Neutrino Detectors

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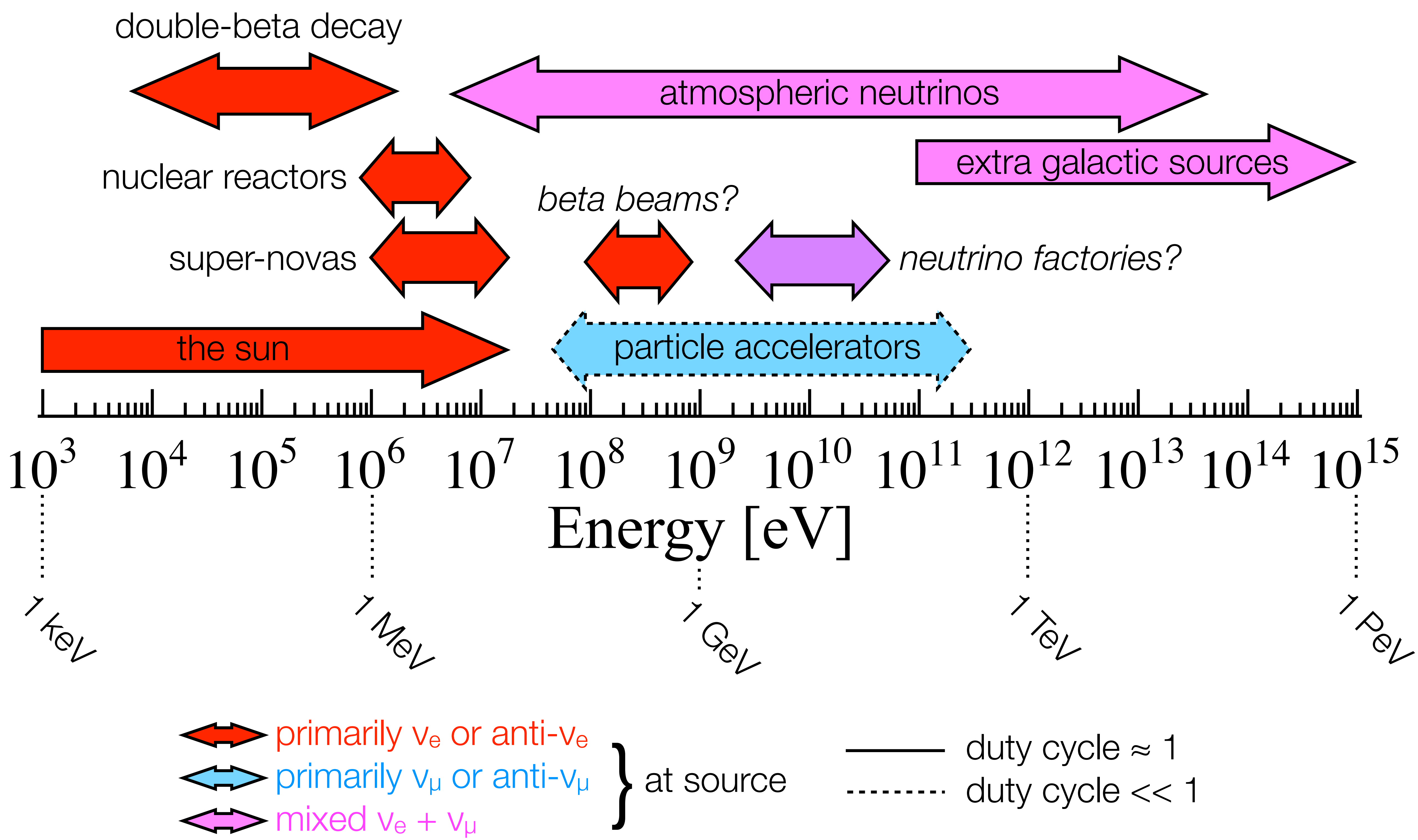
What do neutrinos look like?

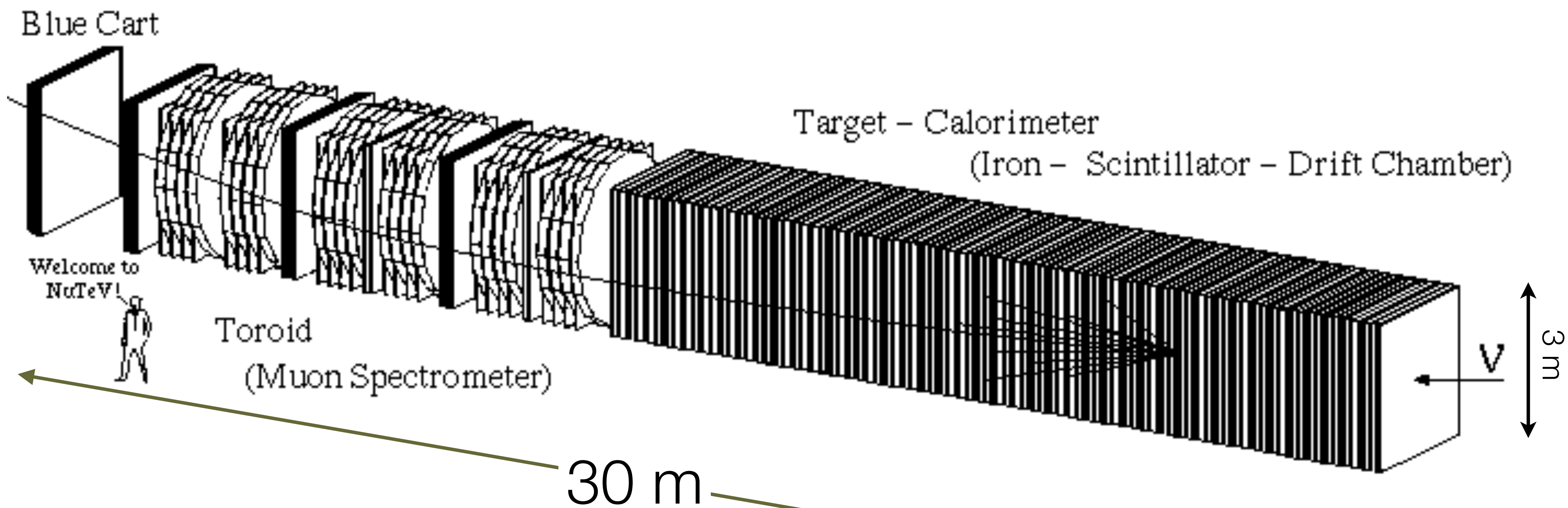
- **Neutrino detectors are built to detect the particles produced when neutrinos interact with nuclei or the electrons bound to nuclei**

- **With that in mind let's spend a little time talking about:**
  - The important characteristics of neutrinos and the sources of neutrinos that we want to detect that affect detector design
  - Some basics of neutrino interactions and event topologies
  - Some basics of the topologies of the particles produced by neutrino interactions
  - Applications and specific technologies

Neutrino sources



NuTeV Detector
A segmented detector, pulsed source, on the surface



Segmented detector

- Neutrino target: iron planes
- Active detector: drift chamber and scintillator planes

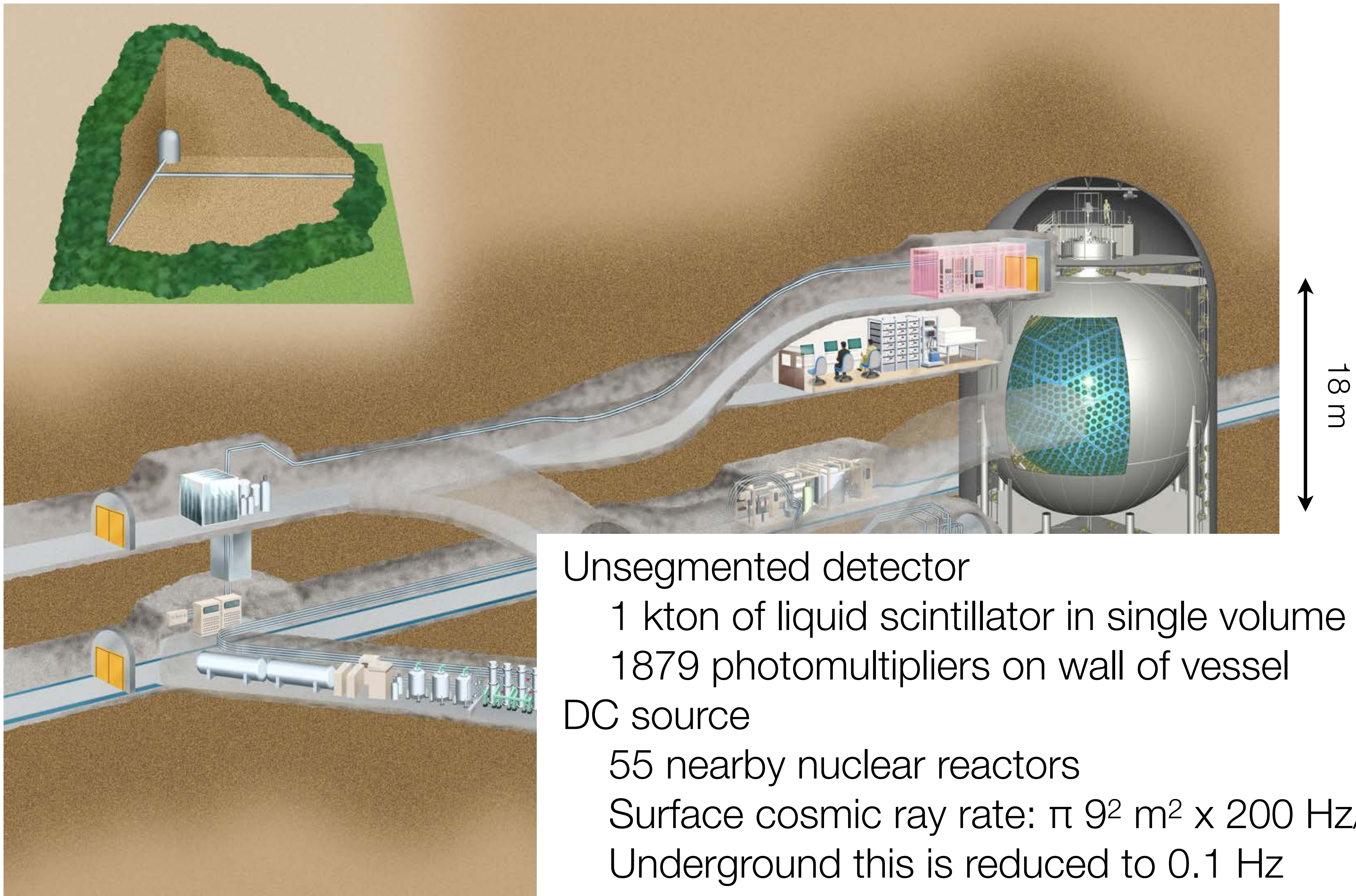
Pulsed source

- FNAL Tevatron: 5 spills/min x 0.002 sec/spill gives duty cycle of 0.00017
- Number of in-spill muons: (3m x 30m x 200Hz/m^2)x(0.002 s) = 40.

Located on surface at FNAL

detector size *cosmic-ray rate* *neutrino pulse duration*

KamLAND
An unsegmented detector, "DC" source, underground



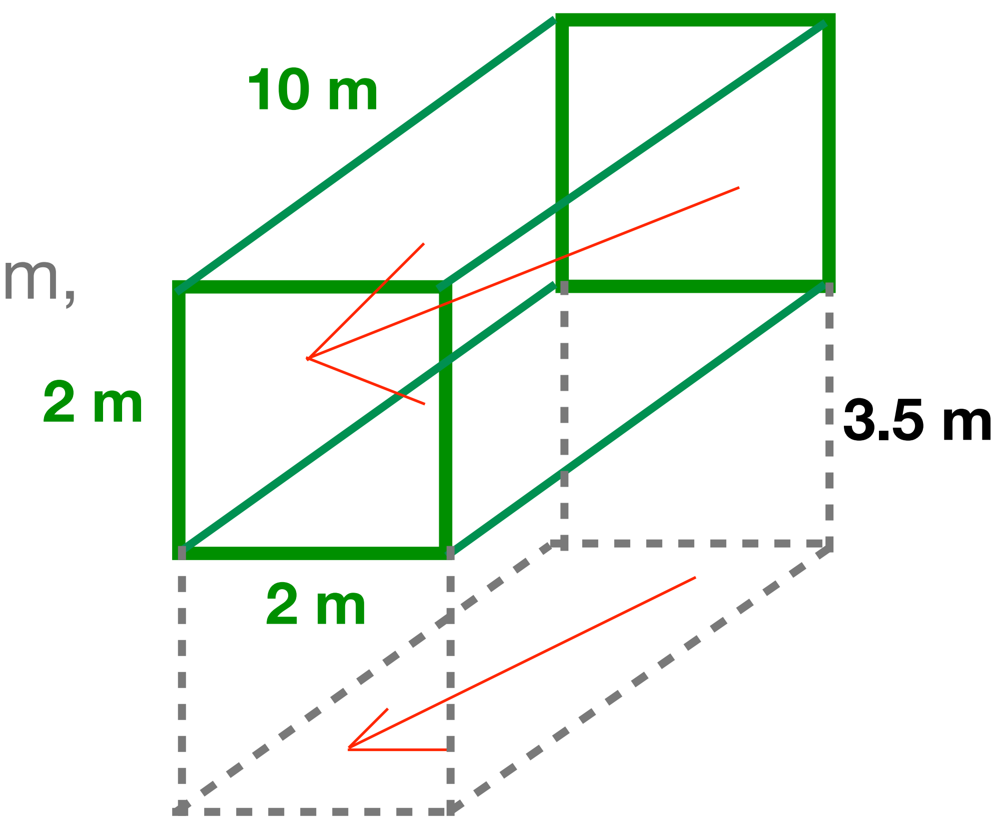
Unsegmented detector
- 1 kton of liquid scintillator in single volume viewed by 1879 photomultipliers on wall of vessel

DC source
- 55 nearby nuclear reactors
- Surface cosmic ray rate: $\pi\ 9^2\ m^2 \times 200\ Hz/m^2 = 50\ kHz$
- Underground this is reduced to 0.1 Hz

Located 1000 m underground near Kamioka, Japan

First check up!

In a large liquid argon detector neutrinos are detected by drifting electrons at a speed of 0.7 cm / usec. Assume that a neutrino event is contained inside a box of sides 2 m x 2 m x 10 m, where one of the 2 m directions is along the direction of drift and that the electrons must be drifted 3.5 meters to be read out.



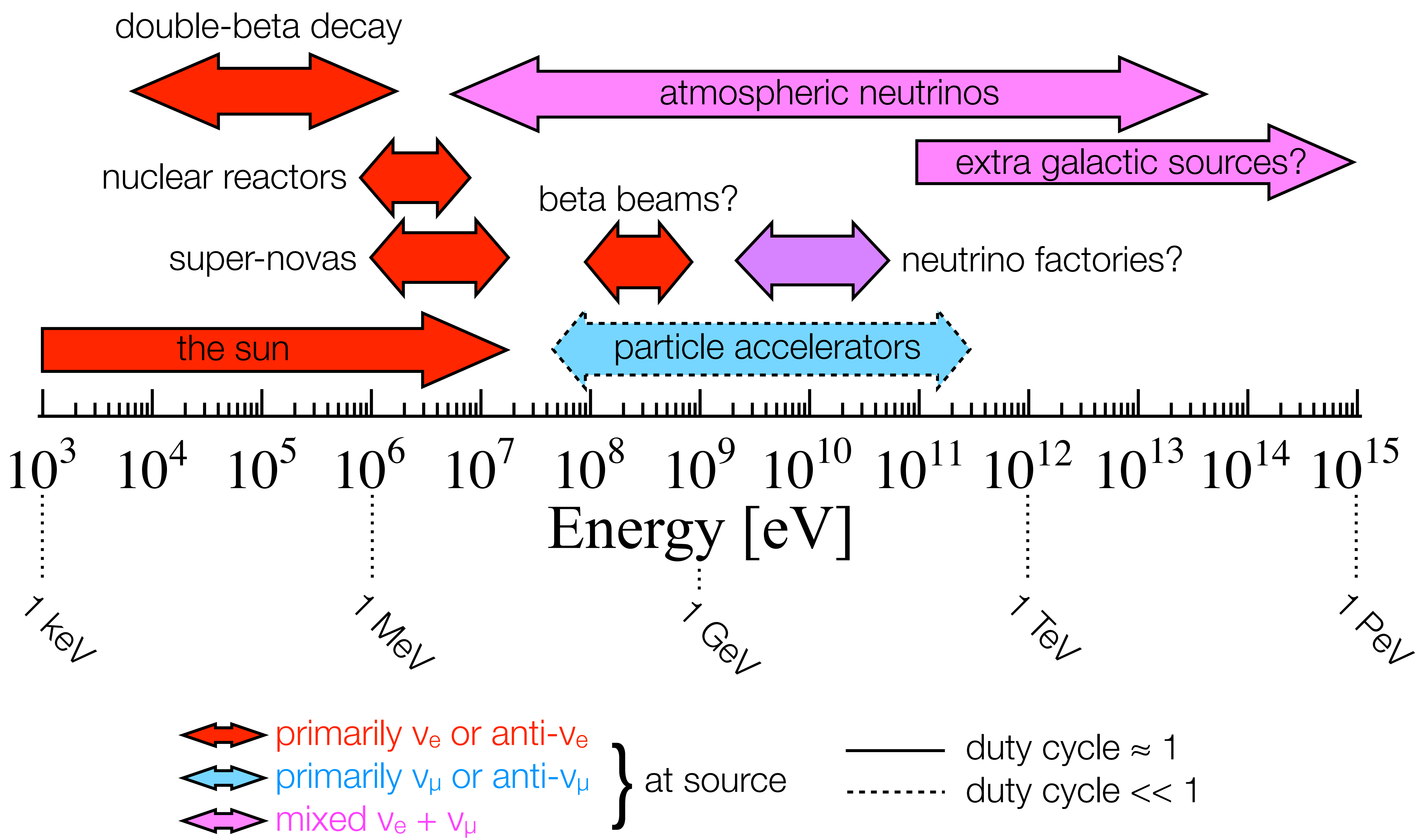
Estimate the number of cosmic rays that would accompany a neutrino in the read out of the detector if it operated at the surface. Recall that at the surface the cosmic ray rate is 200 Hz / m^2.

$$\text{Area} : A = 2 \text{ m} \times 10 \text{ m} = 20 \text{ m}^2$$

$$\text{Time} : t = 350 \text{ cm}/0.7 \text{ cm}/\mu\text{sec} = 500\ \mu\text{sec}$$

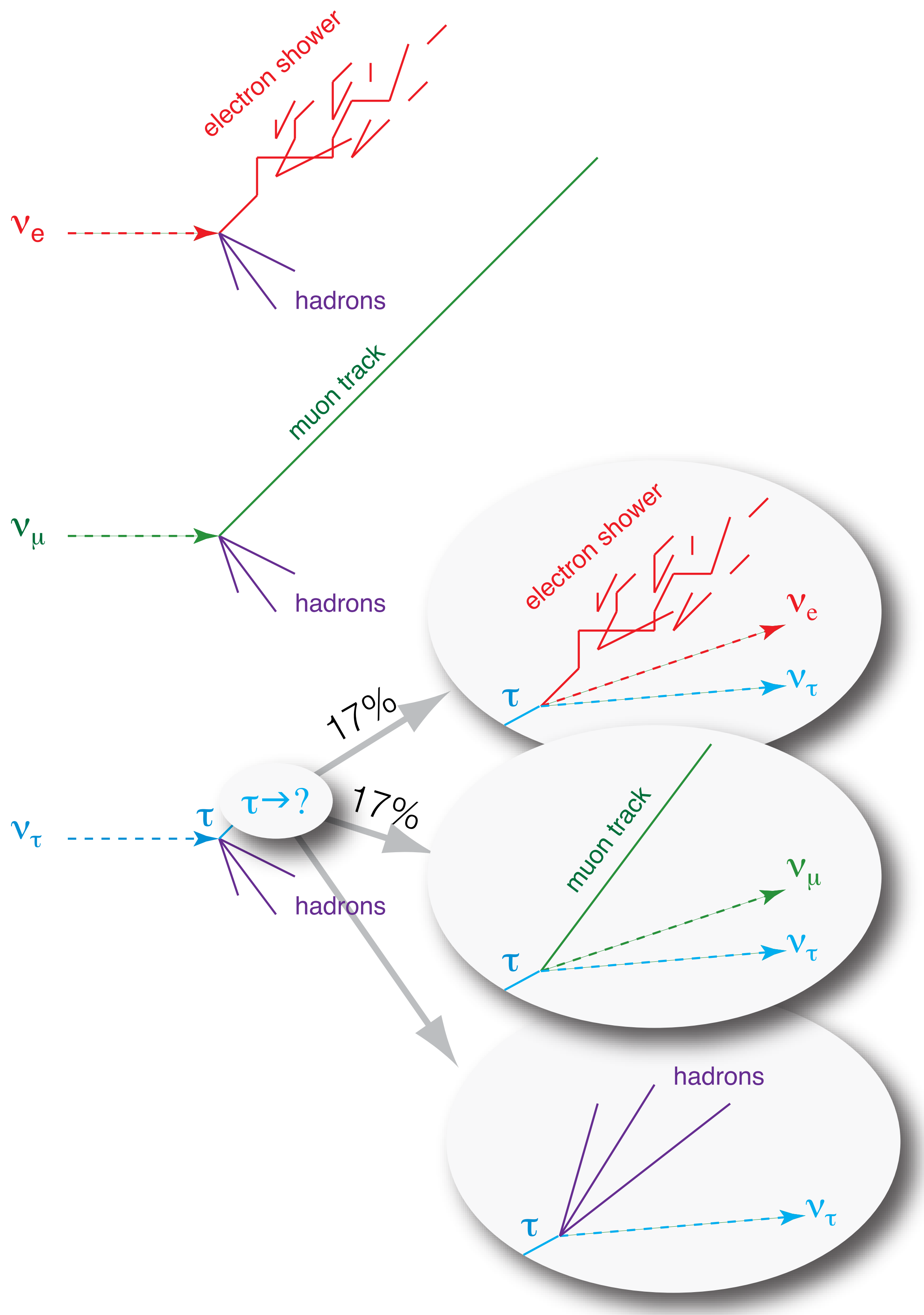
$$N = \frac{200}{\text{s} \cdot \text{m}^2} \cdot 20 \text{ m}^2 \times 500\ \mu\text{sec} = 2$$

Neutrino sources

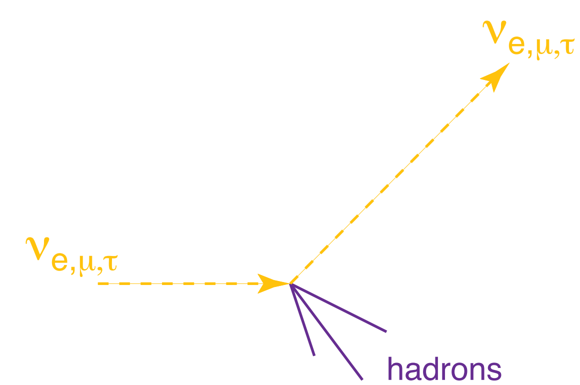


Neutrino detection channels

Charged-current



Neutral-current



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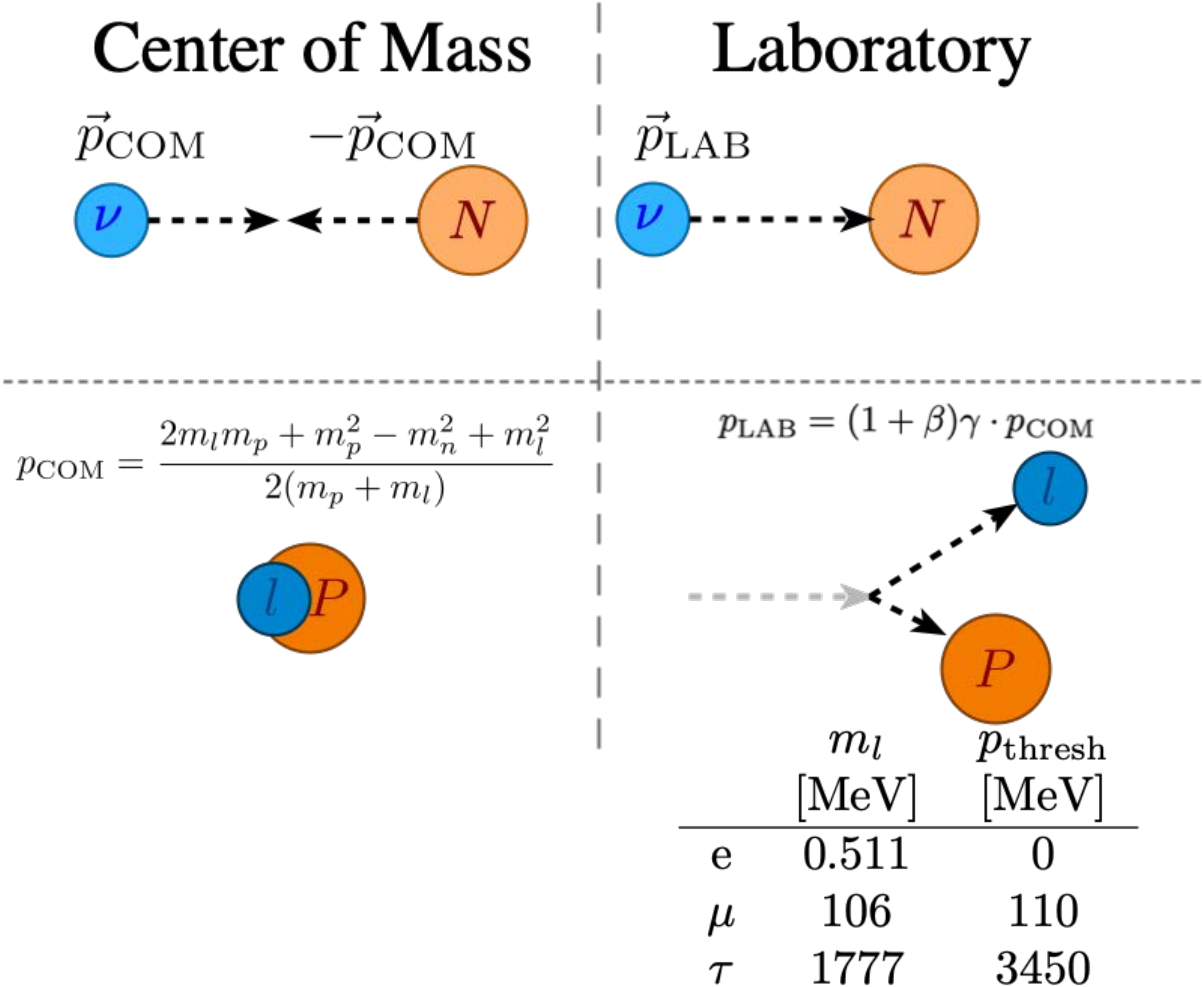
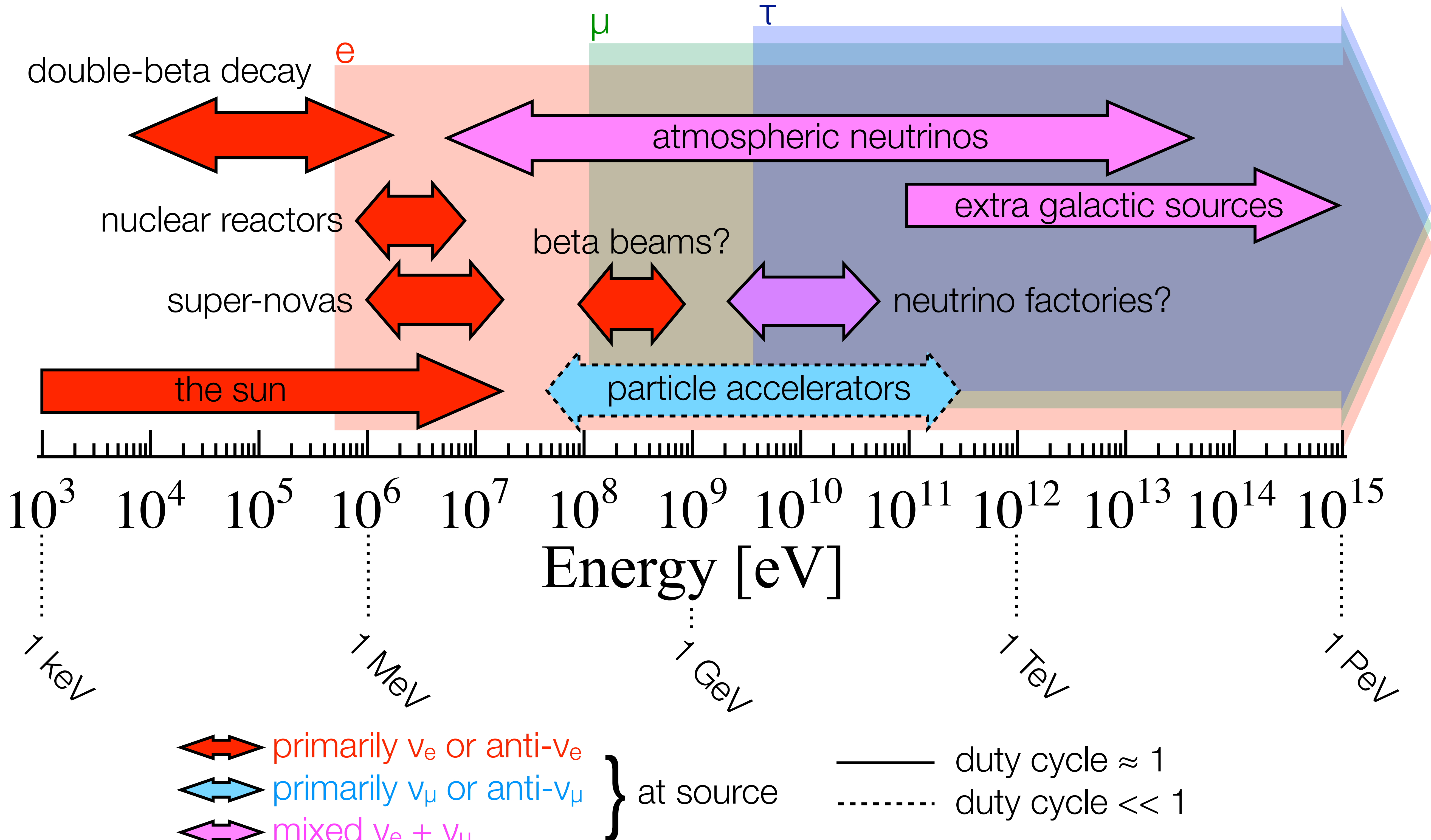
  - *In only a few analyses are NC events considered to be signal. In most cases NC events are backgrounds to the CC processes*



	m_l [MeV]	p_{thresh} [MeV]
e	0.511	0
μ	106	110
τ	1777	3450

Neutrino Sources



Neutrino detection channels

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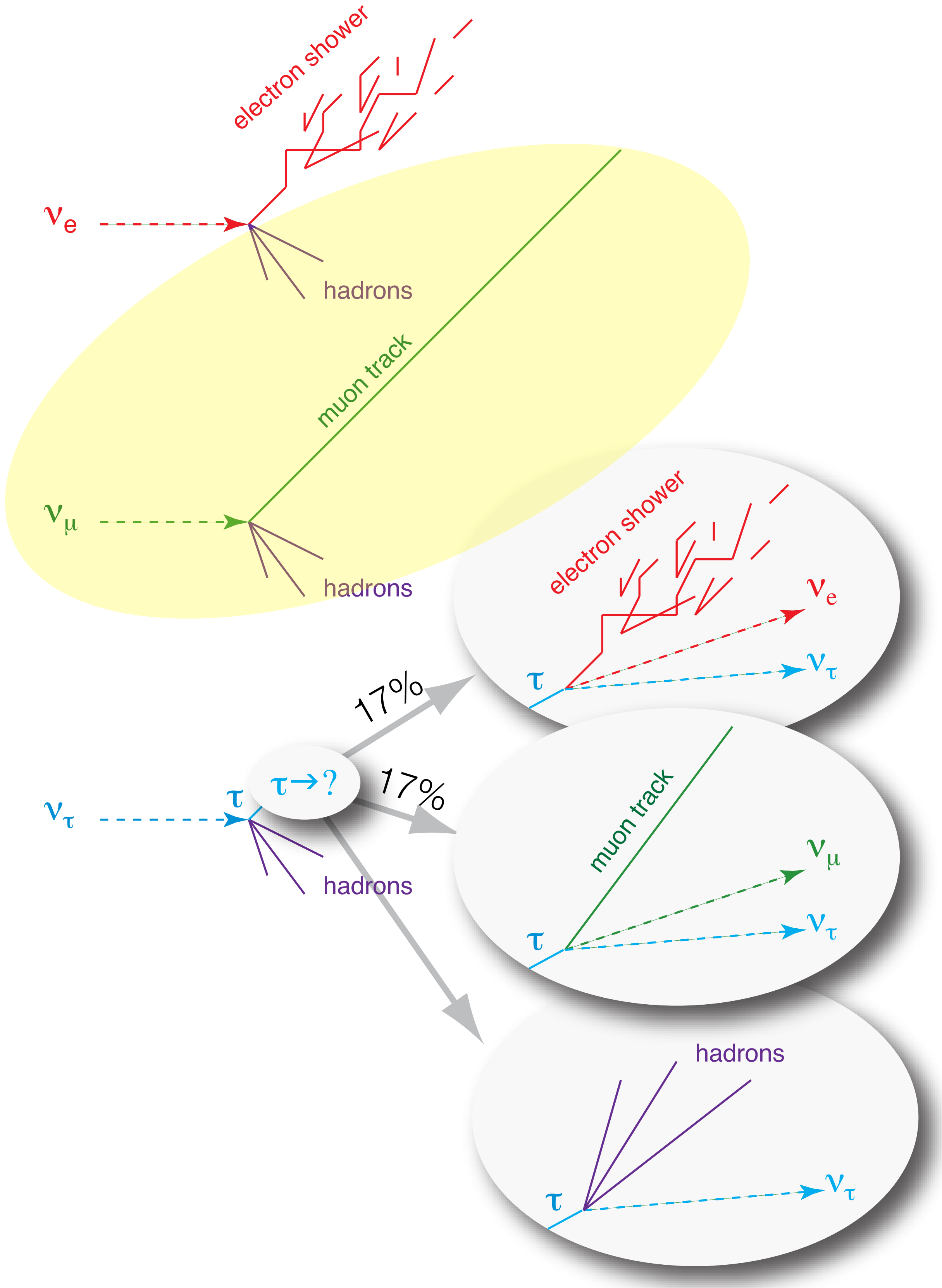

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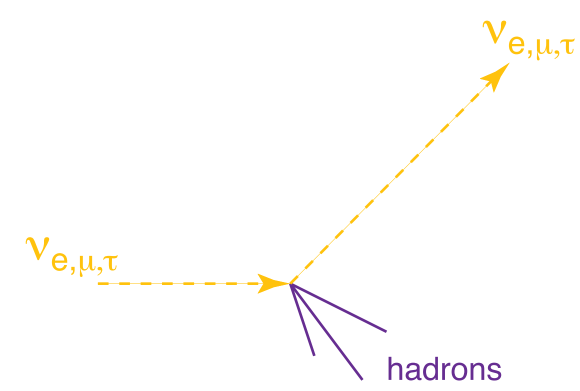

