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Radiation environments and their main effects on electronic devices

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Outline

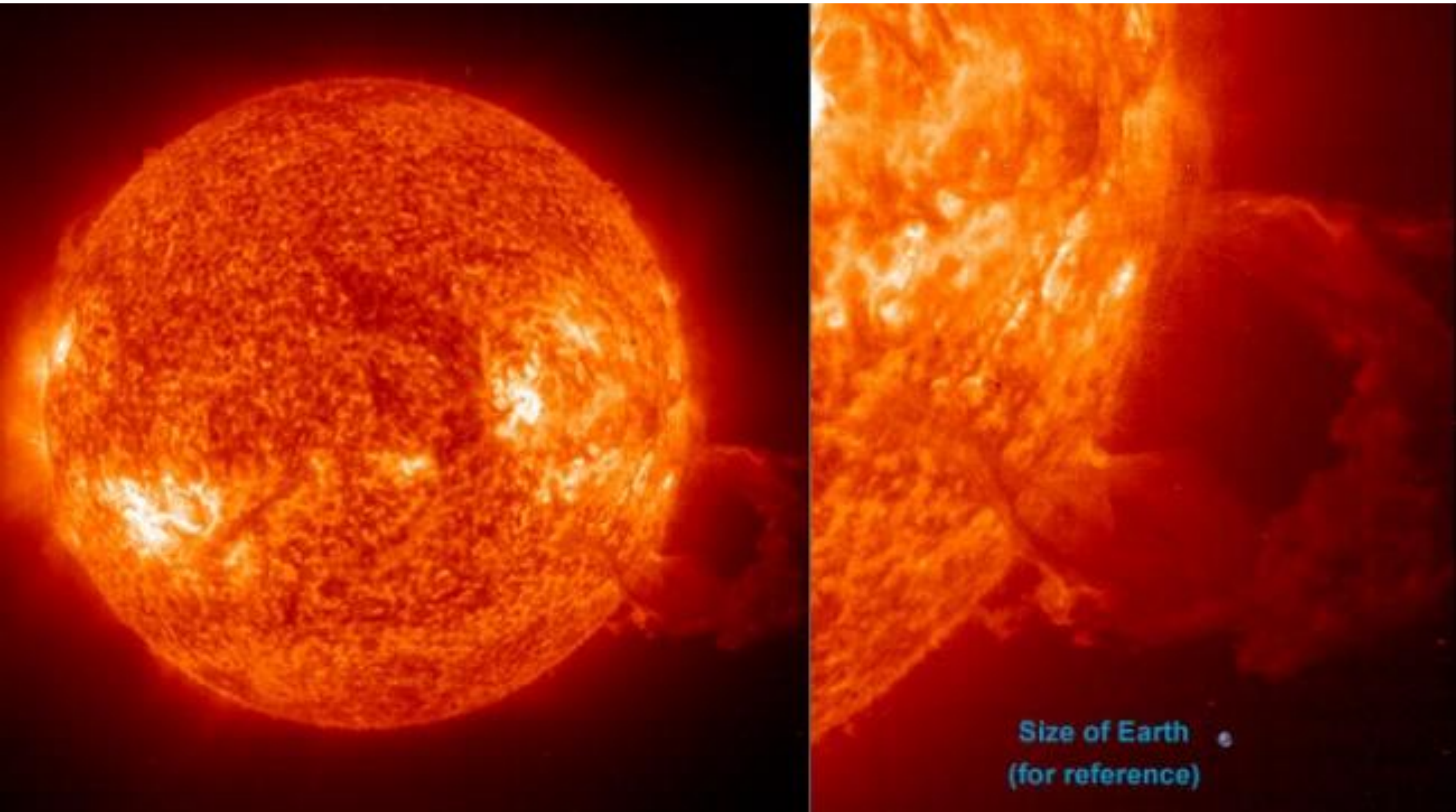
- Particles in Space and in atmosphere
- Useful definitions
- Introduction to particle-matter interaction
- Conclusions

