Neutrino Detectors

Milind Diwan
(Brookhaven National Lab.)

University of Campinas
Brazil. May 9, 2016

My Thanks to Sociedade Brasileira de Física (SBF) and
the American Physical Society (APS)

BROOKHAVEN NATIONAL LABORATORY

Milind’s and Orlando’s excellent adventure in search of tiny orchids in Mogi das Cruzes. Notice that the tiny Orchids actually scintillate !

Outline

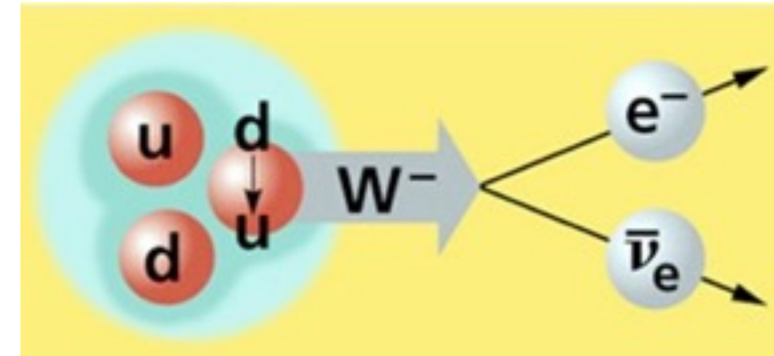
- Generalities concerning detectors.
- Basics on particle signatures in matter.
- Basic components of detectors.
- Neutrino detector types.
- Characteristics of each neutrino detector type.
- Summary.

Extremely Basic

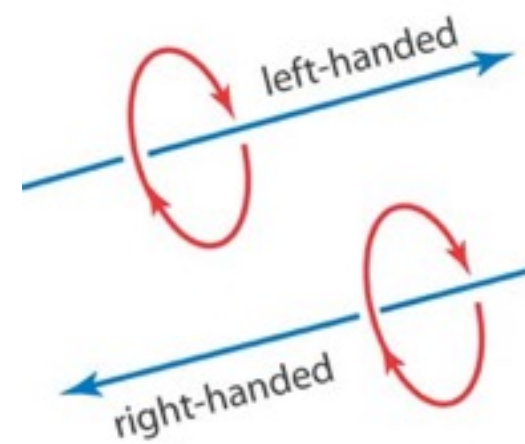
- **We can only measure 4 quantities and their combinations:**
  - **Distance**
  - **Time**
  - **Mass**
  - **Electric Charge**
- **All detectors are built on the principle of charge detection.**
- **Any effect must be first be converted to free electric charge or motion of charge to be detected.**
- **Neutrinos are detected when they interact with ordinary atoms and ionize them, thus making free electrons that can move creating a current or recombine making light.**

What are neutrinos ?

$$n \to p \; e^- \; \bar{\nu}_e$$



- A particle with no electric charge. Predicted in 1930 by Pauli, and detected in 1957 by Reines and Cowan.
- It is emitted in radioactive decay. And has no other types of interactions.
- It has 1/2 unit of spin, and therefore is classified as a Fermion (or particle of matter.)
- Neutrino is extremely light.
- Neutrino comes in flavors !
- Neutrino is left handed ! Or has no mirror image !
- Neutrinos are as numerous as photons in the Universe.
- Important component of dark matter. May be responsible for matter/antimatter asym.



From the Sun:
10^{11} neutrinos/cm^2/sec

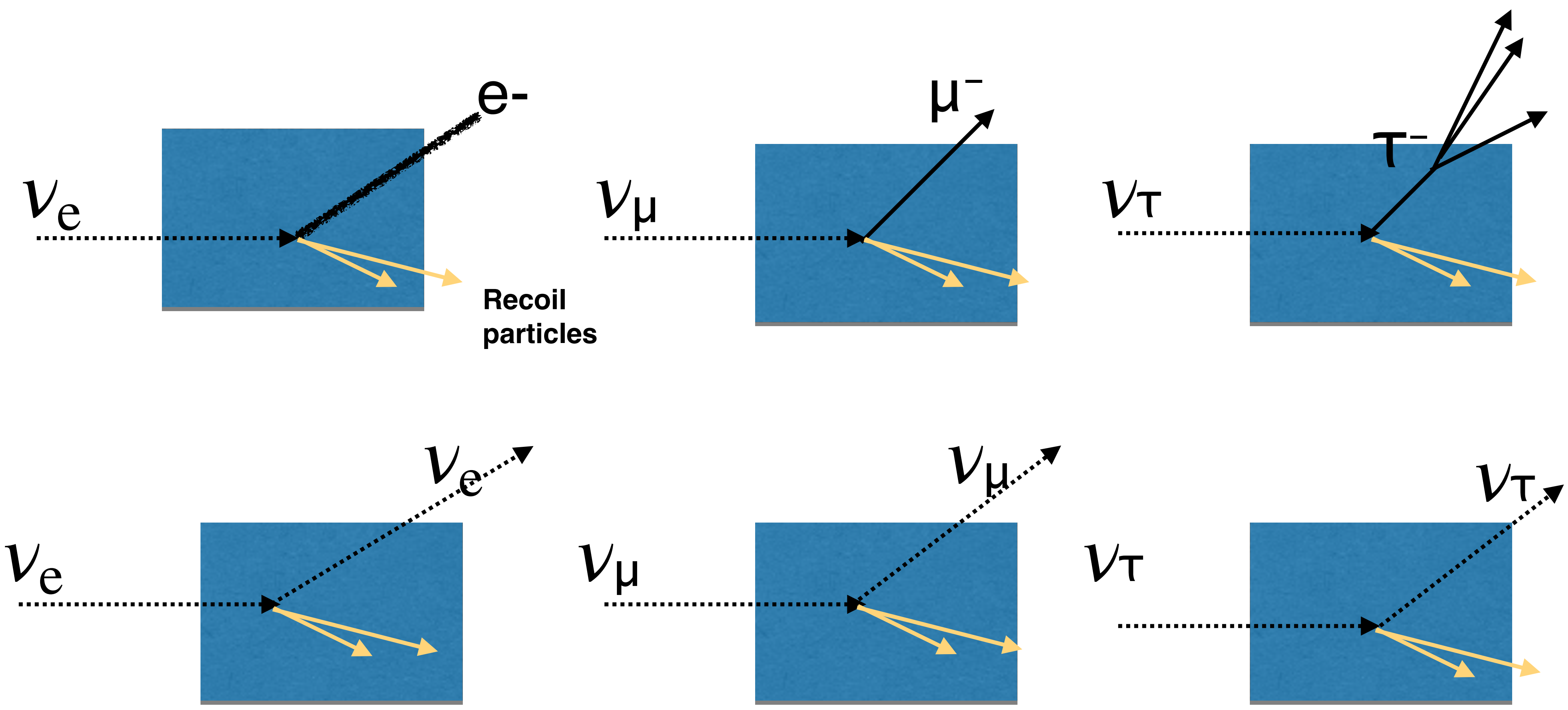
Weak interactions of neutrinos

Particles of a given kind are all identical. All electrons are absolutely identical. There are no birth marks. Nevertheless, there are 3 kinds of electron type particles called flavors.

Particle	Symbol	Mass	Associated Neutrino
Electron	e	1	ν_e
Muon	μ	200	ν_μ
Tau	τ	3500	ν_τ
	Negative Electrical Charged		**Neutral**

All these have anti-particles with opposite charge. However, for neutral neutrinos the exact meaning of having anti-particles is not yet clear.

Neutrino Detection



- **The neutrino has no charge and so it is invisible as it enters a detector. Only very rarely it interacts and leaves charged particles that can be detected.**
- **Neutrino collision on atoms in detectors produces a charged lepton. (Charged Current)**
- **The electron, muon, tau have very different signatures in a detector.**
- **Neutrino can also collide and scatter away leaving observable energy.(Neutral Current)**

How to calculate neutrino event rate ?

- 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 water ~ 6×10^{29} protons and neutrons and ~3×10^{29} electrons
- Practical experiments will have efficiency as a function of energy.
- Typical cross section is 10^{-38} cm^2 x Energy (GeV)
- Neutrinos from various sources have huge energy range: eV to 10^{15} eV.
- Cross sections for low energies can be extremely small.

Detector mass needed for 1000 evts/yr ?

Atmospheric Neutrinos

$$\varphi = 5000\ m^{-2}\sec^{-1}$$
$$E \sim 1\,GeV$$
$$\sigma \sim 10^{-38}\,cm^2$$
$$Nucleons = 6\times10^{29}\,ton^{-1}$$
$$N = \varphi\bullet\sigma\bullet6\times10^{29}\bullet3\times10^{7}\ ton^{-1}yr^{-1}$$
$$N = 0.1\ events/ton/yr$$

Reactor Neutrinos

$$Yield = 2\times10^{20}\sec^{-1}\ for\ each\ GW\ of\ thermal\ power$$
$$Fraction > 3\ MeV \quad F \sim 0.1$$
$$\sigma \sim 8.5\times10^{-43}\,cm^2$$
$$\text{Protons=(2/3)}\times10^{29}\ \text{ton}^{-1}\ \text{(for water)}$$
$$Area = 4\pi\bullet10^{10}\,cm^2 \quad \text{Take length to be 1 km.}$$
$$\varphi = Y/Area = 1.6\times10^{9}\,cm^{-2}\sec^{-1}$$
$$N = \varphi\bullet F\bullet\sigma\bullet(2/3)\times10^{29}\bullet3\times10^{7}\,ton^{-1}yr^{-1}$$
$$N = 270\ ton^{-1}yr^{-1}\ for\ GW$$

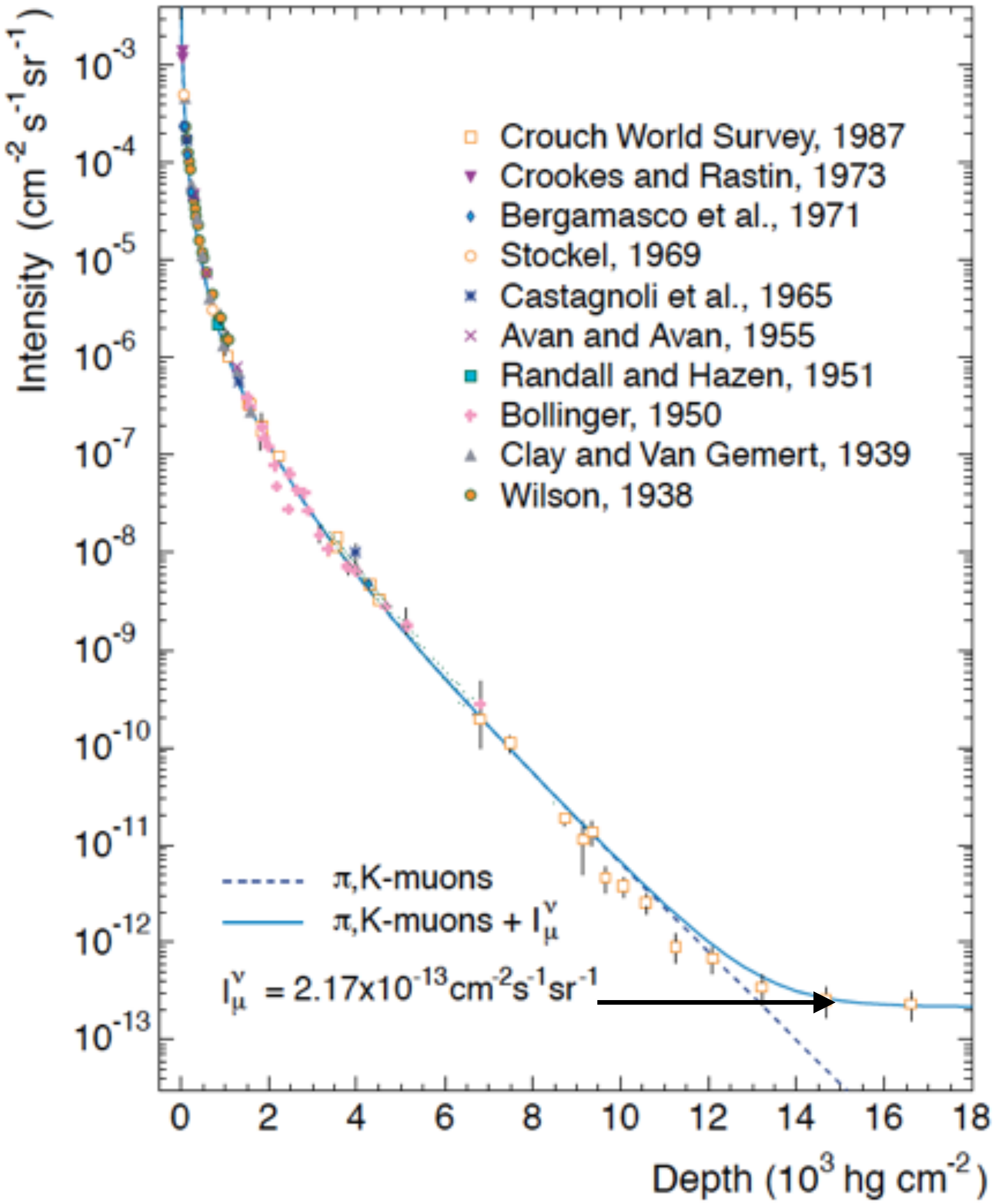
- **The first most important consideration for neutrino detection is the mass of the detector.**
- **Both Energy and Flux need to be known. Cross sections are in first lecture and fluxes are in third lecture.**

Typical Neutrino Detector Technologies

Material	Composition	Density	Signal type	Comment
Water/Ice	H_2O	1.0	Cherenkov Light	Can be huge
Liquid Scintillator	~CH_2	~0.9	Scintillation Light	Low energy Threshold
Plastic Scintillator	~CH_2	~0.9	Scintillation Light	Segmented
Steel planes	Fe	~7.8	Scint./Gas chambers	Magnetized
Liquid Argon	Ar	1.4	Charge/ Scintillation	Can be very fine grained
Radiochemical	Ga, C_2Cl_4 , In	Depends on technololgy	Induced Radioactivity	Extremely Low Thresholds
Water-based Scintillator	H_2O+ ϵCH_2	1.0	Cherenkov + Scint.	Huge with low threshold

Given the emphasis on detector mass, we must choose materials that are inexpensive and produce a signature that can be easily measured by common sensors.

