

# SERESSA 2022

5<sup>th</sup> to 9<sup>th</sup> of December at CERN, Geneva

## Modelling and prediction of Single Event Transient and Single Event Upset

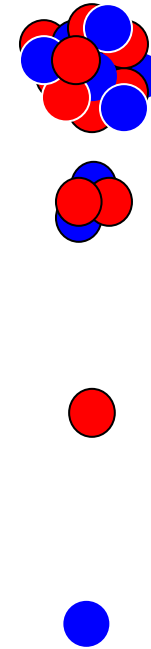
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[frederic.wrobel@umontpellier.fr](mailto:frederic.wrobel@umontpellier.fr)



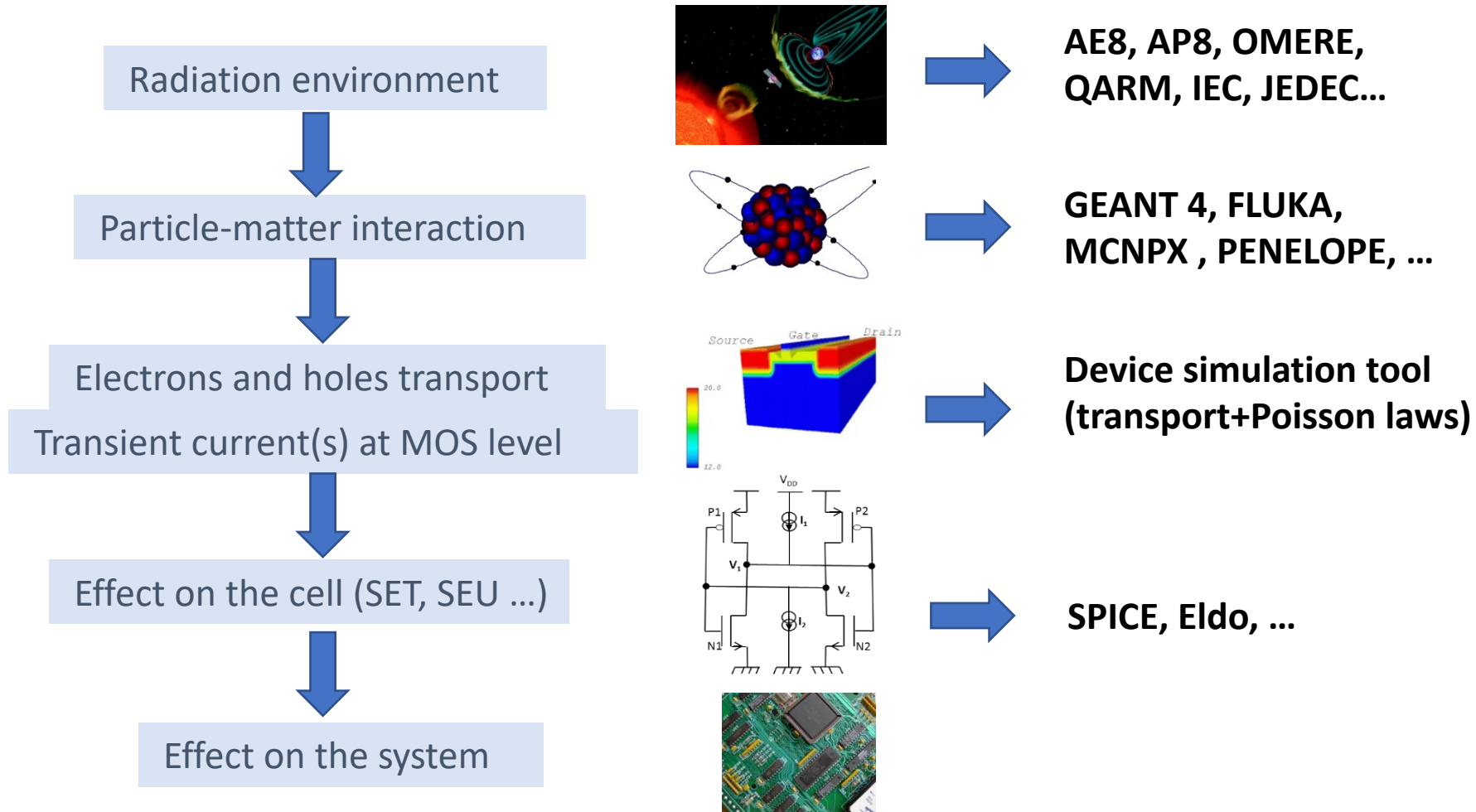
# Particles at play in SEE

- Ions
  - from Space
  - from radioactivity (alpha particle)
- Protons
  - from Space
  - in the upper atmosphere
- Neutrons
  - In atmosphere, even at ground level!



How can we predict the effect of these particles on electronics?

# Multi-scale / Multi-physics

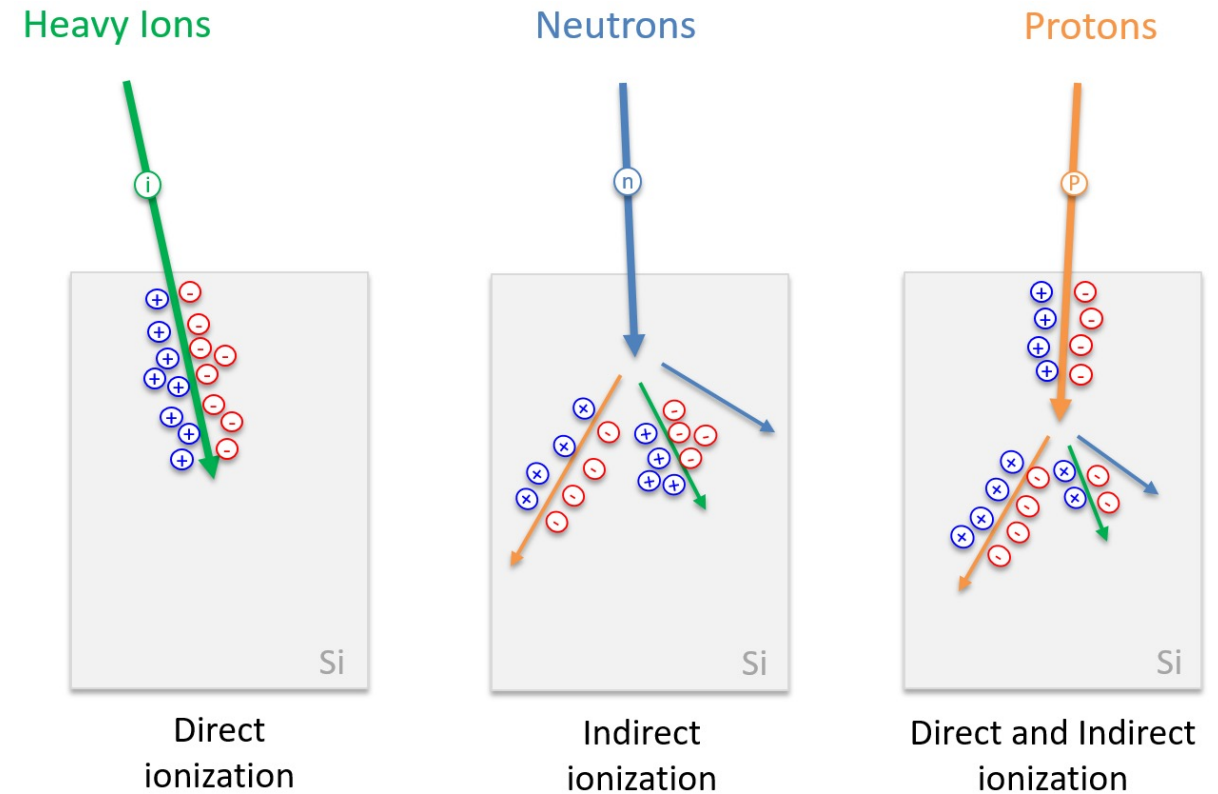


# Agenda

- Context
- **Particle interaction with matter**
- Monte Carlo approach
  - ✓ Monte Carlo?
  - ✓ RPP
  - ✓ Diffusion-Drift model
  - ✓ Tools examples
- Simulation examples
  - ✓ SET sensitivity
  - ✓ SEU sensitivity
- Conclusions

# Particle interaction

SEE are always triggered following the ionization of the device.



Ygor Quadros De Aguiar, PhD Thesis, Univ. de Montpellier, december 2020

- ❑ **Ions:** they ionize directly the matter by interacting with the electrons of the matter
- ❑ **Neutrons:** they indirectly ionize the matter by producing secondary ions
- ❑ **Protons:** they do both!

# Stopping power

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

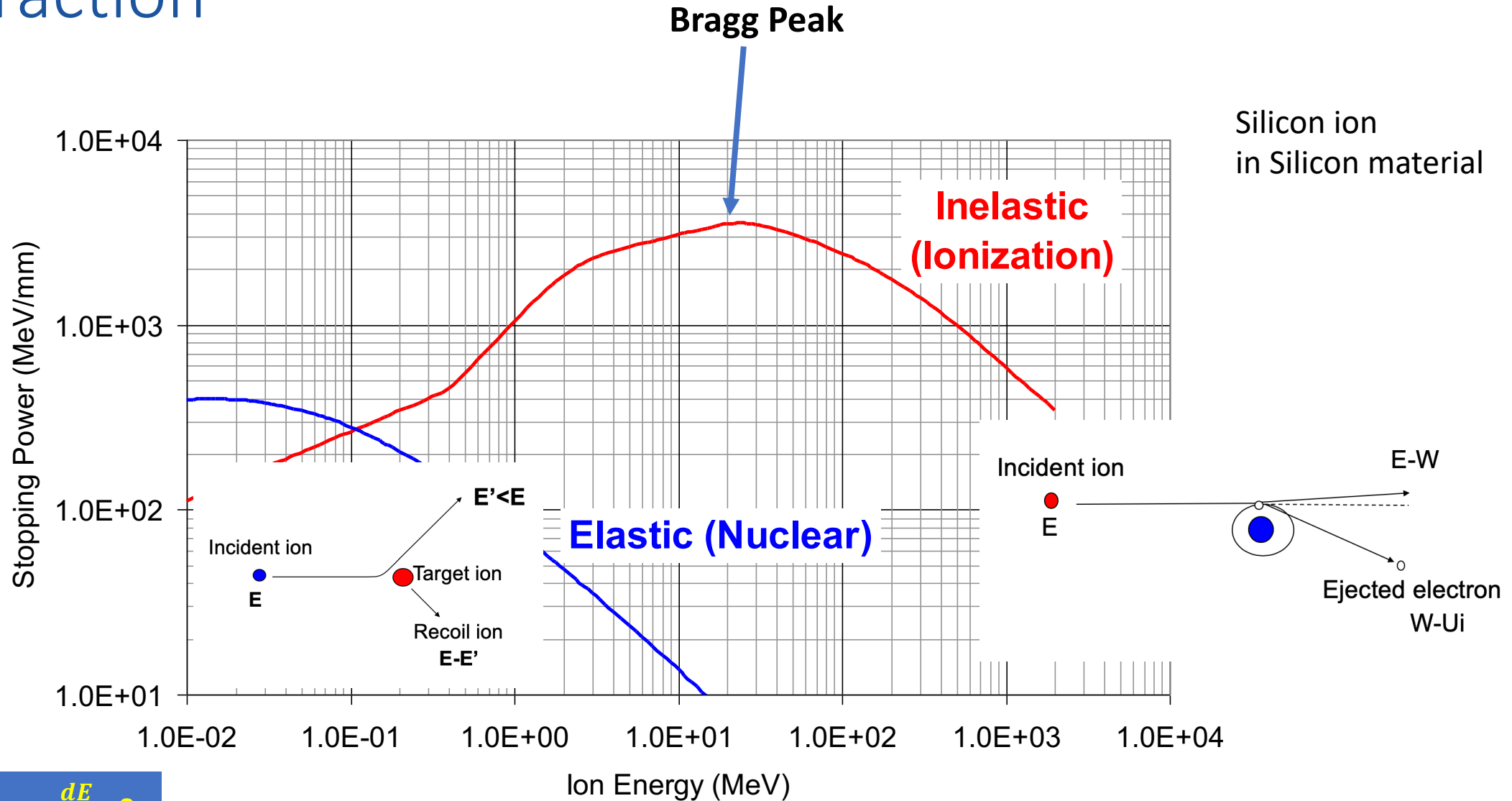
$$\textit{Stopping power} = -\frac{dE}{dx} > 0$$

- 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:

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

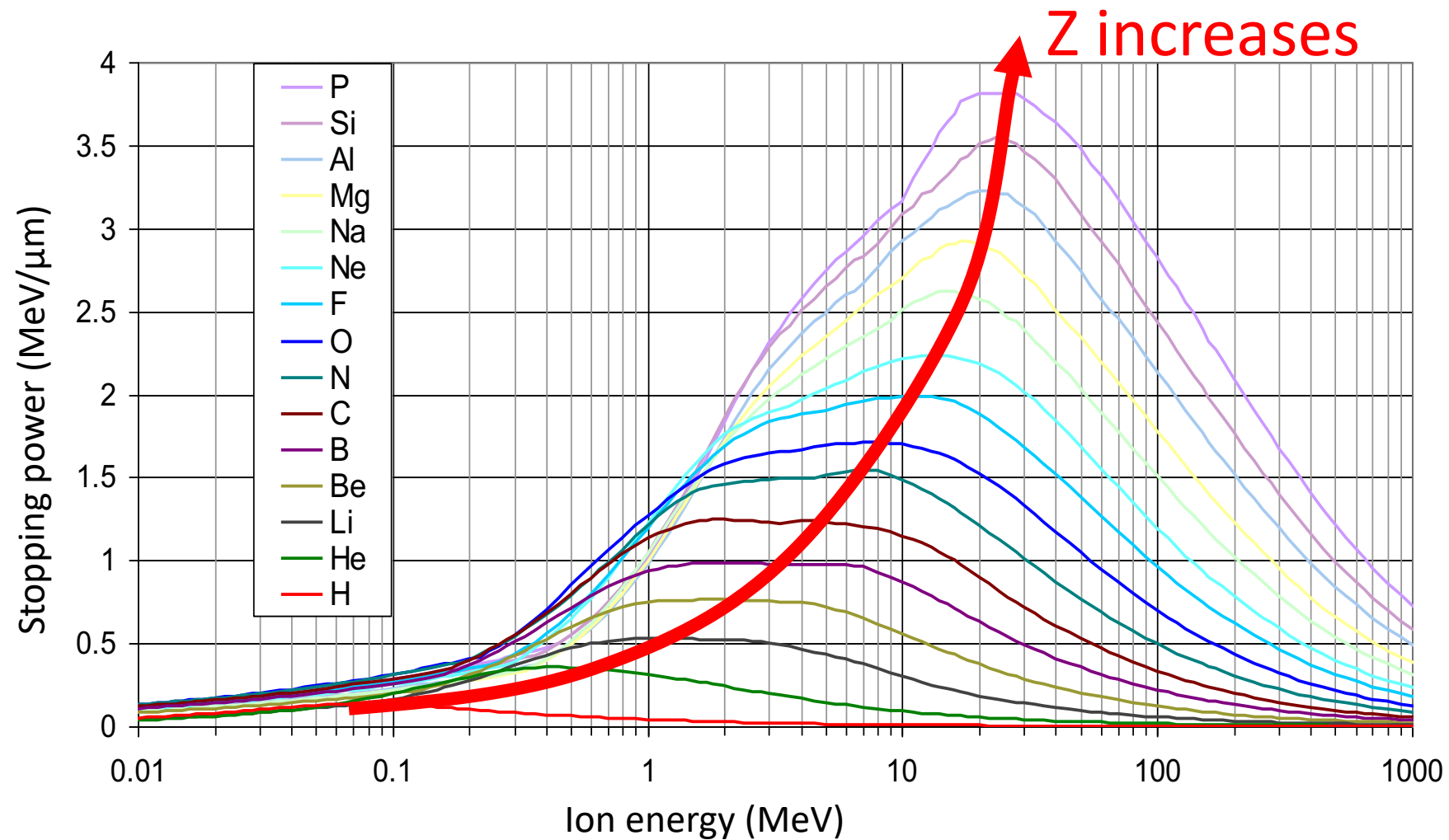
- Therefore, the stopping power is often expressed in **MeV.cm<sup>2</sup>/mg**
  - NB: the volumic mass for silicon is  $\rho=2.32 \text{ g/cm}^3$