Solar Wind

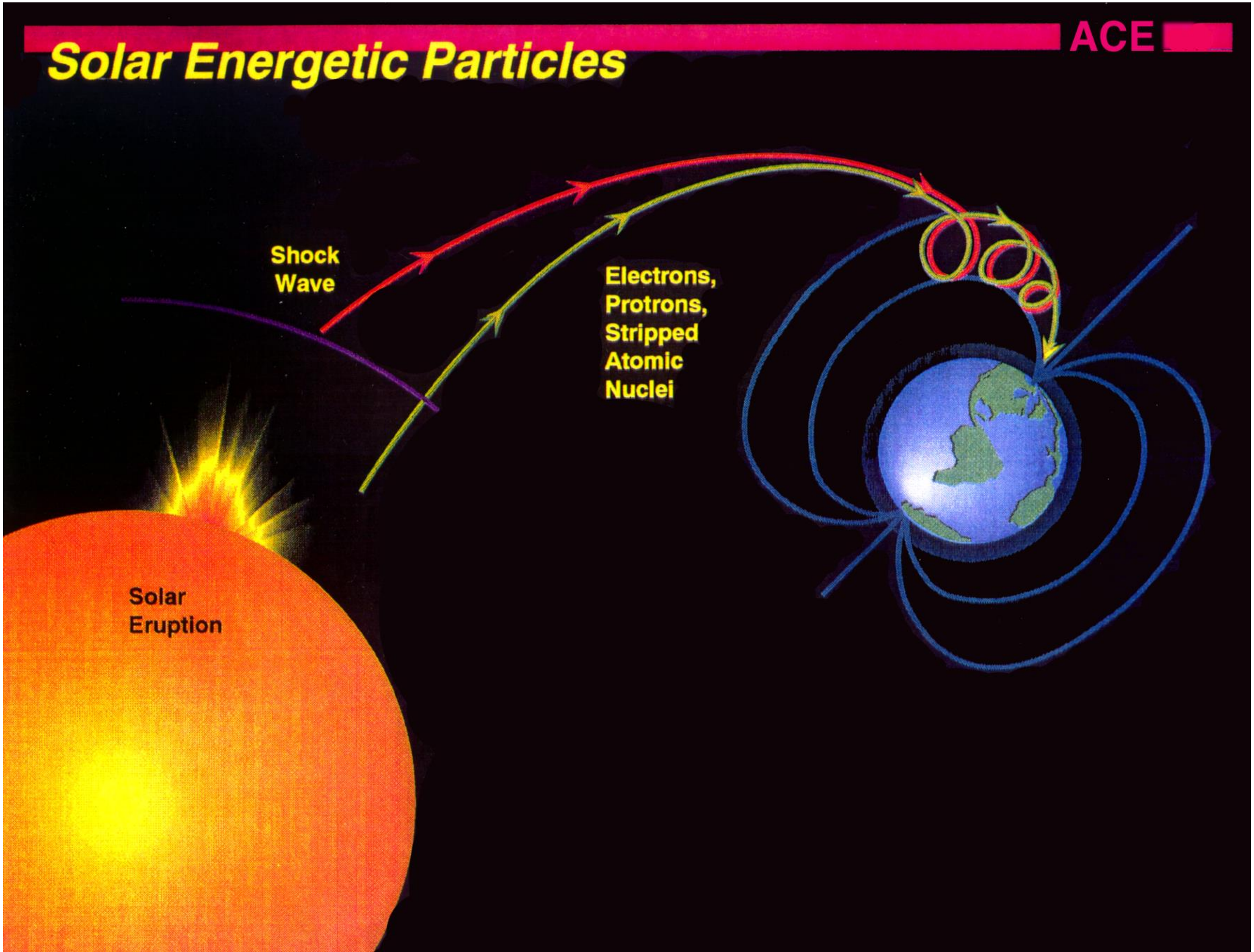

1980 February 16 - white light
High Altitude Observatory/NCAR

Solar flare

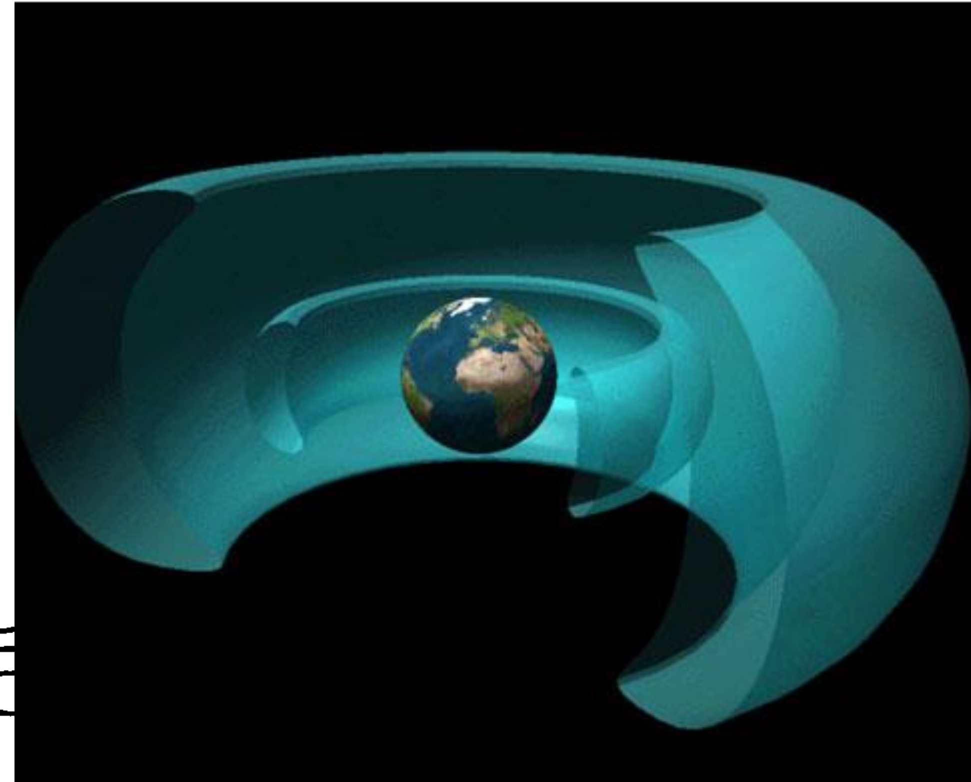
Solar Flare

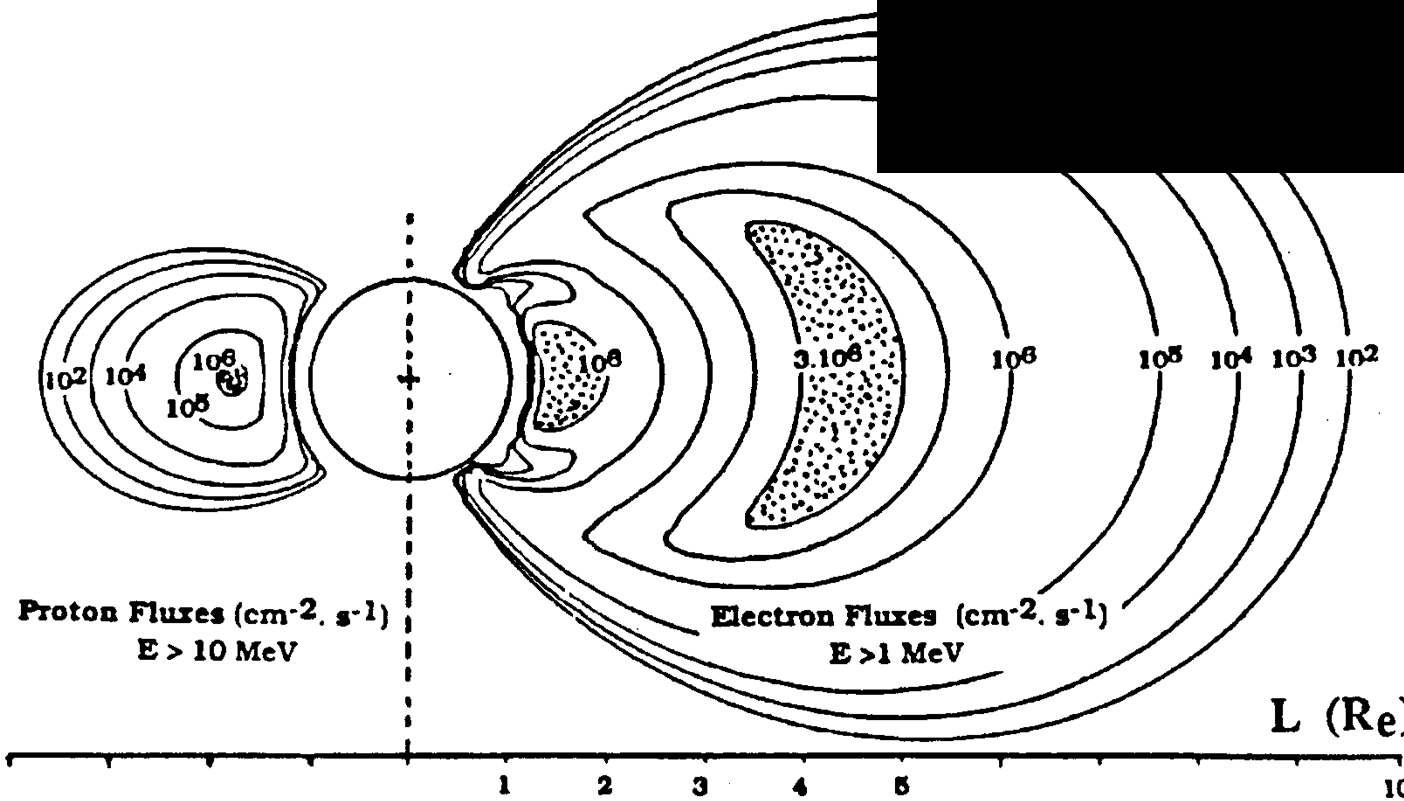


Radiation Belts

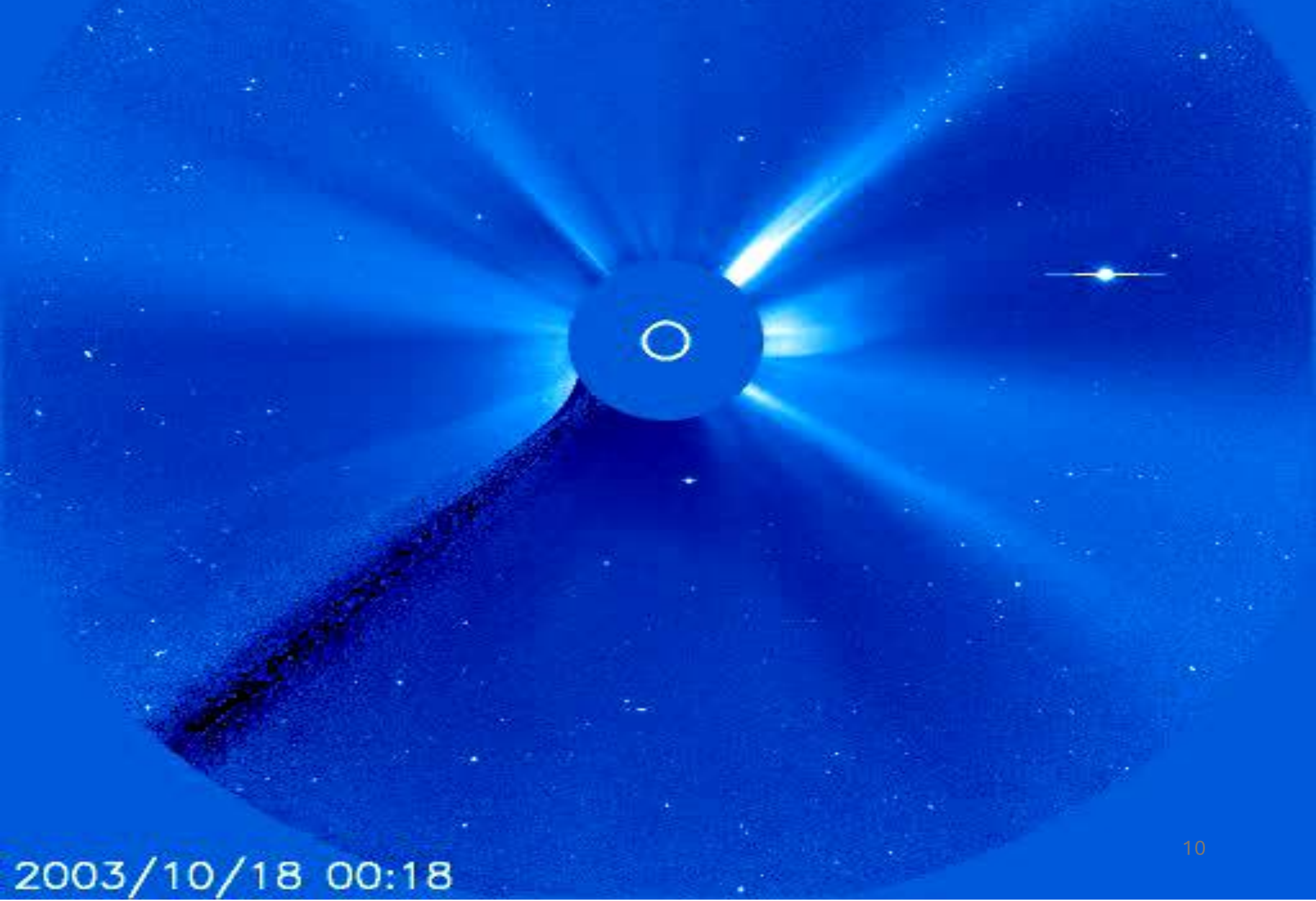


Radiation Belts

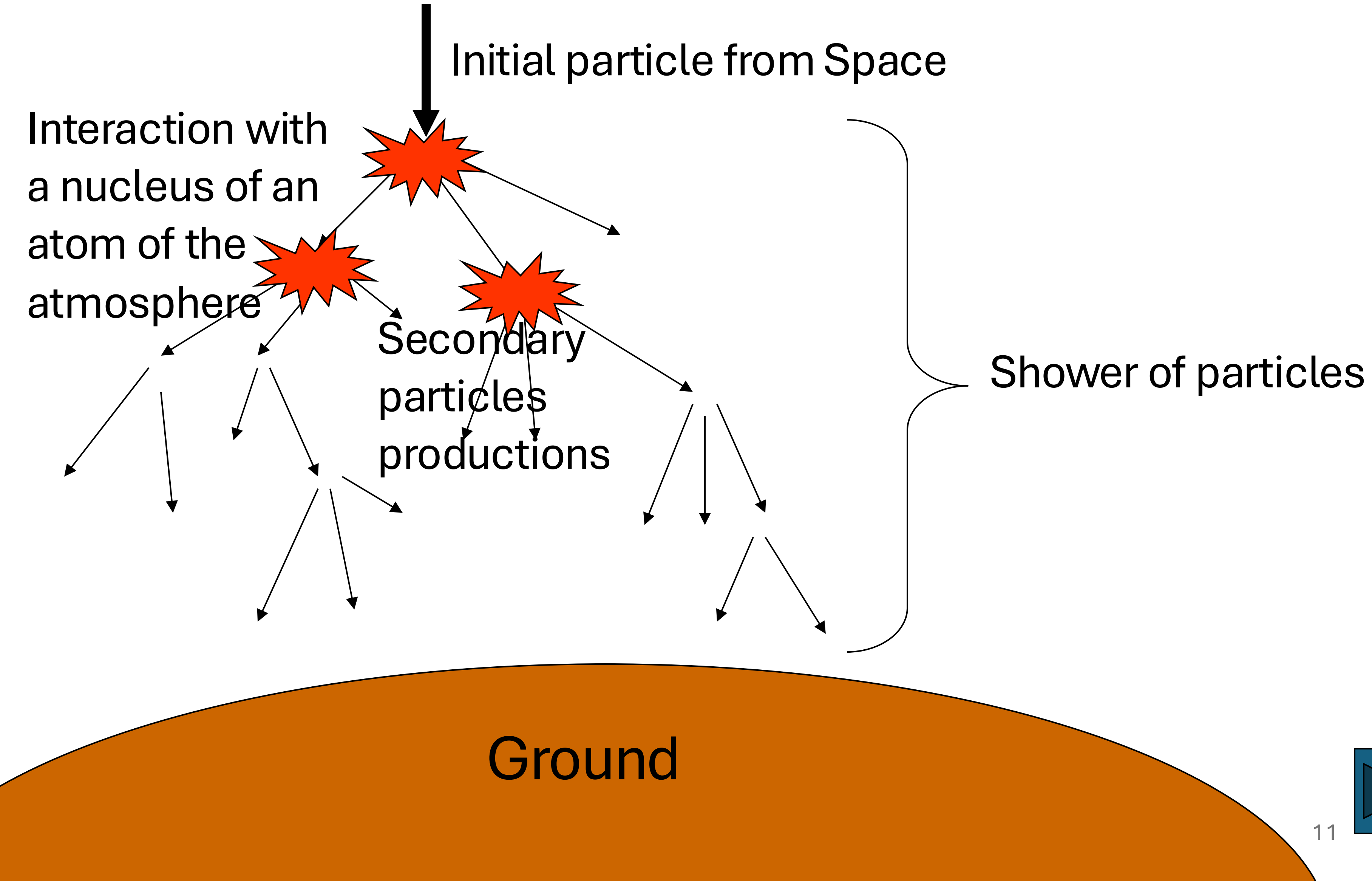


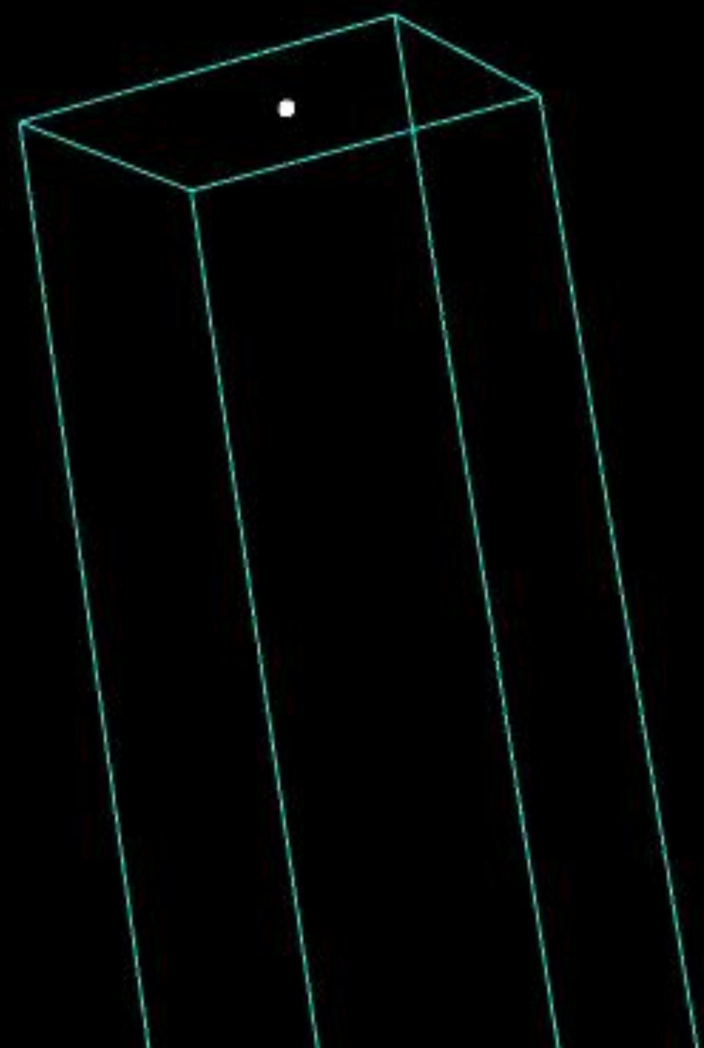


Sun observation with a CCD camera

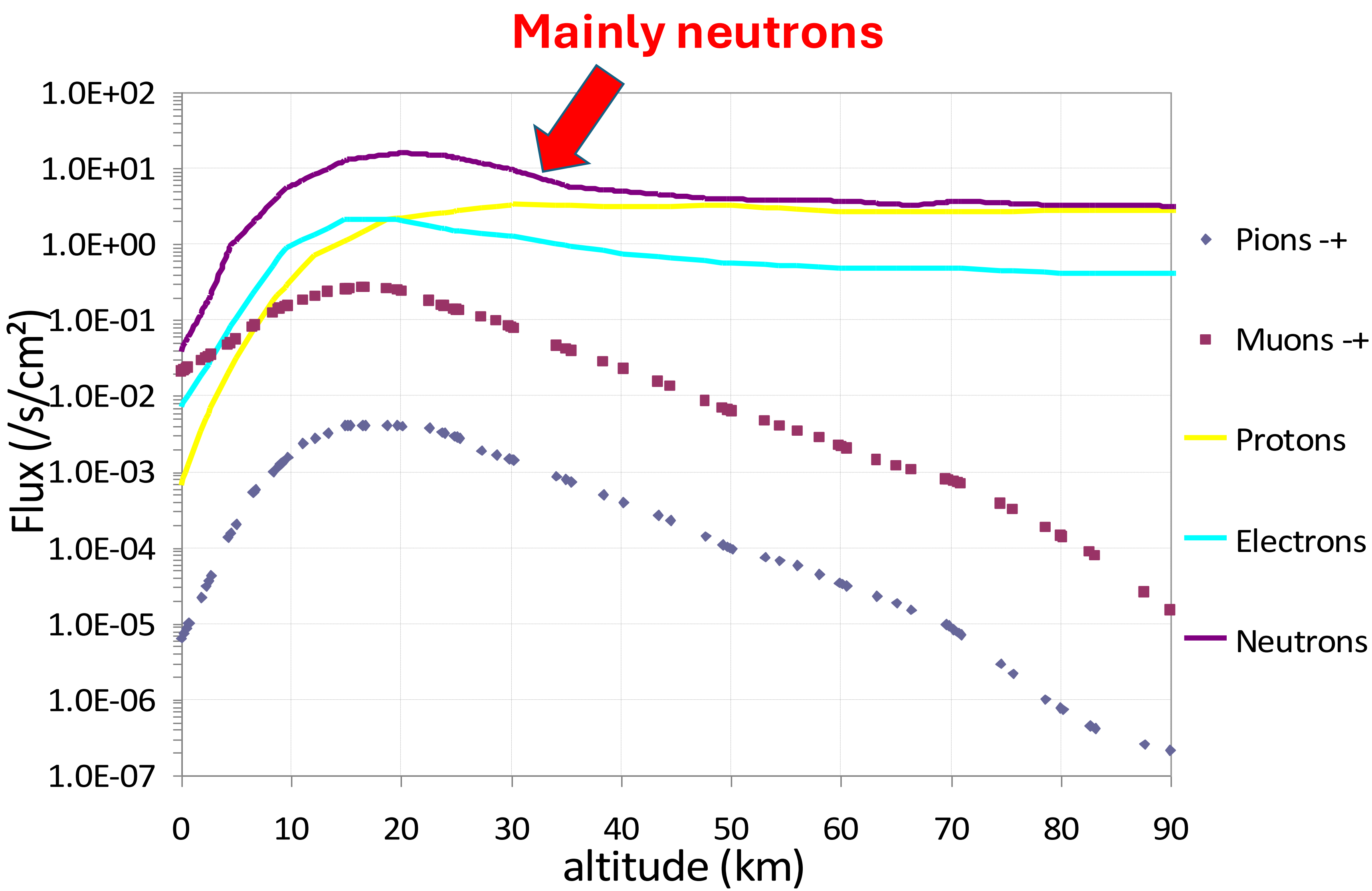


In the Atmosphere



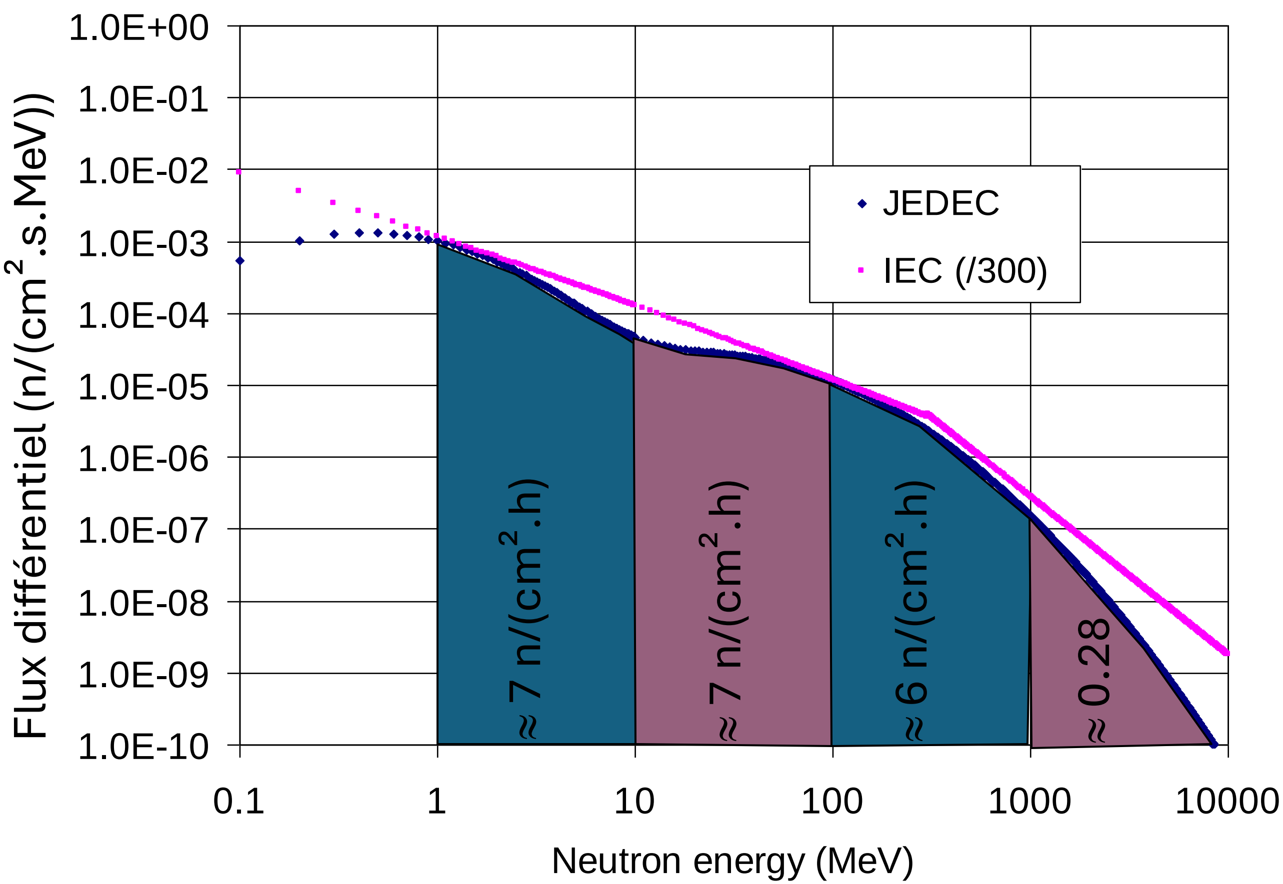


Particle flux in atmosphere



Differential neutron flux in atmosphere

Allows knowing the energy distribution of particles.
Area under the curve represents the particle flux



Around 20 n/(cm^2.h) with energy greather than 1 MeV (after JEDEC).

NB: it actually depends on geolocation and solar activity

Outline

- Particles in Space and in atmosphere
- **Useful definitions**
- Introduction to particle-matter interaction
- Conclusions

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Useful quantities

Energy unit

Flux (fluence rate)

Fluence

Cross section

Soft Error Rate (SER)

Probability of interaction

Mean free path

Stopping Power

Range of a particle

LET-NIEL

Dose

Dose Rate

Energy unit

Two useful units :

- Joule (J)
- electron Volt : **1 eV = 1.6x10^{-19} J**

In silicon, the required energy to produce one electron-hole pair is 3.6 eV.

Therefore, in silicon an energy of 3.6 eV maybe associated to a charge of +/-1.6x10^{-19} C

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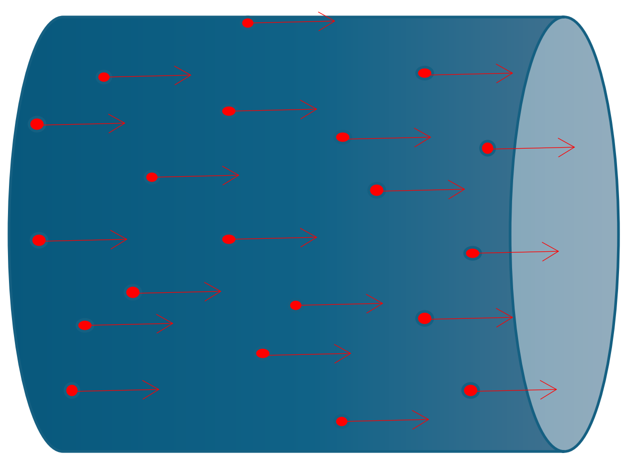
