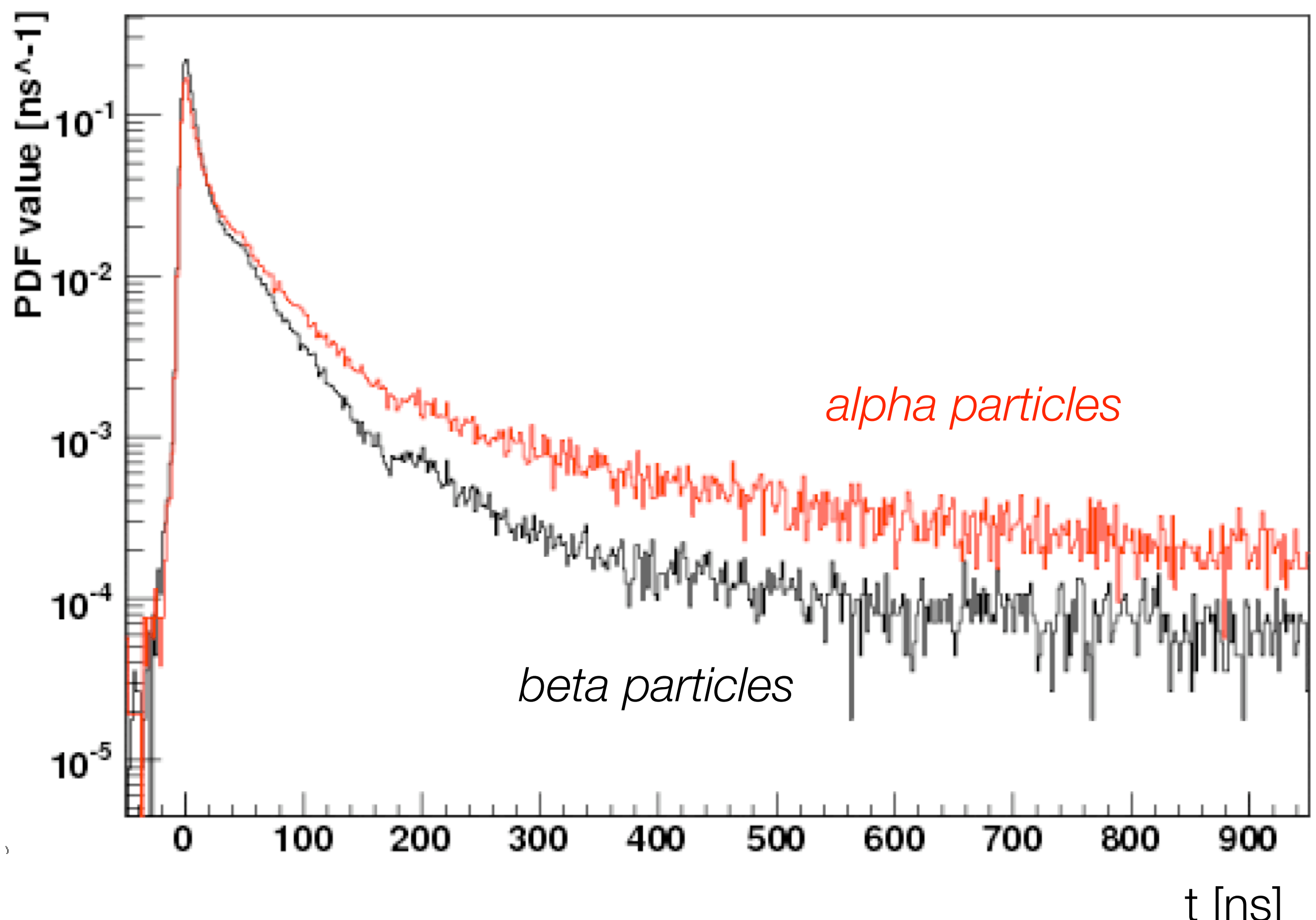


Neutron scope

Project Poltergeist, 1953

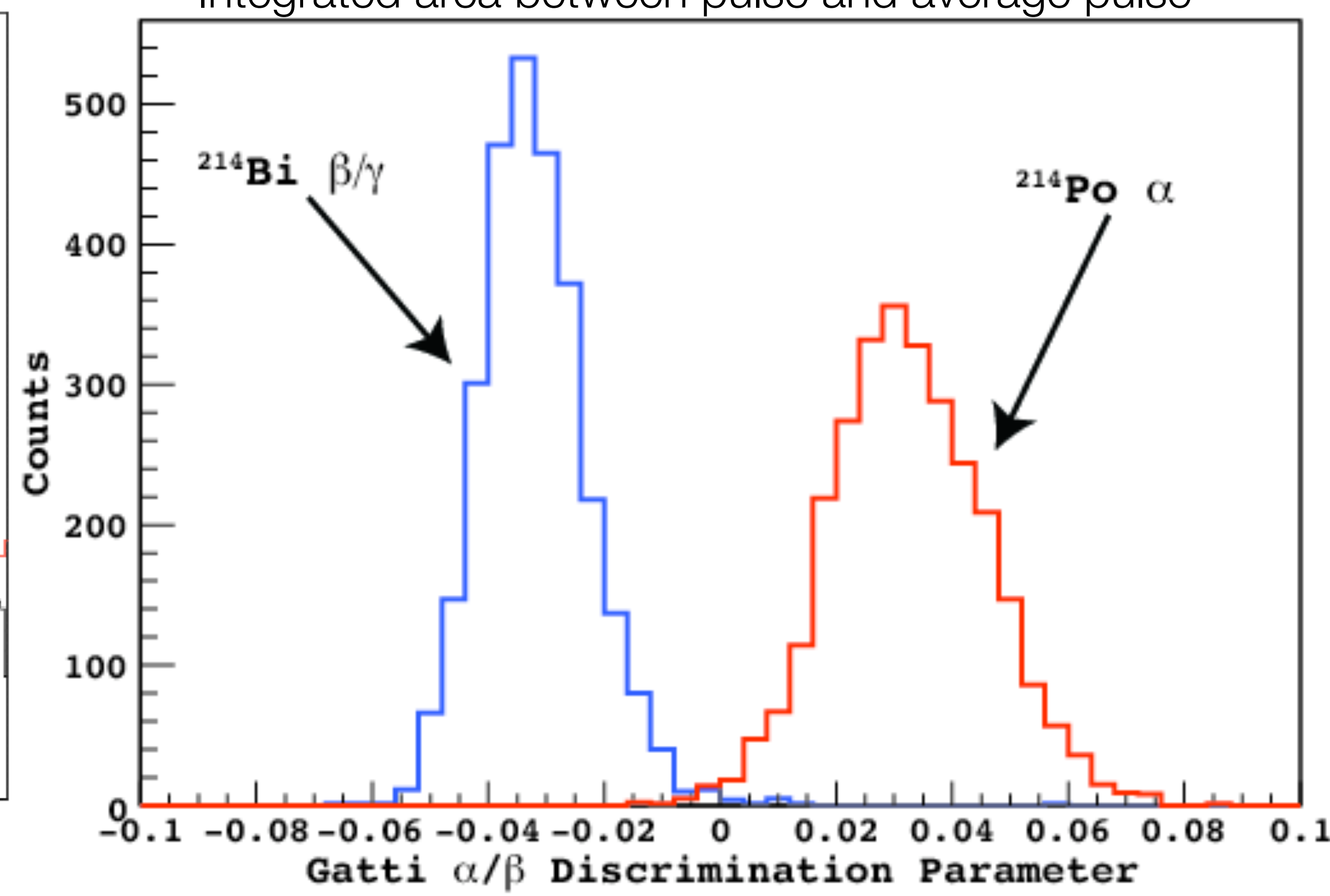
Alpha/Beta discrimination: Borexino

- Can remove events due to alpha emitters based on pulse shape analysis



Highly ionizing alpha particles saturate more of the scintillator and excite more of the states with longer lifetimes

Integrated area between pulse and average pulse



Neutron response

- Fast neutrons are visible in scintillators if they transfer their energy to ionizing particles. Typically this is through (n, p) scattering. Having lots of hydrogen available (mineral oil, plastic) helps transfer this energy. In this case, pulse height discrimination can help separate energy from proton recoils and energy from photons which accompany these scatters and compensate correctly.

- Thermal neutrons can be detected through (n, γ) and (n, α) interactions with nuclei. Scintillators are doped with ^{6}Li or ^{10}B which have high neutron absorption cross-sections to enhance these captures.

