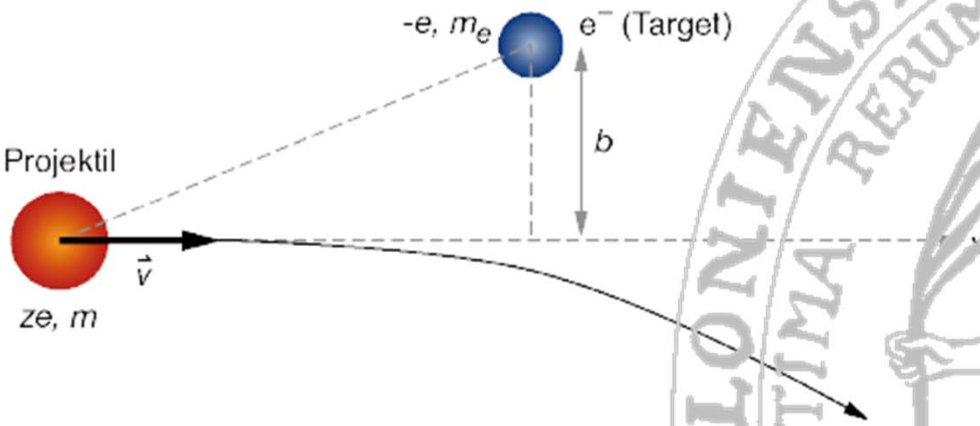
Mathematisch-Naturwissenschaftliche Fakultät

Christian-Albrechts-Universität zu Kiel

Extraterrestrische Physik

Bernd Heber

5 November, 2010

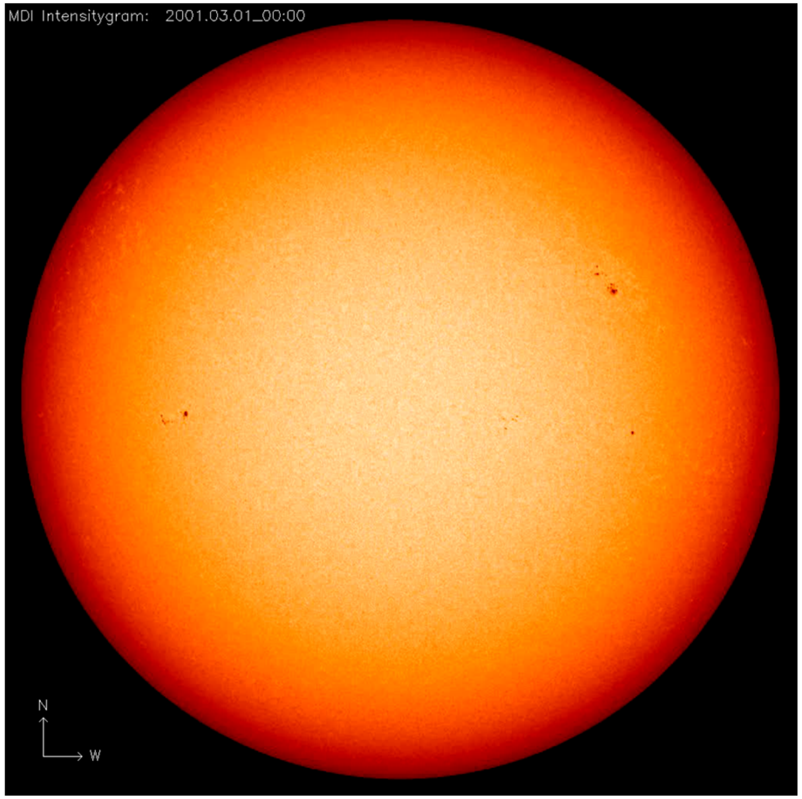


Overview of todays lecture

1. What was left
2. Interaction of heavy charged particles with matter, Bethe-Bloch-Formular
3. Application
4. Electrons
5. Bremsstrahlung
6. Application

