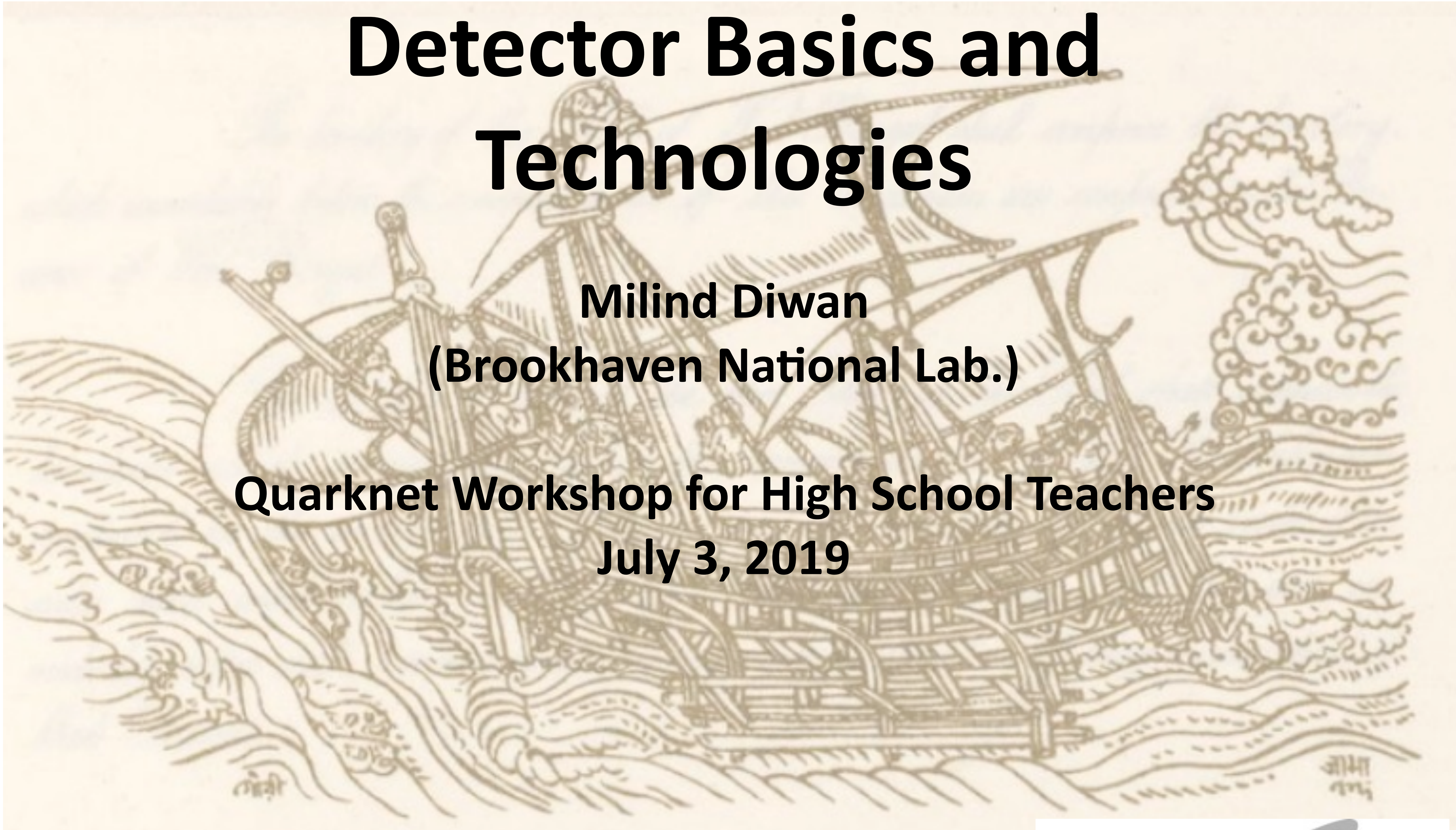

Detector Basics and Technologies

Milind Diwan
(Brookhaven National Lab.)

Quarknet Workshop for High School Teachers
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BROOKHAVEN
NATIONAL LABORATORY

Plan of lecture

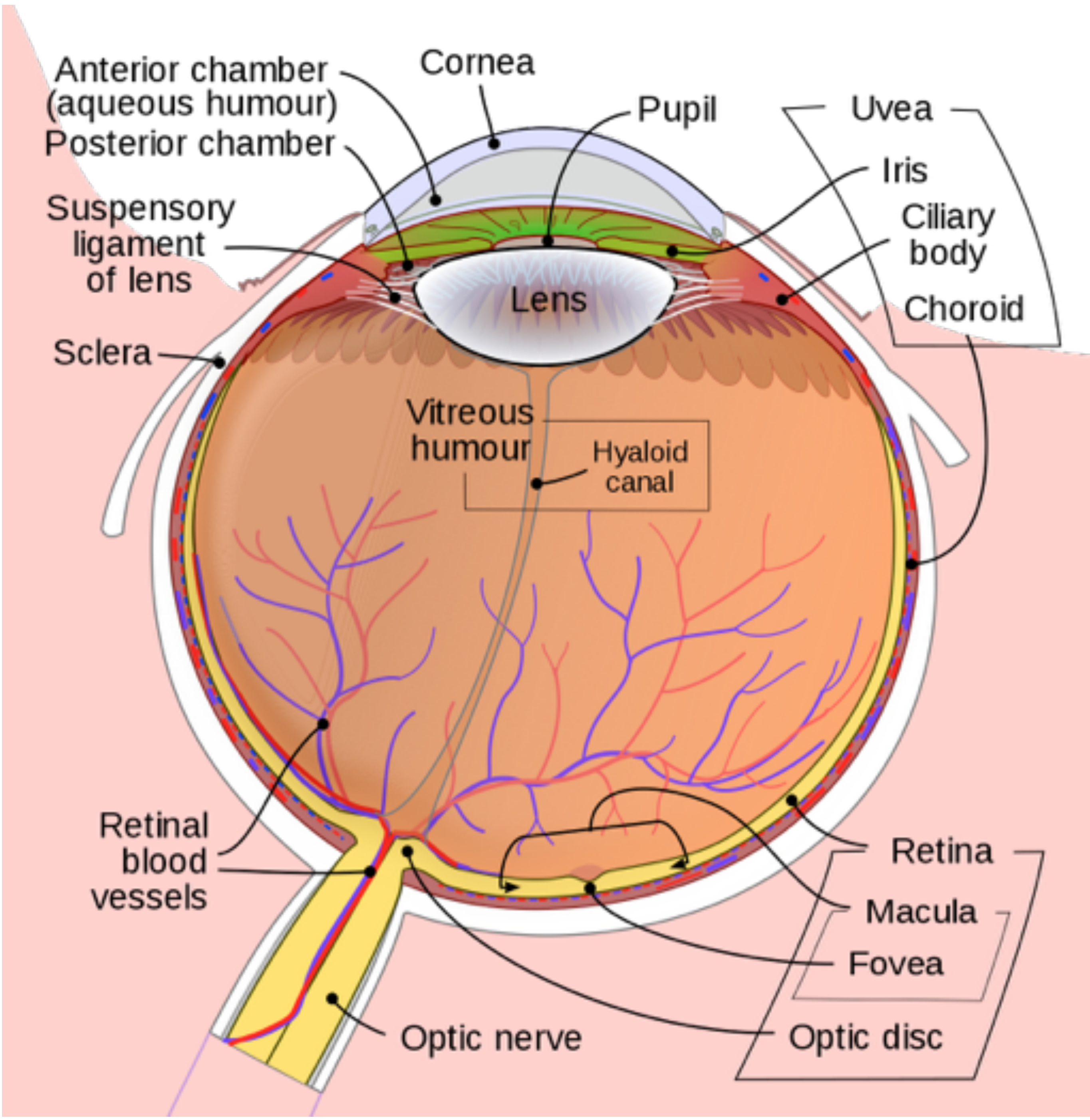
- Basics of Radiation Detectors
- Basics Interactions.
- Particle signatures in matter.
- Basic components of detectors.
- Some examples as time permits.

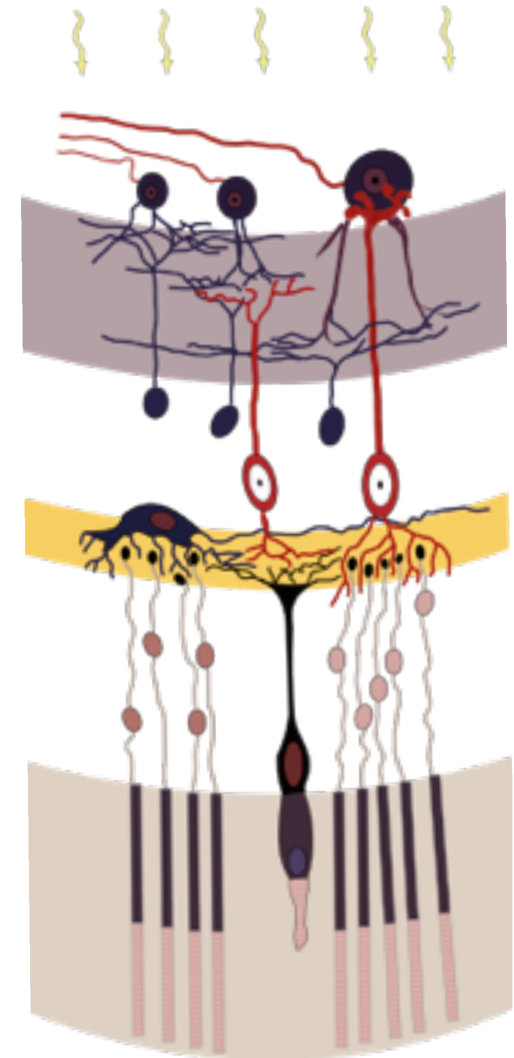
Although some of this is from the point of view of neutrino detection, most of the techniques are common in all radiation detection.

Some Basics

- **We can only measure 4 quantities and their combinations:**
  - **Distance (units are meters)**
  - **Time (units are seconds)**
  - **Mass (units are kilogram)**
  - **Electric Charge (coulomb)**
- **All detectors are built on the principle of charge detection.**
- **Any effect must be first be converted to free electric charge or motion of charge to be detected.**
- **This is regardless of whether detecting light, neutrinos, or gravitational waves.**

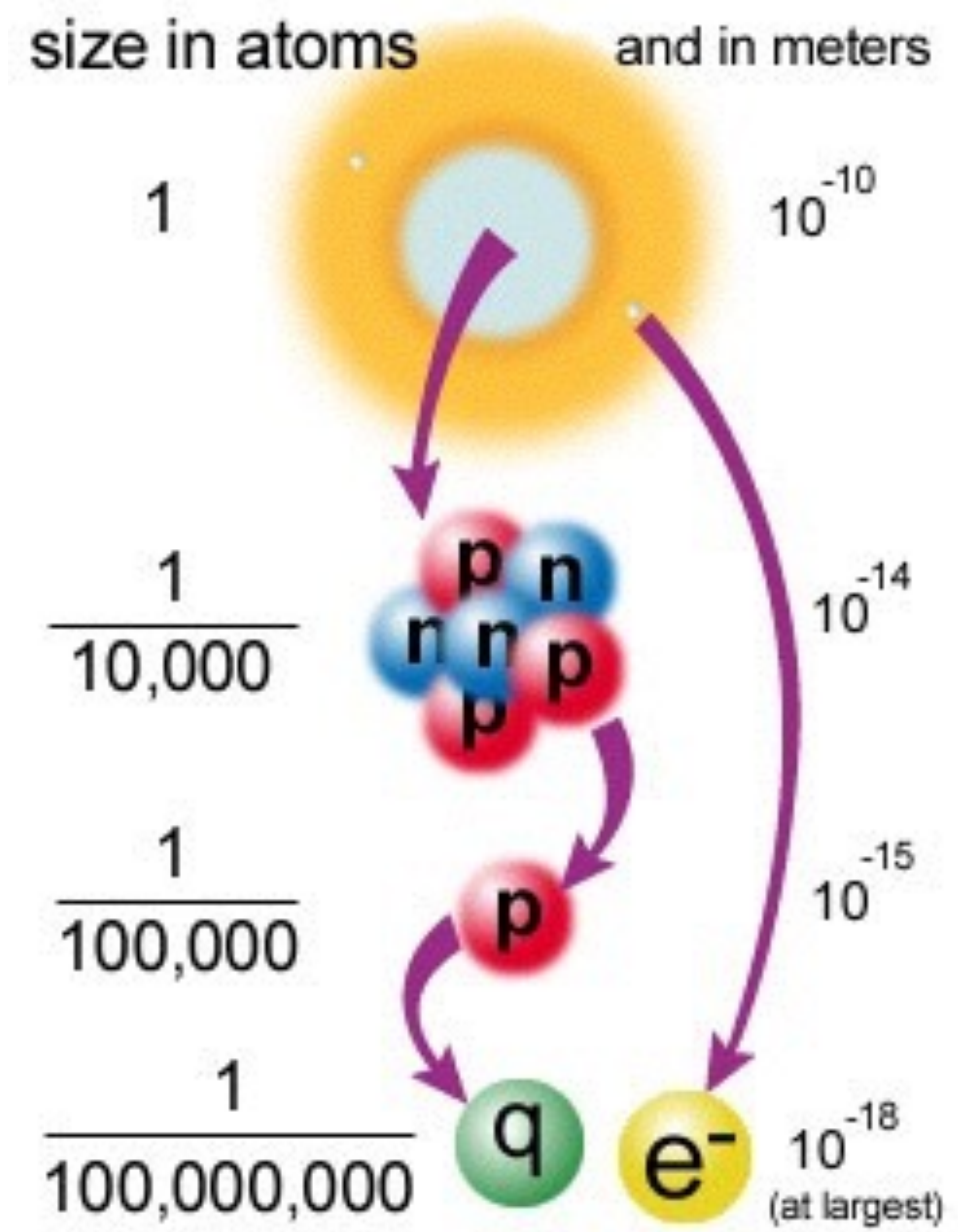
The most important detector of them all.