# Ion interaction



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

# Direct ionization of ions

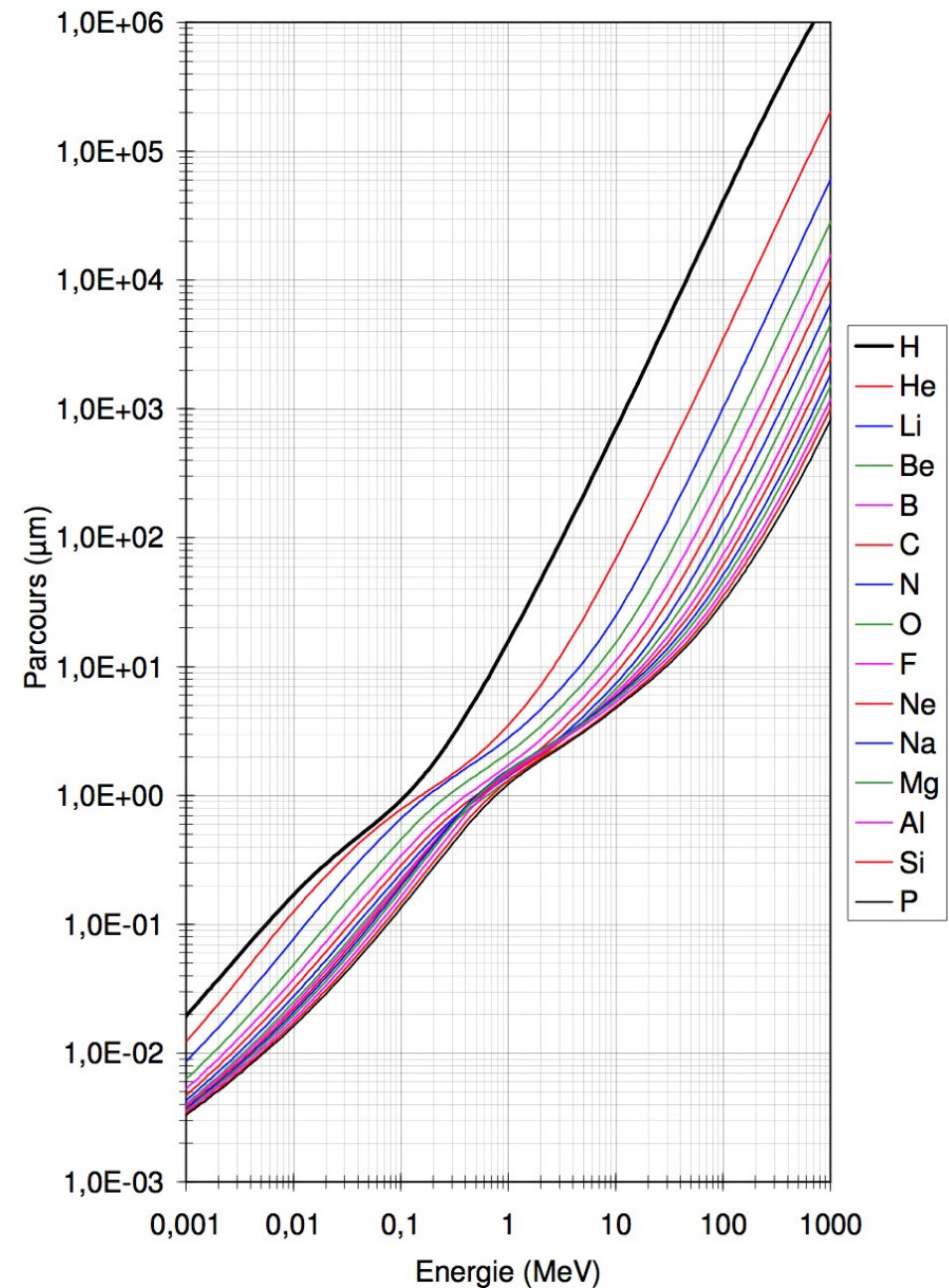


# Range of ions in silicon

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

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

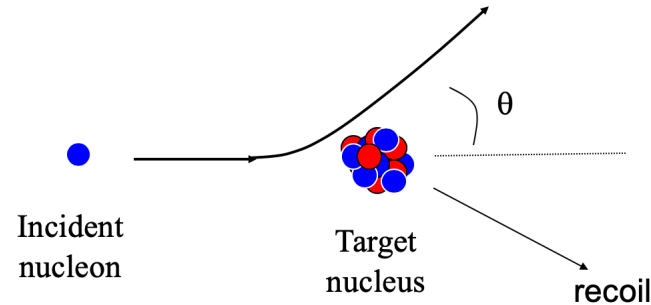
Generally expressed in **cm** or **μm**



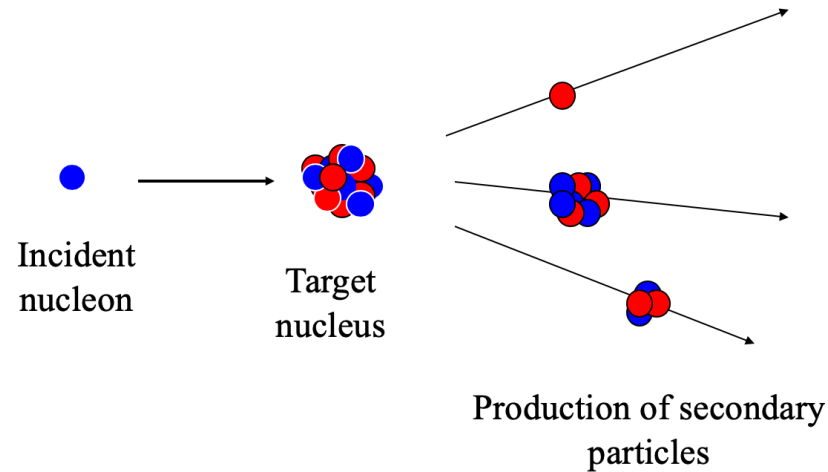
# Nucleons Interactions

The main processes involved in neutrons and protons interactions are:

- Elastic



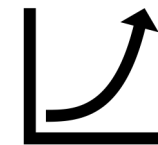
- Nonelastic



Protons are ions: they can also ionize directly the matter!

# First open channel for $n+^{28}\text{Si}$

Reaction products	Threshold (MeV)
$^{29}\text{Si} + \gamma$	0
$^{28}\text{Si} + n$	0
$^{28}\text{Si}^* + n$	1.78
$^{25}\text{Mg} + \alpha$	2.75
$^{28}\text{Al} + p$	4.00
$^{27}\text{Al} + d$	9.70
$^{24}\text{Mg} + n + \alpha$	10.34
$^{27}\text{Al} + n + p$	12.00
$^{26}\text{Mg} + {}^3\text{He}$	12.58
$^{21}\text{Ne} + 2\alpha$	12.99



And they are many others!

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# Monte Carlo method?

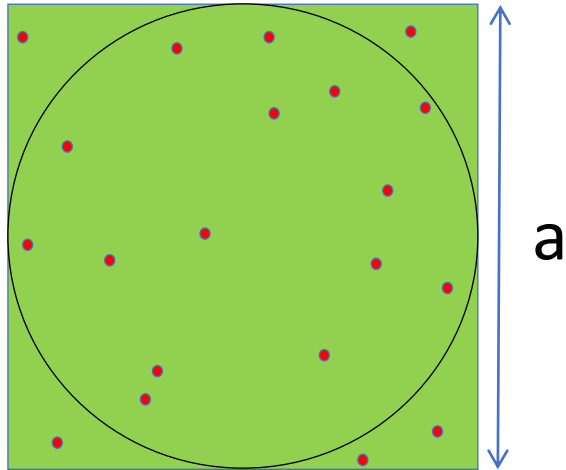
□ During the interaction of particle in the device, there are many possible configurations in terms of:

- Geometry
- Particle nature
- Particle direction
- Particle energy



**Monte Carlo method is very powerful in order to mimic the multitude of scenarii. It uses (pseudo-) random numbers.**

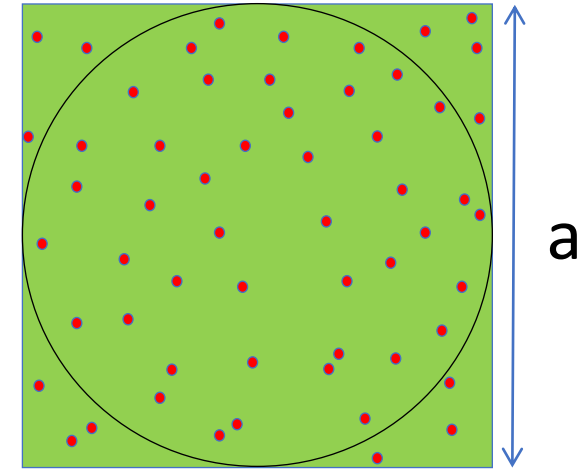
# Example: Calculation of $\pi$ by Monte Carlo



$$N \propto \text{square area} = a^2$$

$$n \propto \text{circle area} = \frac{\pi}{4}a^2$$

$$\pi \approx 4 \frac{n}{N}$$



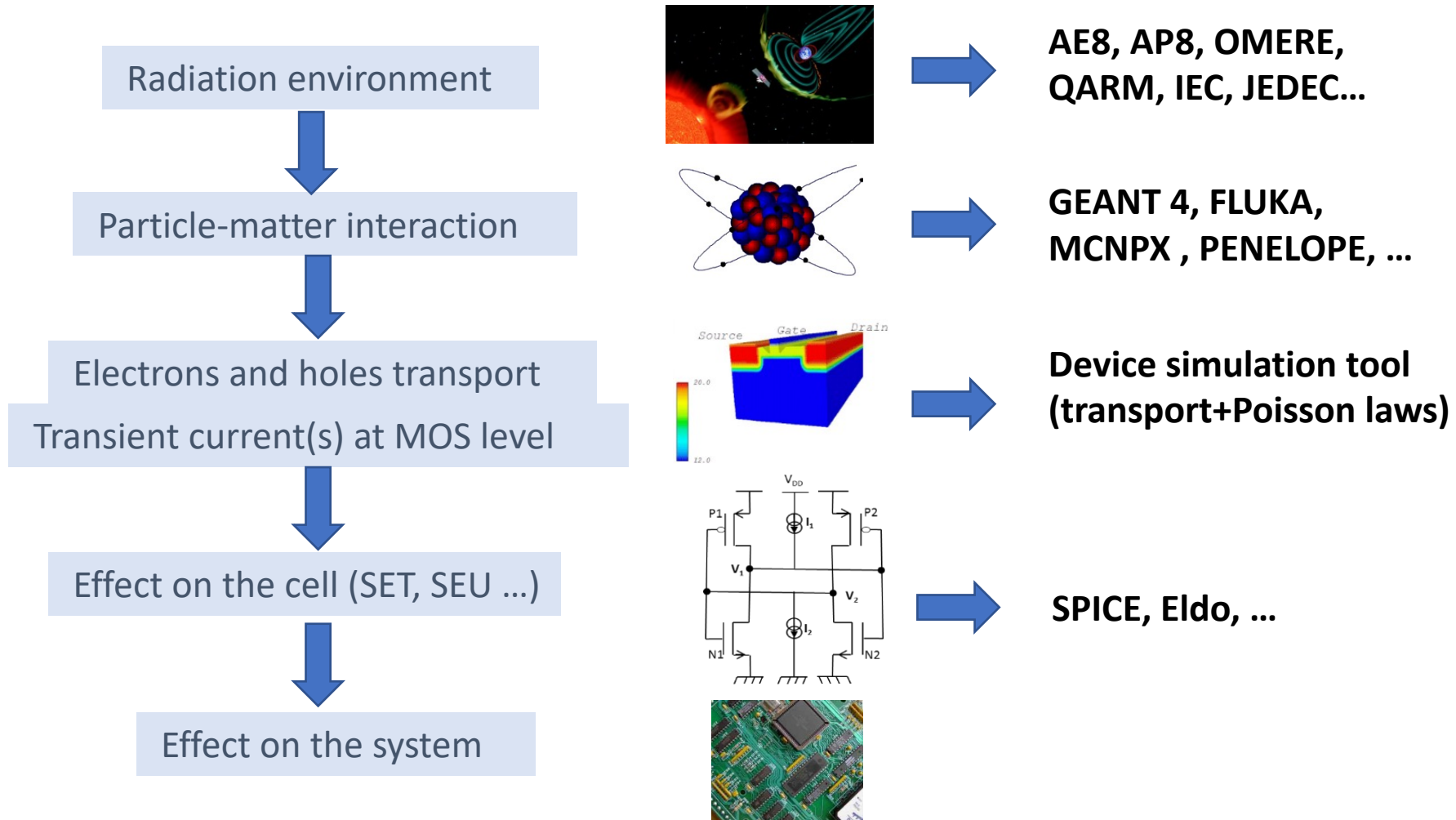
$$\pi \approx 4 \frac{15}{20} = 3.0000$$

$$\pi \approx 4 \frac{44}{56} = 3.1428$$

By increasing the number of points, the accuracy on  $\pi$  is better and better:

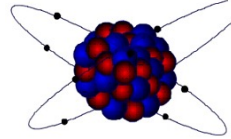
$$\pi = \lim_{N \rightarrow \infty} \left( 4 \frac{n}{N} \right)$$

# Monte Carlo steps



# Particle-matter interaction

Particle-matter interaction



**GEANT 4, FLUKA,  
MCNPX , PENELOPE, ...**

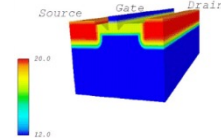
- ✗ **Some useful method and assumptions to decrease calculation time:**
  - Nuclear physics can be pre-computed in database (DHORIN)
  - Ions tracks are assumed to be linear
  - Gamma can be ignored for SEE
  - Secondary neutrons are ignored

# Agenda

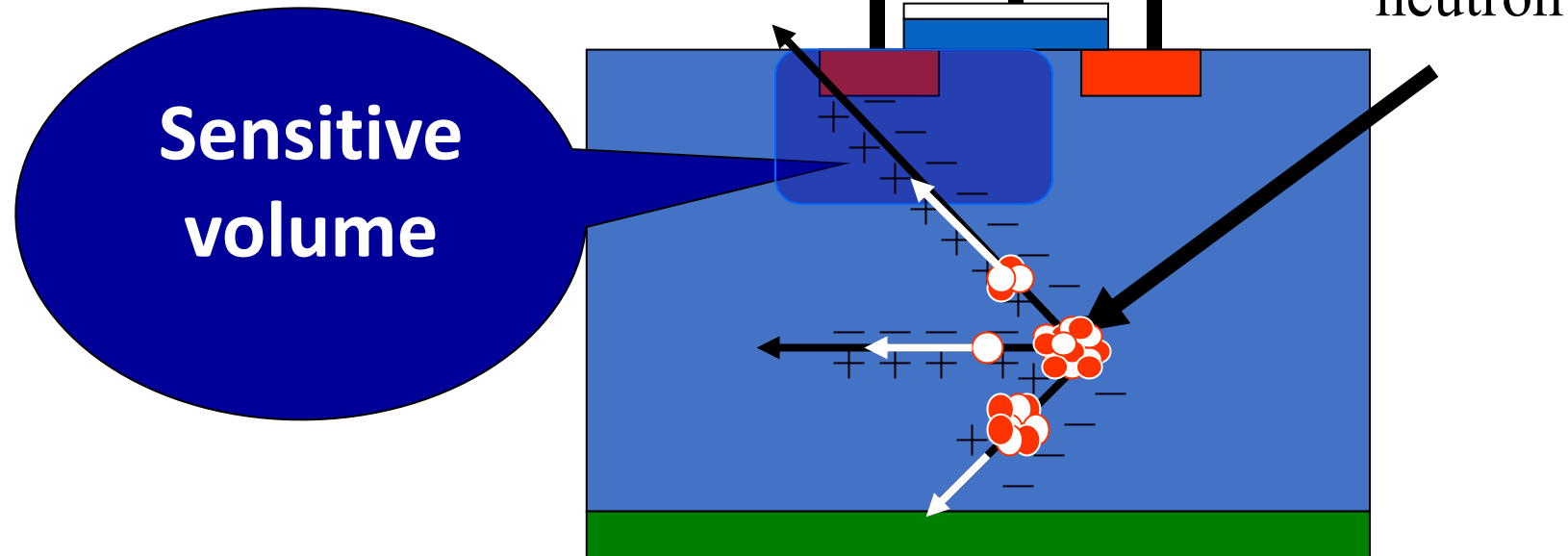
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# The RPP approach

