Scuola Nazionale di Legnaro
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Single Event Effects: Introduction

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OUTLINE

- Introduction and definitions
- Classification of SEE
- Charge generation by an ionizing particle in Si (and SiO_2)
  - Collection mechanisms
  - Evolution with Moore's law
- Single Event Effects
  - Sources
  - Testing methods
- Summary

- **Single Event Effect (SEE)**: perturbation of the behavior of electronic (optoelectronic) devices, circuits and/or systems produced by a single ionizing particle

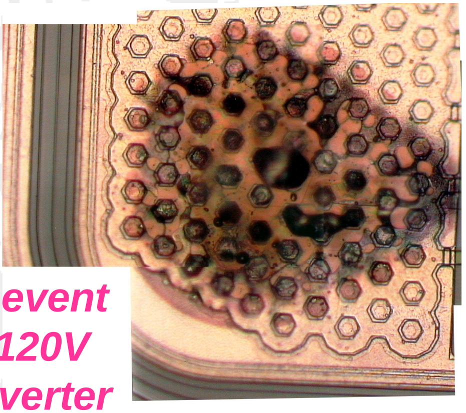
- "Timely testing avoids cosmic ray damage to critical auto electronics", *John Wood and Earl Caustin, MOSAID Systems, 15/6/2006*
- "Cosmic rays damage automotive electronics", *Martin Mason, Actel Corporation, 31/5/2006*
- "Alpine lab enters rarified air of soft-error test", *Junko Yoshida, 25/9/2006*

- If (some of) the charge generated by a **single high LET particle** is collected by a **sensitive node** of the device/circuit, and this charge is larger than the **critical charge** required to start an anomalous behavior, an ***effect*** (**Single Event Effect**) may be seen, affecting the electrical performance of the device/circuit:
  - **Soft errors**
  - **Hard (destructive) errors**

Classification of SEE's

- **Non-destructive (soft errors)**:
  - Single Event Transient (SET)
  - Single Event Upset (SEU)
    - Single Bit Upset (SBU)
    - Multiple Bit Upset (MBU)
  - Single Event Functional Interruption (SEFI)
  - Single Event Latchup (SEL or SELU)… *may be also destructive*
- **Destructive (hard errors)**:
  - Single Event Burnout (SEB)
  - Single Event Gate Rupture (SEGR)
  - Stuck Bits

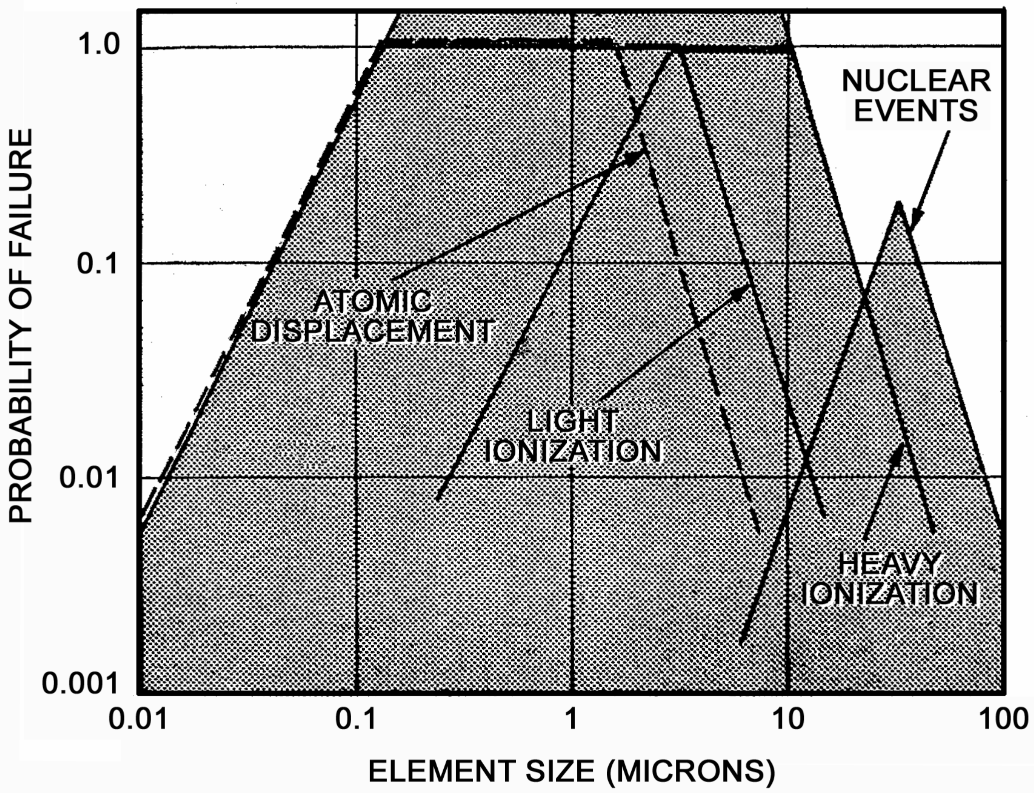
• Power devices do not follow down-scaling dimensions and voltages: they exhibit larger sensitivity to neutron-induced effects, even at sea level



Destructive event in a COTS 120V DC-DC Converter

K. LaBel, EWRHE 2004

Early warning of SEE's at sea level



J.T. Wallmark and S.M. Marcus, Proc IRE, 1962

First reported reliability effect (May & Woods, Intel, 1979) due to alpha particles in DRAMs from natural radioactive pollutants in circuit packaging

Current interests in SEE's

- *Societal needs for more reliable electronics*
- Reliability in advanced ICs is improving down to some **10-100 FIT**
- Electronics is now introduced in **Active Security**, especially visible in everyday vehicles (Airplanes, Automotives, Railways,…)
- **Avionic and space industry** has a long standing tradition of radiation testing, especially Single Event Effects
- More recently the SEE issue has been seriously investigated for its reliability implications **even at sea level** in everyday life by:
  - – Semiconductor *companies*: IBM (since'80s), Intel, STMicroelectronics, TI, Infineon, Cypress, Xilinx,…, but few SEE comprehensive data from companies are available in open literature
  - – Semiconductor IC *customers*: even less prone to show their interest, basically no data available
- SEE at sea level is dominated by **Soft Errors (SE)** leading to the **Soft Error Rate (SER)** figure of merit; if not properly mitigated, SER may reach **10^5 FIT**

“Soft errors have become a huge concern in advanced computer chips because, uncorrected, they produce a failure rate that is higher than all the other reliability mechanisms combined!”

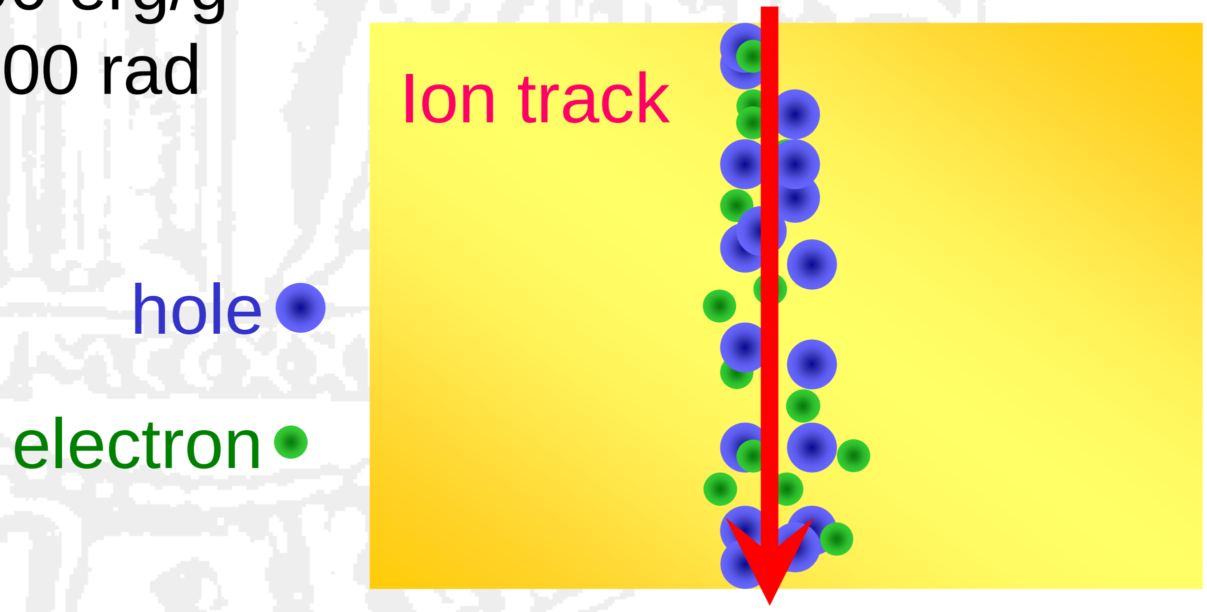
R. Baumann, IEEE-TDMR, 2005

“Since chip SER is viewed by many as a legal liability (selling something that you know may fail), the public literature in this field is sparse and always makes management nervous”

