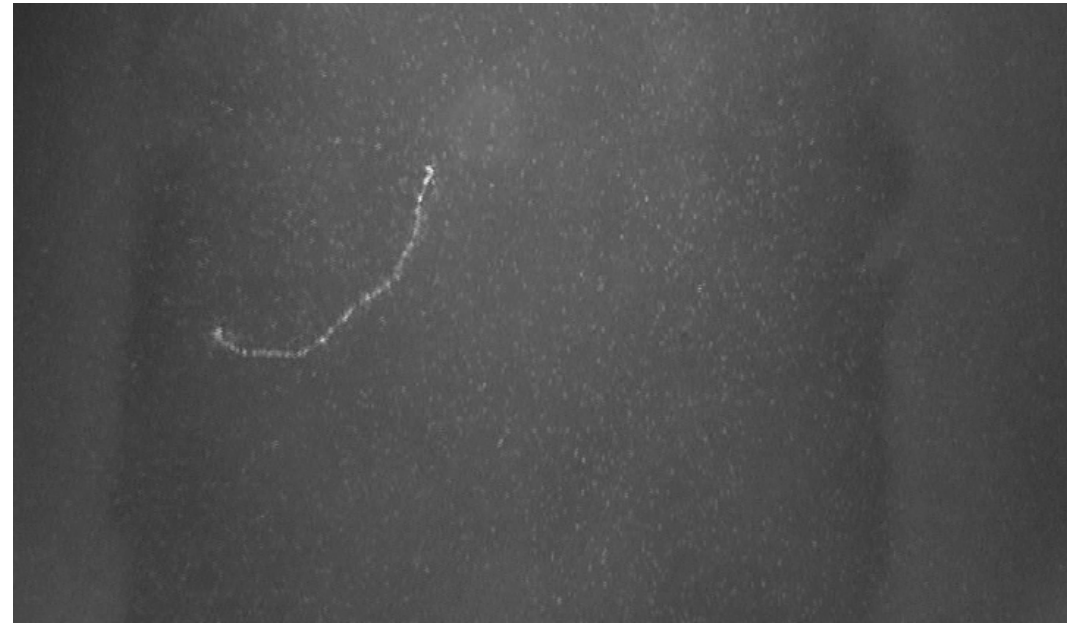
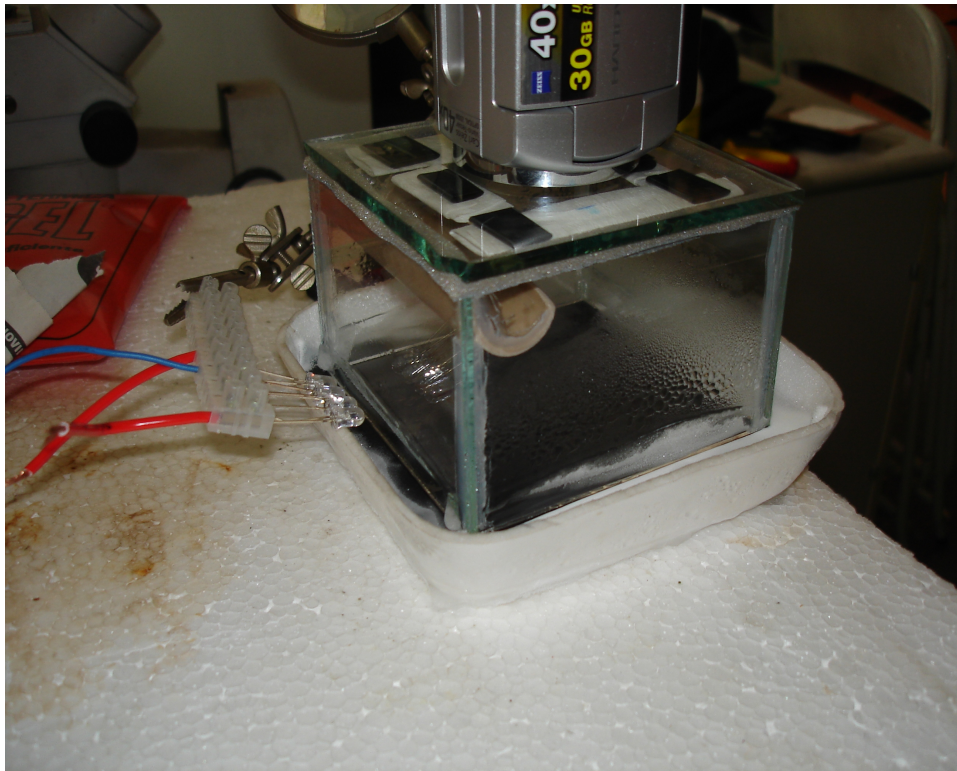


- **Objetivo:** Estudar a interação de partículas carregadas com a matéria (**princípio dos detectores**)
- **Motivação:** Entender traços como **este** observados numa **câmara de nuvens**



- Interação de partículas carregadas* com a matéria: **ionização e excitação atômica**
- A taxa de perda de energia ao atravessar um material: (Bethe-Bloch equation)

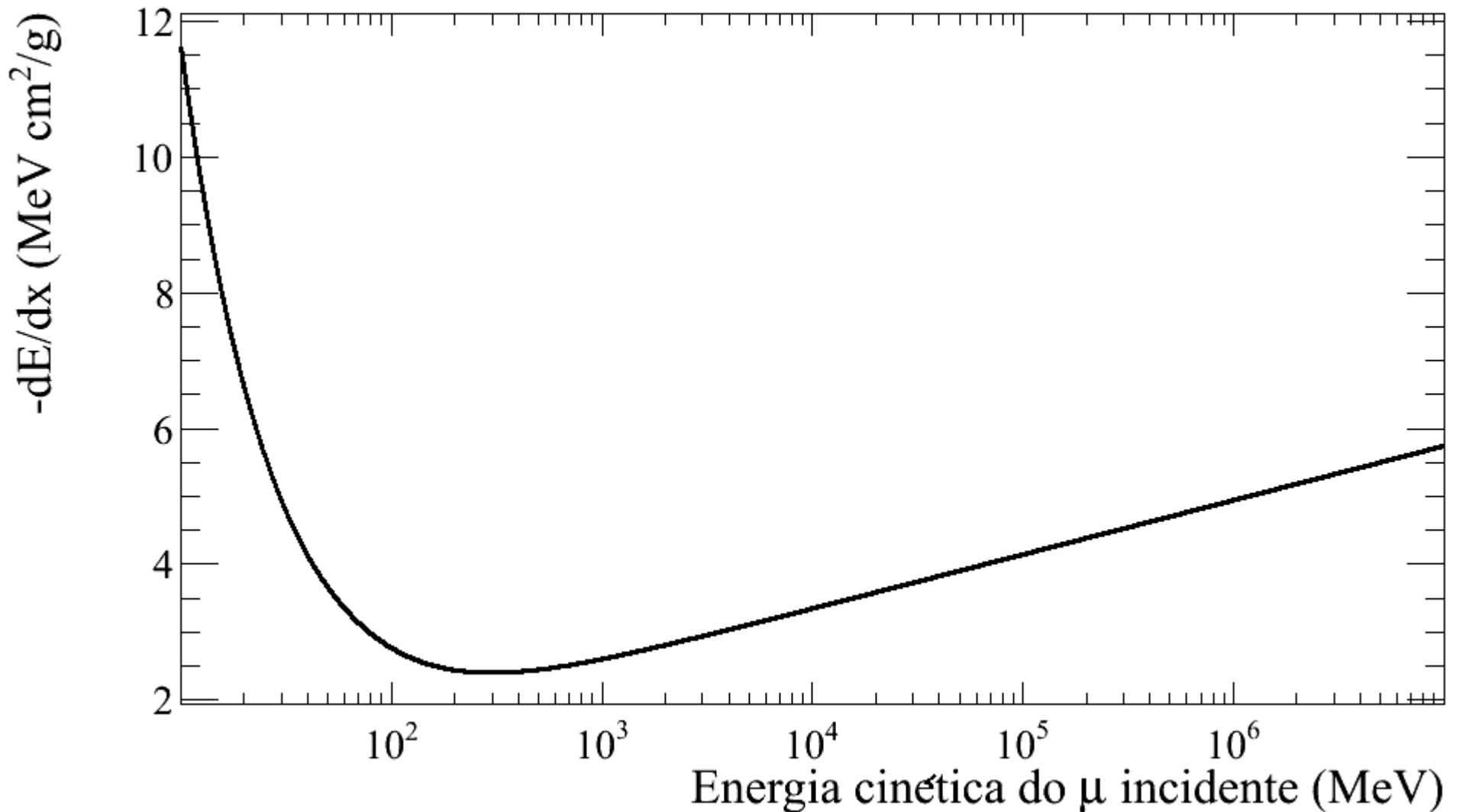
27.2. Electronic energy loss by heavy particles [1–22, 24–30, 82]

