Effets des rayonnements naturels sur l'électronique : applications spatiales, avioniques et terrestres

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Outline

- Natural radiation environment
- Main effects vs main applications
- The case of single event effect
  - Mechanisms
  - Ingredients for simulations
- Conclusion

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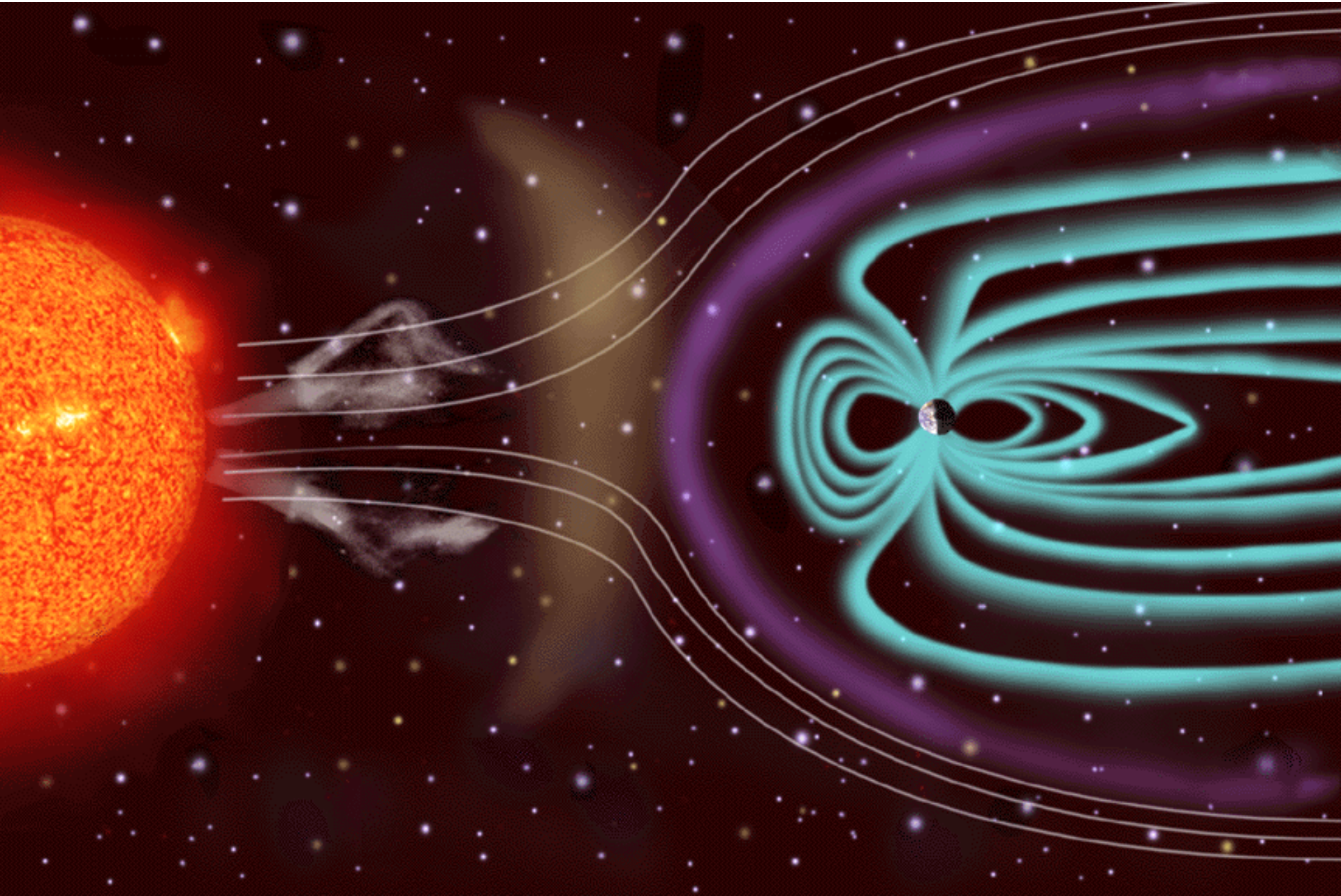
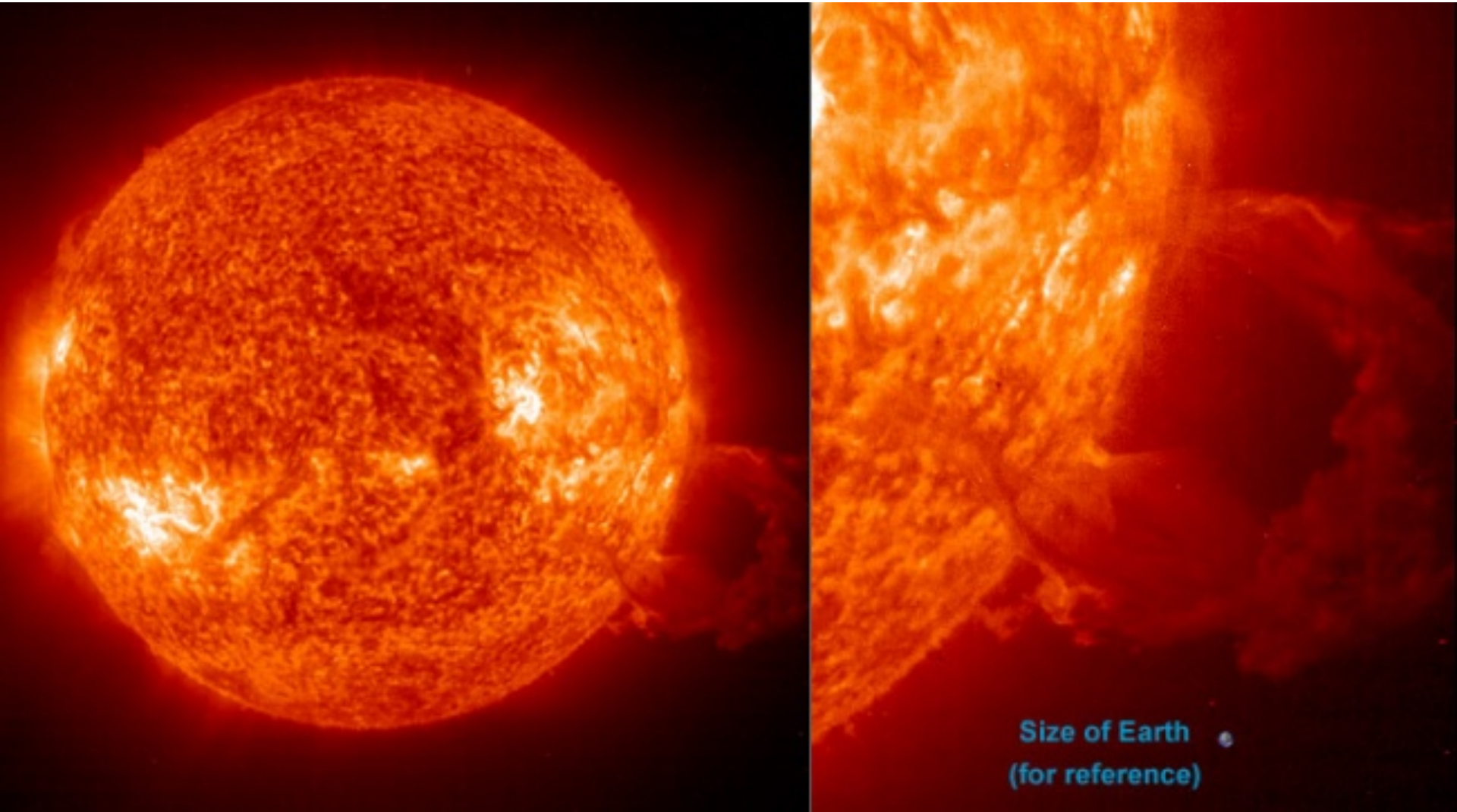
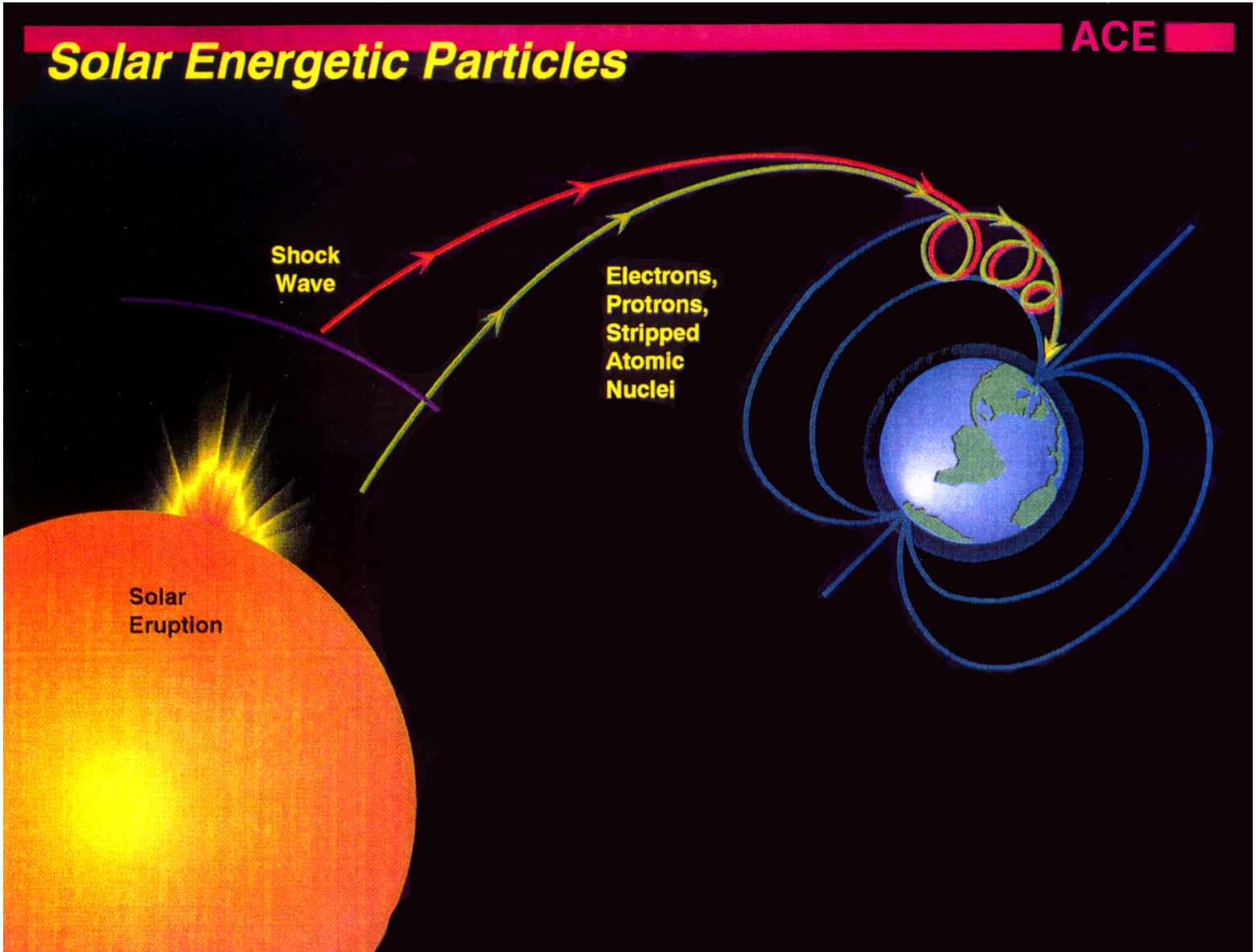
Radiations in Space