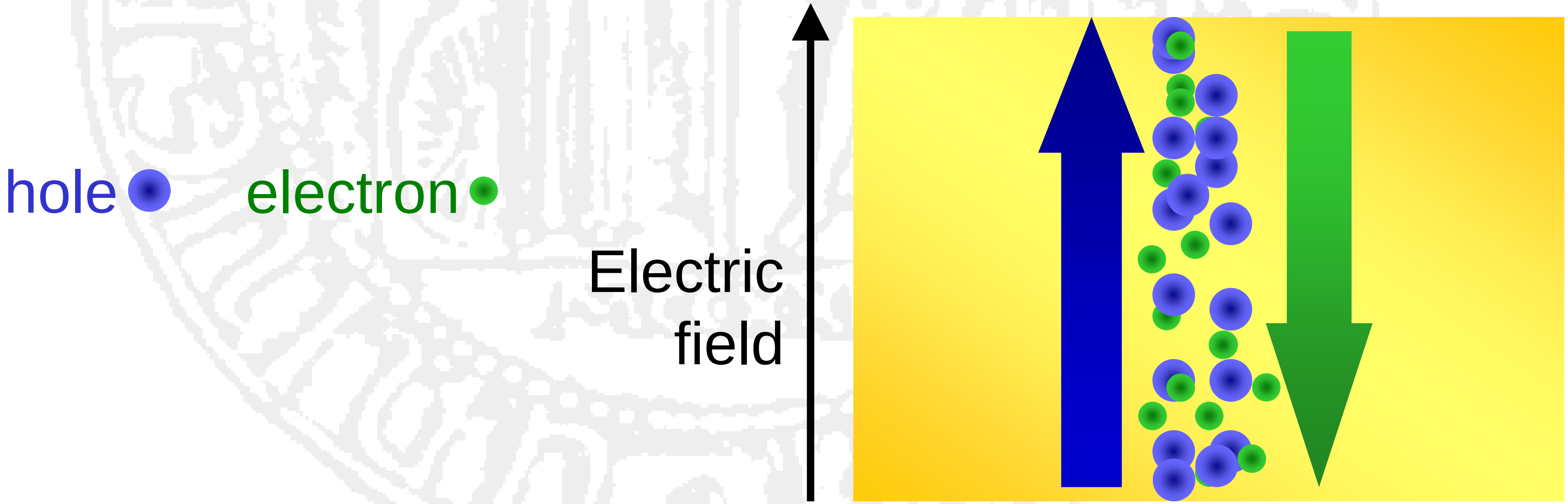
J. Ziegler and H. Puchner, “SER-History, Trends and Challenges”, Cypress Semiconductors, 2004

Charge generation

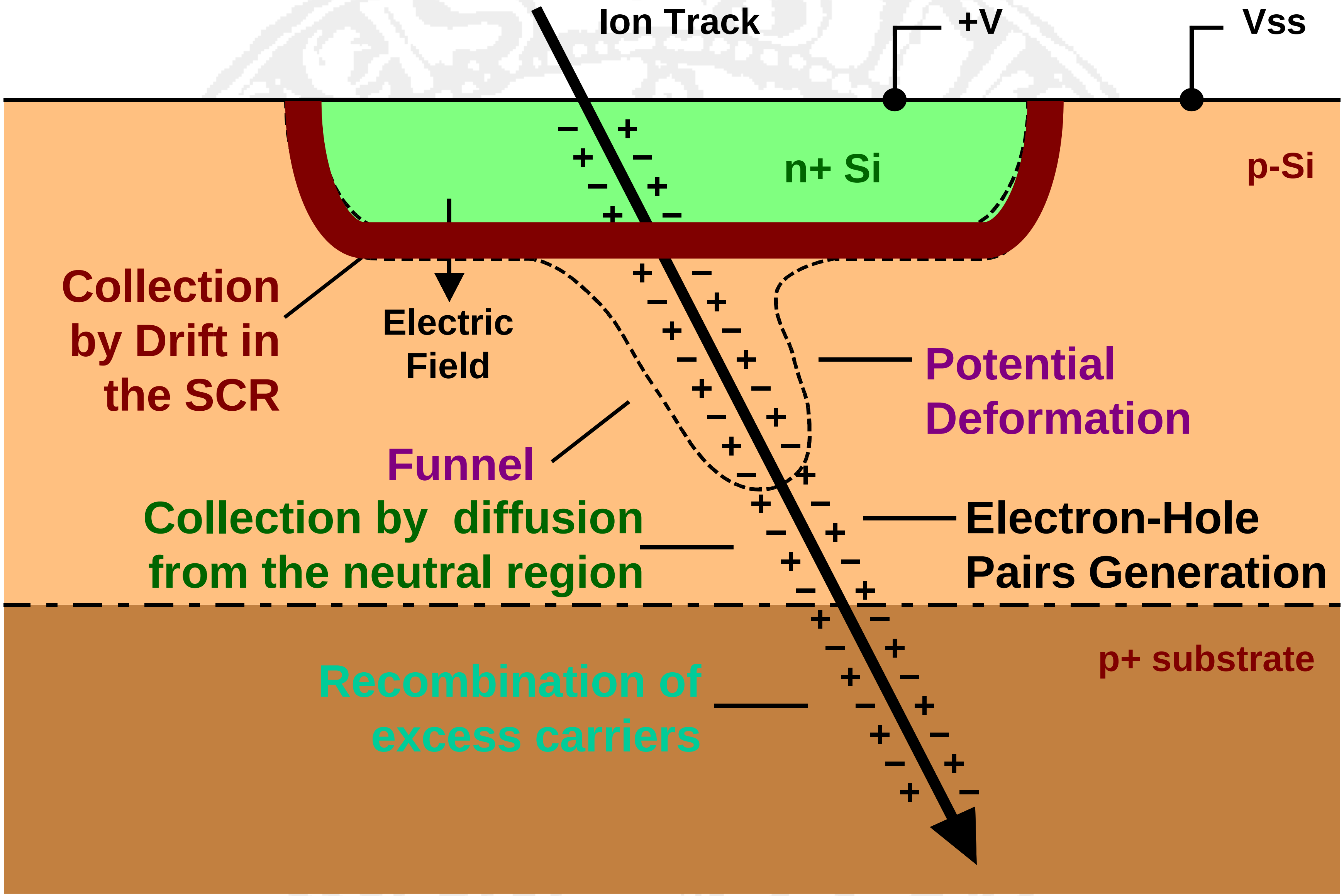
- An ionizing particle generates a (dense) track of electron-hole pairs in semiconductors **(Silicon)** and dielectrics **(SiO_2)**
- The number of generated carriers is proportional to the particle **Linear Energy Transfer (LET)** coefficient ($MeVcm^2/mg$), i.e., the ionizing energy loss/unit path length (Energy / e-h pair: **3.6 eV in Si**, **17 eV in SiO_2**)
- Dosimetry: 1 rad = 100 erg/g
  1 Gy = 1 J/kg = 100 rad



- Under an external electric field the two columns of carriers recombine and drift: many electrons and holes survive in Si, fewer in SiO_2
- Eventually, a net negative/positive charge can be collected at sensitive nodes: if this charge exceeds a threshold value (**critical charge**) an event may be observed affecting the circuit