Moderately relativistic charged particles other than electrons lose energy in matter primarily by ionization and atomic excitation. The mean rate of energy loss (or stopping power) is given by the Bethe-Bloch equation,

$$-\frac{dE}{dx} = Kz^2 \frac{Z}{A} \frac{1}{\beta^2} \left[\frac{1}{2} \ln \frac{2m_e c^2 \beta^2 \gamma^2 T_{\max}}{I^2} - \beta^2 - \frac{\delta(\beta\gamma)}{2} \right]. \quad (27.1)$$

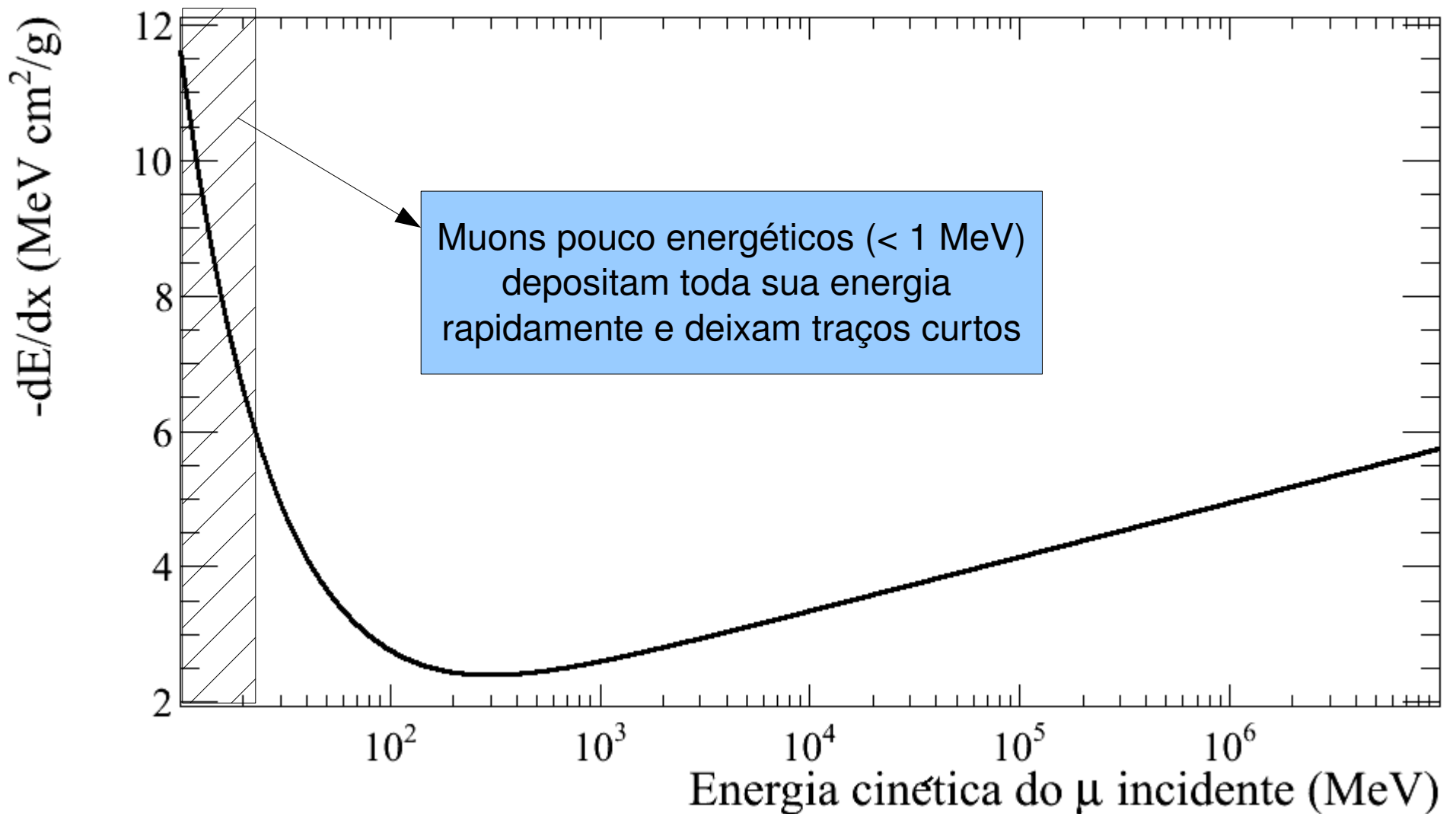
Here T_{\max} is the maximum kinetic energy which can be imparted to a free electron in a single collision, and the other variables are defined in Table 27.1. With K as defined in Table 27.1 and A in g mol^{-1} , the units are $\text{MeV g}^{-1}\text{cm}^2$.

- Câmara de nuvens: vapor supersaturado de álcool



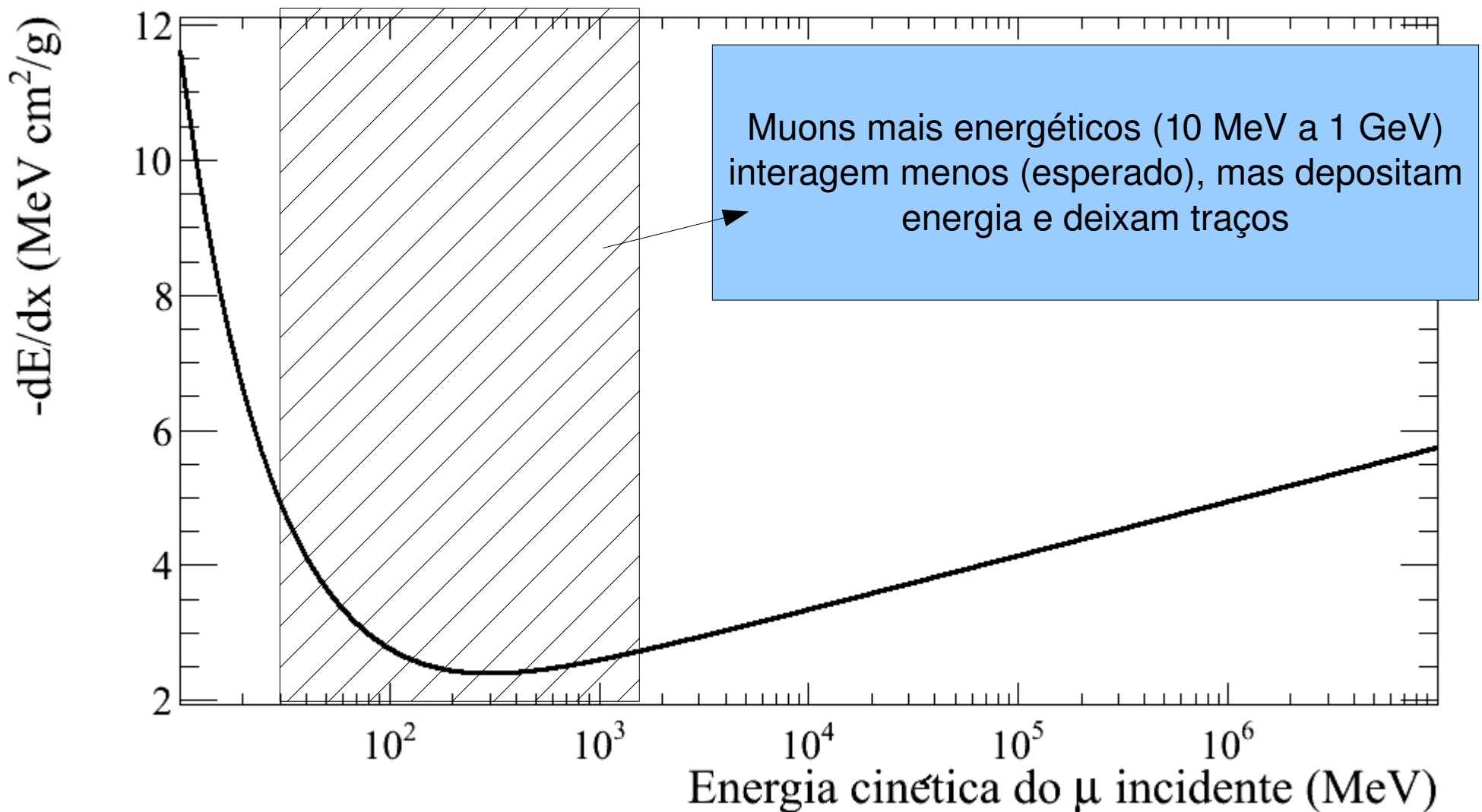
Taxa de energia de muons depositada em álcool isopropílico
(C₃H₇OH, Z_{eff} = 34, A = 60 g/mol)