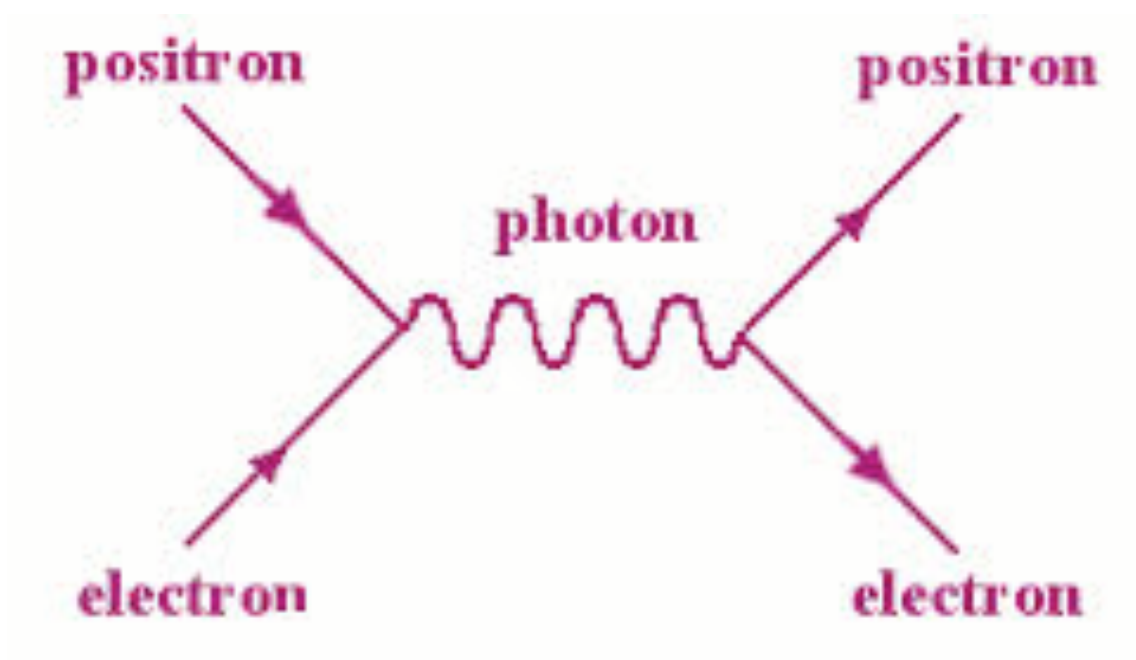
When light interacts with Rhodopsin, a large amplification reaction happens in the rod cells. Essentially an electrical signal is transmitted by means of chemical reactions.

- Particle physics is the study of constituents of atoms or subatomic particles.
- We must also understand how the constituents interact.
- The rules of interactions are governed by quantum mechanics and relativity.



Particle Interactions

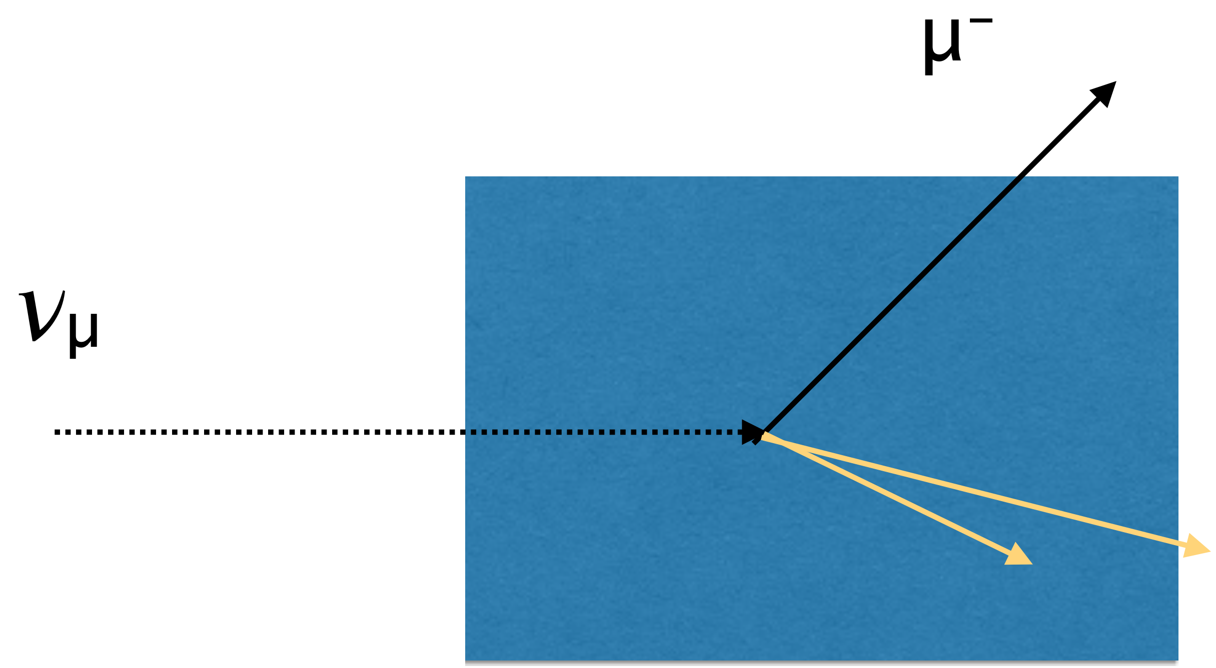
Atoms and particles **emit and absorb other particles**, either repelling or attracting each other.



Subatomic interactions are often depicted by simple diagrams called **Feynman diagrams**.

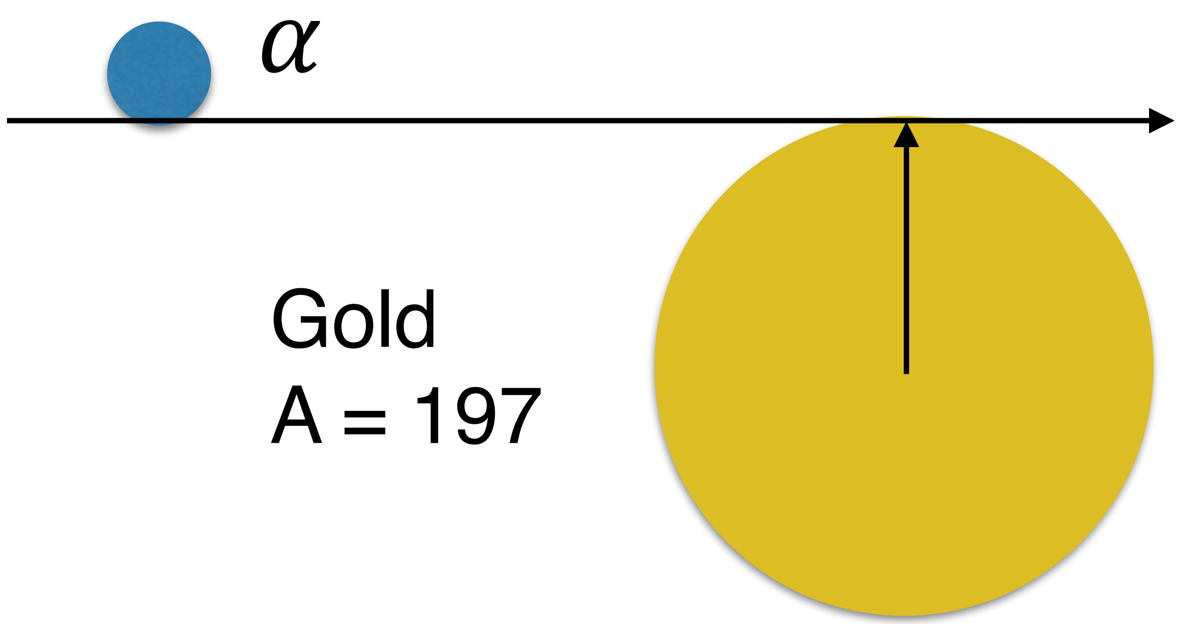
These can be used to calculate the **probability of interaction** between two particles thru the **force carrier** or the particle that is exchanged.

Particles are detected through their interactions with matter. The interaction must produce a charged particle which leaves evidence in the detector.



- ***<u>The neutrino is invisible as it enters a detector. Rarely interacts and when it does leaves charged particles that can be detected.</u>***
- ***Some Neutrino collision on atoms in detectors produces a charged muon.***
- ***The muon or other charged particle cause ionization which can be measured***

Cross section for particle collisions



Radius of a gold nucleus is

$$R = 1.2 \times \sqrt[3]{197}\, fm = 7\, fm$$

fm is $10^{-15} m$

Cross section for alpha particle is then

$$\sigma \approx \pi R^2 \approx 1.5 \times 10^{-24}\, cm^2$$

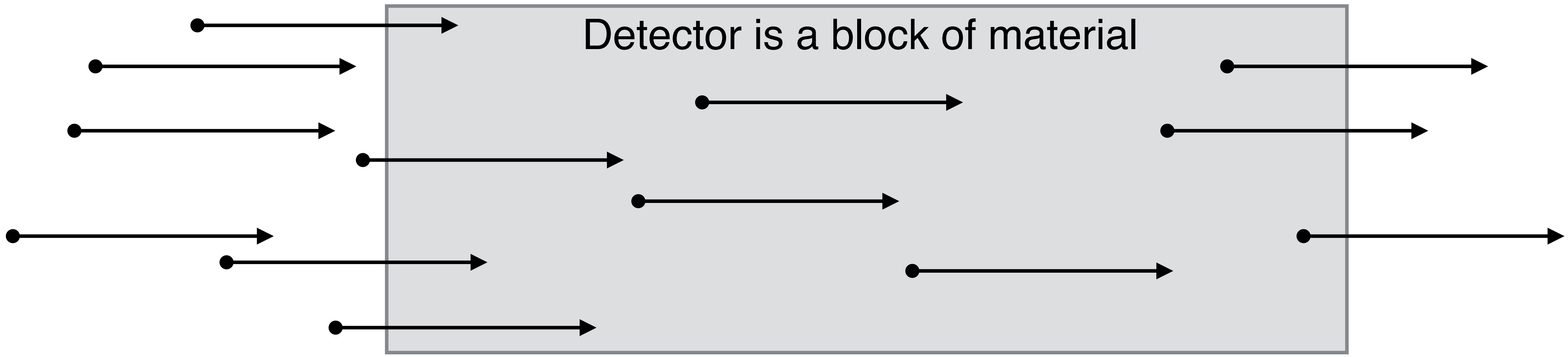
In particle physics, the cross section between any two particles is the area transverse to their relative motion within which they must meet to order to interact. It is the effective size.

More about cross section

- ***Quantum physics is very strange. There are no hard spheres and the cross section depends on many things:***
  - ***The two types of particles. (alpha and Gold …)***
  - ***Their spin orientation if any.***
  - ***Their relative velocities.***
  - ***The type of interaction that they exhibit: electrical, weak, or strong !***

Example: Neutrinos have extremely small cross section. Even for Neutrino on Gold.
Cross section can be specified as a function of the final state also. Such as cross section for back scattering.

