Advanced detectors (not really)

2026 Quark Net Workshop for High School Teachers

We will continue and describe the mechanism for actual readout of the detectors.

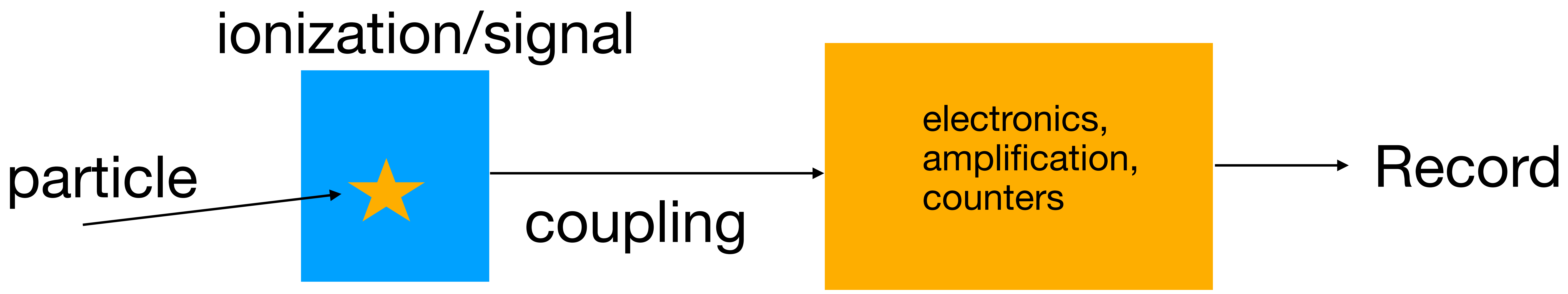
Milind Diwan June 29, 2026

Plan of lecture

- Reminder of Basics of Radiation Detectors
- Basic components of detectors.
- Detector components and how they work.

I will use neutrino and cosmic ray detection in my examples, but most of the techniques are common in all radiation detection.

Radiation Detection



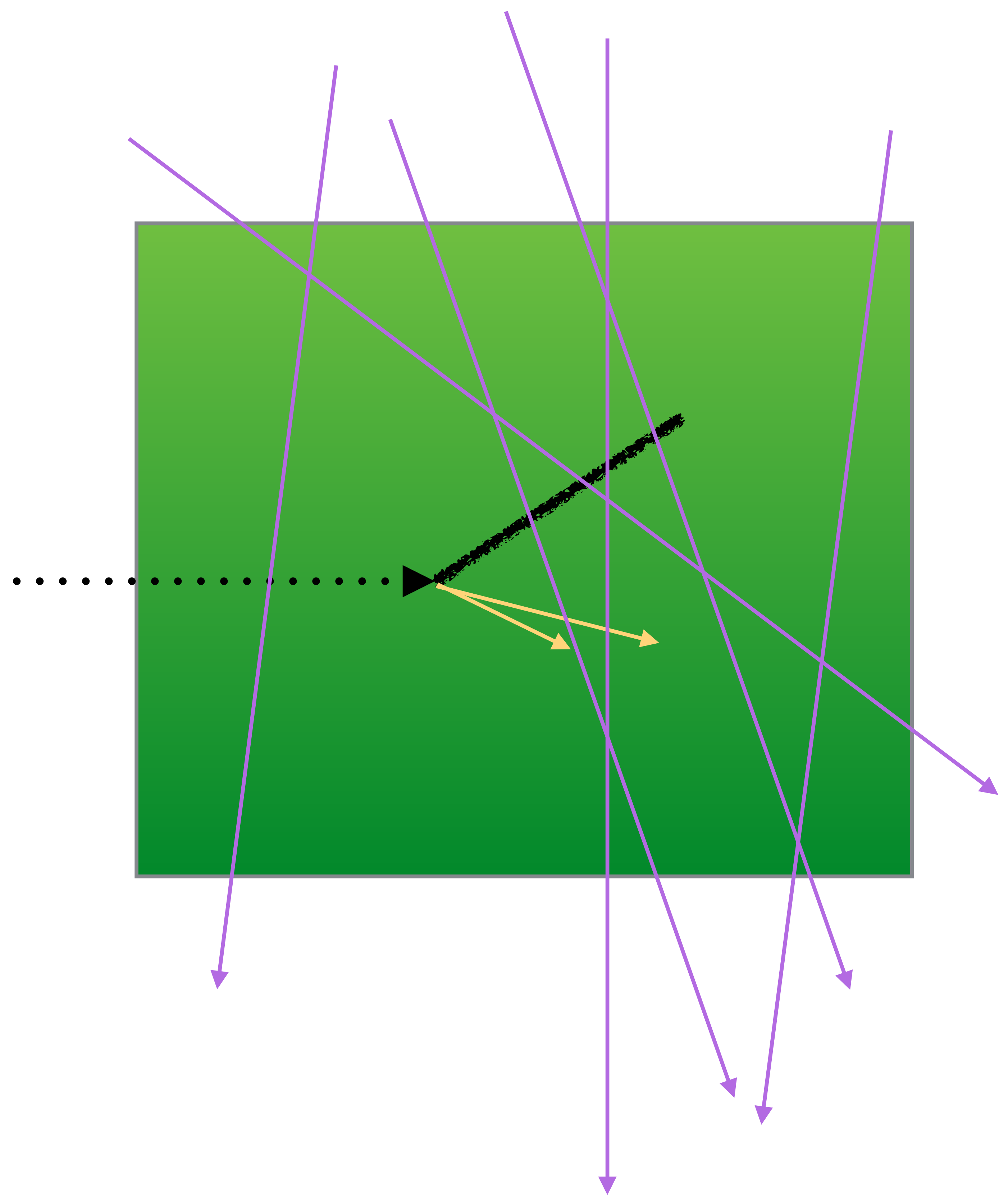
- ***Fast particles produce ionization in materials.***
- ***Ionization produces free charges which can be moved/ manipulated to produce a signal in wires.***
- ***Ionization also produces light in some materials. This light can be sensed in various ways.***
- ***Both ideas require understanding amplification and noise, and basics of electric circuits.***

Units

Most of physics can be approached by understanding the value of numbers that are assigned to quantities. All values come with a units. Detector physics has its own language of units.

- Charge: Coulombs. electrons have $1.602 \times 10^{-19} C$
- Current: Ampere = Coulombs/sec.
- Power: $Watts = \text{Joules/sec} = (\text{kg m}^2/\text{sec}^2)/\text{sec} = \text{Newton m/sec} = \text{Volt} \times \text{Ampere}$
- $\text{Volts} = \text{Joules/Coulomb}$
- An electron that goes through 1 Volt then has 1.602×10^{-19}joule = 1 eV
- This is used throughout physics as a defining units for energy, mass, and momentum.
- energy: eV Mass: eV/c^2 and momentum: eV/c
- MeV: 10^6eV GeV: 10^9eV etc.
- We often set c = 1, and just state quantities in eV. When actual number is needed we place the proper power of c to get the right answer.

Summarize so far

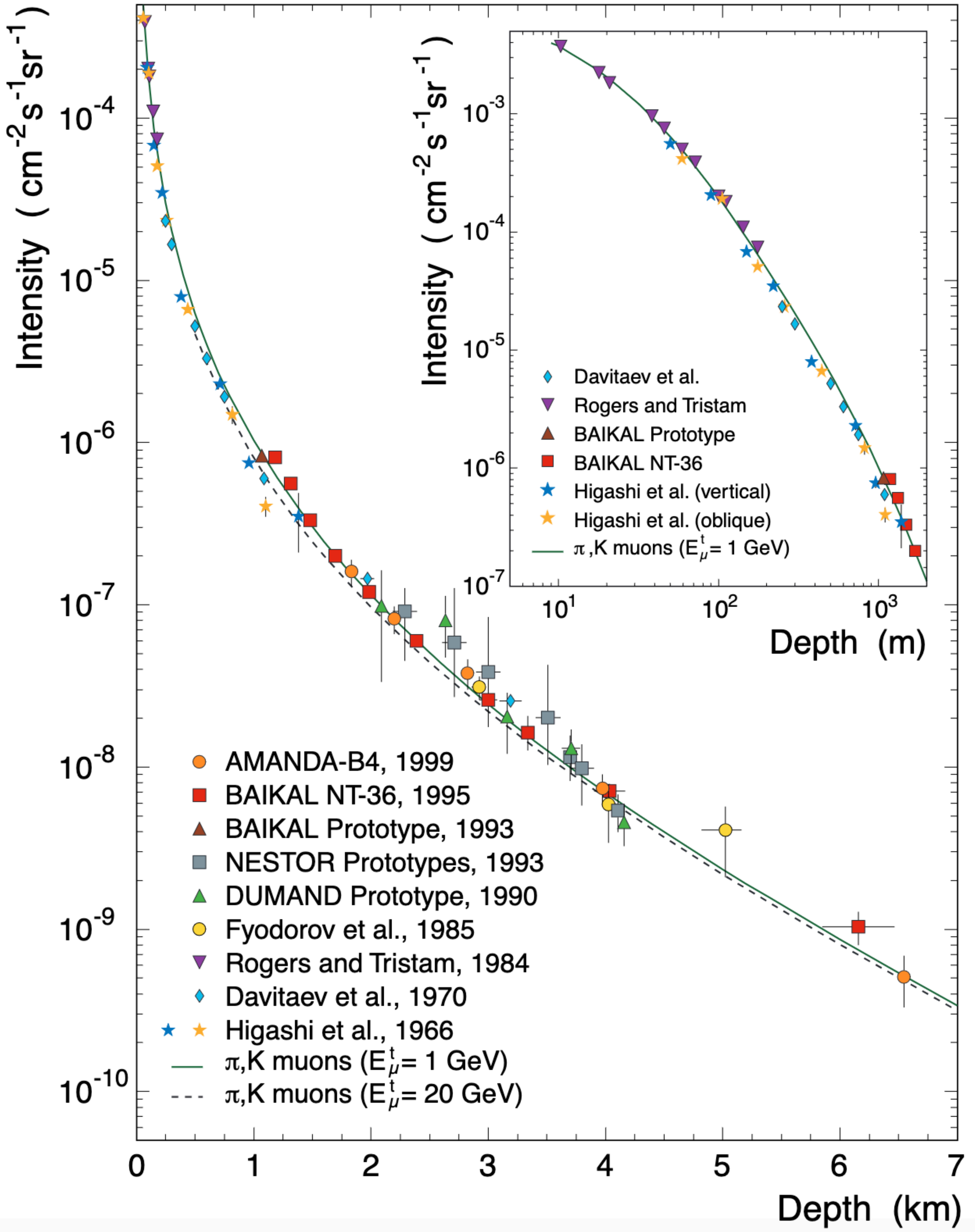


- ***Radiation particles interact in blocks of material and leave energetic charged particles including cosmic rays.***
- ***The energetic charged particles ionize the material as they slow down freeing electrons from atoms making negative charged electrons, and positive ions.***
- ***This ionization causes physical effects:***
    - ***bubbles in cloud chambers,***
    - ***dark spots in photographic plates***
    - ***current in properly made sensors***
    - ***florescence in special materials.***
- ***We register these effects by various means. pictures, electronics ?***
- ***We will focus on light and charge detection here.***

Cosmic rays

Cosmic muons are always present in any laboratory to test detectors.

- Get code from https://github.com/milinddiwan/Ecomug-music-muons
- This code uses a parametrization of cosmic ray spectra at the surface. (called ECOMUG)
- Then it can generate muons to specified depth into the earth (or water). Using code called Music.
- Muons tend to be vertical, but have an angular dependence as $\sim \cos^2(\theta_z)$
- The intensity drops with intensity as a power law $\sim E^{-2.7}$
- In the laboratory, they tend to have ~1-4 GeV/c and ~100 Hz/m^2
- It is easy to measure them with any radiation detector.

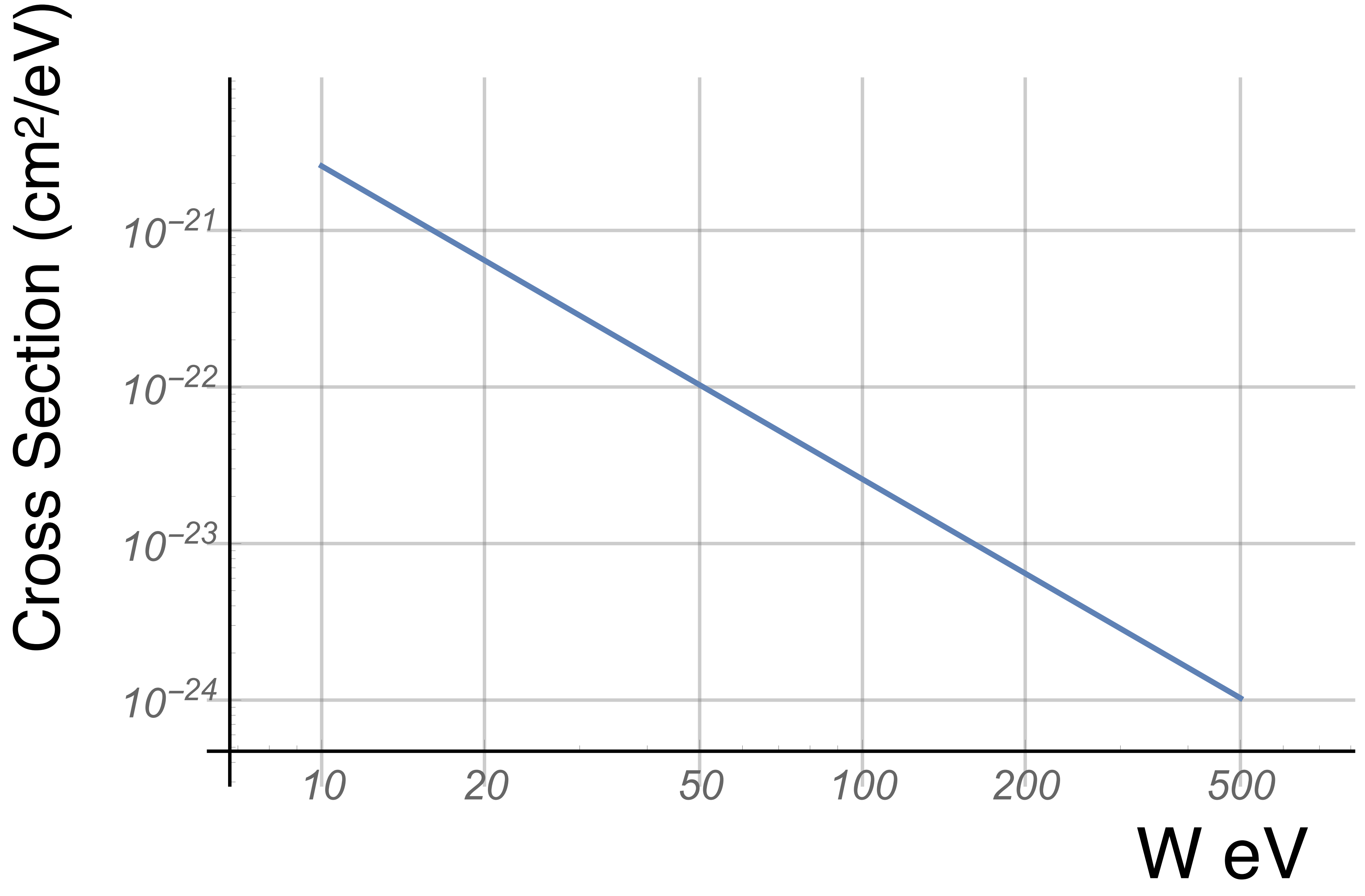


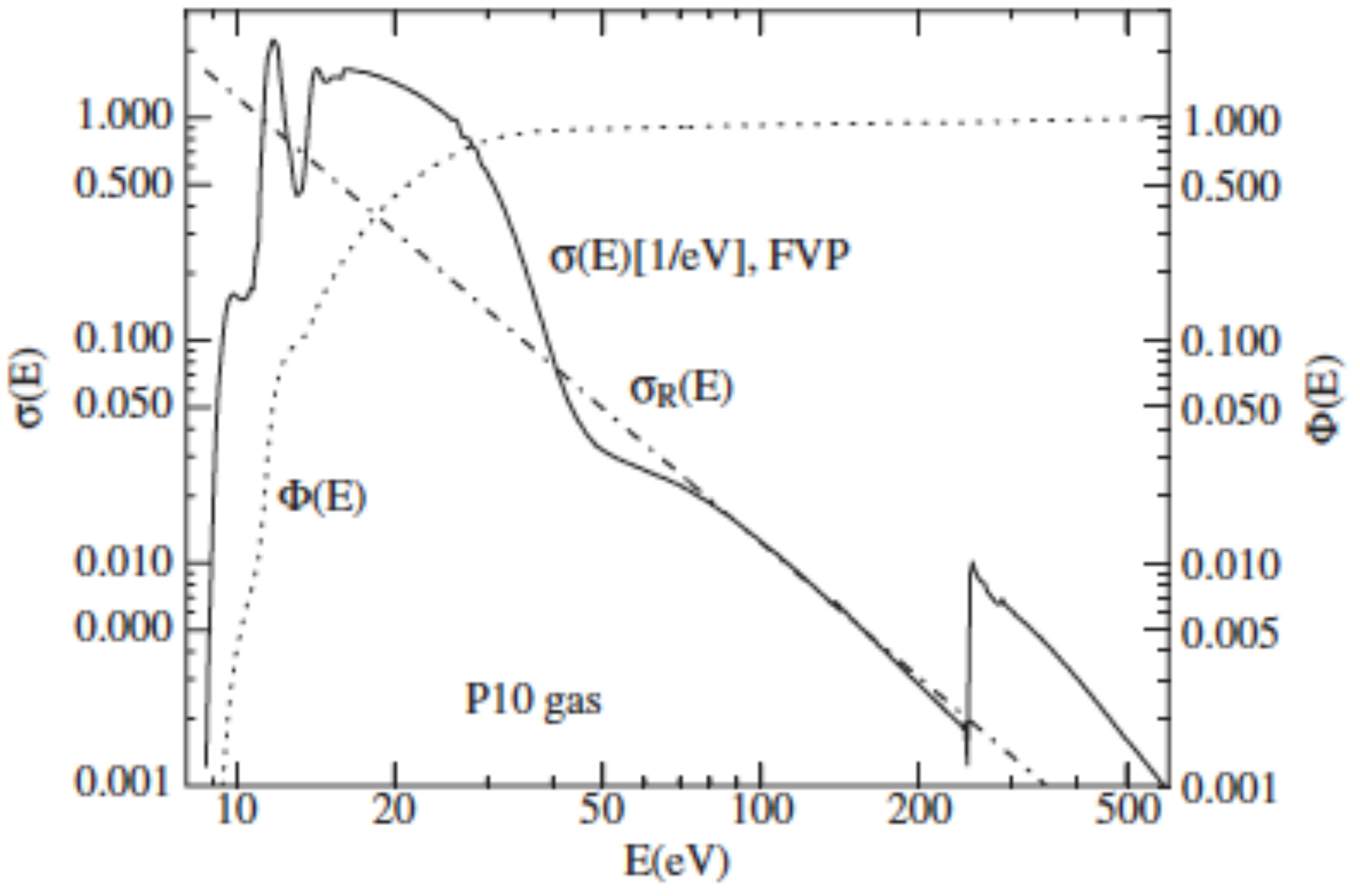
Energy Loss

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.