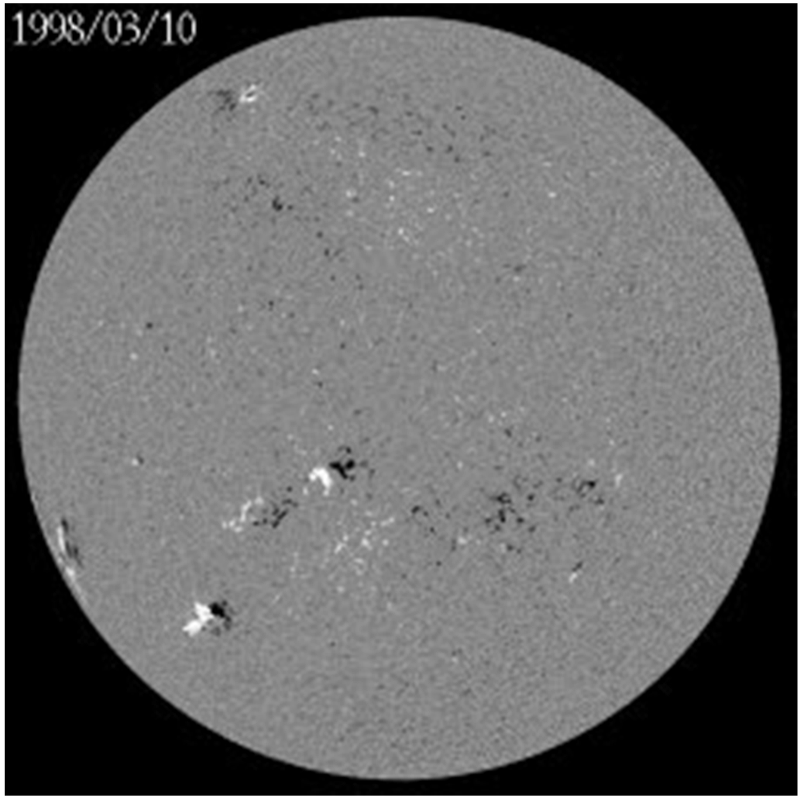
PHOTOSPHERE - CHROMOSPHERE - CORONA

Photosphere



SOHO / ESA

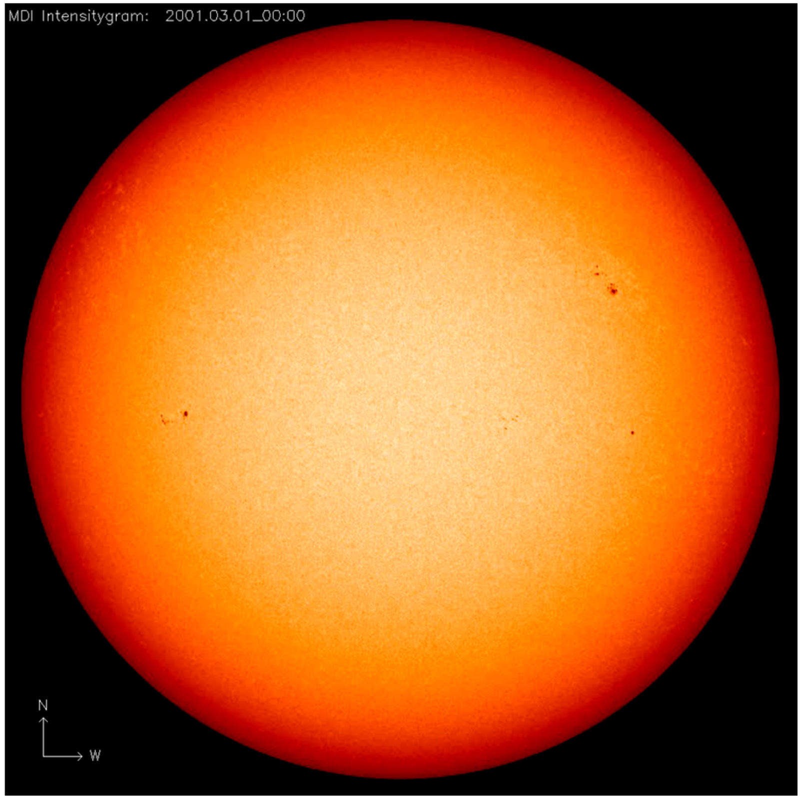
A magnetized Star



SOHO / ESA

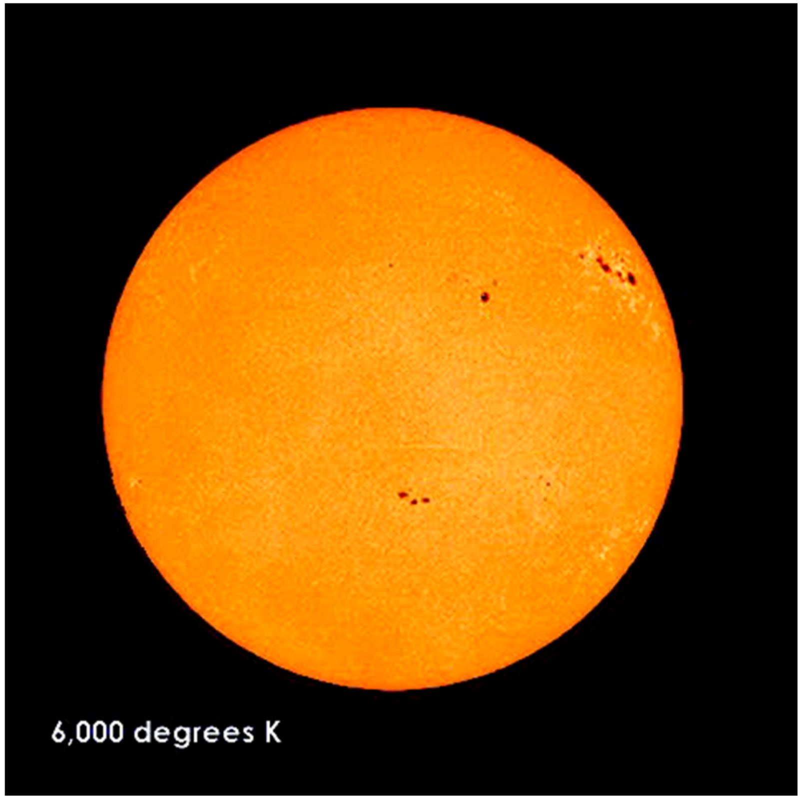
PHOTOSPHERE - CHROMOSPHERE - CORONA

Photosphere



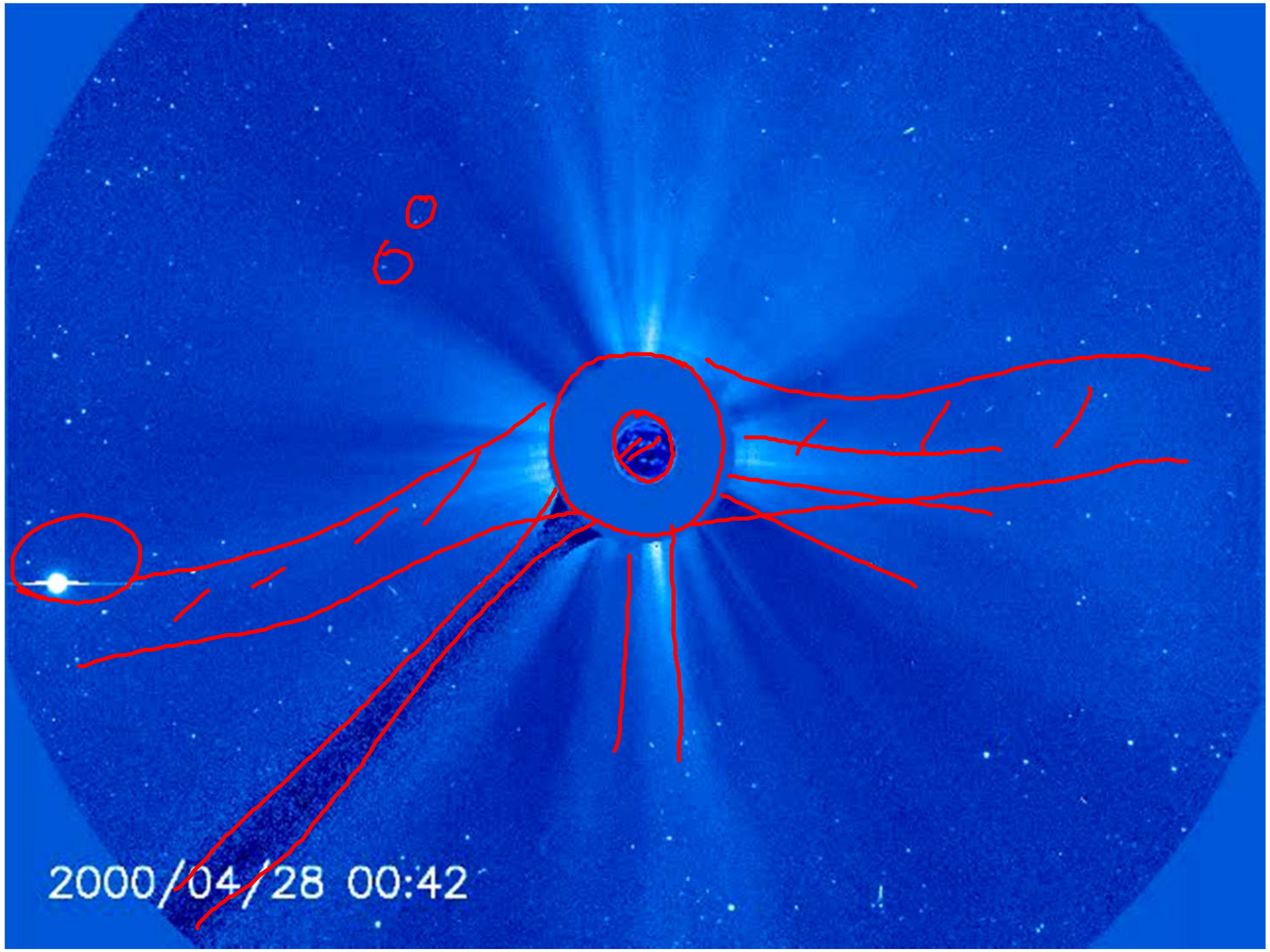
SOHO / ESA

Chromosphere and Corona



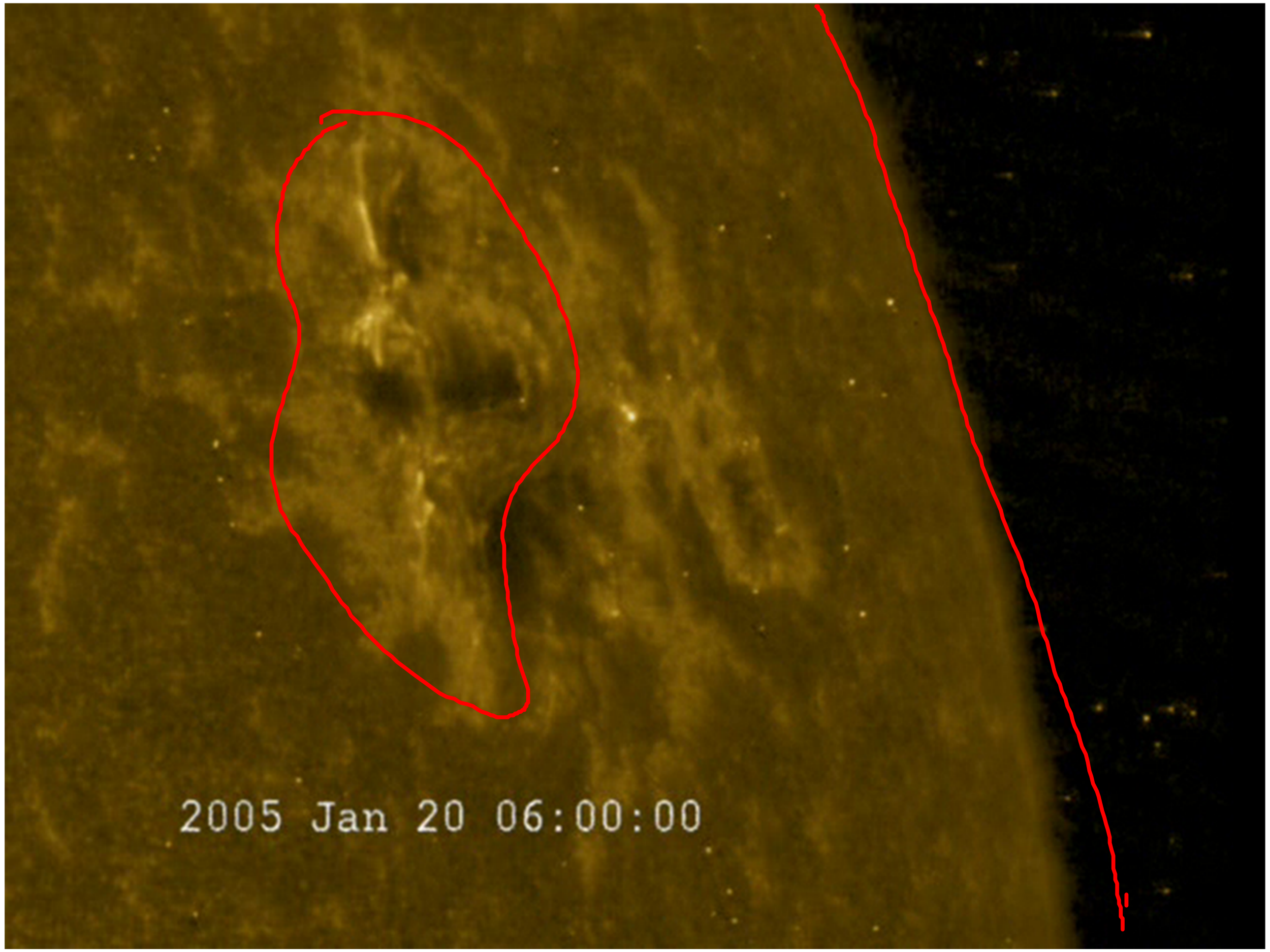
SOHO / ESA

The expansion of the solar atmosphere – the solar wind (Biermann, Parker,…)



THE ACTIVE SUN
Flares

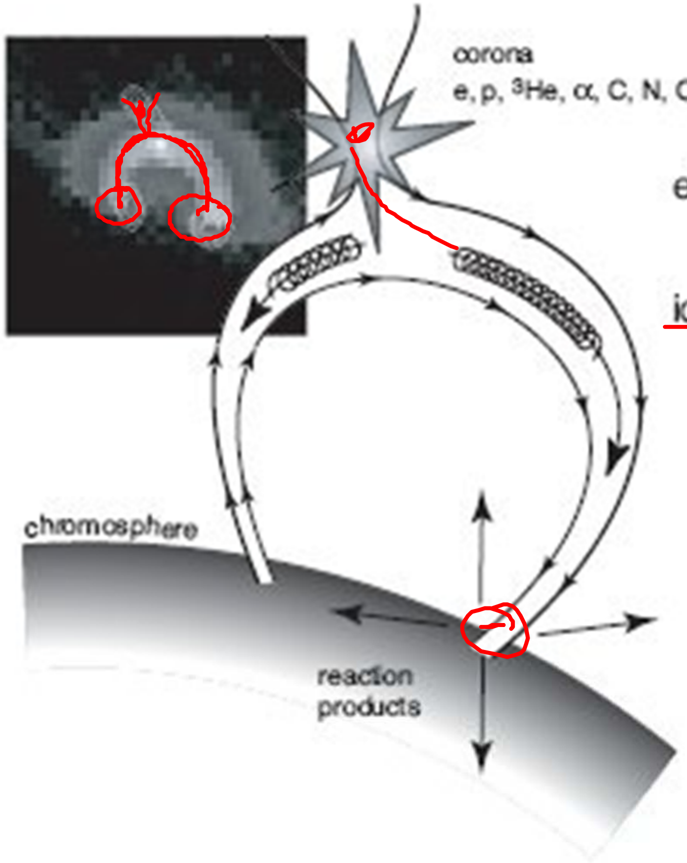
TRACE / NASA



Solar Flare

Energy: ~ 10^{25} Ws

The Sun as a Particle Accelerator: Energetic photons and neutrons



electrons: X- and γ-ray bremsstrahlung

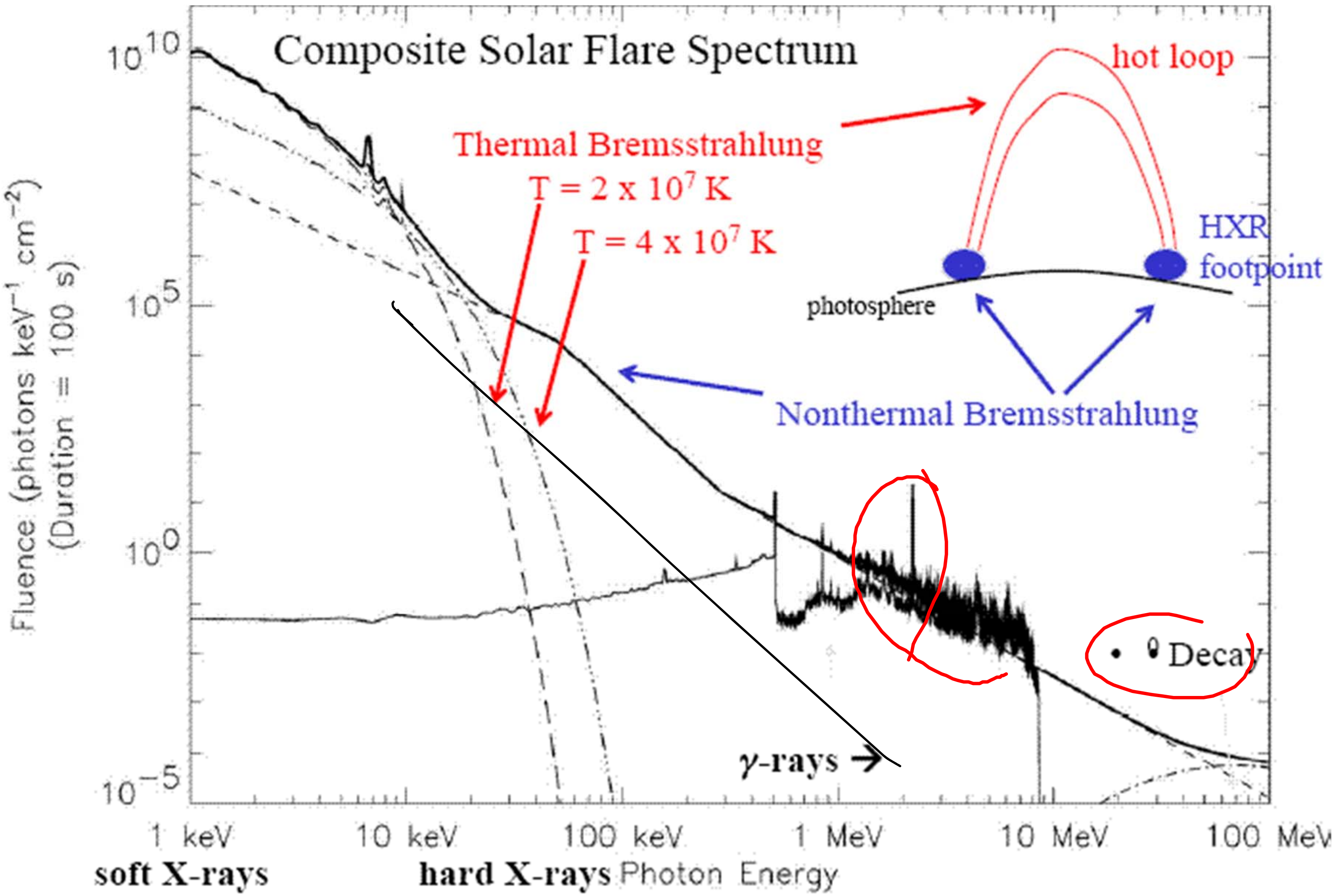
ions: excited nuclei $\rightarrow$ γ-ray line radiation (1– 8 MeV)

