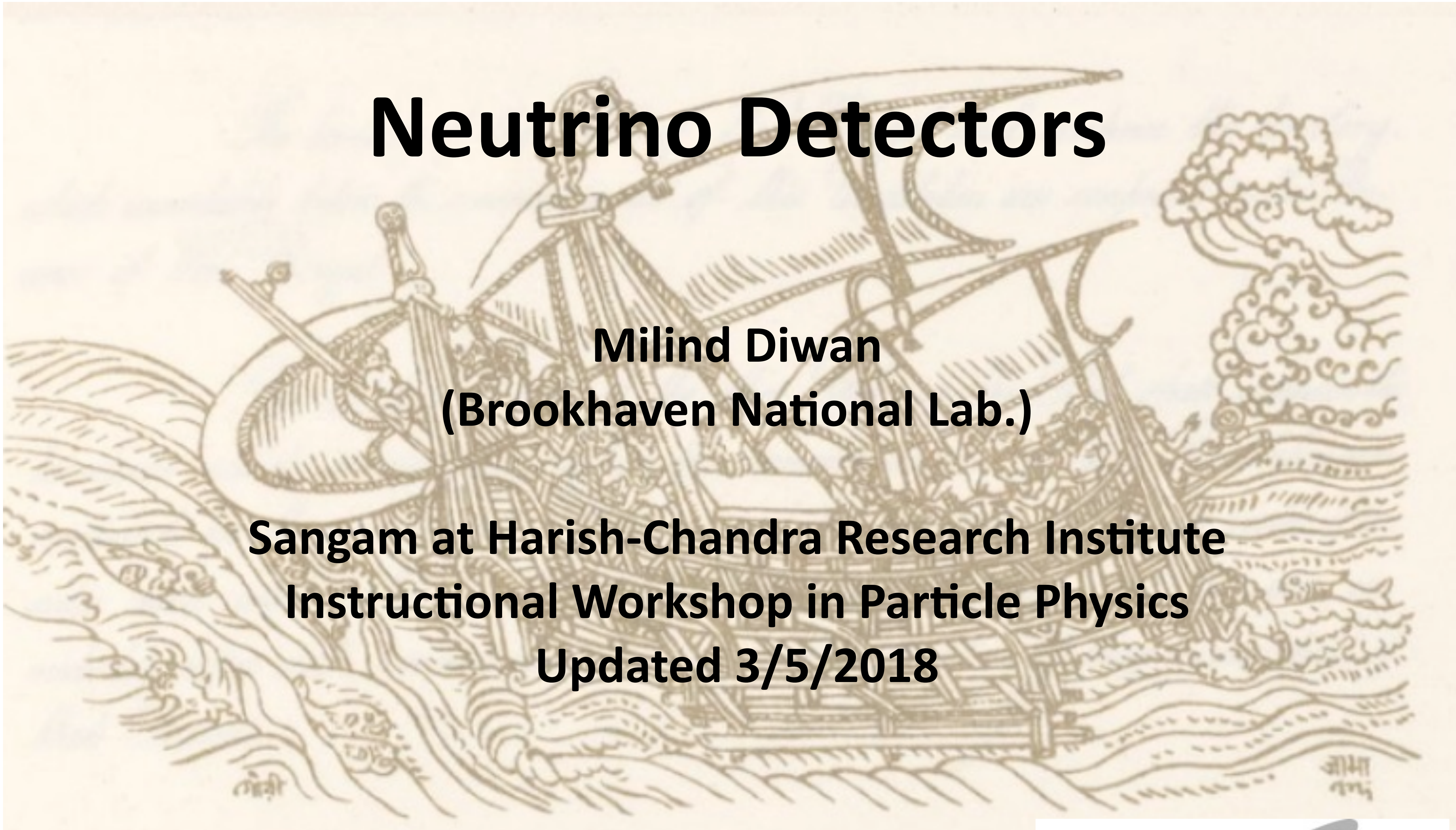

Neutrino Detectors

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Sangam at Harish-Chandra Research Institute
Instructional Workshop in Particle Physics
Updated 3/5/2018

BROOKHAVEN
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Plan of lectures

- Neutrino Detectors
- Neutrino Sources
- Basic mathematical tools for detector design and analysis.

Outline

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

Although detector physics is described from the point of view of neutrino detection, most of the techniques are common in all radiation detection.

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.**

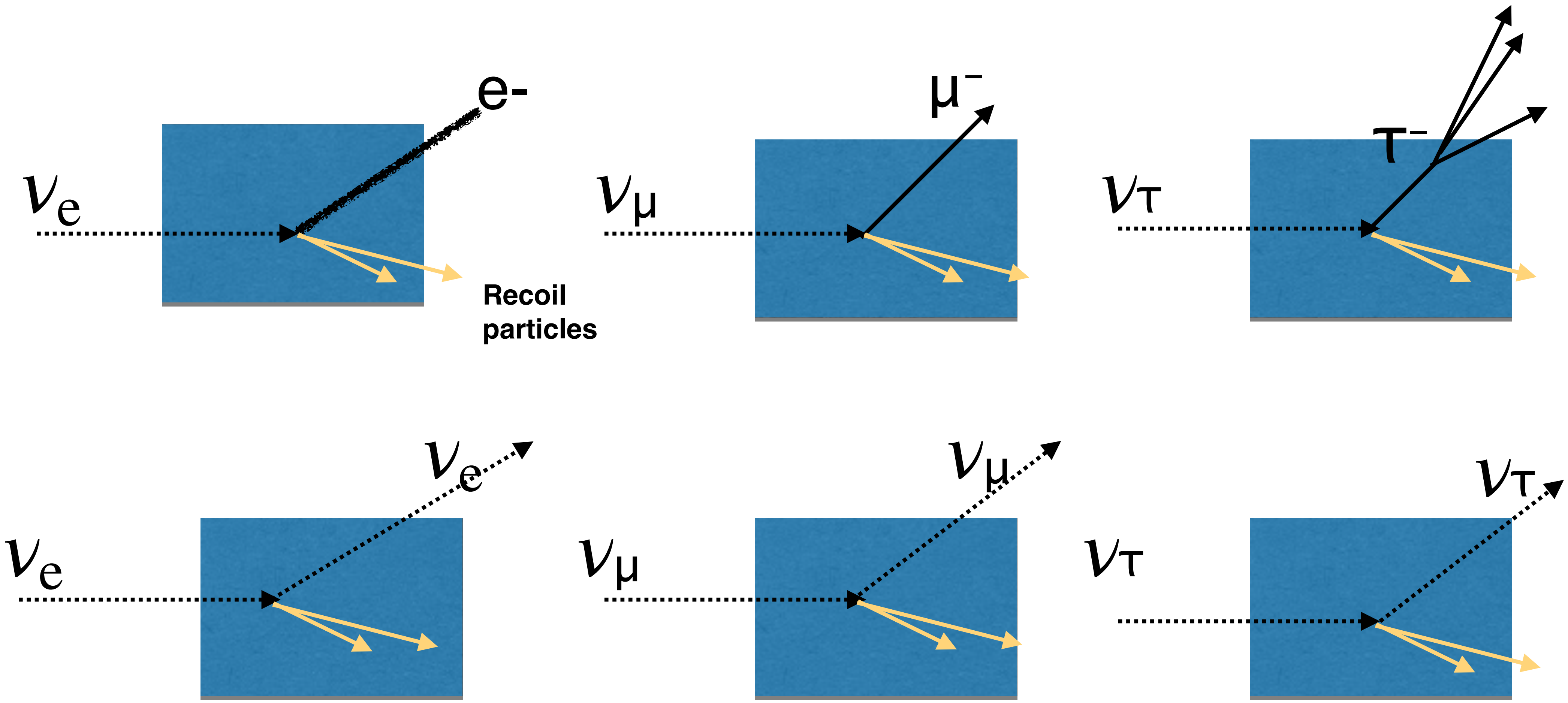
Weak interactions of neutrinos

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**
- **Events = Trajectories(cm)*cross-sec(cm^2)*Target density (/cm^3)/sec (think of this as a tube around a trajectory)**
- **Targets are the number of particle targets in a detector volume. Detector itself serves as the target for interactions.**
- **1 ton of anything as ~ 6 x 10^{29} protons and neutrons and**
- **1 ton of anything has ~3x10^{29} electrons**
- **Practical experiments 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.**

More about cross sections in the third lecture

Detector mass needed for 1000 evts/yr ?

Atmospheric Neutrinos

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

$$E \sim 1\, GeV$$

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

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

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

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

Reactor Neutrinos

$$Yield = 2\times 10^{20}\sec^{-1}\ for\ each\ GW\ of\ thermal\ power$$

$$Fraction > 3\ MeV \quad F \sim 0.1$$

$$\sigma \sim 8.5\times 10^{-43}\, cm^2$$

$$\text{Protons}=(2/3)\times 10^{29}\ \text{ton}^{-1}\ \text{(for water)}$$

$$Area = 4\pi \bullet 10^{10}\, cm^2 \quad \text{Take length to be 1 km.}$$

$$\varphi = Y / Area = 1.6\times 10^{9}\, cm^{-2}\sec^{-1}$$

$$N = \varphi \bullet F \bullet \sigma \bullet (2/3)\times 10^{29} \bullet 3\times 10^{7}\, ton^{-1} yr^{-1}$$

$$N = 270\ ton^{-1} yr^{-1}\ \ for\ GW \sim 1 ton^{-1} day^{-1}\ for\, GW$$

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

Can we detect a nuke with a neutrino detector ?

Assume a 6 kton nuke from 900 km distance into a 1 kt detector.

$$6kton\ of\ TNT = 6\times10^{3}\ ton \times 4.18\times10^{9}\ {}^{Joule}\!/_{ton}$$

$$= 25\times10^{12}\ Joule$$

$$1GW \times day = 8.6\times10^{13}\ Joule$$

$$Events = \frac{1000ton \times 1km^{2}}{900^{2}\,km^{2}} \times 1(evt/ton) \times \frac{25\times10^{12}\,J}{8.6\times10^{13}\,J}$$

$$= 0.0004\ events$$

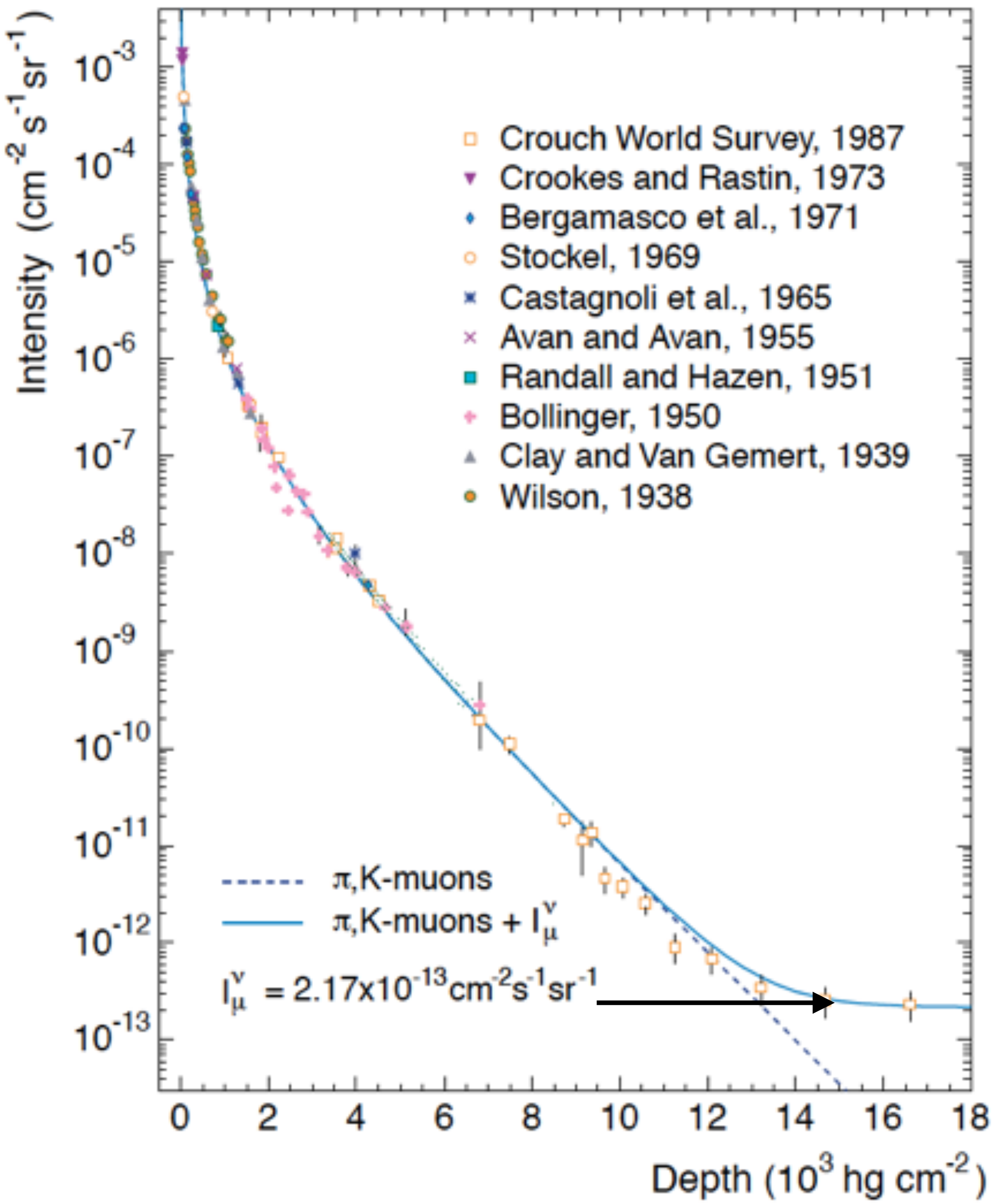
Assuming that the fission processes are roughly the same in a nuke and a reactor. A detector at 1 km would certainly see hundreds of events.

Typical Neutrino Detector Technologies

Material	Composition	Density	Signal type	Comment
Water/Ice	H_2O	1.0	Cherenkov Light	Can be huge
Liquid Scintillator	$\sim CH_2$	~0.9	Scintillation Light	Low energy Threshold
Plastic Scintillator	$\sim CH_2$	~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	$H_2O + \epsilon CH_2$	1.0	Cherenkov + Scint.	Huge with low threshold

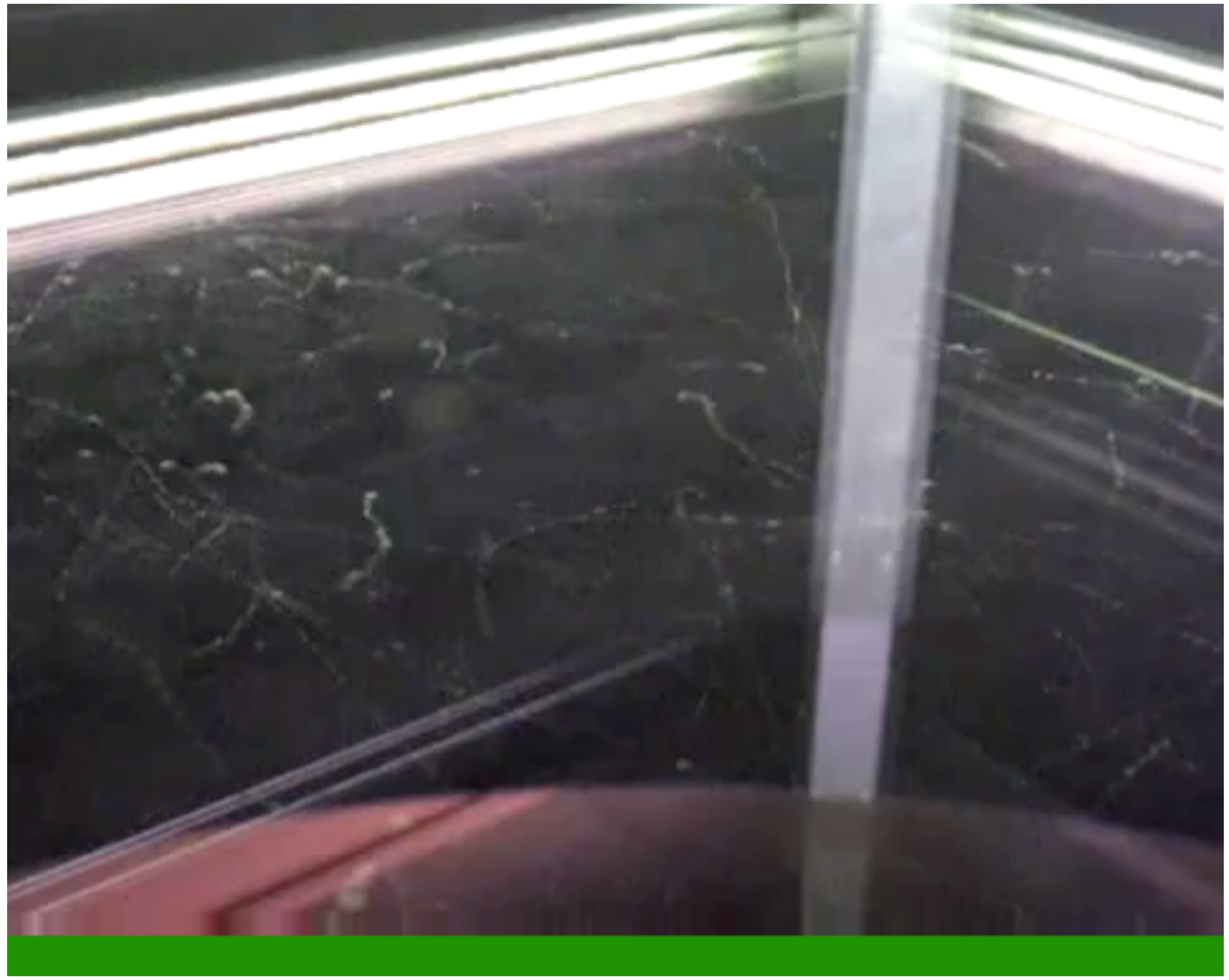
Given the emphasis on detector mass, we must choose materials that are inexpensive and produce a signature that can be easily measured by common sensors.