Maximum energy loss in single collision on free electrons.

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



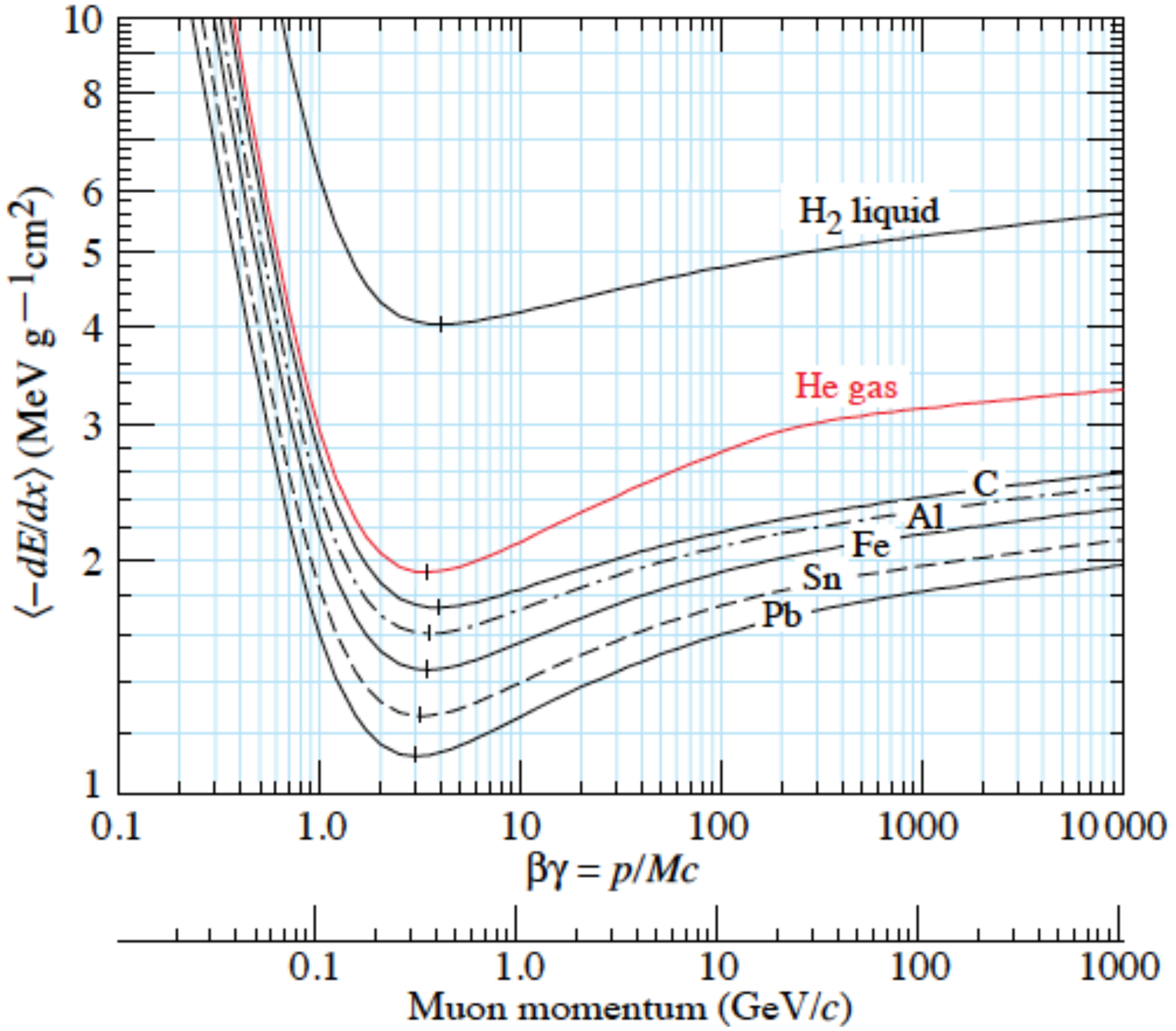


$$\frac{d\sigma(W,\beta)}{dW} = \frac{k_r}{\beta^2}\frac{(1-\beta^2 W / W_{\max})}{W^2}$$

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

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



Sternheimer Density correction

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

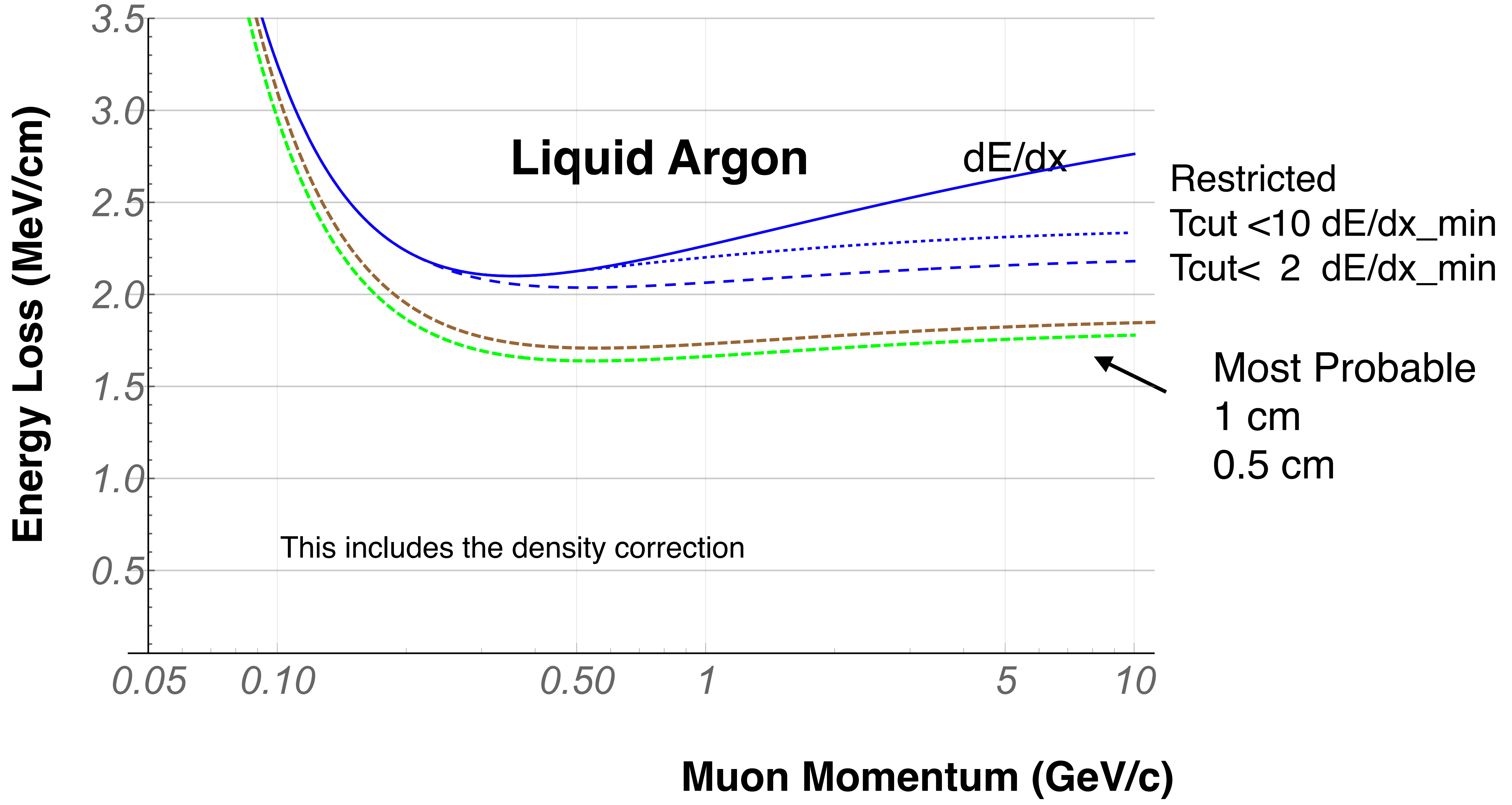
$K = 0.31\ MeV\ mol^{-1}cm^2,\ I = Mean\ Ionization\ Energy$

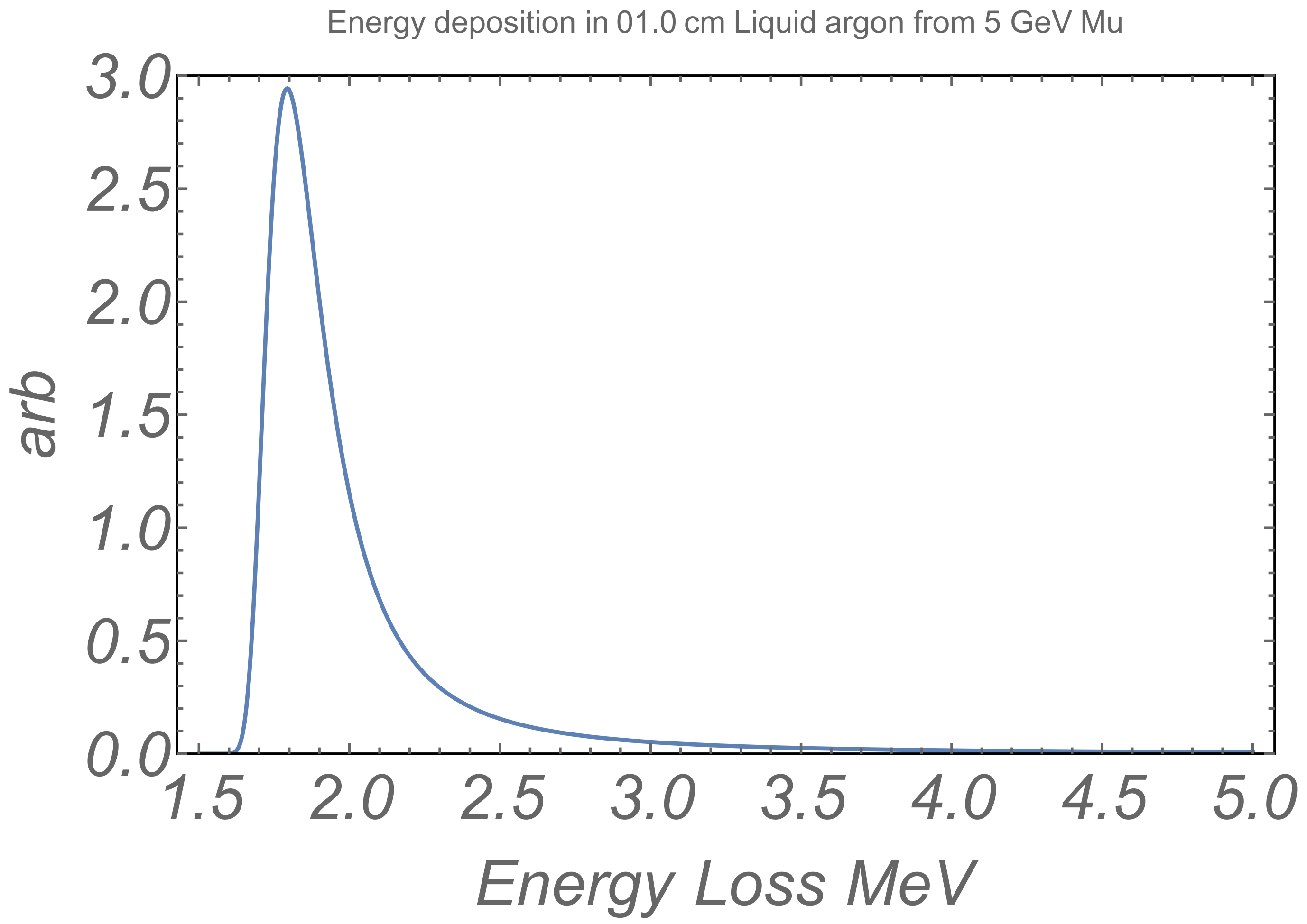
$$W_{\max} \approx 2m_e\beta^2\gamma^2 / (1 + 2\gamma m_e / M)$$

Max energy transfer in single collision.
~100 MeV for a muon with kinetic energy = 1 GeV

- Various interactions produce 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

Most probable loss and fluctuations.