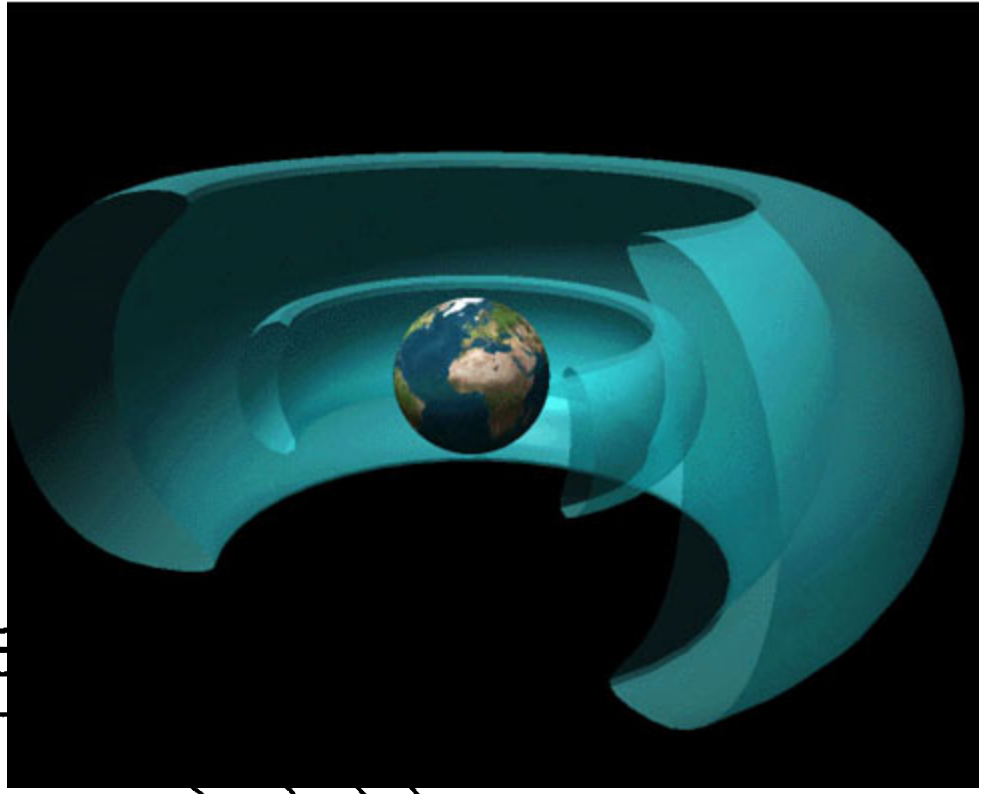
Solar Flare

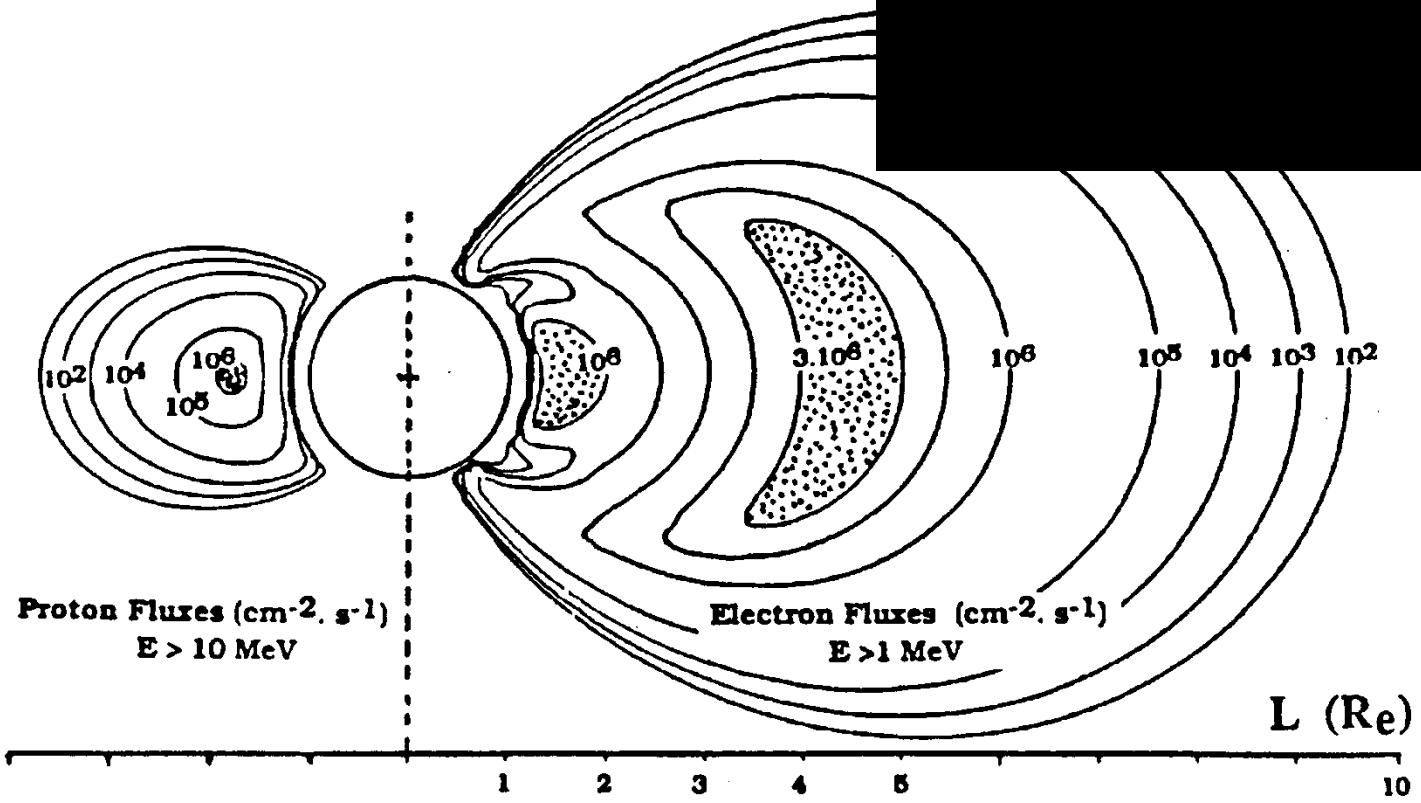


Radiation Belt

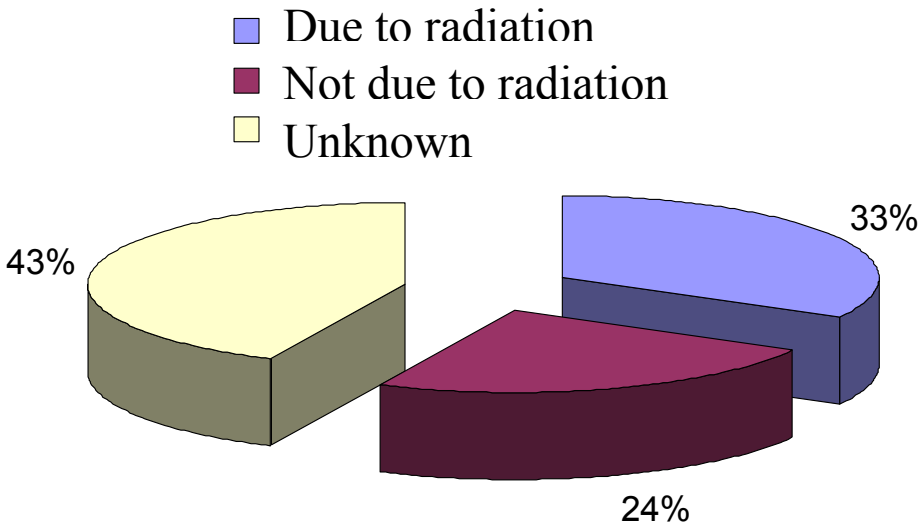


Radiation Belt



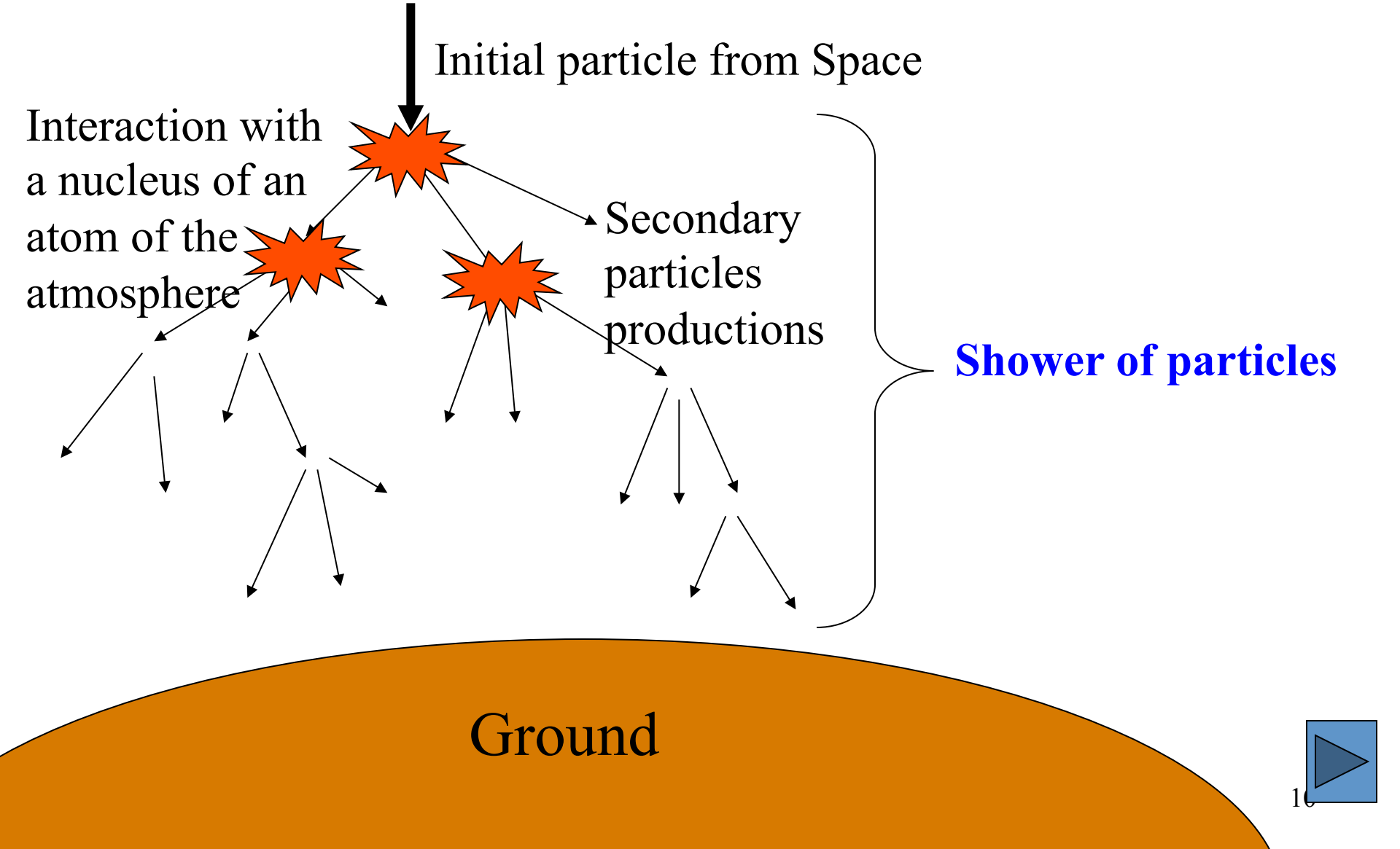


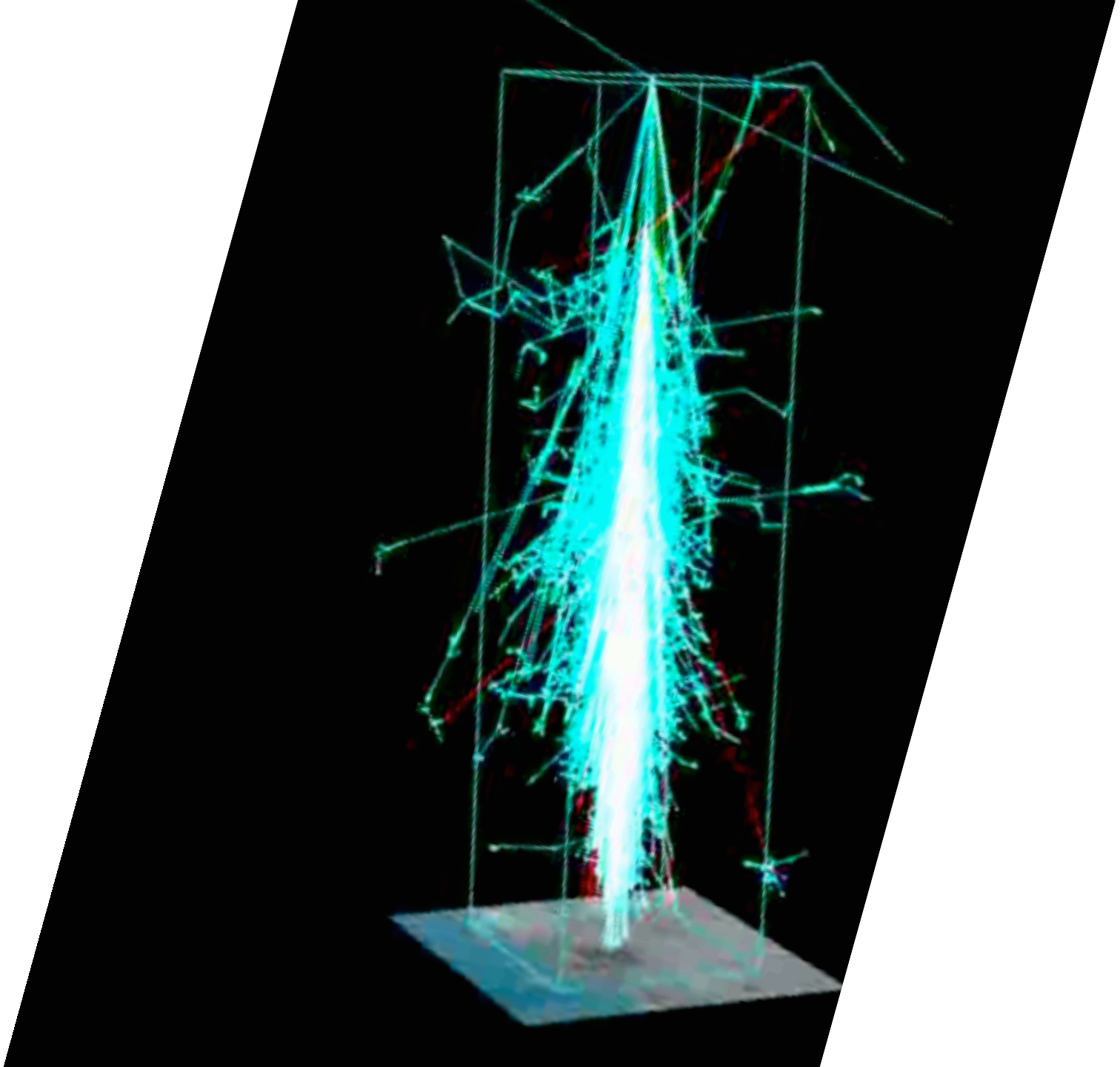
Radiation induced dysfunction in satellites



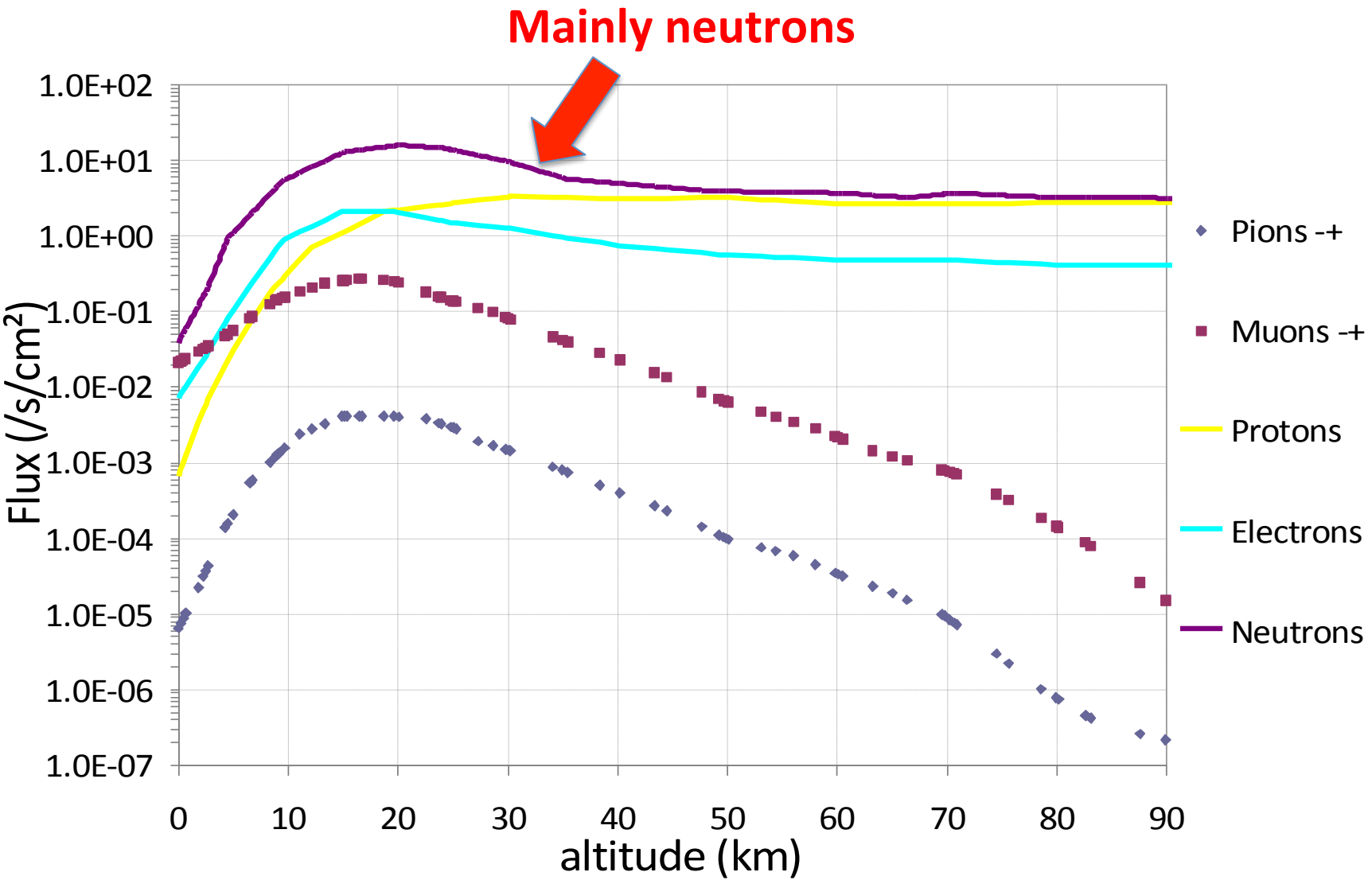
Particles are travelling in Space and can arrive in the vicinity of the Earth. They can be:

- Deflected by the magnetic field
- Trapped in the magnetic field
- Pass through the magnetic field and enter the atmosphere


Initial particle from Space
Interaction with a nucleus of an atom of the atmosphere
Secondary particles productions
Shower of particles
Ground



Particle flux in atmosphere



Radiations from space to ground level?

altitude

36 000 km

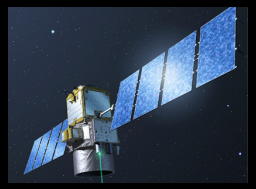
500 km

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

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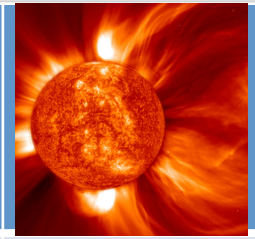
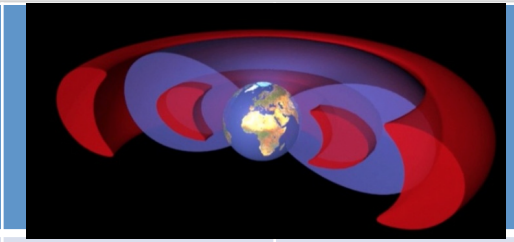
Main effects vs main applications

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

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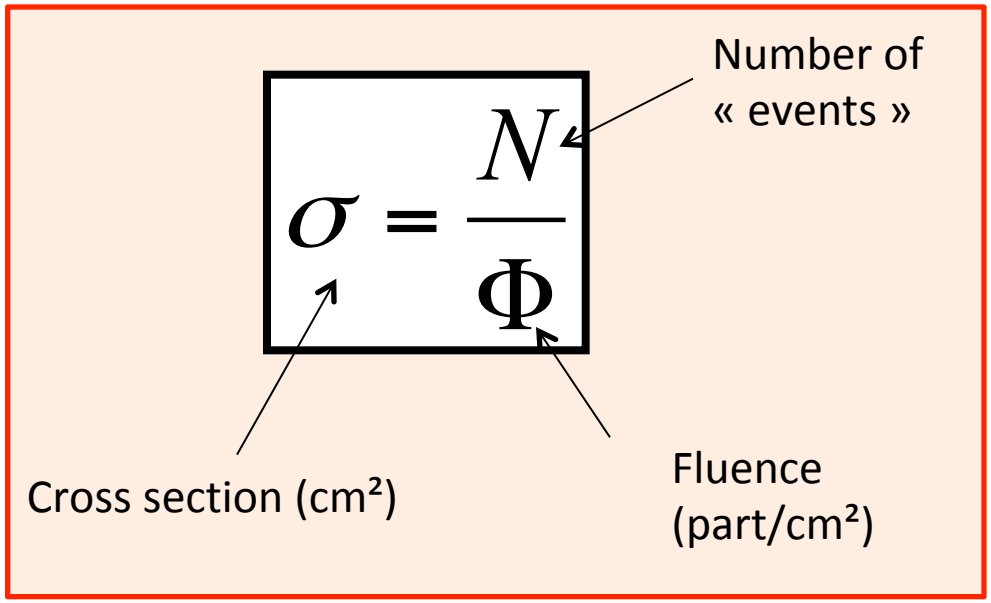
Single Event Effects

- SET = Single Event Transient
- SEU = Single Event Upset
- SBU = Single Bit Upset
- MCU = Multiple Cell Upset
- MBU = Multiple Bit Upset (=MCU in the same word)
- SEFI = Single Event Functional Interupt
- SEL = Single Event Latchup
- SEB = Single Event Burnout
- SEGR = Single Event Gate Rupture
- …

Cross section

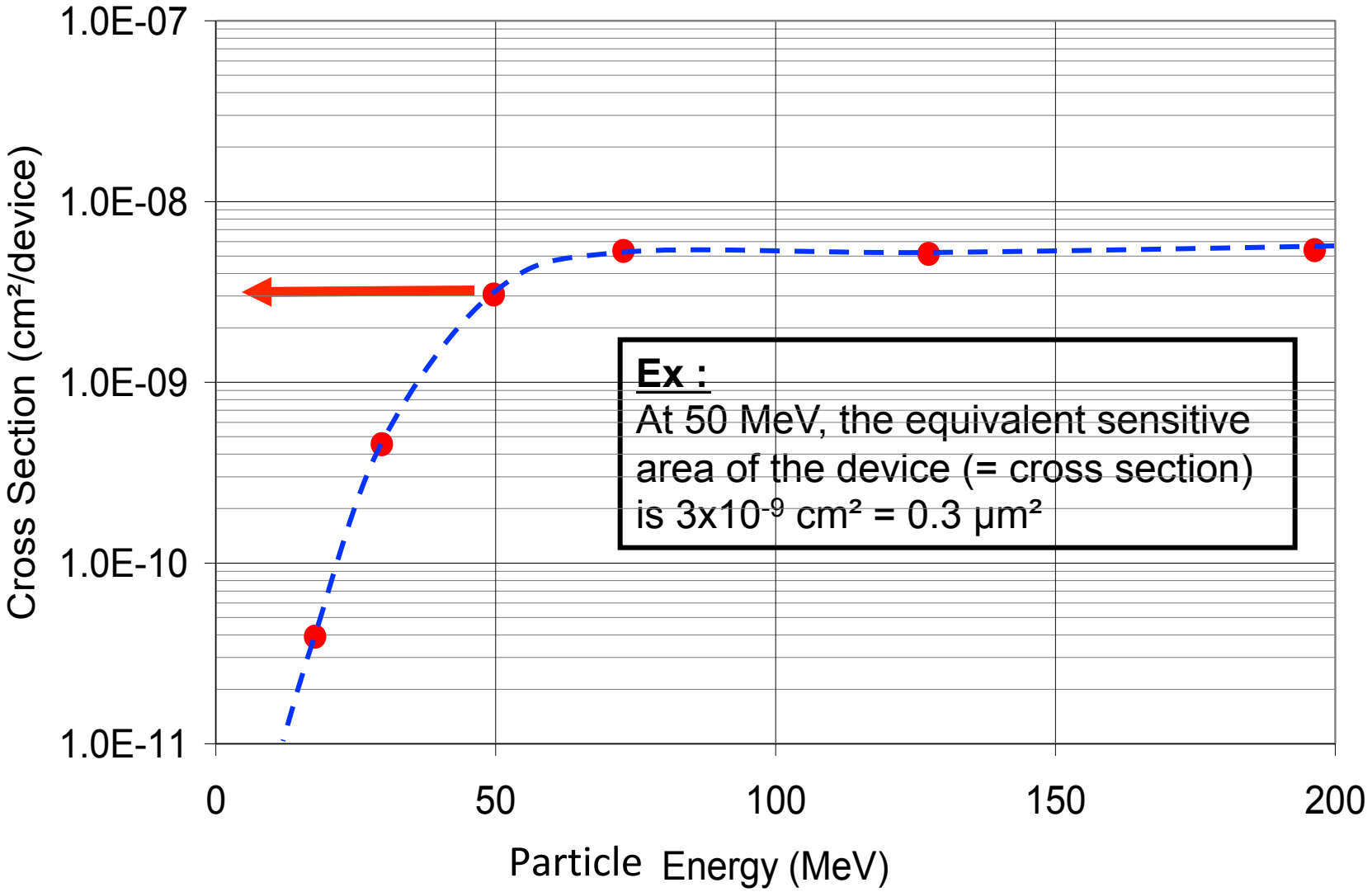
The concept of a **cross section** is used to express the probability of a process (e.g. particle interaction).
More generally the cross section is defined by:



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

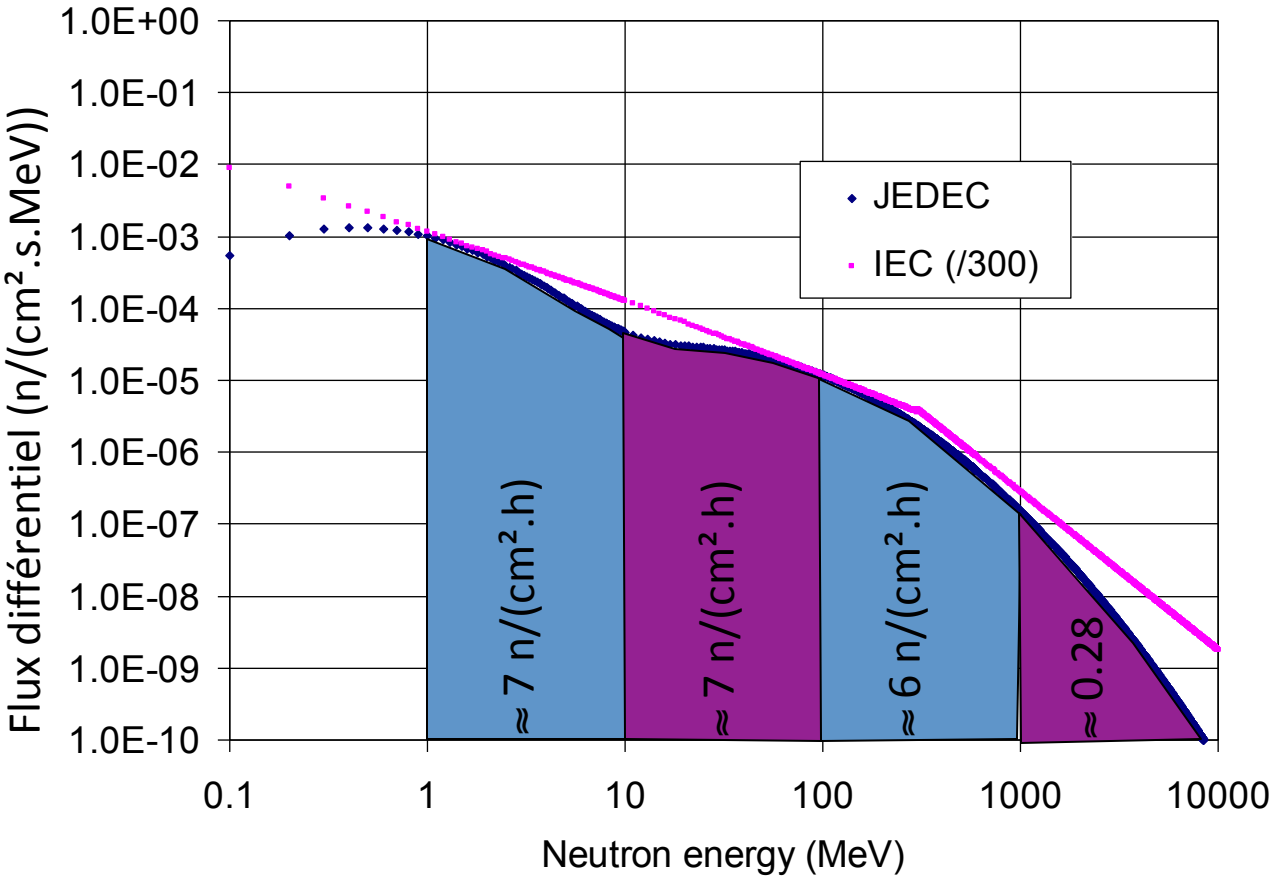
- particle that interacts
- particle that deposits more than a given energy

Electronics under beam
SEU in SRAM



Differential neutron flux in atmosphere

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

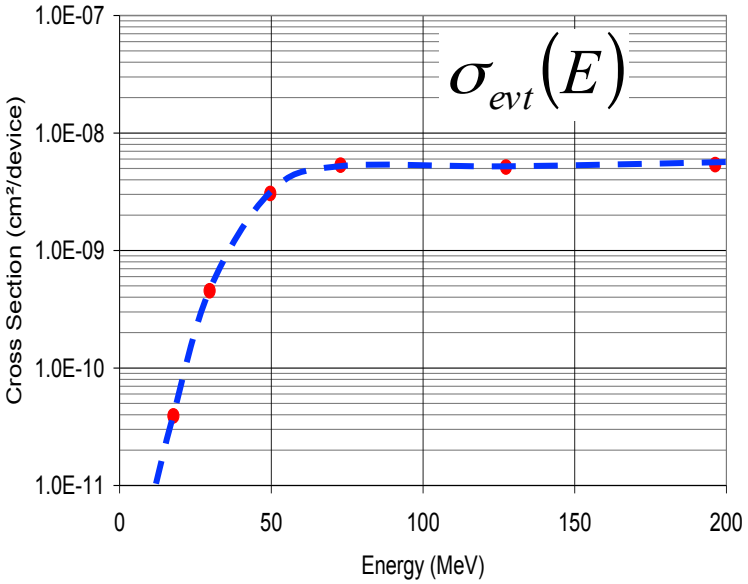


Around 20 n/(cm².h) with energy greather than 1 MeV (after JEDEC).