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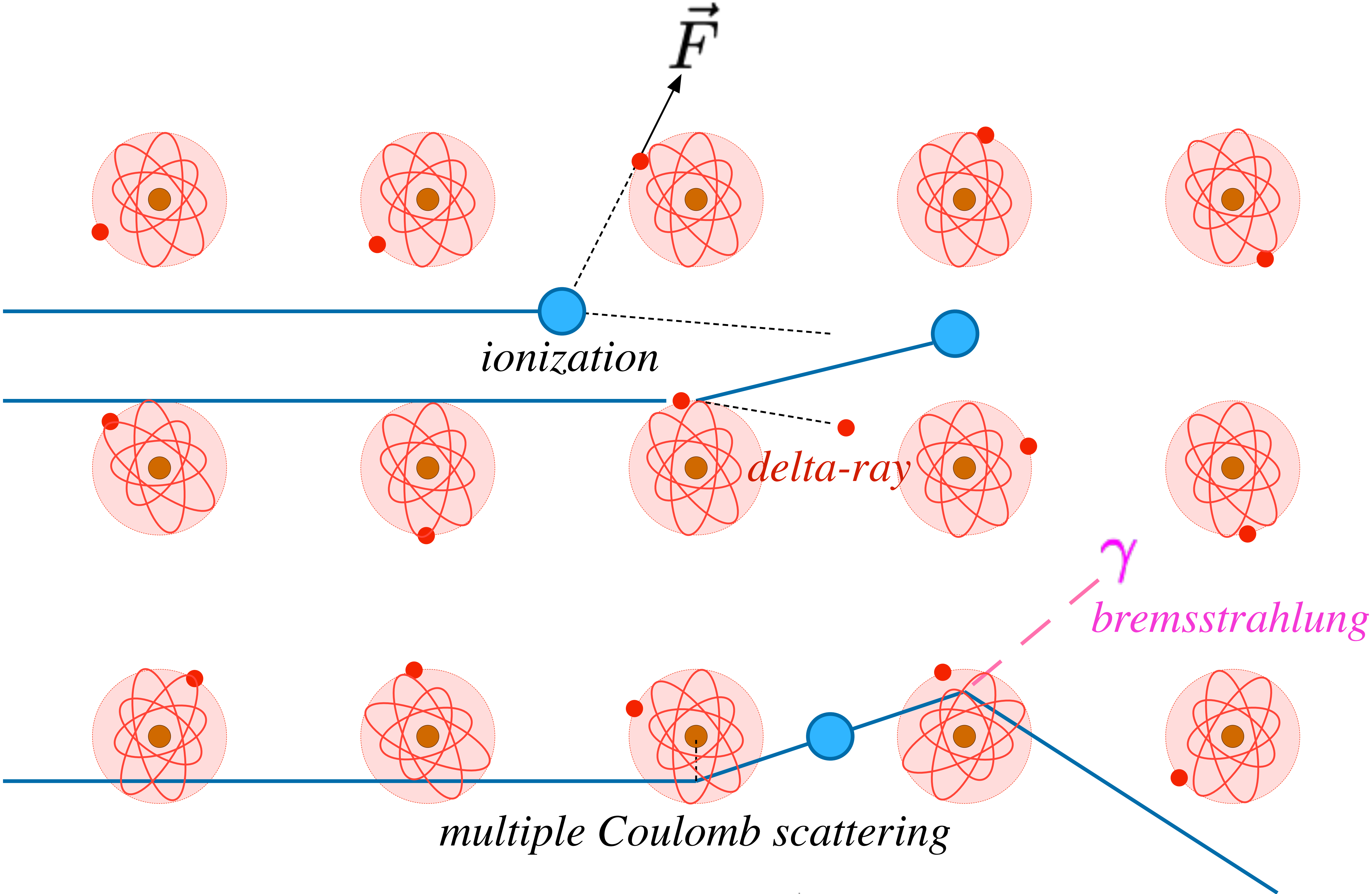
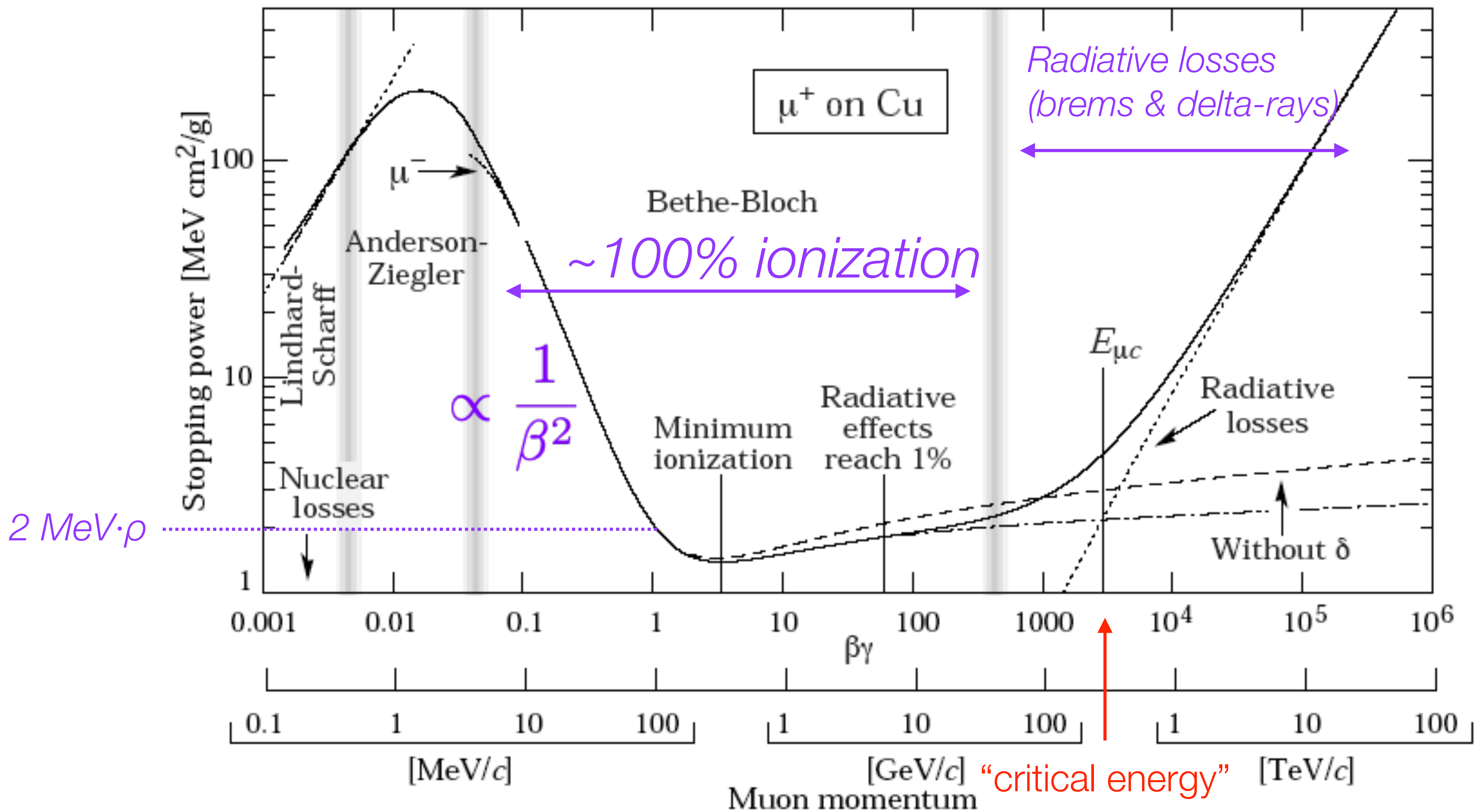


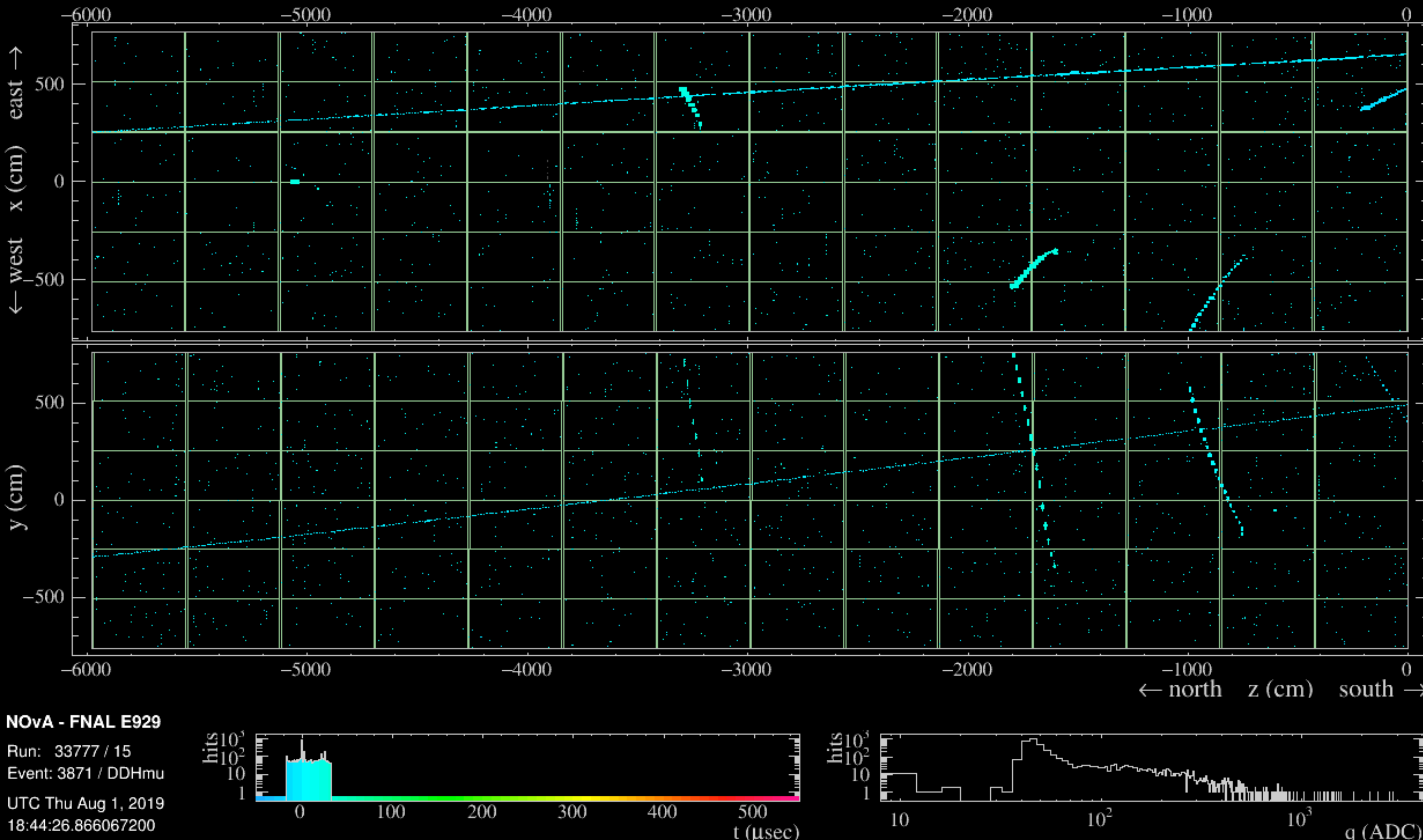
Passage of muons through matter



$$-\frac{dE}{dx} = Kz^2\frac{Z}{A}\frac{1}{\beta^2}\left[\frac{1}{2}\ln\frac{2m_ec^2\beta^2\gamma^2T_{\max}}{I^2} - \beta^2 - \frac{\delta(\beta\gamma)}{2}\right]$$

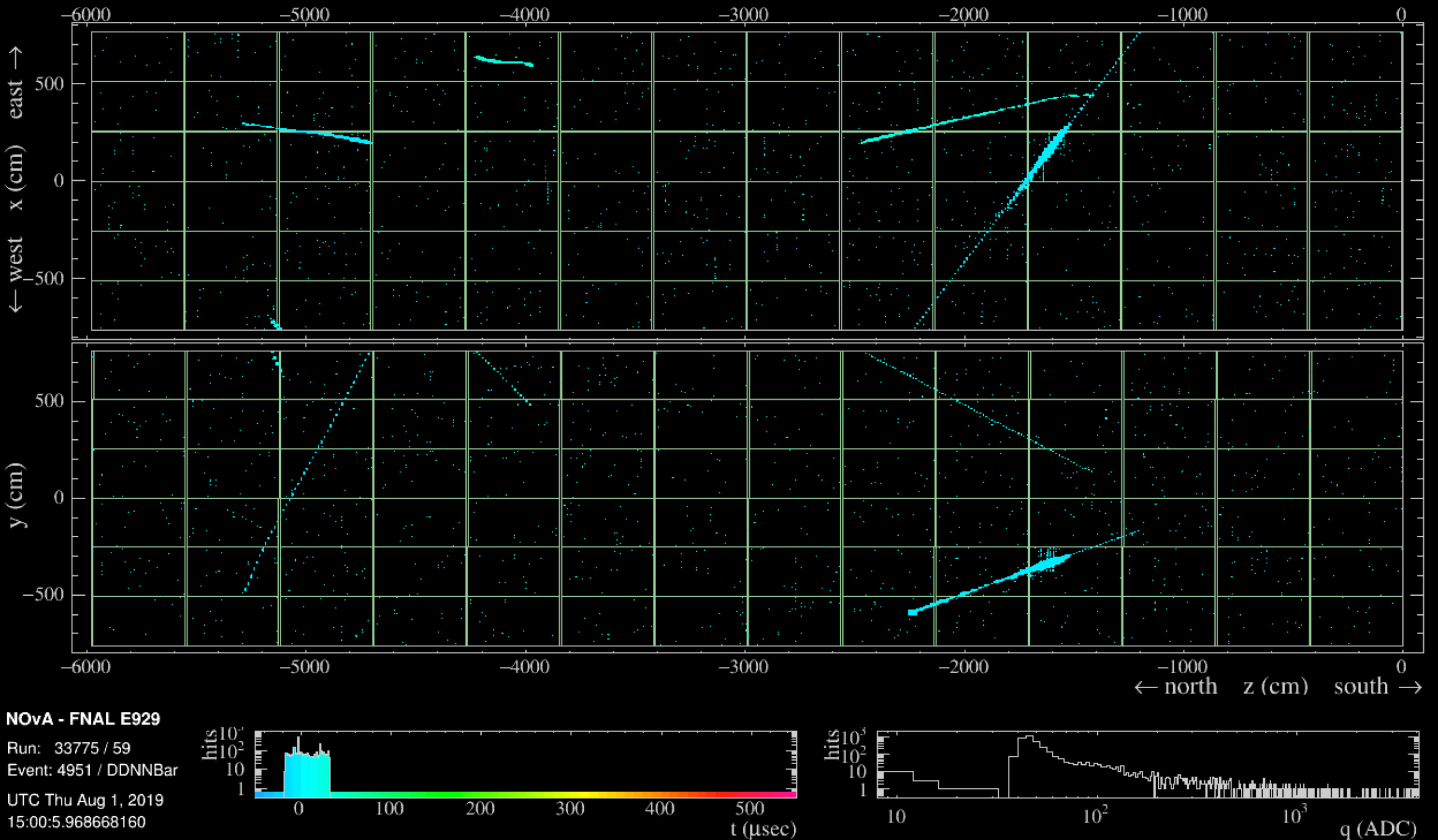
Muon energy loss: Bethe-Bloch

Which of these muons do you think has p>10 GeV?



Cosmic ray muons in the NOvA detector, density ~1 g/cc

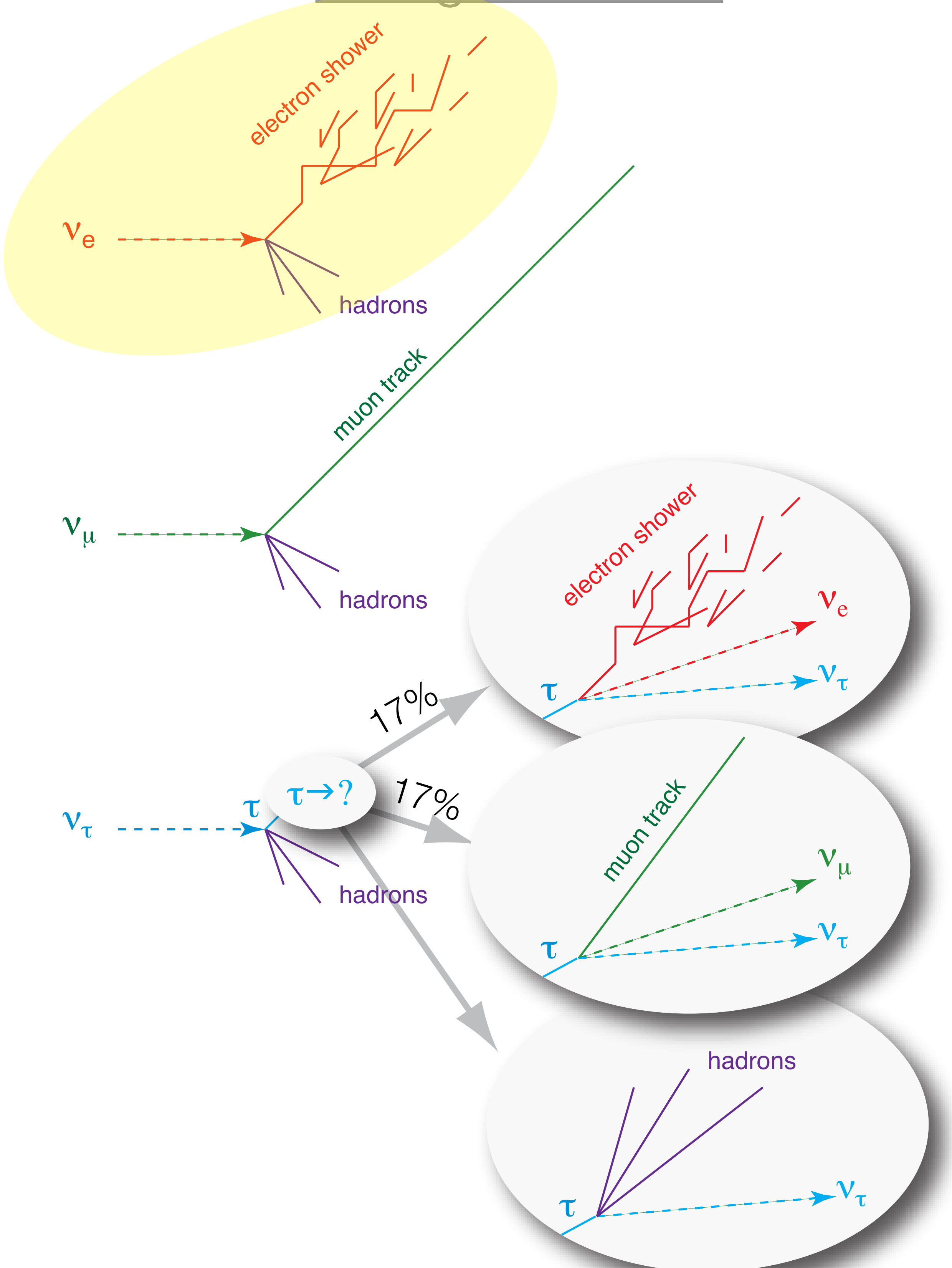
Which of these muons do you think has p>10 GeV?



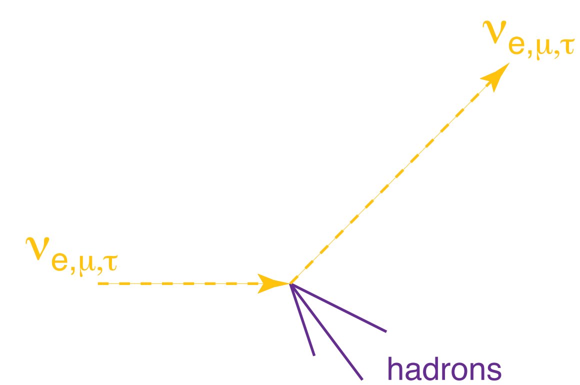
Cosmic ray muons in the NOvA detector, density ~1 g/cc

Neutrino detection channels

Charged-current



Neutral-current



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Electrons: Critical energy

W.-M. Yao et al., Journal of Physics G 33, 1 (2006)
available on the PDG WWW pages (URL: http://pdg.lbl.gov/)

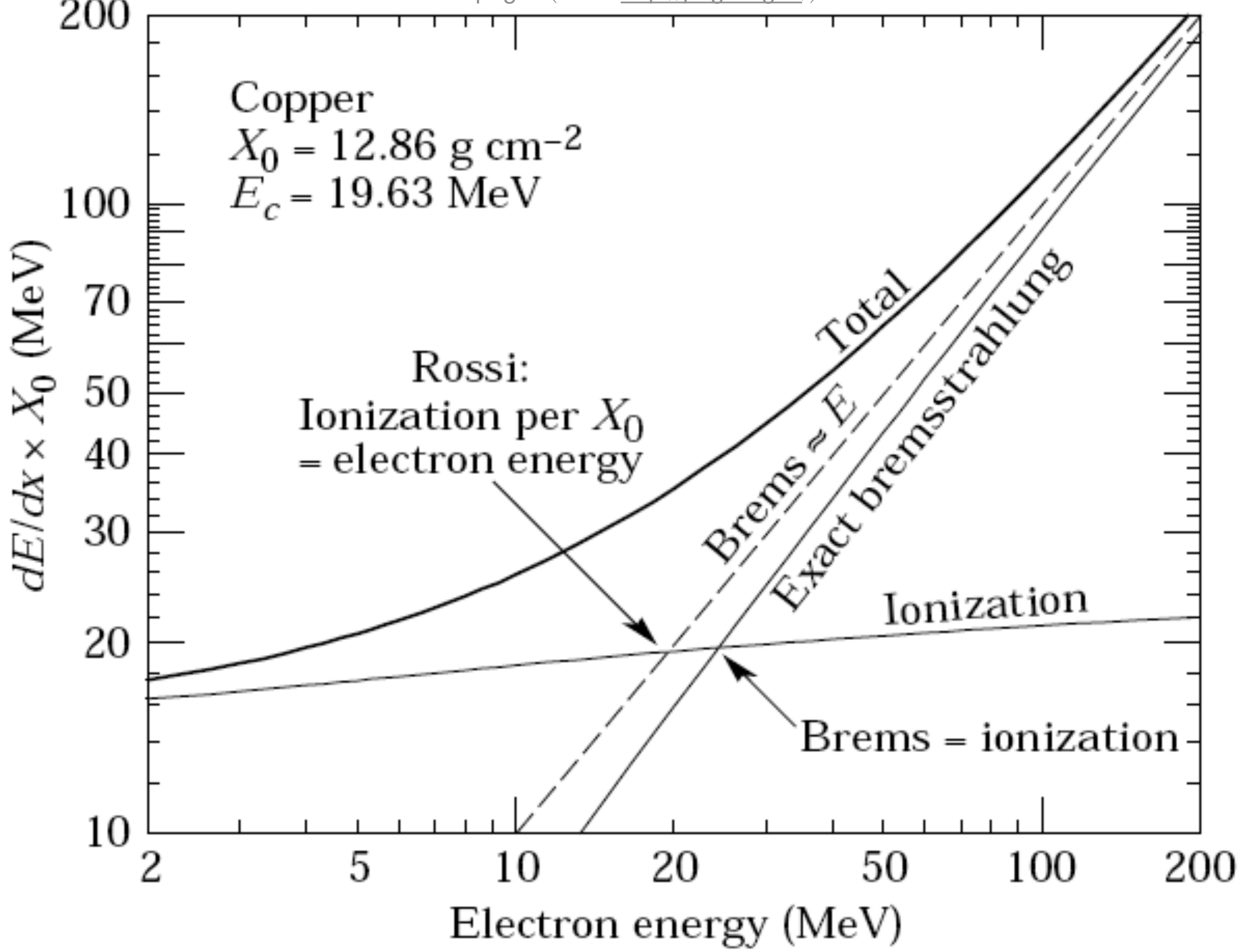


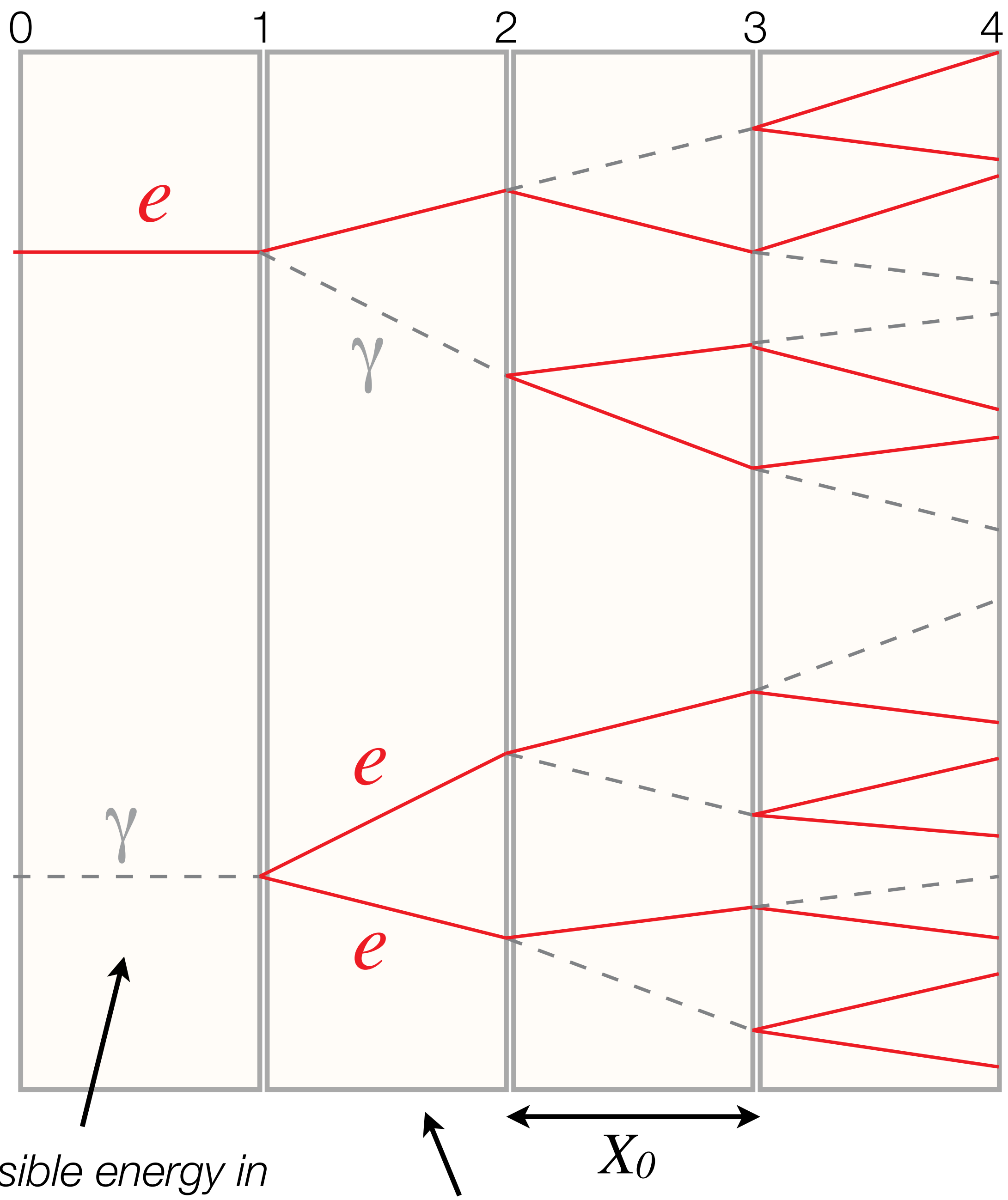
Figure 27.12: Two definitions of the critical energy E_c.

$\left(\frac{dE}{dx}\right)_{\text{rad}} = \left(\frac{dE}{dx}\right)_{\text{col}}$ *seems to be in more common usage*

- Due to their relatively small mass, energy losses due to bremsstrahlung ("brems") are more important for electrons than for muons.
- Above a critical energy, E_c, electrons lose energy mostly to brems. Ionization losses are only important below the critical energy.
- Approximately:

$$E_C = \frac{800 \text{ MeV}}{Z + 1.2}$$

Electromagnetic showers



No visible energy in photon shower inside first conversion distance

Visible start of photon shower has twice as much energy as the visible start of the electron shower

Simple model of shower development:

- e^+/e^-'s with $E>E_c$ travel one X_0 then brem a γ with energy $E/2$. E_c is a "critical energy" at which energy losses due to brems and ionization are equal. Typically $E_c \cong 20+$ MeV.
- γs with $E>E_c$ travel ~one X_0 then pair produce e^+/e^- each with energy $E/2$
- When $E<E_c$ electrons lose their energy through collisions and don't radiate

This model is simple and useful. However, it does have limitations:

I) You may be temped to assume that the number of particles at some particular depth obeys Poisson statistics. However, fluctuations in the particle numbers at any given layer are correlated with what happens in previous layers.

II) Fluctuations occur such that a certain point in the shower there may only be only γs creating gaps in the shower, an effect which this model fails to capture

Electrons: Radiation length and Moliere radius

- The radiation length, X_0, of a material is defined as the distance over which an electron loses $1/e$ of its energy via radiation. X_0 is measured in cm or in g/cm^2

$$X_0 \simeq 180 \frac{A}{Z^2} \text{ g/cm}^2$$

- X_0 is about 36 cm in water, 14 cm in Lq Ar, 38 cm in liquid scintillator
- Roughly speaking, an electron emits one photon through bremsstrahlung for every $1\ X_0$ traversed

$$\lambda_{\text{pair}} = \frac{9}{7} X_0$$

- X_0 also controls the distance over which photons pair produce
- Approximate formula for X_0:

$$X_0 = \frac{716.4A}{Z(Z+1)\ln(287/\sqrt{Z})} \left[\frac{\text{g}}{\text{cm}^2}\right] \qquad \propto \frac{A}{Z^2}$$

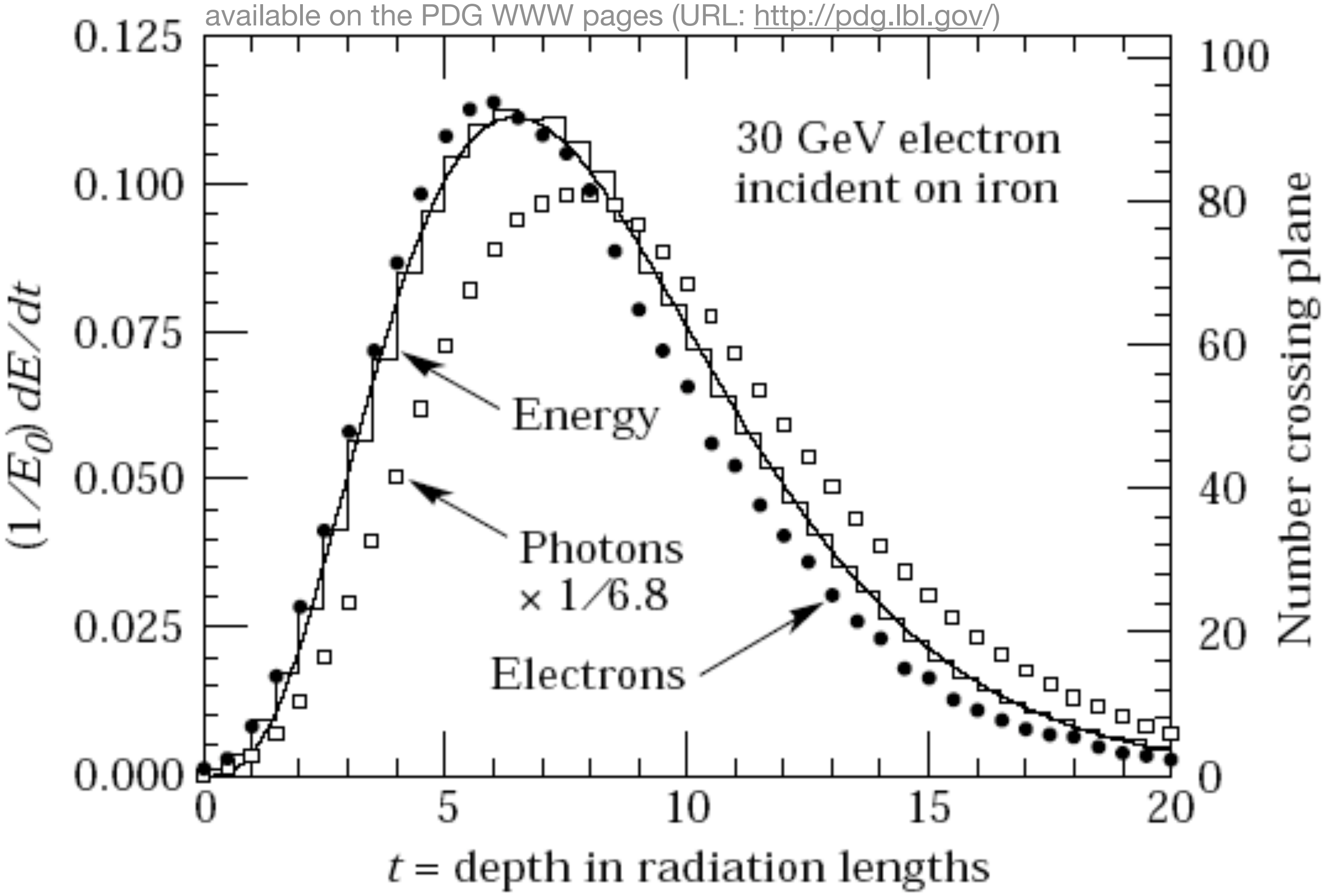
- Development in the transverse direction scales with the Moliere radius:

$$R_{\text{M}} = \frac{21.2 \text{ MeV}}{E_c} X_0 = 0.0265(Z+1.2)X_0 \qquad \propto \frac{A}{Z}$$

-

Topology of electromagnetic showers: Longitudinal development

W.-M. Yao et al., Journal of Physics G 33, 1 (2006)
available on the PDG WWW pages (URL: http://pdg.lbl.gov/)



longitudinal depth →

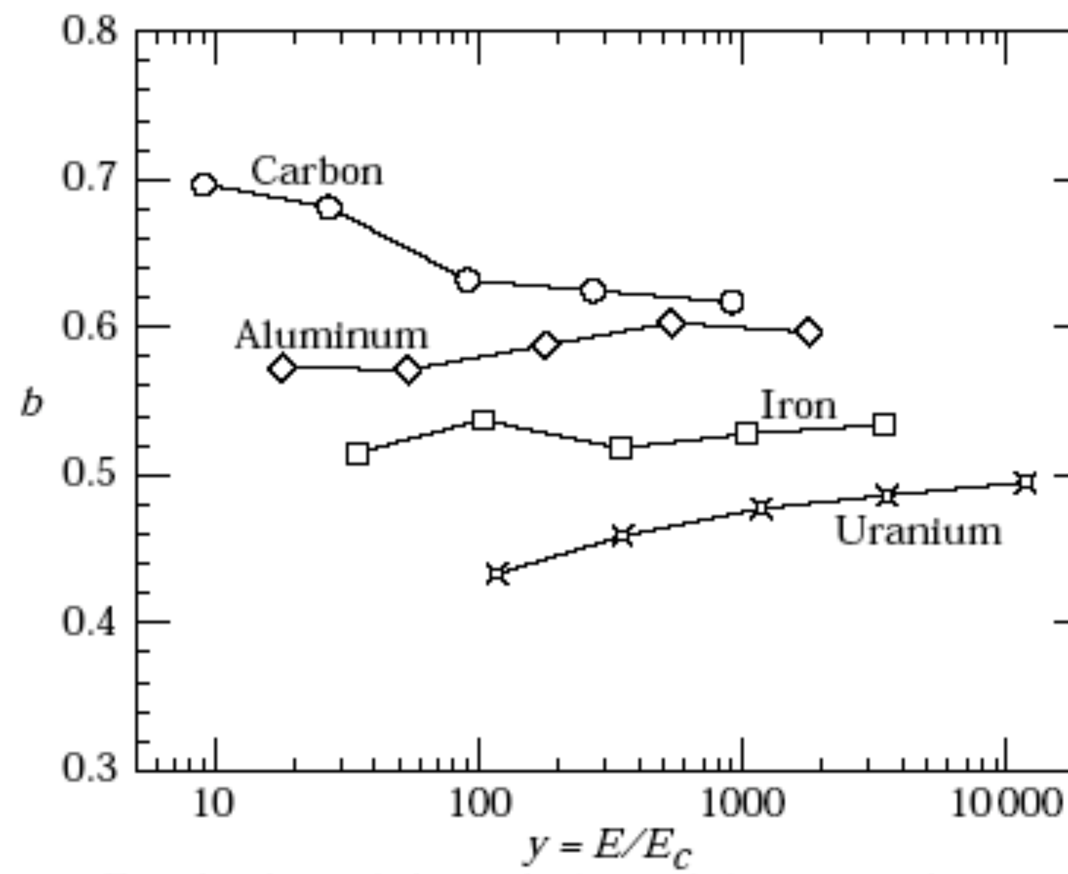
$$\frac{dE}{dt} = E_0 b \frac{(bt)^{a-1} e^{-bt}}{\Gamma(a)}$$

$$\frac{X_0}{b} \equiv \text{"the shower length"}$$

Shower maximum occurs at

$$t_{max} = \frac{a-1}{b} = \ln\frac{E_0}{E_C} + C_i$$

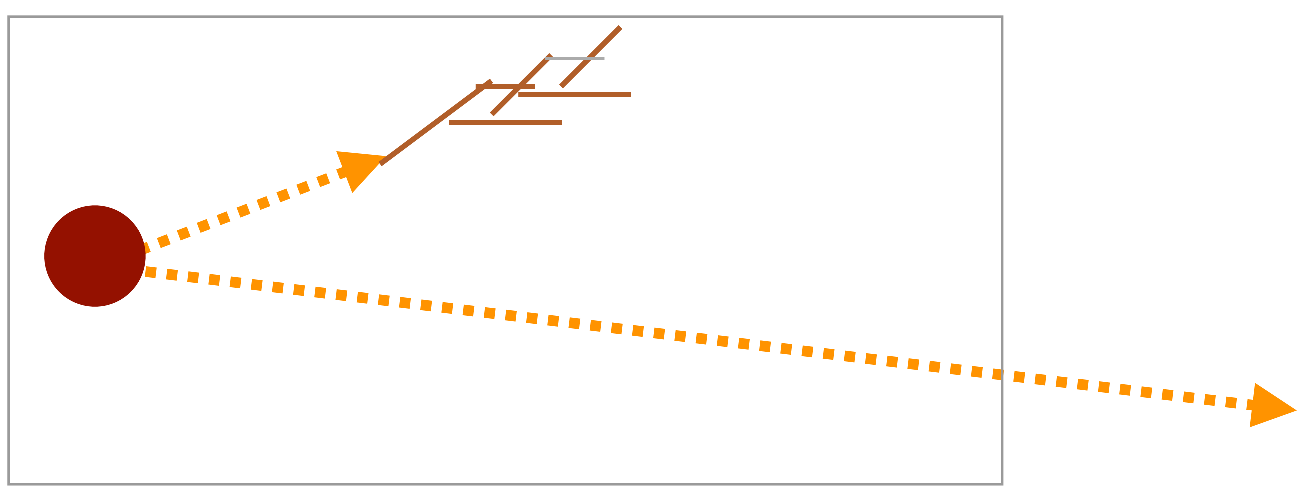
where $C_{i=e}$ = *-0.5* for electron showers and $C_{i=\gamma}$ = *+0.5* for gamma showers.
The parameter b has been tabulated for several materials:



EM checkup

	Radiation length		Moliere radius	
	g/cm^2	cm	g/cm^2	cm
liquid H_2	61.28	866	3.57	50.49
liquid Ar	19.55	14.0	9.95	7.12
C	42.70	18.8	8.15	3.59
Fe	13.84	1.76	10.71	1.36
Air	36.66	30420	7.62	6322
H_2O	37.08	36.1	8.31	8.32
SiO_2	27.05	12.3	8.61	3.91
Polystyrene scintillator	43.72	42.4	8.50	8.25
Liquid scintillator	51.07	43.9	8.93	7.68

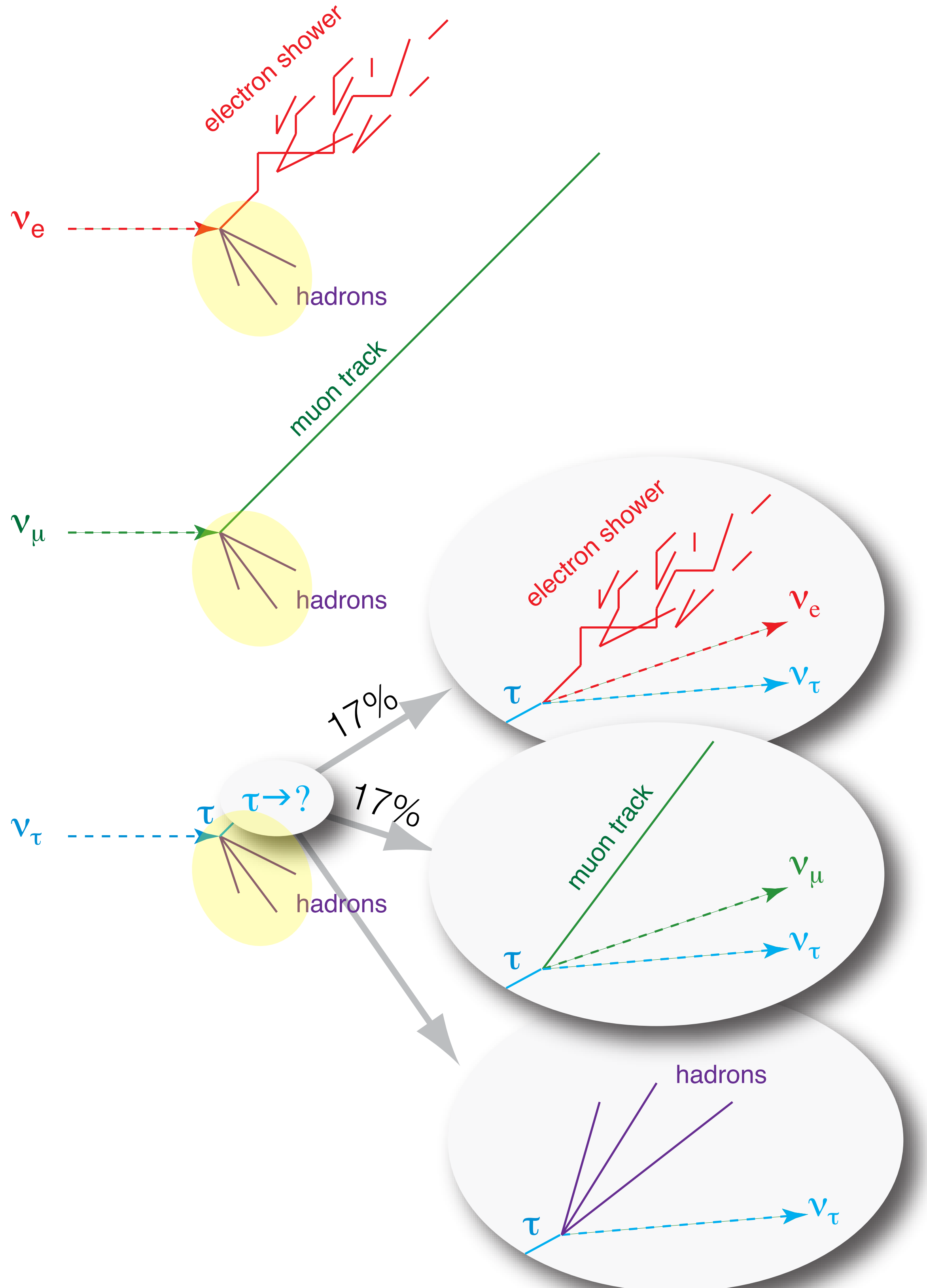
Q: A detector composed of solid scintillator has a depth of 170 cm. Roughly what fraction of the photons produced in pi-zero decay will escape the detector undetected?



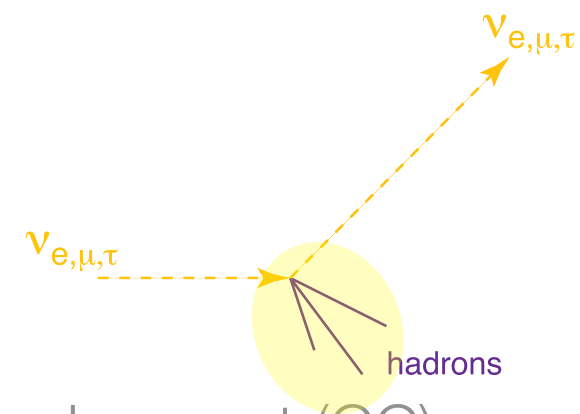
$$1 - P_C = 1 - \int_0^d \frac{1}{\lambda_C} e^{-x/\lambda_C} dx = e^{-d/\lambda_C} \left\{ \begin{array}{rcl} \lambda_C & = & \frac{11}{9} 42.4 \text{ cm} = 51.8 \text{ cm} \\ d & = & 170 \text{ cm} \end{array} \right\} = e^{-170/51.8} = 4\%$$

Neutrino detection channels

Charged-current



Neutral-current



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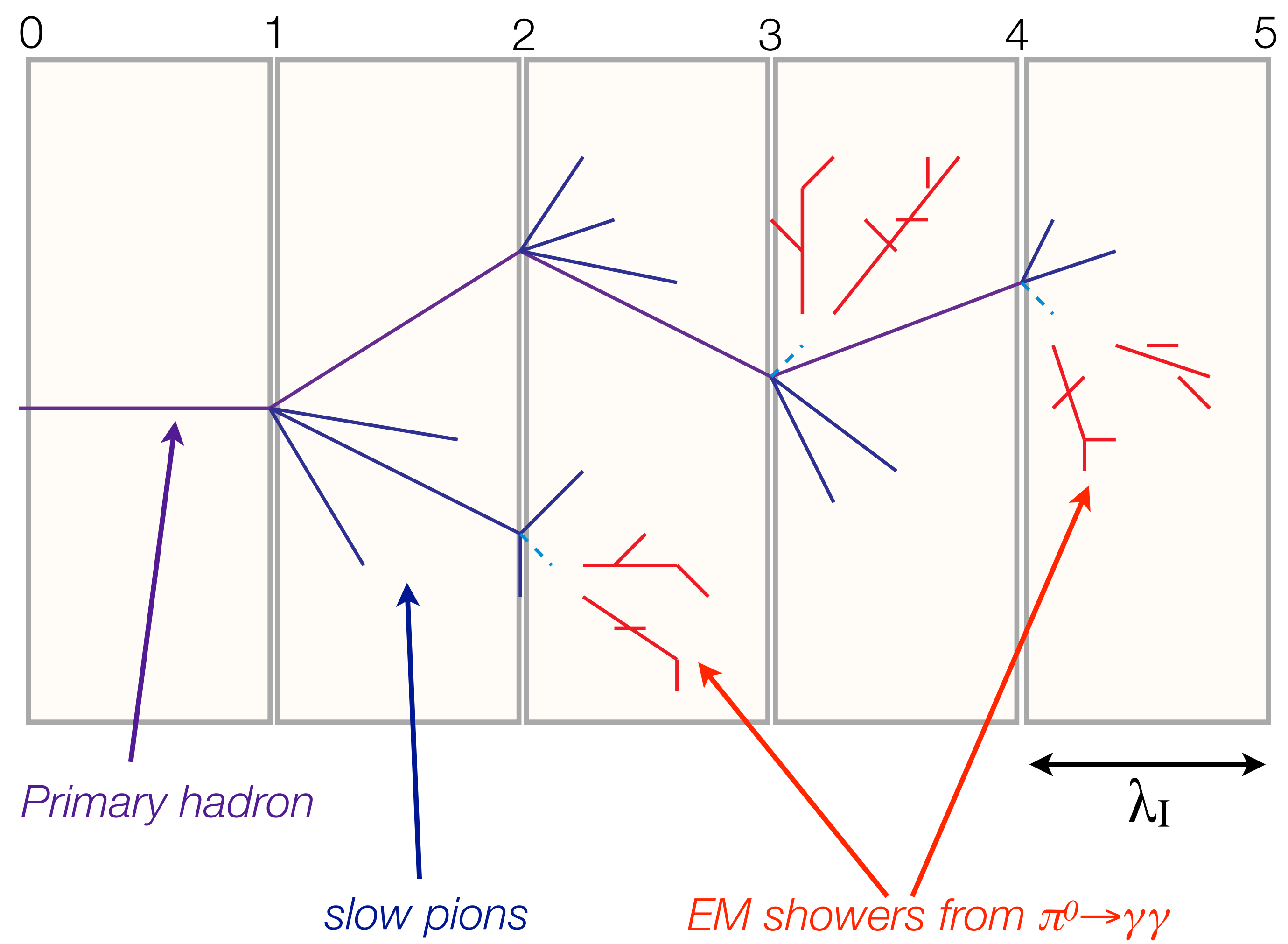
Hadron showers

Hadrons will interact strongly in a material after traversing one "interaction length" ≡ λ_I

Hadrons can produce tracks or showers depending on the relative importance of energy loss due to collisions and energy loss due to strong interactions. When:

- range due to ionization < λ_I ➜ track
- range due to ionization > λ_I ➜ shower



Simple hadron shower model:

I) Hadron travels one interaction length and interacts strongly
II) ~1/2 of the energy is carried by a single secondary hadron
III) Remaining energy carried off by several slow pions
IV) Process continues until secondary hadrons lose all their energy through collisions

Depending on rate of π^0 production, hadron showers will have EM showers embedded in them

Comparison of EM and hadron shower

- Angle of photon emission for bremsstrahlung is $\approx m_e/E$
- Hadronic processes typically produce particles with P_T~= 300 MeV/c
- For 1 GeV:
  - $\theta_{EM} \approx 0.5$ mrad
  - $\theta_{Had} \approx 300$ mrad

➡*EM showers are compact in the transverse direction compared to hadron showers which tend to be more diffuse in the transverse direction*

- Example at right shows 15 GeV e and π in glass (Z~=11).

CHARM-II collaboration, NIM A277 (1989) 83-91.

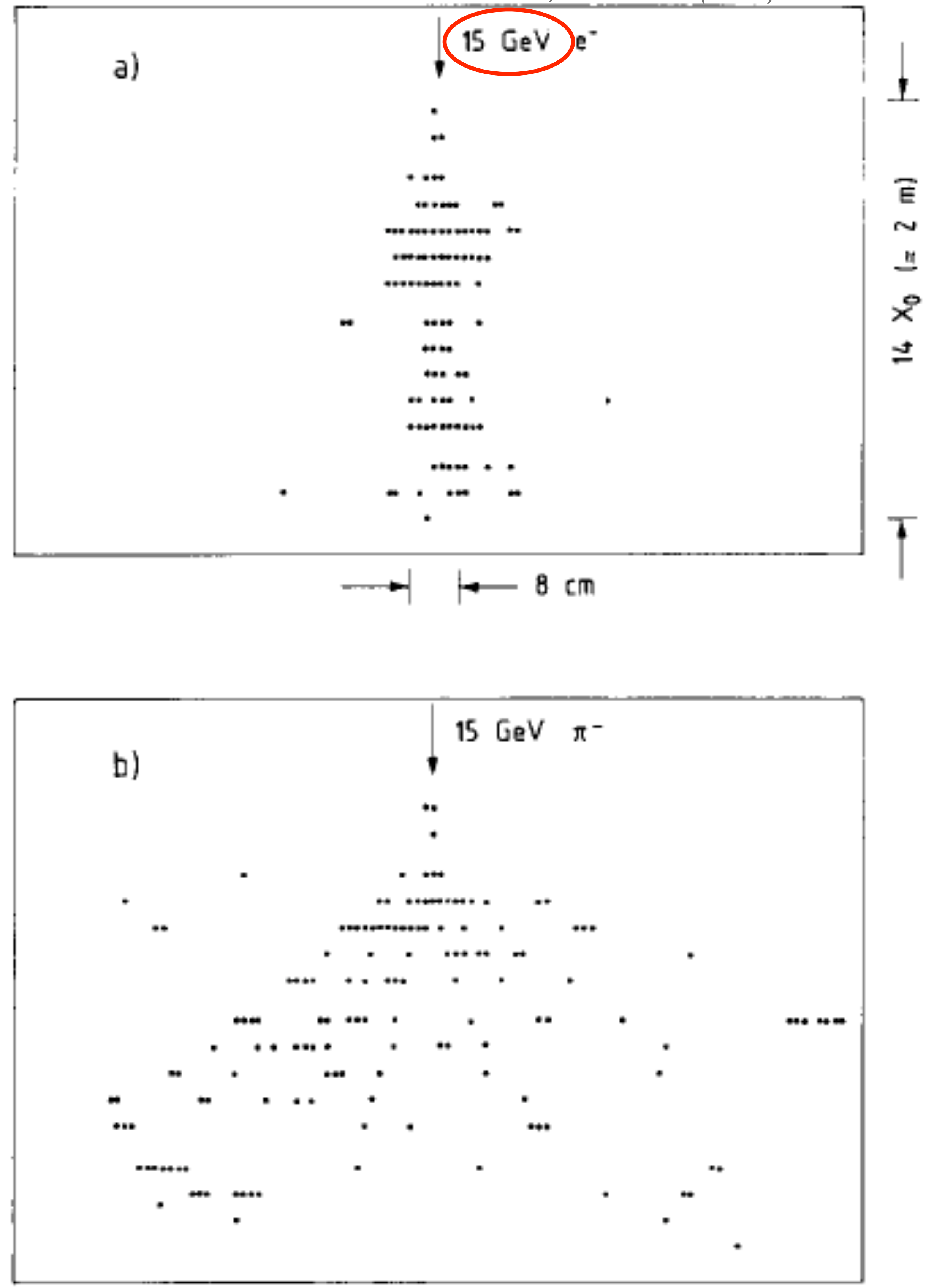
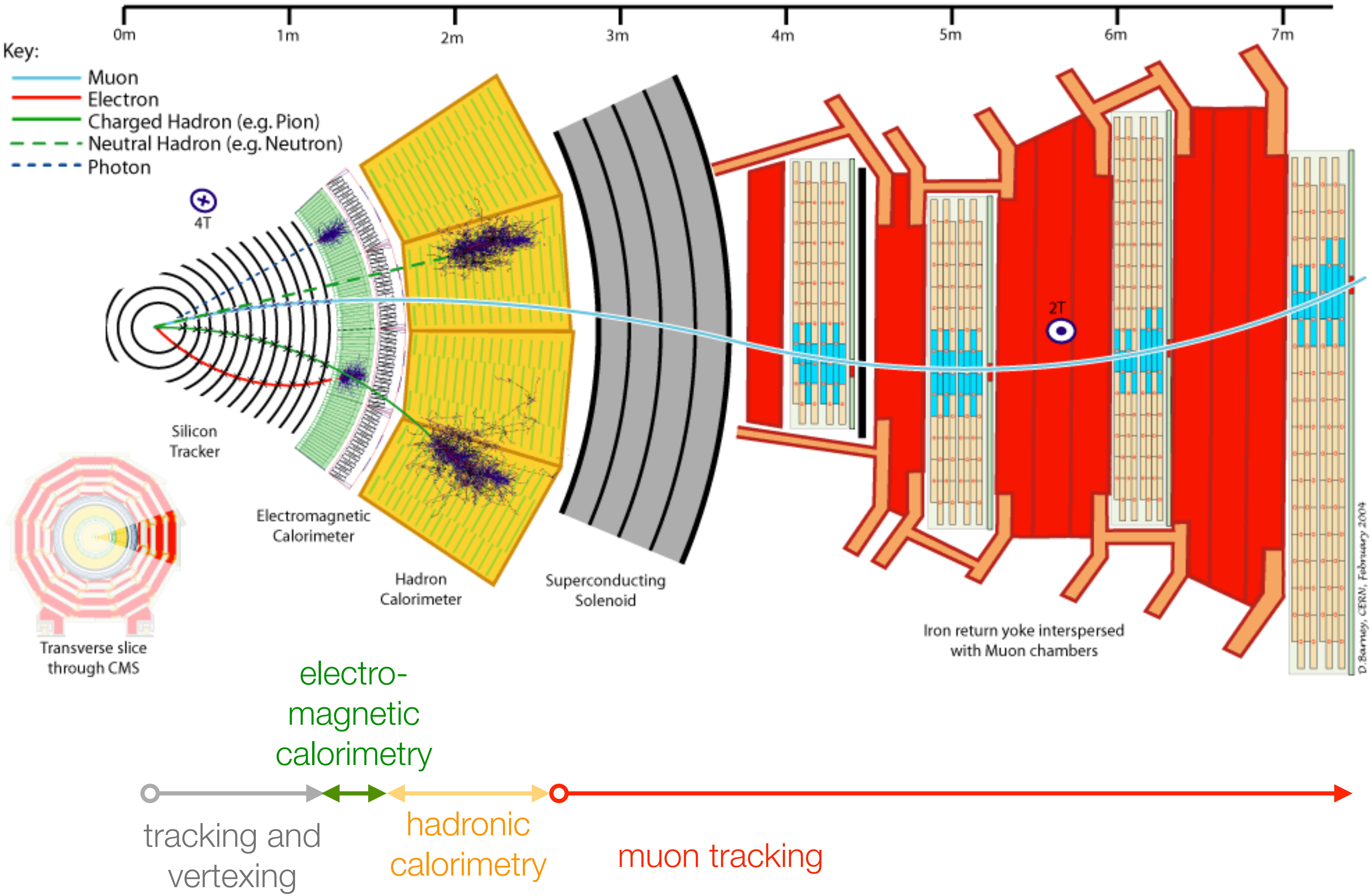


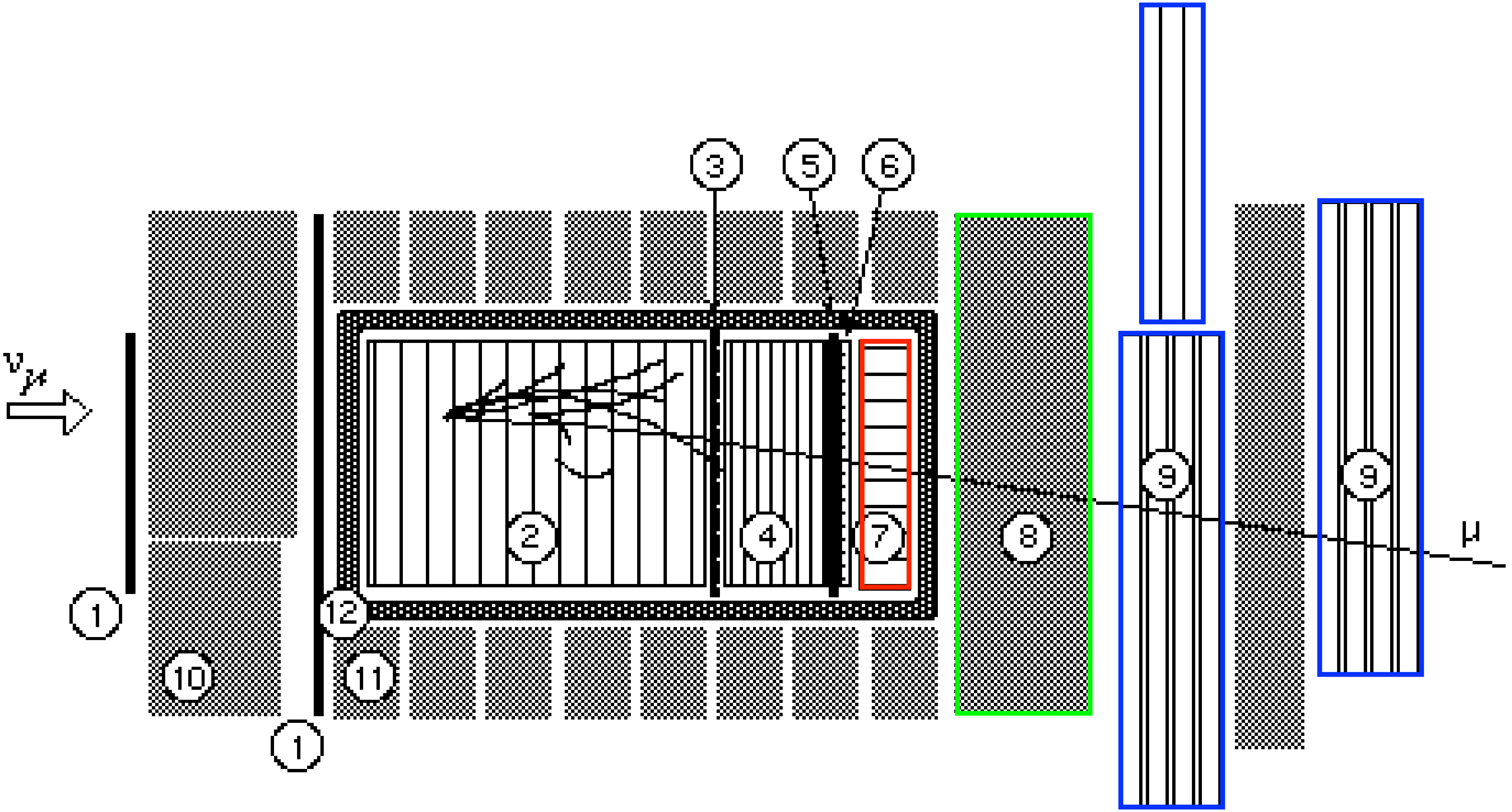
Fig. 13. Pattern of tube hits for two typical events: (a) electron-induced, (b) pion-induced.

Putting it al together: CMS (a typical collider detector)



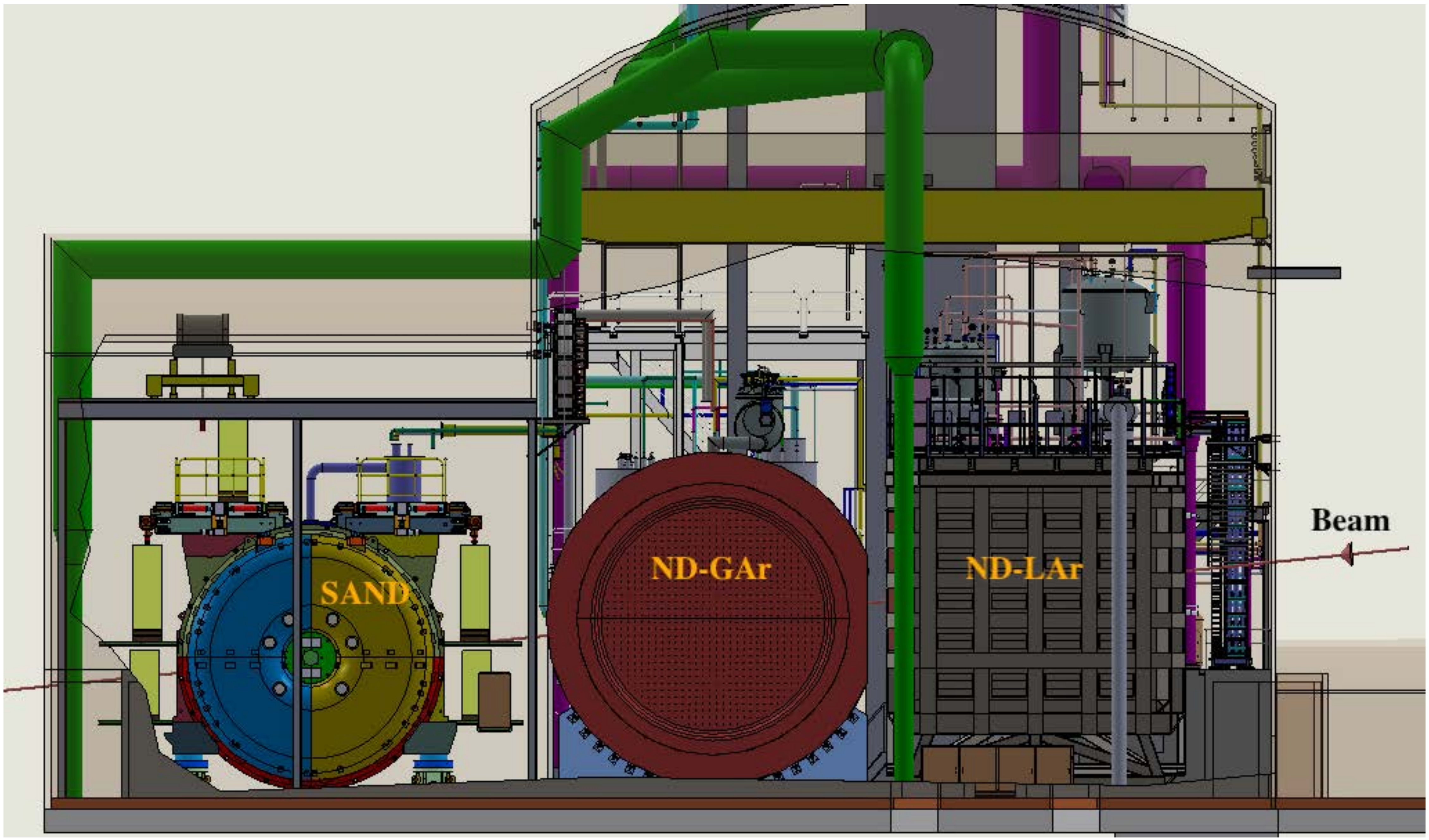
David Barney, https://cms-docdb.cern.ch/cgi-bin/PublicDocDB/ShowDocument?docid=4172

ν_μ CC event in the NOMAD detector



(1) Veto wall
(2) Drift chambers
(3) Trigger plane
(4) Transition radiation tracker
(5) Trigger plane
(6) Preshower region
(7) Electromagnetic calorimeter
(8) Hadron calorimeter
(9) Muon tracking
(10) Forward calorimeter
(11) Magnet return yoke
(12) Magnet

The DUNE Near Detector



Muon tracking

Muon tracking + high resolution vertex activity

Neutrino target and calorimetry

Neutrino detection channels

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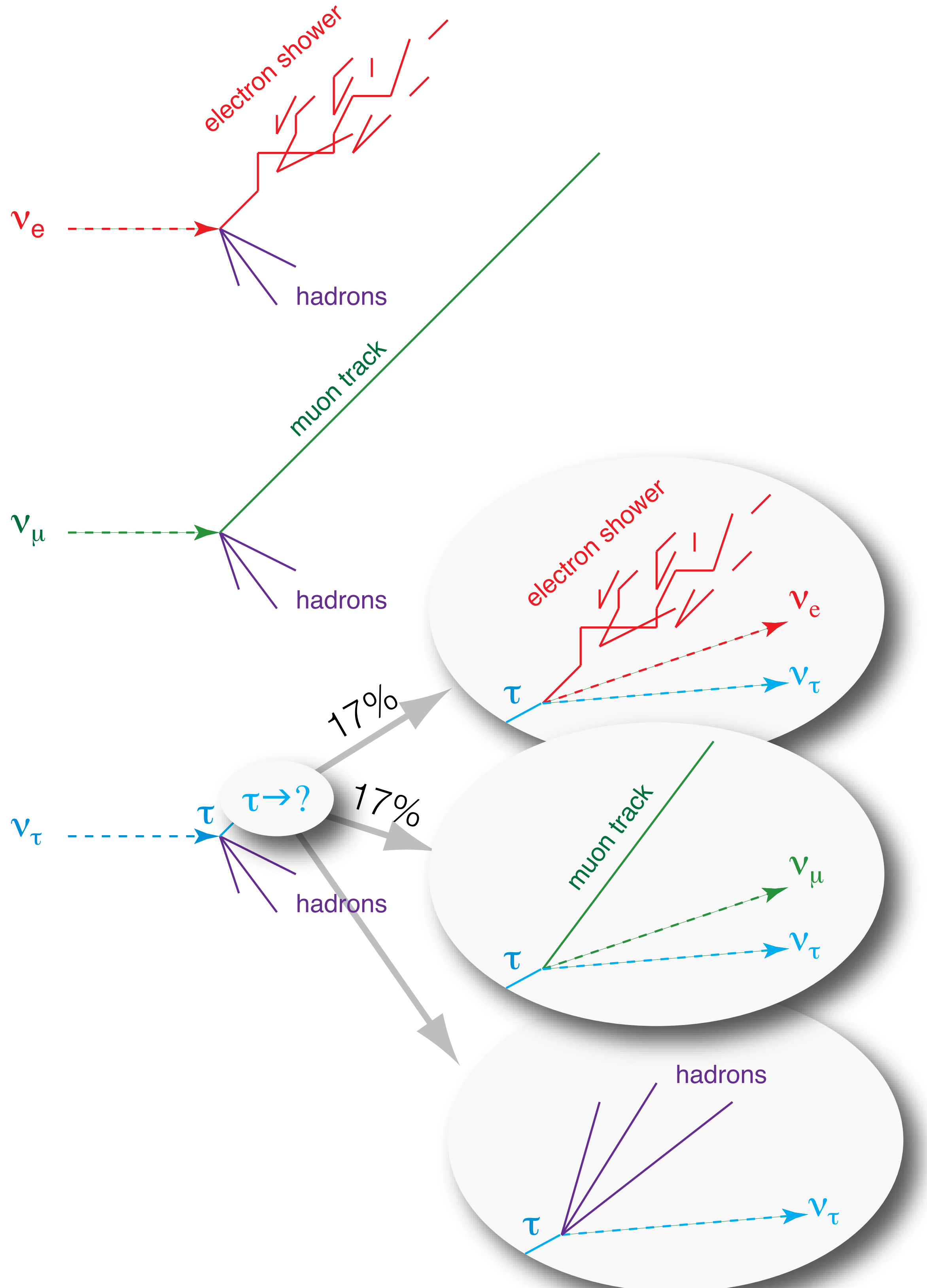

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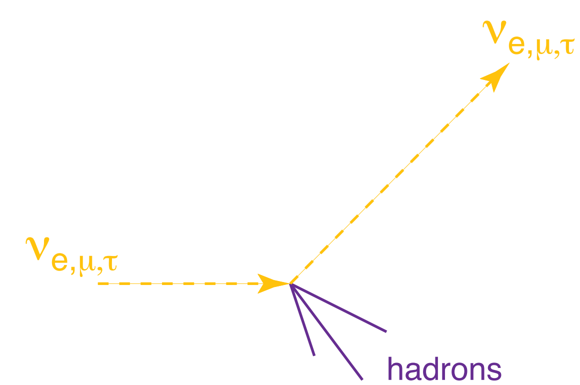

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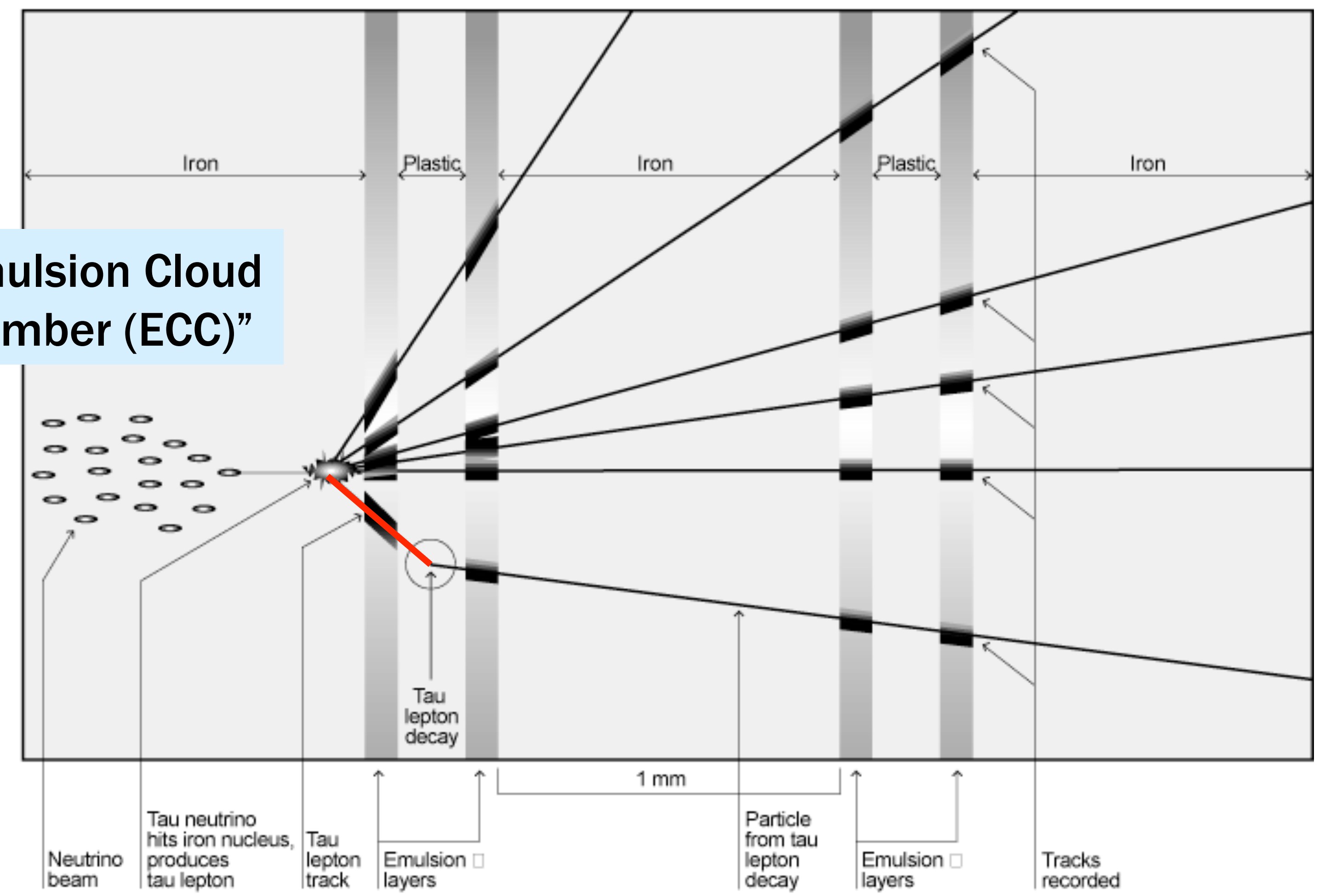
Tau Neutrino Detection

- Several experiments look for tau neutrinos
- Observed by DONUT experiment
- Sought from oscillations by CHORUS and OPERA

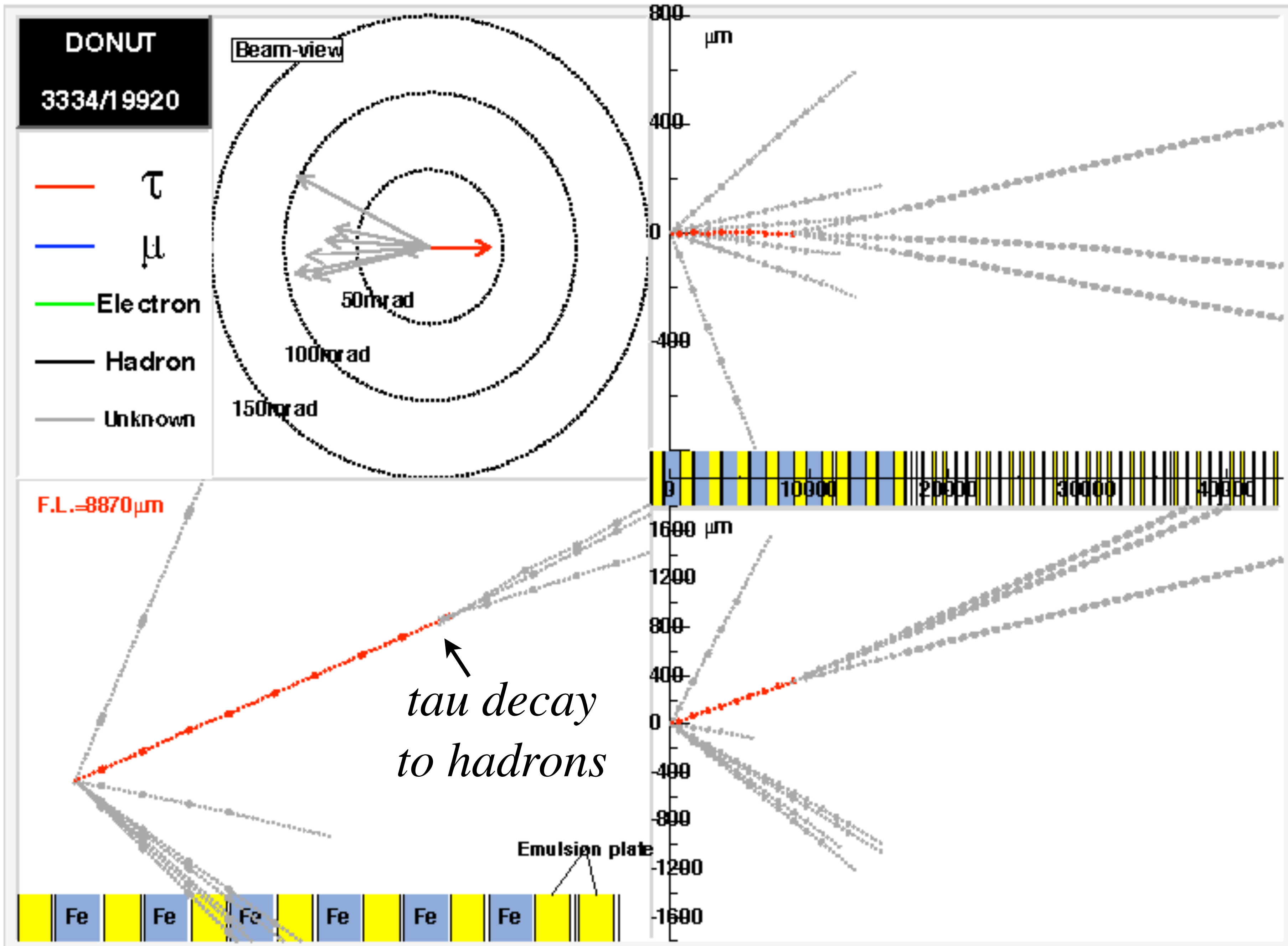
- All of the above experiments have used thin films of photographic emulsions placed between target layers
- Use of emulsion allows for resolution of short tau track and search for its decay either through a track kink or to multi-prongs
- Emulsion target followed by other detectors which provide tracking and tell you where you had a neutrino interaction and which emulsions you should develop

Detecting a Tau Neutrino



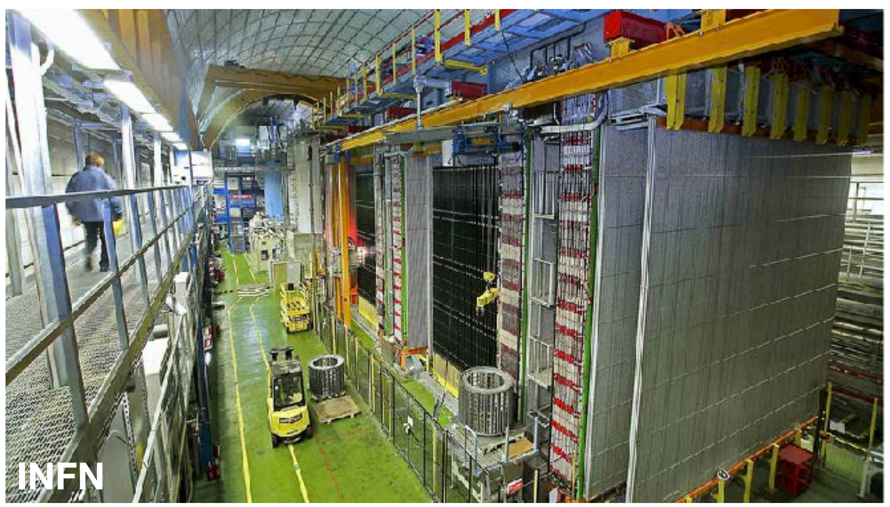
Of one million million tau neutrinos crossing the DONUT detector, scientists expect about one to interact with an iron nucleus.