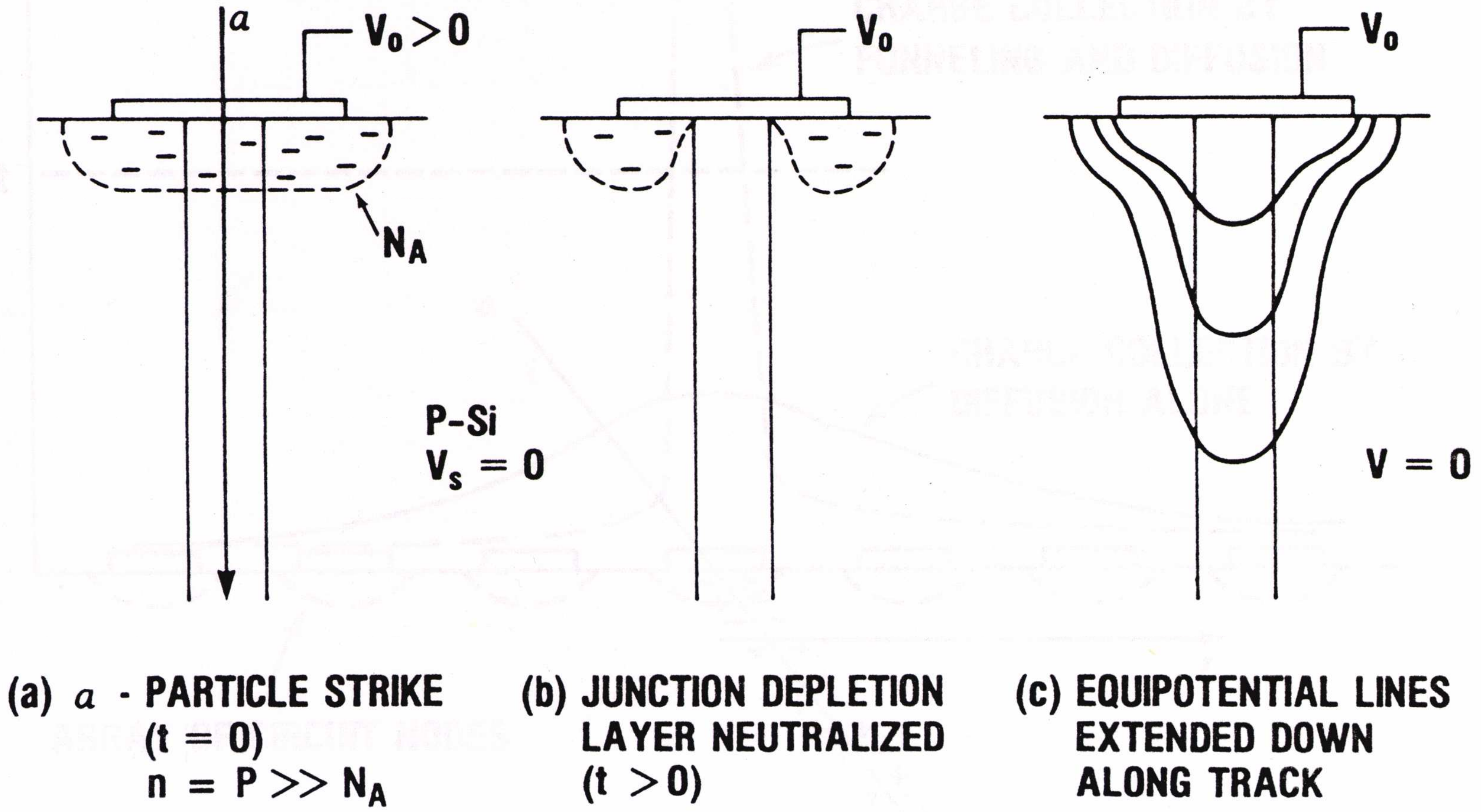


Charge collection in a reverse biased p-n junction



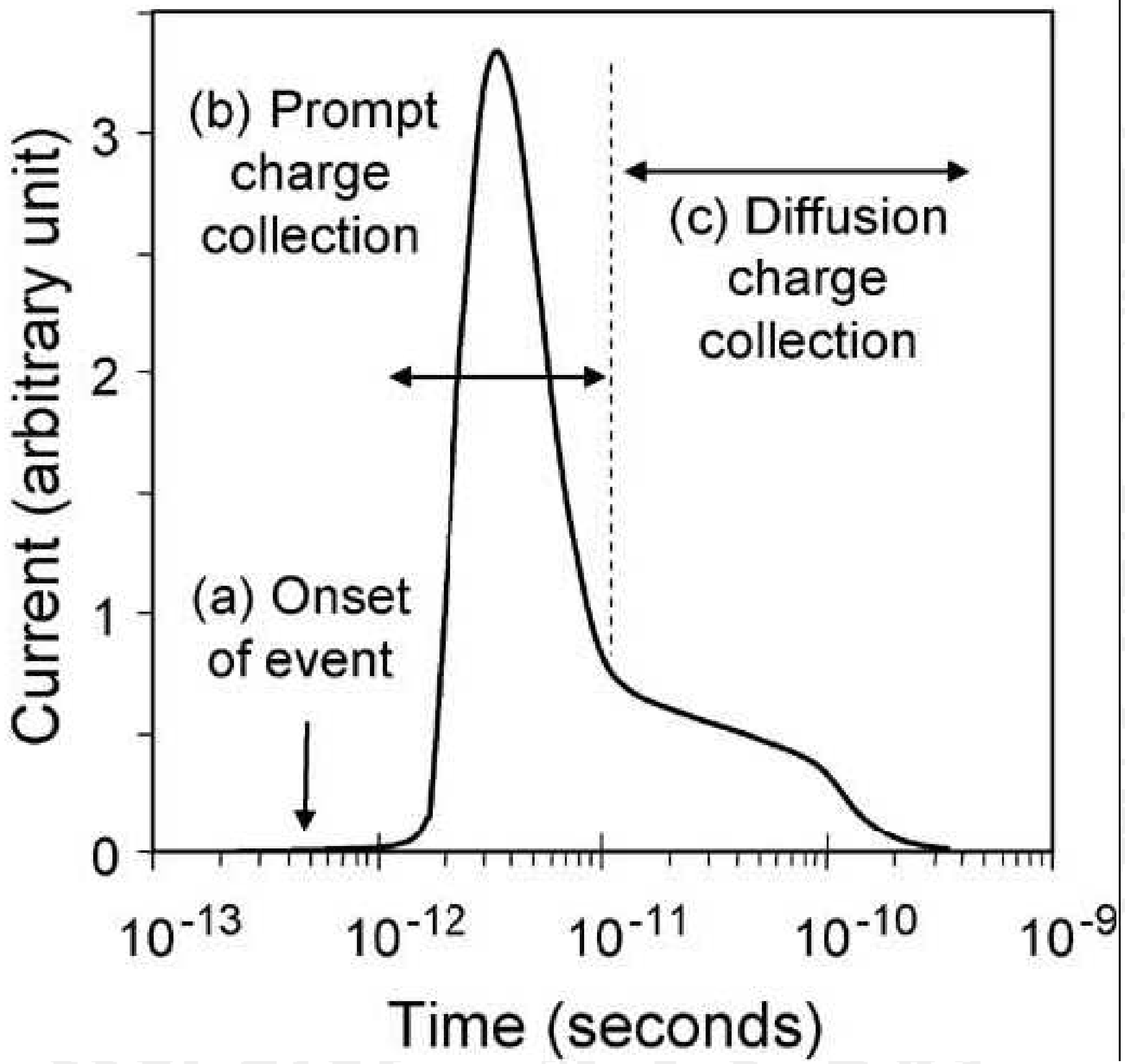
Charge funneling mechanism

- Funneling on a Schottky diode



F.B. McLean and T.R. Oldham, IEEE-TNS29, 1982

