

Single Event Effects: the effects of Single particles on electronics

Space, aerospace and ground

Jean-Luc Autran, Daniela Munteanu
Aix-Marseille University & CNRS
IM2NP Laboratory, Marseille, France

Im2np



The authors are also with the **Radiation Effects & Electrical Reliability (REER) Joint Laboratory**
IM2NP-STMicroelectronics



A few words about us...



REER Joint Laboratory

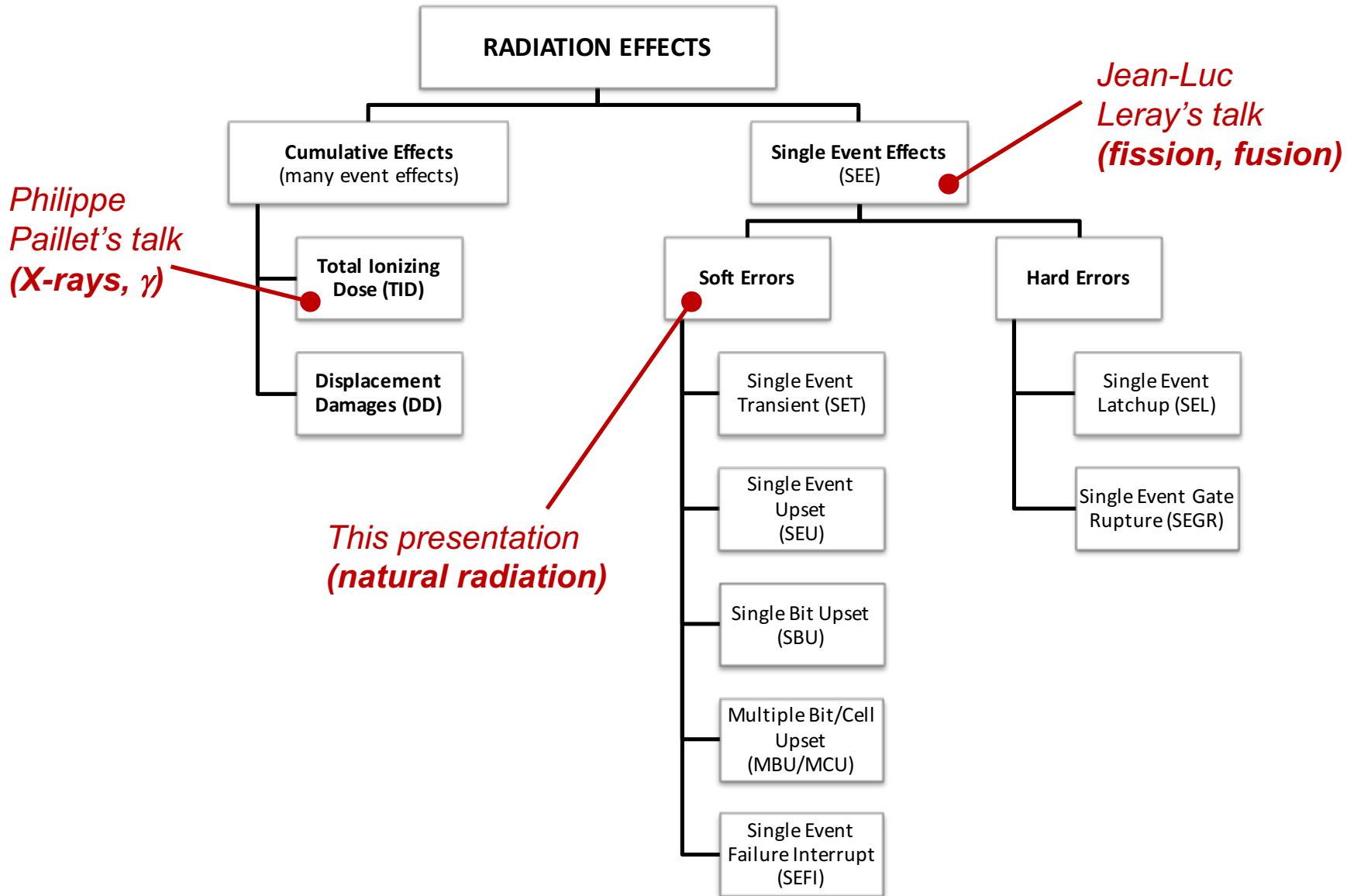


Underground test platform



Altitude test platform

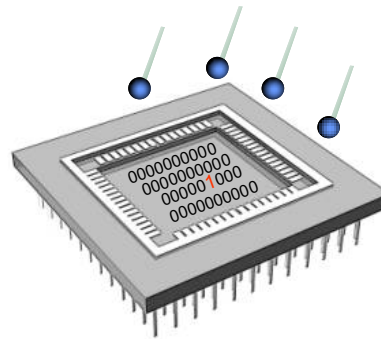




Outline

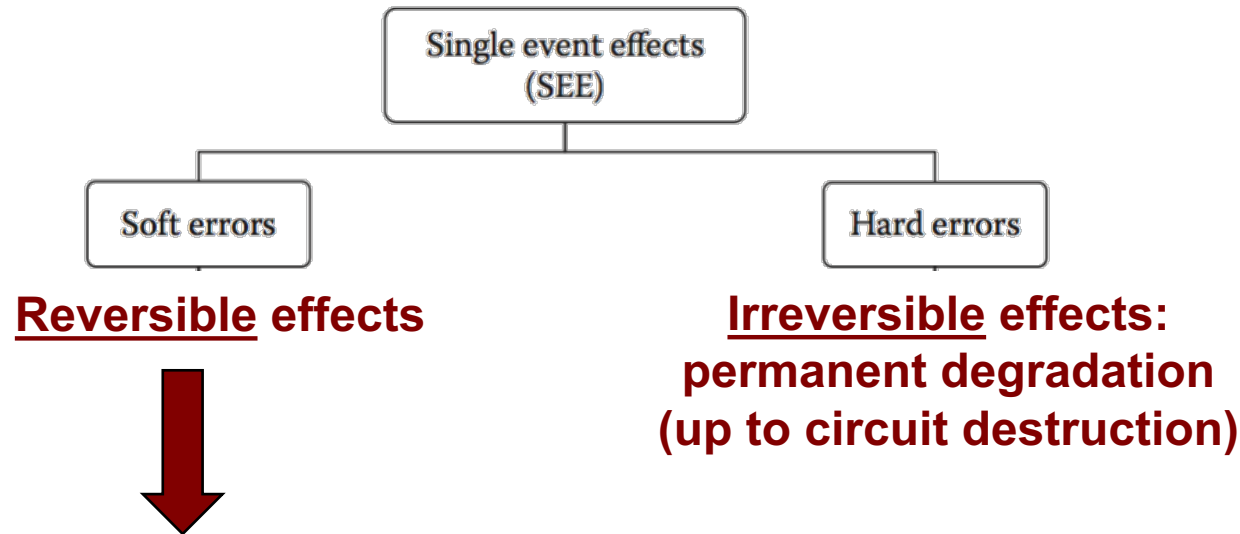
- Introduction – Definition of soft error
- Sources of soft errors
- Mechanisms of soft errors
- Characterization of soft errors
- Modeling and simulation issues
- Scaling effects in deca-nanometer CMOS
- Current work on FDSOI 28nm technology
- To conclude: open problems in characterization, modeling and simulation

I – Introduction



Introduction

Single event effects indicate any measurable or observable change in state or performance of a microelectronic device, component, subsystem, or system (digital or analog) resulting from a single, energetic particle strike.



Soft errors are related to the most benign form of radiation effects on the circuitry, where radiation directly or indirectly induces a localized ionization capable of upsetting internal data states.

Introduction

The Soft Error Rate (SER) quantifies the occurrence of soft error in time:

$$SER = \int_{E_{min}}^{\infty} \sigma(E) \phi(E) dE$$

Soft Error Rate [s⁻¹]

FIT = Failure-In-Time

= 1 fail / 10⁹ h

= 1 fail / 114,707 years

Differential flux of the energetic particles inducing soft errors
[cm⁻²s⁻¹eV⁻¹]

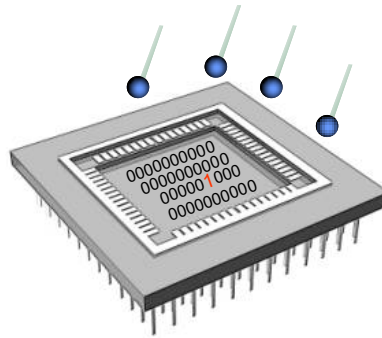
Device/circuit cross section for the considered energetic particles
[cm⁻²]

Define the radiation environment in which the device/circuit works

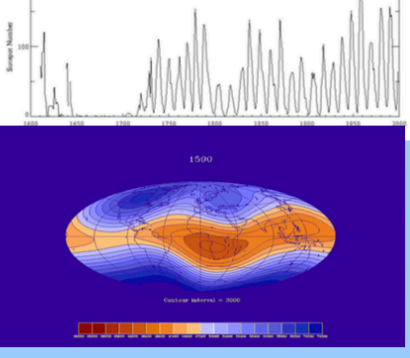
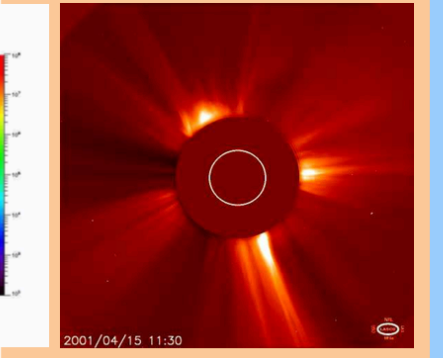
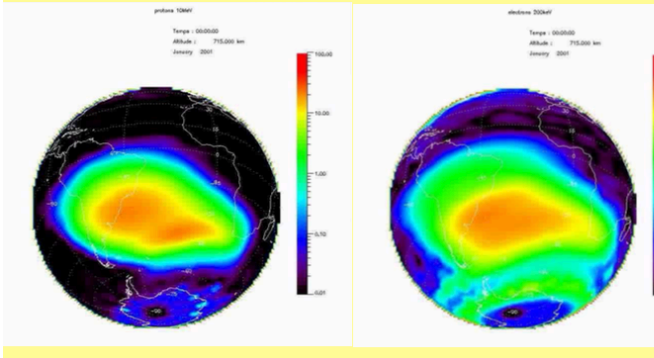
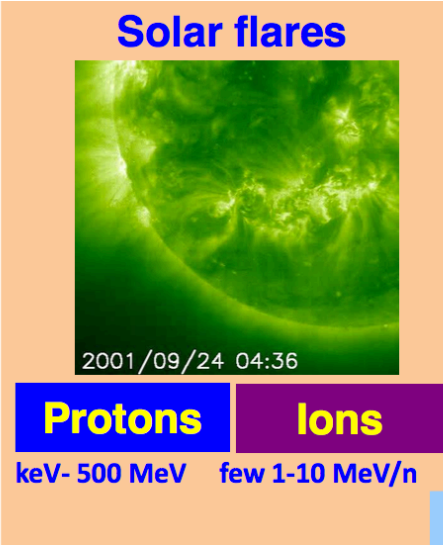
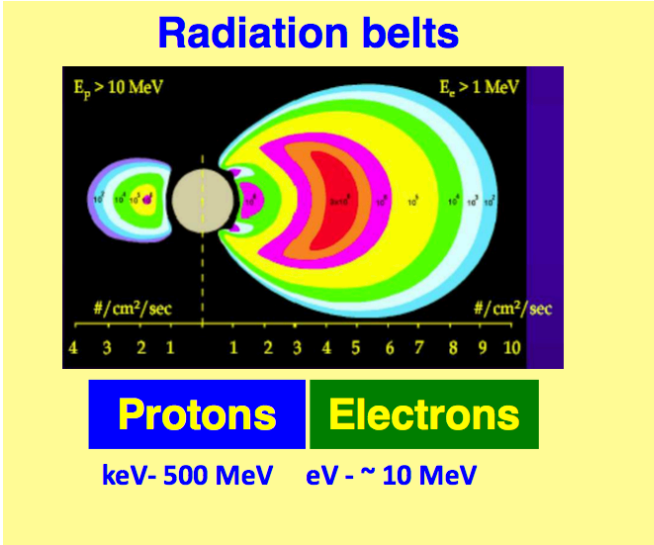
$$\sigma(E) = \frac{\text{Number of soft error events}}{\Phi(E)T}$$

Define the device/circuit sensitivity to a given radiation

II – Sources of Soft Errors

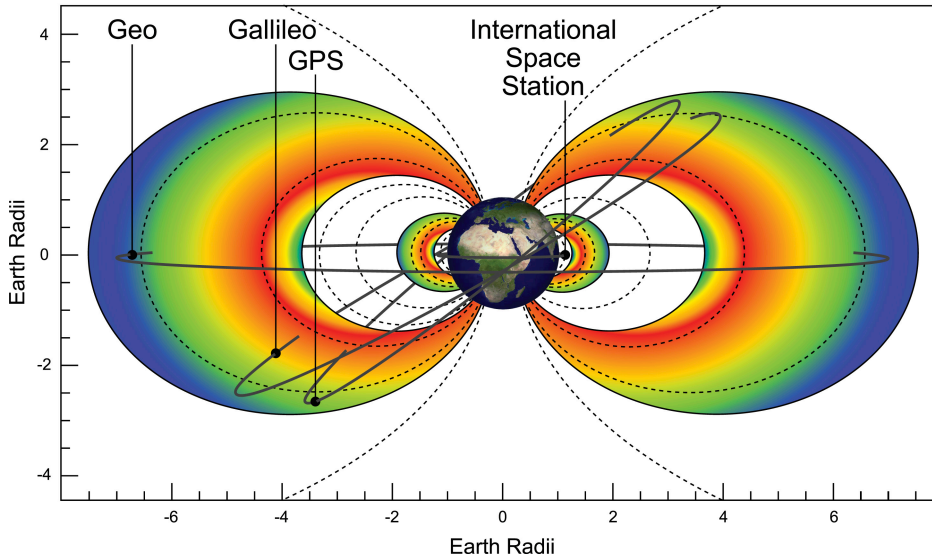


Soft Errors in space are primarily due to energetic particles (protons, electrons, ions) coming from deep space, Sun or trapped in the Earth's radiation belts

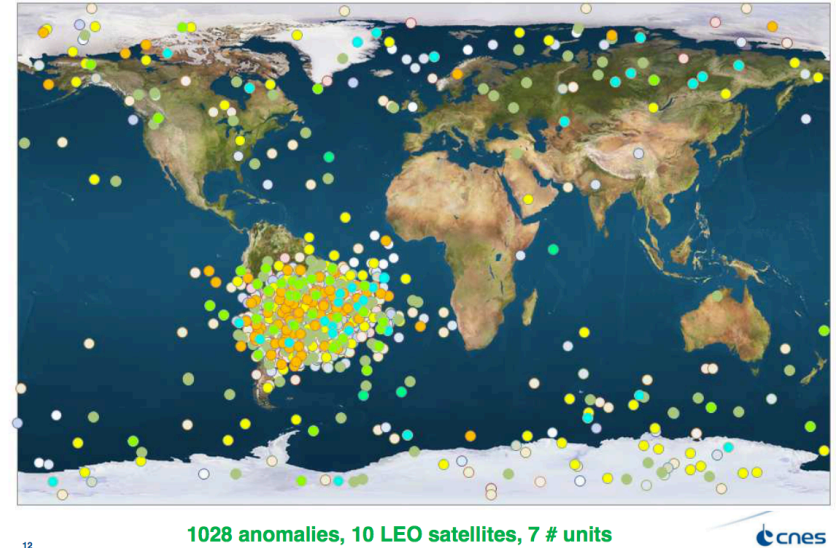


Courtesy of Robert Ecoffet (CNES)

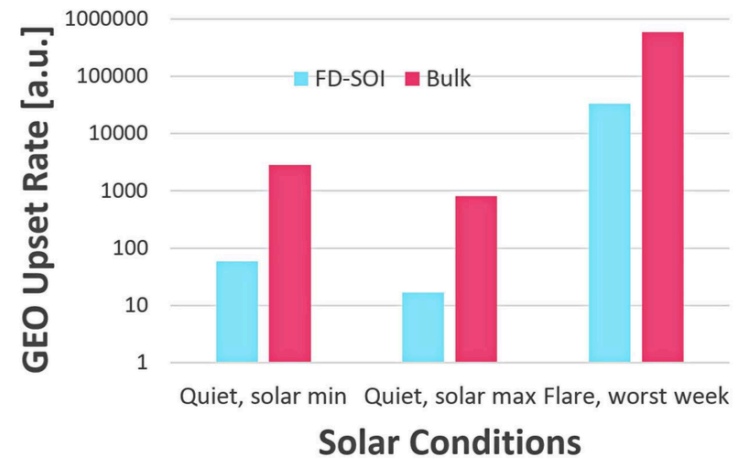
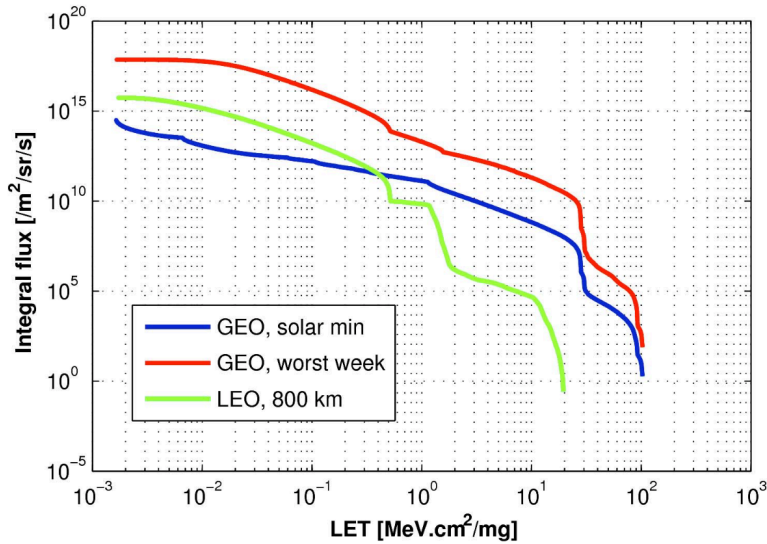
Satellite orbits and the van Allen radiation belts



Low Earth Orbit missions feedback



Courtesy of Robert Ecoffet (CNES)



CREME simulation (NASA/Vanderbilt)

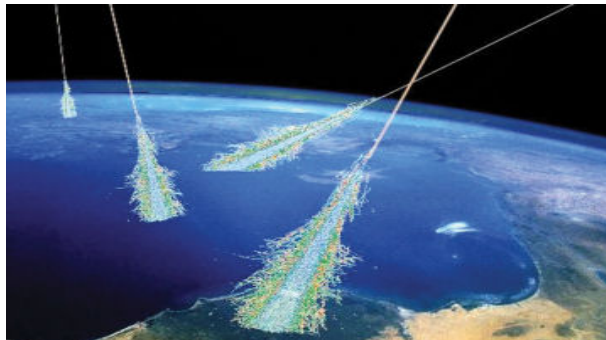
V. Malherbe et al. IEEE TNS 64, 2017

Introduction

Soft Errors at **atmospheric** or **ground level** can be induced by two different types of radiation constraints