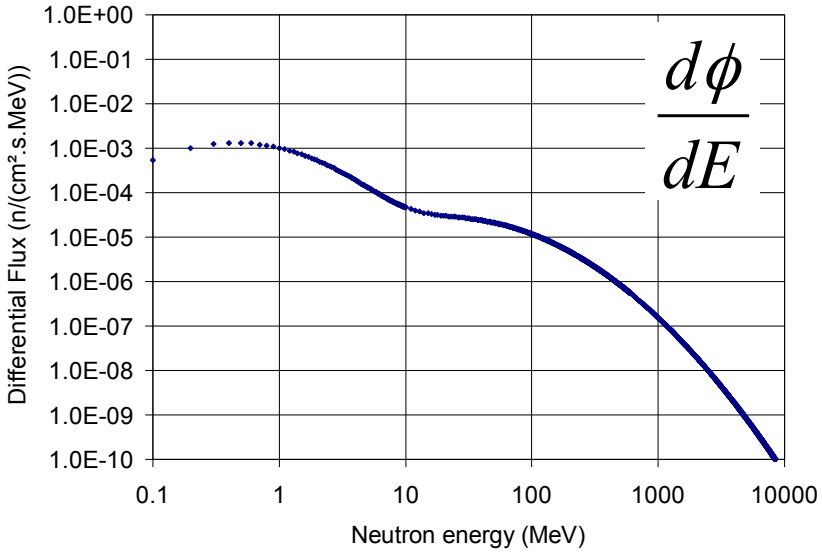
NB: it actually depends on geolocation and solar activity

Soft Error Rate (SER)

Device



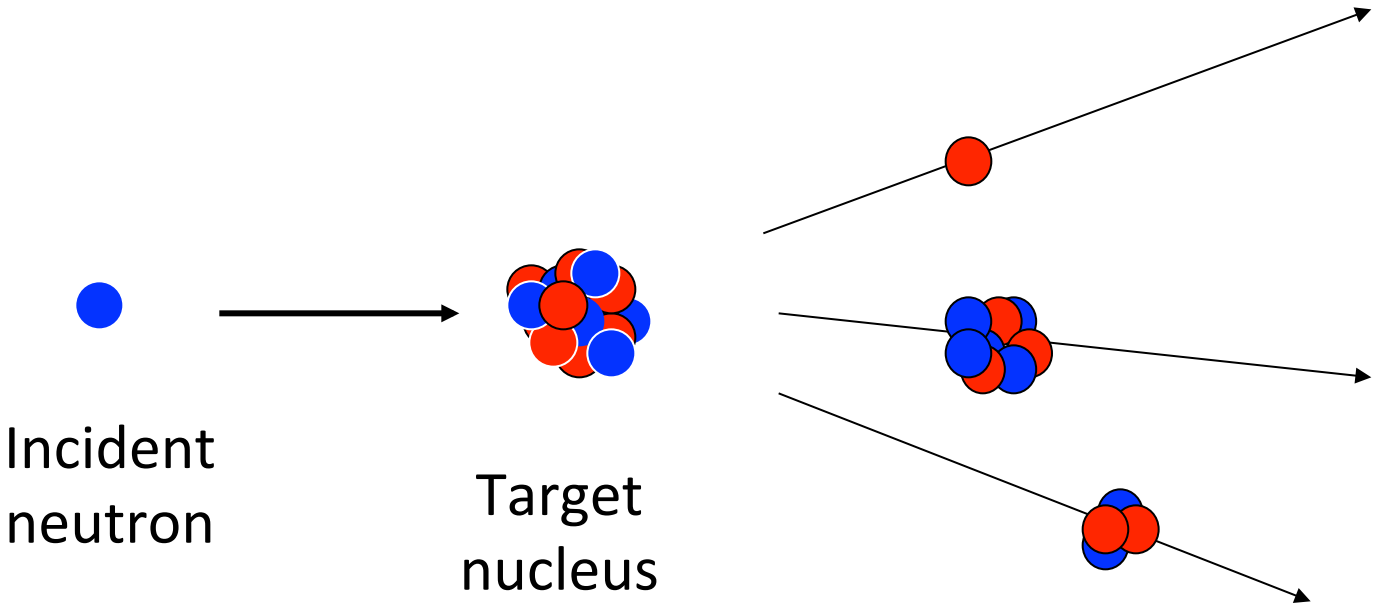
Environment



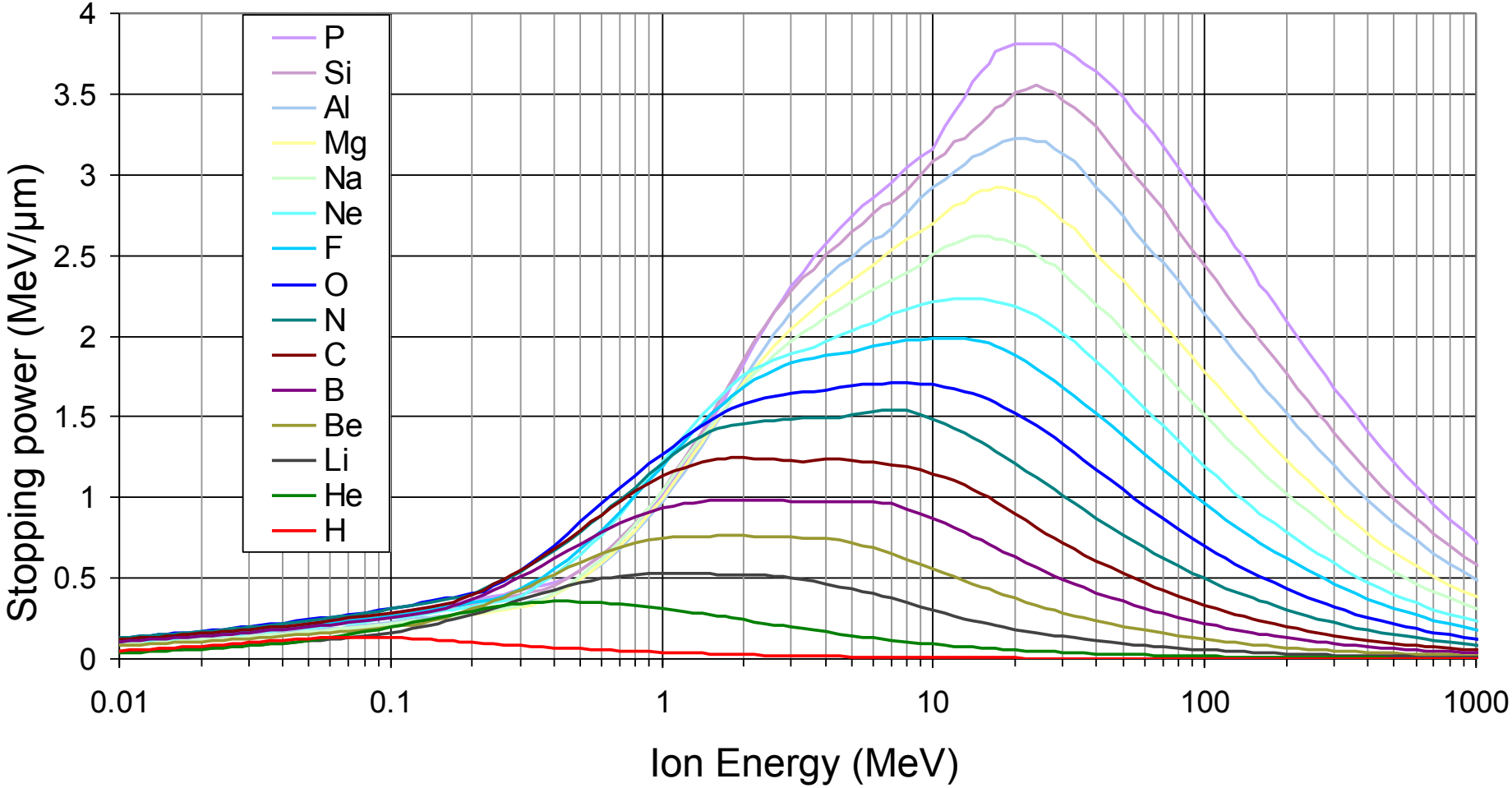
$$SER = \int \frac{d\varphi}{dE} \cdot \sigma_{evt}(E)\, dE$$