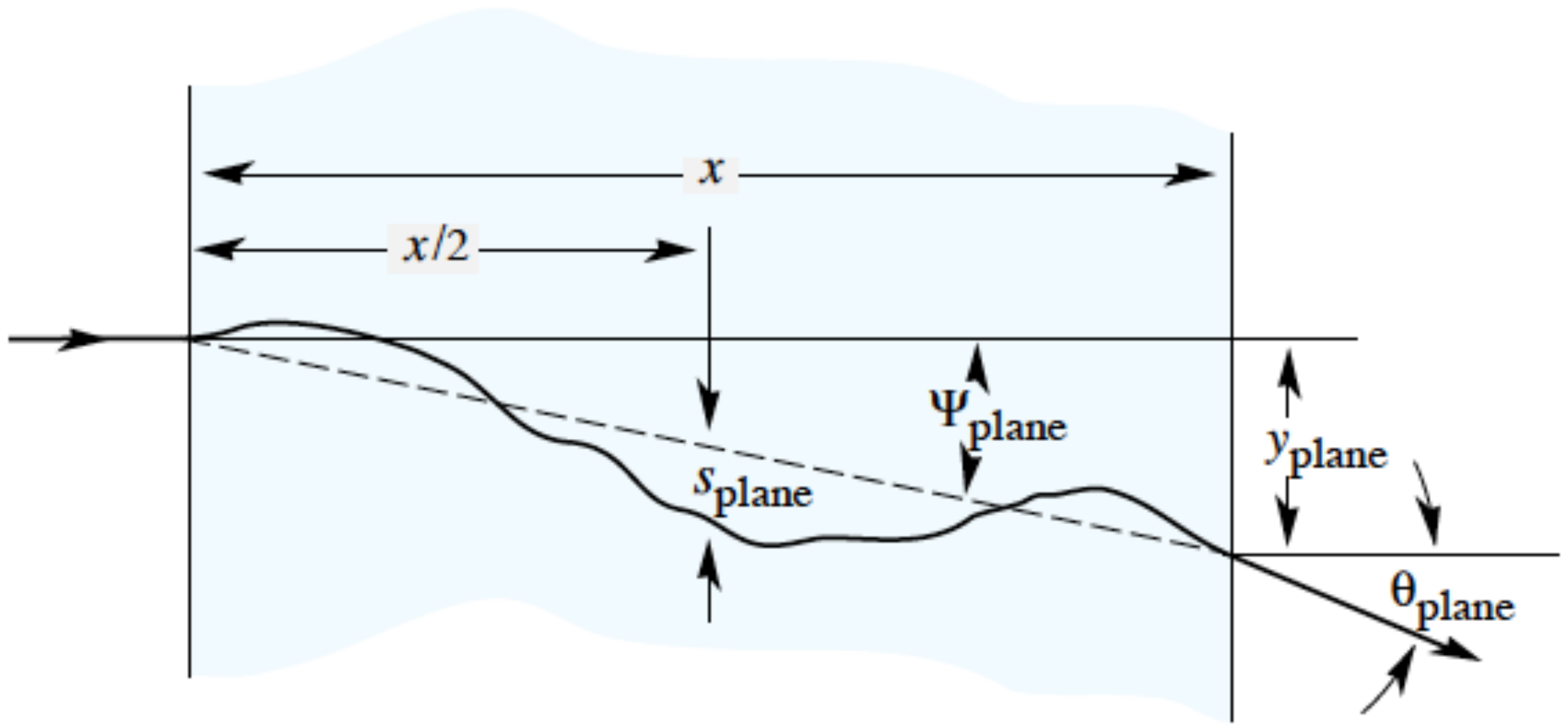


$$\Delta_p = \xi \left[Log \frac{2m_e \beta^2 \gamma^2}{I} + Log \frac{\xi}{I} + 0.2 - \beta^2 - \delta(\beta\gamma) \right] \qquad FWHM \approx 4\xi$$

$\xi = (K/2)(Z/A)(x/\beta^2)$ 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 the Landau/Vavilov distribution.
- The code for doing many of these calculations: https://github.com/milinddiwan/energyloss

Scattering



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

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

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

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

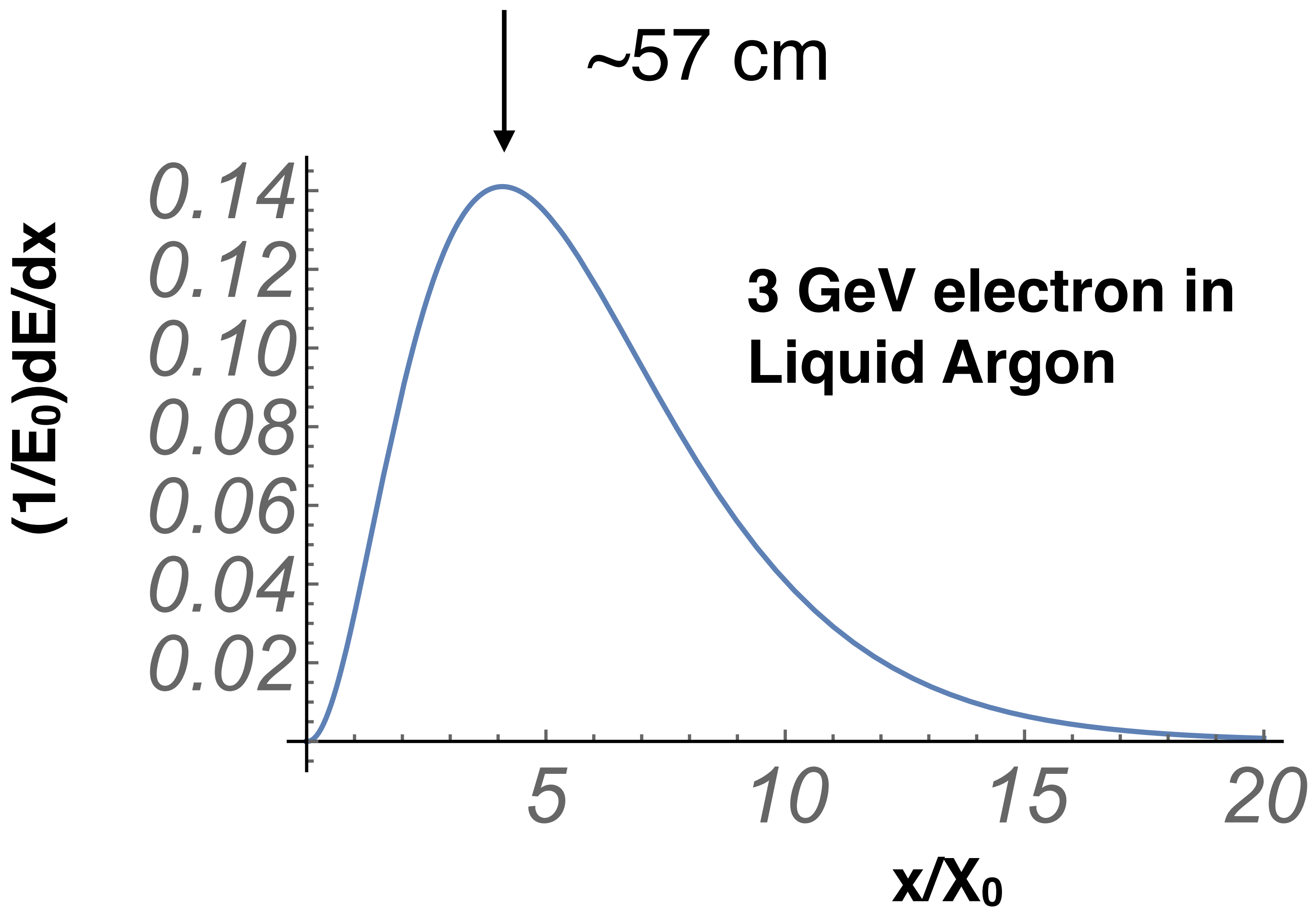
$$1/X_0 \approx (1/716) \bullet \frac{Z^2}{A} \bullet Log(\frac{184}{\sqrt[3]{Z}})\,(gm/cm^2)^{-1}$$

$For\ Z > 4$

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

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

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

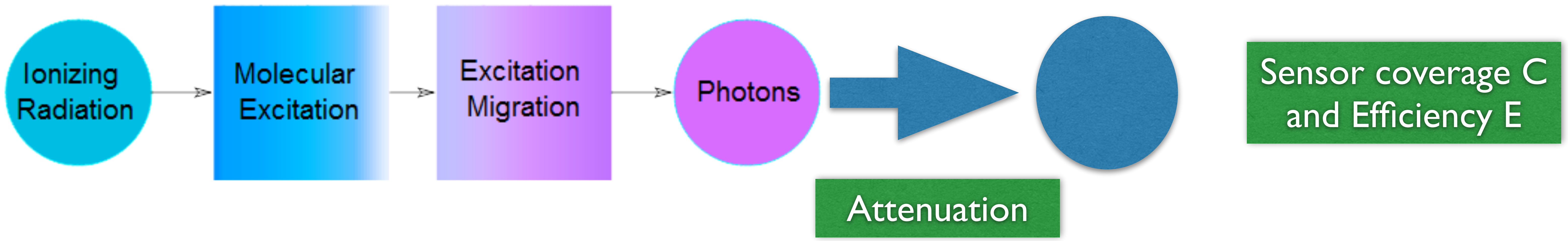


- Low E ($E_{critical}$ ~20 MeV/c) electron/positrons lose energy similarly as heavy particles with corrections.
- High energy electrons lose energy by radiating photons. Fraction (1-1/e) energy is lost after mean distance X_0
- $E_{critical}$ when ionization=Bremsstrahlung
- Photons convert to pairs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

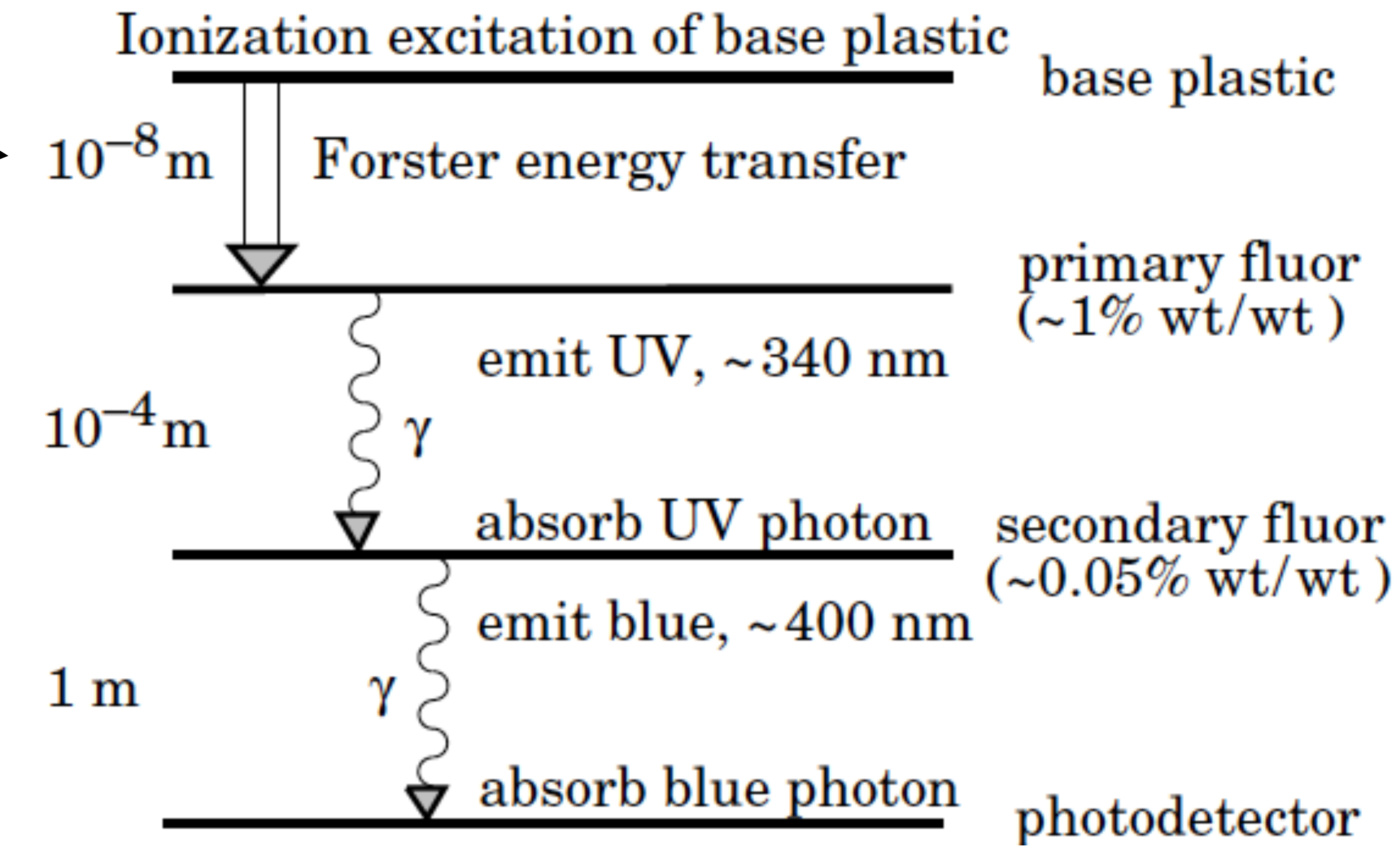
Material	Ecritical(MeV)
LAr	30.5
Water	78.3
Liquid Scint.	~102
Fe	21.7