Electrons and holes transport  
Transient current(s) at MOS level



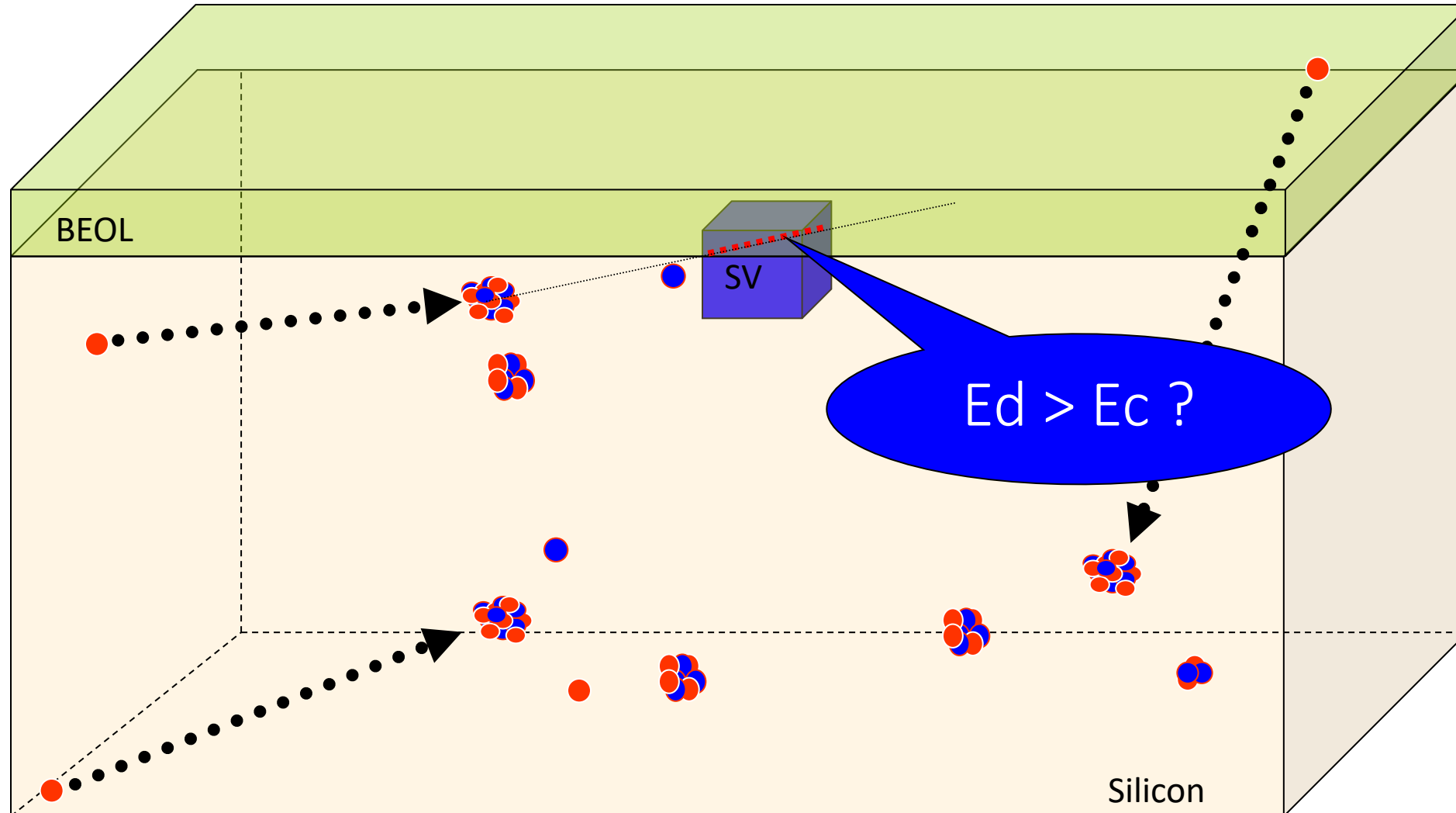
Device simulation tool  
(transport+Poisson laws)



An SEE occurs if:

- an ion crosses the sensitive volume, AND
- the deposited energy is high enough (>critical energy)

# SEU simulations



# Cross section

The concept of a **cross section** is used to express the probability of triggering an SEE. It is defined by:

The diagram shows the formula for cross section,  $\sigma = \frac{N}{\Phi}$ , enclosed in a black-bordered box. Three arrows point from labels outside the box to the variables in the formula: one from the top-right to  $N$ , one from the bottom-right to  $\Phi$ , and one from the bottom-left to  $\sigma$ . The labels are: "Number of « events »" for  $N$ , "Fluence (part/cm<sup>2</sup>)" for  $\Phi$ , and "Cross section (cm<sup>2</sup>)" for  $\sigma$ . The entire diagram is set against a light yellow background within a red border.

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

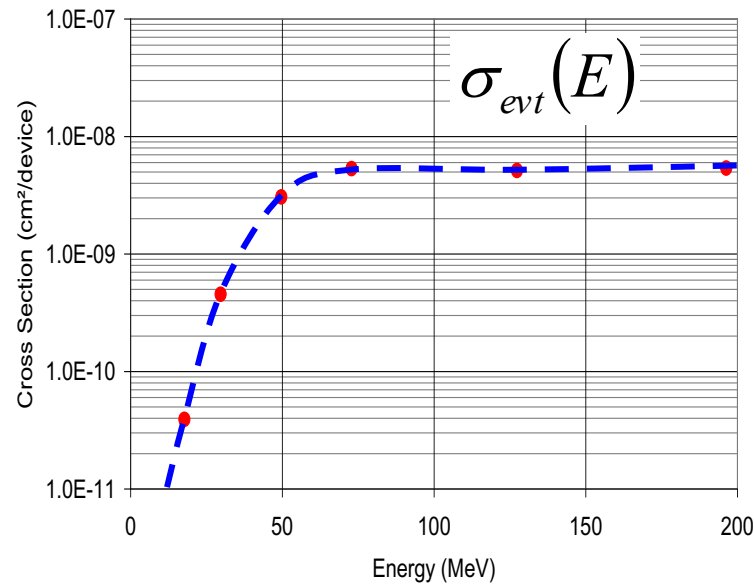
Number of « events »

Fluence (part/cm<sup>2</sup>)

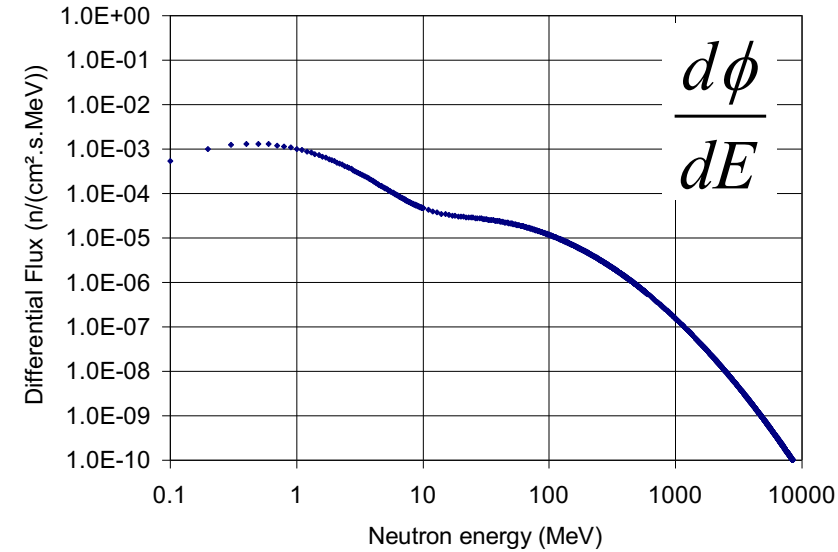
Cross section (cm<sup>2</sup>)

# Soft Error Rate (SER)

Device



Environment

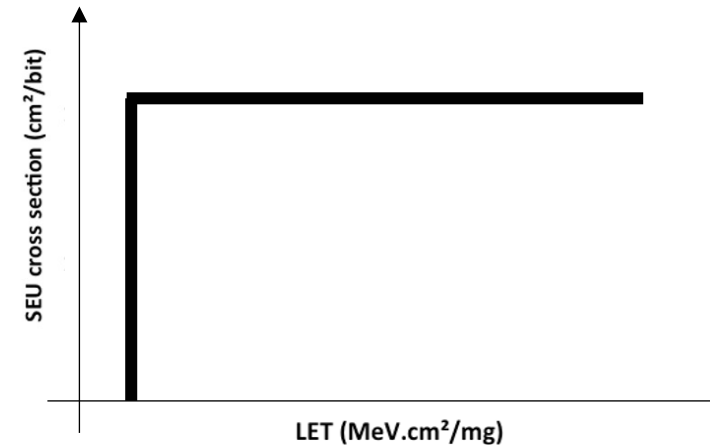
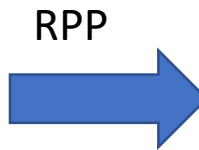
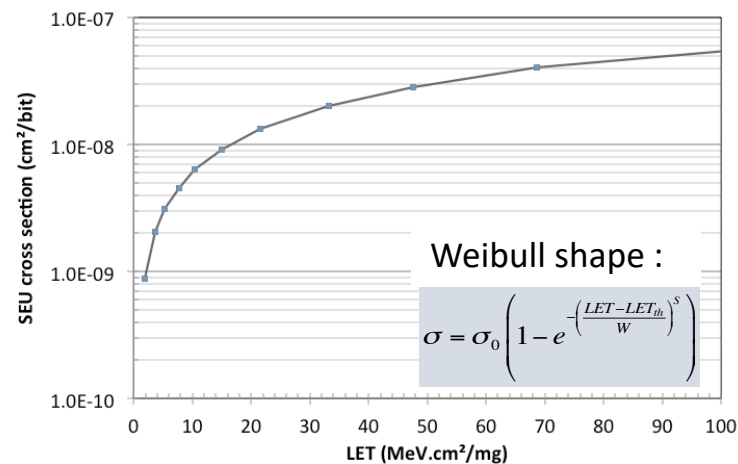


$$SER = \int \frac{d\phi}{dE} \cdot \sigma_{evt}(E) dE$$

# Limitations

The method is often used to obtain general trends but it has 3 main limitations:

- ❑ Requires 2 empirical parameters: sensitive volume size + critical energy (critical charge)
- ❑ No time dependence: SET?
- ❑ Does not actually reproduce heavy ion cross section (only gives a step function)

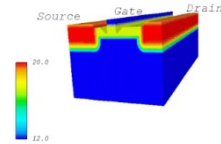


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# Transient current at MOS level