Neutrino Cross sections are extremely small compared to alpha on Gold



As particles penetrate material, there is a reduction in the flux (particle/area/sec)

$$F(x) = F(0)e^{-\sigma\rho x}$$

$$\lambda = 1/(\sigma\rho)$$

λ is the mean free path

σ is the cross section

ρ is the density of targets

(In water $\rho \sim 6 \times 10^{23} cm^{-3}$)

For 1 GeV neutrino interactions $\sigma \sim 10^{-38}$ and

$$\lambda = \frac{1}{10^{-38} \bullet 6 \times 10^{23}} \approx 10^{12}\, meters!$$

In ordinary matter neutrinos just penetrate through with very rare interactions.

How to calculate event rate for neutrinos ?

- ***Events = Flux ($/cm^2/sec$)*Cross-section(cm^2)*Targets***

- **Targets are the number of particle targets in a detector volume. Detector itself serves as the target for interactions.**

- **1 ton of anything has ~ 6×10^{29} protons and neutrons and**
- **1 ton of anything has ~3×10^{29} electrons**
- **Typical cross section is 10^{-38} cm^2 x Energy (in billion eV)**
- **Neutrinos have huge energy range: eV to 10^{15} eV.**
- **Cross sections for low energies can be extremely small.**

- **1 eV = Energy to move 1 electron through 1V=$1.6 \; 10^{-19}$Joule**

Detector mass needed for 1000 evts/yr ?

$$\varphi = 5000\ m^{-2}\sec^{-1}$$

$$E \sim 1\ GeV$$

$$\sigma \sim 10^{-38}\ cm^{2}$$

$$Nucleons = 6\times 10^{29}\ ton^{-1}$$

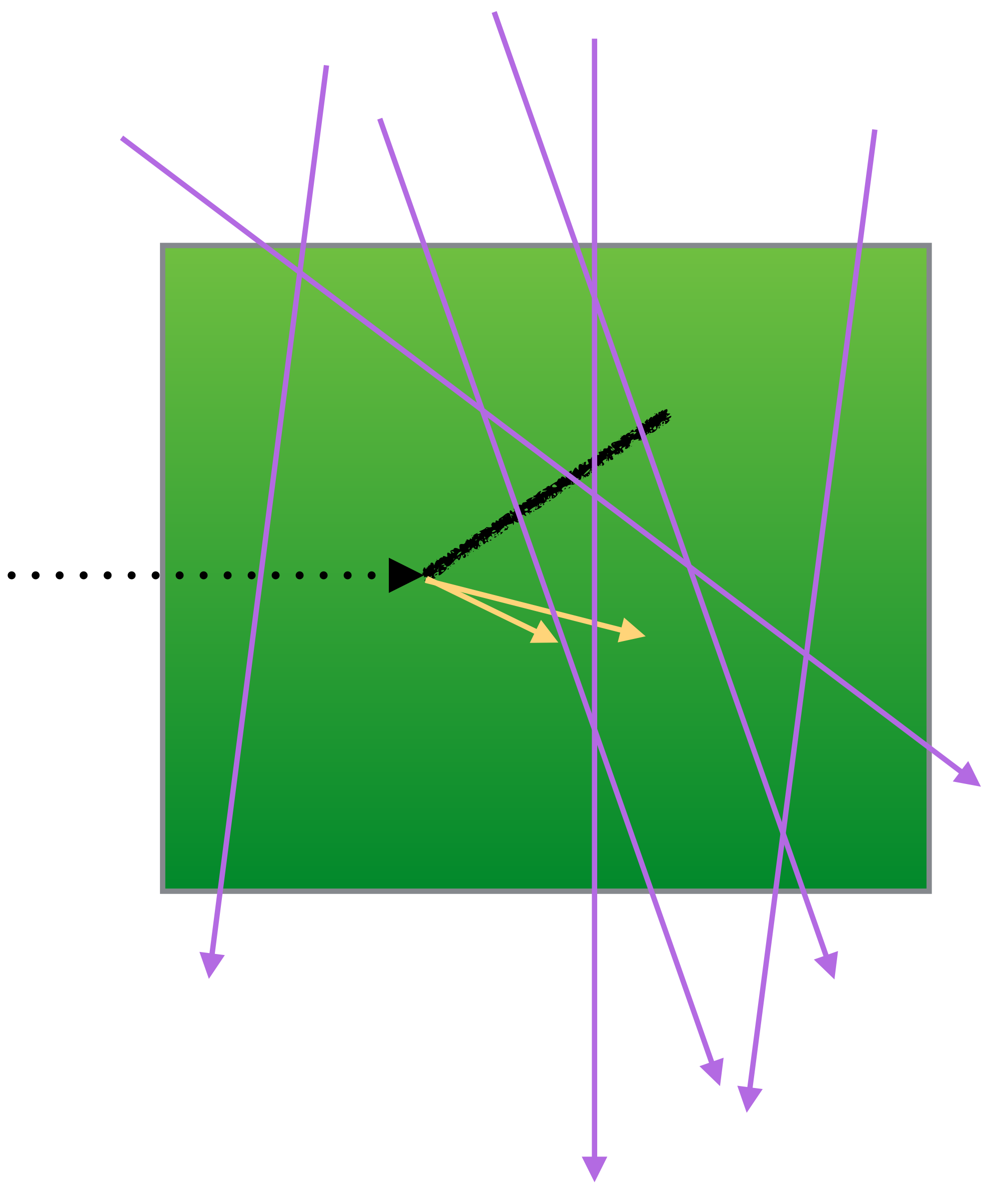
$$N = \varphi \bullet \sigma \bullet 6\times 10^{29} \bullet 3\times 10^{7}\ ton^{-1} yr^{-1}$$

$$N = 0.1\ events / ton / yr$$

Example using Atmospheric Neutrinos

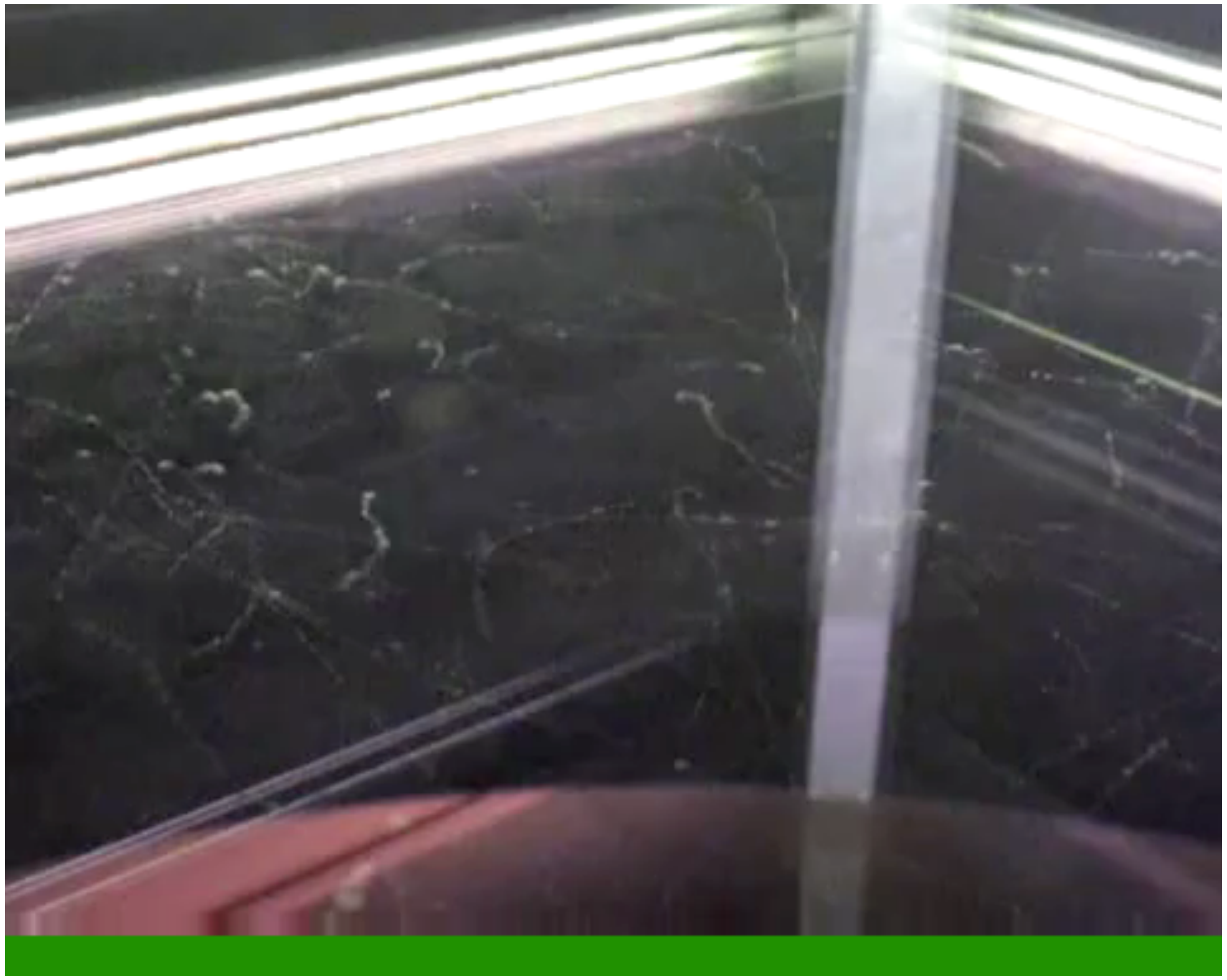
- ***The first most important consideration for neutrino detection is the mass of the detector. (thousands of tons are needed for many experiments).***
- ***If flux is high mass can be lowered.***
- ***Both Energy and Flux need to be known.***

Summarize so far



- ***Any detector is based on the principle of charge detection.***
- ***Any interaction between particles must result in charged particles.***
- ***The charged particle produced ionized or excited atoms that can be detected by proper sensors.***
- ***Particle interactions are quantified by using the cross-section. The cross section can be very small for interesting interactions.***
- ***Interesting events can be masked by background interactions such as cosmic rays.***
- ***How do we register the deposited charged particles in our electronics ?***

Let's now look at some data



It would be impossible to see a neutrino interaction in this !

the vapor trails are evidence of ionization caused by cosmic ray muons !

Cosmic ray cloud chamber at the New York Hall of Science

The surface rate is ~100 $m^{-2}sec^{-1}sr^{-1}$
Mean ~4 GeV
Flat below 1 GeV. $E^{-2.7}$ above 10 GeV.
Angular ~ Cos^2(Theta)

Units

Electronvolt is the amount of kinetic energy gained or lost by a single electron accelerating from rest through an electric potential differenceof one volt in vacuum. Hence, it has a value of one volt, 1 J/C, multiplied by the electron's elementary charge $e = 1.6021 \times 10^{-19}\ C$.
Therefore, one electronvolt is equal to $1.602 \times 10^{-19}\ J$