Flux – Fluence Rate



n = density of particles
v = velocity of particles

The Fluence rate $\frac{dF}{dt}$ is defined by: $$\frac{dF}{dt} = n \times v$$

n: /cm^3 ; v: cm/s

Fluence rate is often called flux density or flux.
It is expressed in **cm^{-2}.s^{-1}**

Fluence

Fluence is the integration of Fluence Rate over time:

$$\Phi = \int_0^{t_{irr}} \frac{d\Phi}{dt} dt = \int_0^{t_{irr}} n \times v dt$$

If the fluence rate is constant (which is often the case):

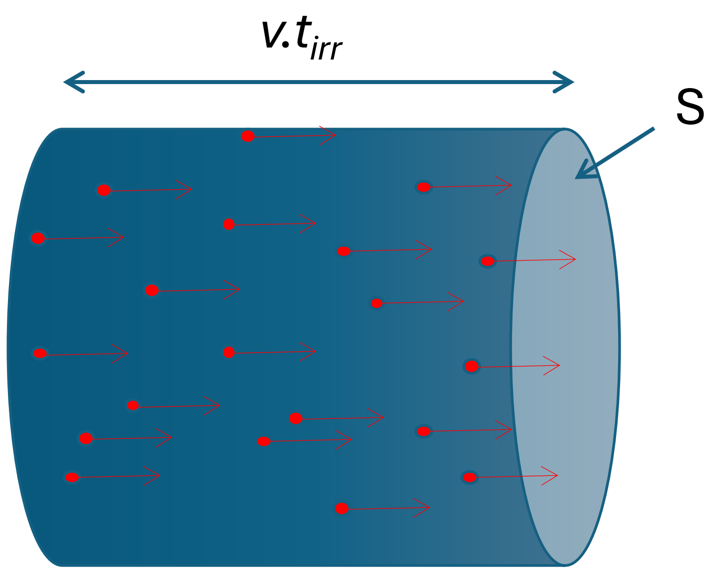
$$\Phi = \frac{d\Phi}{dt} \times t_{irr}$$

/cm^2

Irradiation time

Fluence - Fluence Rate: link with the number of emitted particles

Let us assume that *N* is the number of particles emitted with a velocity *v* and during a time t_{irr}.
At the end of irradiation, all the particles belong to a cylinder of area *S* and length $v.t_{irr}$



The density is thus:

$$n = \frac{N}{S \times v \times t_{irr}}$$

The fluence rate is:

$$\frac{dF}{dt} = n \times v = \frac{N}{S \times t_{irr}}$$

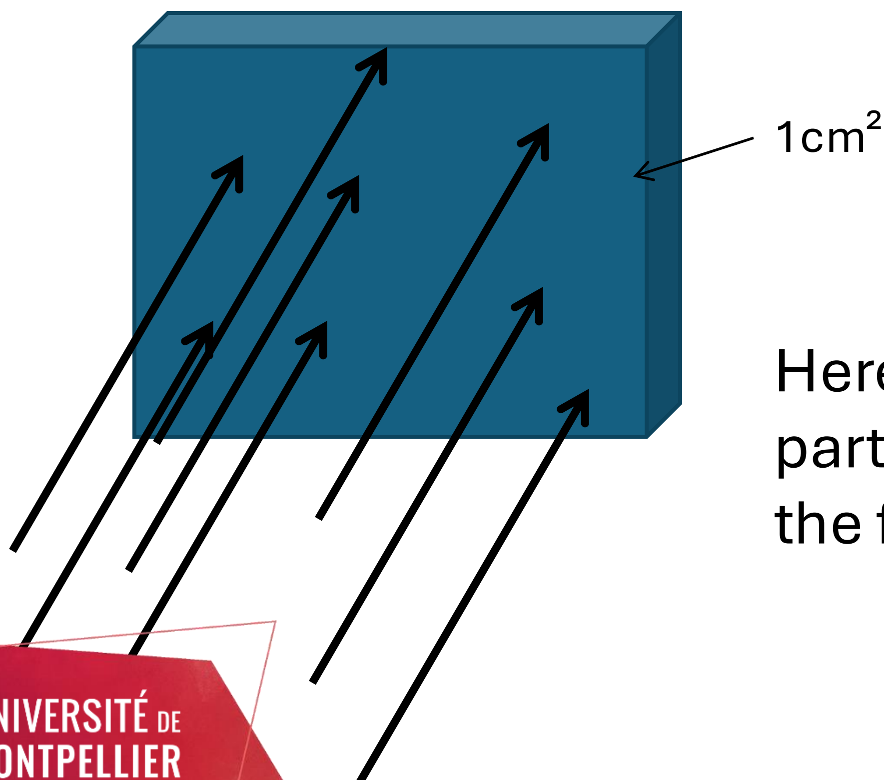
and the rate is: $$F = \frac{dF}{dt} t_{irr} = \frac{N}{S}$$

Finally, the fluence can be seen as the number of particle per area un

Fluence: example

The fluence can be seen as the number of particles per unit of area

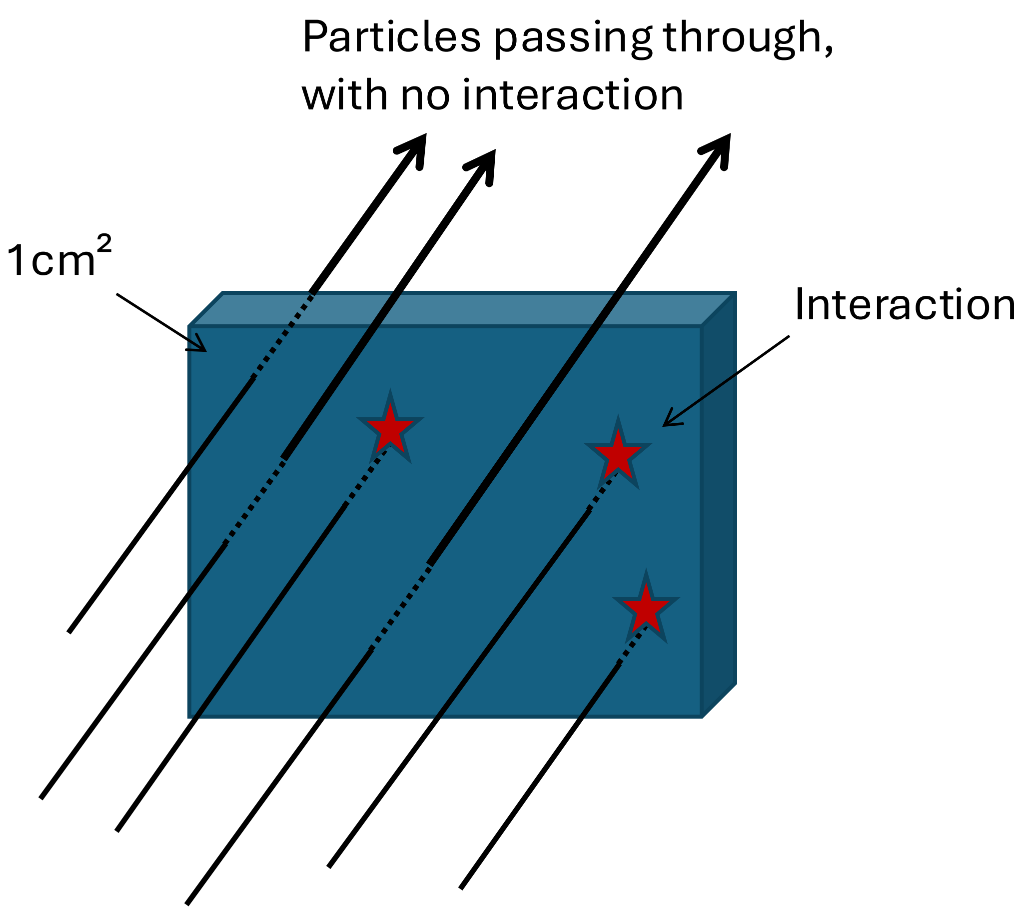
Unit : **part/cm^2**



Here, each arrow being a particle,
the fluence is 8 part/cm^2

Cross section

The concept of **cross section** is used to express the probability of a process (e.g. particle interaction).