- **Câmara de nuvens:** vapor supersaturado de álcool



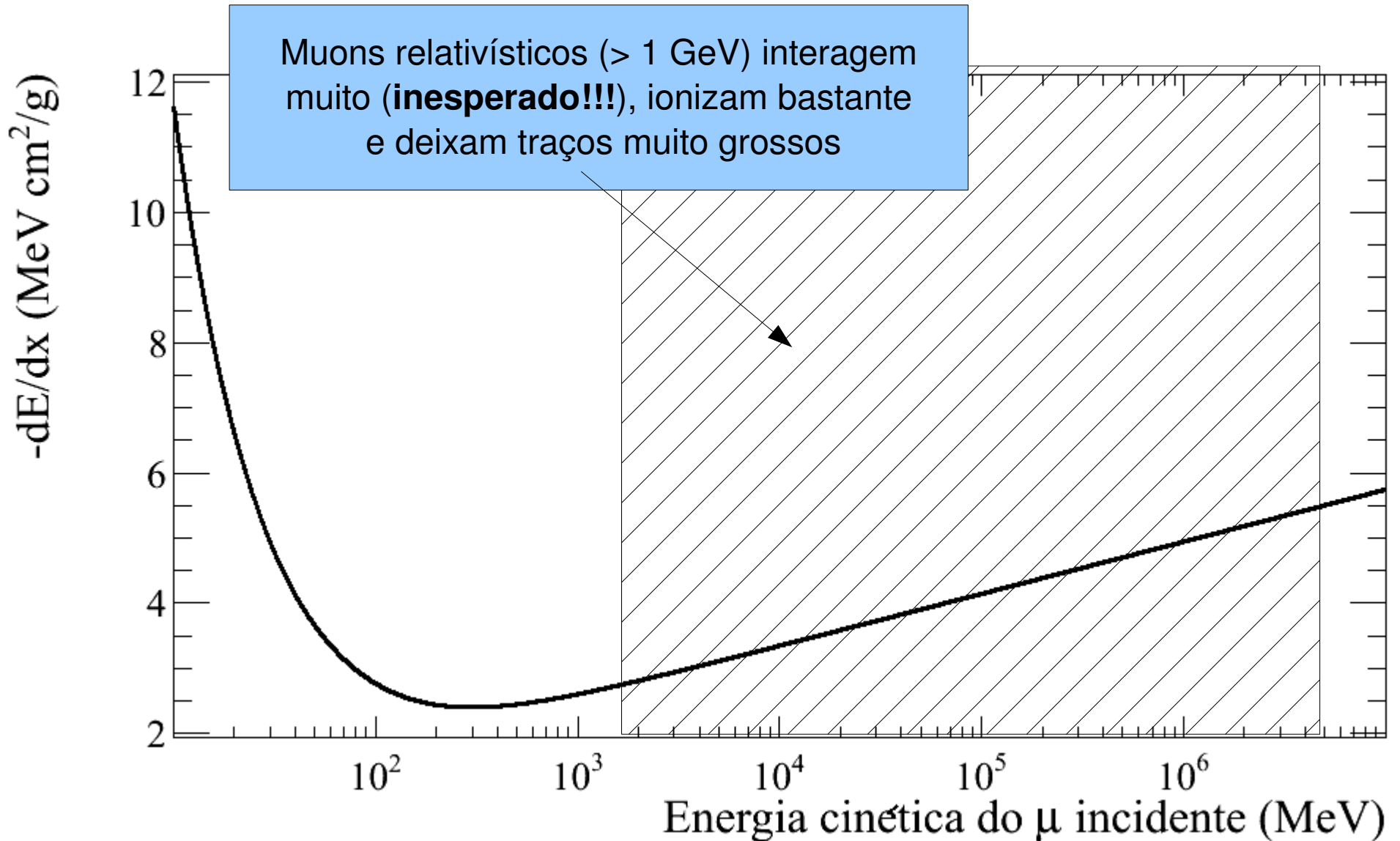
Taxa de energia de muons depositada em álcool isopropílico
(C₃H₇OH, Z_{eff} = 34, A = 60 g/mol)

- **Câmara de nuvens:** vapor supersaturado de álcool



Taxa de energia de muons depositada em álcool isopropílico
(C₃H₇OH, Z_{eff} = 34, A = 60 g/mol)

- Câmara de nuvens: vapor supersaturado de álcool



Taxa de energia de muons depositada em álcool isopropílico
(C₃H₇OH, Z_{eff} = 34, A = 60 g/mol)

O que se observa numa câmara de nuvens?