radioactive nuclei $\rightarrow e^+ \rightarrow \gamma_{511}$

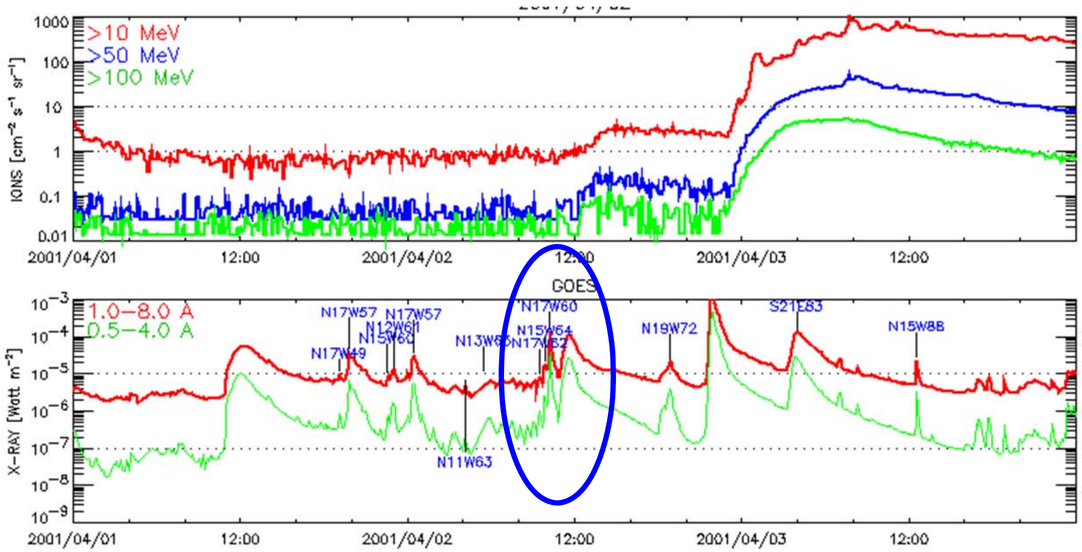
$\pi \rightarrow \gamma$ (decay, $e^{\pm}$ bremsstrahlung, γ_{511})

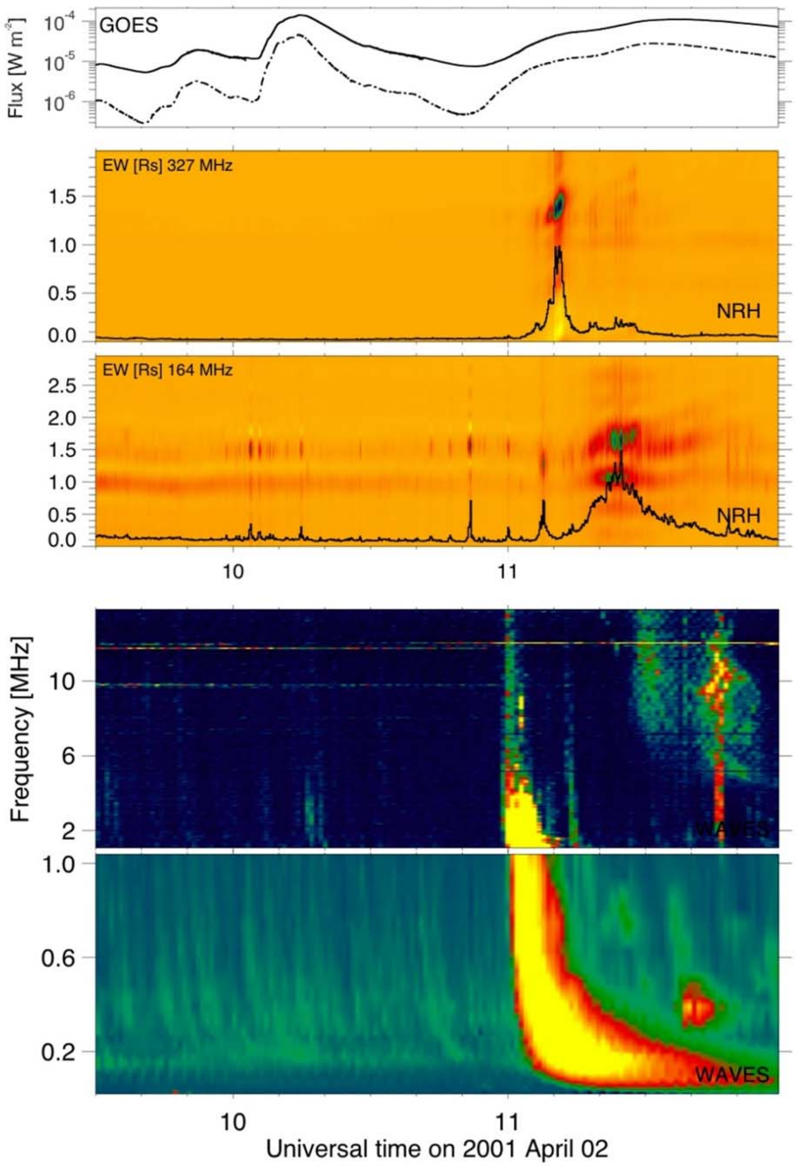
neutrons $\rightarrow \begin{cases} \text{escape to space} \\ \text{capture on H} \rightarrow \text{2.223 MeV line} \end{cases}$

The Sun as a Particle Accelerator: Energetic photons



Flares and SEP: the role of magnetic confinement (Klein et al., 634)