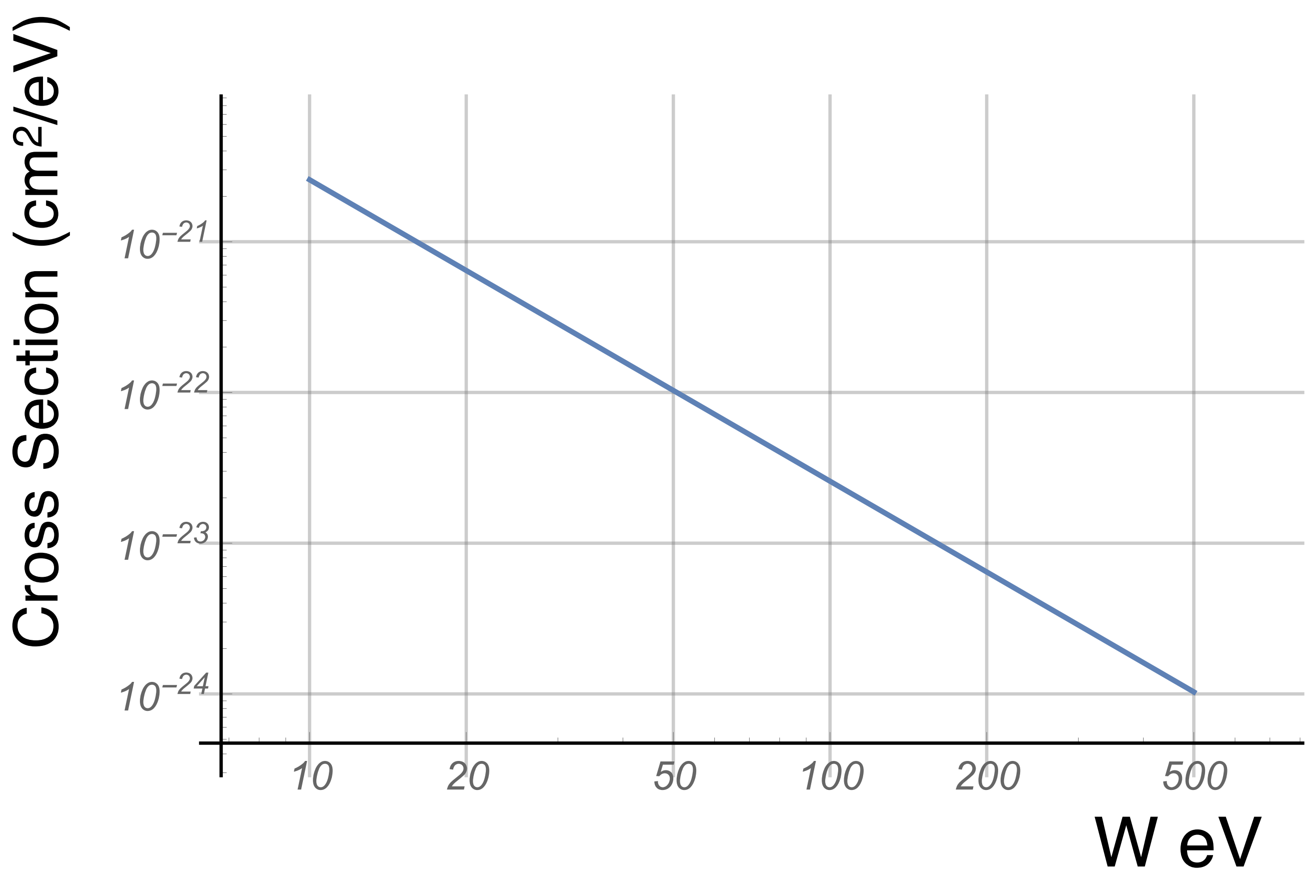
Measurement	Unit	SI value of unit
Energy	eV	$1.602\,176\,634 \times 10^{-19}$ J
Mass	eV/c^2	$1.782\,662 \times 10^{-36}$ kg
Momentum	eV/c	$5.344\,286 \times 10^{-28}$ kg·m/s
Temperature	eV/k_B	$1.160\,451\,812 \times 10^{4}$ K
Time	$\hbar$/eV	$6.582\,119 \times 10^{-16}$ s
Distance	$\hbar c$/eV	$1.973\,27 \times 10^{-7}$ m

Energy Loss

Most of the energy loss of fast charged particles is due to single collisions with atomic electrons. In most collisions energy W is lost with W < 100 eV. (See the Mathematica notebook to calculate all this)

There is a Maximum energy loss in single collision on free electrons.

$$W_{\max} \approx 2m_e\beta^2\gamma^2 / (1+2\gamma m_e / M)$$



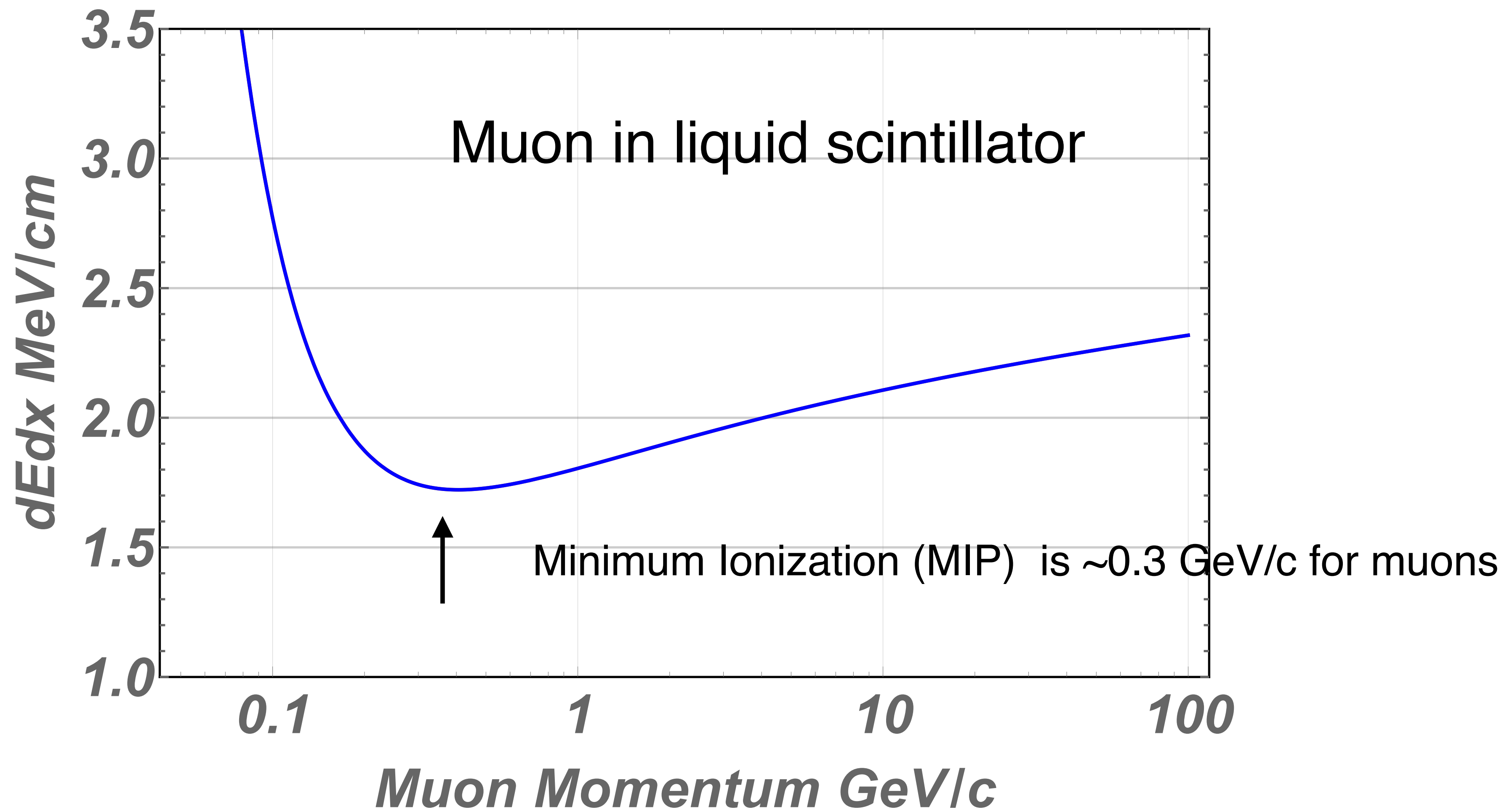
$$\frac{d\sigma(W,\beta)}{dW} = \frac{k_r}{\beta^2}\frac{(1-\beta^2 W / W_{\max})}{W^2}$$

$$k_r = 2\pi r_e^2 m_e z^2 = 2.54955\times10^{-19} z^2 \cdot eV \cdot cm^2$$

We know how to calculate and simulate this in great detail in our detectors.

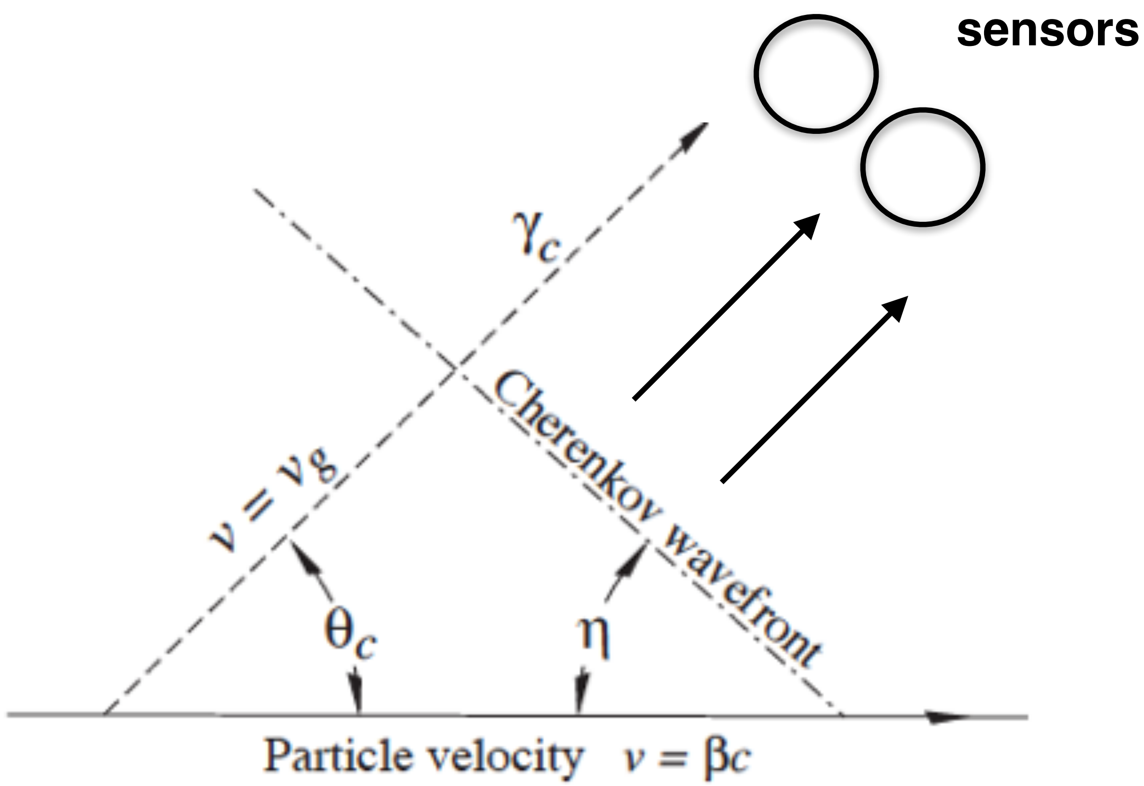
This is called ionization energy loss

Energy loss of charged heavy particles



- ***The energy loss has a minimum and rises very quickly as particle slows.***
- ***This lost energy causes to 1) free electric charge, 2) scintillation light, 3) physical (bubbles) and chemical changes (photographic plates).***
- ***Energy loss depends on velocity. At very high energies most of the loss is due to radiation (or emission of gamma rays rather than ionization).***