- Raios cósmicos primários (alta atmosfera) 1 GeV a 100 TeV

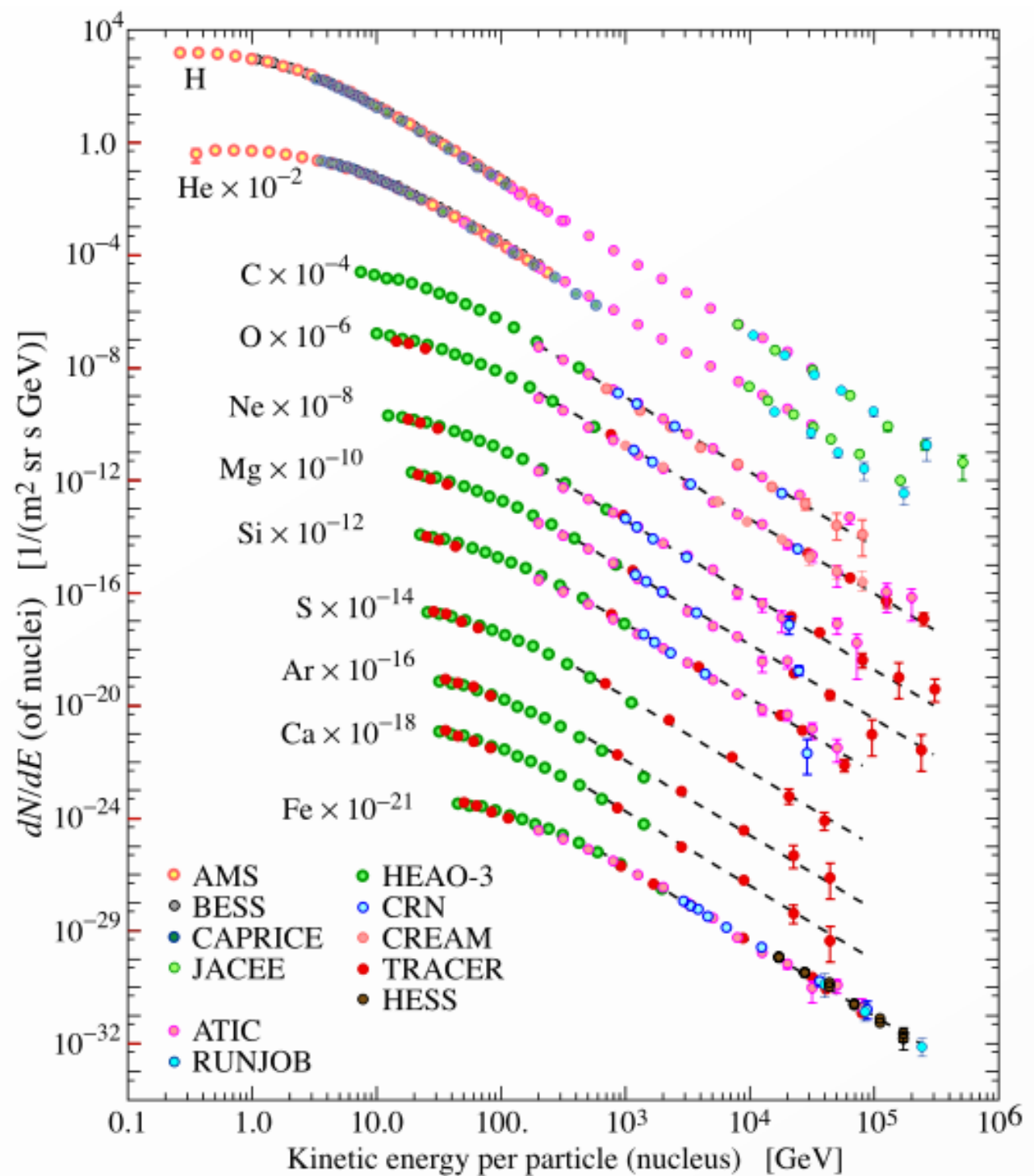


Figure 24.1: Major components of the primary cosmic radiation from Refs. [1–12]. The figure was created by P. Boyle and D. Muller.

O que se observa numa câmara de nuvens?

- **Nível do mar:** múons
- **Muons:** perdem ~ 2 GeV até atingirem a superfície terrestre, onde chegam com ~ 4 GeV (PDG)

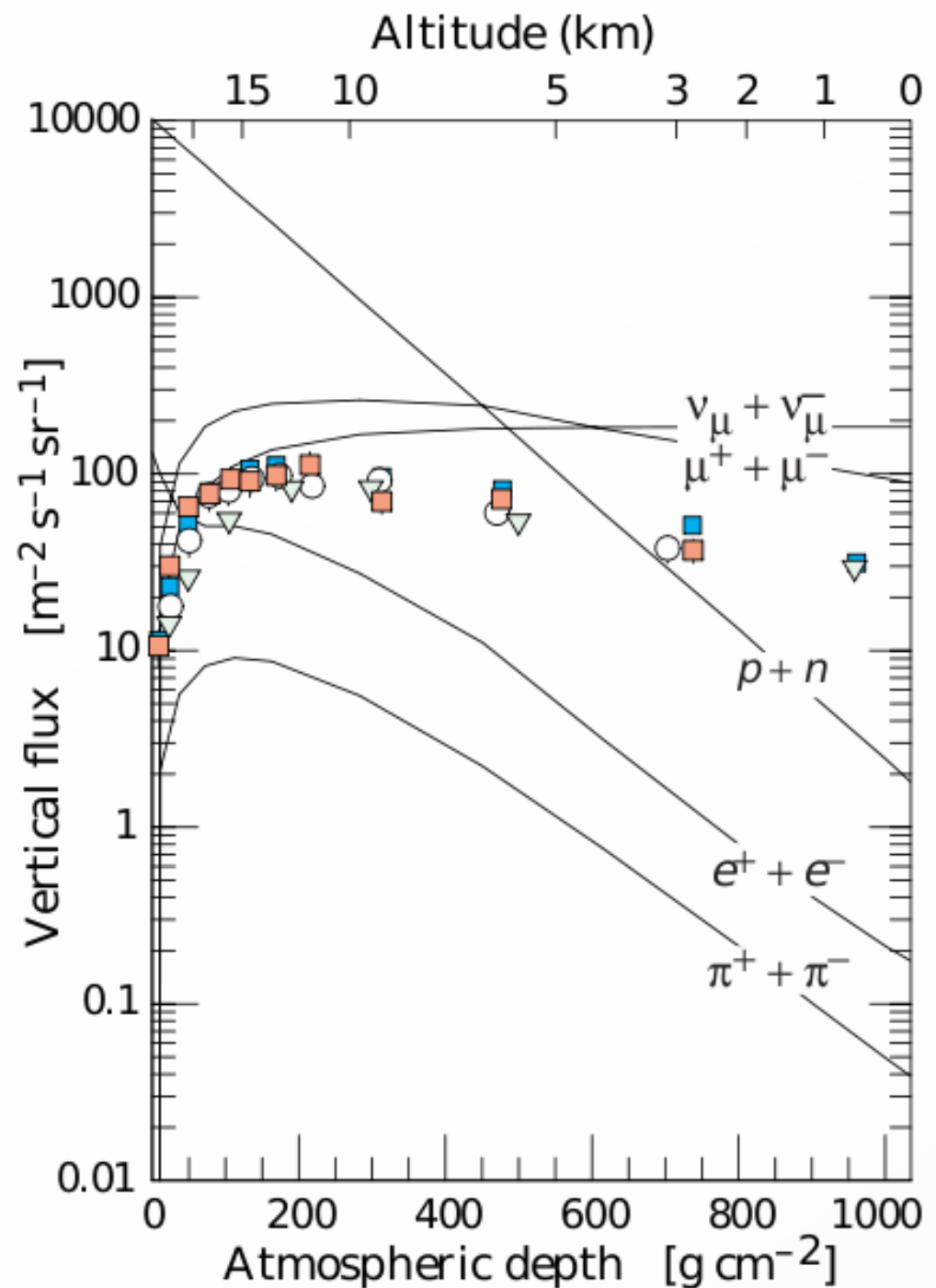
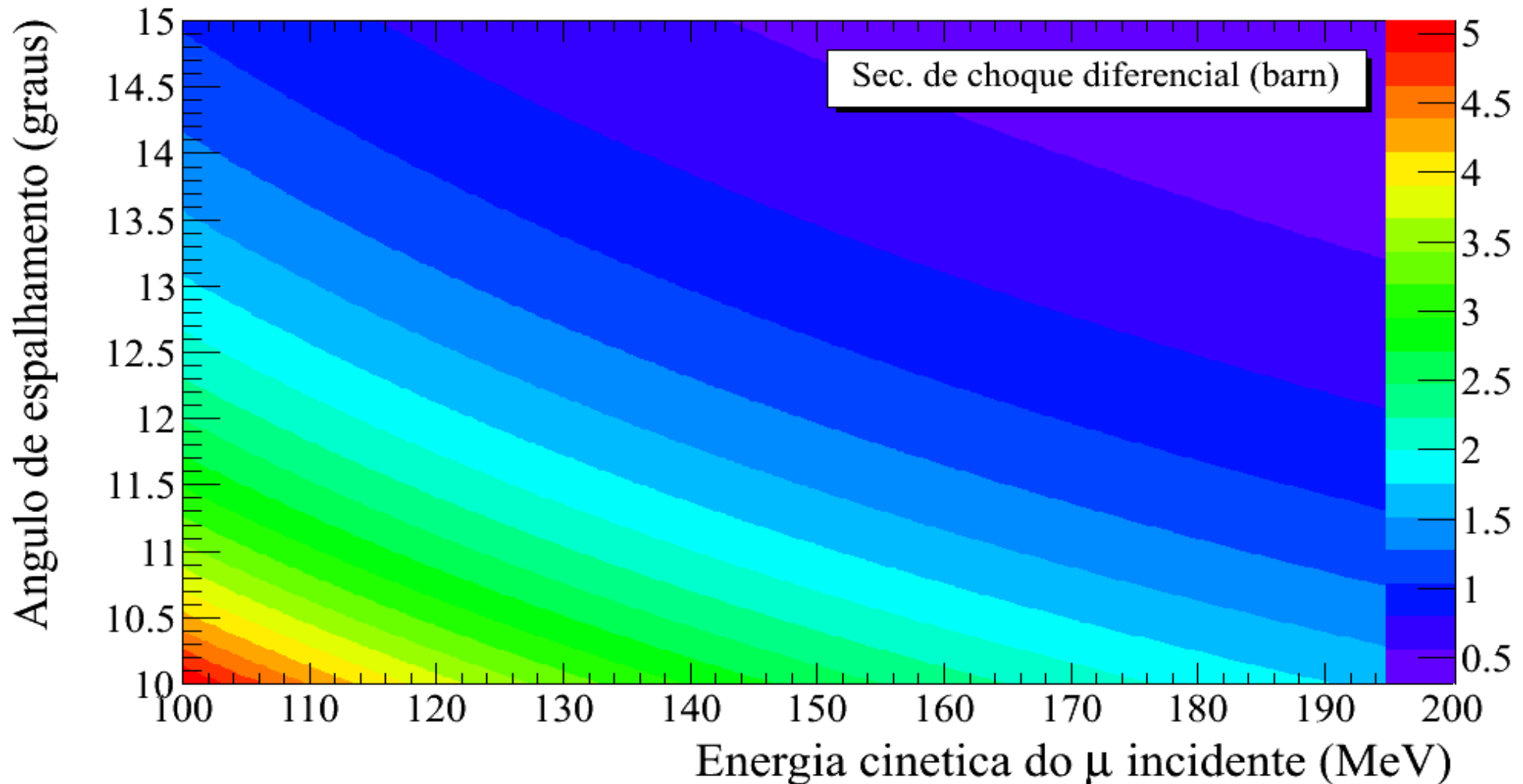


