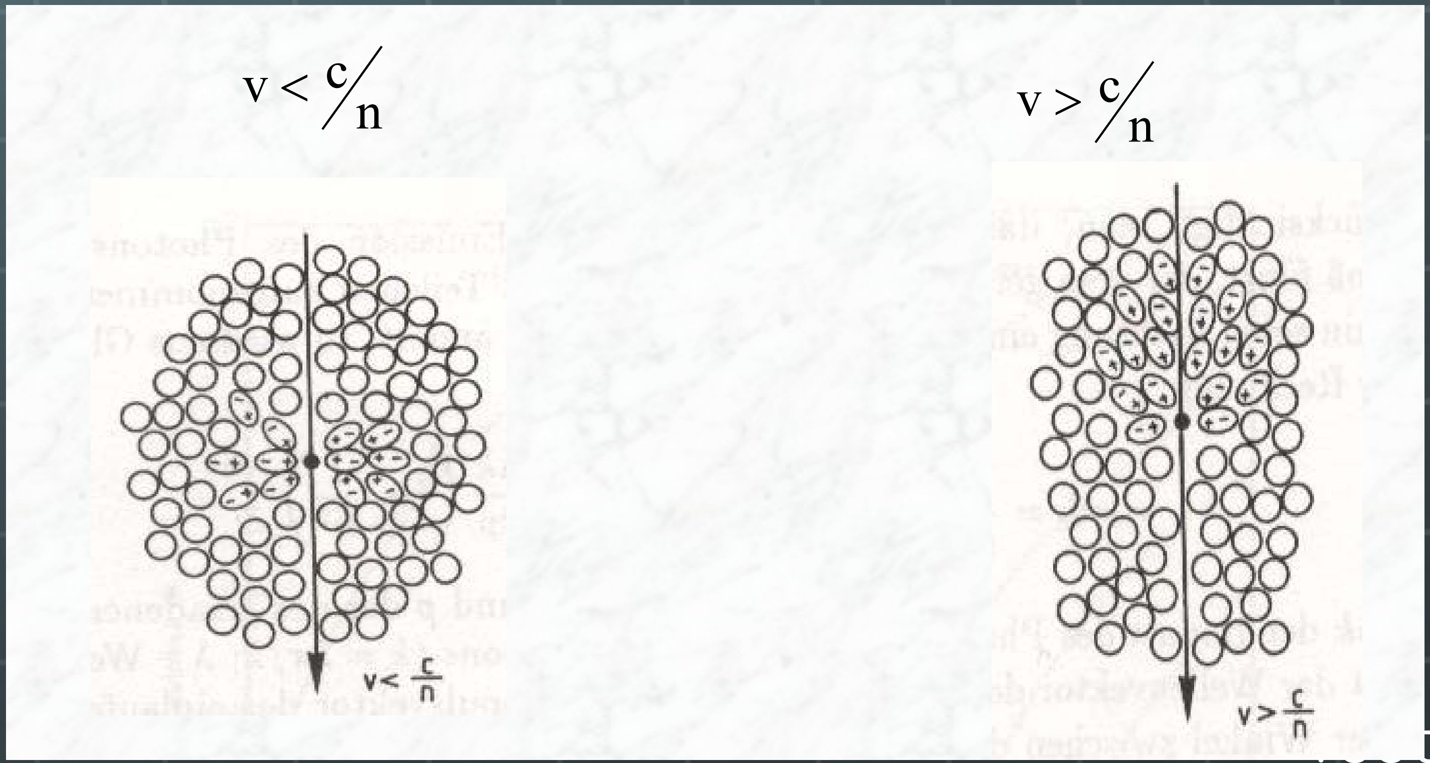
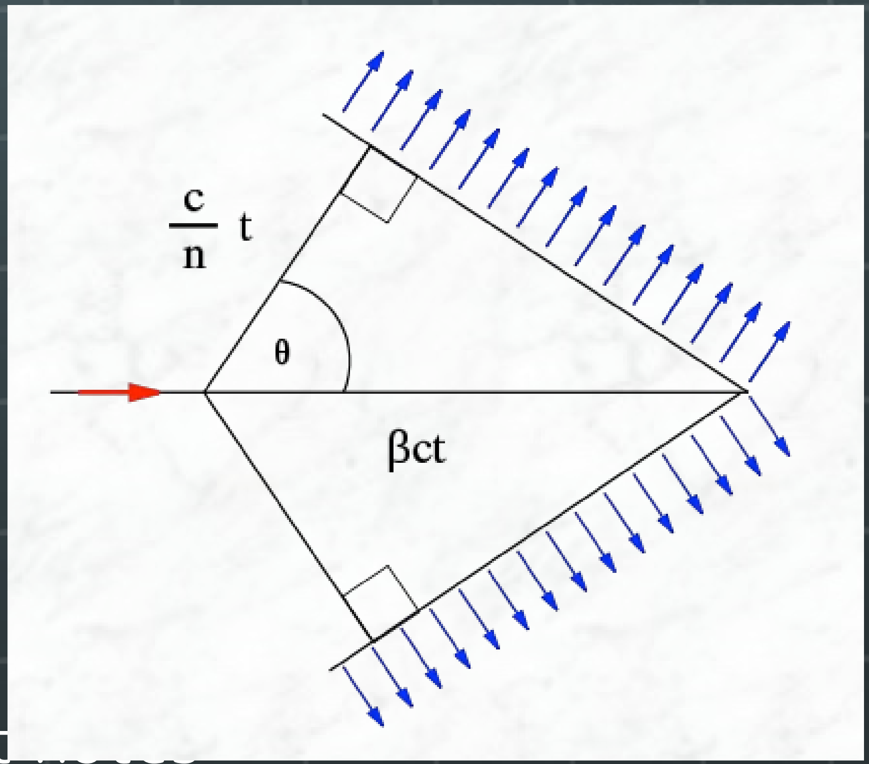
Cherenkov radiation

- In 1934, P.A. Cherenkov observe new type of luminescence irradiating gamma rays into uranyl salt.
  - Originated by charged particle
  - Not to be radiative origin
  - Observed at a certain angle along particle direction





Refractive indices, Cherenkov threshold values

Material	$n-1$	β-Schwelle	γ-Schwelle
festes Natrium	3.22	0.24	1.029
Bleisulfit	2.91	0.26	1.034
Diamant	1.42	0.41	1.10
Zinksulfid ($ZnS(Ag)$)	1.37	0.42	1.10
Silberchlorid	1.07	0.48	1.14
Flintglas (SFS1)	0.92	0.52	1.17
Bleifluorid	0.80	0.55	1.20
Clerici-Lösung	0.69	0.59	1.24
Bleiglas	0.67	0.60	1.25
Thalliumformiat-Lösung	0.59	0.63	1.29
Szintillator	0.58	0.63	1.29
Plexiglas	0.48	0.66	1.33
Borsilikatglas	0.47	0.68	1.36
Wasser	0.33	0.75	1.52
Aerogel	0.025 - 0.075	0.93 - 0.976	4.5 - 2.7
Pentan (STP)	$1.7 \cdot 10^{-3}$	0.9983	17.2
CO_2 (STP)	$4.3 \cdot 10^{-4}$	0.9996	34.1
Luft (STP)	$2.93 \cdot 10^{-4}$	0.9997	41.2
H_2 (STP)	$1.4 \cdot 10^{-4}$	0.99986	59.8
He (STP)	$3.3 \cdot 10^{-5}$	0.99997	123

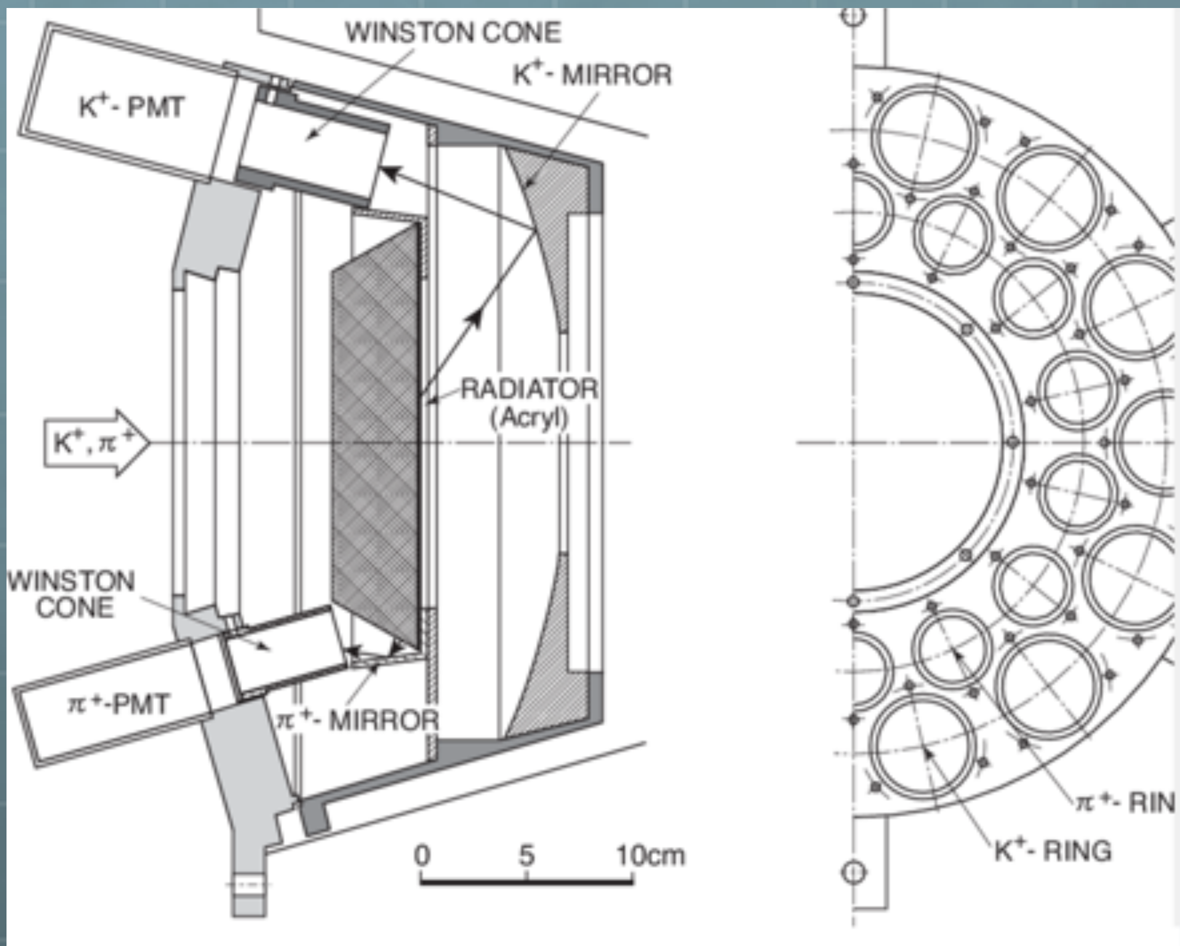
Tabelle 6.2: Cherenkov-Radiatoren [94, 32, 313]. Der Brechungsindex für Gase bezieht sich auf $0°C$ und $1\,atm$ (STP). Festes Natrium ist für Wellenlängen unterhalb von 2000 Å transparent [373, 209].