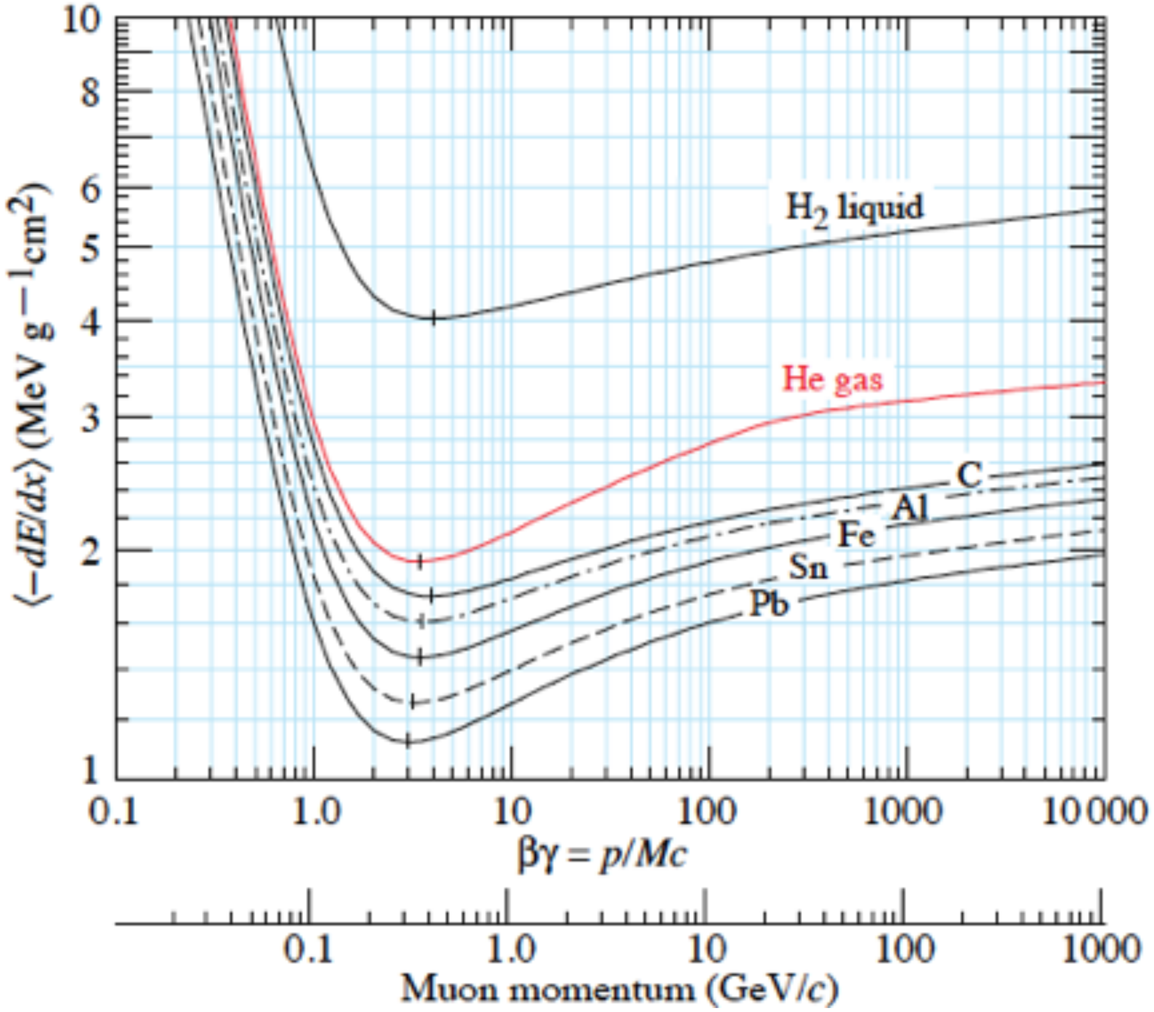
Cosmic Ray backgrounds



$1\ \text{km.w.e} = 10^5\ g\ cm^{-2}$ of standard rock

- Central issue in neutrino detection is background from cosmic rays; reduced by overburden or depth.
- The needed depth depends on the physics signals.
- The spectrum of muons at shallow depth is ~few GeV with $\mathrm{Cos}^2\theta$ distribution. At surface ~70 Hz/m^2
- Beyond ~2 km, the spectrum is constant around ~300 GeV and the angular distribution becomes steeper.
- For very low energies cosmogenic neutrons are important.

Energy loss of charged heavy particles



Density correction

$$\frac{dE}{dx} = -\frac{K}{\beta^2} z^2 \frac{Z}{A}\left[\frac{1}{2} Log \frac{2m_e\beta^2\gamma^2 W_{\max}}{I^2} - \beta^2 - \frac{\delta(\beta\gamma)}{2}\right]$$

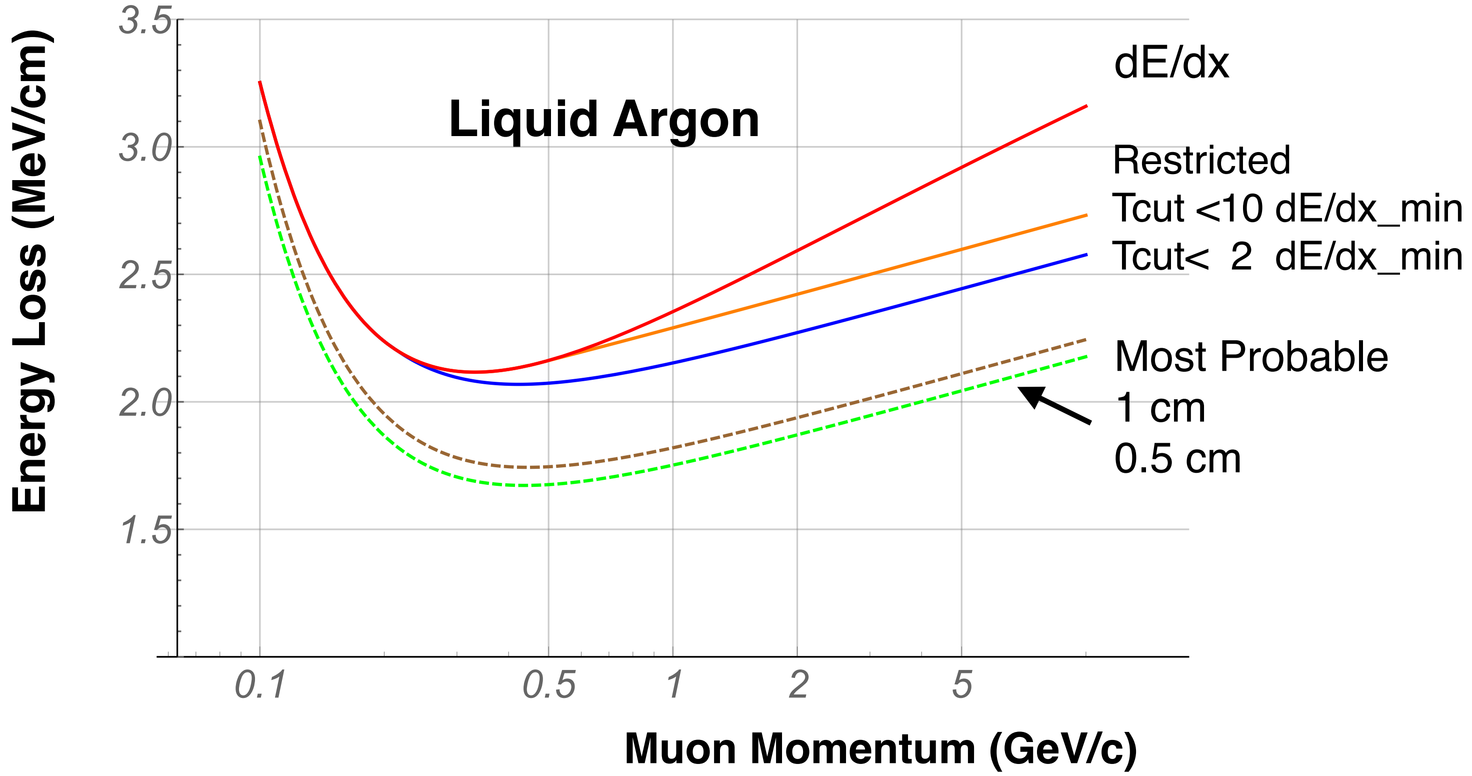
$K = 0.31\ MeV\ mol^{-1} cm^2$, $I = Mean\ Ionization\ Energy$

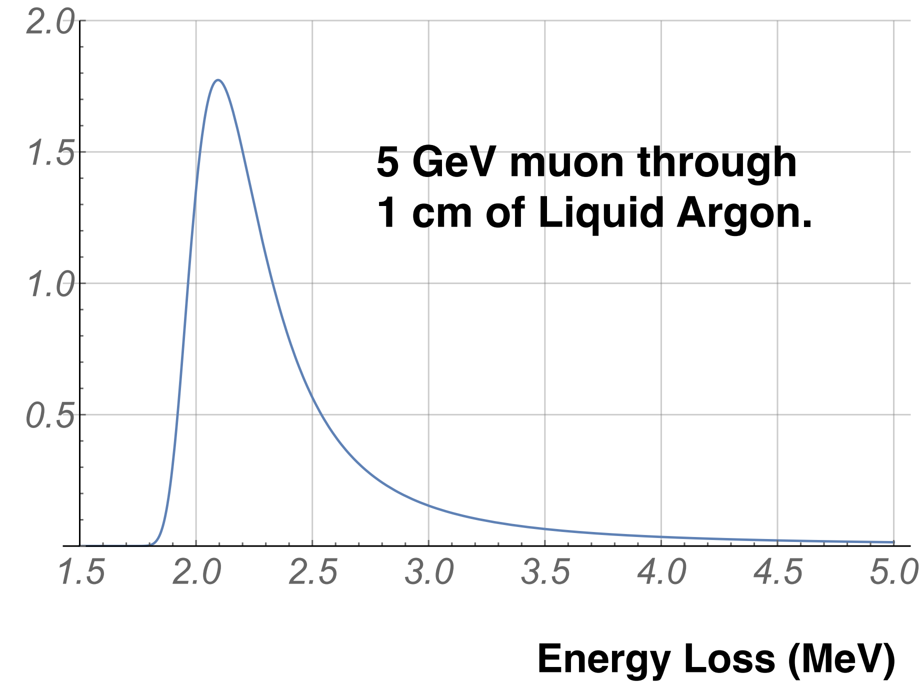
$$W_{\max} \approx 2m_e\beta^2\gamma^2 / (1 + 2\gamma m_e / M)$$

Max energy transfer in single collision.
~84 MeV for a 1 GeV/c muon

- Neutrinos interact producing charged particles that ionize atoms. This energy loss is to be measured in detectors.
- Energy loss depends on velocity. At very high energies radiation takes over.
- The mean energy loss is actually dominated by a few high energy collisions. e.g.
  - Liquid argon Z = 18, A = 40, Density = 1.4 gm/cc, I = 180 eV
  - for 1 GeV, 5 GeV muons: 2.35 MeV/cm and 2.9 MeV/cm

Most probable loss and fluctuations.