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 $\text{Cos}^2\theta$ 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.



Cosmic ray cloud chamber at the New York Hall of Science

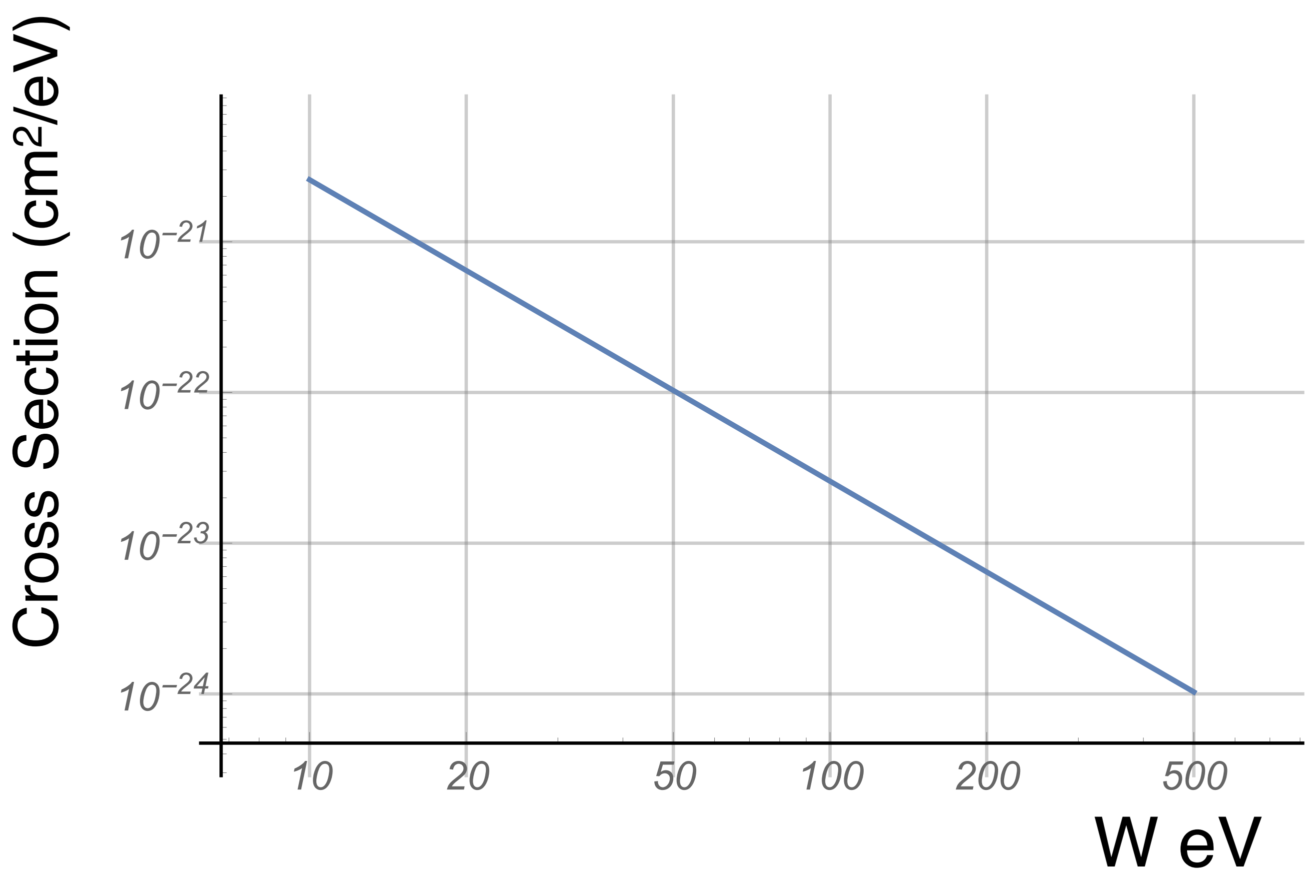
The surface rate is ~100 $m^{-2}sec^{-1}sr^{-1}$
Mean ~4 GeV
Flat below 1 GeV. $E^{-2.7}$ above 10 GeV.
Angular ~ Cos^2(Theta)

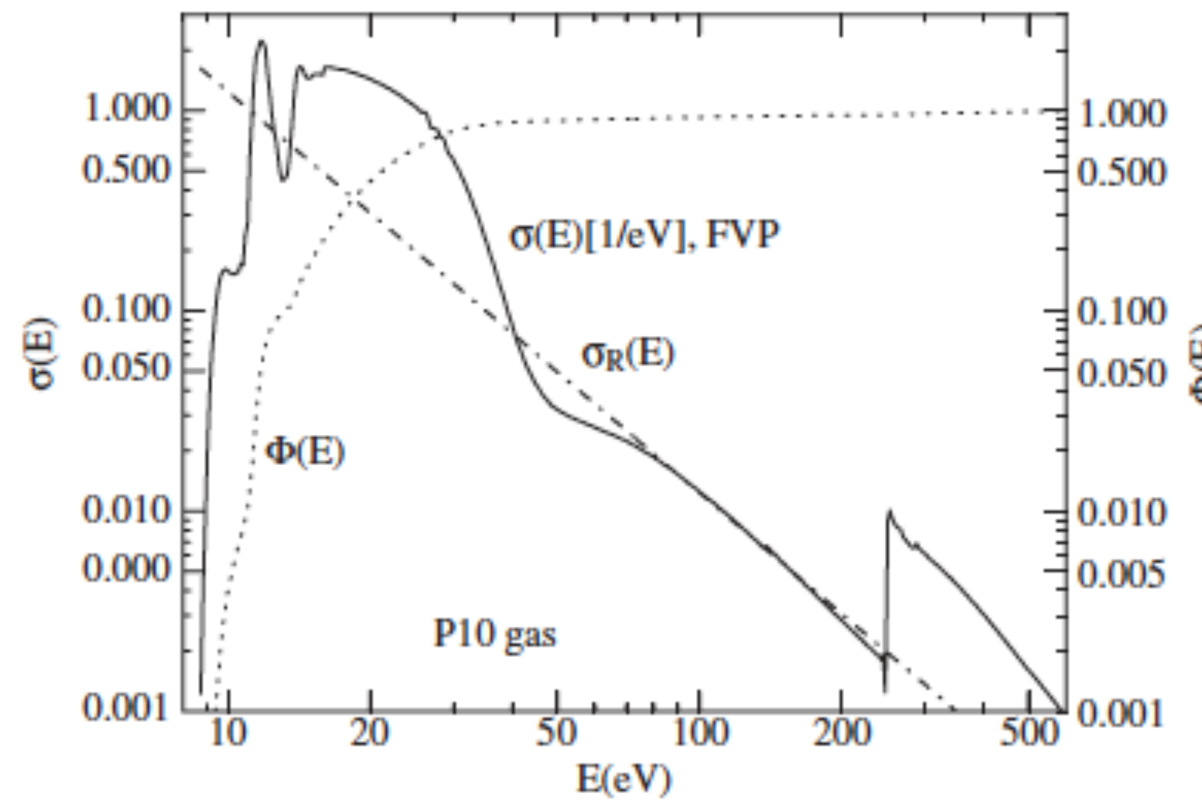
Energy Loss

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. (Problem: how is this changed in liquids and solids ?)

Maximum energy loss in single collision on free electrons.

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



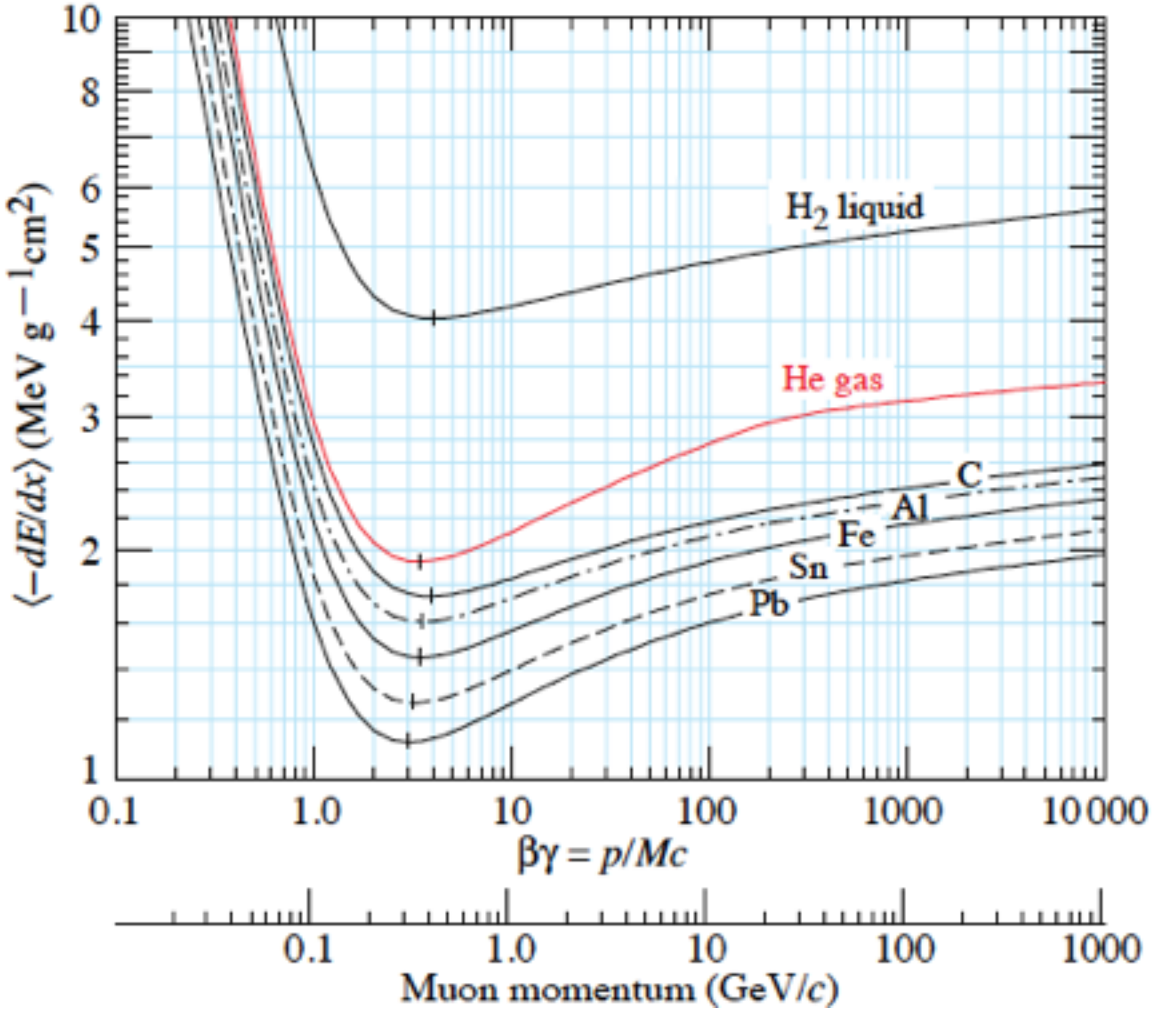


$$\frac{d\sigma(W,\beta)}{dW} = \frac{k_r}{\beta^2} \frac{(1 - \beta^2 W / W_{\max})}{W^2}$$

$$k_r = 2\pi r_e^2 m_e z^2 = 2.54955 \times 10^{-19} z^2 \cdot eV \cdot cm^2$$

In reality atomic energy levels cause significant change in this cross section. H. Bichsel (2006) calculation for βγ = 3.6

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
  - mean loss for 1 GeV, 5 GeV muons: 2.35 MeV/cm and 2.9 MeV/cm

Z = 24

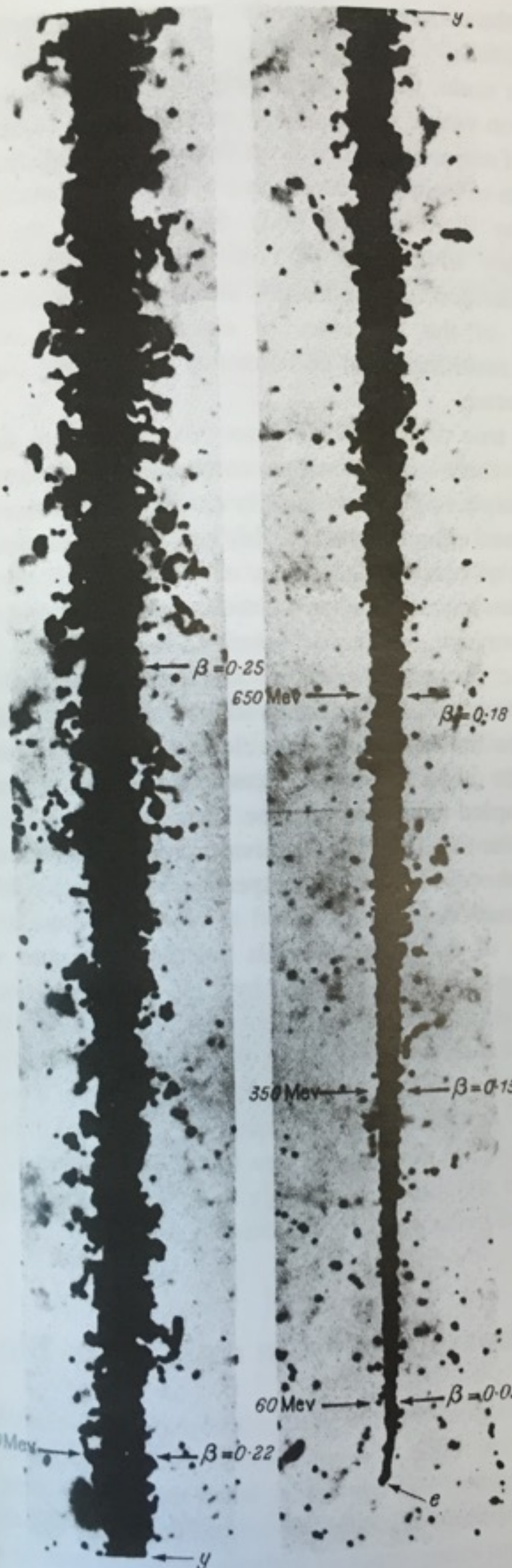
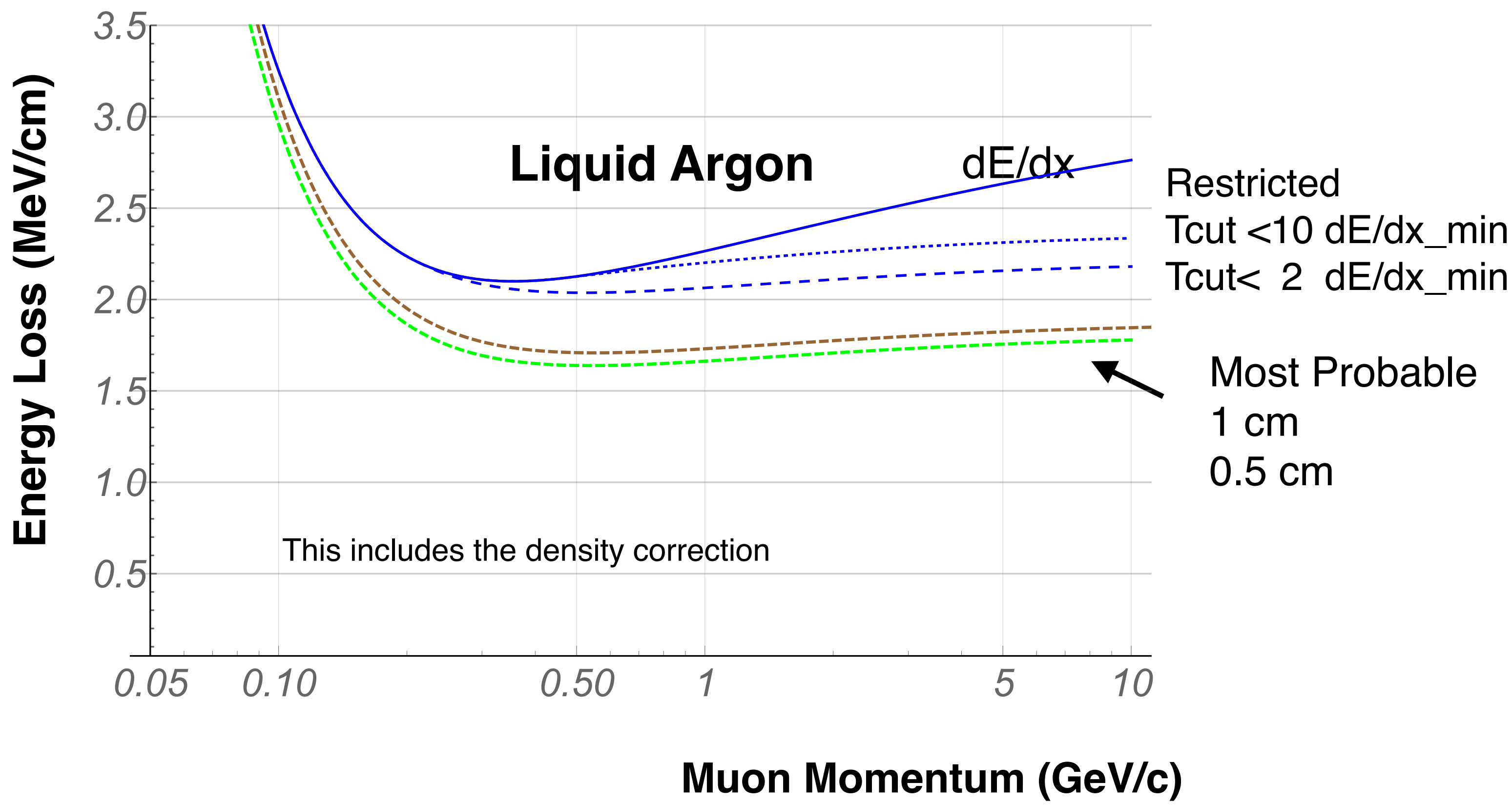
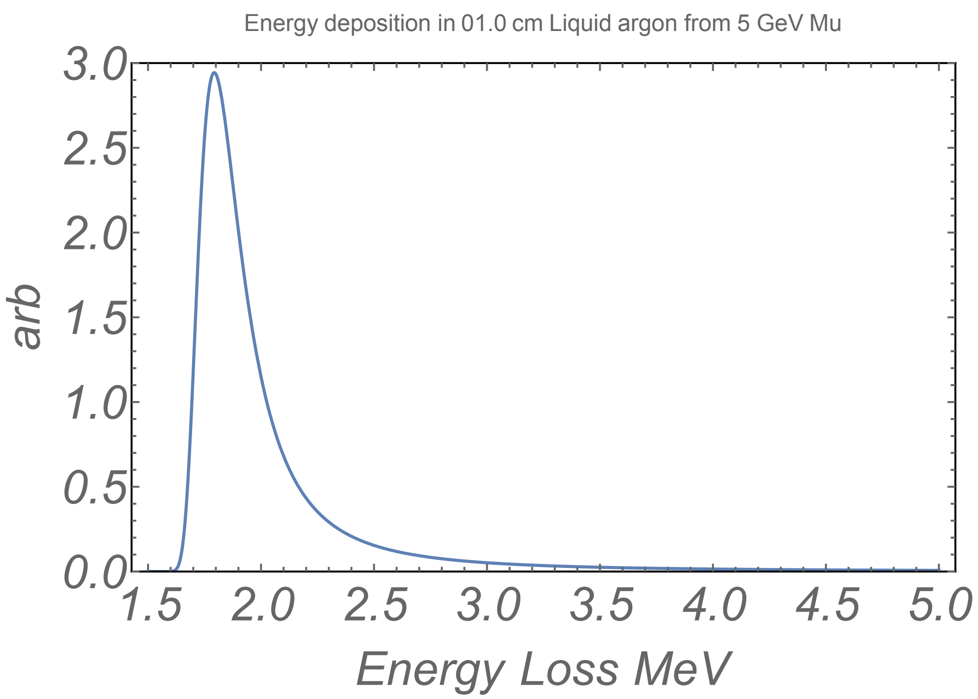