Neutrons induced nuclear reactions

Neutrons interact by nuclear reactions



Example : stopping power of ions in silicon

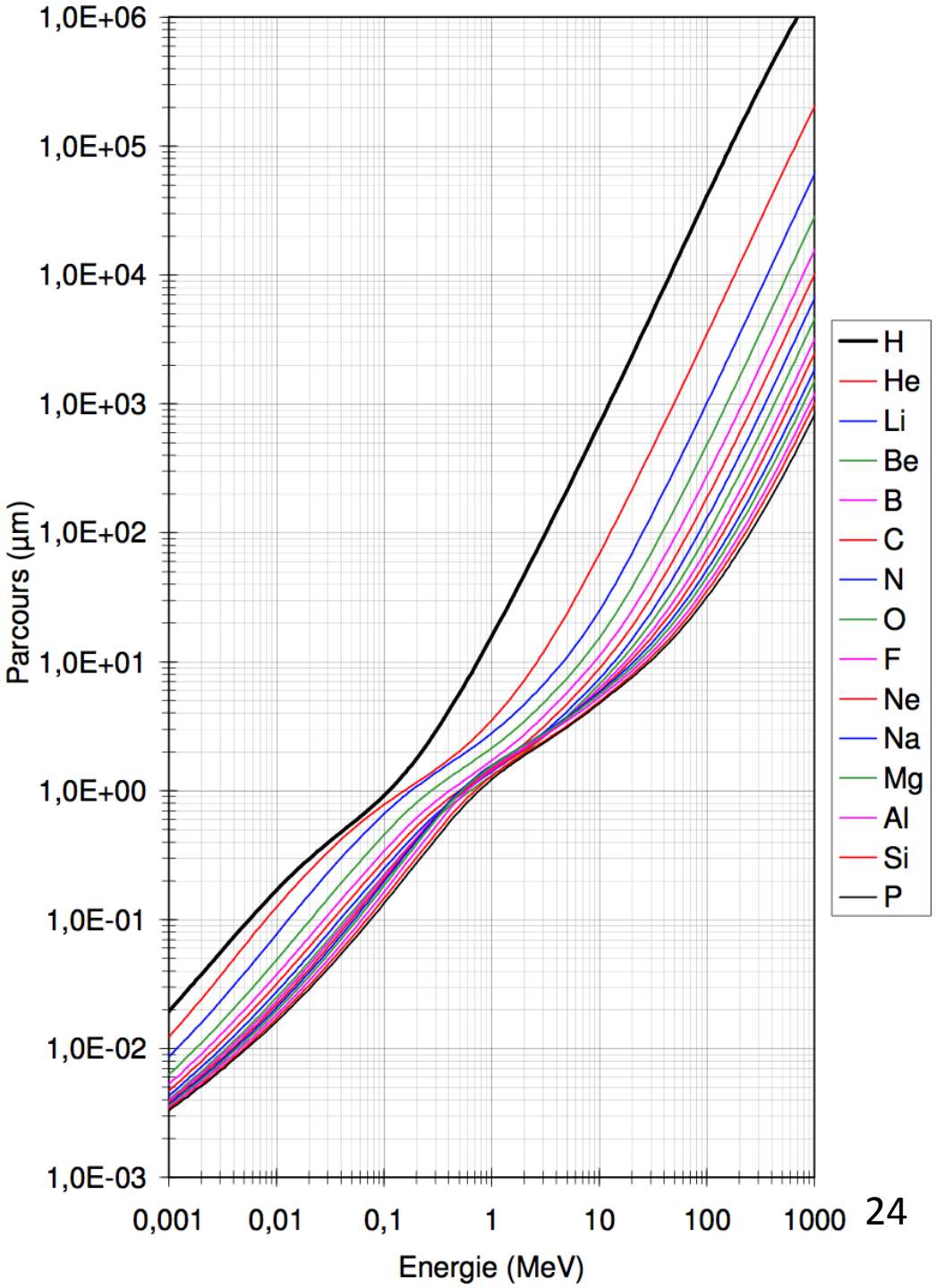


SRIM code by J. Ziegler

Range of light ions in silicon

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

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

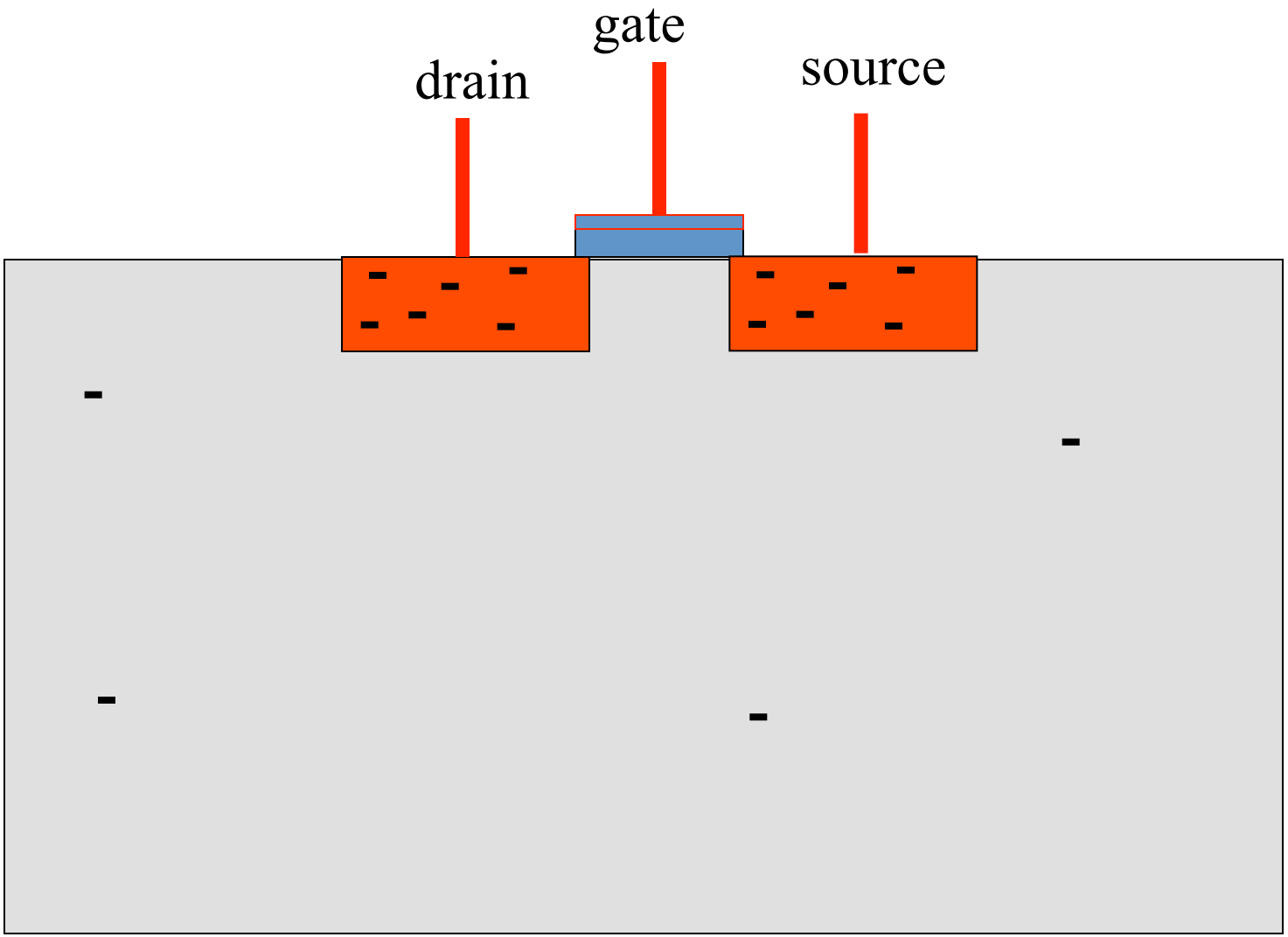


SET: Single Event Transient

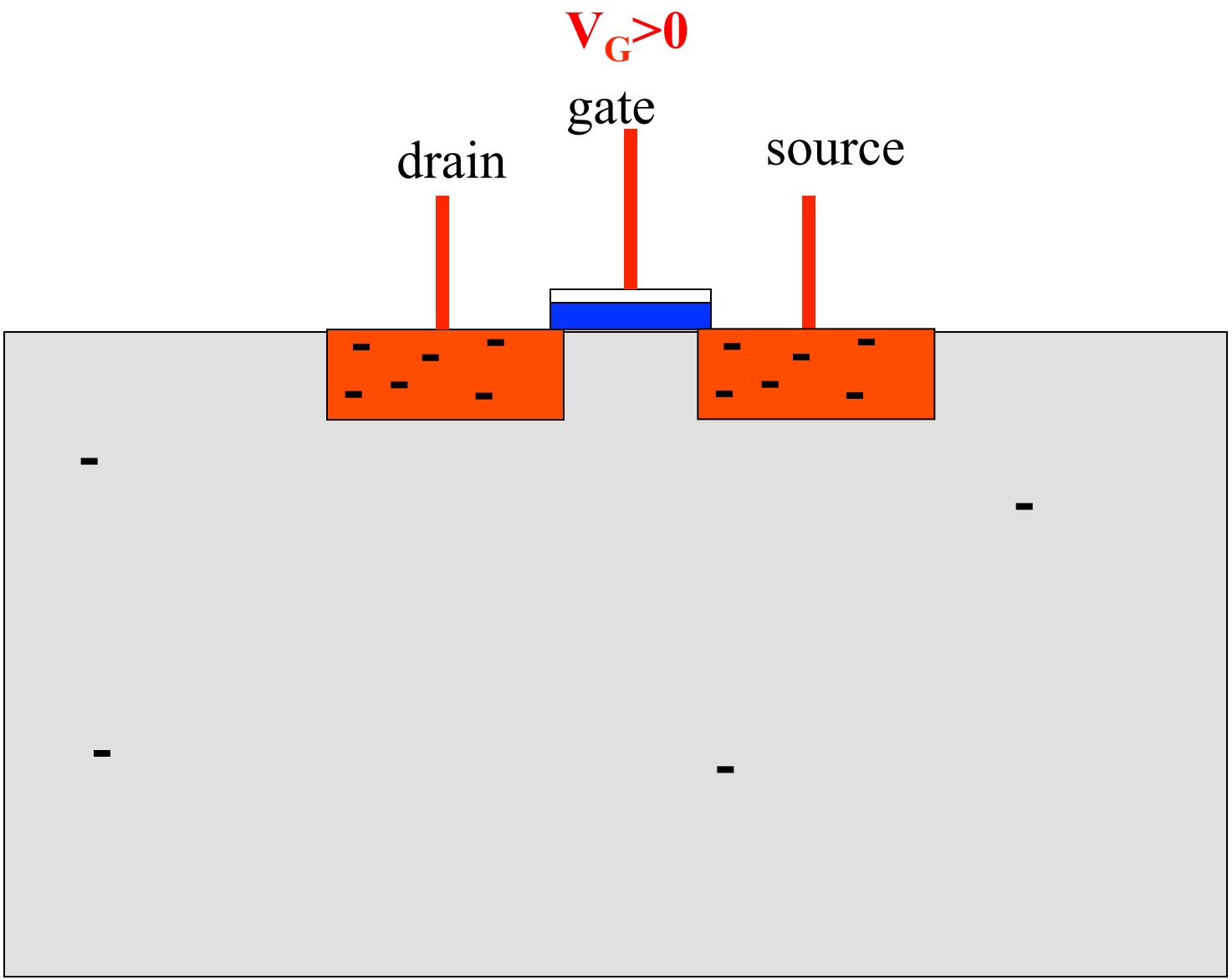
- A momentary voltage excursion (voltage spike) at a node in an integrated circuit caused by a single energetic-particle strike.

- Although an SET does cause a transient in the gate output struck by the particle, it may propagate through subsequent gates and can cause an SEU when it reaches a memory element.