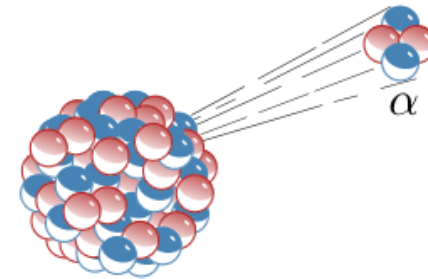
ATMOSPHERIC Terrestrial cosmic rays



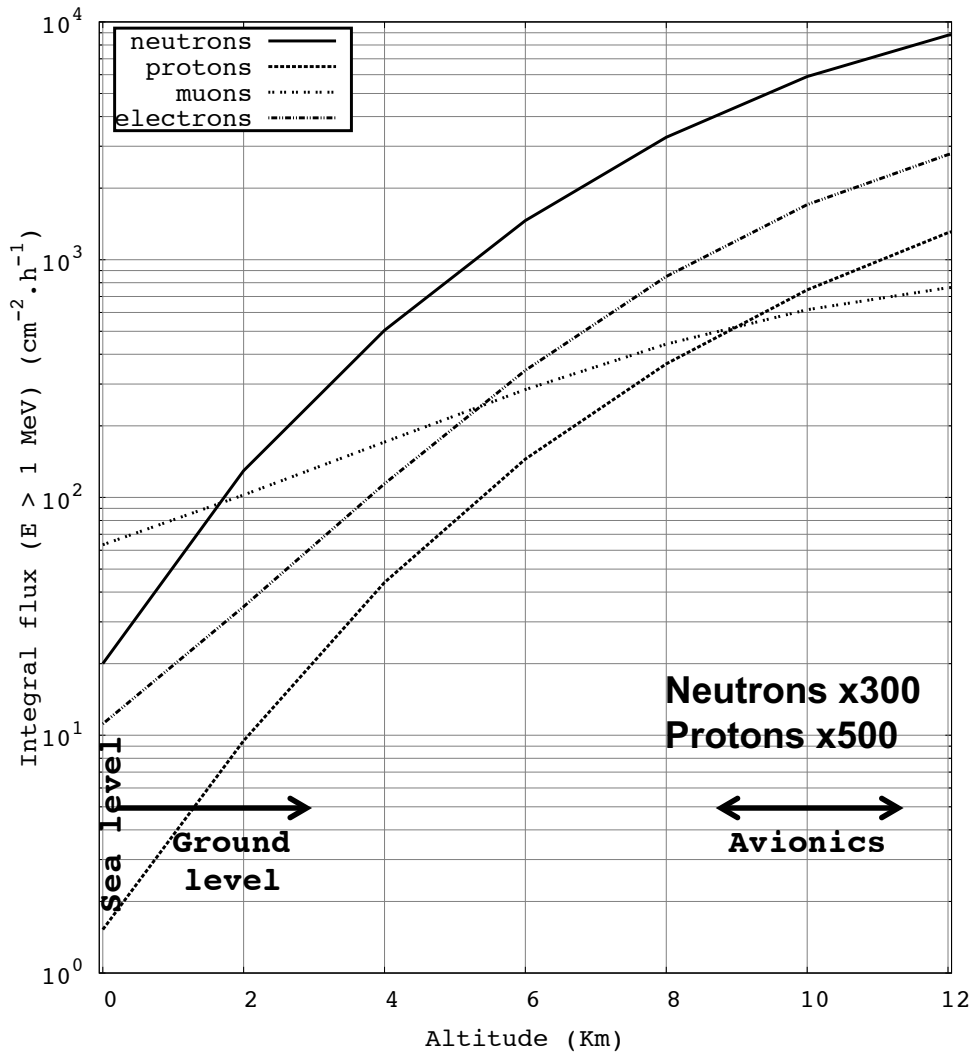
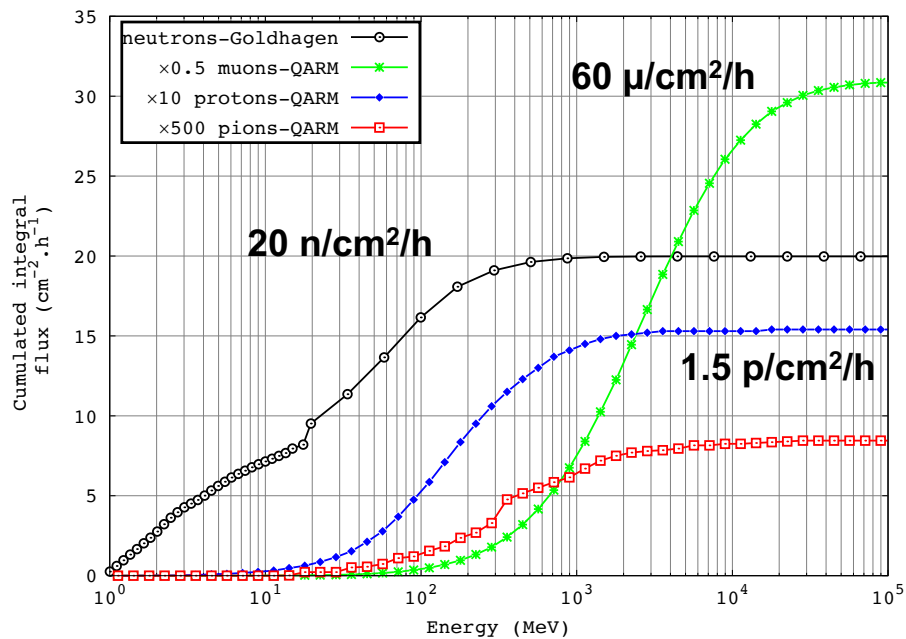
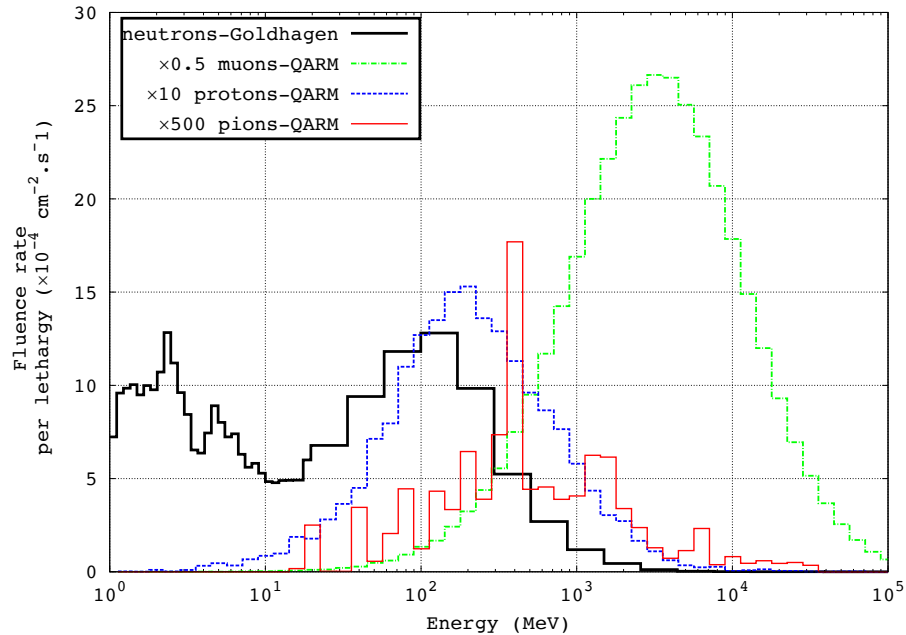
- **High energy neutrons**
interactions with IC material
- **Low energy (thermal) neutrons**
interactions with ^{10}B
- **Also protons and muons**



INTERNAL Alpha-particle emitters



- **U/Th contamination at sub-ppb concentrations**
- **Natural α -emitter isotopes (Hafnium, Platinum)**
- **Radon and Thoron gases**

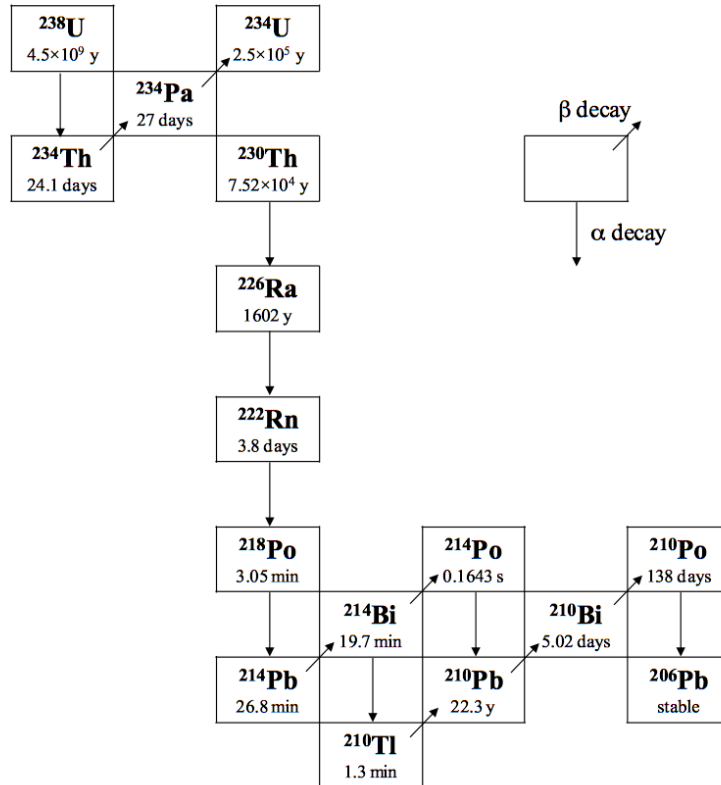




Internal sources : radioactive isotopes

→ Use of **Silicon** wafers, ceramic packages and contact bumps contaminated with **Uranium** and **Thorium** elements at ppb levels

Uranium	92
Protactinium	91
Thorium	90
Actinium	89
Radium	88
Francium	87
Radon	86
Astatine	85
Polonium	84
Bismuth	83
Lead	82
Thalium	81



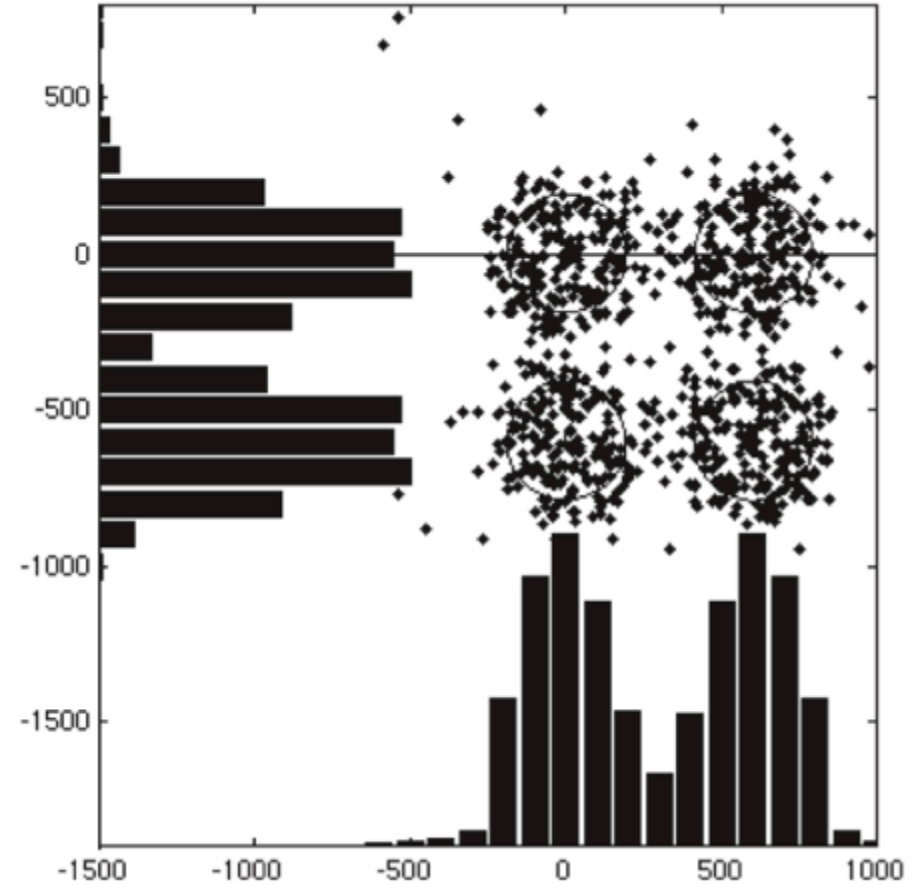
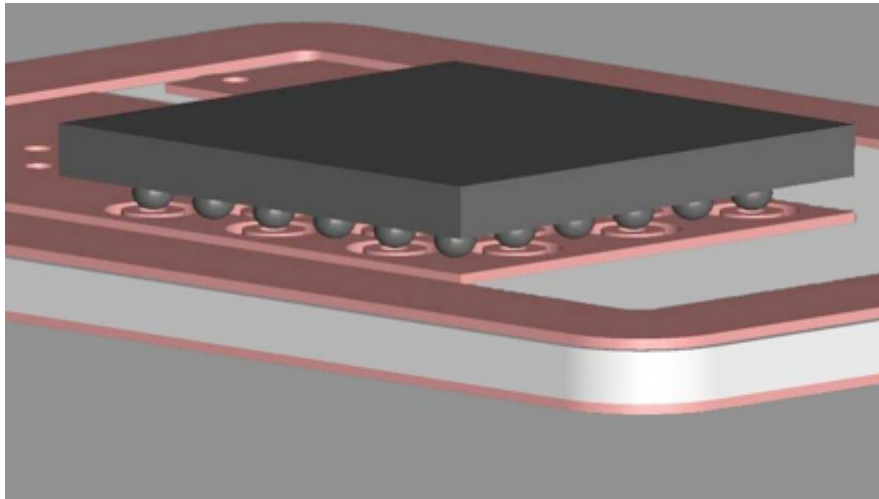
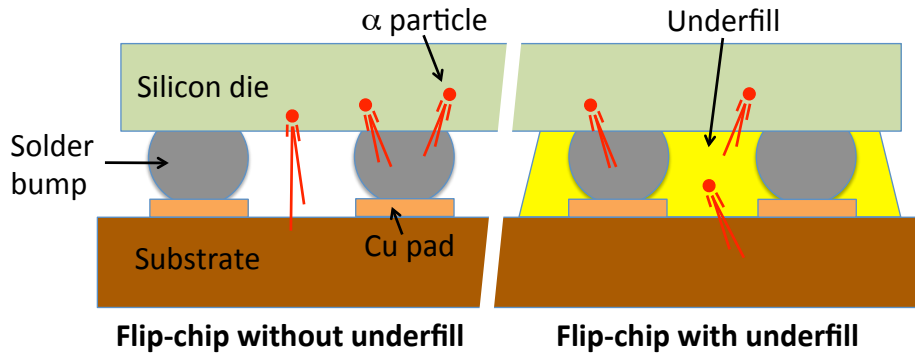
→ 0.5 ppb of ^{238}U in Silicon
 = 425 Bq/m³
 = 0.18 Bq/kg

→ Compared to:
 sea water: 12 Bq/kg
 spring water: 0.1 Bq/kg



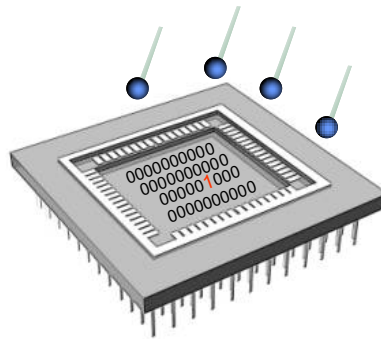
0.5 ppb of ^{238}U in Silicon
 = 2.28×10^{-3} $\alpha/\text{cm}^2/\text{h}$

Internal sources : radioactive isotopes

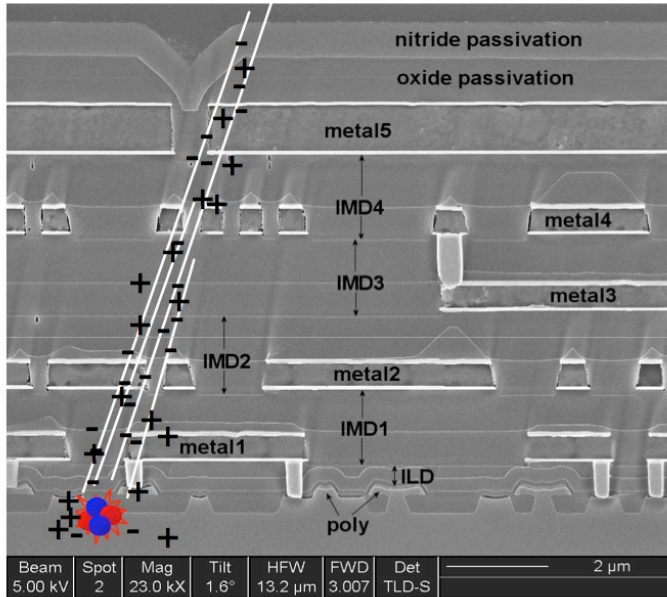


After Wilkinson et al.

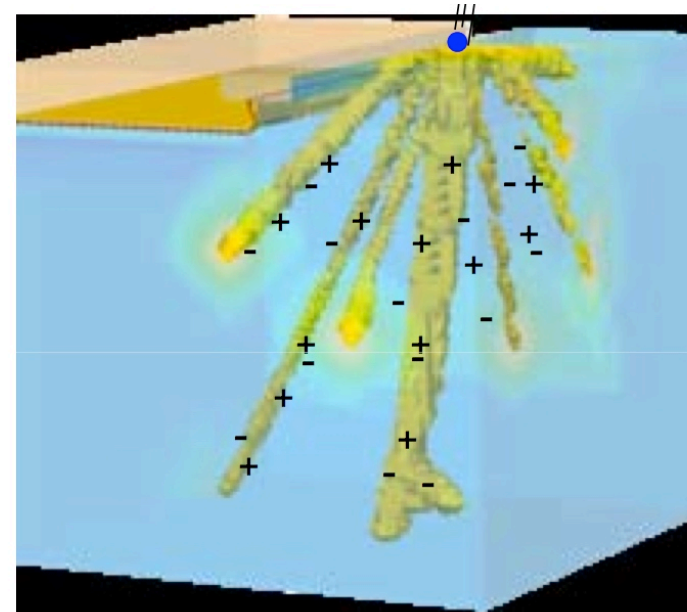
III – Mechanisms of Soft Errors



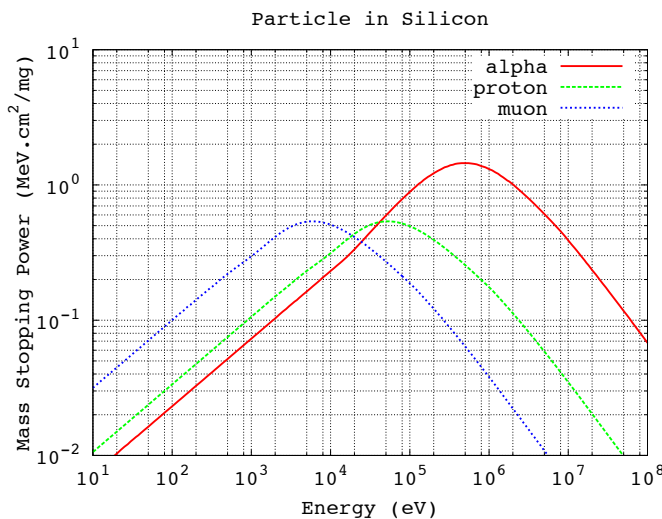
→ Direct ionization (α , p , μ)



→ Indirect ionization (n , $p > 100$ MeV)



Source: Vanderbilt University



Creation of a e^-/h^+ pair in silicon requires 3.6 eV

→ 278,000 e^- for a 1 MeV α

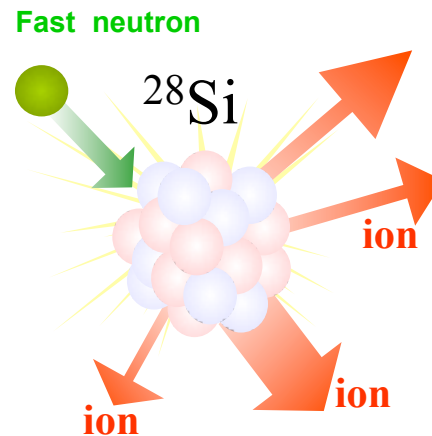
Silicon: $1\text{MeV}/(\text{mg}/\text{cm}^2) \approx 10\text{fC}/\mu\text{m}$