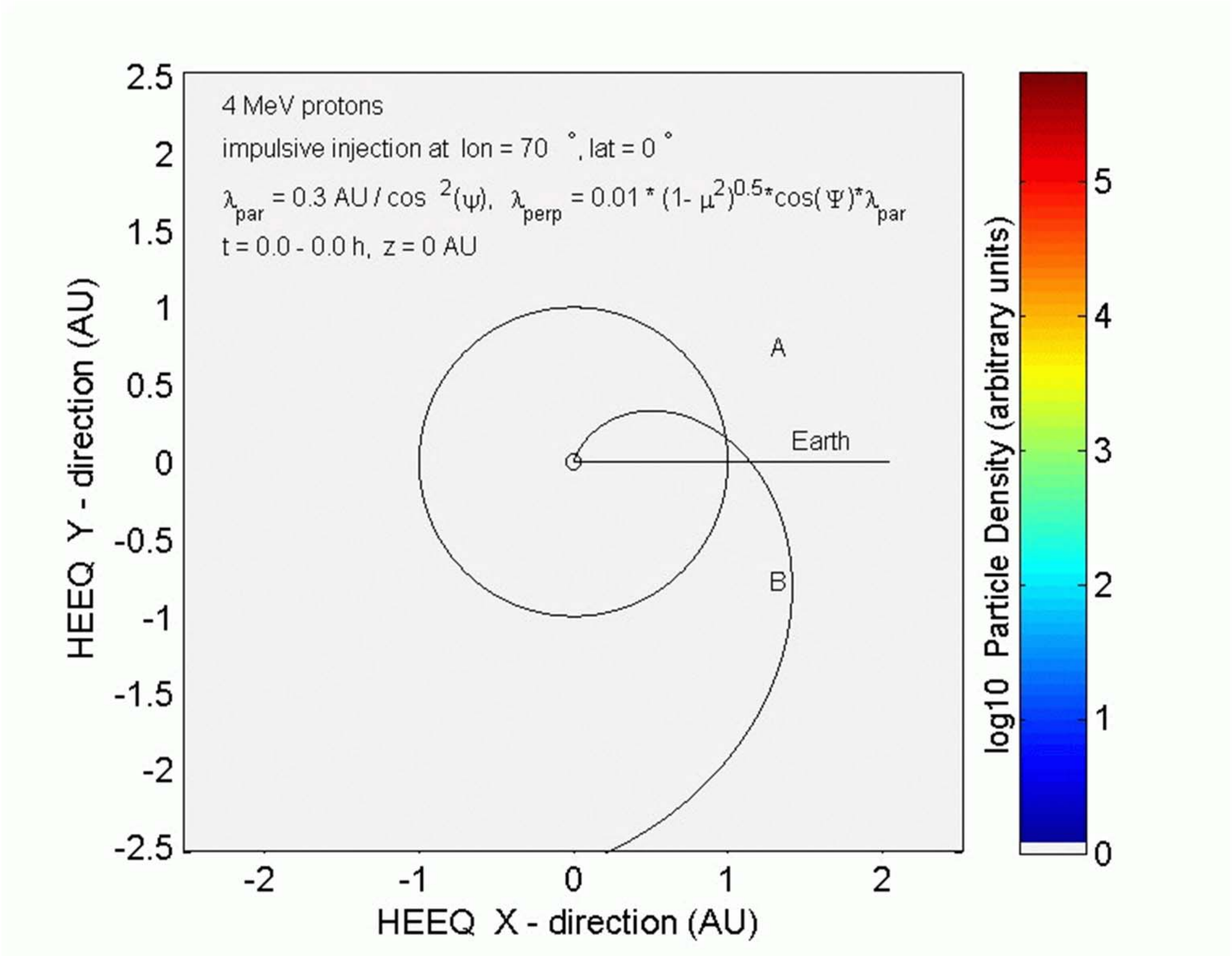


CME-less flare 2001 Apr 02 was followed by

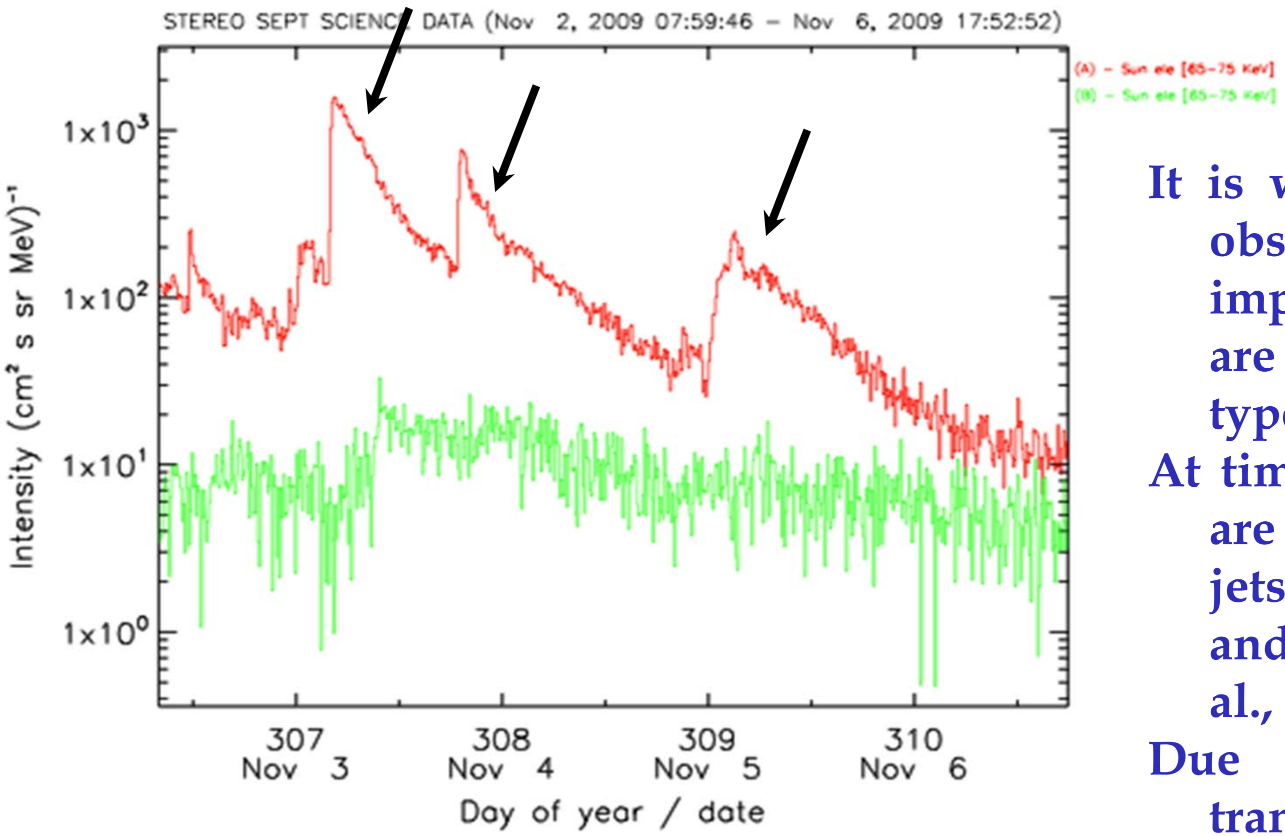
- an 'eruptive' flare from a neighbouring AR
- Radio dm-m-λ: moving IV
- strong type III (particle escape to IP space)

=> SEP (GOES)

High Light SH-2: 3-D Particle Propagation – The role of perpendicular Transport

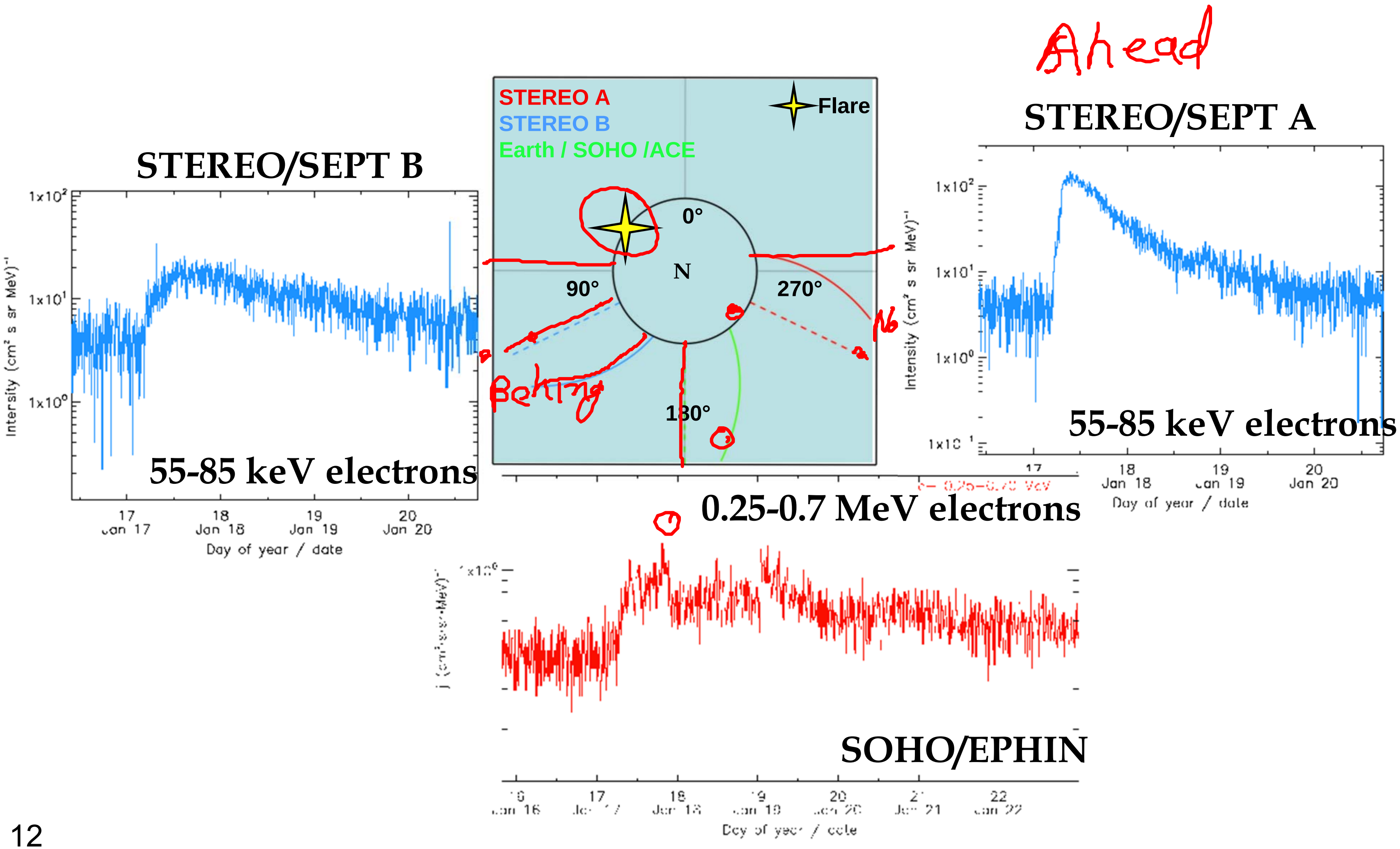


Electron measurements at 1 AU



- It is well known that in-situ observed near-relativistic impulsive electron events are well correlated with type III radio bursts.
- At times type III radio bursts are associated with X-ray jets (e.g. Aurass et al., 1994) and EUVI jets (e.g. Wang et al., 2006).
- Due to interplanetary transport "normal" SEP event observation last hours.

January 17, 2010



The Earth magnetic field as a spectrometer (De Simone et al., 2010)

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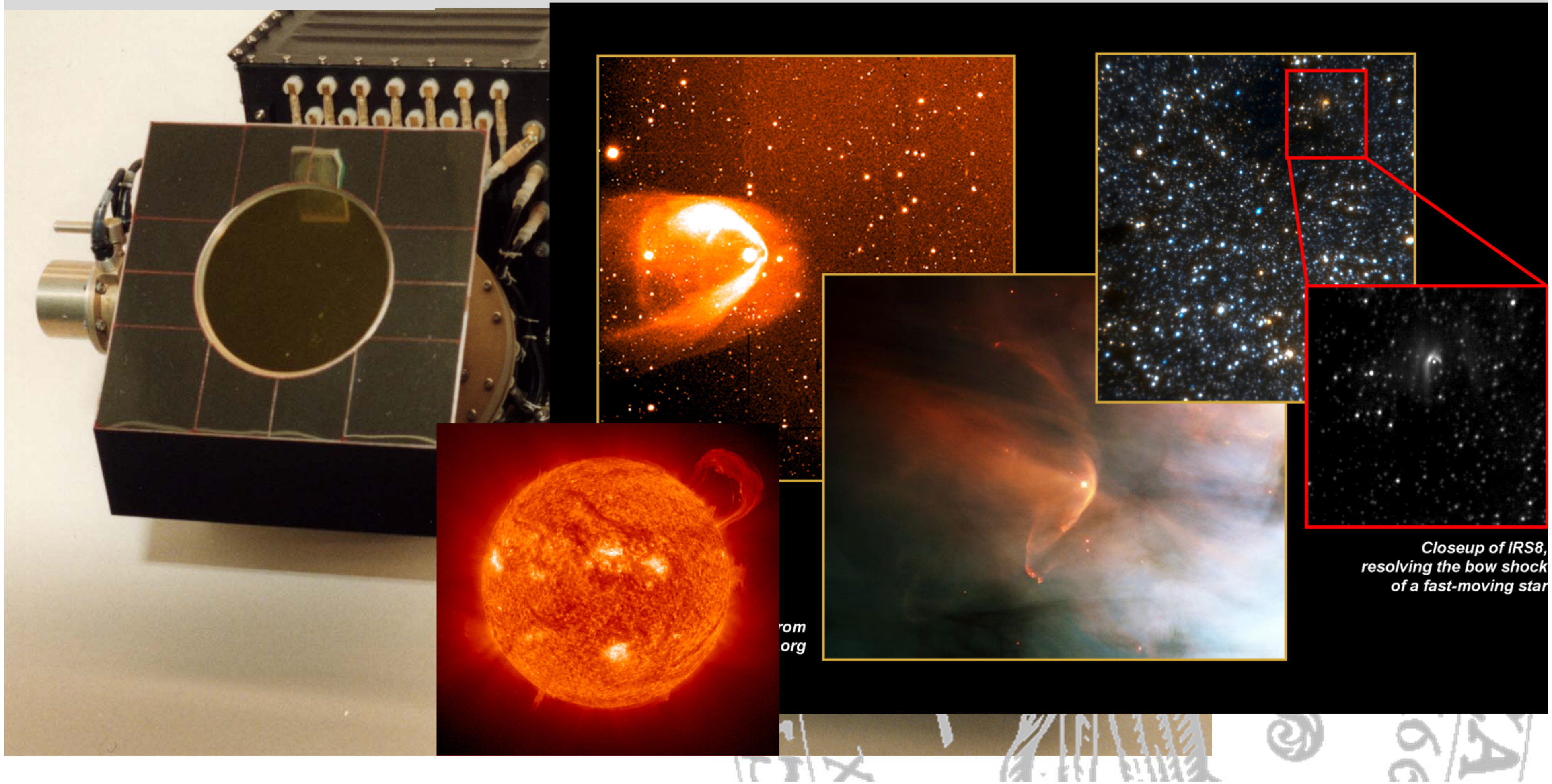
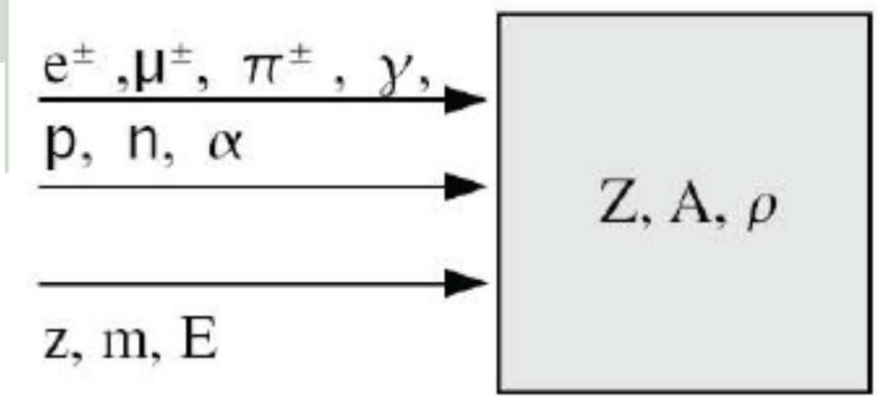
Extraterrestrial Physics I – Grundlagen und Messmethoden



