Scintillation detectors, photo tubes, detection of muons

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Cosmic Neutrino Observations at Ultra High Energy course
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Cosmic ray interaction in the earth’s atmosphere development of extensive air shower

Top

100 $g.cm^{-3}$

200

300

400

500

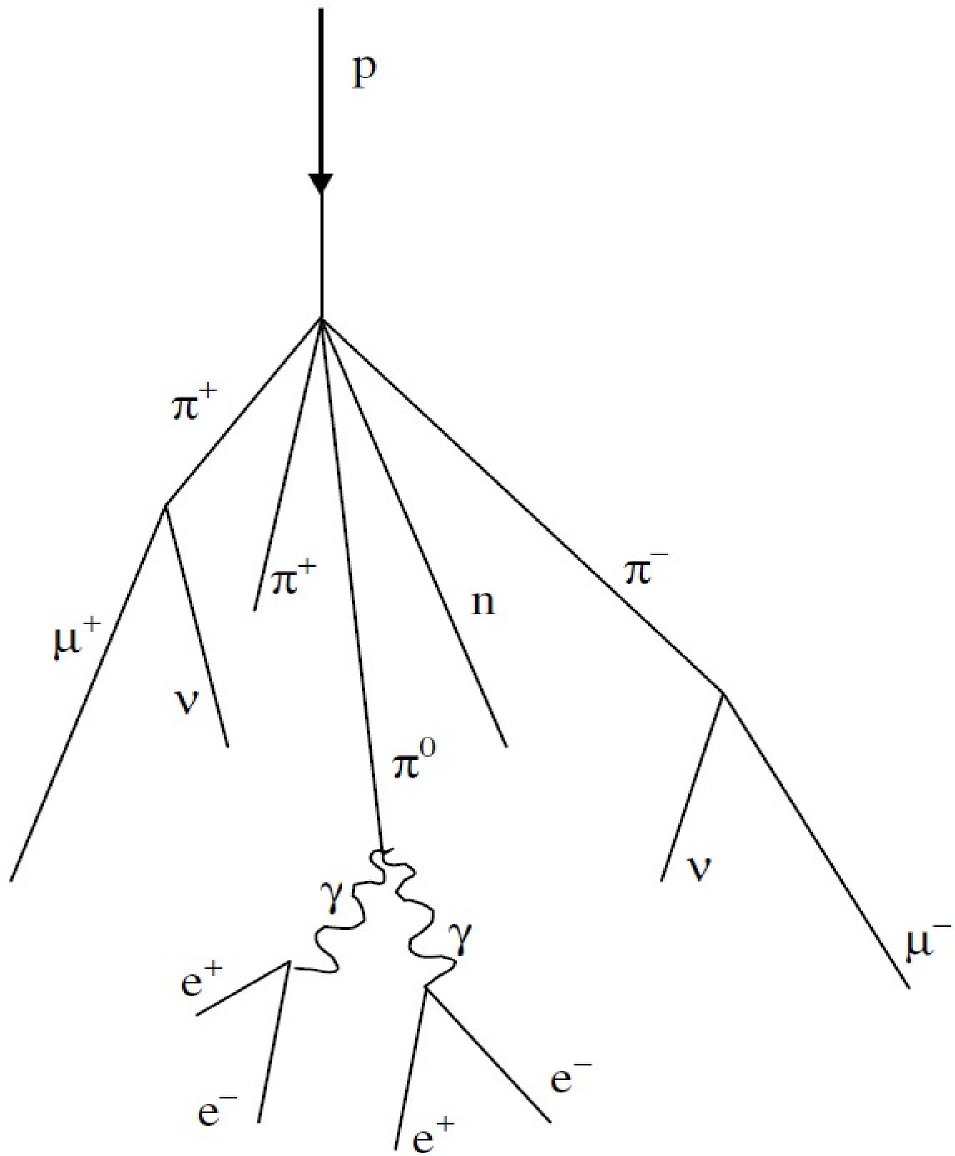
600

700

800 Ooty

900

1000 Mumbai



Extensive air shower

Particles multiply and at lower altitude one gets

1. e^-, e^+, γ : Electromagnetic components (90%)
2. μ^-, μ^+ : muonic or penetrating component (8-10%)
3. π^-, π^+ π^0, K^-, K^+, K^0: hadronic component (1%)
4. Neutrinos largely pass through the earth undetected

At Ooty for E = 10^{14} eV (100 TeV), N=20000 spread over 1000 m^2

Shower size N and lateral spread is proportional to primary energy E

Density of particles measured by an array of detectors is used to estimate the shower size which in turn is used to obtain the primary energy E through Monte simulations (will be discussed by Fahim Varsi on 21 Dec 2019)

The arrival time of particles are used to estimate the direction of the shower

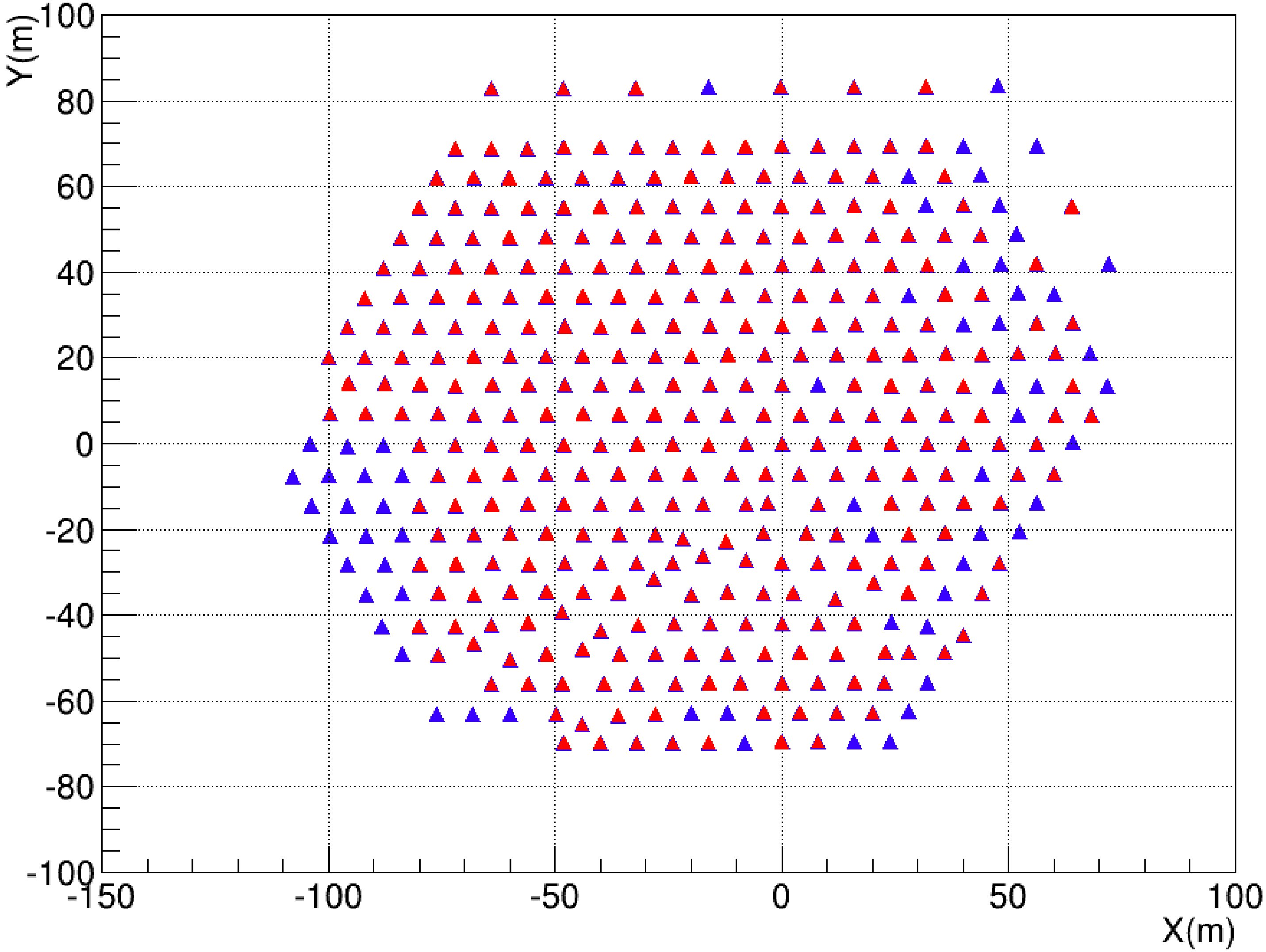
GRAPES-3 experiment at Ooty

400 Plastic Scintillator detectors (1 m^2 area)

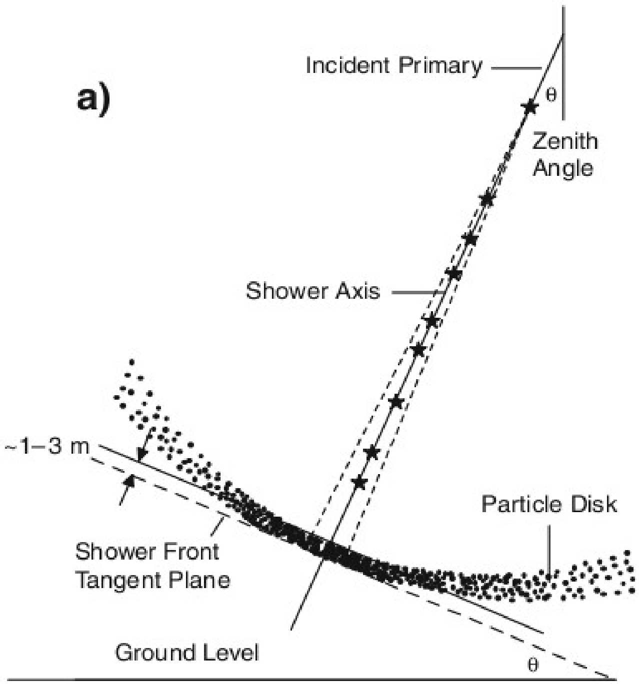
560 m^2 muon telescope (E_μ=1 GeV) (11.4N, 76.7E)

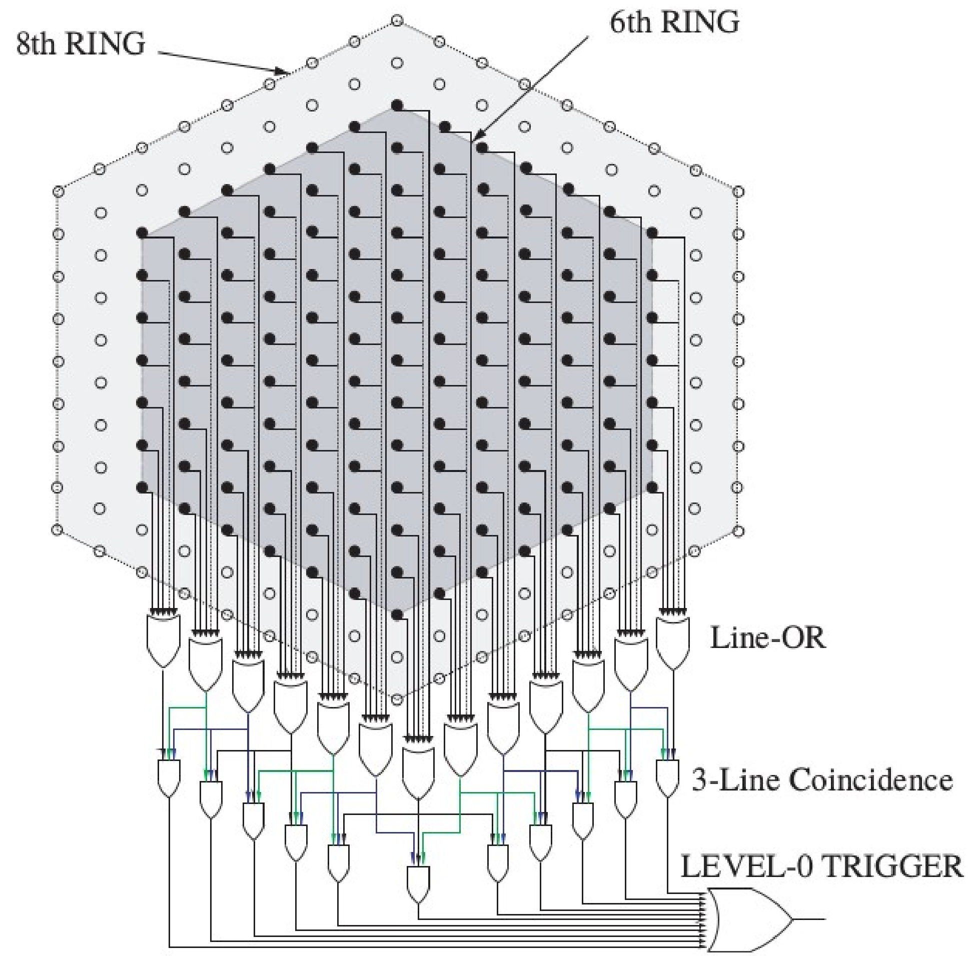
3712 Proportional Counters (6m x 0.1m x 0.1m)