Mechanisms of Soft Errors

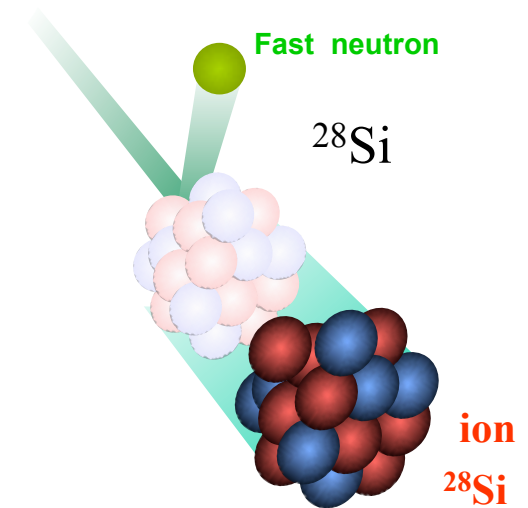
Products of reaction Threshold energy (MeV)

$^{28}\text{Si} + n$	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
$^{27}\text{Mg} + 2p$	13.90
$^{24}\text{Na} + p + \alpha$	15.25
$^{26}\text{Al} + t$	16.74
$^{15}\text{N} + ^{14}\text{N}$	16.97
$^{12}\text{C} + ^{16}\text{O} + n$	17.35
$^{27}\text{Si} + 2n$	17.80
$^{26}\text{Mg} + p + d$	18.27
$^{12}\text{C} + \alpha + ^{13}\text{C}$	19.65
$^{20}\text{Ne} + n + 2\alpha$	20.00

→ High energy neutrons ($E > 1 \text{ MeV}$) and protons ($E > 50 \text{ MeV}$) indirectly ionizes matter by production of secondary products or silicon recoils



≈ 40%

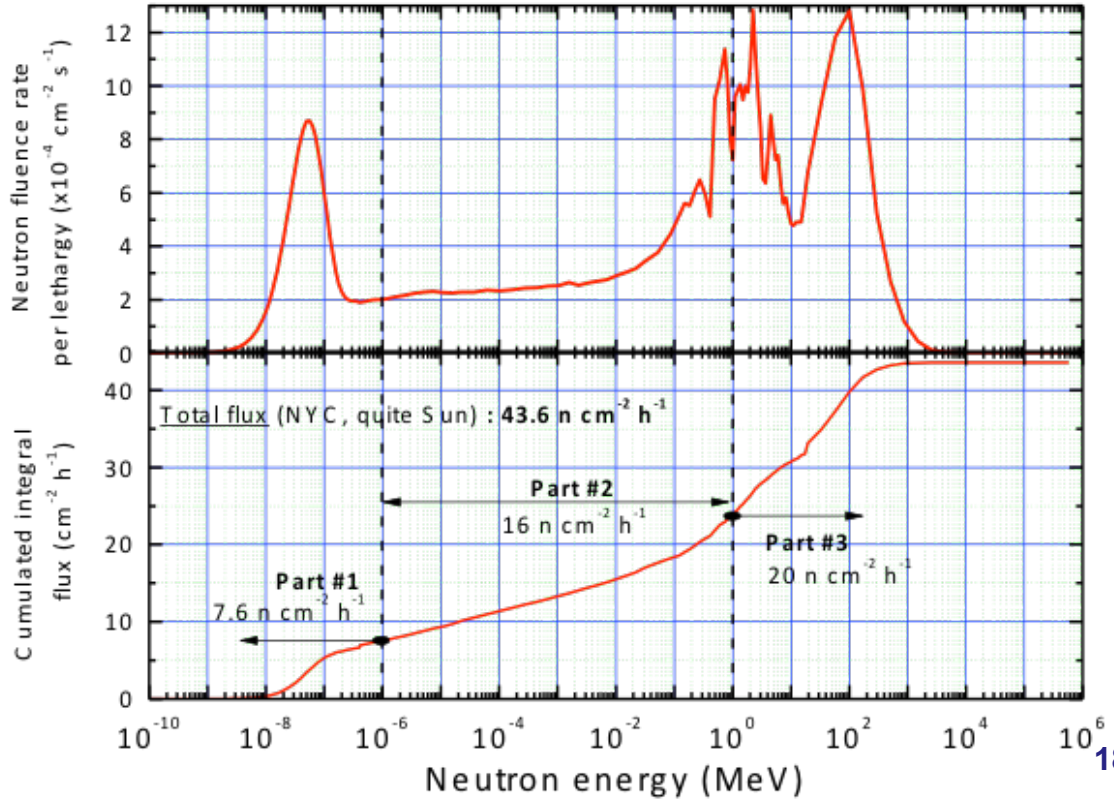
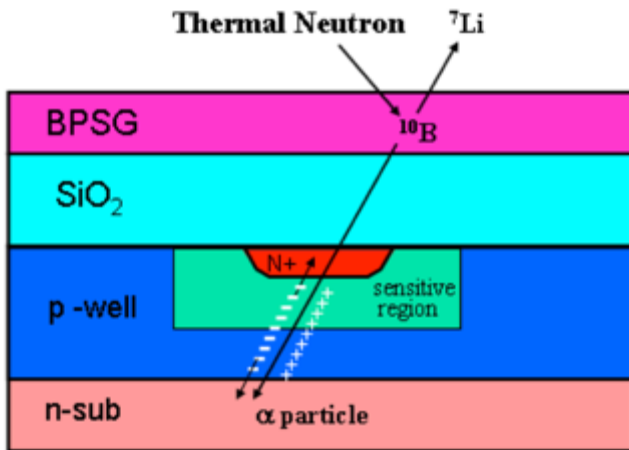
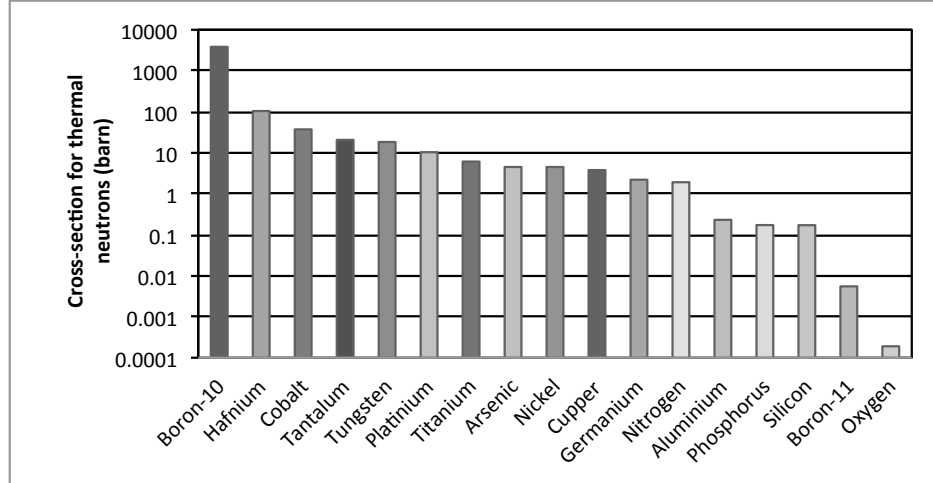
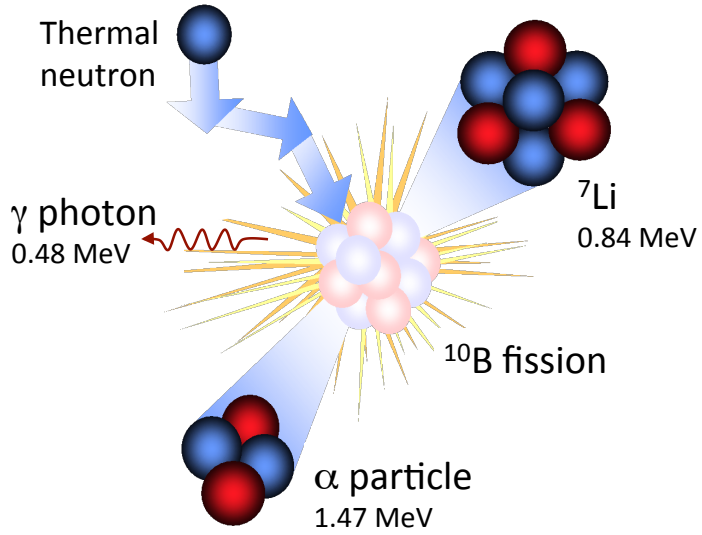


≈ 60%

(for atmospheric neutrons)

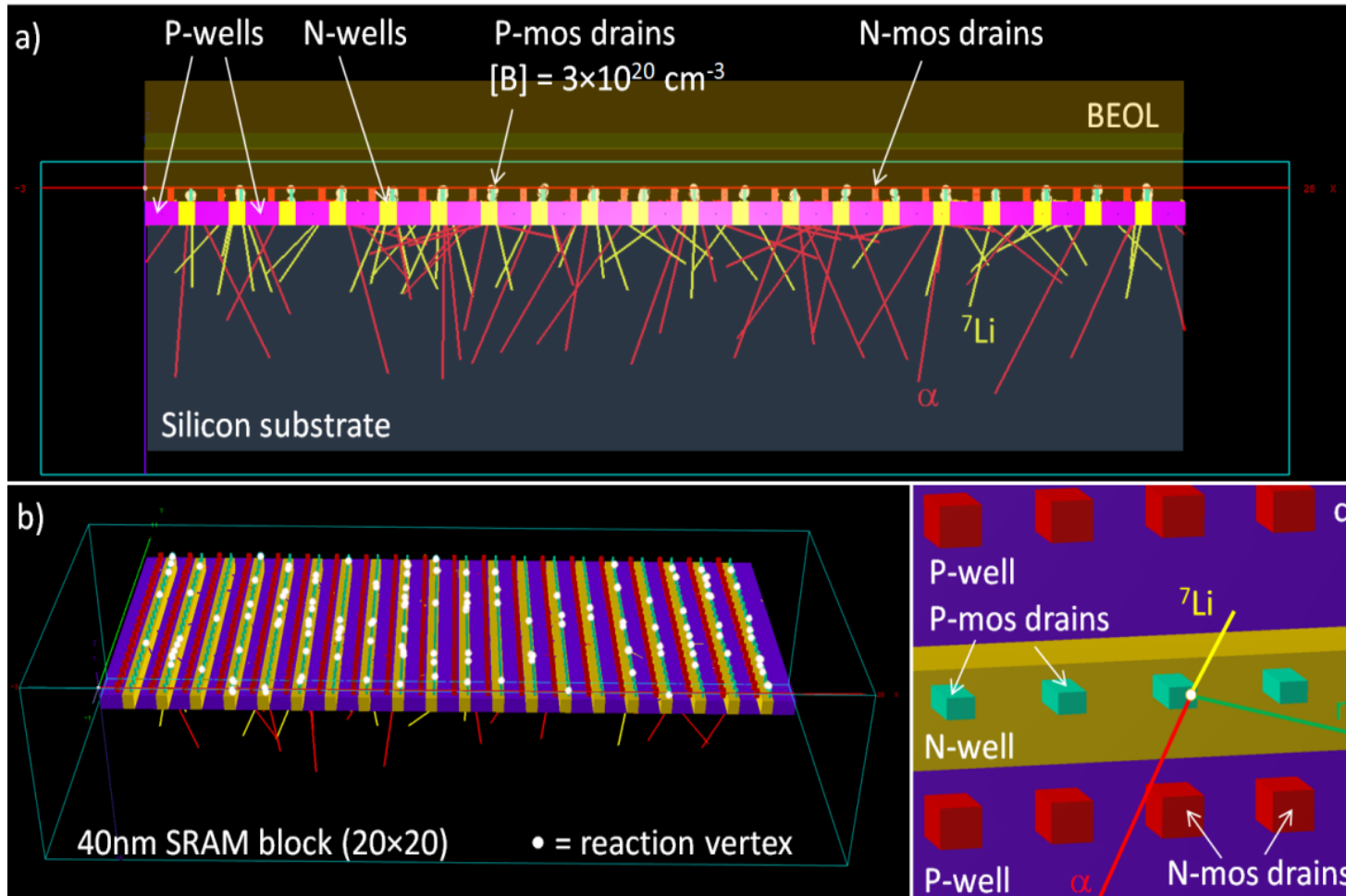
After F. Wrobel (IEEE TNS 2000)

Mechanisms of Soft Errors



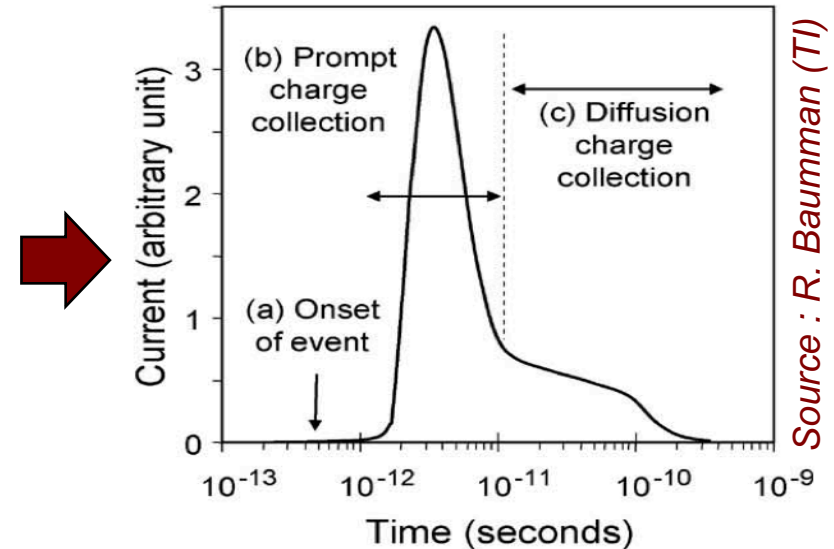
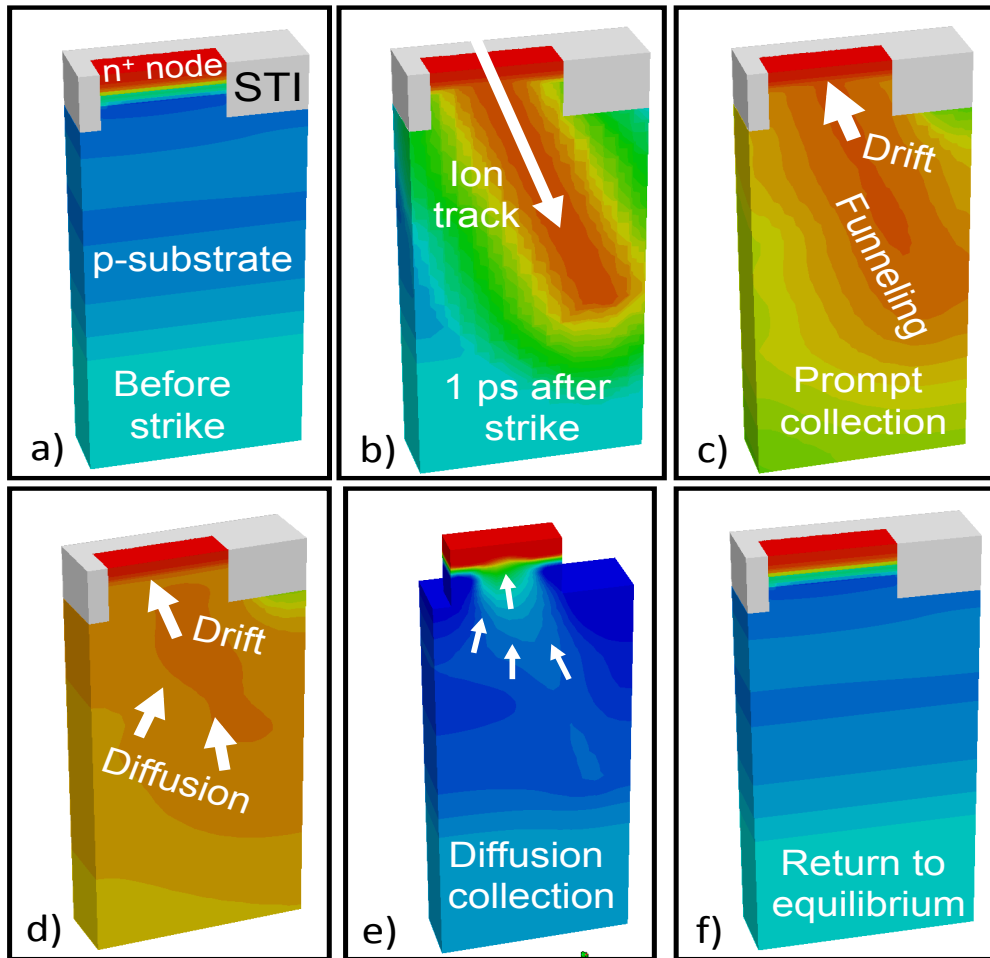
Mechanisms of Soft Errors

Thermal neutrons remains a problem at source/drain level



Mechanisms of Soft Errors

Occurrence of Single Event Effects (SEE) in devices and circuits

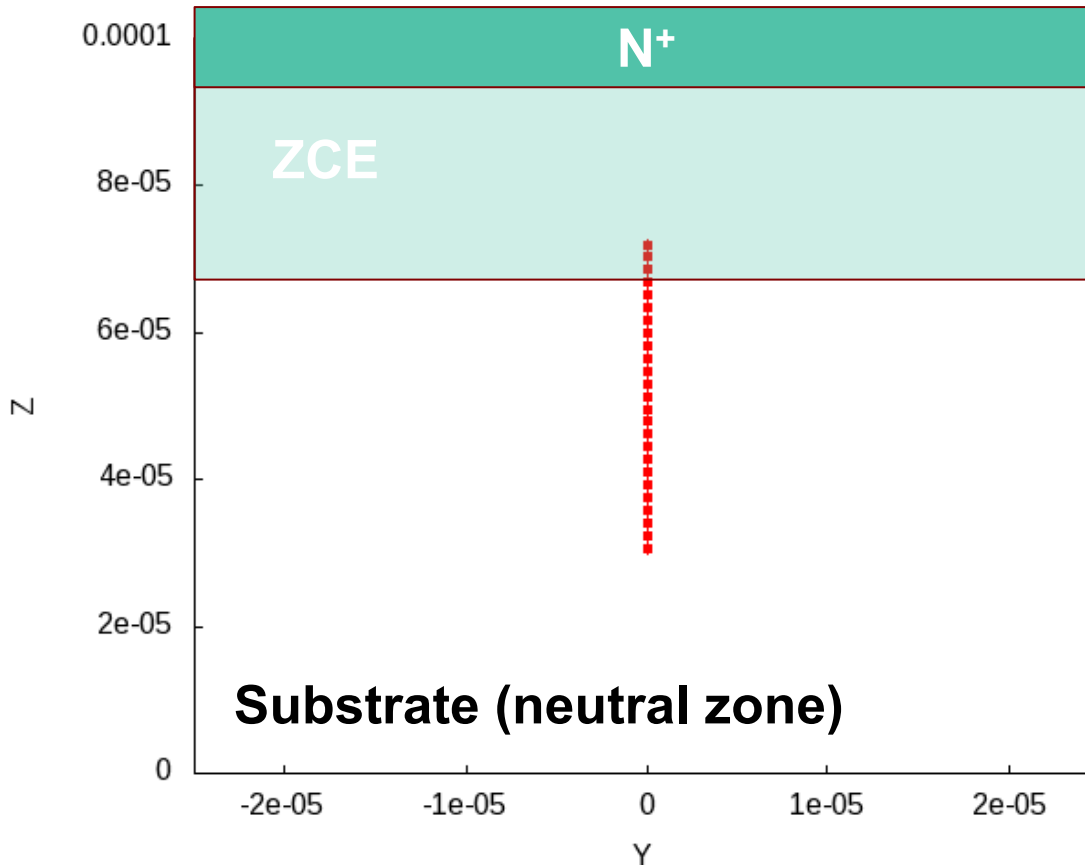


Source : R. Baumann (TI)