Interaction of charged particles with matter

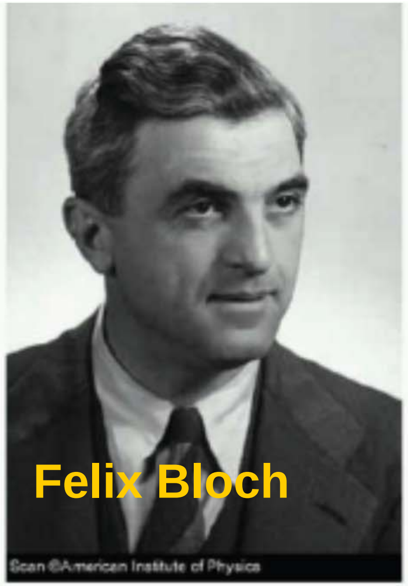


Energetic charged particles:

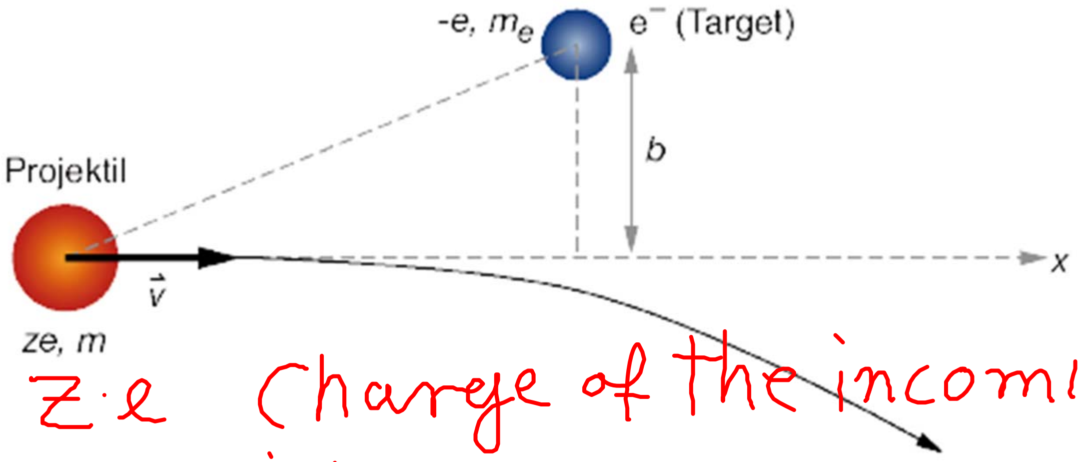
1. Ionize and excite atoms and moleculs
2. Loose energy
3. Are scattered in the material
4. Undergo nuclear Interaction
5. May destroy the material/cristalls
6. Generate hadronic and electron showers in matter

dE/dx History

- N. Bohr, classical derivation
- Bethe, Bloch: quantenmechanical treatement
- L. Landau: Distribution function
- E. Fermi: Density correction
- ...



Energy loss of heavy charged particles by ionization



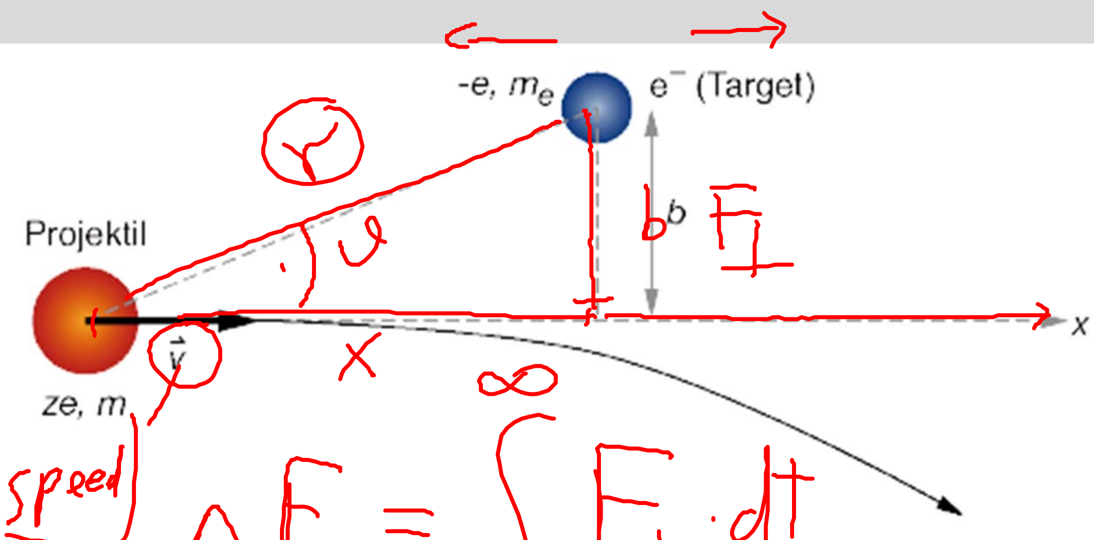
$z \cdot e$ charge of the incoming particle

m it's mass

electron, $-e$

closest approach $= b$

Energy loss of heavy charged particles by ionization



$$\Delta E = \int_{-\infty}^{\infty} F_\perp \cdot dt$$

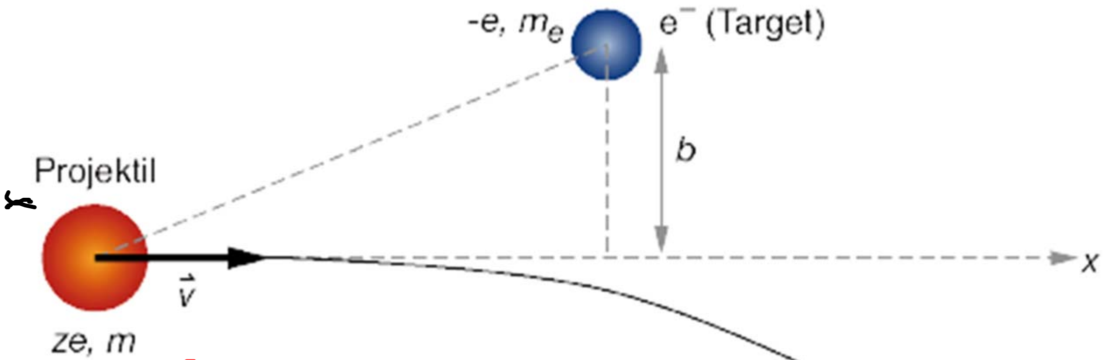
$$\boxed{\sin\vartheta = \frac{b}{r}} \quad (3)$$

$$\boxed{F_\perp = \frac{z \cdot e^2}{4\pi\varepsilon_0 \cdot r^2} \cdot \sin\vartheta} \quad *$$

$$\boxed{dt = \frac{dx}{v}} \quad (1)$$

$$\boxed{\tan\vartheta = \frac{b}{x}} \quad (2)$$

Energy loss of heavy charged particles by ionization



$$\frac{b}{x} = \tan\vartheta$$

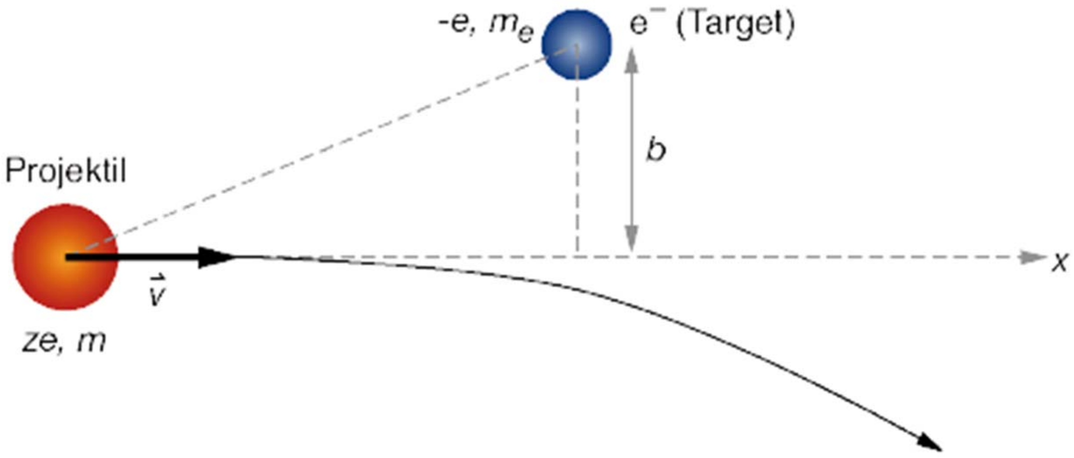
$$\rightarrow r = b/\sin\vartheta$$

$$dx = \frac{b}{\sin^2\vartheta}\, d\vartheta$$

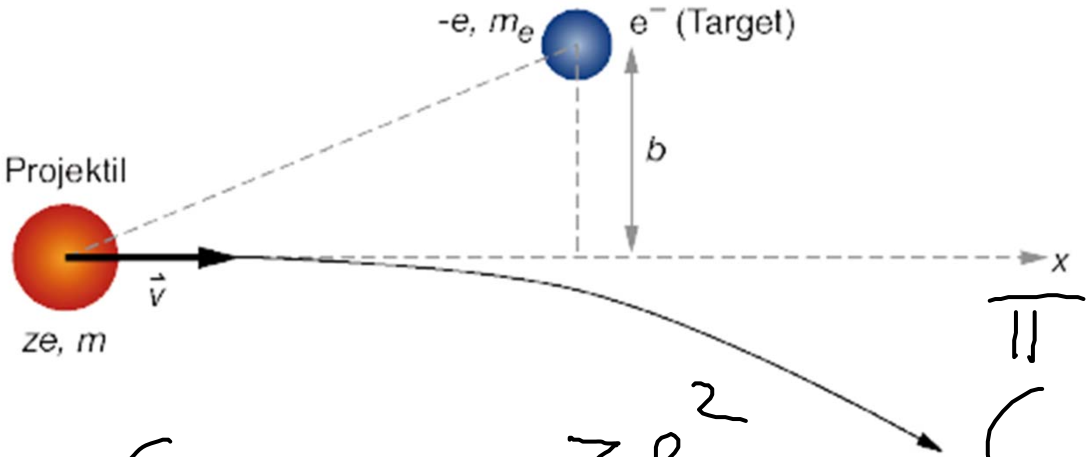
$$\int_{-\infty}^{\infty} F_\perp\, dt = \int F_\perp \cdot \frac{b \cdot d\vartheta}{\sin^2\vartheta \cdot v} =$$

$$= \int_0^{\pi} \boxed{\frac{ze^2}{4\pi\varepsilon_0}} \left(\frac{\cancel{\sin\vartheta}}{b}\right)^2 \frac{\cancel{b} \cdot d\vartheta}{\cancel{\sin^2\vartheta} \cdot v} \frac{\sin\vartheta}{} =$$