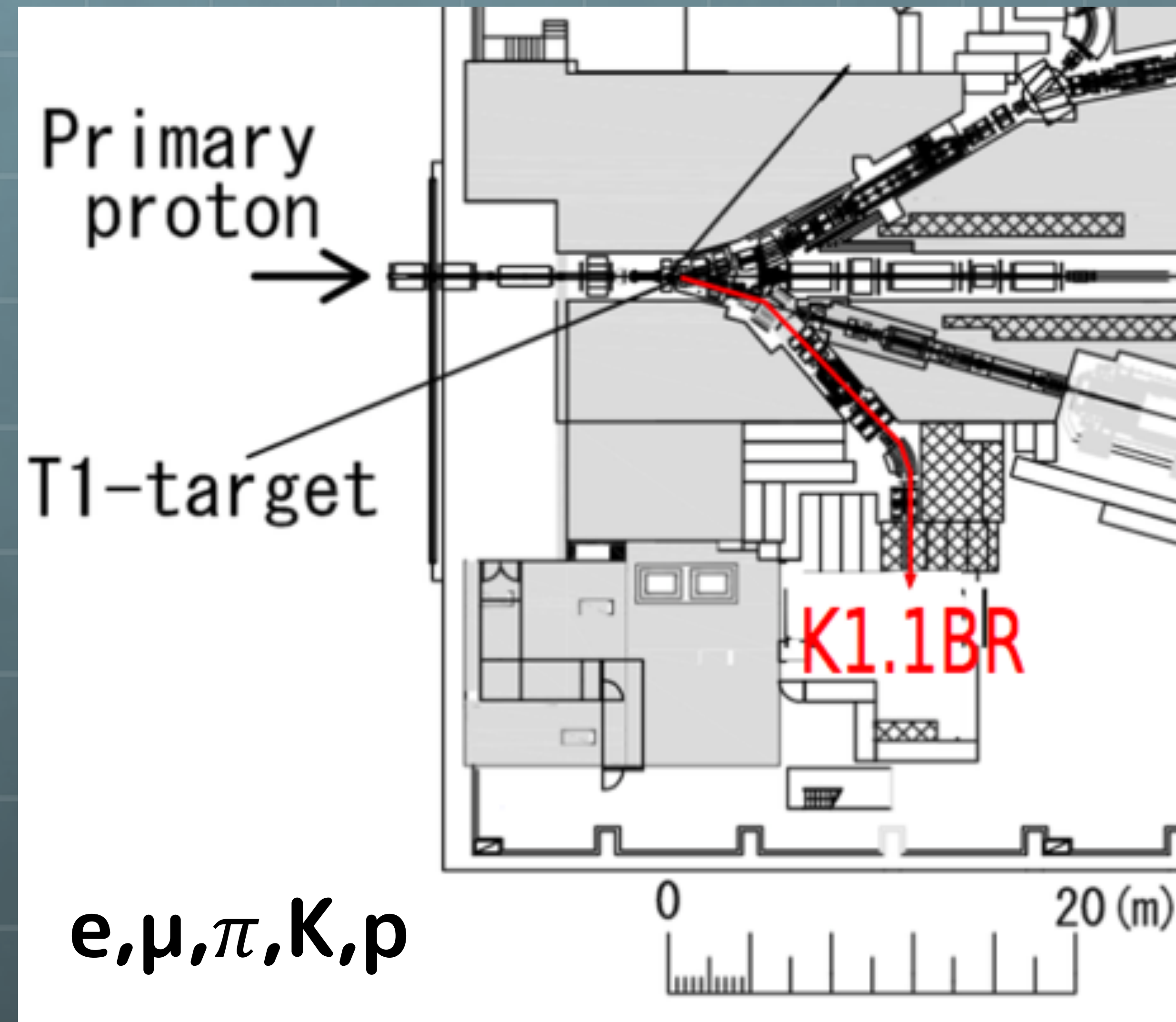
problematic: region between liquids and gases

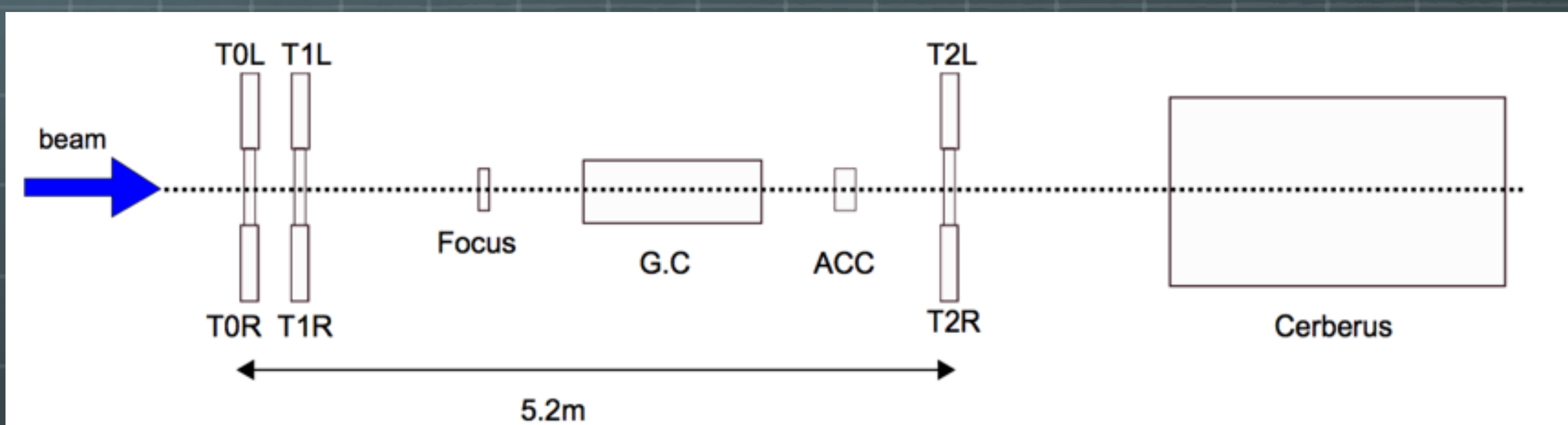
Aerogel: mixture of
m (SiO_2) + 2m (H_2O)

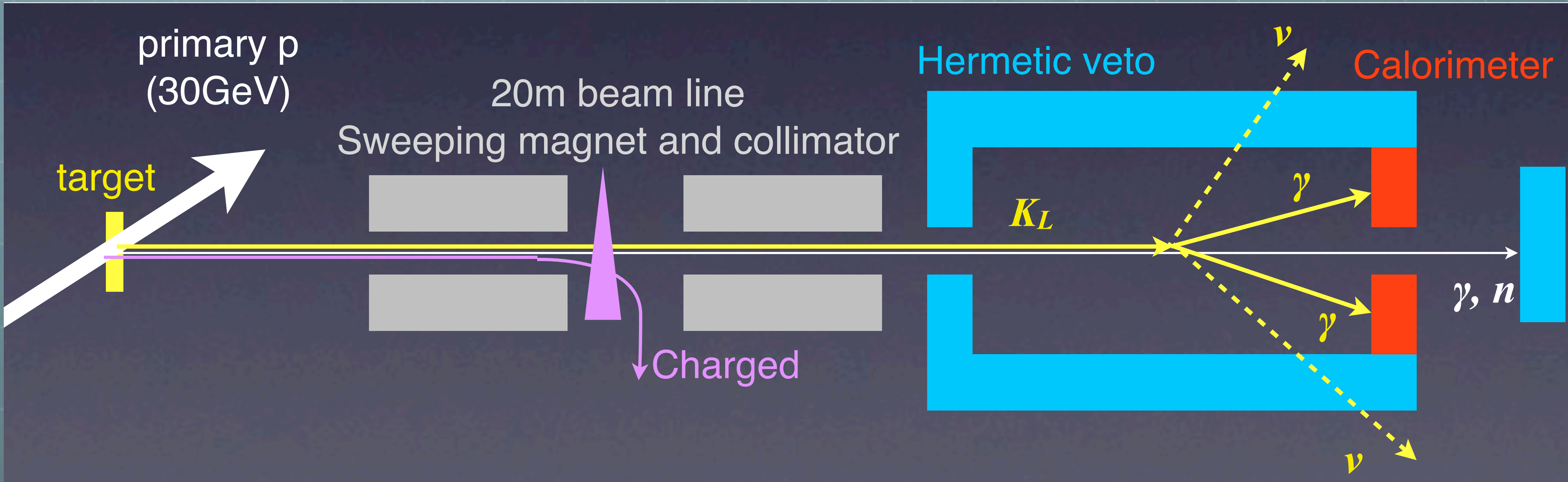
light structure with inclusions of air, bubbles with diameter $< \lambda_{Licht}$

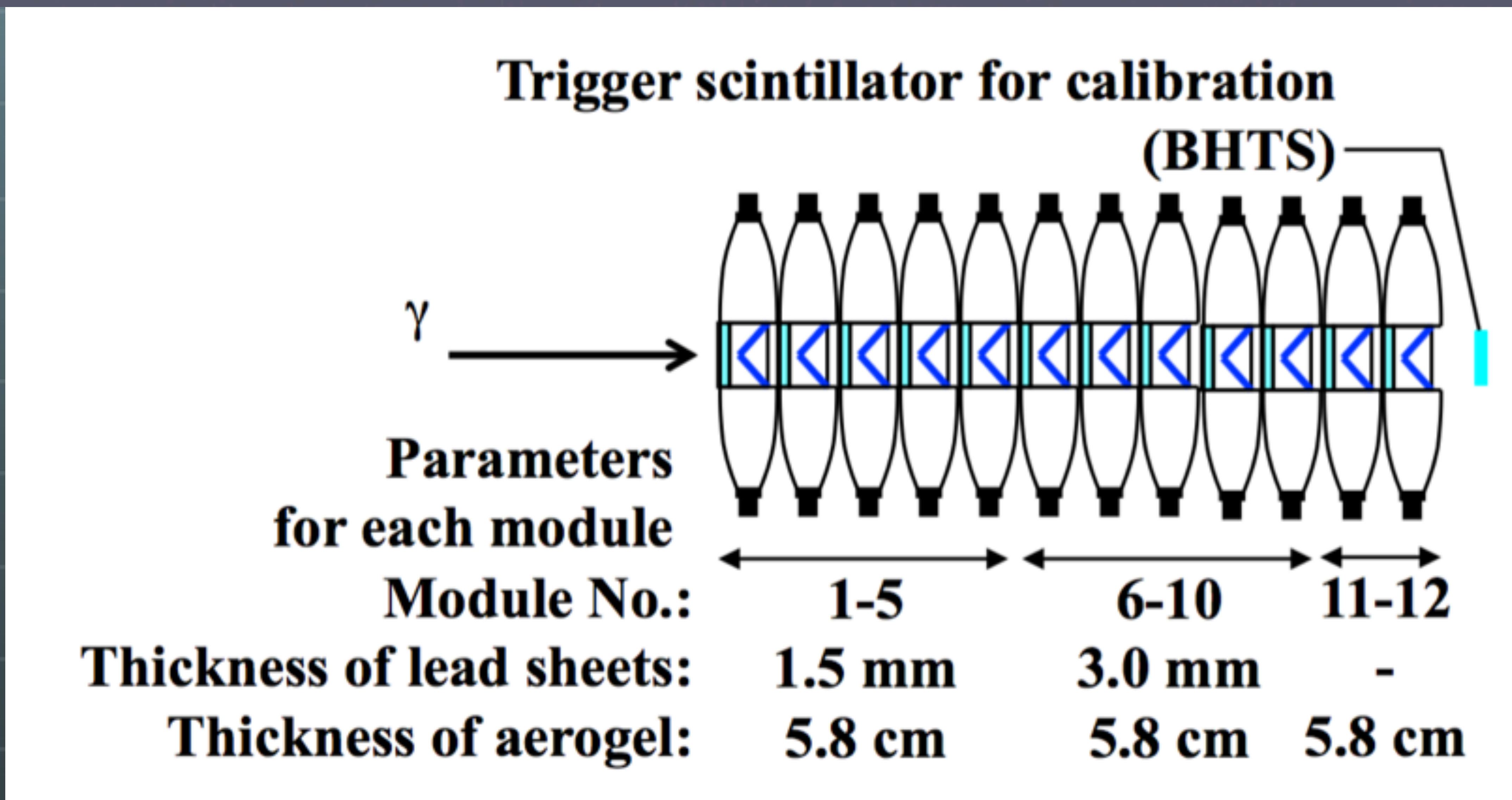
$\rightarrow$ n: average from n_{air}, n_{SiO2}, n_{H2O}


WINSTON CONE
K+- MIRROR
K+- PMT
RADIATOR (Acryl)
K+, π+
WINSTON CONE
π+-PMT
π+- MIRROR
0 5 10cm
π+- RIN
K+- RING


Primary proton
T1-target
K1.1BR
e,μ,π,K,p
0
20 (m)