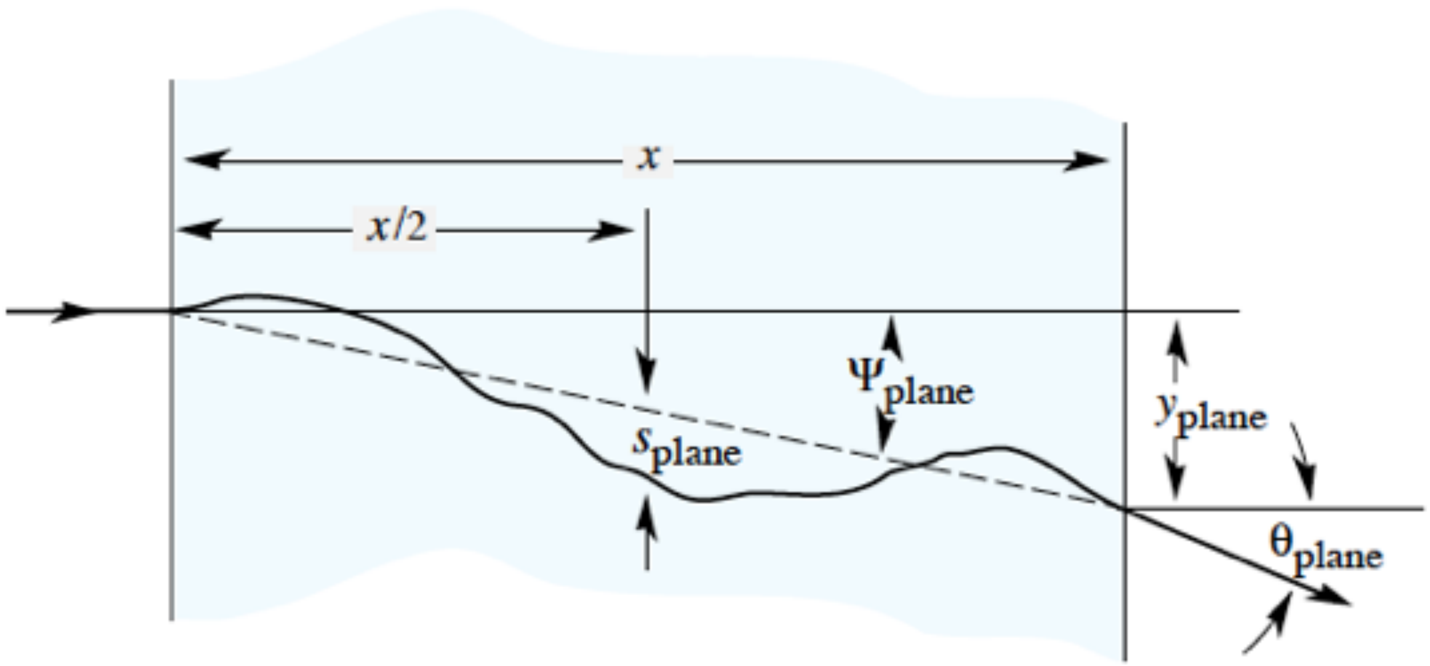


$$\Delta_p = \xi \left[Log \frac{2m_e \beta^2 \gamma^2}{I} + Log \frac{\xi}{I} + 0.2 - \beta^2 - \delta(\beta\gamma) \right] \qquad FWHM \approx 4\xi$$

$\xi = (K/2)(Z/A)(x/\beta^2)$ where x is thickness

- The observed most probable energy loss in a thin detector slice can be quite a bit smaller
- The distribution can have very long tails. This is characterized by Landau distribution.

Scattering



$$\theta_{plane}^{rms} = \theta_0 = \frac{1}{\sqrt{2}}\theta_{space}^{rms}$$

$$\theta_0 = \frac{13.6MeV}{\beta \bullet P} z\sqrt{x / X_0}(1 + 0.038 Log(x / X_0))$$

$$P = Momentum; x / X_0 = Radiation\ Lengths$$

For liquid argon X_0= 14 cm

P = 100 MeV electron
x = 1 cm

Scattering will be ~50 mrad

or ~3 deg.

- Particles scatter as they traverse material.

Energy loss of electrons and photons

$$1/X_0 \approx (1/716)\bullet\frac{Z^2}{A}\bullet Log(\frac{184}{\sqrt[3]{Z}})\,(gm/cm^2)^{-1}$$

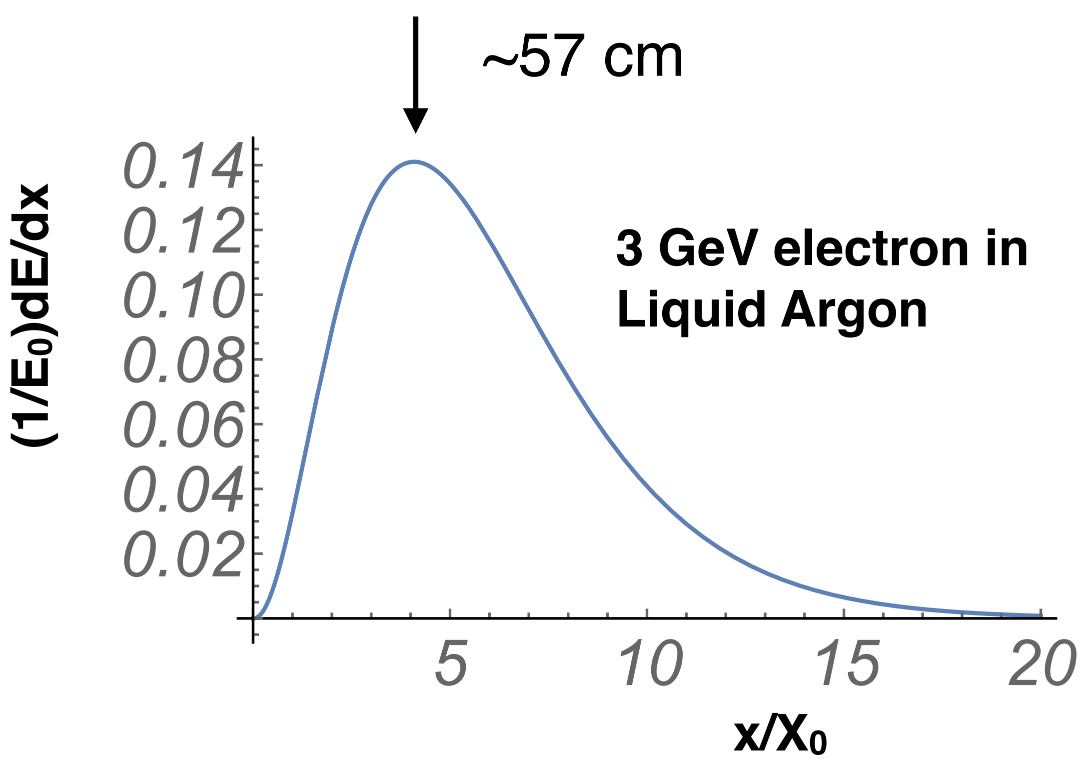
$$For\ Z > 4$$

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

$$t_{\max} = (a-1)/b = Log[E_0/E_c \pm 0.5]\{\pm for\ e/\gamma$$

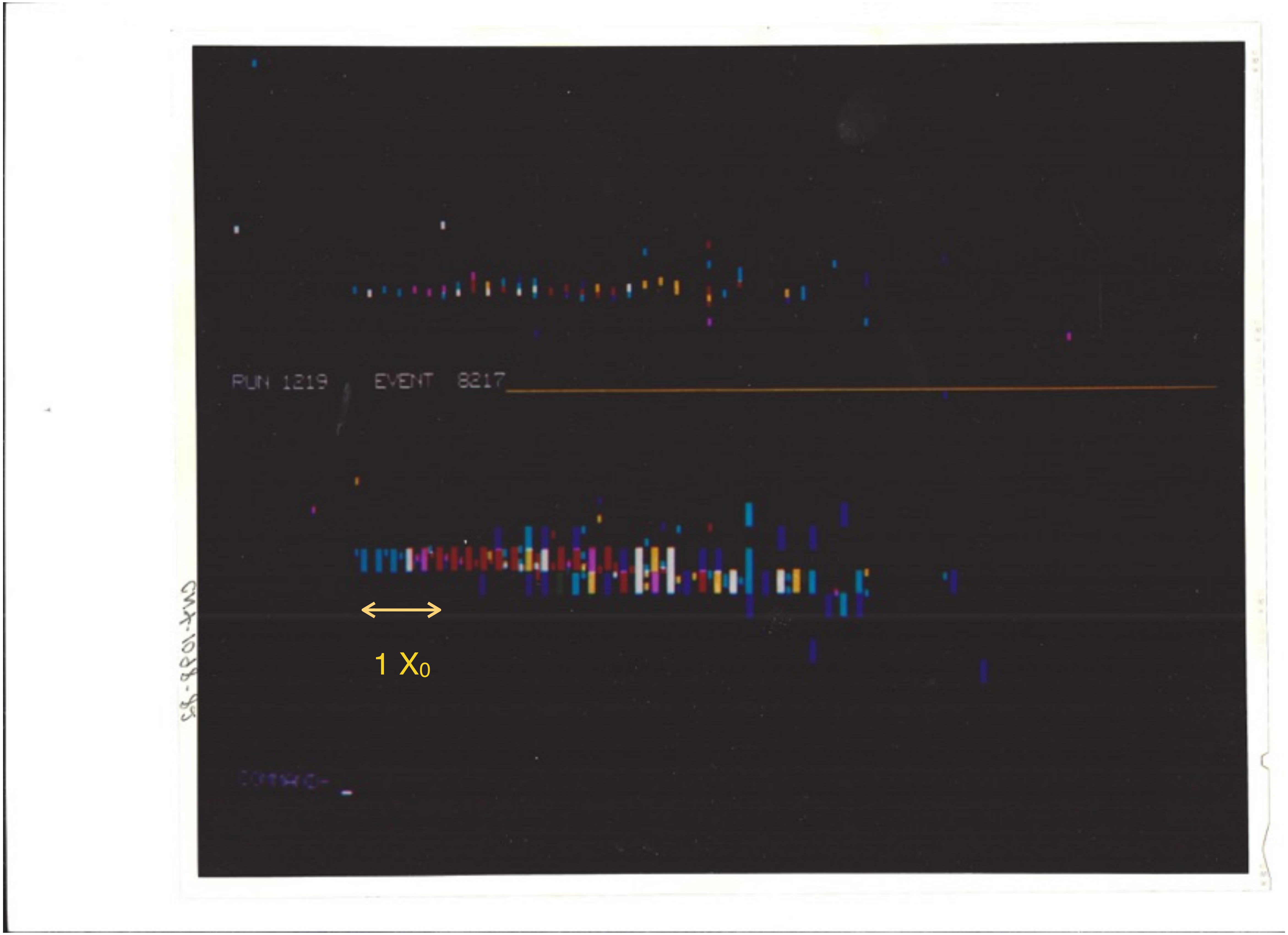
$$b \sim 0.5\{Material\ dependent$$

- Low E ($E_{critical}$ ~20 MeV/c) electron/ positrons lose energy similarly as heavy particles with corrections.
- High energy electrons lose energy by radiating photons. Fraction (1-1/e) energy is lost after mean distance X_0
- $E_{critical}$ when ionization=Bremsstrahlung
- Photons convert to pairs after (7/9)X_0