Energy loss of heavy charged particles by ionization



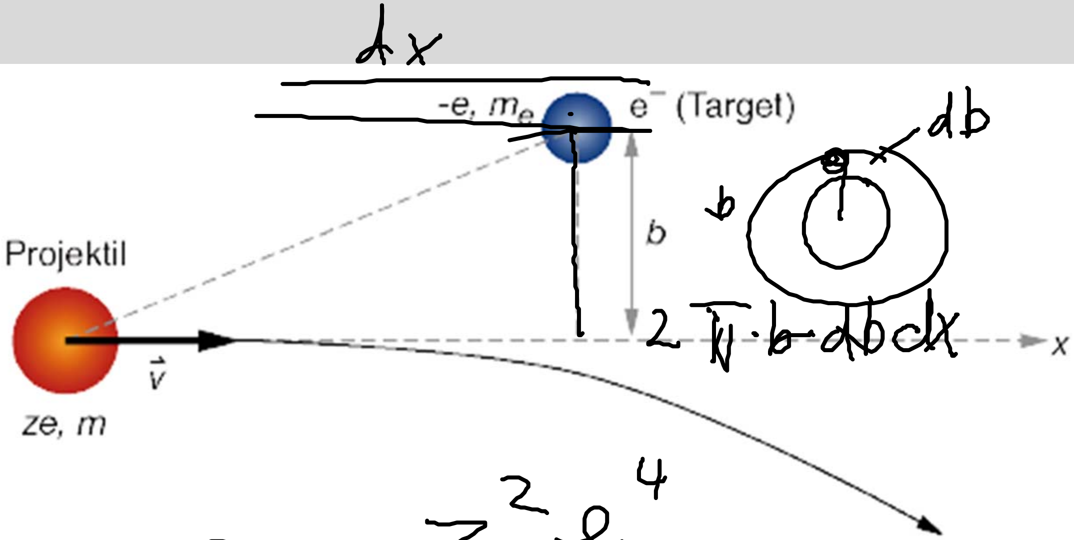
Energy loss of heavy charged particles by ionization



$$\int F_\perp \, dt = \frac{ze^2}{4\pi\varepsilon_0 b\cdot v}\underbrace{\cancel{\int_0^\pi \sin\vartheta \, d\vartheta}}_{2}$$

$$\boxed{\Delta p = \frac{ze^2}{2\pi\varepsilon_0 b\cdot v}}$$

Energy loss of heavy charged particles by ionization



Energy transfer:

$$\Delta E = \frac{(\Delta p)^2}{2m_e}$$

$$\Delta E = \frac{z^2 e^4}{8\pi^2 \cdot \varepsilon_0^2 b^2 v^2 m_e}$$

per interaction

Averaged energy transfer: Integrate from b_{min} to b_{max} ; 2) macroscopic scales

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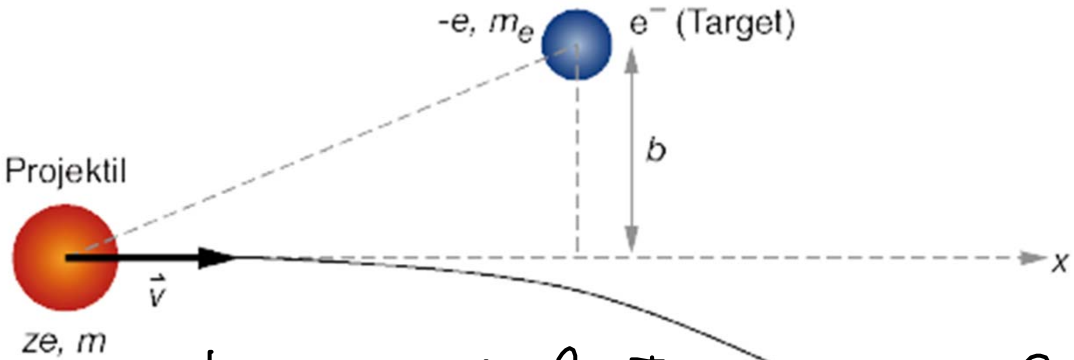
Energy loss of heavy charged particles by ionization



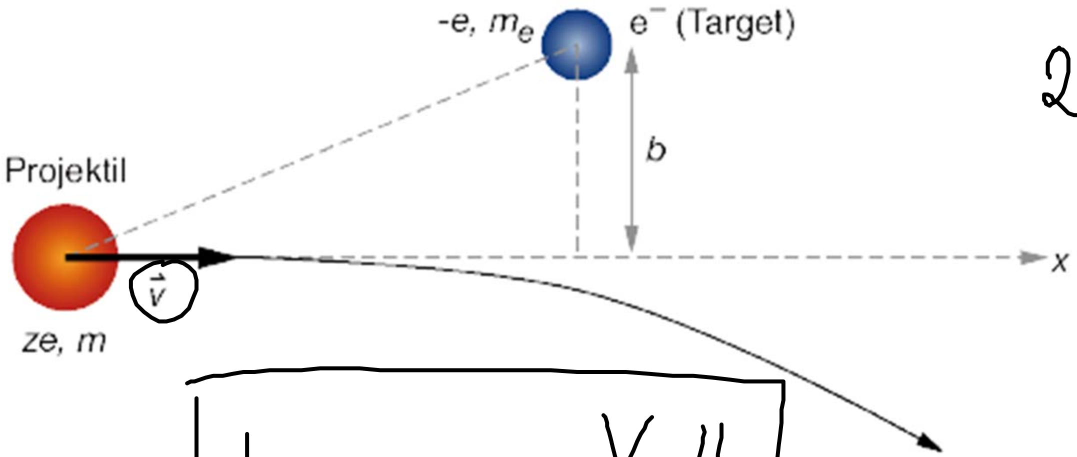
electron density

Number of electrons : $2\pi b \cdot db \cdot dx \cdot N_e$

$$dE(dx) = \int_{b_{min}}^{b_{max}} N_e \cdot 2\cancel{\pi} \cdot \cancel{b} \cdot db \cdot dx \cdot \frac{z^2 e^4}{8 \pi^2 \cdot \varepsilon_0^2 \cdot b^2 \cdot m_e v^2}$$

$$\frac{dE}{dx} = \frac{z^2 e^4}{4\pi\varepsilon_0 v^2 m_e} \ln\left(\frac{b_{max}}{b_{min}}\right)$$

Energy loss of heavy charged particles by ionization



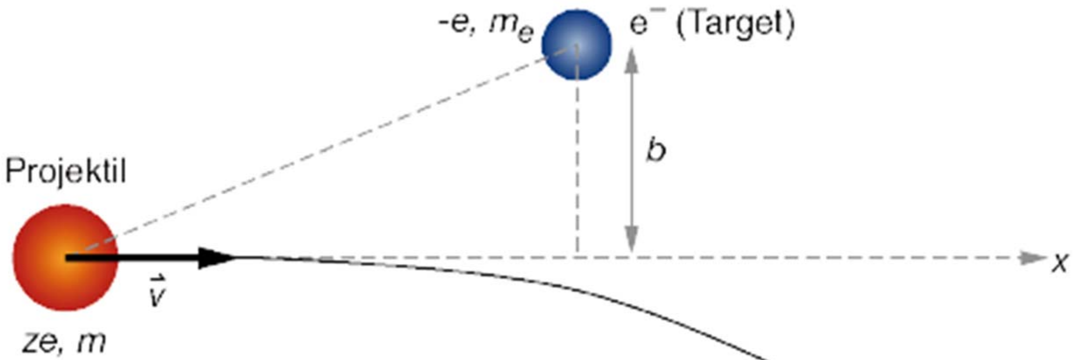
$$2 m_e v = \frac{z e^2}{4\pi\varepsilon_0 \cdot b_{min}}$$

$$\boxed{b_{min} = \frac{z e^2}{8\pi\varepsilon_0 m_e v}}$$

$$\boxed{b_{max} \simeq \frac{v\gamma}{\omega_0}}$$

$2 m_e v$ head elastic collision

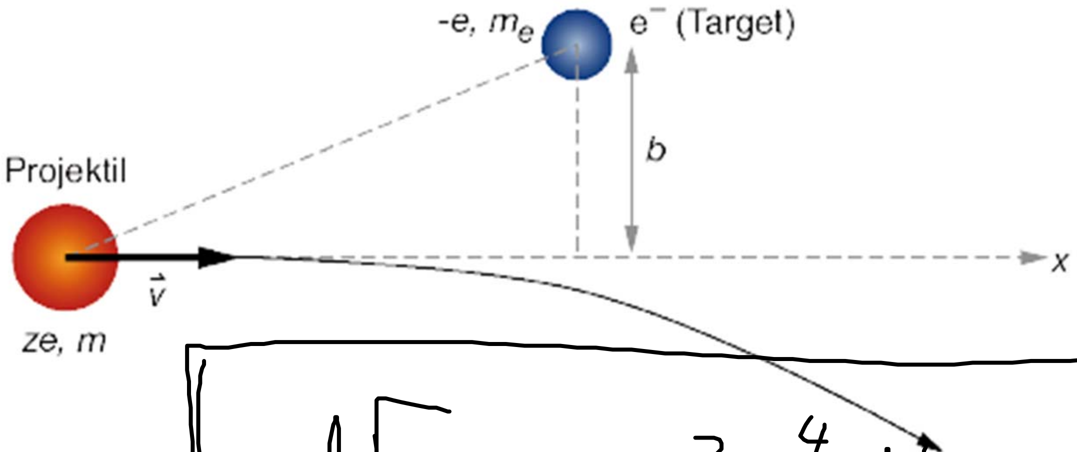
Energy loss of heavy charged particles by ionization



$$\frac{dE}{dx} = \frac{z^2 e^4}{4\pi \varepsilon_0 v^2 \cdot m_e} \ln\left(\frac{8\pi m_e \cdot \varepsilon_0 v^2}{Z e^2} \cdot \frac{v \pi}{\omega_0}\right)$$