6 incident particles
1 cm^2 sample
Fluence = 6 part/cm^2

6 incident particles
3 interactions
1 cm^2 sample
We can consider that only 3/6 of the area sample is efficient :
Interaction cross section = 0.5 cm^2

Cross section

The concept of **cross section** is used to express the probability of a process (e.g. particle interaction).
More generally the cross section is defined by:

$$\sigma = \frac{N}{\Phi}$$

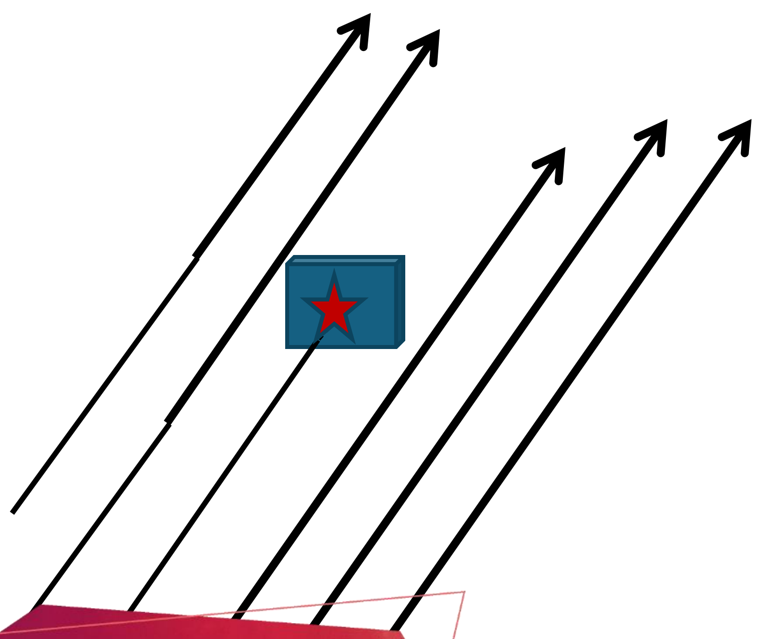
- N: Number of « events »
- σ: Cross section (cm^2)
- Φ: Fluence ($part/cm^2$)

NB: the considered cross section is associated to a given process.
For example :

- particle that interacts
- particle that deposits more than a given energy

Cross section

If we reduce the size of the sample, the cross section obviously decreases



$$\sigma = \frac{N}{\Phi}$$

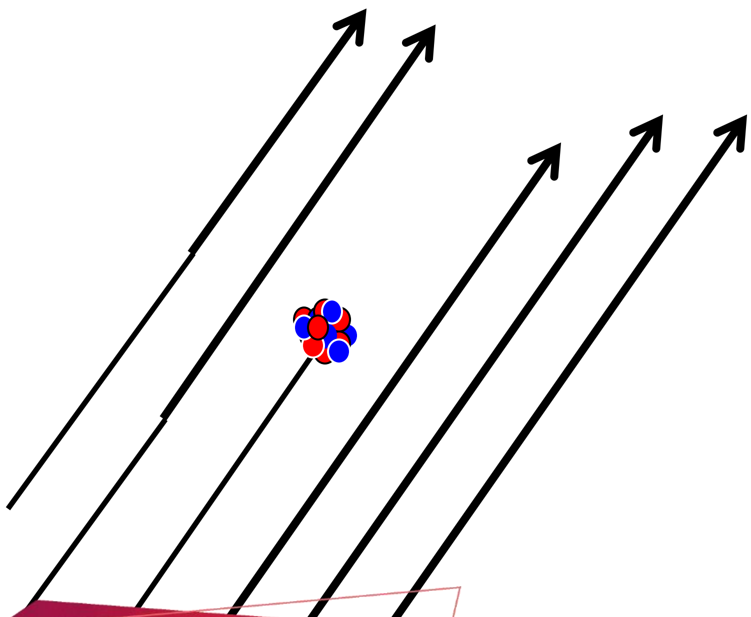
Number of « events »

Cross section (cm^2)

Fluence (part/cm^2)

Cross section

If we reduce the size of the sample, the cross section obviously decreases.
If we reduce the size so that the sample is a unique atom (or nucleus) the obtained cross section is the "microscopic cross section" or "nuclear cross section".
It expresses the probability of interaction between the incident particle and the target nucleus.
As the involved area is small, the unit of barn is useful : **1 barn =10^{-24} cm^2**



$$\sigma = \frac{N}{\Phi}$$

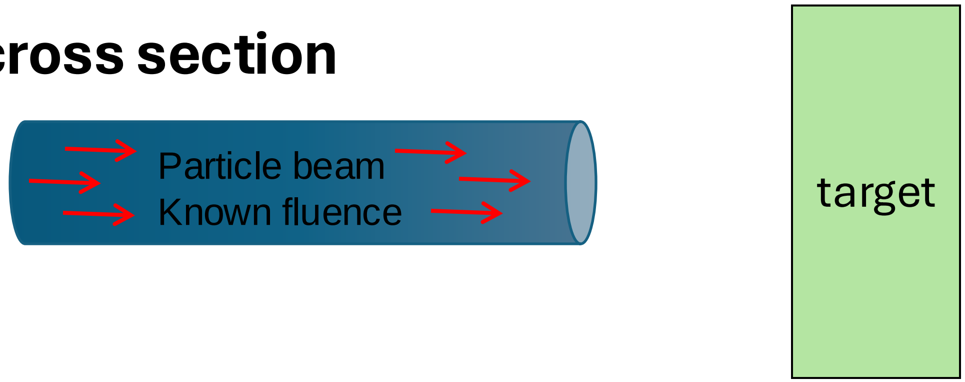
Number of « events »

Cross section (cm^2)

Fluence (part/cm^2)

Cross section: practically

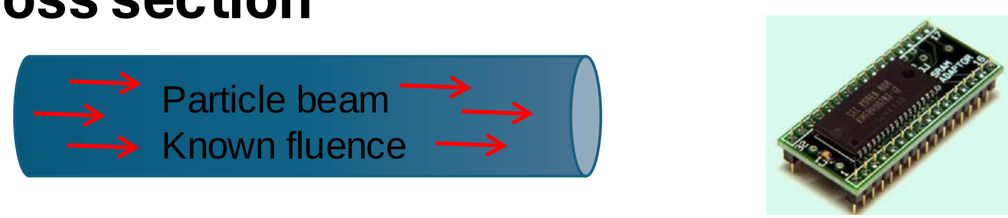
Nuclear cross section



$$\sigma = \frac{N}{\Phi}$$

N = Number of interactions

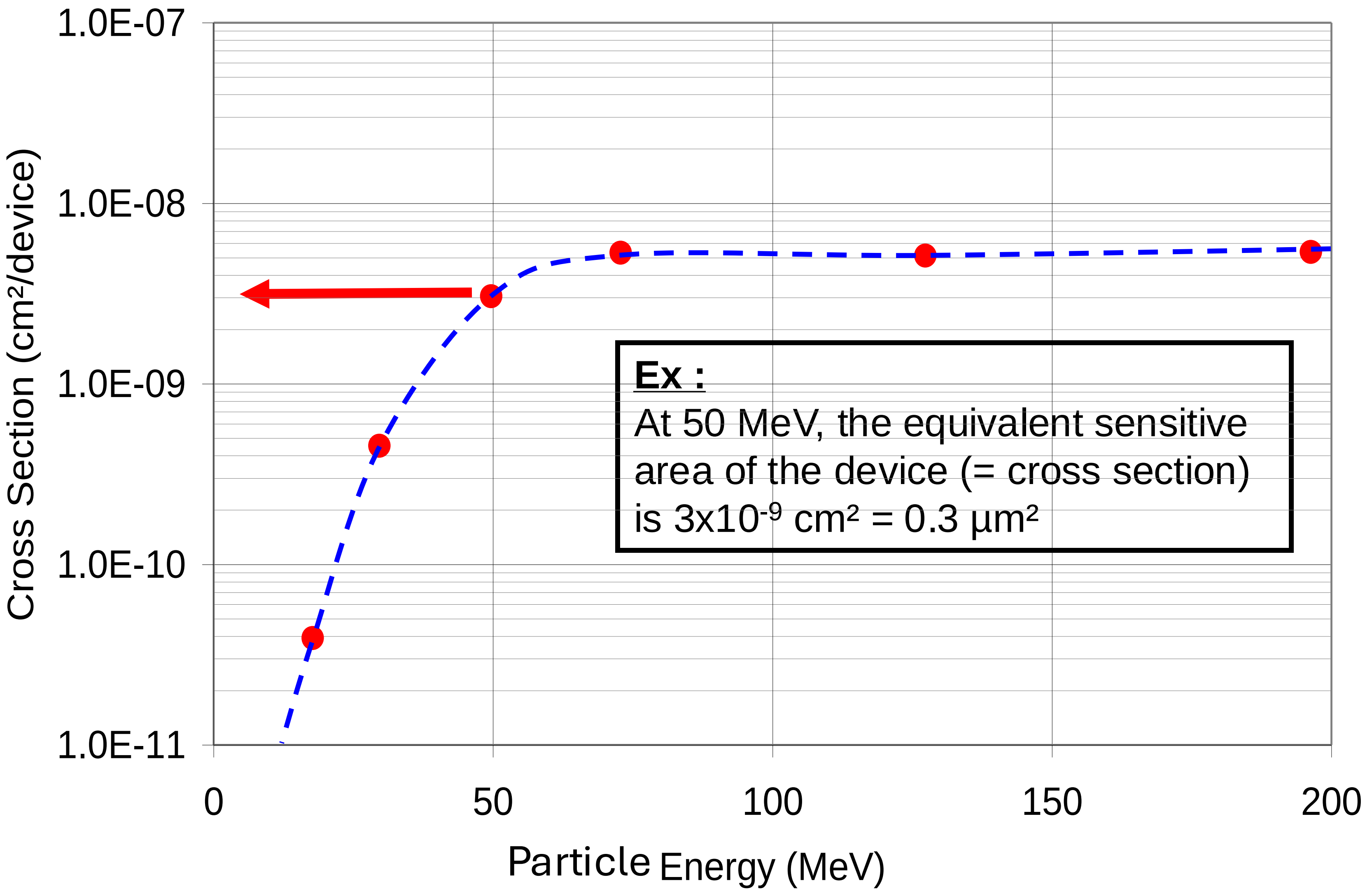
Failure cross section



$$\sigma = \frac{N}{\Phi}$$

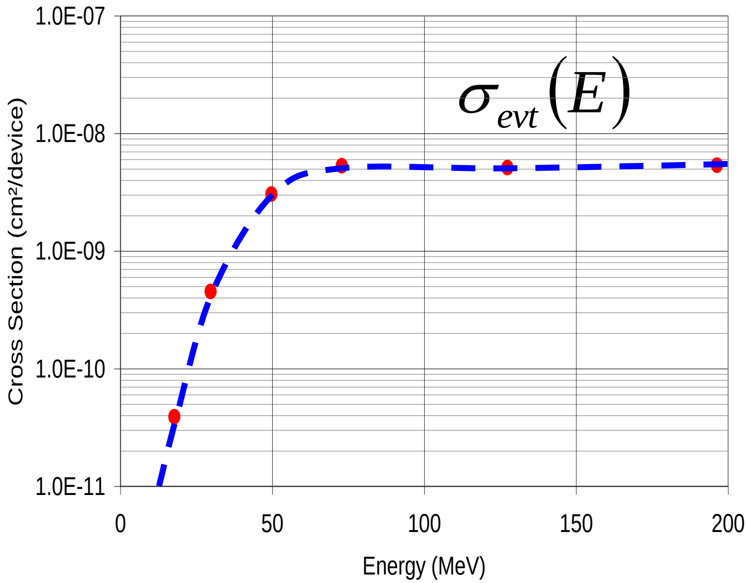
N = Number of failures

Electronics under beam

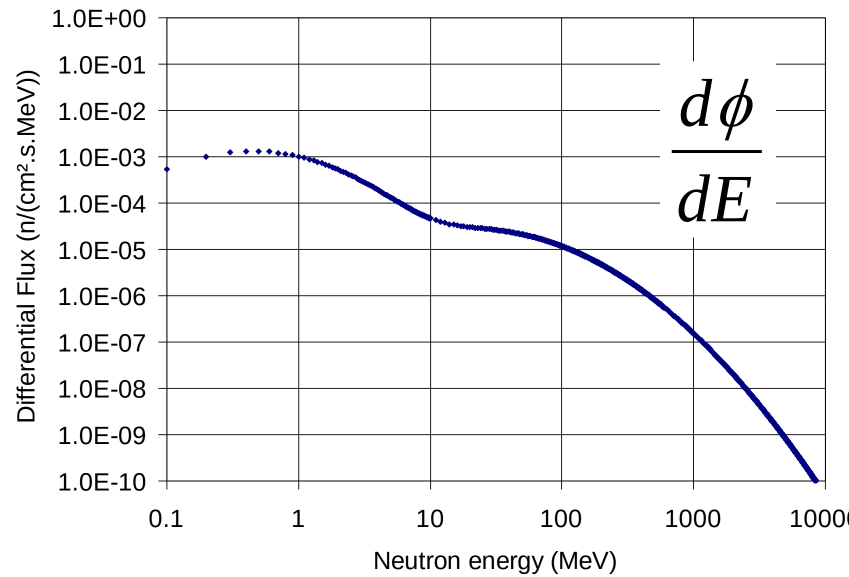


Soft Error Rate (SER)