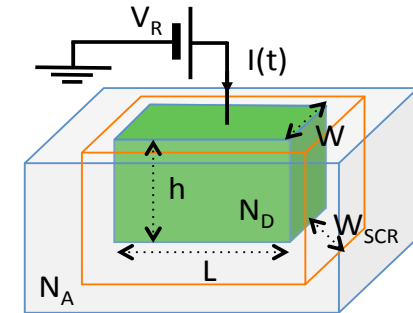
Radiation-induced current transient: the key signature of a SEE at silicon level

Mechanisms of Soft Errors

Particle Monte Carlo Simulation (Random Walk Drift Diffusion RWDD model – IM2NP)



Analytical 3D model
(abrupt/gradual junction)



```
class Drain
{
private:
    Box DrainRegion;
    Box SpacechargeRegion;
    double NA;
    double ND;
    double WSCR;
    double Emax;
    double VR;
    int NumCollectedPacket;

public:
    Drain();
    ~Drain();

    //Drain constructor (Center, W, L, h, NA, ND, VR)
    Drain(Point, double, double, double, double, double, double);

    //Set drain reverse voltage and update WSCR and Emax
    void SetVR(double);

    //Get the extension of the Space Charge Region (SCR)
    int GetWR() {return WR;};

    //Get the maximum of the electric field
    int GetEmax() {return Emax;};

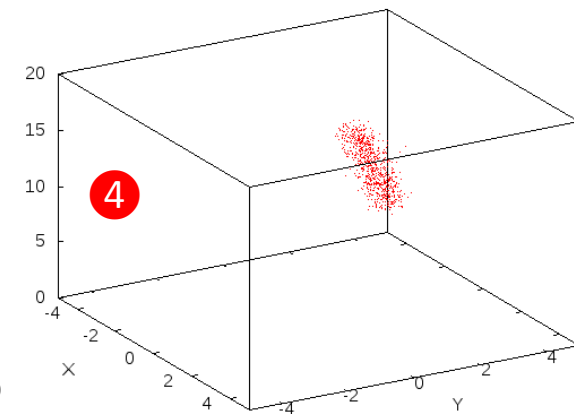
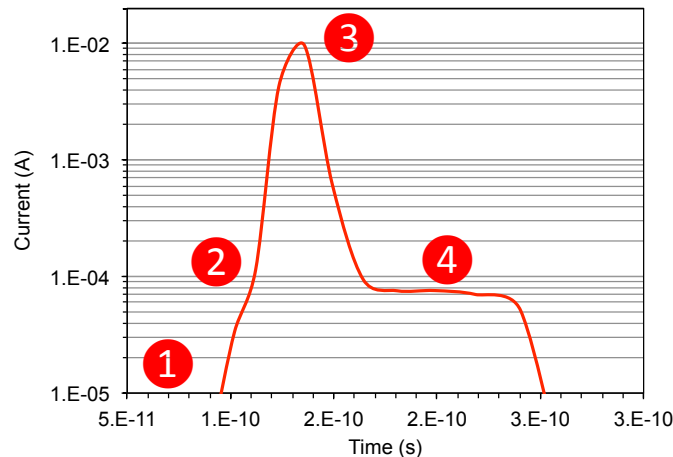
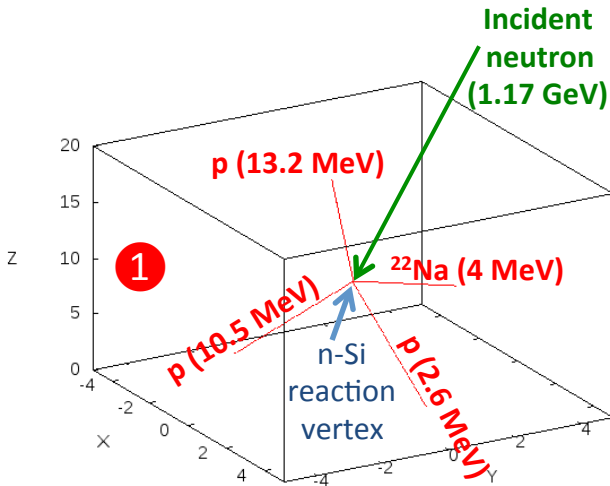
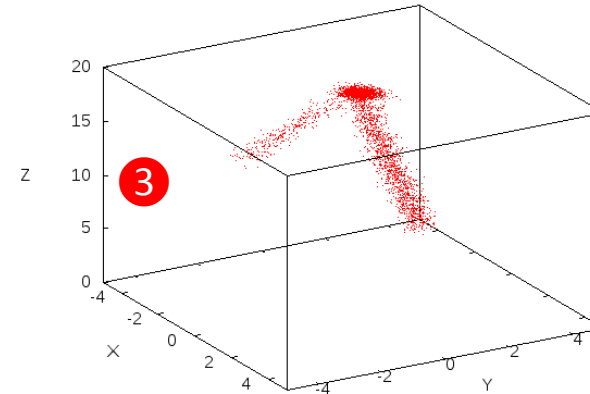
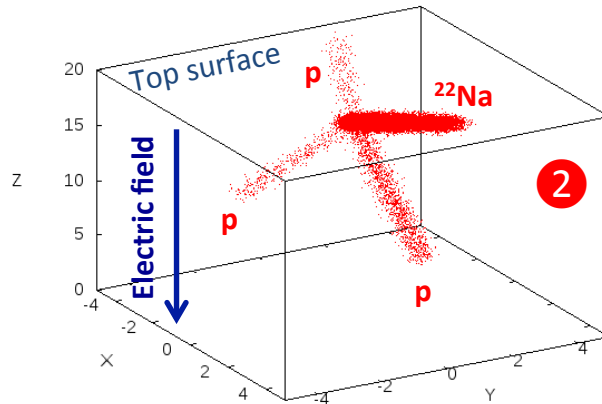
    //Get the number of collected packets
    int GetNumCollectedPacket() {return CollectedPacket;};

    //Test if a given packet (point) is in the SCR or is collected
    bool IsCollected(Point);
    bool IsInSpaceCharge(Point);

    //Get Electric field at a given point
    Vector GetEfield(Point);
};
```

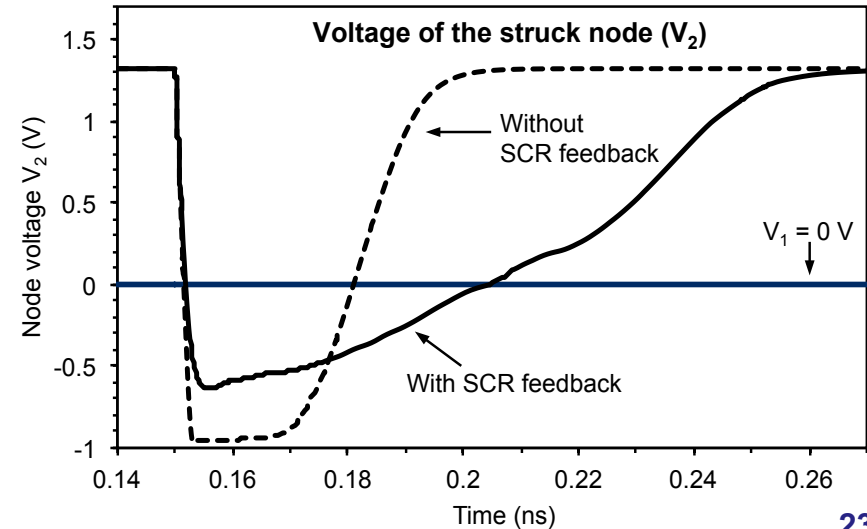
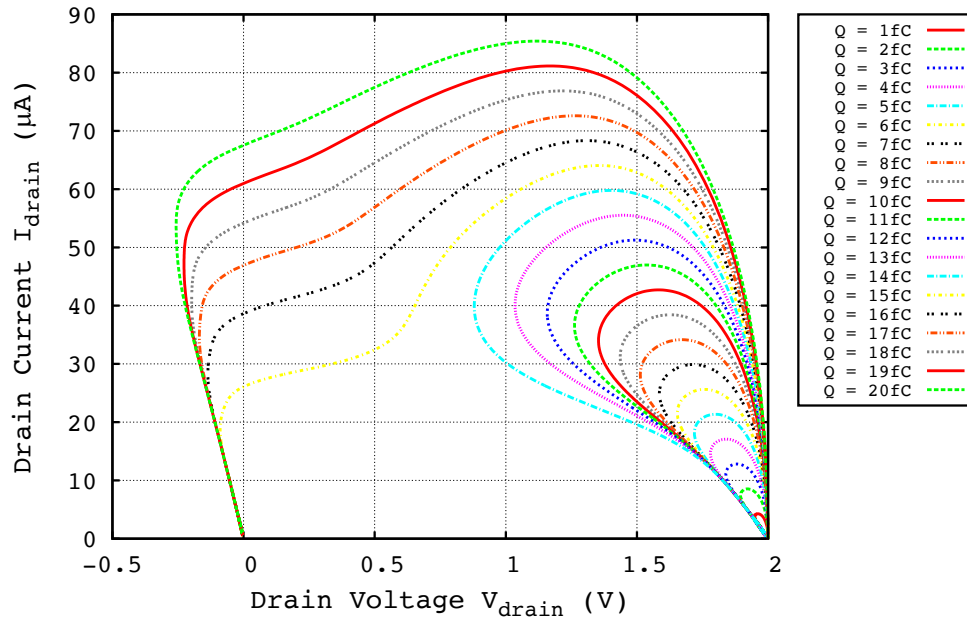
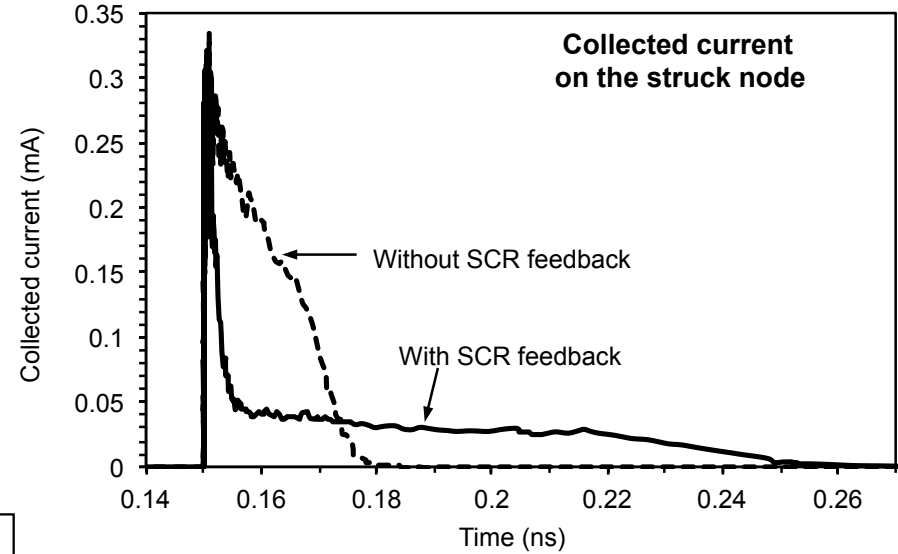
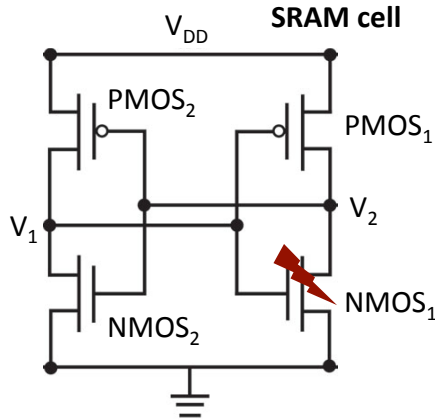
Mechanisms of Soft Errors

Particle Monte Carlo Simulation (RWDD model – IM2NP)



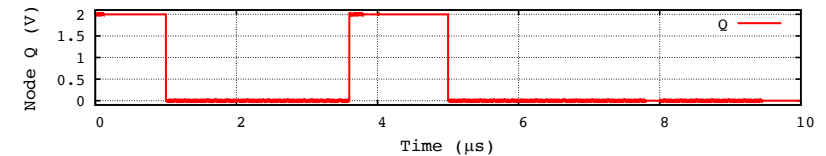
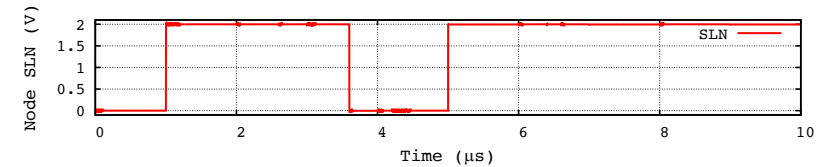
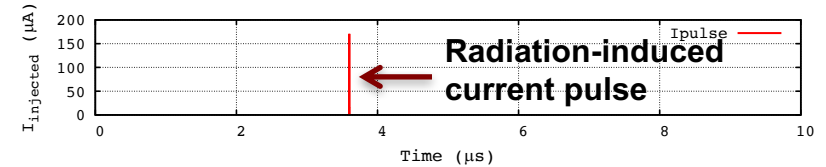
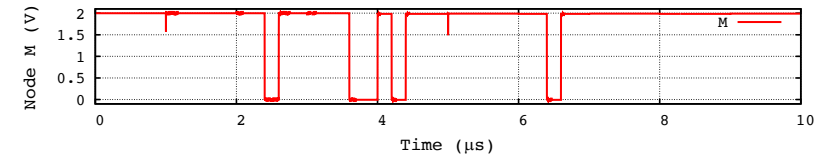
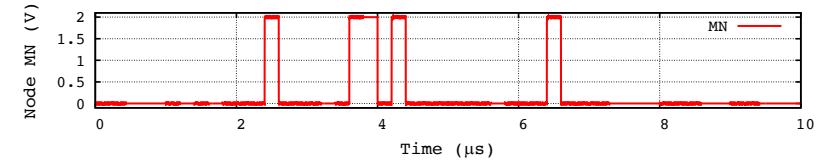
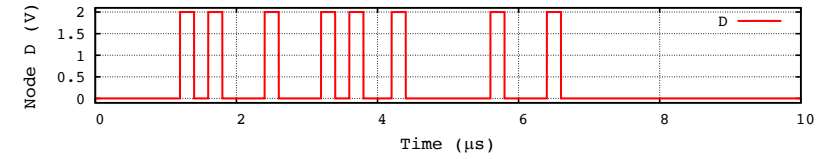
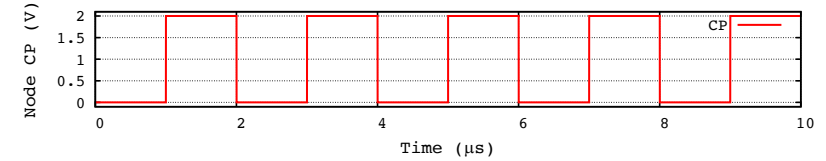
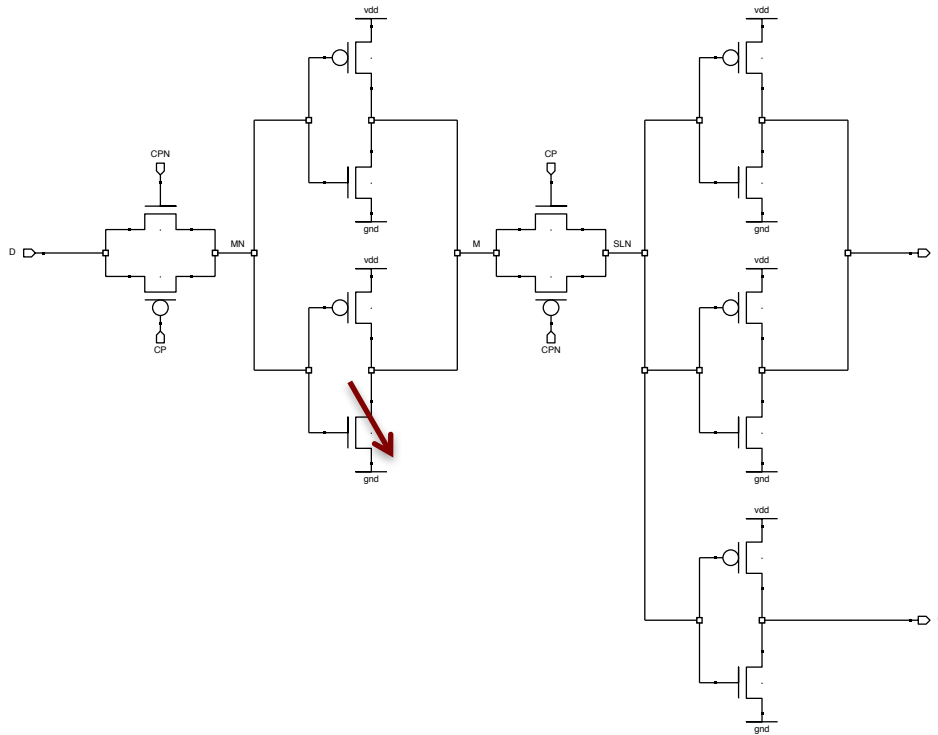
Mechanisms of Soft Errors

✓ SRAM cell

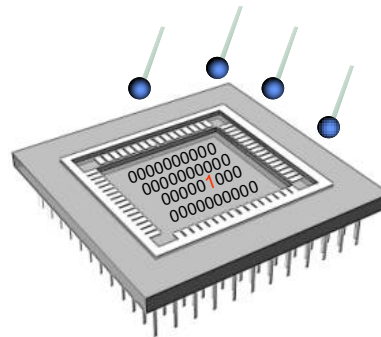


Mechanisms of Soft Errors

✓ Flip-flop (sequential logic)



IV – Characterization of Soft Errors



SER measurement methods



Accelerated Tests

- *Use intense particle beams or sources (emulating the natural radiation with a higher flux)*
- *Fast technique*
- *Single device characterization*
- *Various test conditions can be explored in a short time (days)*



Real-time (Life-Testing) measurements

- *Considers a large population of circuits working in the natural radiation environment*
- *The intensity of the natural atmospheric radiation can be increased by deploying the test in altitude*
- *Measurements take several months (years)*



Are these methods equivalent ?