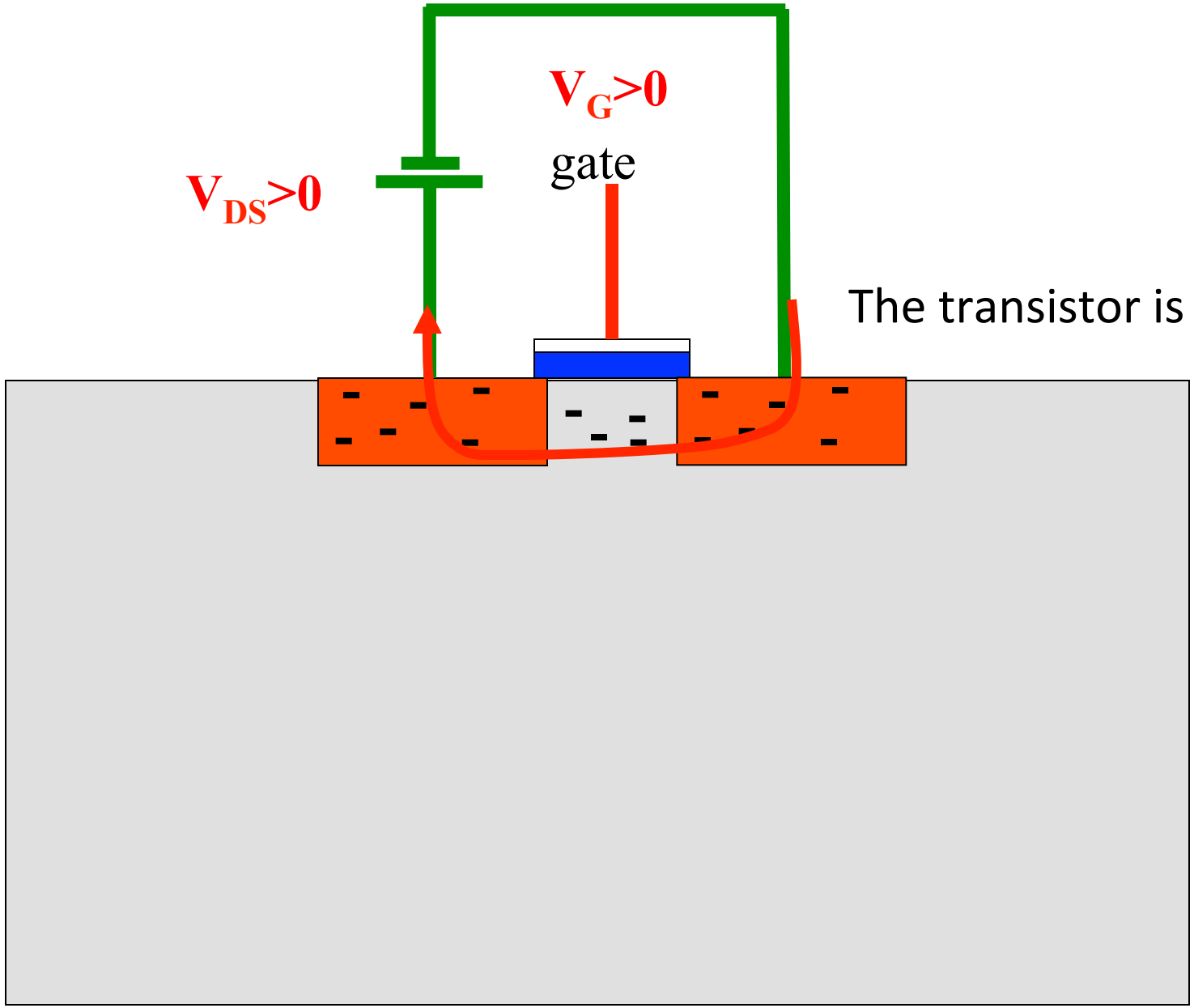
MOS transistor



MOS transistor

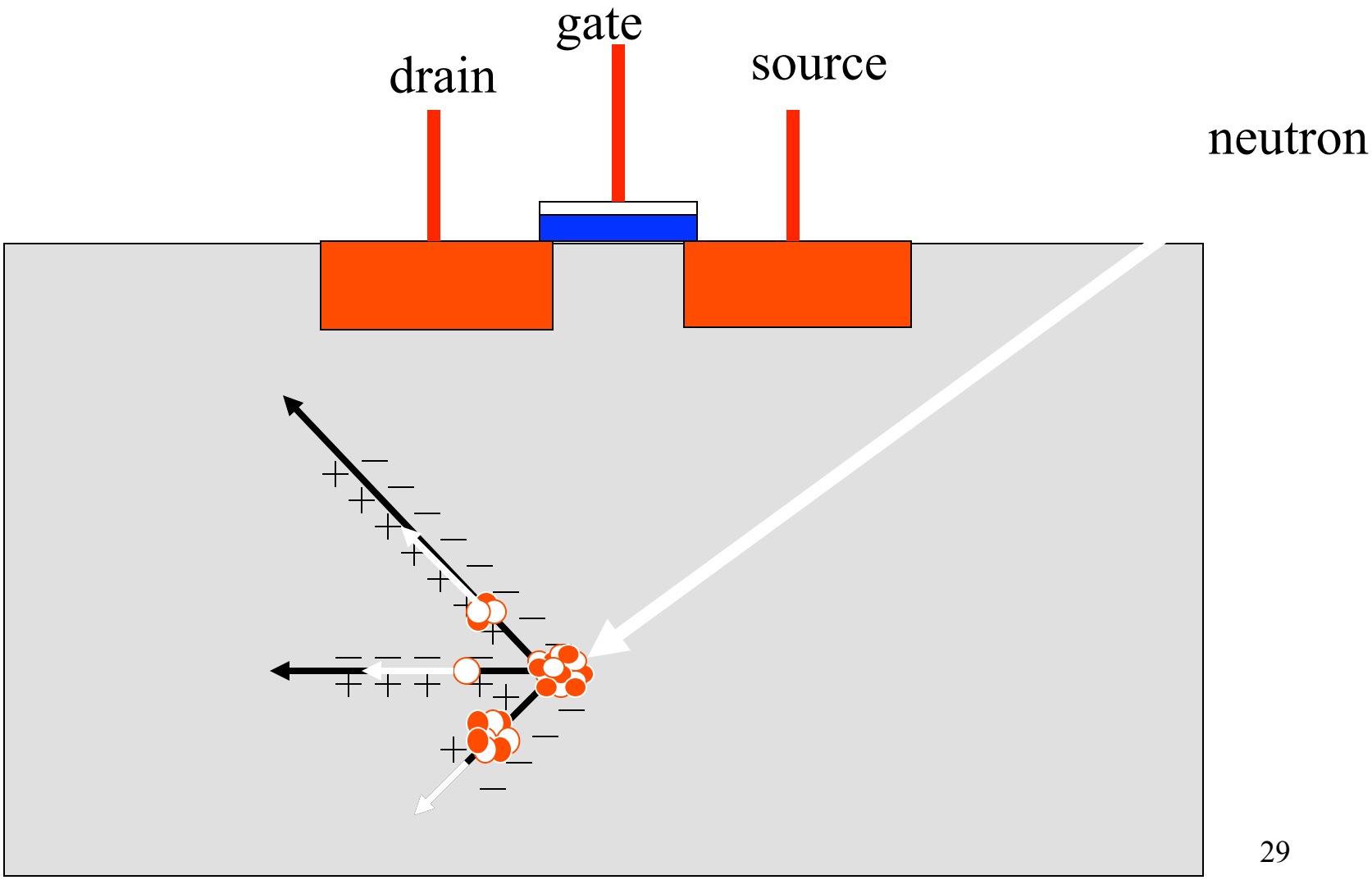


MOS transistor

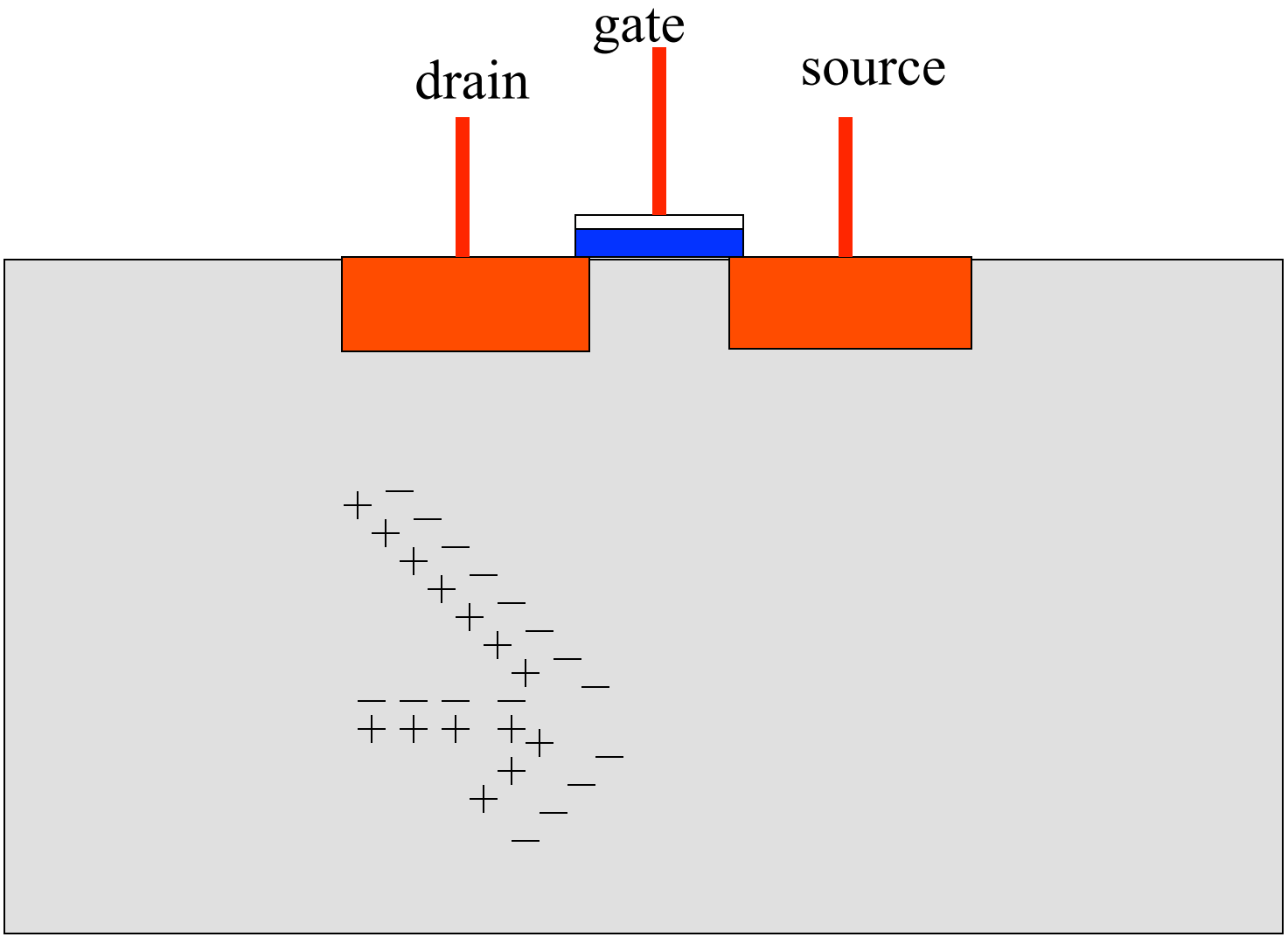


The transistor is ON

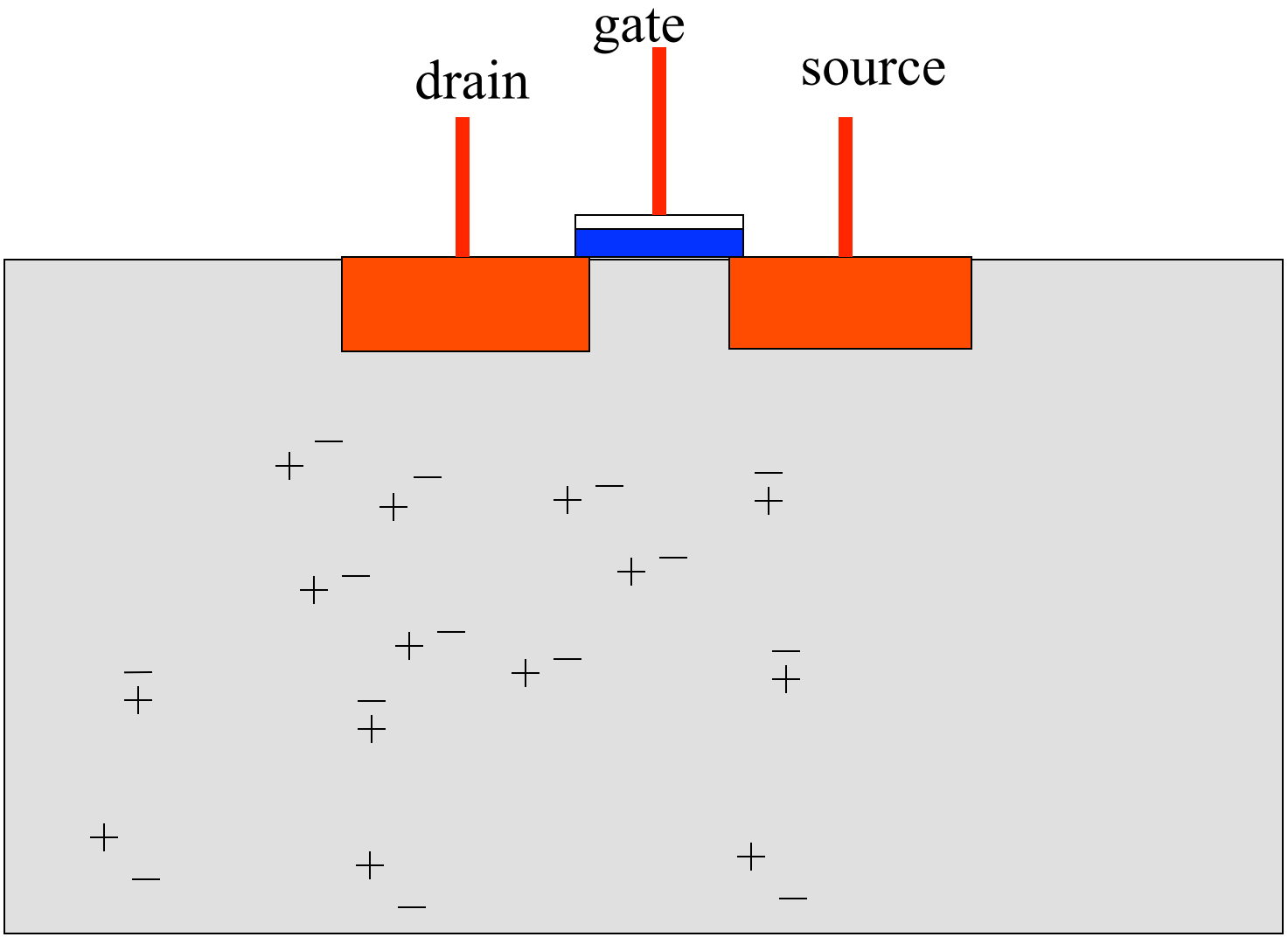
Nuclear reaction



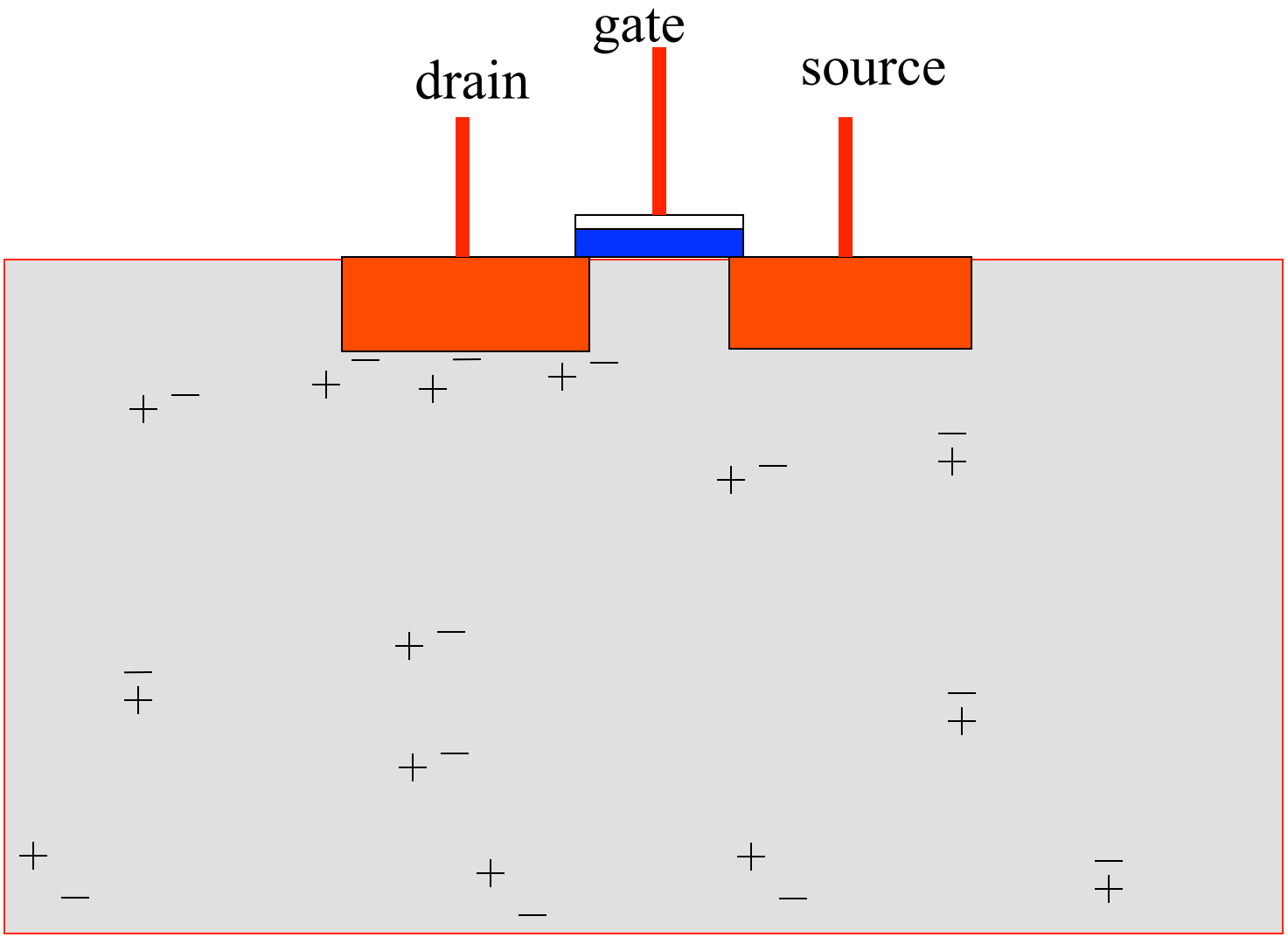
Ionization



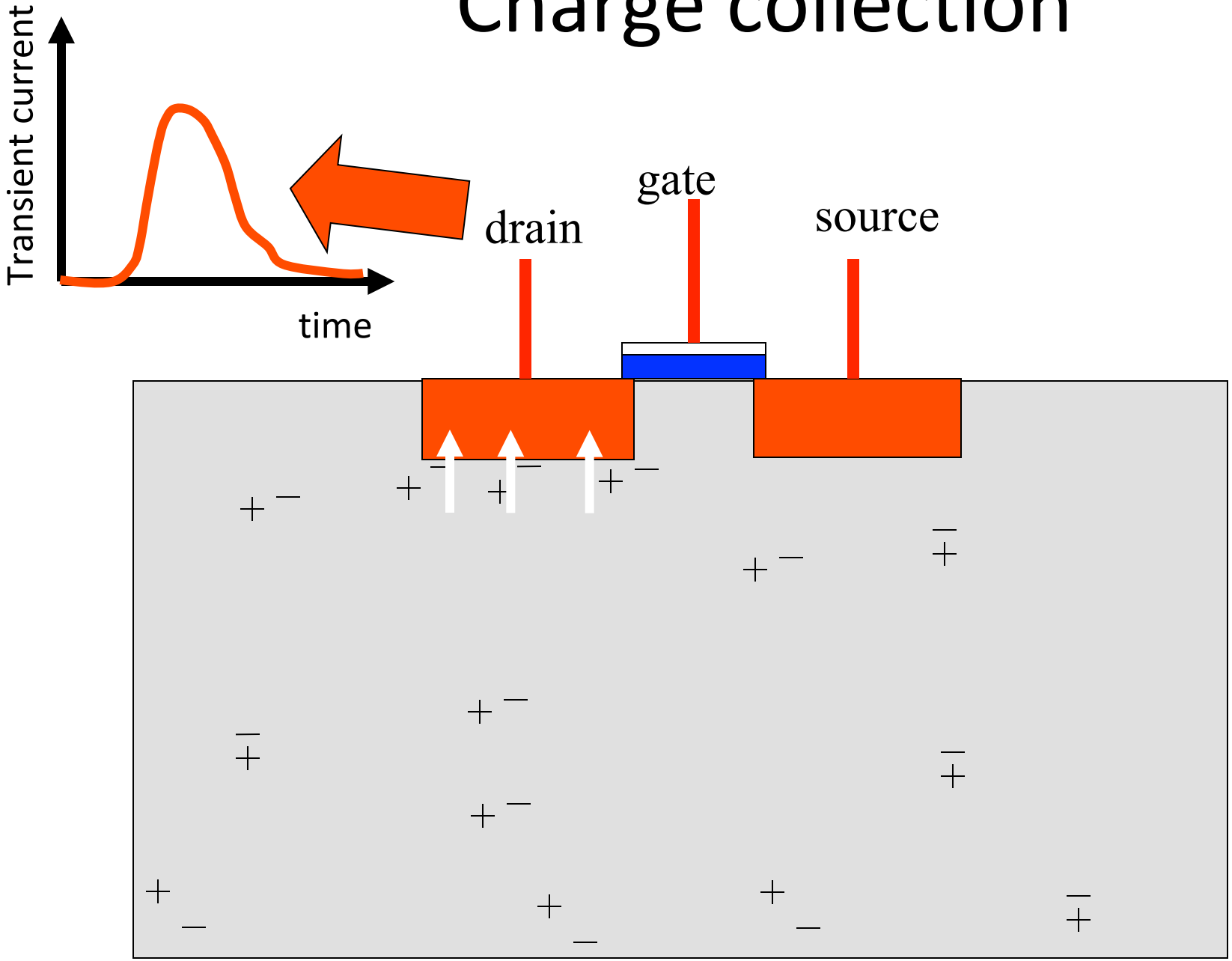
Electron-hole pairs diffusion



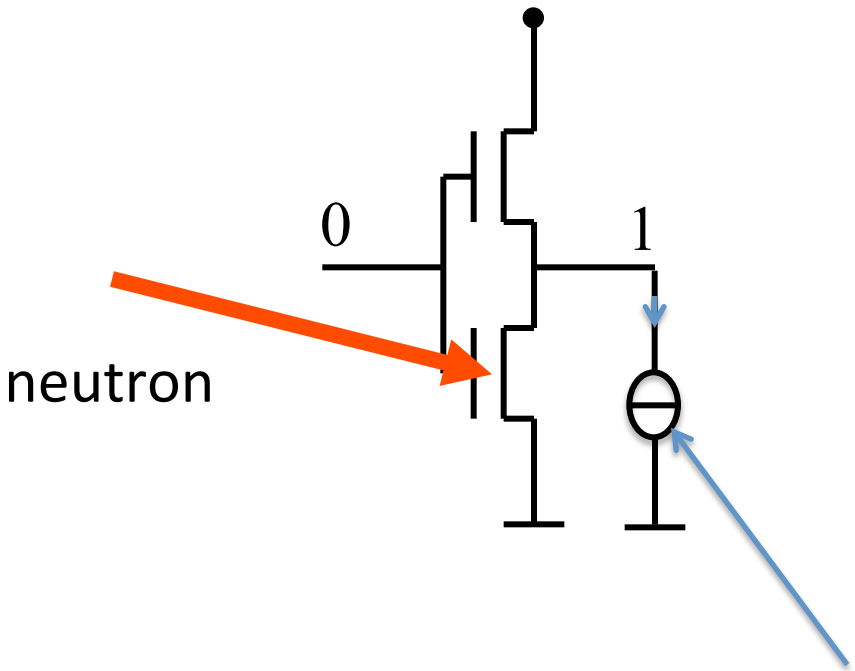
Electron-hole pairs diffusion

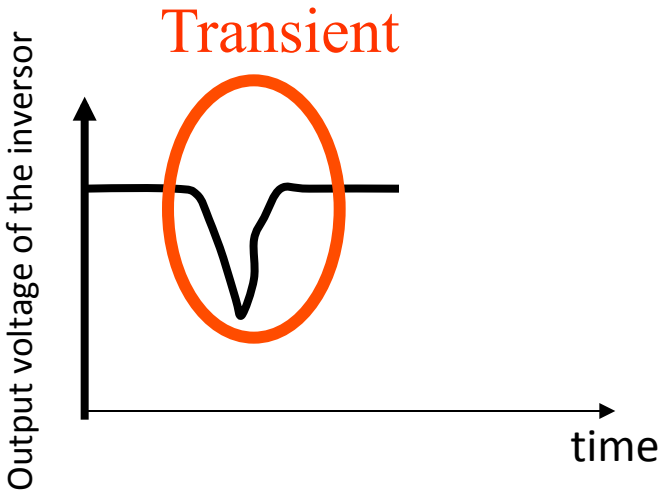


Charge collection



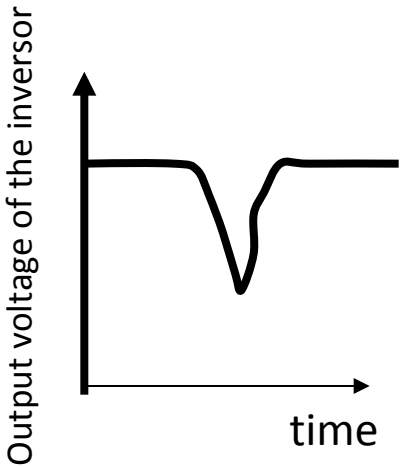
Single Event Transient





Current source representing the transient current generated by the ionizing particle.

Single Event Transient



If the transient is :

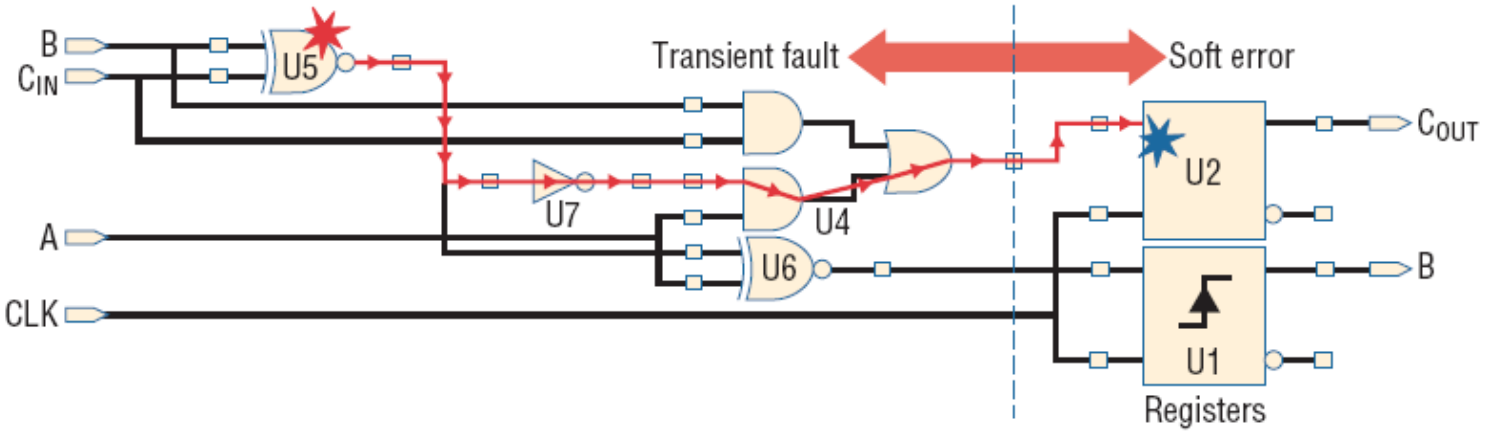
- long enough

and

- high enough

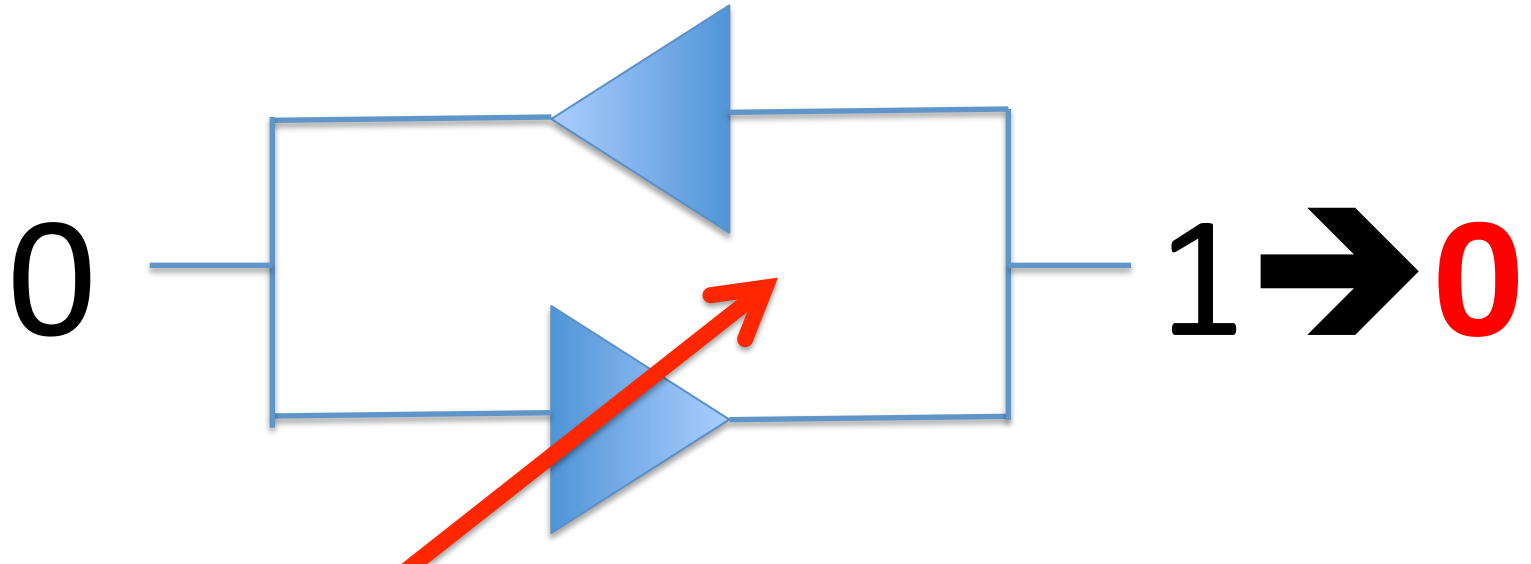
Then the logical state can:

- change for a while
- be propagated

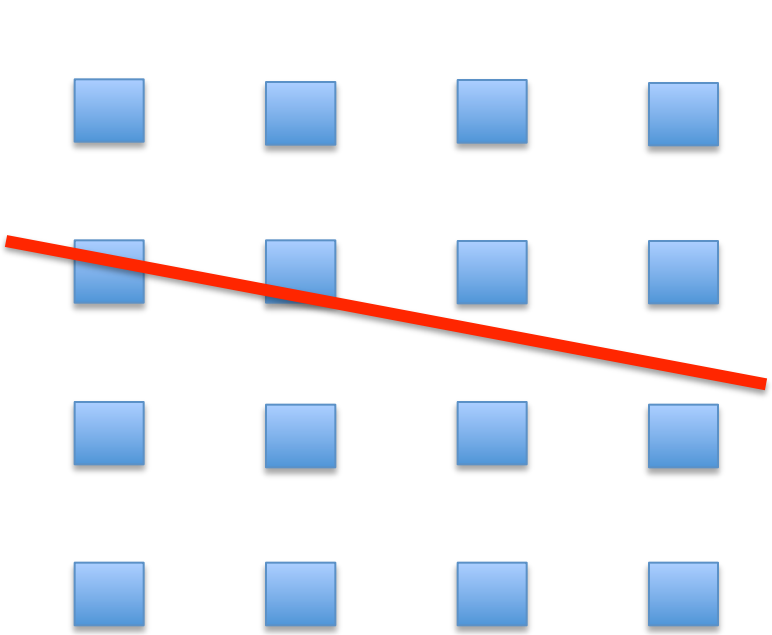


SEU: Single Event Upset

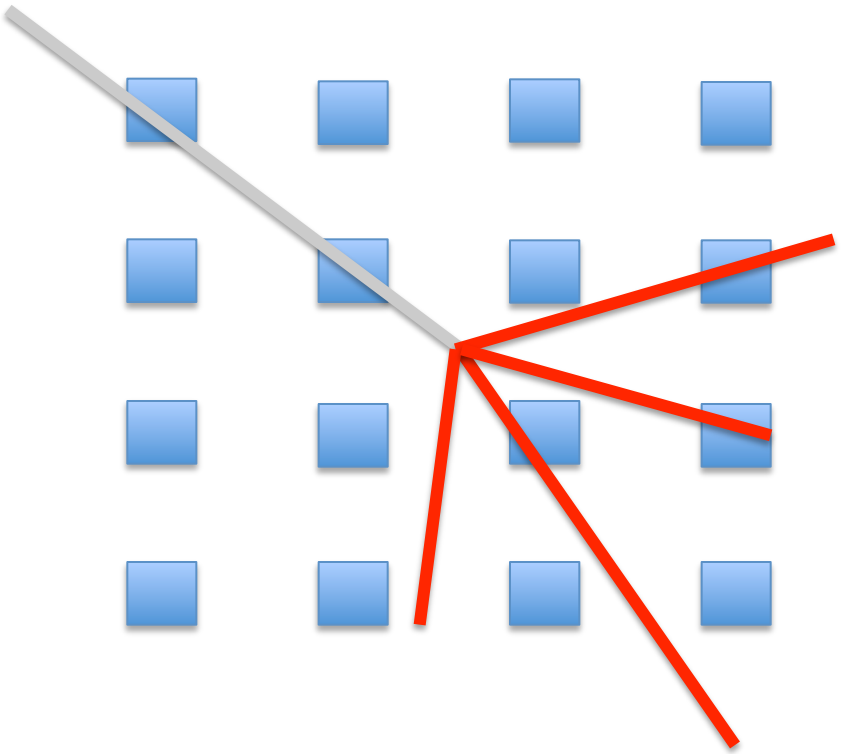
- Change of state in storage element (memory cell or registers)
- This is a particular case of a SET which locks a memory cell.