Device



Environment



$$SER = \int \frac{d\phi}{dE} \cdot \sigma_{evt}(E)\, dE$$

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Soft Error Rate (SER)

$$SER = \int \frac{d\varphi}{dE} \cdot \sigma_{evt}(E)\, dE$$

<u>Unit :</u> events per unit of time

- **<u>Avionic applications (IEC) :</u>**

  Events per hour

- **<u>Ground level applications (JEDEC) :</u>**

  Event/10^9 hours (≈ events/100 000 years)

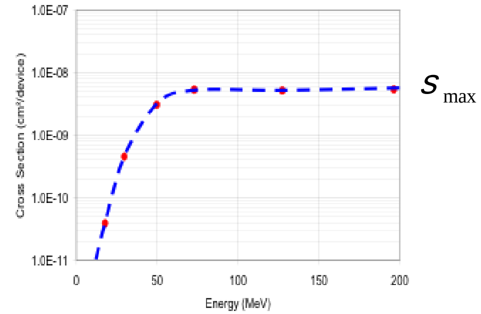
  This is called FIT (Failure In Time)

1 FIT = 1 event /1 billion of hours

Example of quick calculations

Device under beam

$$SER = \int \frac{d\varphi}{dE} \cdot \sigma_{evt}(E)\, dE$$



$$SER < \int \frac{d\varphi}{dE} \cdot \sigma_{\max}\, dE = \sigma_{\max} \int \frac{d\varphi}{dE} dE = \sigma_{\max} \times \varphi$$

$5x10^{-14}$ cm²/bit 12 000 n/cm²/heure

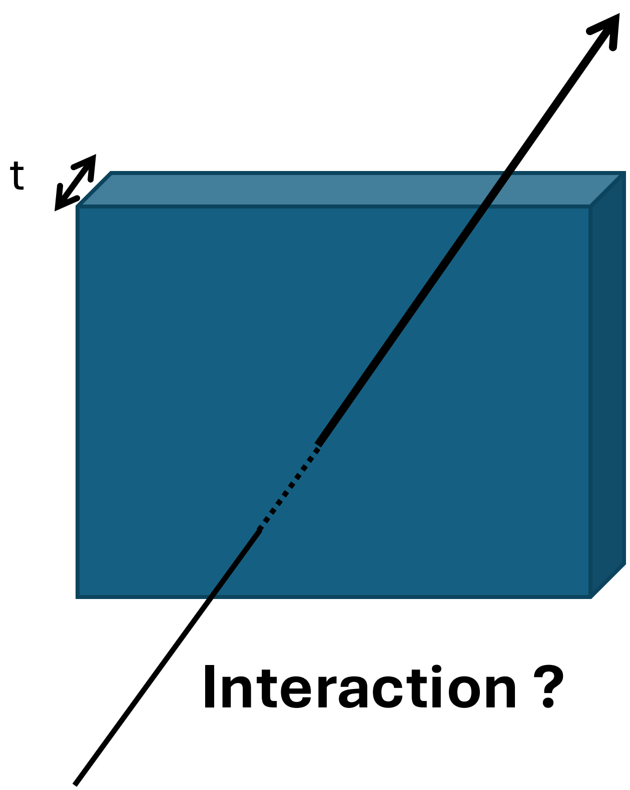
SER < $6x10^{-10}$ SEU/bit/hour

SER < 0.6 SEU/bit/billion of hours

SER < 630 000 FIT/MBit

Probability of interaction

Knowing the interaction cross section σ, it is easily possible to calculate the probability for a **single** incident particle to interact in a foil of thickness *t* and with N_{at} atoms/cm³:



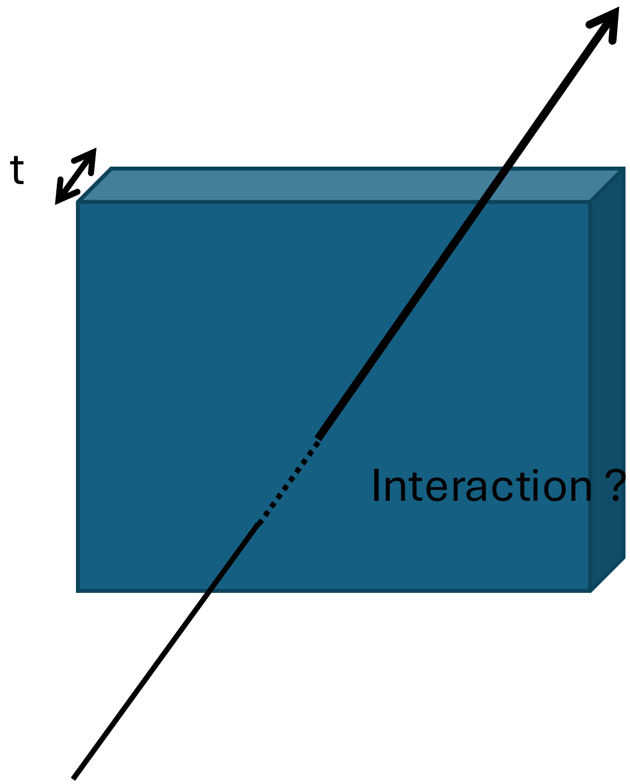
Probability of non-interaction

$$P_{trans} = e^{-N_{at}\sigma t}$$

Probability of interaction

$$P_{\text{int}} = 1 - e^{-N_{at}\sigma t}$$

Absorption coefficient



The probability of transmission for a particle is:

$$P_{trans} = 1 - P = e^{-N_{at}\sigma t}$$

If N_0 is the number of incident particles, the number of transmitted particles is:

$$N_{trans} = N_0 e^{-N_{at}\sigma t}$$

which is called the BEER law

$N_{at}\sigma$ is called the absorption coefficient (unit: **cm^{-1}**)

Mean free path

We have seen that the probability of interaction is given by:

$$P_{\text{int}} = 1 - e^{-N_{at}\sigma t}$$

The mean free path is defined by:

$$\boxed{\lambda = \frac{1}{N_{at}\sigma}}$$

It expresses the typical range of particle before interacting

Unit : generally **cm**

If the particle travels a distance equal to λ it has a probability of interaction which is:

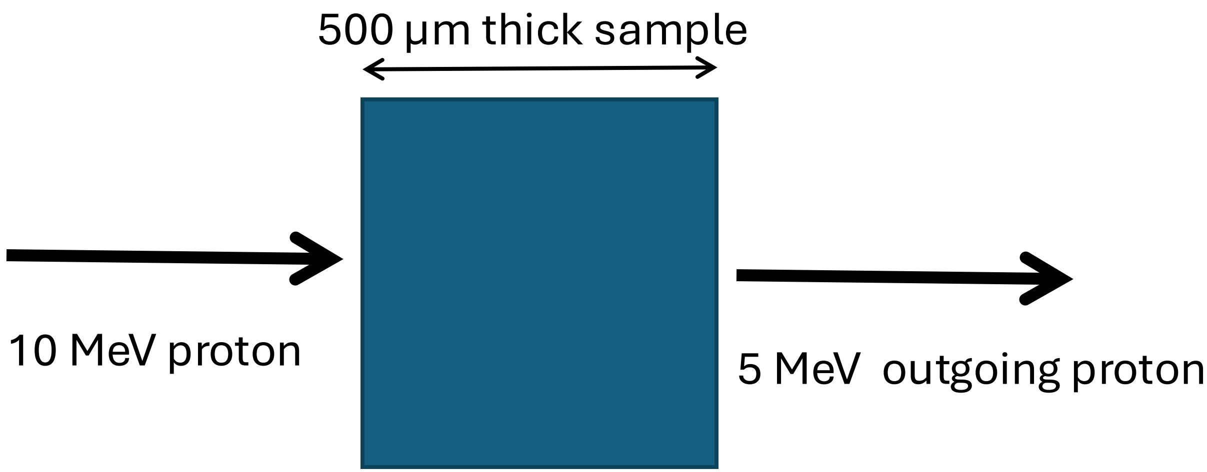
$$P(\lambda) = 1 - e^{-N_{at}\sigma\lambda} = 1 - e^{-1} = 0.63$$

Stopping Power

The stopping power is defined as the energy loss of a particle per unit of length:

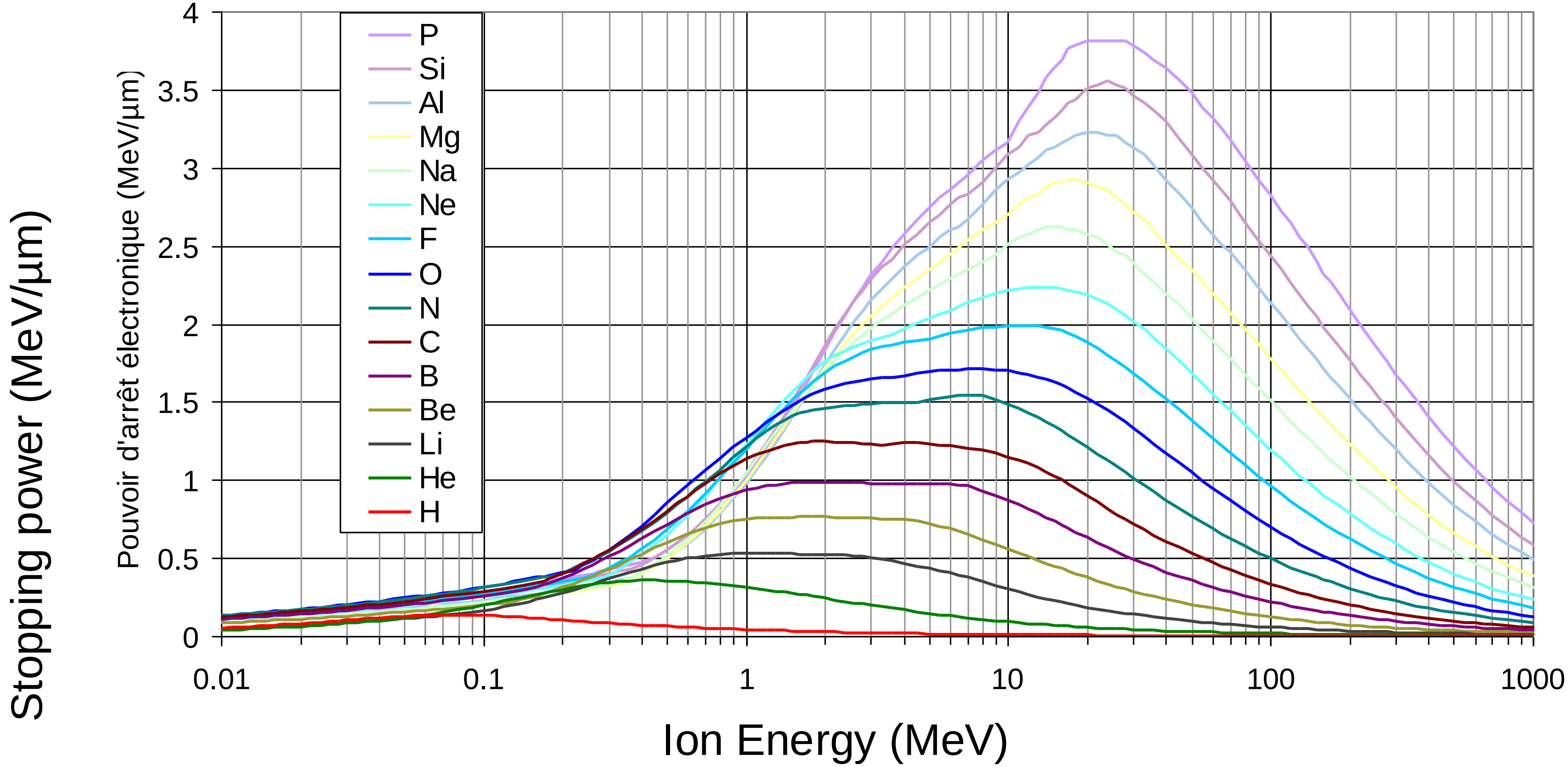
$$S = Stopping\ power = -\frac{dE}{dx} > 0$$

Natural unit: **MeV/cm** or **MeV/µm**



$$Mean\ stopping\ power = \frac{-\Delta E}{t} = \frac{-(5-10)MeV}{500\ \mu m} = 10keV/\mu m$$

Example: stopping power of ions in silicon



SRIM code by J. Ziegler

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Stopping power: unit

- Natural unit: **MeV/cm** or **MeV/µm**
- In order to have a stopping power which does not depend on the material state (gas, solid, liquid), it is useful to divide the « natural » stopping power by the volumic mass:

$$\textit{Stopping power} = -\frac{1}{r}\frac{dE}{dx} > 0$$

in mg/cm^3

- Therefore, the stopping power is often expressed in **$MeV.cm^2/mg$**
- NB: the volumic mass for silicon is $\rho = 2.32\ g/cm^3$