Bohr-Modell $\quad E = \frac{1}{2} \hbar \omega_0$

Energy loss of heavy charged particles by ionization



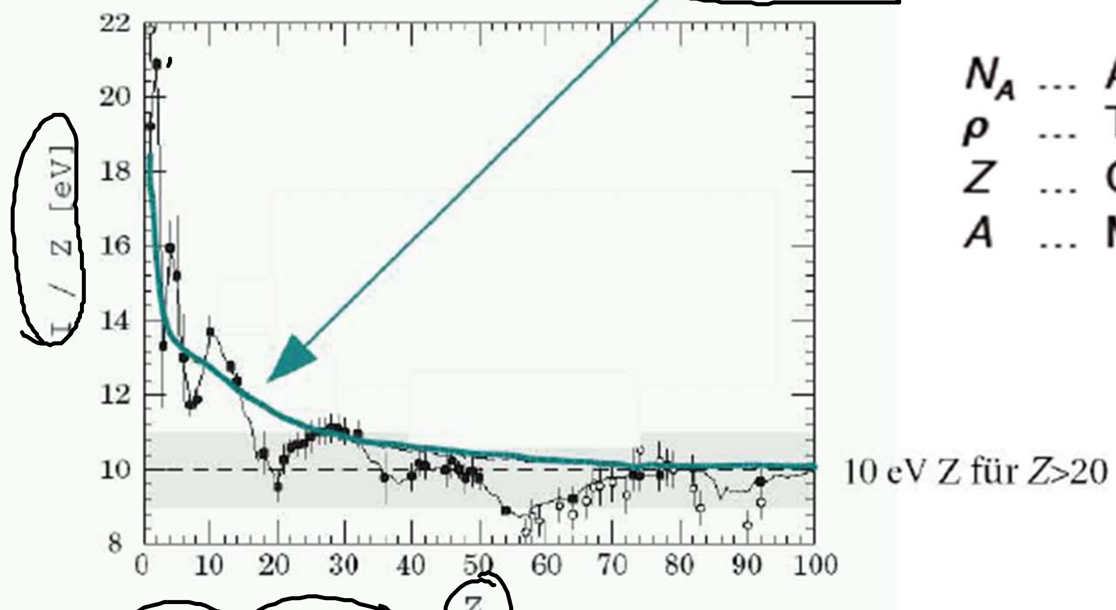
$$\boxed{\frac{dE}{dx} = \frac{z^2 e^4 N_e}{4\pi \varepsilon_0 v^2 \cdot m_e} \ln\left(\frac{2 m_e v^2}{I}\right)}$$

Das Ionisationspotential

$$-\frac{dE}{dx} = \frac{z^2 e^4 N_e}{4\pi \varepsilon_0^2 v^2 m_e} \ln\left(\frac{\pi m_e v^2}{I}\right)$$

$$n_e = N_A \rho \frac{Z}{A}$$

I charakteristisch für das bremsende Material $I = 16\, Z^{0.9}$ eV für $Z > 1$



N_A ... Avogadrozahl
ρ ... Targetdichte
Z ... Ordnungszahl des Targets
A ... Massenzahl des Targets

Beispiel Argon: $Z = 18$, I = 215 eV, gemessen 190.8 eV

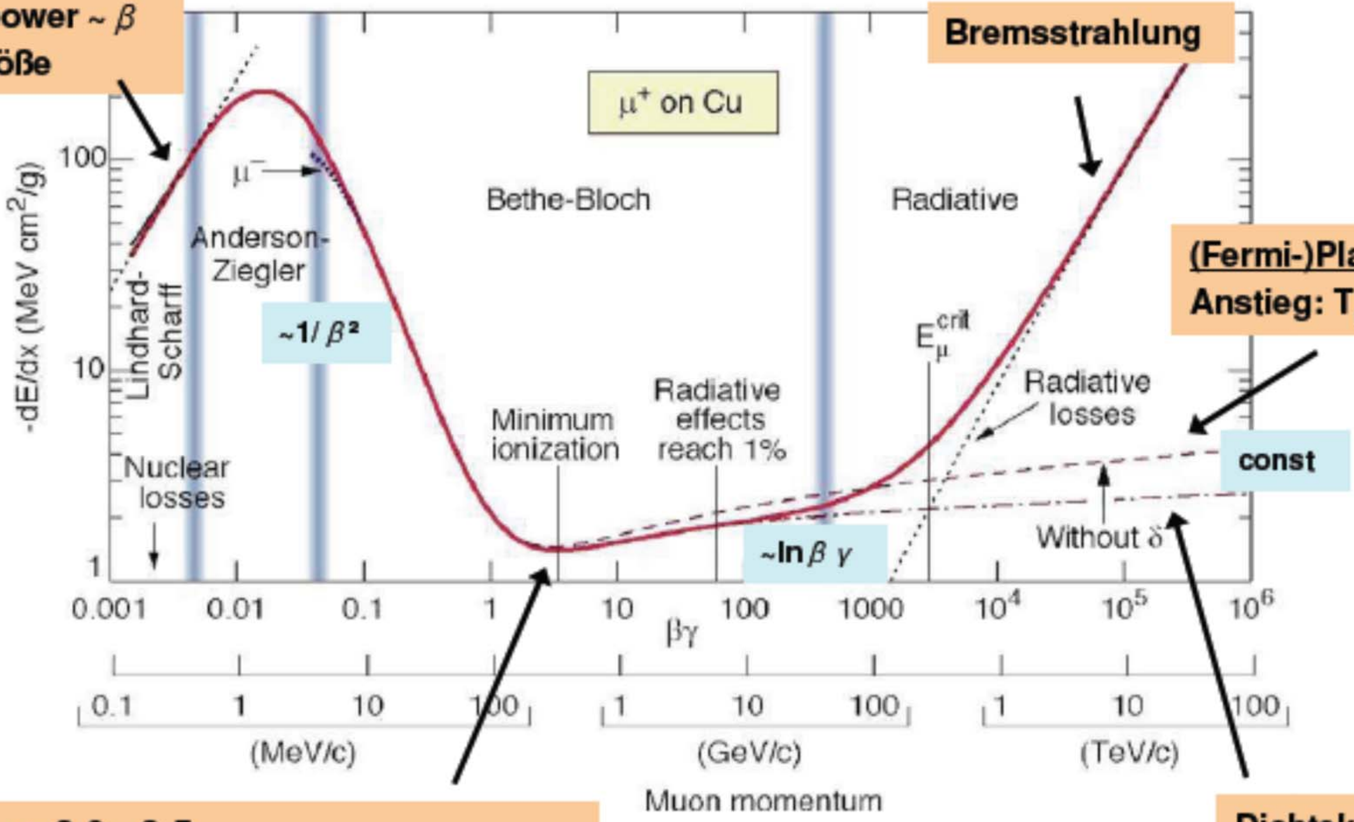
$$-\frac{dE}{dx} = Kz^2\frac{Z}{A}\frac{1}{\beta^2}\left[\frac{1}{2}\ln\frac{2m_ec^2\beta^2\gamma^2T_{\max}}{I^2} - \beta^2 - \frac{\delta}{2}\right]$$ [MeV cm^2 / g]

ze	Charge of incident particle	
I	Mean excitation energy	eV
Z	Atomic number of absorber	
A	Atomic mass of absorber	g mol^{-1}
δ	Density effect correction to ionization energy loss Fermi	
T_{max}	**Maximum E_{kin} transferred to e in a single collision**	
K/A	$4\pi N_A r_e^2 m_e c^2/A$	0.307 075 MeV g^{-1} cm^2 for A = 1 g mol^{-1}
r_e	Classical electron radius $e^2/4\pi\epsilon_0 m_e c^2$	2.817 940 325(28) fm
N_A	Avogadro's number	6.022 1415(10) $\times 10^{23}$ mol^{-1}

Electronic stopping power ~ β
Nicht-ionisierende Stöße

Bremsstrahlung

(Fermi-)Plateau
Anstieg: $T_{max} \sim \beta^2\gamma^2$

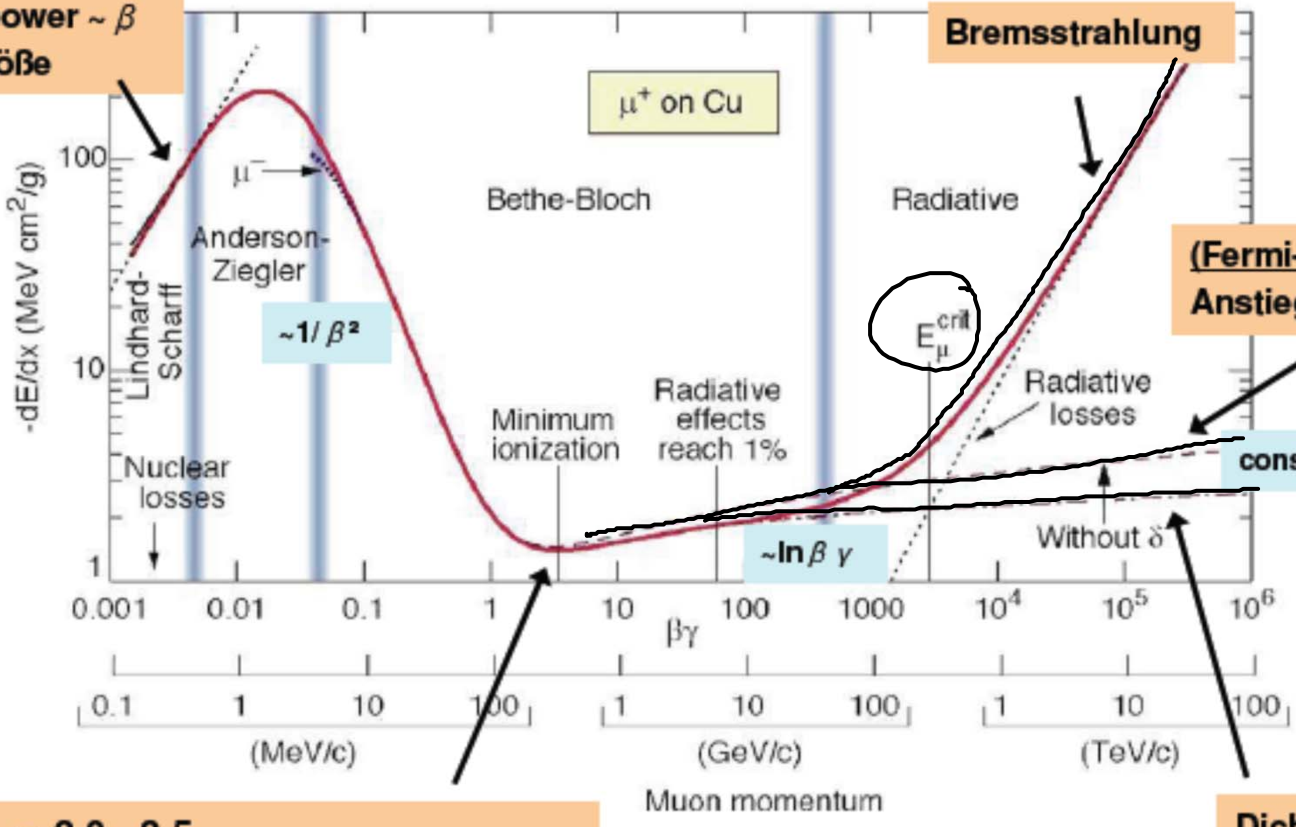


Dichtekorrektur

Minimum bei $\beta\gamma \approx 3.0 - 3.5$
→ Minimum Ionizing Particle (MIP)
Größenordnung am Minimum (für alle Teilchen):
$-dE/dX \approx 2\ MeV/gcm^{-2}$

