LNL
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Introduction *to radiation damage: concepts, quantities, environments*

Elementary overview

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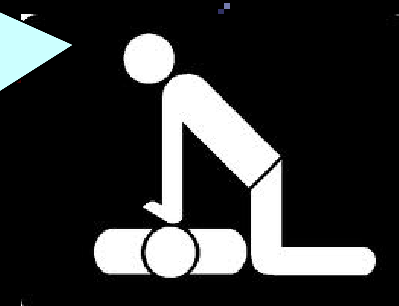
pedestrian and spiral approach

- ❑ *Introduction*
- ❑ *"exposure" to radiation concepts*
- ❑ *"exposure" to damage in electronics and environments*

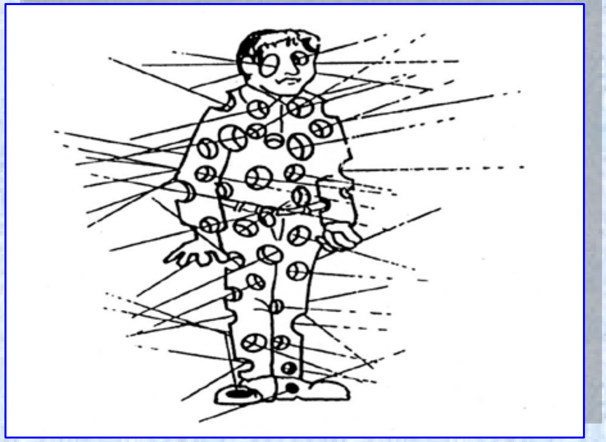
3-4 hour elementary course!
MANY more slides than time!
In this 2 hour talk I will only emphasize ionization concepts (ionization dose, LET, range, SEE cross-section).
I have left all the slides for "completeness" (self-study).



PART 1:
Introductive overview

GLOSSARY

Radiation:



In this context RADIATION = "The transfer of **energy and momentum** by means of a <u>quantum</u> (particle or photon)."

Note: electromagnetic radiations with energy below the X-ray band are here not included. Excluded: UV (well..), visible, thermal, microwave and radio-wave radiations.

in this regime

Wave-like behavior → particle behavior

UV

energy

overview

RADIATION: ubiquitous
hazard, problem, tool

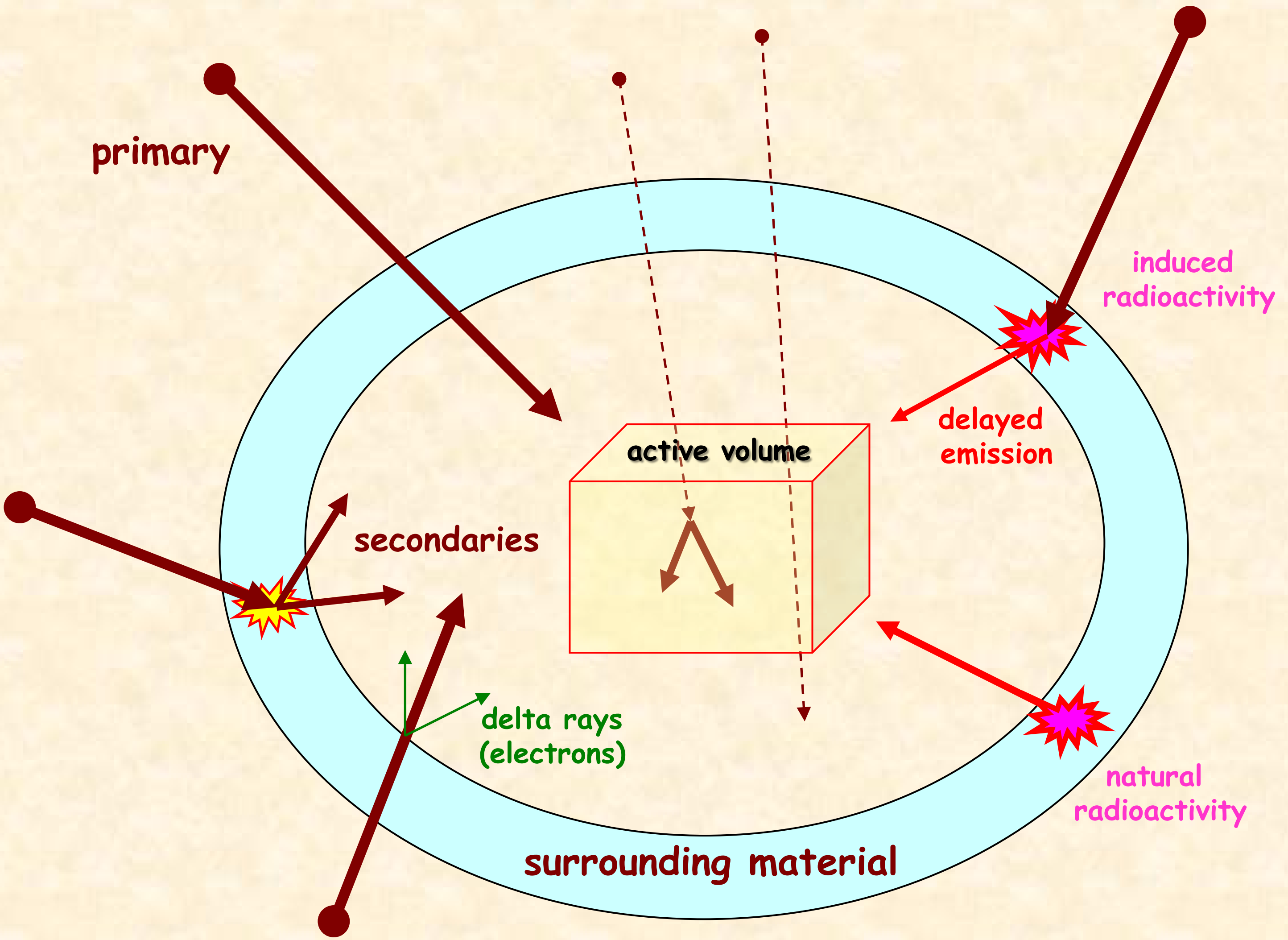
NATURAL human environment (all of us)	EXTENDED NATURAL environment	ARTIFICIAL environment
• high altitude cosmics ← • natural radioactivity of materials • sea level cosmics	high altitude cosmics • satellites (various orbits) • space station • moon missions • deep space missions	• nuclear reactors • HEP experiments (collider halls) • radiation therapy facilities • industrial accelerators and sources