Accelerated tests – REER test campaigns



CEA LLB
Thermal neutrons



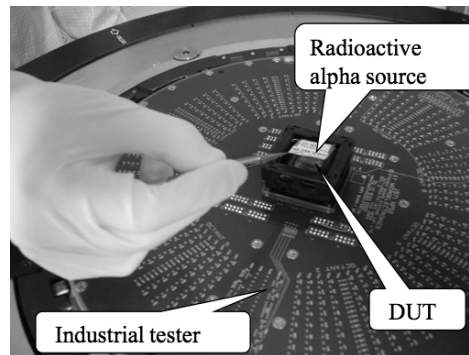
LPSC Grenoble
Mono-energetic neutrons



TRIUMF Vancouver
Atmospheric-like neutrons



TRIUMF Vancouver
Muons



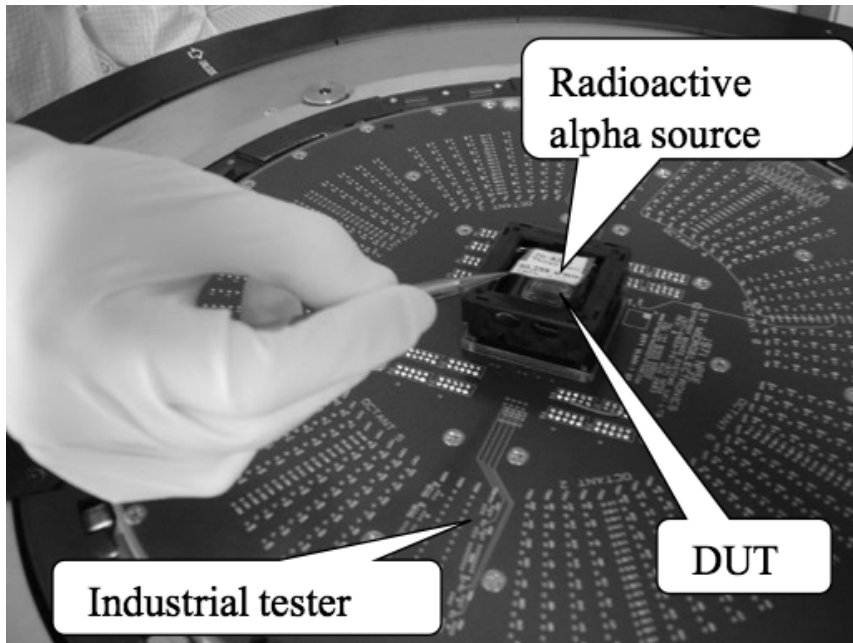
ST Crolles
Alpha source



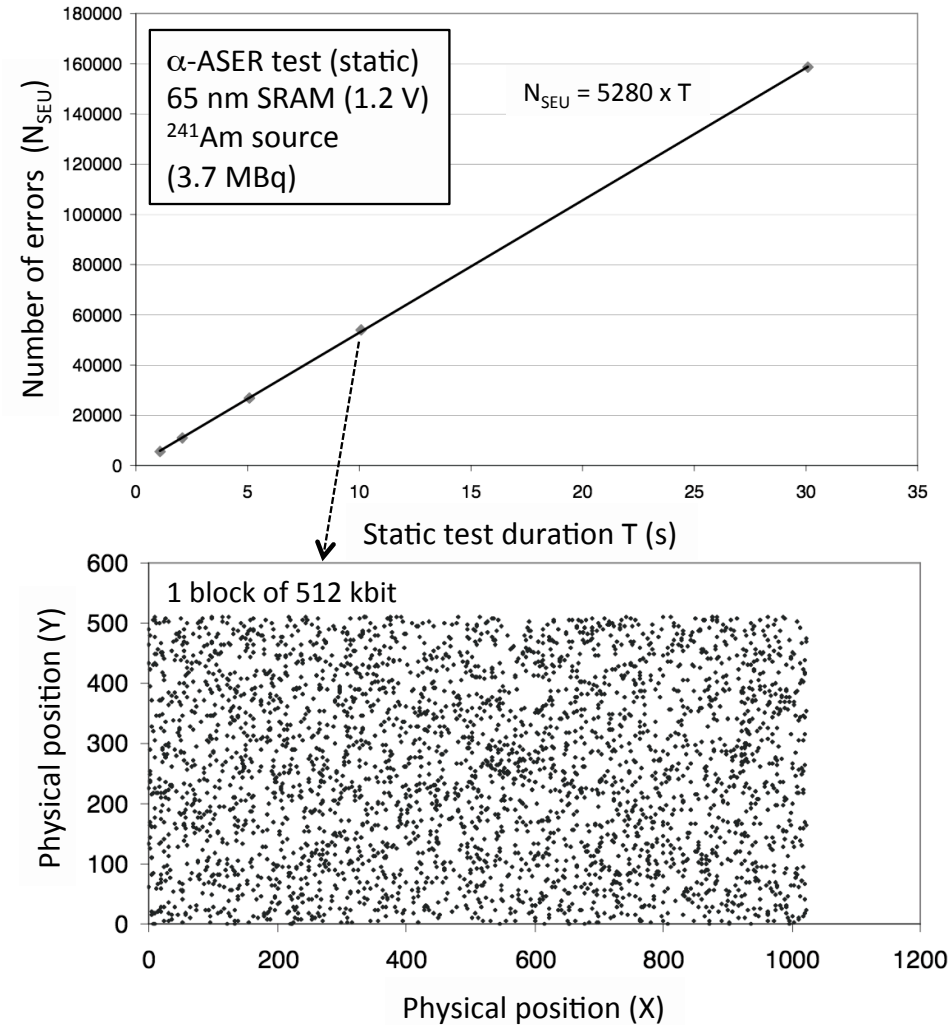
ONERA Toulouse
Co60

Accelerated tests

Example of irradiation tests using an intense solid-state source (3.7 MBq)

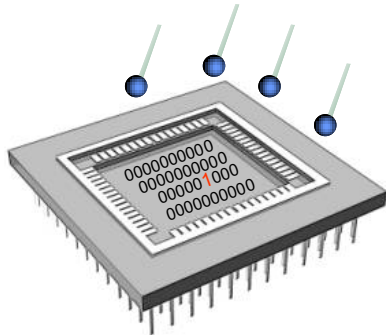


ST Crolles - Alpha source



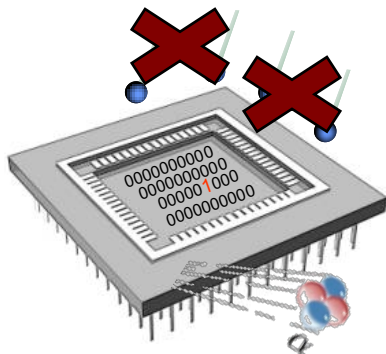
Real-time (Life Testing) Approach

- Methodology: long-term (several months/years) exposure of a large amount (*Gbits*) of circuits to natural radiation



In altitude: to amplify the atmospheric neutron flux (by an acceleration factor – AF– with respect to sea-level)
→ SER dominated by neutrons

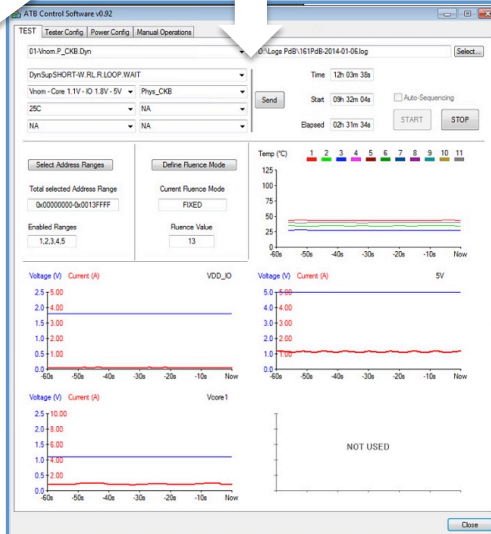
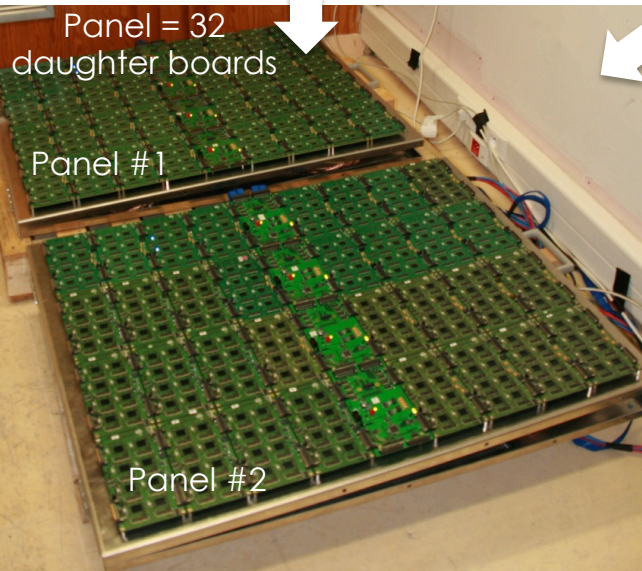
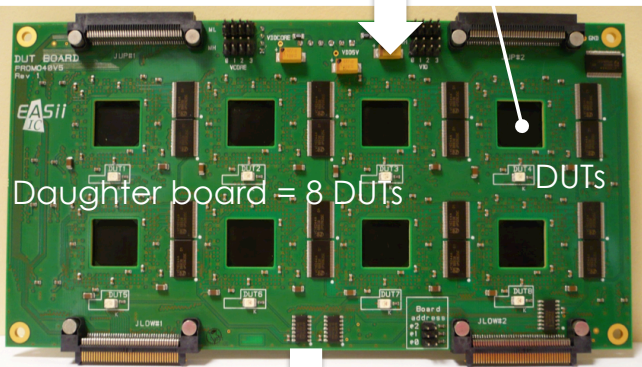
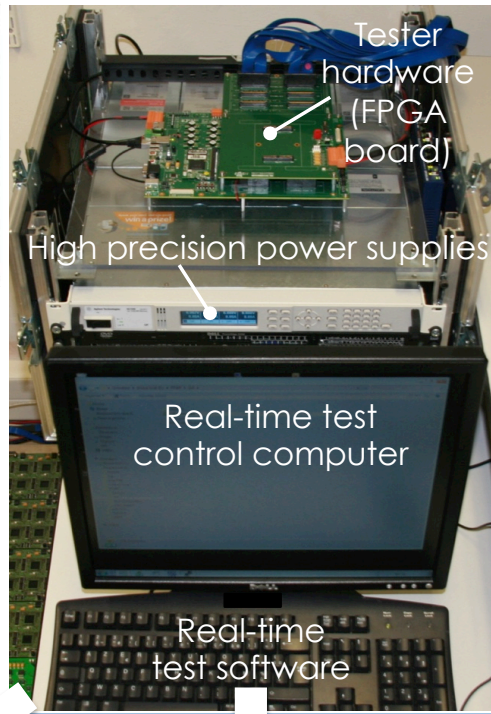
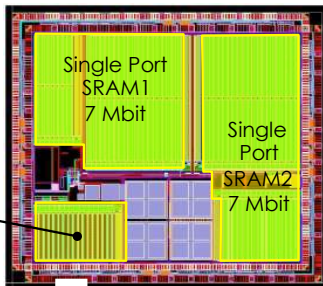
$$\text{SER} \Big|_{\text{altitude}} = \text{AF} \times \text{neutron-SER} \Big|_{\text{sea level}} + \alpha\text{-SER}$$



Underground: to remove the atmospheric neutron contribution and to detect soft-errors induced by alpha particles emitted from traces of radioactive contaminants → directly gives the α -SER

⇒ Consider different altitude tests or combine altitude/underground tests to separate neutron from alpha contributions

512 devices under test (7168 Mbit)



IM2NP/REER Test platforms



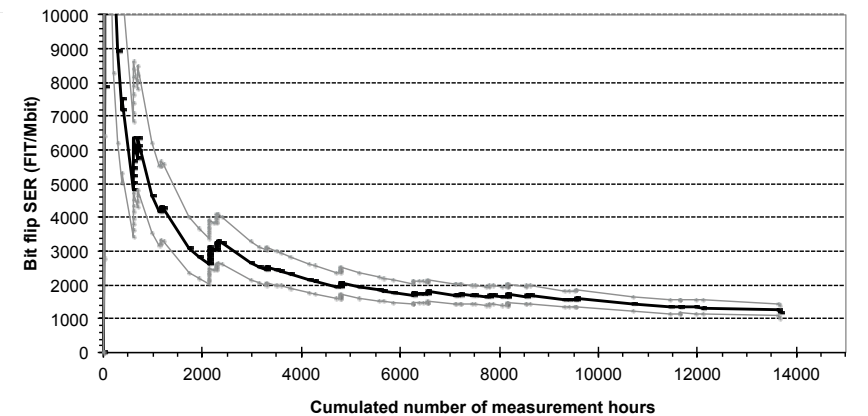
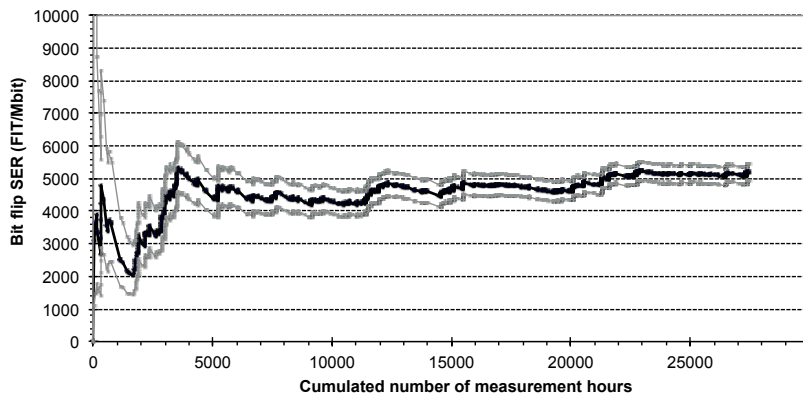
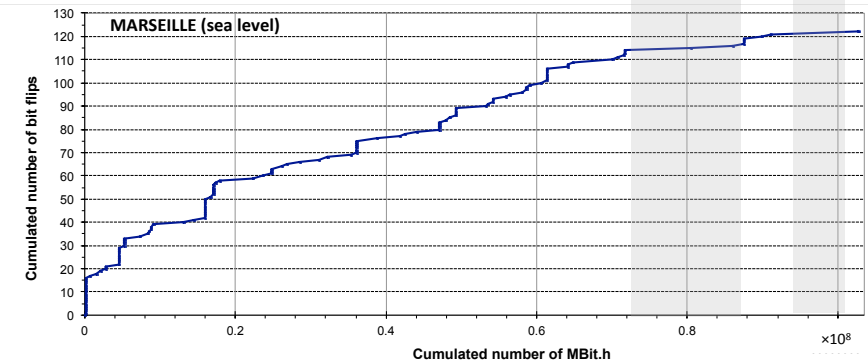
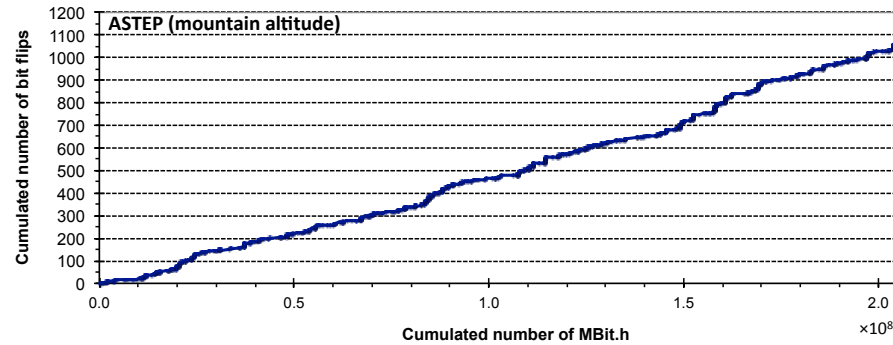
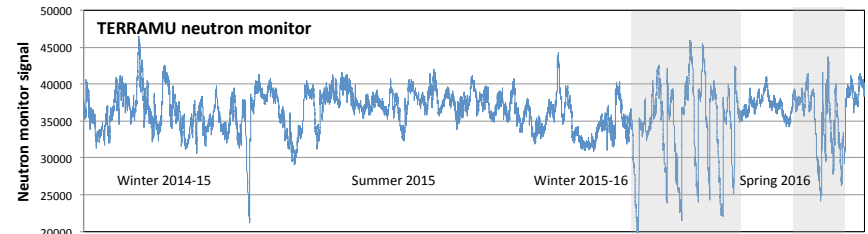
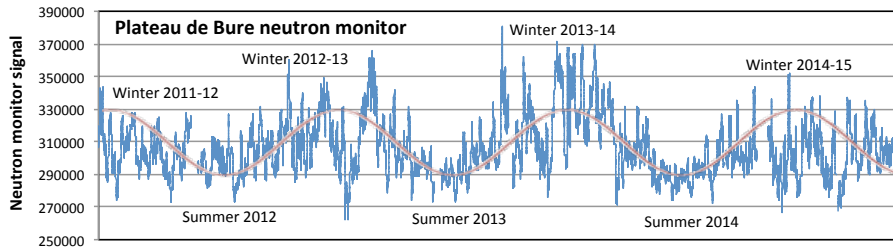
-1700 m
under rock



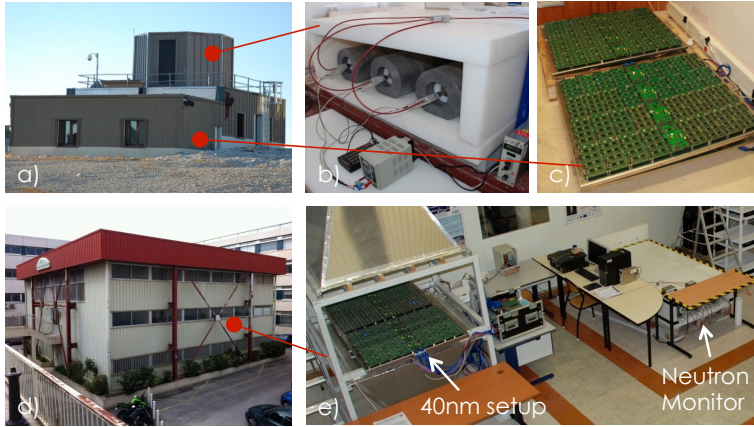
+2552 m in Alp
mountains



Real-time (Life Testing) Approach

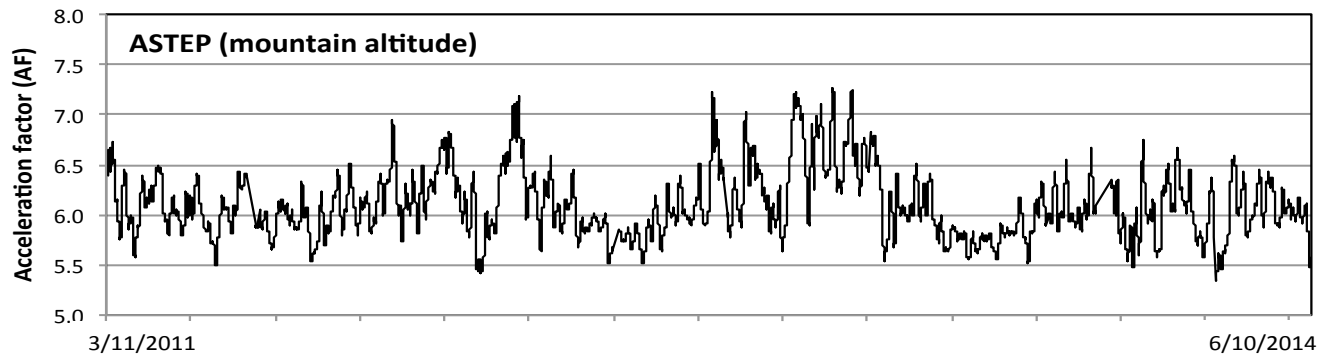
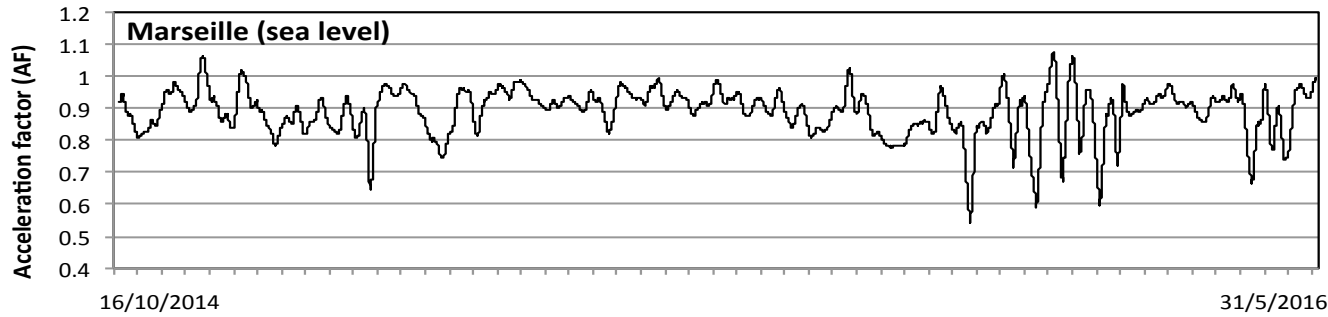