Range of a particle

The range of a particle is simply the distance travelled by the particle before being stopped:

$$R = \int_0^R dx = \int_E^0 \frac{dx}{dE} dE = \int_E^0 \frac{1}{\frac{dE}{dx}} dE = \int_0^E \frac{1}{-\frac{dE}{dx}} dE = \int_0^E \frac{1}{S} dE$$

$$R = \int_0^E \frac{1}{Stopping\ power} dE$$

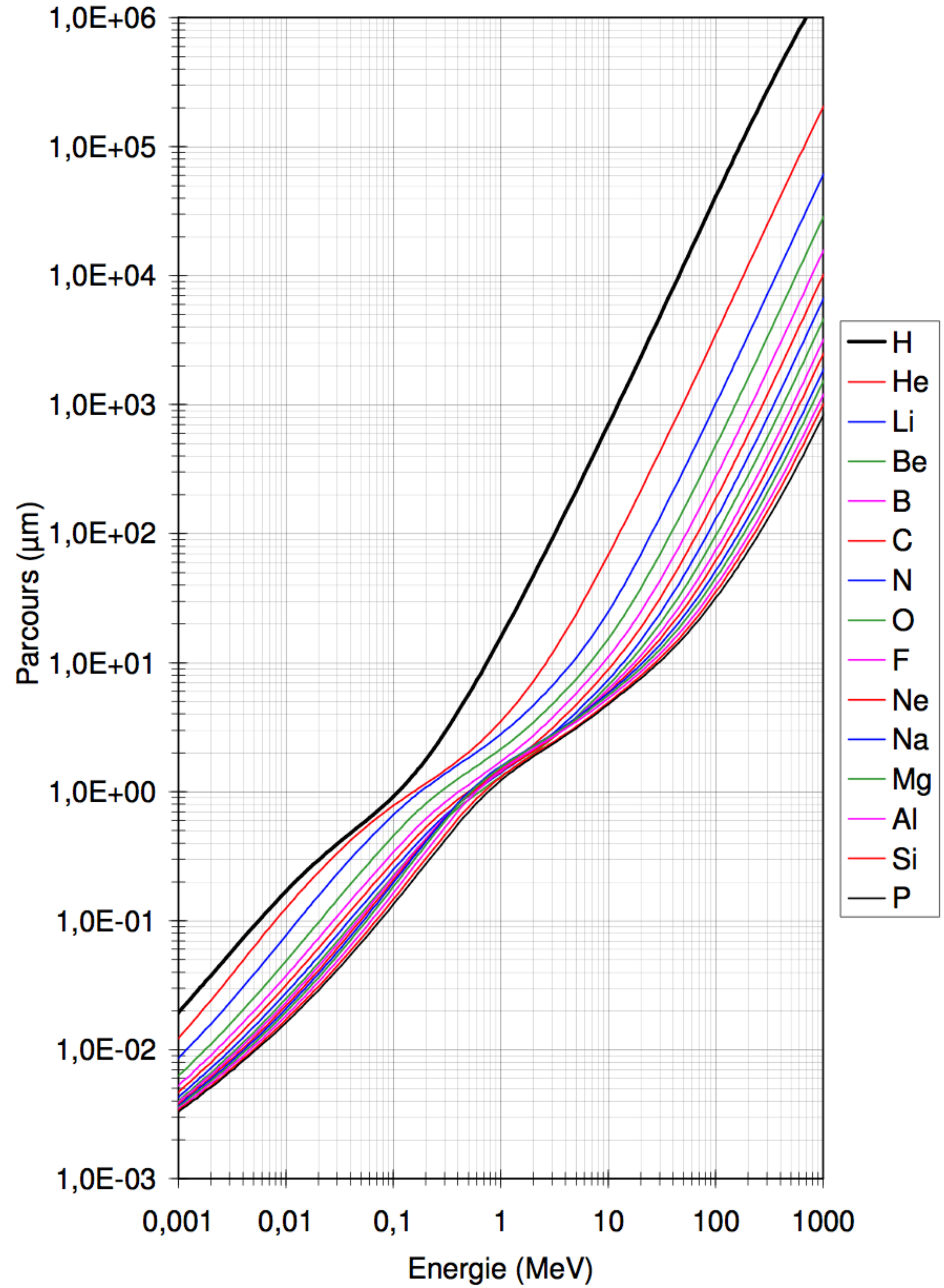
in MeV/cm or MeV/µm

in **cm** or **µm**

Range of light ions in silicon

The range is the distance of a particle before being stopped.

Generally expressed in **cm** or **µm**



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LET-NIEL

Particles loose their energy by interacting either with electrons of atoms (ionization) or with nucleus of atom.
The stopping power can thus be written:

$$Stopping\ power = \left(-\frac{dE}{dx}\right)_{electron} + \left(-\frac{dE}{dx}\right)_{nuclear}$$

$$\left(-\frac{dE}{dx}\right)_{nuclear} = \left(-\frac{dE}{dx}\right)_{vibration} + \left(-\frac{dE}{dx}\right)_{displacement}$$

LET-NIEL

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$$\left(-\frac{dE}{dx}\right)_{nuclear} = \left(-\frac{dE}{dx}\right)_{vibration} + \left(-\frac{dE}{dx}\right)_{displacement}$$

Called Linear Energy Transfer or LET
Unit: MeV.cm²/mg

Called Non Ionizing Energy Loss or NIEL
Unit: MeV.cm²/mg

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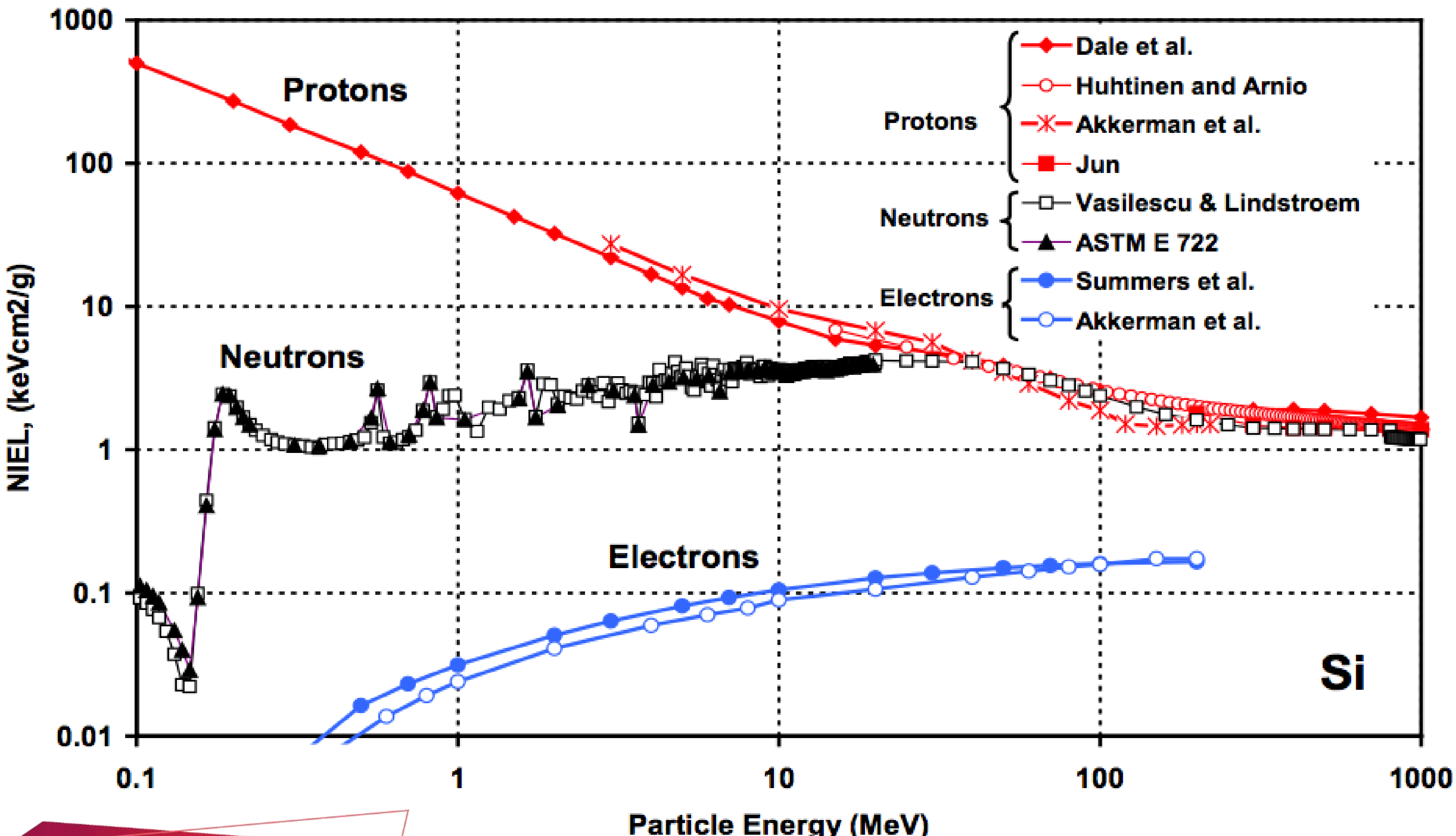
NIEL in Silicon



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Dose

Absorbed dose is used for purposes of radiation protection and assessing dose or risk to humans and materials in general terms.

Absorbed dose is the amount of radiation absorbed in a material.

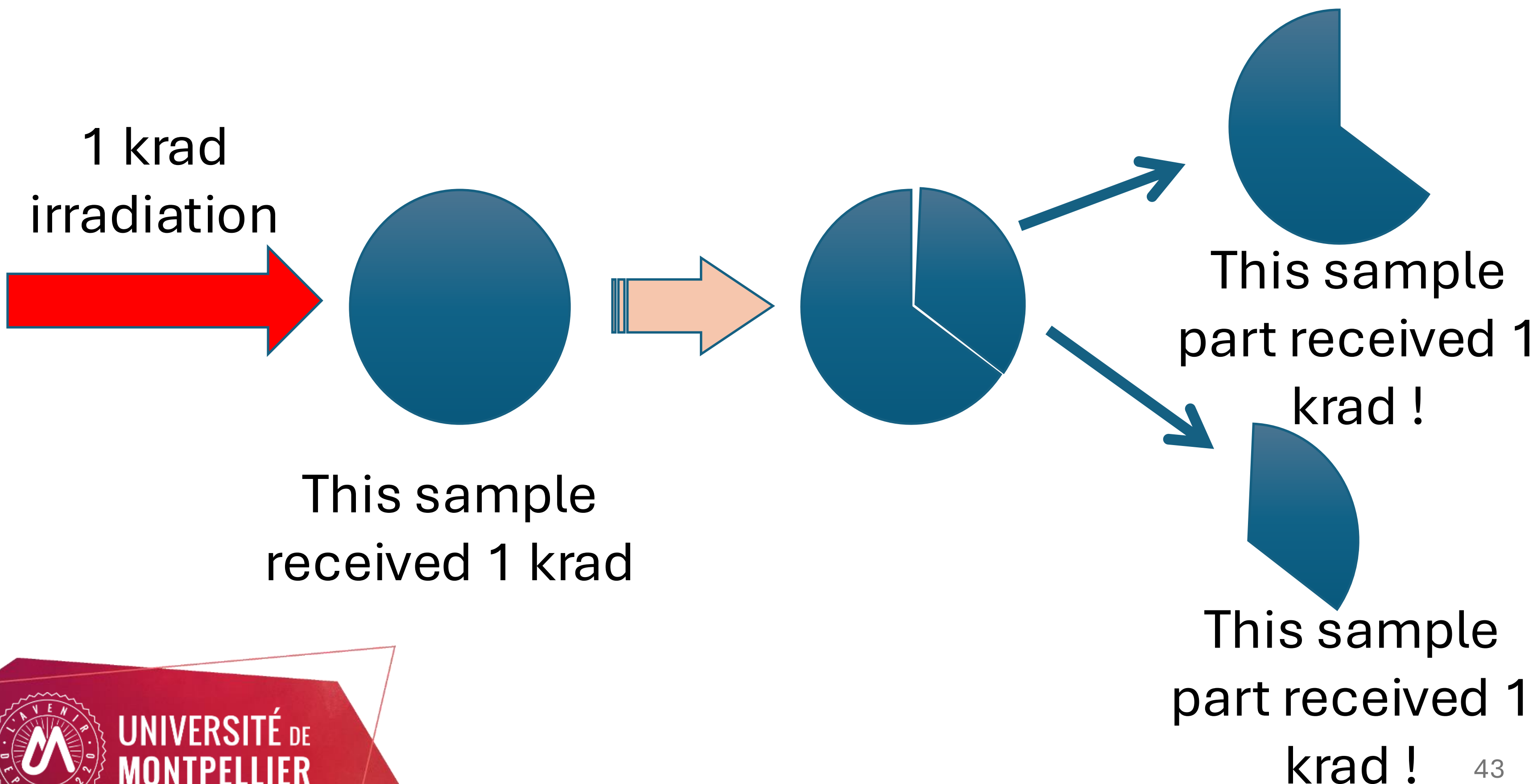
Absorbed dose is usually defined as energy deposited (joule) per unit of mass (kilogram).