Run No. 0, Event No. 4347, 2015-01-01 00:00:10.431762100



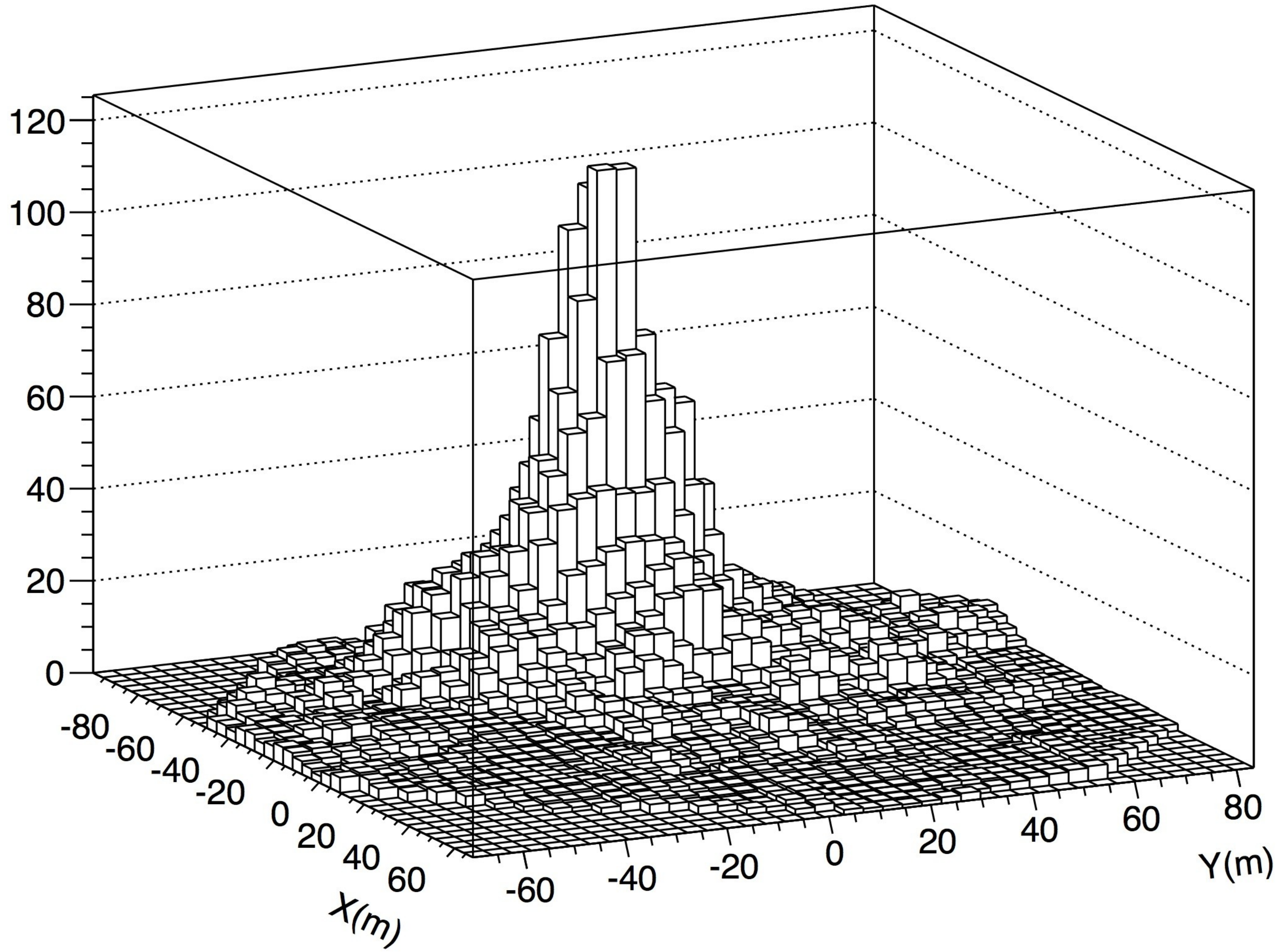
GRAPES-3 shower trigger





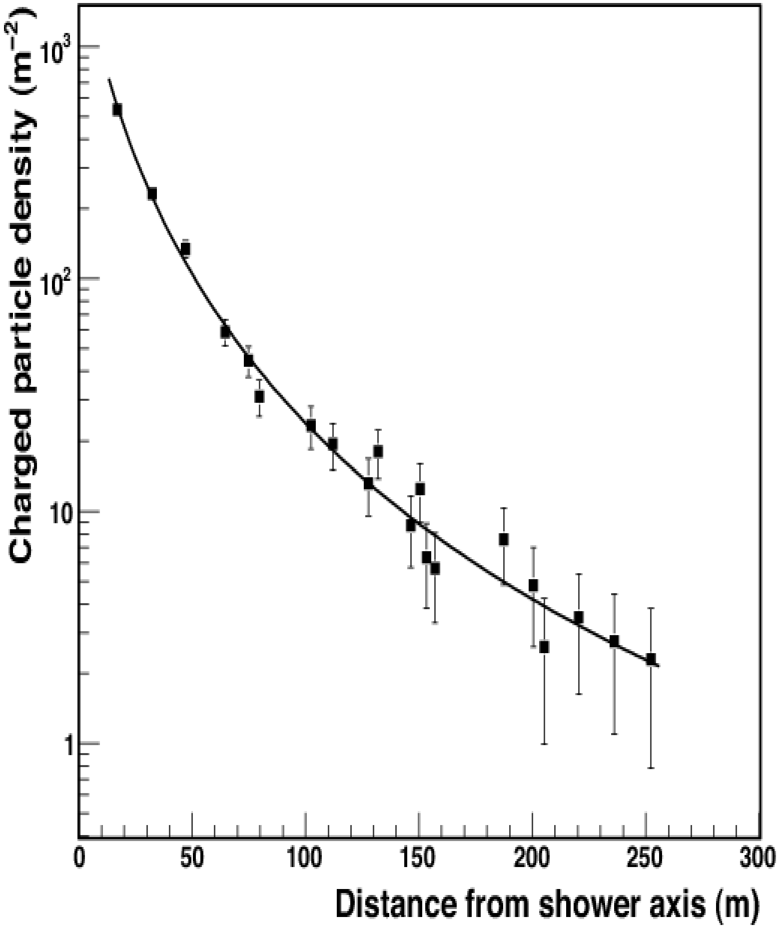
GRAPES-3 array records 3 million showers per day

Particle density profile of a shower at GRAPES-3



Fitting lateral distribution function to obtain;

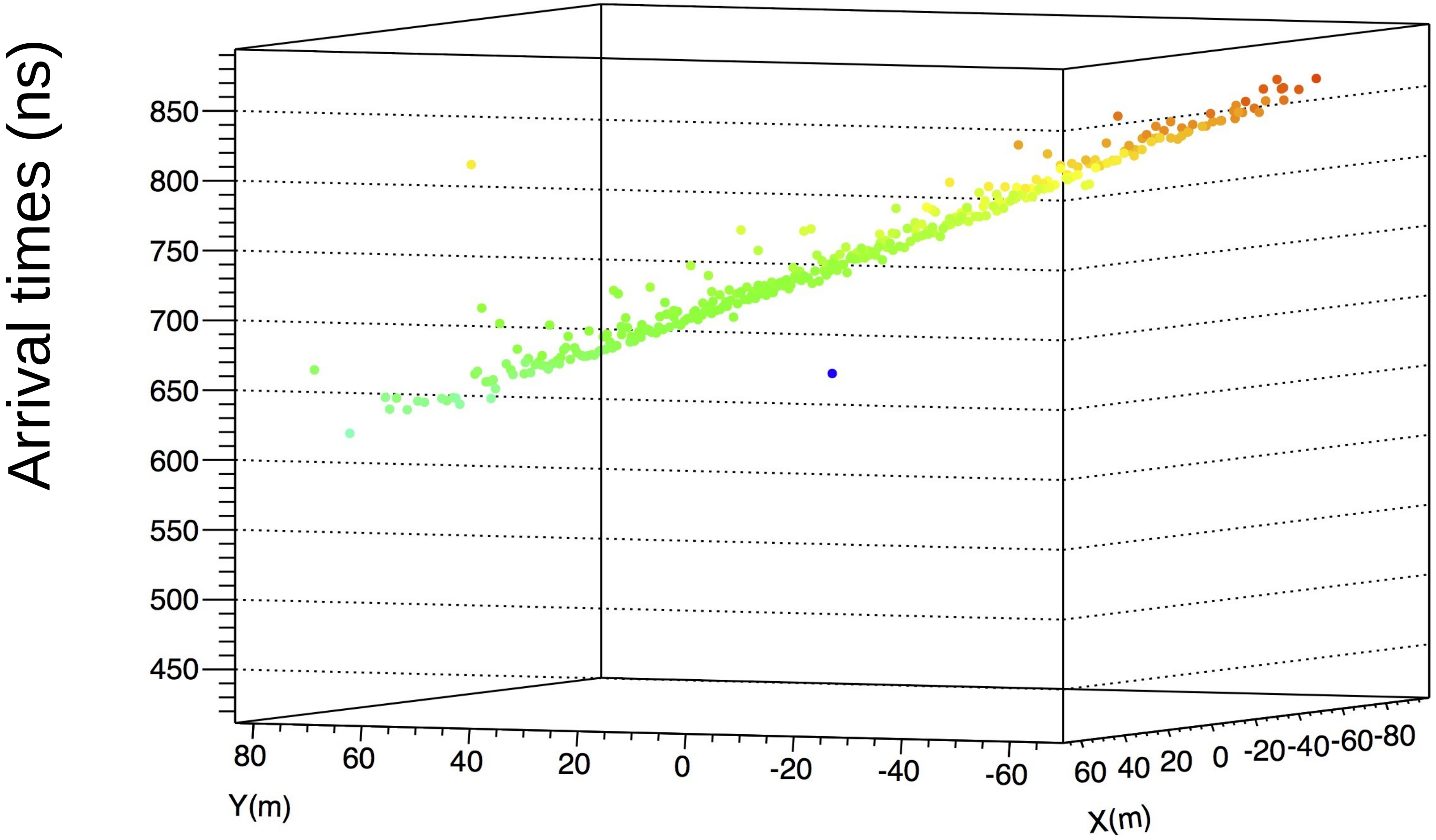
1. shower core (x_c, y_c)
2. shower size (N_e)
3. shower age (s)



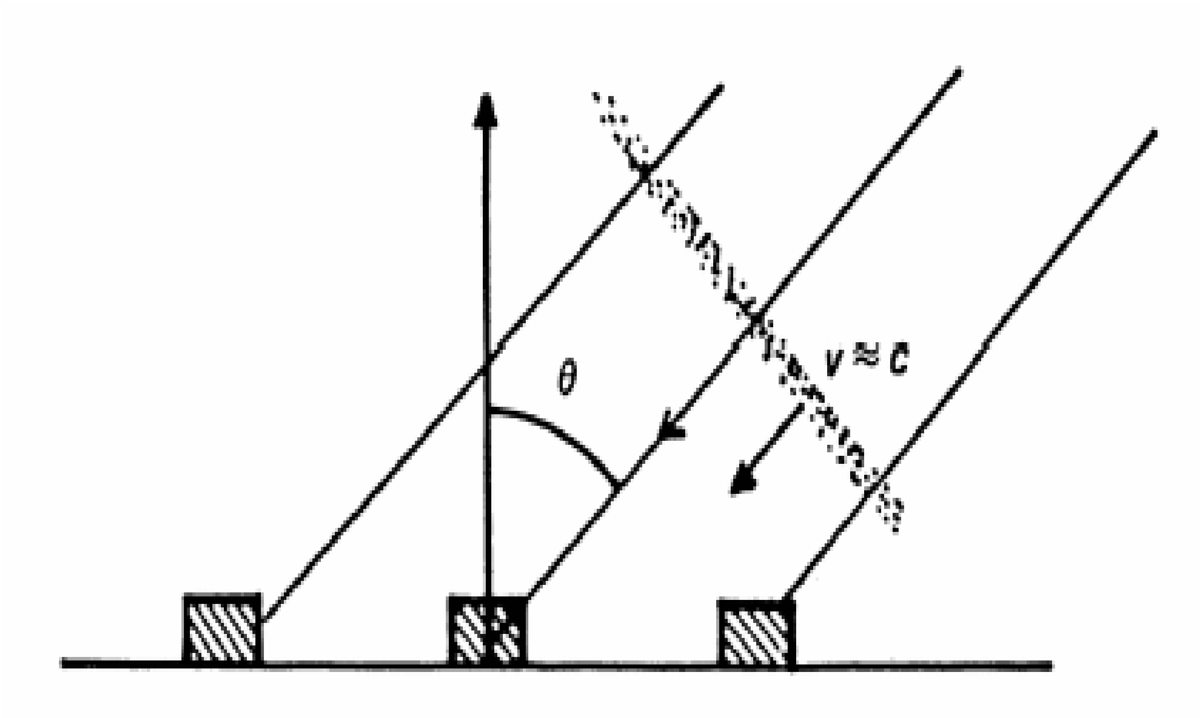
NKG (Nishimura-Kamata-Greisen) function

$$\Delta(\mathrm{N_e}, \mathrm{r}) = \frac{\mathrm{N_e}}{2\pi \mathrm{r_0^2}} \frac{\Gamma(4.5-\mathrm{s})}{\Gamma(\mathrm{s})\Gamma(4.5-2\mathrm{s})} \left(\frac{\mathrm{r}}{\mathrm{r_0}}\right)^{(\mathrm{s}-2)} \left(1+\frac{\mathrm{r}}{\mathrm{r_0}}\right)^{\mathrm{s}-4.5}$$