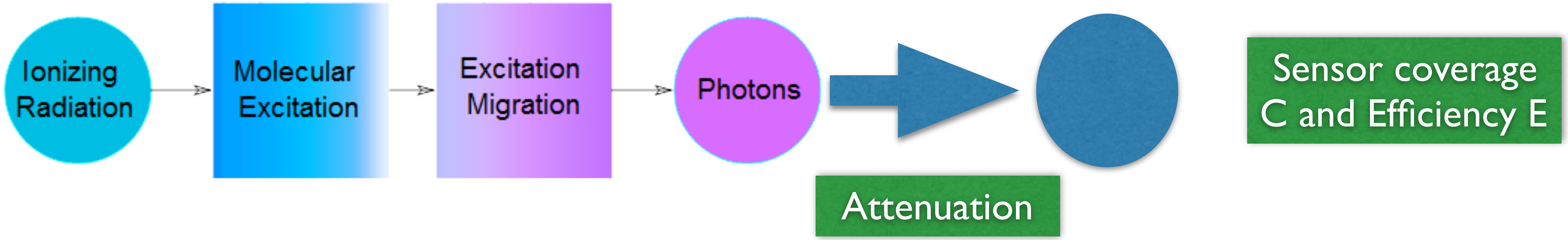
Cherenkov Radiation



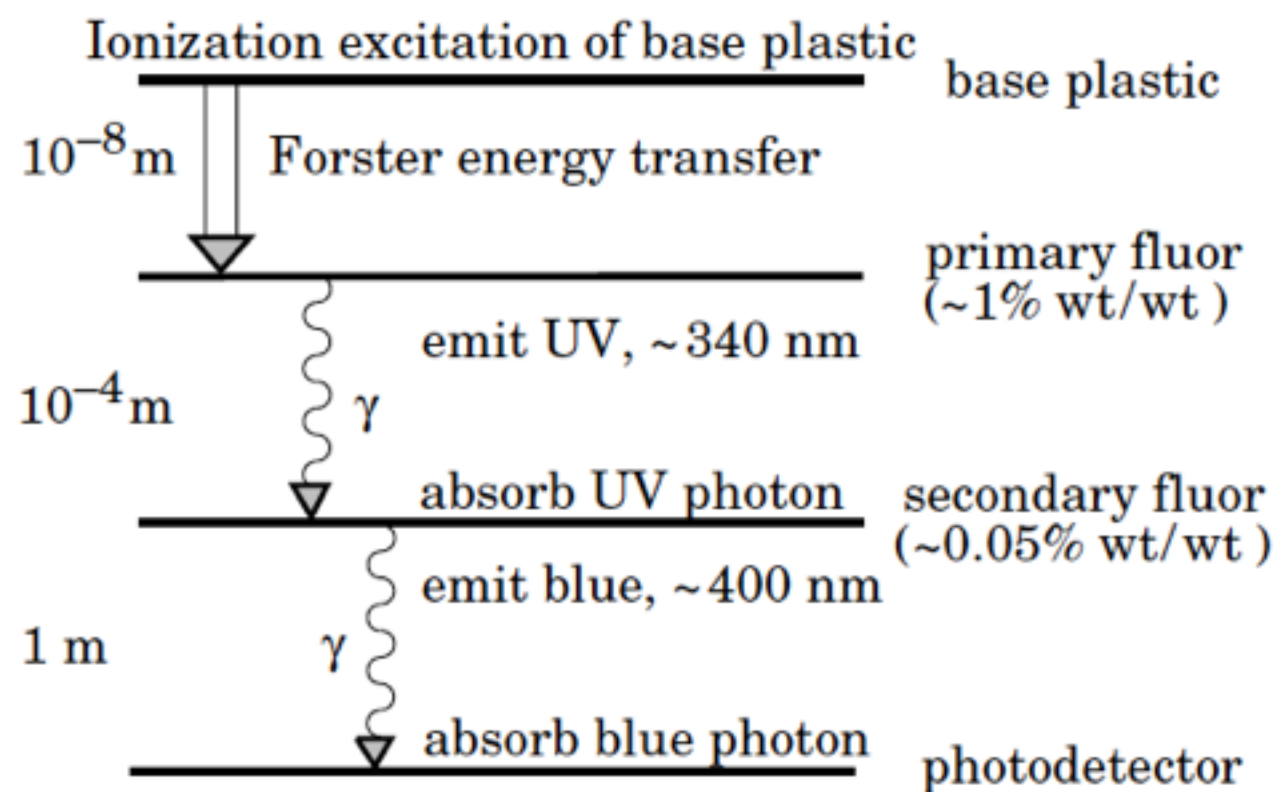
$$\cos\theta_c = (1/n\beta)$$
$$\theta_c + \eta \approx \pi/2 \quad \textit{because of dispersion}$$

- Cherenkov radiation: happens when particle moves faster than speed of light in a medium. This is used with gas, acrylic, and water.
- This radiation can be detected in sensors to reconstruct the particle. But it must have sufficient momentum to be above threshold. $\beta > 1/n$

Scintillation from ionization in plastics



Time scale ~ few ns due to first fluor (rise time)

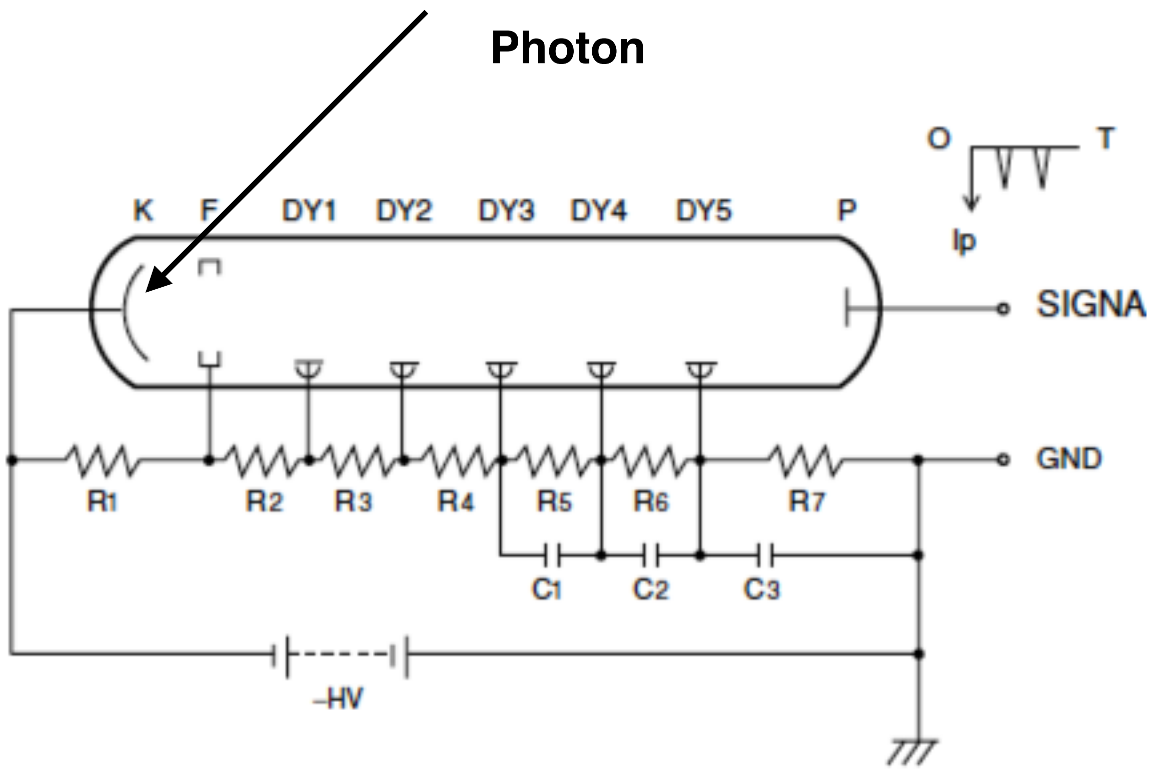


$$Typical \quad L \sim 10^4 \; photons \,/\, MeV$$

$$Yield = L \bullet C \bullet QE \bullet e^{-PathLength/\lambda}$$

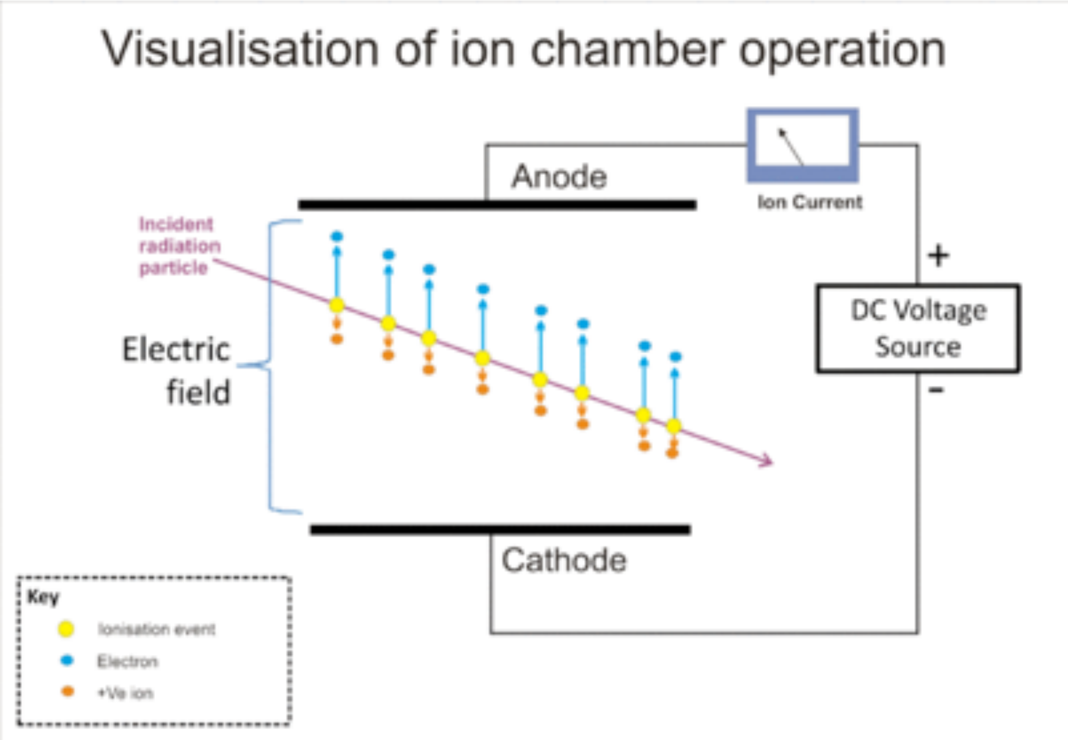
- There are many scintillation mechanisms. Organic scintillators and noble liquids are important for neutrino physics.

Photo-Multiplier Tube

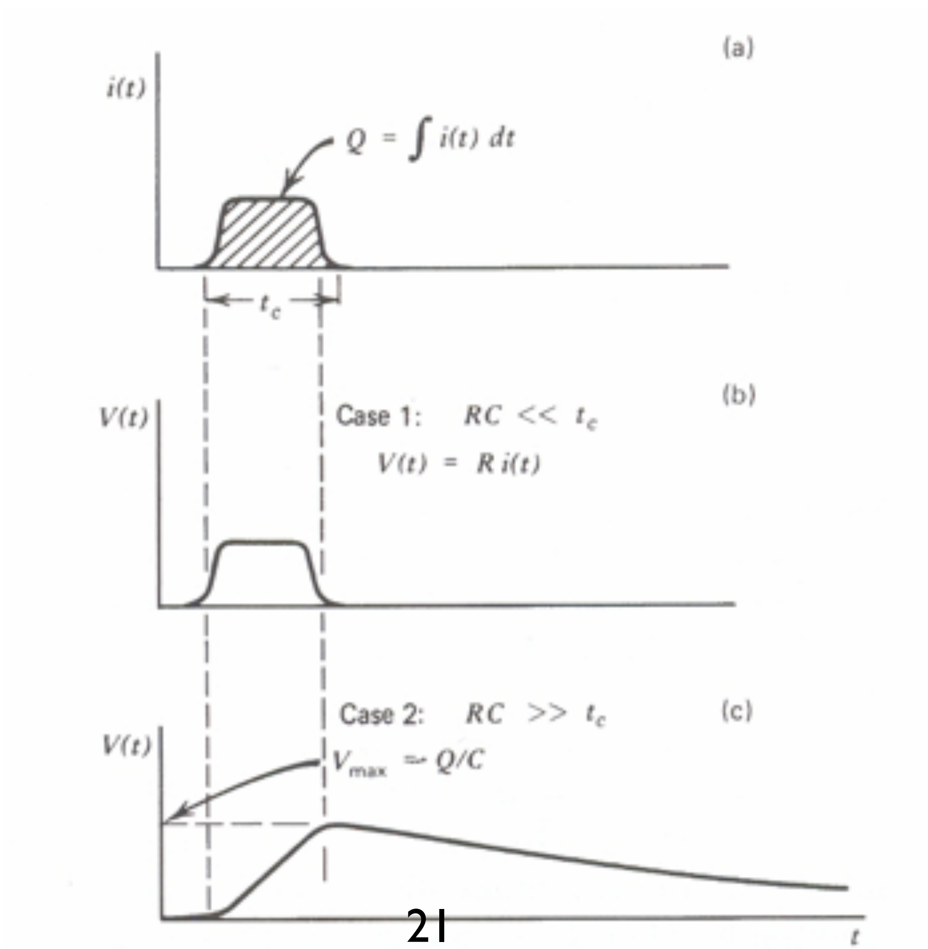


- Photons are converted to charge by a photocathode with low work function.
- Electric fields accelerate and multiply the primary electron in several stages. Each stage has multiplication of ~4-5.
- Gain can be few 10^6
- There are Many clever geometries.
- New types of photon sensors are always being developed.