Plateau de Bure – ASTEP (Lat. +44° 38' 02'', Long. -5° 54' 26'', Alt. 2555 m)



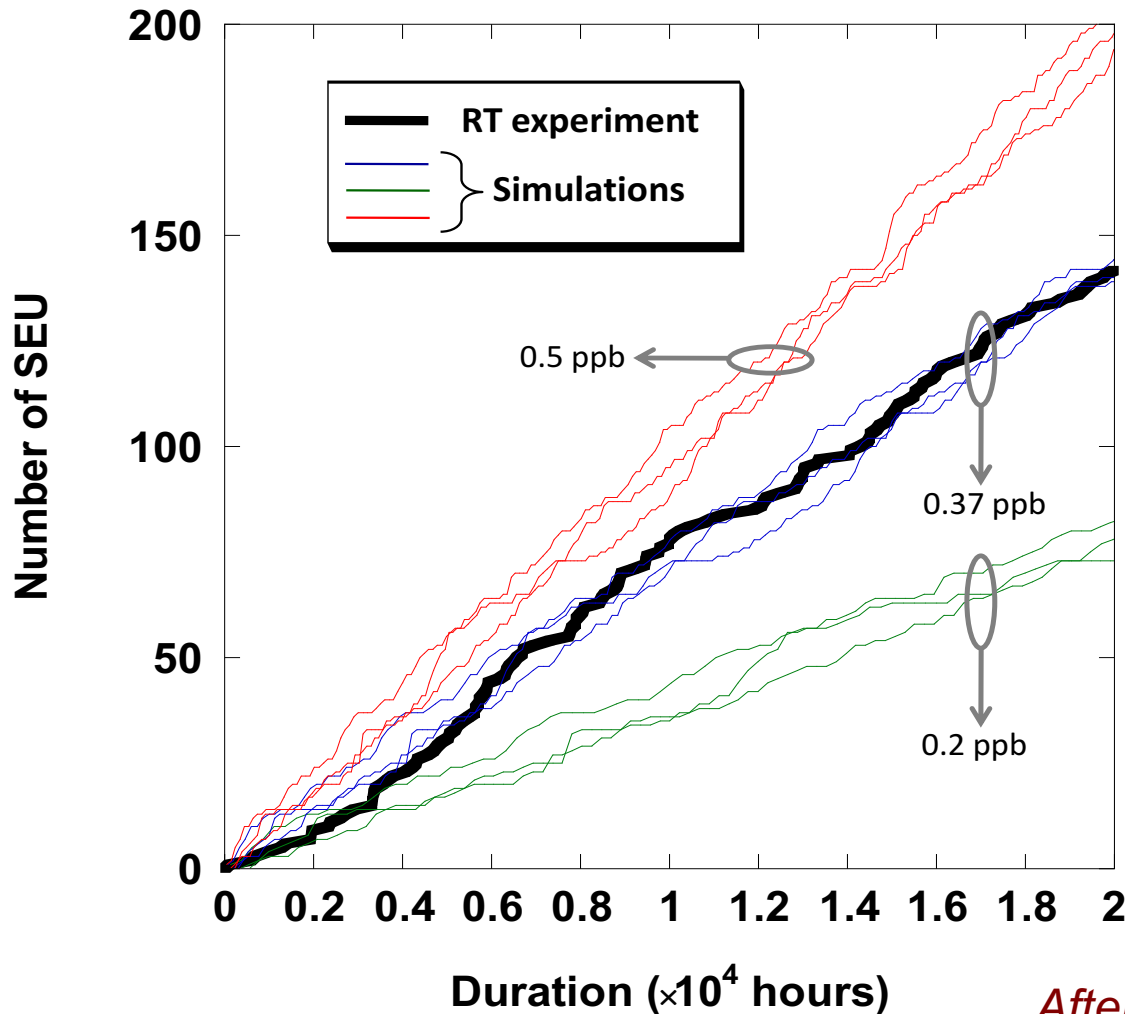
Marseille – TERRAMU (Lat. +43° 20' 16'', Long. -5° 24' 43'', Alt. 130 m)

Values deduced from	SER component	Bit flip SER (FIT/Mbit) Normalized to New York City
Real-time Experiments (Tables 1 and 2)	Neutron	795
	Alpha	513
	TOTAL	1308
Accelerated tests using intense sources	TRIUMF facility	623 ^a
	Alpha (²⁴¹ Am source)	625 ^b
	TOTAL	1248
Monte-Carlo simulation (TIARA code)	Neutron (JEDEC)	486
	Alpha	820 ^c



Underground RT-SER Experiments

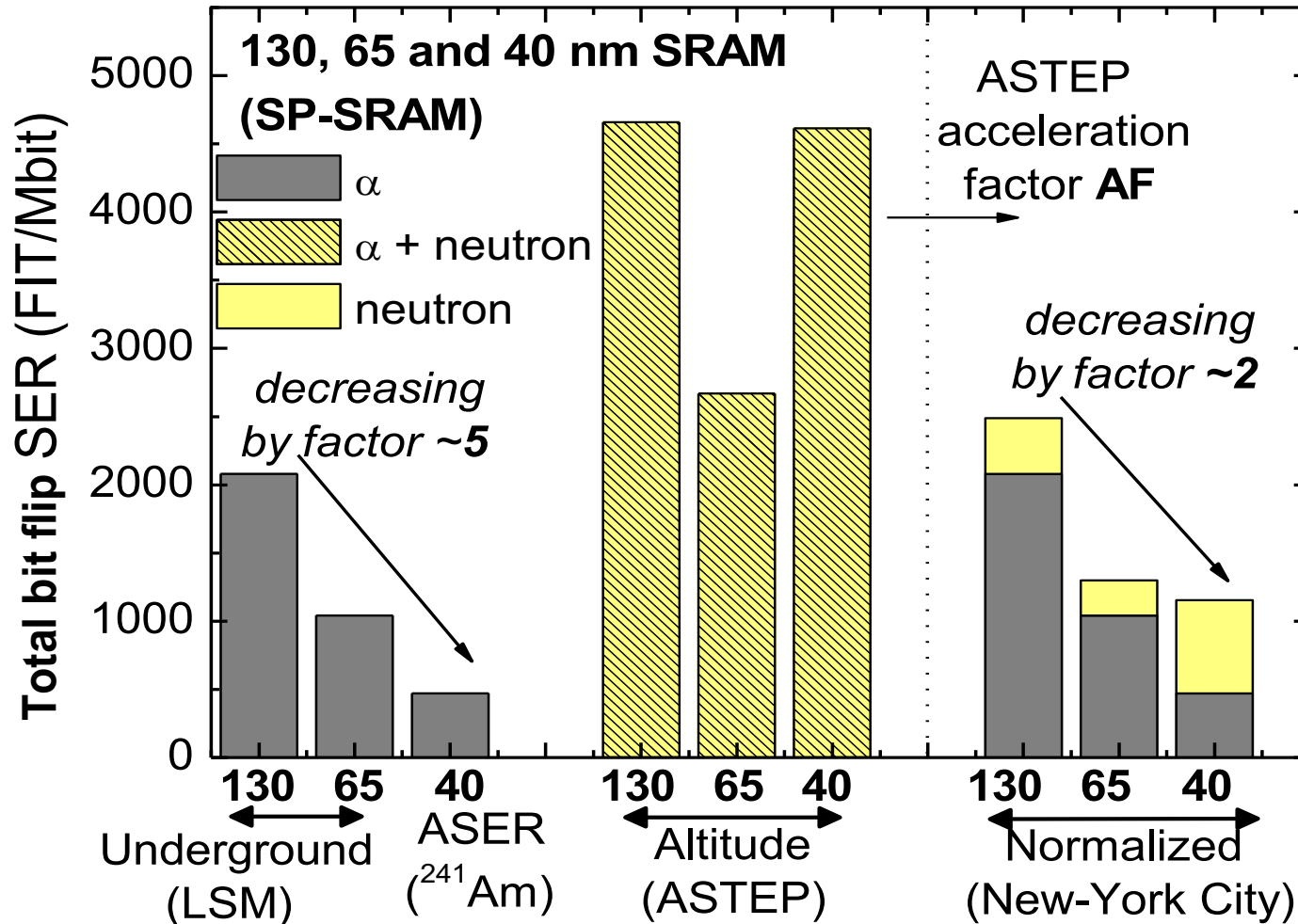
• Long duration cave experiment (LSM) – 130 nm Single-Port SRAM



- Up to **20,000 h** of cave characterization
- Monte-Carlo simulation gives a contamination level by ^{238}U impurities of **0.37 ppb**
- Very good agreement with wafer-level characterization (alpha emissivity) in the range **[0.2-0.5] ppb**

After Martinie et al. (TNS 2010)

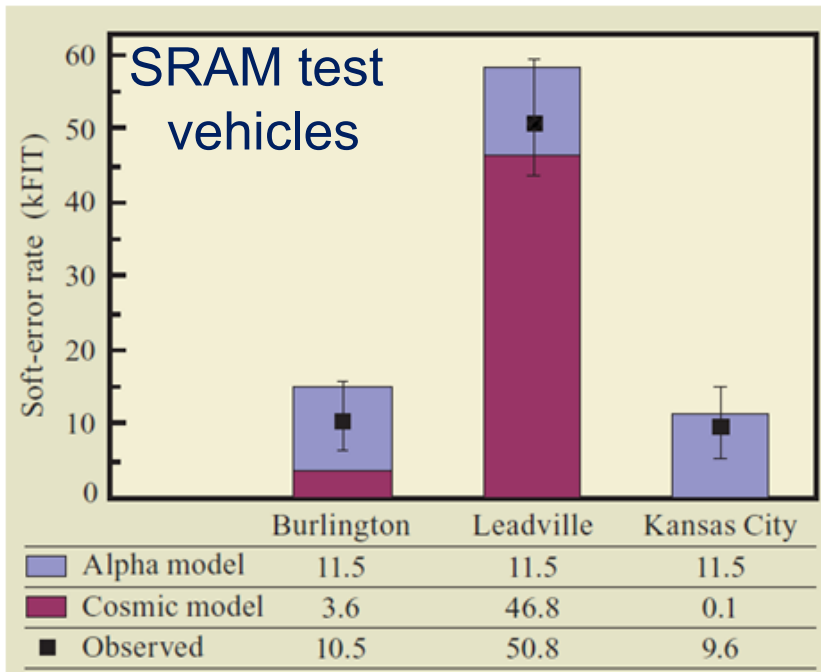
Synthesis: 8 years of real-time tests



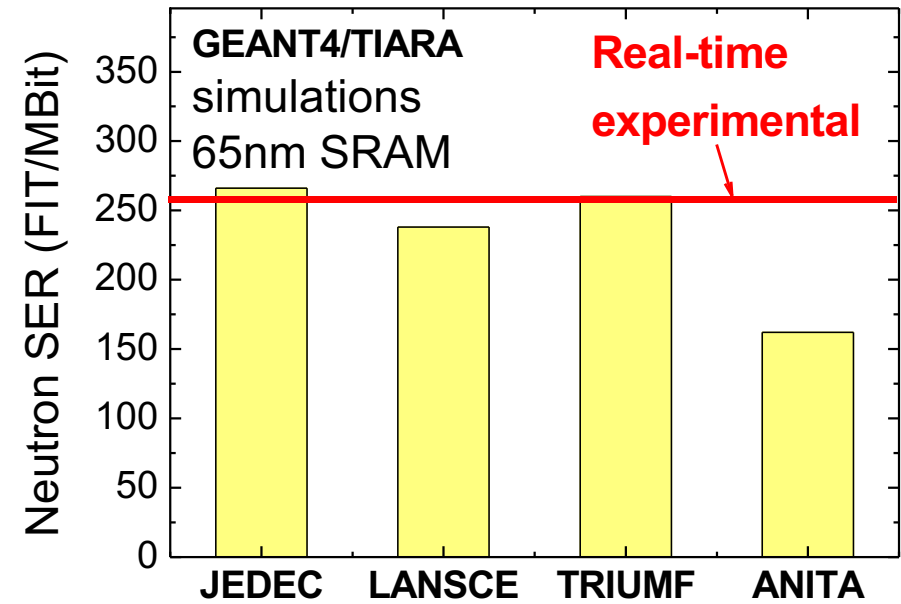
Links with accelerated tests and simulation

- RT-SER values are fundamental to validate accelerated test procedures
- Code and model verification on the basis of RT-SER data is also a fundamental issue for the development of predictive codes

Monte Carlo SEMM-2 model



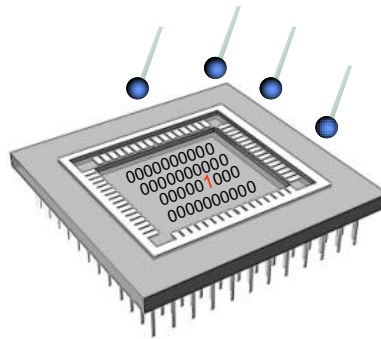
TIARA Monte Carlo SER simulation platform



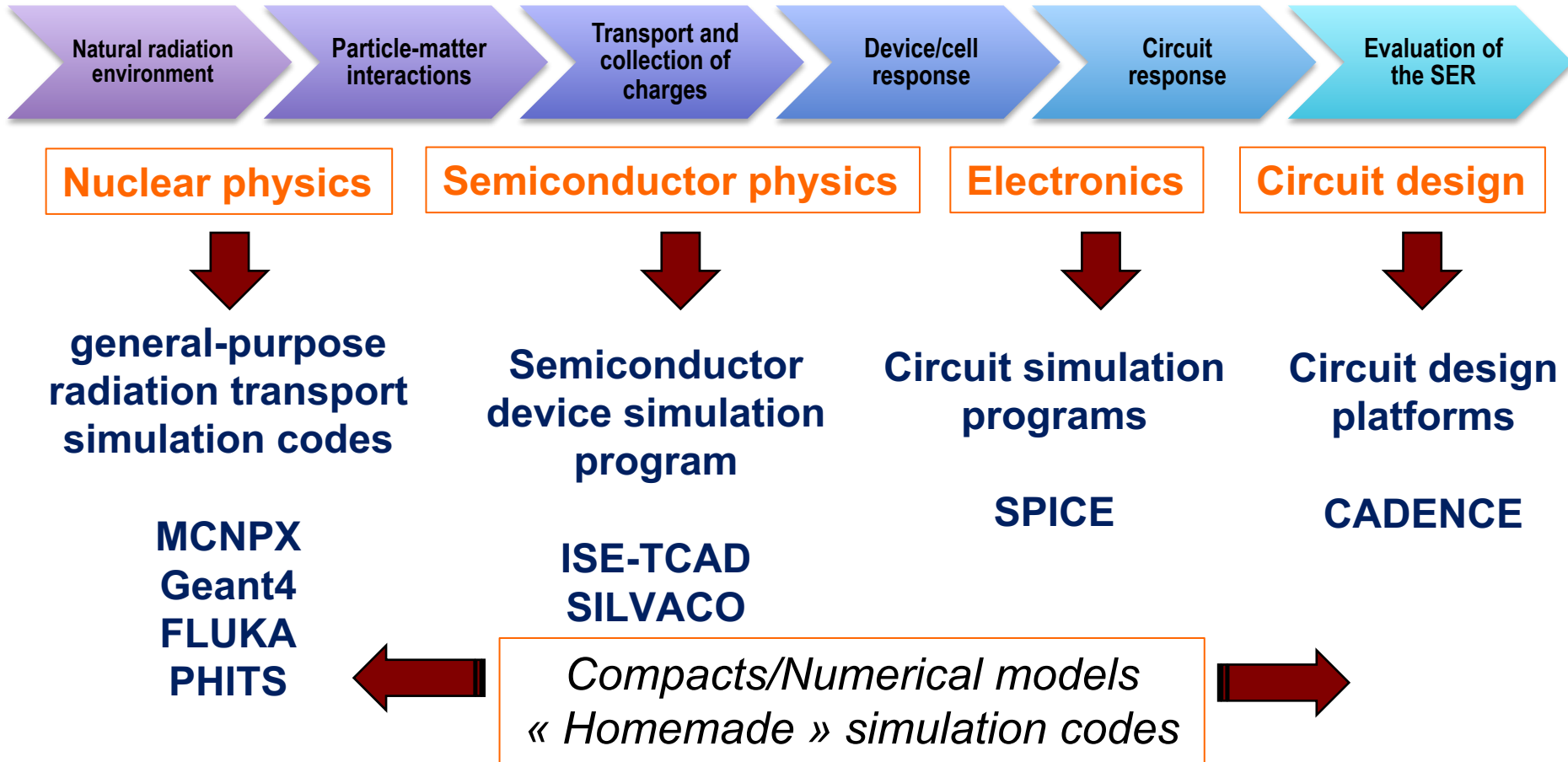
After S. Serre et al. (IEEE TNS 2012)

After M.S Gordon (IBM J. Res. Dev. 2008)

V – Modeling and Simulation Issues



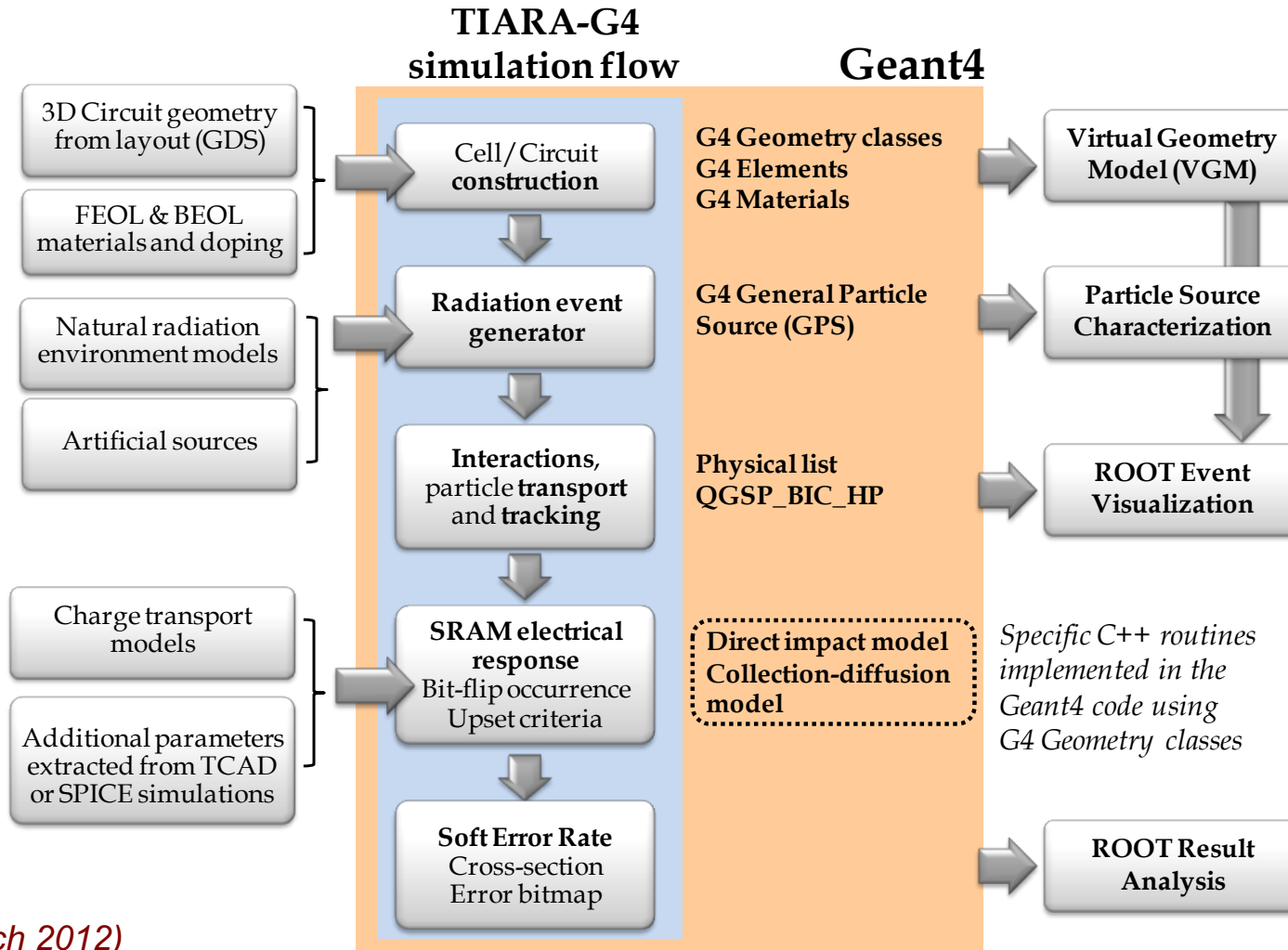
A multi-scale & multi-physics chain of simulation