Fig. 6.3 Track of a primary cosmic ray chromium nucleus ($Z = 24$) observed in nuclear emulsion flown on a balloon. The track, of total length 400μm, is shown in two adjacent sections, starting from left top, and terminating at bottom right. As the ionization is proportional to Z^2, the track is initially very dense in comparison with that of the singly charged antiproton in Fig. 6.2. As the nucleus slows down, its velocity becomes comparable with that of electrons in the chromium atom, so it successively collects electrons into the various shells K, L, and so on, the track tapers down and finally it comes to rest as a chromium atom. Had this been an antinucleus of order 100 secondary pions would have been produced as the antinucleus slowed down and annihilated.

Most probable loss and fluctuations.

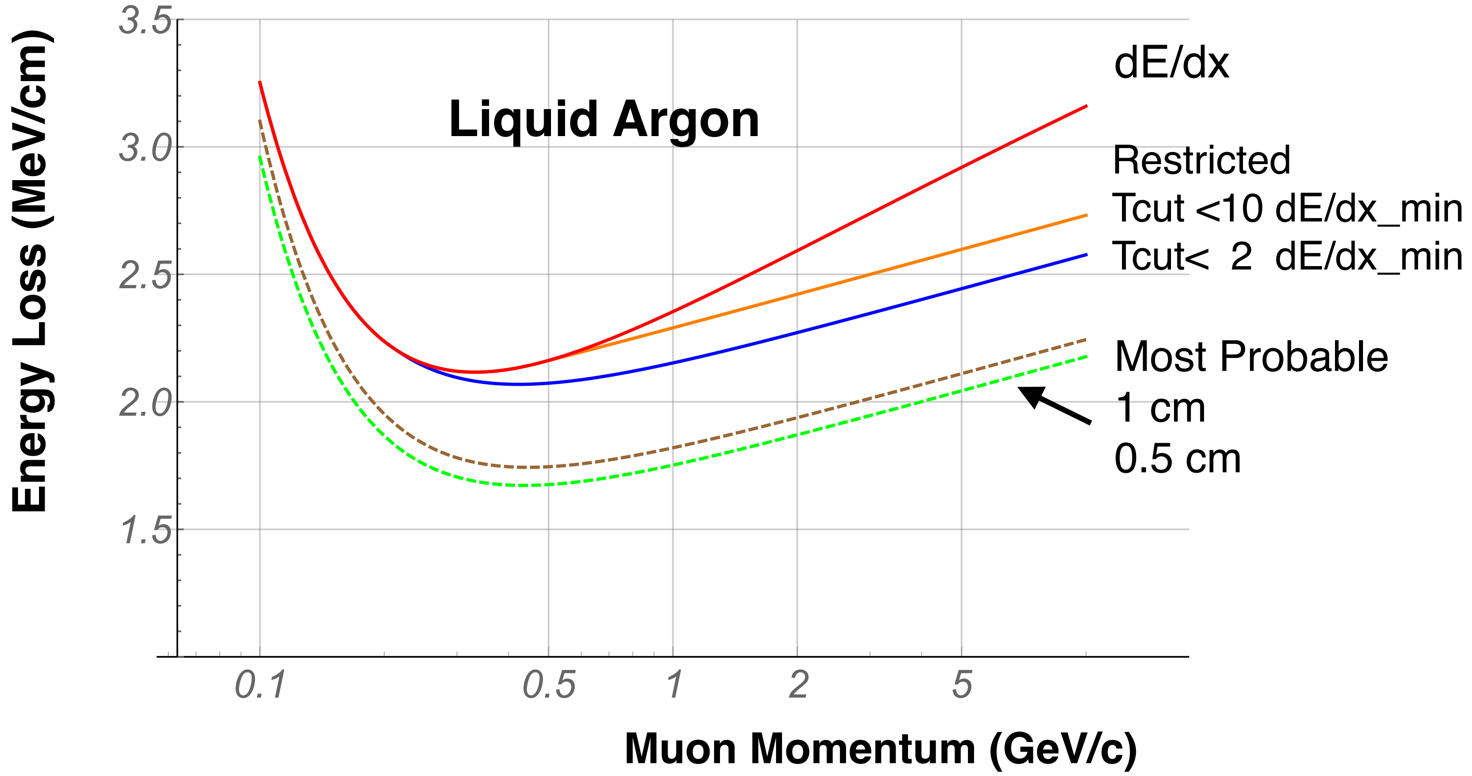




$$\Delta_p = \xi \left[Log \frac{2m_e \beta^2 \gamma^2}{I} + Log \frac{\xi}{I} + 0.2 - \beta^2 - \delta(\beta\gamma) \right] \qquad FWHM \approx 4\xi$$

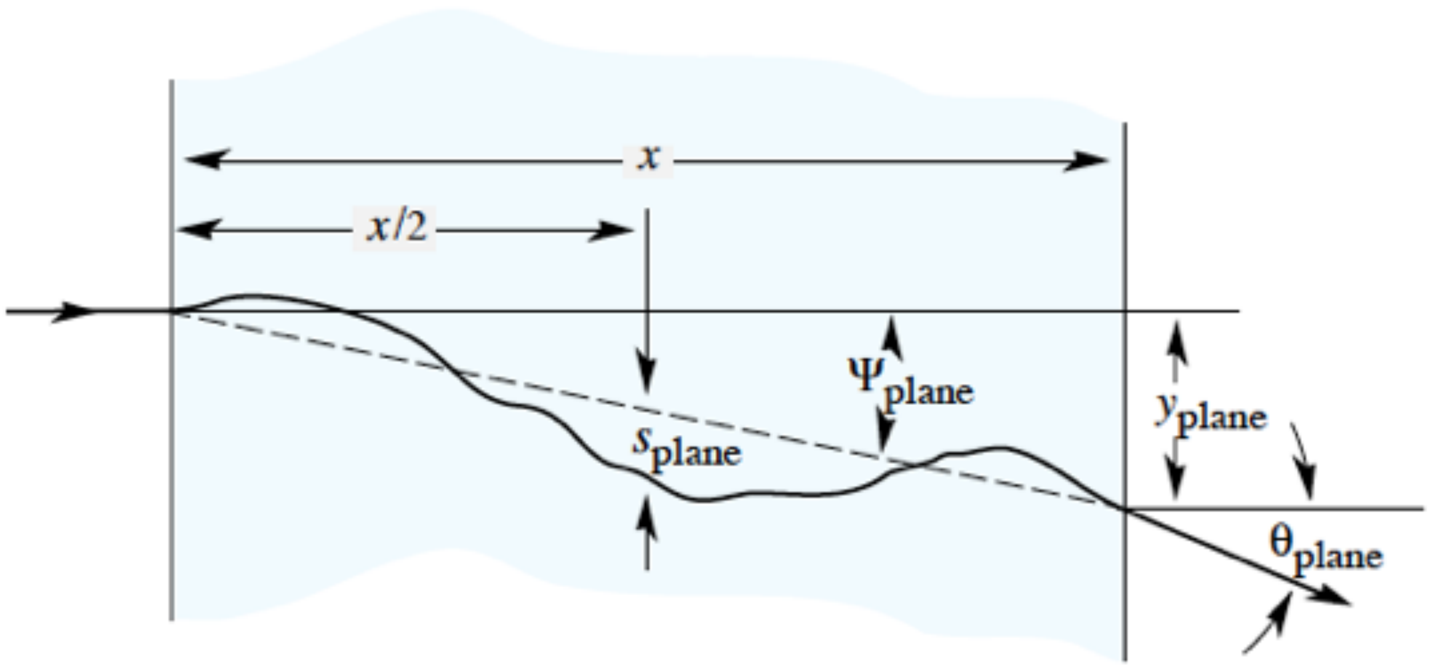
$\xi = (K/2)(Z/A)(x/\beta^2)$ where x is thickness

- 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.



The density effect lowers the energy loss at high energies and flattens the response. This plot is without the density effect.

Scattering



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

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

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

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

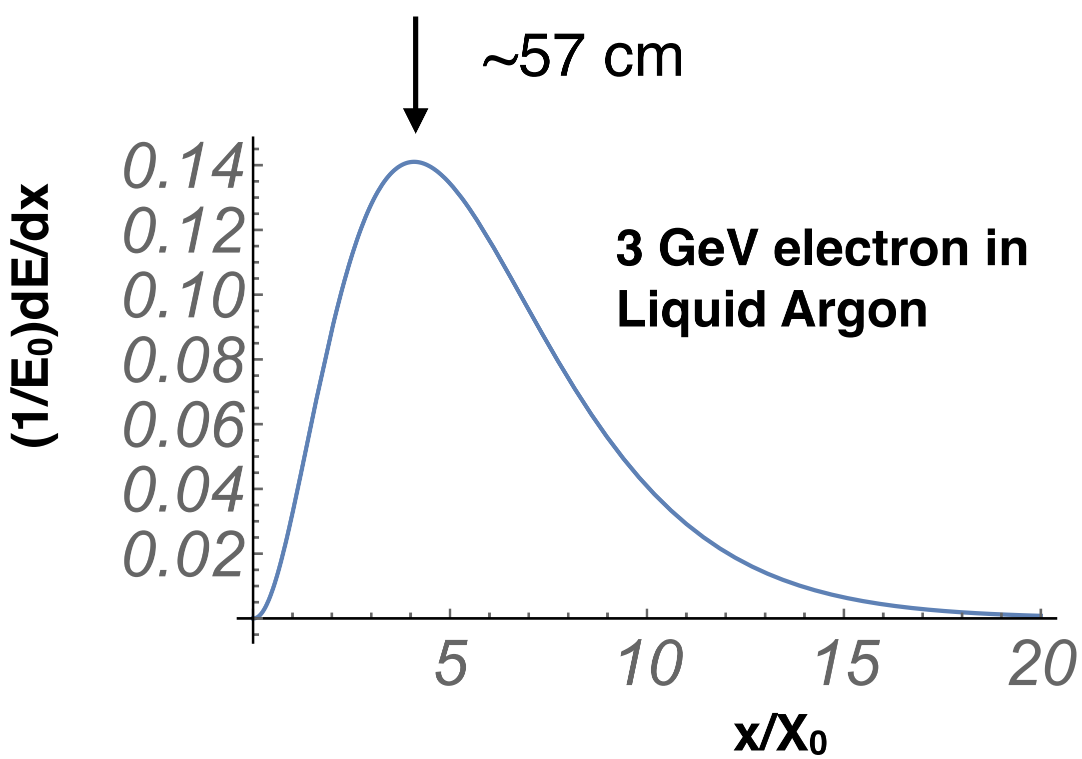
$$1/X_0 \approx (1/716)\bullet\frac{Z^2}{A}\bullet Log(\frac{184}{\sqrt[3]{Z}})\,(gm/cm^2)^{-1}$$

$$For\ Z>4$$

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

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

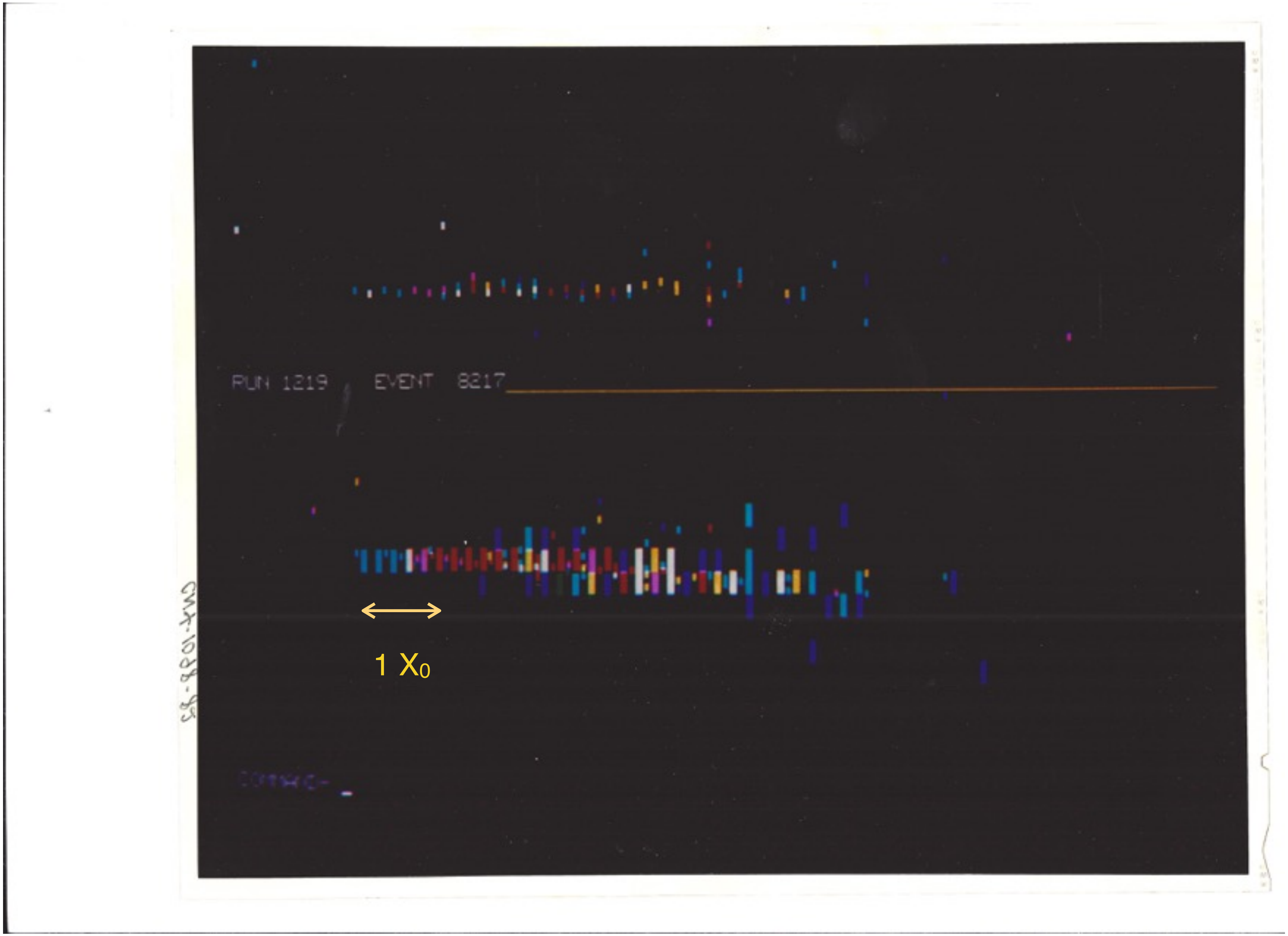
$$b \sim 0.5\{Material\ dependent$$



- 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 $(7/9)X_0$

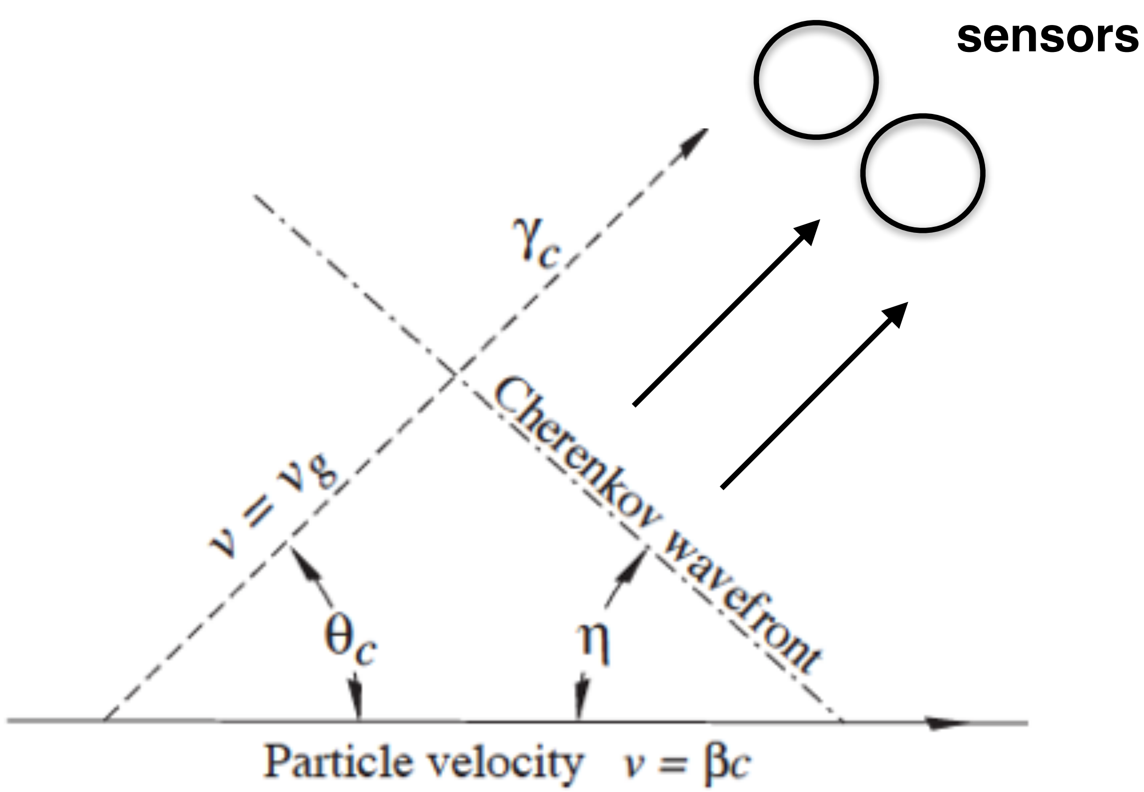
Material	Ecritical(MeV)
LAr	30.5
Water	78.3
Liquid Scint.	~102
Fe	21.7