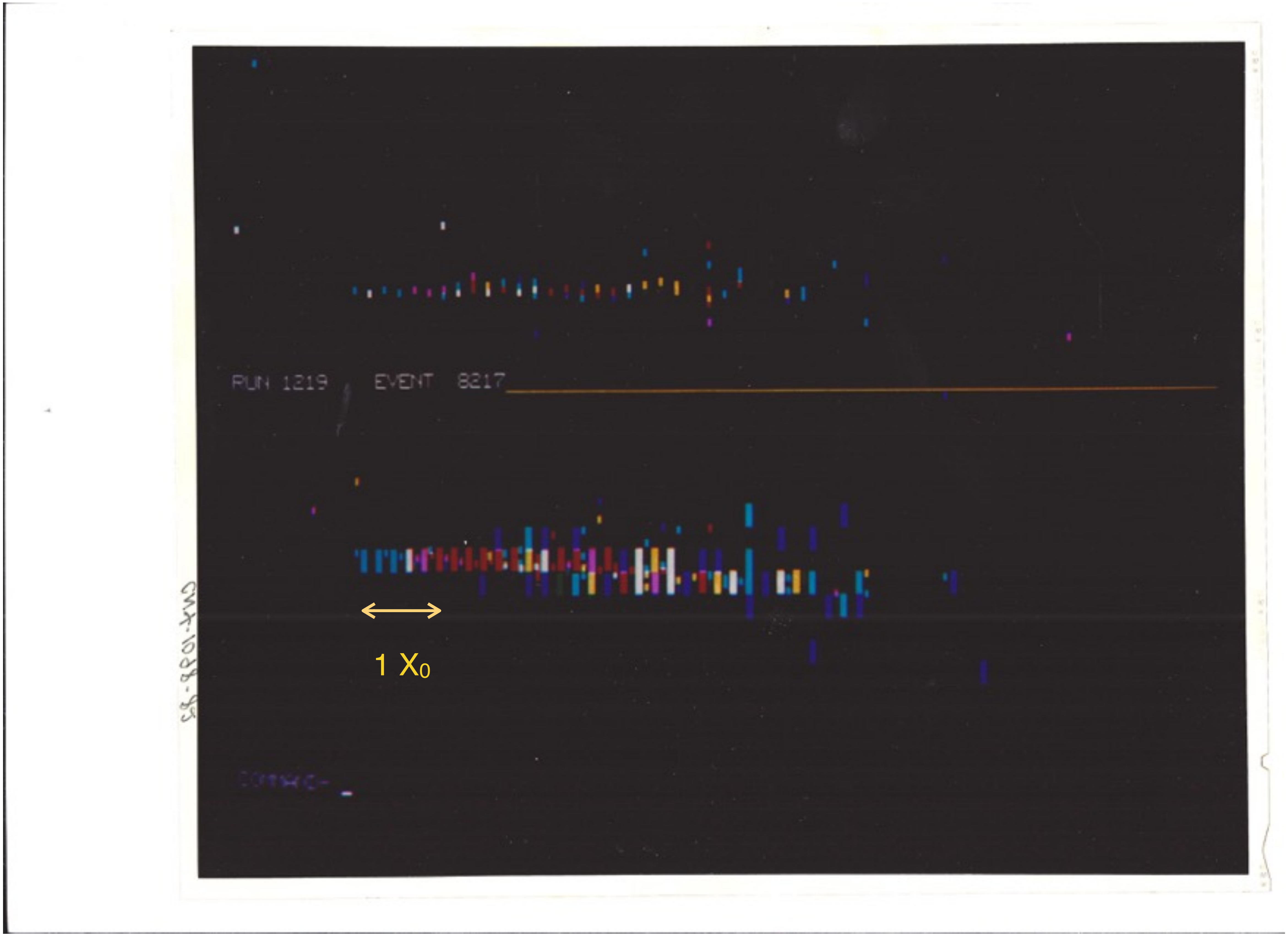
Ionization detectors



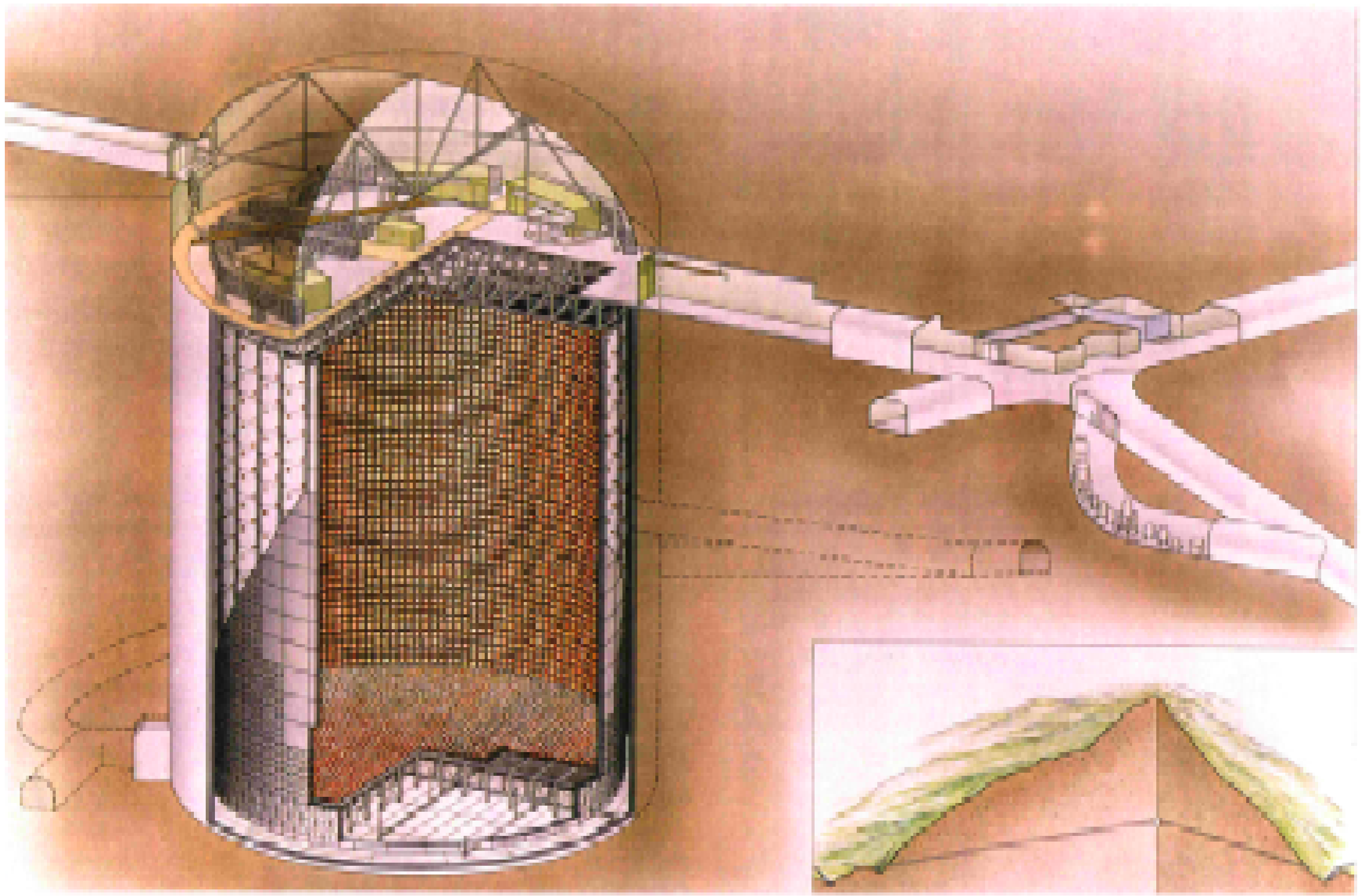
material	W (ev/pair)
LAr	23.6
LXe	15.6
Silicon	3.6
Germanium	2.9
Diamond	~13
CdTe	5.2
LNe	36
LKr	19



- In gases, semiconductors, and pure insulators, ionization creates electron-ion pairs.
- Electrons generally move about 1000 times faster than ions.
- This current can be measured as voltage across a resistor (case 1) or pulse across a capacitor (case 2)

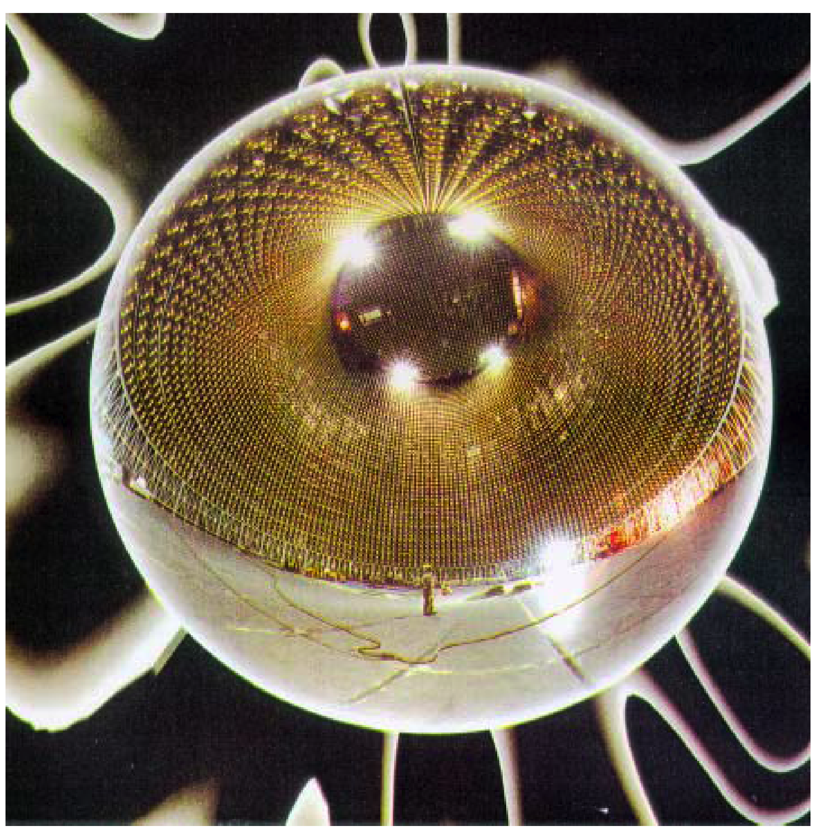


Electromagnetic shower from Experiment E734 in 1986. Example of neutrino electron elastic scattering. This is in liquid scintillator. Energy ~ 2 GeV.



Water Cherenkov SuperKamiokaNDE

Dimensions	**42m(H)X39m(W)**
Material	**Pure Water**
Attentuation	**~80 m (400nm)**
Total mass	**40000 ton**
Fiducial mass	**22000 ton**
inner PMTs	**11146**
Outer PMTs	**1885**
PMT dim. Inner(outer)	**50 cm (20cm)**
Inner coverage	**~40%**
Wavelength	**350 nm - 600 nm**



It took 4-5 years to dig and build the detector.

Ave. Depth ~ 1 km rock

Cosmic rate ~ 2 Hz

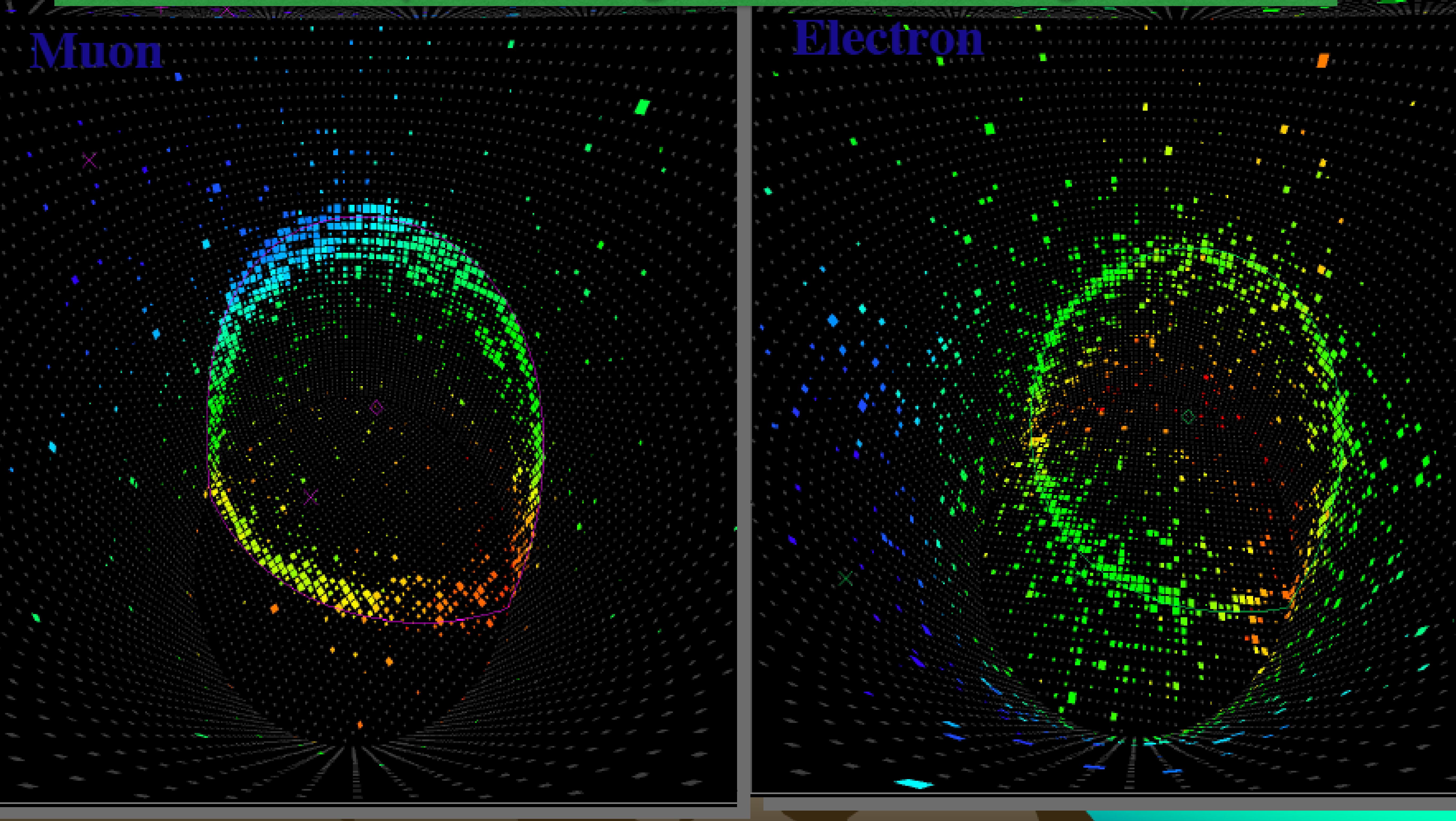
$$Yield = 370 \bullet \mathrm{Sin}^2\,\theta_c \bullet 0.4 \bullet 0.2 \approx 10\ pe/cm$$

↑ Coverage X Photon detector efficiency

Technical issue: PMTs have to withstand huge pressure.