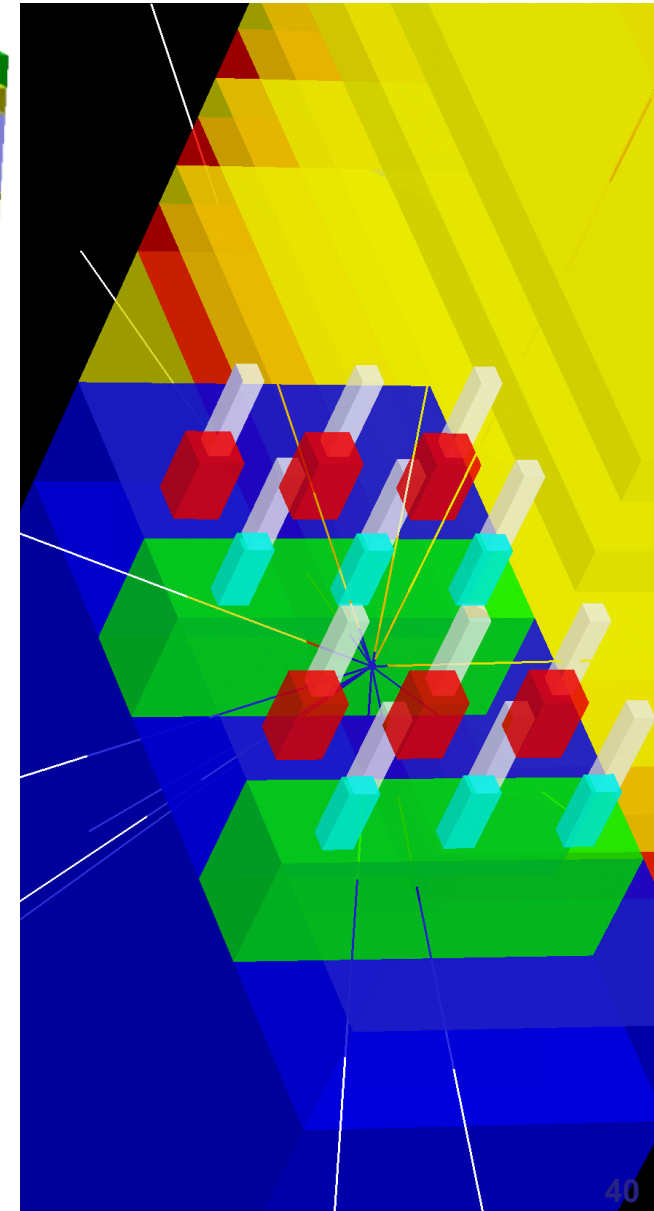
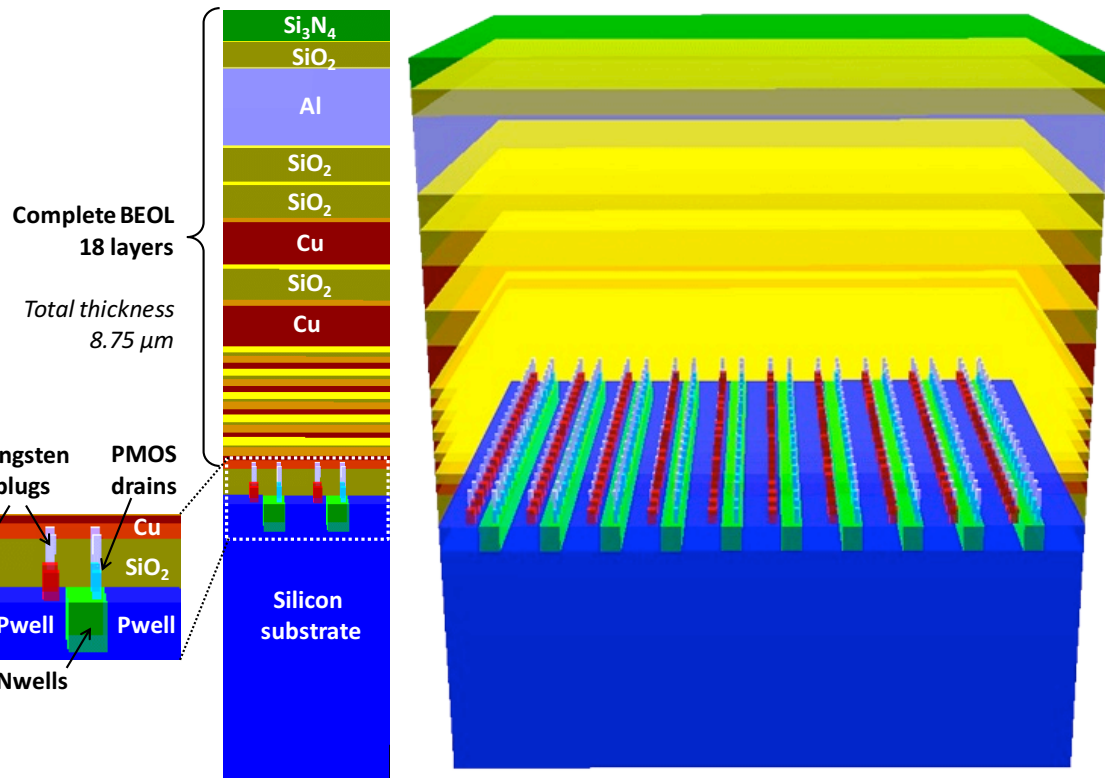


Due to the complexity of each element of the simulation chain, the use of "key-codes" is mandatory (Geant4, Spice, Cadence,...)

TIARA-G4: Tool suite for rAdiation Reliability Assessment

STMicroelectronics - Aix-Marseille University – CNRS proprietary code
(C++ code – 27,000 lines – linked with GEANT4, ROOT and SPICE)





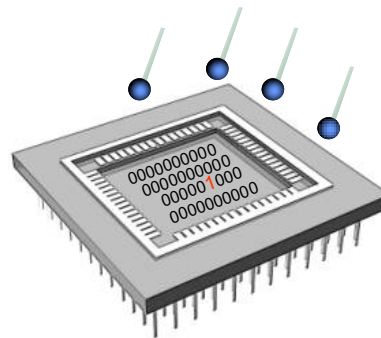
Event #2359425

Incident particle: neutron
 Energy (MeV): 5.664161e+01
 Physical process: NeutronInelastic
 Volume name: P-substrate
 Reaction vertex positions (x,y,z): -5.656377e+00 -1.377065e+00 -5.347320e+00

Number of secondary particles produced: 5

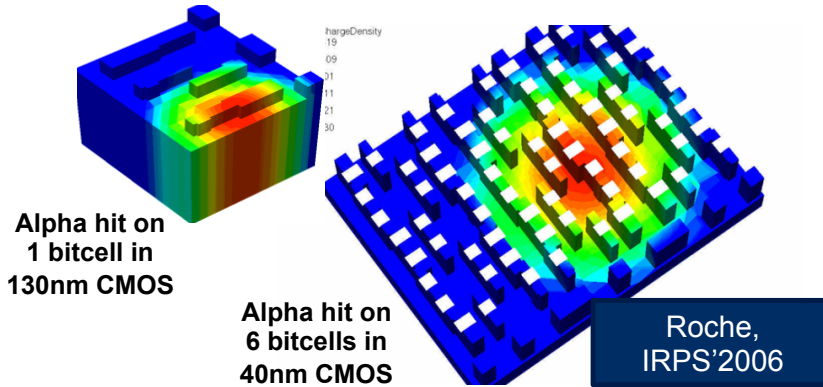
Particle	Energy (MeV)	Px	Py	Pz
Alpha	3.197153e+01	6.097439e-01	-5.070998e-01	6.091488e-01
Neutron	1.697277e+00	-9.311596e-01	3.551987e-01	8.231417e-02
Gamma	9.051714e+00	3.281911e-01	-6.857286e-02	9.421191e-01
Gamma	1.377447e+00	2.331650e-01	8.485282e-01	4.750095e-01
Mg24 [0.0]	2.554443e+00	-7.370831e-01	6.733902e-01	5.704476e-02

VI - Scaling effects in current technologies

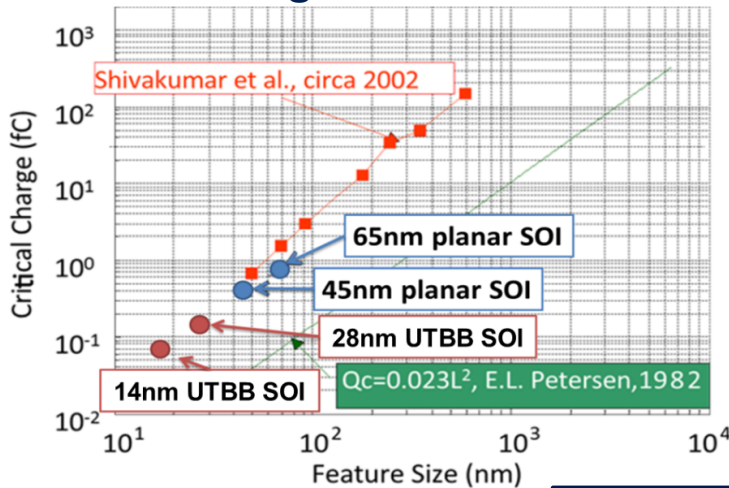


Scaling effects in current technologies

- Multiple node collection

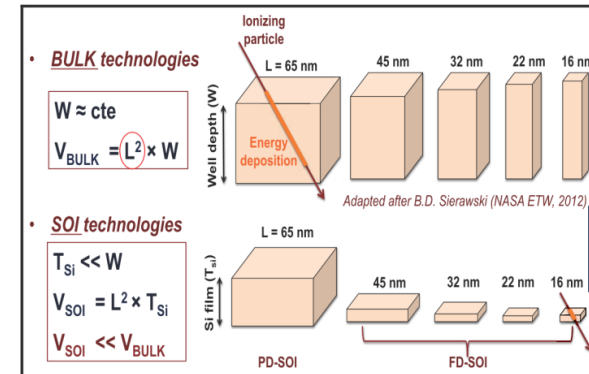


- Critical charge decreases

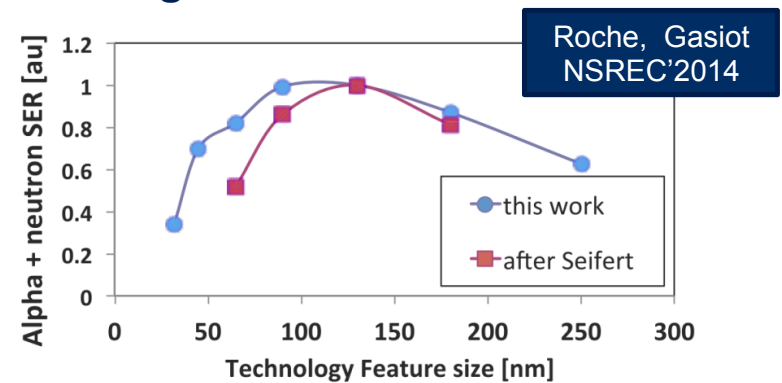


Roche, IEDM'2013

- Sensitive volume decreases



- SER/bit decreases in advanced technologies



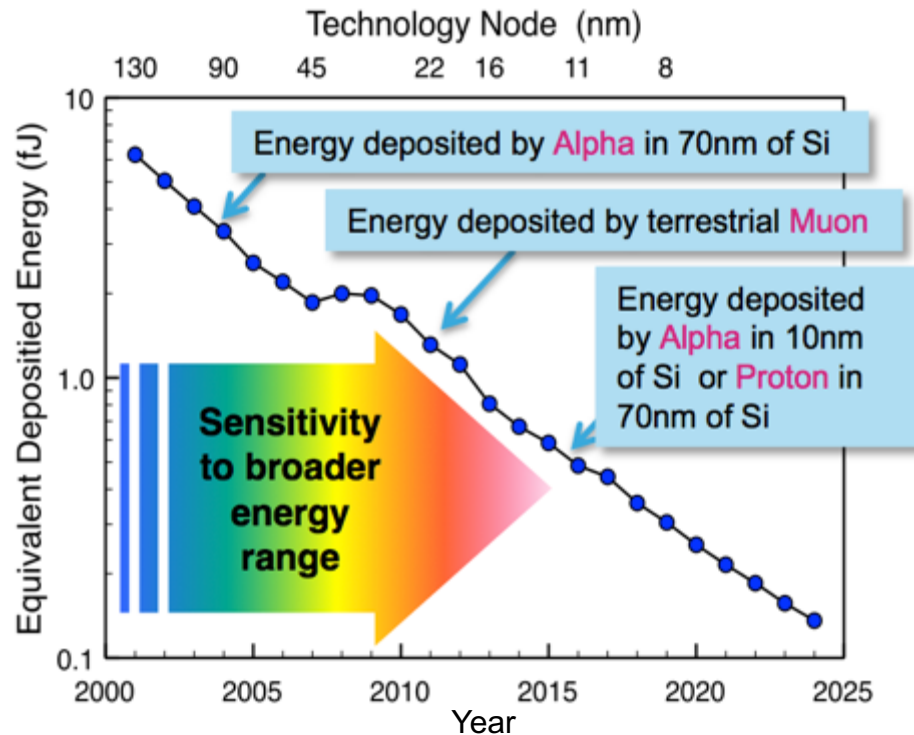
- SER per chip increases due to the larger number of devices per chip

Increasing sensitivity to background radiation

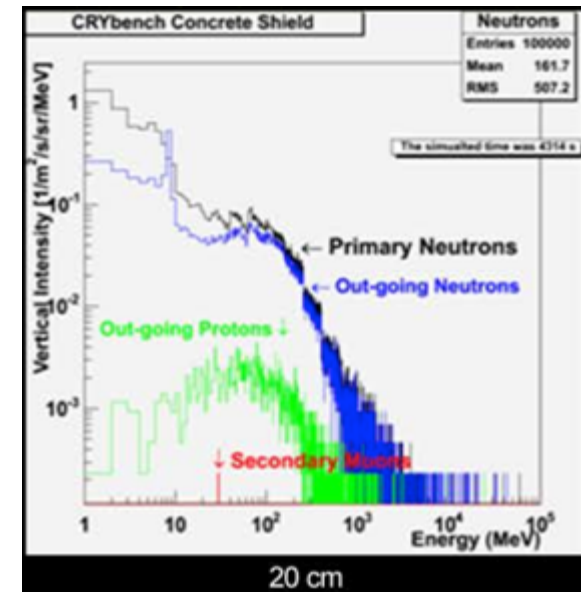
- New particles & interaction processes are susceptible to impact future nanometer-scale circuits

- Importance of the local environment for future technologies that can generate/amplify low energy particle flux

Concrete shield (20 cm)



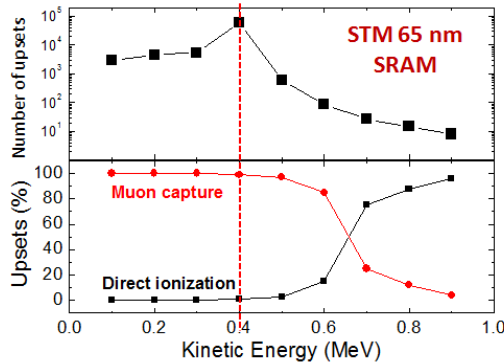
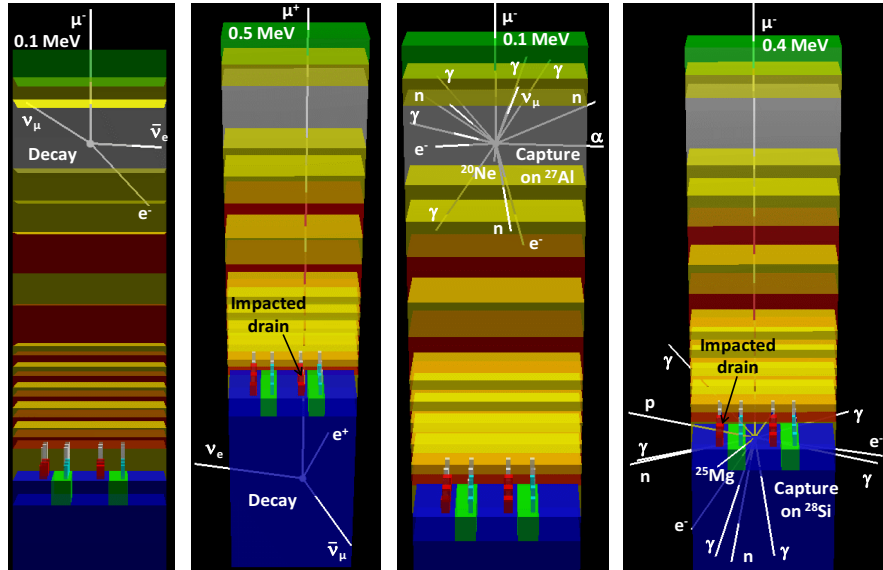
Adapted after L.W. Massengill (IRPS 2012)



After E. Aguayo et al. (PNNL report 20693, 2011)

Increasing sensitivity to background radiation

Atmospheric muons



After S. Serre et al. (RADECS 2012)