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



$$\cos\theta_c = (1/n\beta)$$

$$\theta_c + \eta \approx \pi/2 \quad \textit{because of dispersion}$$

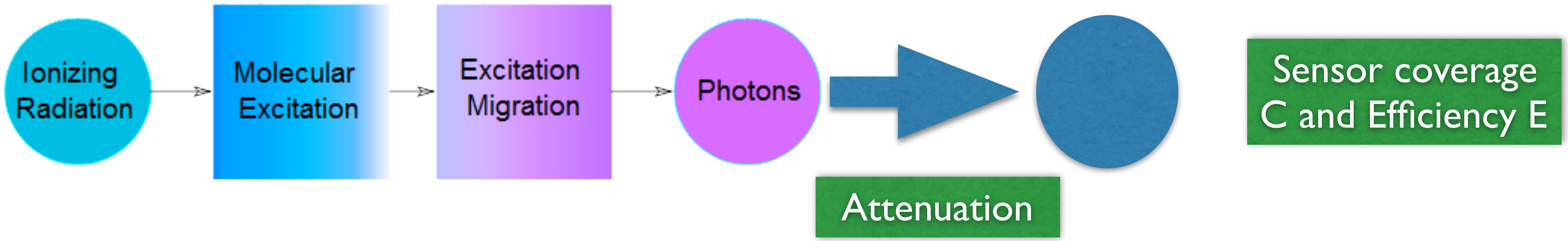
$$\frac{d^2N}{dEdx} = \frac{2\pi\alpha z^2}{hc}\sin^2\theta_c$$

$$\approx 370\sin^2\theta_c \ \mathrm{ev^{-1}cm^{-1}} \times (D_{eff})$$

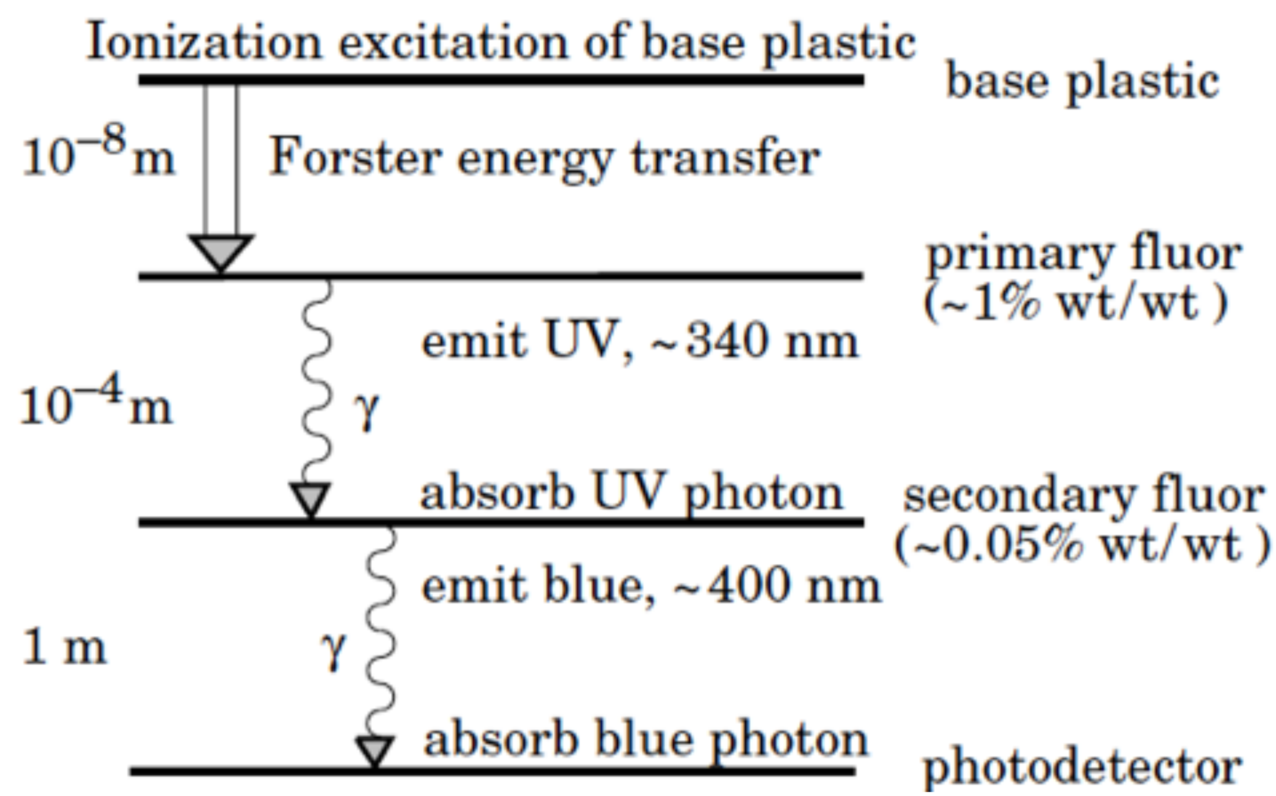
Water (20°C)	n=1.33
θc water for β =1	41.2°
Electrons	0.58 MeV/c
Muons	120.5 MeV/c
Pion	159.2 MeV/c
Proton	1070.0 MeV/c

- 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. $\beta > 1/n$
- 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 (rise time)



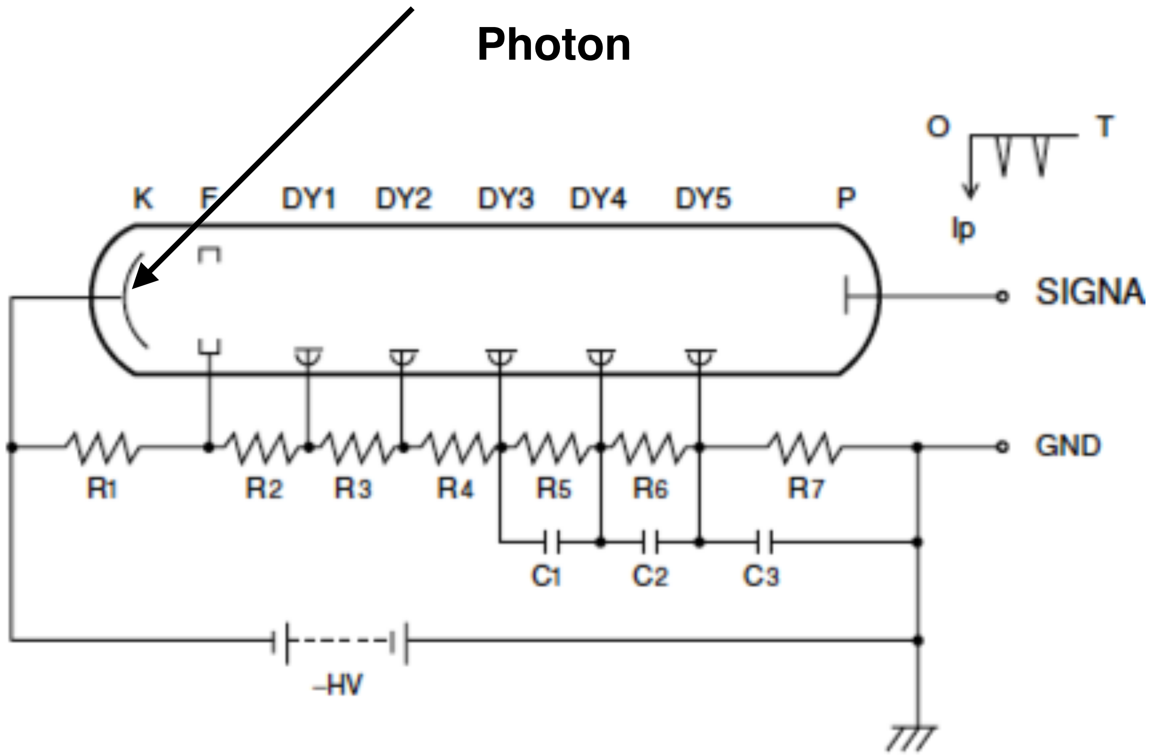
$$\frac{dL}{dx} = L_0 \frac{dE/dx}{1 + k_{Birk} dE/dx}$$

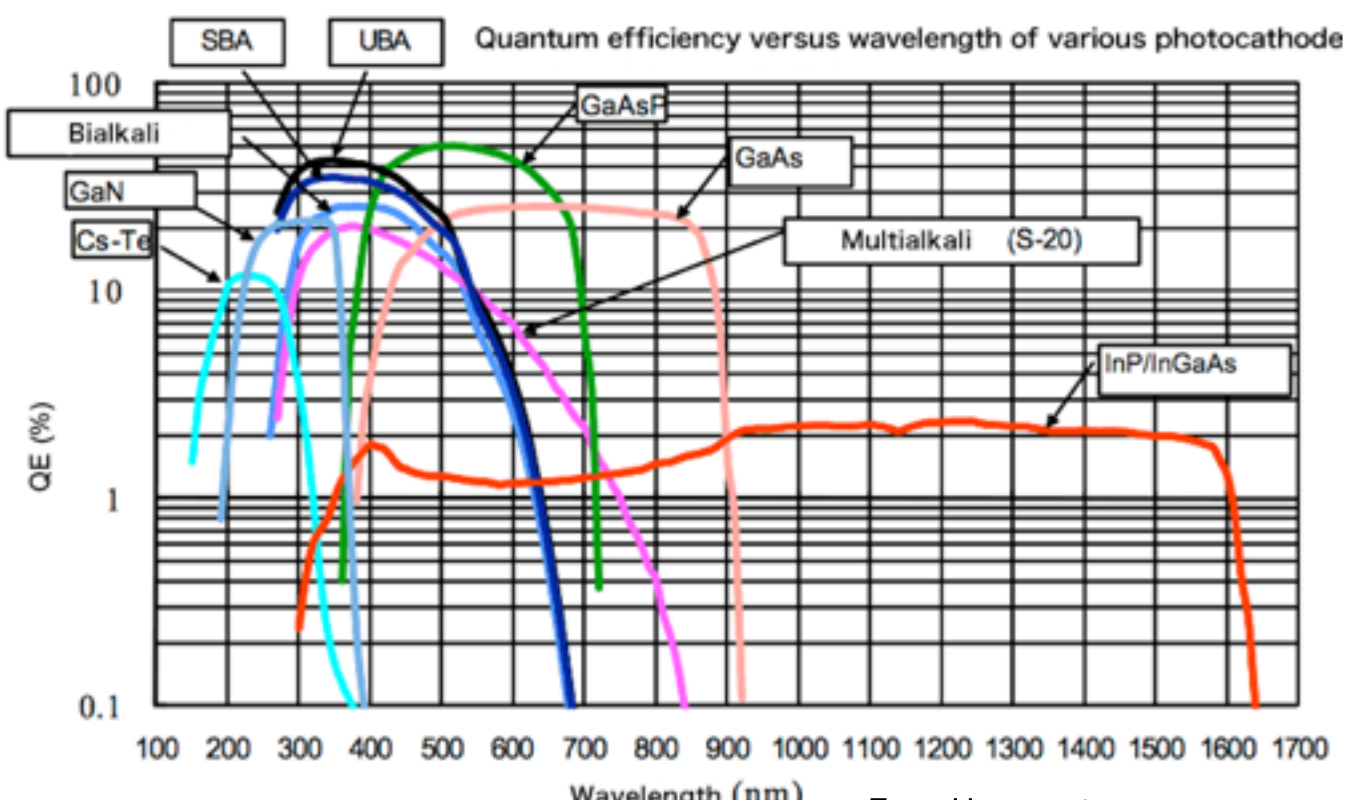
$$Typical \quad L_0 \sim 10^4 \, MeV^{-1}$$