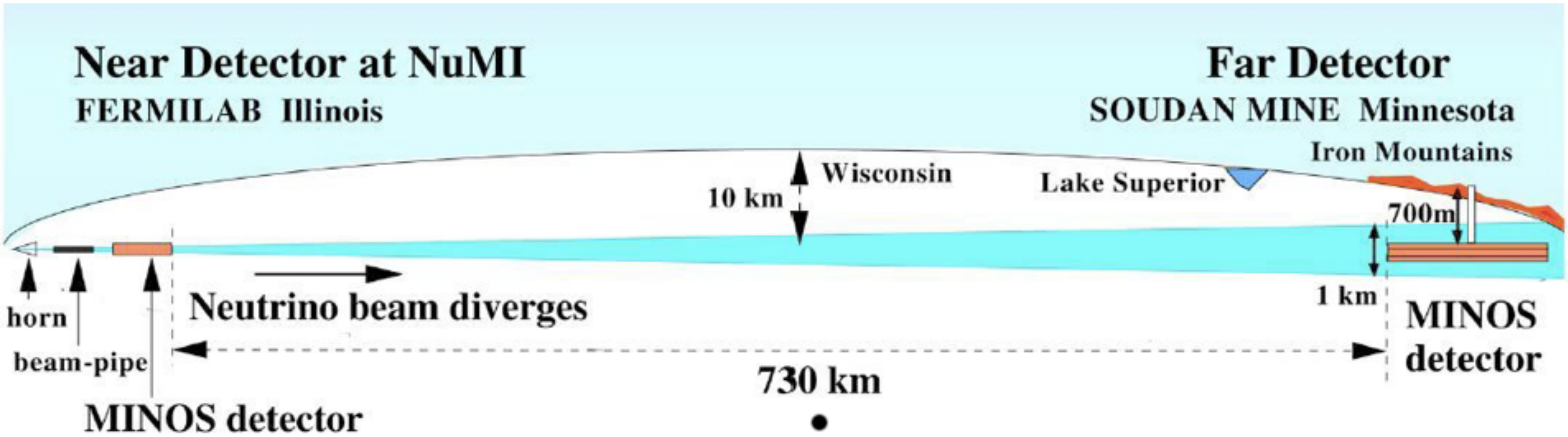
Particle Identification

The SuperK discovered that neutrinos from the atmosphere change their flavor in flight

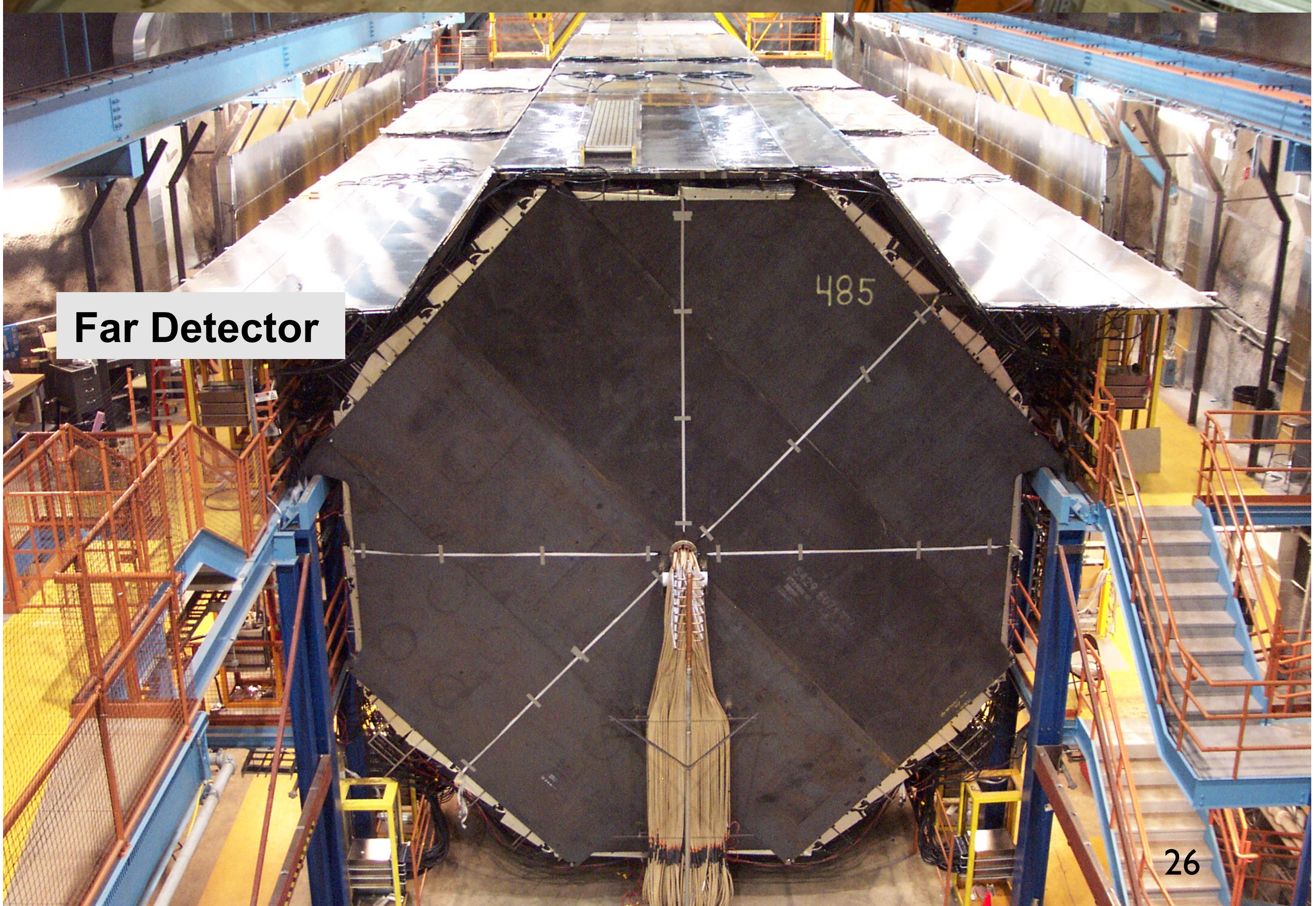


MINOS

- Prepare a pure beam of muon neutrino beam.
- Aim it towards a large muon detector.
- Observe spectrum of muon neutrinos to see oscillations in energy.



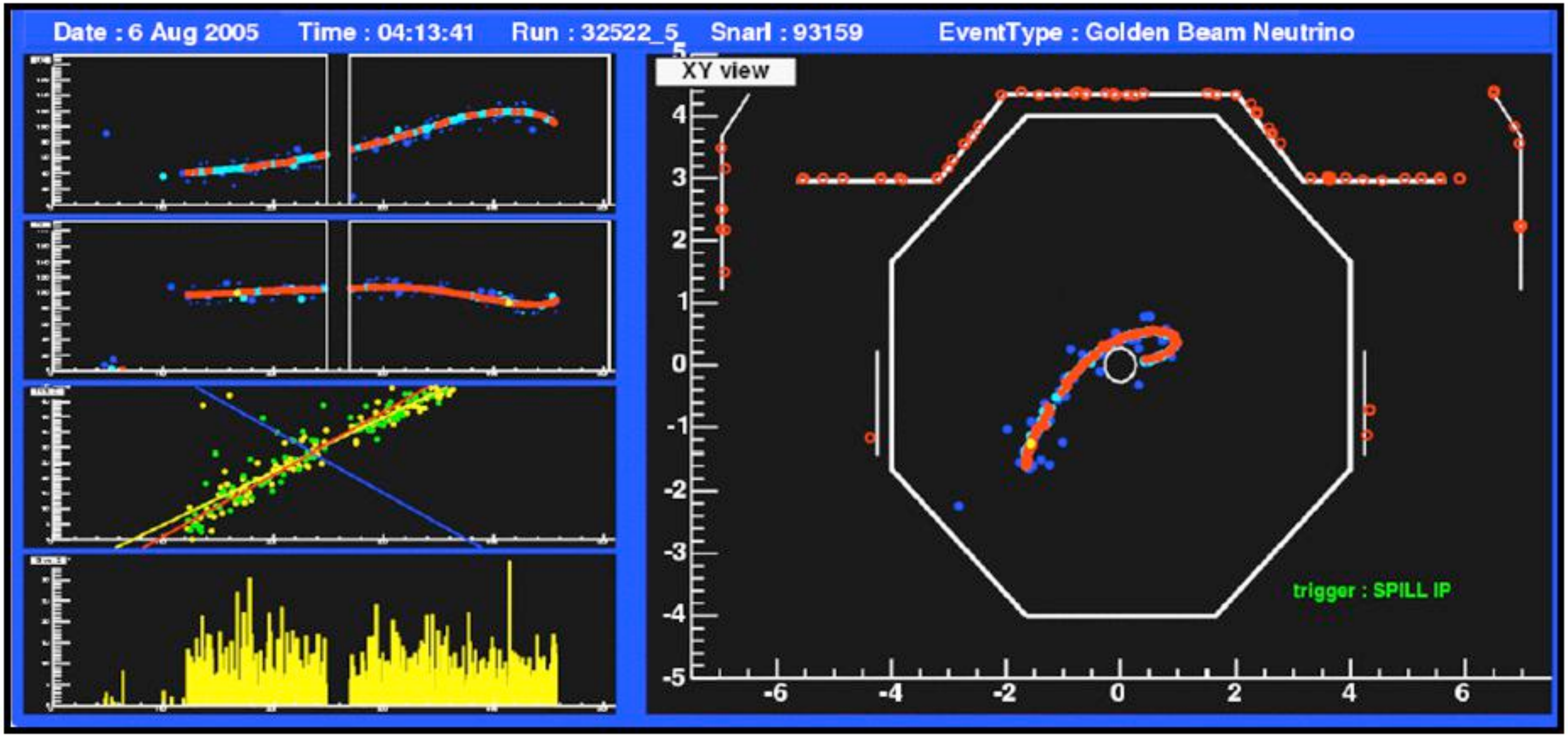
MINOS Detectors



- Massive
  - 1 kt Near detector (small fiducial)
  - 5.4 kt Far detector
- Similar as possible
  - steel planes
    - 2.5 cm thick
    - 1 Muon ~ 27 planes
    - 1.4 radiation lengths
  - scintillator strips
    - 1 cm thick
    - 4.1 cm wide
    - Molier radius ~3.7 cm