Figure 24.3: Vertical fluxes of cosmic rays in the atmosphere with $E > 1$ GeV estimated from the nucleon flux of Eq. (24.2). The points show measurements of negative muons with $E_{\mu} > 1$ GeV [29–32].

Interação “profunda” dos múons na câmara (QED)

Seção de choque do espalhamento de um μ por uma molécula de álcool isopropílico ($Z = 36$).

$$\frac{d\sigma}{d\Omega} = \left(\frac{Z\alpha\hbar c}{2T(T + 2mc^2) \sin^2 \frac{\theta}{2}} \right)^2 \left((mc^2)^2 \sin^2 \frac{\theta}{2} + (T + mc^2)^2 \cos^2 \frac{\theta}{2} \right) \quad (1)$$



Estimar a energia de um muon através da forma de sua trajetória!

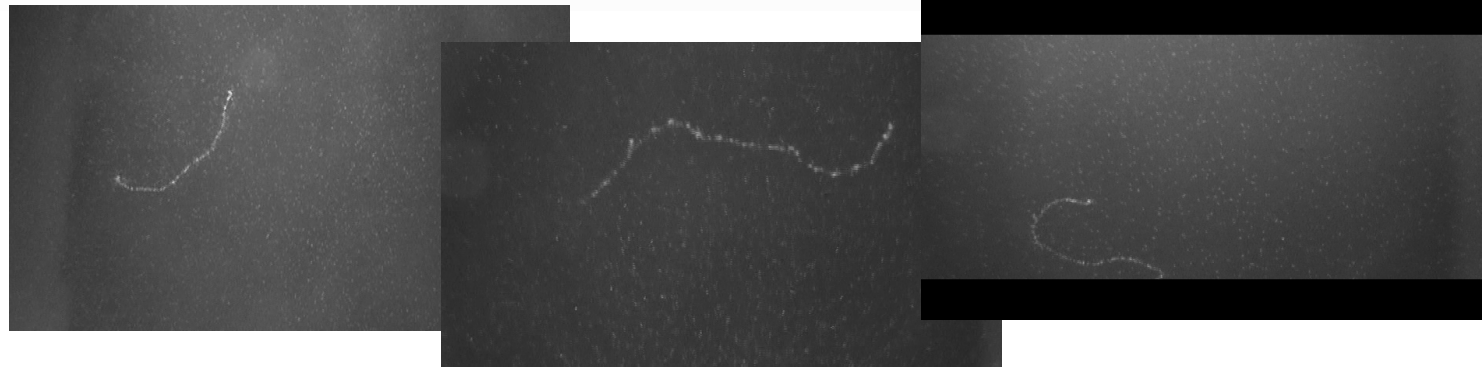
2 Caminho livre médio

Vapor supersaturado de álcool isopropílico $\rho = 8 \times 10^{20}$ (moléculas/cm³)