Time evolution of charge collection



R. Baumann, IEEE-TDMR, 2005

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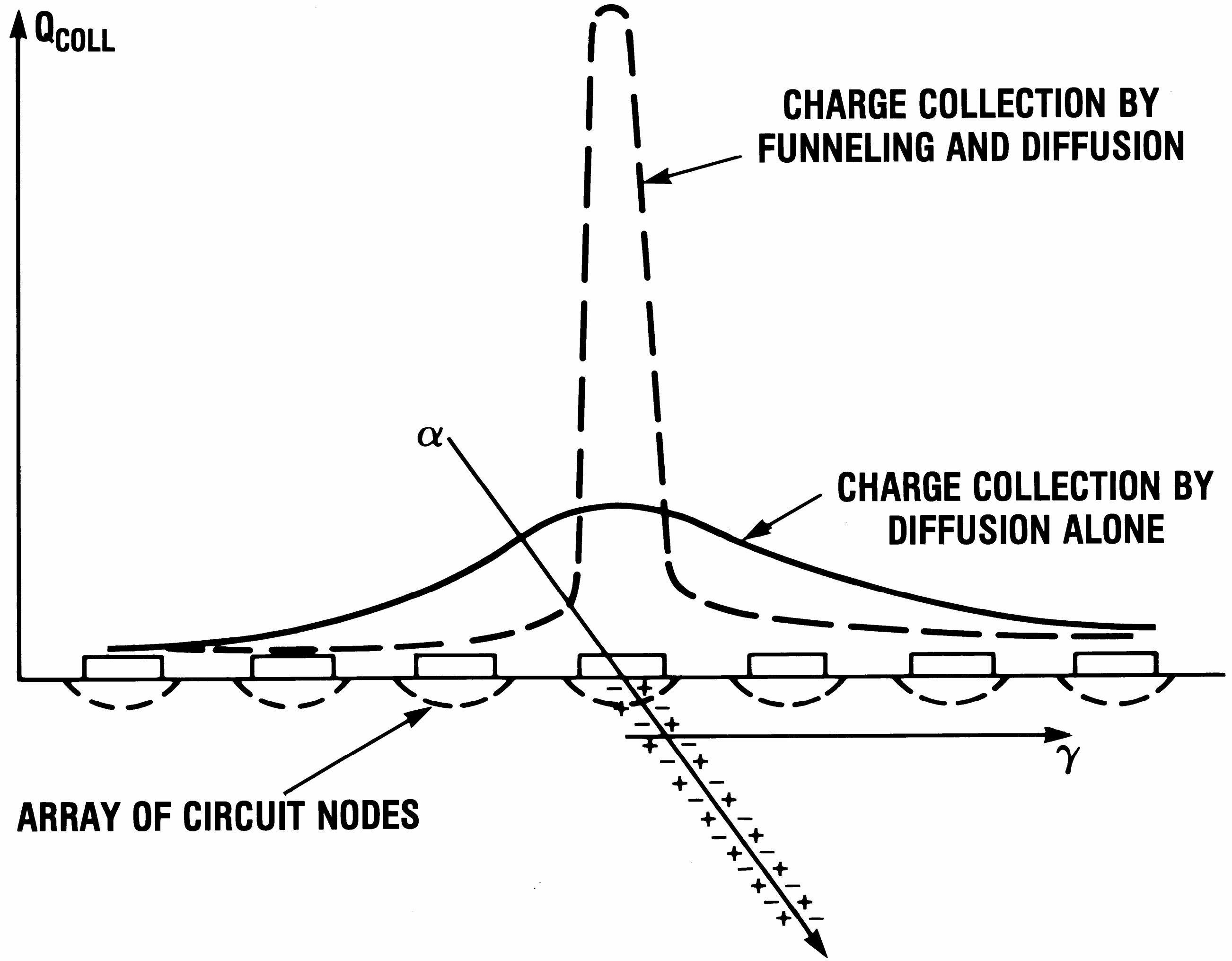
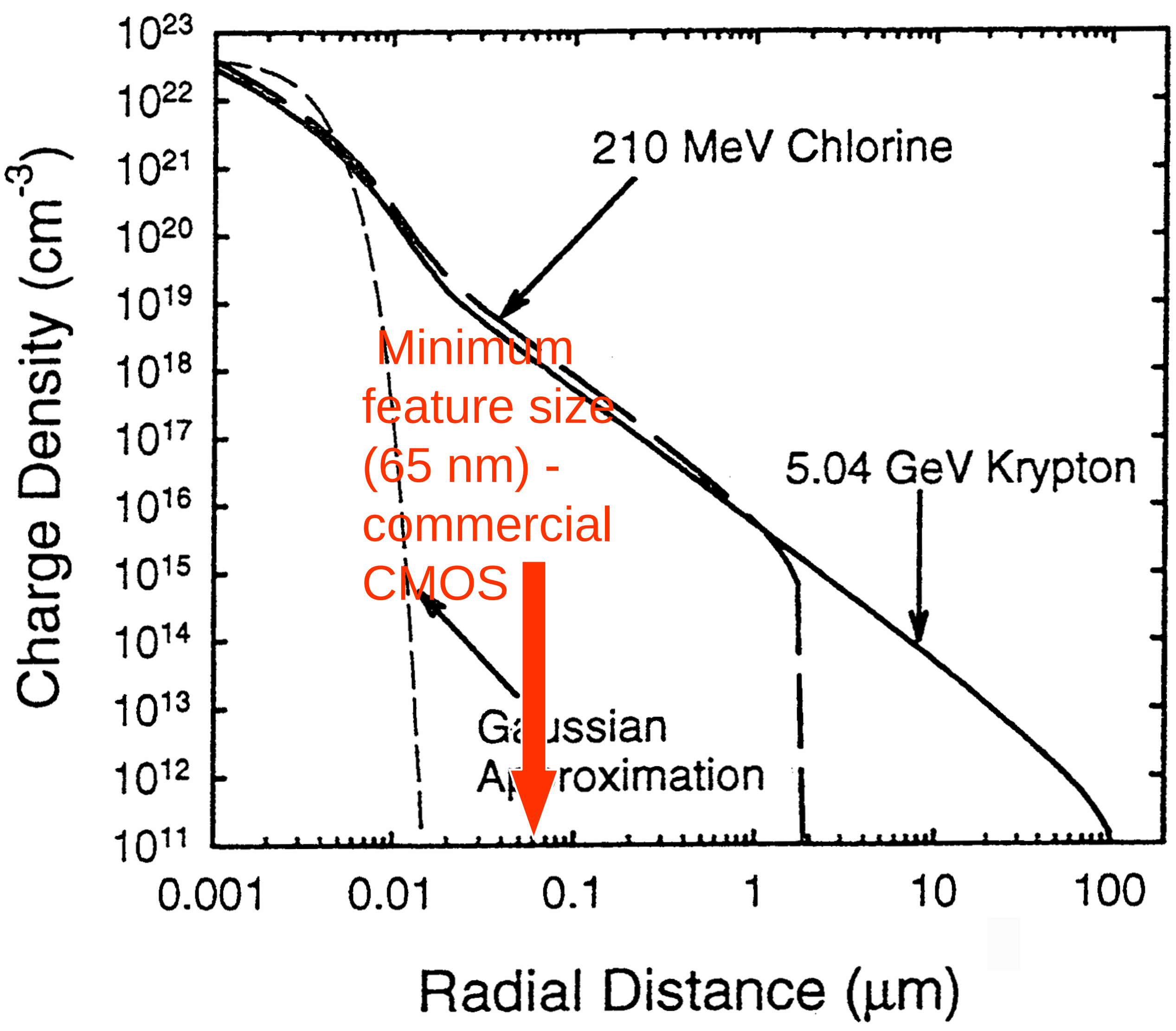
Charge collection across circuits