Electrons and holes transport  
Transient current(s) at MOS level

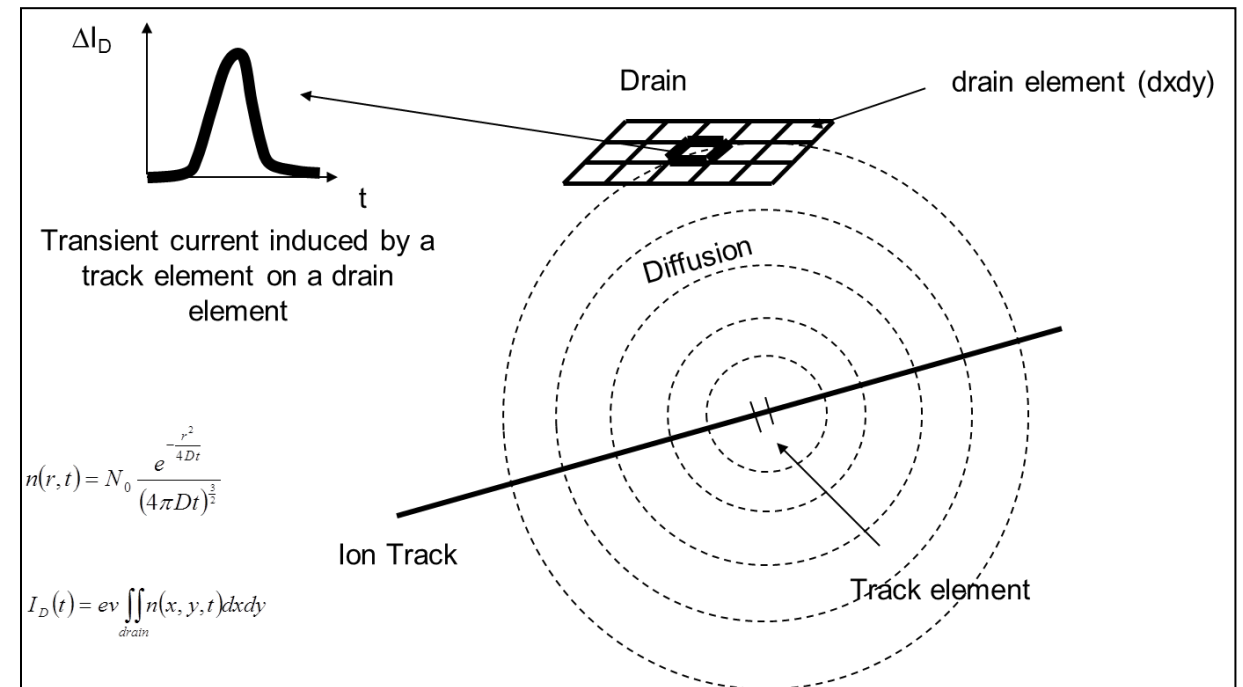


**Device simulation tool  
(transport+Poisson laws)**

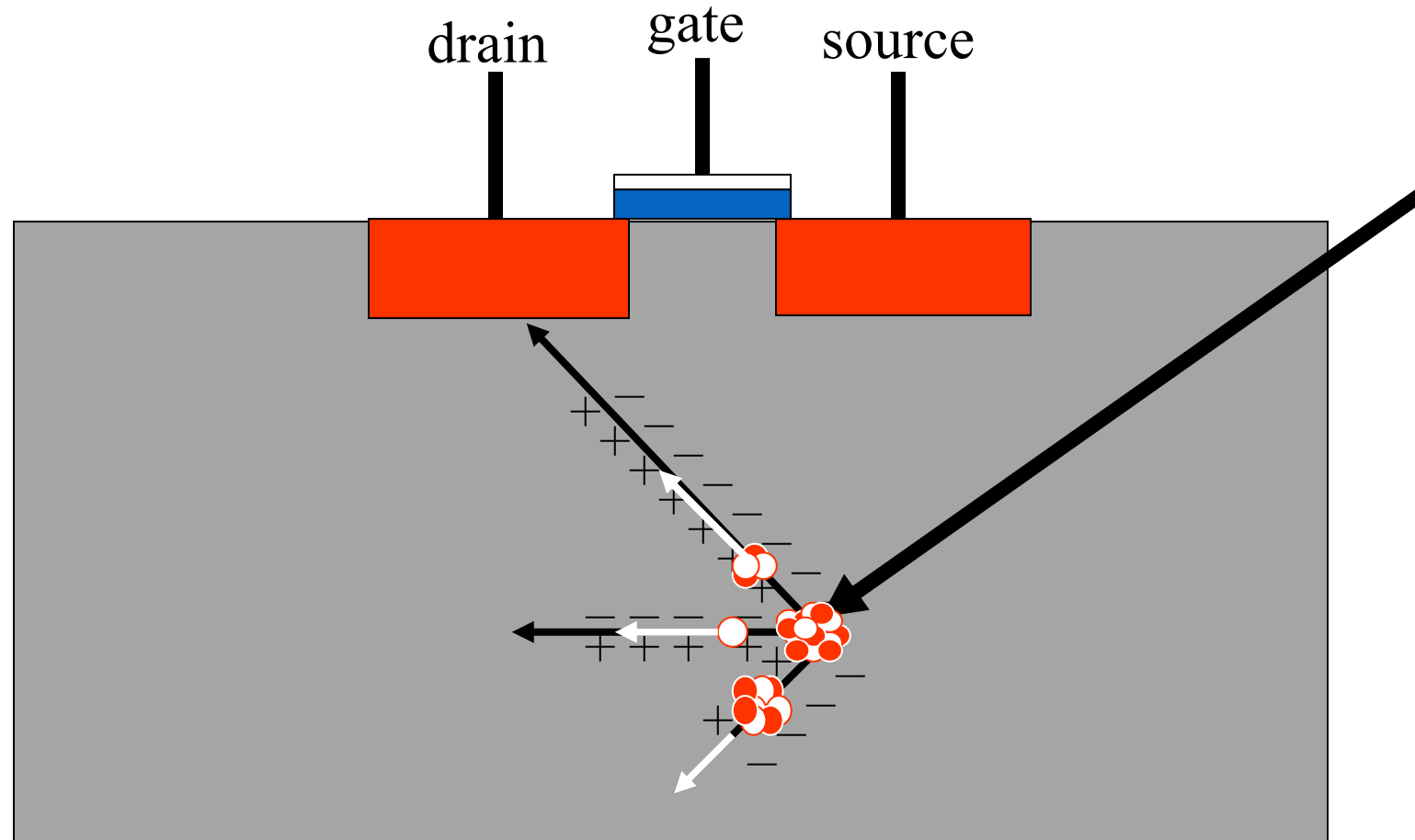
- ❑ Device simulation tool are very CPU-consuming
- ❑ They solve transport and Poisson laws
- ❑ The structure must be well known

Alternately,

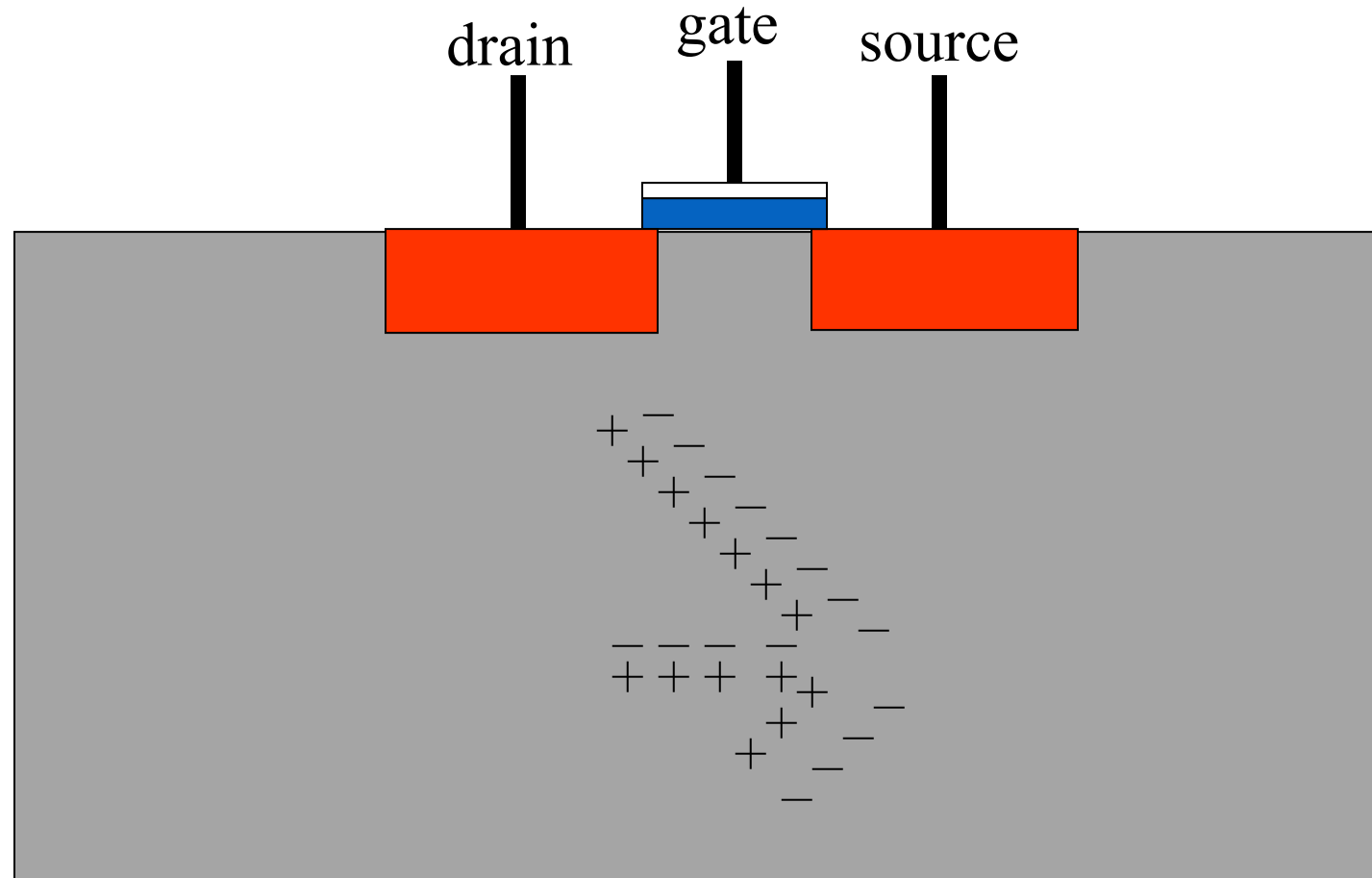
- ❑ The diffusion-collection model allow estimating the transient current
- ❑ No mesh but an integration over the track and the drain area as a function of time
- ❑ A basic structure is used