- It can happen in ALL kind of memory. Nevertheless SRAM are the most sensitive.



Multiple Cell Upset (MCU)



1 ion, 2 SEU



1 neutron, 4 ions, 3 SEU

MBU: Multiple Bits Upset

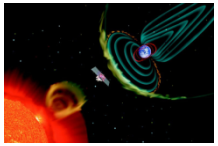
- A multiple-cell upset (MCU) in which two or more error bits occur **in the same word**.
- An MBU cannot be corrected by a simple single-bit ECC.
- To avoid MBU, bits in same word are placed as far as possible one from each other by using appropriate scrambling in the memory design.

Some general ways to address the radiation effects on electronics

- Test under beam (neutrons, protons, ions)
- Laser Test
- Test @ altitude
  - Mountain
  - Onboard
- Test underground
- Simulations

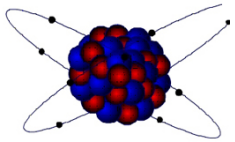
Simulation STEPS … Ideally

Radiative environment



AE8, AP8, OMERE, QARM, IEC, JEDEC…

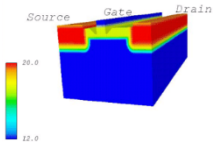
Particle-matter interaction



GEANT 4, FLUKA, MCNPX , PENELOPE, …

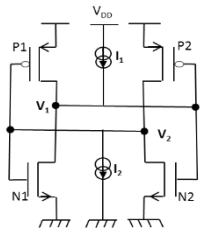
Electrons and holes transport

Transient current(s) at the MOS level



Device simulation tool (transport+Poisson laws)