T0L T1L
T2L
beam
Focus
G.C
ACC
T0R T1R
T2R
Cerberus
5.2m

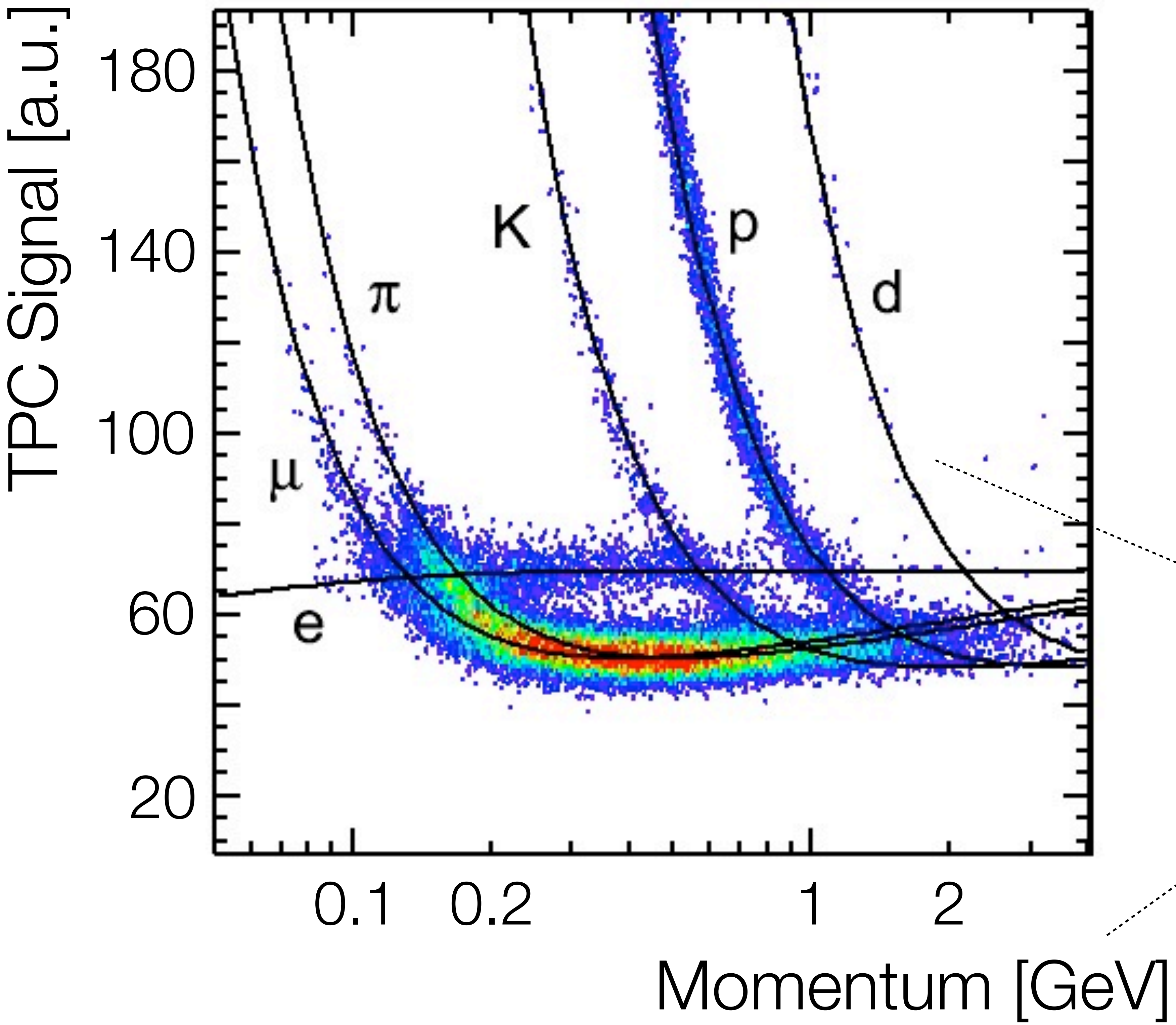

primary p
(30GeV)
target
20m beam line
Sweeping magnet and collimator
Charged
Hermetic veto
Calorimeter
K_L
γ
γ
ν
ν
γ, n


Trigger scintillator for calibration
(BHTS)
γ
Parameters
for each module
Module No.: 1-5 6-10 11-12
Thickness of lead sheets: 1.5 mm 3.0 mm -
Thickness of aerogel: 5.8 cm 5.8 cm 5.8 cm

Measured

energy loss

[ALICE TPC, 2009]

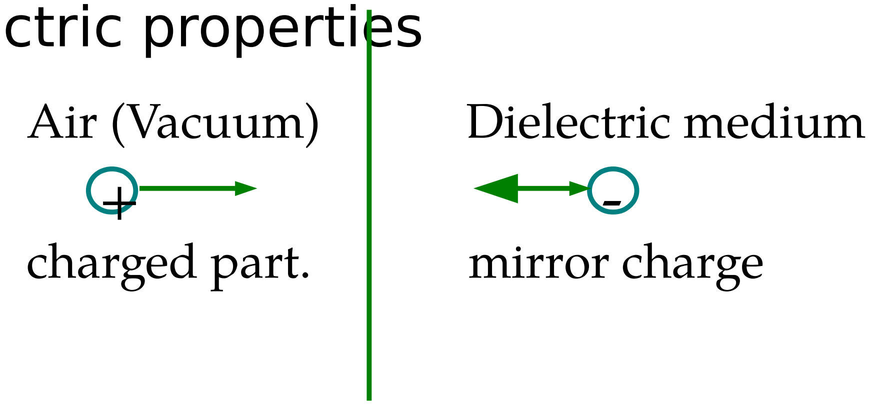


Bethe-Bloch

Remember:
dE/dx depends on β!

Transition radiation (TRD)

Charged particle passes through materials with different dielectric properties
→ particle forms dipole with the mirror charge
→ dipole changes with time
→ radiation



- radiated energy W proportional to the energy of particle!

$$W = \frac{1}{3}\alpha\hbar\omega_p\gamma$$

- with ω_p Plasma frequency

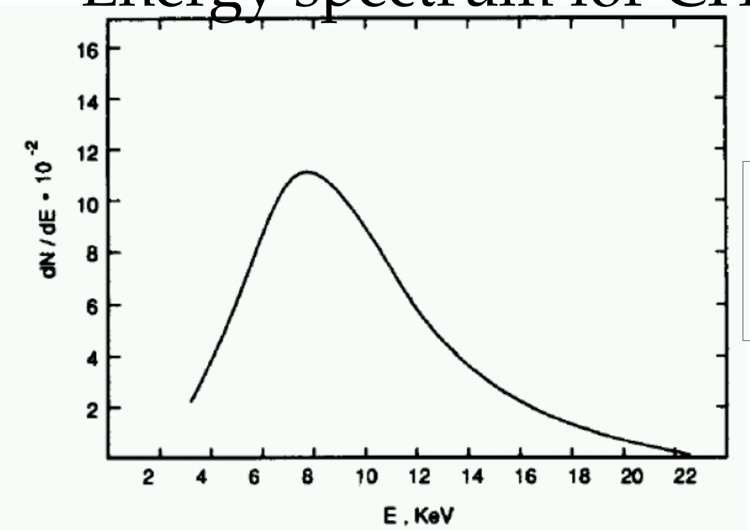
$$\omega_p = \sqrt{\frac{N_e e^2}{\epsilon_0 m_e}} \qquad \hbar\omega_p = 20\,eV$$

- only important for highly relativistic particles

- energy: keV (x-rays)

- $\theta \propto 1/\gamma$: emission in very forward direction

Energy spectrum for CH_2 foil



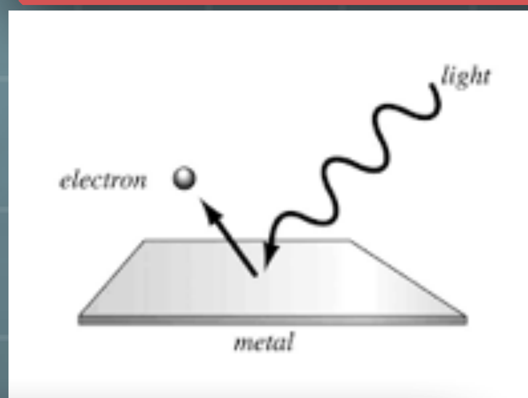
keV!

- probability for photon emission very small → many transitions (foils with gaps)
- # photons <N> ~ W / hν ~ O (α)=1/137 α fine structure constant
- energy loss due to TRD negligible for single transition
- important for particle ID at high energies, other effects used for PID ∝ β (β≃1)
  Review article: B. Dolgoshein; NIM A 326 (1993) 434