Tau Neutrino Detection by DONUT Collaboration

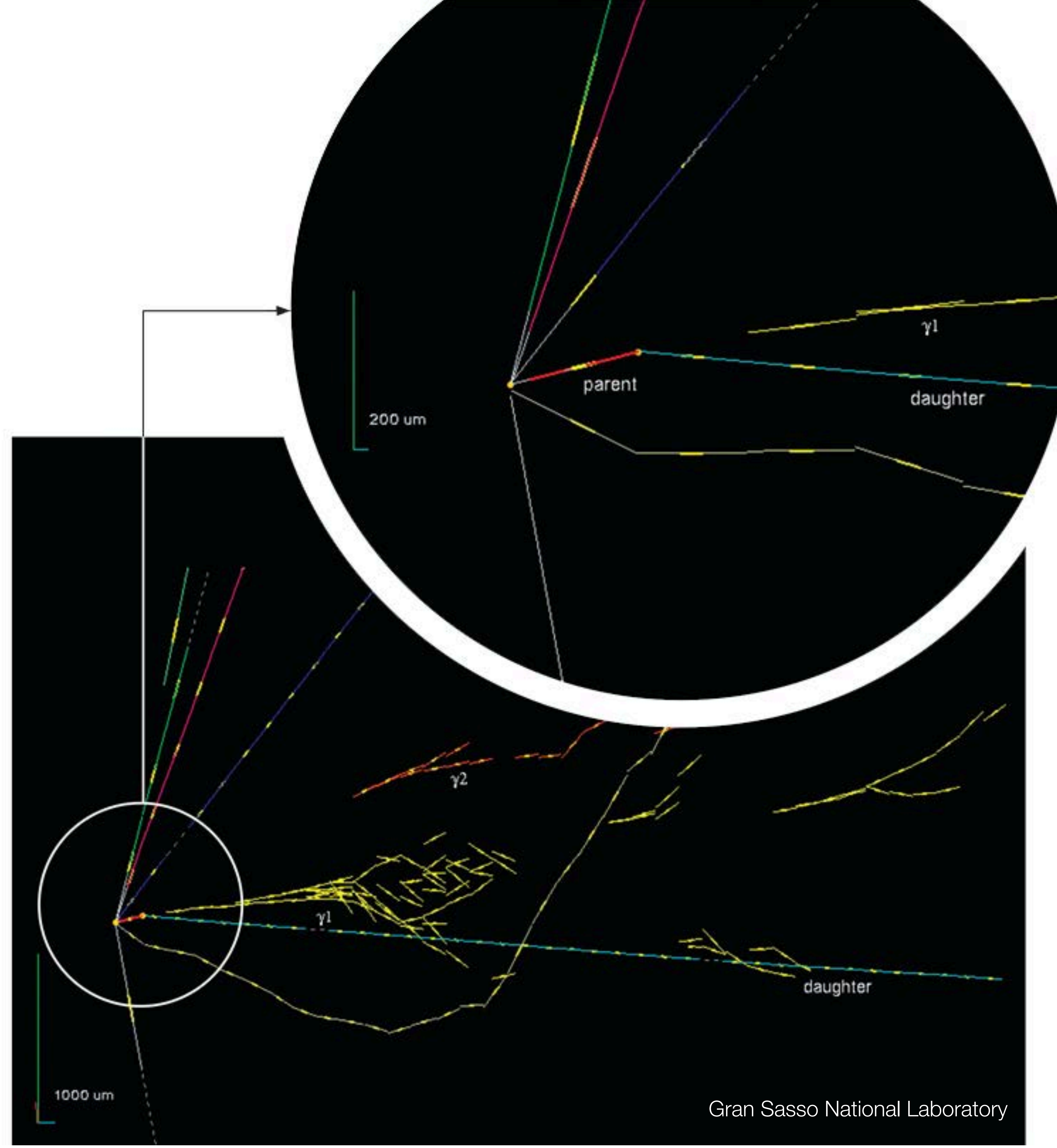


OPERA Experiment In CNGS beam

OPERA uses bricks of lead/ emulsion embedded in a solid scintillator-based tracking system + downstream muon spectrometer



τ^- decay channels	Signal ÷ Δm^2 (Full mixing)		Background
	2.5×10^{-3} (eV^2)	3.0×10^{-3} (eV^2)	
$\tau^- \to \mu^-$	2.9	4.2	0.17
$\tau^- \to e^-$	3.5	5.0	0.17
$\tau^- \to h^-$	3.1	4.4	0.24
$\tau^- \to 3h$	0.9	1.3	0.17
ALL	10.4	15.0	0.76



$$\tau \to \rho + \nu_\tau$$

$$\rho \to \pi^- + \pi^0$$

$$\pi^0 \to \gamma + \gamma$$

Facts of life for the neutrino experimenter...

Numerical example for typical accelerator-based experiment

$$N_{\rm obs} = \left[\int \mathcal{F}(E_\nu)\sigma(E_\nu,\ldots)\epsilon(E_\nu,\ldots)dE_\nu d\ldots\right]\frac{M}{A\,m_N}T$$

N_{obs} : number of neutrino events recorded

$\mathcal{F}$: Flux of neutrinos $(\#/{\rm cm}^2/{\rm s})$

σ : neutrino cross section per nucleon $\simeq 0.7\frac{E_\nu}{[{\rm GeV}]}\times 10^{-38}{\rm cm}^2$

ϵ : detection efficiency

M : total detector mass

A : effective atomic number of detector

m_N : nucleon mass

T : exposure time

typical "super-beam" flux at 1000 km

typical accelerator up time in one year

$$N_{\rm obs} = \left[\frac{1}{{\rm cm}^2{\rm s}}\right]\left[0.7\times 10^{-38}\frac{E_\nu}{\rm GeV}{\rm cm}^2\right][\epsilon]\,[1\ {\rm GeV}]\left[\frac{M}{20\cdot 1.67\times 10^{-27}\ {\rm kg}}\right]\left[2\times 10^7\ {\rm s}\right]$$

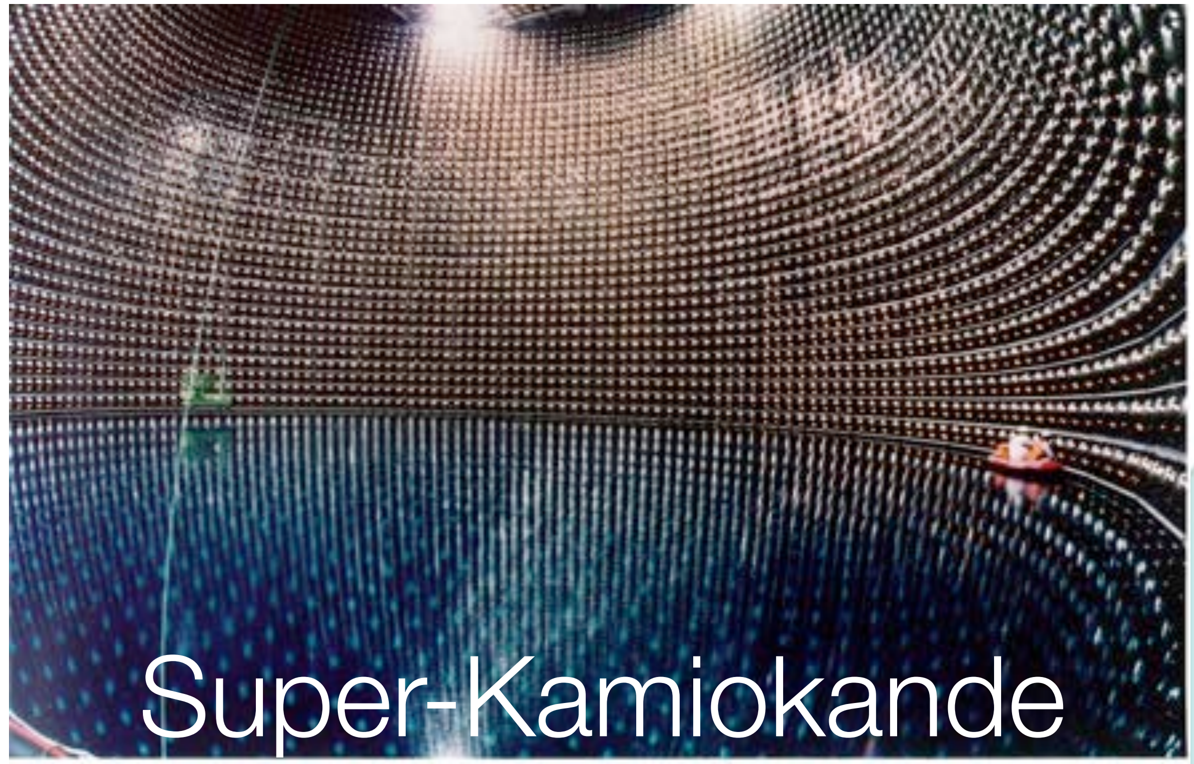
work at high energies if you can

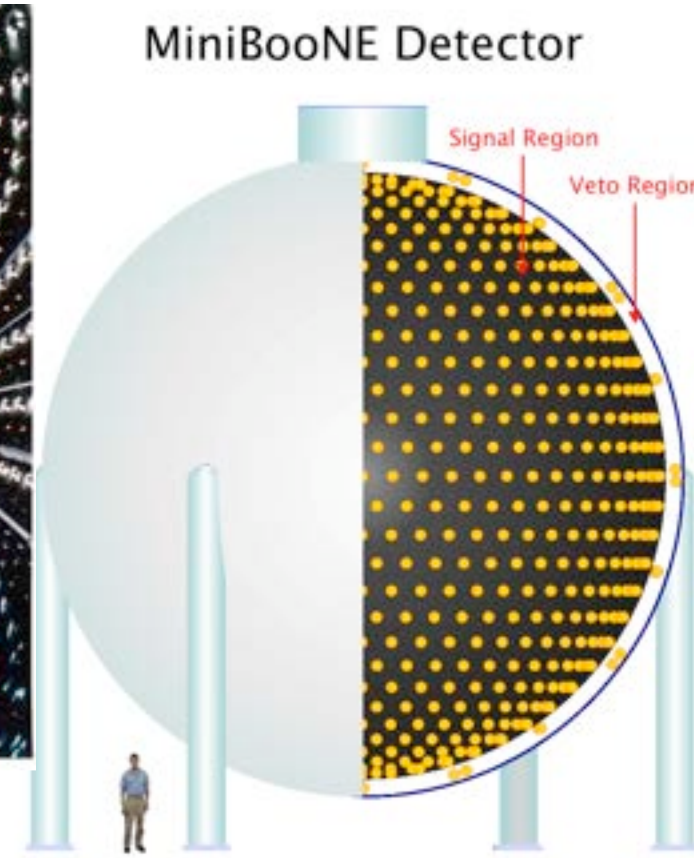
$$N_{\rm obs} \simeq 4\times 10^{-6}\,\frac{E_\nu}{[{\rm GeV}]}\cdot\epsilon\cdot\frac{M}{{\rm kg}]}$$

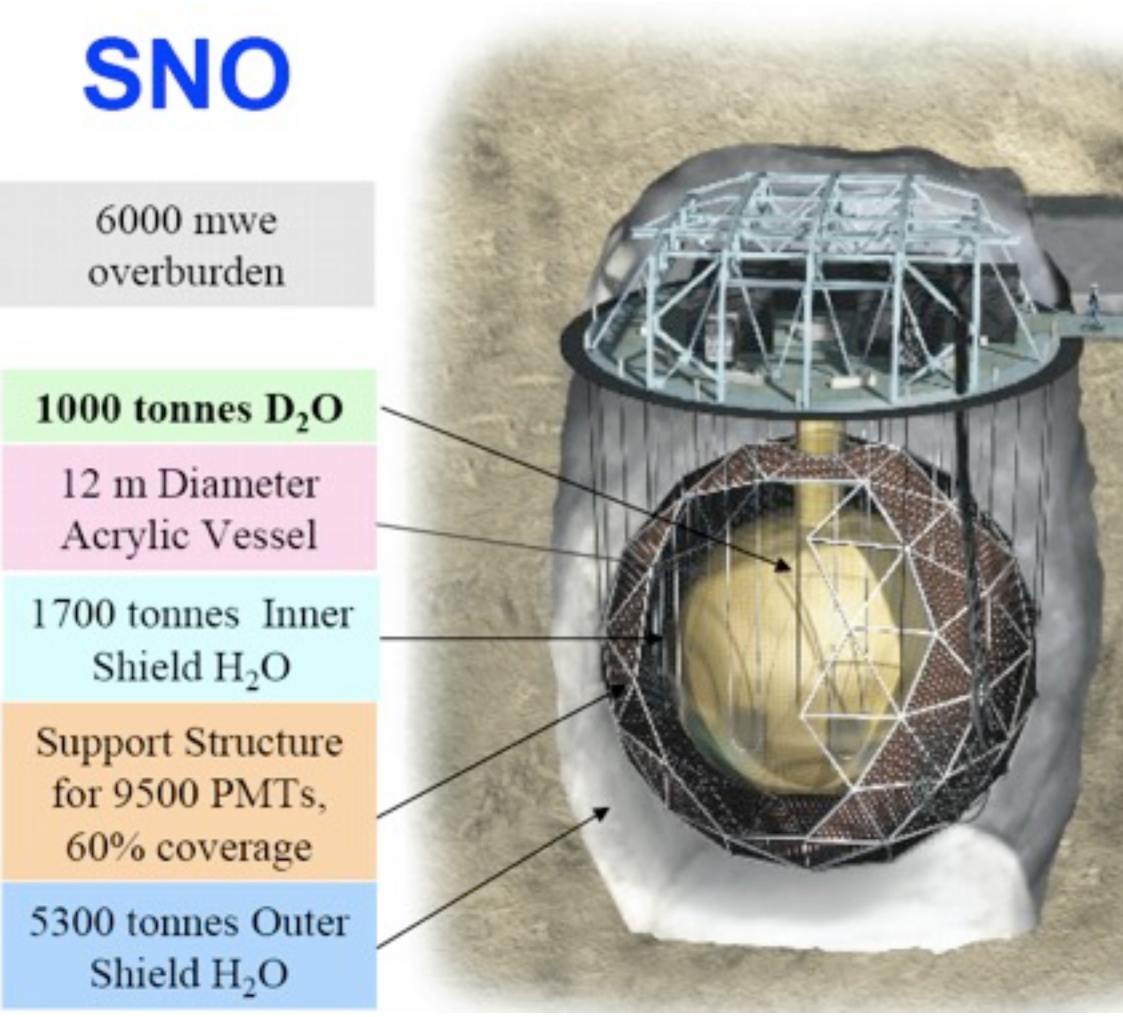
need detector masses of 10^6 kg = 1 kton to get in the game

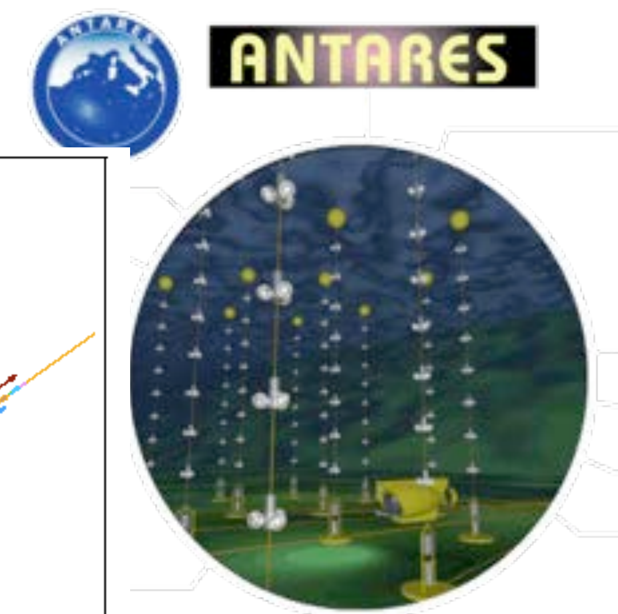
push this as high as you can

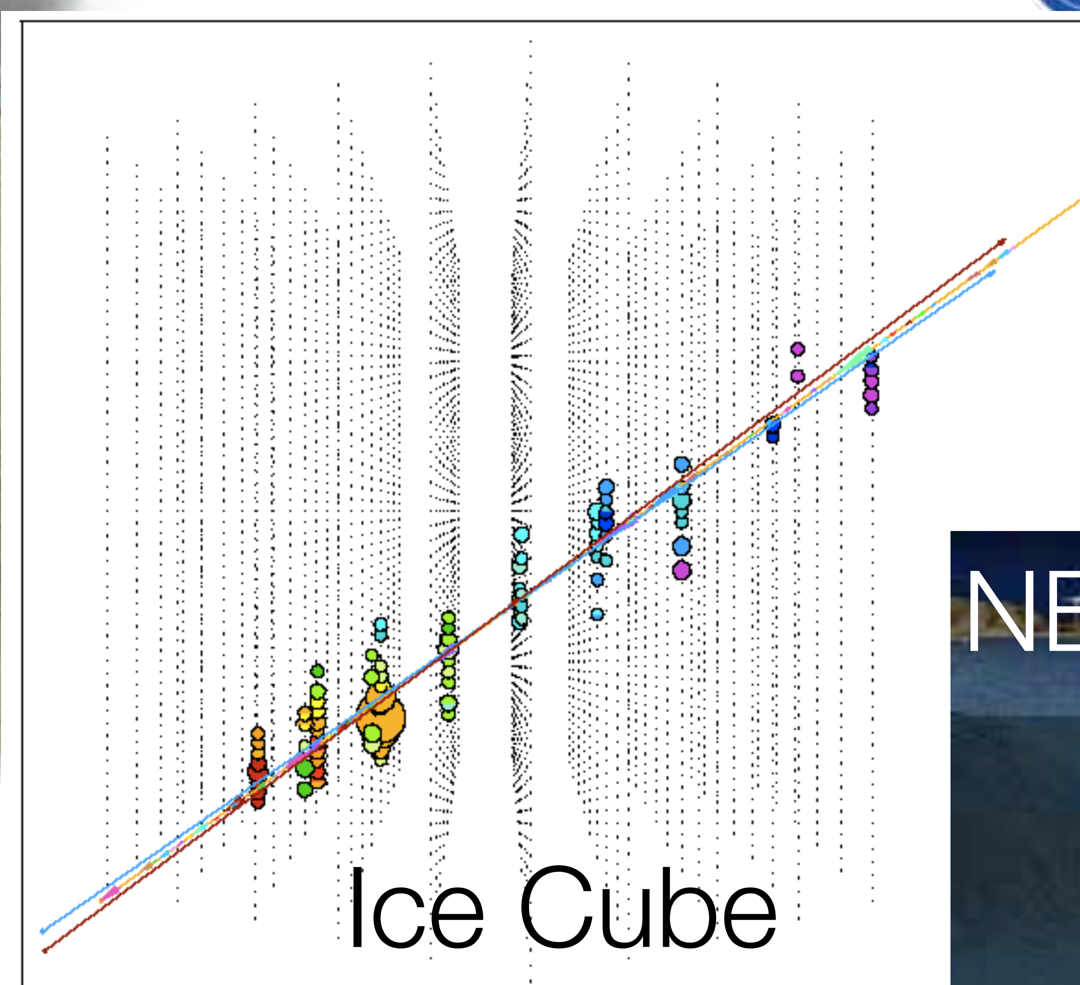
Cherenkov detectors



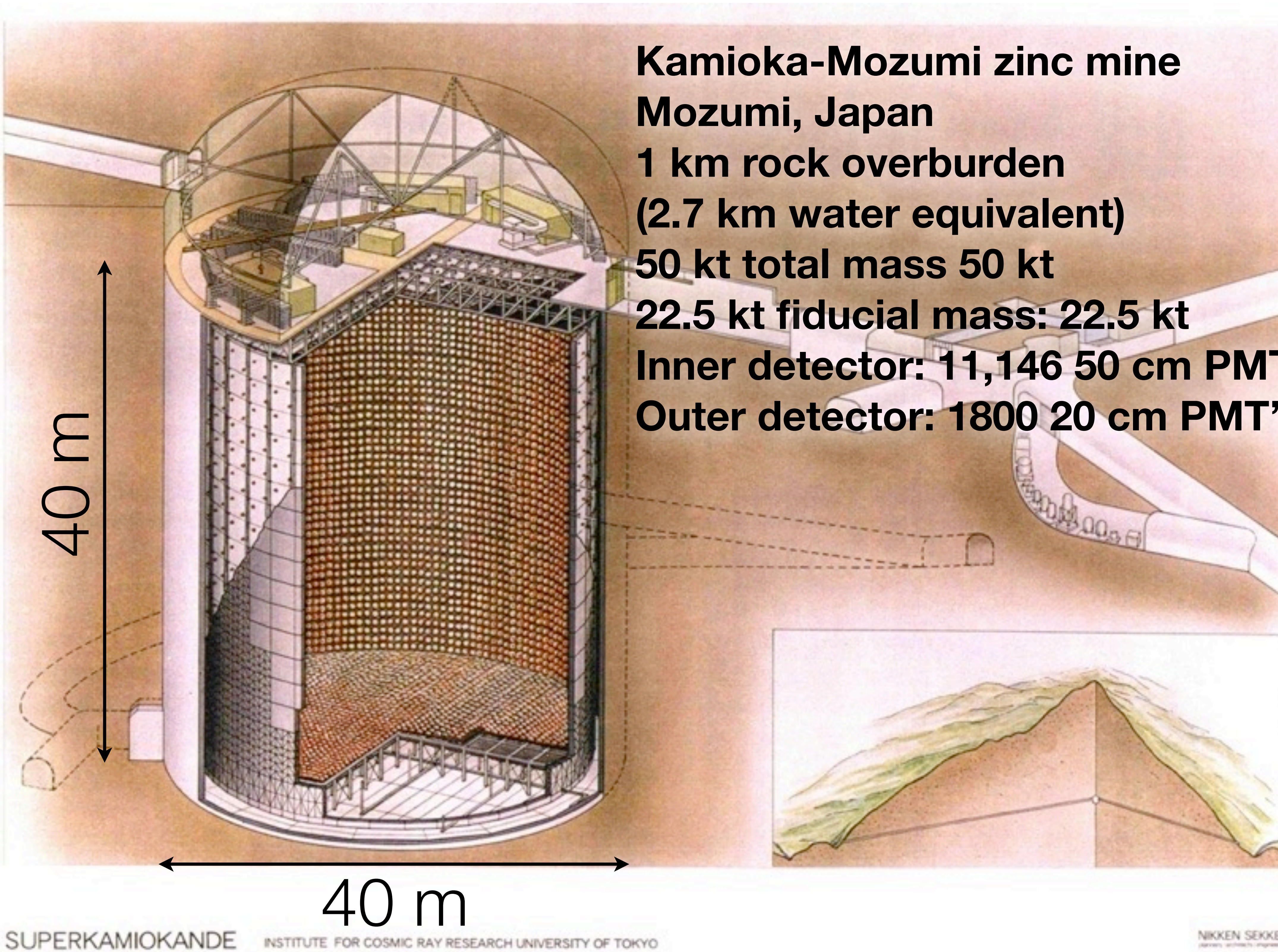








Super-Kamiokande



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

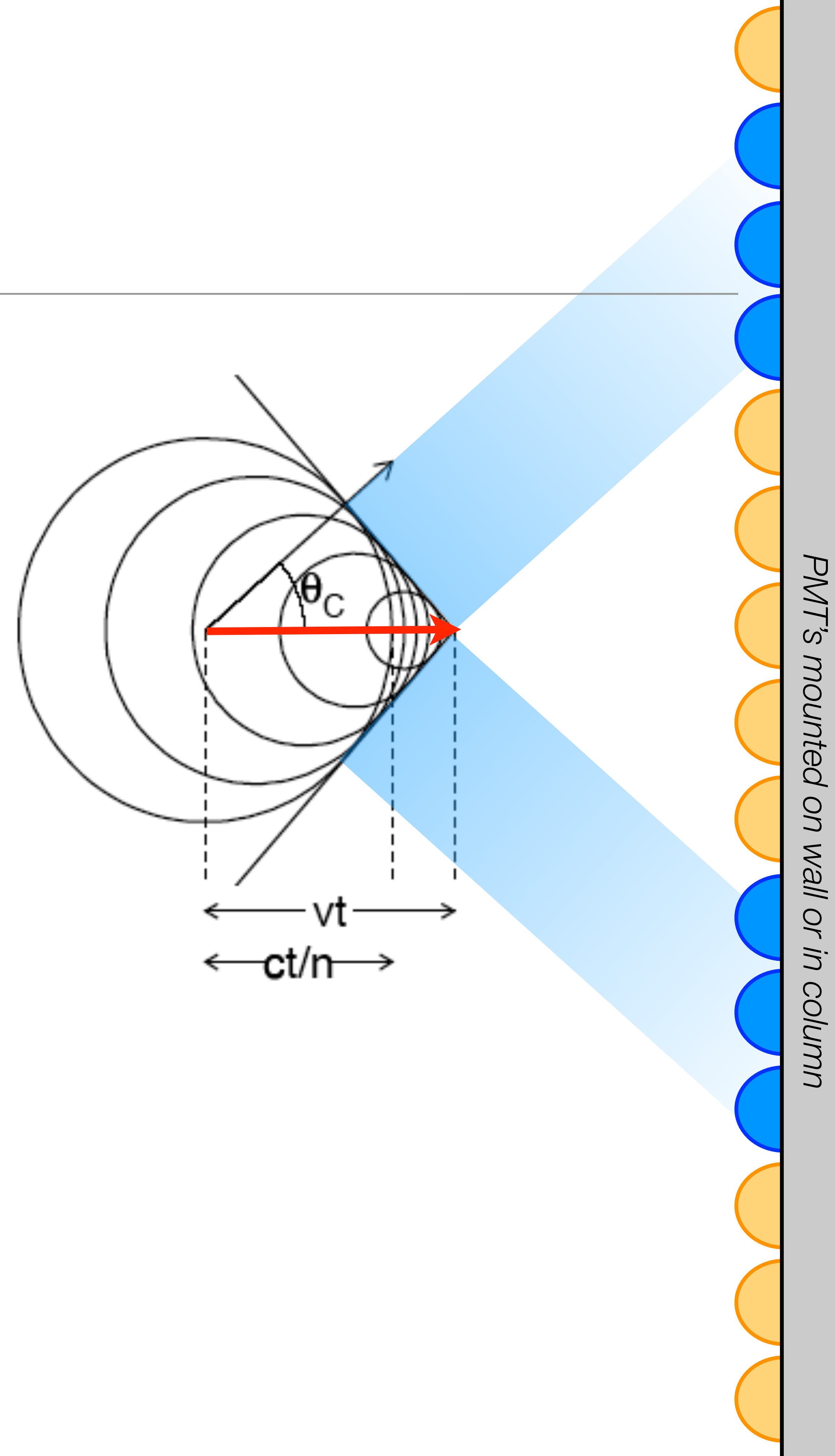
- If speed of charged particle exceeds speed of light in a dielectric medium of index of refraction *n*, a “shock wave” of radiation develops at a critical angle:

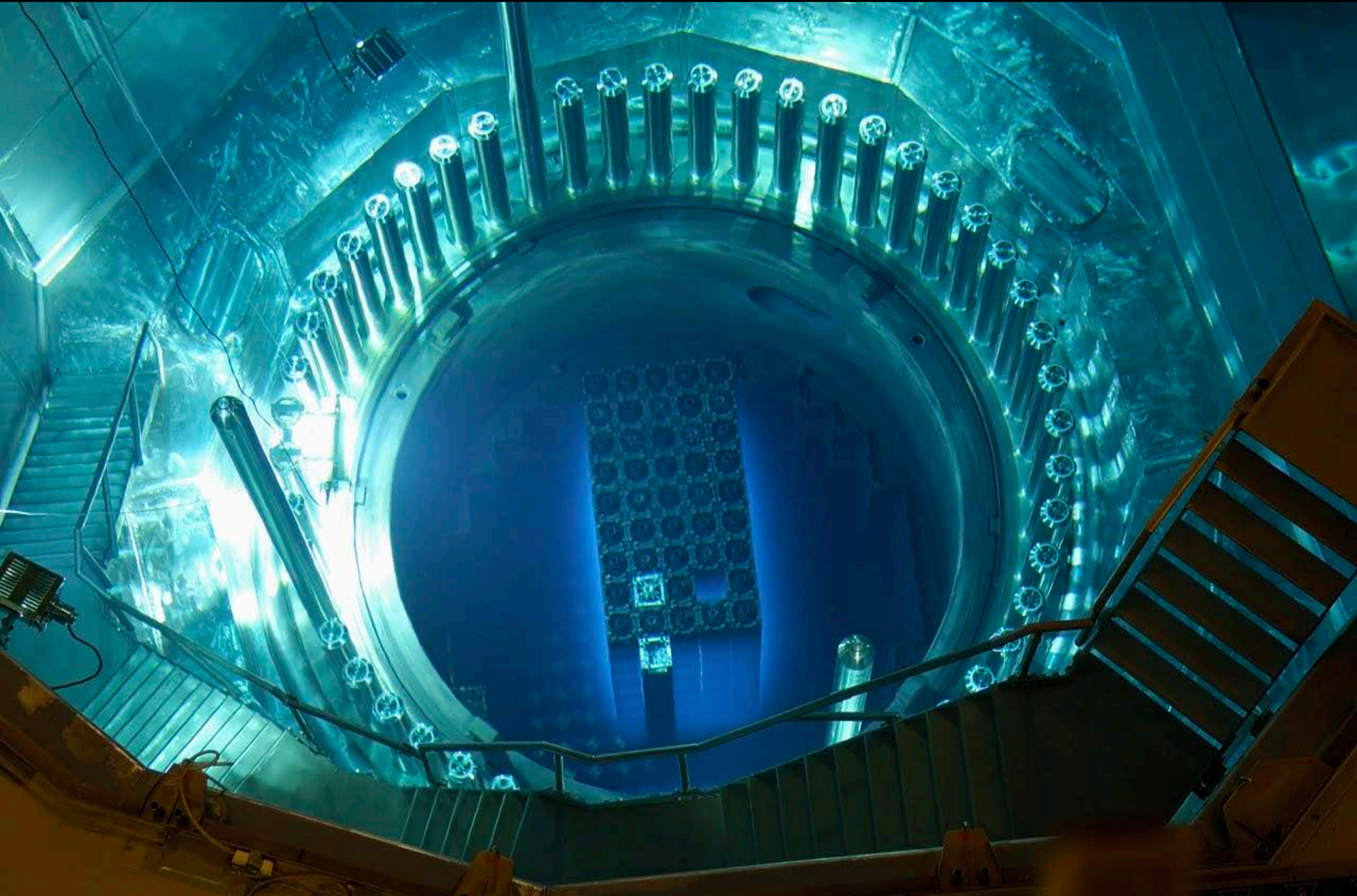
$$\cos\theta_C = \frac{1}{\beta n}, \beta > \frac{1}{n}$$

- This requirement imposed a threshold on particle detection:

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

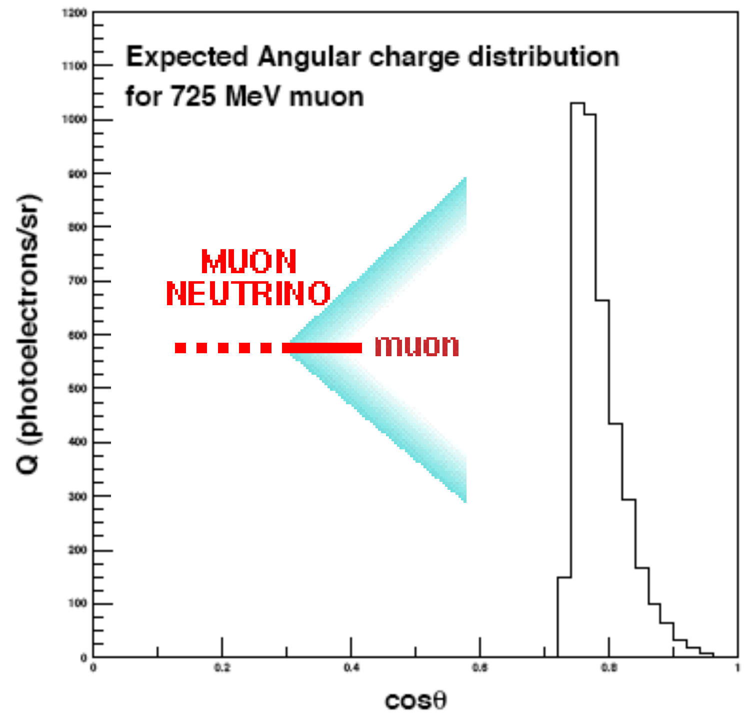
- For water (n=1.3):
  - electron threshold is 0.6 MeV
  - muon threshold is 120 MeV
  - pion threshold is 160 MeV
  - proton threshold is 1.1 GeV

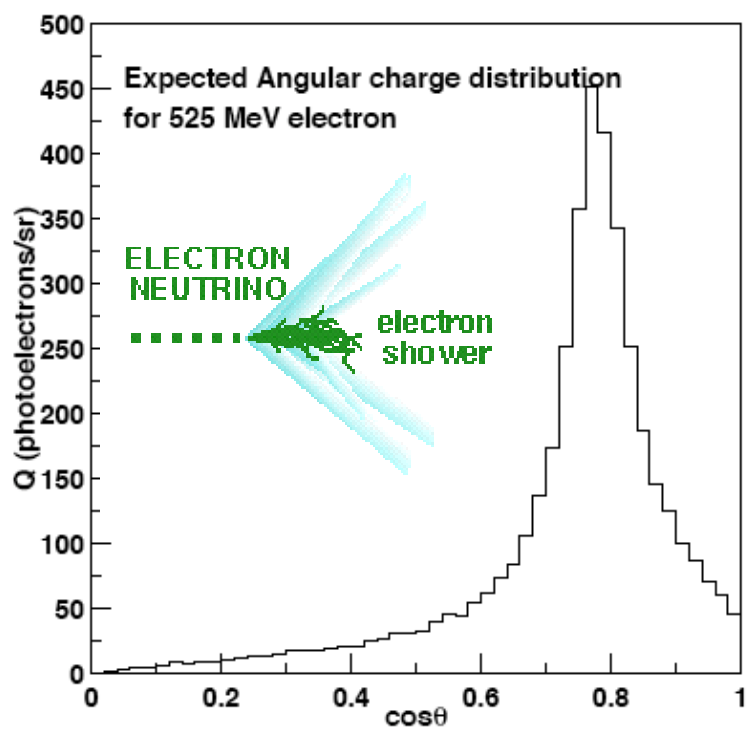




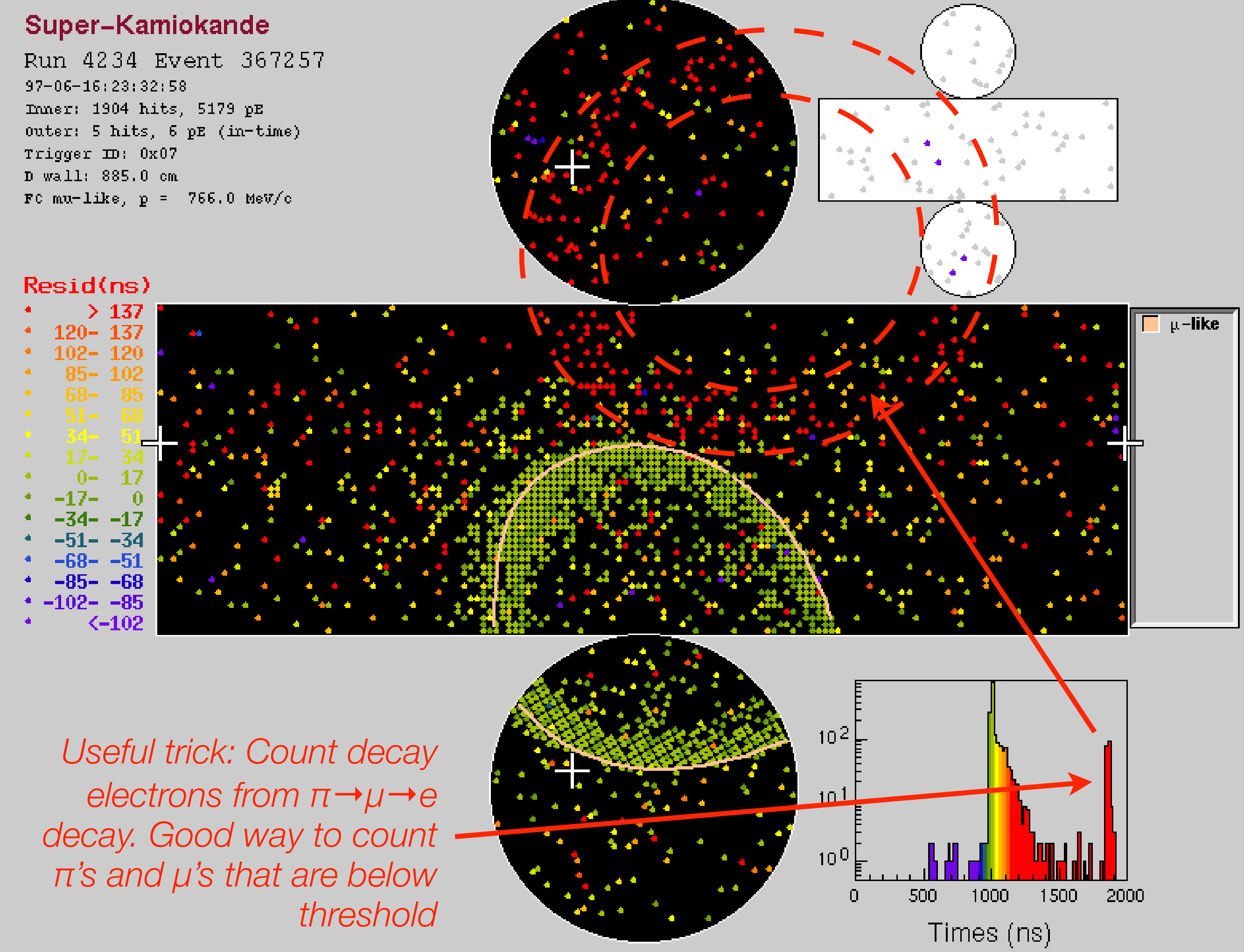
Water Cherenkov: e/μ identification

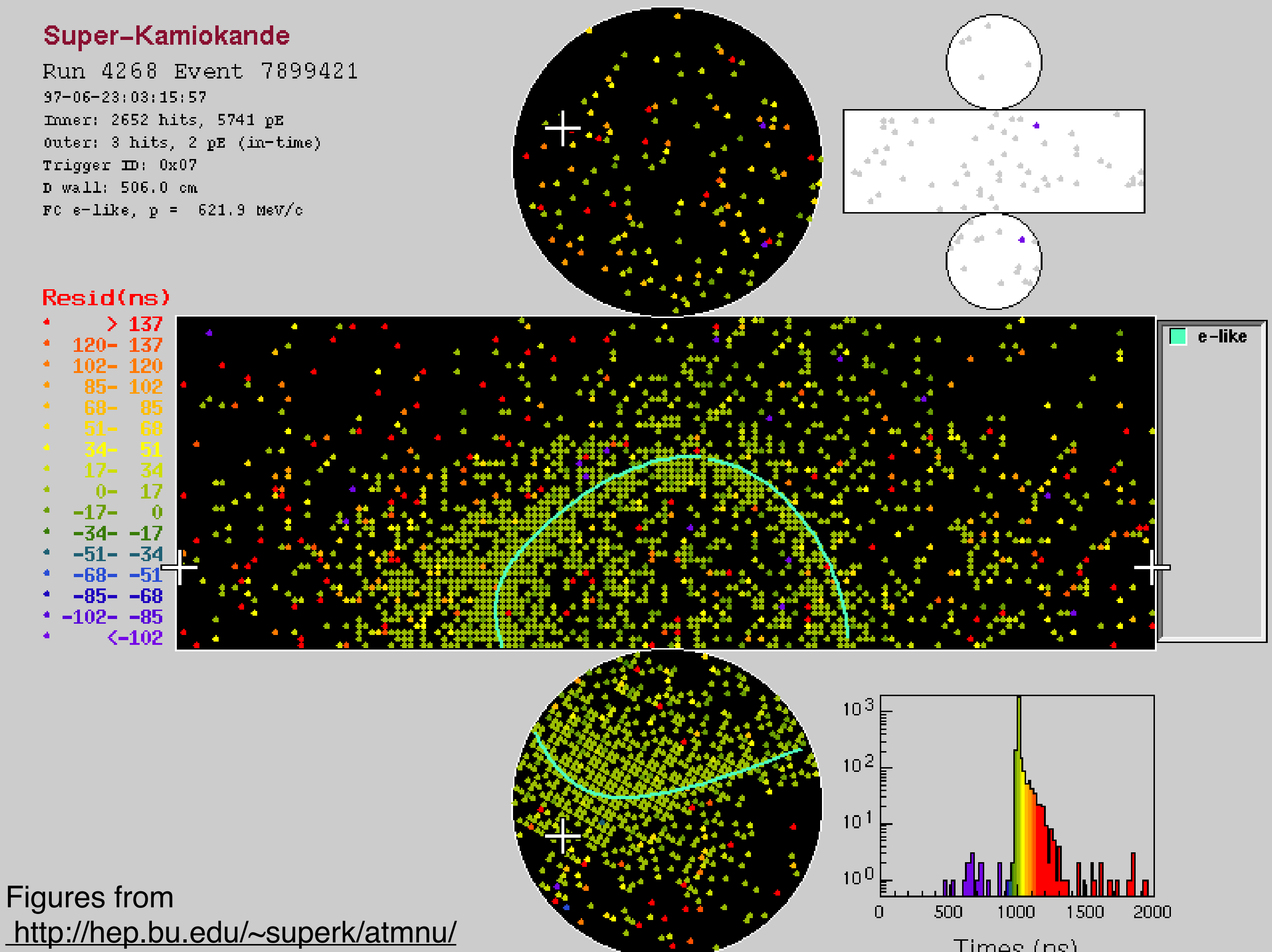
- At low momenta one can correlate the particle visible energy with the Cherenkov angle. Muons will have “collapsed” rings while electrons are ~always at 42°.
- At higher momenta, look at the distribution of light around Cherenkov angle. Muons are “crisp”, electron showers are “fuzzy”. See plots and figures at the right.





Figures from M. Earl’s PhD Thesis

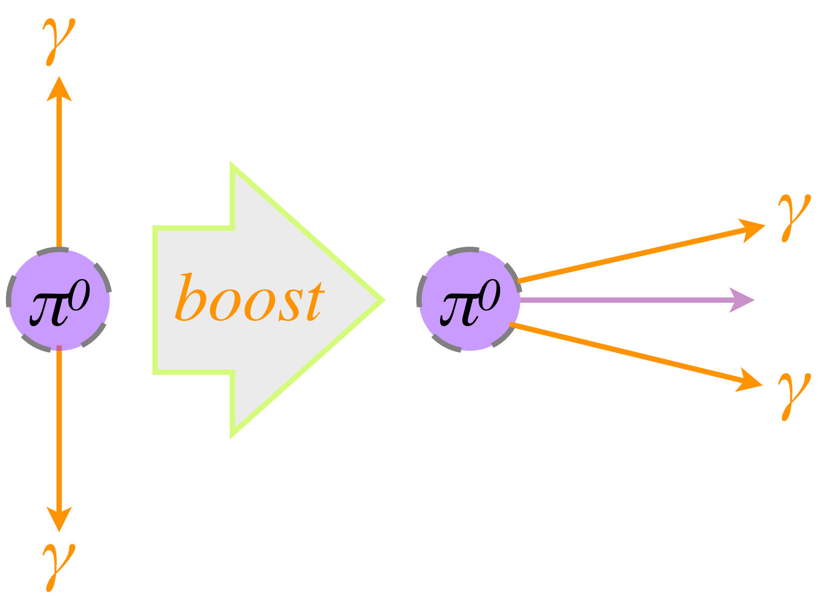


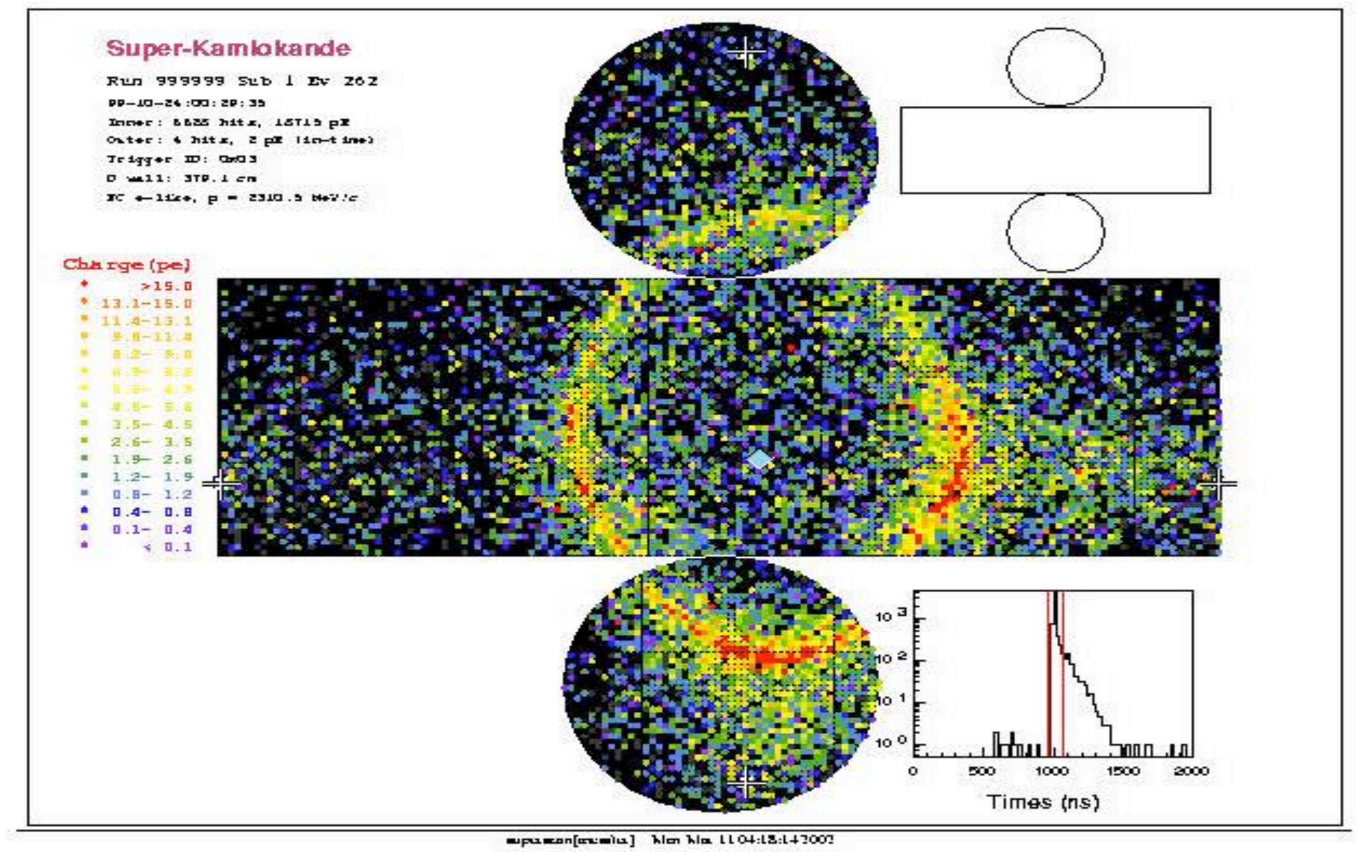


Figures from
http://hep.bu.edu/~superk/atmnu/

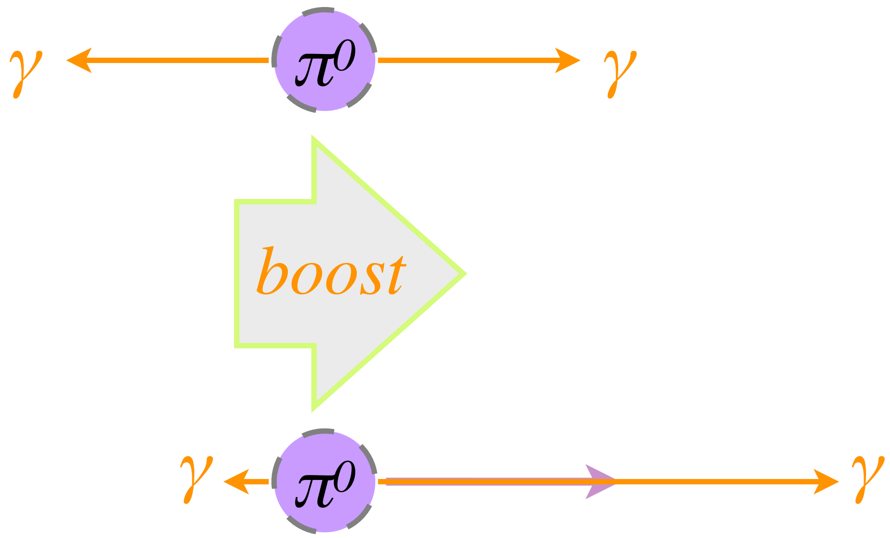
2 GeV visible energy
One is signal, the other background

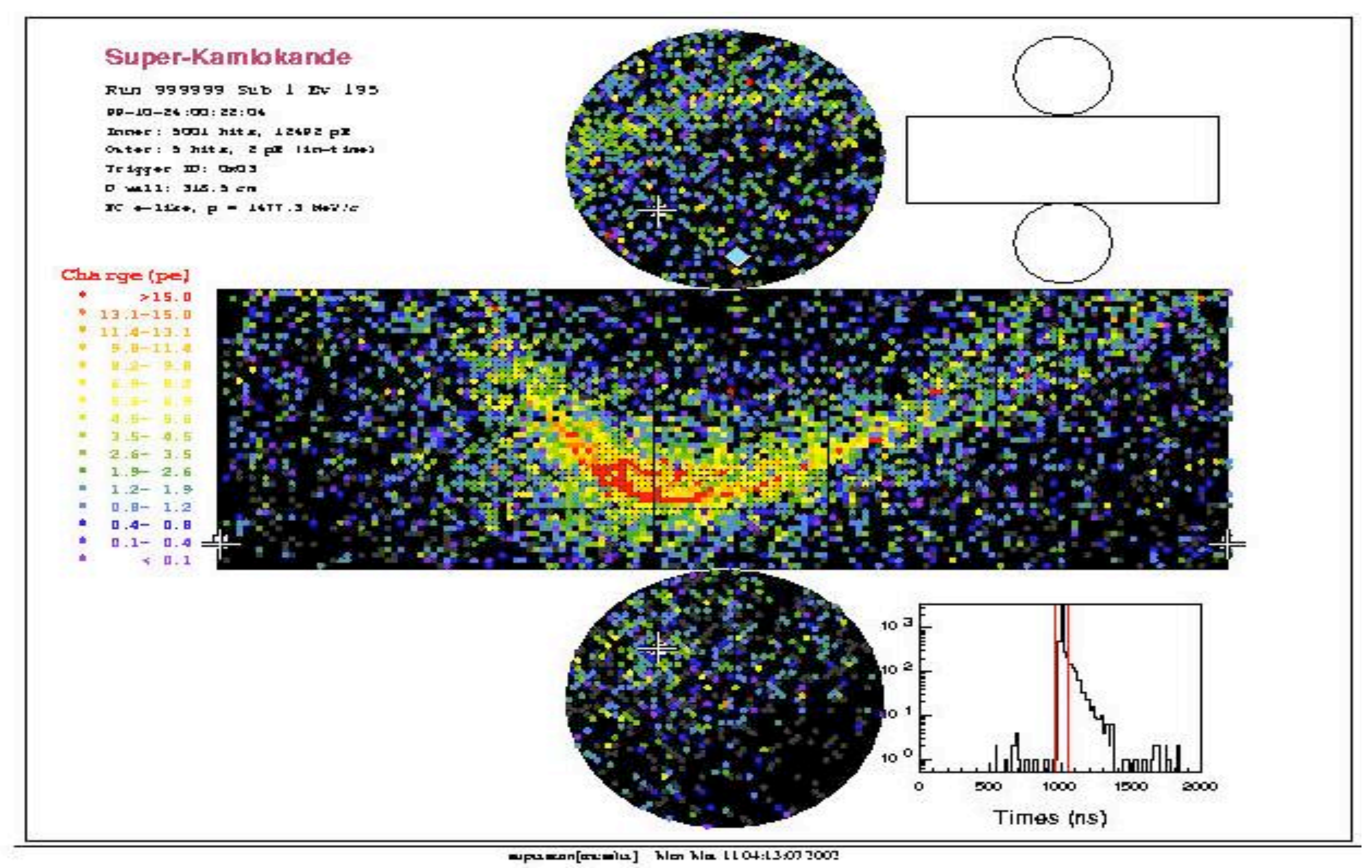
π0 decay at high energy





ν_e CC



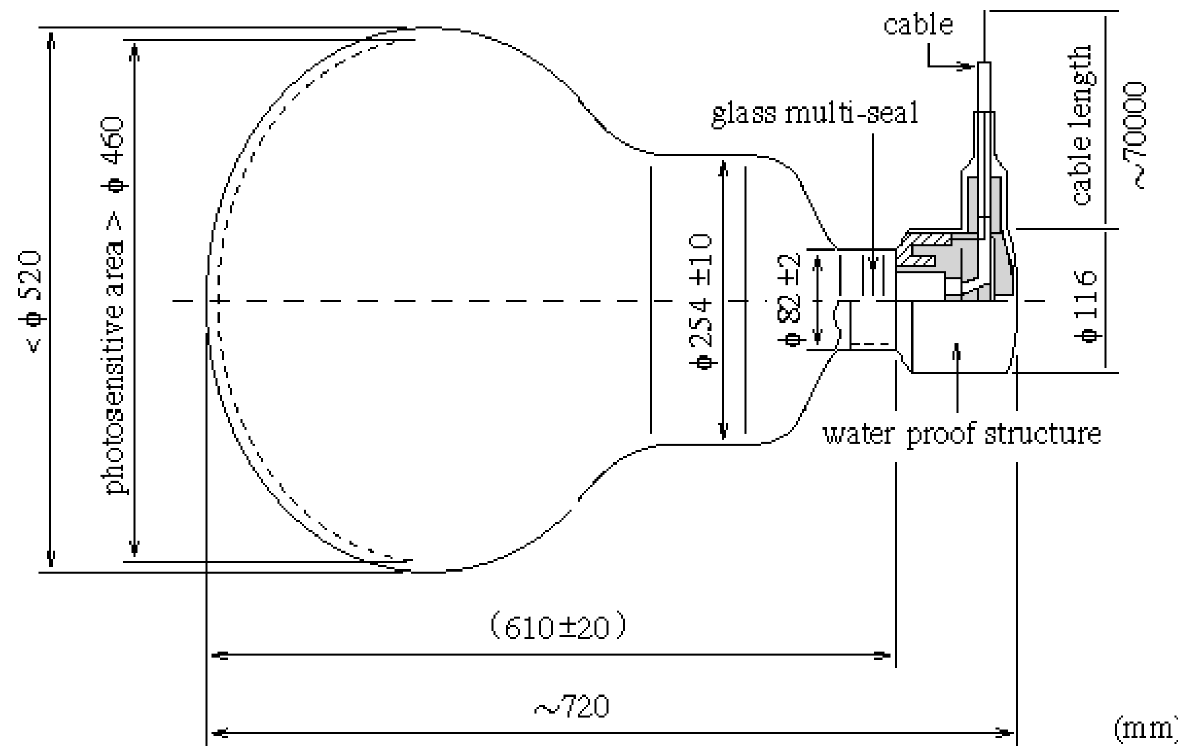


NC π^0

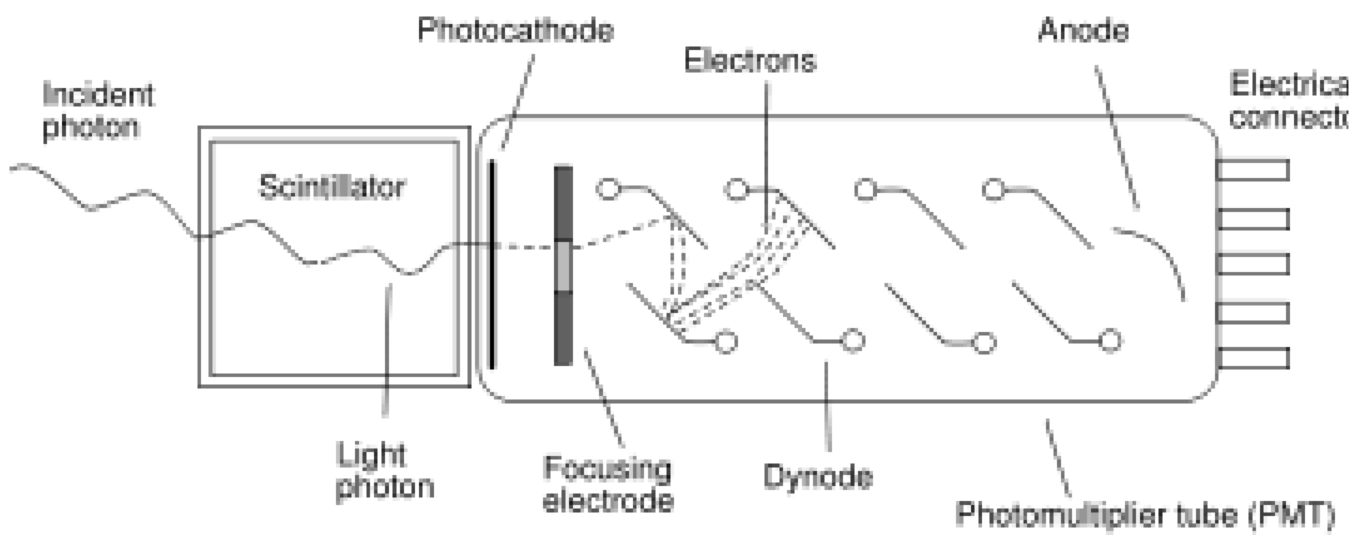
Photomultiplier tubes

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.

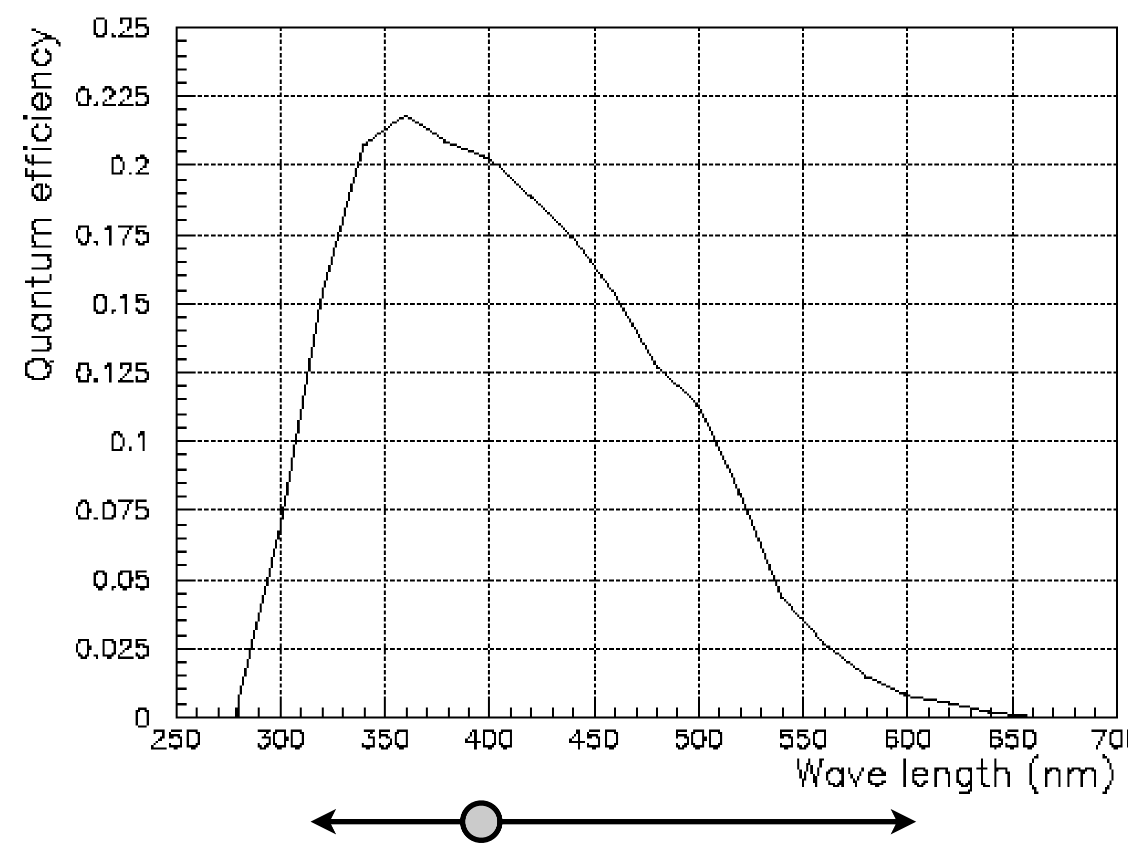
Output signal is seen as a current delivered to the ***anode***. Typical ***gains*** are 10^6 yielding pC-scale currents



100 ns transit time, 2.2 ns time resolution



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***.

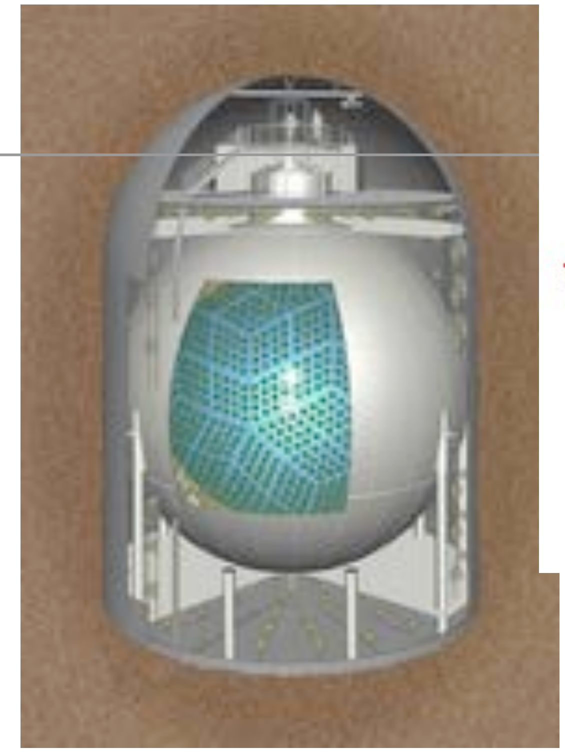


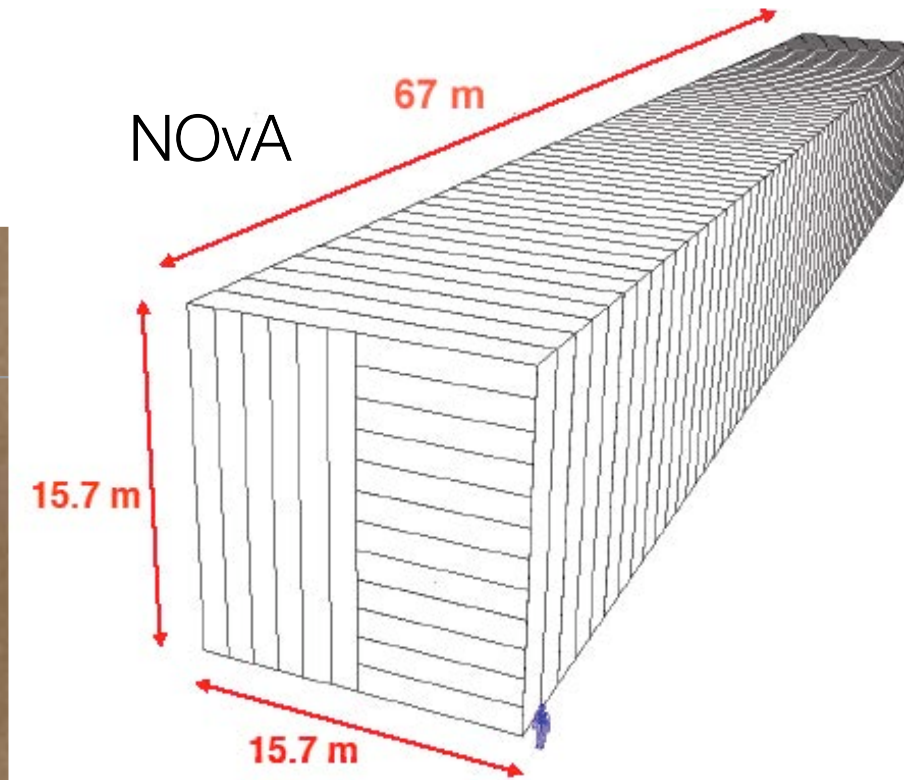
wavelength of Cherenkov photons in water

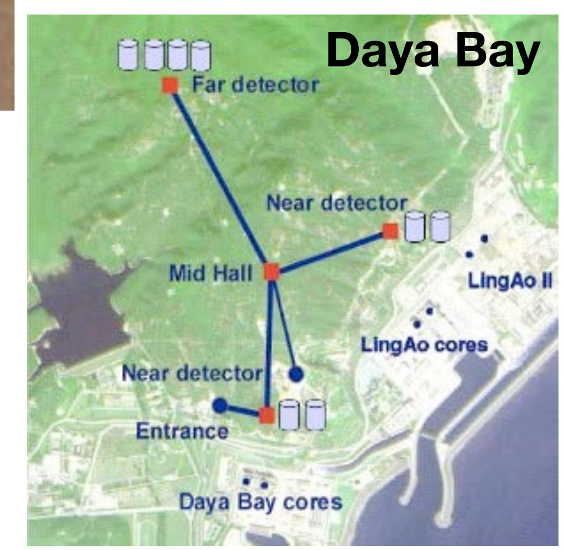
Scintillator detectors

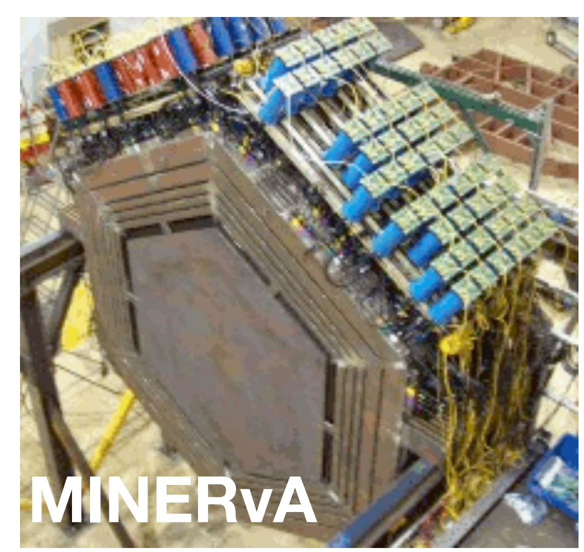
- Large volume of liquid scintillator viewed by PMT's
- Anti-electron neutrino detection from reactors at ~3.5 MeV
- Electron neutrino detection via elastic scattering from Sun at 0.7 MeV
- Scintillator allows for larger light collection (~200 photons/MeV) than water
- Used for detection of anti-neutrinos 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