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

- 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

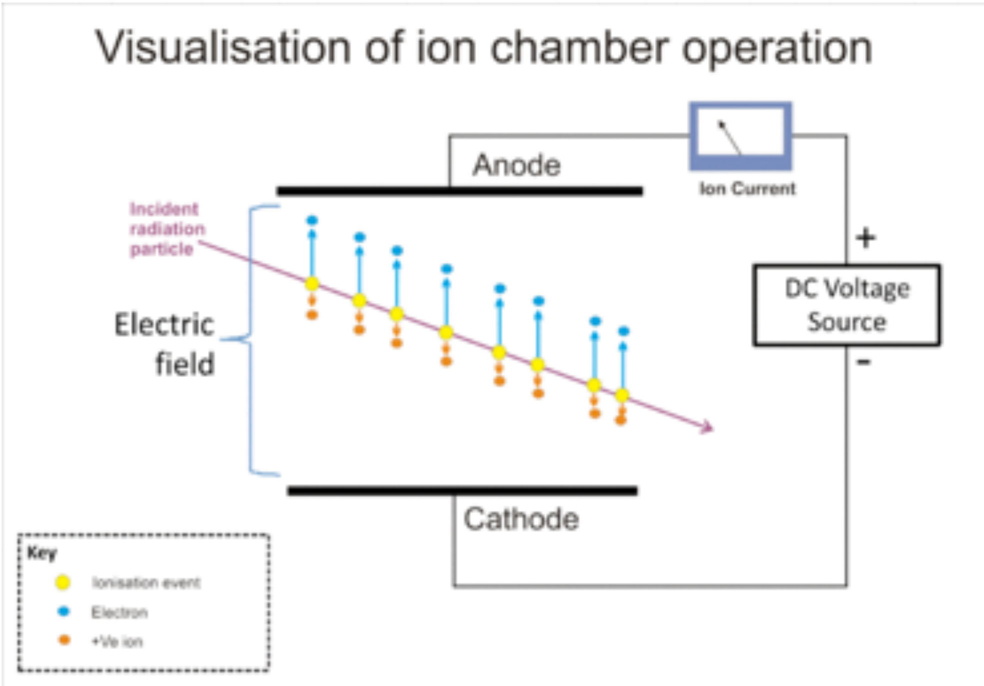




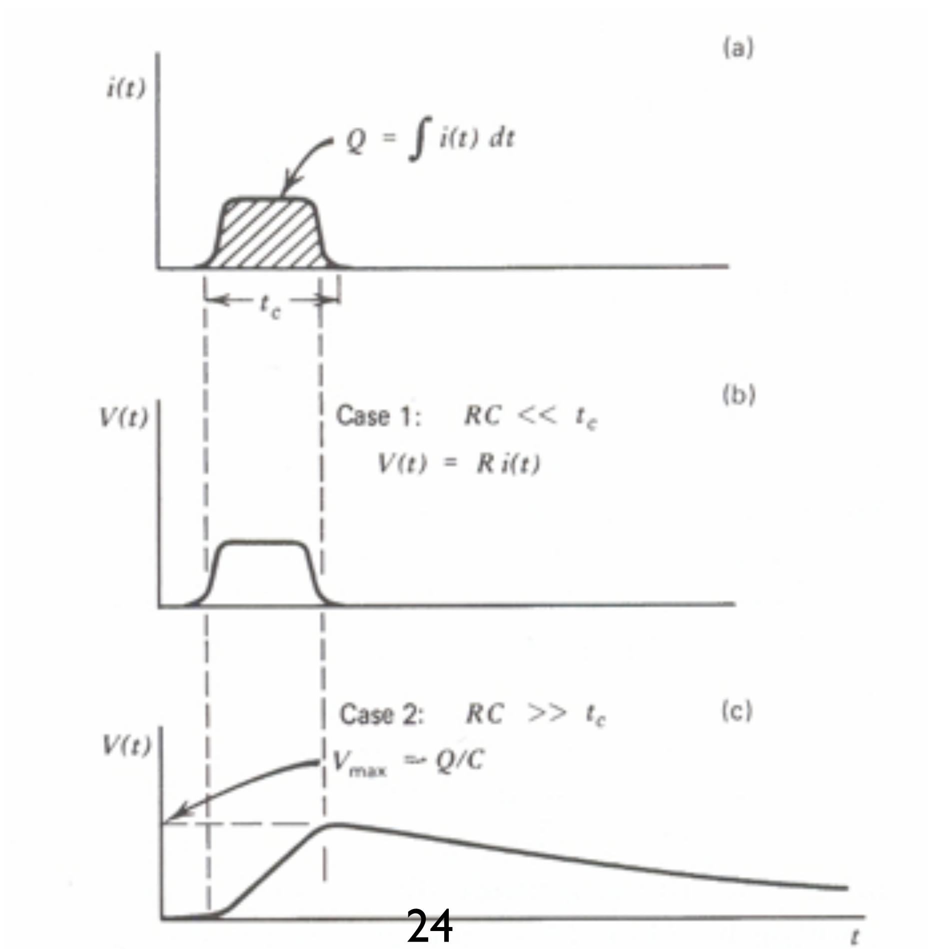
From Hamamatsu

- 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

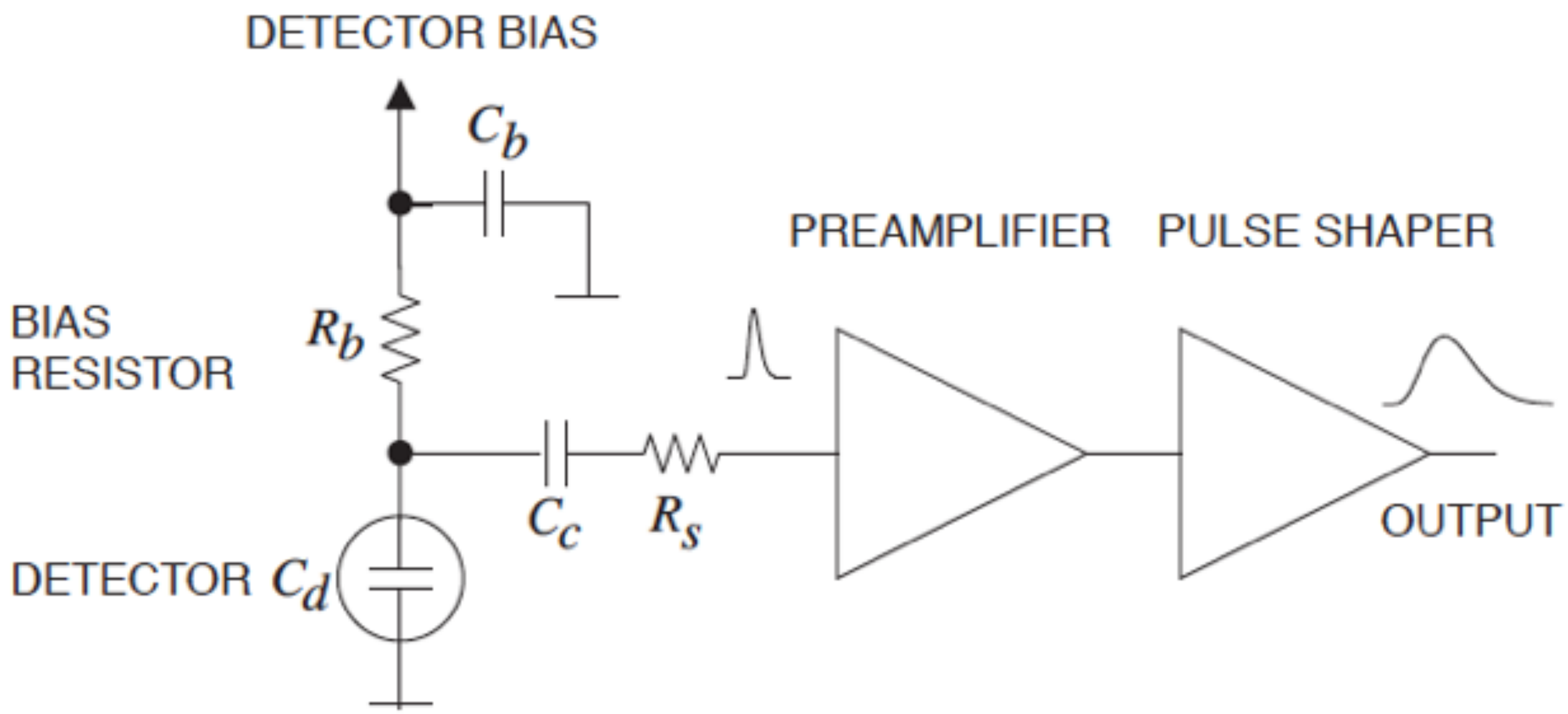


material	W (ev/pair)
LAr	23.6
LXe	15.6
Silicon	3.6
Germanium	2.9
Diamond	~13
CdTe	5.2
LNe	36
LKr	19



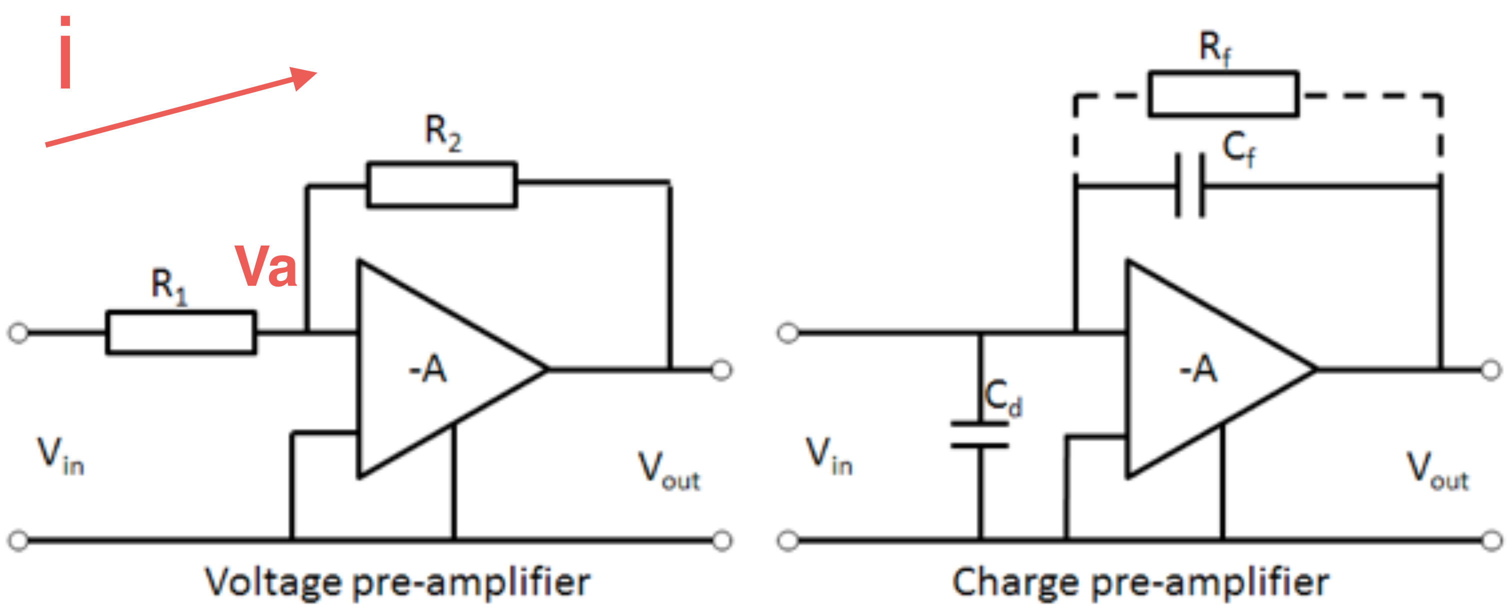
- In gases, semiconductors, and pure insulators, ionization creates electron-ion pairs.
- Electrons generally move about 1000 times faster than ions.
- This current can be measured as voltage across a resistor (case 1) or pulse across a capacitor (case 2)

Front end electronics (General Principles)



- 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 and then a shaper will eliminate unwanted signal structure.

Amplifiers



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

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

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

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

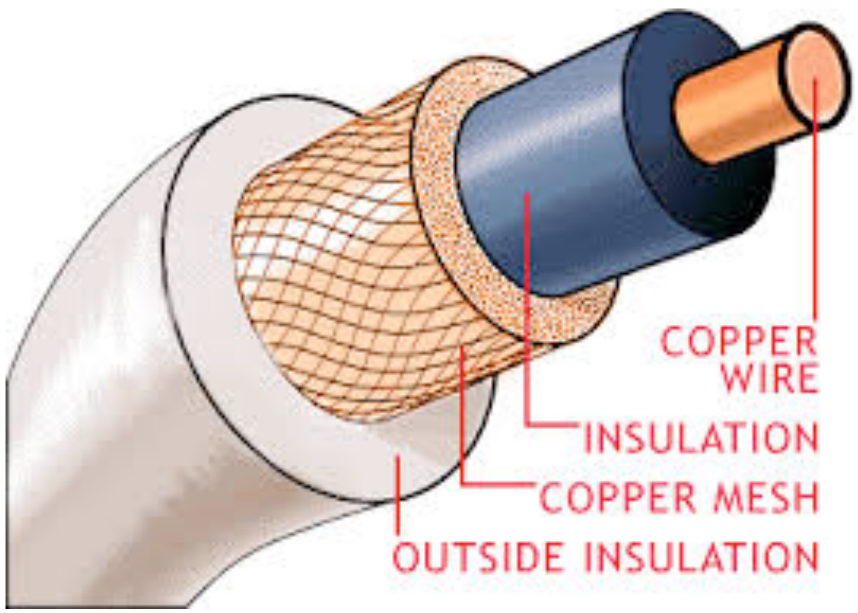
$$V_o = -AV_a$$

$$i = \frac{V_a - V_{in}}{R_1} = \frac{V_o - V_a}{R_2}$$

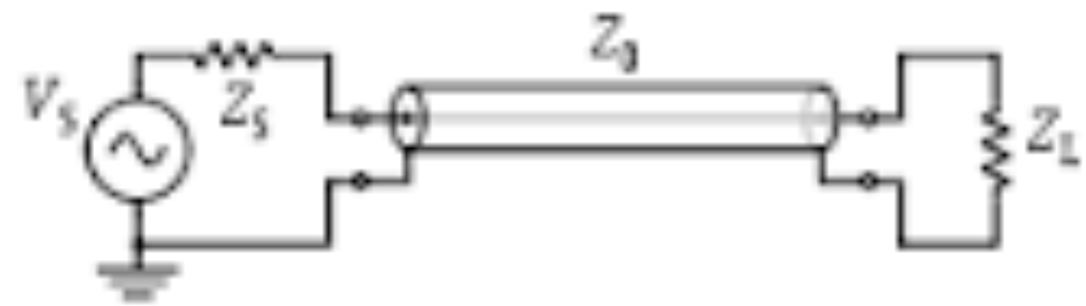
$$V_o = -V_{in} \frac{R_2}{R_1} \left[1 + \frac{(R_1 + R_2)}{R_1 A} \right]^{-1}$$

- Analysis of such circuits can be done using the ideal Op-amp in which A is infinite, and the input has infinite impedance.
- Voltage 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.

Co-axial Cables



- Shielded construction to minimize pickup noise.
- Very effective above 100 kHz. Not so good at low frequencies.



Typical parameters:

impedance: 50 - 300 Ohm

Capacitance: ~ 100 pF/m

Attenuation: depends on frequency. > 400 Mhz, few percent per meter.

Signal speed ~ 2/3 c

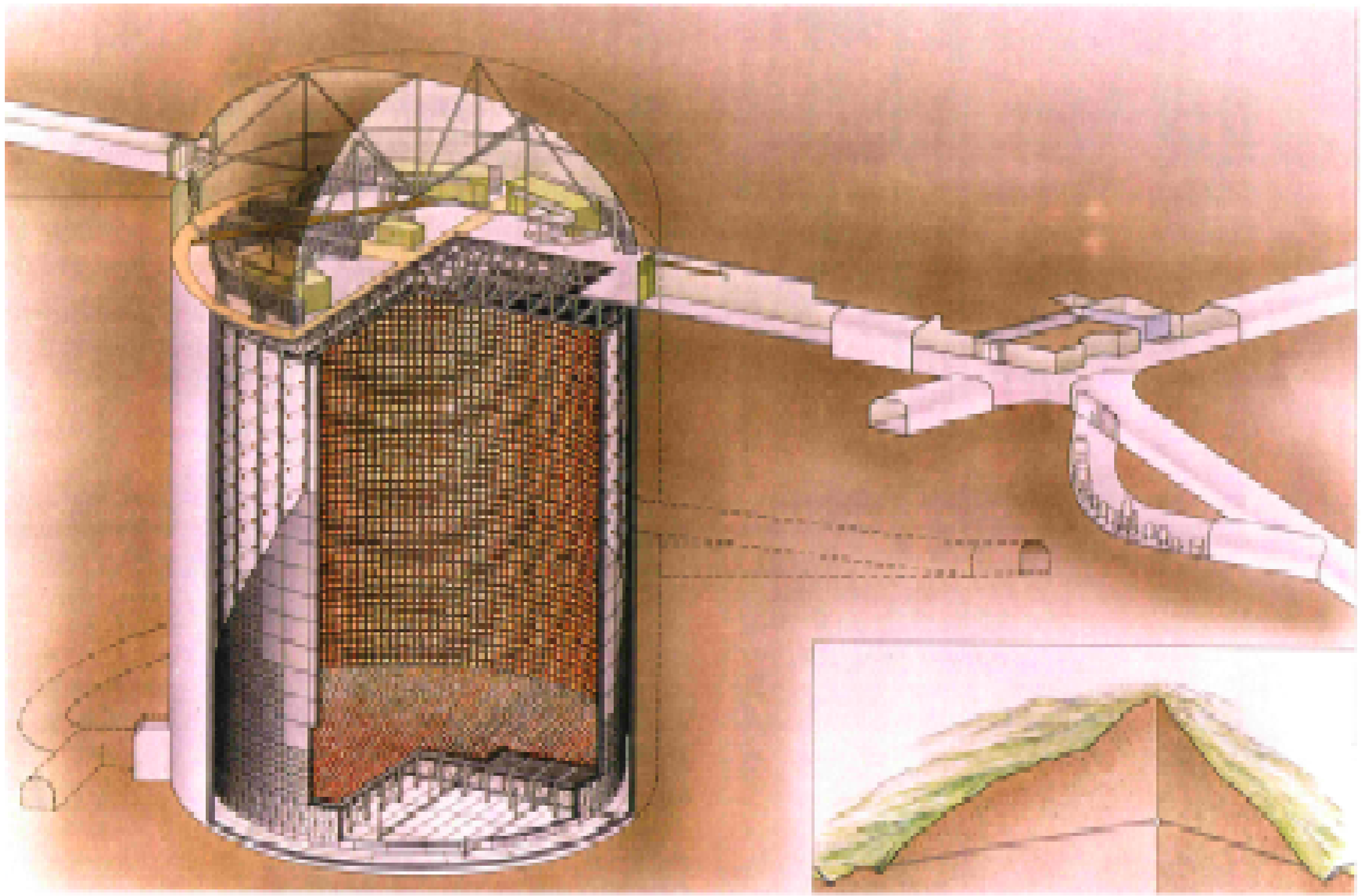
As voltage step is applied at the input, current is drawn to charge up successive segments of the cable. And infinite cable therefore acts like a resistor. If the termination has the same resistance as the cable impedance, then the same current continues to be drawn.

Termination	Reflection
0	-V
0 to Z_o	-V to 0
Z_o	0
> Z_o	0 to +V

Energy loss parameters

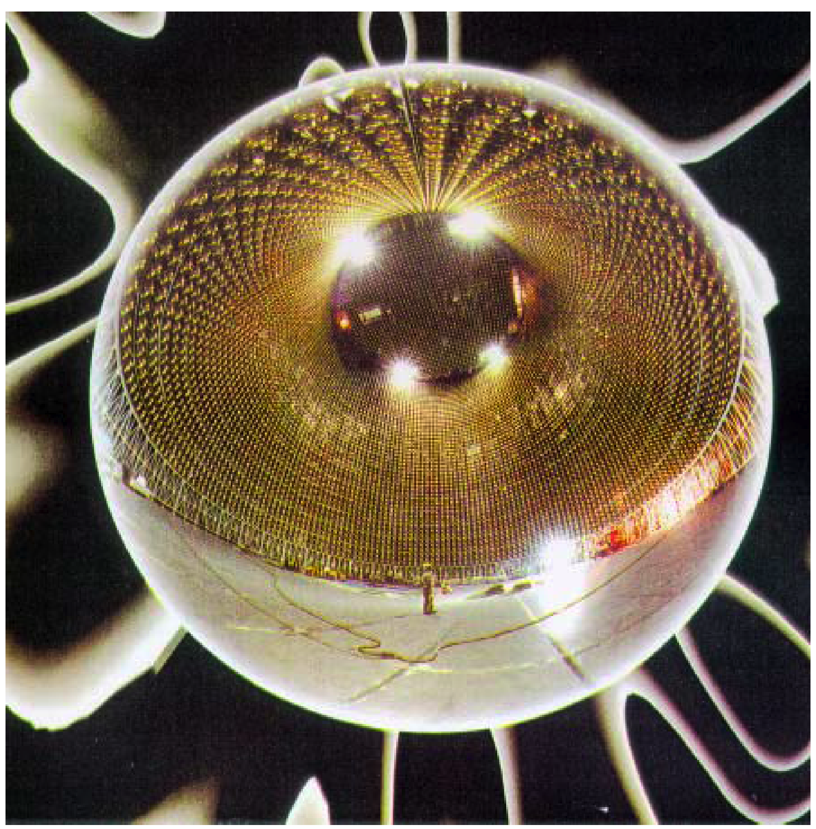
Material	Composition	Density	Z/A	Ecritical (MeV)	Radiation Length	Nuclear Collision Length	dE/dx_min
Water/Ice	H_2O	1.0	0.55	78.3	36 cm	58 cm	1.99 MeV/cm
Liquid Scintillator	~CH_2	~0.9	~0.57	102	~50cm	~60 cm	1.87 MeV/cm
Steel	Fe	~7.87	0.46	21	1.75 cm	10.4 cm	11.4 MeV/cm
Liquid Argon	Ar	1.4	0.45	30.5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