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

Scintillation from ionization in plastics



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

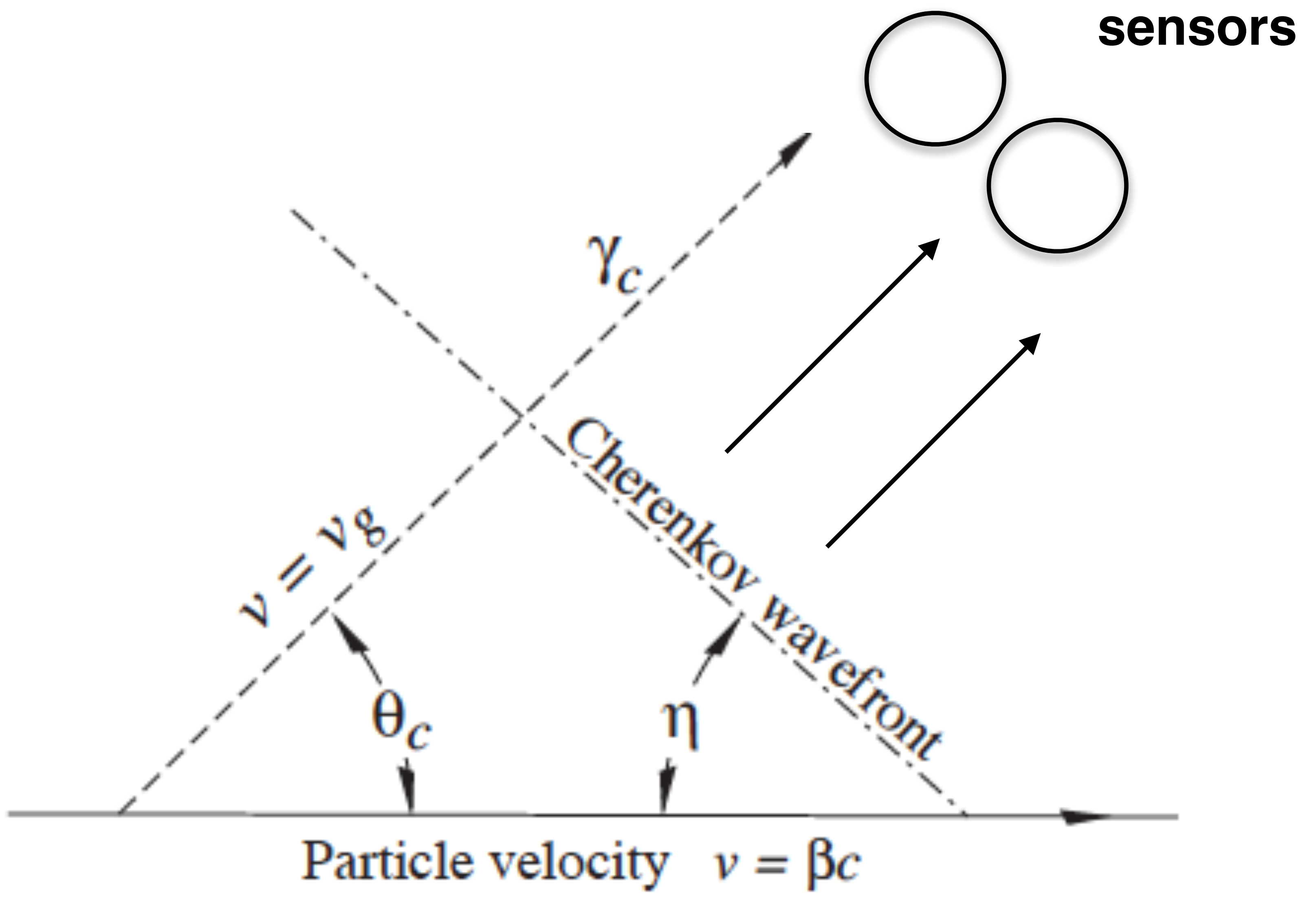


$$Typical \quad L \sim 10^4 \; photons / MeV$$

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

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

Cherenkov Radiation

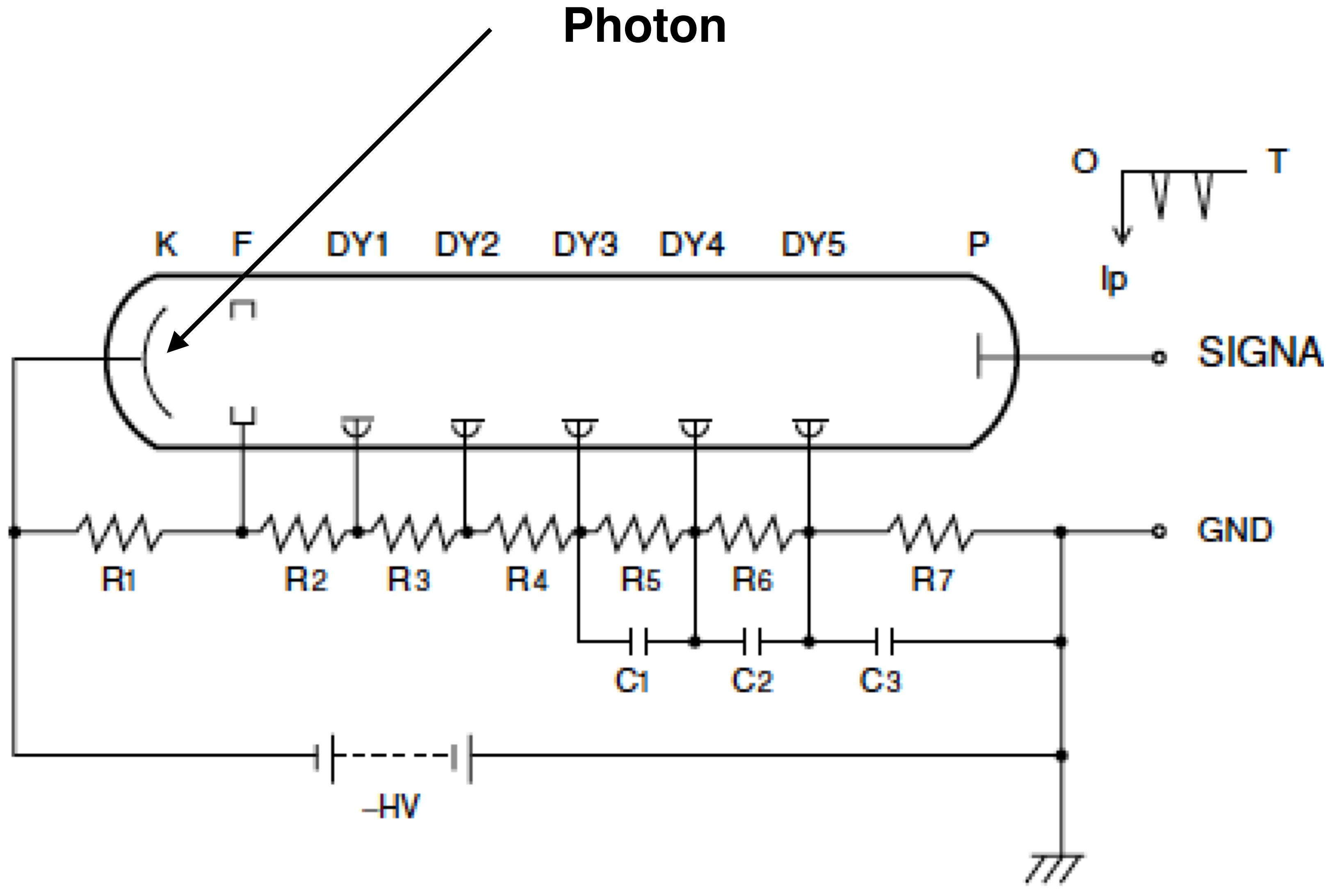


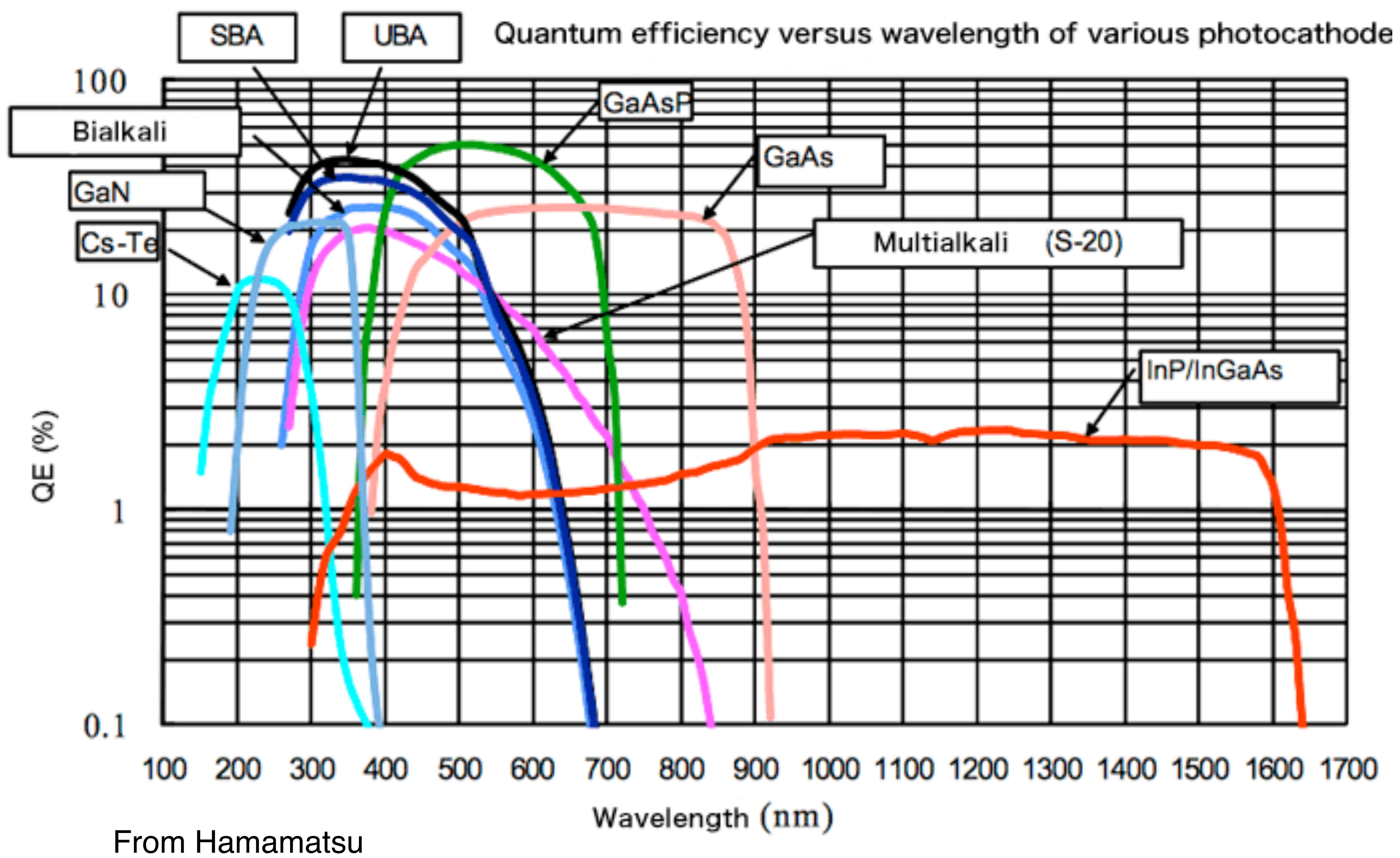
$$\cos\theta_c = (1/n\beta)$$

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

- 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. $\beta > 1/n$

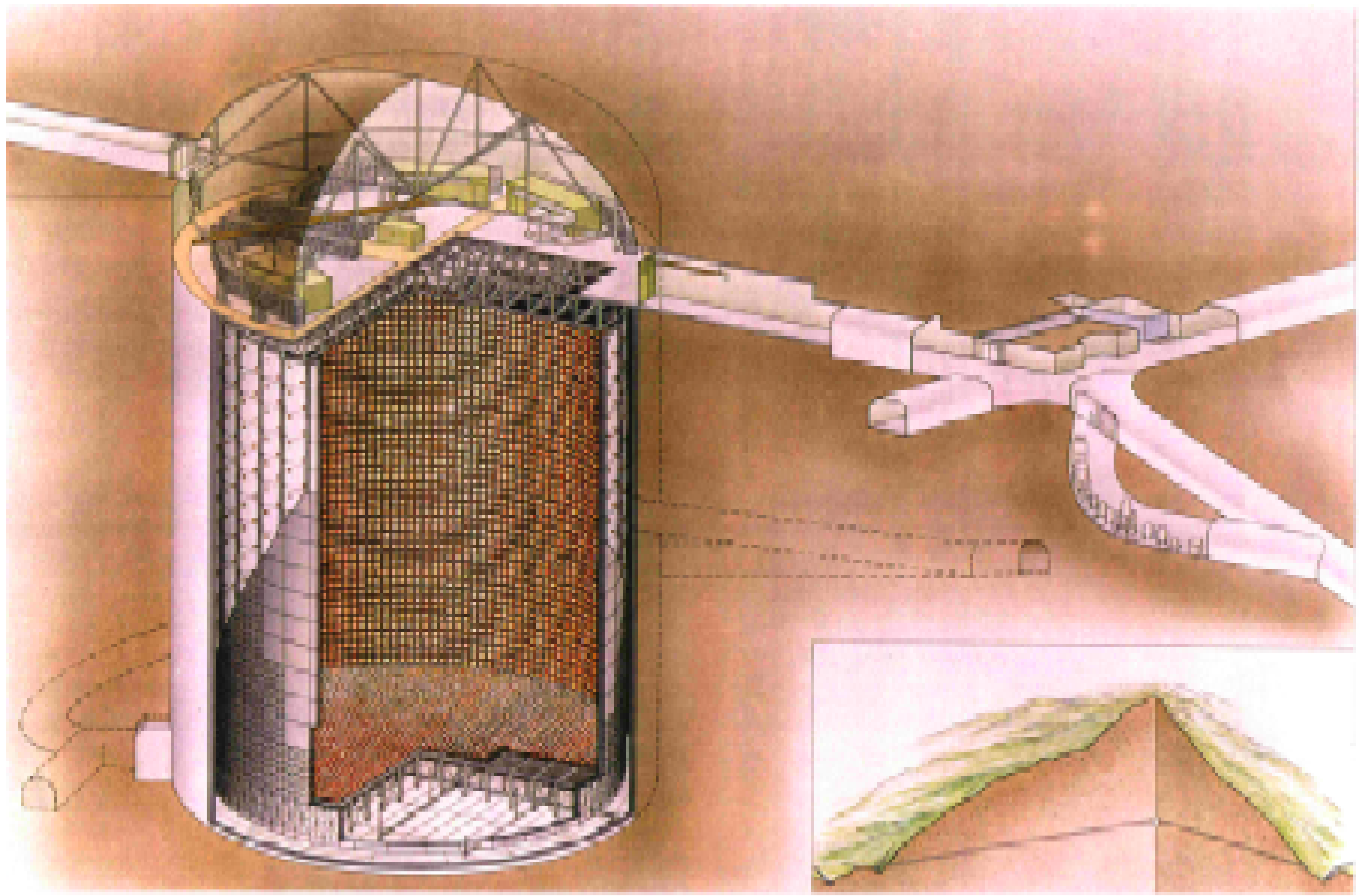
Photo-Multiplier Tube (Einstein's detector)





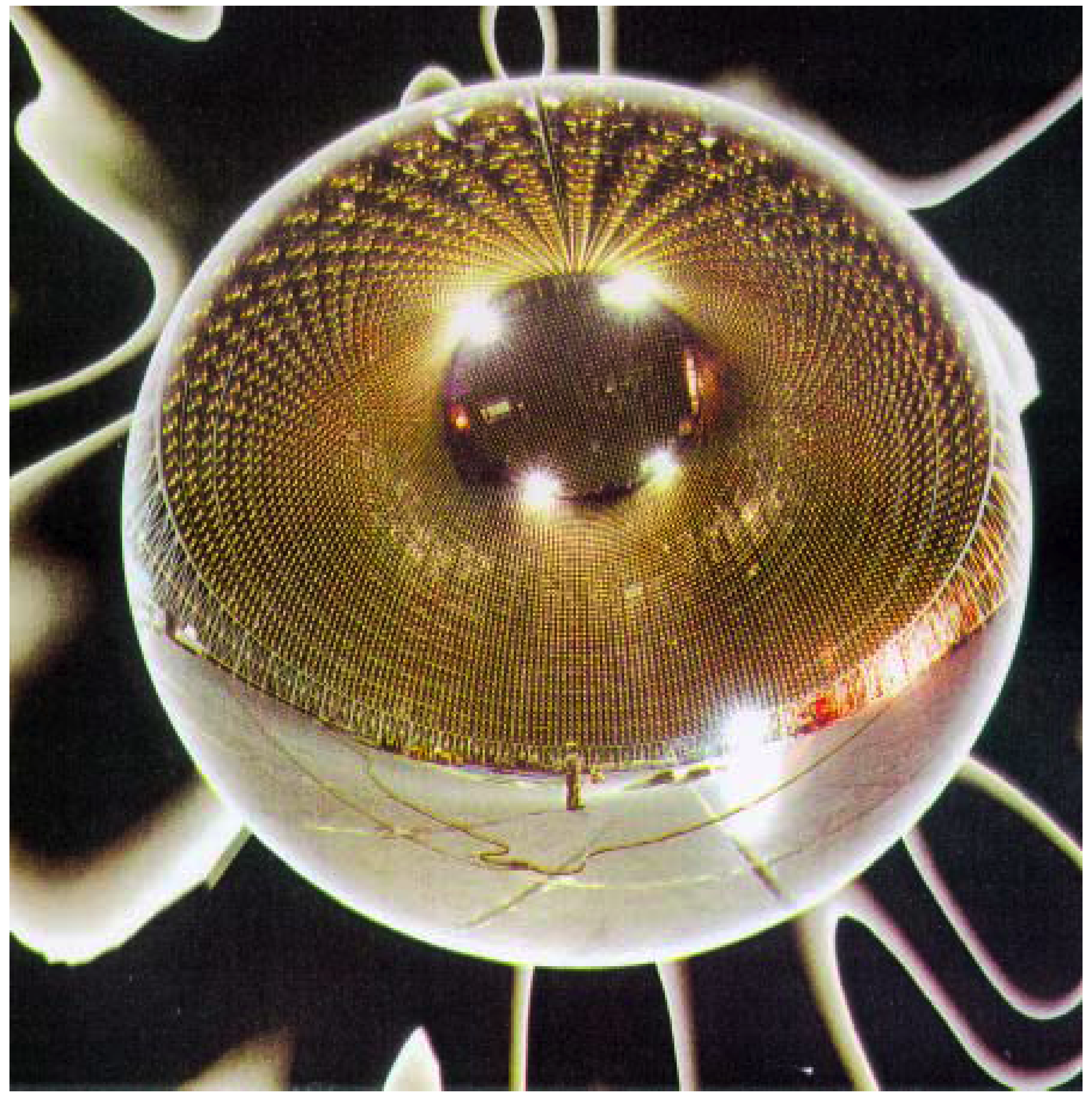
From Hamamatsu

- 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.



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

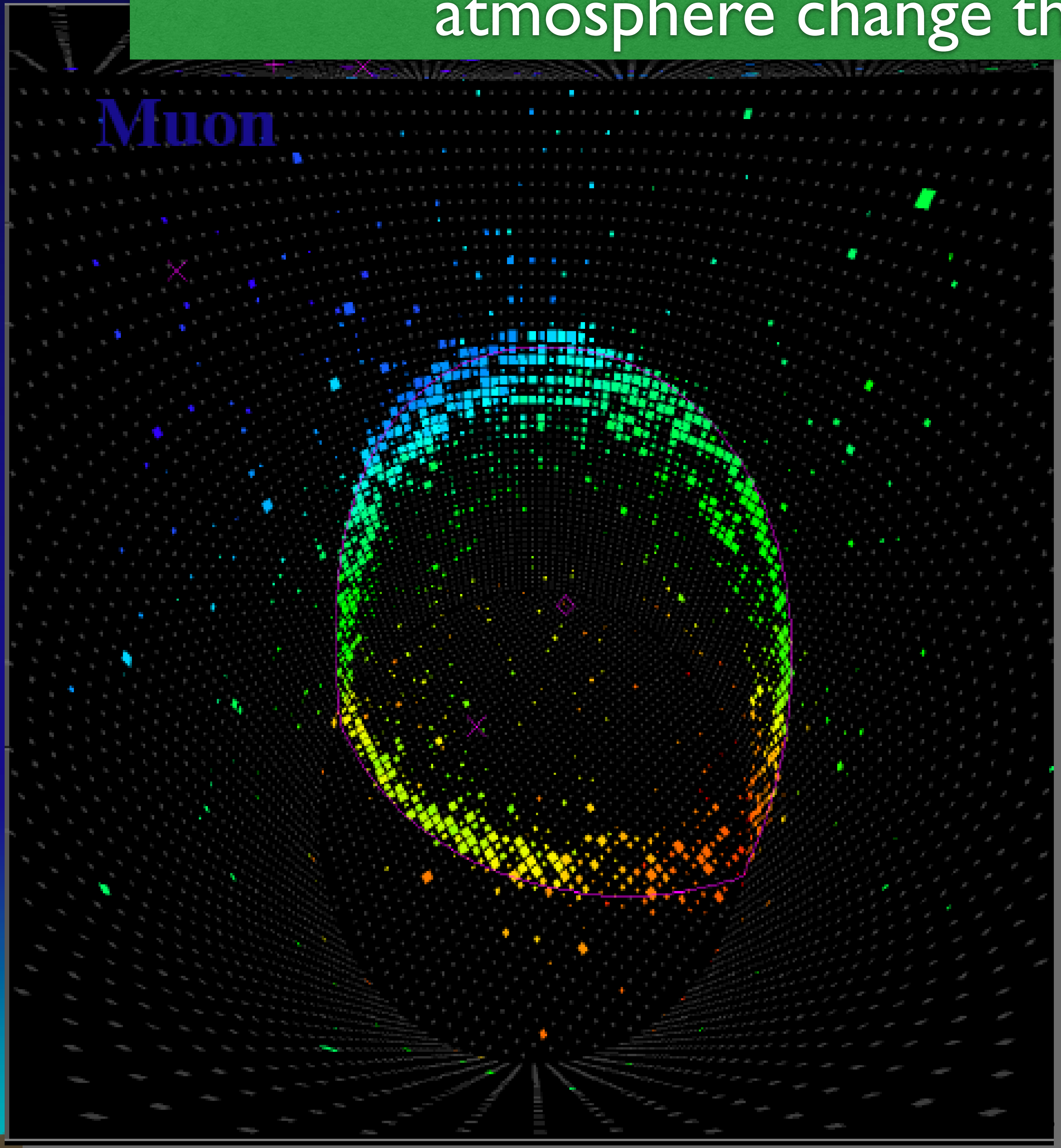
$$Yield = 370 \bullet \mathrm{Sin}^2\theta_c \bullet 0.4 \bullet 0.2 \approx 10\ pe/cm$$