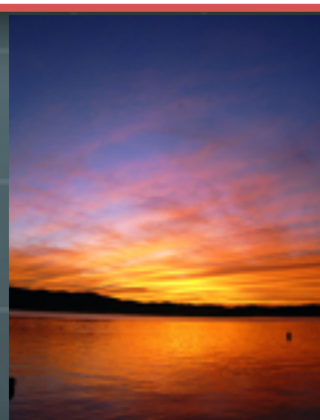
Interaction of photons

Interaction of photons

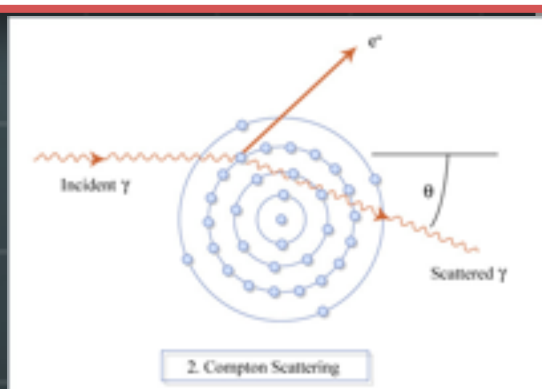
Photoelectric effect

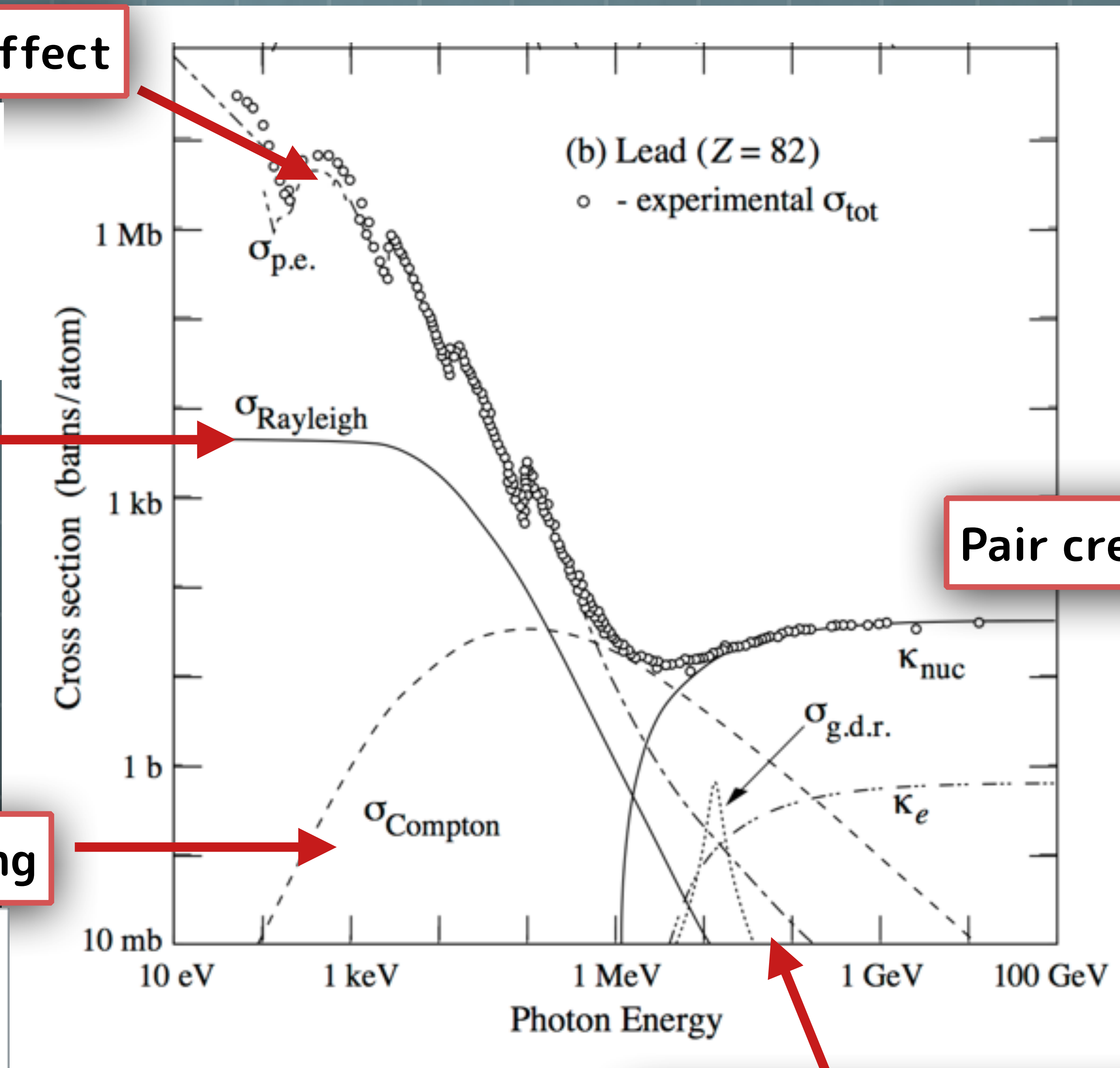


Rayleigh scattering



Compton scattering

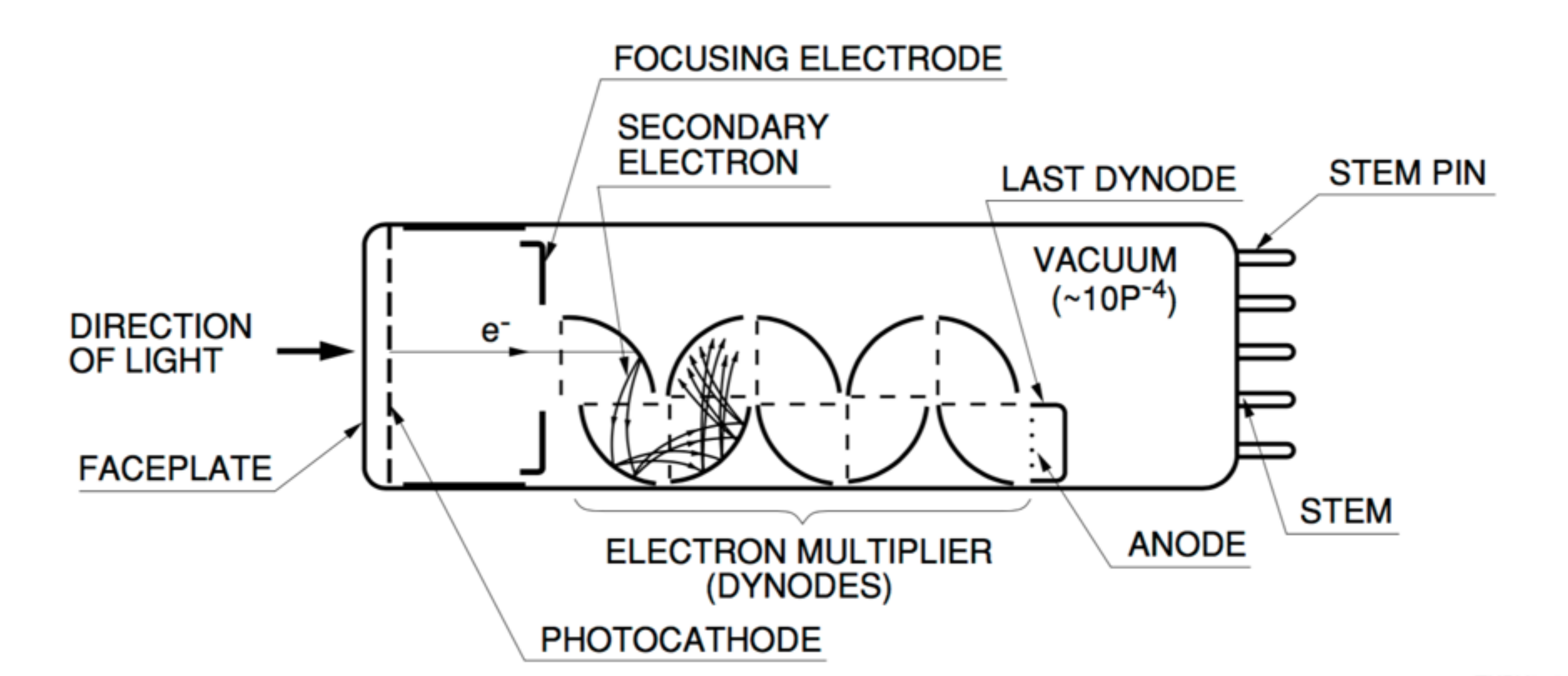




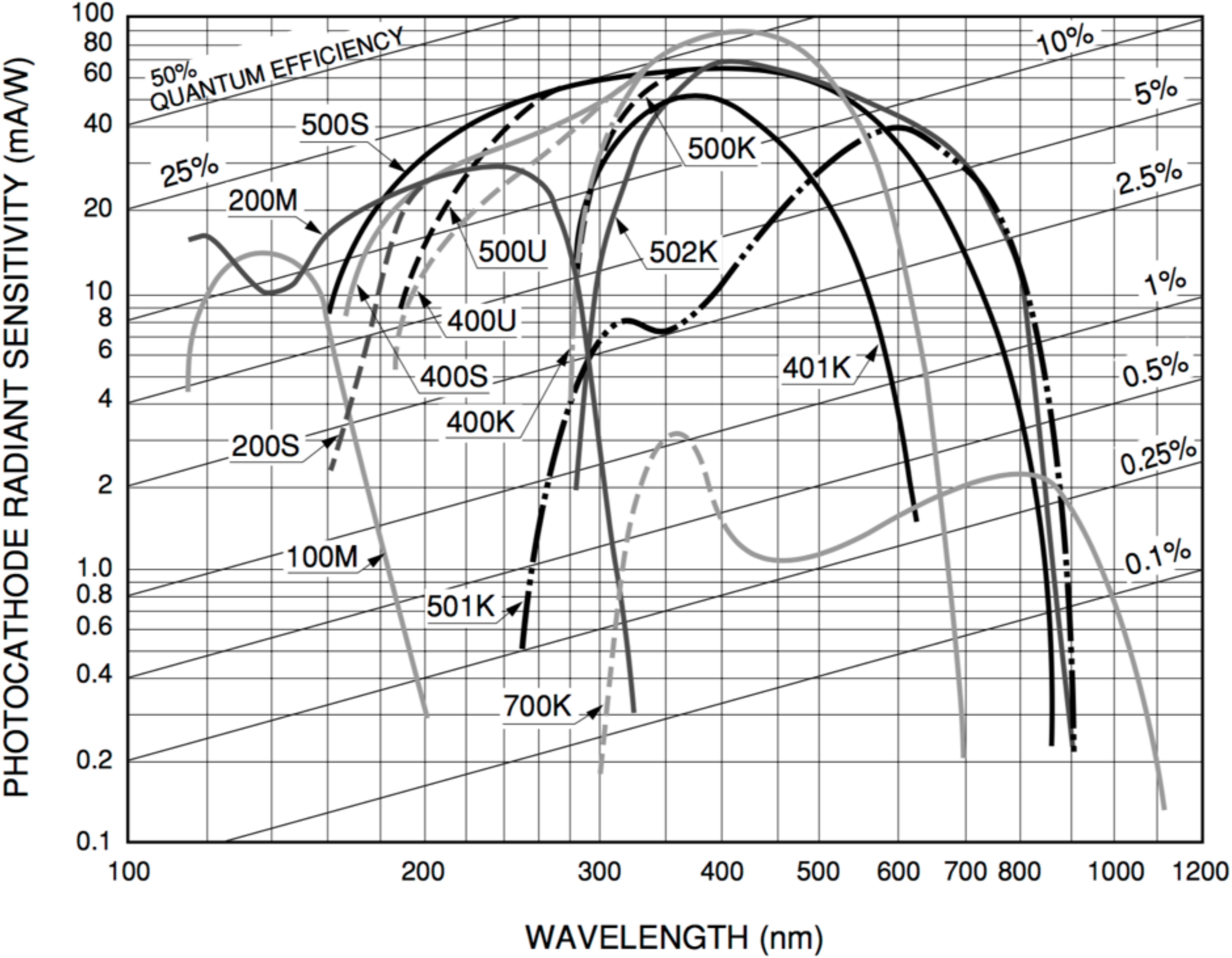
Pair creation

Photonuclear interaction

PMT


FOCUSING ELECTRODE
SECONDARY ELECTRON
LAST DYNODE
STEM PIN
VACUUM (~10P-4)
DIRECTION OF LIGHT
e-
FACEPLATE
STEM
ANODE
ELECTRON MULTIPLIER (DYNODES)
PHOTOCATHODE

Transmission Mode Photocathodes



Transmission mode photocathodes

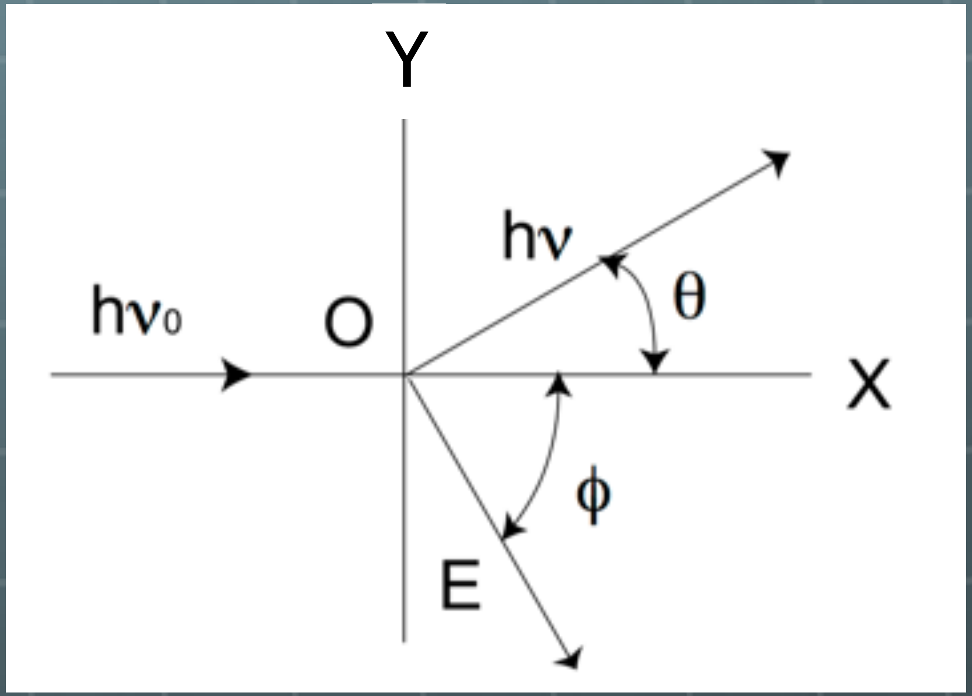
Curve Code (S number)	Photocathode Material	Window Material	Luminous Sensitivity (Typ.) (μA/lm)	Spectral Response					
				Spectral Range (nm)	Peak Wavelength				
					Radiant Sensitivity		Quantum Efficiency		
					(mA/W)	(nm)	(%)	(nm)	
100M	Cs-I	MgF_2	—	115 to 200	14	140	13	130	
200S	Cs-Te	Quartz	—	160 to 320	29	240	14	210	
200M	Cs-Te	MgF_2	—	115 to 320	29	240	14	200	
400K	Bialkali	Borosilicate	95	300 to 650	88	420	27	390	
400U	Bialkali	UV	95	185 to 650	88	420	27	390	
400S	Bialkali	Quartz	95	160 to 650	88	420	27	390	
401K	High temp. bialkali	Borosilicate	40	300 to 650	51	375	17	375	
500K (S-20)	Multialkali	Borosilicate	150	300 to 850	64	420	20	375	
500U	Multialkali	UV	150	185 to 850	64	420	25	280	
500S	Multialkali	Quartz	150	160 to 850	64	420	25	280	
501K (S-25)	Multialkali	Borosilicate	200	300 to 900	40	600	8	580	
502K	Multialkali	Borosilicate (prism)	230	300 to 900	69	420	20	390	
700K (S-1)	Ag-O-Cs	Borosilicate	20	400 to 1200	2.2	800	0.36	740	
—	GaAsP(Cs)	—	—	300 to 720	180	580	40	540	
—	GaAs(Cs)	—	—	380 to 890	85	800	14	760	
—	InP/InGaAsP(Cs)	—	—	950 to 1400	21	1300	2.0	1000 to 1300	
—	InP/InGaAs(Cs)	—	—	950 to 1700	24	1500	2.0	1000 to 1550	

Compton Scattering

$$h\nu = \frac{h\nu_0}{1 + \left(\frac{h\nu_0}{m_e c^2}\right)(1 - \cos\theta)},$$

$$E = h\nu_0 - h\nu = m_e c^2 \frac{2(h\nu_0)^2 \cos^2\phi}{(h\nu_0 + m_e c^2)^2 - (h\nu_0)^2 \cos^2\phi},$$

$$\tan\phi = \frac{1}{1 + \left(\frac{h\nu_0}{m_e c^2}\right)} \cot\frac{\theta}{2},$$