Arrival time profile



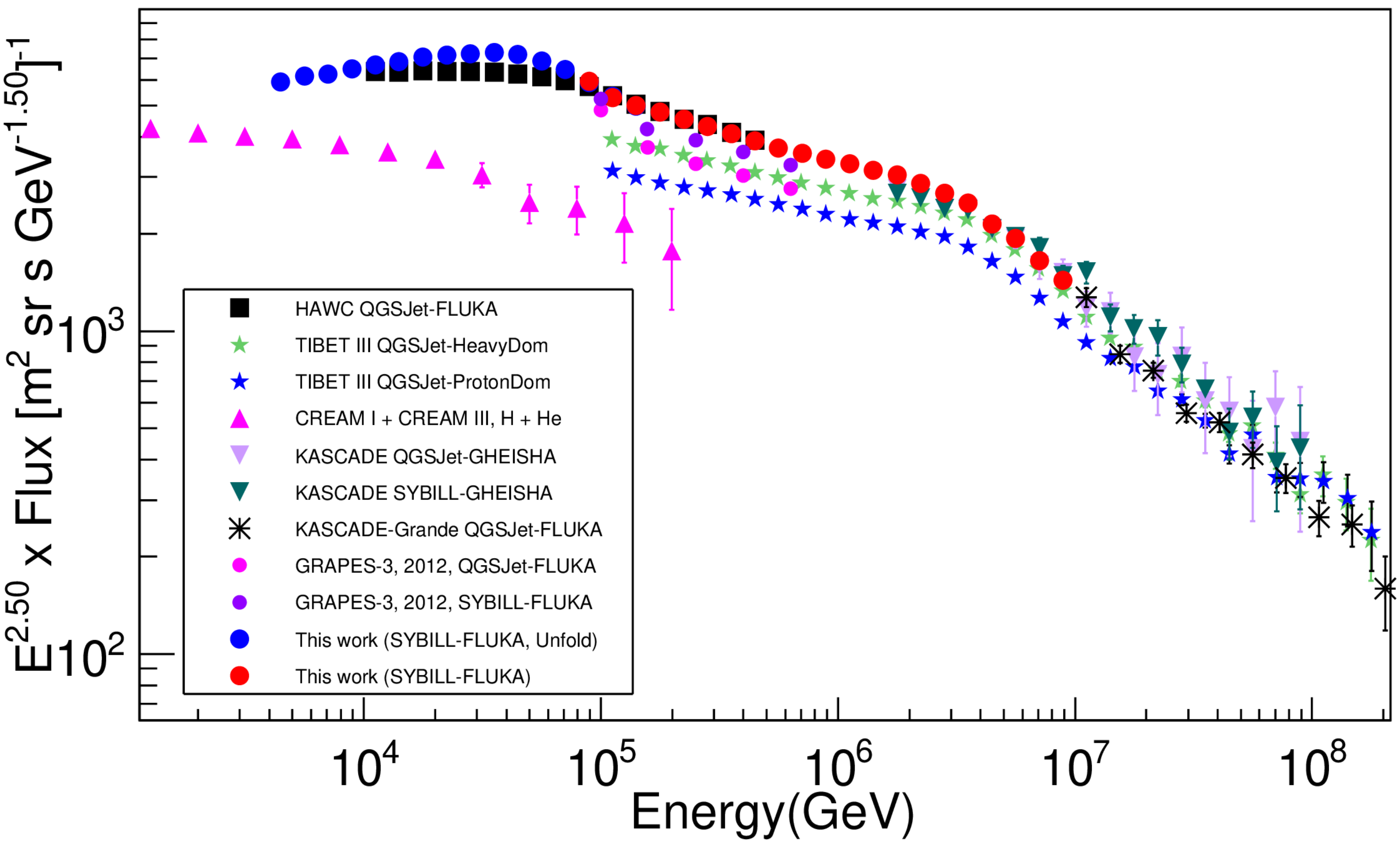
Arrival direction determination



$$t_2 - t_1 = D_{21} \sin\theta / c$$

D_{21} is the separation between detector 1 and 2

GRAPES-3 CR Energy Spectrum



Power law (100 TeV – 500 TeV)

$\Gamma = -2.729 \pm 0.001$

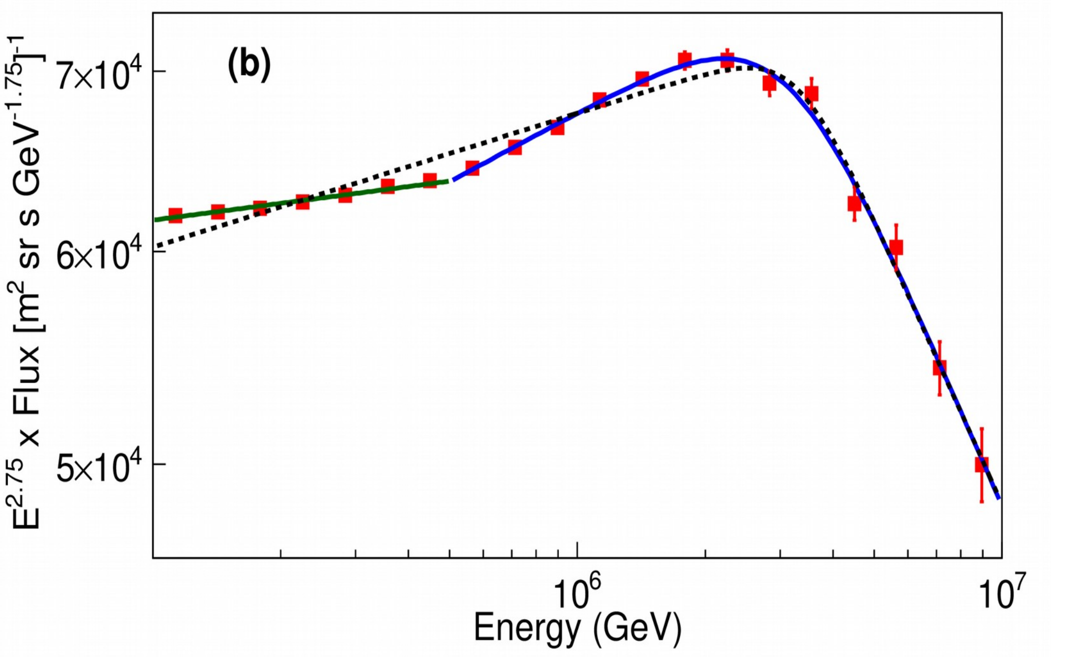
Broken power law

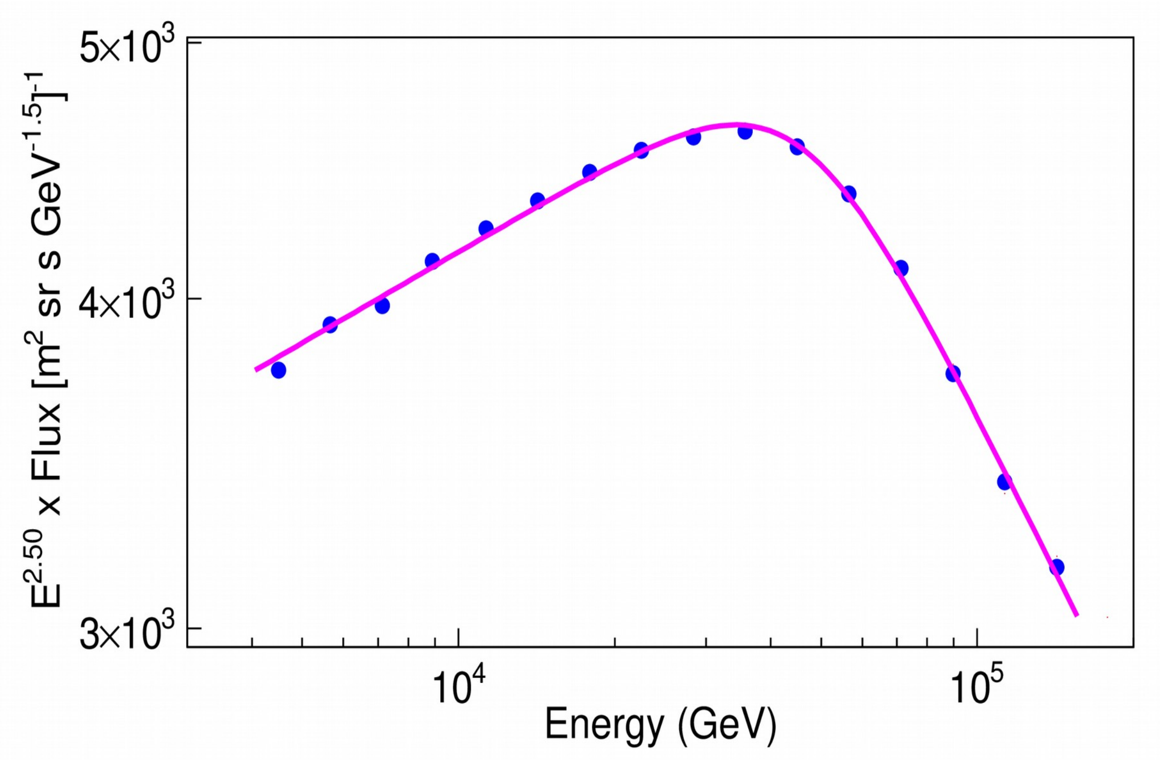
(500 TeV – 10 PeV)

$\gamma_1 = -2.664 \pm 0.007$

$\gamma_2 = -3.116 \pm 0.064$

Knee = 3.1 ± 0.3 PeV





Broken power law (5 TeV – 150 TeV)

$\gamma_1 = -2.386 \pm 0.002$

$\gamma_2 = -2.898 \pm 0.004$

$E_{break} = 45.4 \pm 0.3$ TeV

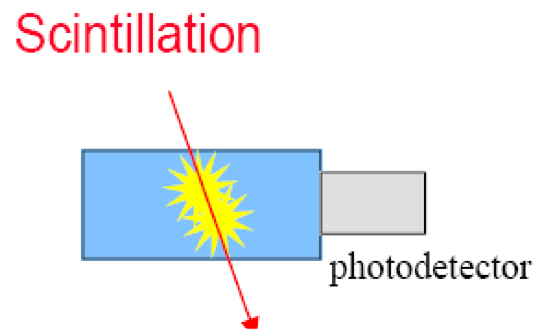
Scintillation detectors

1. **Energy deposition in scintillator by ionizing particle**

2. **Conversion of energy to scintillation photons**

3. **Transporting scintillation photons to photodetector**

4. **Photon to electrical signal**



- Fast light emitting medium on passage of charged particle
  - Inorganic Scintillators (Slow response, high light o/p)
    Response time 10-1000ns, Ex. NaI, CsI, BaF_2
  - Organics Scintillators (Fast response, low light o/p)

Organic Scintillators

Liquid and plastic scintillators: Composed of solvent (base) + primary solute (scintillation in UV) + secondary solute as wavelength shifter (from UV to visible)

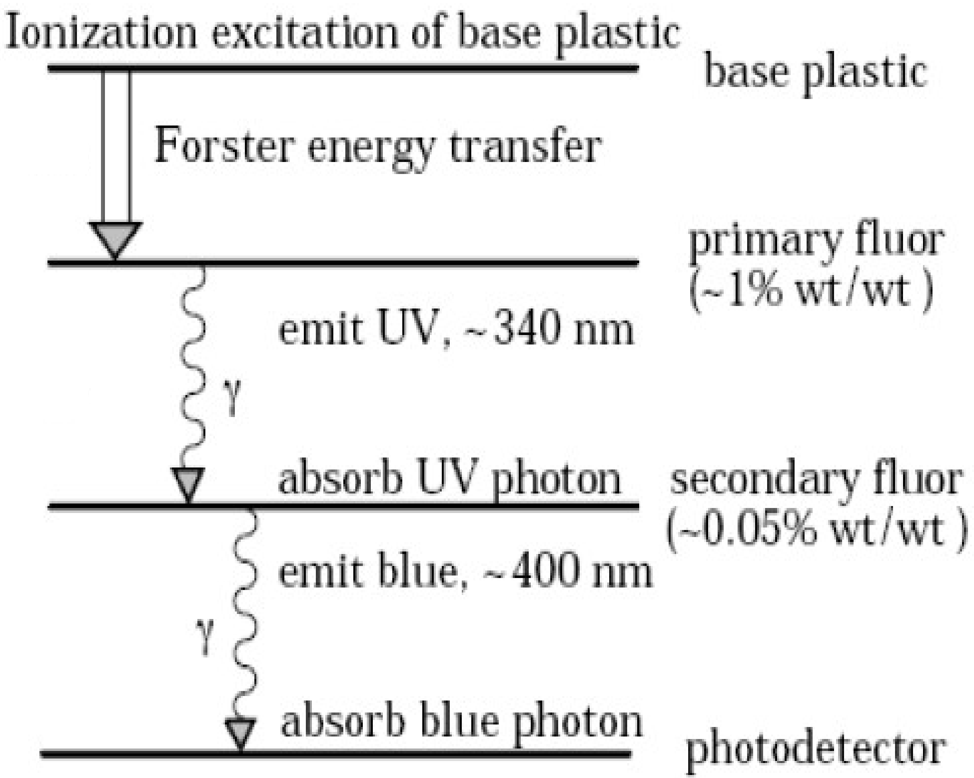
Organic scintillators are cheap and have fast time response (~ few ns)

Some widely used solvents and solutes

	solvent	primary solute	secondary solute
Liquid scintillators	Benzene Toluene Xylene	p-terphenyl DPO PBD	POPOP BBO BPO
Plastic scintillators	Polyvinylbenzene Polyvinyltoluene Polystyrene	p-terphenyl DPO PBD	POPOP TBP BBO DPS

Plastic scintillators are most suitable in cosmic ray air shower experiments due to their rugged nature.