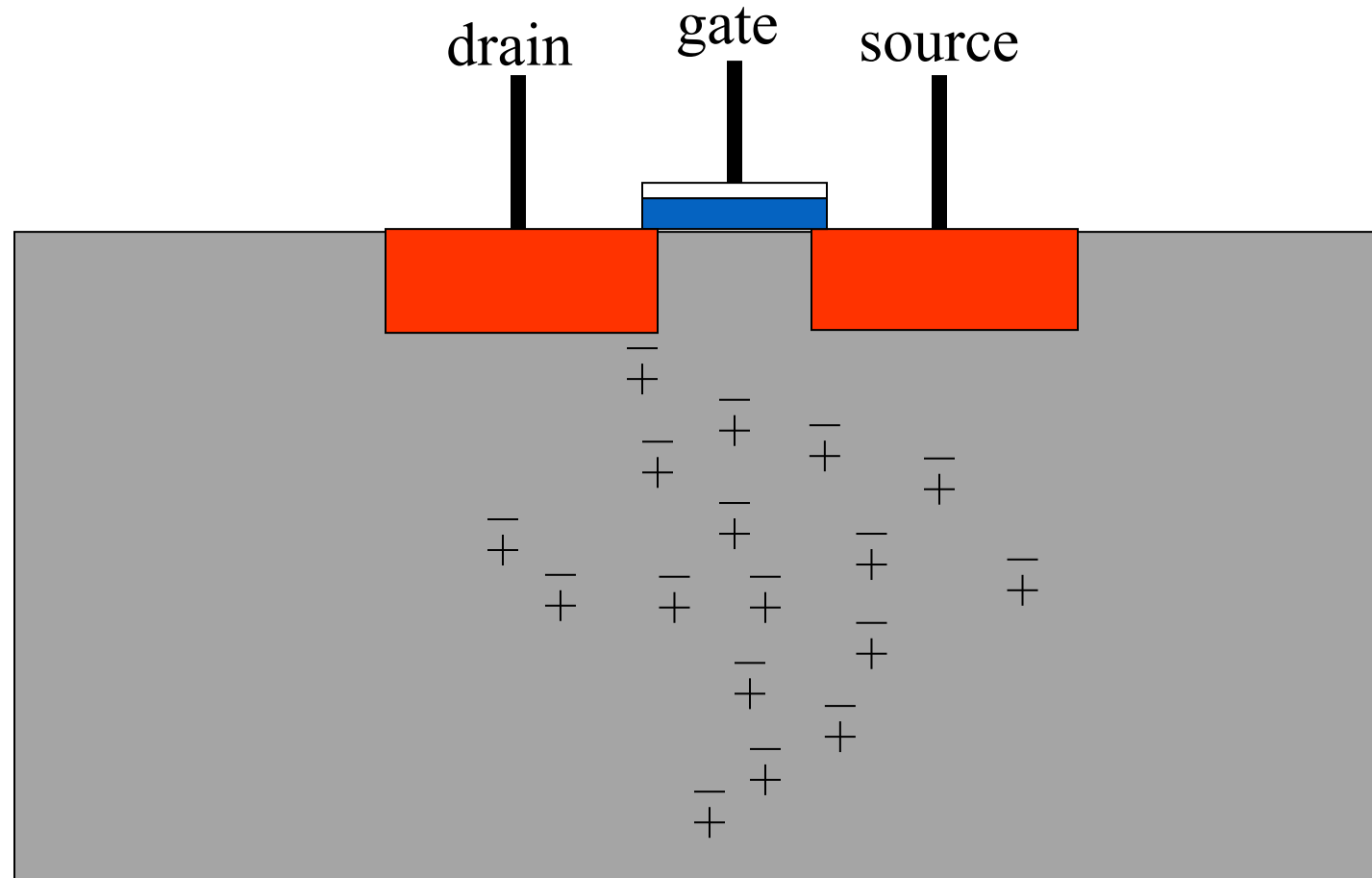
# The diffusion-drift model



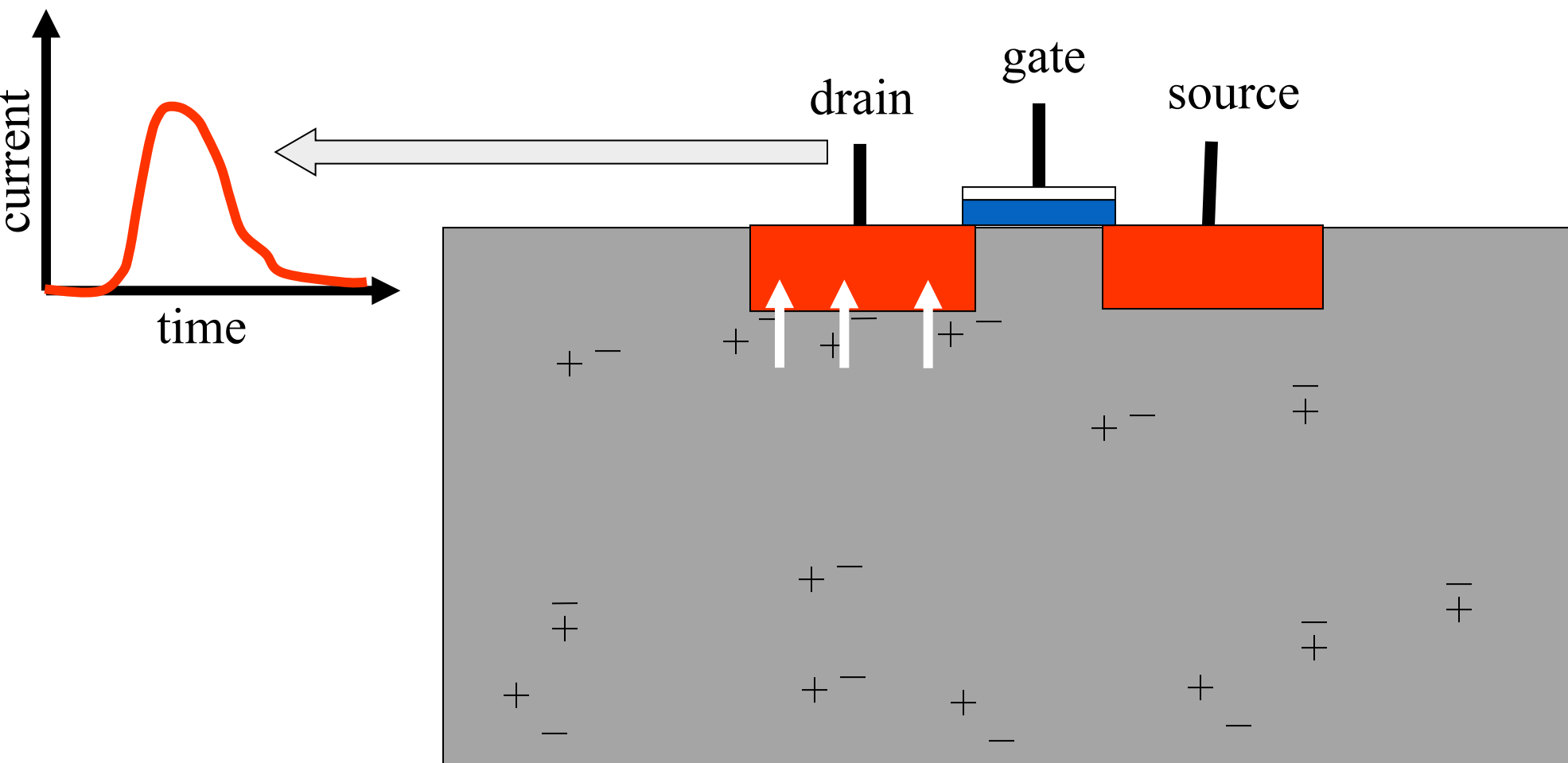
# The diffusion-drift model



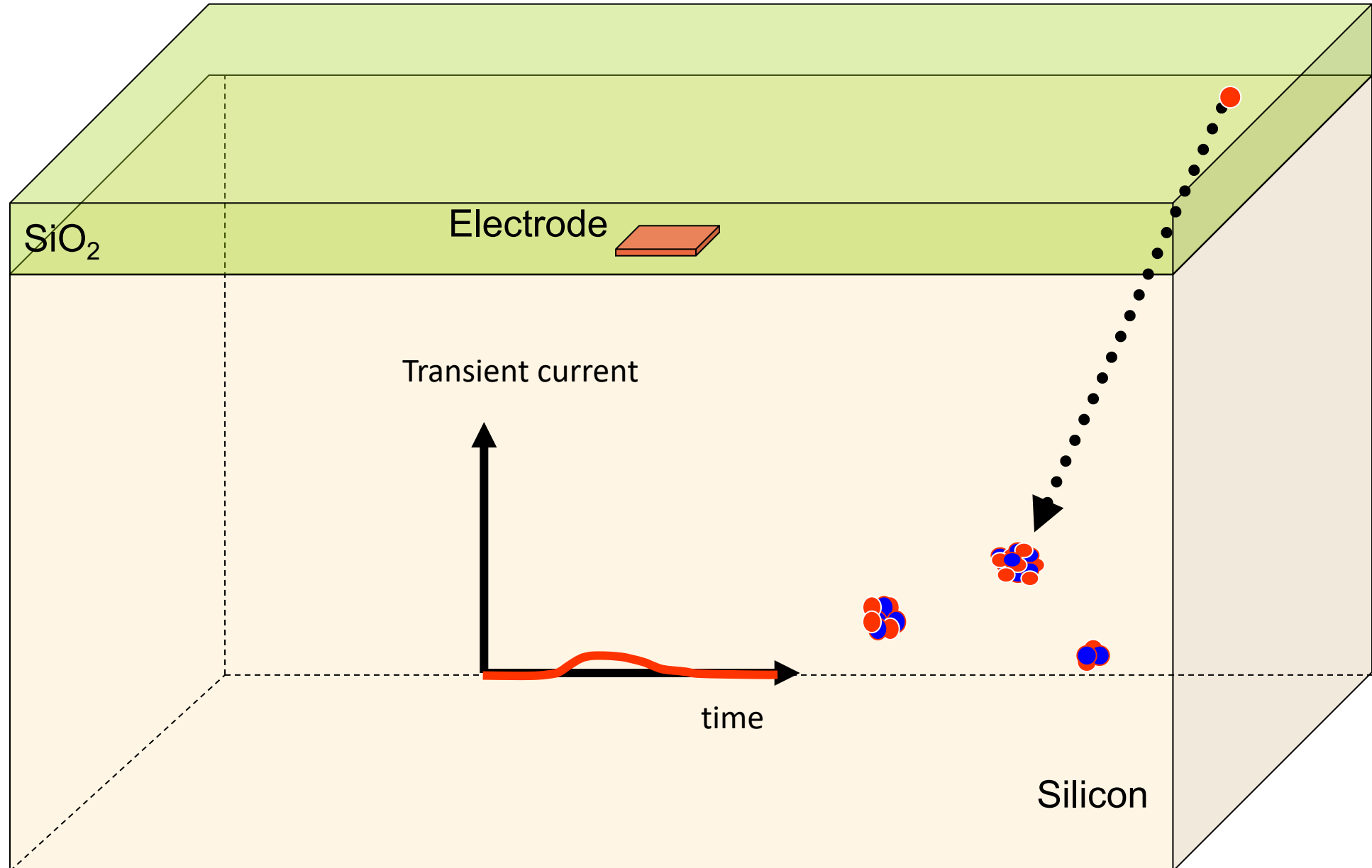
# The diffusion-drift model



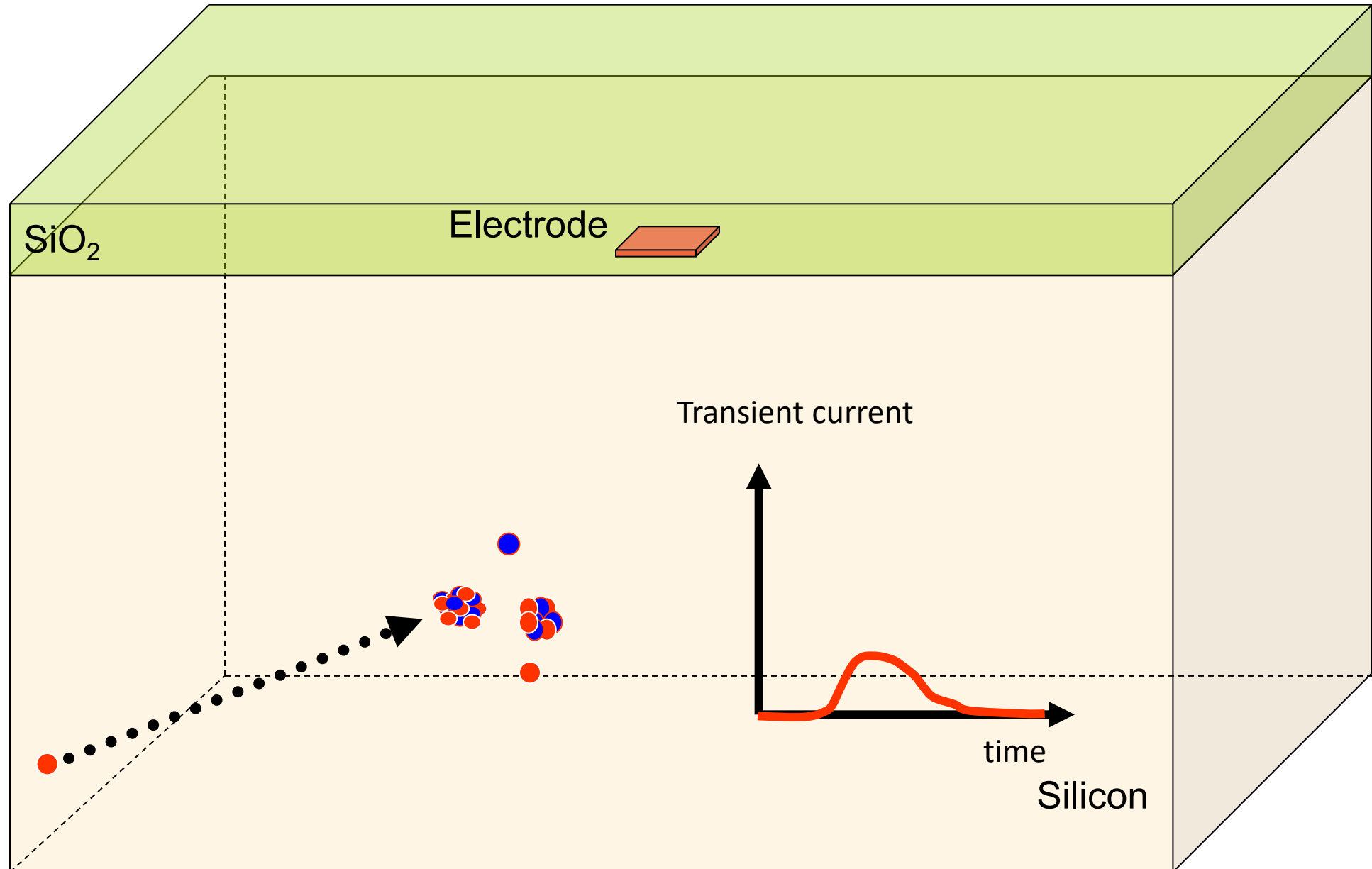
# The diffusion-drift model



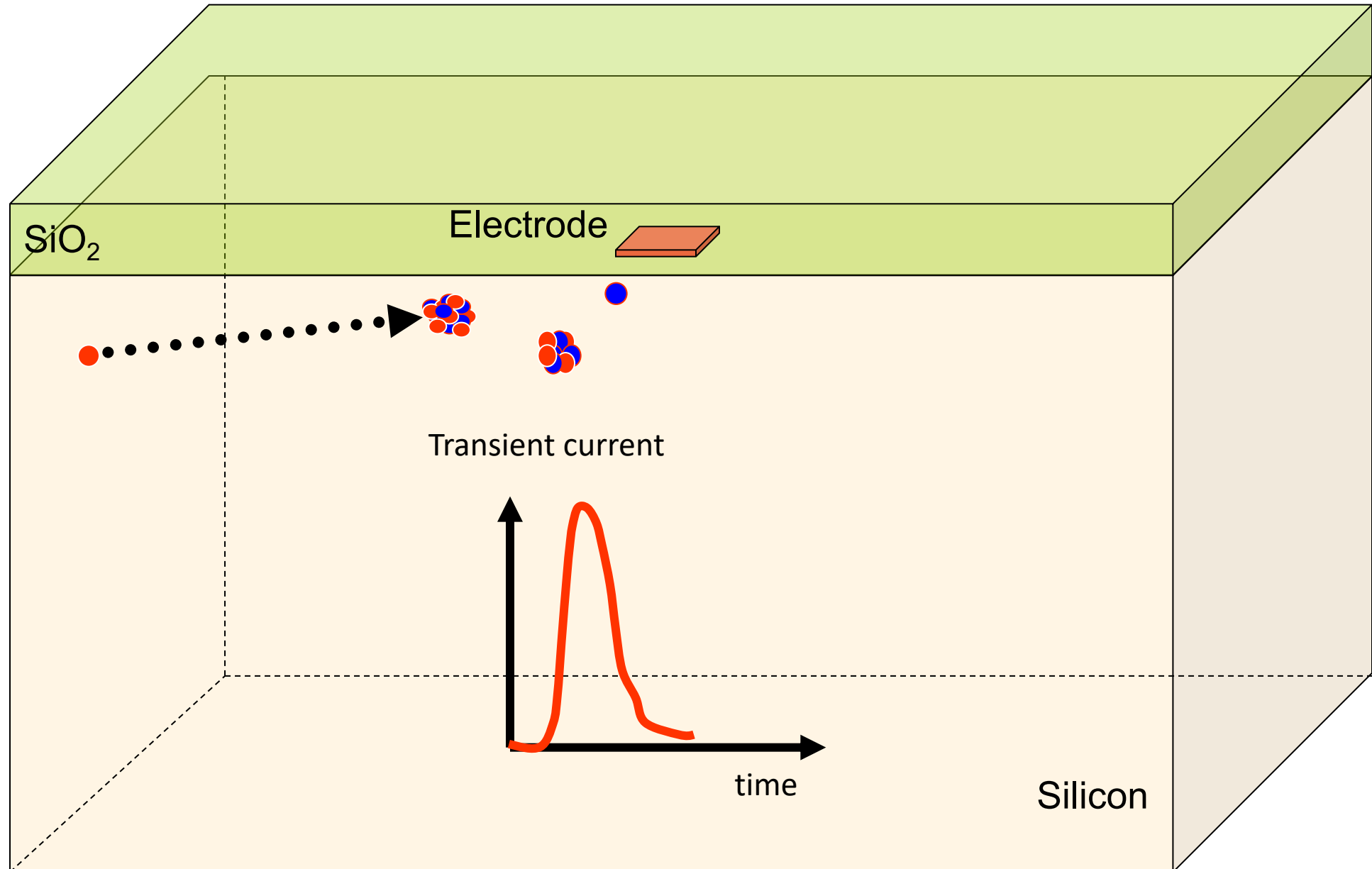
# SET Monte Carlo simulation



# SET Monte Carlo simulation



# SET Monte Carlo simulation



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# Monte Carlo tools

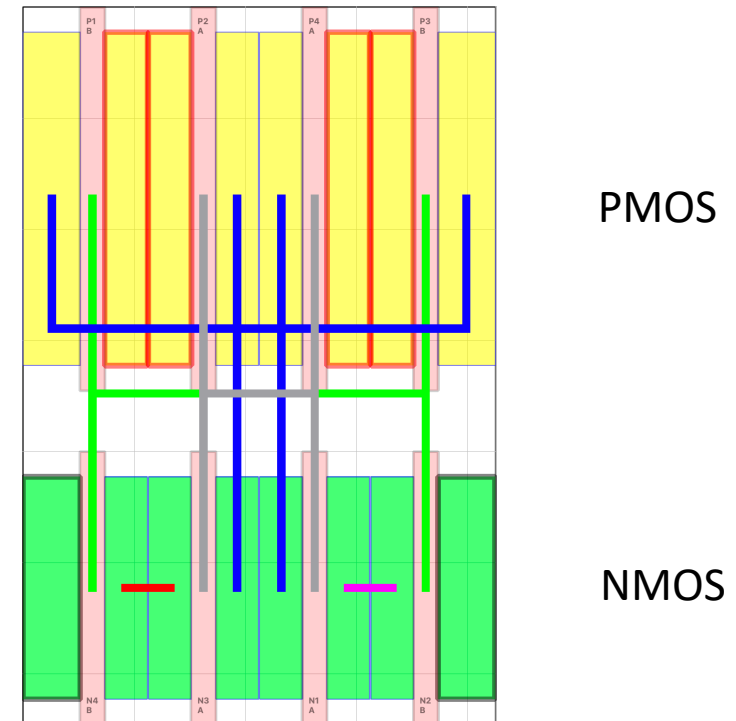
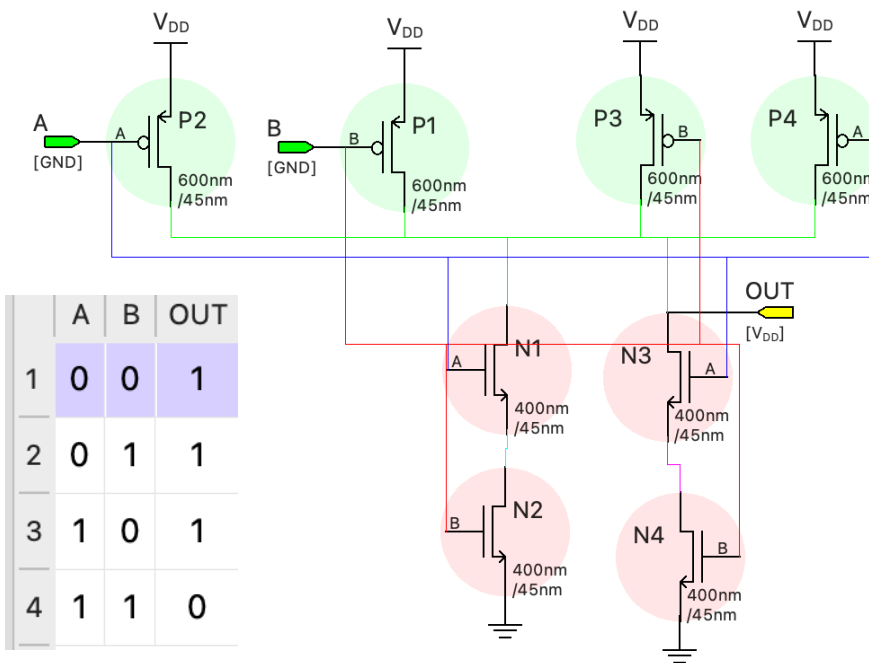
□ Tools are generally proprietary. Some examples:

Company	Tool
Airbus	DASIE
ST-Microelectronics	TIARA
Onera	MUSCA
IBM	SEMM
Clemson University	CUPID
Vanderbilt University	MRED
G4-SEE	CERN
Montpellier University	MC-ORACLE then PredicSEE

# Circuit in PredicSEE

## □ Impact on the sensitivity of digital circuits considering:

- different transistor layout design approaches (i.e., sizing, placement, folding)
- the implications of the input stimuli