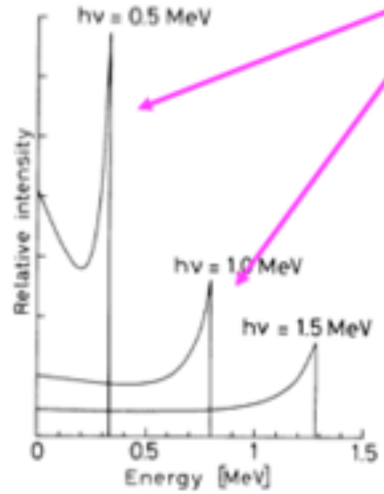
We can also calculate the recoil kinetic energy (T) spectrum of the electron:

$$\frac{d\sigma}{dT} = \frac{\pi r_e^2}{m_e c^2 \gamma^2}\left(2 + \frac{s^2}{\gamma^2(1-s)^2} + \frac{s}{(1-s)}\left(s - \frac{2}{\gamma}\right)\right) \quad \text{with } s = T / E_{\gamma,in}$$

This cross section is strongly peaked around T_{max}:

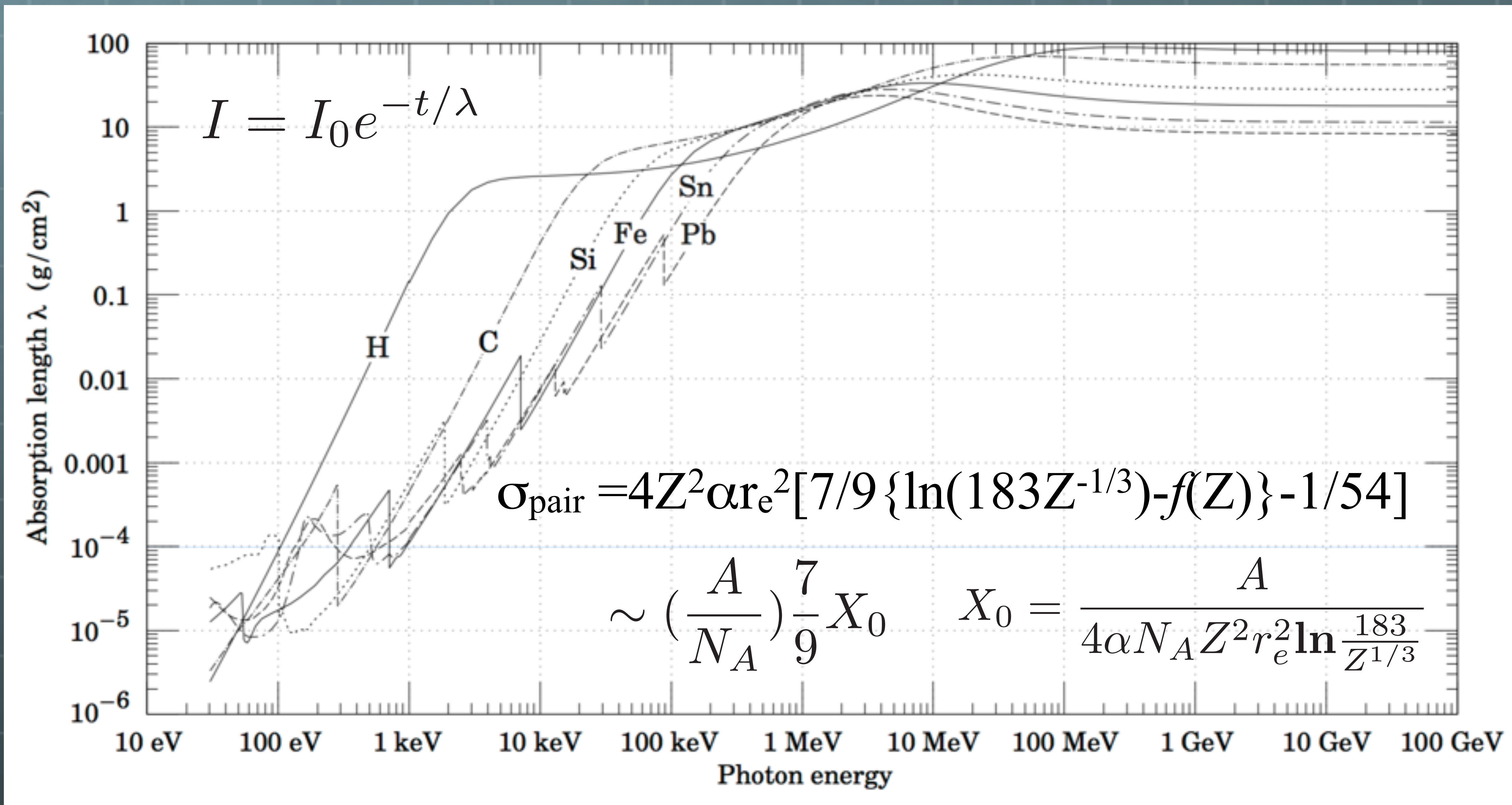
$$T_{max} = E_{\gamma,in} \frac{2\gamma}{1 + 2\gamma}$$

T_{max} is known as the Compton Edge



Kinetic energy distribution of Compton recoil electrons

Pair Production



$$I = I_0 e^{-t/\lambda}$$

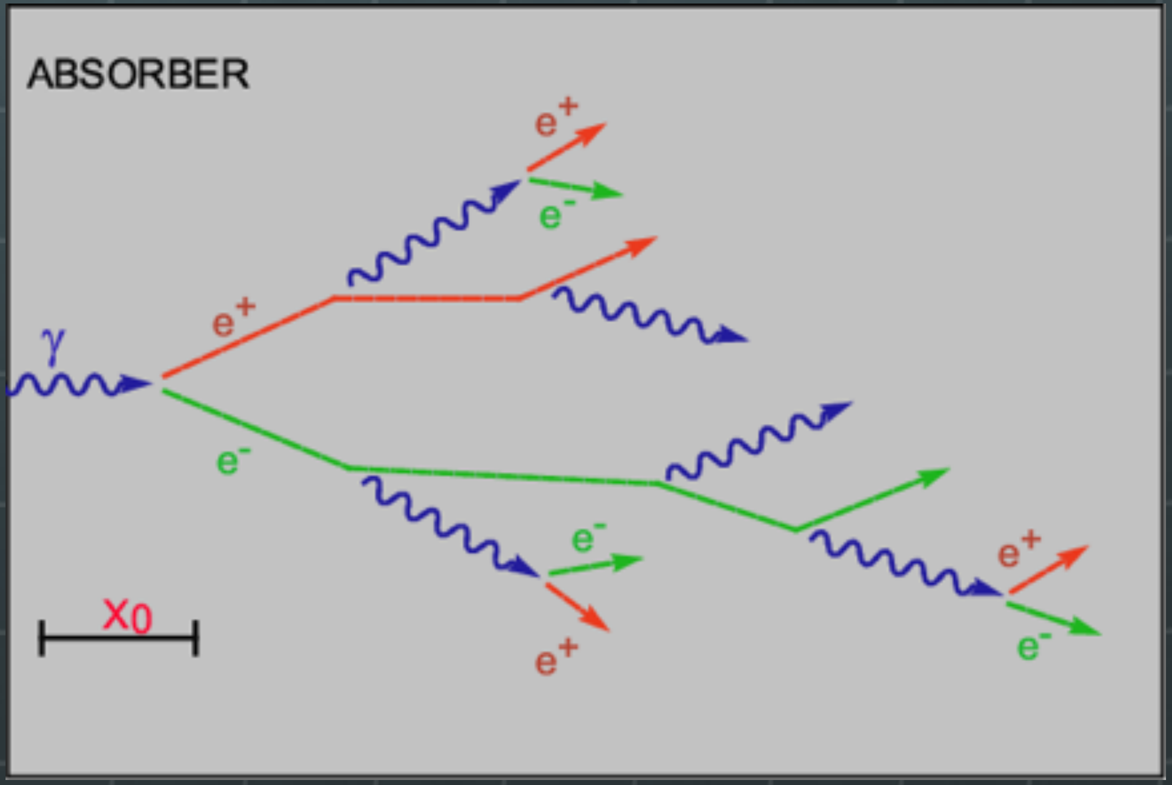
$$\sigma_{pair} = 4Z^2\alpha r_e^2[7/9\{\ln(183Z^{-1/3}) - f(Z)\} - 1/54]$$

$$\sim (\frac{A}{N_A})\frac{7}{9}X_0 \qquad X_0 = \frac{A}{4\alpha N_A Z^2 r_e^2 \mathbf{ln}\frac{183}{Z^{1/3}}}$$

Electromagnetic Shower

Electromagnetic shower

- Electromagnetic calorimeter uses a successive generation of secondaries - EM shower.
- High energy photon occurs pair creation dominantly.
- High energy electron-positron pair loses its energy by bremsstrahlung.



Radiation Length (Xo)

- Characteristic amount for energy loss of (high energy) photon and electron
  - mean distance over which a electron loses its energy as 1/e by bremsstrahlung
  - 7/9 of the mean free path for pair production by a photon