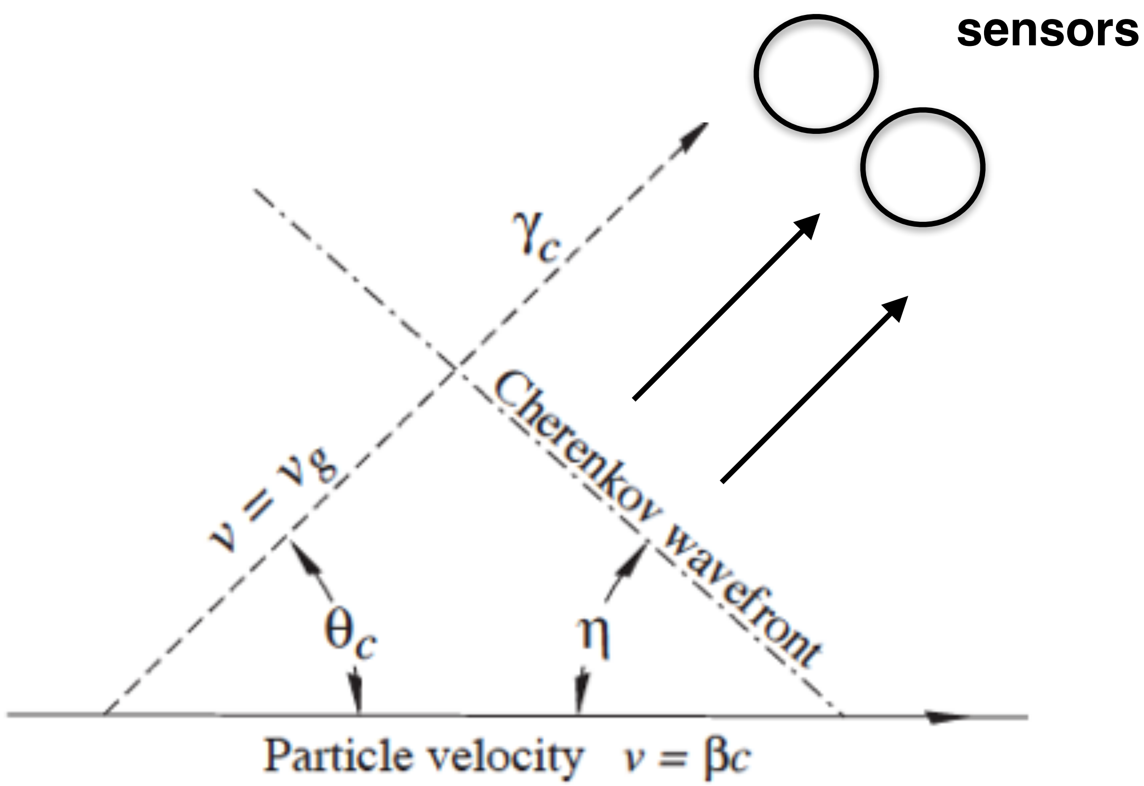
Material	Ecritical(MeV)
LAr	30.5
Water	78.3
Liquid Scint.	~102
Fe	21.7

Get to know http://pdg.lbl.gov/2015/AtomicNuclearProperties/



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

Cherenkov Radiation



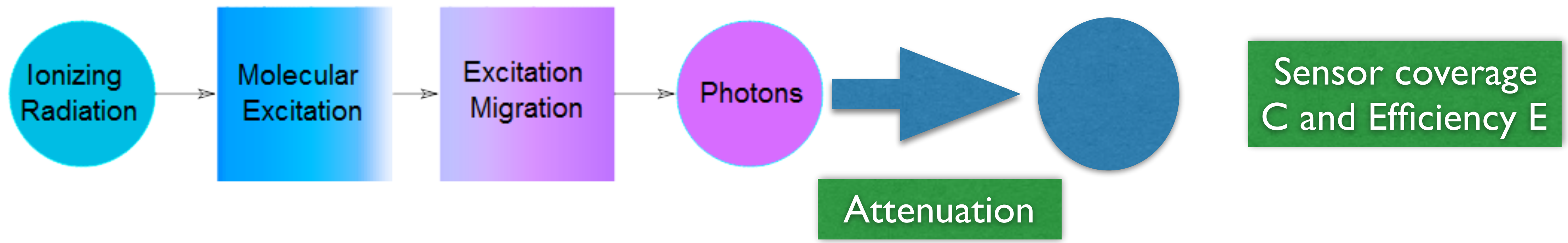
$$\frac{d^2N}{dEdx} = \frac{2\pi\alpha z^2}{hc}\sin^2\theta_c$$
$$\approx 370\sin^2\theta_c \text{ ev}^{-1}\text{cm}^{-1} \times (D_{eff})$$

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

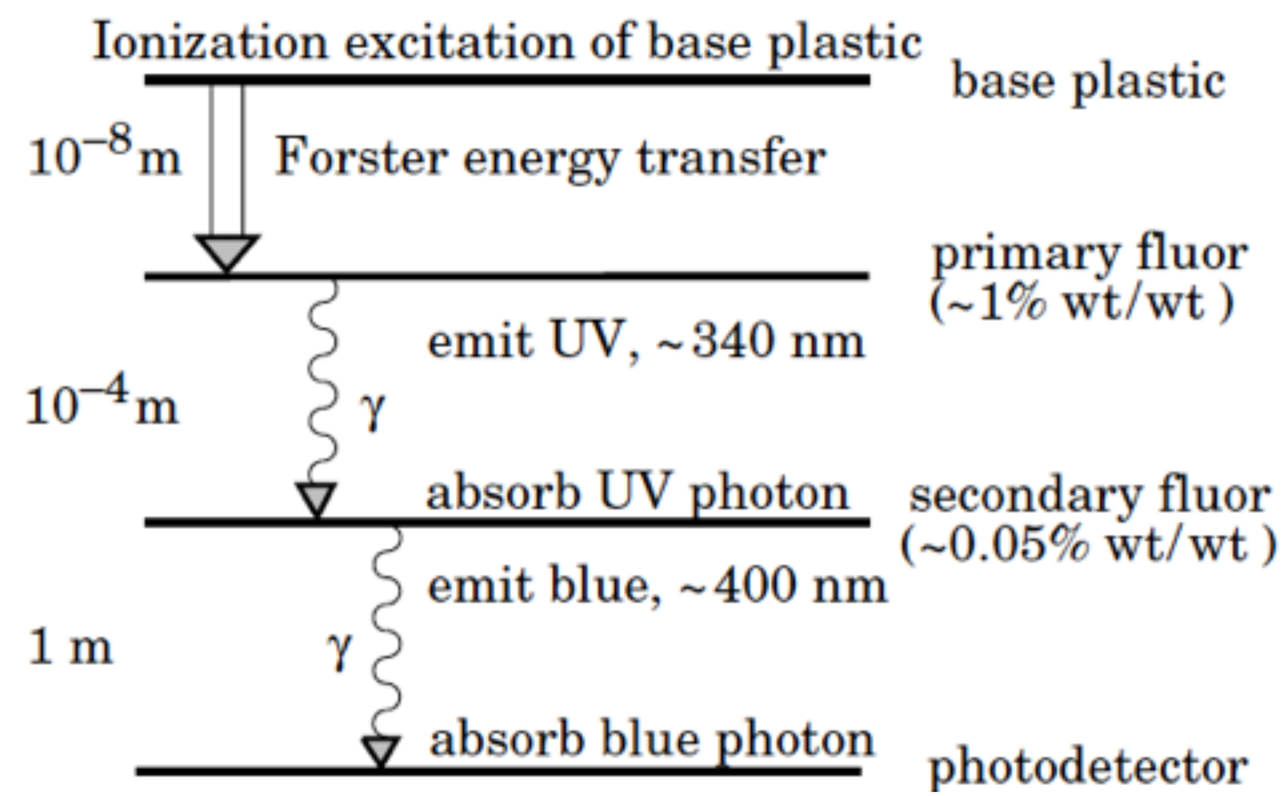
Water (20°C)	n=1.33
θc water for β =1	41.2°
Electrons	0.58 MeV/c
Muons	120.5 MeV/c
Pion	159.2 MeV/c
Proton	1070.0 MeV/c

- 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. β>1/n
- Transition radiation: happens when particles cross from one medium to another with different indices of refraction.

Scintillation



Time scale ~ few ns
due to first fluor



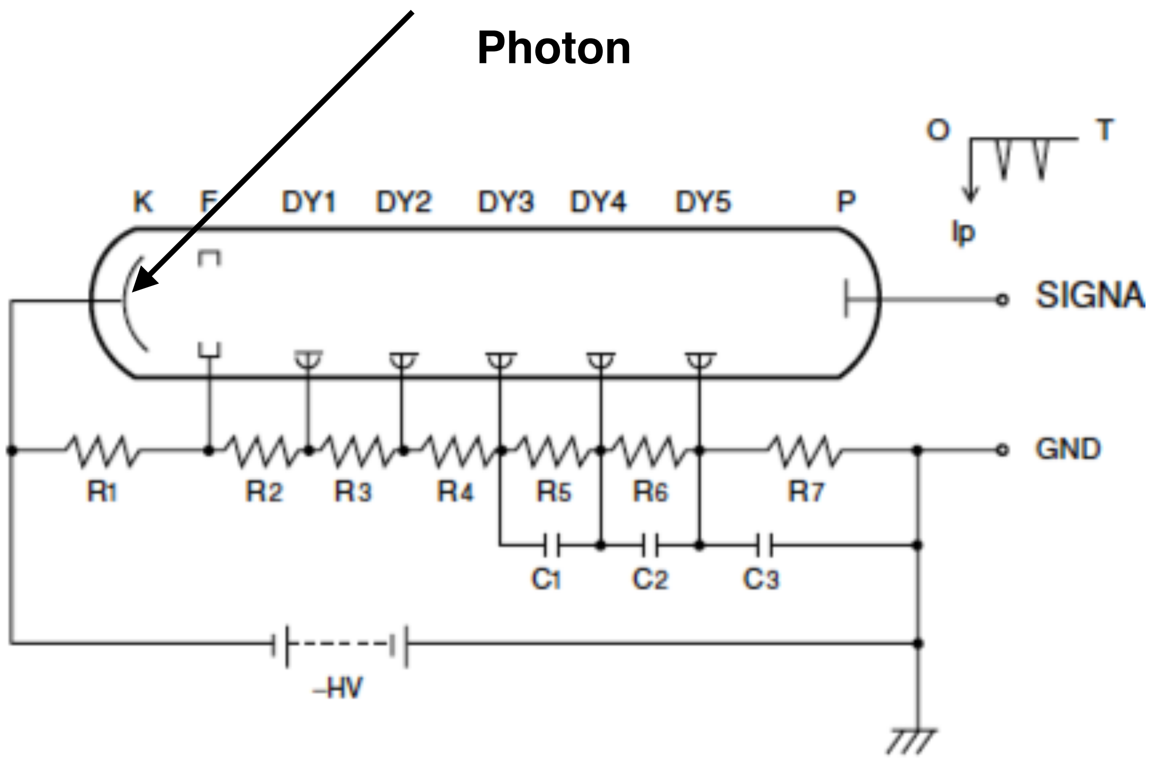
$$\frac{dL}{dx} = L_0 \frac{dE/dx}{1 + k_{Birk} dE/dx}$$

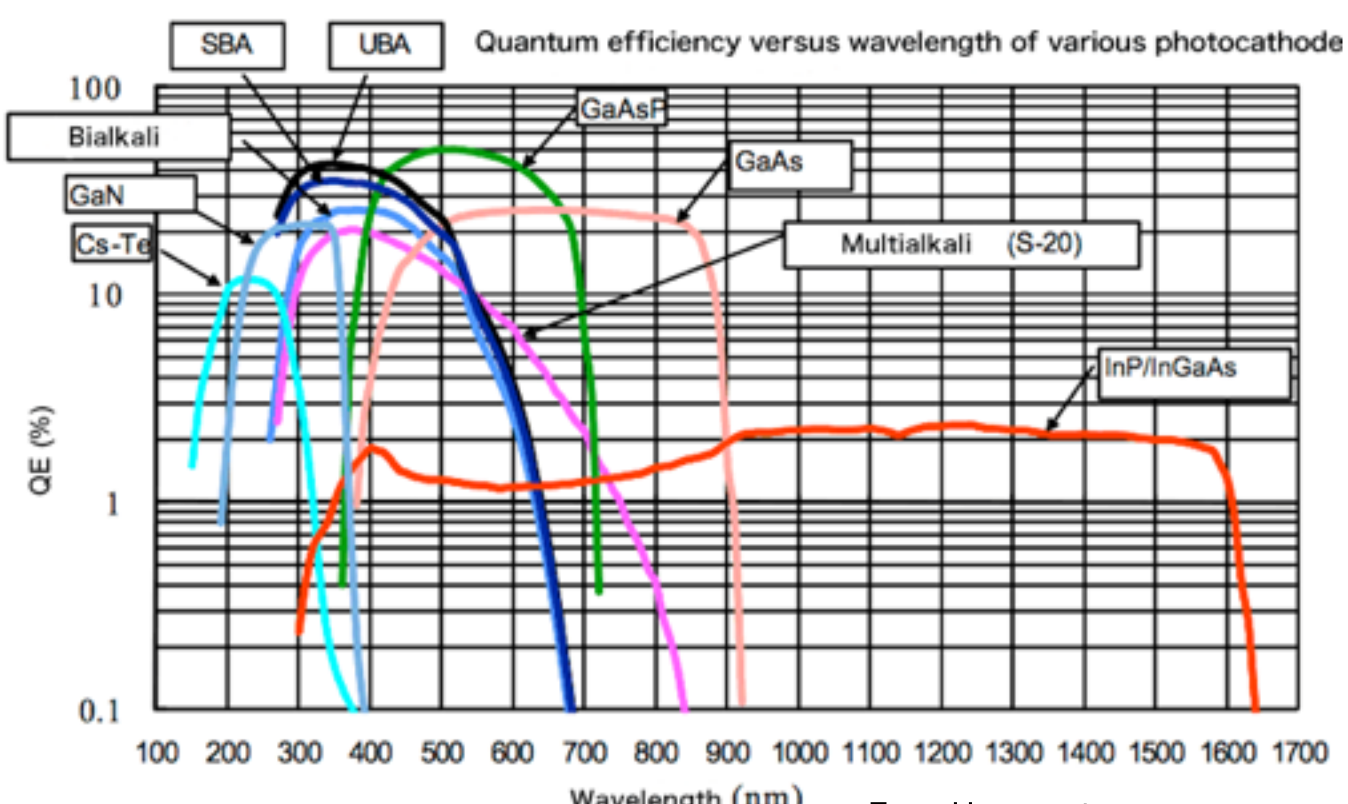
$$Typical \quad L_0 \sim 10^4 \, MeV^{-1}$$

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

- There are many scintillation mechanisms. Organic scintillators and noble liquids are important for neutrino physics.
- Inorganic crystal scintillators have not played an important role in neutrino detection.