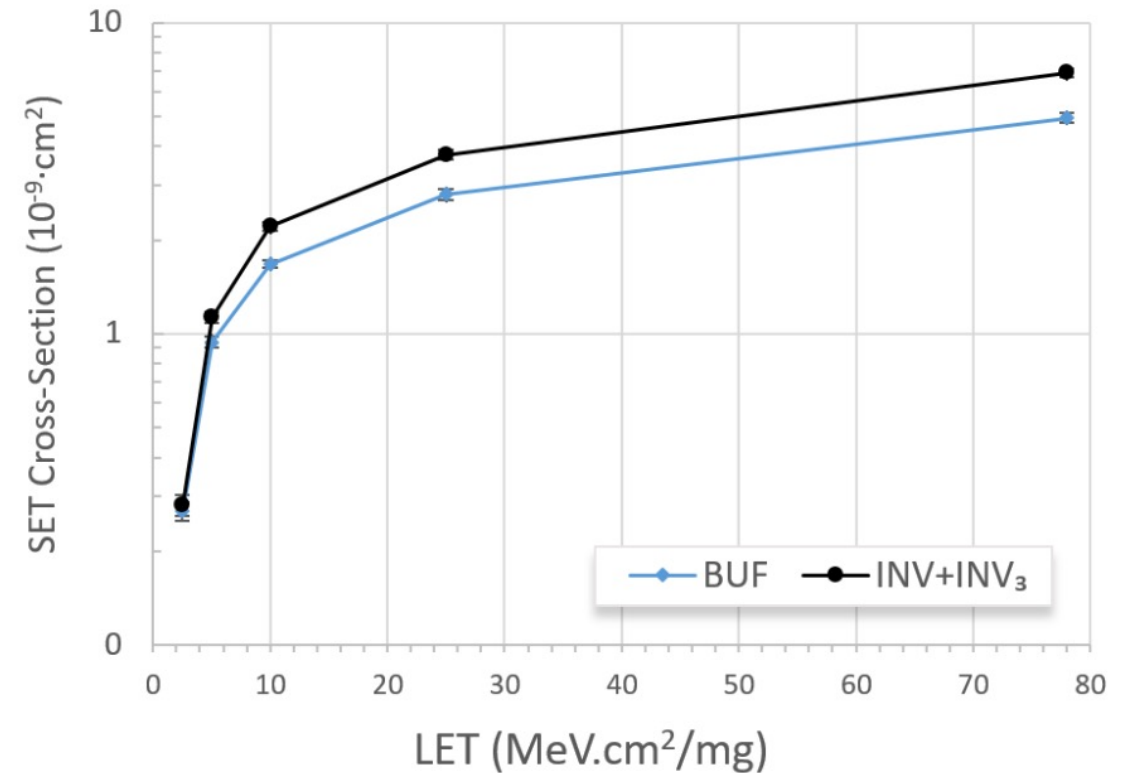
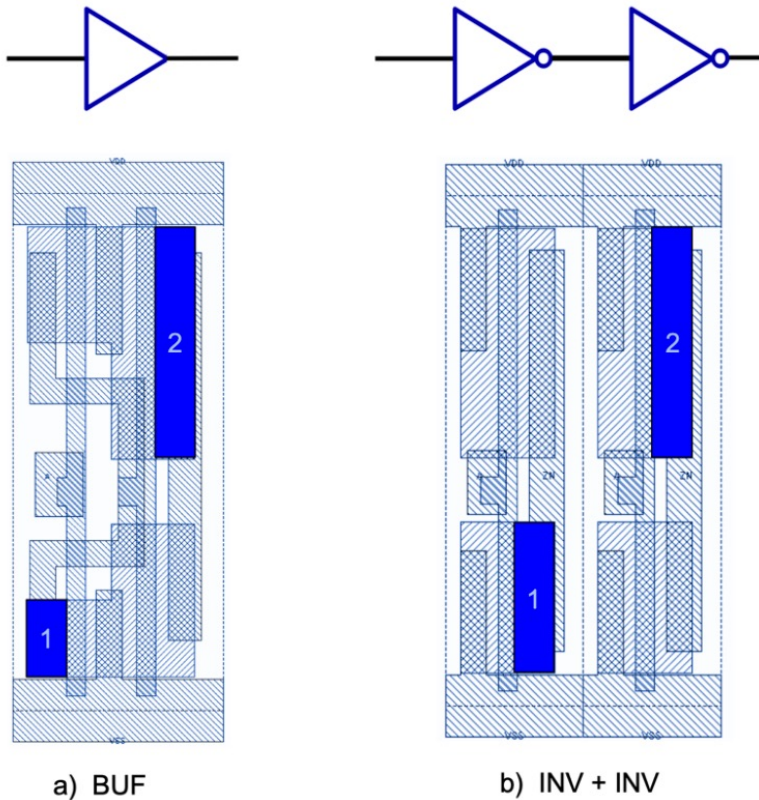


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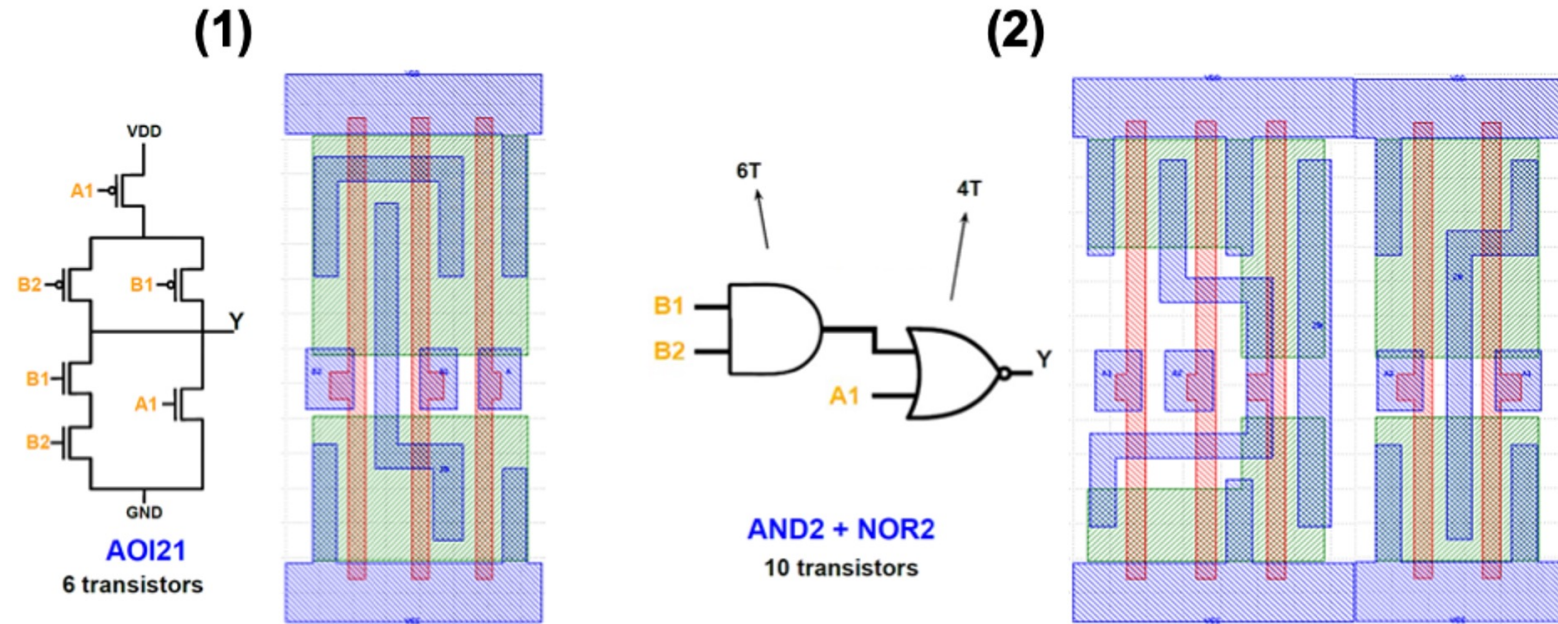
# Case Study: Buffer (45nm)

□ Functions can be implemented in different ways



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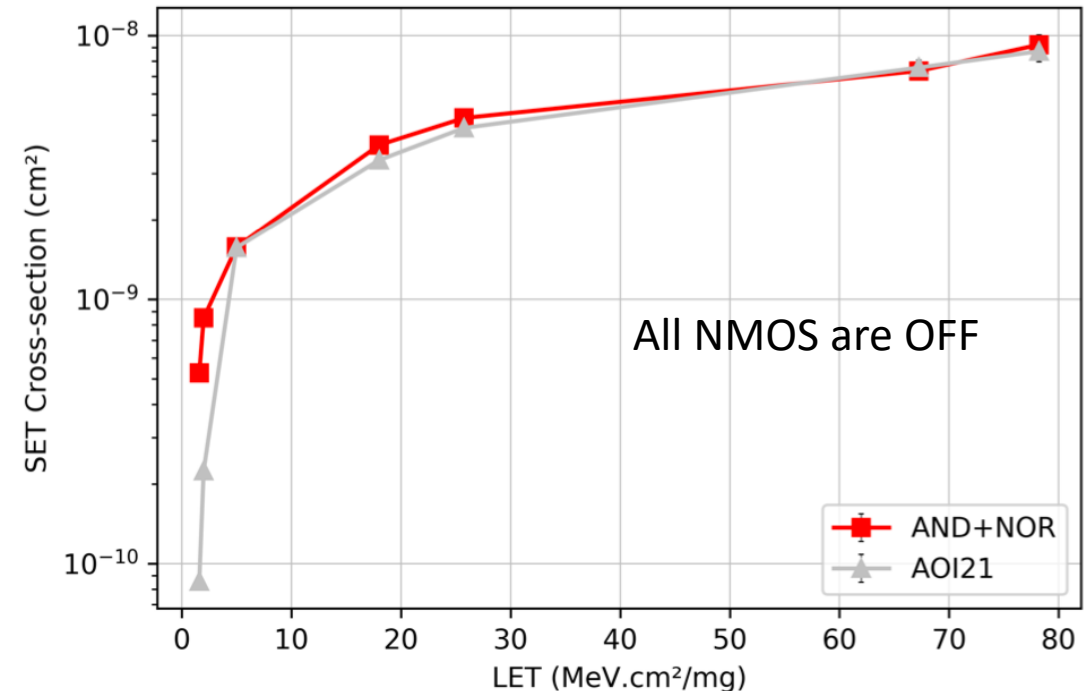
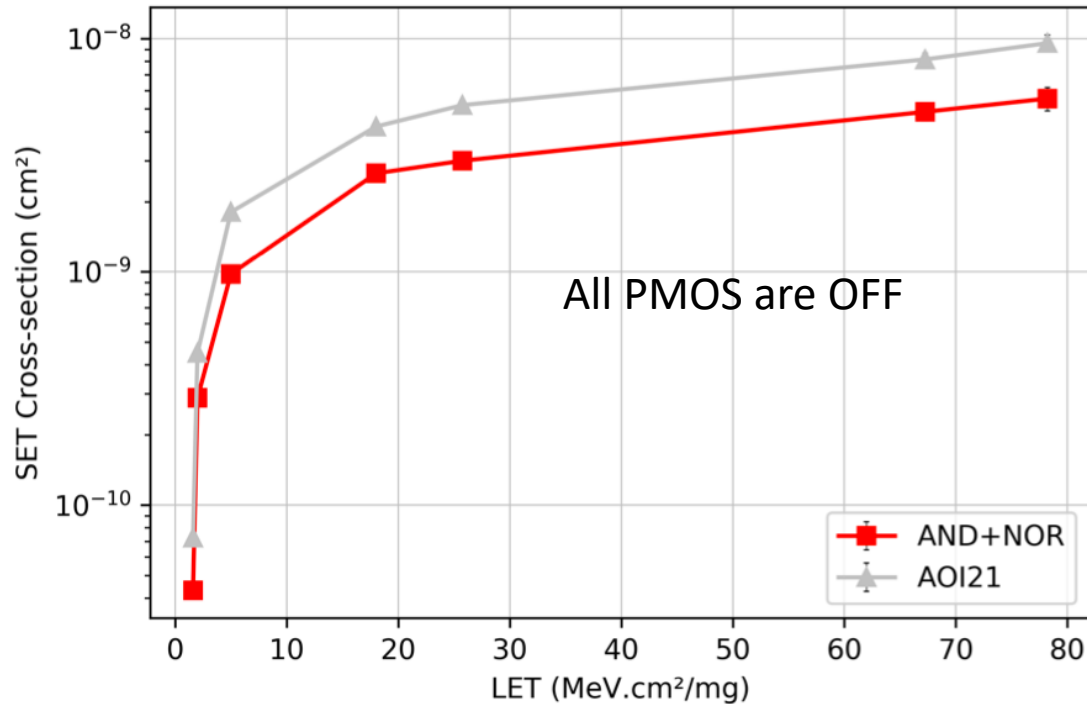
# Case Study: AOI21



- ❑ Functions can be implemented in different ways
- ❑ AOI21 is smaller, faster and with a lower consumption
- ❑ What about SET sensitivity?

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# Case Study: AOI21



Sensitivity depends on function implementation but also on pin assignment!

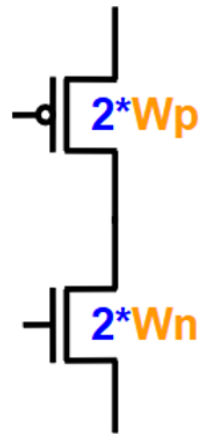
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# Gate sizing & Transistor stacking

Original Design



Gate Sizing



Transistor Stacking

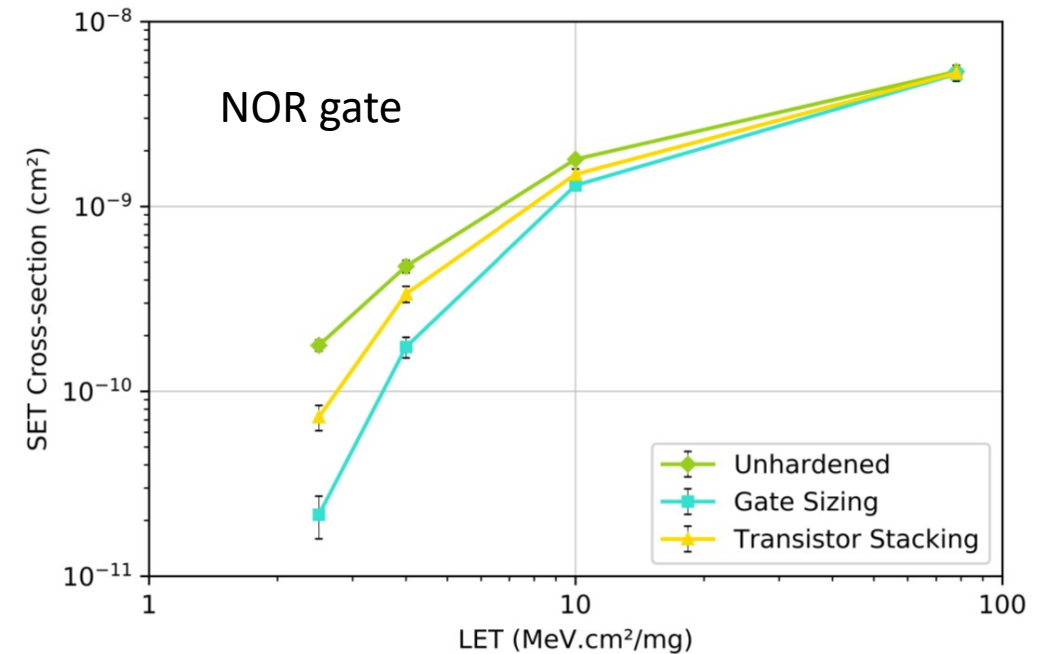
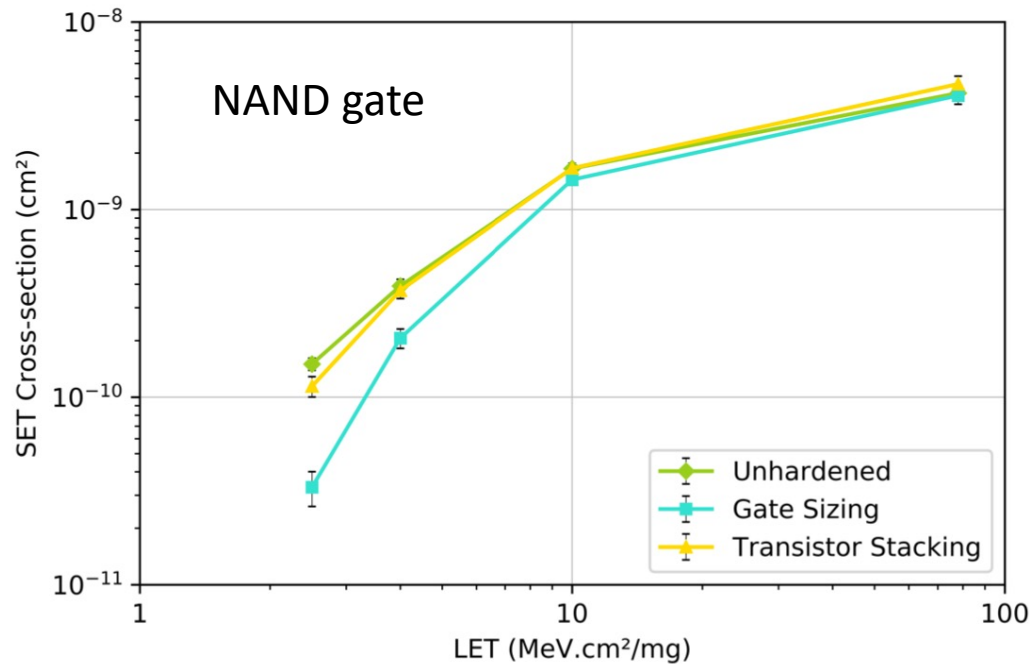
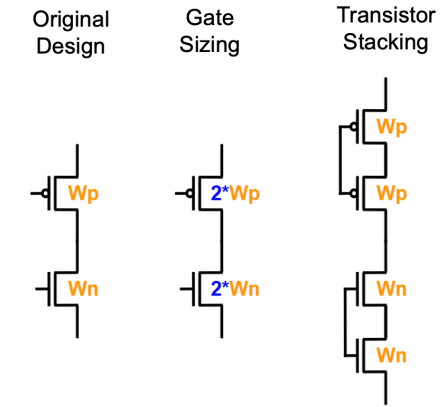


$$\begin{cases} Q_{crit} = C_{circuit} \times V_{DD} \\ C_{circuit} \propto WL \end{cases}$$