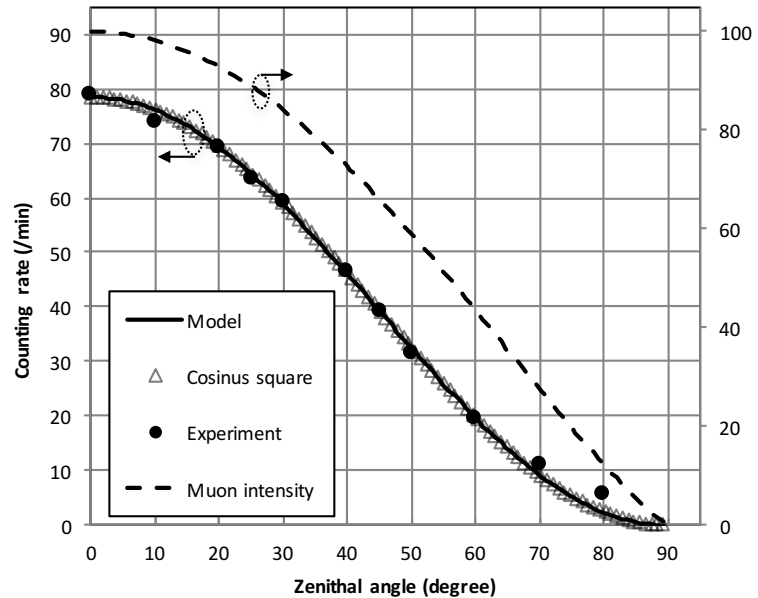


Increasing sensitivity to background radiation

Atmospheric muons



Im2np

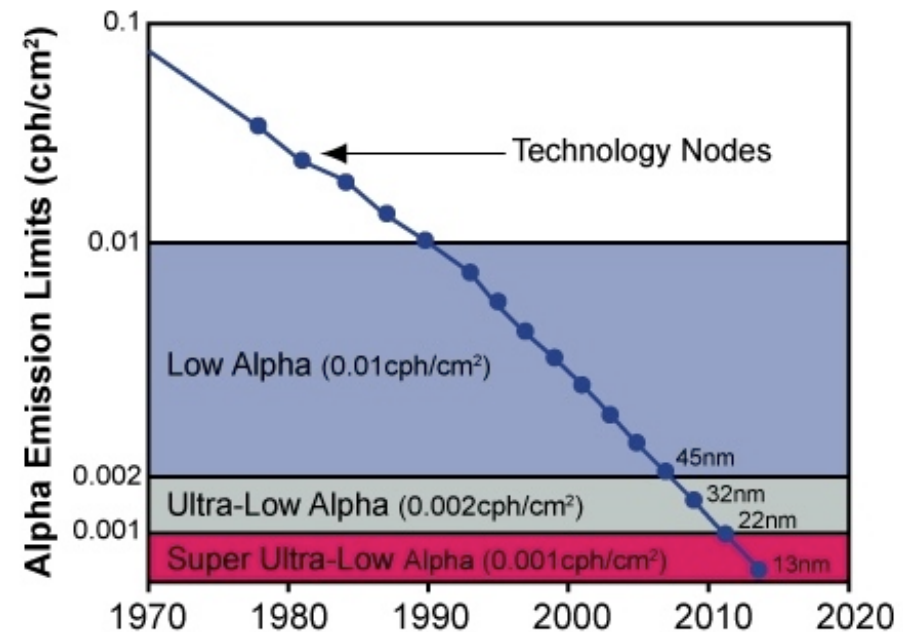
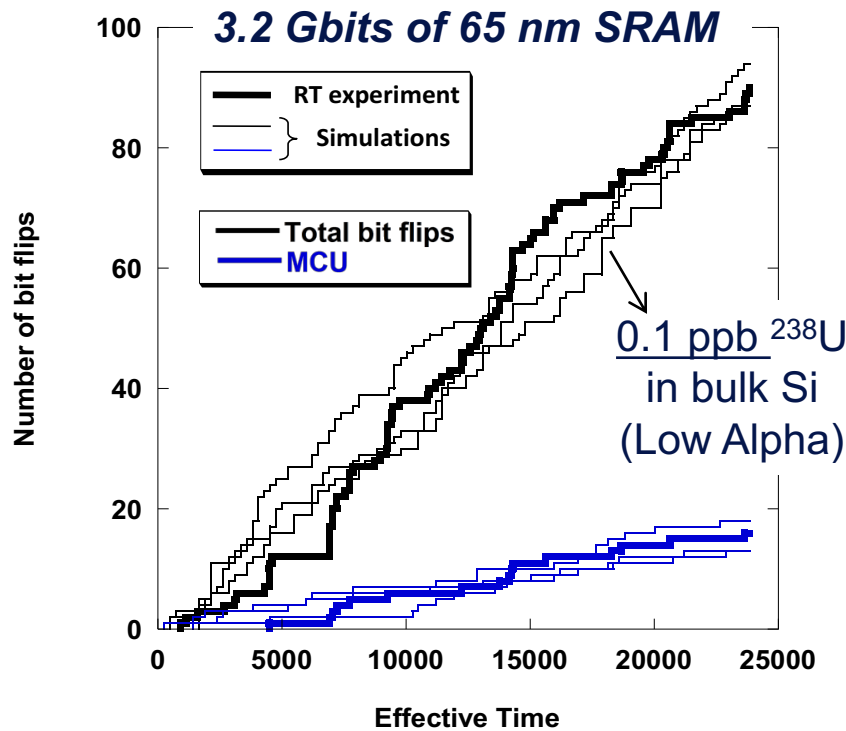


JLA et al., NIM-A (2017)

Increasing sensitivity to background radiation

Low alpha material issue

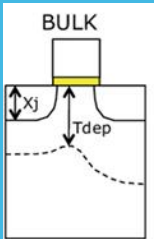
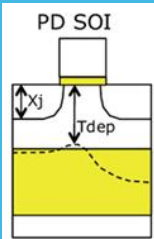
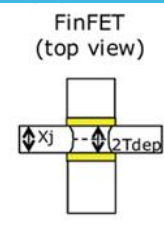
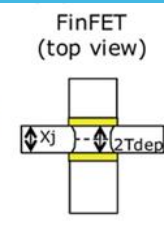
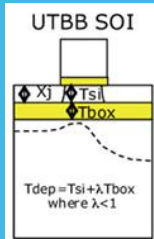
With the CMOS downscaling, alphas will have a growing SER impact
 → need of ultra-low α -emitting materials at both FEOL and BEOL levels



From underground real-time test at LSM
 After S. Martinie et al. (IEEE TNS 2012)

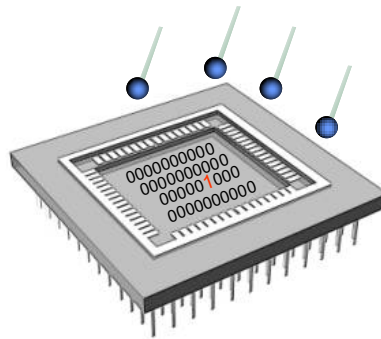
After B.M. Clark – Honeywell International 2012
 White paper (available online)

Expected SER performances between Bulk, FinFET and SOI 1

	PD-SOI	Bulk FinFET	SOI FinFET	UTBB-FDSOI
				
Critical charge min. charge to upset	0.1fC	<0.1fC	<0.1fC	<0.1fC
Sensitive depth charge collection	Gate thicker body Gate area	Drain drain volume substrate extension	Gate fin height gate area	Gate very thin body gate area
Parasitic bipolar charge amplification	Significant without ties >10	Very limited substrate tied to gate	Low Bipolar simulated ~2-8	Very low Bipolar simulated ~2-3
Neutron-SER	÷5 to ÷20	÷2.5 to ÷3.5	÷10	÷50 to ÷110
Muon-SER	New (1000x) SER risk under evaluation			
Thermal-SER	New (2x) SER risk under evaluation			
Low-energy proton-SER	New SER risk under evaluation			
SEL ion-induced LU	Immune by construct	no data yet from literature	Immune by construct	Immune including hybrid devices
TID Gamma and X-rays	Mrad with body ties/taps	100's krad with large fins	Mrad with narrow fins	100's krad under full evaluation

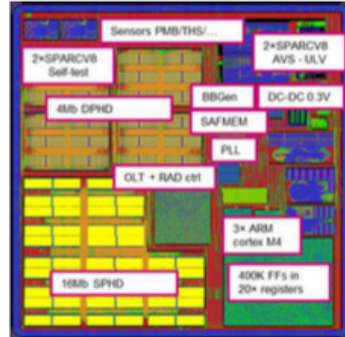
References: M.L. Alles et. al, SOI Conference 2011, N. Seifert, IEEE TNS 2012, D. Munteanu, J.L. Aufran, IEEE TNS 2009, P.Roche, short course SOI conference 2006, K. Rodbell, NSREC short course 2013. E.Simoen, TNS 2014, M. Gaillardin, RADECS 2012.

VII – Recent work on FDSOI 28nm technology



New Real-time SER experiment on FD-SOI 28nm (oct. 2016)

256 circuits under test



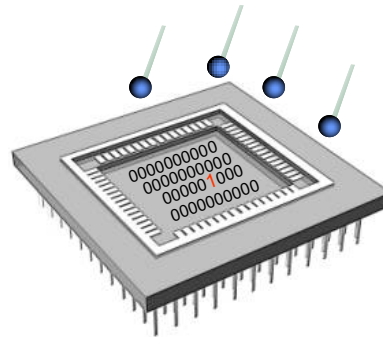
- **Advanced rad-hard qualification blocks**
 - 330kFF, 17 flavors, self test at high speed
 - 20Mb SRAMs + rad-hard FFs + sensors
- **Rad-hard ARM-M4**
 - ECC + dual clock tree + rad-hard FF dual CK
- **0.3V - 1.3V demonstrators**
 - ARM-M4 and SPARCV8 RISC
 - AVS thru FBB with critical path monitors
 - 0.3/0.45V DC-DC + all-digital freq. multiplier



Three experiments running in parallel in Marseille, Modane and ASTEP during 5 years (2016-2021)



VIII – To conclude: open problems in characterization, modeling and simulation

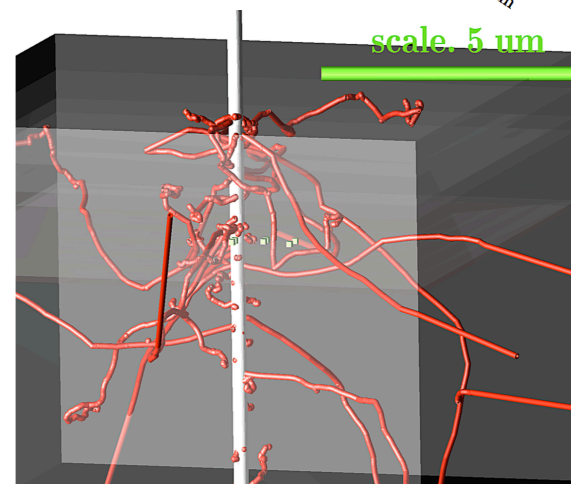
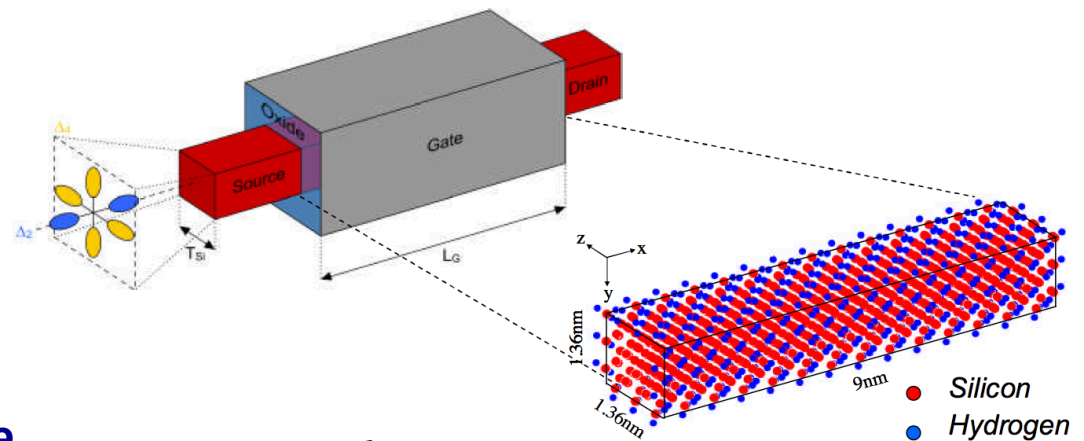


Open problems in characterization, modeling and simulation



Interactions of particles with nanometer volumes

- Ion track structure – Energy and charge deposition profile
- Particle “trajectories”
- Ballistic effects (δ electrons)
- Ionizing properties of nanomaterials (band structure effects)



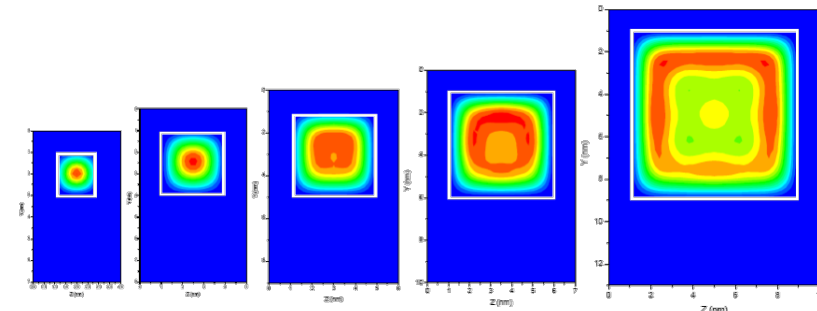
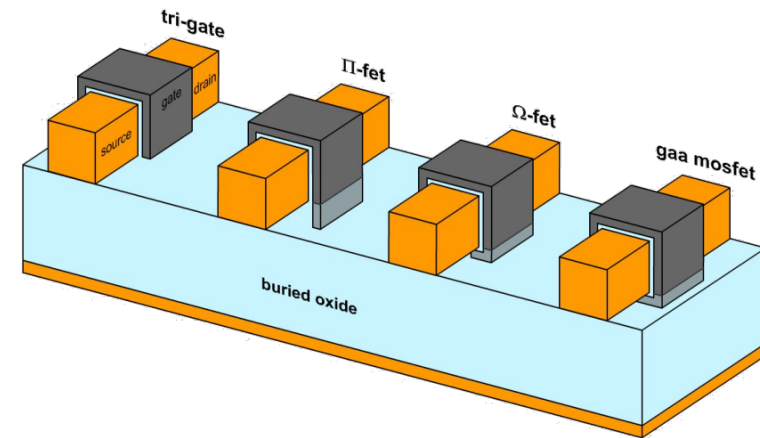
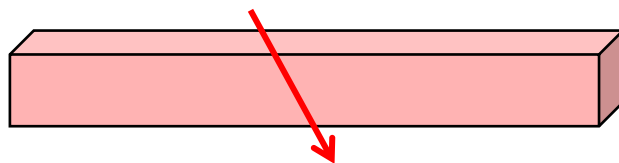
After M. King
(Vanderbilt Univ.)

Open problems in characterization, modeling and simulation



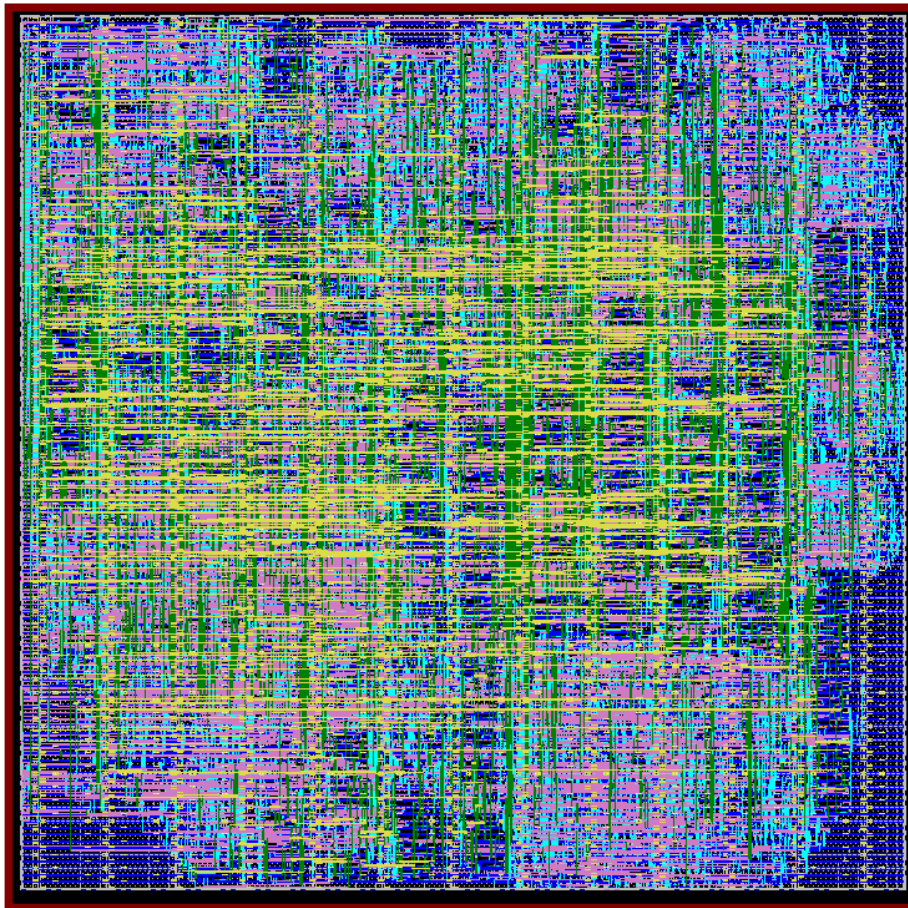
Transport and collection of charges through nanometer-scale layers and volumes

- Quantum-mechanical effects (confinement, tunneling) modify charge transport and collection
- A fundamental case study: a biased silicon nanowire impacted by an ion



Electron density in nanowires

Open problems in characterization, modeling and simulation

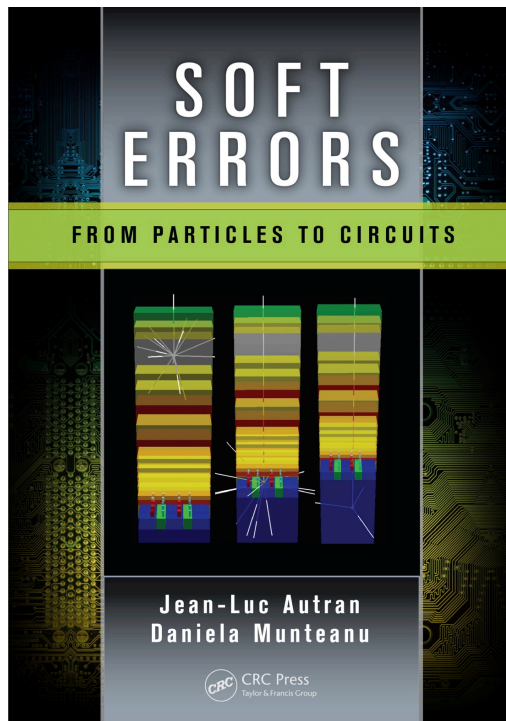


**test and simulate
complex (real) designs**

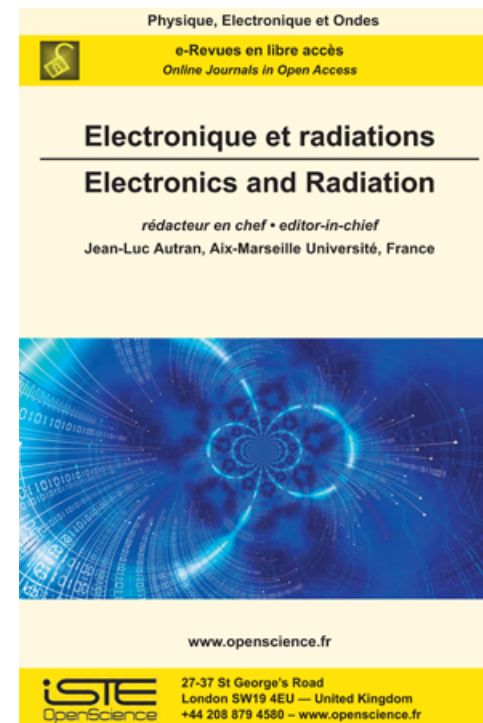
- *New computational methods, approaches and techniques to treat complex designs with 1-100 kilo transistors*
- *Massively parallel computing (GPU, distributed computers)*

Thank you for your attention!

jean-luc.autran@univ-amu.fr



An Open Access initiative



www.openscience.fr/Electronics-and-Radiation