T. Oldham, NSREC Short Course, 2003

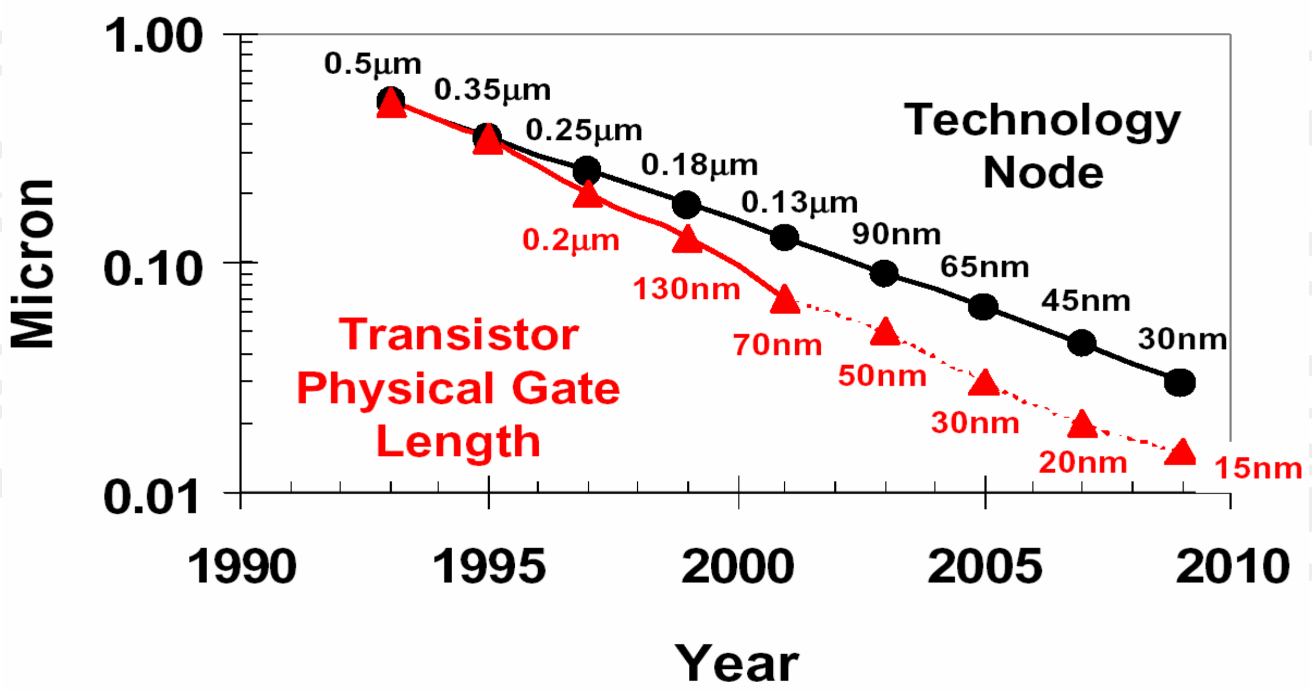
- "Traditional" view of charge collection in Si circuits fabricated with relaxed CMOS technologies
- Only particles at low impact angles may affect different devices, if diffusion charge collection is excluded

Calculated e-h track structure in Si



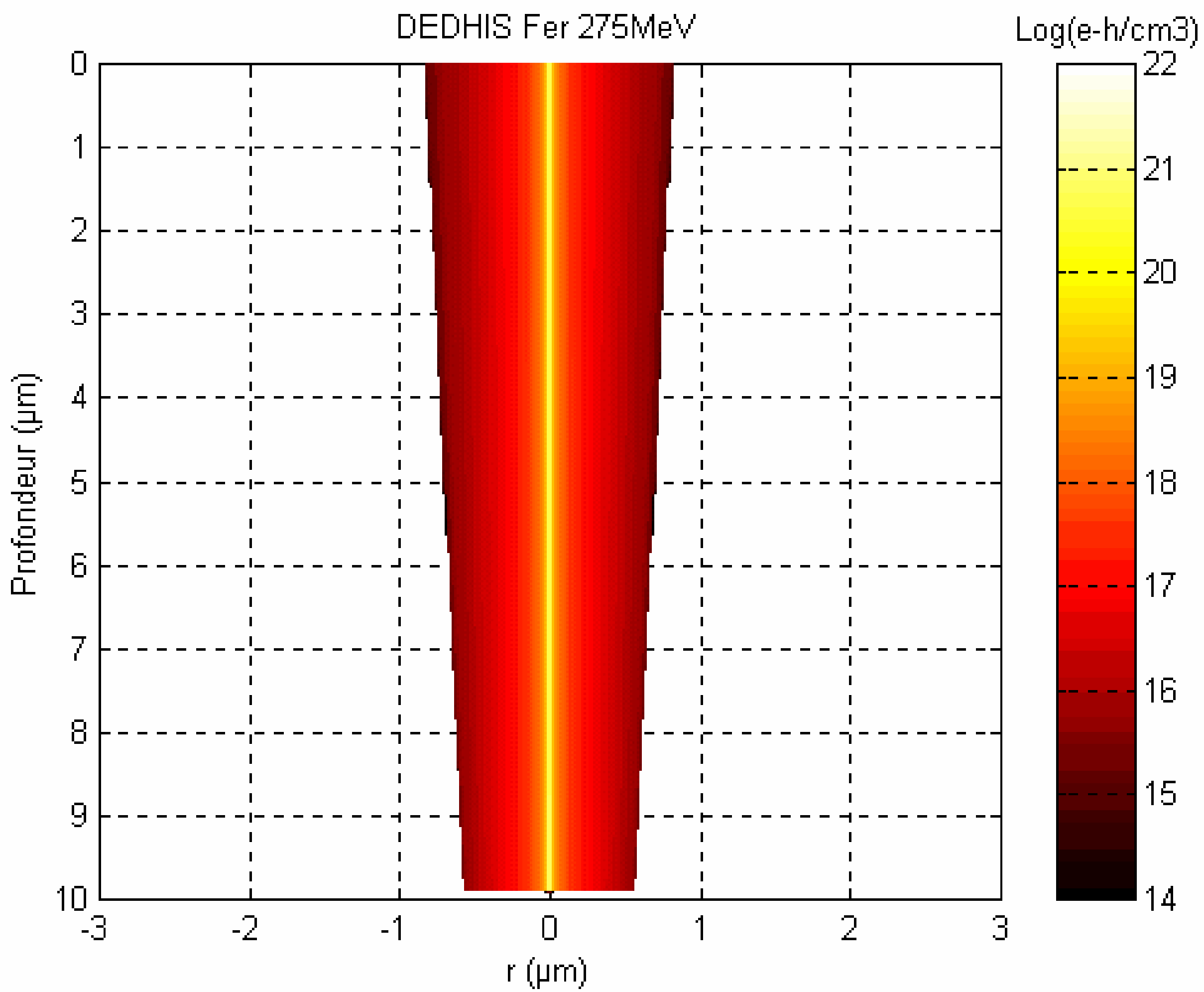
P. Dodd, et al., IEEE-TNS45, 1998

Moore’s law is (self-)validated by reducing the device dimension over the years, by scaling down the minimum feature size of the CMOS technology node



Source: INTEL

Simulated heavy ion e-h track in Si



Electron-Hole density (cm^{-3})

Fe ions 275 MeV
LET=24 $MeVcm^2/mg$

LET metrics in Si:

1 $MeVcm^2/mg$

↓

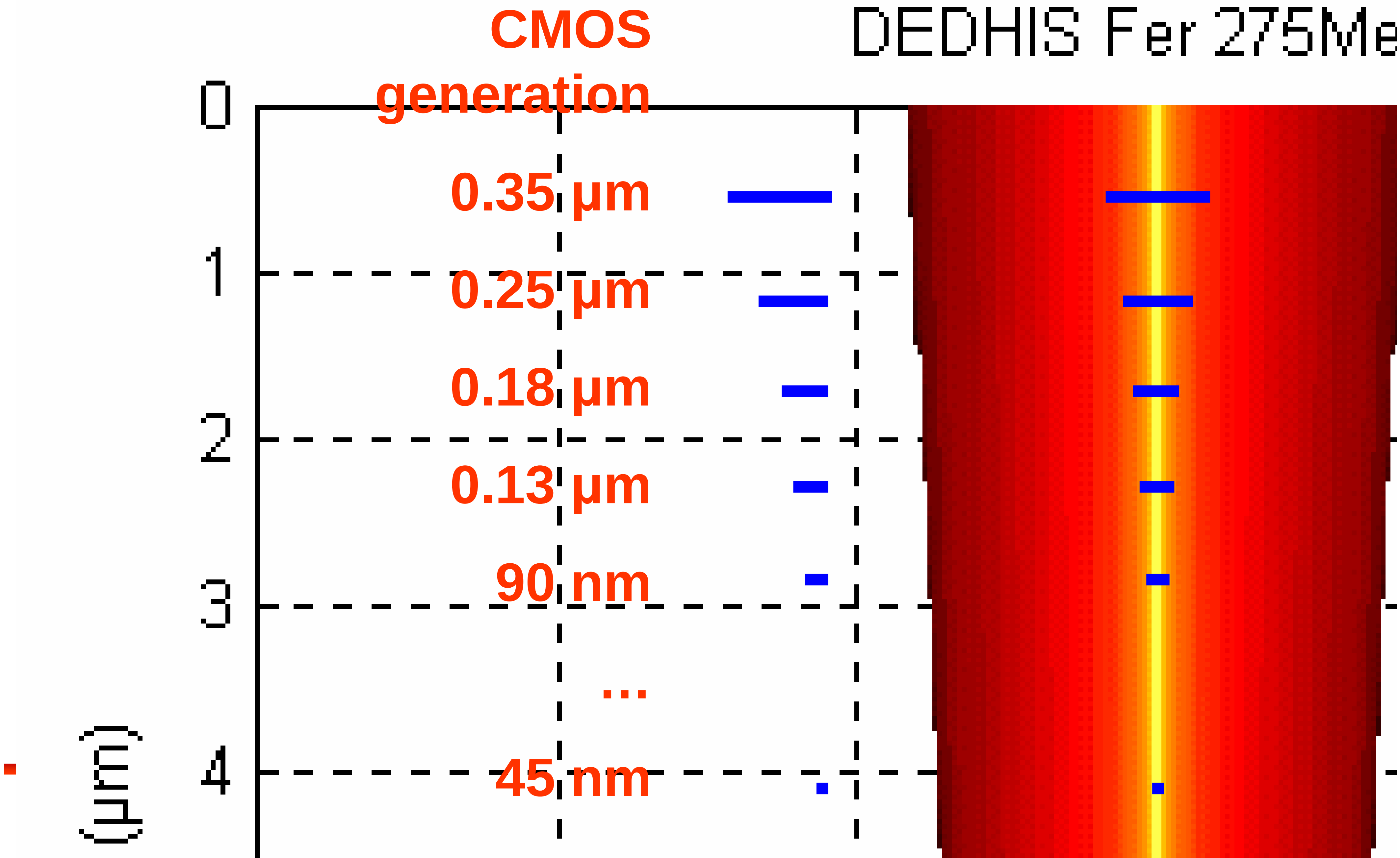
$6.4 \cdot 10^4$ e-h pairs/µm

↓

10 fC/µm

P. Foulliat, EWRHE 2004

Heavy ion e-h track in Si vs. CMOS minimum size

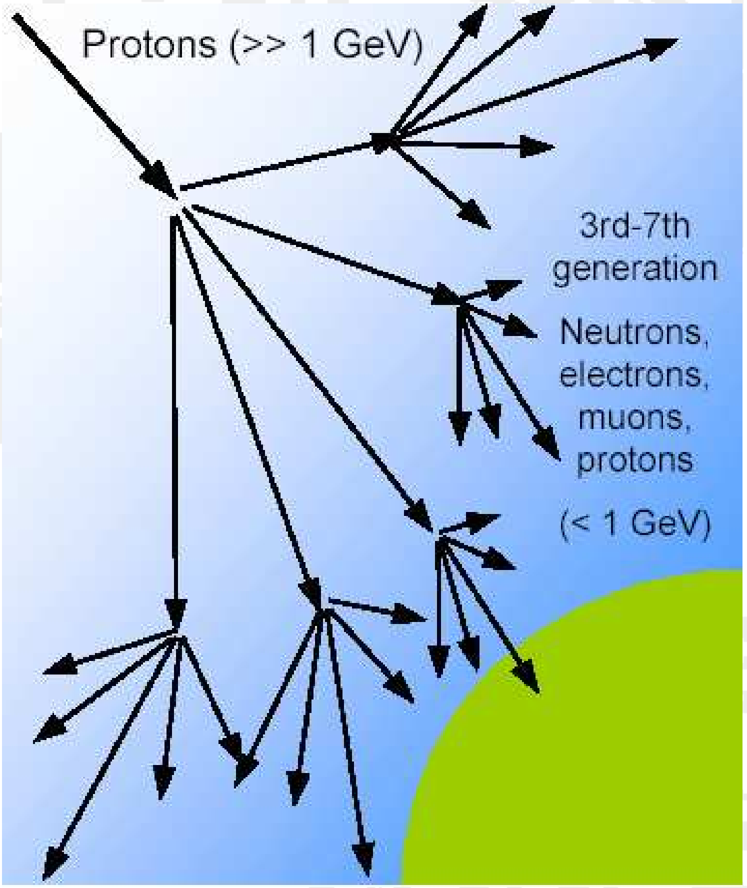


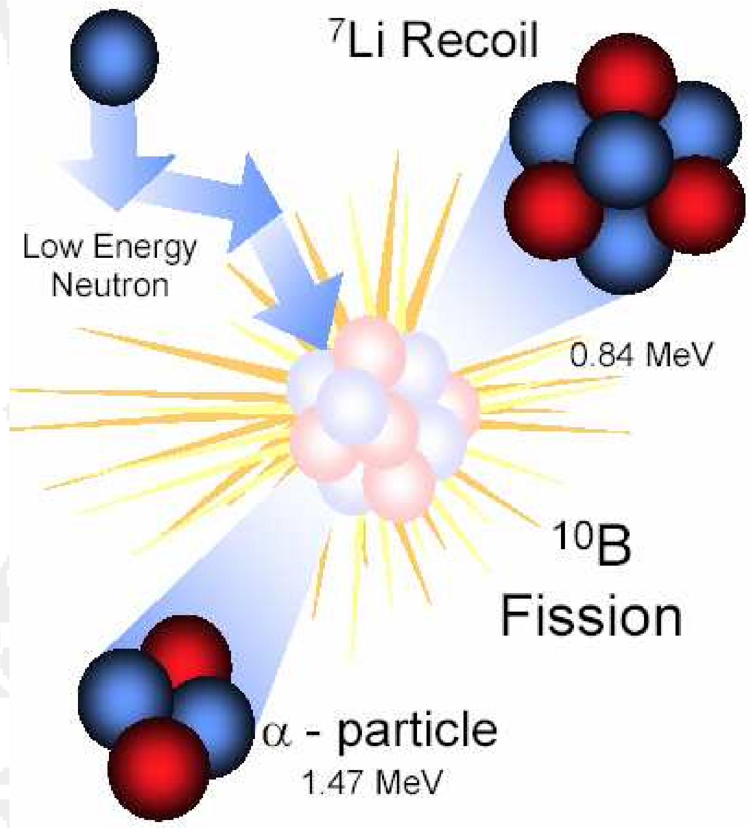
Sources of Single Event Effects

- Space applications:
  - **High-energy heavy ions**
    - Long range in Si, large LET, direct interaction
  - **High-energy protons** (trapped, solar, cosmic)
    - Direct / Indirect interaction through nuclear reactions
- Terrestrial and avionic applications:
  - **High energy neutrons** (cosmic ray byproducts)
    - Indirect interaction through nuclear reactions
  - **Low energy neutrons** (thermal)
    - Indirect interaction via ^{10}B nuclear reaction
  - **Alpha particles** from radioactive decay of contaminants (from U, Th decay chains) in the chip/package/solder
    - Short range in Si, small LET, direct interaction