KamLAND



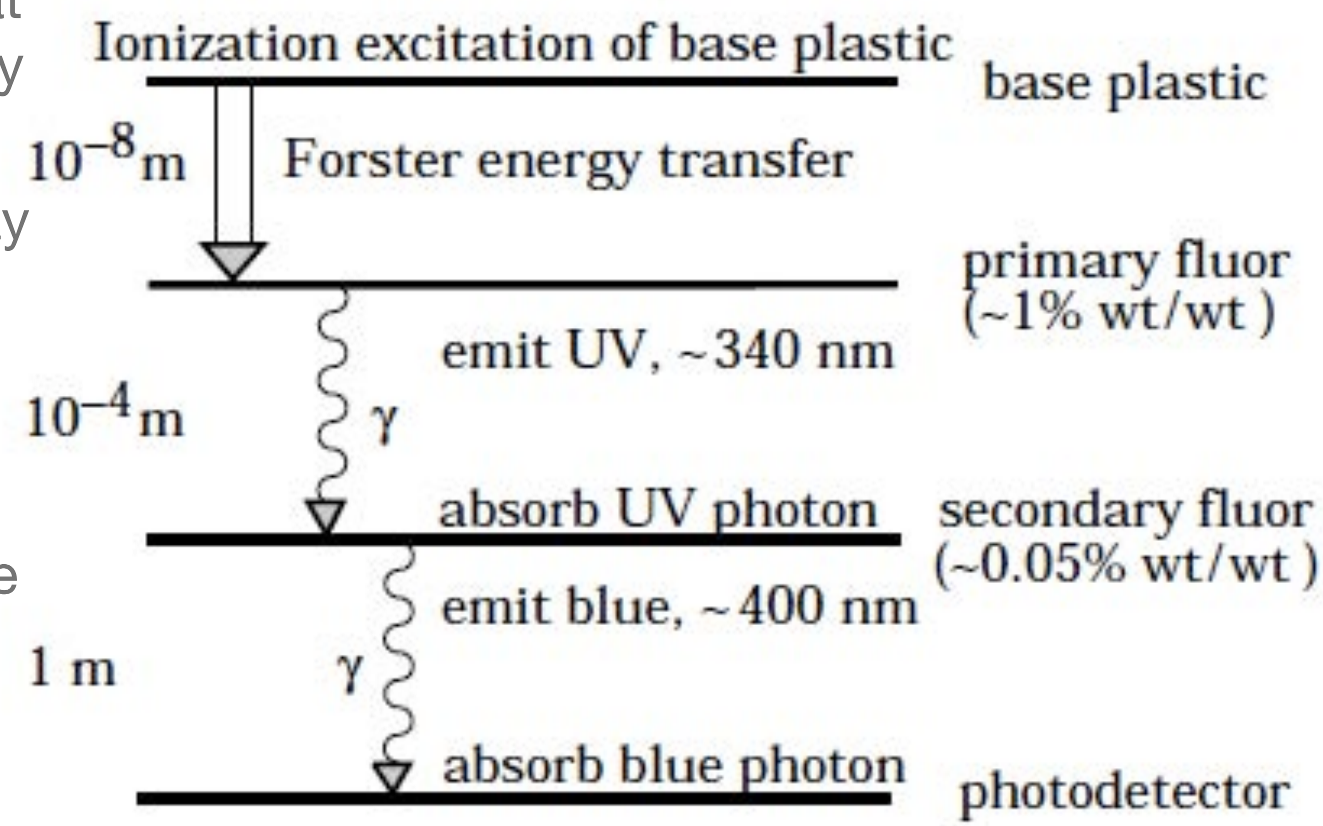






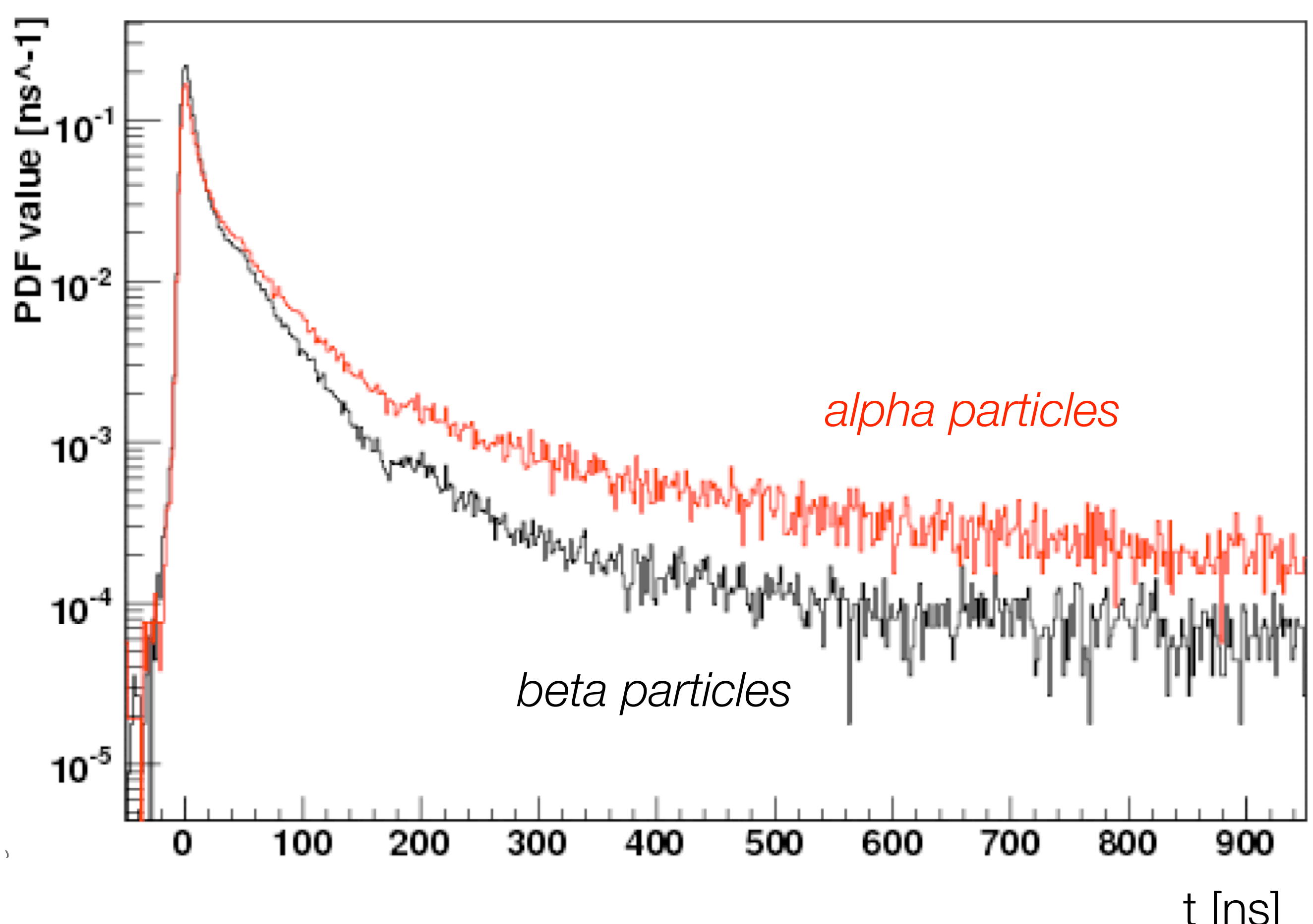
Scintillation process

- 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.



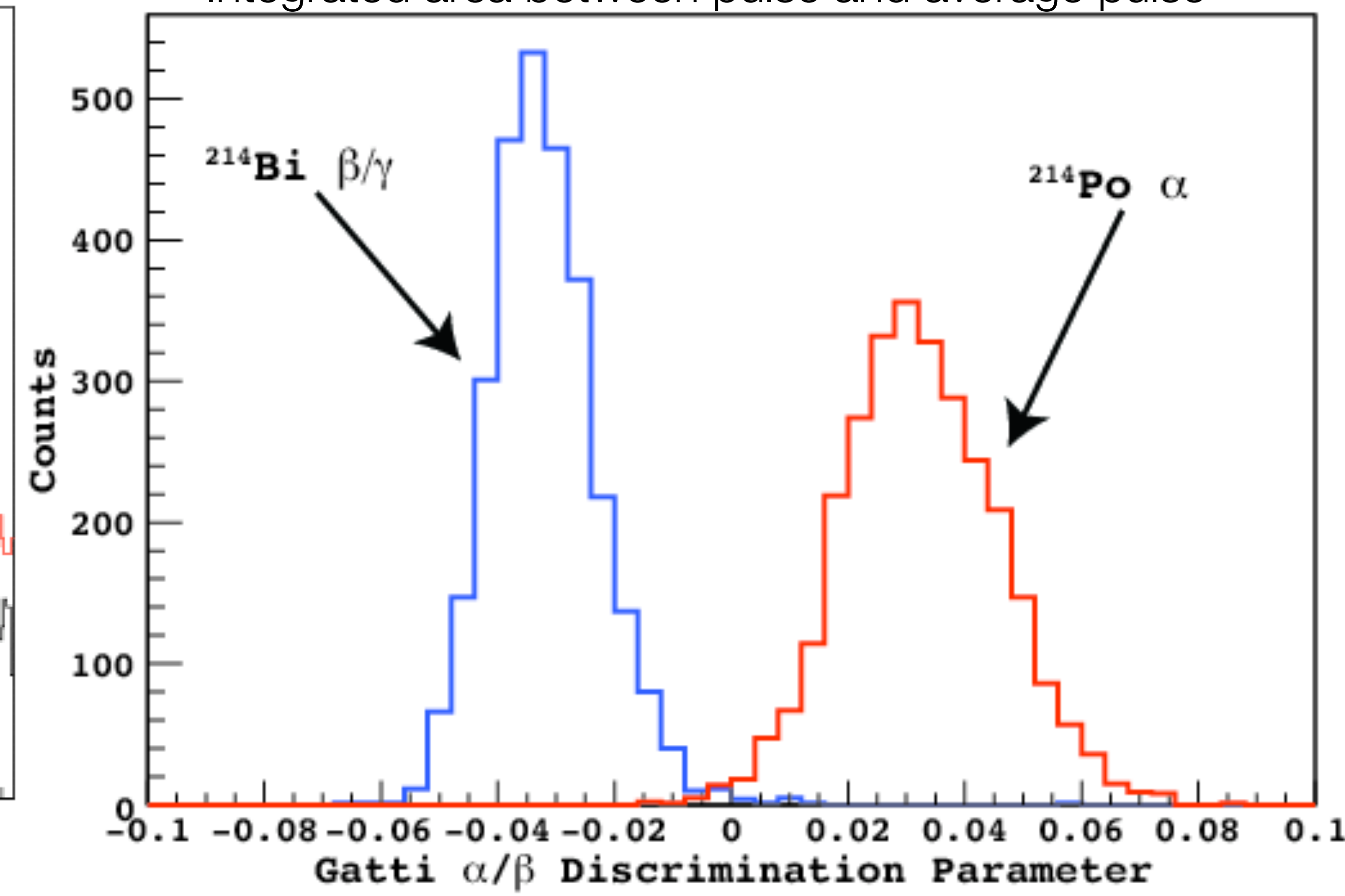
Alpha/Beta discrimination: Borexino

- 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

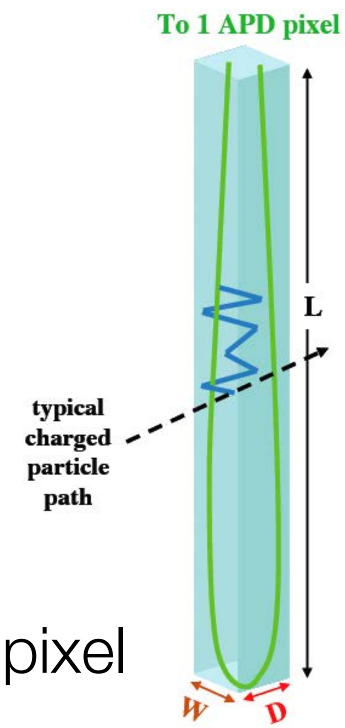


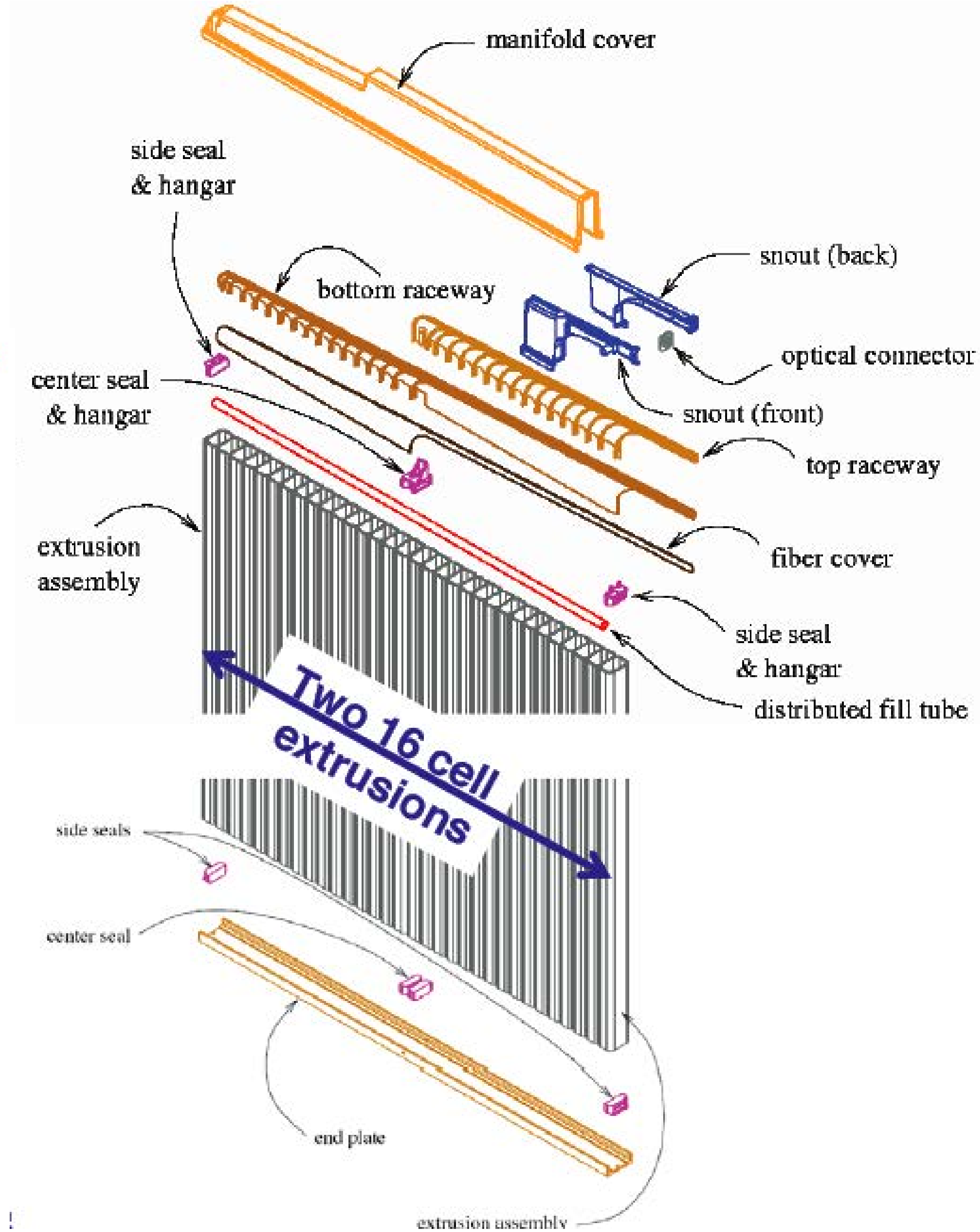
Liquid scintillator
(14.8M liters, 12.6 ktons)
Contained in 3.9 x 6.6 cell cells of length 15.7 m
-18 m attenuation length
-5.5% pseudocumene

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

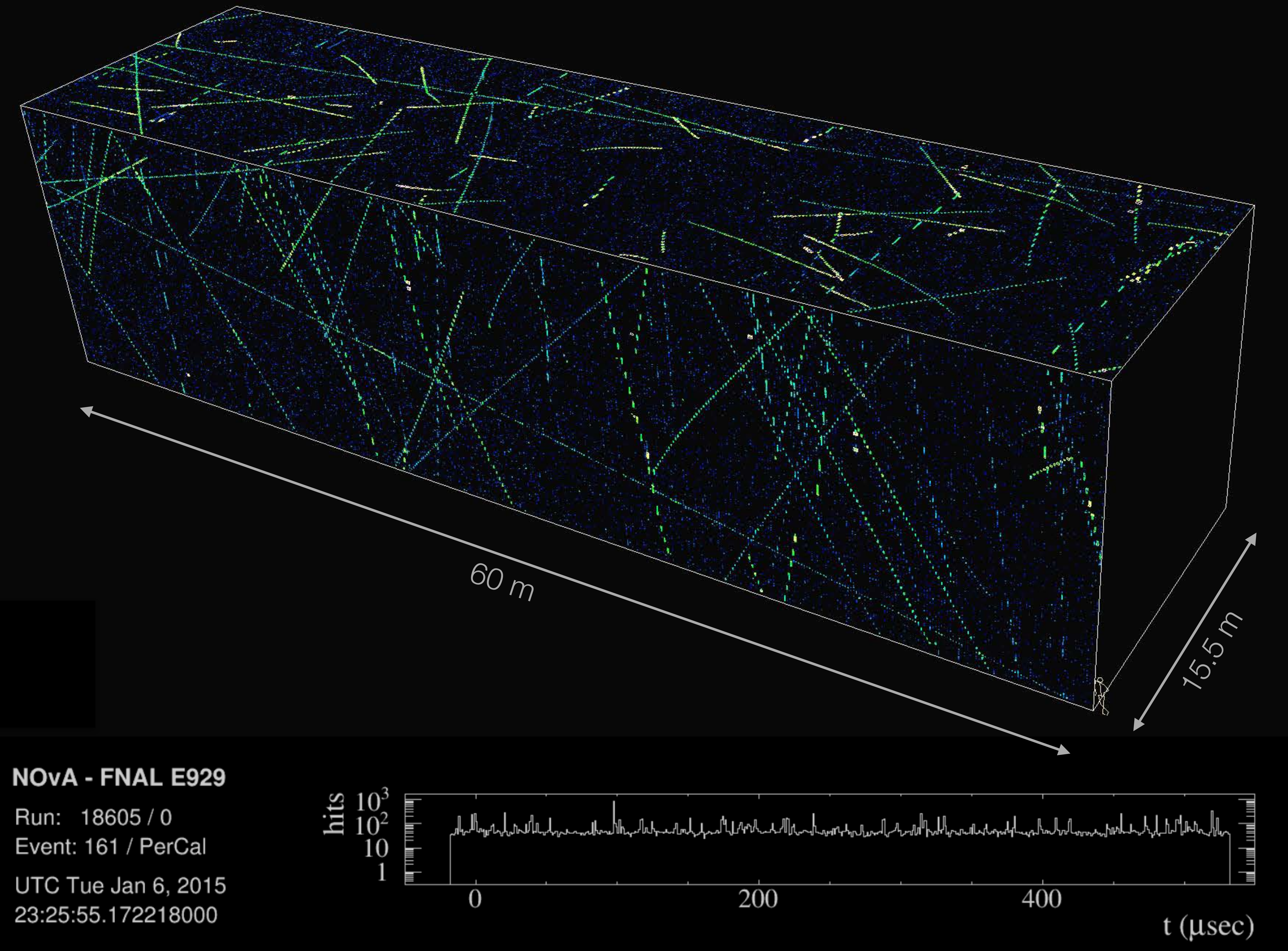
Wavelength shifting fiber
(18k km)
- 0.7 mm diameter
- Looped, both ends to same readout pixel

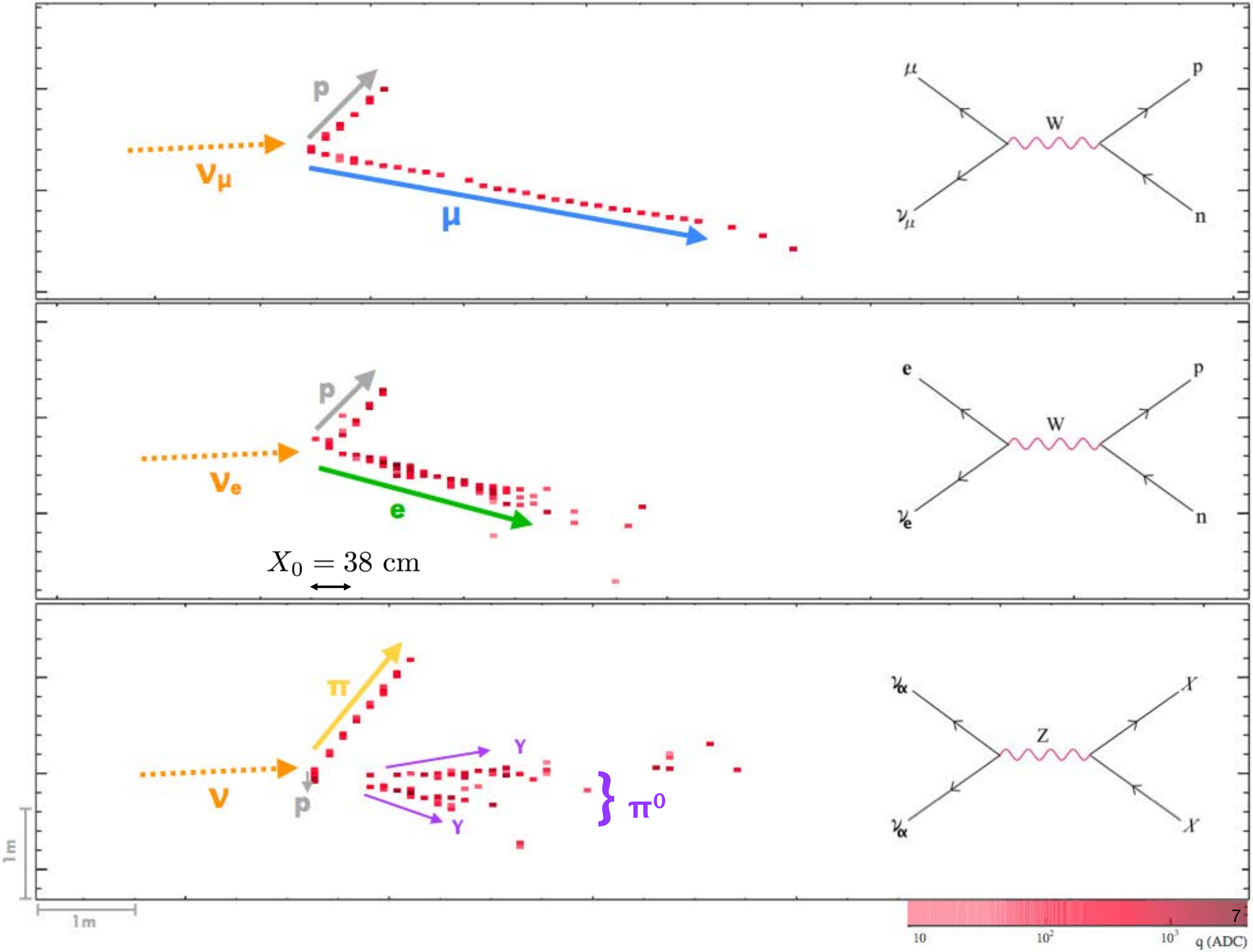
Avalanche photodiodes (APD)
(14k boards, 32 channels each)
- 85% quantum efficiency at long wavelengths
- Collect 30 photoelectrons per muon crossing at far end of cell



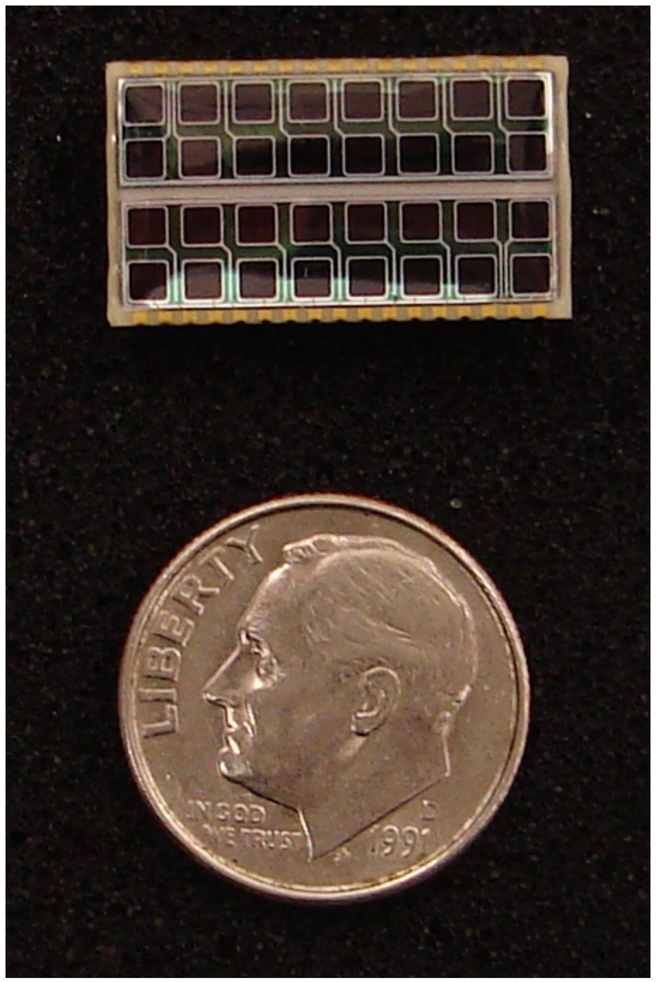


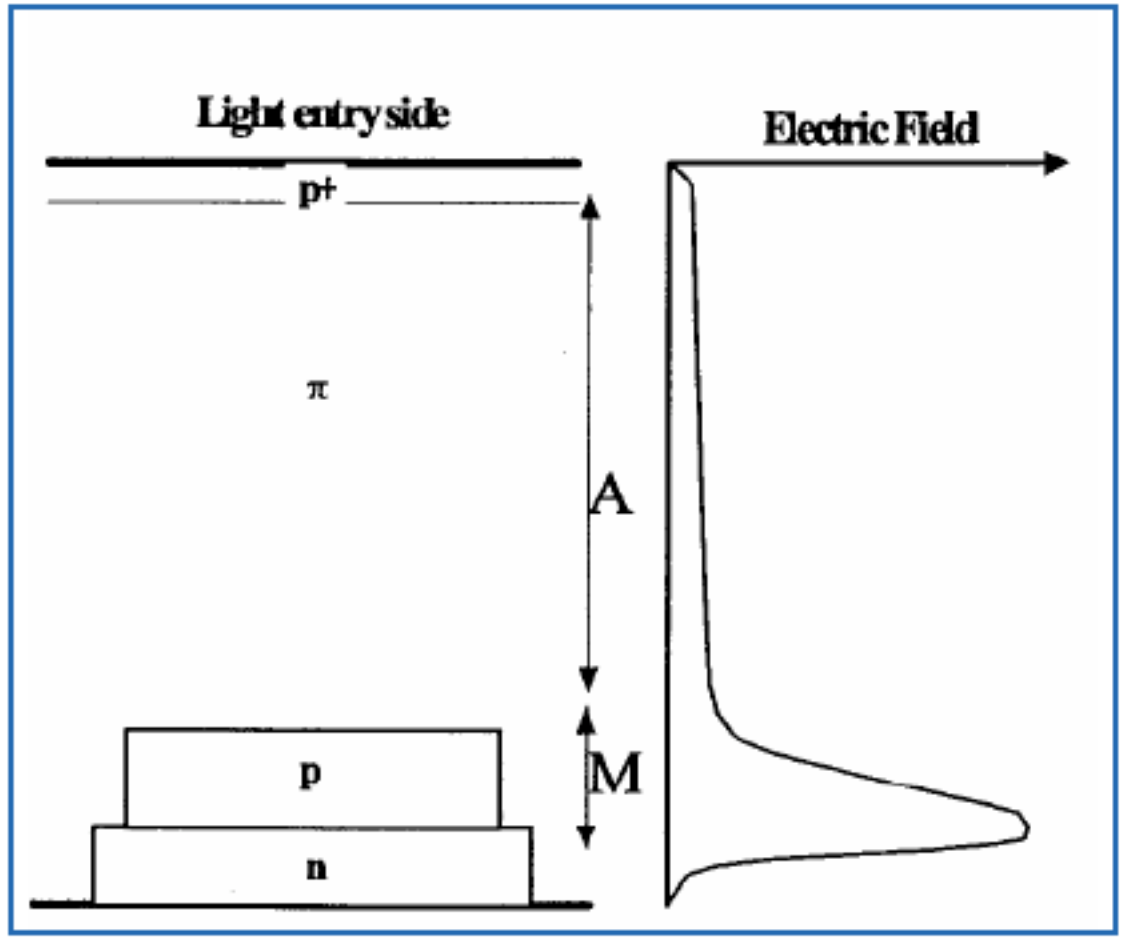
Detector design


60 m
15.5 m
NOvA - FNAL E929
Run: 18605 / 0
Event: 161 / PerCal
UTC Tue Jan 6, 2015
23:25:55.172218000
hits
1
10
10²
10³
0
200
400
t (μsec)


p
νμ
μ
μ
p
W
νμ
n
p
νe
e
$X_0 = 38$ cm
e
p
W
νe
n
π
ν
p
γ
γ
π0
να
X
Z
να
X
1 m
1 m
10
10^2
10^3
q (ADC)

Avalanche photo diodes (APD)





Absorption region

Multiplication region

High (80%) quantum efficiency even into UV

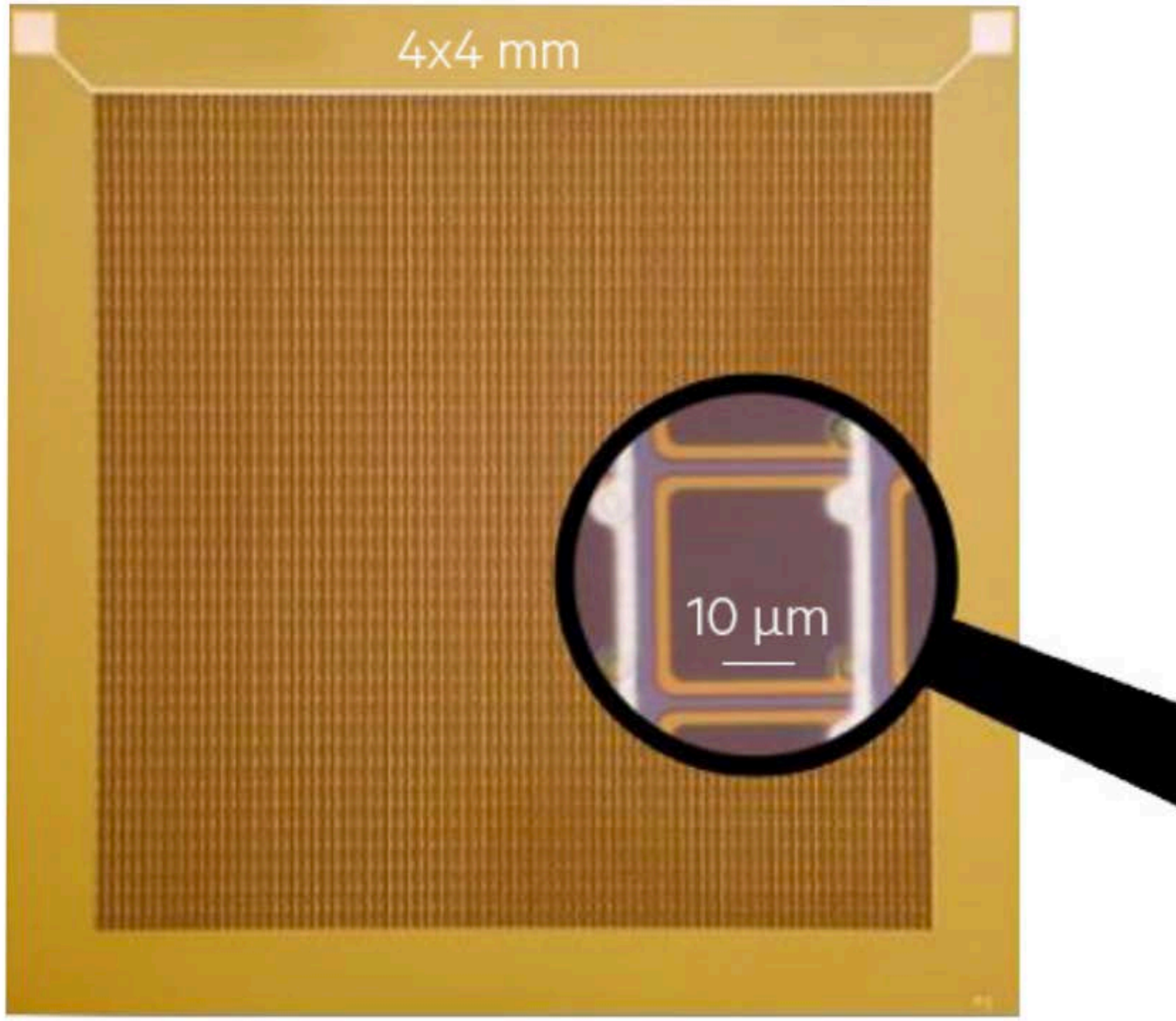
Large dark currents - must be cooled to -10^{o}C to get noise down to ~10 pe equivalent

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

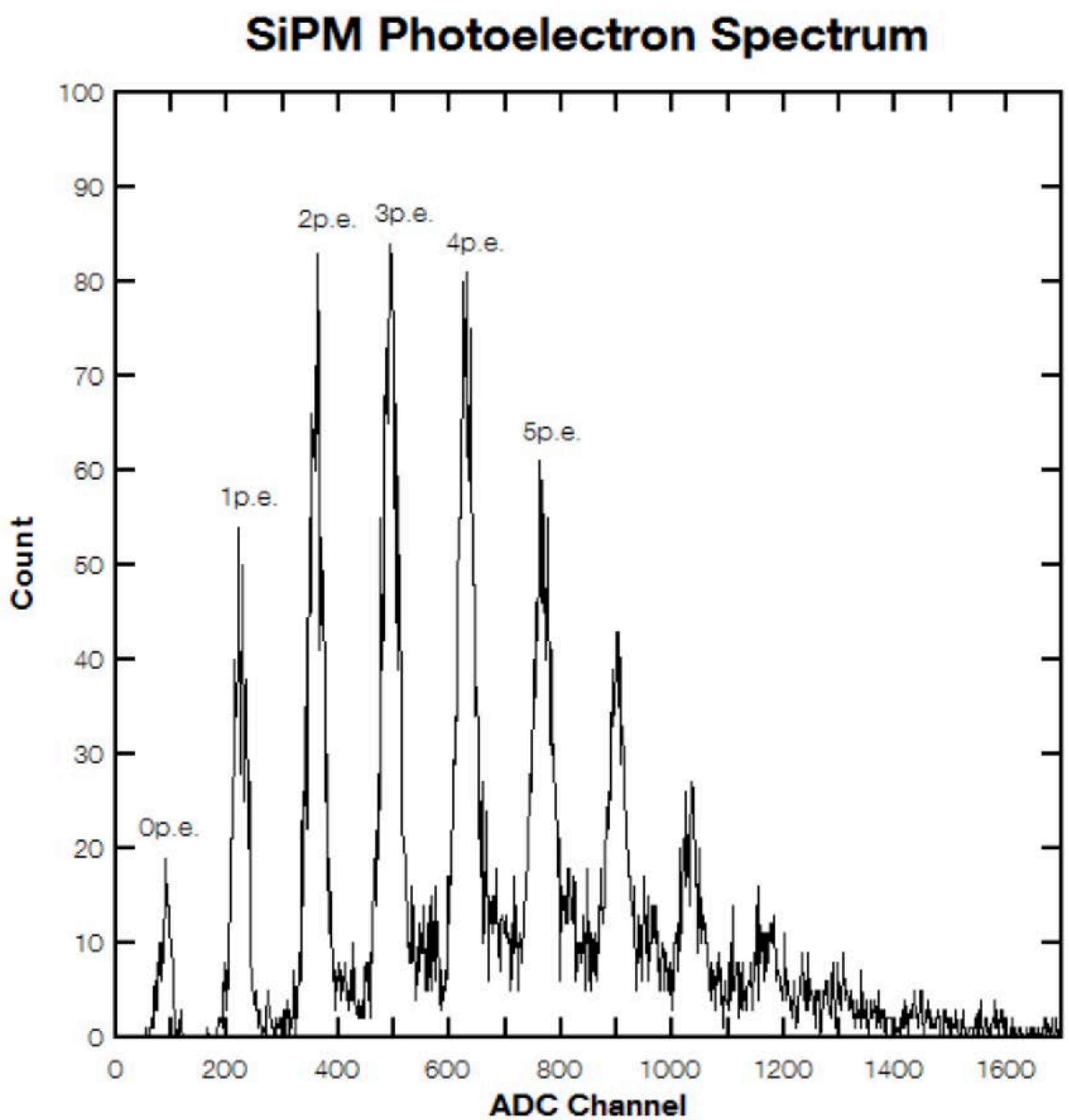


Figure 7, Photoelectron spectrum of the SiPM, achieved using brief, low-level light pulses, such as those from Fig. 6.