Photo-Multiplier Tube

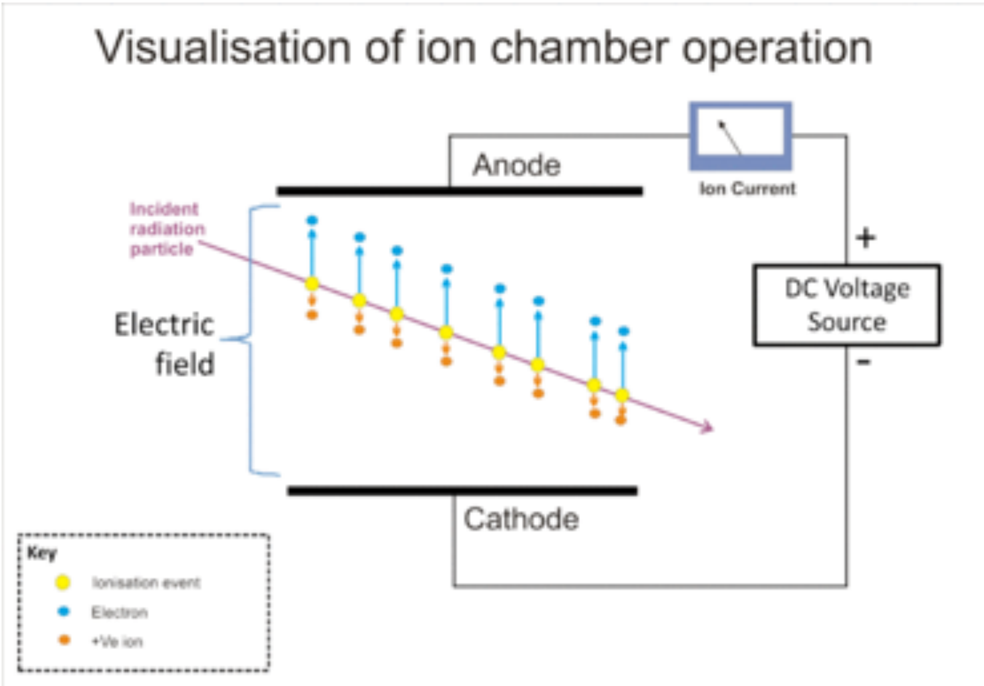




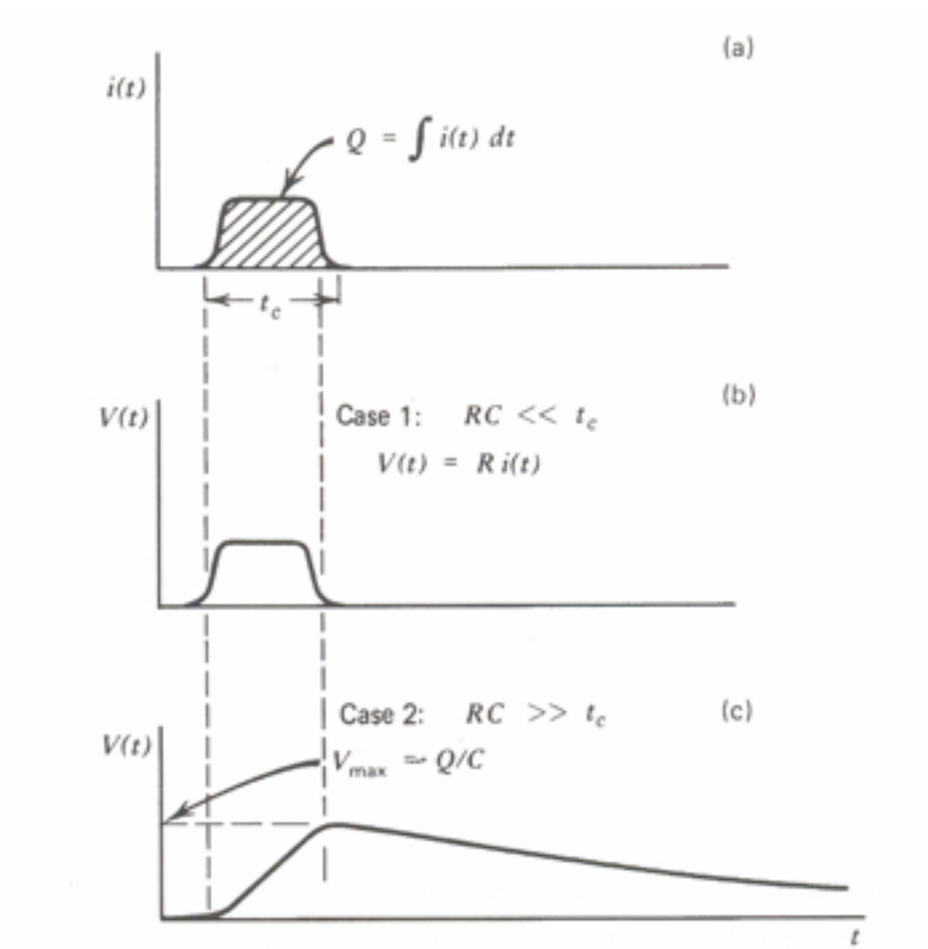
From Hamamatsu

- 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.
- Typical Gain = $AV^{kn} \sim 10^6 - 10^7$ where V is the typical voltage ~ few 1000 V.
- Time resolution < 10 ns.
- Transit time can be <1 microsec
- PMT first stage is sensitive to small magnetic fields.
- Many clever geometries.
- I have not covered new silicon based photon sensors. SiPMs.

Ionization detectors

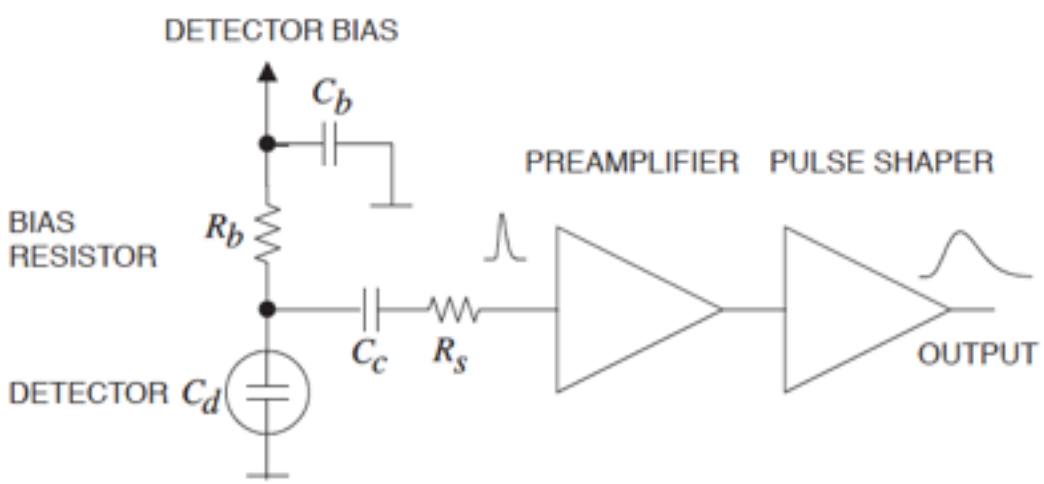


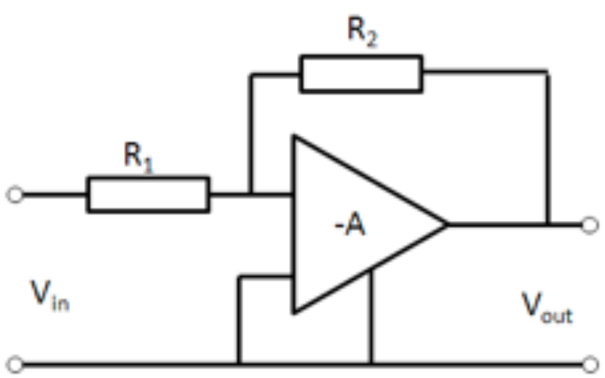
material	W (ev/pair)
LAr	23.6
LXe	15.6
Silicon	3.6
Germanium	2.9
Diamond	~13
CdTe	5.2
LNe	36
LKr	19



- 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)

Front end electronics (General Principles)