foot notes

Longitudinal shower development

- **Number of secondaries**

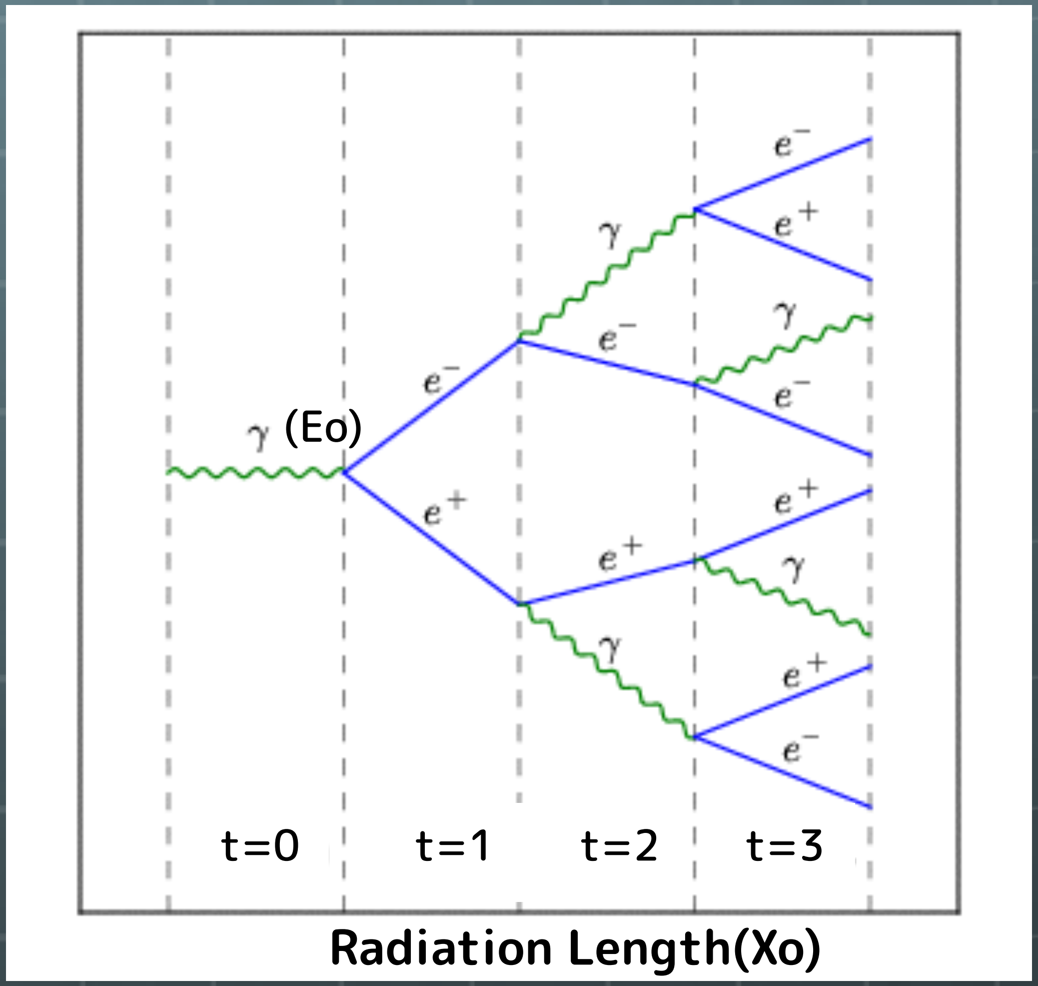
$$N = 2^t$$

- **Average Energy**

$$E(t) = E_0/2^t$$

- **Shower development stops at**

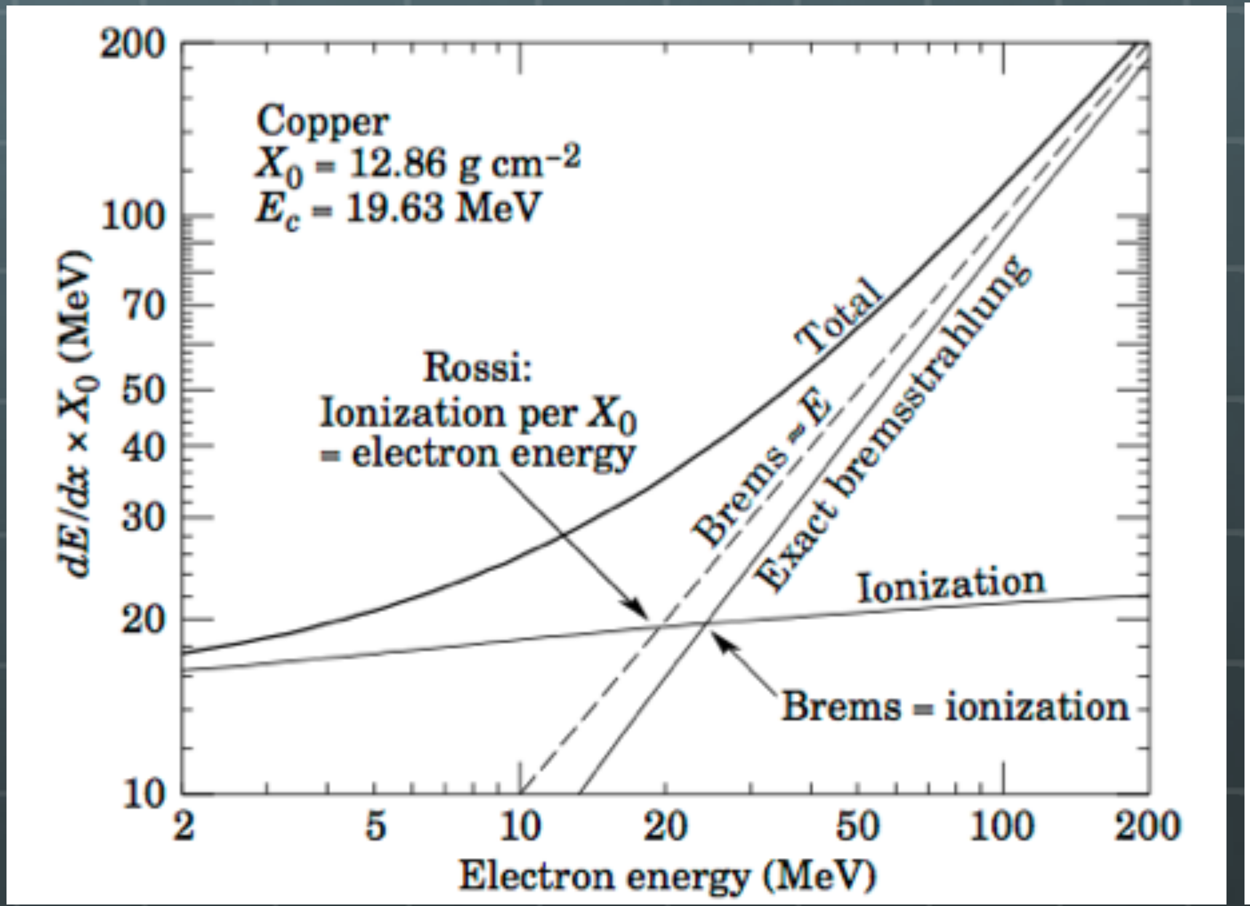
$$E(t) = Ec$$

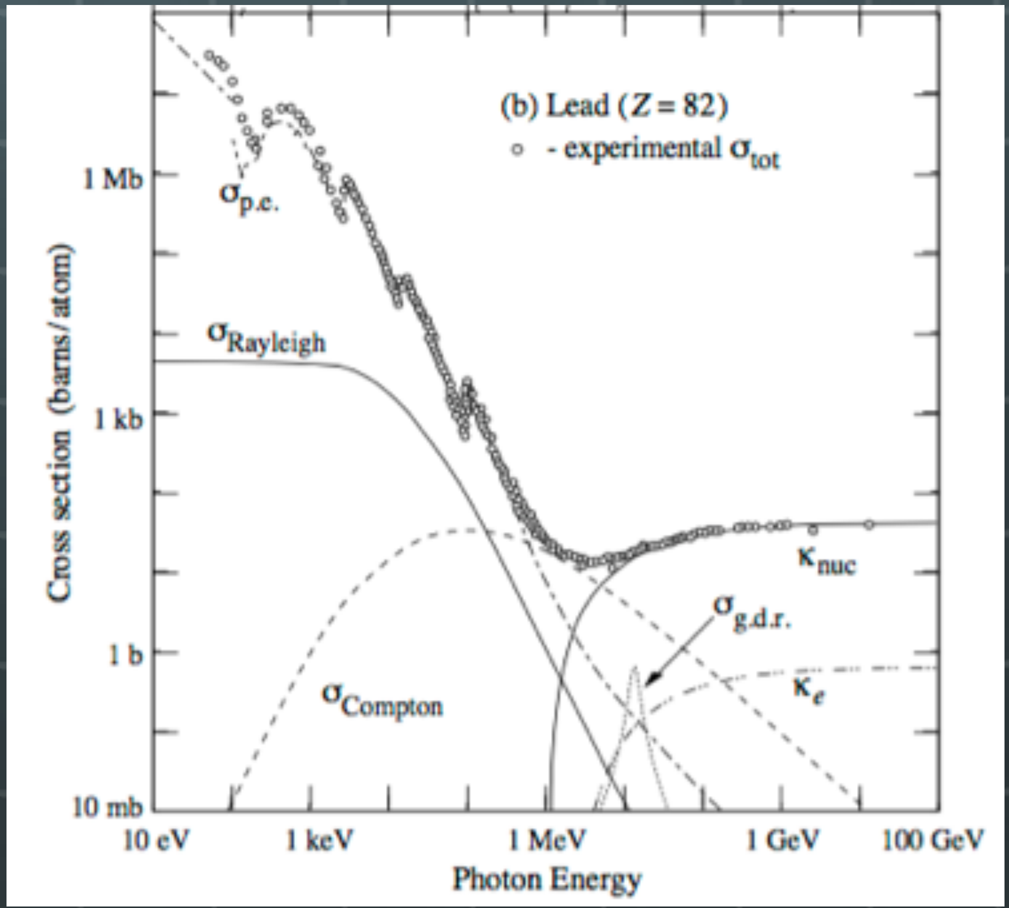


foot notes

Critical energy (Ec)

- Energy at which a electron losses its energy as same amount by bremsstrahlung and ionization.
- Energy at which the ionization loss per Xo is equal to the electron energy.





Longitudinal shower development

- **Number of secondaries**

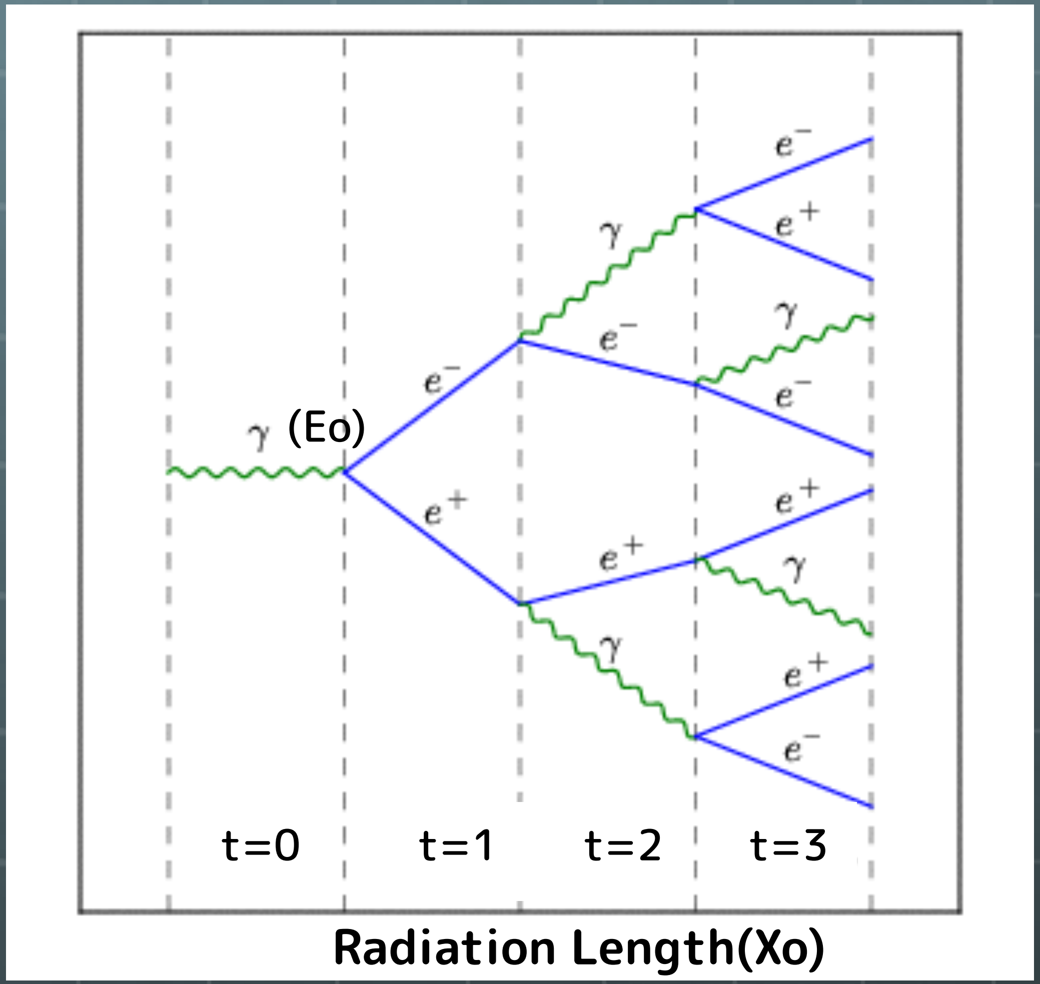
$$N = 2^t$$

- **Average Energy**

$$E(t) = E_0/2^t$$

- **Shower development stops at**

$$E(t) = Ec$$



- **Maximum number of shower particles at which their energy is critical energy ;**

$$Ec = E_0/2^{t_{max}} \qquad t_{max} = \ln(\frac{E_0}{Ec})/\ln 2$$

Energy deposit

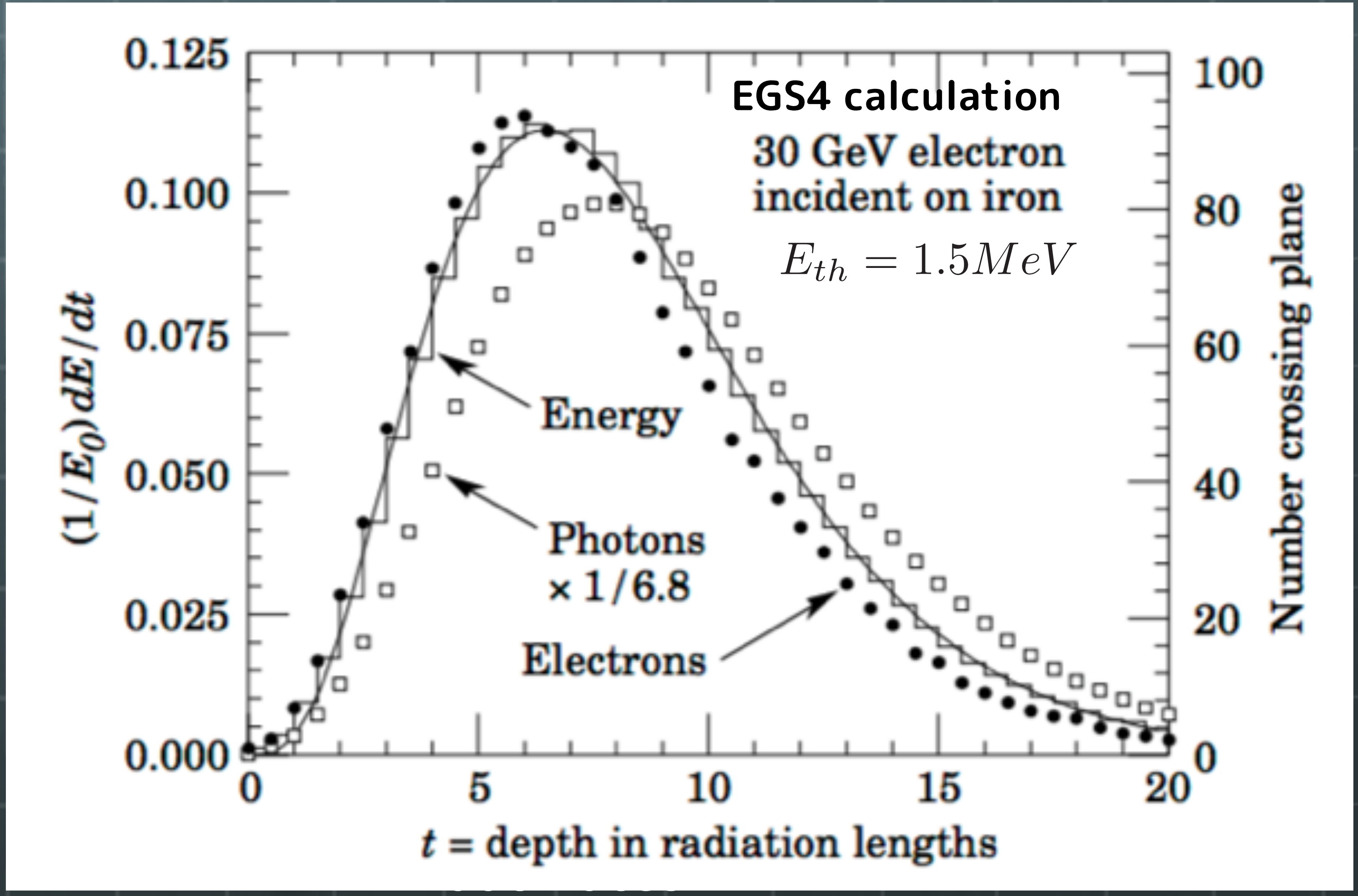
- Energy deposit ∝ total integrated charged track length