https://www.osti.gov/pages/servlets/purl/1253950

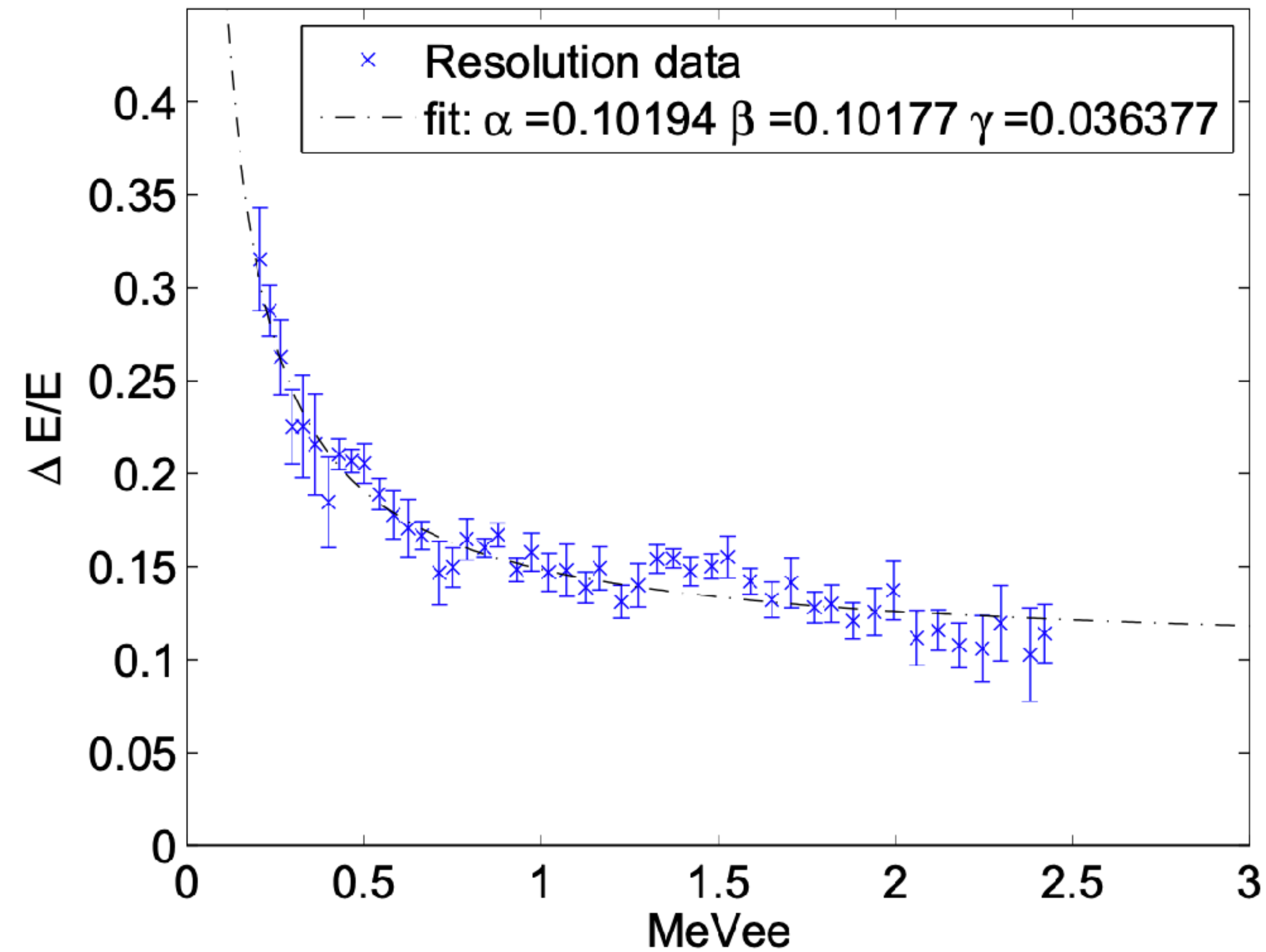
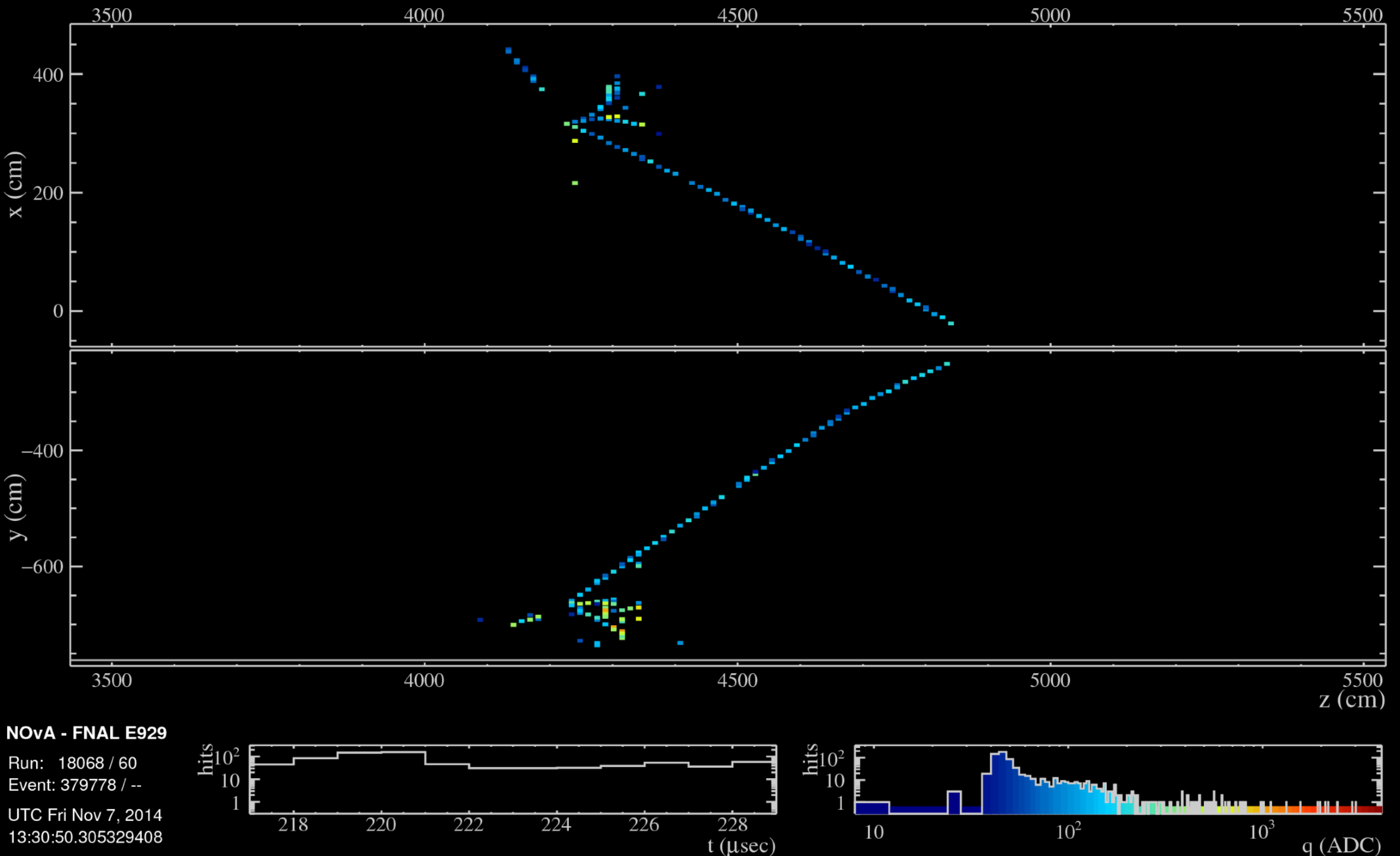


Figure 15: The energy resolution data and fit for 12.7-by-12.7 cm EJ-309 liquid scintillation detector.

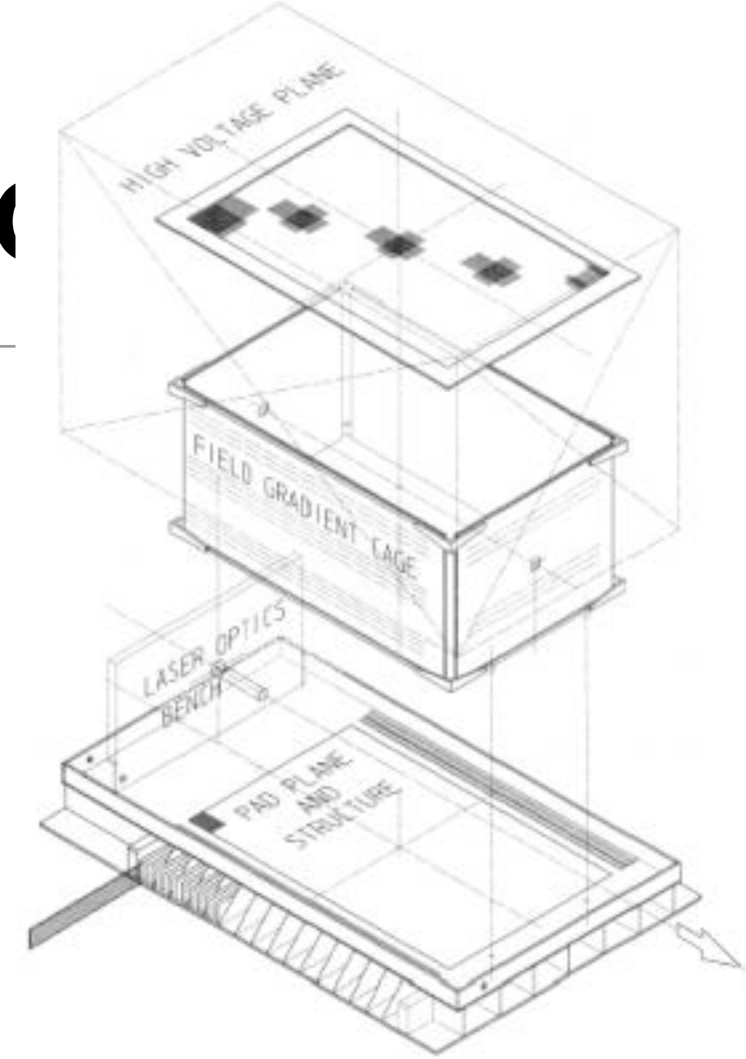


3500
4000
4500
5000
5500
400
200
0
x (cm)
−400
−600
y (cm)
z (cm)
NOvA - FNAL E929
Run: 18068 / 60
Event: 379778 / --
UTC Fri Nov 7, 2014
13:30:50.305329408
hits
10^2
10
1
218
220
222
224
226
228
t (µsec)
q (ADC)