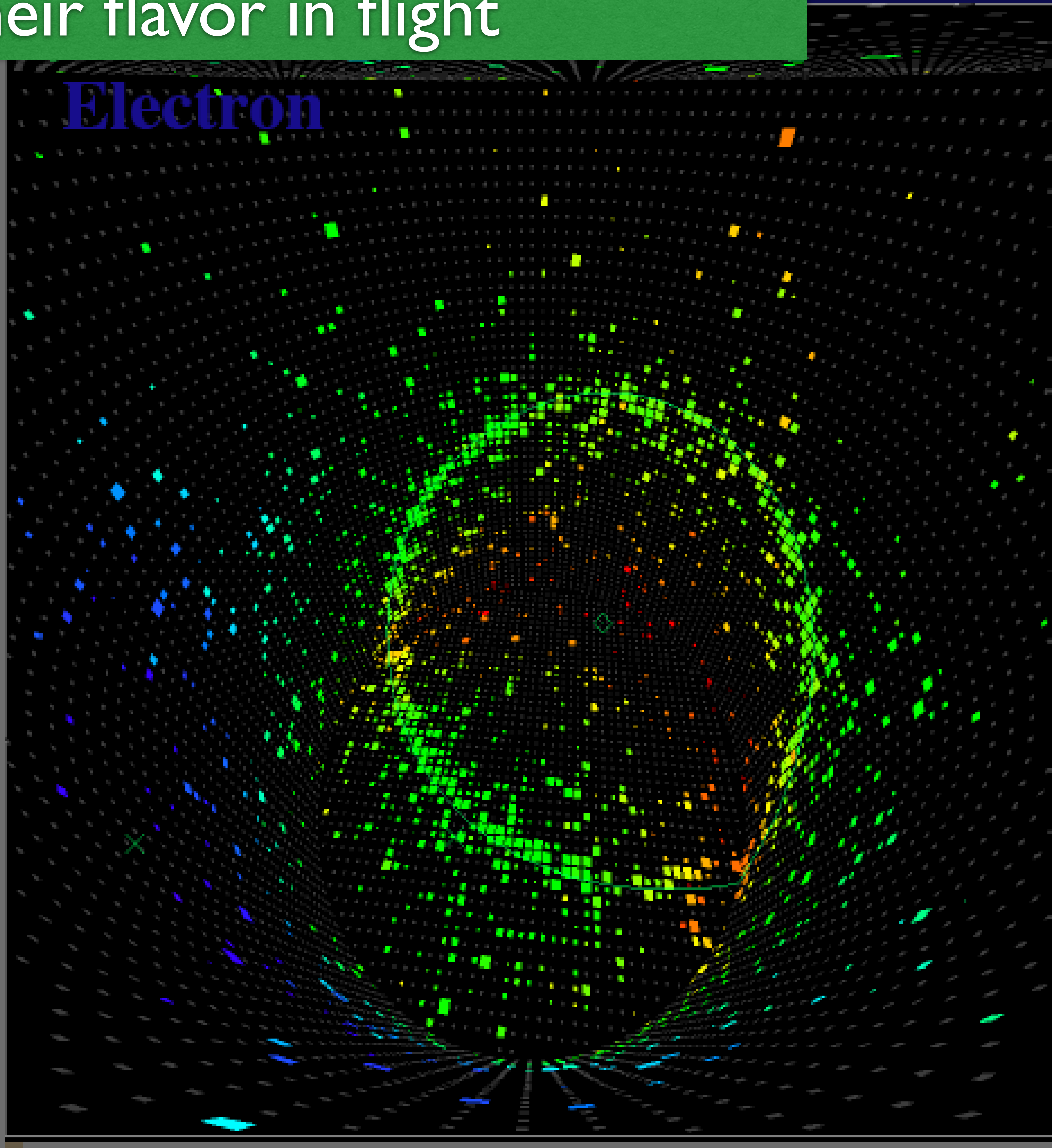
↑ Coverage X Photon detector efficiency

Technical issue: PMTs have to withstand huge pressure.

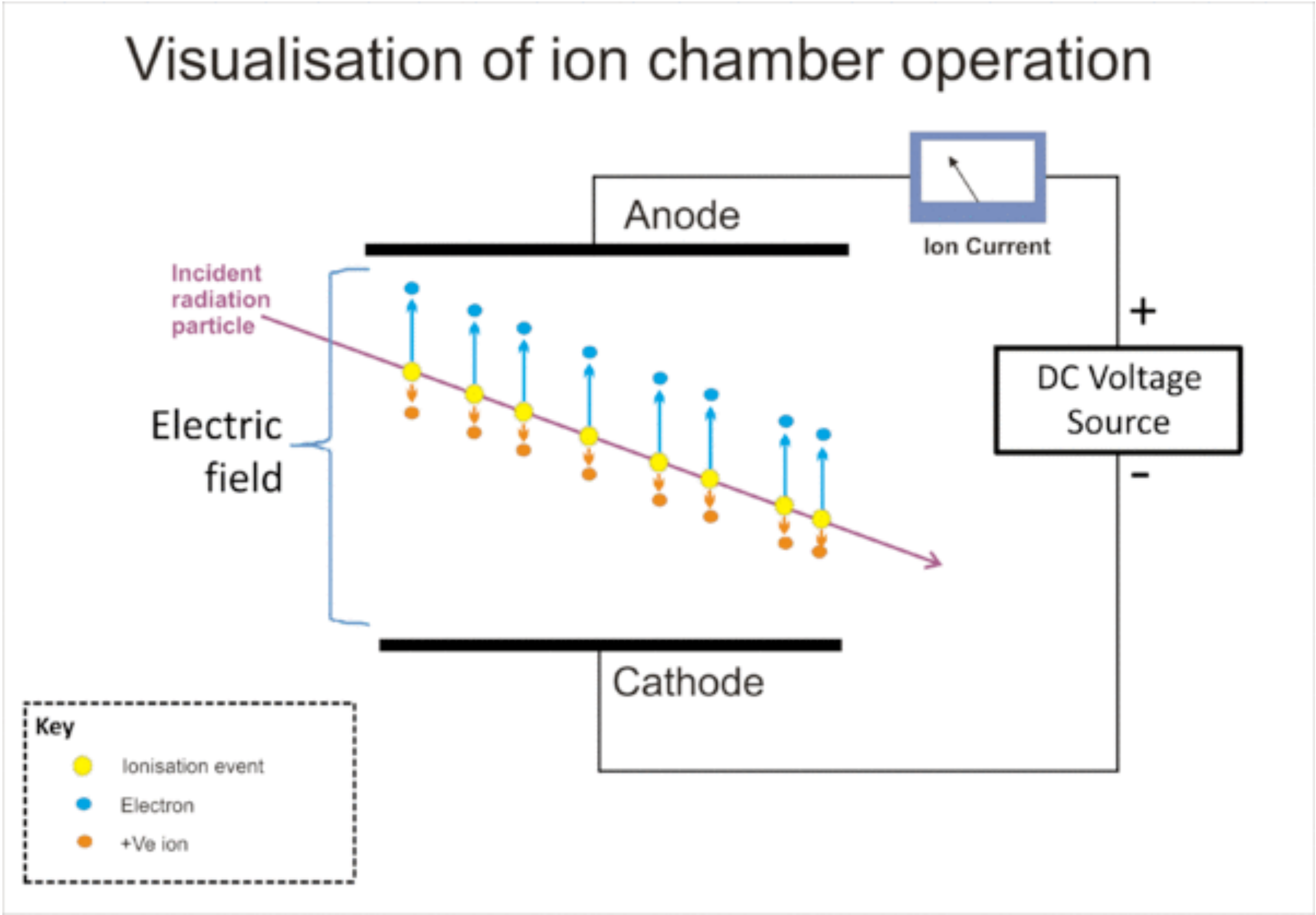
Particle Identification

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

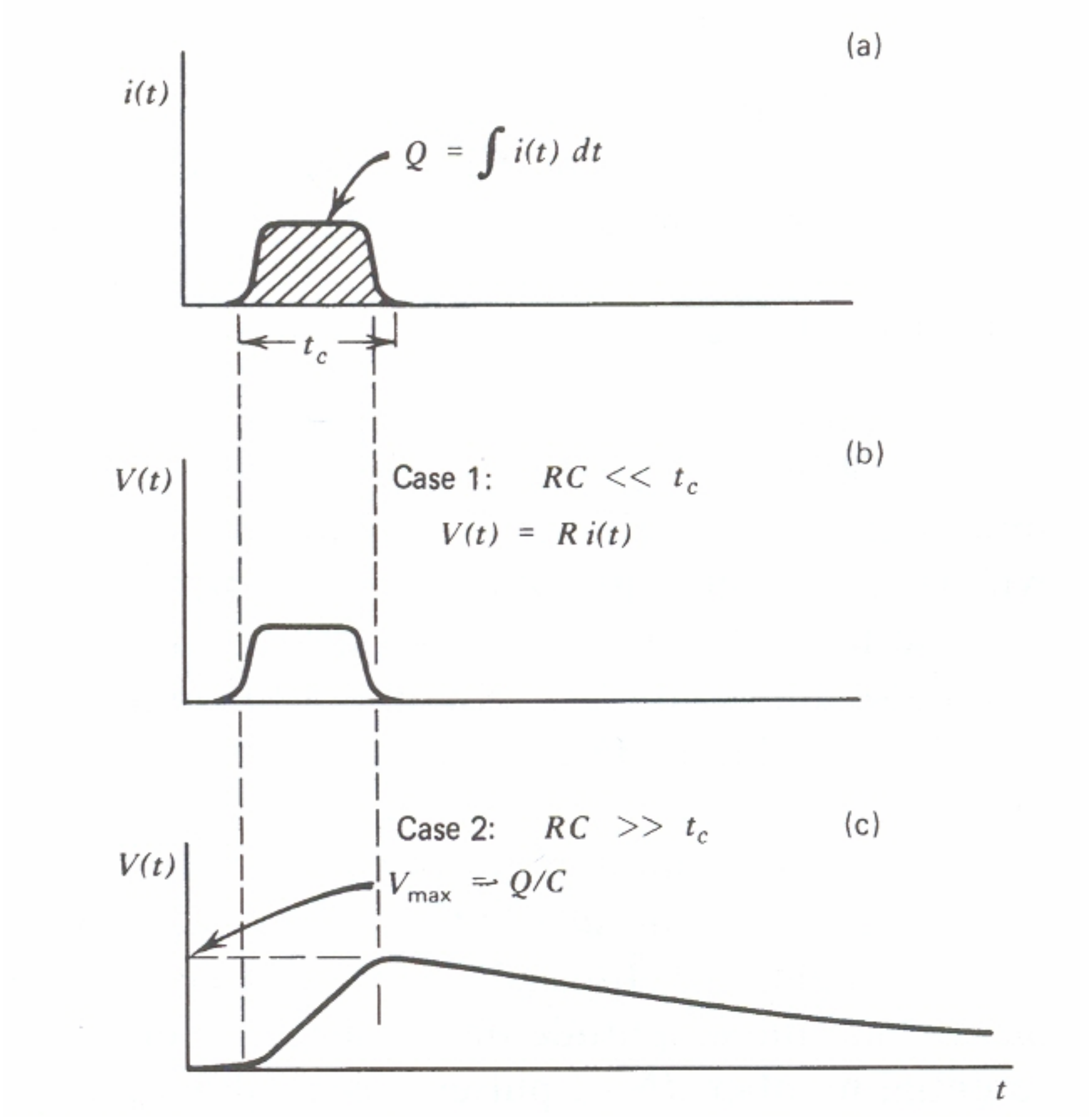




Ionization detectors

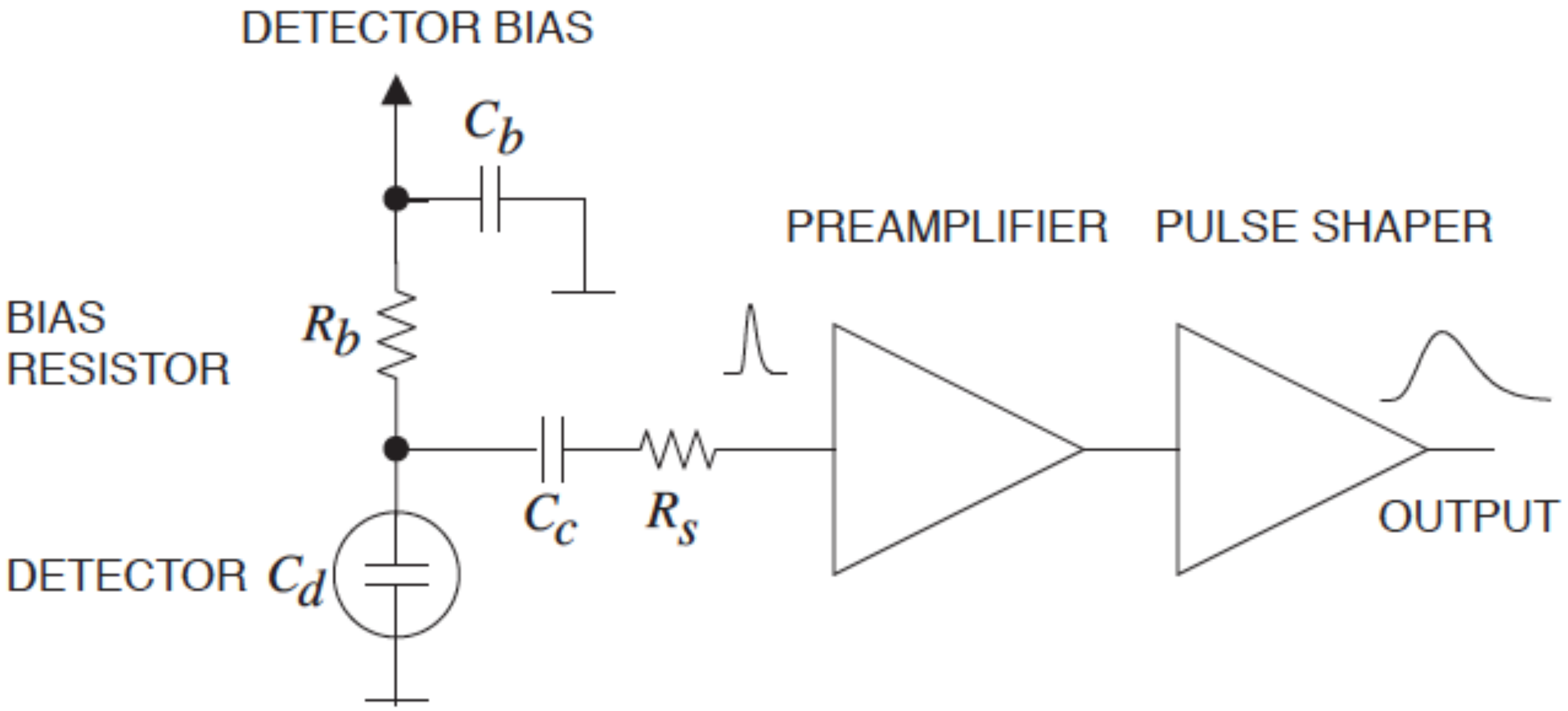


material	W (ev/pair)
LAr	23.6
LXe	15.6
Silicon	3.6
Germanium	2.9
Diamond	~13
CdTe	5.2
LNe	36
LKr	19