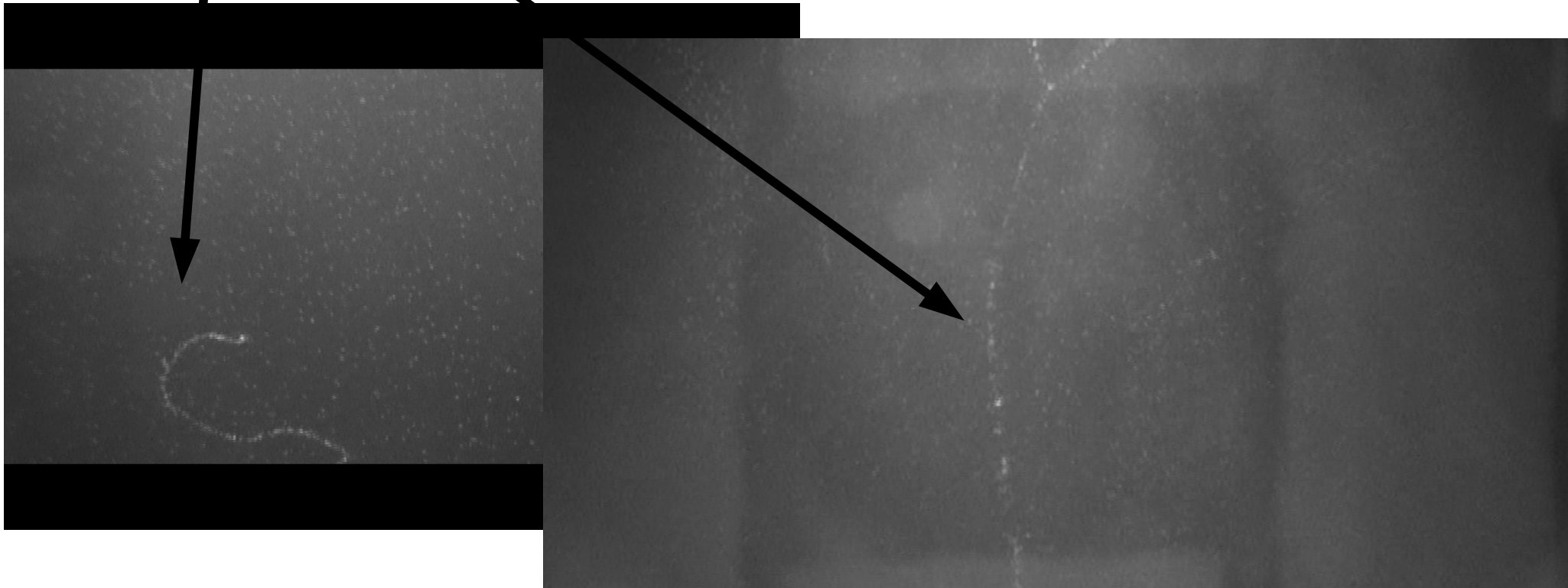
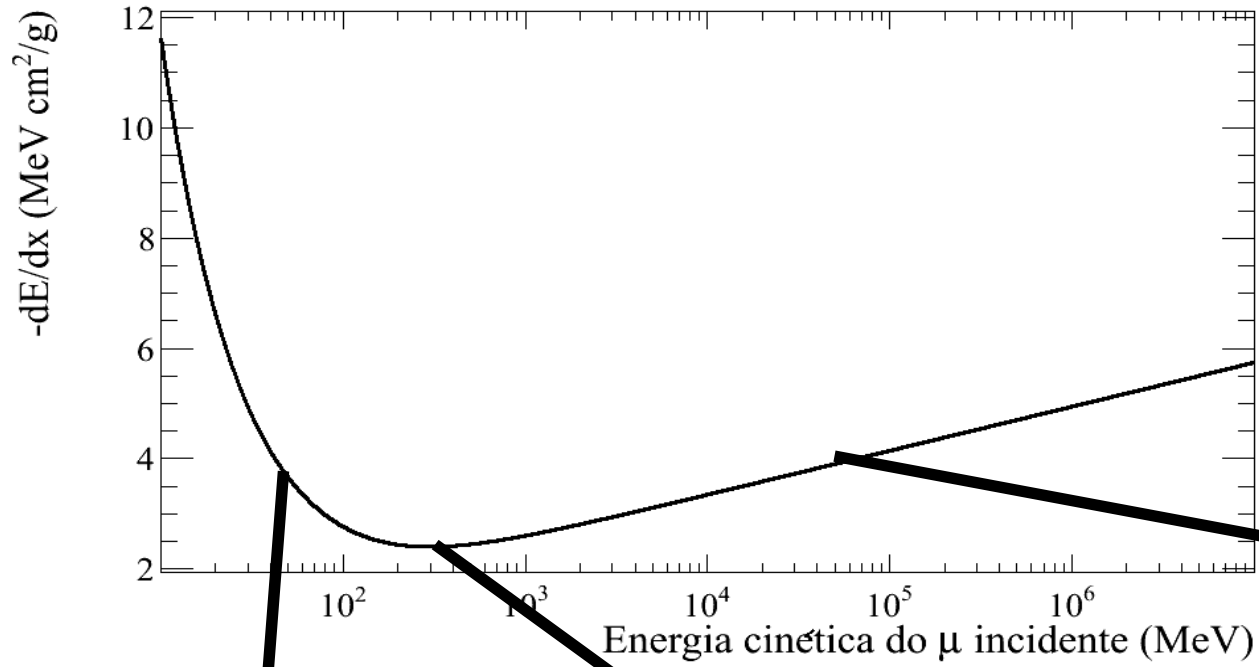
$$l = \frac{1}{\sigma\rho} \quad (2)$$

E_μ (MeV)	l (cm)
10	0.18
50	3.6
100	11.6
500	175

Table 1: Caminho livre médio do μ em função de sua energia cinética. Foram considerados ângulos de espalhamento maiores que 1 grau no cálculo da seção de choque total.



Conclusão:



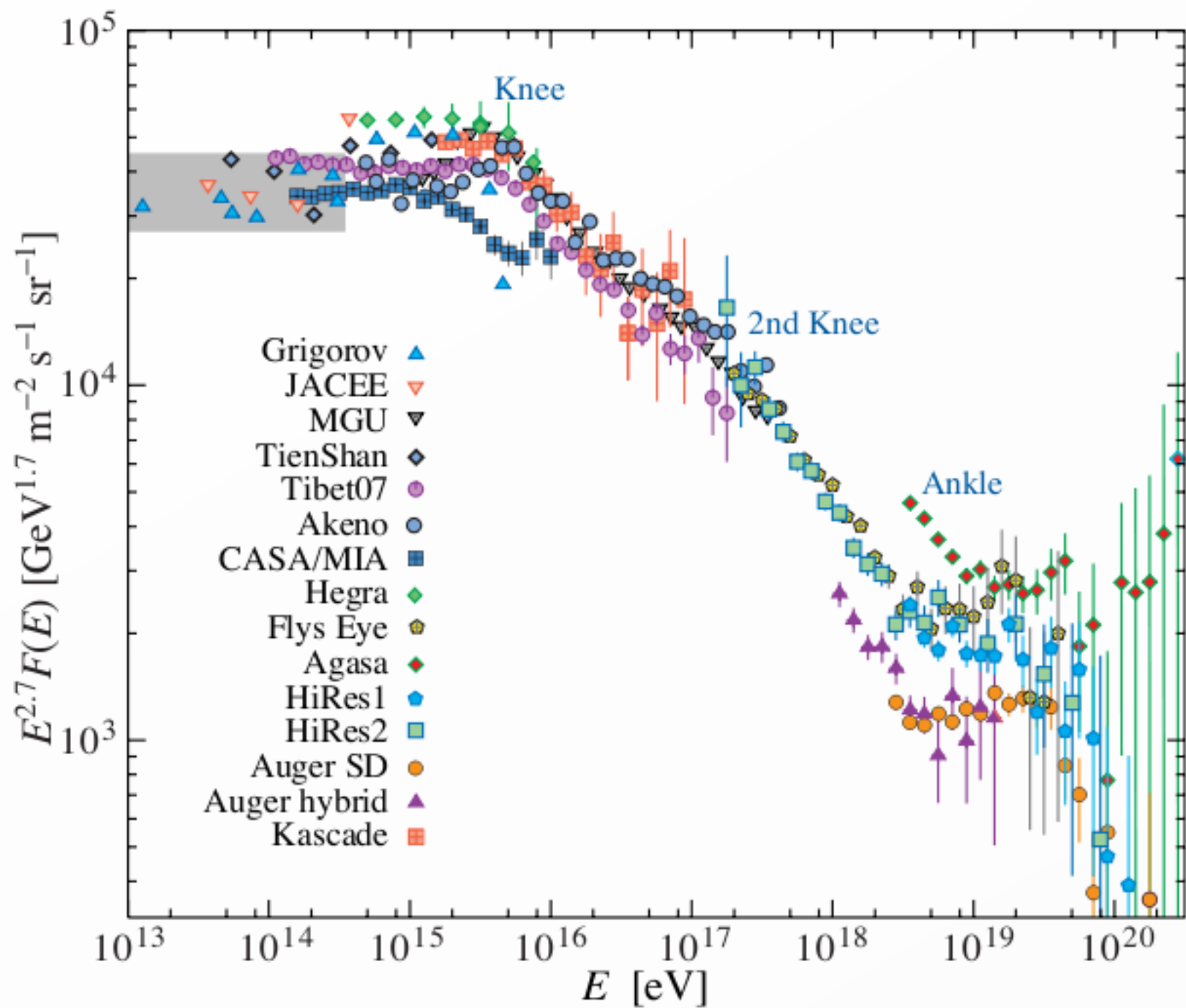
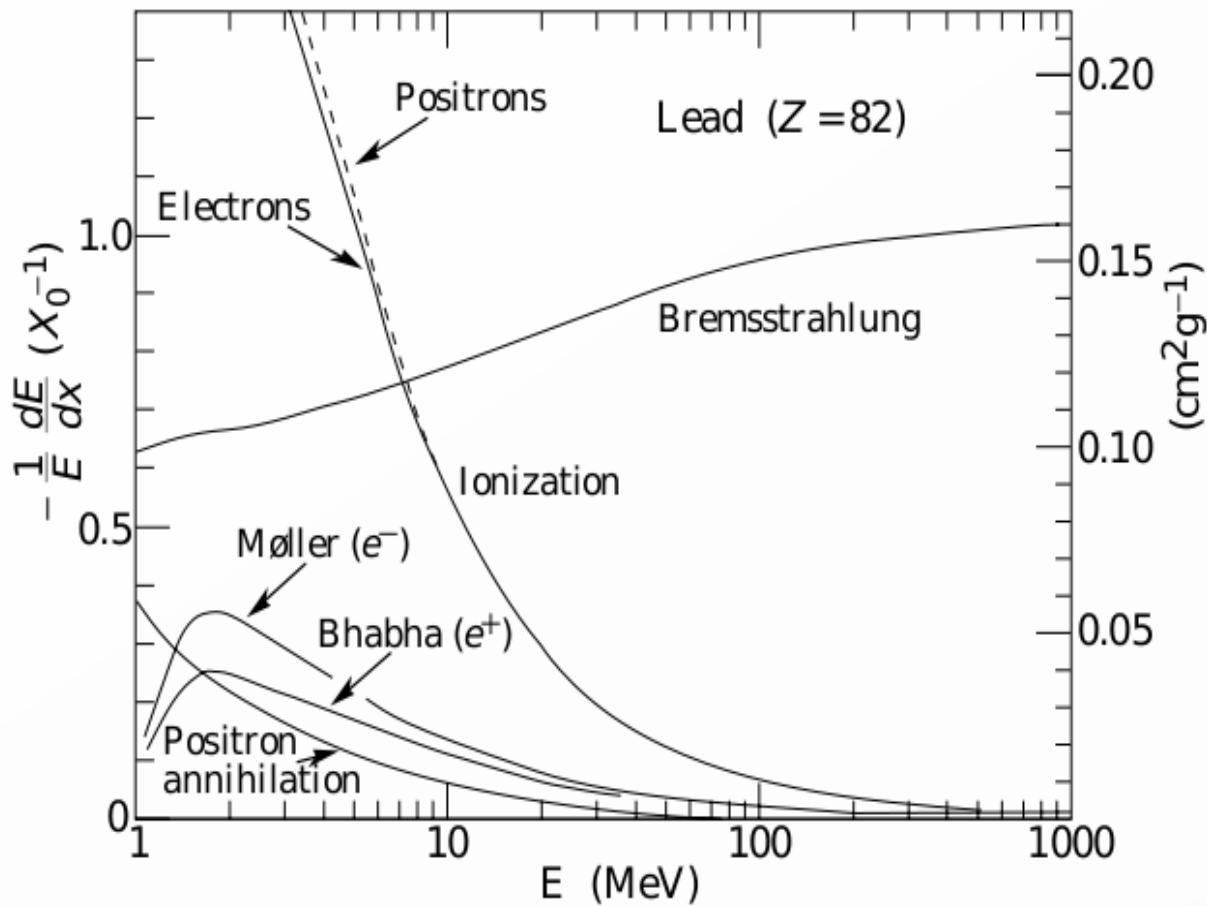