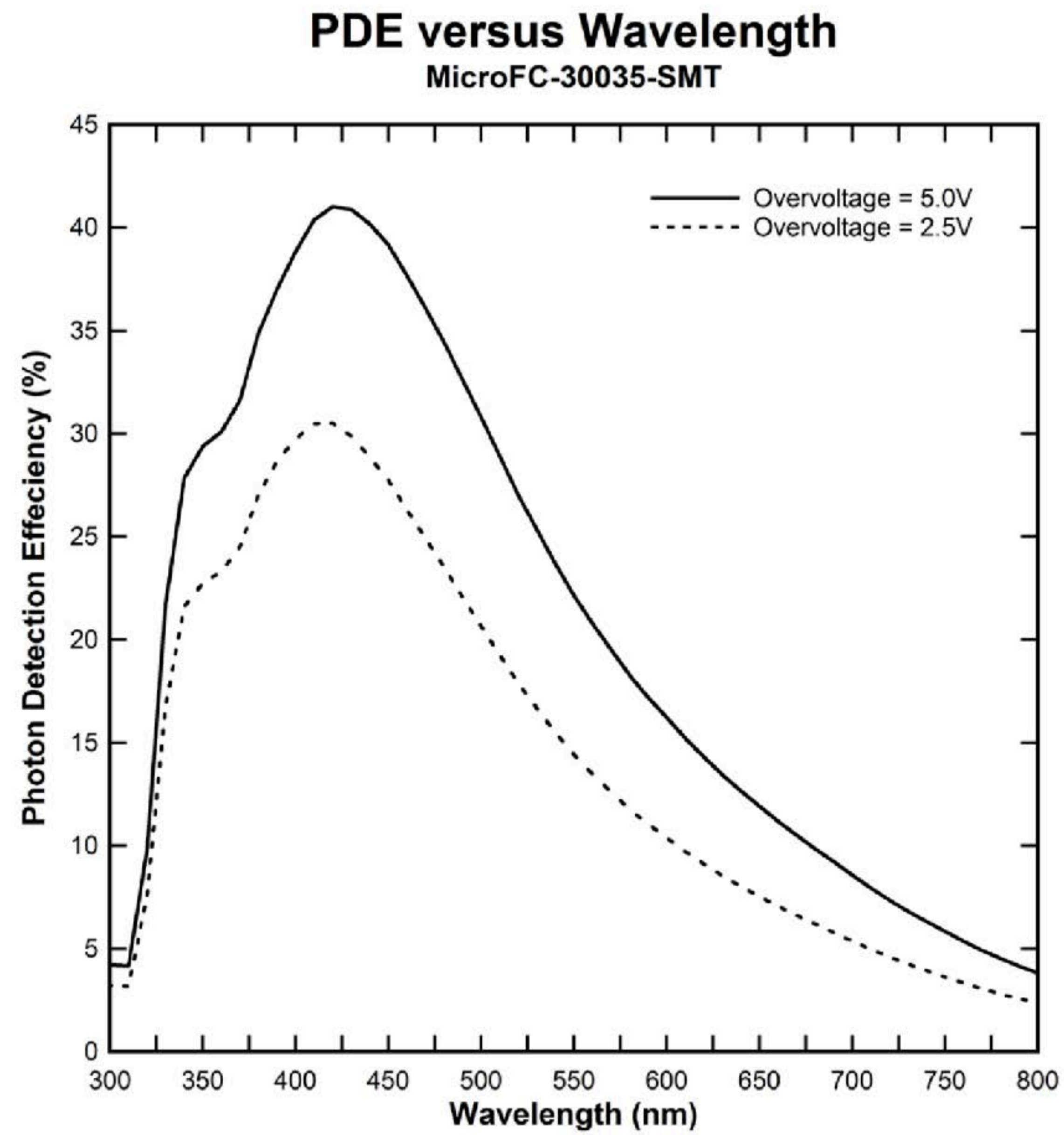
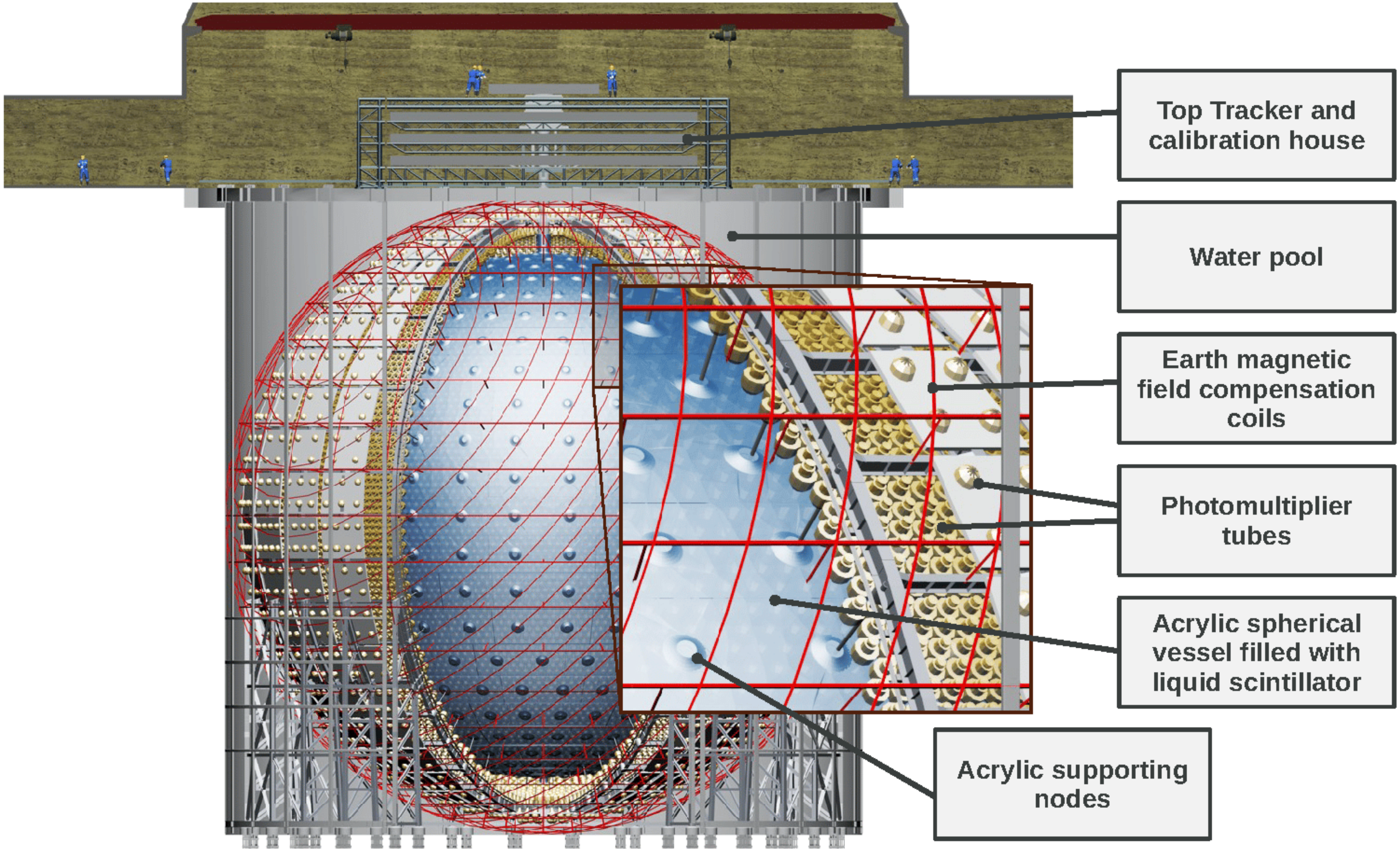


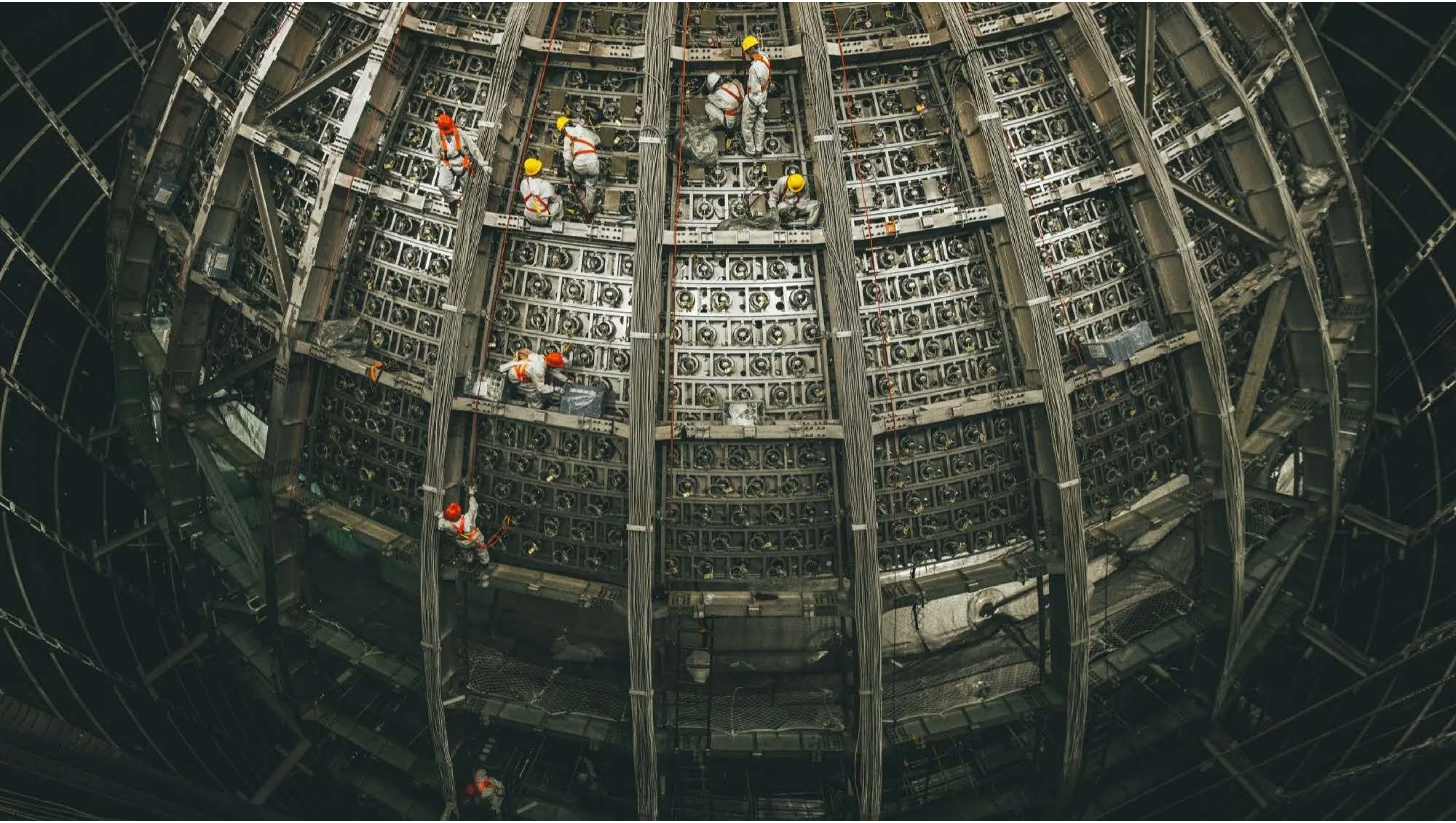
Figure 16, PDE as a function of wavelength for different overvoltages.

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



(a) *JUNO detector scheme.*

Instruments **2022**, *6*(3), 26; **https://doi.org/10.3390/instruments6030026**



The JUNO Detector

Popular Science, Sep. 2023

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

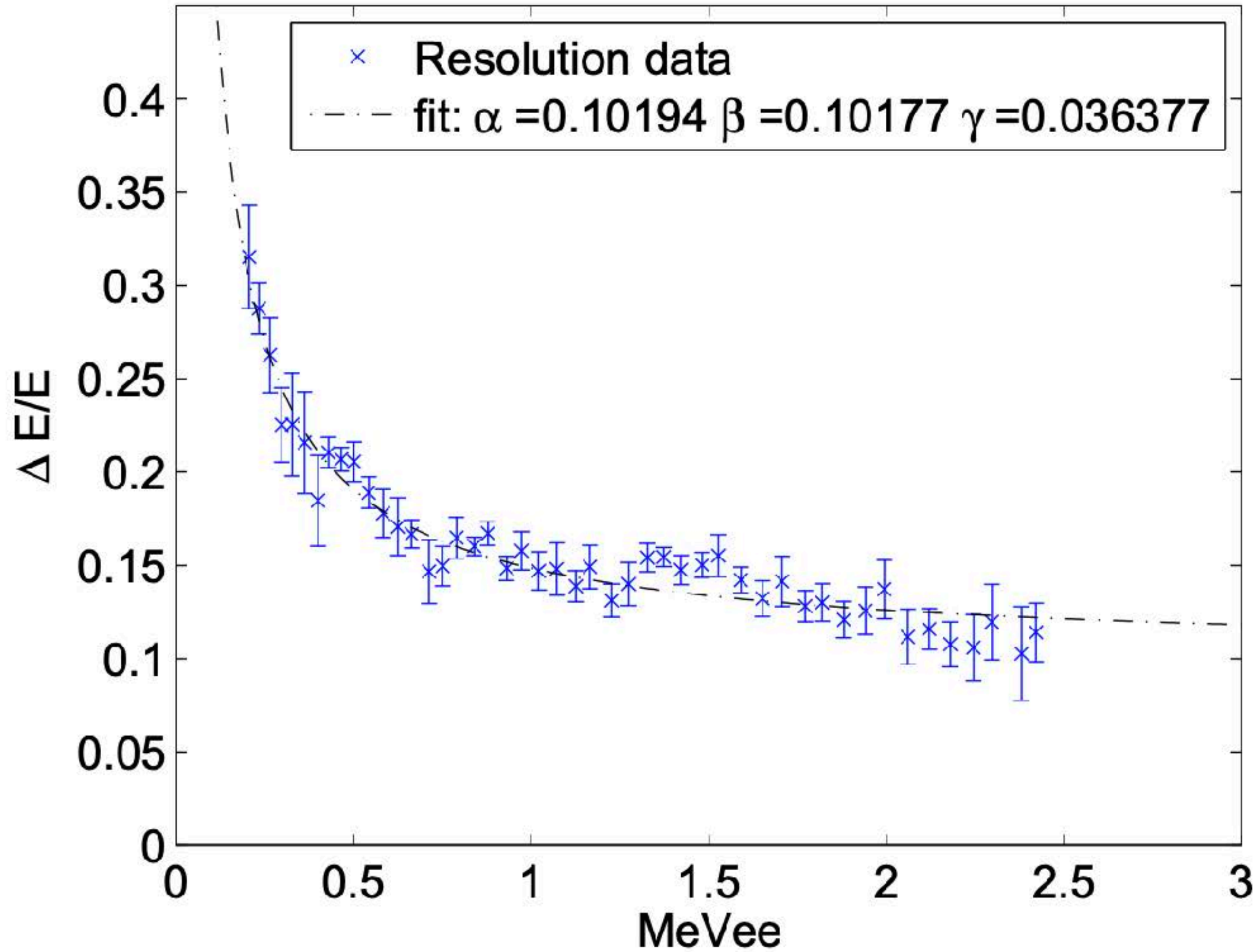
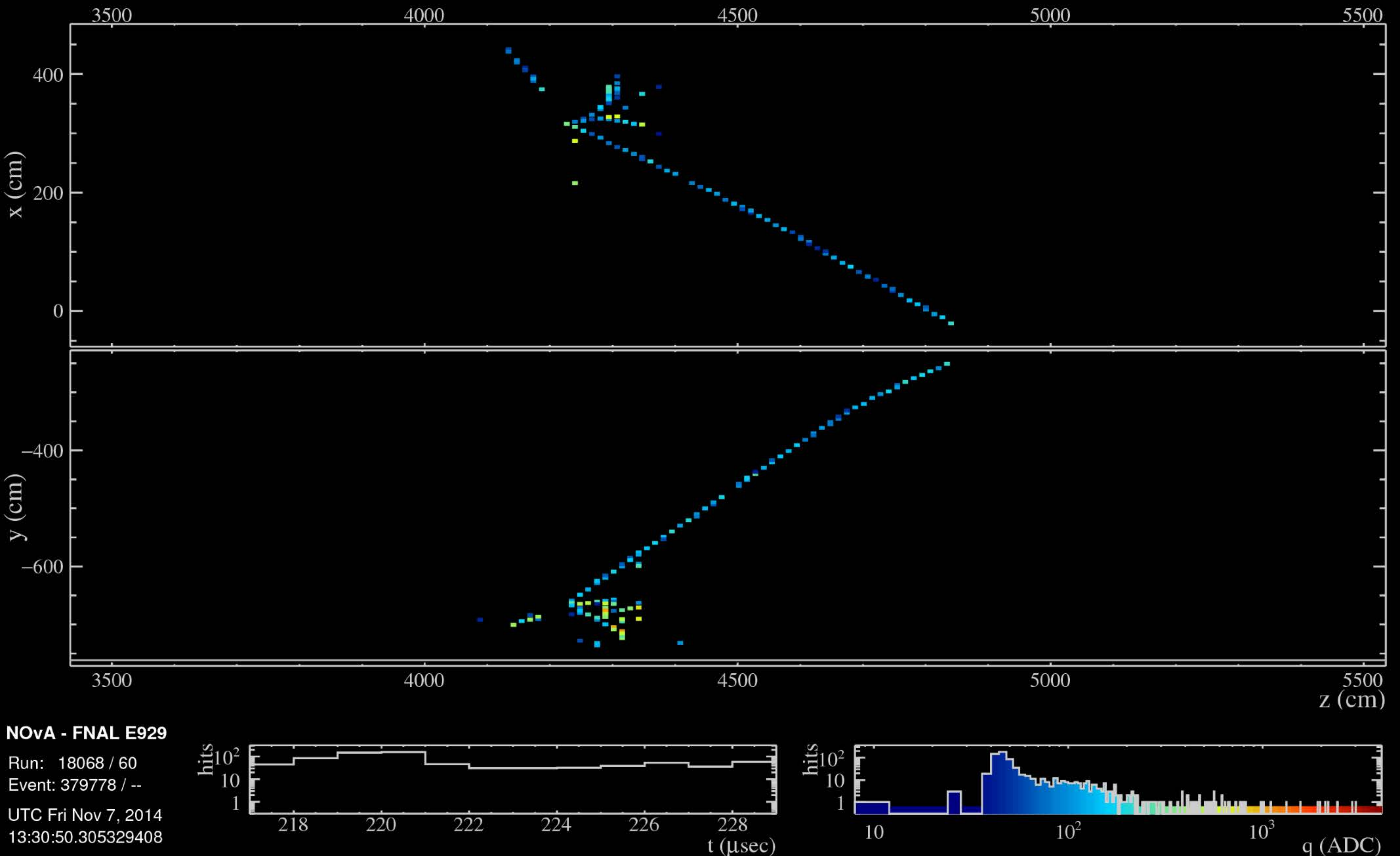
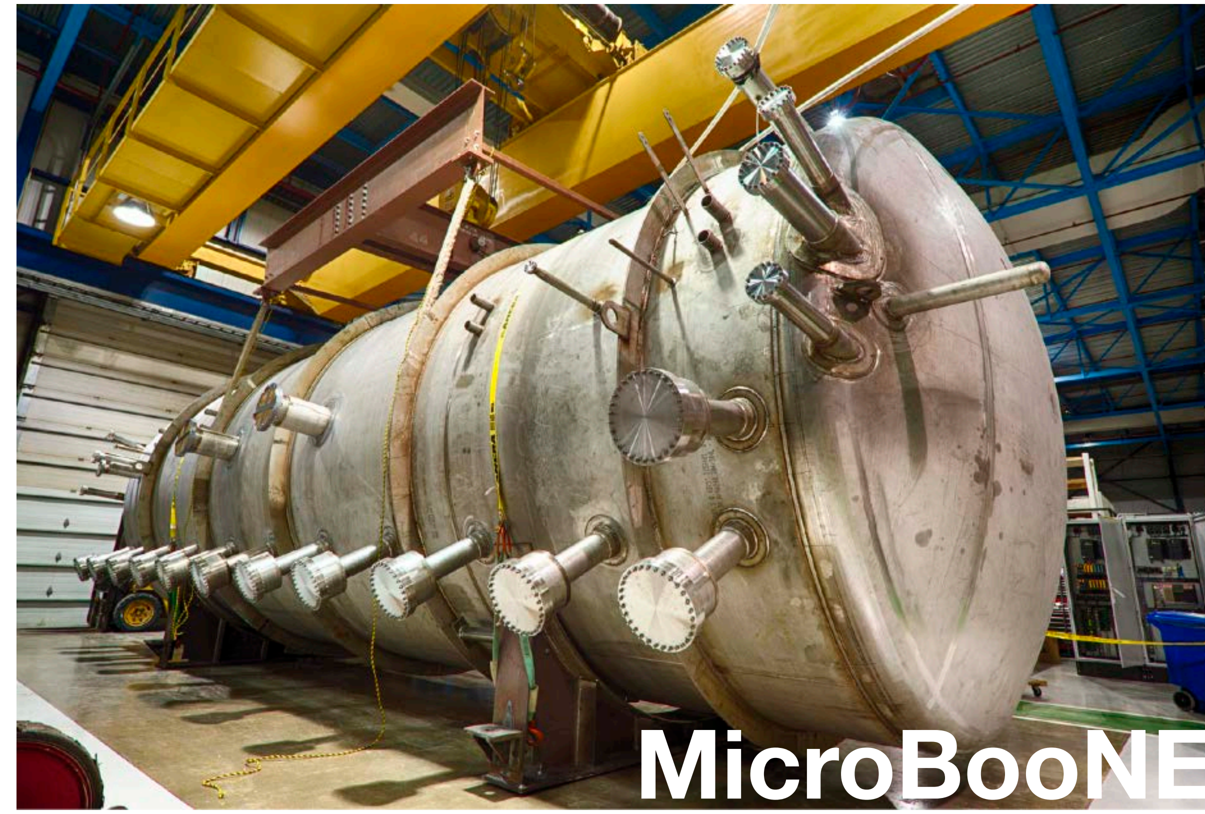


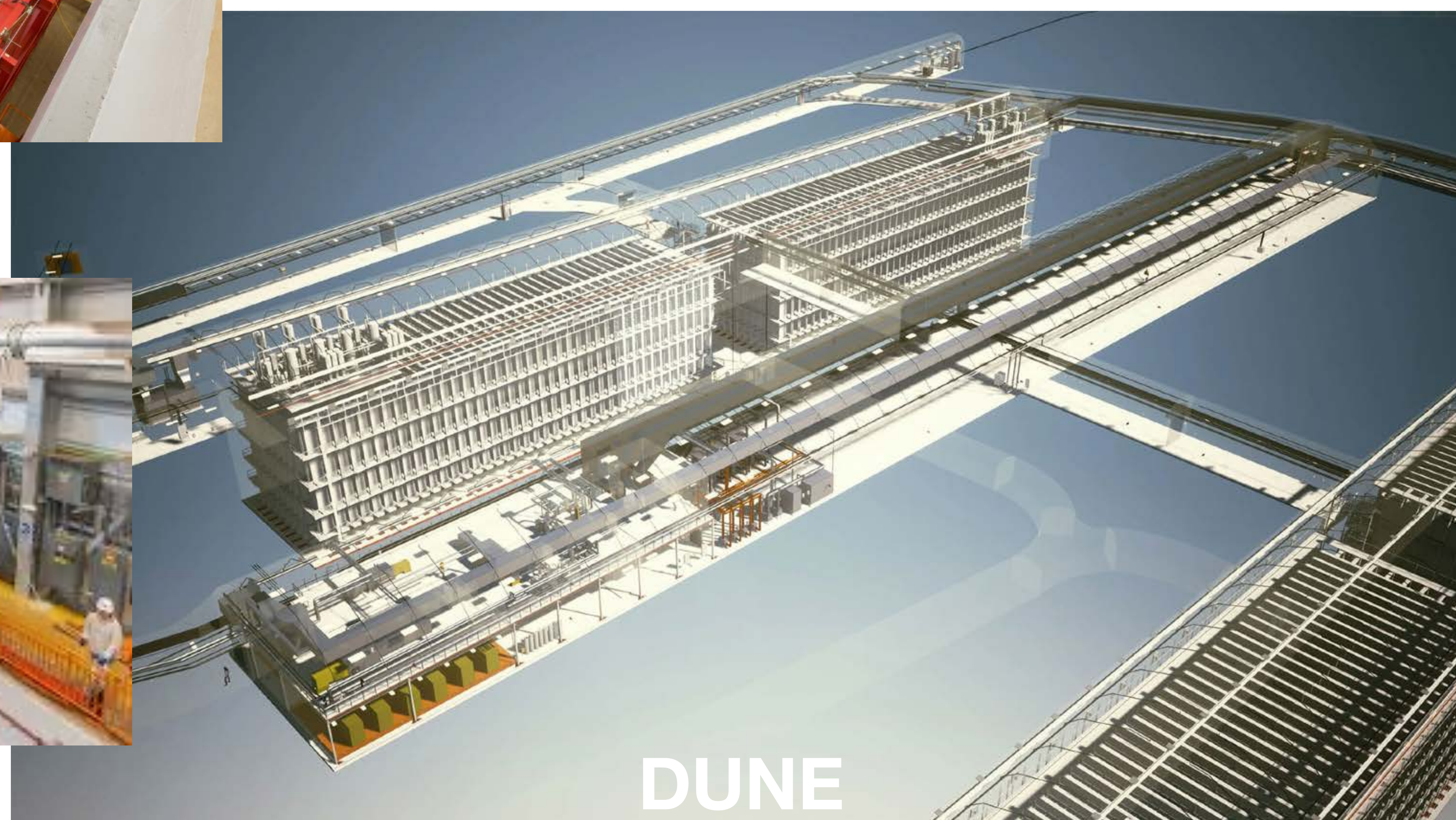
Figure 15: The energy resolution data and fit for 12.7-by-12.7 cm EJ-309 liquid scintillation detector.



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

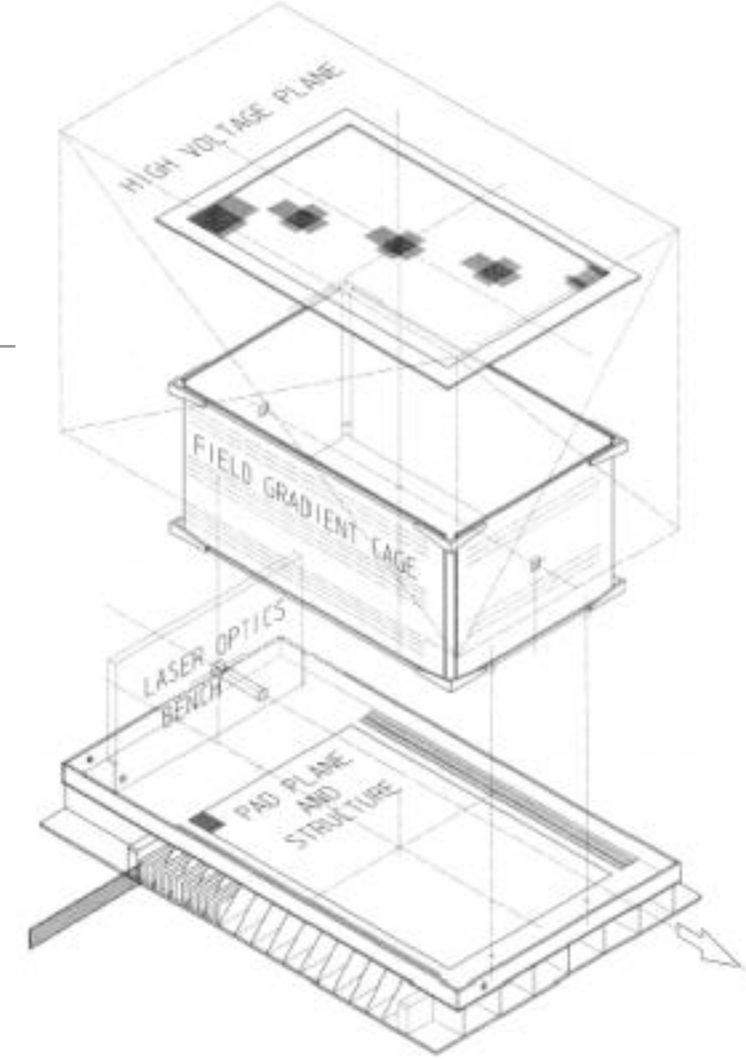
Time Projection Chambers



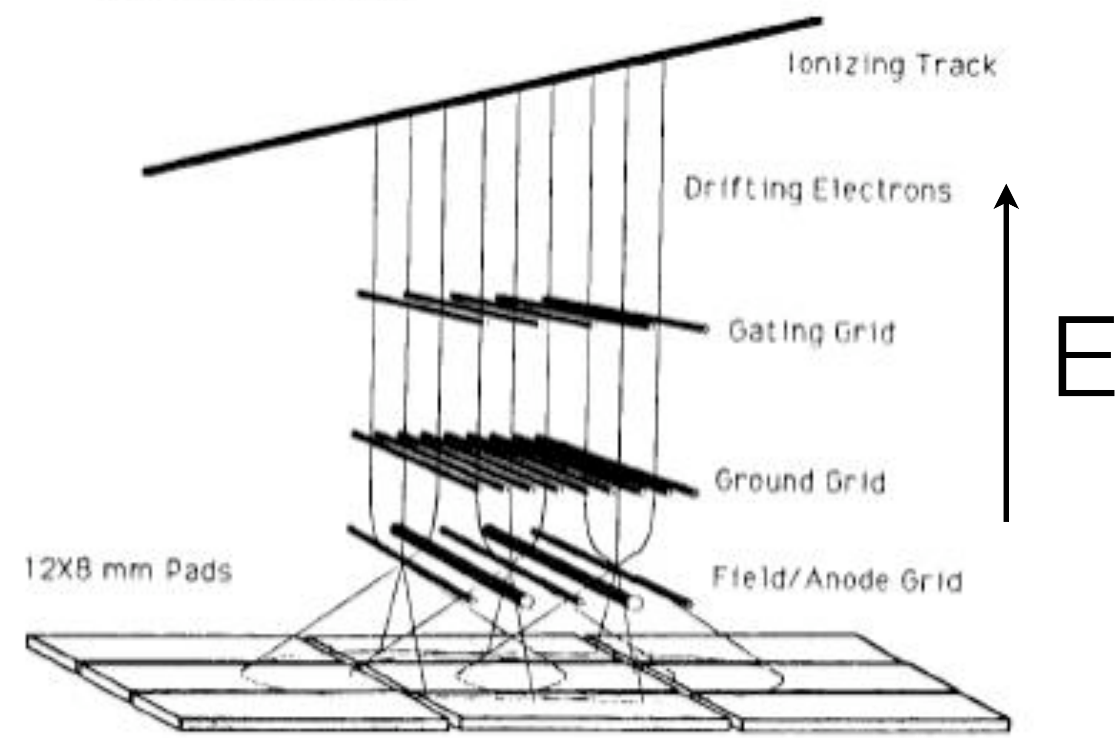


Time projection chambers (TPCs)

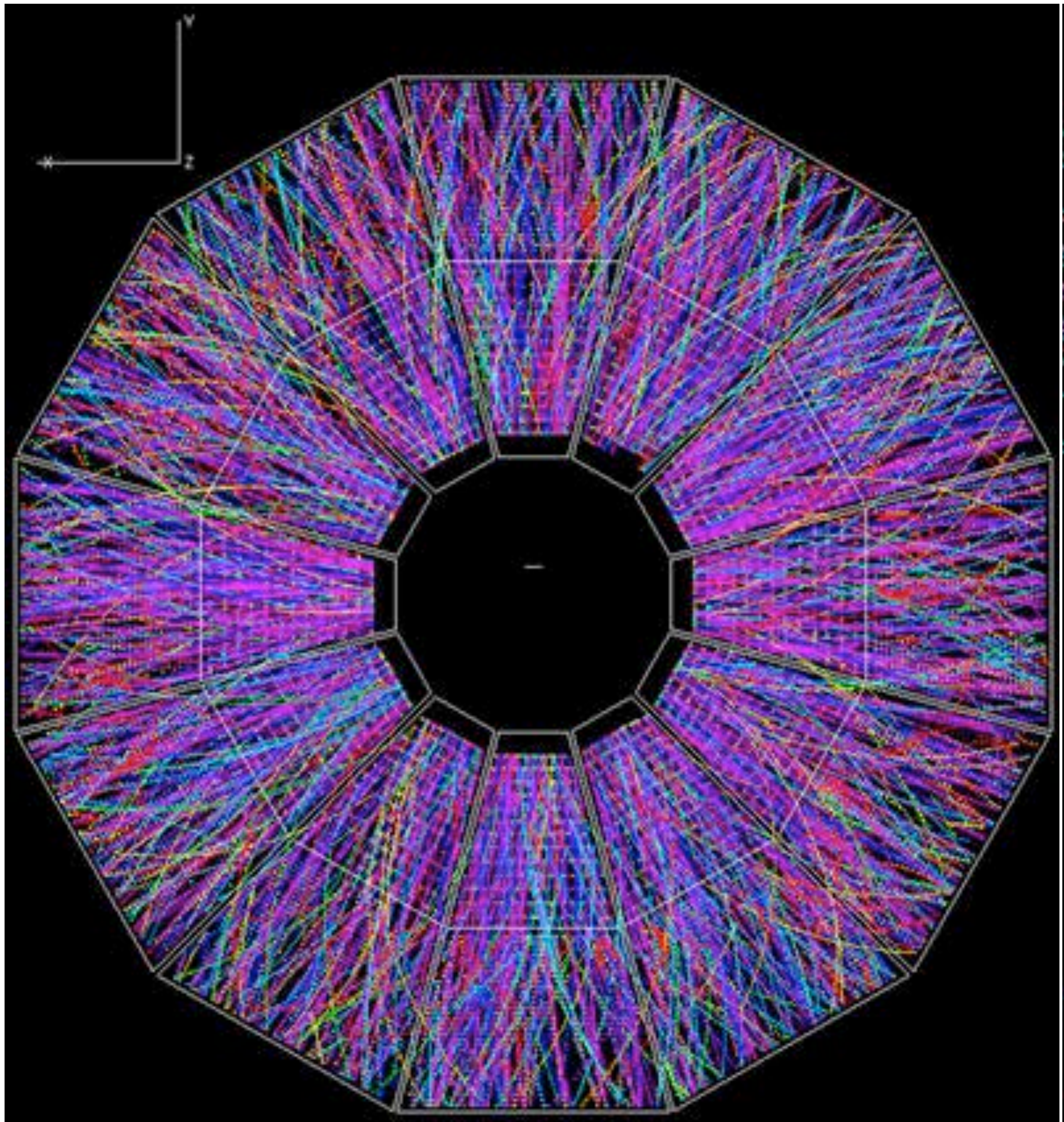
- Gas TPC’s have been widely used by a number of high energy and nuclear experiments
- Provide 3D tracking with ~mm resolution.
- Particle ID possible below 1 GeV using <dE/dx>
- A very common gas Argon-Methane gas mixture. Nobel gas allows for long electron drifts and methane boosts ionization yield.
- 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.