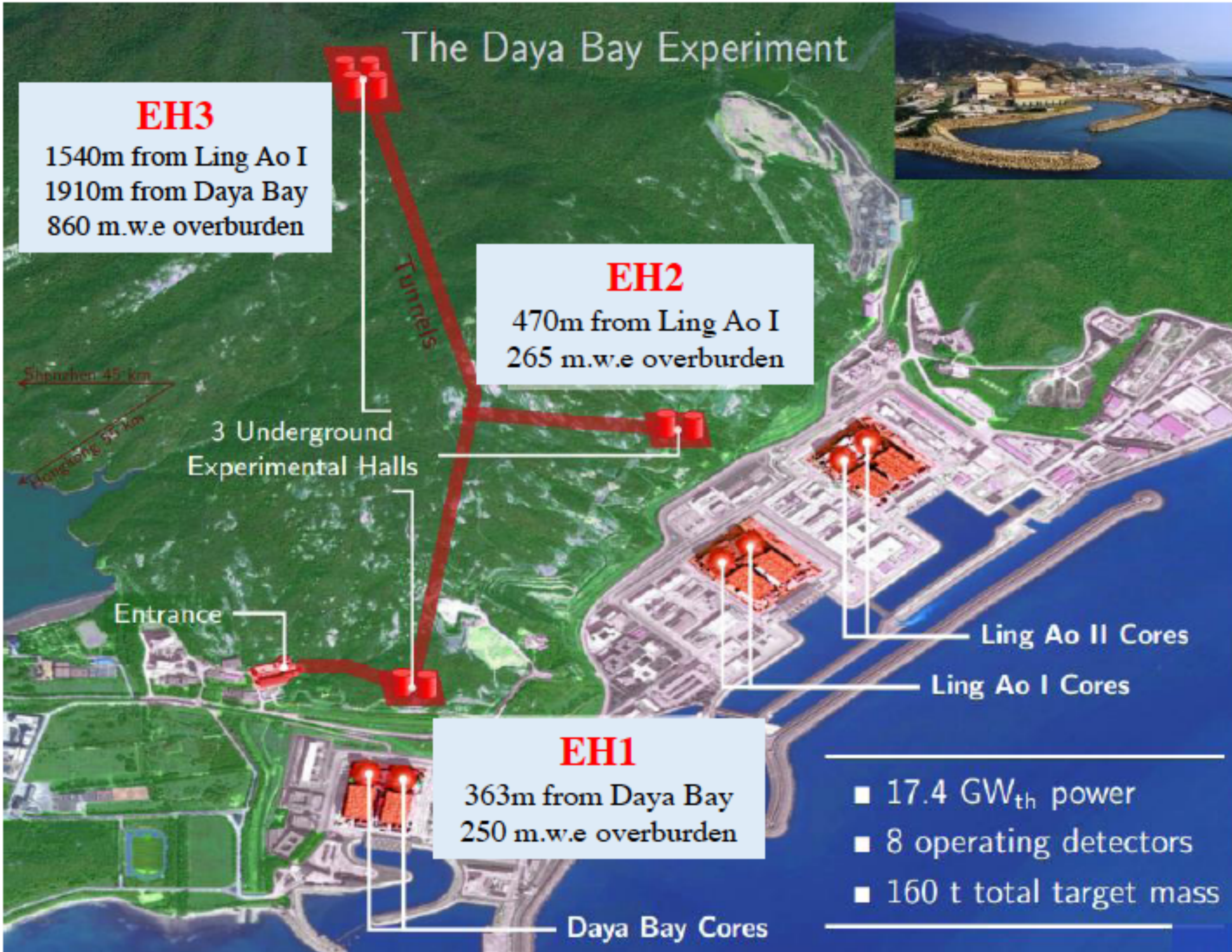
  - Wavelength shifting fibre optic readout
  - Multi-anode PMTs
  - Magnetised (~1.3 T)

Far Detector Neutrinos



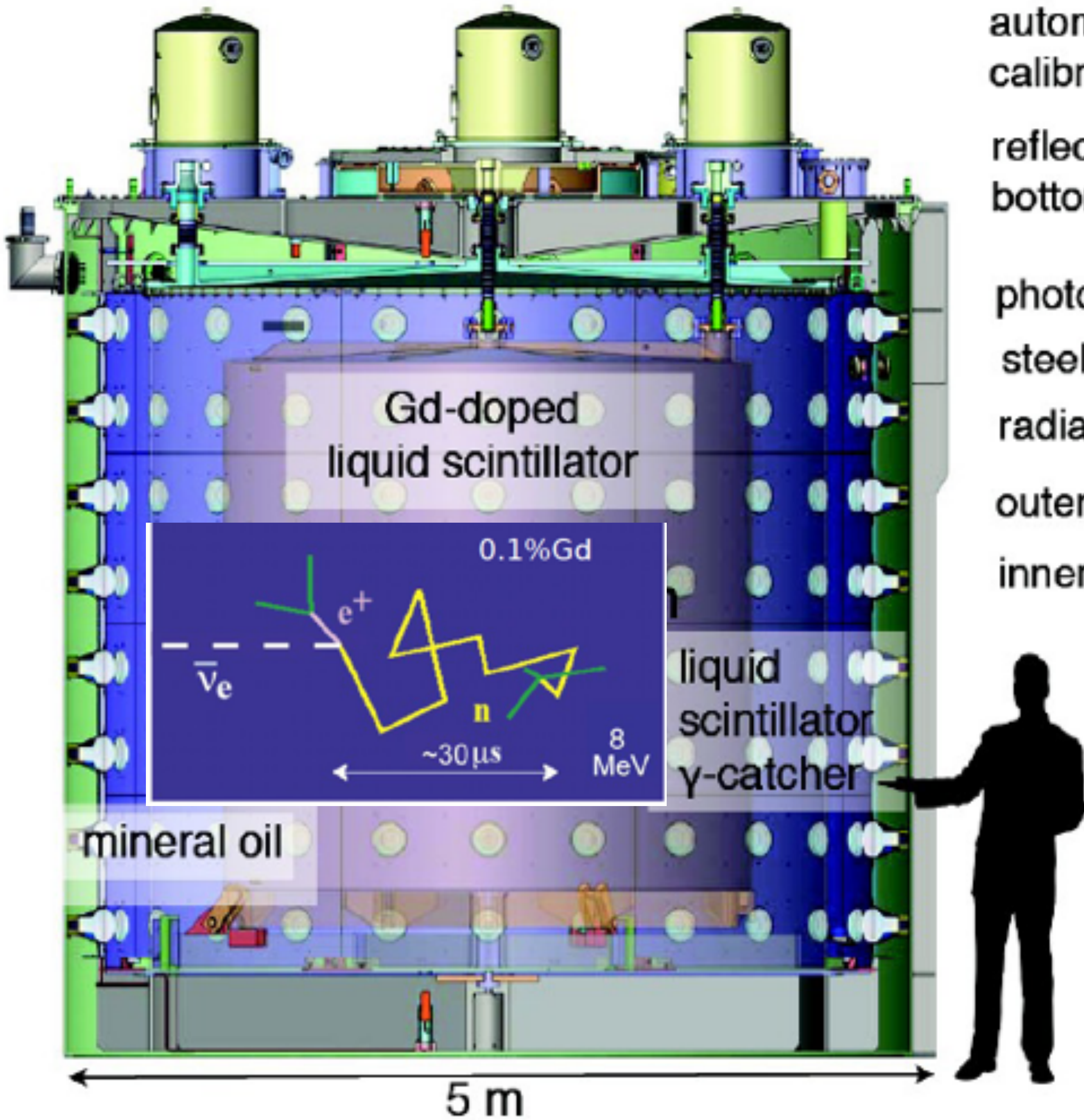
Online event display: http://farweb.minos-soudan.org/events/

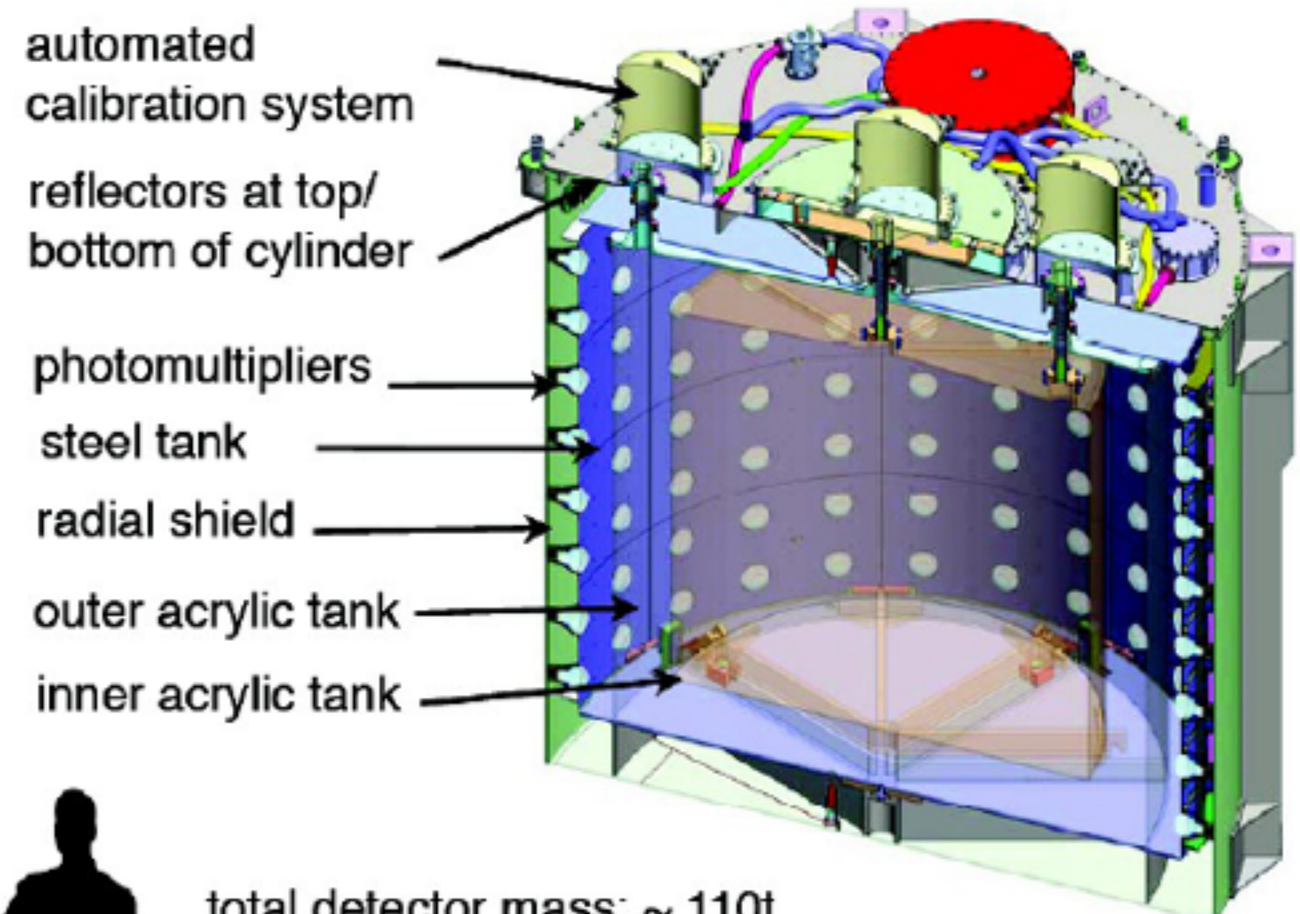
MINOS saw that muon type neutrinos disappear on their way to the far site. This allowed precise measurement of neutrino mass squared difference.



The Daya Bay Experiment
EH3
1540m from Ling Ao I
1910m from Daya Bay
860 m.w.e overburden
Tunnels
EH2
470m from Ling Ao I
265 m.w.e overburden
3 Underground
Experimental Halls
Entrance
Ling Ao II Cores
Ling Ao I Cores
EH1
363m from Daya Bay
250 m.w.e overburden
Daya Bay Cores
17.4 GW$_{th}$ power
8 operating detectors
160 t total target mass

Daya Bay Antineutrino Detectors (AD)





total detector mass: ~ 110t

inner: 20 tons Gd-doped LS (d=3m)

mid: : 22 tons LS (d=4m)

outer: 40 tons mineral oil buffer (d=5m)

photosensors: 192 8"-PMTs

$$Yield = 10^4\,MeV^{-1} \times Coverage \times QE$$
$$= 10^4 \times 0.08 \times 0.2 \sim 160\ pe/MeV$$

8 "functionally identical", 3-zone detectors reduce systematic uncertainties.

Very well defined target region

Conclusion

- This lecture was about the basics of detectors.
  - Many techniques are common for all detectors.
- Detectors are designed to measure light emission or charge deposition from particle interactions.
- For each application additional considerations must be made
  - Energy threshold and resolution
  - Time and location measurement of events
  - Particle identification through a variety of means