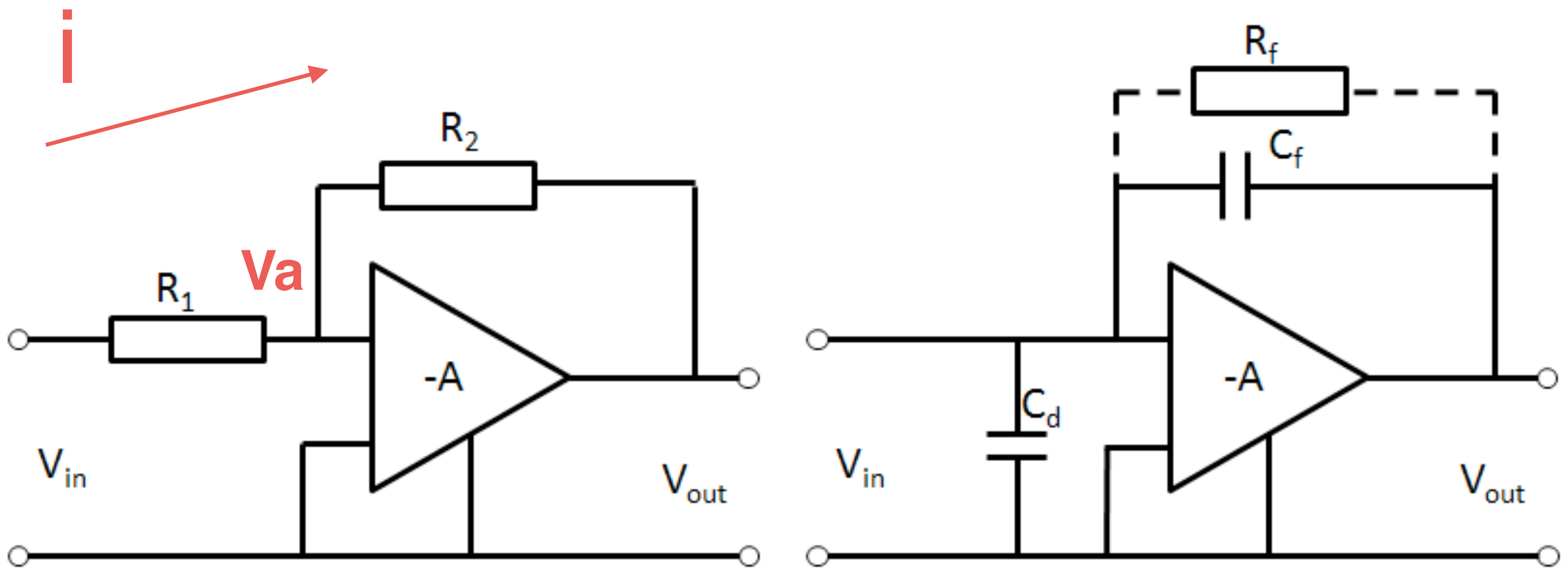
- In gases, semiconductors, and pure insulators, ionization creates electron-ion pairs.
- Electrons generally move about 1000 times faster than ions.
- This current can be measured as voltage across a resistor (case 1) or pulse across a capacitor (case 2)

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



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

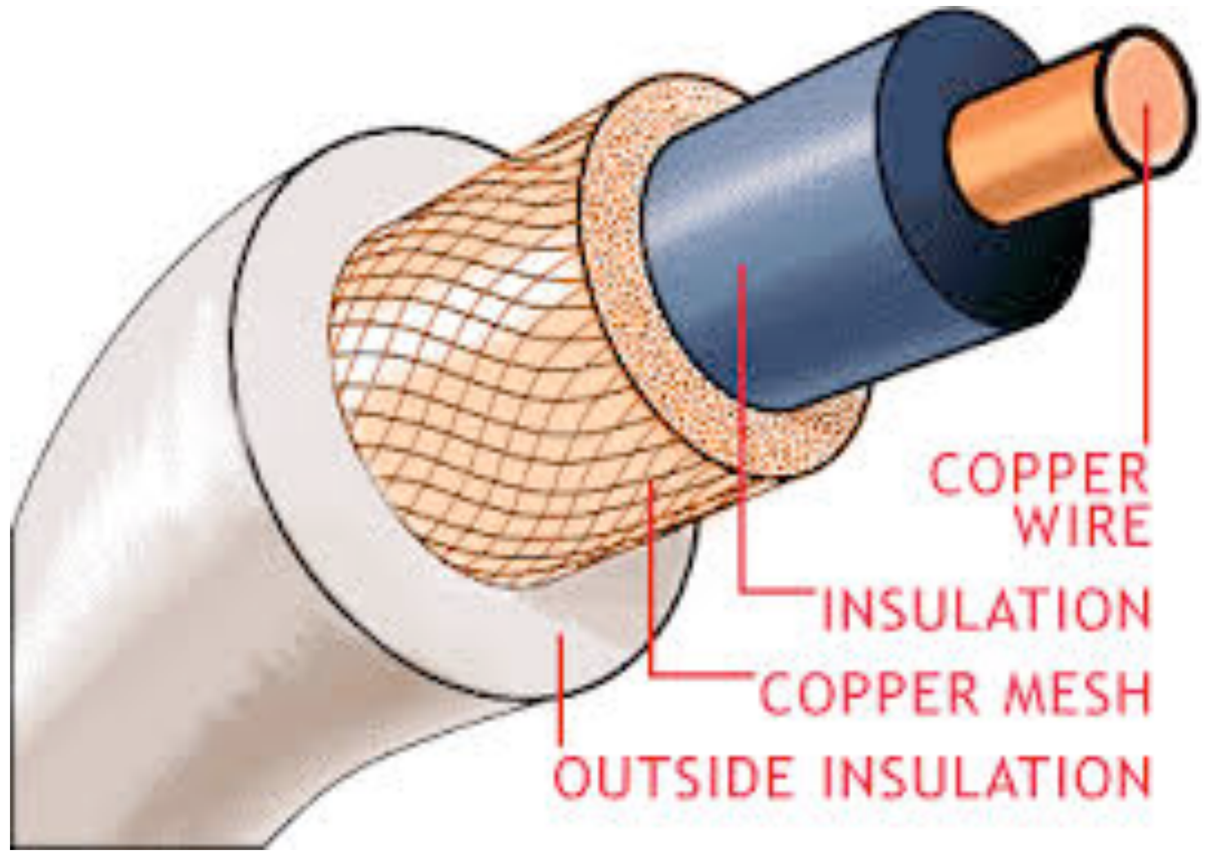
$$V_o = -AV_a$$

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

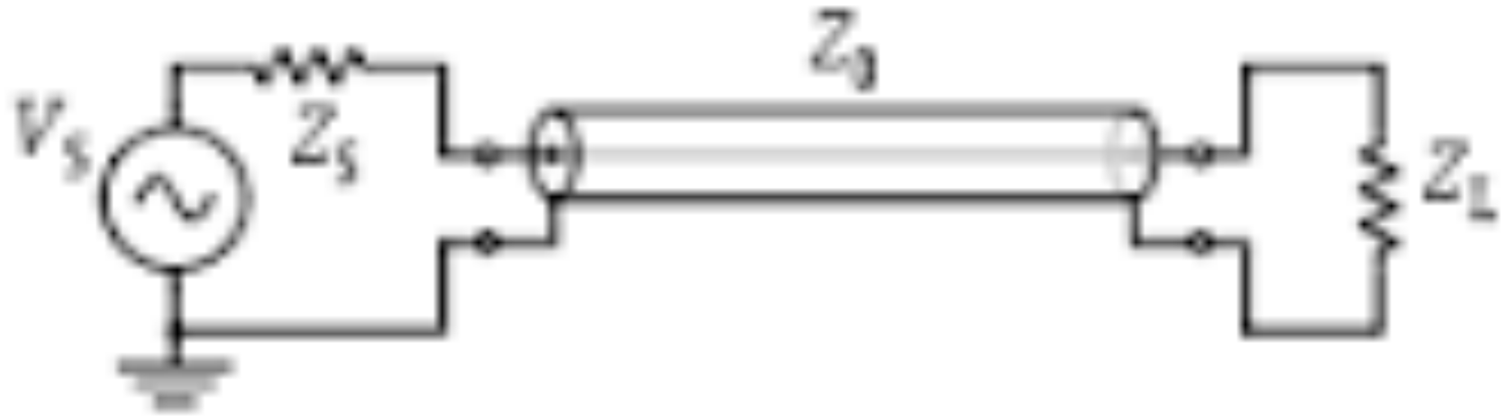
$$V_o = -V_{in} \frac{R_2}{R_1} \left[1 + \frac{(R_1 + R_2)}{R_1 A} \right]^{-1}$$

- 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

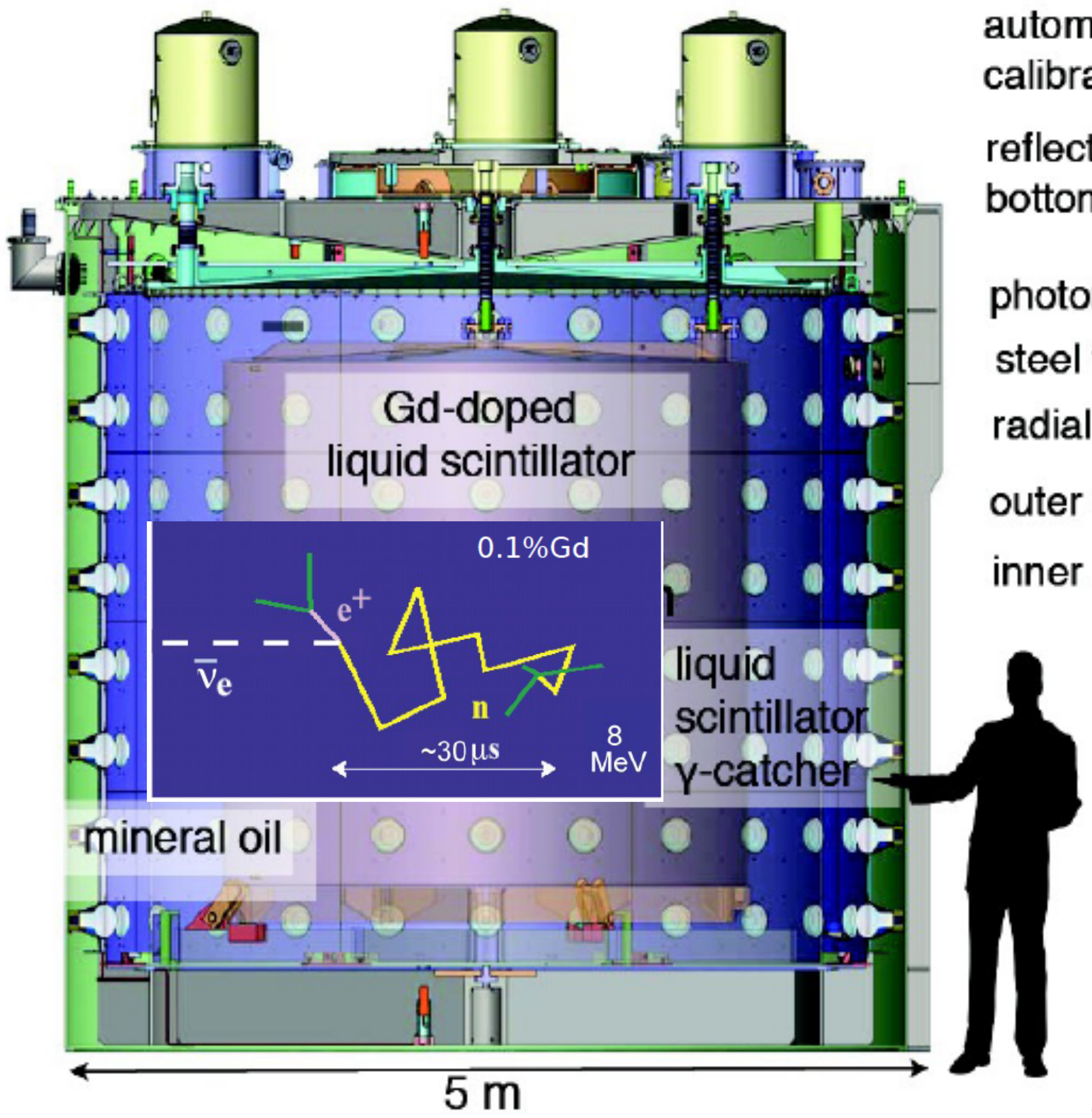
Attenuation: depends on frequency. > 400 Mhz, few percent per meter.

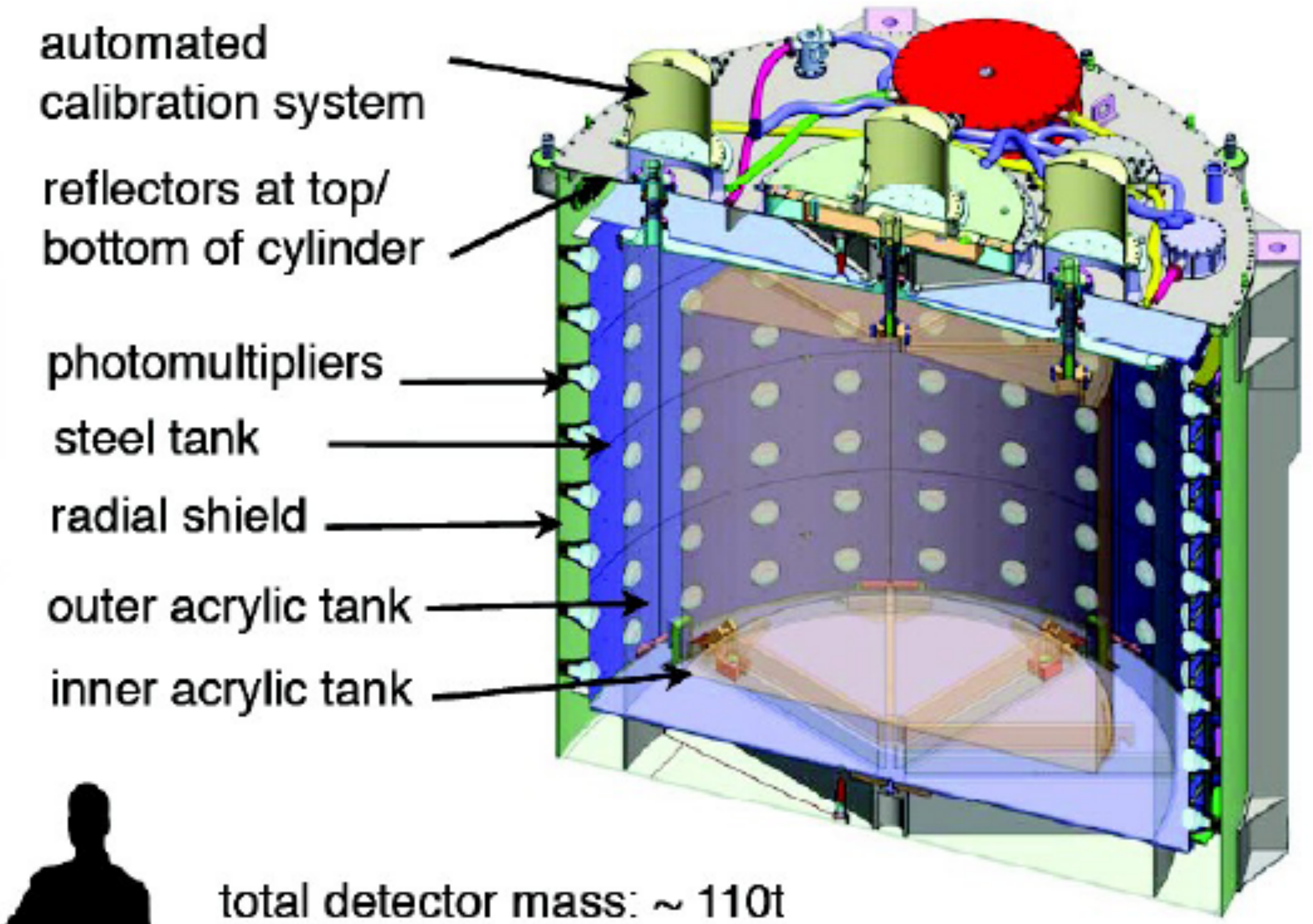
Signal speed ~ 2/3 c

As voltage step is applied at the input, current is drawn to charge up successive segments of the cable. If the termination has the same impedance as the cable, then the same current continues to be drawn.