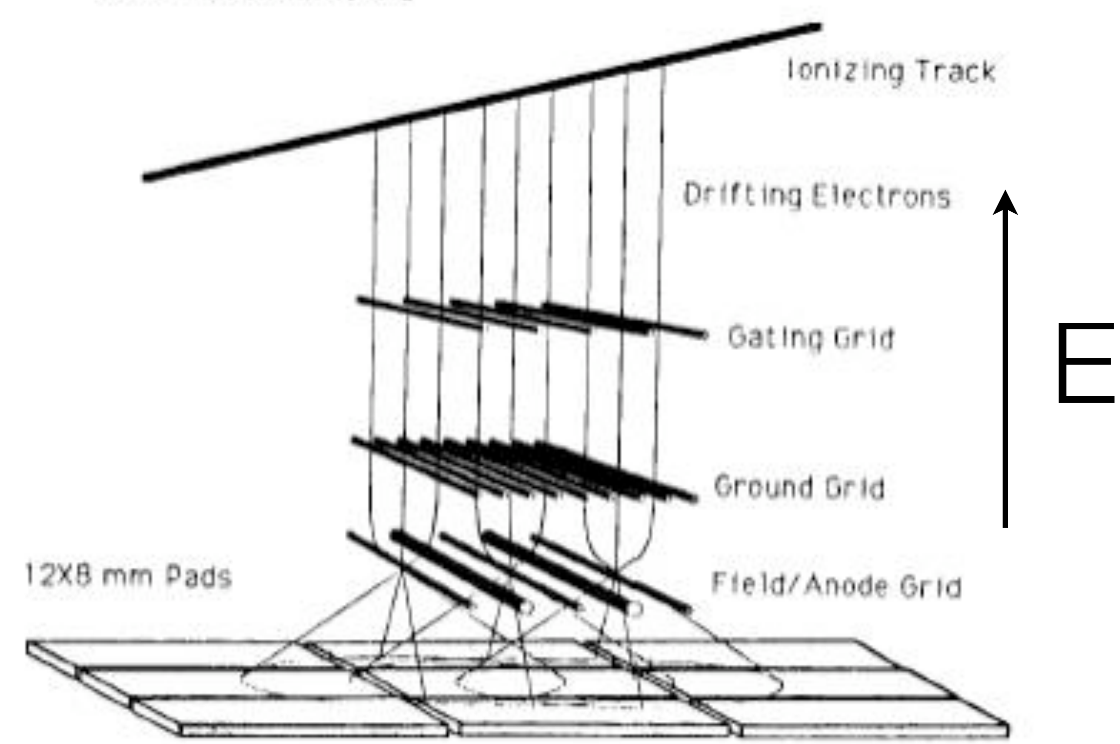
Time Projection Chambers

Time projection chambers (TP

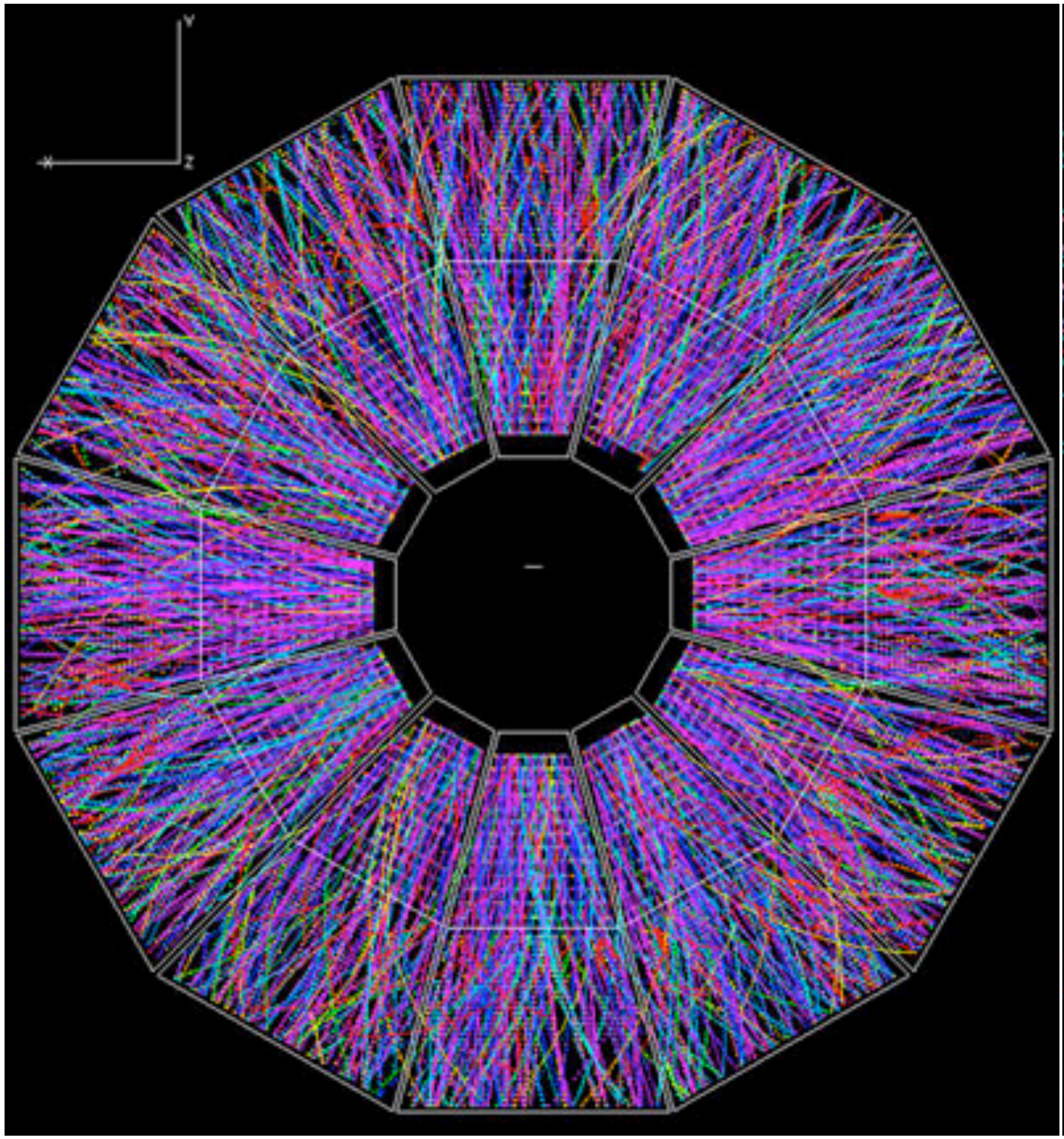
- Gas TPC’s have been widely used by a number of high energy and nuclear experiments
- Provide 3D tracking with ~mm resolution.
- Particle ID possible below 1 GeV using <dE/dx>
- A very common gas Argon-Methane gas mixture. Nobel gas allows for long electron drifts and methane boosts ionization yield.
- Electric fields typically 200 V/cm
- Electron clouds reach terminal velocity at about 5 cm/usec.
- Pads or wire chambers provide 2-D track projection. Arrival times provide 3rd dimension.