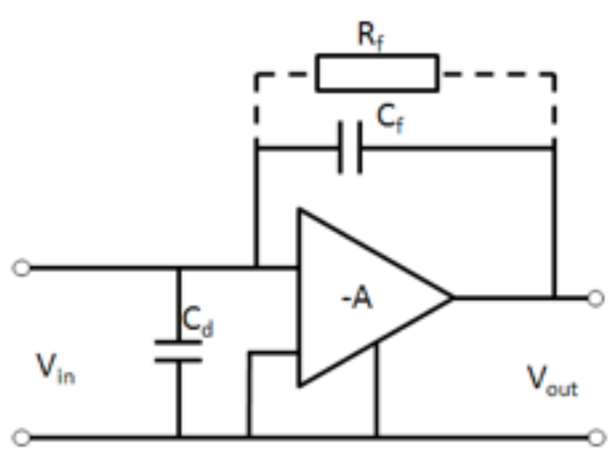




Voltage pre-amplifier

$$V_{out} \cong -\frac{R_2}{R_1} V_{in}$$

If $\frac{R_2}{R_1} \ll A$



Charge pre-amplifier

$$V_{out} \cong -\frac{Q}{C_F}$$

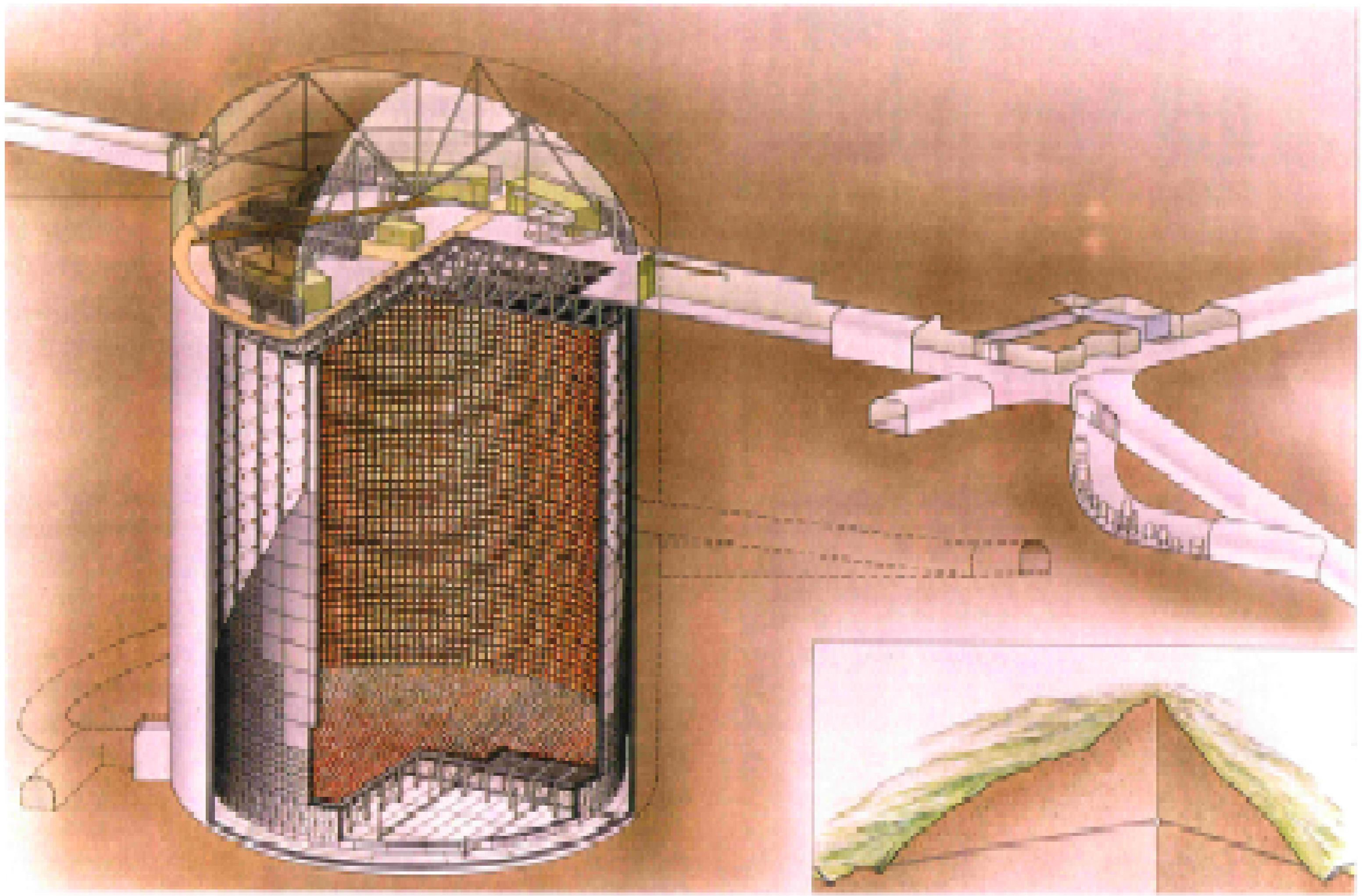
If $\frac{C_f + C_i}{C_f} \ll A$

- Detector is assumed to produce a current pulse i(t)
- Detector is modeled by capacitance C_d
- There has to be a bias voltage to create the current. This is blocked from the amplifier by a capacitor C_c. The current will go through a path of resistance R_s to the preamp
- Preamp amplifies the voltage at the input if the detector capacitance is constant.
- It is usual in particle physics to have a charge sensitive preamp since detector capacitance can vary.
- The pulse is shaped for optimum S/N.
- Cables are very important part of circuit.

Energy loss parameters

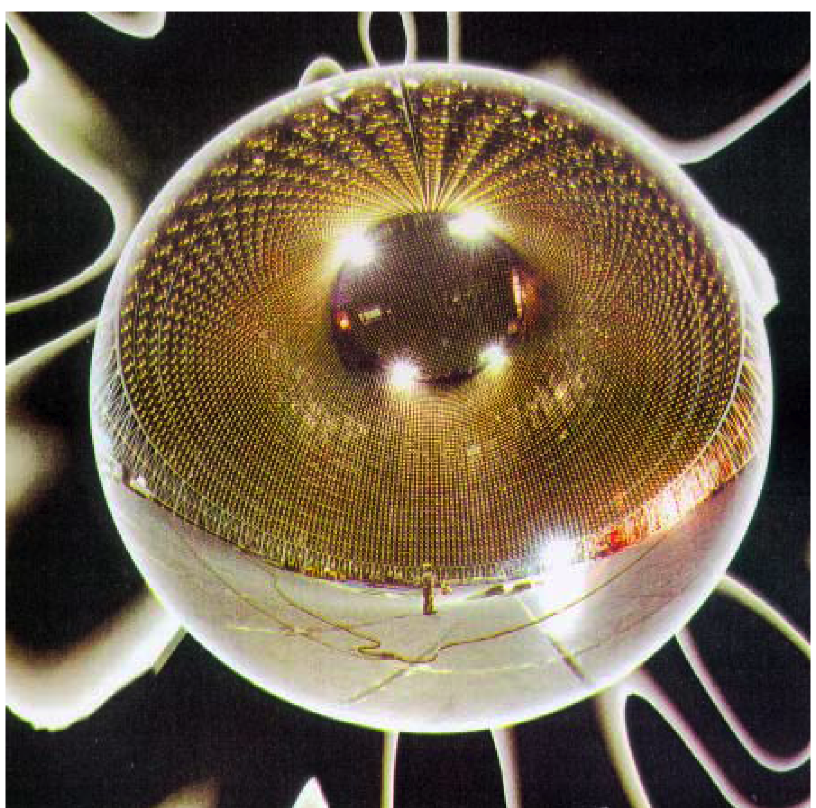
Material	Composition	Density	Z/A	Ecritical (MeV)	Radiation Length	Nuclear Collision Length	dE/dx_min
Water/Ice	H_2O	1.0	0.55	78.3	36 cm	58 cm	1.99 MeV/cm
Liquid Scintillator	$\sim CH_2$	~0.9	~0.57	102	~50cm	~60 cm	1.87 MeV/cm
Steel	Fe	~7.87	0.46	21	1.75 cm	10.4 cm	11.4 MeV/cm
Liquid Argon	Ar	1.4	0.45	30.5	14 cm	54 cm	2.12 MeV/cm

Let's collect the parameters before we go onto some examples. Many famous examples are omitted, such as ICECUBE, Radio detection of Cherenkov radiation, Iron/gas detector sandwiches, etc.



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

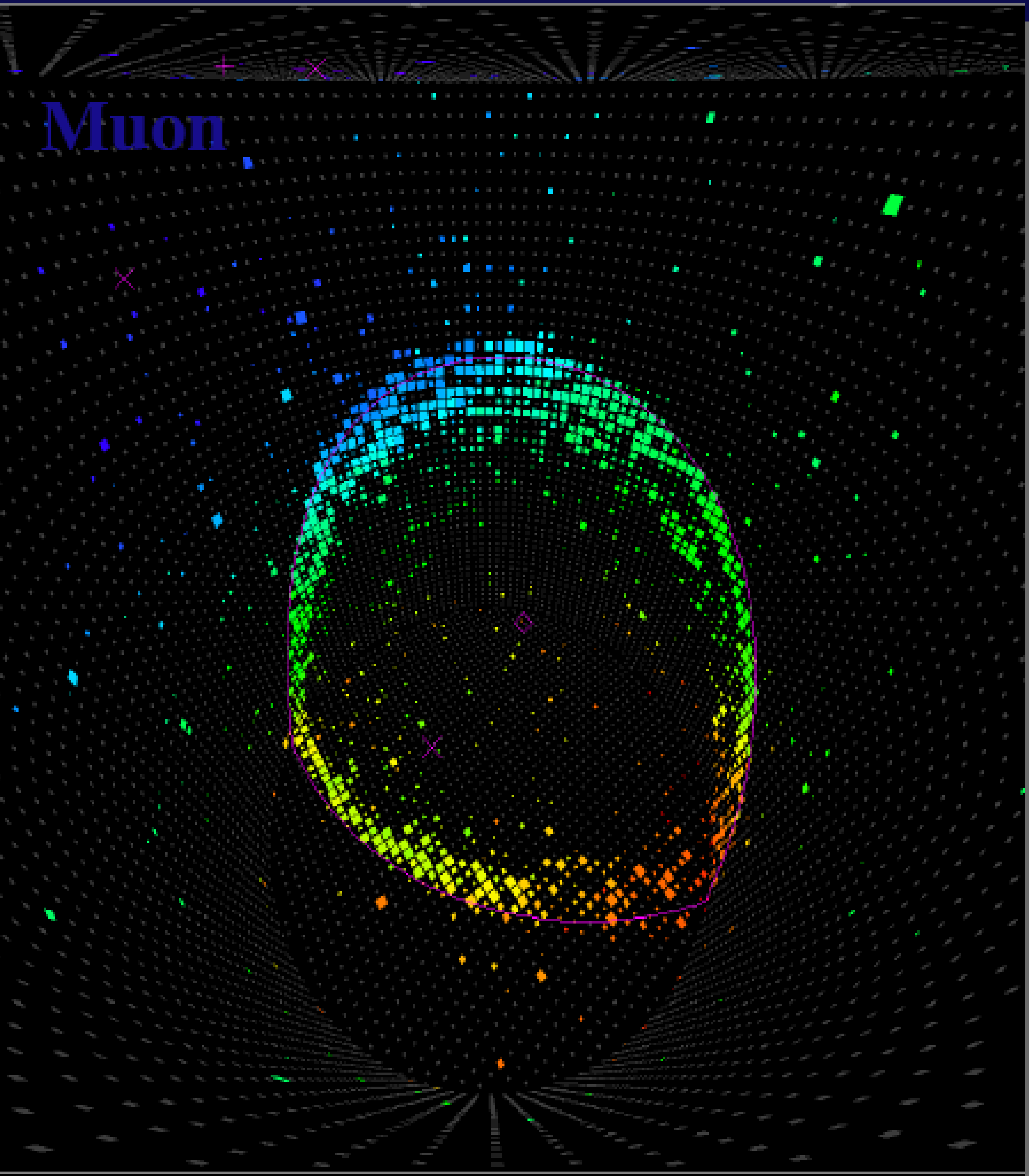
Cosmic rate ~ 2 Hz

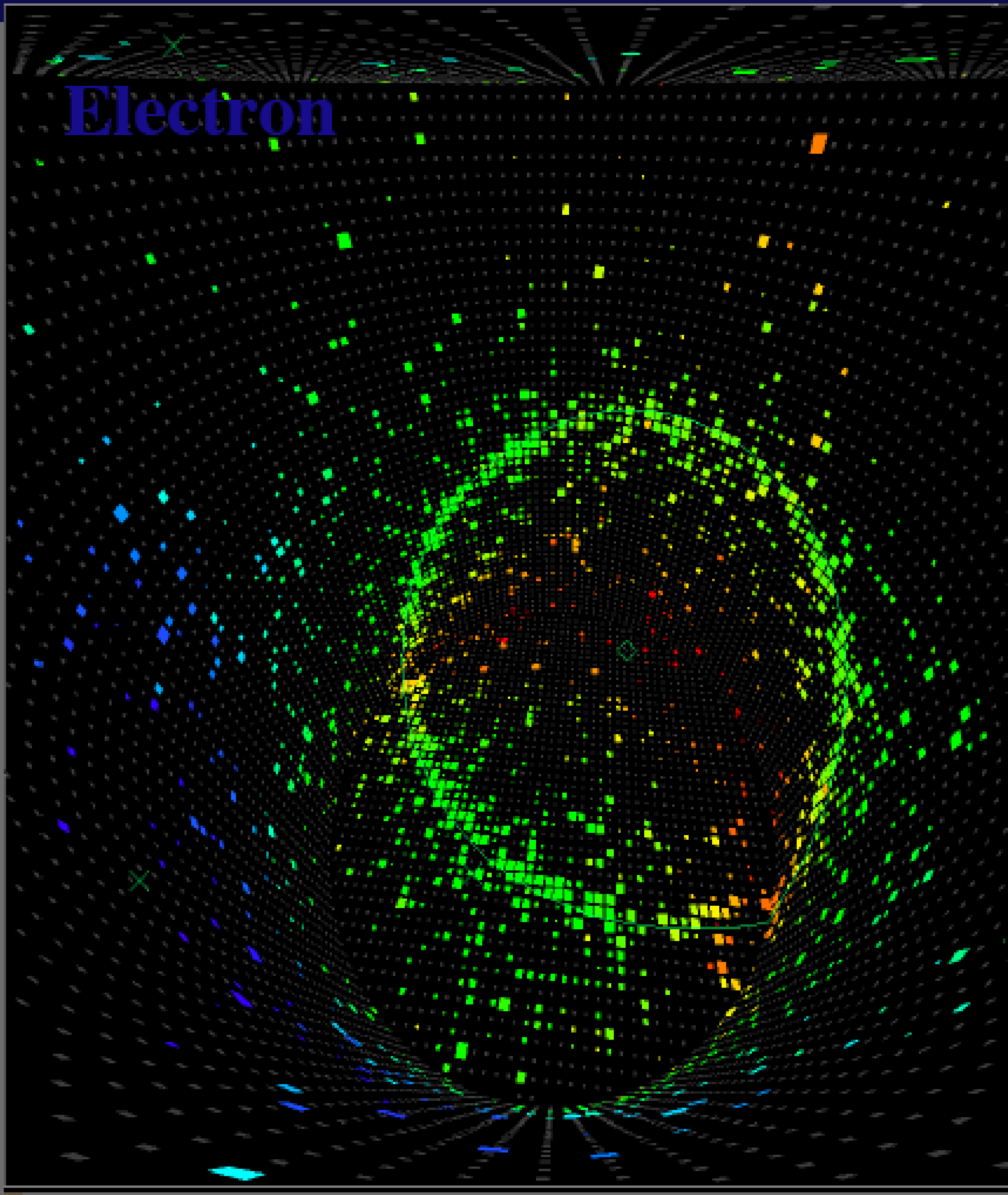
$$Yield = 370 \bullet \mathrm{Sin}^2\,\theta_c \bullet 0.4 \bullet 0.2 \approx 10\ pe/cm$$