Scintillation mechanism



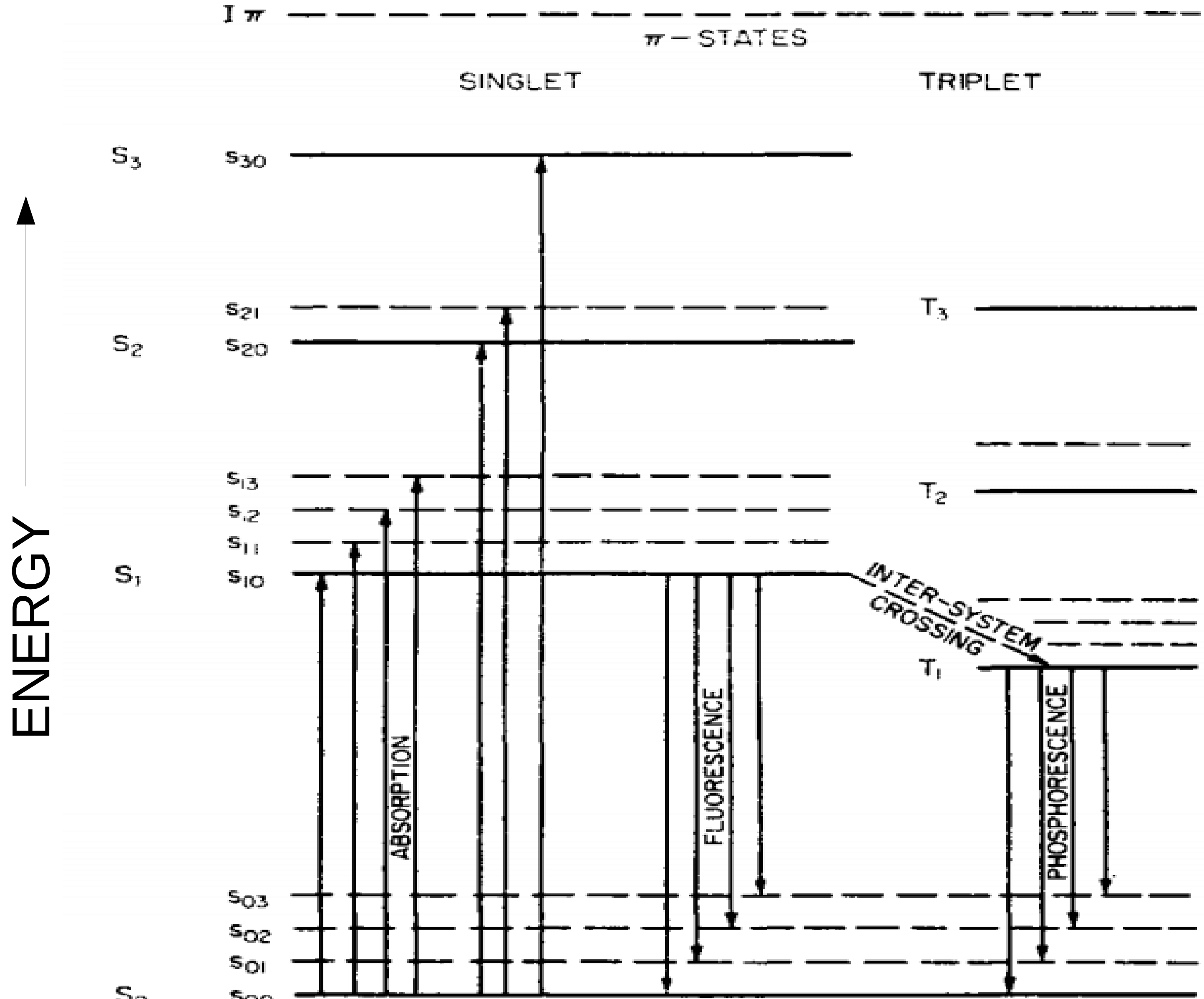
Polyvinyltoluene, Polystyrene

p-Terphenyl

POPOP

PMT, SiPM

Scintillation mechanism



Scintillator molecules have various electronics states (S_0, S_1, S_2,...) and vibrational states (S_{00}, S_{01}, S_{02}, ..., S_{10}, S_{11}, S_{12},..............)

Spacing between electronics states is 3 to 4 eV and spacing between vibrational states is about 0.15 eV.

At room temperature, average energy is about 0.025 eV. All molecules are in the S_{00} state.

When charged particle passes through the scintillator, kinetic energy is absorbed by the molecules and electrons are excited to upper levels.

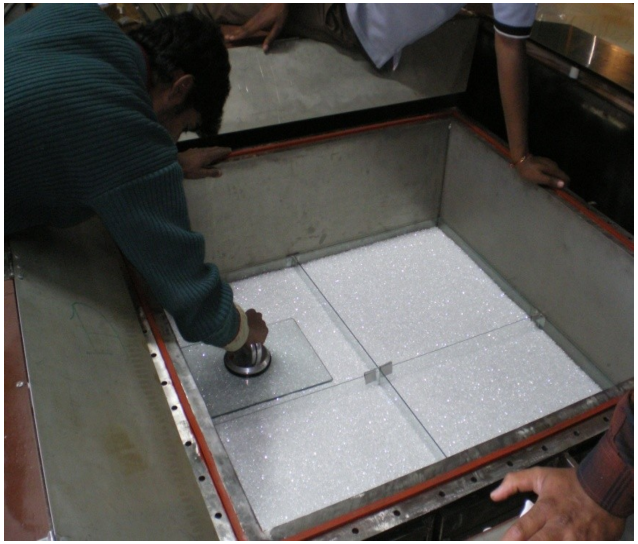
Higher states deexcites to quickly (pico seconds) to S_1 state through radiation loss transitions.

Transition from S_{10} to ground state produces scintillation light. The process is called fluorescence.

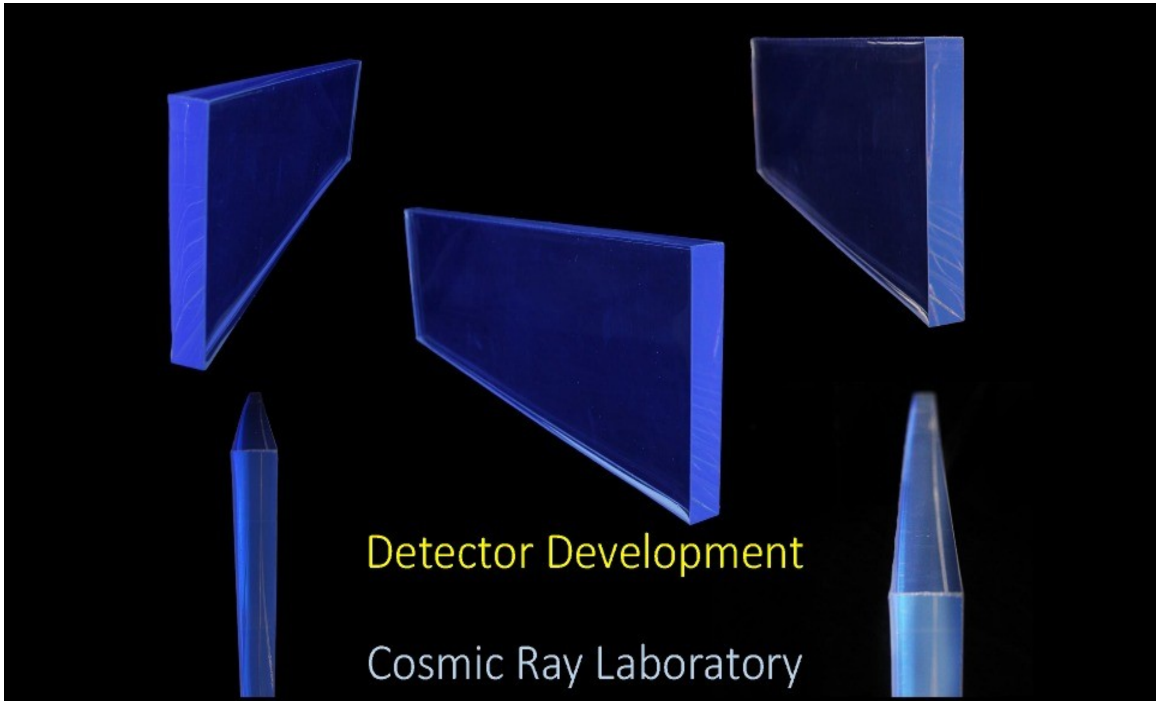
Fluorescence intensity at time t is

$$I = I_0 e^{-t/\tau}, \quad \tau \text{ is few nano seconds}$$

Plastic scintillator fabrication at Cosmic Ray Laboratory in Ooty



Development & fabrication of plastic scintillators



Plastic Scintillator development:

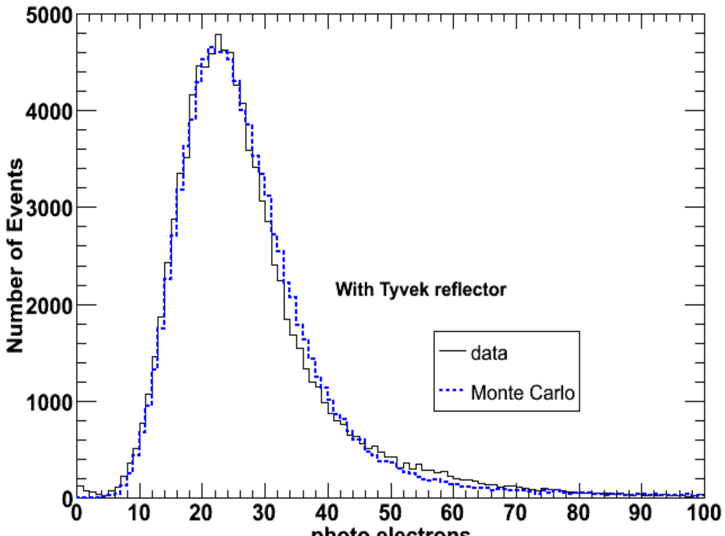
Decay Time= 1.6 ns Light Output = 85% Bicron (54% anthracene)

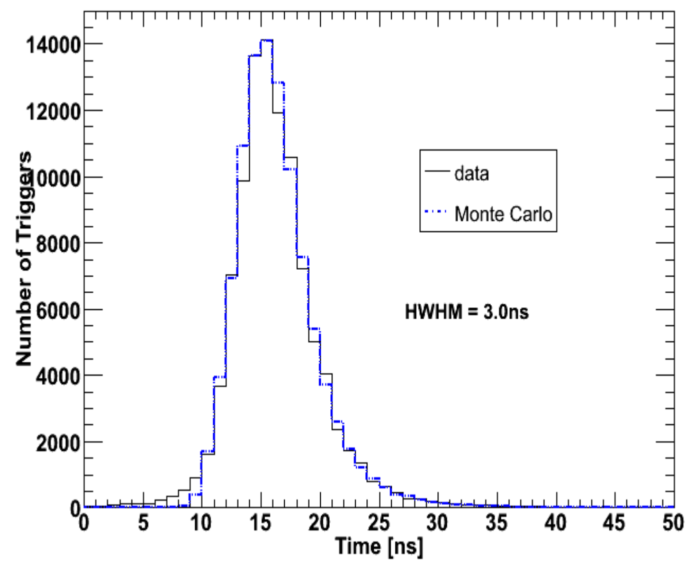
Timing 25% faster Atten. Length λ= 100cm Cost ~30% of Bicron

Max Size 100cmX100cm Total > 2000

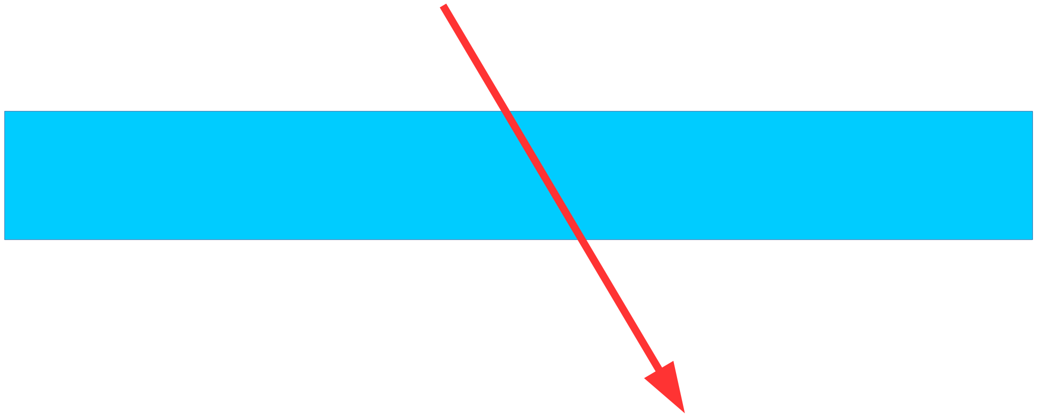
CERN, Osaka, IUAC Delhi, Bose, VECC, BARC, ECIL, Utkal U.