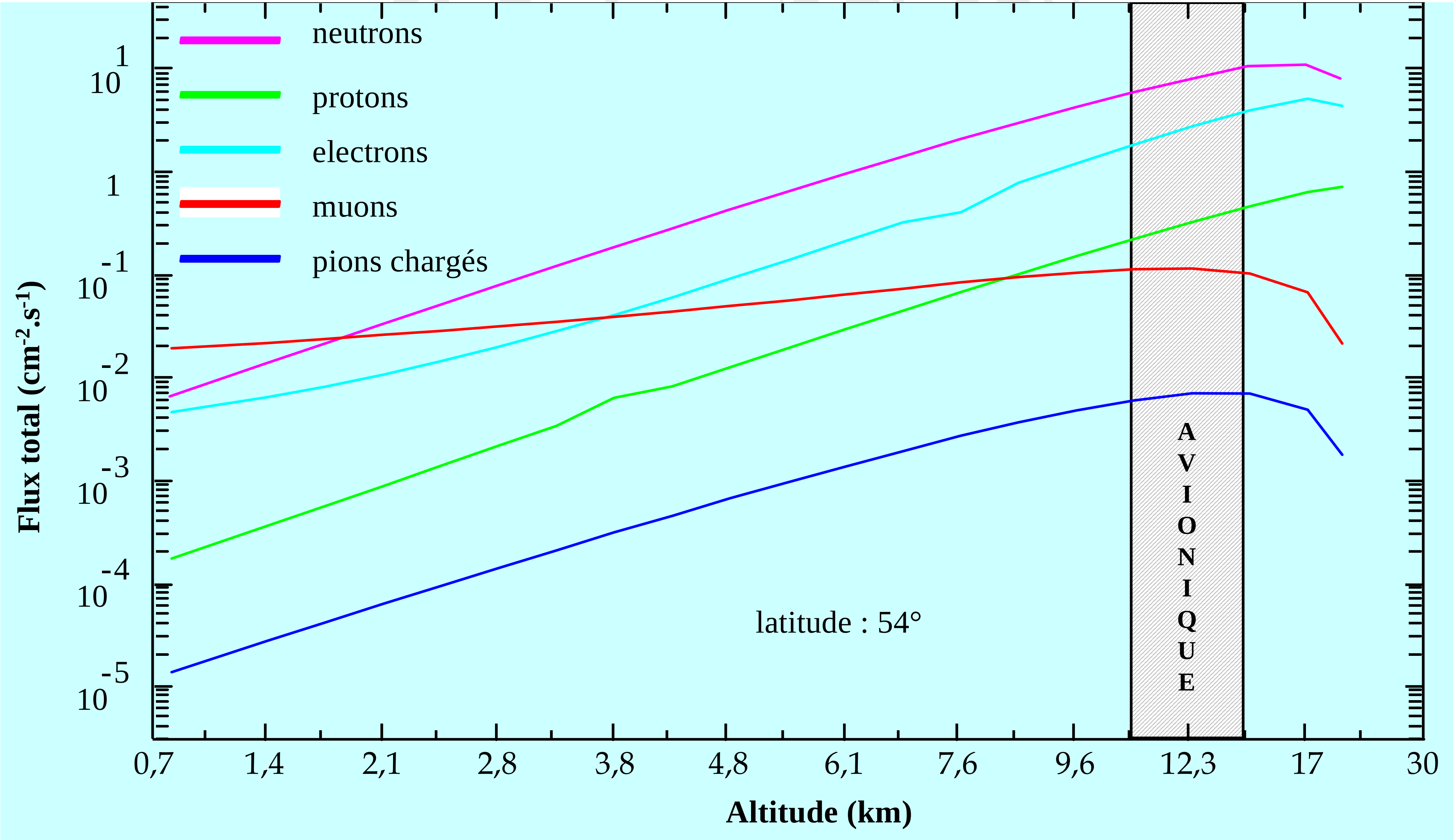
Single Event Effects even at sea level

- High energy neutrons
- Low energy neutrons

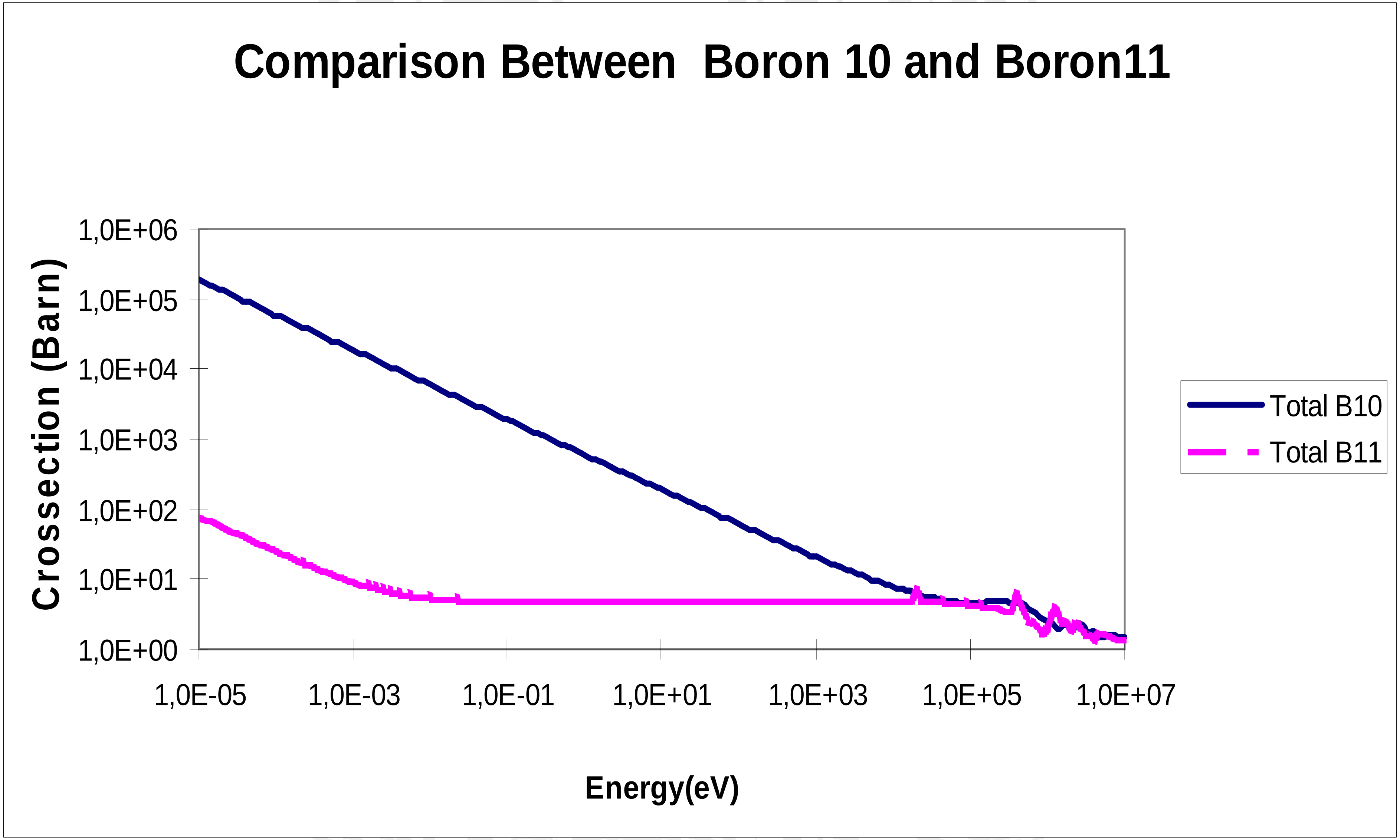




Atmospheric particles flux



Thermal neutrons cross section



Alpha particle emission rates

Material	Emission rate (α/cm^2-hr)
Bare Si	0.00020
Plastic (epoxy)	0.00080
Ceramic lid A	0.15
Ceramic lid B	3.10
Ceramic DIP A	0.02320
Ceramic Dip B	0.03230
Ceramic Dip C	0.02610
Plastic DIP A	0.00109
Plastic DIP B	0.00124

Industrial goal: 10^{-3} Alpha/cm^{2}h as tradeoff between cost and purity

L. Lantz, IEEE-TR45, 1996

SEE countermeasures

The severity of the effect on the device/circuit depends on:

- pulse/charge intensity
- type of effect
- system criticality

Single Event Effects in devices/circuits can be **mitigated** by using different strategies at different levels. For instance:

- **circuit level**, by using specific technologies or processes for fabrication (such as epi-CMOS, SOI, additional capacitors in SRAM, or rad-hardened electronic components)
- **design level**, by using *ad hoc* logic structures aiming to SEE immunity (such as SEE immune latches)
- **system level**, by modifying the software and/or the hardware (such as triple redundancy)

SEE ground testing

- SEE tests are performed to evaluate the expected error / failure rate of the device/system in the specific operating environment (Space, HEP, Avionic, Sea level,…) by using:
  - Ion beams from accelerators
  - Neutron beams
  - Alpha sources
  - Lasers
  - A large number of devices operating under low intensity radiation (*unaccelerated tests: the Rosetta experiment*)

accelerated tests

- The SEE sensitivity of each SEE type (SEU, SEL, SEB, …) in any particular device is evaluated by measuring the corresponding **cross section** vs **LET**:
  - **Cross section** : σ(**LET**) = # Events / particle fluence (cm^2)
- The error rates in operating condition is derived from cross sections and the features (nature of particles, corresponding fluxes, mission duration) of the actual environment
- Error rate = # errors / device day

SEE cross section and threshold LET

- **LET_{th}** is the minimum (threshold) LET to cause the specific SEE
- The saturation cross section σ_{sat} is approached at high LET values
- The σ(LET) curve is obtained by measuring the cross section at a few LET values and fitting data with a Weibull curve

LET_{th}

Device Threshold	*Environment to be Assessed*
LETth < 10 MeV*cm2/mg	Cosmic Ray, Trapped Protons, Solar Flare
LETth = 10-100 MeV*cm2/mg	Cosmic Ray
LETth > 100 MeV*cm2/mg	No analysis required