Termination	Reflection
0	-V
0 to Z_0	-V to 0
Z_0	0
> Z_0	0 to +V

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)

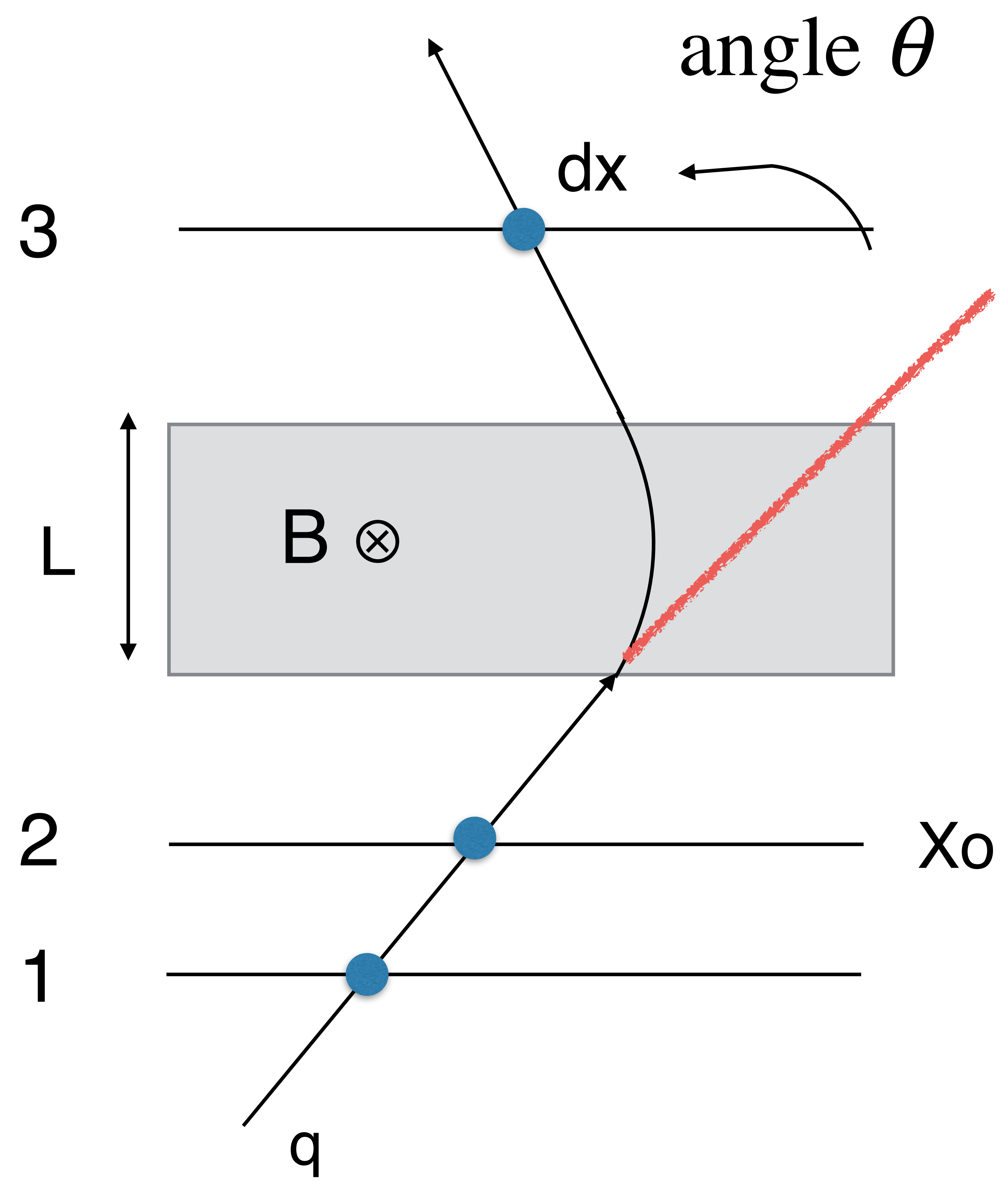
photosensors: 192 8"-PMTs

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

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

Very well defined target region

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 = $\frac{\theta}{S} \approx \frac{\theta}{L}$ (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)

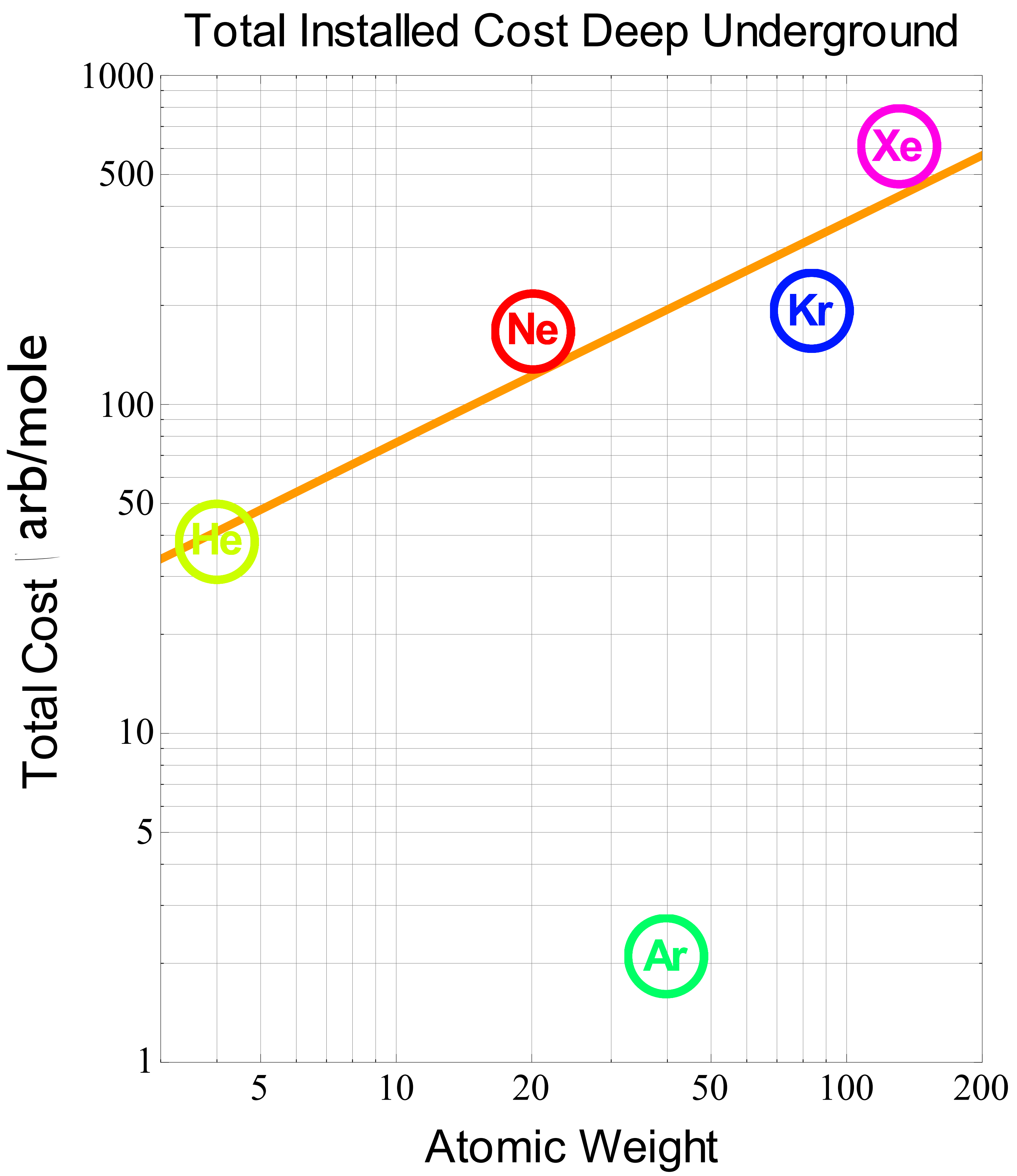
$\frac{\delta p}{p} \sim$ constant for low mom. due to M.S.

$\frac{\delta p}{p} \sim \frac{1}{B \bullet L}$ 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.

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.

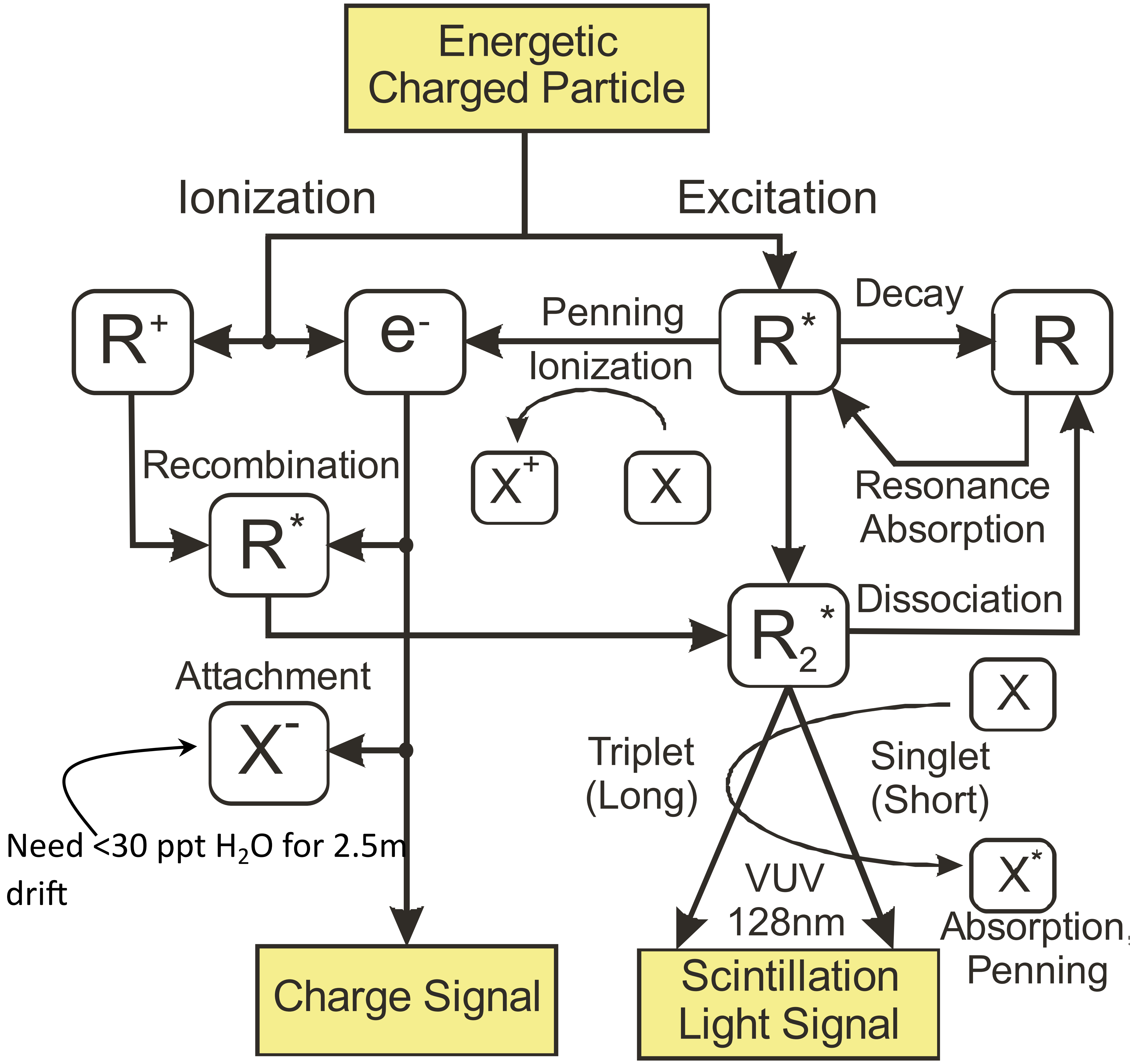


atomic num	In Air (ppm)	In Crust (ppb)	Ionization (eV) (atom)
He (2)	5.2	8	24.6
Ne(10)	18	0.07	21.6
Ar(18)	9300	1200	15.8
Kr(36)	1.14	0.01	14.0
Xe(54)	0.086	0.047	12.1

LAr Cost ~ US $ 10^6 per 1000 tons

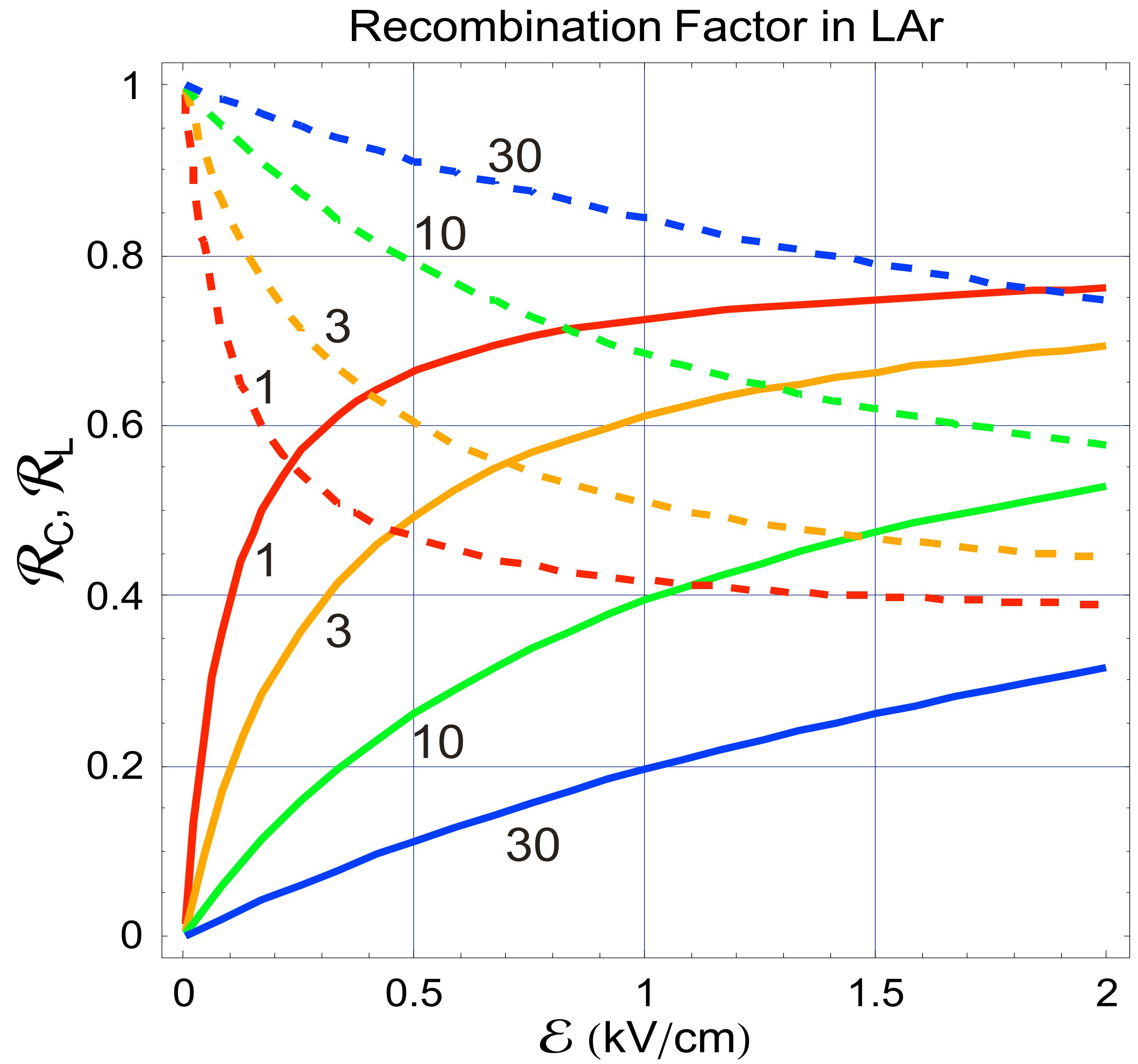
What happens to the energy as a charged particle traverses in LAr? W = 23.6 eV/pair. W is greater than the ionization potential because it includes other energy loss mechanisms.