Figure 24.9: The all-particle spectrum from air shower measurements. The shaded area shows the range of the direct cosmic ray spectrum measurements.

- Outro problema: e essa imagem...?
- Resposta: produção de par (?): elétrons de alta energia ionizam pouco

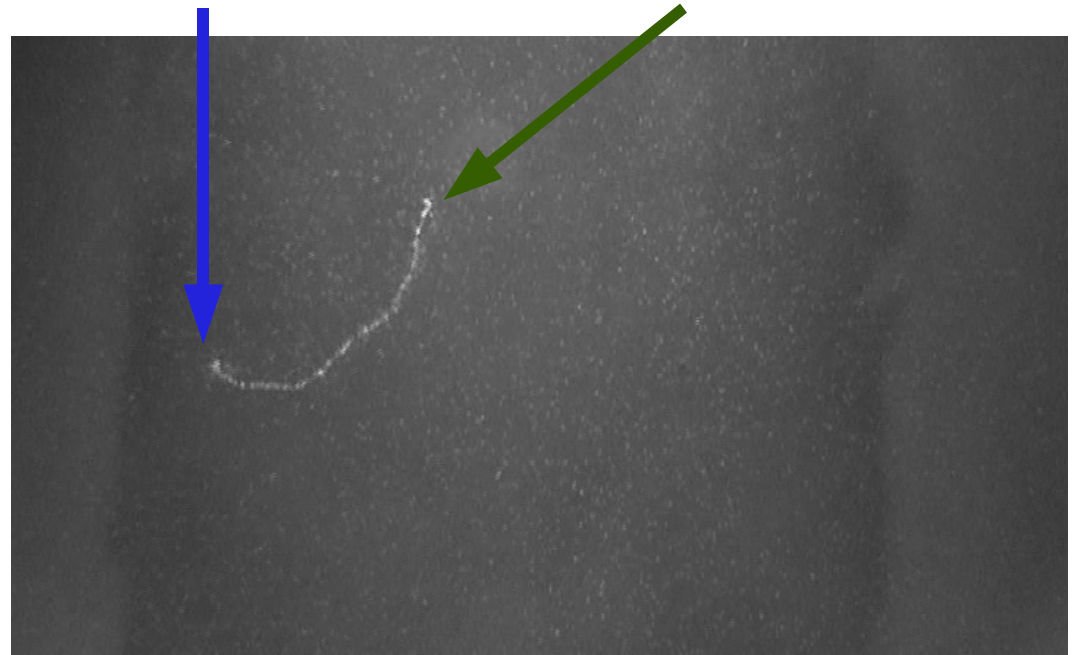


Perspectivas

- Utilizar um campo magnético para estimar a energia das partículas
- Estimar a energia das partículas através da distância percorrida na câmara (Bethe-Bloch)
- SIBYLL cosmic ray simulator
- Montar a câmara de nuvens no CERN no início de 2010 para ver o que aparece por lá!

Questões

- Por que alguns traços *começam* e *terminam*?



- Segundo o PDG, **muons** ~ 4 GeV; segundo minha estimativa, **muons** ~ 10 a 500 MeV! Ar de SP poulido?

Referências

- C. Amsler et al. (Particle Data Group), Physics Letters B667, 1 (2008)
- Hélio Takai
- Wikipedia