P.K. Mohanty et al. Rev. Sci. Instr. **83** 043301 (2012)





Energy loss conversion to scintillation light



Mean energy loss by ionizing particle like muon in scintillator of thickness 1 cm is **2 MeV**

Scintillation photons are produced isotropically along the track of the particle.

Energy loss to photon conversion: 1 photon (3 eV) per 100 eV energy

Number of photon produced per cm is typcially 20,000

It is important to efficiently transport the photons to a photodetector which converts photons to a measurable electrical signal

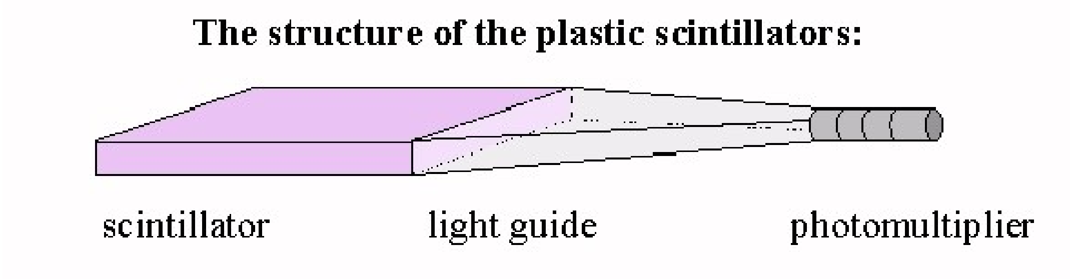
Light guides

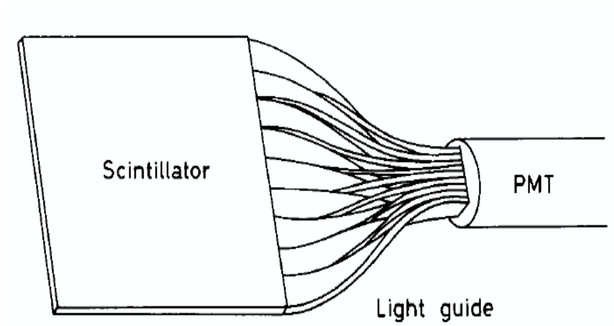
Scintillation light comes out from all surfaces

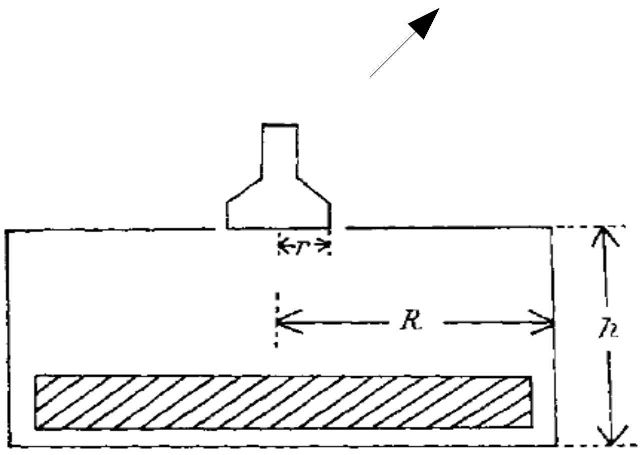
…..Needs to be navigated to photodetector

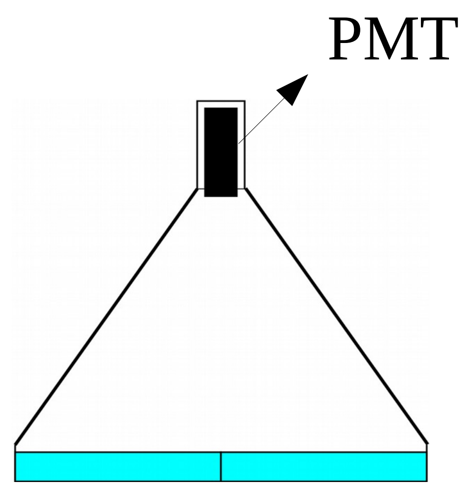
ADIABATIC GUIDE

FISH TAIL

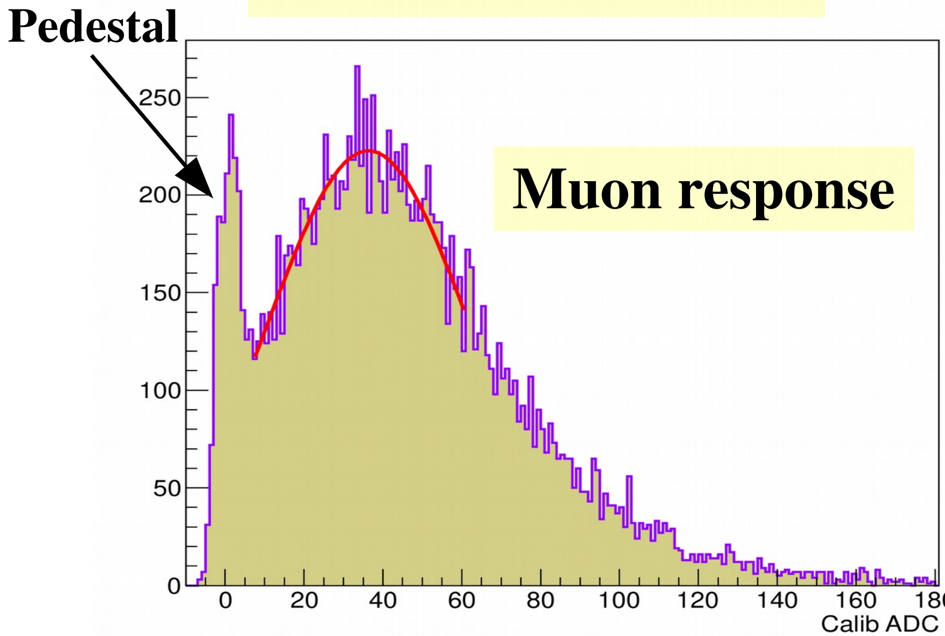


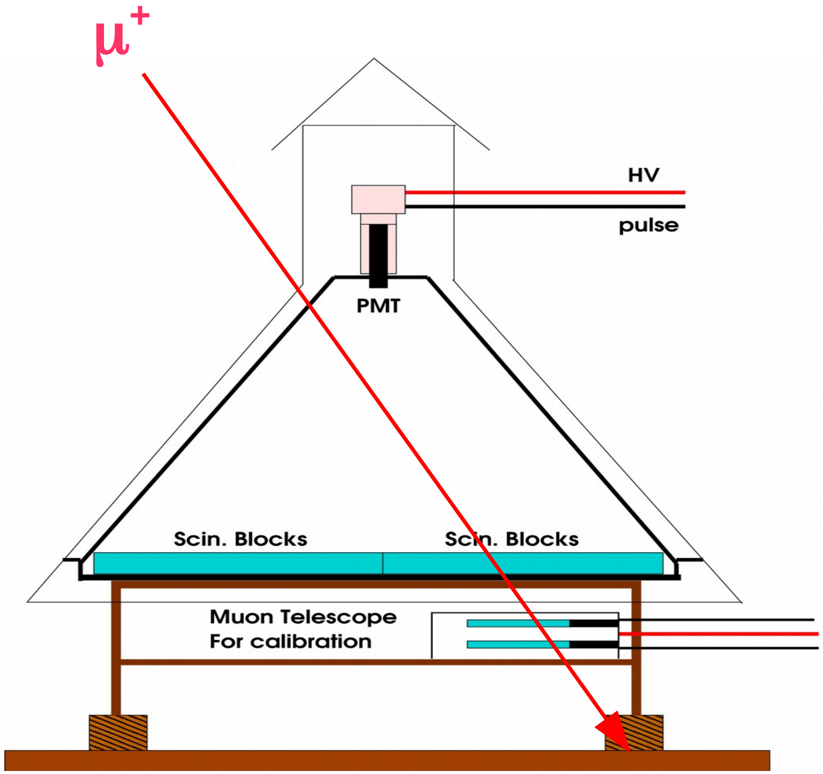




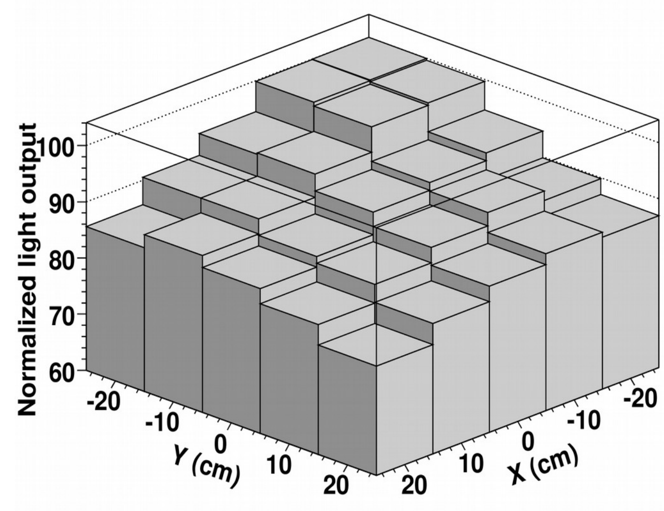


Low Photo-electron Yield (Poor Signal to Noise Separation)



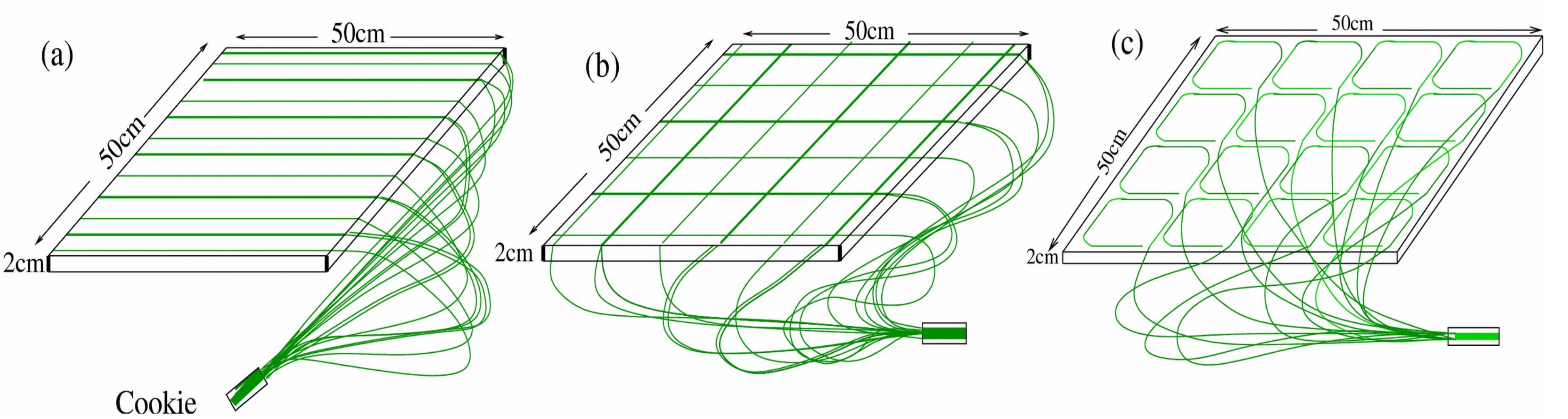


Large Non-uniform Response (~ 30%)



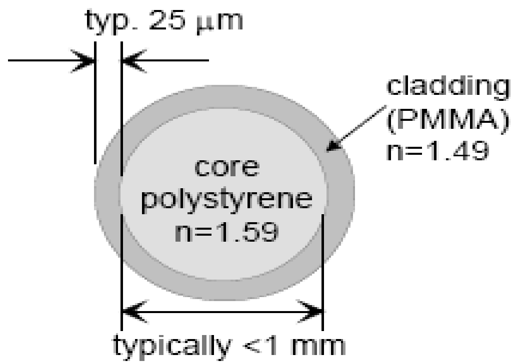
Wave-length shifting fibers

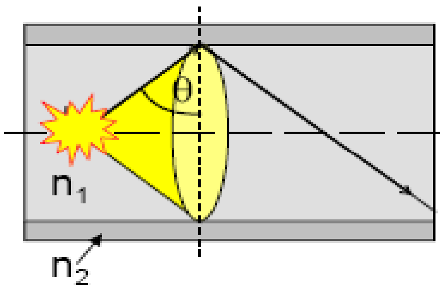
Uniform collection and efficient transport of light from scintillator to photodetector



Wave-length shifting fibers

light transport by total internal reflection





$$\theta \geq \arcsin\frac{n_2}{n_1} \approx 69.6^\circ \qquad \frac{d\Omega}{4\pi} = 3.1\% \quad \text{in one direction}$$

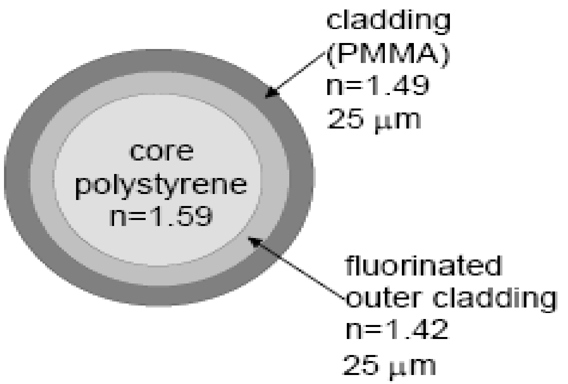
minimize $n_{cladding}$.