Special unit: **1 Gy =1 J/kg**

In the radiation effect community the unit of **rad** is used.
1 Gy=100 rad

Dose

Dose is an intensive property (like temperature)



Dose Rate

- A dose of 1 krad has not the same effect on a device if it is deposited in a short time or a long time.
- The dose rate allows quantifying the rate at which the dose is deposited:

$$\dot{D} = \frac{dD}{dt}$$

- Expressed for example in **krad/h** or **rad/s**

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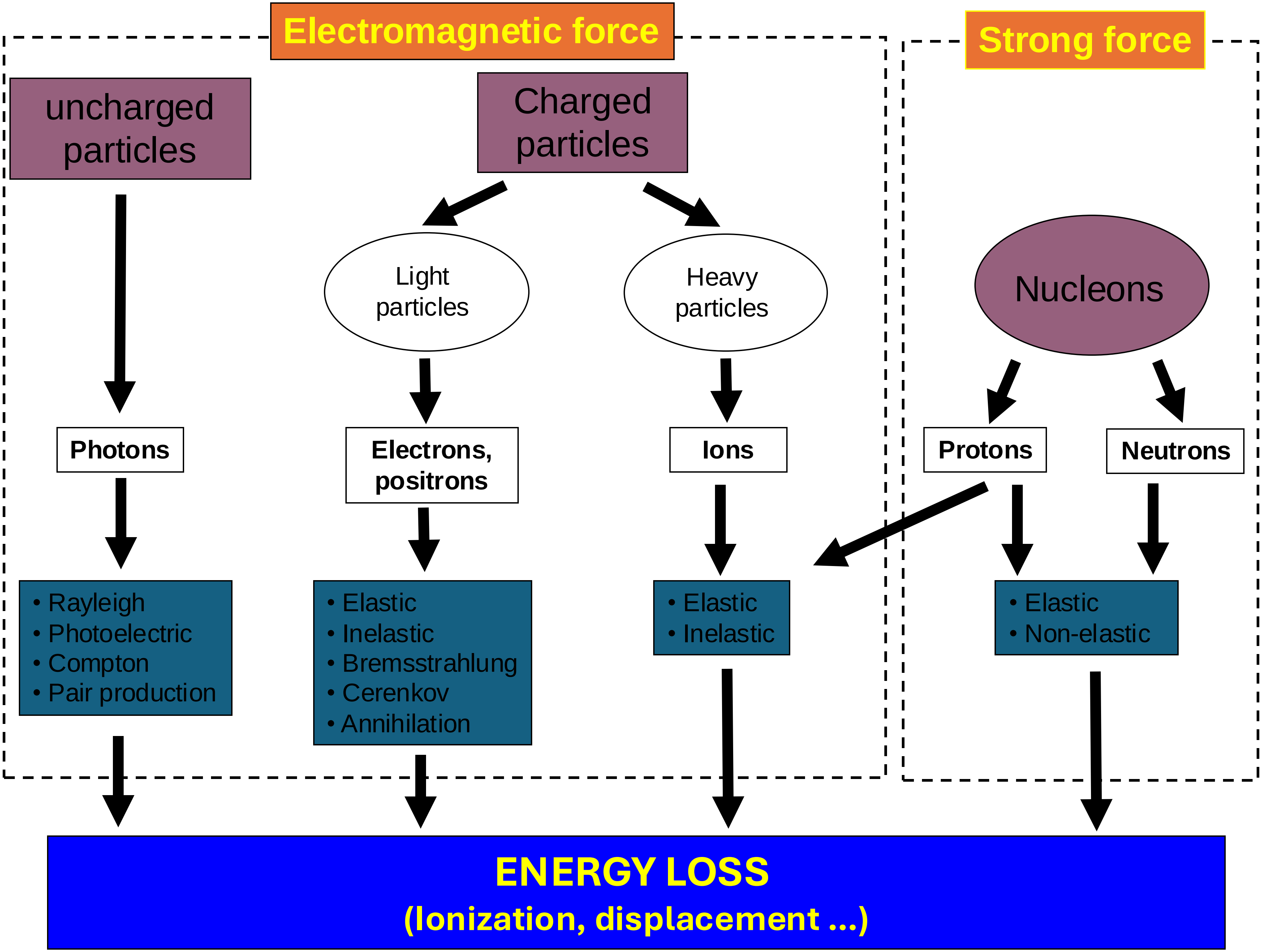
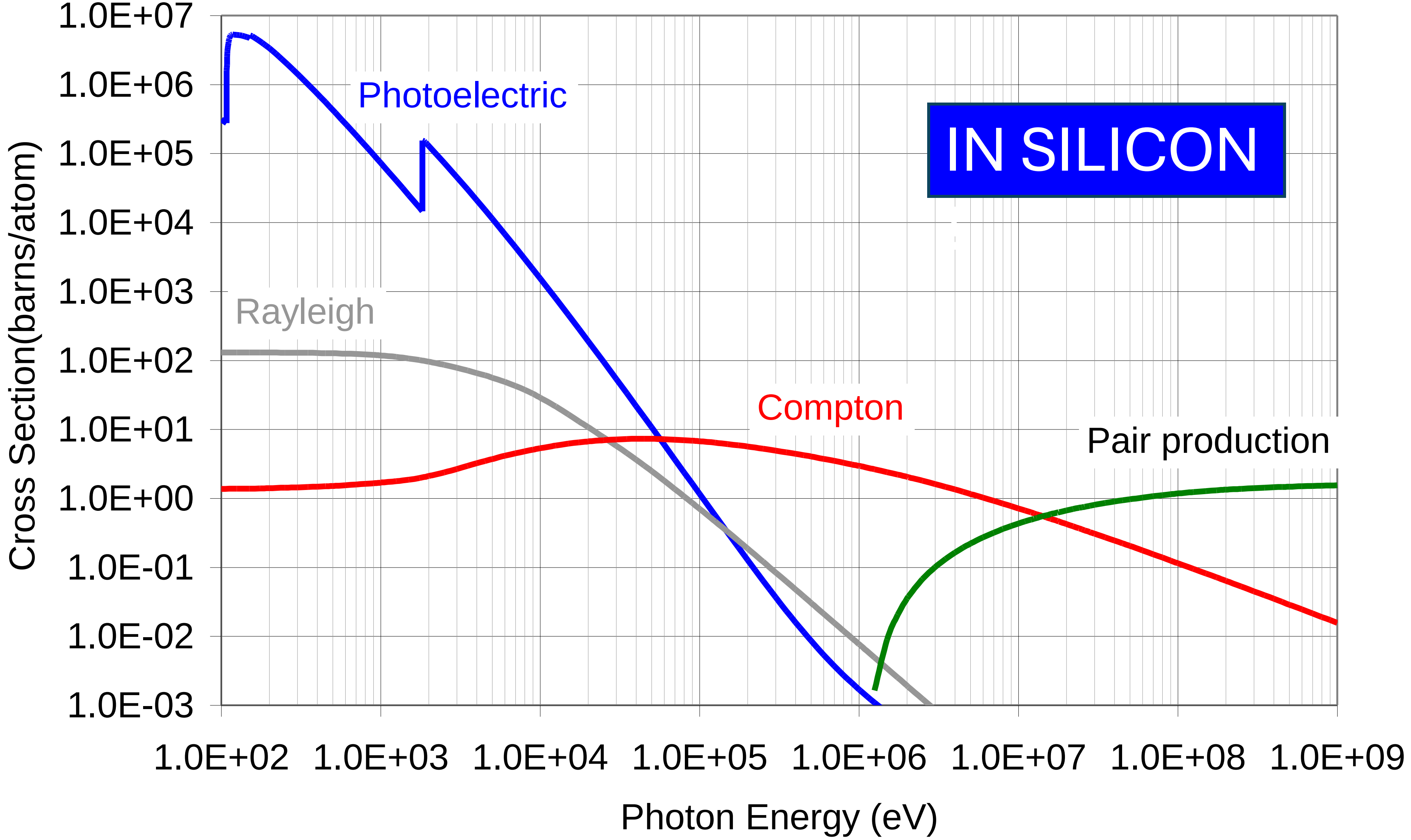
Forces at play

Force	Range of the force (m)	Relative Strength	At play in
Gravitational	∞	10^{-38}	**Astrophysics**
Weak	10^{-18}	10^{-5}	**Nuclear decay**
Electromagnetic	∞	$\alpha = 1/137$	**Radiation matter interaction**
Strong	10^{-15}	1	


Electromagnetic force
Strong force
uncharged particles
Charged particles
Light particles
Heavy particles
Nucleons
Photons
Electrons, positrons
Ions
Protons
Neutrons
• Rayleigh
• Photoelectric
• Compton
• Pair production
• Elastic
• Inelastic
• Bremsstrahlung
• Cerenkov
• Annihilation
• Elastic
• Inelastic
• Elastic
• Non-elastic
ENERGY LOSS
(Ionization, displacement ...)

Photon-matter interaction



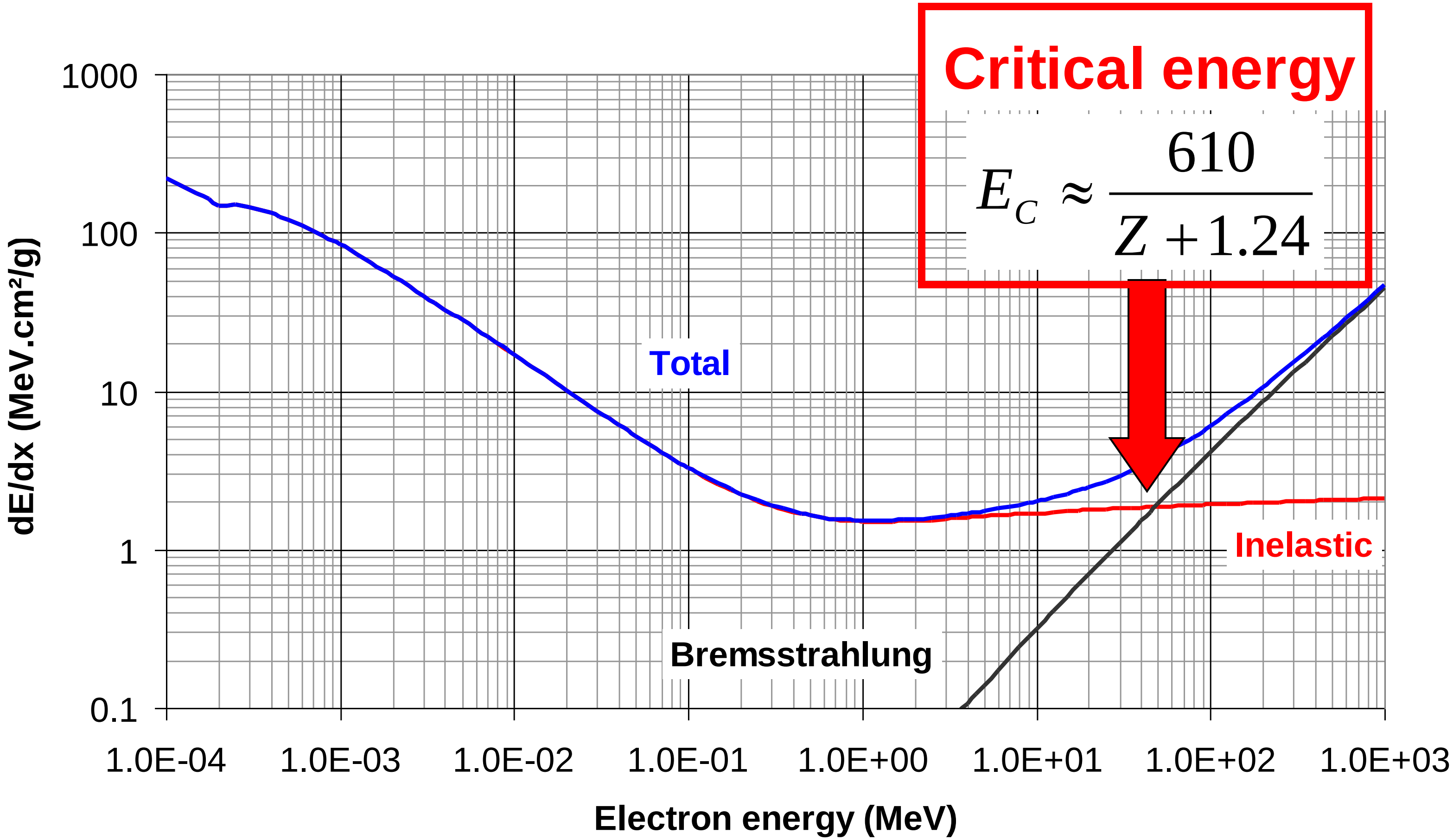
Photons interactions: Summary

Process	**Summary**	**Cross Section**
Rayleigh	• Photon is scattered	Negligible
Photoelectric	• Photon is absorbed • Electron is ejected	$\sigma_{pho} \propto Z^5$
Compton	• Photon is scattered • Electron is ejected	$\sigma_{Com} \propto Z$
Pair production	• Photon is absorbed • e^+e^- is created • Electron may be ejected	$\sigma_{prod} \propto Z^2$

Electrons (and positrons) interactions

Process	Summary	Energy loss
Elastic	• Electron is scattered • No recoil	No energy loss
Inelastic	• Electronic excitation or ionization	Dominant
Bremssthralung	• Electron is deflected • Photon is emitted	Dominant
Cerenkov	• High velocity charged particle in insulator	Neglected
Annihilation	• 2 photons emission	Initial particle is absorbed