$$< T_i(E_0) >= \int_{(i-1)\Delta t}^{i\Delta t} N(E_0, E_{th}, t)dt$$

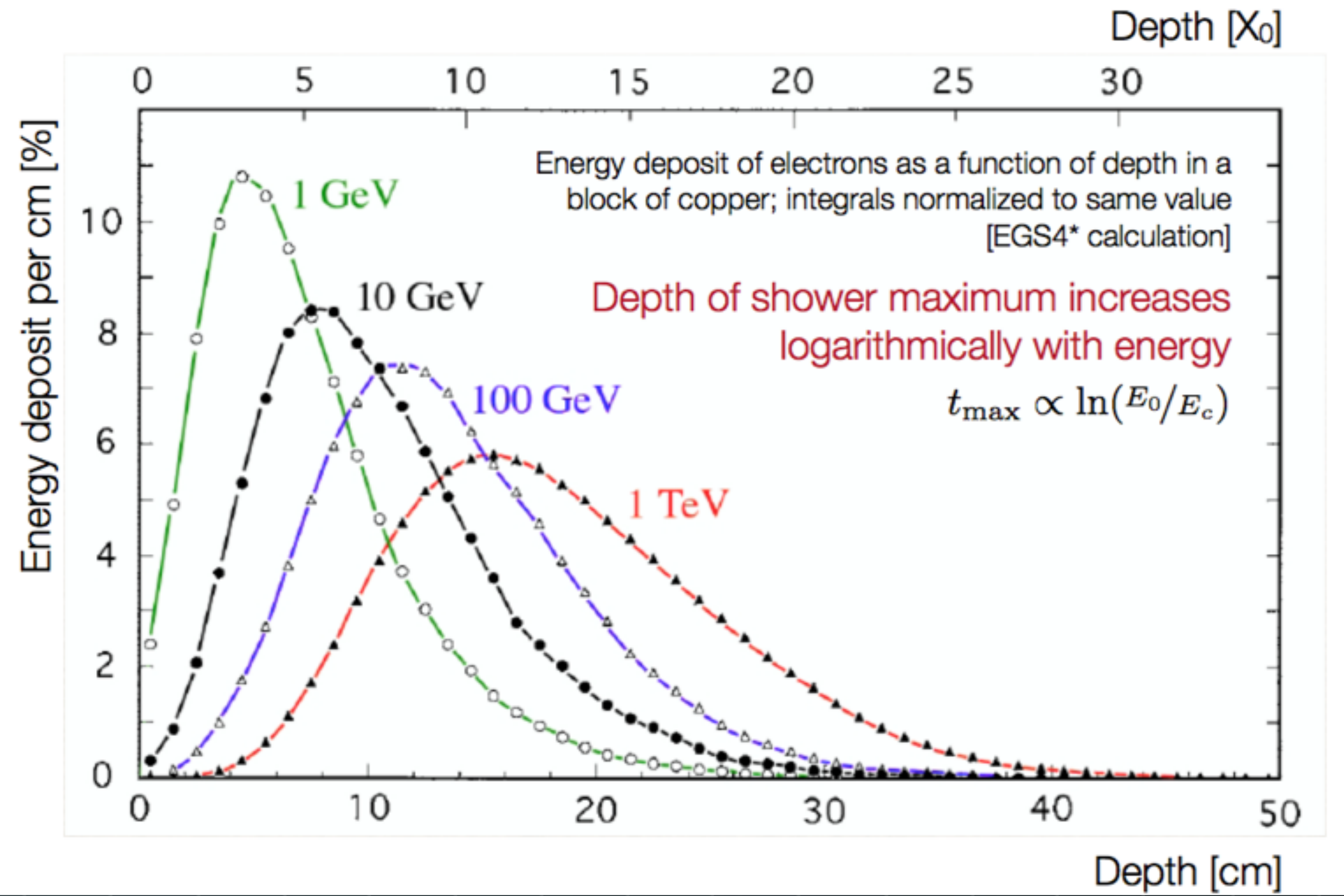
$$\frac{dE}{dx} = E_0 b \frac{(bt)^{(a-1)} e^{-bt}}{\Gamma(a)}$$

$$t_{max(\frac{dE}{dx})} = (a-1)/b$$
$$= \ln(\frac{E_0}{Ec}) + C_j$$

$$C_e = -0.5$$
$$C_\gamma = +0.5$$



Longitudinal shower shape



Ec=19.42
t_max = 5.7 fo
9.0 fo
12.3 fo
15.6 fo
t_max(dE/dx) =
3.4 for
5.7 for
8.0 for
10.3 for

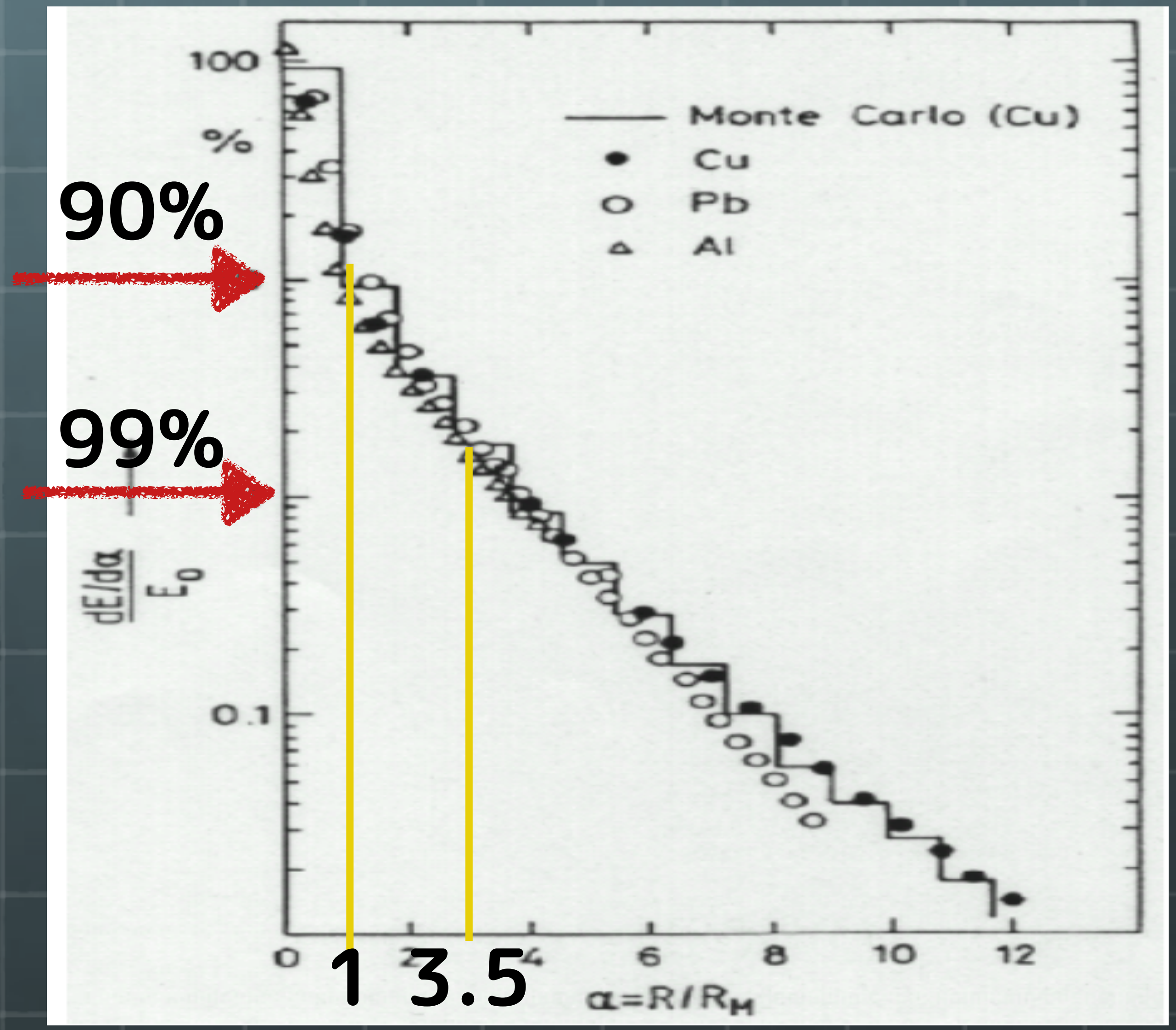
foot notes

Lateral development of EM

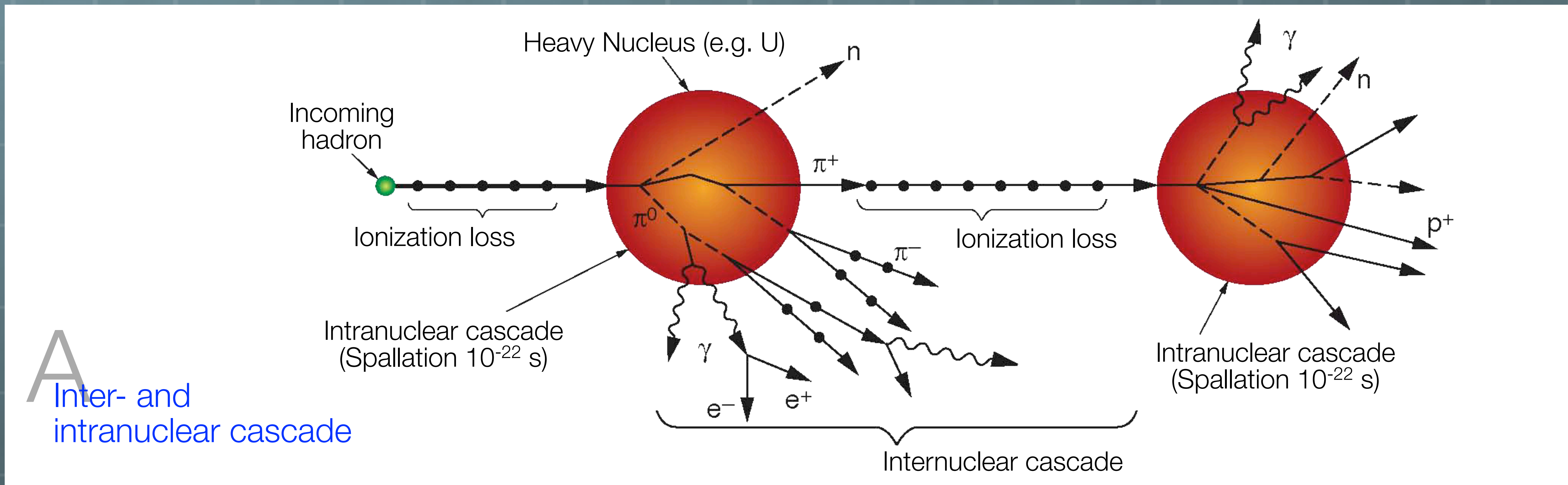
- Mainly due to multiple scattering of low energy electron.
- Moirère Radius (R_M)