Electronic stopping power ~ β
Nicht-ionisierende Stöße

Bremsstrahlung



(Fermi-)Plateau
Anstieg: $T_{max} \sim \beta^2\gamma^2$

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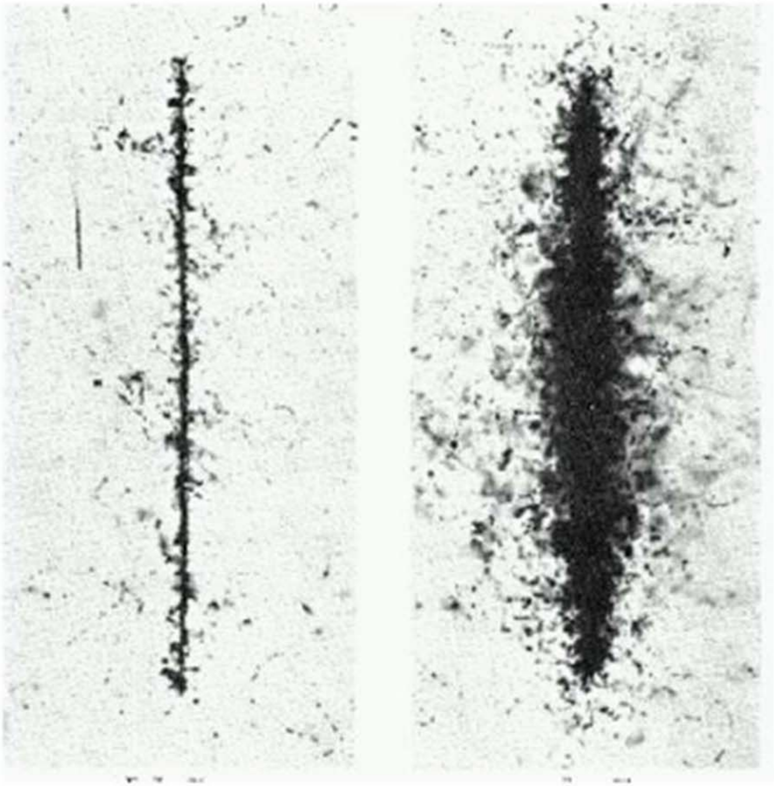
Dichtekorrektur

$$-\frac{dE}{dx} = K z^2 \frac{Z}{A} \frac{1}{\beta^2} \left[\frac{1}{2} \ln \frac{2 m_e c^2 \beta^2 \gamma^2 T_{\max}}{I^2} - \beta^2 - \frac{\delta}{2} \right]$$

Spuren von Ionen in einer Emulsion



Eisen Z = 26 Thorium Z = 90

$\beta\gamma \equiv 3.5$ breites Minimum

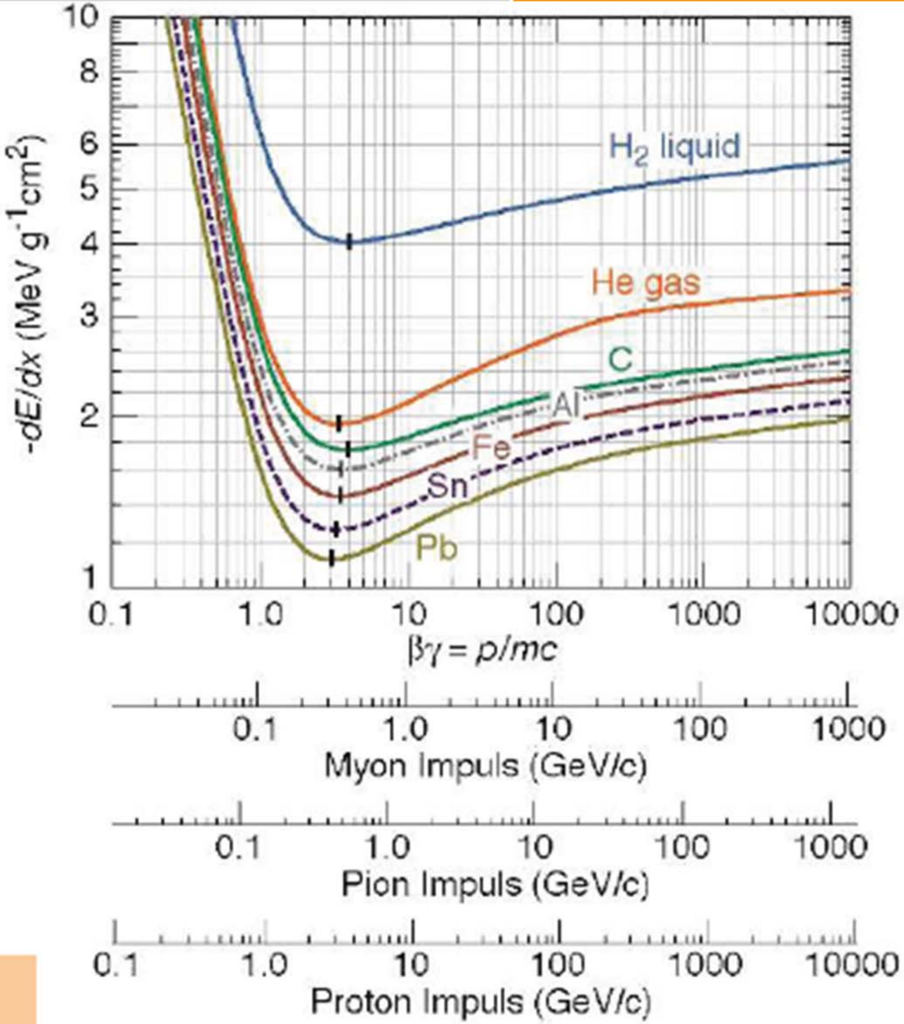
→ minimal ionisierende Teilchen (MIP)

H_2 $Z/A \approx 1$ $dE/dX_{min} \approx 4$ MeV /(g/cm²)

sonst $Z/A \approx 0.5$ $dE/dX_{min} \approx 2$ MeV /(g/cm²)

$dE/dX_{min} \approx 1\text{-}1.7$ MeV /(g/cm²)

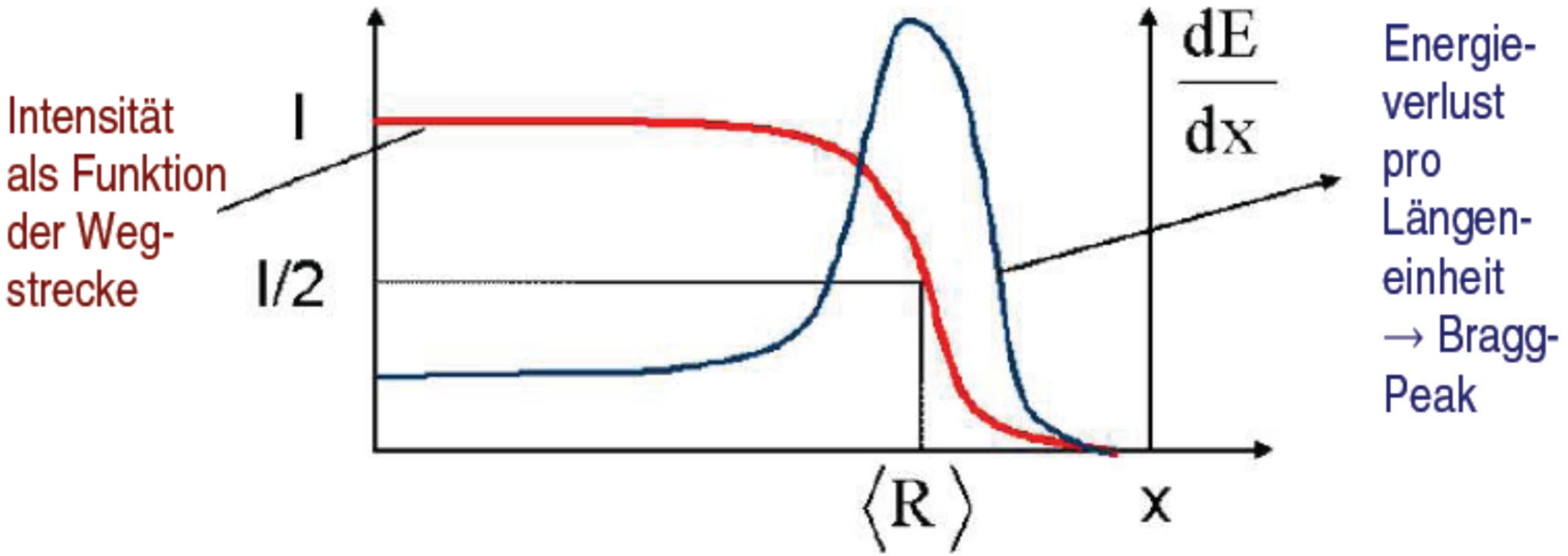
nur schwache Materialabhängigkeit



dE/dx-Kurven für verschiedene Teilchen sind horizontal verschoben um $\ln(M_1/M_2)$

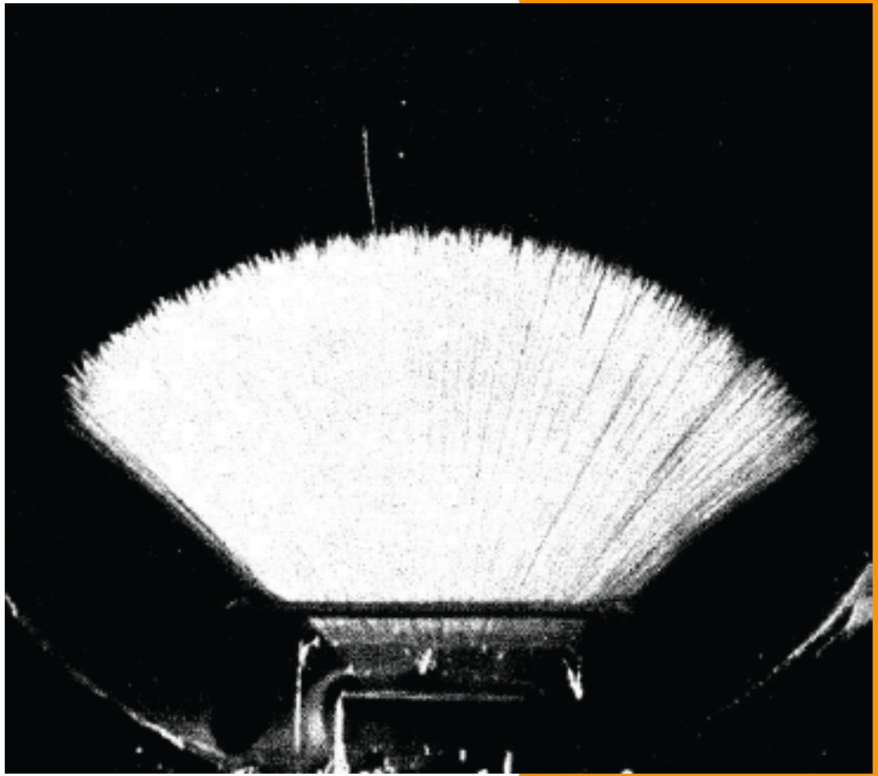
→ Teilchenidentifikation (festes p → verschiedene dE/dx)

BraggKurve und Reichweite



Mittlere Reichweite <R> aus Integration der BBFormel

Spuren von α-Teilchen aus dem Zerfall von Radium in einer Nebelkammer Monoenergetisch, gleiche Reichweite (8.6 cm) Die einzelne längere Spur stammt aus dem Zerfall eines angeregten Kerns



Beispiel 1 GeV Teilchen in Blei

K^+	$M = 493.6$ MeV	$\beta\gamma = 2.02$
	$\rightarrow R/M = 800$ g cm^{-2} GeV^{-1}	
	$R = 395$ g cm^{-2}	
	$ds = R/\rho = 35$ cm in Blei	
Myonen	$R/M = 7000$ g cm^{-2} GeV^{-1}	
	$ds = 64$ cm	
Protonen	$R/m = 220$ g cm^{-2} GeV^{-1}	
	$ds = 18$ cm	

mittlere Reichweite R/M M Projektilmasse