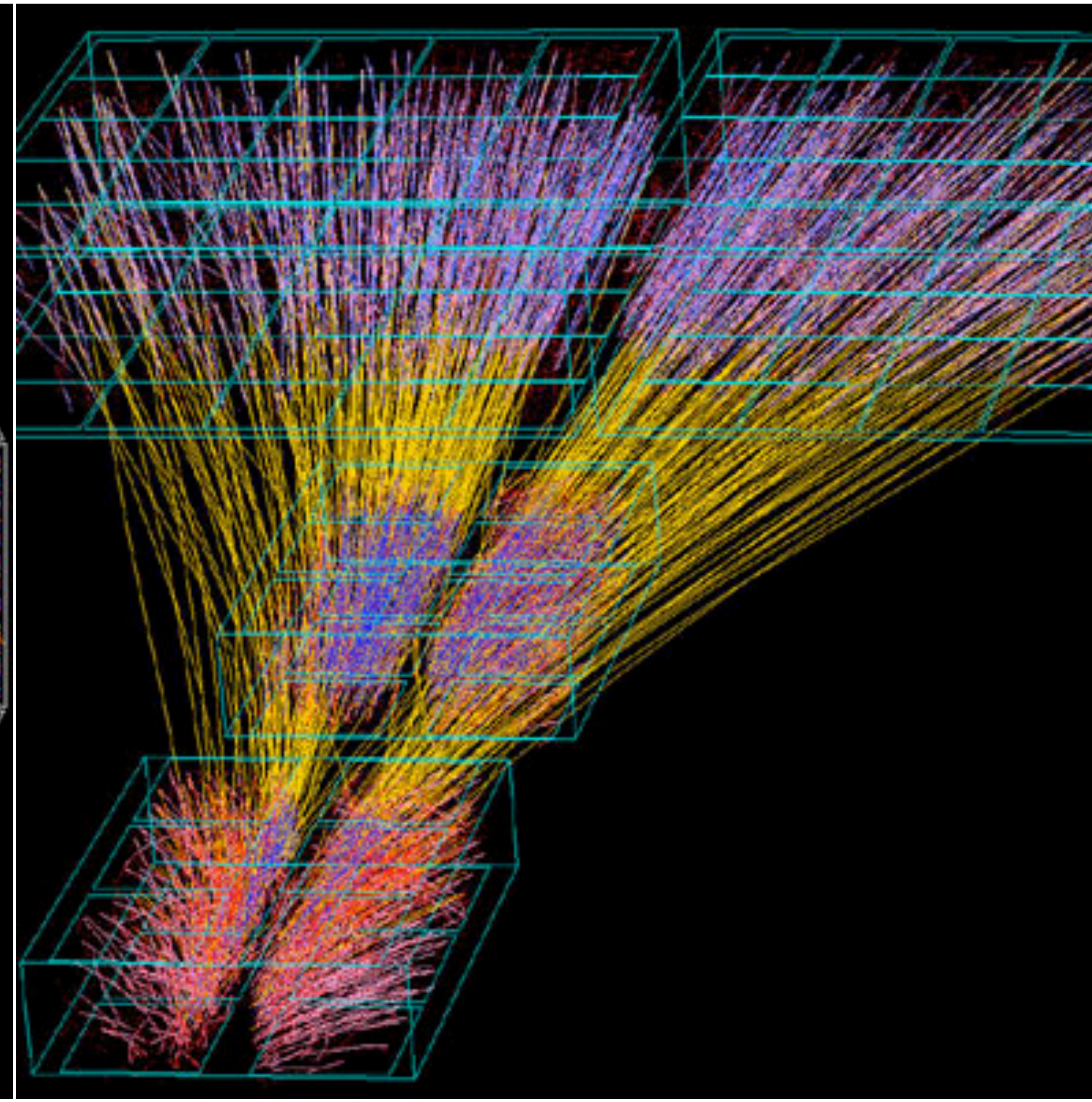
HISS TPC PAD PLANE



TPCs are well suited to high multiplicity environments



Au + Au at 130 GeV in STAR @ BNL

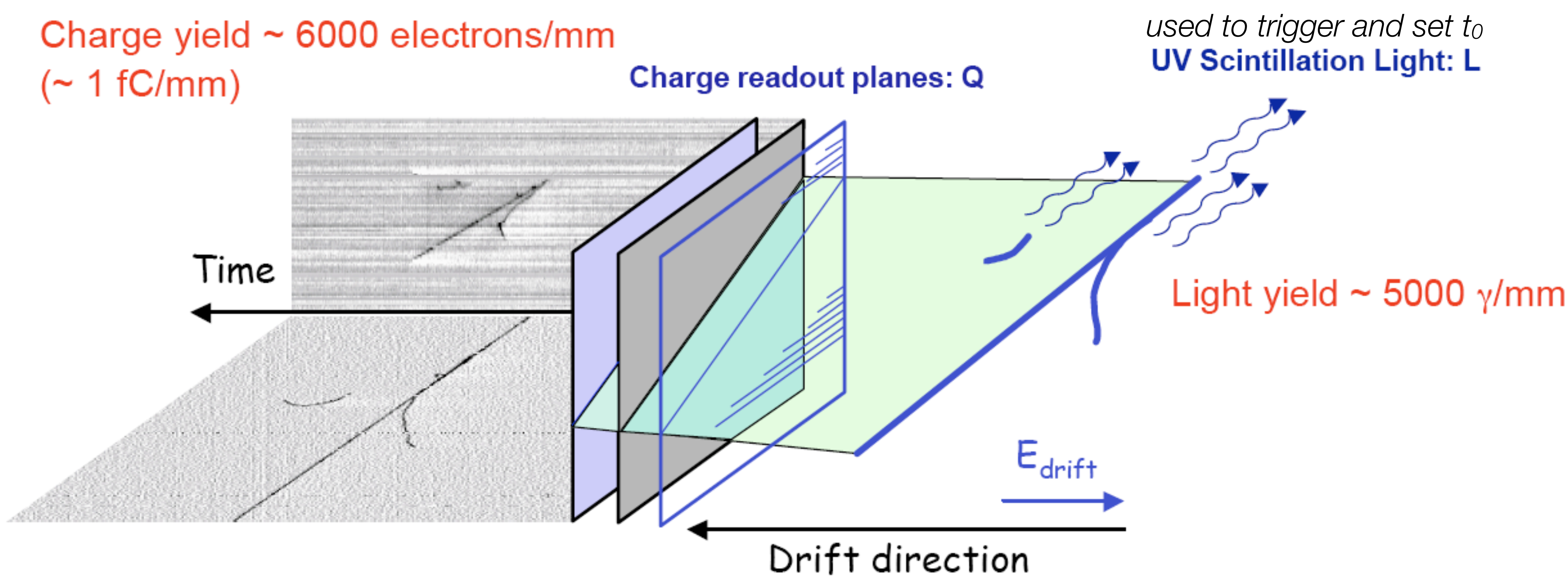


Pb + Pb at 17 GeV in NA49 @ CERN

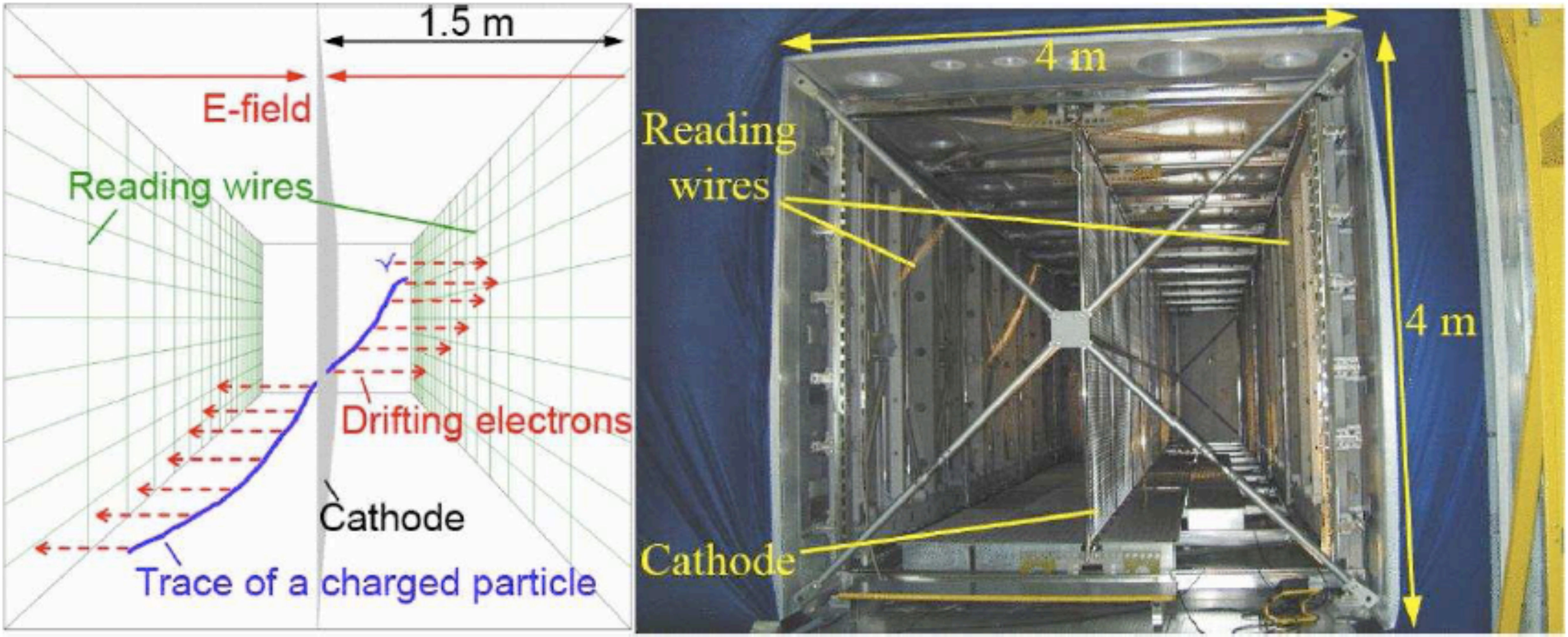
Liquid Argon TPC: Concept

To be applicable to neutrino experiments higher density is required. Use liquid Ar instead of gas. Has potential to reach very large masses (100 kt) with ~mm granularity.

- Boiling point: 87 K (compare to N_2 77 K)
- Density 1.4 g/cc
- Interaction length: 114 cm
- Radiation length: 14 cm
- Moliere radius: 7 cm



The ICARUS LqAr Detector

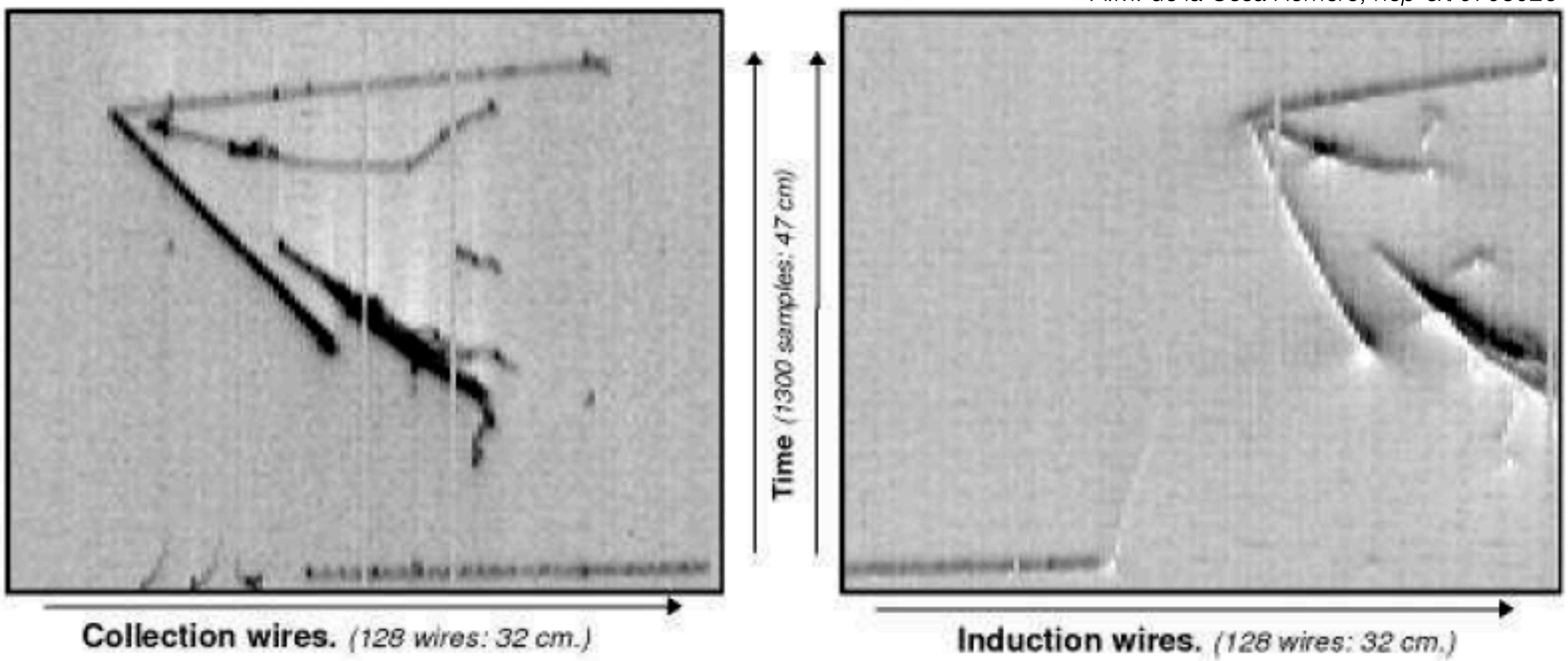


A.M. de la Ossa Romero, hep-ex/0703026

Figure 2.4: Picture of the open T300 ICARUS module during assembly.

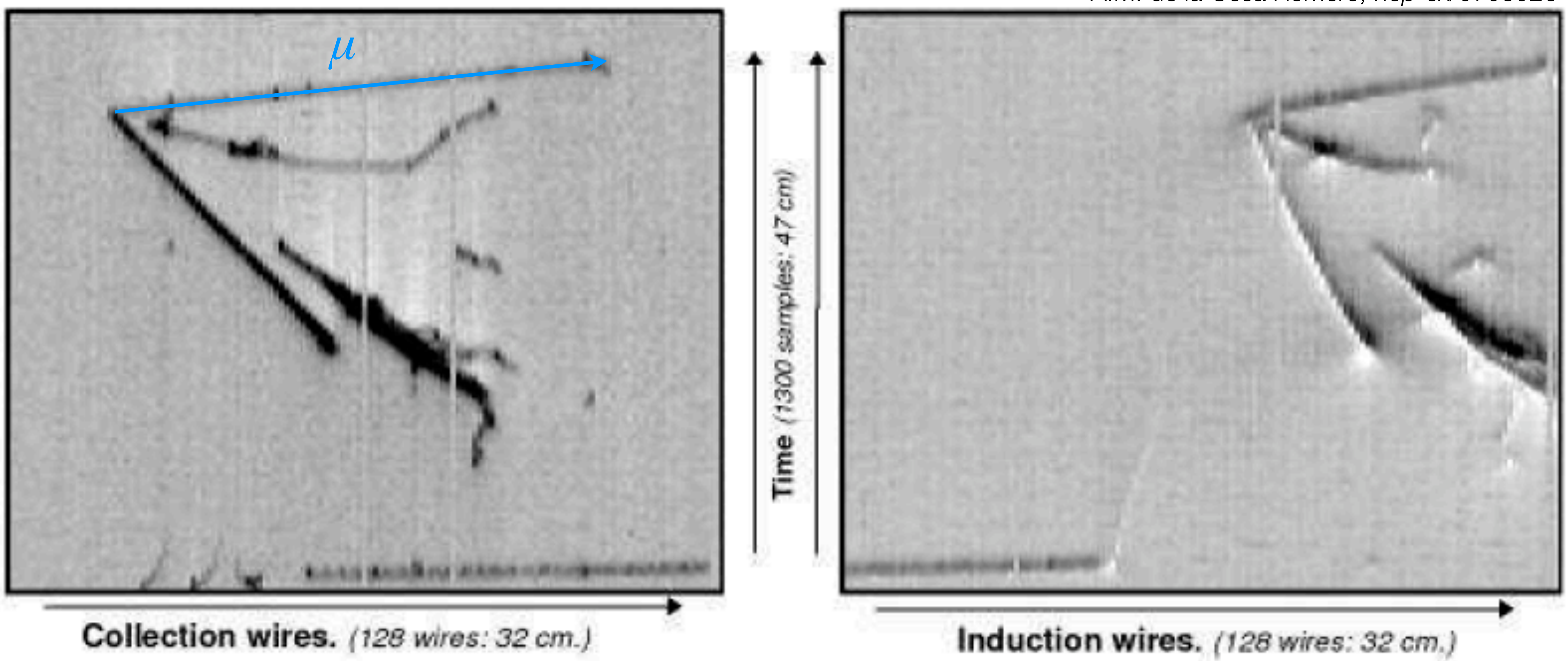
What’s going on in this event?
Recorded by 50L LqAr detector in WANF

A.M. de la Ossa Romero, hep-ex/0703026



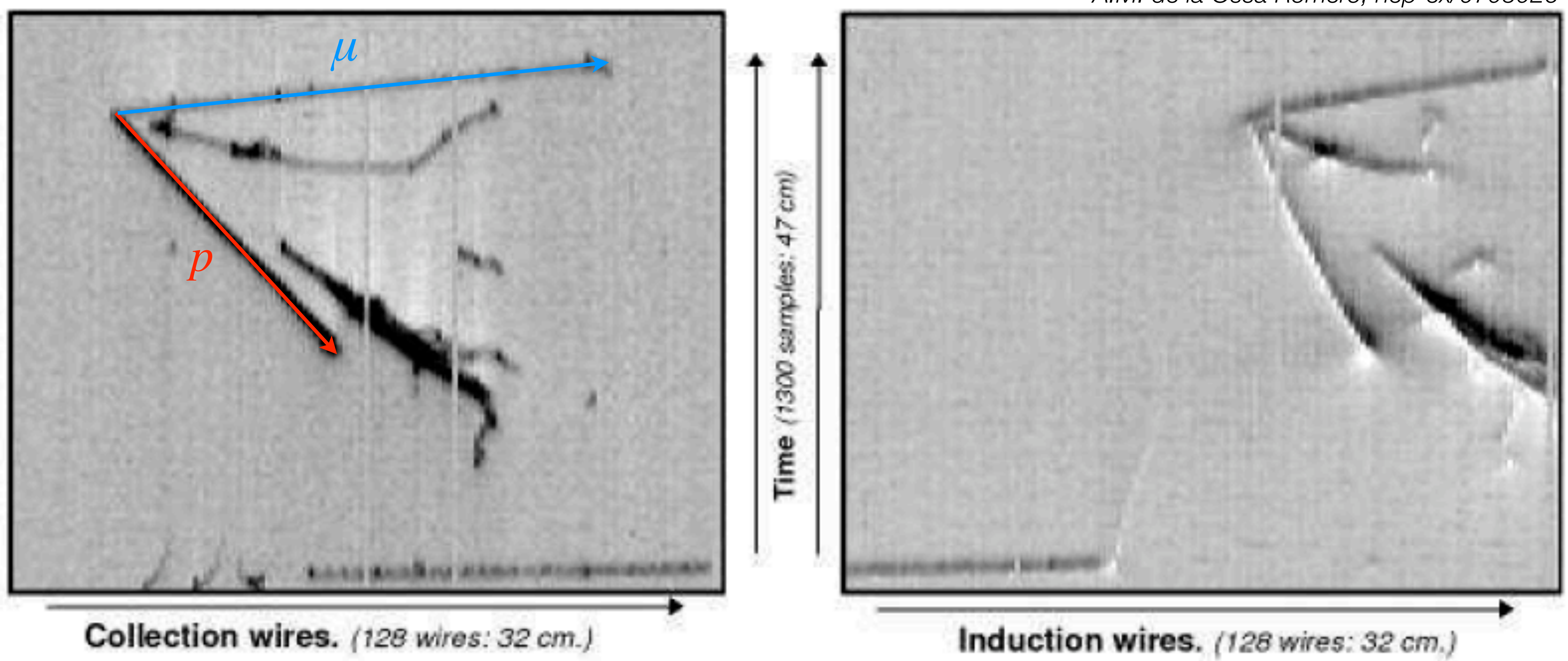
What's going on in this event?
Recorded by 50L LqAr detector in WANF