**Gate Sizing** – increases circuit capacitance and drive current.

**Transistor Stacking** – increases circuit capacitance reduces leakage current.

# Gate sizing & Transistor stacking

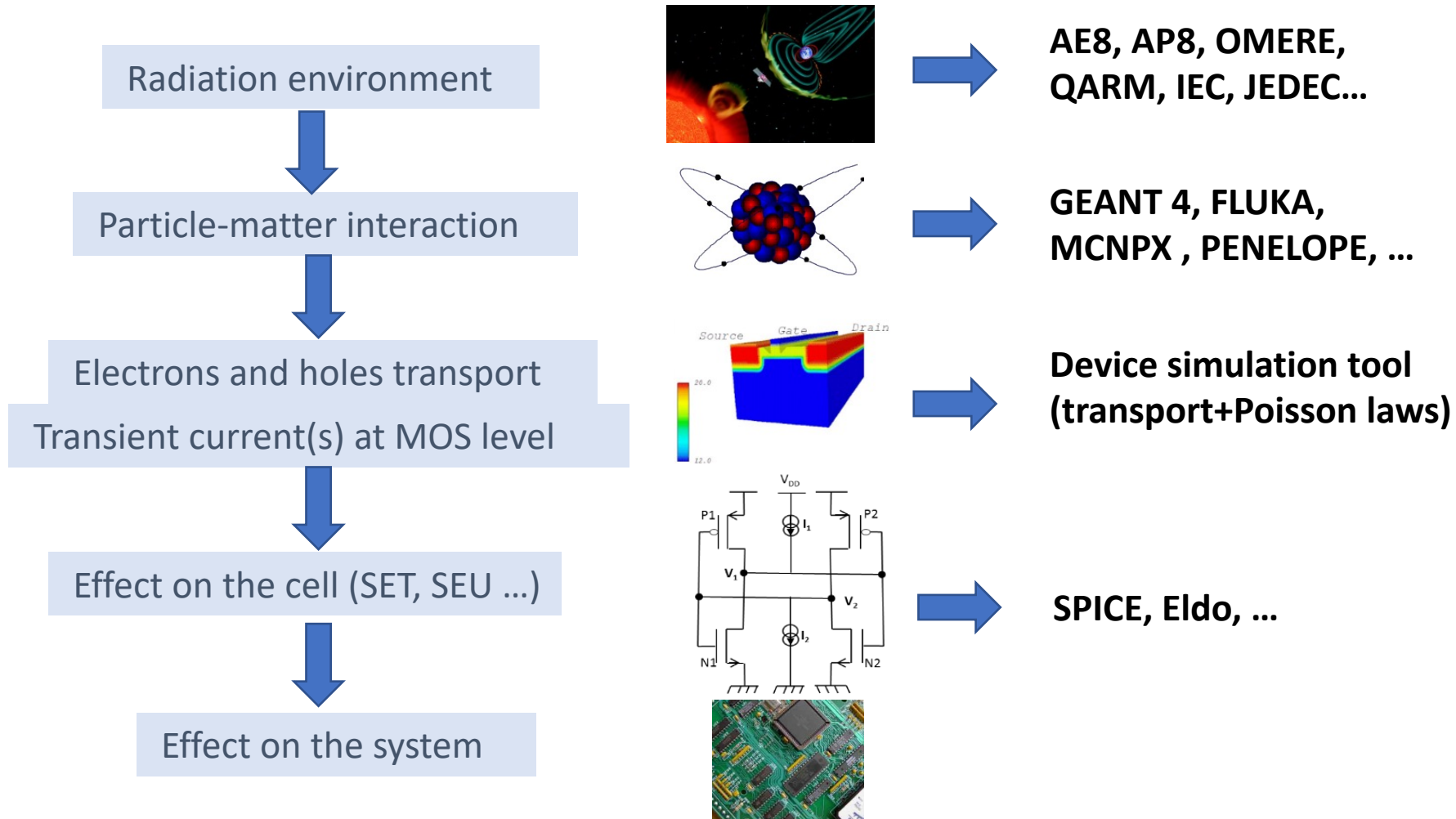


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# Multi-scale / Multi-physics



# Criterion Choice?



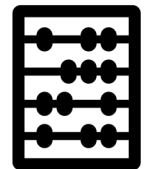
Diffusion-drift + SPICE



More physics



RPP



Less physics

# Criterion Choice?



Diffusion-drift + SPICE

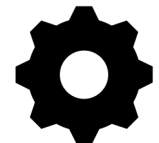


More physics

- Accounting for the circuit effect at the cell level
- *But*, with not « too much » details on the SPICE model

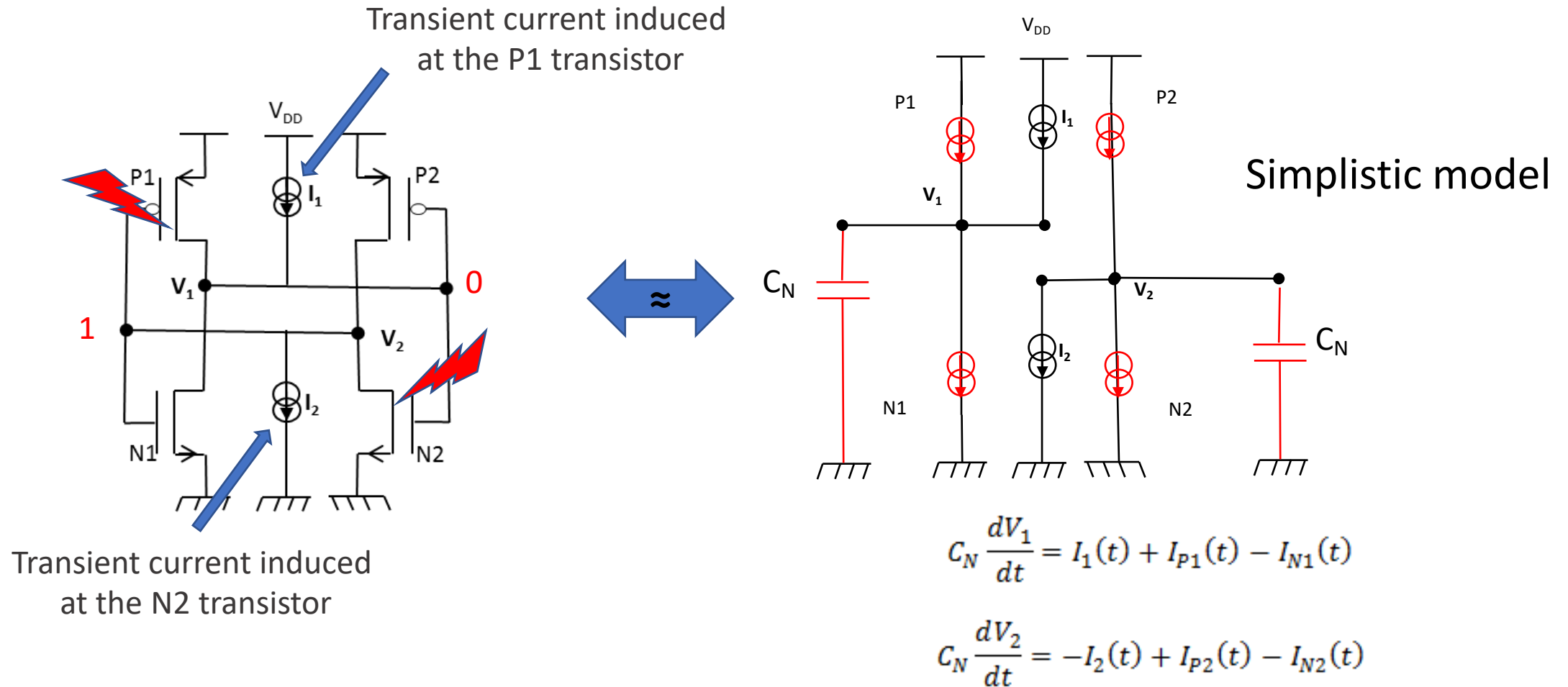


RPP



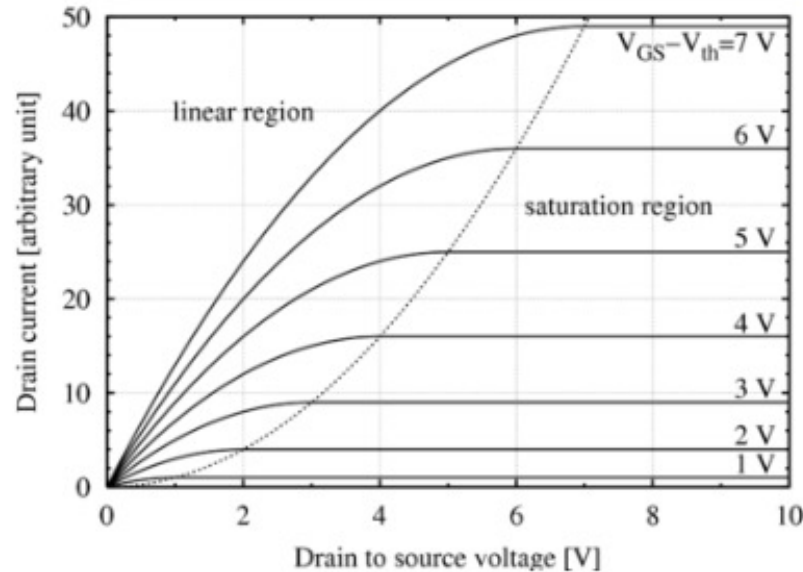
Less physics

# Basic modeling example



# NMOS and PMOS currents ?

□ The simplest:



- Sub threshold if  $V_{GS} < V_T$

$$I_{N,P}(V_{GS}, V_{DS}) = 0 \quad (\text{eq. 1})$$

- Triode if  $V_{GS} \geq V_T$  and  $V_{DS} < V_{GS} - V_T$

$$I_{N,P}(V_{GS}, V_{DS}) = \mu C_{ox} \frac{W}{L} (1 + \lambda V_{DS}) \left( V_{GS} - V_T - \frac{V_{DS}}{2} \right) \times V_{DS} \quad (\text{eq. 2})$$

- Saturation if  $V_{GS} \geq V_T$  and  $V_{DS} \geq V_{GS} - V_T$

$$I_{N,P}(V_{GS}, V_{DS}) = \frac{\mu C_{ox}}{2} \frac{W}{L} (1 + \lambda V_{DS}) (V_{GS} - V_T)^2 \quad (\text{eq. 3})$$

□ Is it enough ? At least better than collected charge consideration.

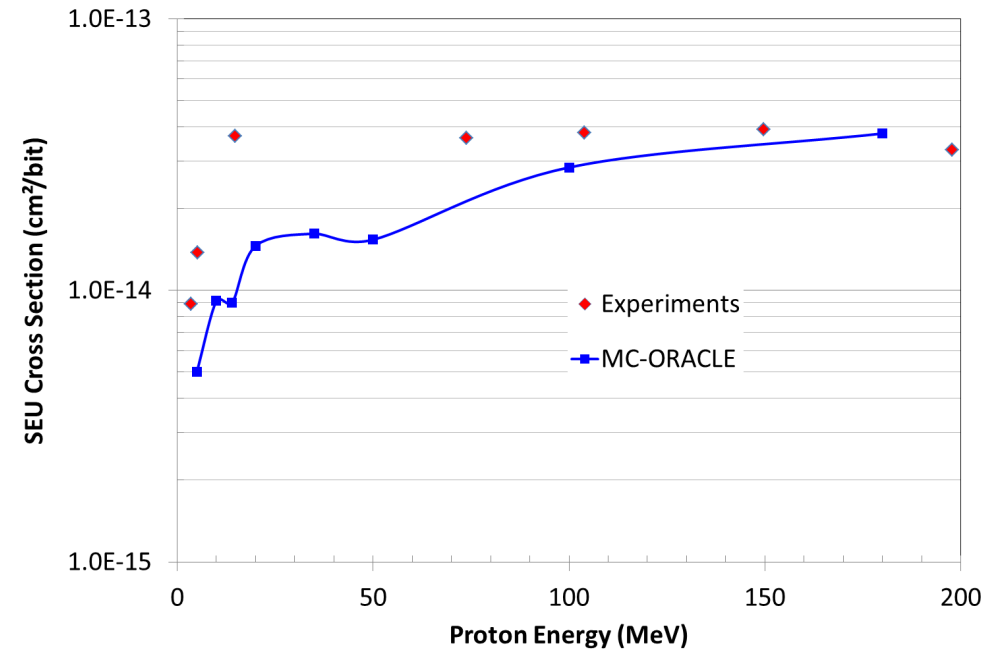
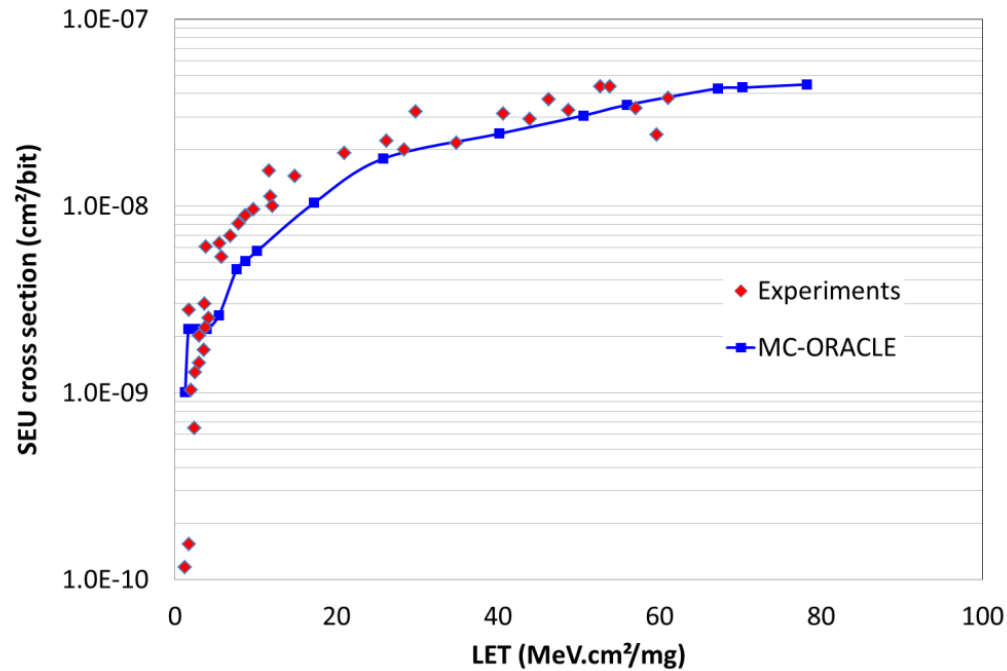
□ Actually not enough for describing the cell in normal application but enough for describing the behaviour of the cell during SEE.