↑ Coverage X Photon detector efficiency

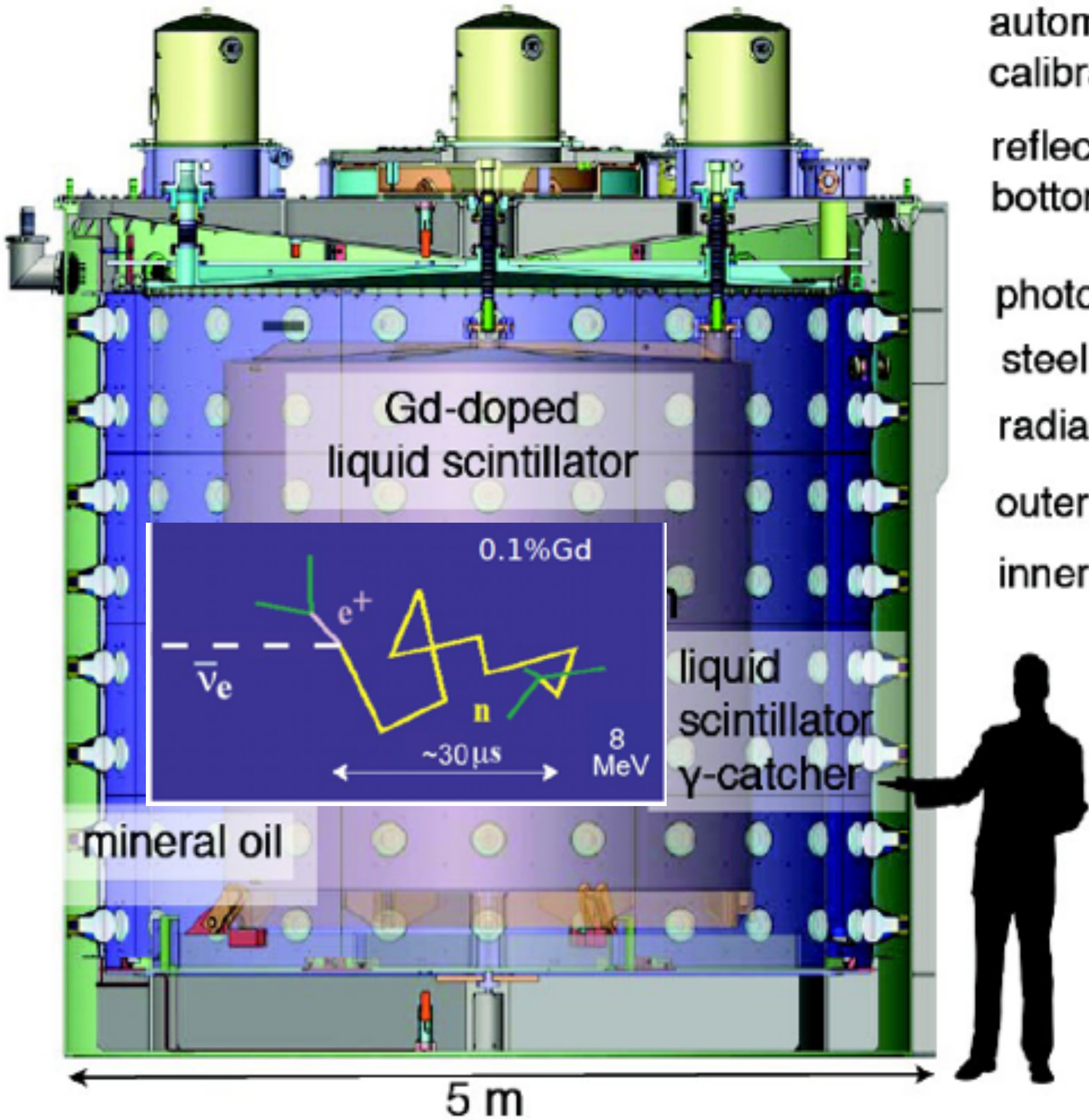
Technical issue: PMTs have to withstand huge pressure.

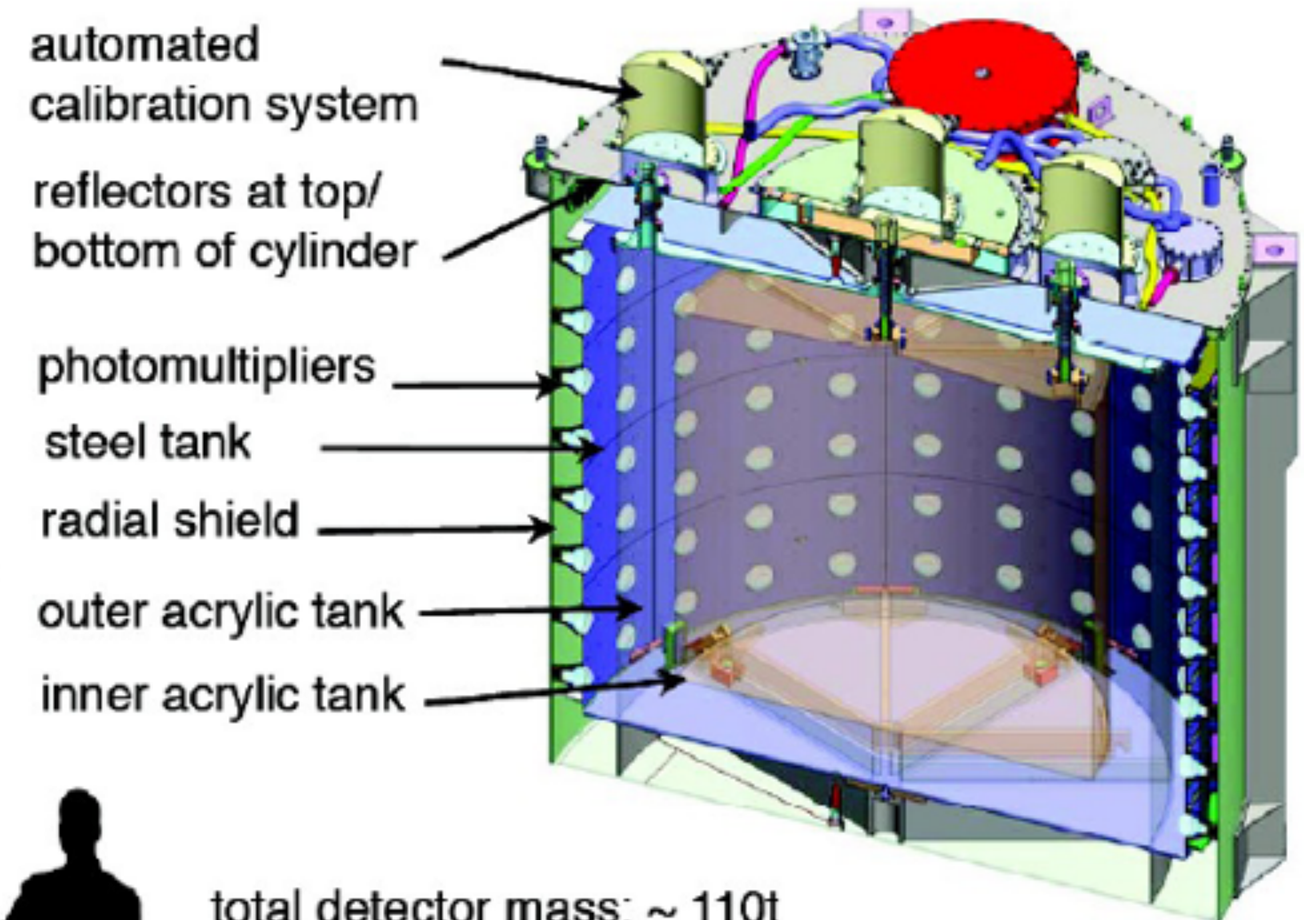
Particle Identification





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

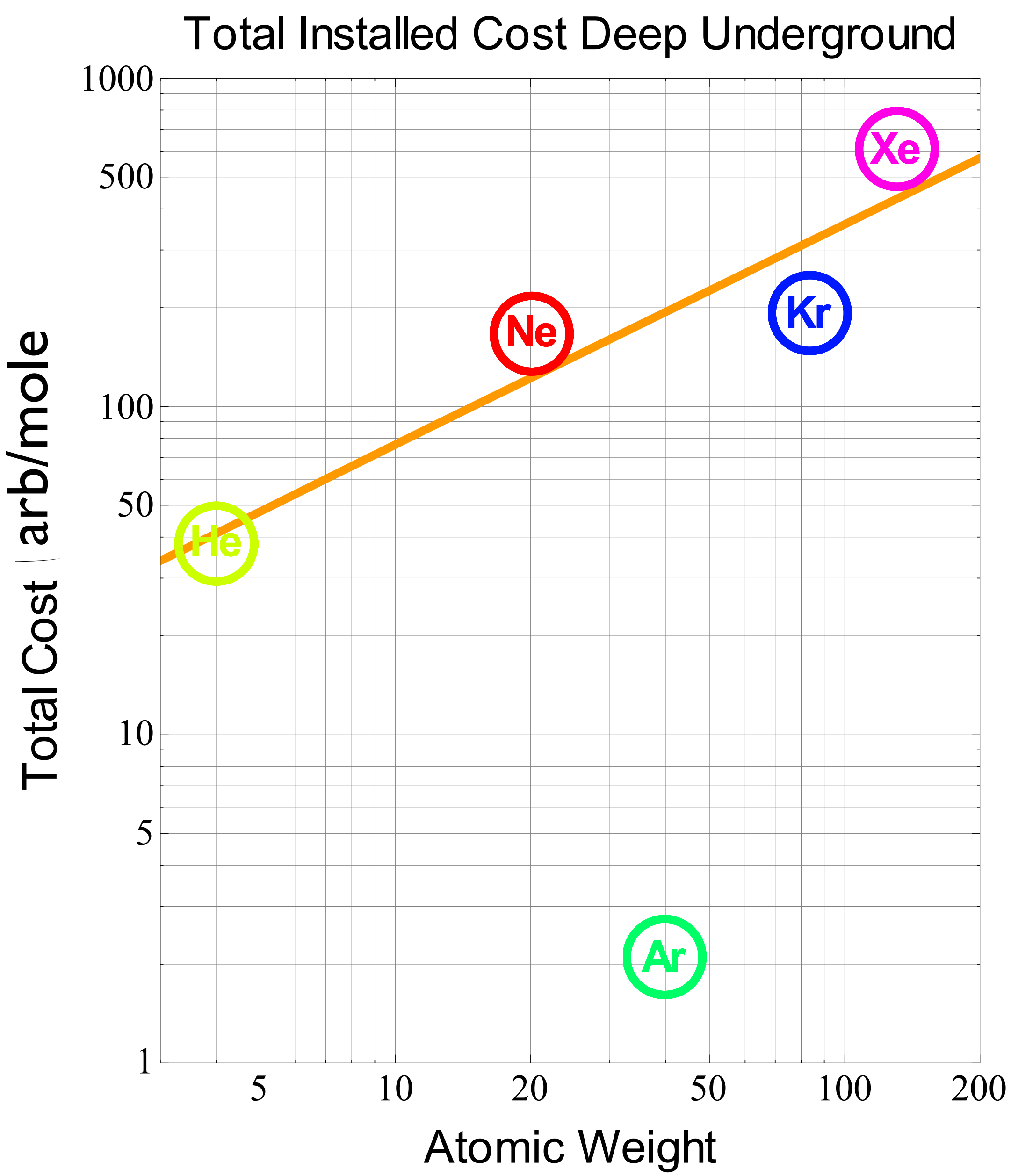
$$Yield = 10^4\,MeV^{-1} \times Coverage \times QE$$
$$= 10^4 \times 0.08 \times 0.2 \sim 160\ pe/MeV$$

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

Very well defined target region

Why Liquid Argon ?