A.M. de la Ossa Romero, hep-ex/0703026



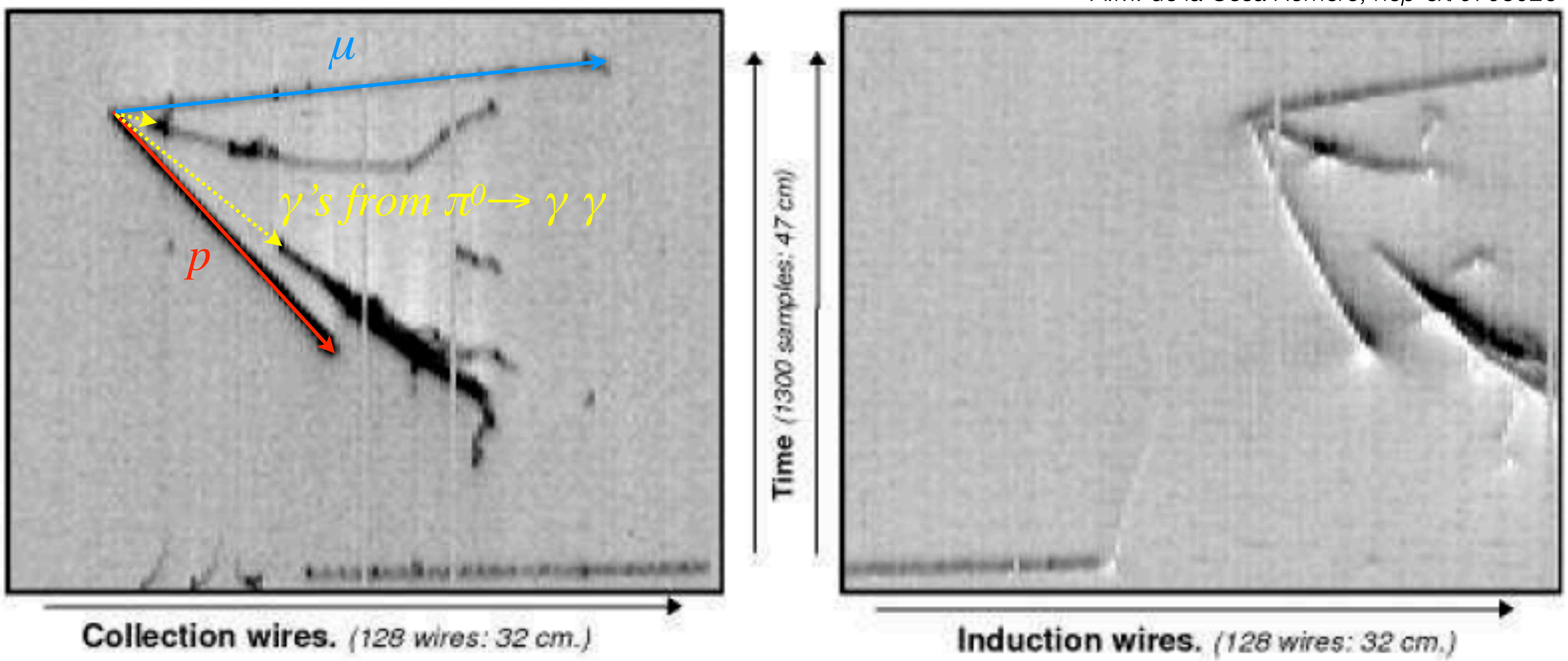
What's going on in this event?
Recorded by 50L LqAr detector in WANF

A.M. de la Ossa Romero, hep-ex/0703026



What's going on in this event?
Recorded by 50L LqAr detector in WANF

A.M. de la Ossa Romero, hep-ex/0703026



What's going on in this event?
Recorded by 50L LqAr detector in WANF

A.M. de la Ossa Romero, hep-ex/0703026

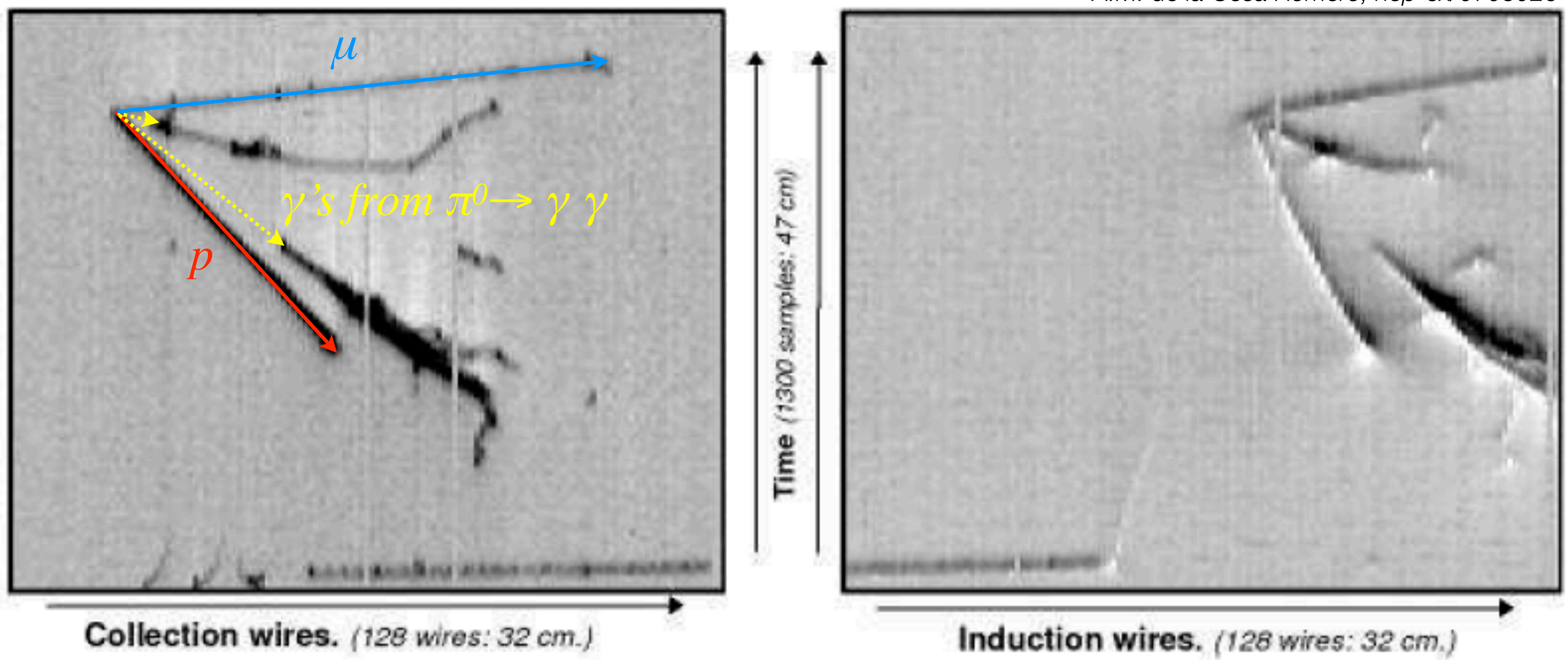
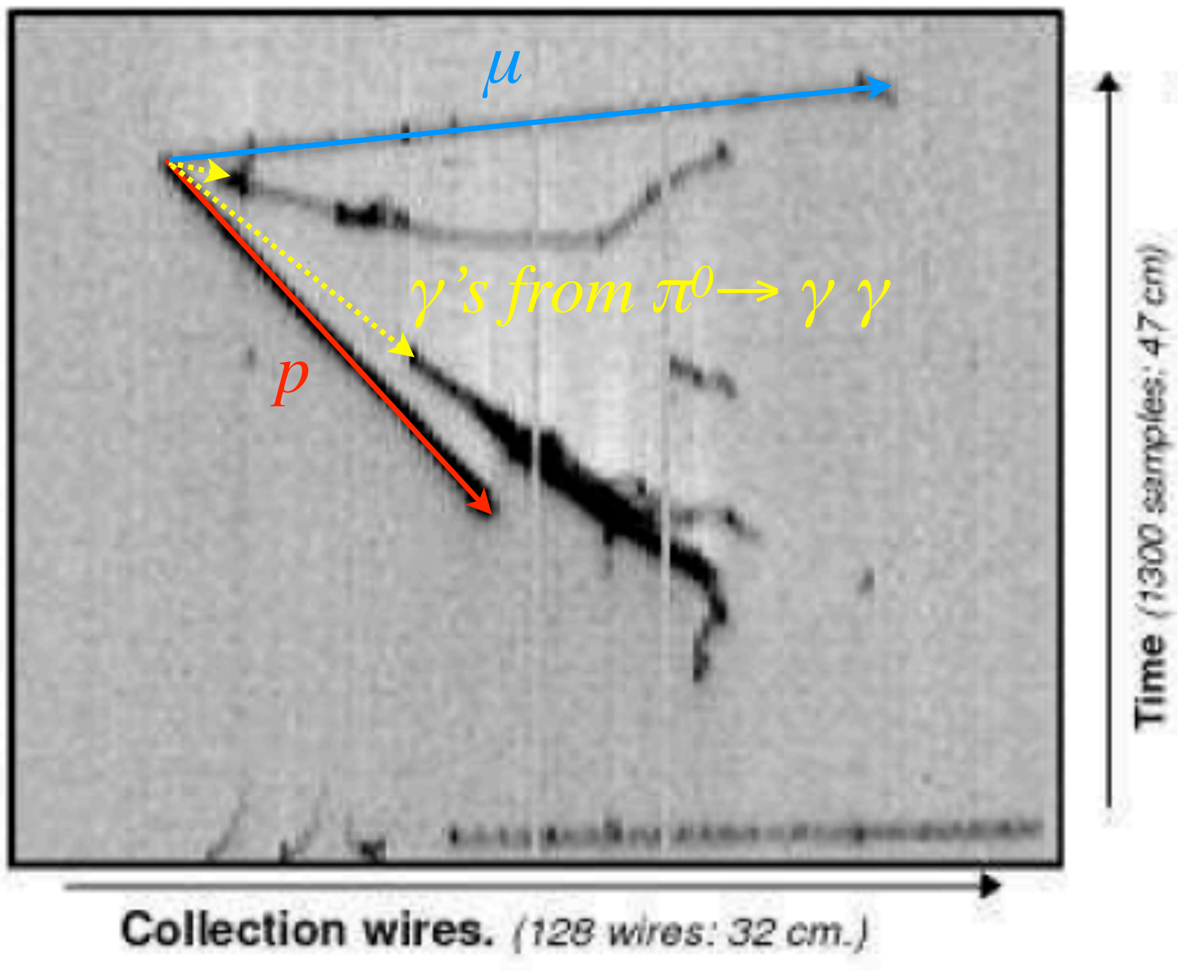


Figure 5.21: The raw image of a low multiplicity real event in the collection (left) and induction plane (right). The event is reconstructed as ($\nu_\mu\ n \rightarrow \mu^-\Delta^+ \rightarrow \mu^-\ p\ \pi^0$) with a mip leaving the chamber, an identified stopping proton and a pair of converted photons from the π^0 decay. When these photons escape from the chamber, the event is tagged as a *golden* event.