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))

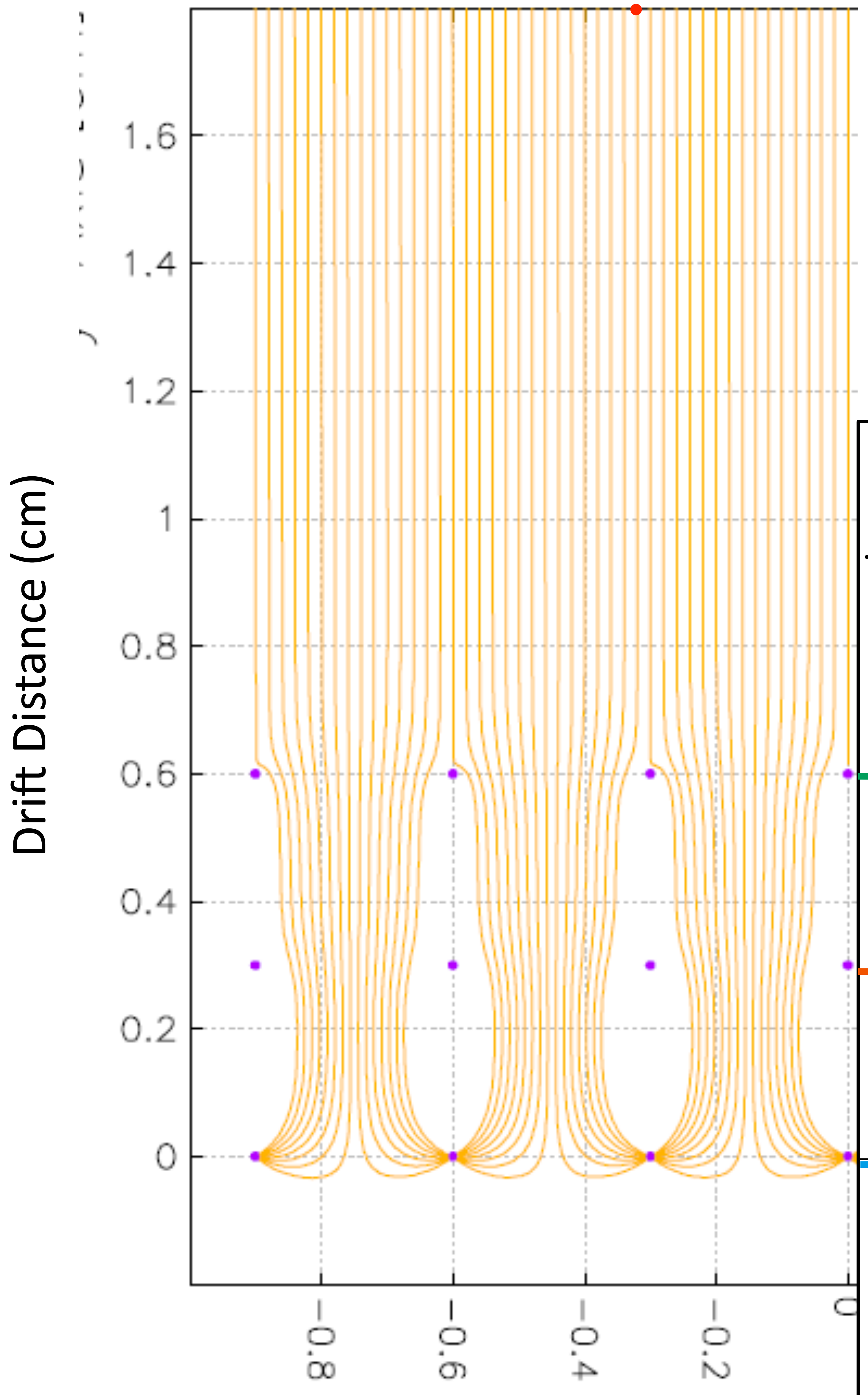


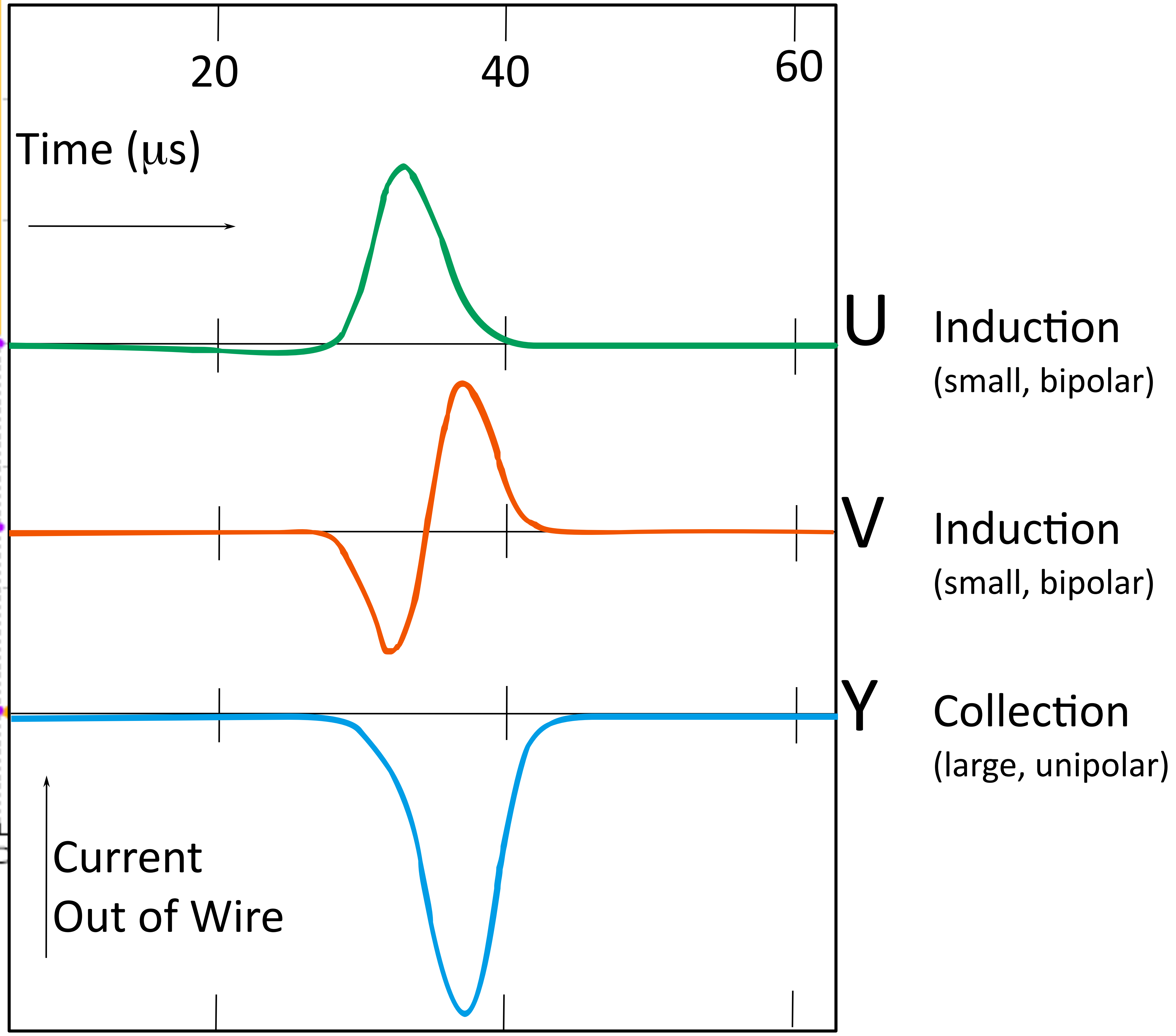
Ratio w/r/t full yield
Solid: charge, Dashed: light
Numbers: Specific Eloss in MIPs

Charge Signal Formation

Induction by
and
Collection of

} electrons on wires

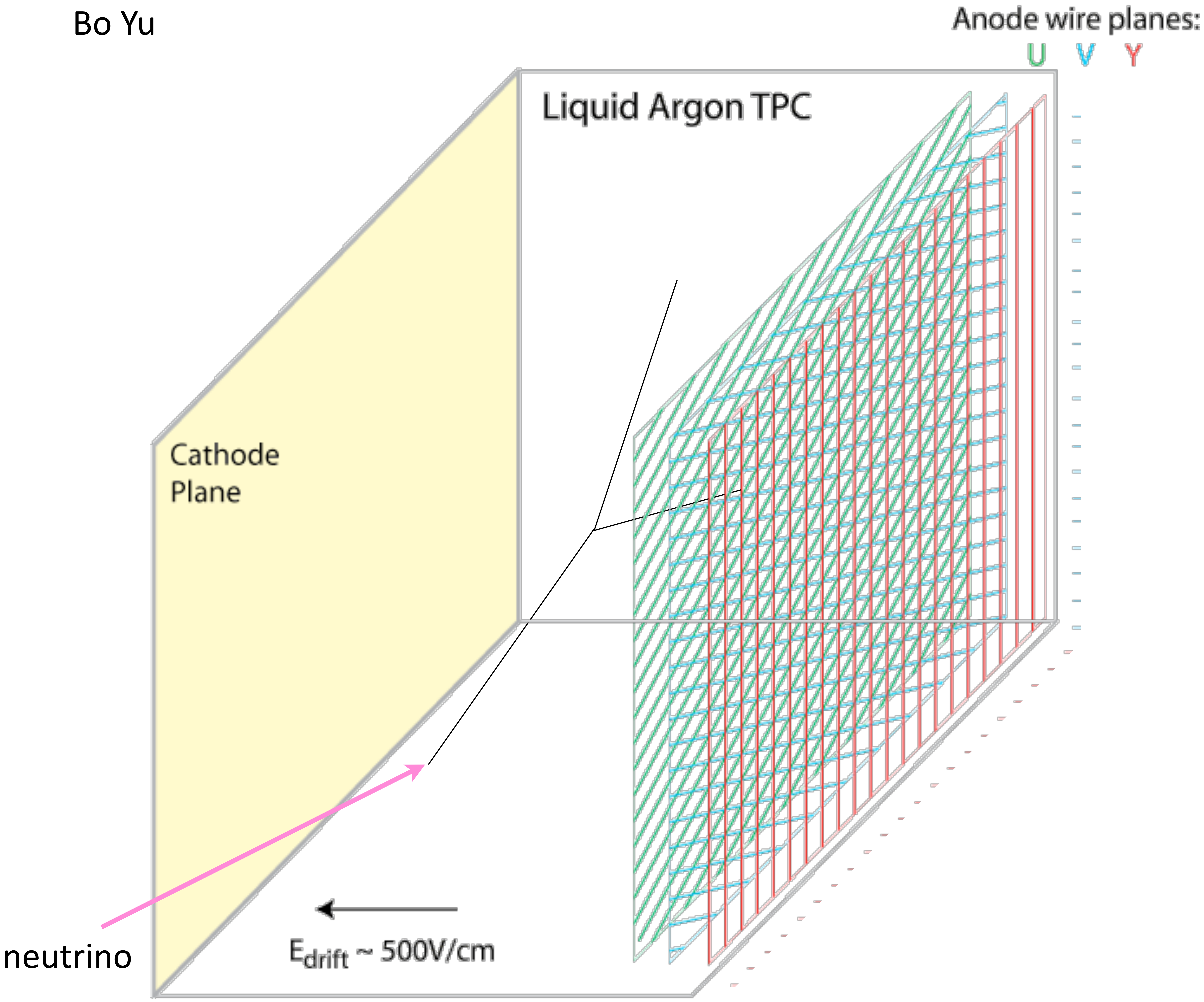




Signal formation starts upon motion of the charge.

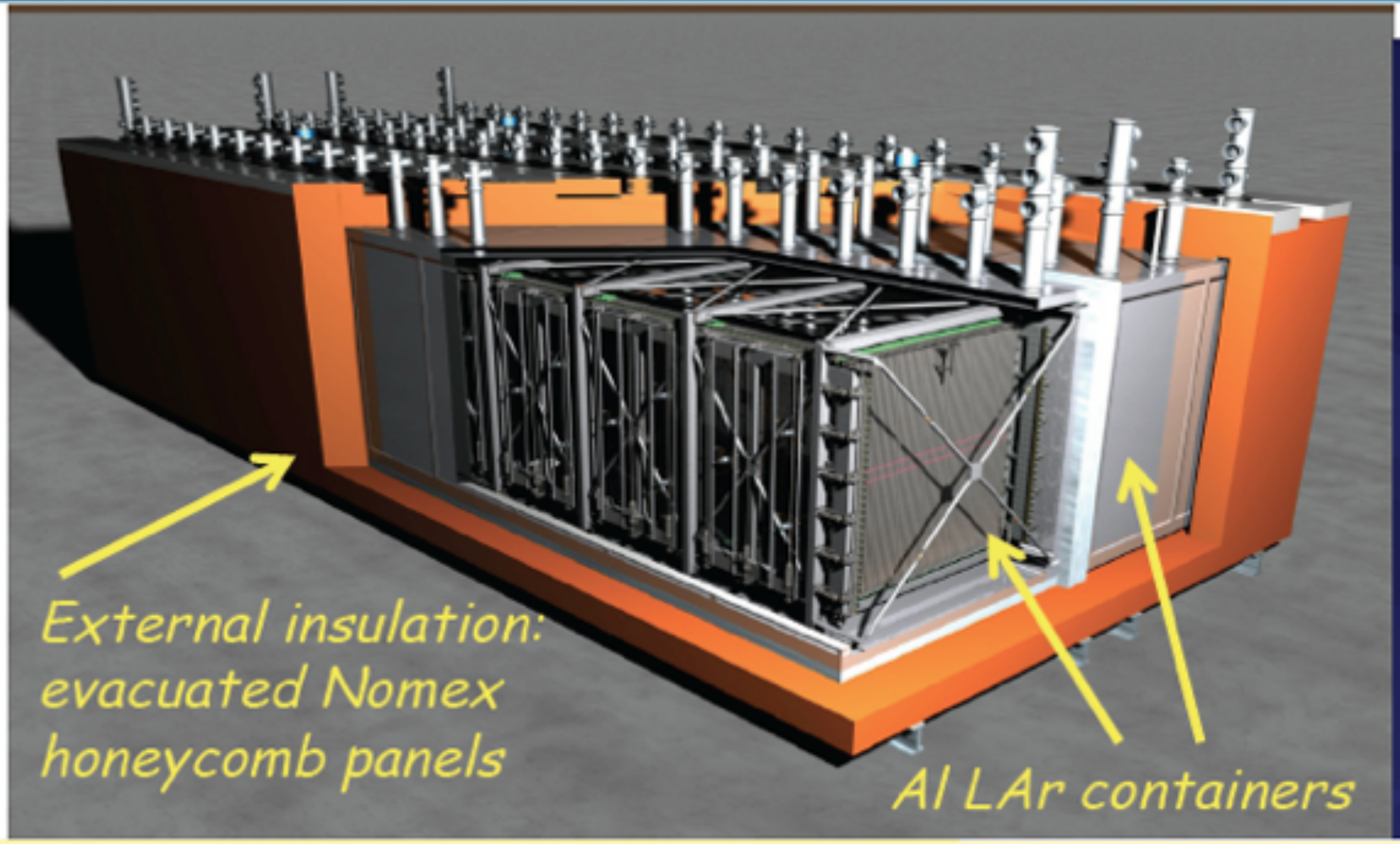
How Does a LArTPC Work?

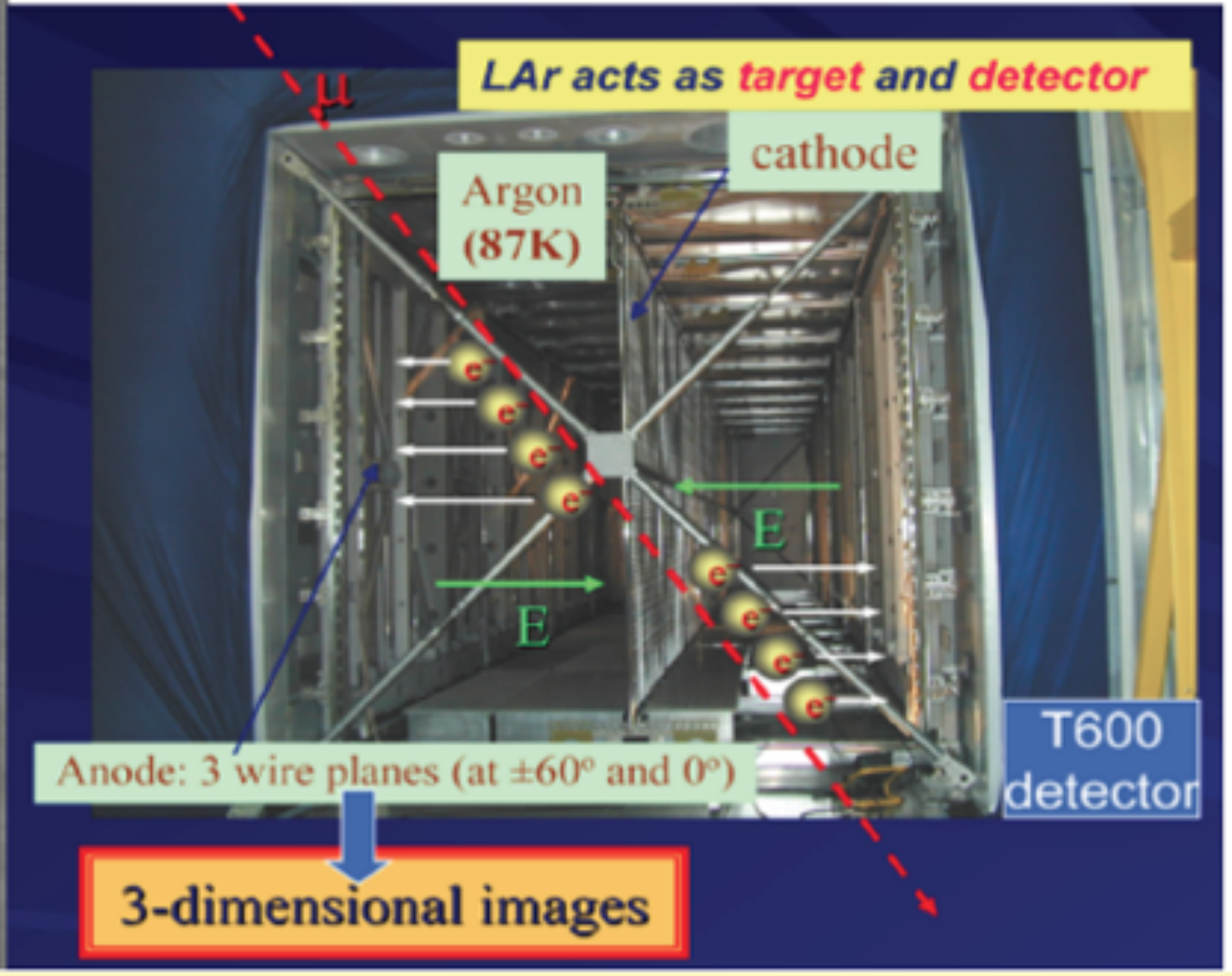
Bo Yu



LAr also scintillates. We intend to detect the light also.

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 further concepts of detectors in particle physics.**
- **Most 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**