Ideal: air (n=1), but impossible due to surface imperfections

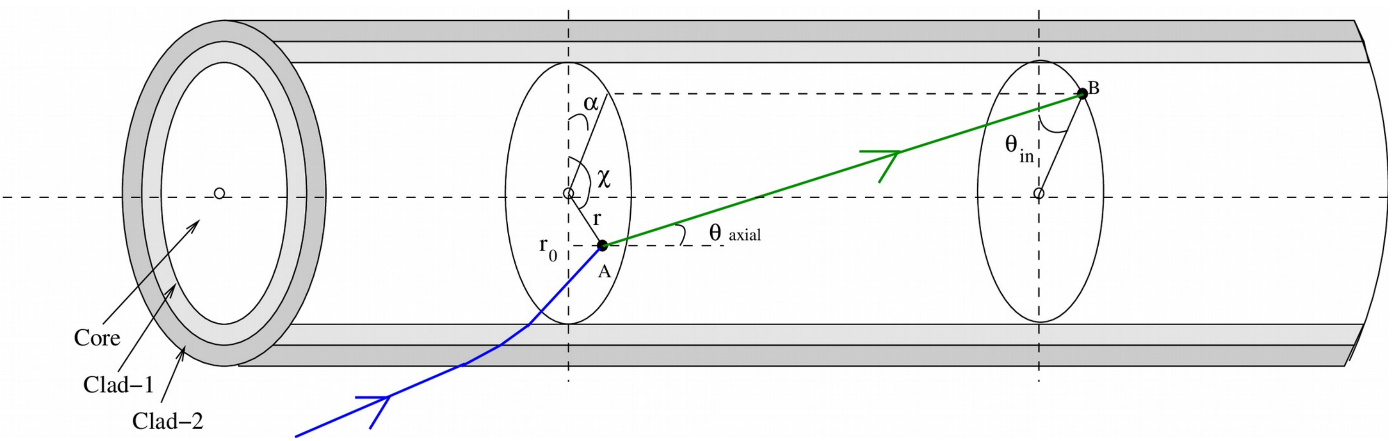
multi-clad fibres
for improved aperture

$$\frac{d\Omega}{4\pi} = 5.3\%$$

and absorption length: λ>10 m for visible light



Photon Trapping in Fiber



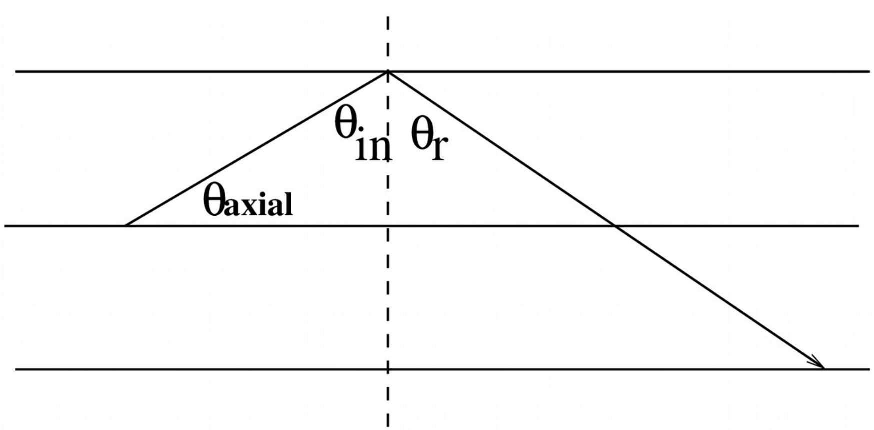
Core: 0.94mm
Refractive index = 1.59

Inner clad: 0.03mm
Refractive index = 1.49

Outer clad: 0.03mm
Refractive index = 1.42

Meridional rays

Incident, normal and reflected ray lie in the same plane



$$\cos(\theta_{in}) = \sin(\theta_{axial})$$

Skew Rays

do not lie in the same plane

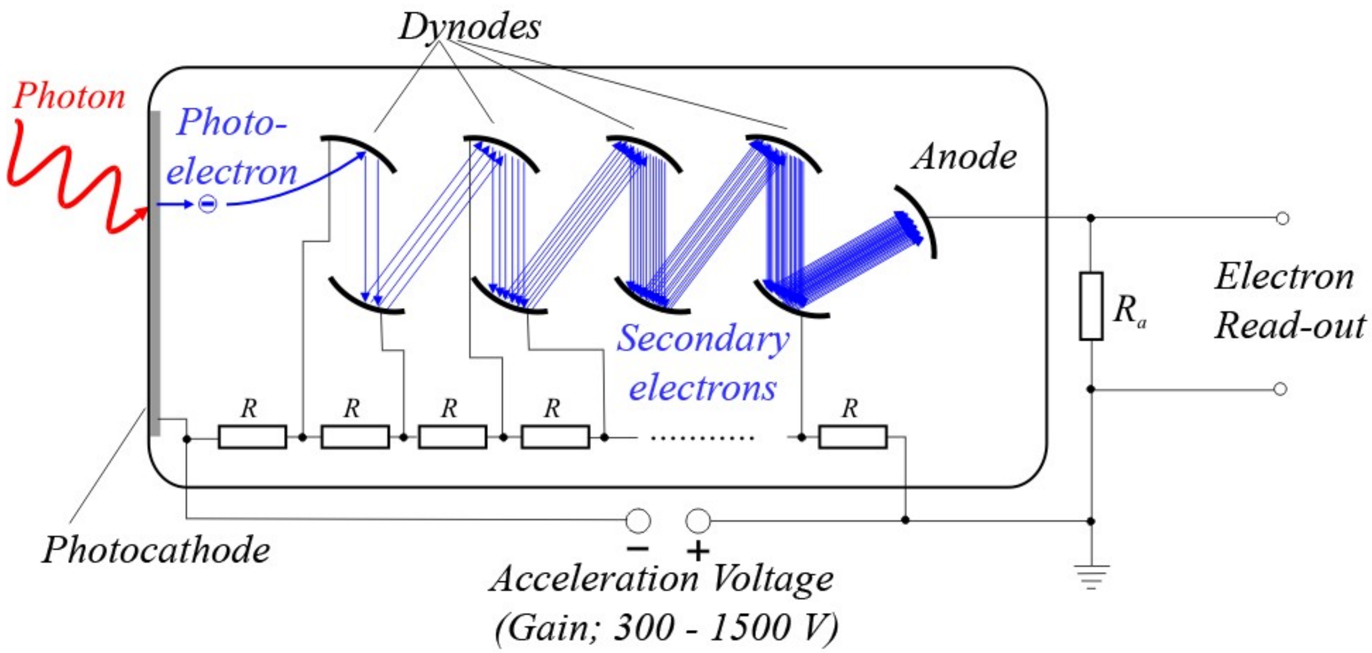
$$\sin(\theta_{axial}) = \cos(\theta_{in})\left\{1 + \left(\frac{r/r_0 \sin(\chi - \alpha)}{1 - r/r_0 \cos(\chi - \alpha)}\right)^2\right\}^{1/2}$$

P.K. Mohanty et al. Rev. Sci. Instrum. 83 (2012) 043301.

Photomultiplier tube

Photomultiplier types and sizes

Photomultiplier tube and its working principle



The photocathode converts incident photon to an electron which is known as photoelectric effect

$$E_{pe} = E_{\gamma} - W$$

Materials with low work function are used for photocathode such as silver-oxygen-caesium (AgOCs), antimony-caesium (SbCs) bi-and trialkali compounds SbKCs, SbRbCs, and $SbNa_2KCs$.

Gain and voltage supply

The amplification factor or gain of a PMT depends on the number of dynodes and secondary emission factor δ.

Where δ is a function of primary energy of electron which depends on the potential difference V_d between dynodes.

$$\delta = K V_d$$

Overall gain of the PMT is

$$G = \delta^n = (K V_d)^n$$

If $\delta=4$, $n=10$, $G \sim 10^6$

Quantum efficiency

$$Q.E. = N_{photoelectron} / N_{photon}$$

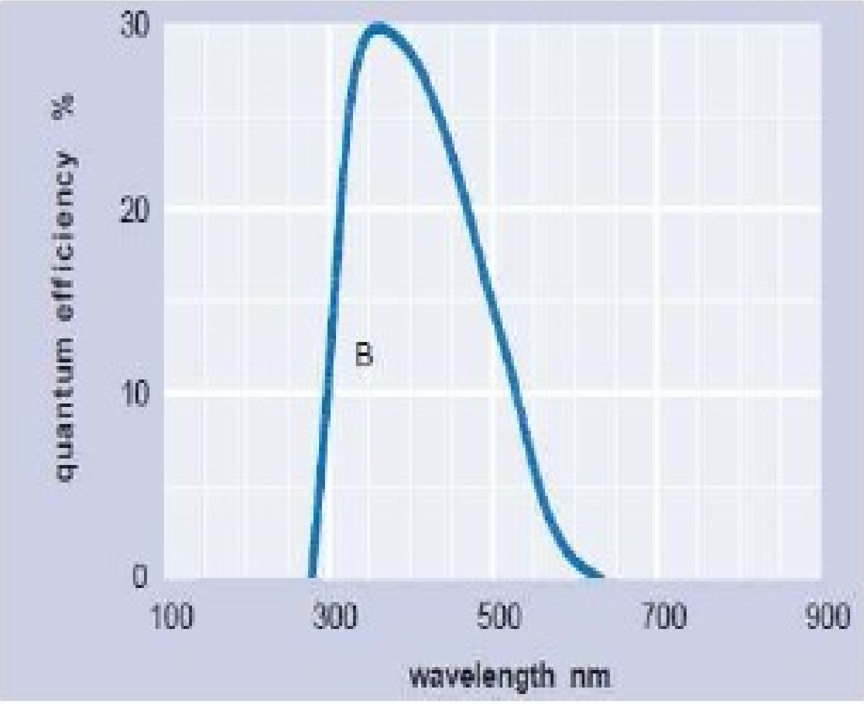
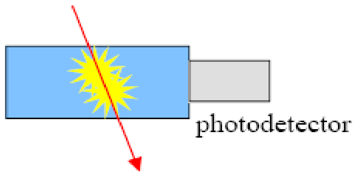


Figure 3.11: Typical quantum efficiency of an ETL PMT (model 9807B) [71].

Estimation of Signal Strength



Charged particle passes through 1cm thick scintillator

↓

Total energy loss by ionization ~ 2MeV

↓

Number of scintillation photons produced ~ 20000 (λ~200-600 nm)

↓

Number of photons captured by WLS fiber ~ 200

↓

Number of photoelectrons produced at photocathode ~ 20

↓

Total number of electrons at PMT last dynode (i/p of preamp) ~ 10^8

Ionization detectors

Primary and total ionization

Fast charged particles ionize the atoms of a gas.

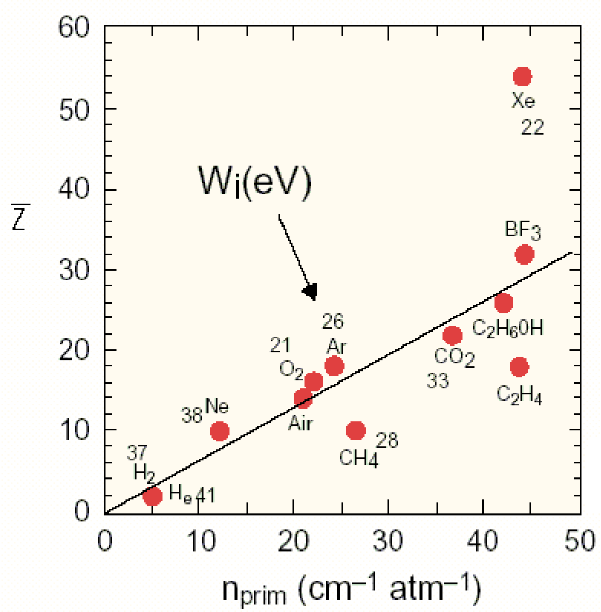
Often the resulting primary electron will have enough kinetic energy to ionize other atoms.

$$n_{total} = \frac{\Delta E}{W_i} = \frac{\frac{dE}{dx}\Delta x}{W_i}$$

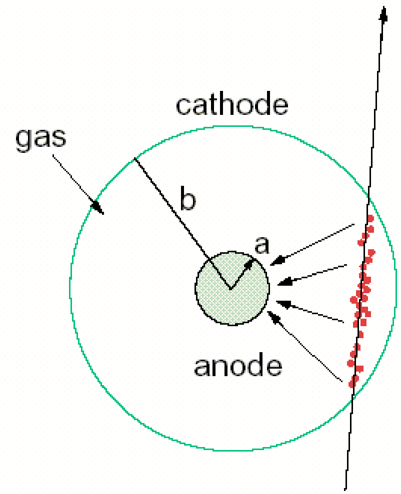
$$n_{total} \approx 3\ldots4 \cdot n_{primary}$$

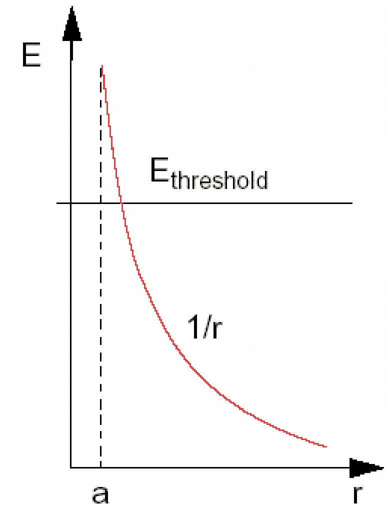
total number of created electron-ion pairs.
ΔE = total energy loss
W_i = effective <energy loss>/pair

Number of primary electron/ion pairs in frequently used (detector) gases.