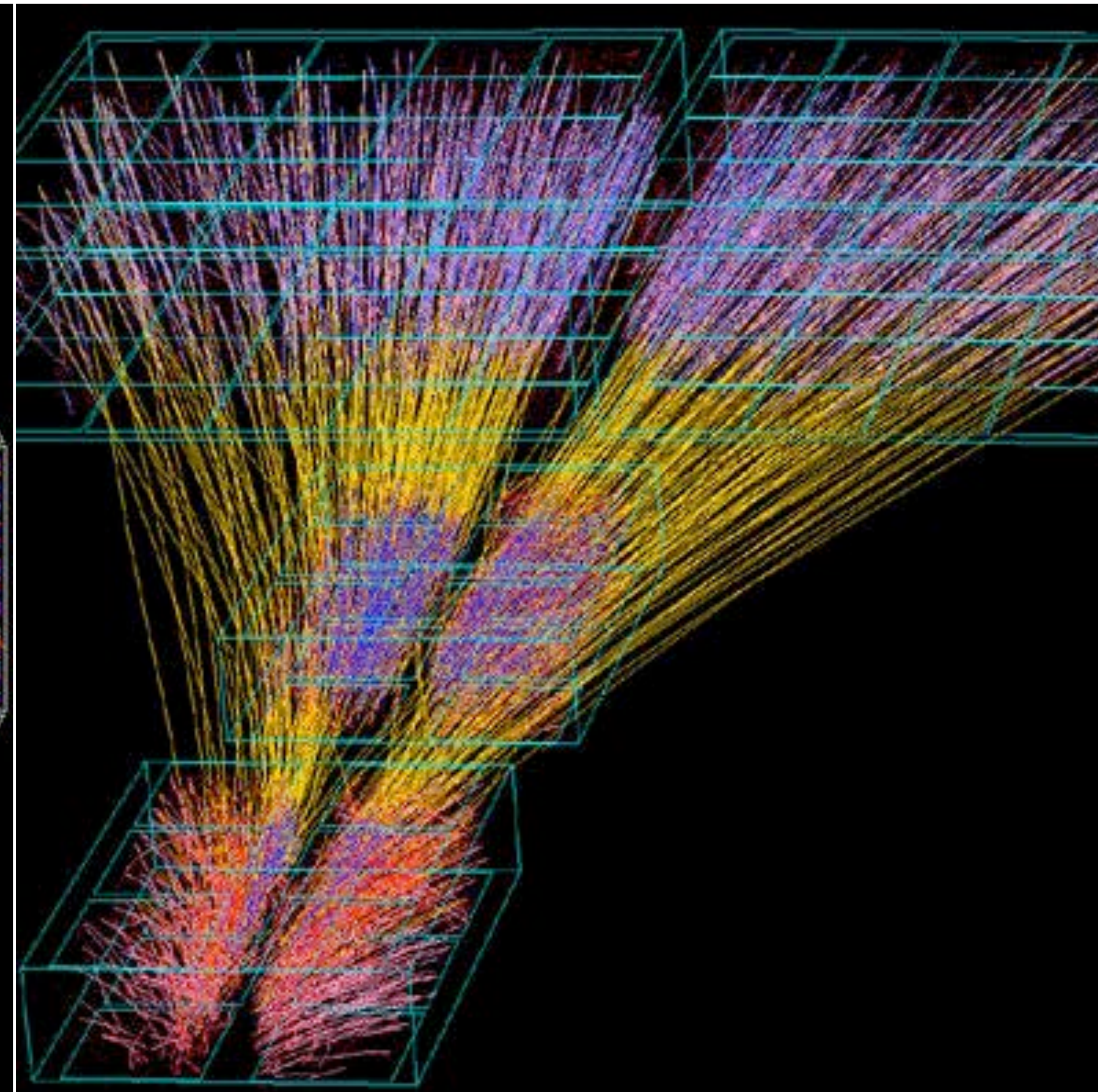
HISS TPC PAD PLANE



TPCs are well suited to high multiplicity environments



Au + Au at 130 GeV in STAR @ BNL

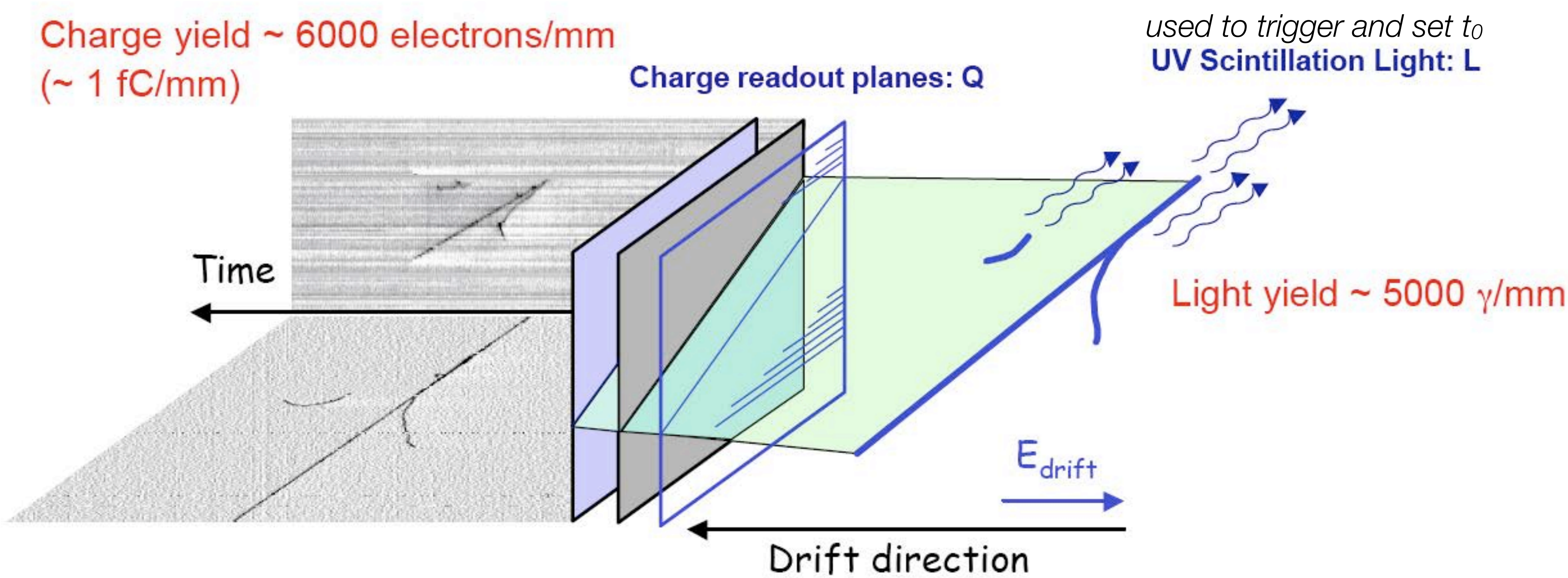


Pb + Pb at 17 GeV in NA49 @ CERN

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

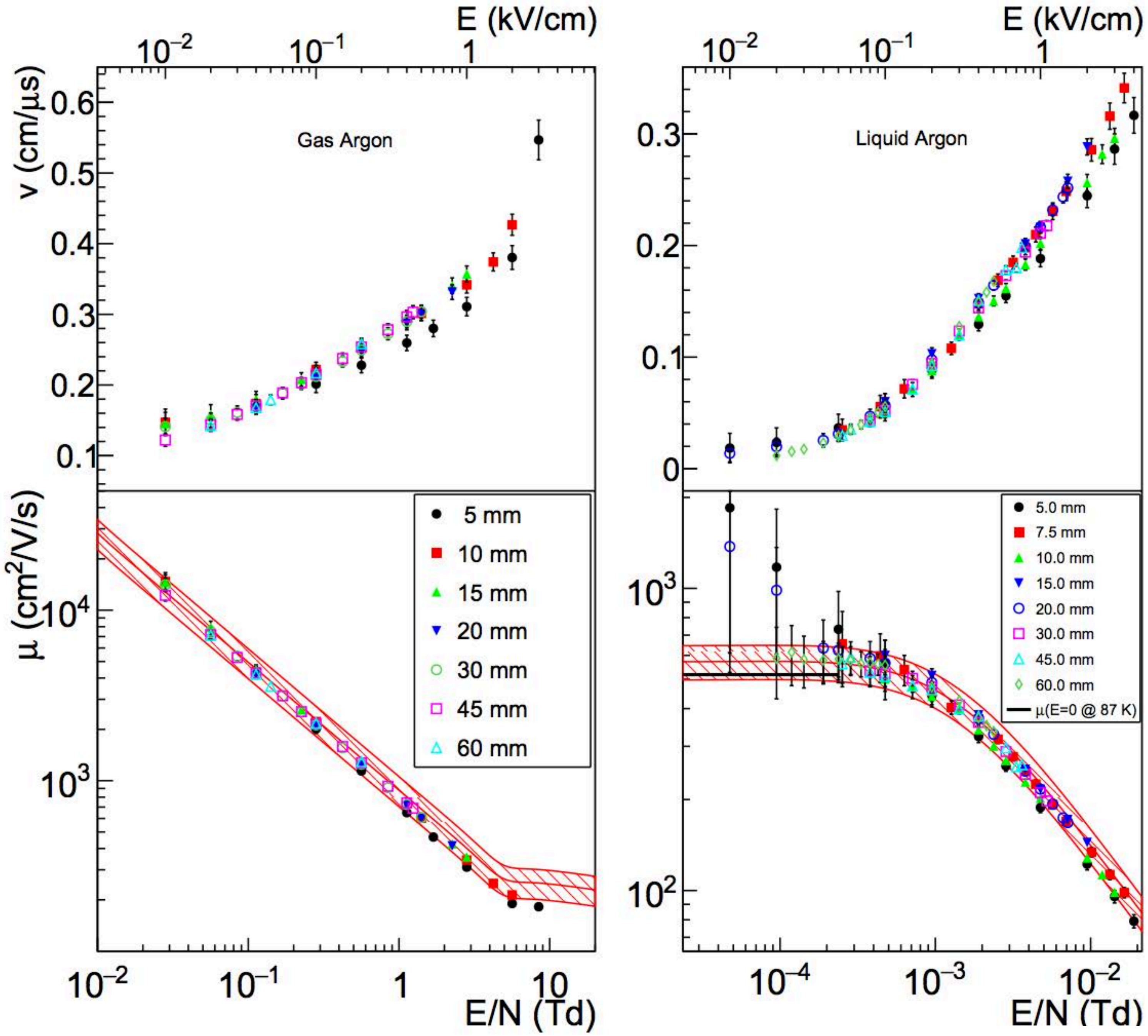


Ionization drift

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

$$\mu \equiv v/E$$

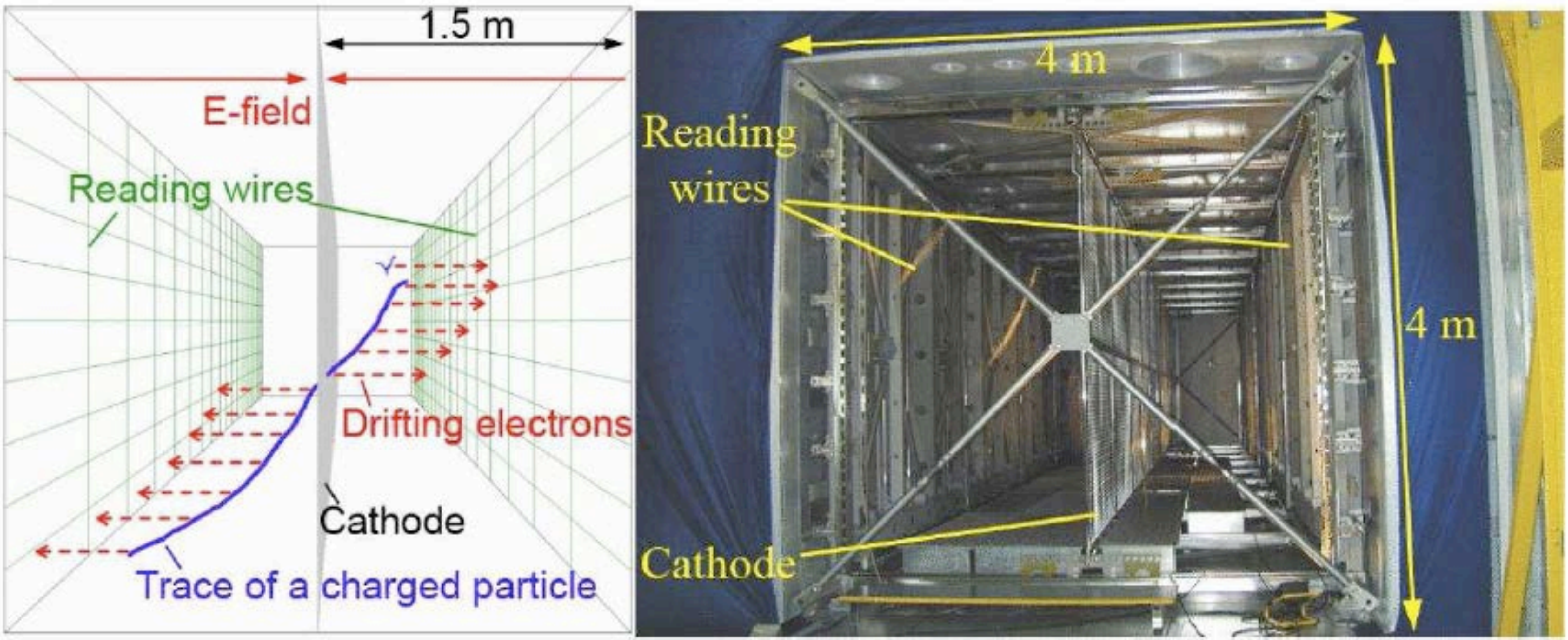
where v is the drift velocity and E is the applied electric field.



arXiv:1508.07059v2

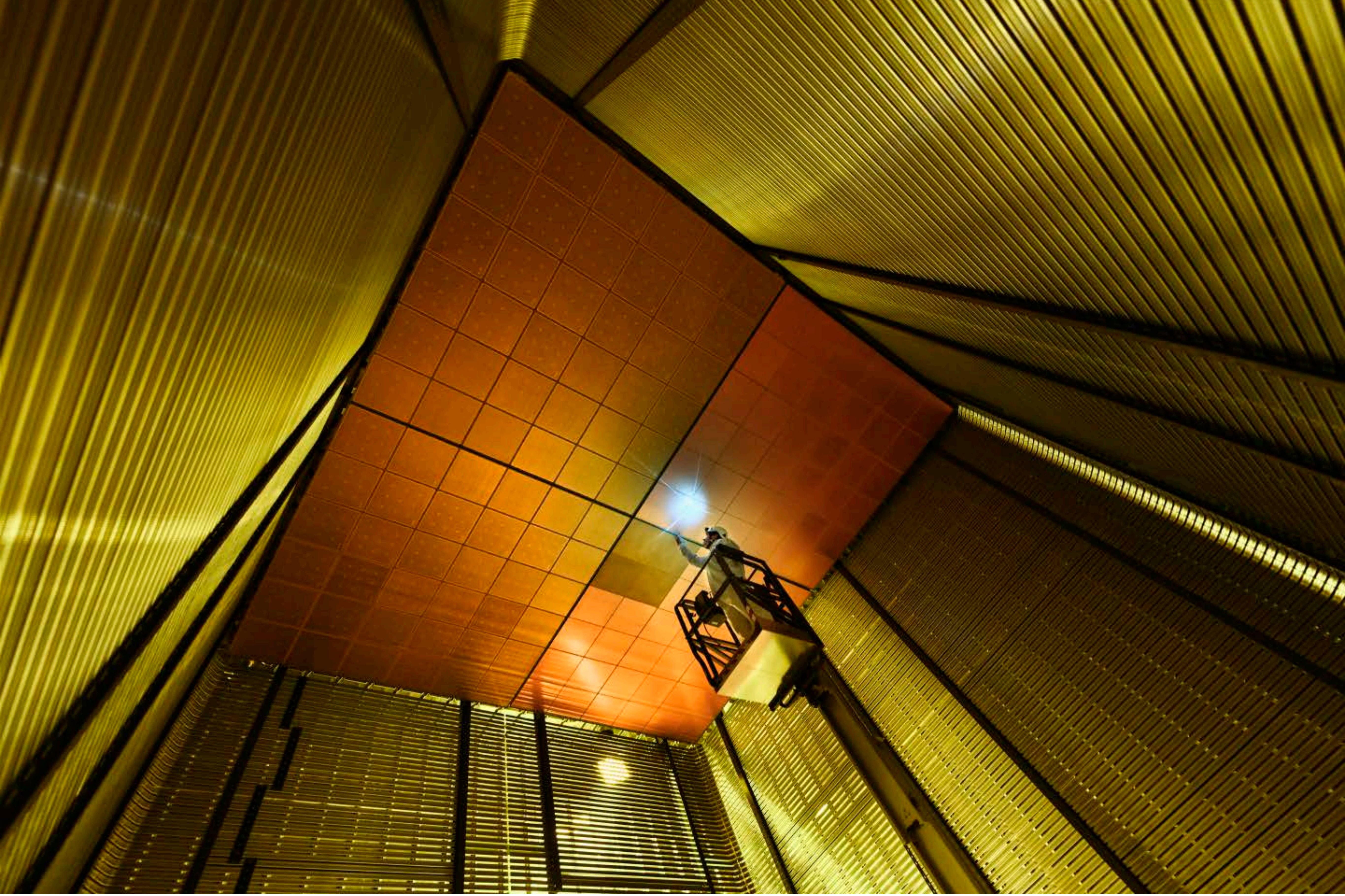
DUNE expects to use a field of ~500 V/cm giving a drift velocity of 2 mm/usec. For the design drift distance of 3600 mm that gives a drift time of ~1.8 ms and Vmax = 180 kV

The ICARUS LqAr Detector



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

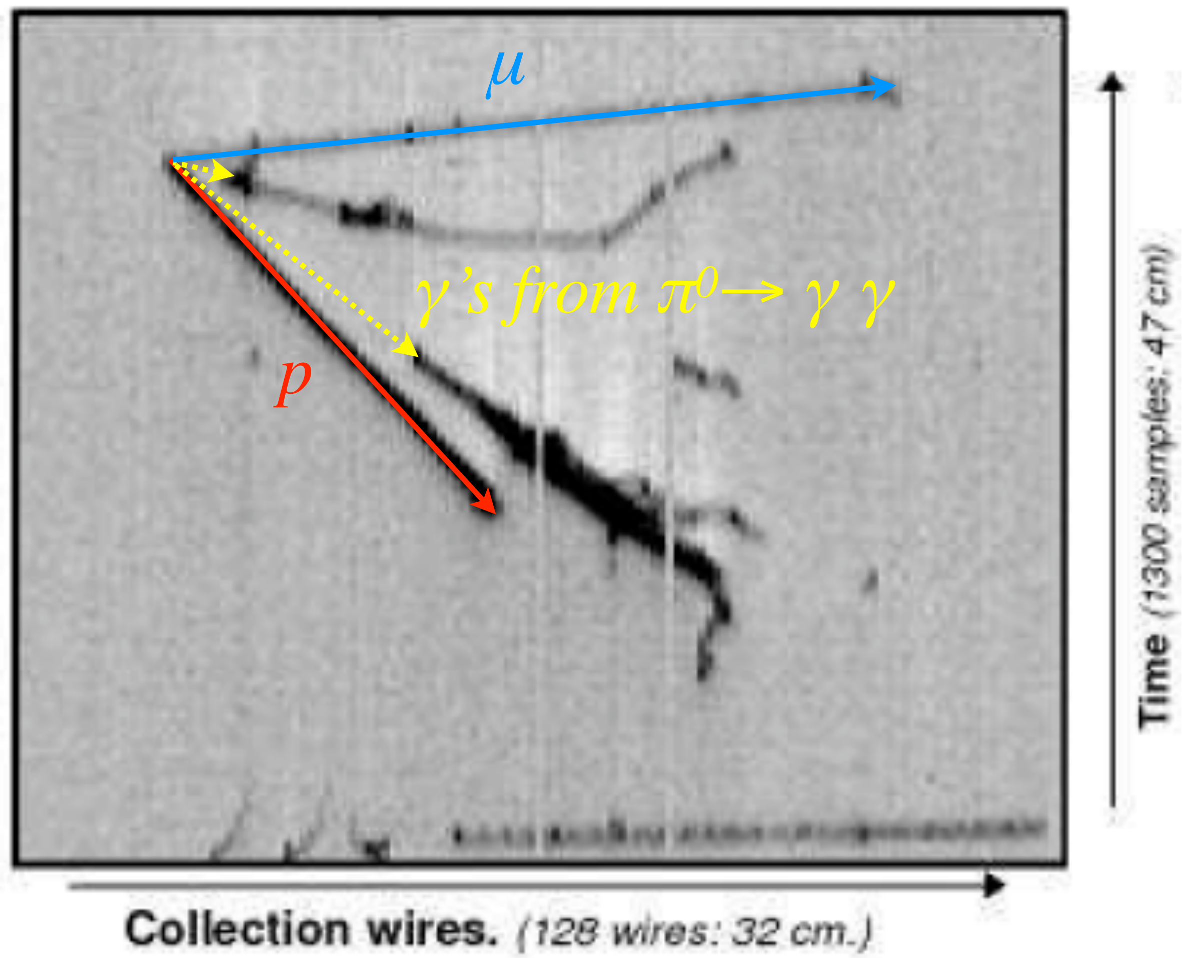
Figure 2.4: Picture of the open T300 ICARUS module during assembly.

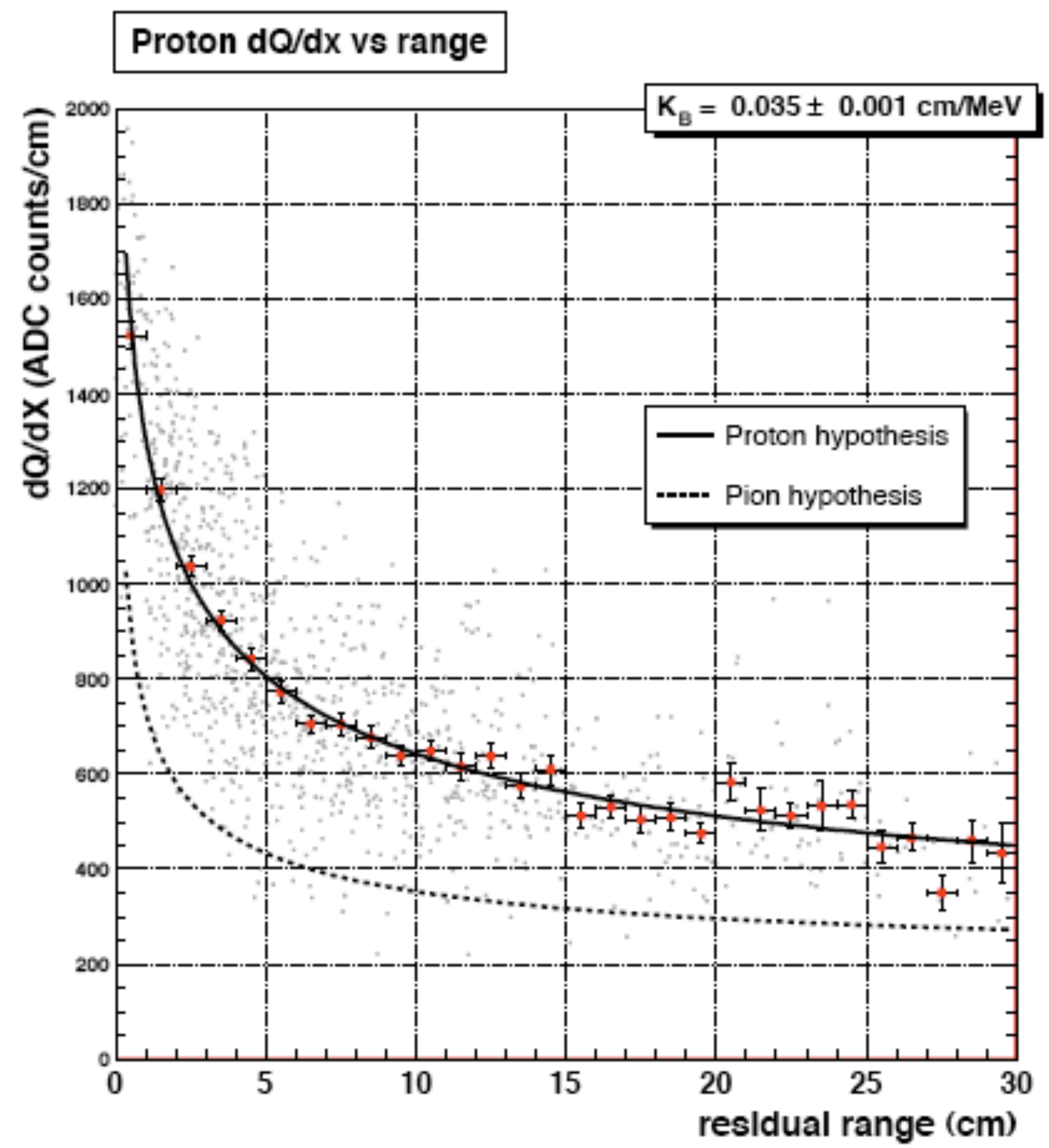


DUNE dual phase prototype

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

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





Ionization drift

As the ions drift, they compete against recombination:

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

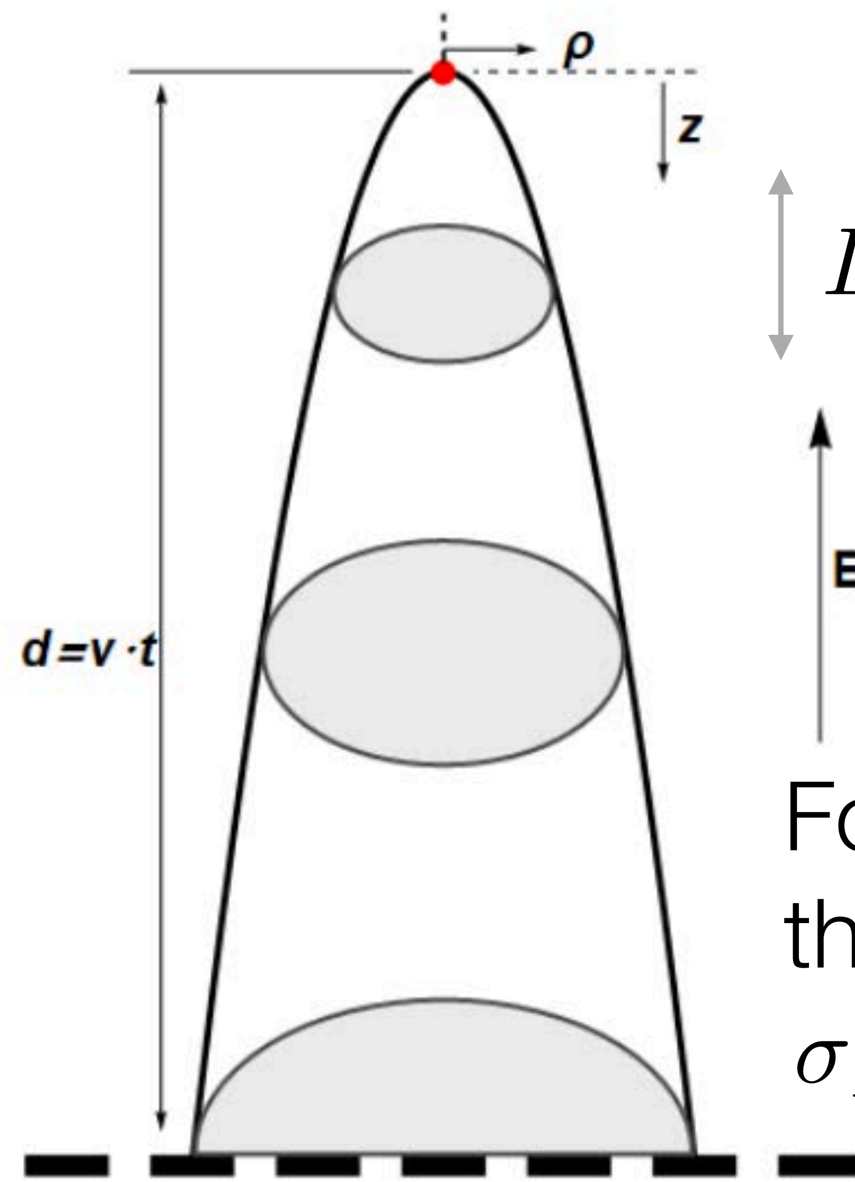
and attachment:

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

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

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

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



arXiv:1508.07059v2

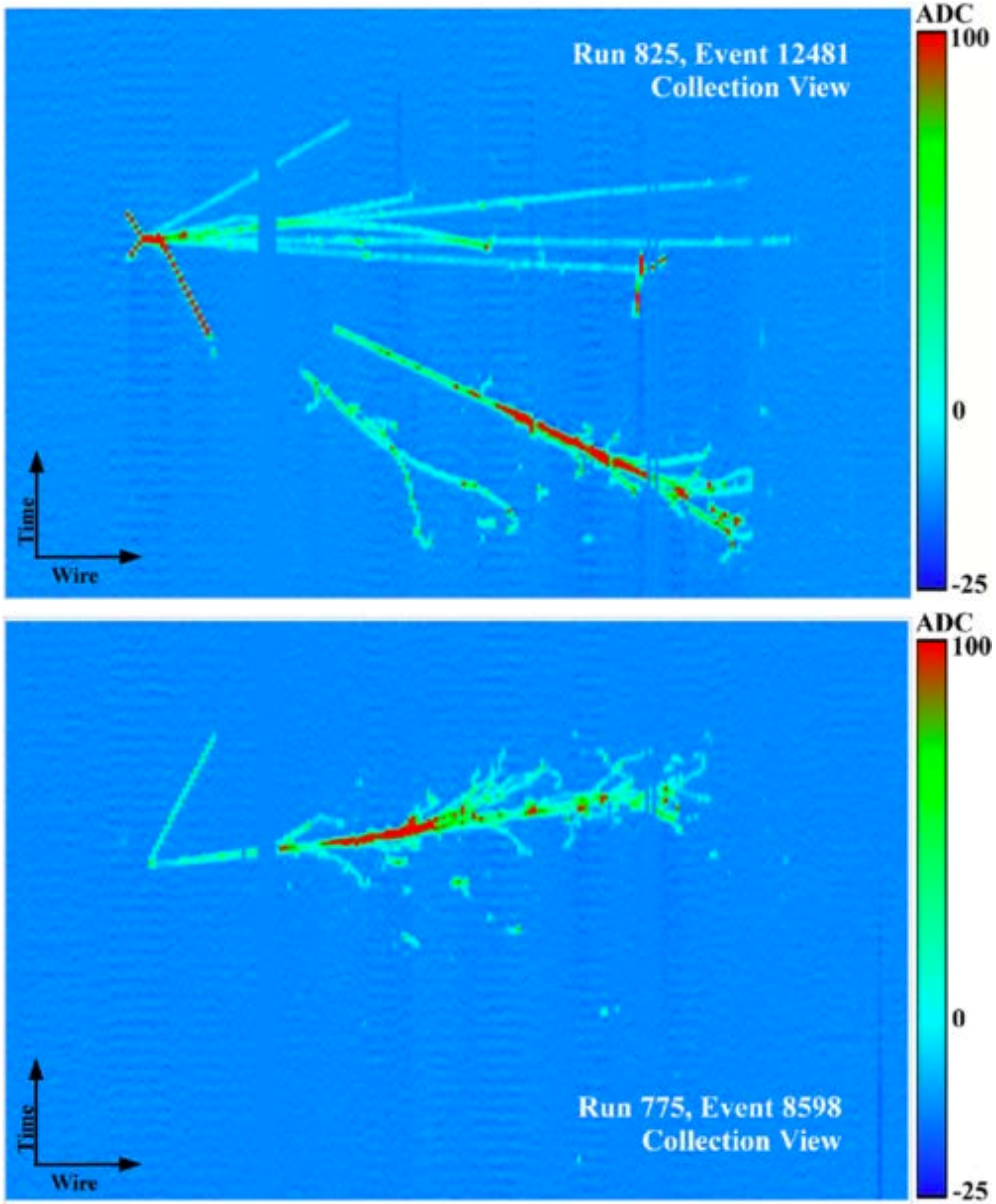
$$D_L = 7.2\ \mathrm{cm^2/s}$$

For t=1.7 ms, these give:

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

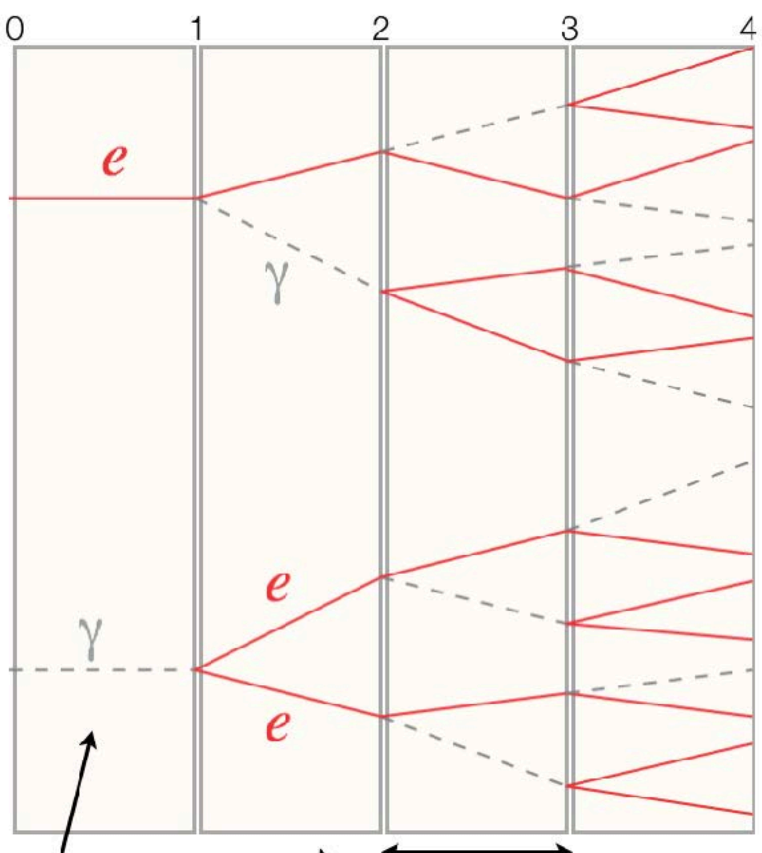
First observation of low energy electron neutrinos in a liquid argon time projection chamber

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



No visible energy in photon shower inside first conversion distance

Visible start of photon shower has twice as much energy as the visible start of the electron shower

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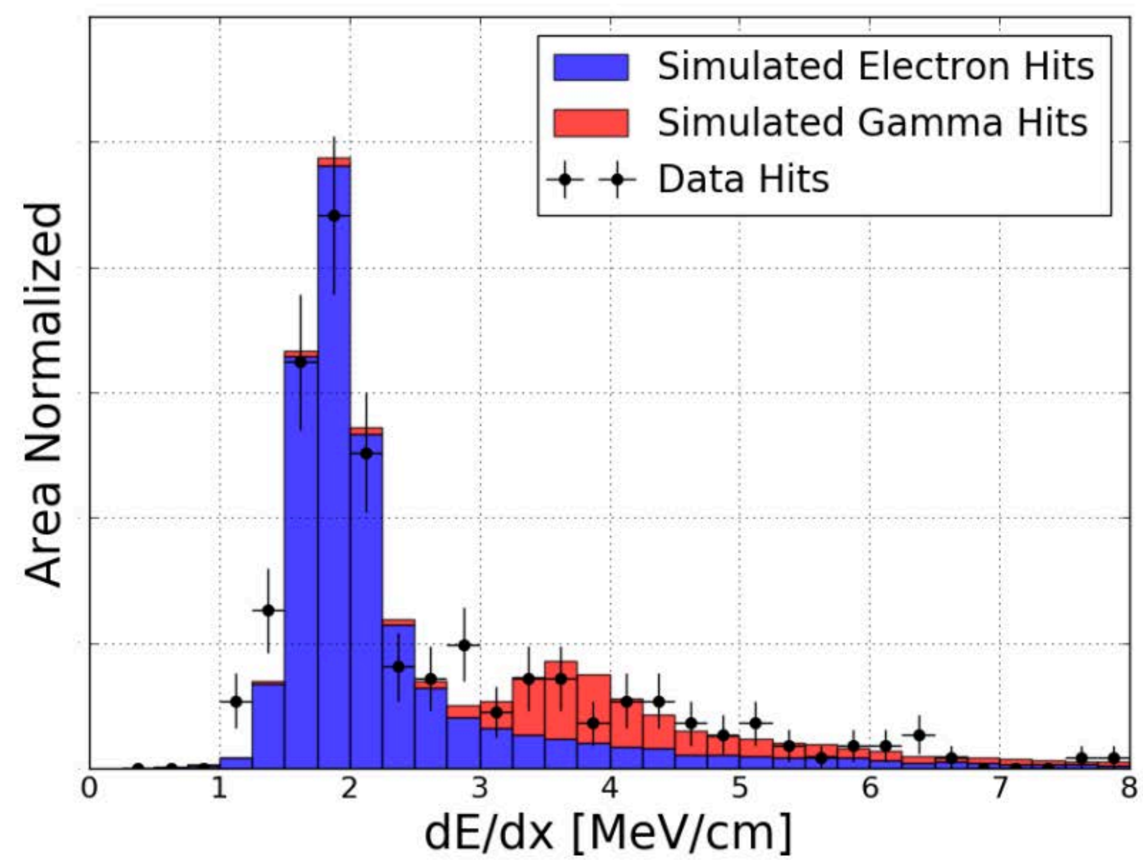

Figure 11. dE/dx for all the hits from the electron candidate data sample, compared to a sample of Monte Carlo comprised of 80% electrons and 20% gamma.

Thanks for listening!

- For more information on passage of particles through materials, event shapes, etc. etc. the **Particle Data Groups "Passage of particles through matter"** is a great start: https://pdg.lbl.gov/2023/reviews/rpp2023-rev-passage-particles-matter.pdf. I also like the textbooks by **Fernow ("Introduction to Experimental Particle Physics")** and Leo **("Techniques for Nuclear and Particle Physics")** which are somewhat "old school" books but still very useful when learning the basics of how to think about particles in your detector.

- The next big three detectors for neutrino physics are:

  - **JUNO** - large liquid scintillator detector to observe neutrinos from nuclear reactors

  - **Hyper-Kamiokande** - large water Cherenkov detector to observe neutrinos from the J-PARC accelerator, the Sun and the Atmosphere

  - **DUNE** - large liquid argon TPC to observe neutrinos from the Fermilab accelerators, the atmosphere and the Sun