What's going on in this event?

Recorded by 50L LqAr detector in WANF

A.M. de la Ossa Romero, hep-ex/0703026



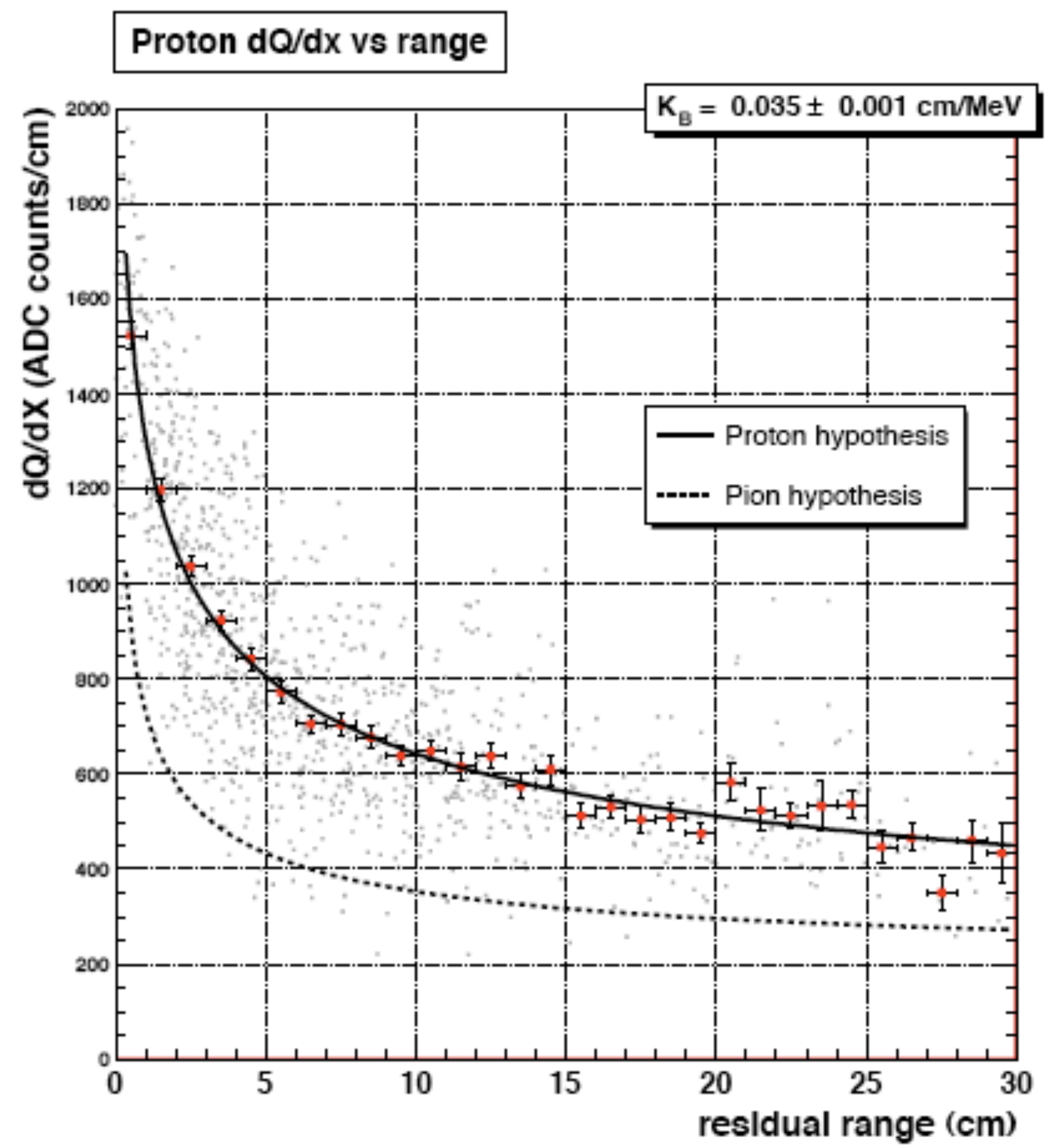


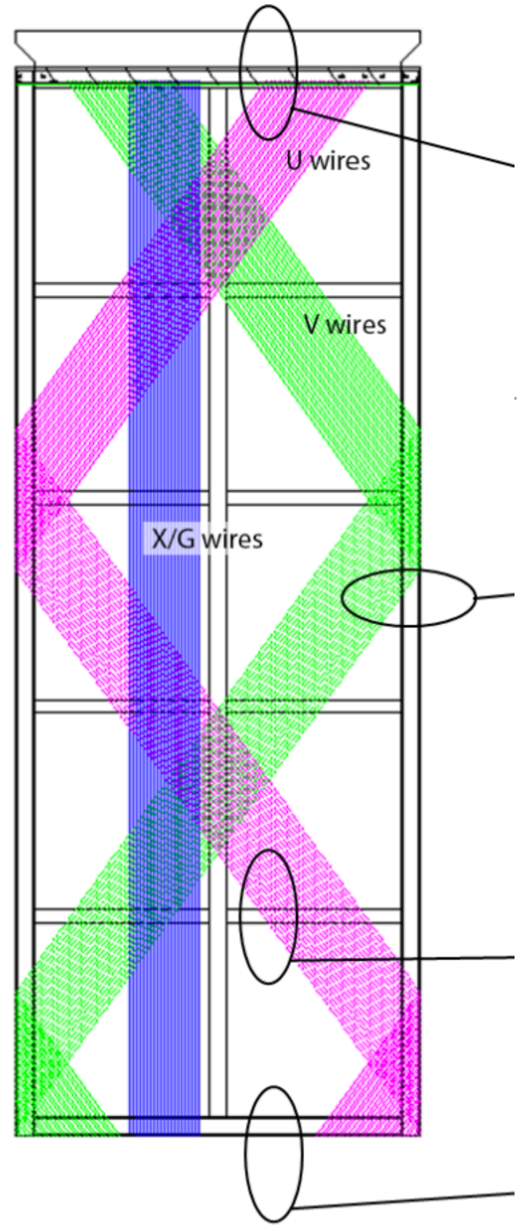
Figure 5.21: The raw image of a low multiplicity ... on plane (right). The event is reconstructed as (ν_μ ... he chamber, an identified stopping proton and a pair ... en these photons escape from the chamber, the event is tagged as a *golden* event.