Electron total energy loss



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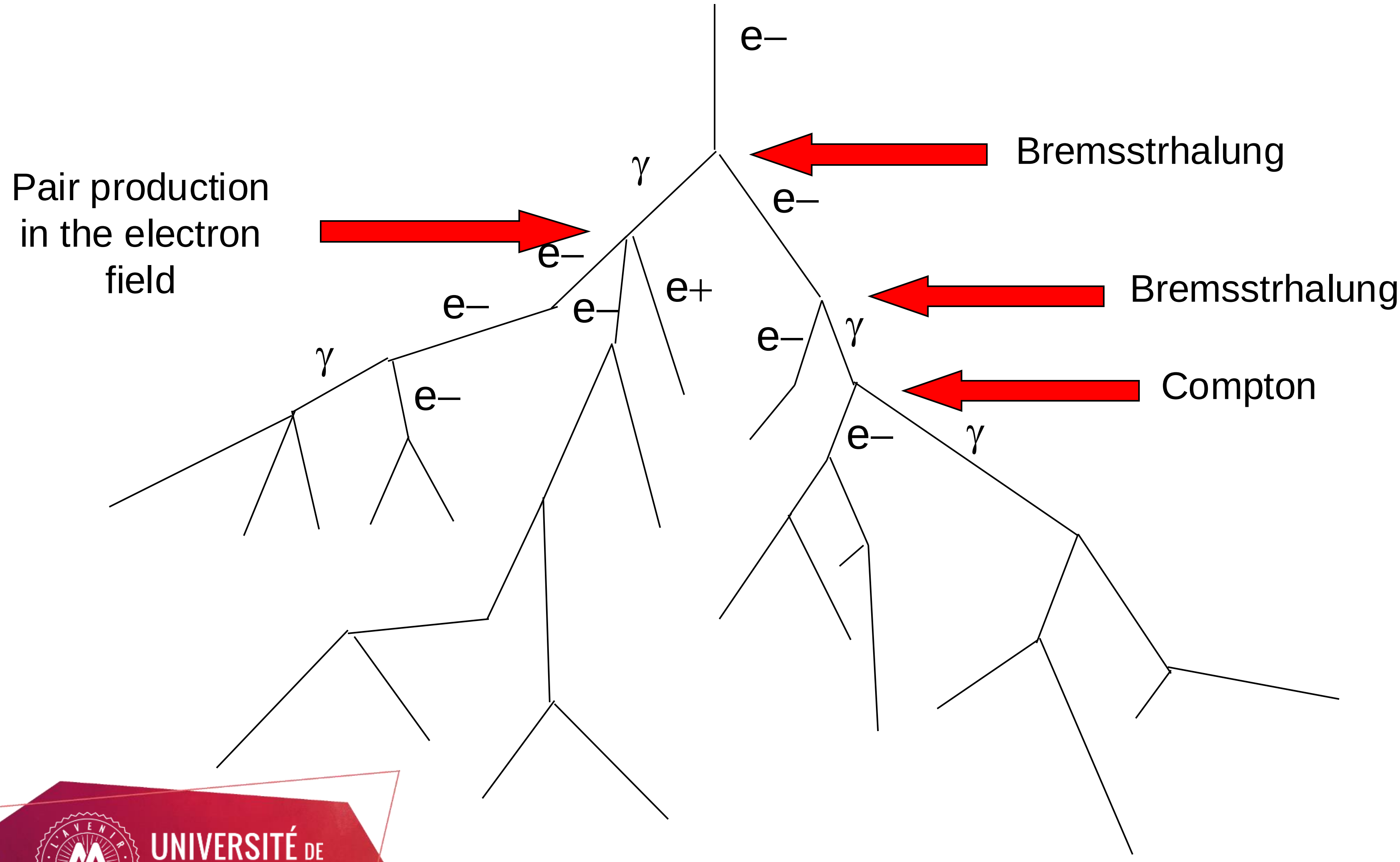
Shower of particles



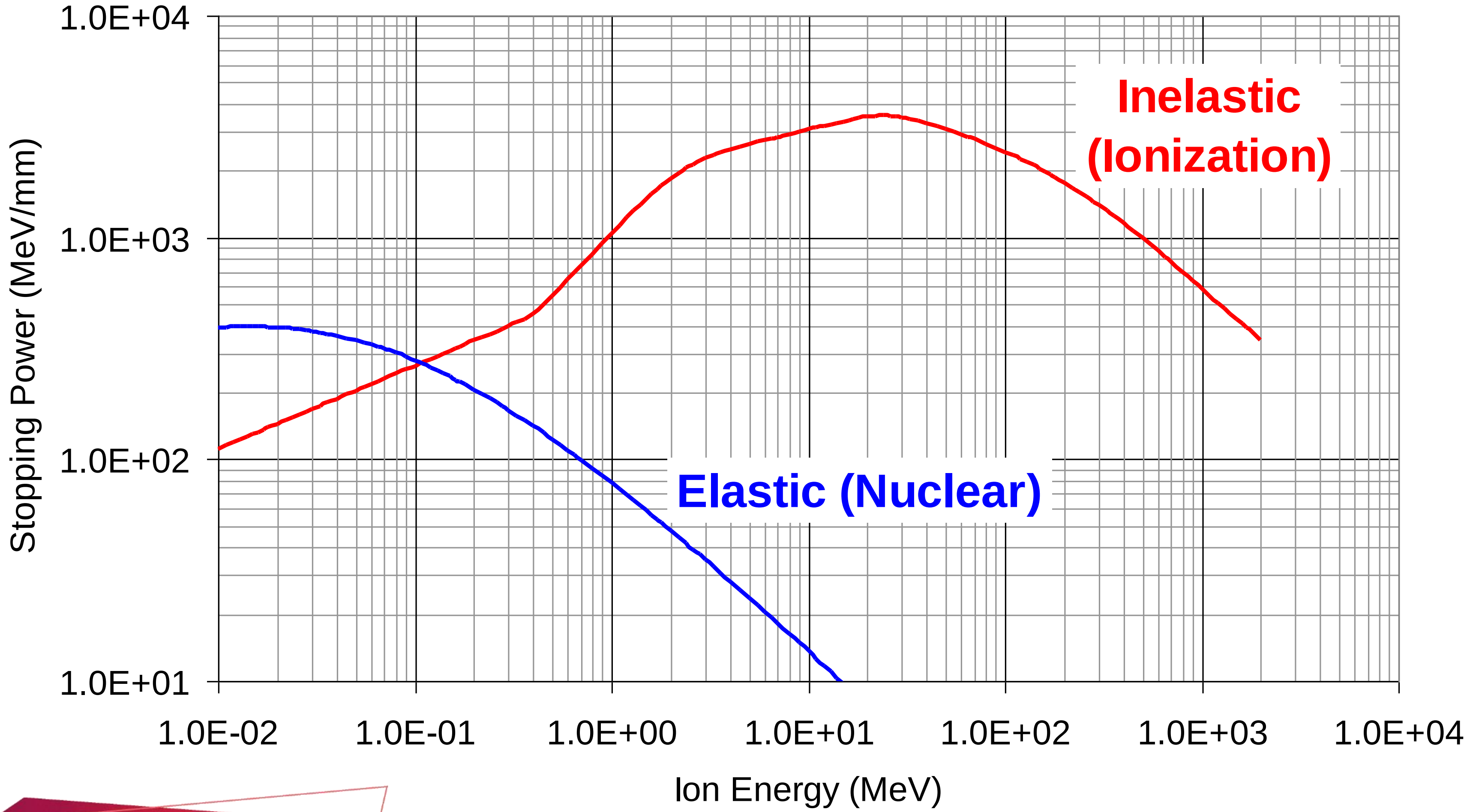
Ions Interactions

When an ion enters a target material there are 2 main effects that cause an energy loss:

- Elastic collisions with the nuclei of the target material
- Inelastic collisions with the electrons of the medium

- As for e- and e+ Bremssthralung emission is possible but due to the ion mass, the effect is negligible
- Generally, ions do not have relativistic speed : no Cerenkov effect

Stopping Power



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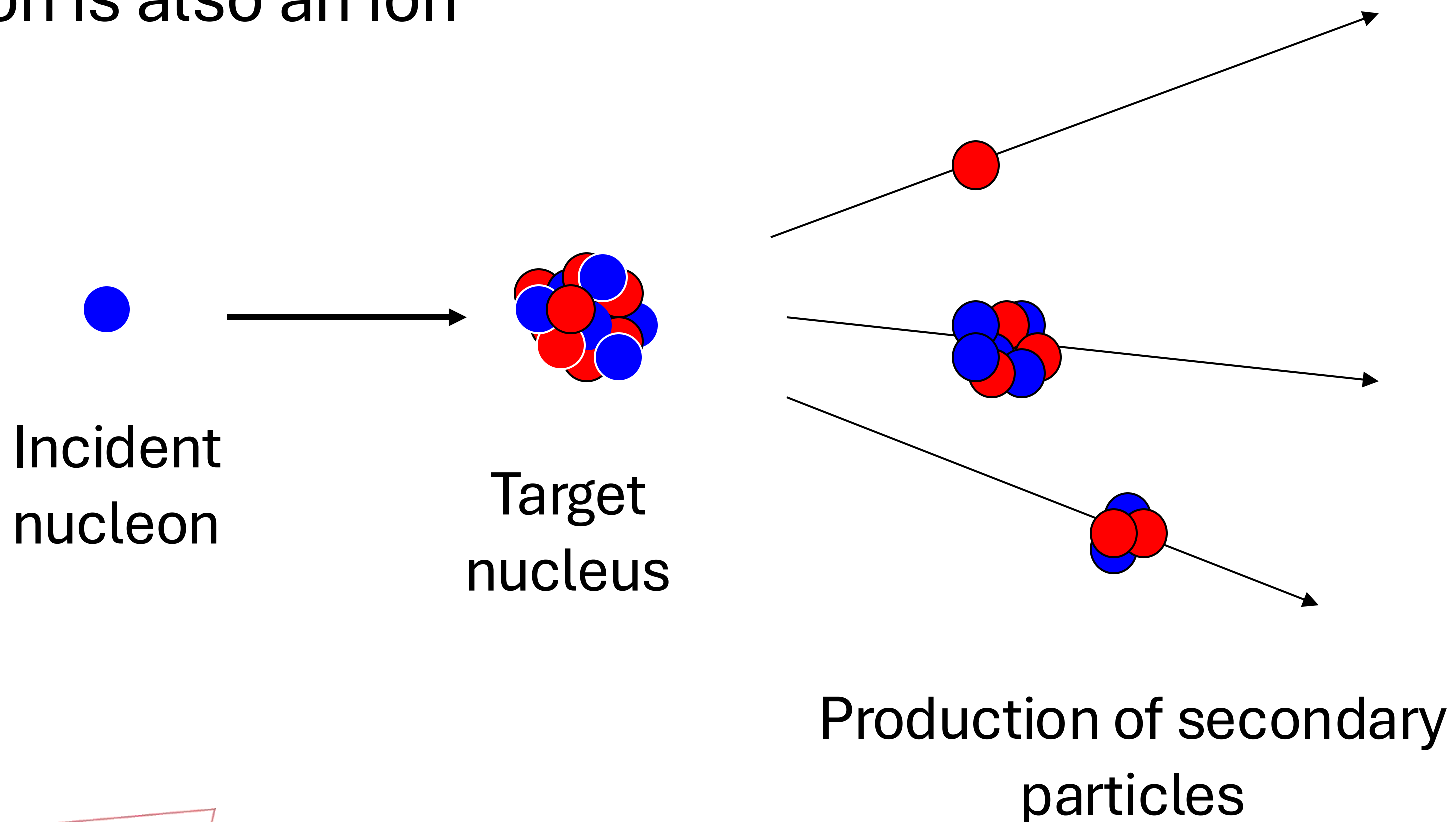
Neutrons and protons induced nuclear reactions

Neutrons and protons interact by nuclear reactions

NB: proton is also an ion



Particles	Processes	Secondary particles	Main effect for microelectonics
Photons	•Rayleigh •Photoelectric •Compton •Pair production	e-, e+, photons	Ionization
Electrons, positrons	•Elastic •Inelastic •Bremssthralung •Cerenkov •Annihilation	e-, e+, photons	Ionization
Ions	•Elastic •Inelastic	Ions, e-	Ionization and Displacement
Nucleons	•Elastic •Nonelastic	Ions, photons, nucleons (pions …)	Ionization and Displacement

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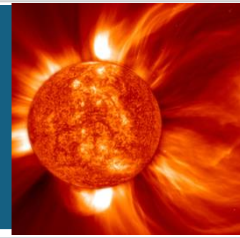
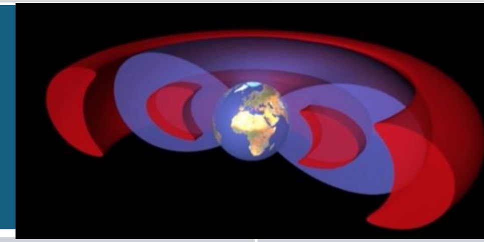
Conclusions

- Space and atmosphere are radiative environments
  - Space: ions, protons, electrons
  - Atmosphere: mainly neutrons
- There is a specific terminology for describing the properties of particles
- Each kind of particles interacts differently with matter and it is necessary to understand the fundamental on radiation-matter interaction

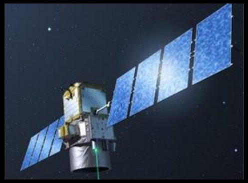
Conclusions

					
	Ions	Protons (solar flares)	Protons	Electrons	Neutrons
Single events	X	X	X		X
Ionising dose		X	X	X	
Displacement damage		X	X	x	

Radiations from space to ground level?

altitude

36 000 km



500 km

100 km

20 km

10 km

0 km

Less particles at lower altitudes

BUT

The number of devices is greater at ground level

+

Technologies are more and more integrated