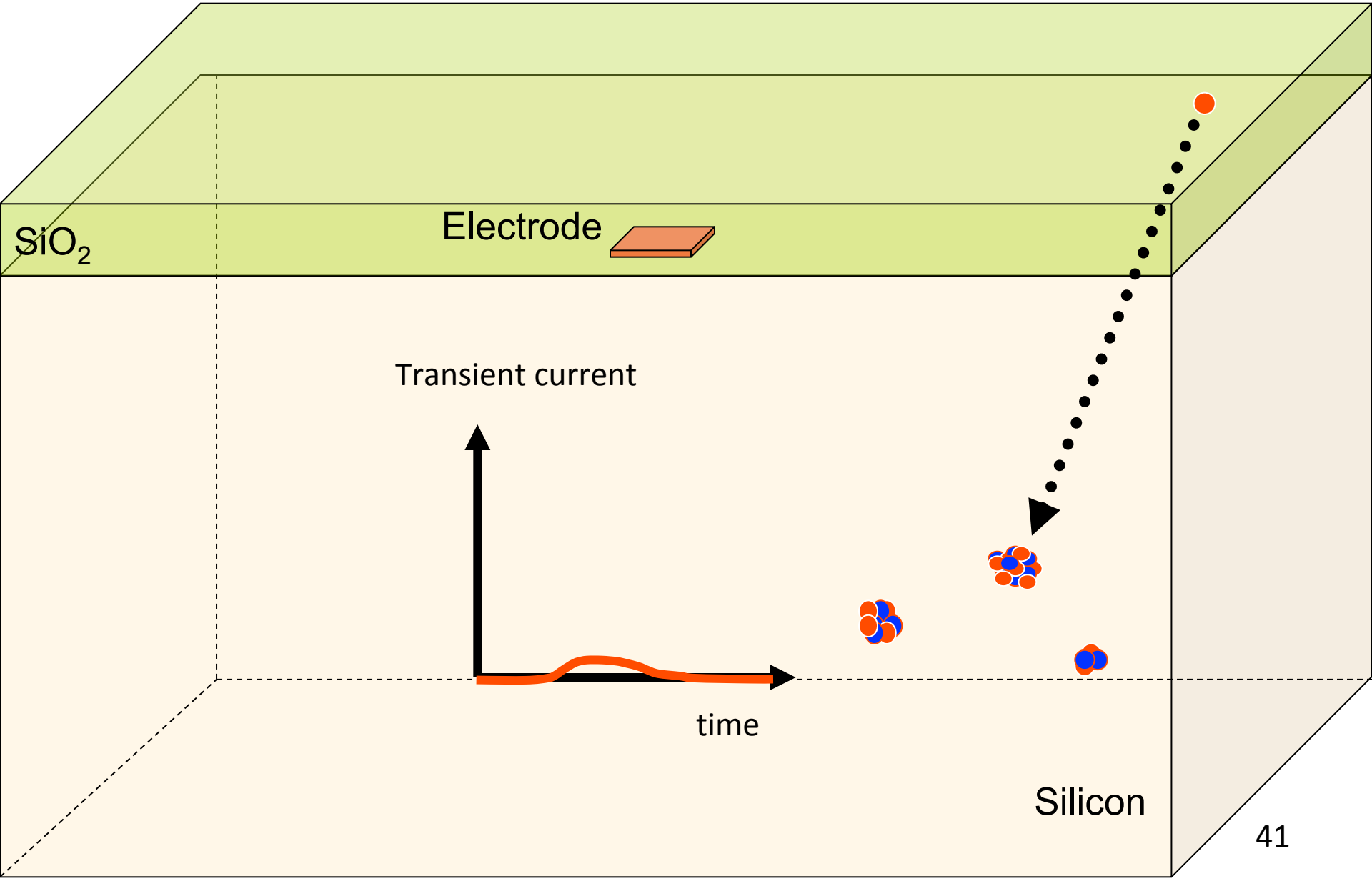
Effect on the cell (SET, SEU …)



Spice, Eldo, …

Effect on the system

SET Monte Carlo Simulation



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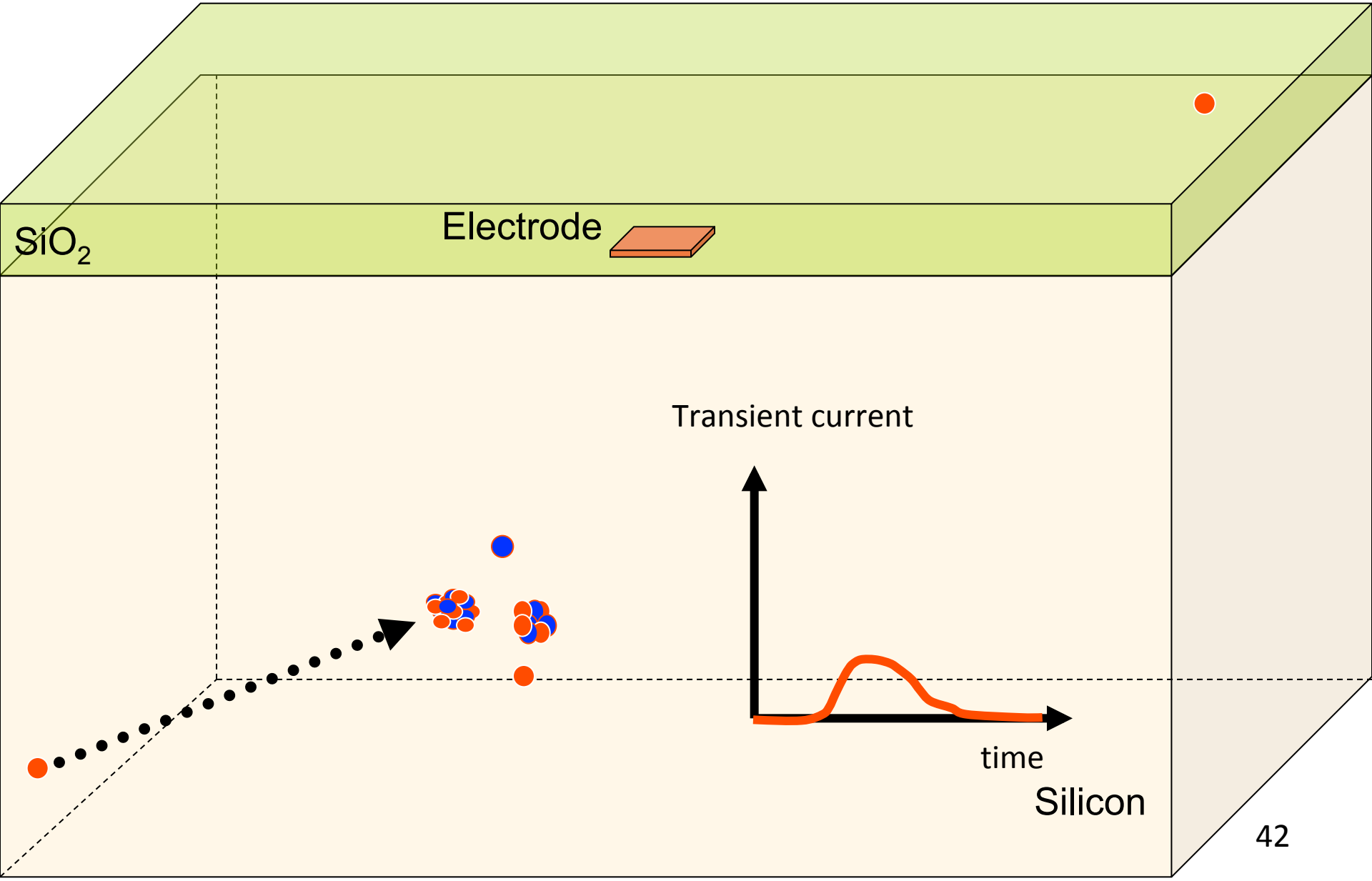
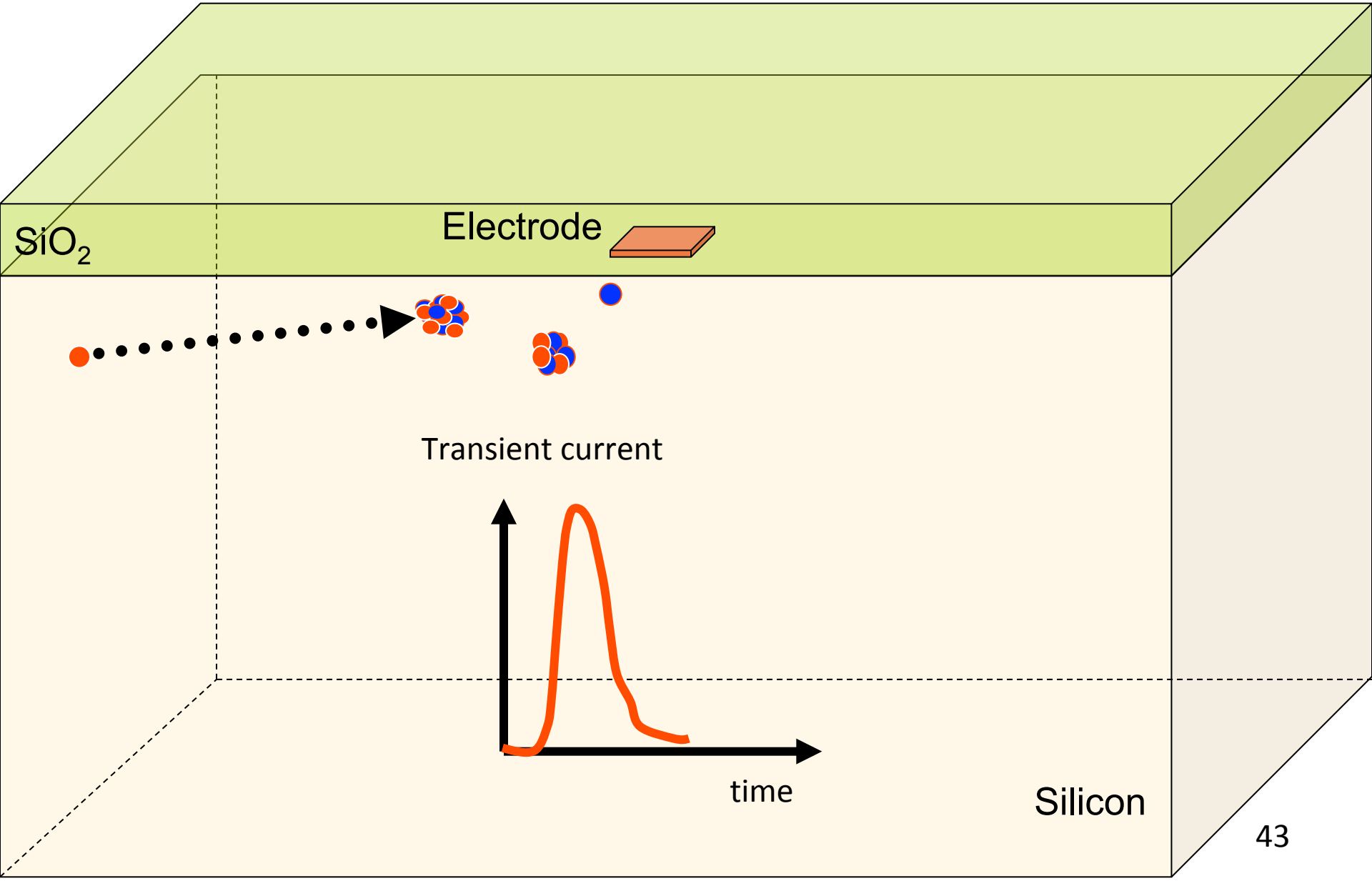
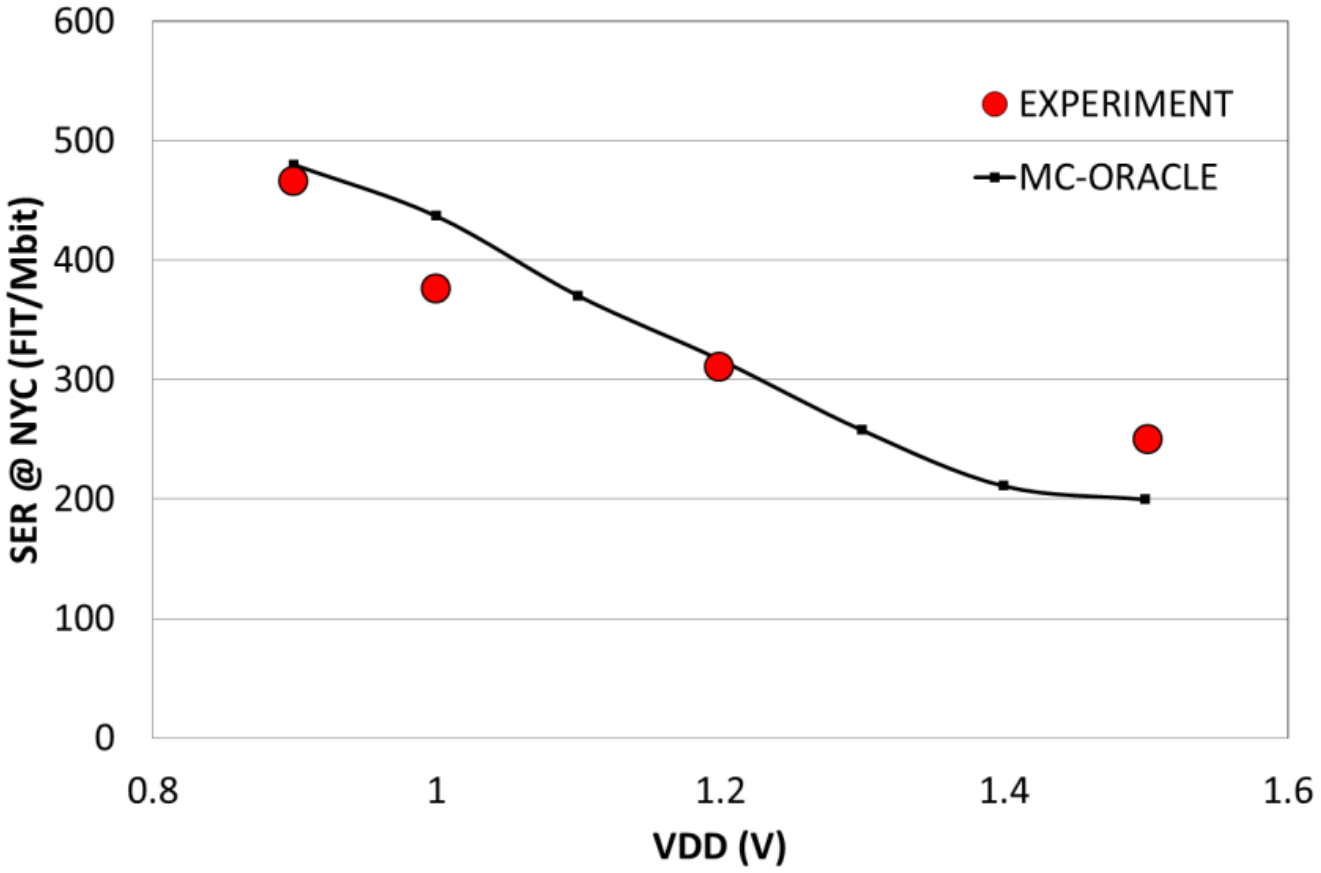


SET Monte Carlo Simulation



Neutrons results example for a 65-nm SRAM



B.D. Sierawski, K. M. Warren, R. A. Reed, R. A. Weller, M. M. Mendenhall, R. D. Schrimpf, R. C. Baumann, and V. Zhu, "Contribution of low-energy (<10MeV) neutrons to upset rate in a 65 nm SRAM," IRPS 2010, IEEE International, pp. 395-399, 2010.

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Conclusion

- In space: protons + electrons + ions
- In atmosphere: neutrons
- 3 family effects: single event, ionizing dose, displacement damage
- For ground level application intrinsic radioactivity (alpha-emitters) are also a concern
- SEE cross section give the sensitivity of device which depends on particle kind and energies
- Most common way to address the sensitivity
  - Experiments (beam or in altitude)
  - Simulations (especially Monte Carlo simulations)