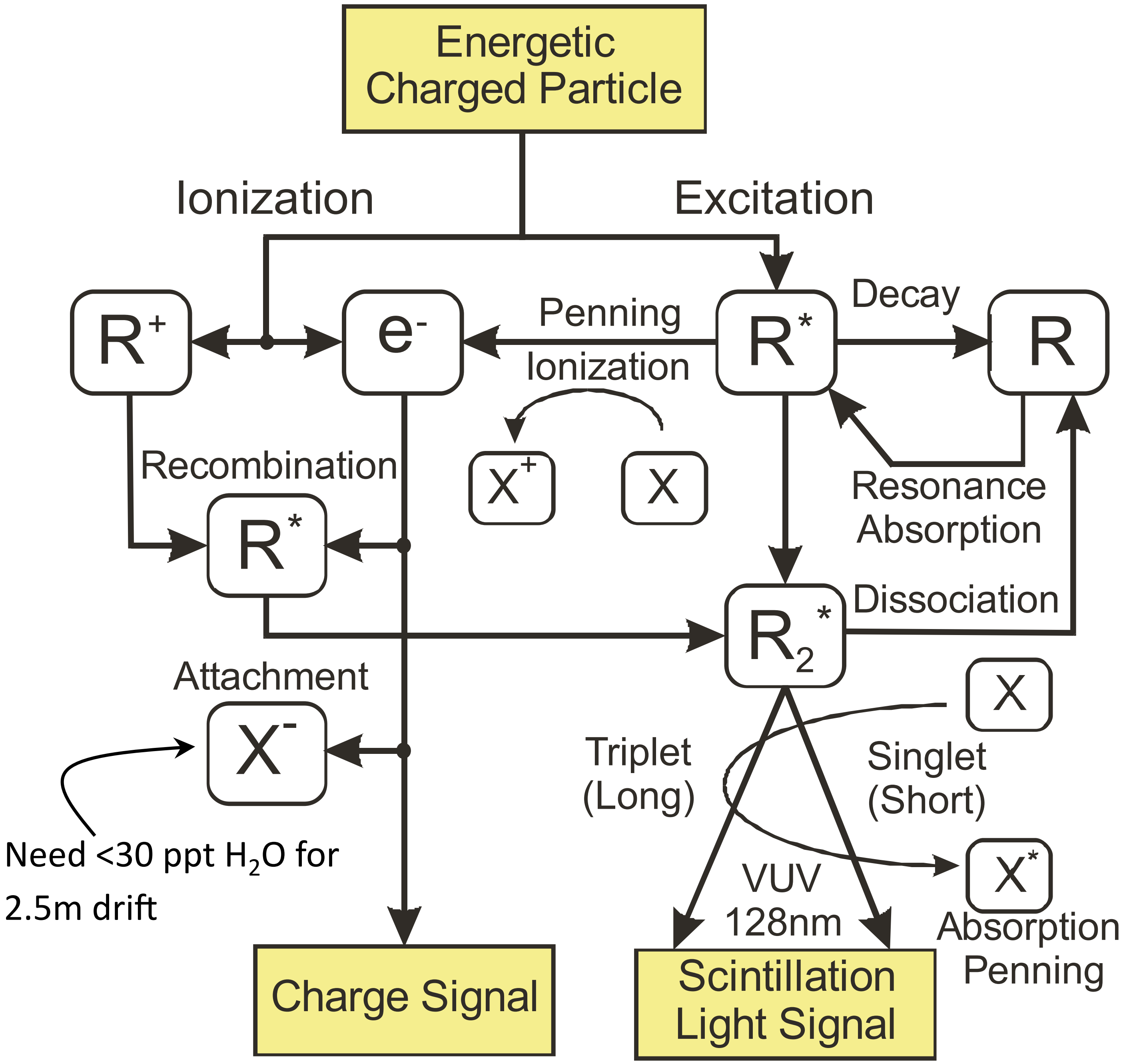
- It is one of the few pure and inexpensive substances that allow long electron lifetime, therefore can be used for ionization detection.



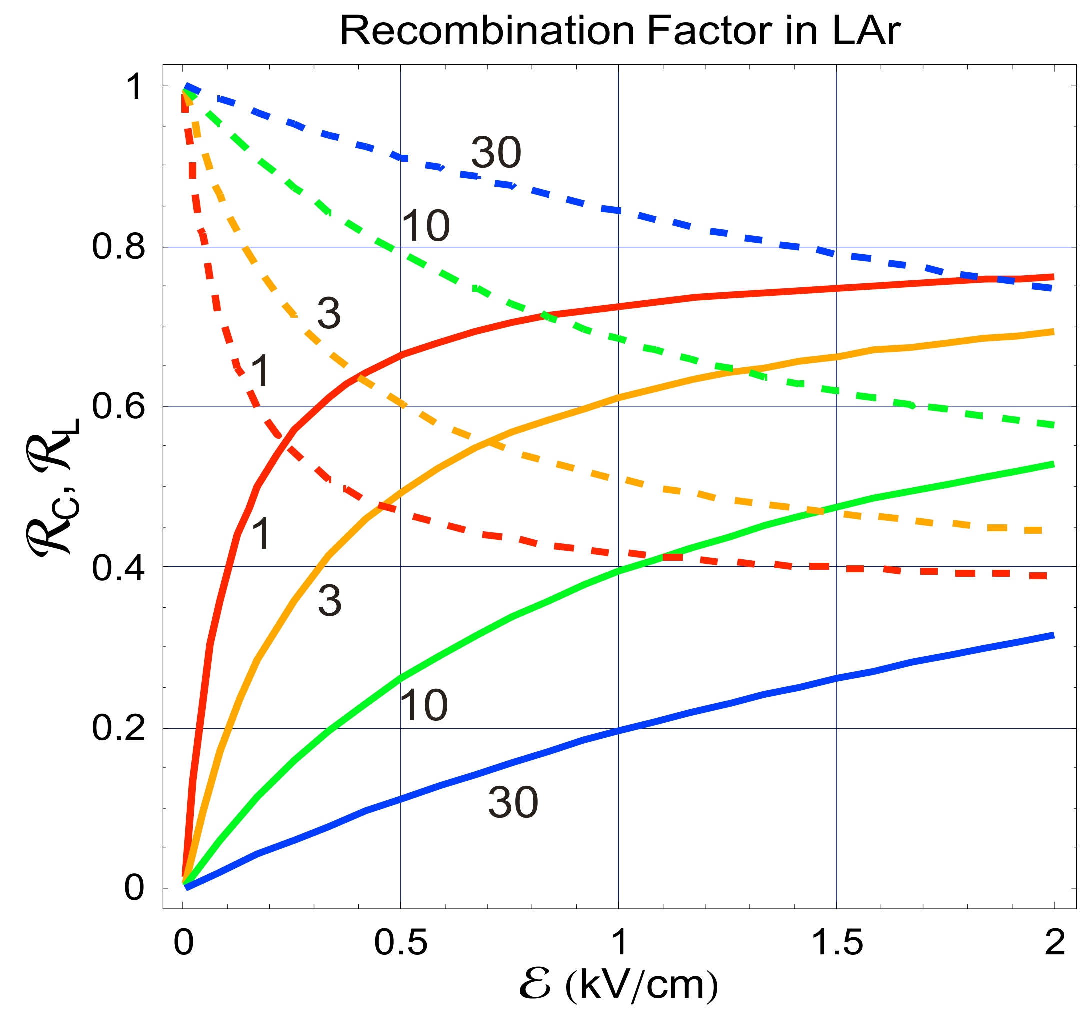
atomic num	In Air (ppm)	In Crust (ppb)	Ionization (eV) (atom)
He (2)	5.2	8	24.6
Ne(10)	18	0.07	21.6
Ar(18)	9300	1200	15.8
Kr(36)	1.14	0.01	14.0
Xe(54)	0.086	0.047	12.1

LAr Cost ~ US $ 10^6 per 1000 tons

What happens to the energy as a charged particle traverses in LAr? W = 23.6 eV/pair



R={LNe, LAr, LKr, LXe}
X={N_2, O_2, H_2O, …}



E→∞
42,000 e/MeV
8980 e/mm for MIP

E→0
51,300 ph/MeV
10,900 ph/mm for MIP

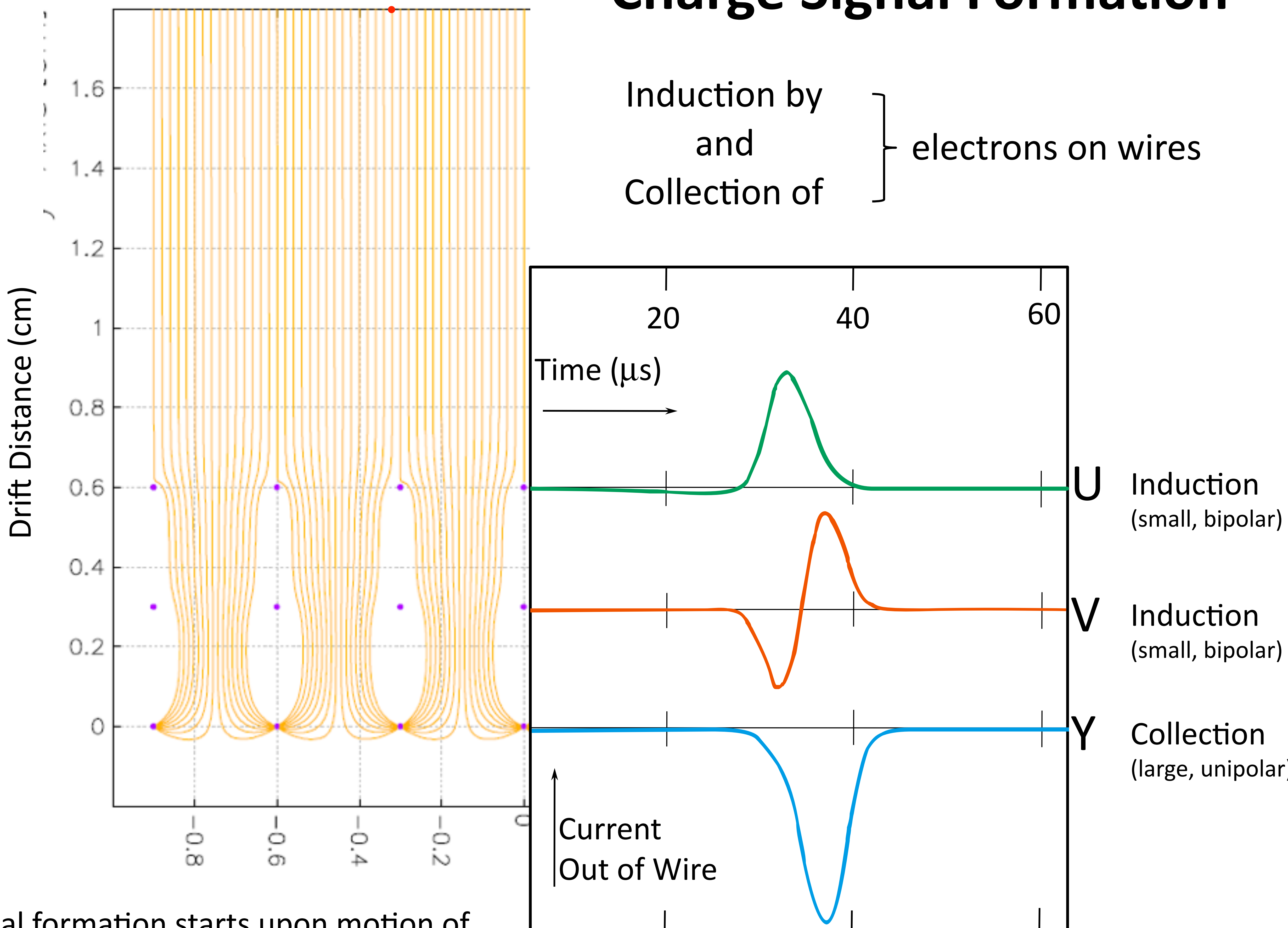
(40,000 for NaI(Tl))

Ratio w/r/t full yield
Solid: charge, Dashed: light
Numbers: Specific Eloss in MIPs

Charge Signal Formation

Induction by
and
Collection of

} electrons on wires



Signal formation starts upon motion of the charge.

Conclusion

- **This lecture was about the basics of neutrino detectors.**
- **The most important feature is inexpensive mass.**
- **Detectors are designed to measure light emission or charge deposition from neutrino 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**