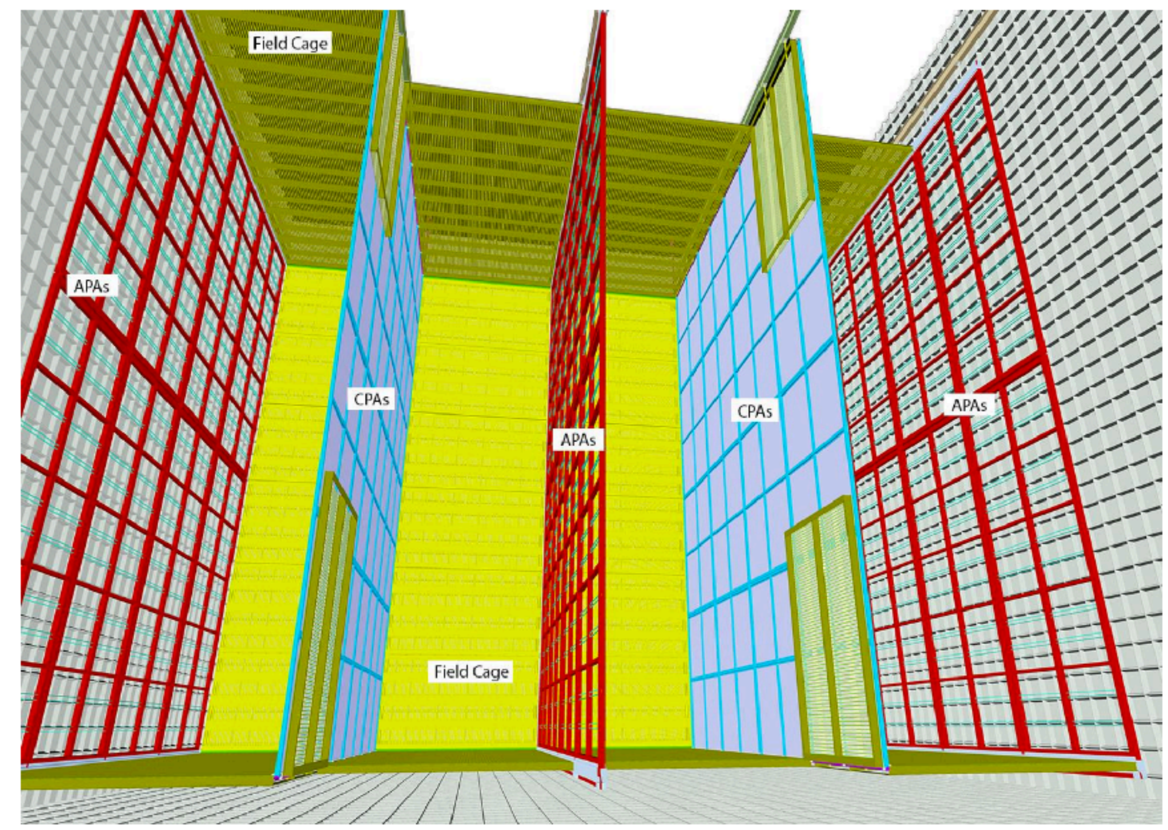
DUNE Module

- 10 kT LqAr
- Active TPC volume 12 m x 14.5 m x 58 m

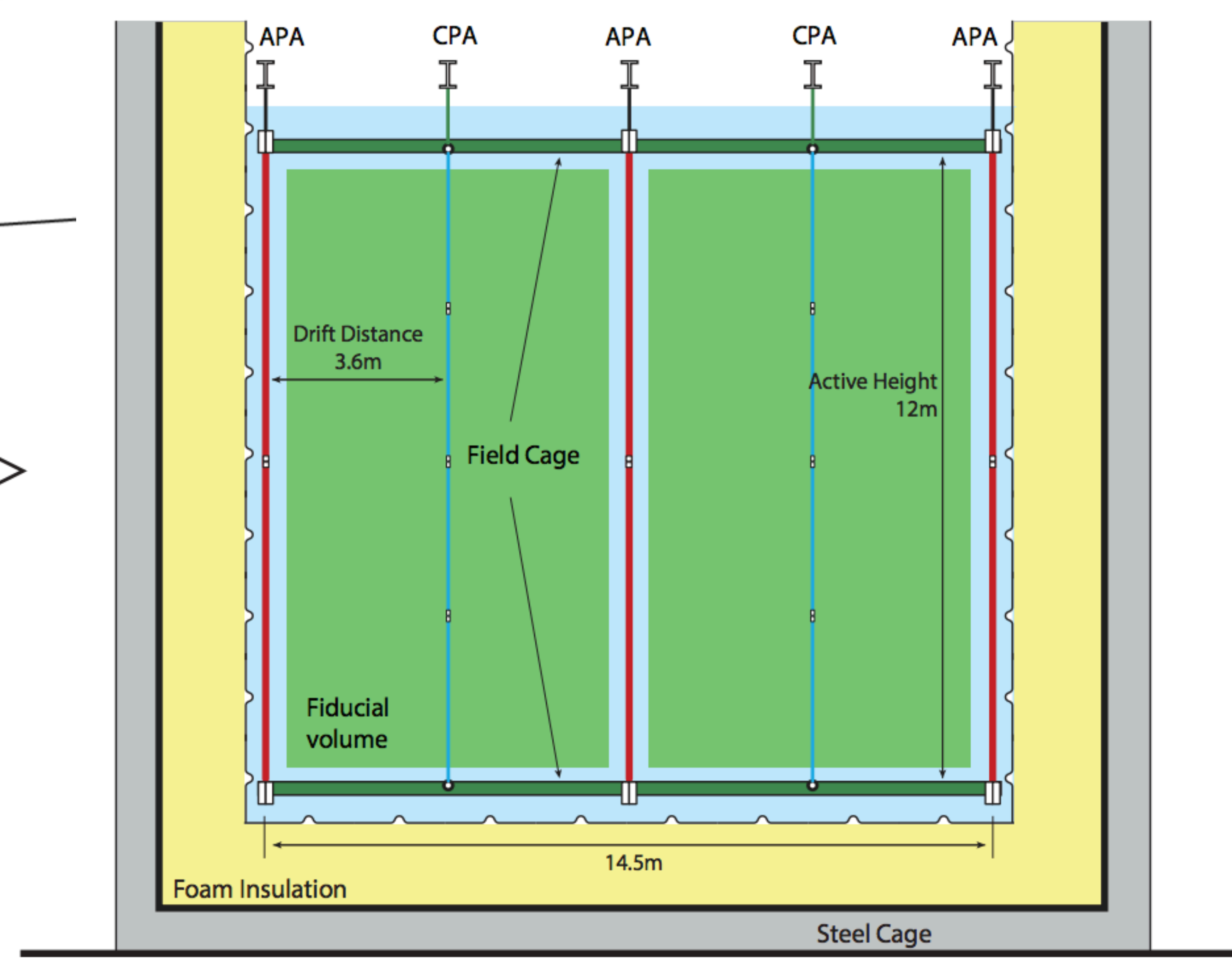
- Readout in 3 wire planes with 5 mm pitch in “UVX” arrangement
- 3.6 m drift distance
- 1.8 ms drift time

a)





DUNE

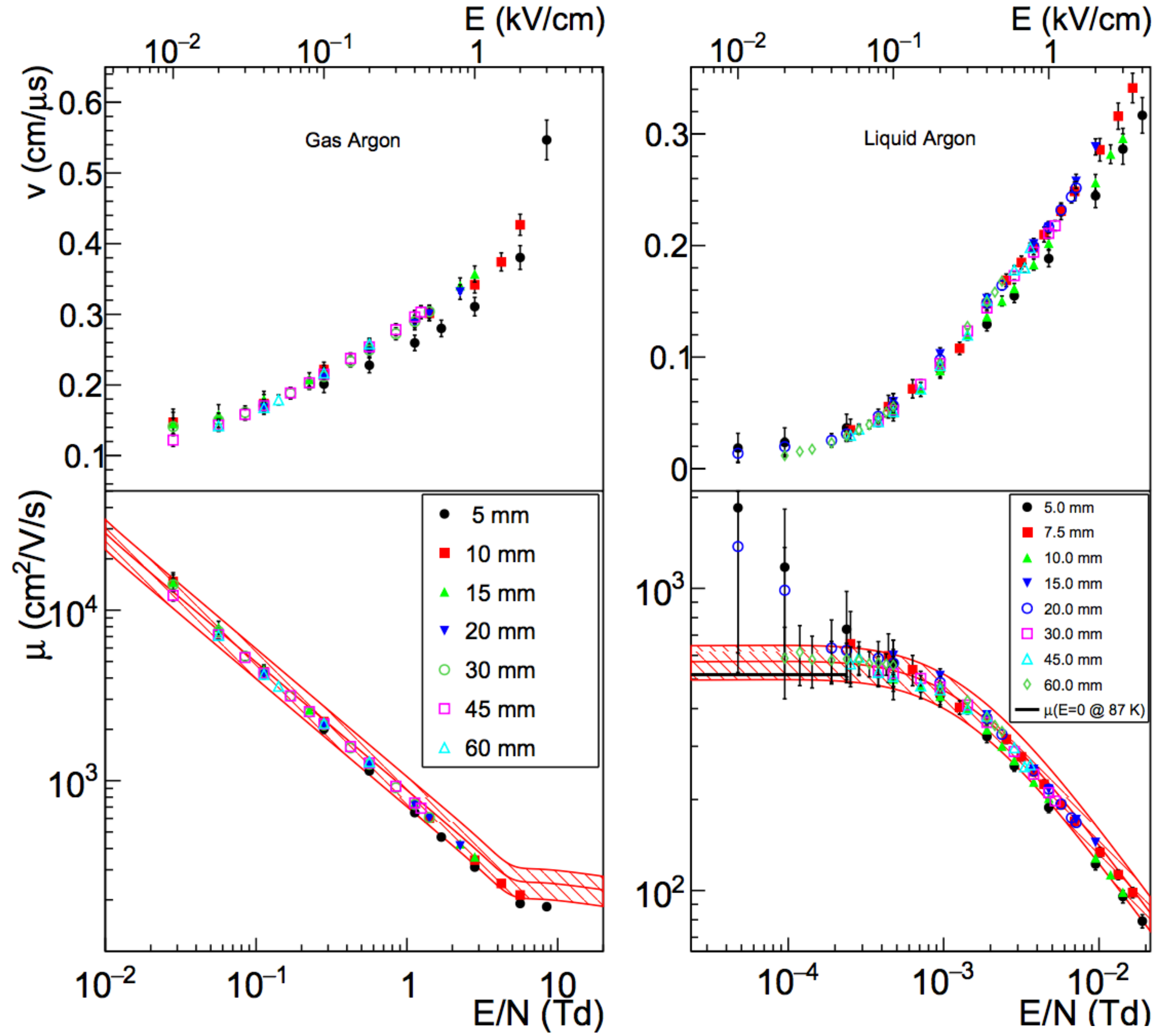


Ionization drift

Drift velocity depends ~linearly on the applied field. Often useful to work in inverse units of “electron mobility”

$$\mu \equiv v/E$$

where v is the drift velocity and E is the applied electric field.



arXiv:1508.07059v2

DUNE expects to use a field of ~500 V/cm giving a drift velocity of 2 mm/usec. For the design drift distance of 3600 mm that gives a drift time of ~1.8 ms and Vmax = 180 kV

Ionization drift

As the ions drift, they compete against recombination:

$$X^+ + e^- \to X + h\nu$$

and attachment:

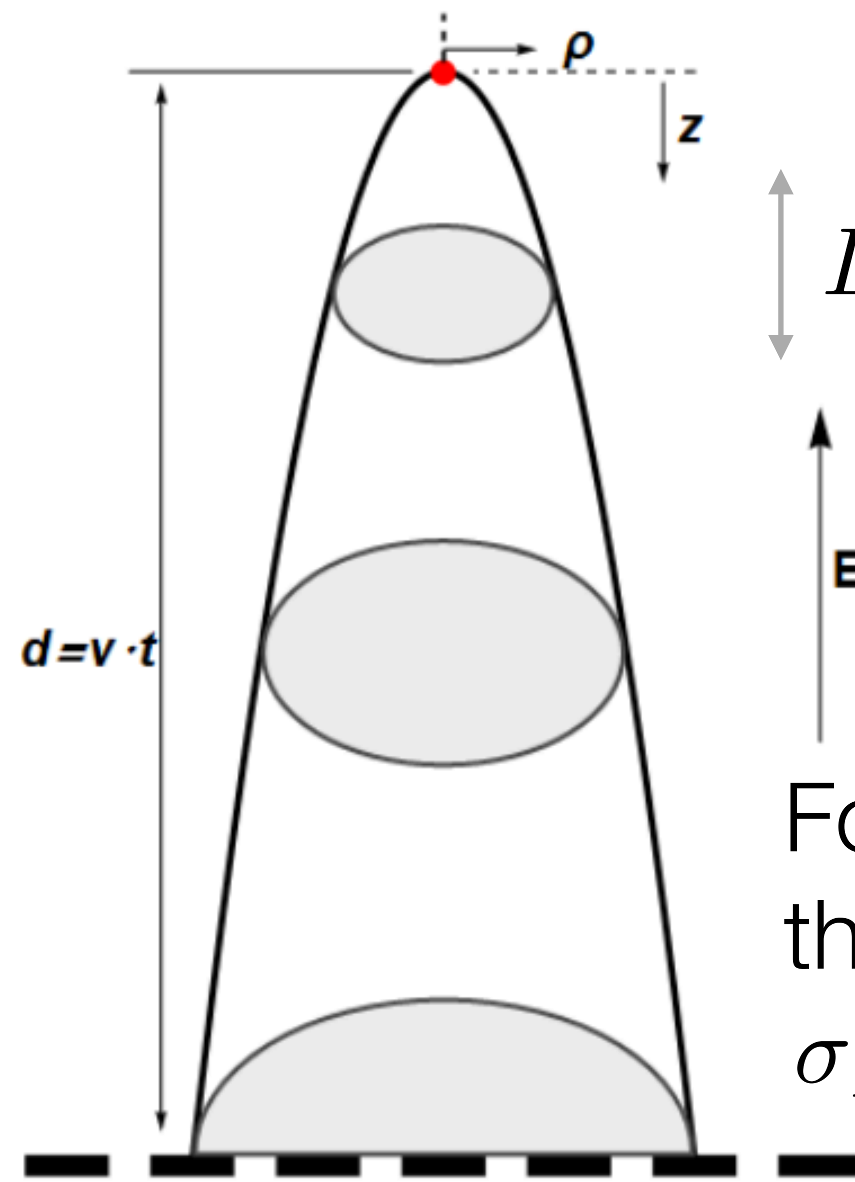
$$e^- + X \to X^- + h\nu$$

During the drift the electron cloud diffuses with size growing according to

$$\sigma_r = \sqrt{6Dt}$$

$$D_T = 12 \text{ cm}^2/\text{s}$$

$$D_L = 7.2 \text{ cm}^2/\text{s}$$



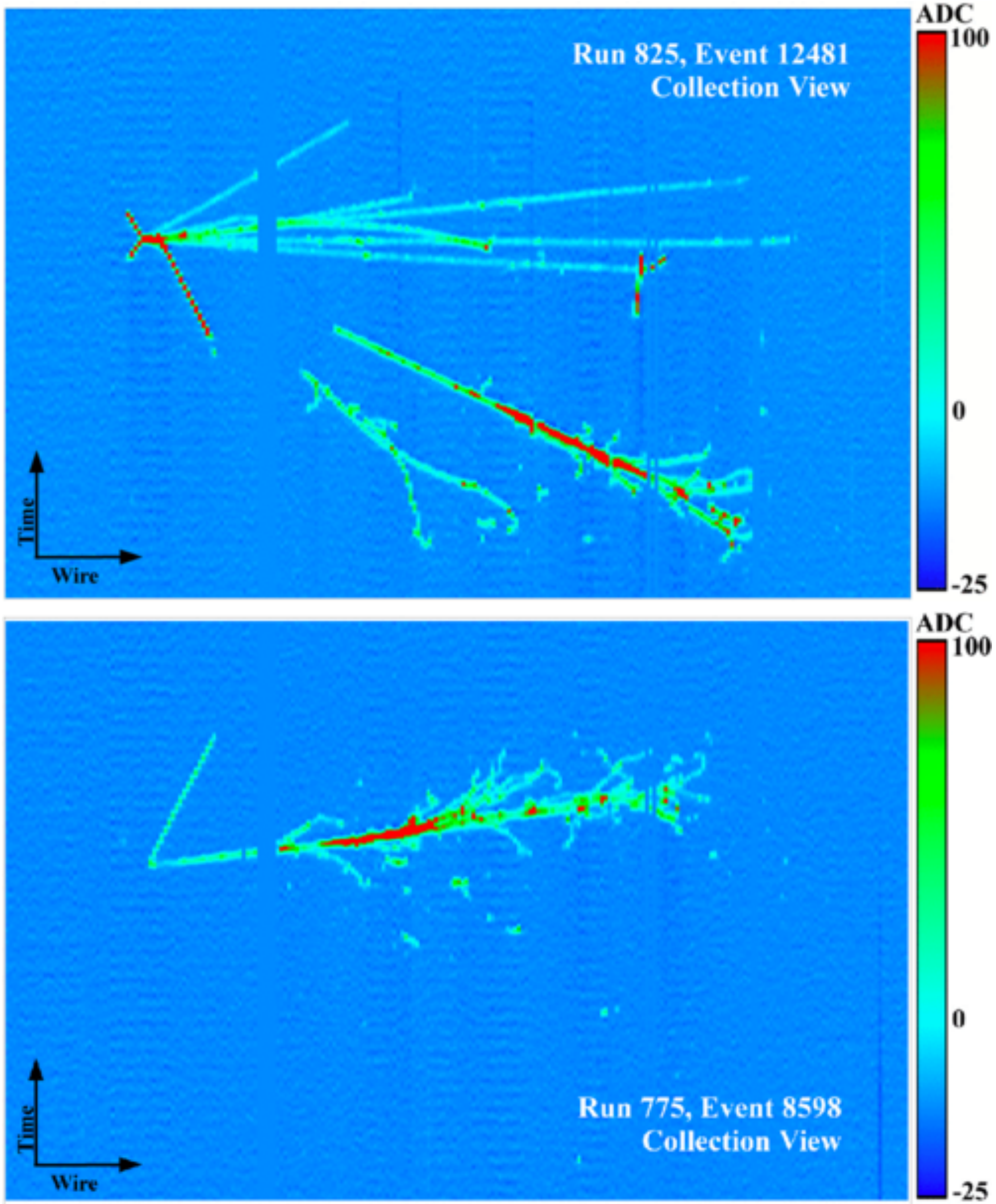
arXiv:1508.07059v2

For t=1.7 ms, these give:

$$\sigma_L \simeq \sigma_T = 3 \text{ mm}$$

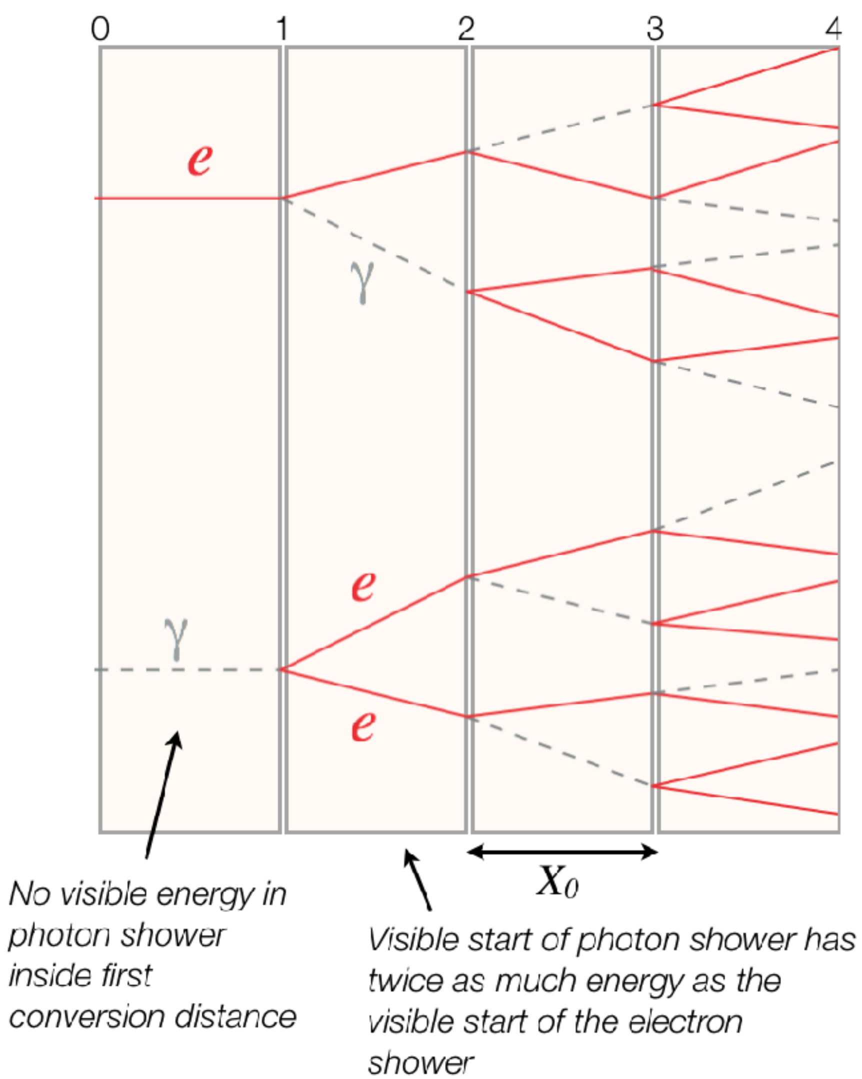
First observation of low energy electron neutrinos in a liquid argon time projection chamber

R. Acciarri *et al.* (ArgoNeuT Collaboration)
Phys. Rev. D **95**, 072005 – Published 6 April 2017



Electron / Photon Separation

TPC's provide many samples per radiation length. Allows for e/gamma separation by checking dE/dx at start of shower



First observation of low energy electron neutrinos in a liquid argon time projection chamber

R. Acciarri *et al.* (ArgoNeuT Collaboration)
Phys. Rev. D **95**, 072005 – Published 6 April 2017

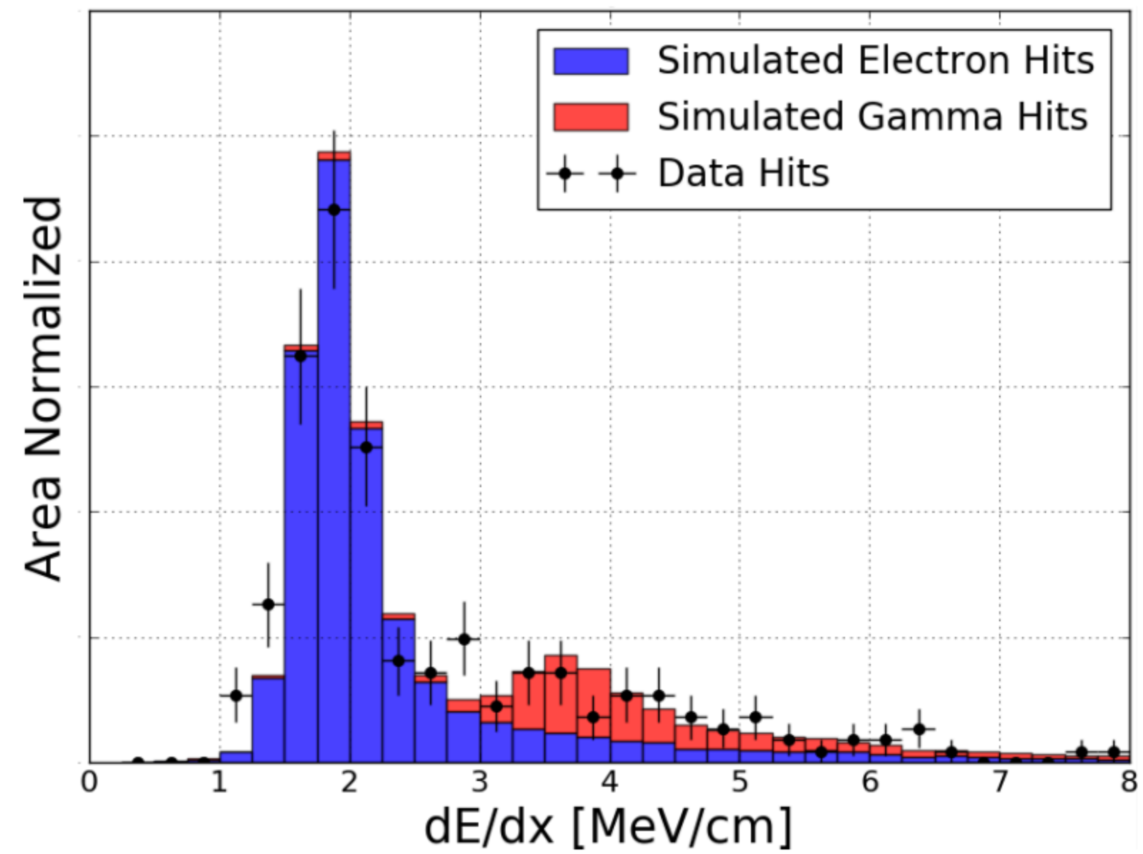


Figure 11. dE/dx for all the hits from the electron candidate data sample, compared to a sample of Monte Carlo comprised of 80% electrons and 20% gamma.

Send me a message or a question

https://forms.gle/gUYf7JzRpZUziyV38

Throughout the lectures I've given specific references to papers where appropriate. The material here leans heavily on these three texts:

- W.R. Leo, Techniques for Nuclear and Particle Physics Experiments, A How-to-Approach.
- Richard Fernow, Introduction to experimental particle physics.
- Christopher Tully, Elementary Particle Physics in a Nutshell.
- Passage of particles through matter, Particle Data Group.