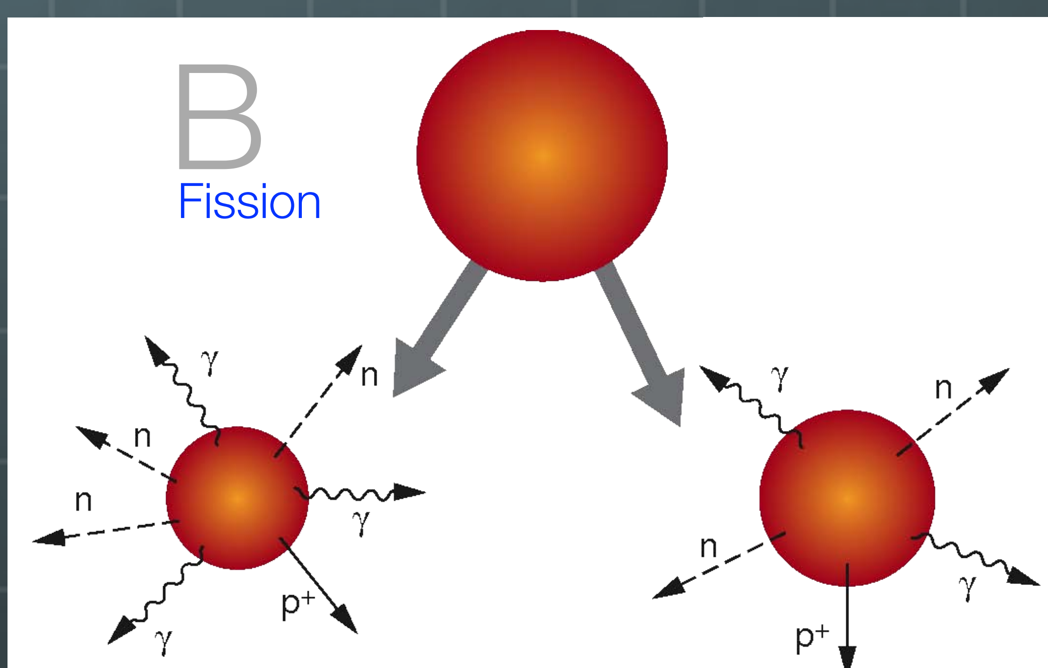
$$R_M = \frac{21MeV}{E_c} X_0$$

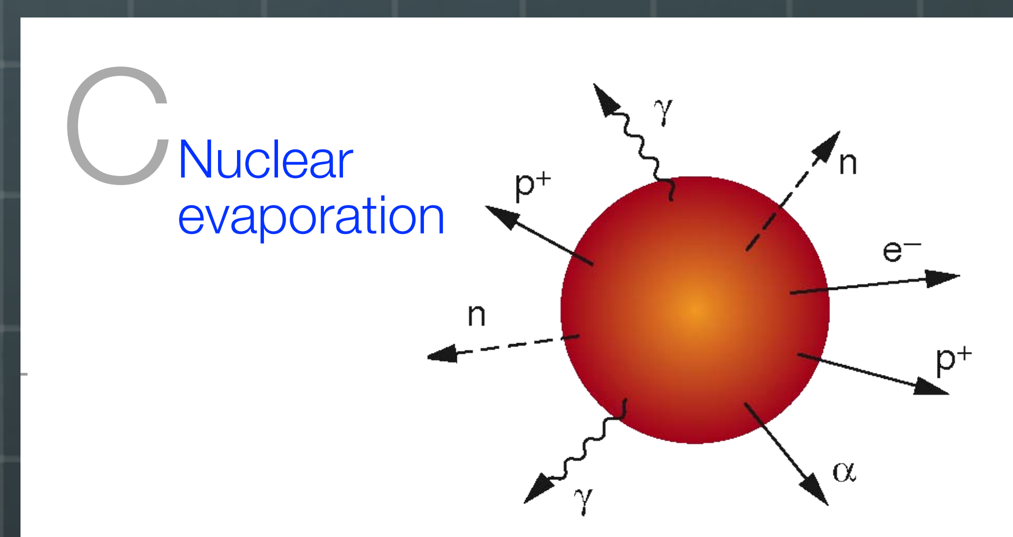
$$\sim \frac{7A}{Z} [g/cm^2]$$



Hadronic Shower







foot notes

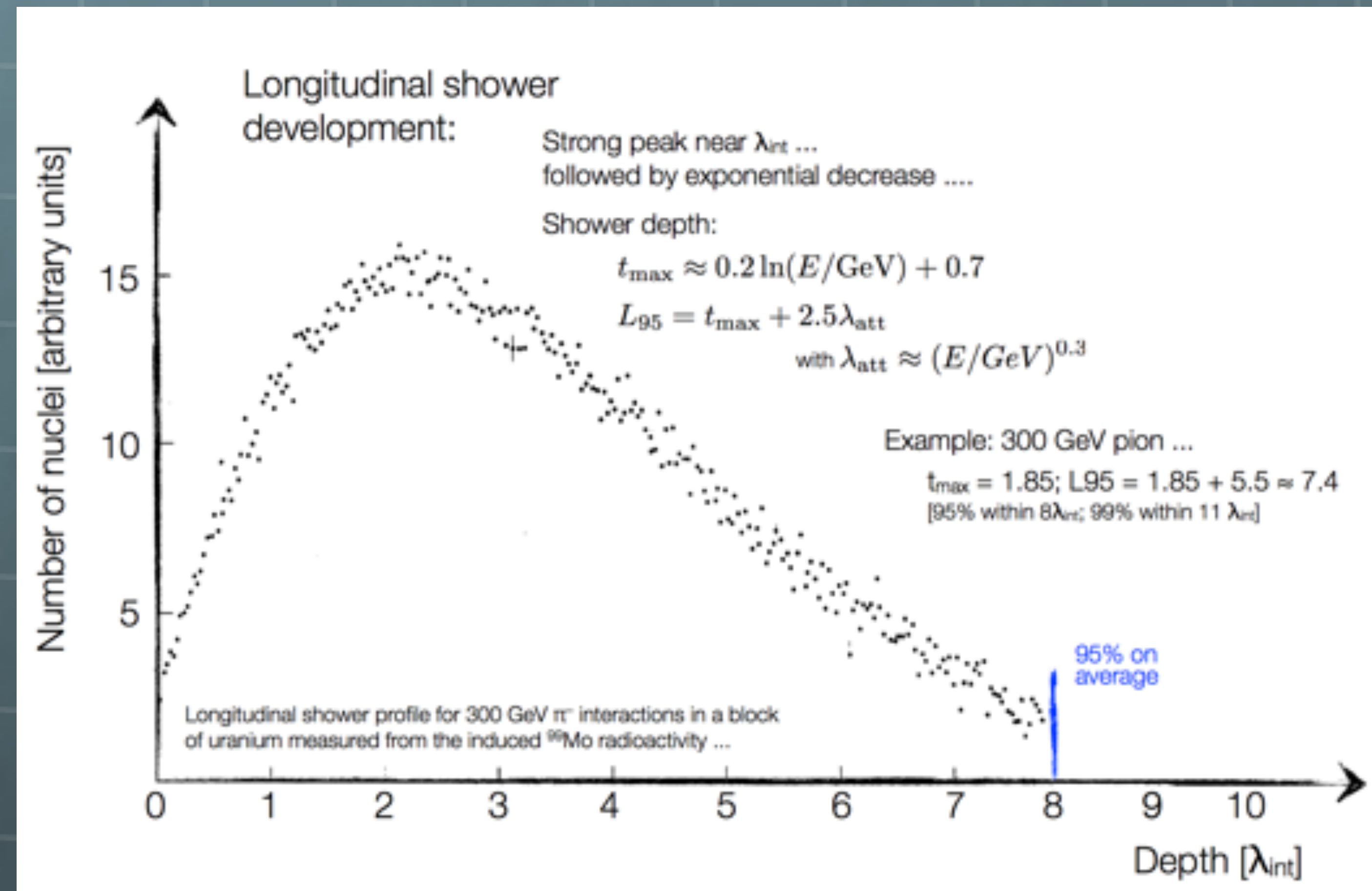
Hadronic shower

$$\lambda_I \approx 35\ g/cm^2 \cdot A^{\frac{1}{3}}$$

$$N(x) = N_0 e^{-\frac{x}{\lambda_I}}$$

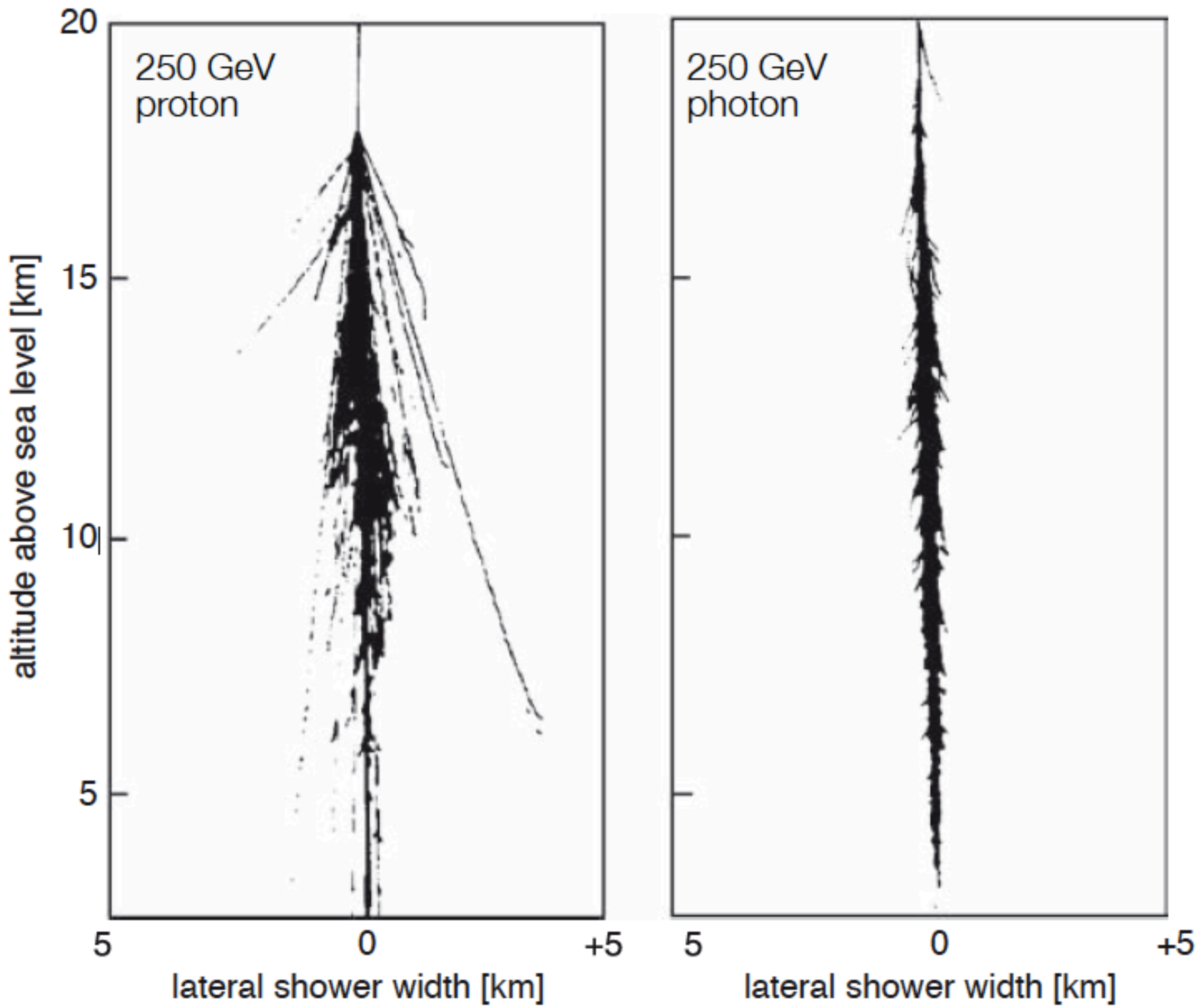
Typical
Longitudinal size: 6 ... 9 λ_{int}
[95% containment]

Typical
Transverse size: one λ_{int}
[95% containment]



	λ_I	X_0	$R=(\lambda_I/X_0)$		λ_I	X_0	$R=(\lambda_I/X_0)$
Fe	16.78	1.76	9.54	Scin.	78.93	42.62	1.85
Cu	15.32	1.44	10.68	CsI	38.03	1.86	20.44
Pb	17.59	0.56	31.33	$PbWO_4$	20.28	0.89	22.77

Comparison hadronic vs EM showers



Simulated air showers

50