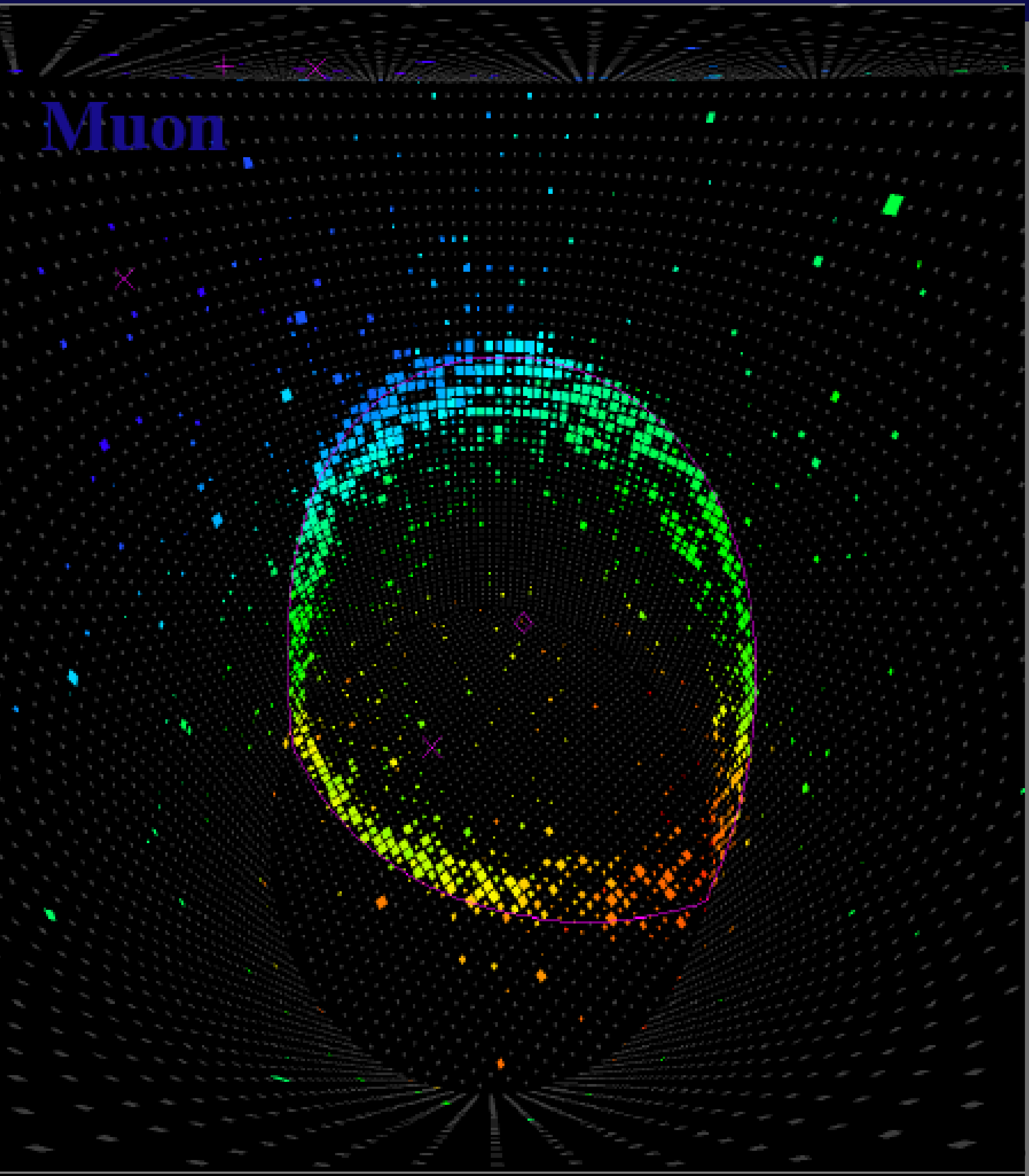
$$Yield = 370 \bullet \mathrm{Sin}^2 \theta_c \bullet 0.4 \bullet 0.2 \approx 10 \ pe/cm$$

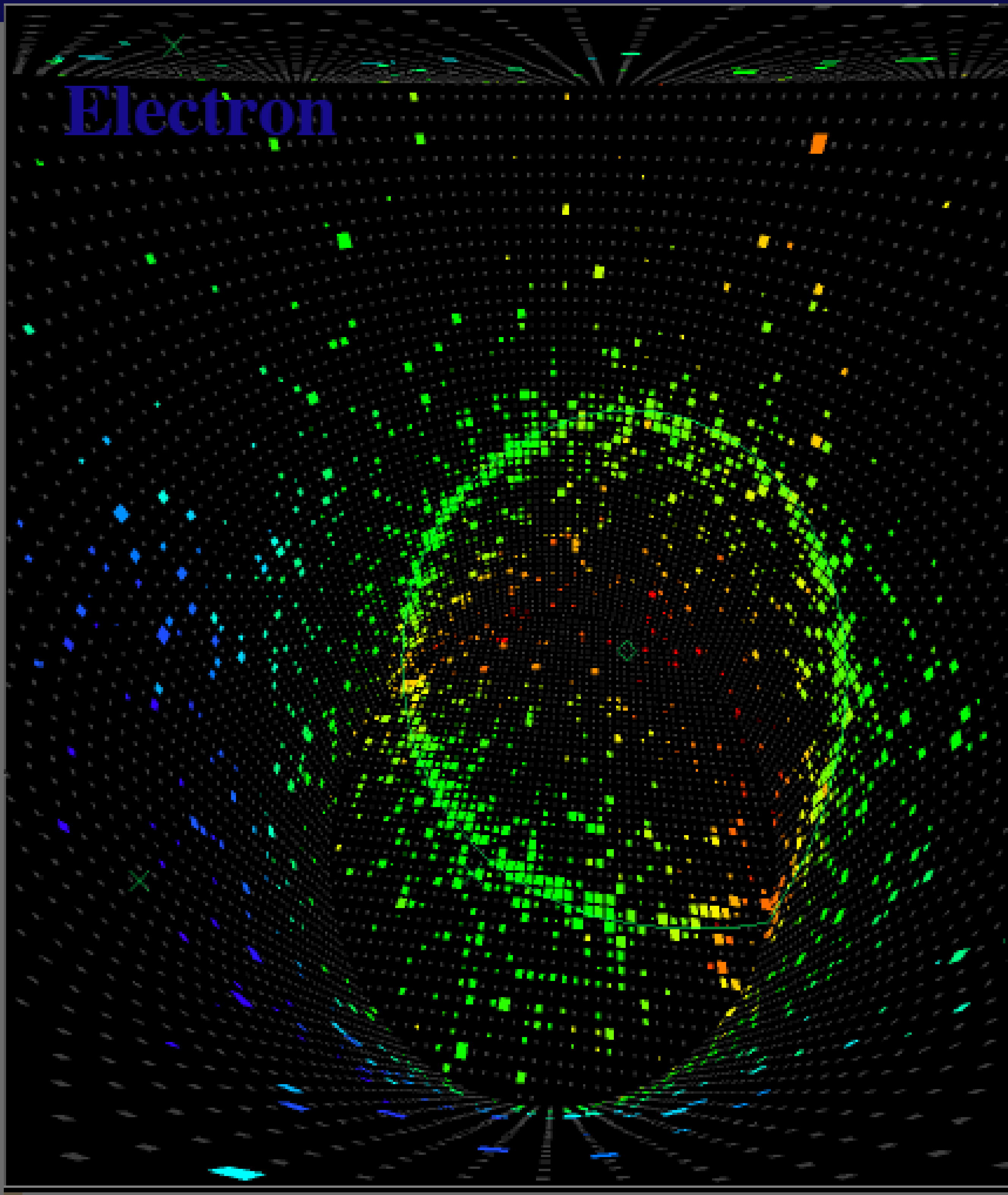
↑

Coverage X Photon detector efficiency

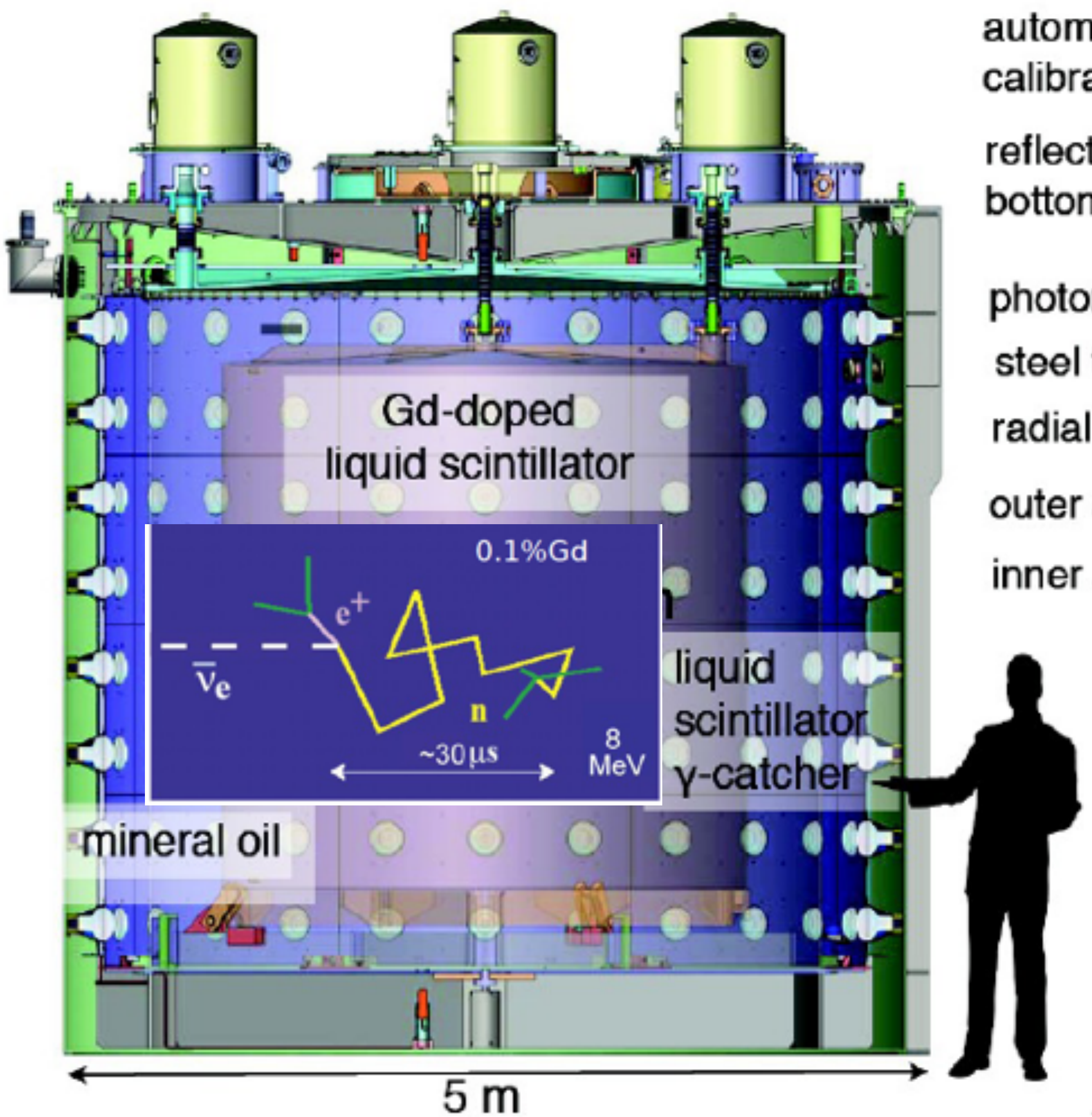
Technical issue: PMTs have to withstand huge pressure.

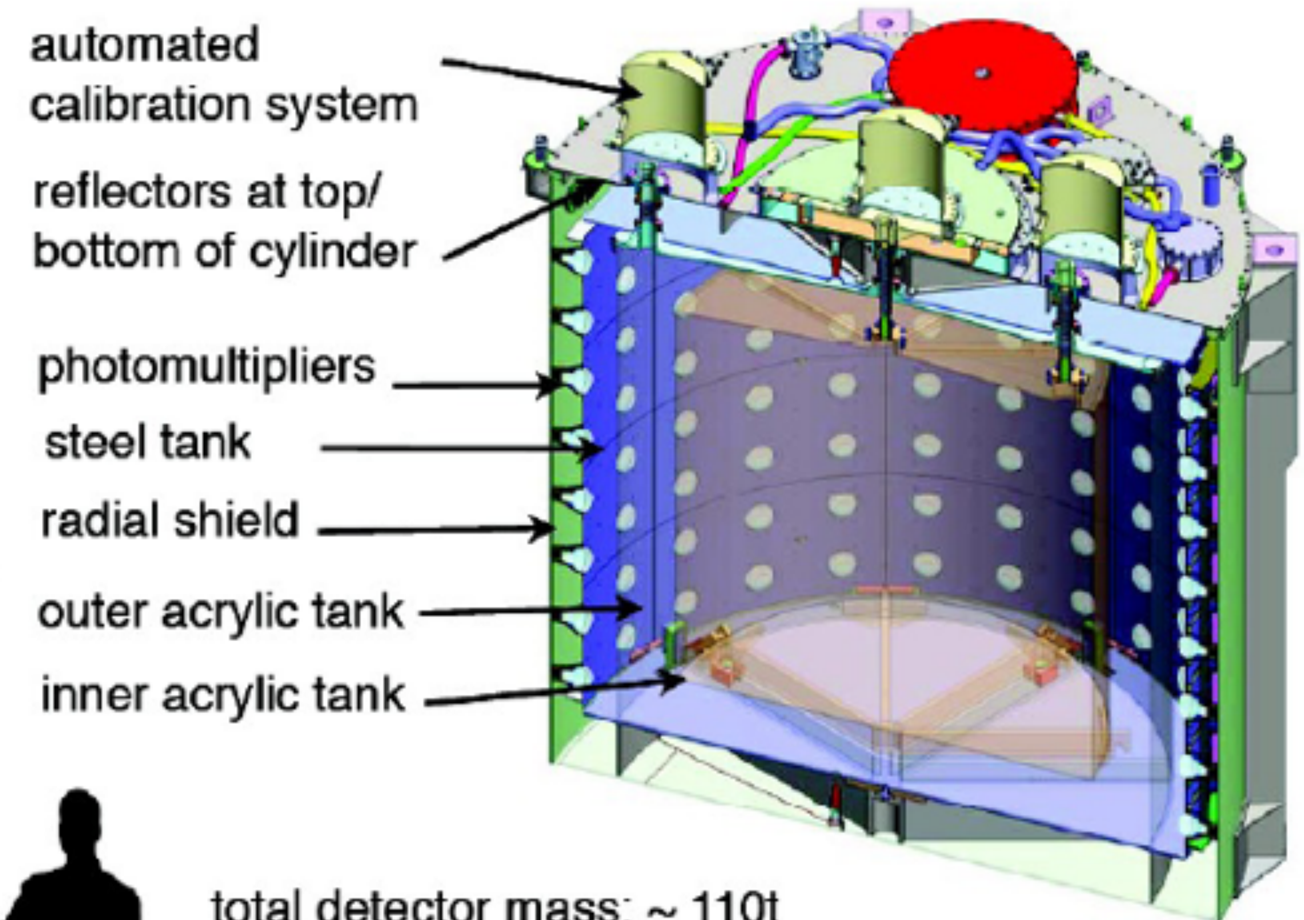
Particle Identification





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

magnetized steel detector (INO)

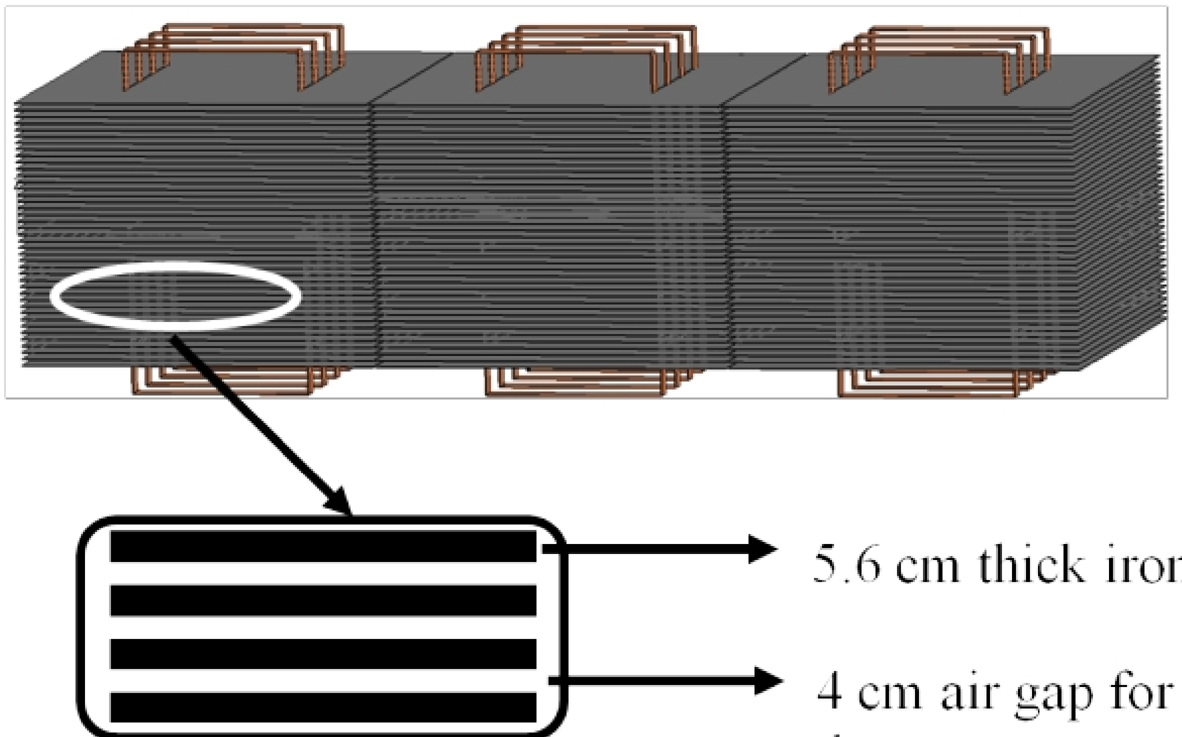
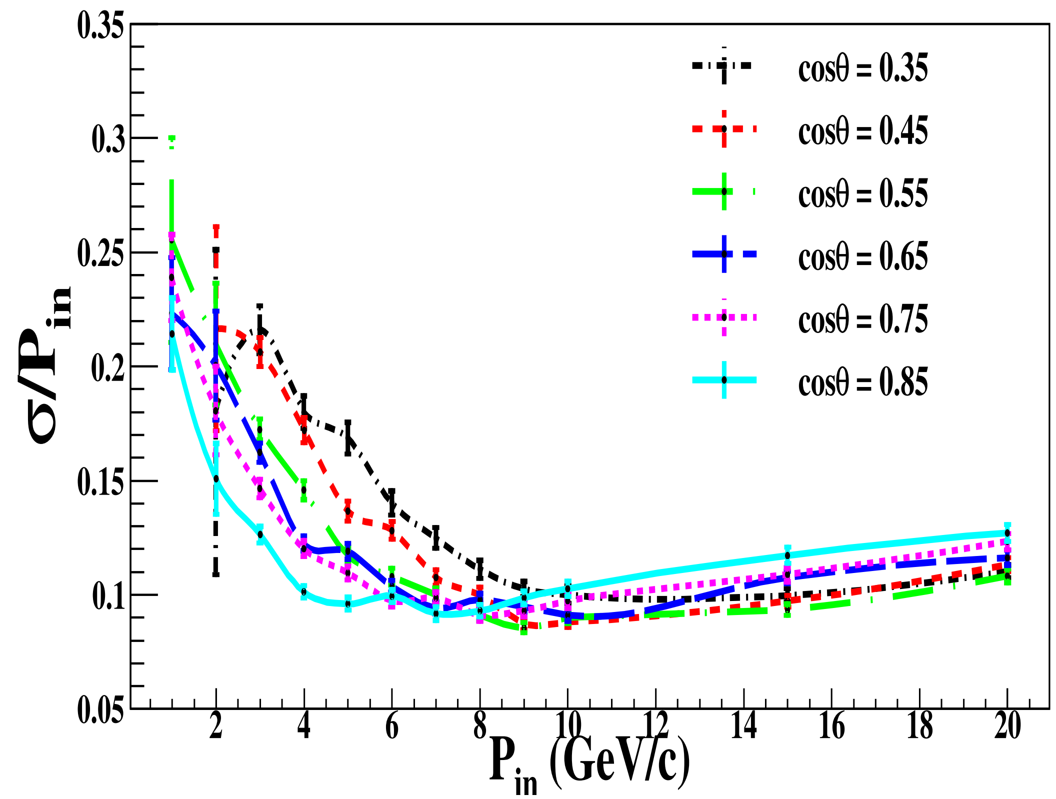