(Lohse and Witzeling, Instrumentation In High Energy Physics, World Scientific, 1992)

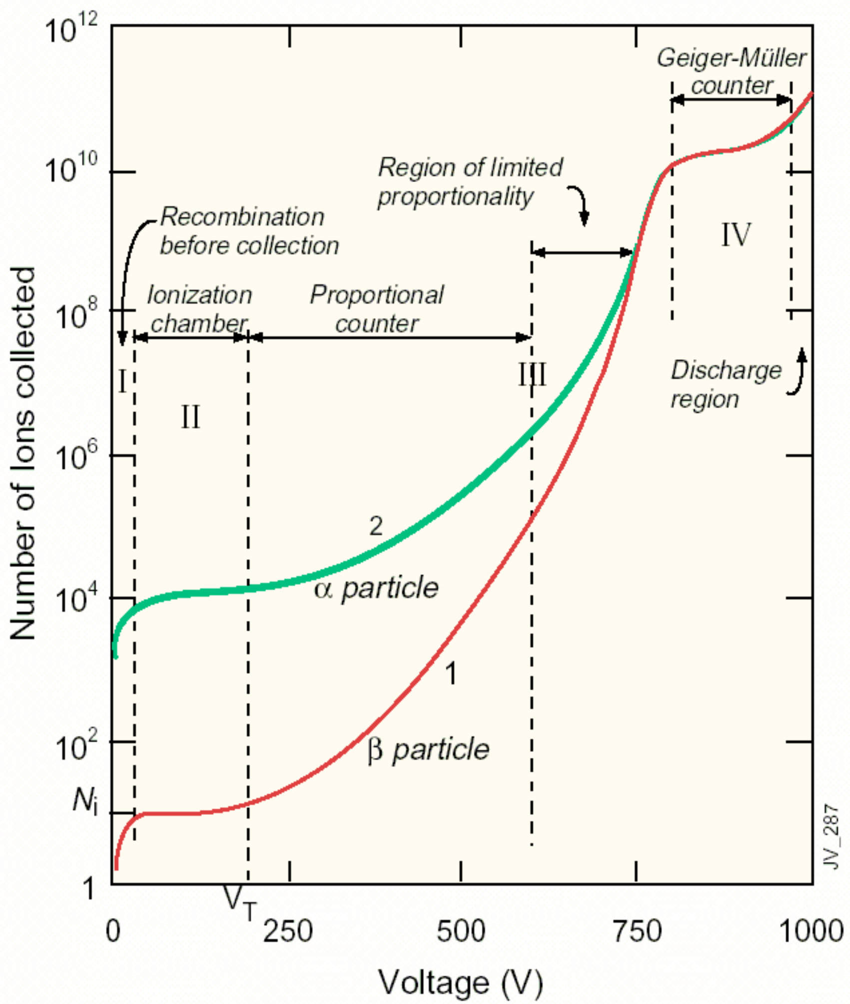




$$E(r) = \frac{CV_0}{2\pi\varepsilon_0}\frac{1}{r} \quad and \quad V(r) = \frac{CV_0}{2\pi\varepsilon_0}\ln\frac{r}{a}$$

Close to the anode wire the field is sufficiently high (some kV/cm), so that e- gain enough energy for further ionization → exponential increase of number of e--ion pairs.

Operation modes



Region I: At very low voltage charge begins to be collected but **recombination** dominates

Region II: All electron-ion pairs are collected before recombination (plateau)

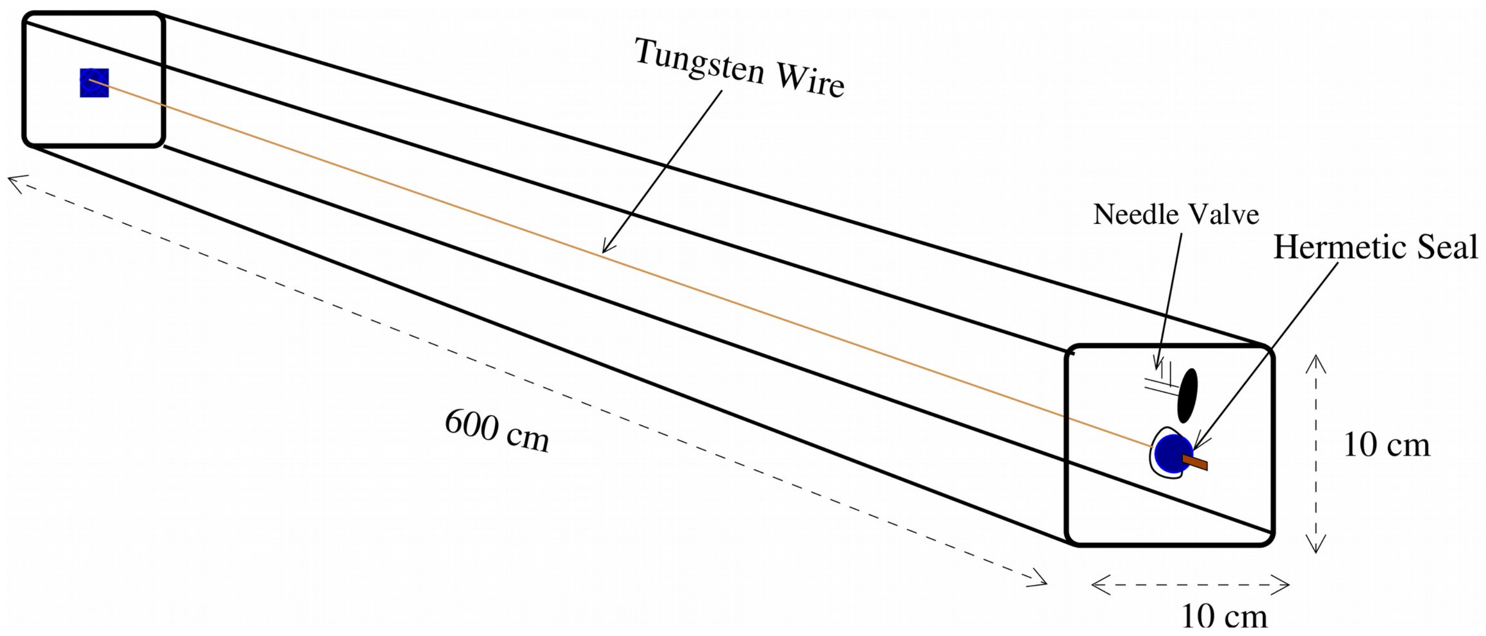
Region III: Above the threshold voltage V_T the field is strong enough to allow multiplication and in the proportional mode gains >10^4 can be achieved with the detected charge proportional to the original energy deposition**.**

Eventually the proportionality begins to be lost due to space charge build-up around the anode which distorts the E field.

Region IV: In the Geiger-Muller mode photons emitted from the de-exciting molecules spread to other parts of the counter triggering a chain reaction with many avalanches along the length of the anode

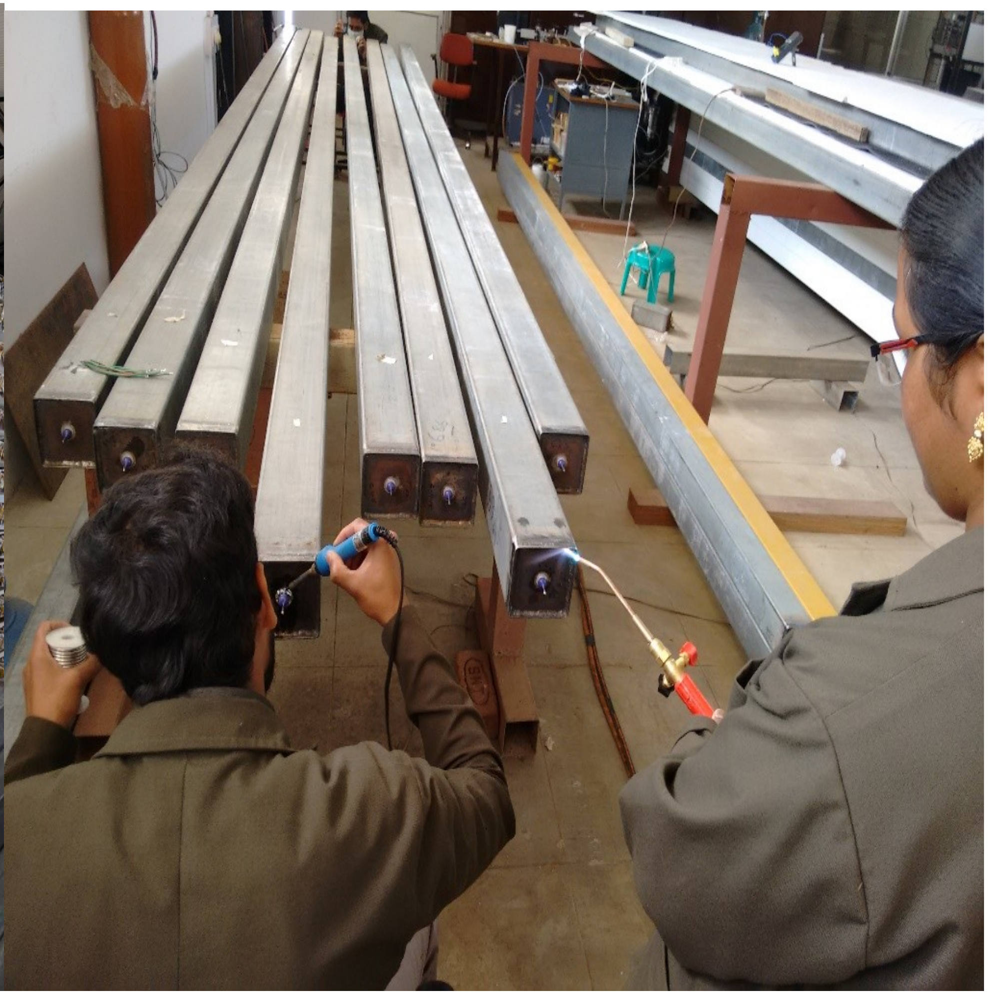
Proportional counter in GRAPES-3 experiment

GRAPES-3 proportional counter

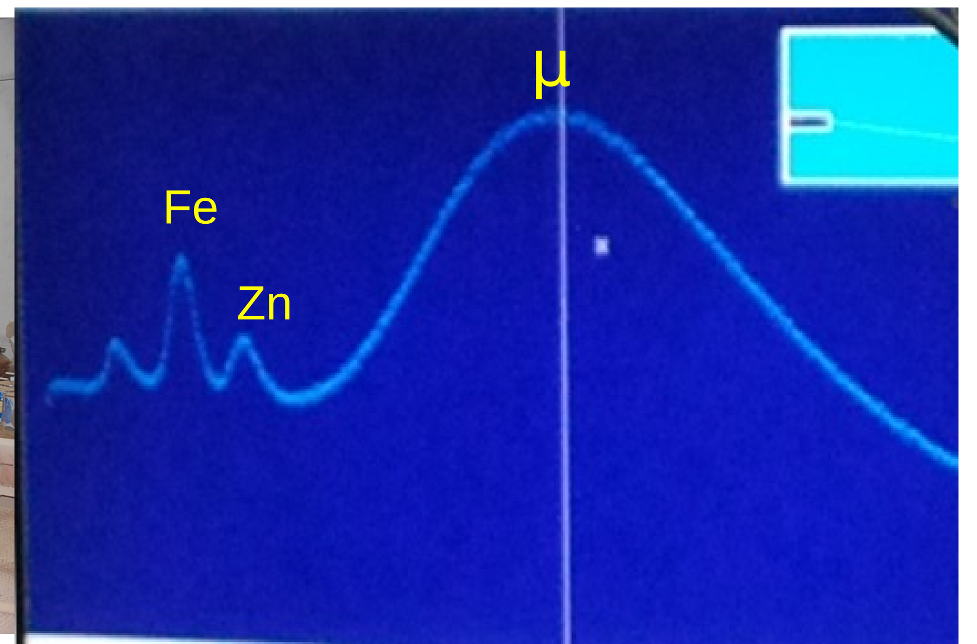


Filling gas: P10 (90% Argon + 10% methane)