R. Velazco, EWRHE 2004

The **cross section (σ)** for Single Event Effects is $\sigma = N_{SEE} / \Phi$

N_{SEE}: **number (counts) of SEE observed**

Φ: **uniform fluence over some fiducial area**

practical flux set by dead-time of DUT (typical few $10 \div 10^4$ ions $cm^{-2}s^{-1}$)

- **Statistical Error improves with Fluence**
- however **Fluence Limited by Total Dose**

WEIBULL FIT of threshold curve

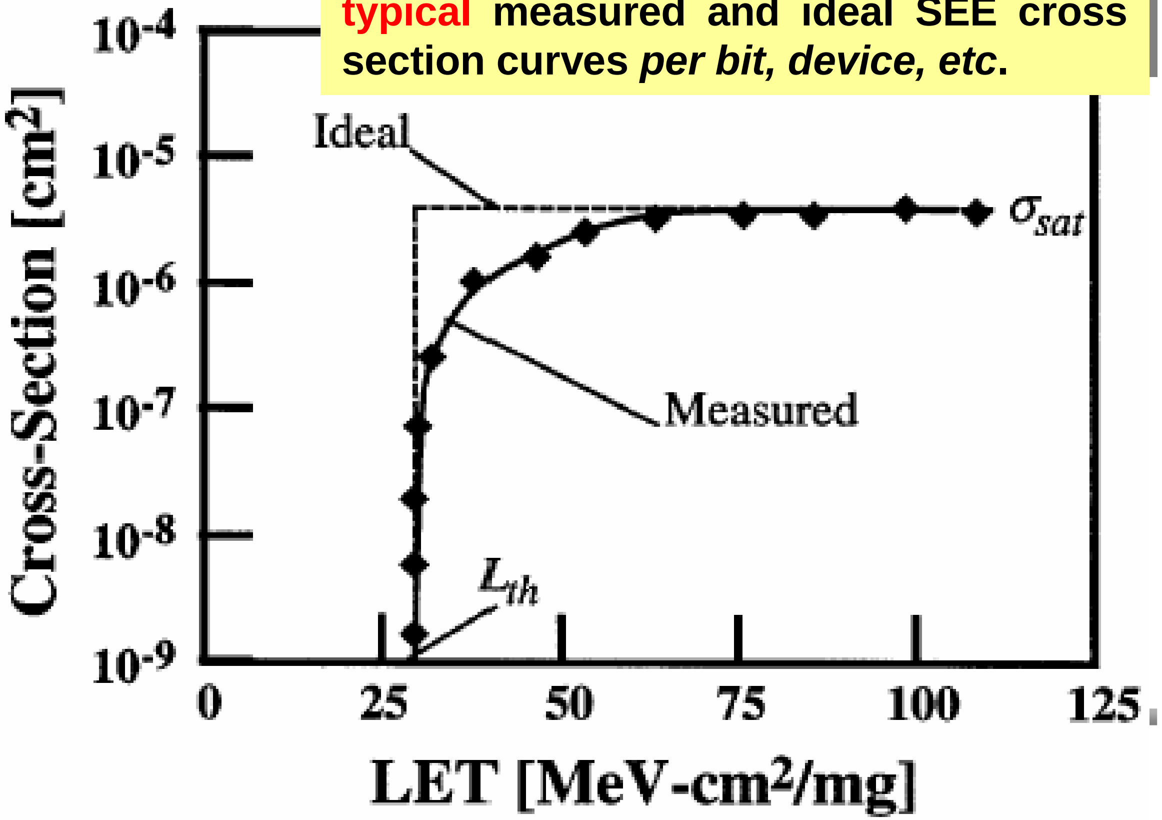
$$\sigma = \sigma_{sat} \times \{1-\exp[-(L-L_{th})/W]^s\}$$

σ_{sat}: **saturation value**

L_{th}: **threshold LET value**

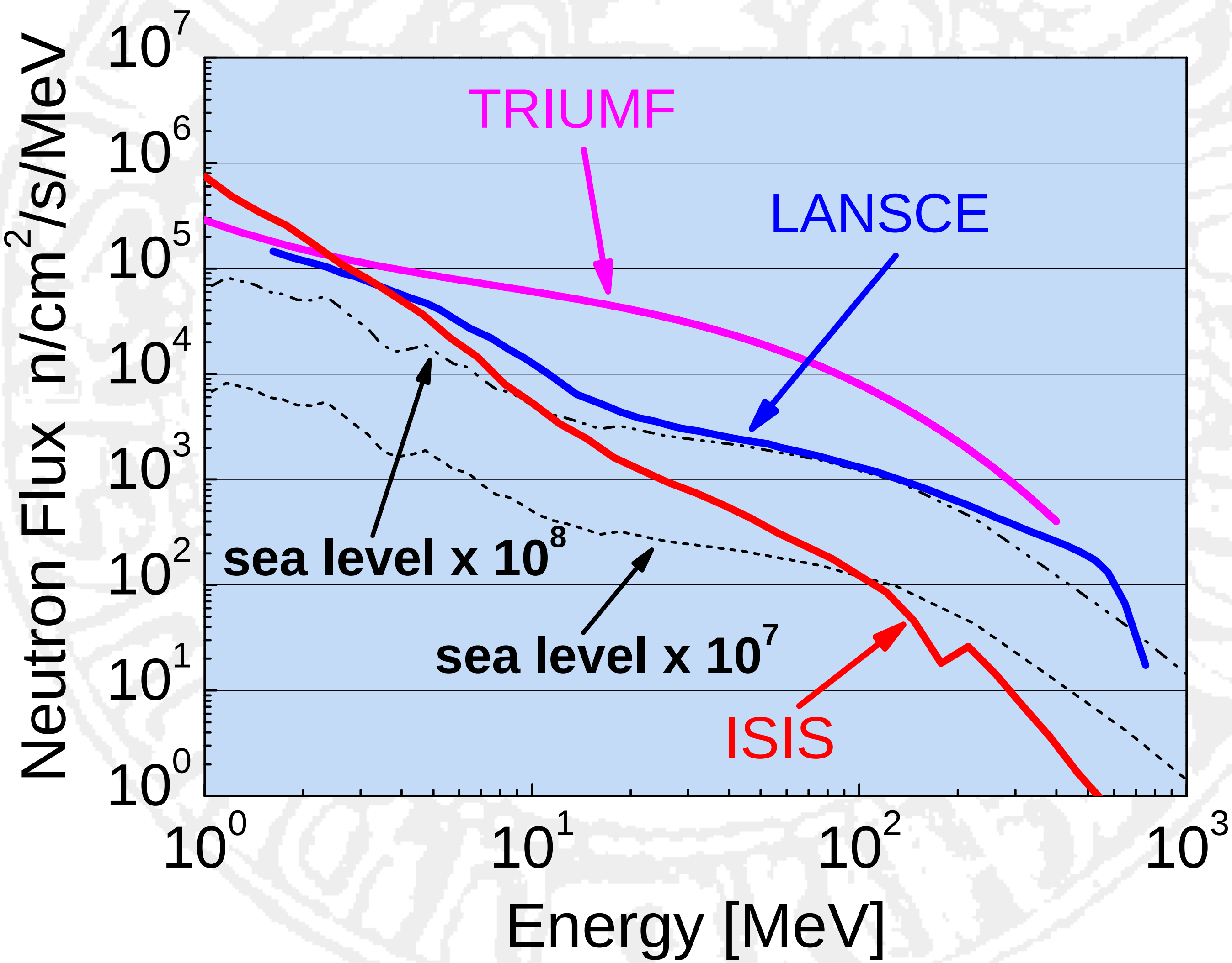
W and s are fitting parameters

typical measured and ideal SEE cross section curves *per bit, device, etc*.



Broad spectrum n facilities

The terrestrial n spectrum features a ~$1/E^{\alpha}$ characteristic ($\alpha > 1$): few laboratories worldwide may provide a flux similar to the terrestrial with an **acceleration factor** between **10^7 and 10^8**



Summary

- Single event effects are produced by collecting the charge generated (usually in the semiconductor) by a single ionizing particle: charge > critical charge
- The e-h track may include more than one active device (e.g., MOSFET)
- Different SEE's may occur depending on the device type, being either soft or hard in nature
- Each SEE for a specific device is characterized by its cross section and threshold LET
- SEE's are expected not only in radiation harsh environments but also at sea level