# Current source parameters?

- It is easy to have order of magnitude of the parameters involved in the previous set of equations:

	150-nm	90-nm	65-nm
$V_T$	0.4 V	0.4 V	0.24 V
$\mu_N (\text{cm}^2/\text{Vs})$	140	140	140
$\mu_P (\text{cm}^2/\text{Vs})$	35	35	35
$t_{\text{ox}}$	2.5 nm	1.2 nm	1.2 nm
$W/L$	0.2 $\mu\text{m}$ /0.15 $\mu\text{m}$	0.11 $\mu\text{m}$ /0.09 $\mu\text{m}$	0.12 $\mu\text{m}$ /0.065 $\mu\text{m}$
$\lambda$	0	0	0
$Q_{\text{crit}}$	3 fC	1.2 fC	0.8fC
$V_{\text{DD}}$	1.5 V	3.3-1 V	2.5-1 V

# Results for the 150-nm

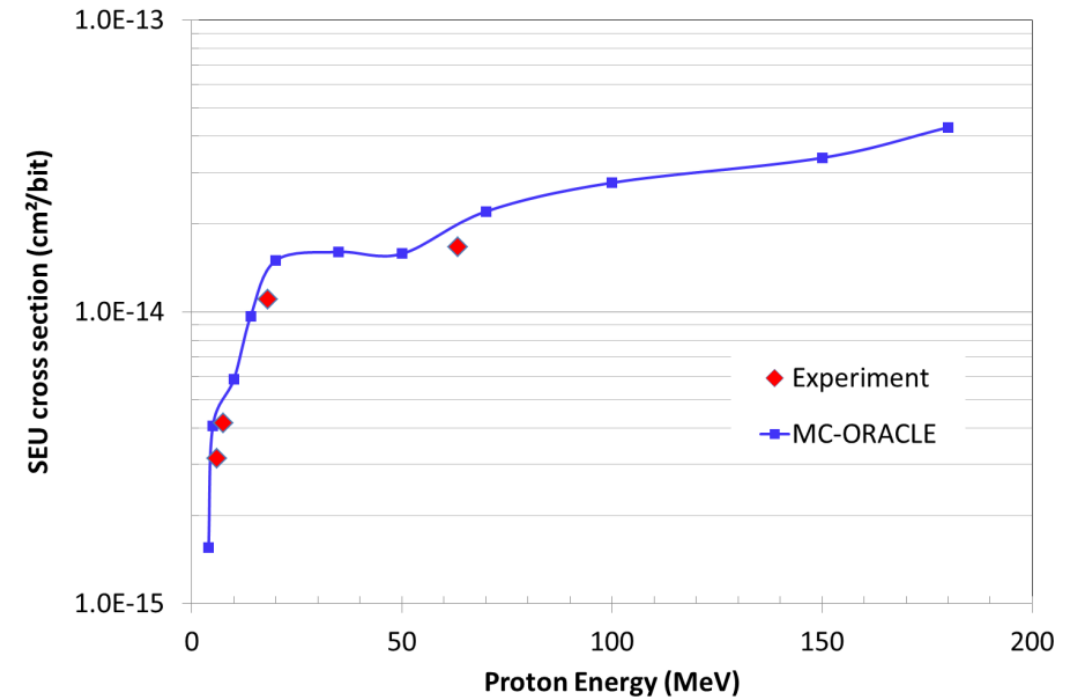
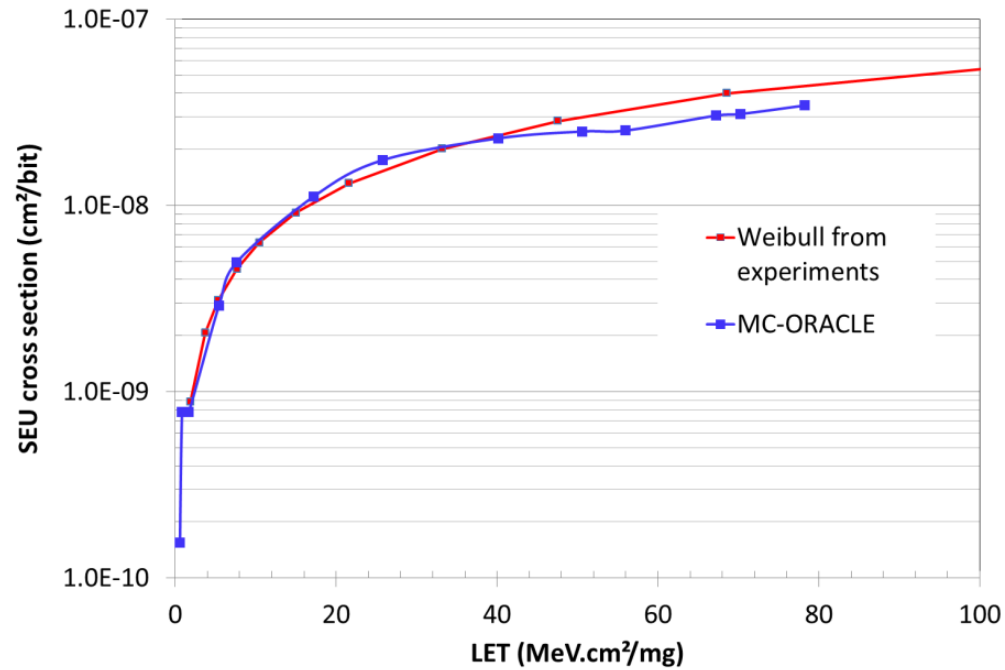


- Default parameters for the 150nm.
- No fitting parameters.

Experimental data from:

R. Koga, J. George, G. Swift, C. Yui, L. Edmonds, C. Carmichael, T. Langley, P. Murray, K. Lanes and M. Napier,  
“Comparison of Xilinx Virtex-II FPGA SEE sensitivities to protons and heavy ions,” IEEE Trans. Nucl. Sci., vol 51, NO 5, pp. 2825-2833, Oct 2004.

# Results for the 90-nm



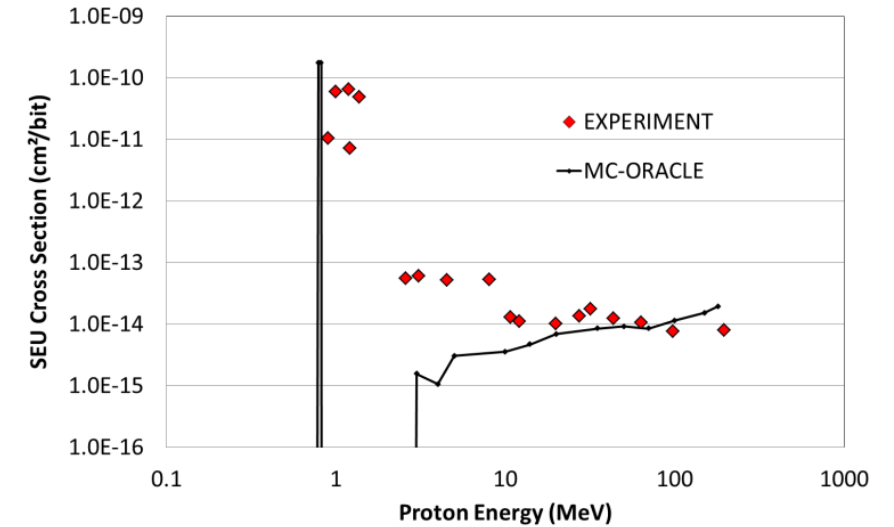
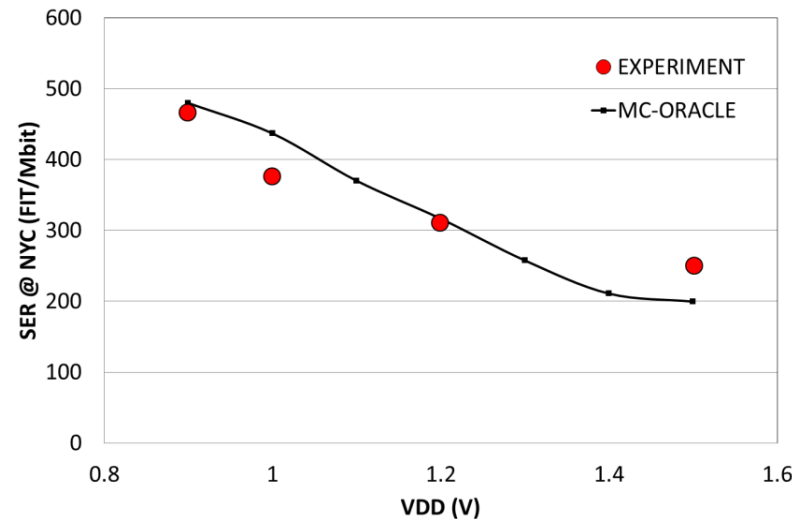
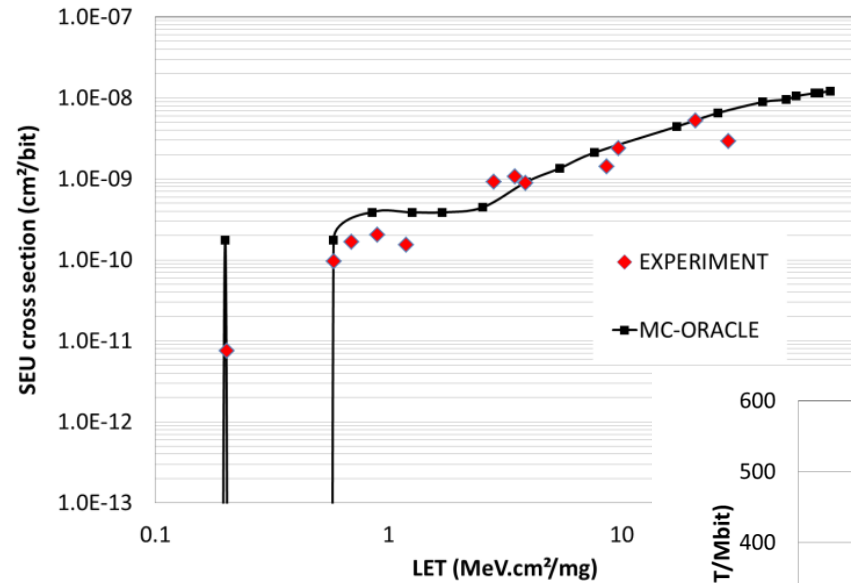
- Default parameters for the 90nm.
- No fitting parameters.

Experimental data from:

Swift, G.M.; Allen, G.R.; Chen Wei Tseng; Carmichael, C.; Miller, G.; George, J.S.;

"Static Upset Characteristics of the 90nm Virtex-4QV FPGAs," Radiation Effects Data Workshop, 2008 IEEE , vol., no., pp.98-105, 14-18 July 2008.

# Results for the 65-nm



- Default parameters for the 65nm.
- No fitting parameters.

Experimental data from:

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.

# More accurate simulations?

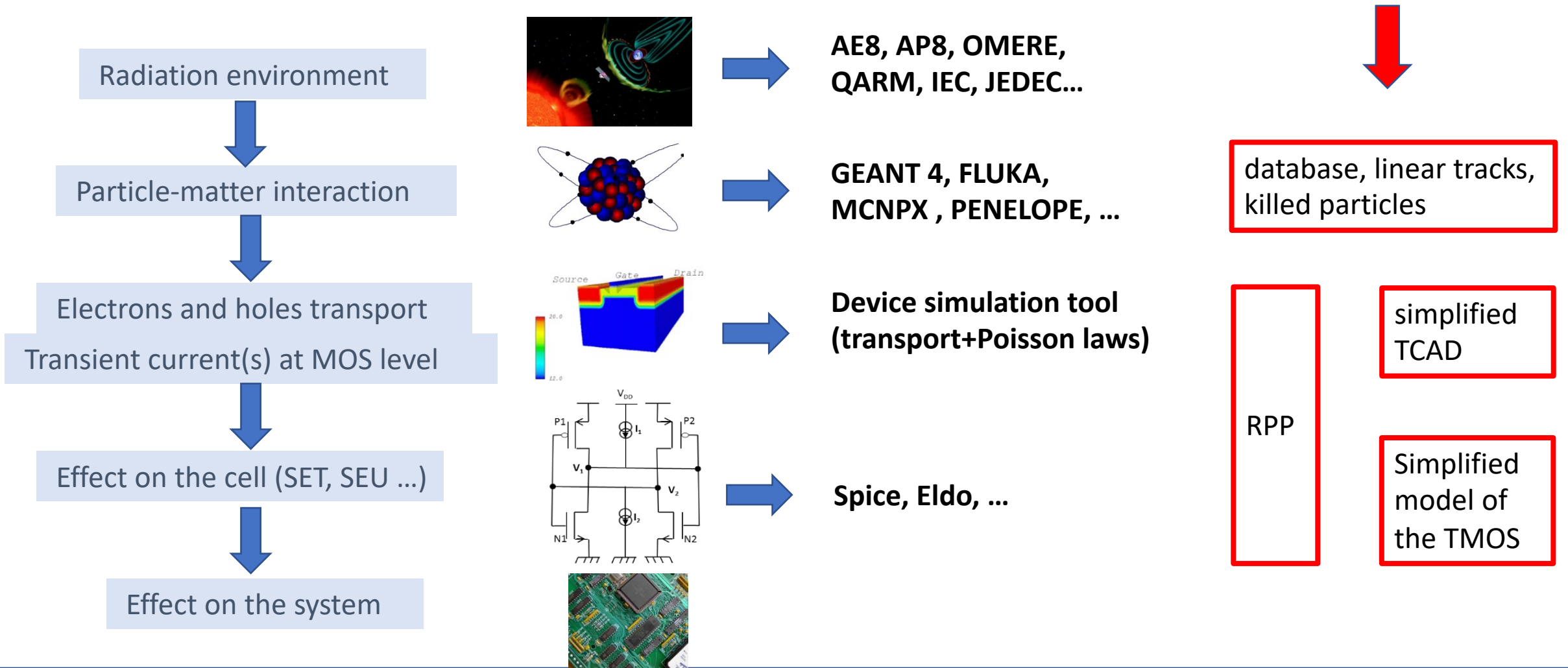
- ❑ If more accurate parameters are known they can obviously be used.
- ❑ The more accurate method being when the spice model is used (but not often available).
- ❑ It is also possible to fit these parameters to experimental data in order to accurately estimate the sensitivity for another particle.

	150-nm	90-nm	65-nm
$V_T$	0.4 V	0.4 V	0.24 V
$\mu_N (\text{cm}^2/\text{Vs})$	140	140	140
$\mu_p (\text{cm}^2/\text{Vs})$	35	35	35
$t_{\text{ox}}$	2.5 nm	1.2 nm	1.2 nm
W/L	0.2 $\mu\text{m}$ /0.15 $\mu\text{m}$	0.11 $\mu\text{m}$ /0.09 $\mu\text{m}$	0.12 $\mu\text{m}$ /0.065 $\mu\text{m}$
$\lambda$	0	0	0
$Q_{\text{crit}}$	3 fC	1.2 fC	0.8fC
$V_{\text{DD}}$	1.5 V	3.3-1 V	2.5-1 V

# Agenda

- Context
- Particle interaction with matter
- Monte Carlo approach
  - ✓ Monte Carlo?
  - ✓ RPP
  - ✓ Diffusion-Drift model
  - ✓ Tools examples
- Simulation examples
  - ✓ SET sensitivity
  - ✓ SEU sensitivity
- **Conclusions**

# Conclusions



# Conclusions

- ❑ Monte Carlo tools are powerful tools that can mimic:
  - various kind of primary particles (neutron, proton, ion, alpha pollutant)
  - a large variety of interaction modes
  - complex geometry with different materials
  - electric consideration
- ❑ They allow investigating:
  - SEE sensitivity
  - different kinds of SEE : SEU, SET, MCU, MBU, SEL ...
  - parameters effects (sizing, VDD, pin assignment, ...)
- ❑ They can use different levels of complexity

# SERESSA 2022

5<sup>th</sup> to 9<sup>th</sup> of December at CERN, Geneva

## Modelling and prediction of Single Event Transient and Single Event Upset

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**Thank you! Any questions?**