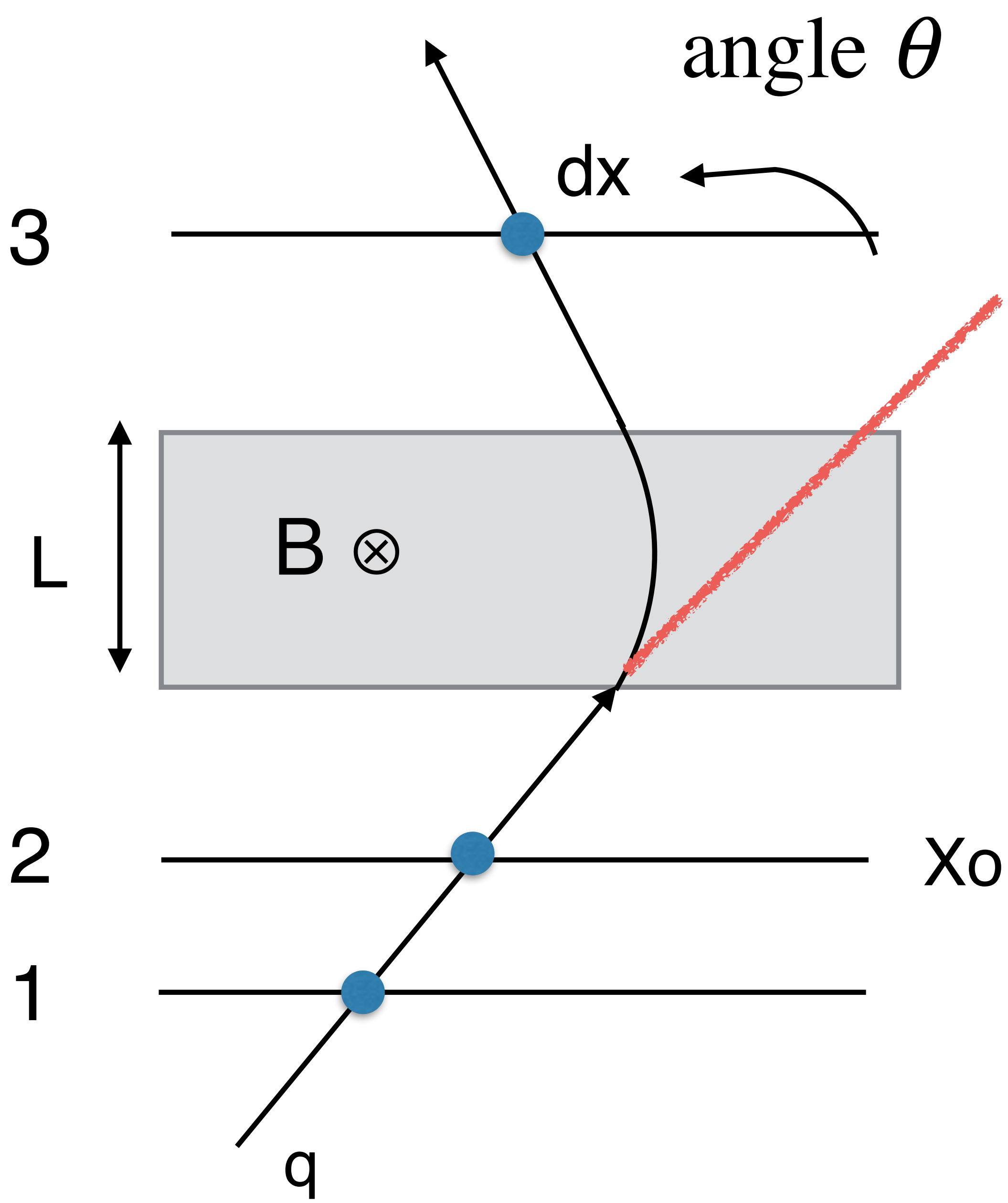
Figure 1.3: Schematic view of the 50 kt ICAL detctor



Modules	3
Module area	16 x 16 m
Layers	151
Fe thickness	5.6 cm
Gap	4 cm
Field	1.5 T
Mass	17 ktons

RPC dims	2 m x 2 m
strip width	3 cm
RPC/layers	64
RPC/module	~10000
Total channels	3.9 M (x/y)

Magnetic spectrometer analysis



A complete analysis requires a fit to the points (x_i, z_i), but we will perform a back of envelope analysis of a simple setup

$p\cos(\lambda) = 0.3z\,B\,R$ (To measure momentum we need R)

p is particle momentum in GeV/c, λ is the pitch angle.
B is in Tesla and R is in meters. z is the particle charge in e.

There are 3 planes with measurement error (δx)

k = 1/R = curvature = $\dfrac{\theta}{S} \approx \dfrac{\theta}{L}$ (S is the pathlength.)

$dk^2 = dk_{res}^2 + dk_{ms}^2$ (resolution and multiple scattering)

$$dk_{res}^2 \approx \frac{1}{L^2}\left(2\frac{\delta x_1^2}{D^2} + 2\frac{\delta x_2^2}{D^2} + \frac{\delta x_3^2}{D^2}\right)$$ (assume D intra-plane dis.)

$$dk_{ms} \approx \frac{0.016}{Lp\beta\cos^2\lambda}\sqrt{X_0}$$ (p in GeV/c, X_0 is rad. len. fraction)

Basic magnetic spectrometer analysis

$$\frac{\delta p}{p} = \frac{\delta k}{k} = \frac{p\cos(\lambda)}{0.3B}\delta k$$

$$\frac{\delta p}{p} = \frac{\cos(\lambda)}{0.3\,B\,L}\left[\frac{5p^2}{D^2}\delta x^2 + \frac{0.016^2}{\beta^2\cos^4(\lambda)}X_0\right]^{1/2}$$

$\frac{\delta p}{p} \sim \frac{1}{B}$ Always improves with B

$\frac{\delta p}{p} \sim \frac{1}{L^2}$ with small M.S. contribution (D~L)

$\frac{\delta p}{p} \sim p \bullet \delta x$ with small M.S. contribution

Numerical factor 5 depends on the number of measurements and their locations. see (Gluckstern '63)

$\frac{\delta p}{p} \sim$ constant for low mom. due to M.S.

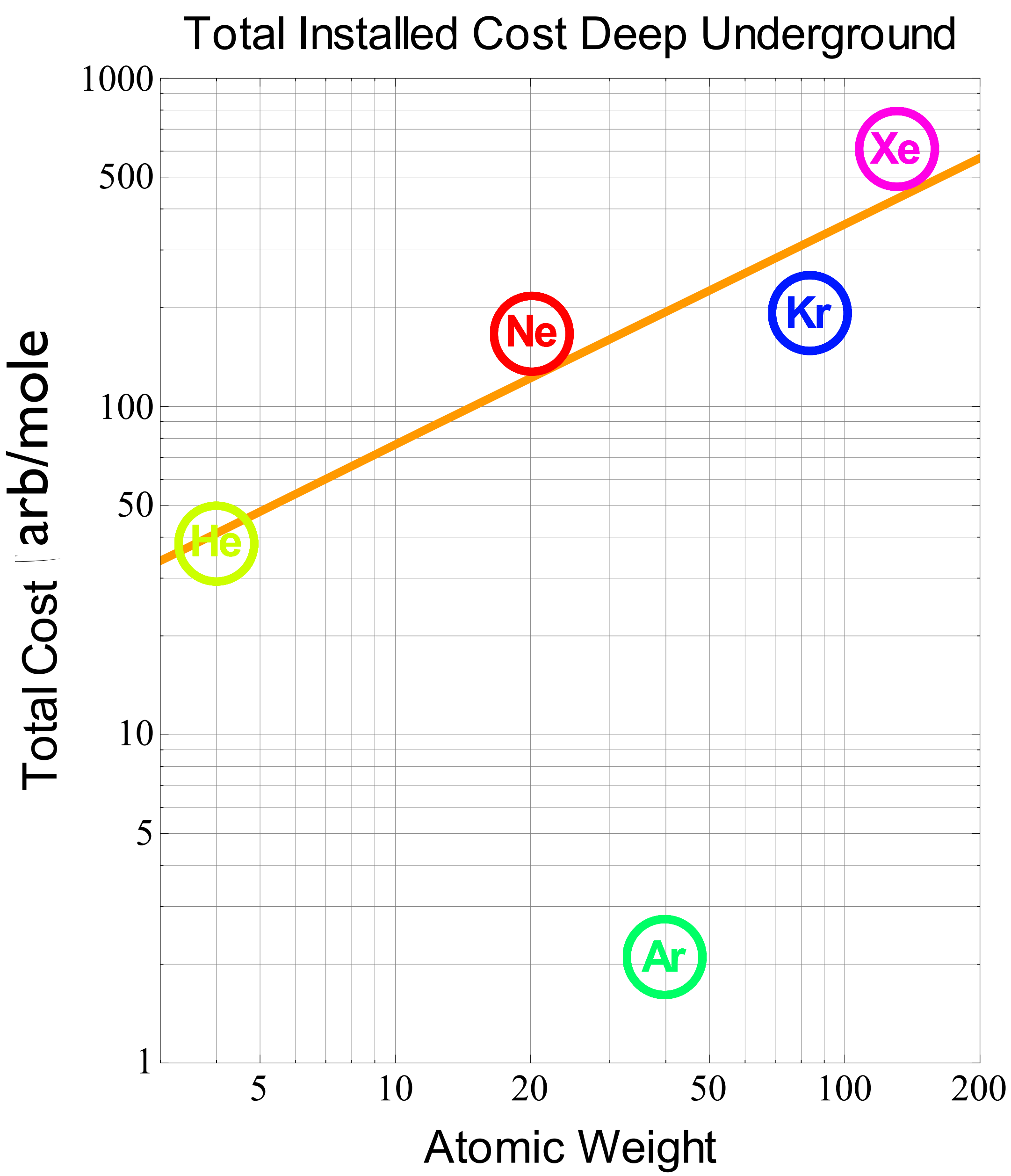
$\frac{\delta p}{p} \sim \frac{1}{B \bullet L}$ for M.S. dominated measurement

Notice that M.S. contributes less if the second measurement station #2 is close to the magnet $\Rightarrow$

If the measurements are inside the field, it is important that the measurement spacing is uniform.

What about Liquid Argon ?

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

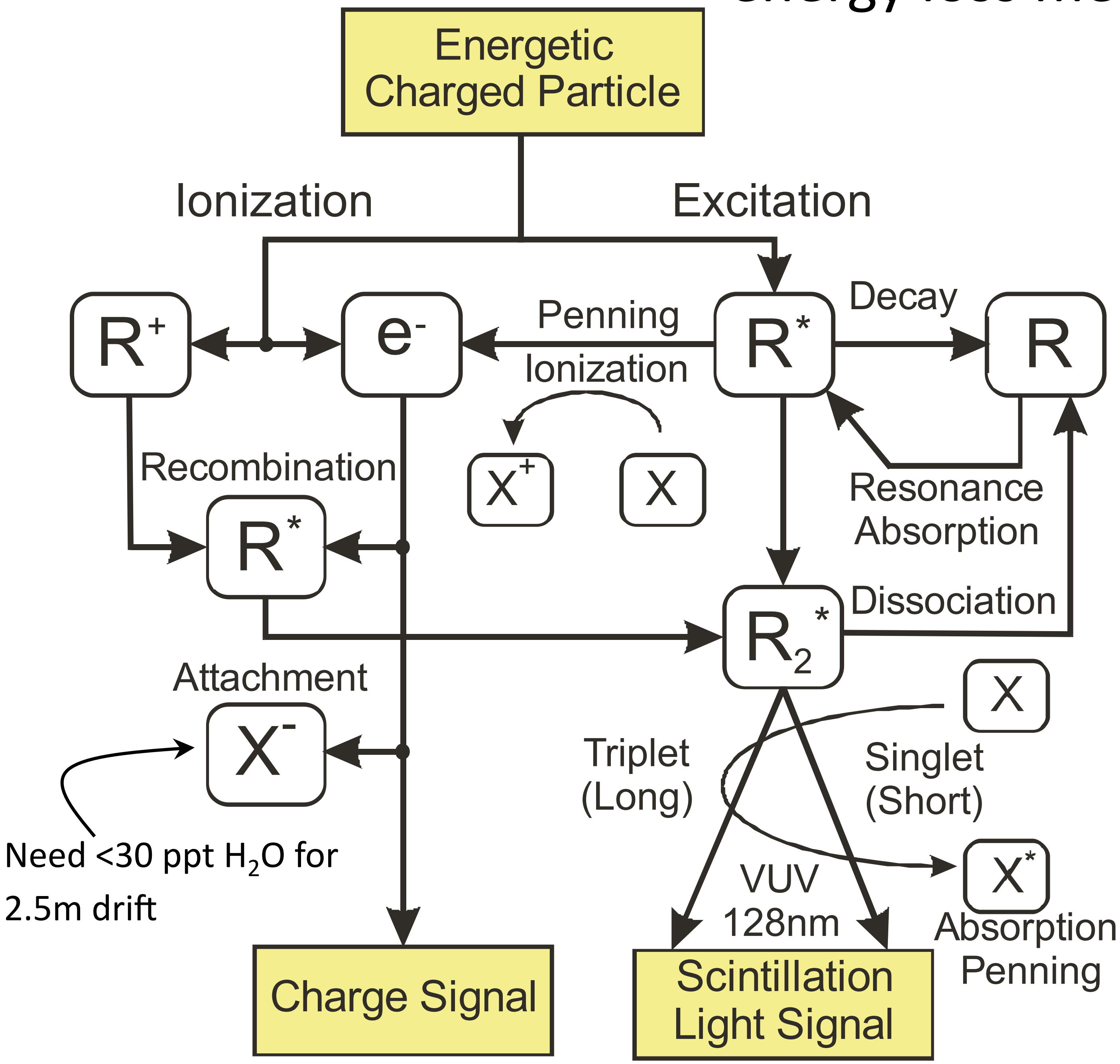


atomic num	In Air (ppm)	In Crust (ppb)	Ionization (eV) (atom)
He (2)	5.2	8	24.6
Ne(10)	18	0.07	21.6
Ar(18)	9300	1200	15.8
Kr(36)	1.14	0.01	14.0
Xe(54)	0.086	0.047	12.1

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. W is greater than the ionization potential because it includes other energy loss mechanisms.