Créditos

- Caio Laganá, caiolagana@gmail.com

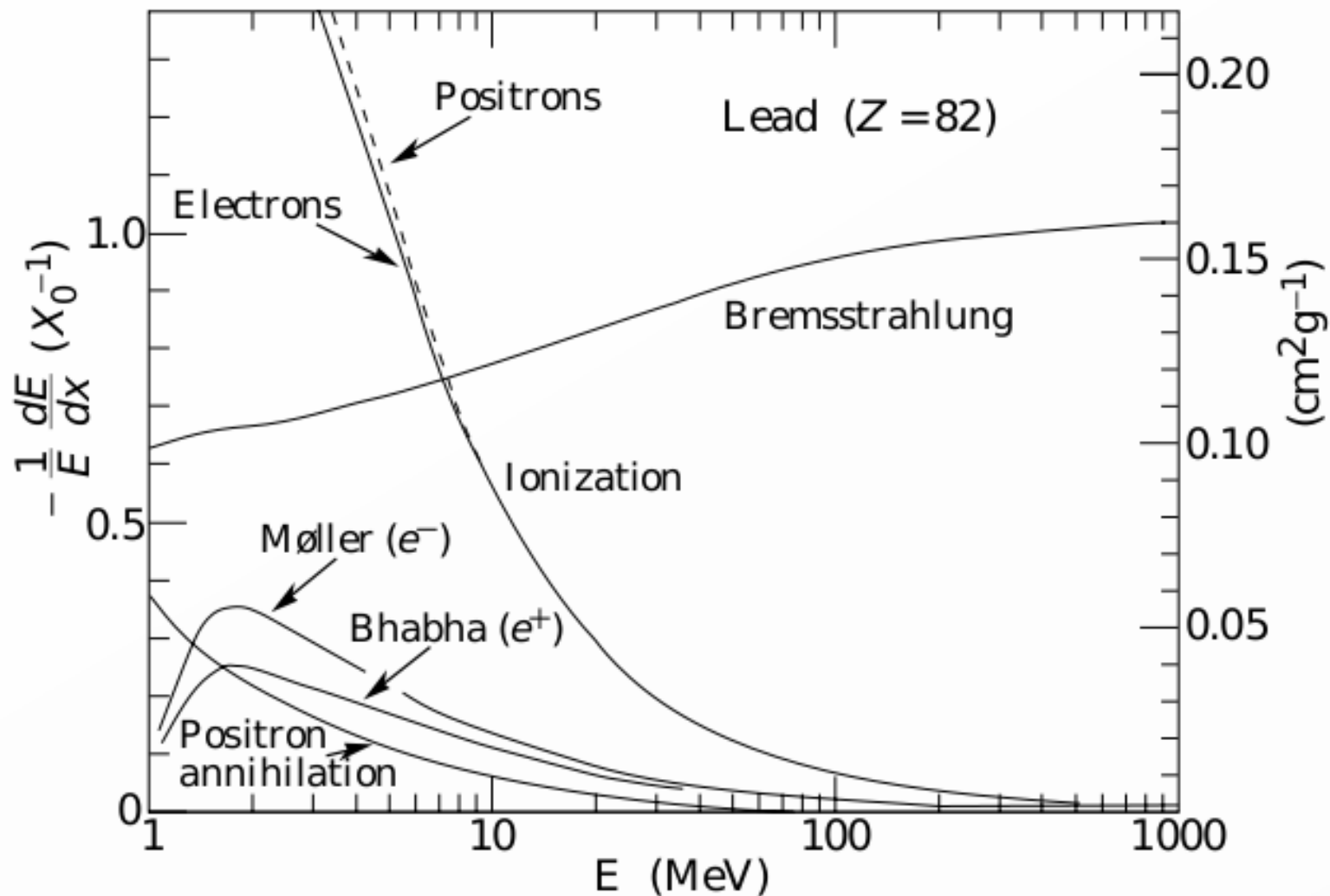


Figure 27.10: Fractional energy loss per radiation length in lead as a function of electron or positron energy. Electron (positron) scattering is considered as ionization when the energy loss per collision is below 0.255 MeV, and as Møller (Bhabha) scattering when it is above. Adapted from Fig. 3.2 from Messel and Crawford, *Electron-Photon Shower Distribution Function Tables for Lead, Copper, and Air Absorbers*, Pergamon Press, 1970. Messel and Crawford use $X_0(\text{Pb}) = 5.82 \text{ g/cm}^2$, but we have modified the figures to reflect the value given in the Table of Atomic and Nuclear Properties of Materials ($X_0(\text{Pb}) = 6.37 \text{ g/cm}^2$).

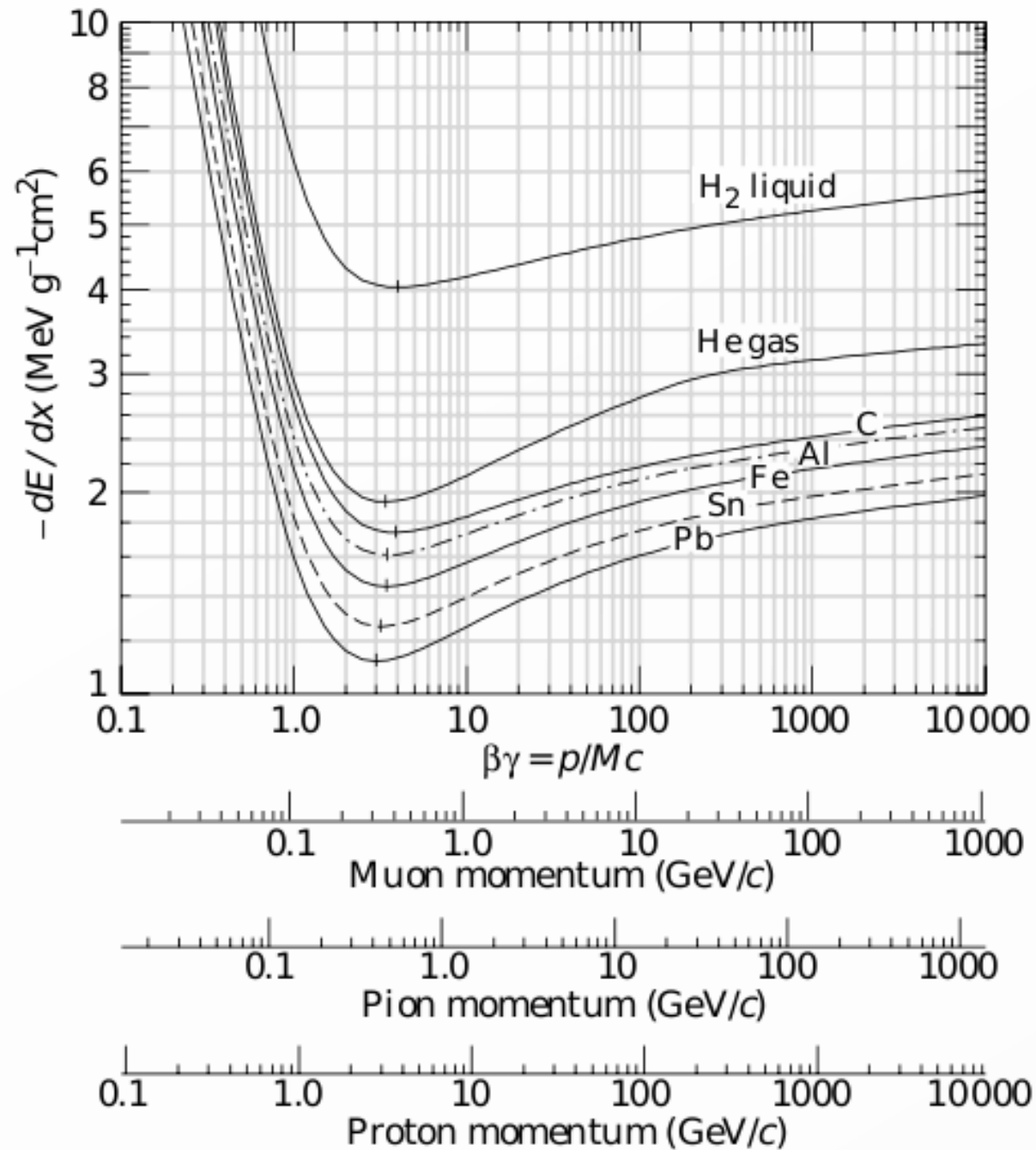


Figure 27.3: Mean energy loss rate in liquid (bubble chamber) hydrogen, gaseous helium, carbon, aluminum, iron, tin, and lead. Radiative effects, relevant for muons and pions, are not included. These become significant for muons in iron for $\beta\gamma \gtrsim 1000$, and at lower momenta for muons in higher- Z absorbers. See Fig. 27.21.

Table 28.6: Properties of rare and molecular gases at normal temperature and pressure (NTP: 20° C, one atm). E_X , E_I : first excitation and ionization energy; W_I : average energy per ion pair; $dE/dx|_{\min}$, N_P , N_T : differential energy loss, primary and total number of electron-ion pairs per cm, for unit charge, minimum ionizing particles.

Gas	Density, mg cm^{-3}	E_x eV	E_I eV	W_I eV	$dE/dx _{\min}$ keV cm^{-1}	N_P cm^{-1}	N_T cm^{-1}
Ne	0.839	16.7	21.6	30	1.45	13	50
Ar	1.66	11.6	15.7	25	2.53	25	106
Xe	5.495	8.4	12.1	22	6.87	41	312
CH ₄	0.667	8.8	12.6	30	1.61	37	54
C ₂ H ₆	1.26	8.2	11.5	26	2.91	48	112
iC ₄ H ₁₀	2.49	6.5	10.6	26	5.67	90	220
CO ₂	1.84	7.0	13.8	34	3.35	35	100
CF ₄	3.78	10.0	16.0	54	6.38	63	120