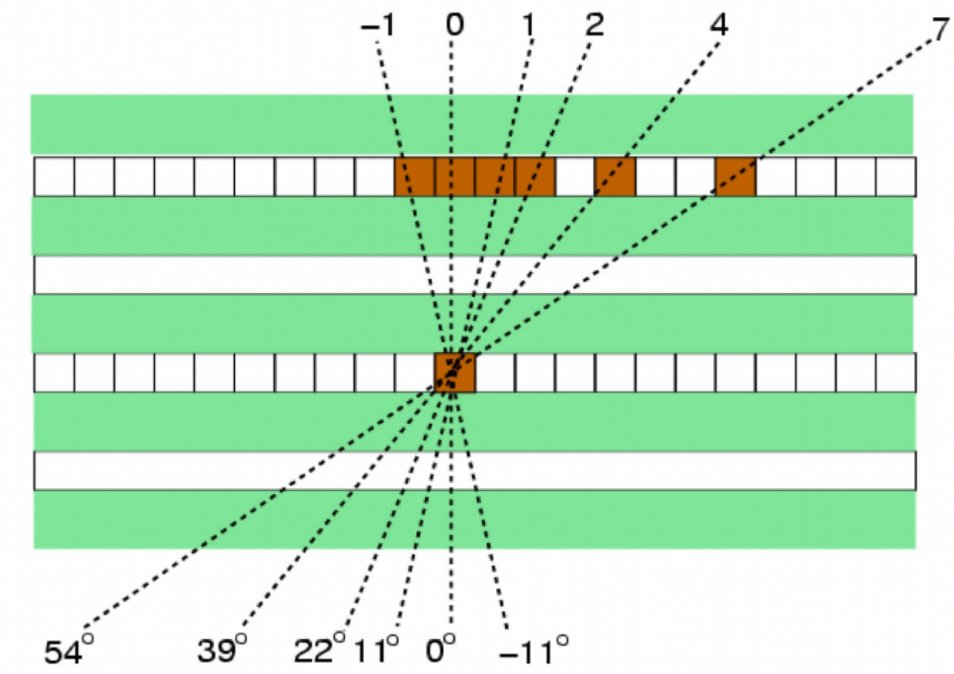
Fabrication of proportional counter



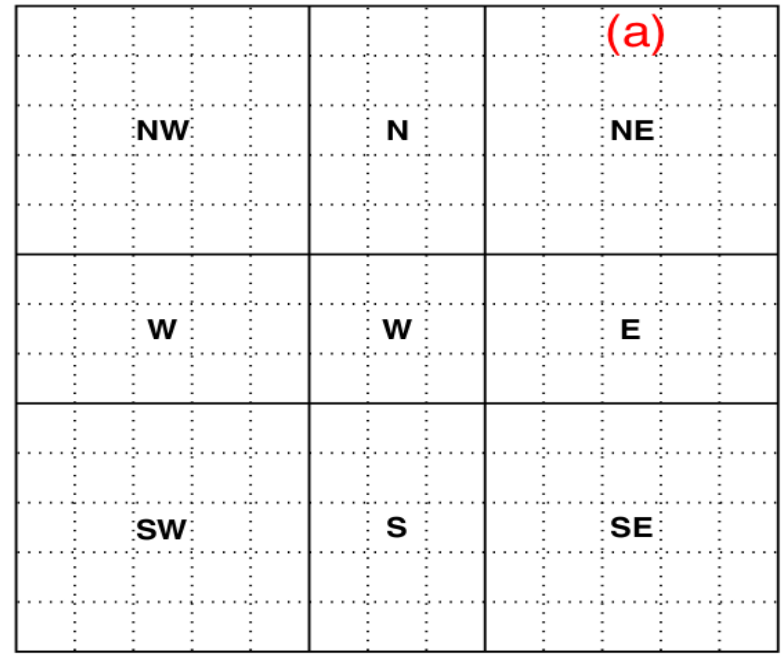
Fabrication of proportional counter



GRAPES-3 Muon Telescope (Ooty, India, 11.4°N, 76.7°E, Rc = 17 GV). Records 4 x 10^9 muons per day, Sensitivity: 1 part in 10^4



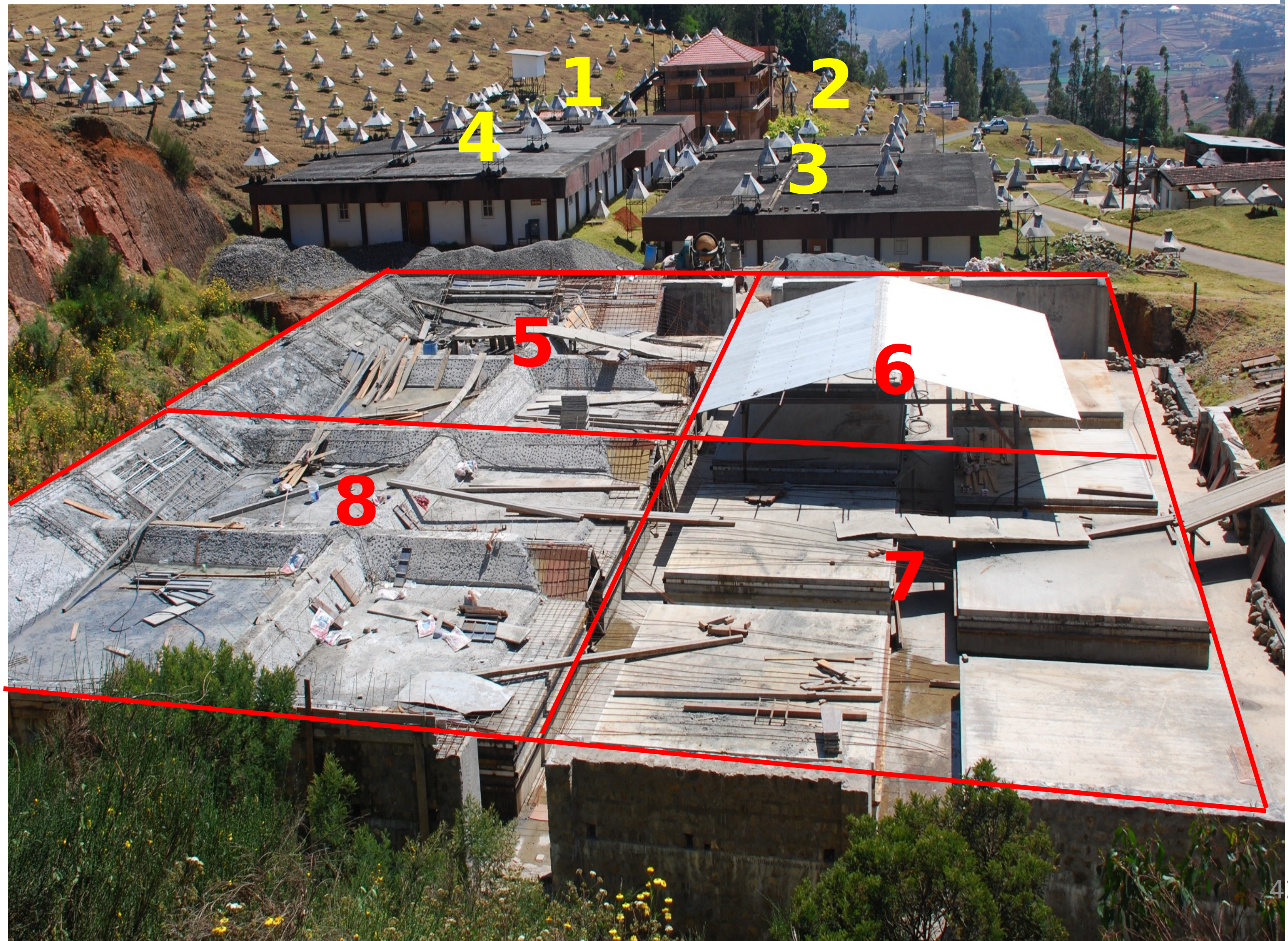
−1
0
1
2
4
7
54°
39°
22°
11°
0°
−11°



(a)
NW
N
NE
W
W
E
SW
S
SE

New Muon telescope will add another 560 m^2

70% larger field of view compared to old one



THANK YOU

Quenching gases

Polyatomic gases (CH_4) absorbs photons over wide energy range due to its copious vibrational and rotational energy levels

Energy dissipation by collision or dissociation into smaller molecules

Methane absorbs photons in the range of 7.9-14.5 eV

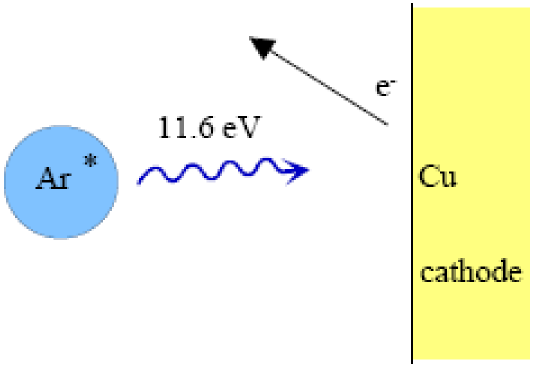
90%Ar + 10%CH_4 (P10) is one of the widely gas used in the proportional counter

Choice of Gases

Dense noble gases. Energy dissipation mainly by ionization! High specific ionization.

De-excitation of noble gases only possible via emission of photons, e.g. 11.6 eV for Argon.

This is above ionization threshold of metals, e.g. Copper 7.7 eV.



→ new avalanches → permanent discharges !

Energy loss by Ionization: Bethe-Bloch formula

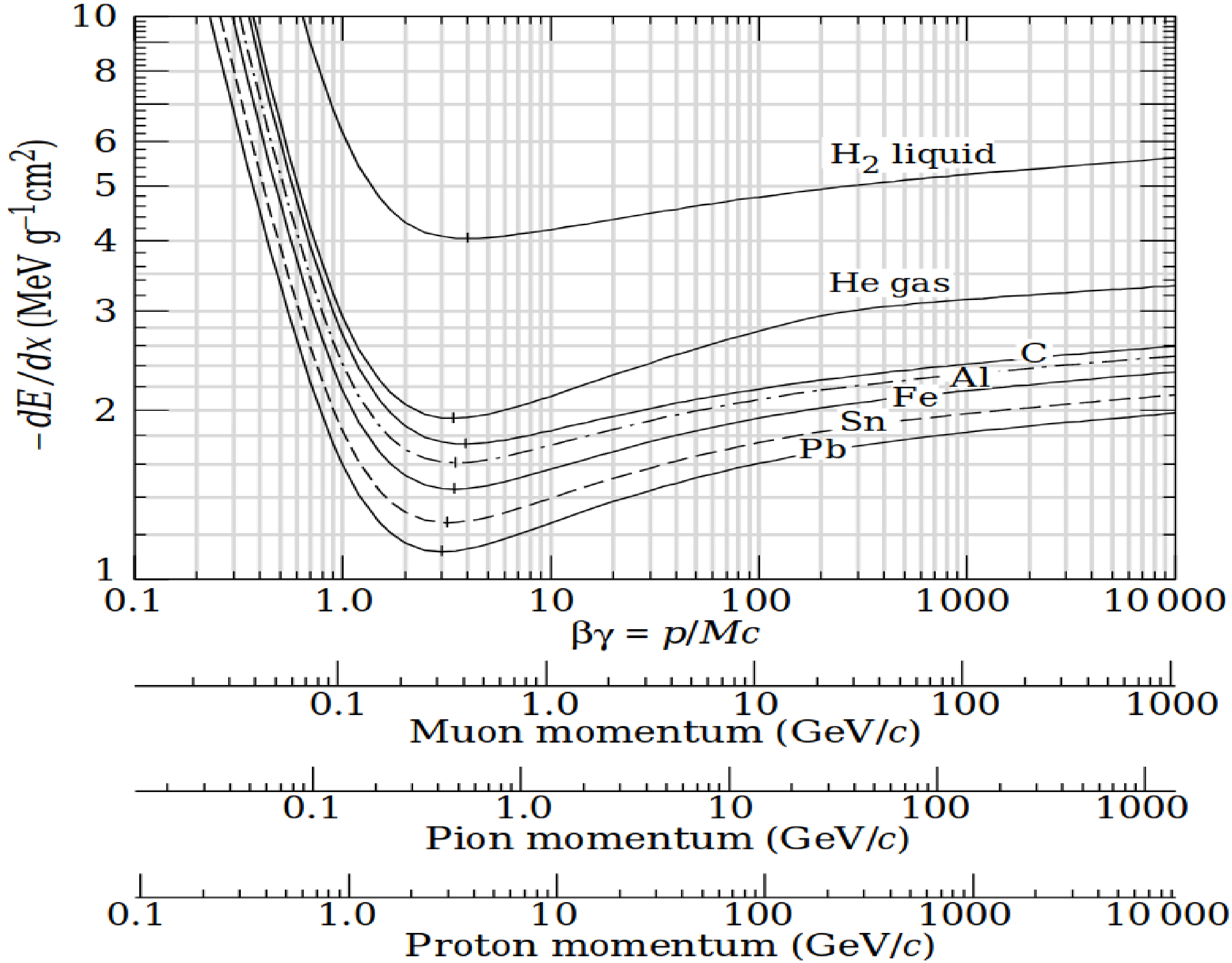
Bethe-Bloch formula describes the mean energy loss of a charged particle traversing through matter

For a particle with velocity v, charge z and energy E, traversing into distance x into a target with electron density n and mean excitation potential I, the formula is given by

$$-\left\langle \frac{dE}{dx} \right\rangle = \frac{4\pi}{m_e c^2} \cdot \frac{n z^2}{\beta^2} \cdot \left(\frac{e^2}{4\pi\varepsilon_0} \right)^2 \cdot \left[\ln\left(\frac{2 m_e c^2 \beta^2}{I \cdot (1 - \beta^2)} \right) - \beta^2 \right]$$

Electron density n of the material can be caclulated by

$$n = \frac{N_A \cdot Z \cdot \rho}{A \cdot M_u}$$



10
8
6
5
4
3
2
1
$-dE/dx$ (MeV g^{-1}cm^2)
H_2 liquid
He gas
C
Al
Fe
Sn
Pb
0.1
1.0
10
100
1000
10 000
$\beta\gamma = p/Mc$
0.1
1.0
10
100
1000
Muon momentum (GeV/c)
0.1
1.0
10
100
1000
Pion momentum (GeV/c)
0.1
1.0
10
100
1000
10 000
Proton momentum (GeV/c)