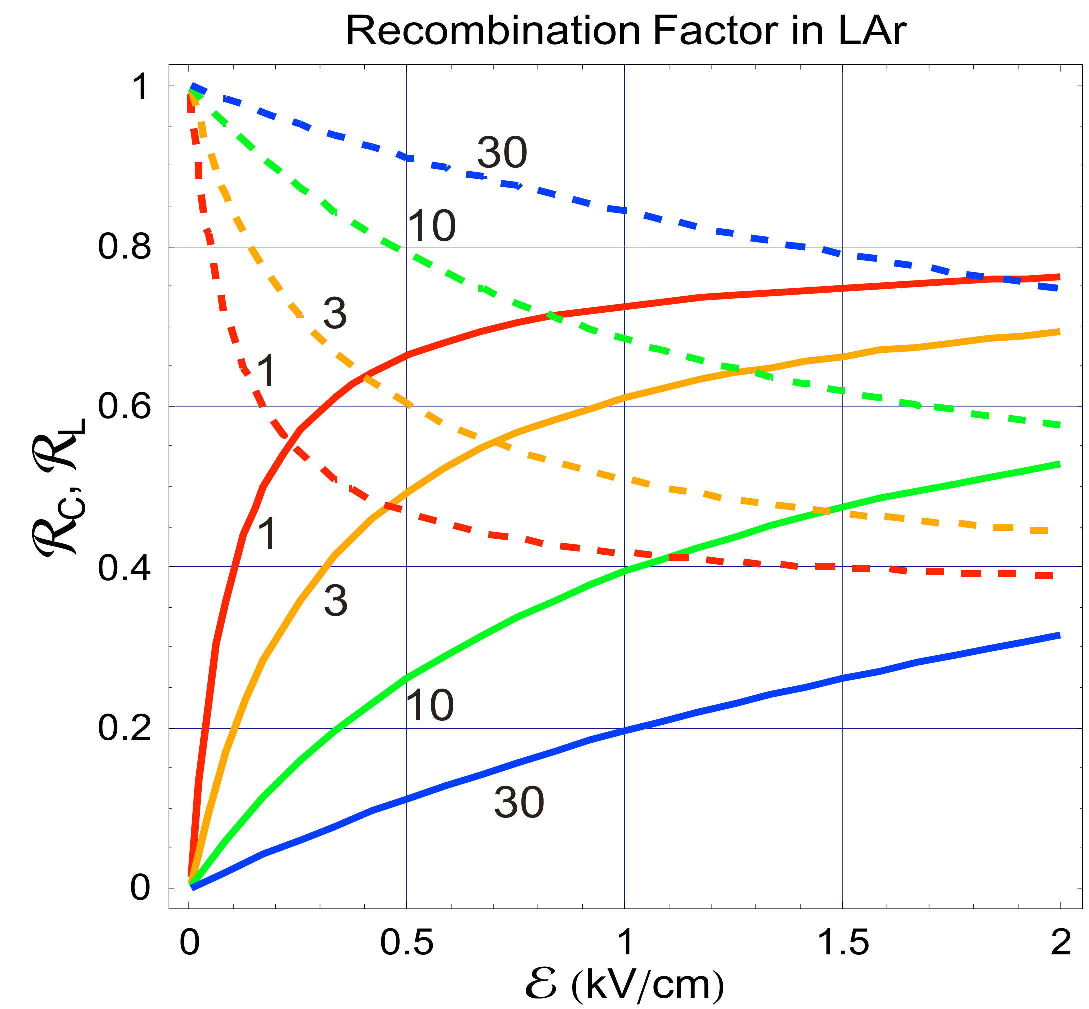
R={LNe, LAr, LKr, LXe}
X={N_2, O_2, H_2O, …}



E→∞
42,000 e/MeV
8980 e/mm for MIP

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

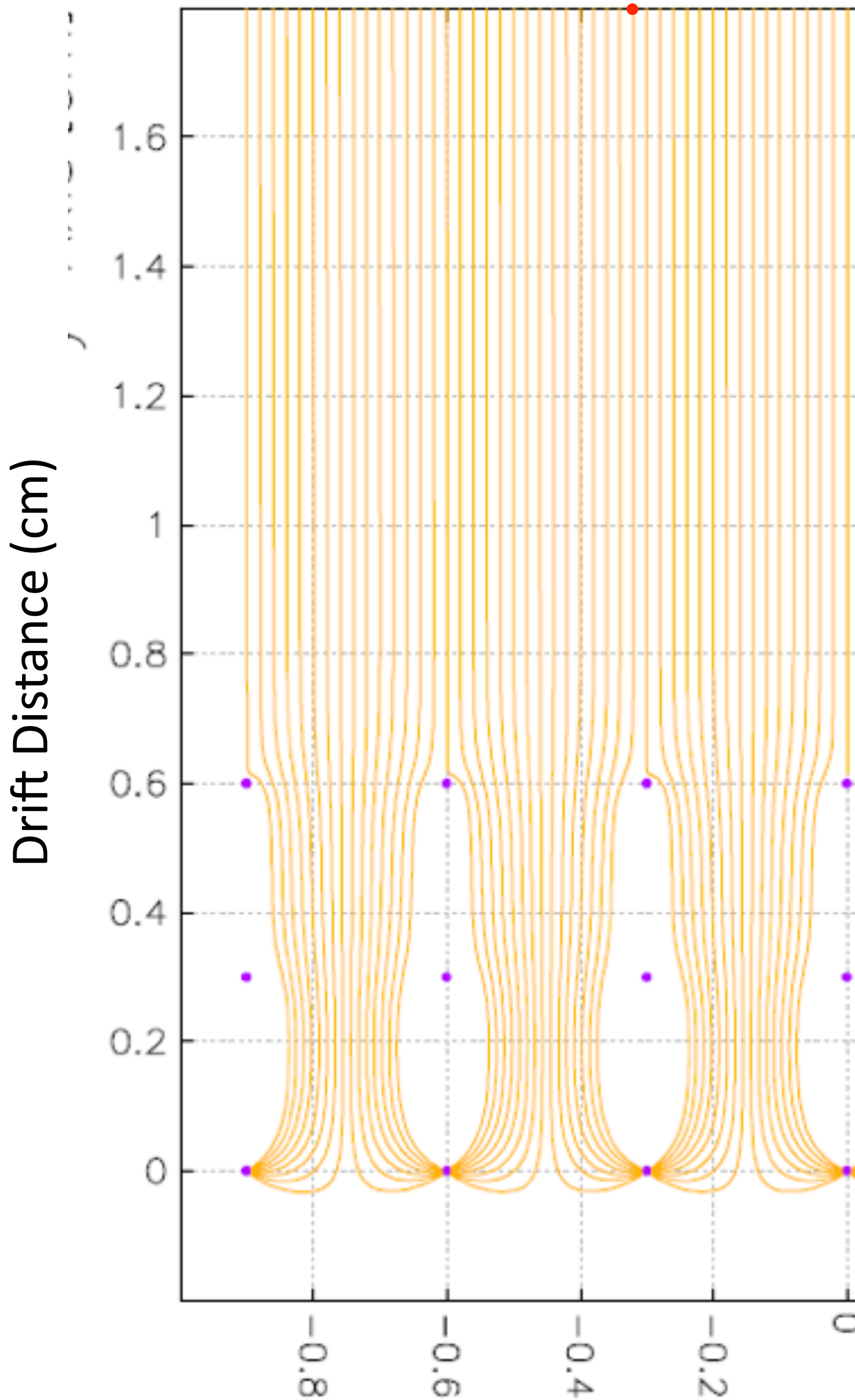
(40,000 for NaI(Tl))

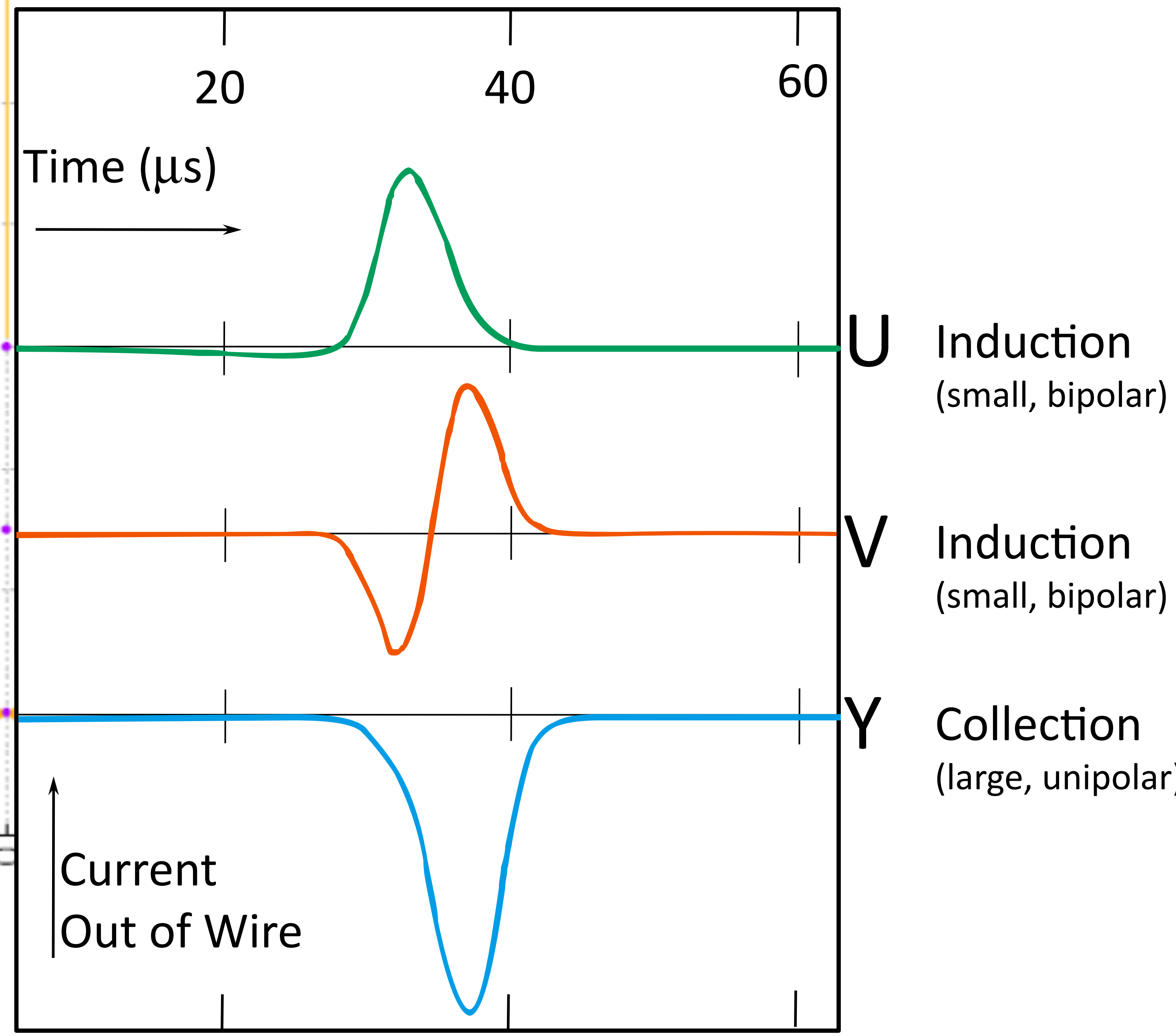


Ratio w/r/t full yield
Solid: charge, Dashed: light
Numbers: Specific Eloss in MIPs

Charge Signal Formation

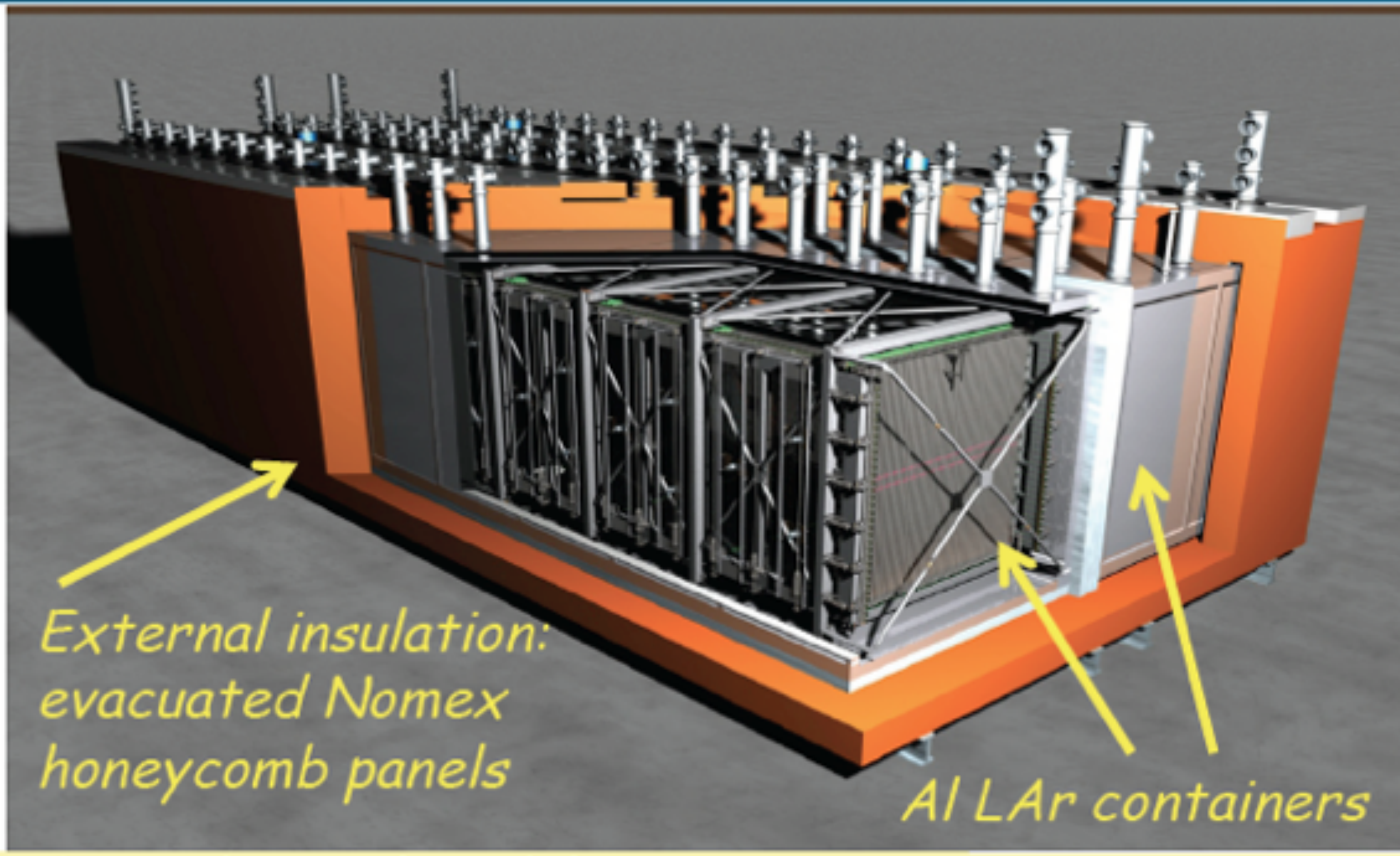
Induction by
and
Collection of
} electrons on wires

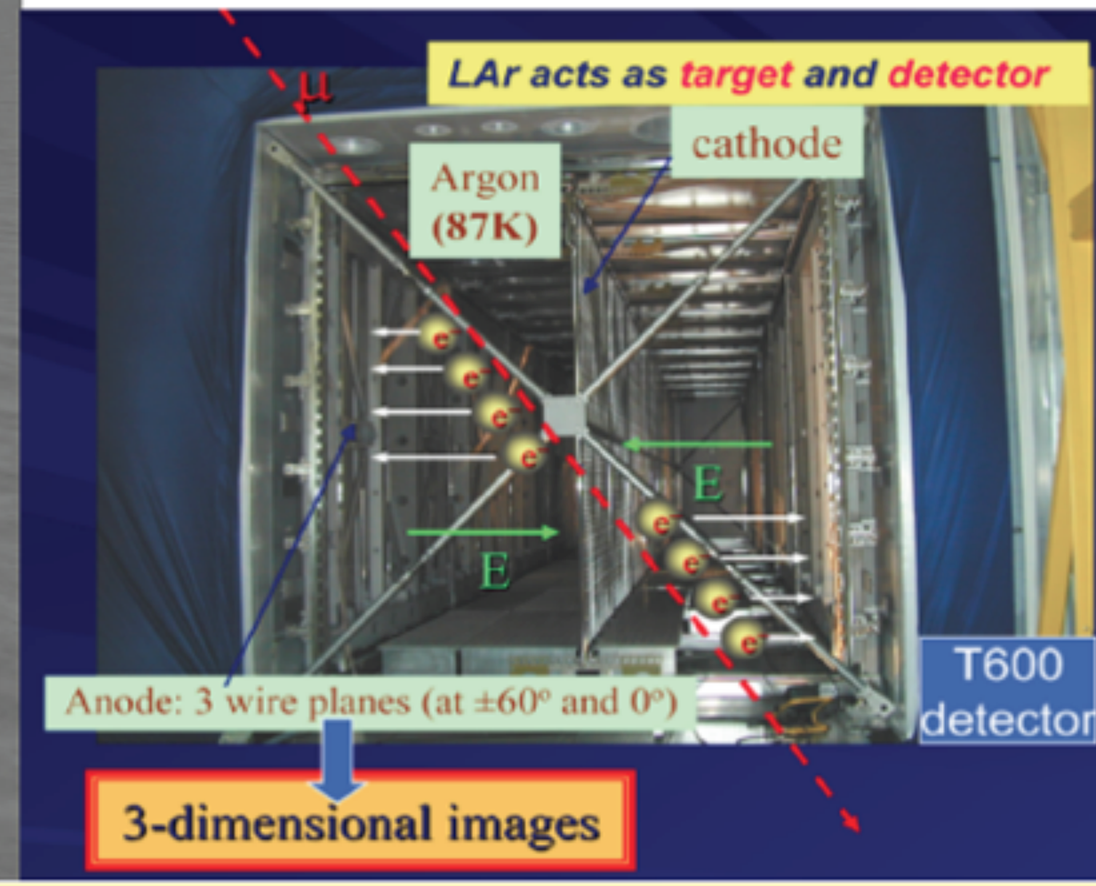




Signal formation starts upon motion of the charge.

The ICARUS single-phase T600 LAr-TPC





- *Two identical modules*
  - *3.6 x 3.9 x 19.6 ≈ 275 m³ each*
  - *Liquid Ar active mass: ≈ 476 t*
  - *Drift length = 1.5 m (1 ms)*
  - *HV = -75 kV; E = 0.5 kV/cm*
  - *v-drift = 1.55 mm/μs (~1ms max drift time)*
  - *Sampling time 0.4μs (sub-mm resolution in drift direction)*
- *4 wire chambers:*
  - *2 chambers per module*
  - *3 "non-distructive" readout wire planes per chamber wires at 0,±60° (up to 9 m long)*
  - *Charge measurement on collection plane*
  - *≈ 54000 wires, 3 mm pitch, 3 mm plane spacing*
- *20+54 PMTs , 8" Ø, for scintillation light detection:*
  - *VUV sensitive (128nm) with wave shifter (TPB)*

Conclusion

- This lecture was about the basics of neutrino detectors.
  - But many techniques are common for all detectors.
- Most important feature for neutrino detectors 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