accelerator environments		
SCIENCE	MEDICINE	INDUSTRIAL
• High Energy Physics • structure of matter (synchrotron facilities) • materials science • ...	• diagnostics (X-rays, PET) • artificial isotopes • oncologic treatment • sterilization	• plastics • composite materials • semiconductors • ecology • ...

overview

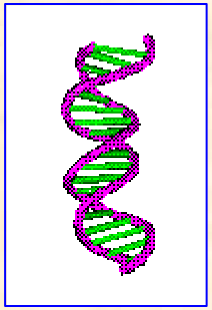
Radiation deposits energy and momentum:

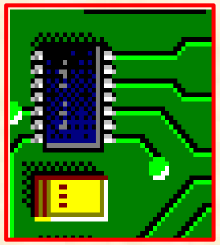
- **natural** (radioactivity of materials, geological and technological history)
- **prompt** (directly associated with accelerated beam or exposure; ON/OFF)
- **induced** (residual activation with beam off due to previous exposure; half-life)



"The behavior of active volumes may be perturbed by radiation."

biological





electronic

effects of radiation in matter

☞ Will discuss only standard electronic materials: silicon and its oxide.

Radiation effects can be divided into two parts:

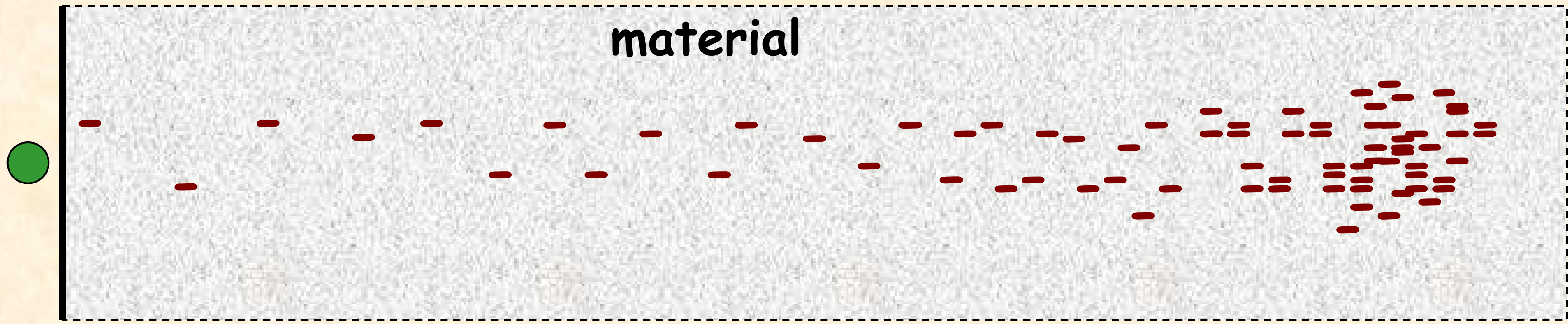
1) **ionization effects**
2) **atomic displacement effects**

Electronics, because of the thin (shallow) sensitive layer, tend to be most sensitive to ionization and the associated accumulation of charge in the material.

Detectors and sensors are sensitive to both effects, with the most important deterioration of characteristics often coming from damage to the bulk (lattice).

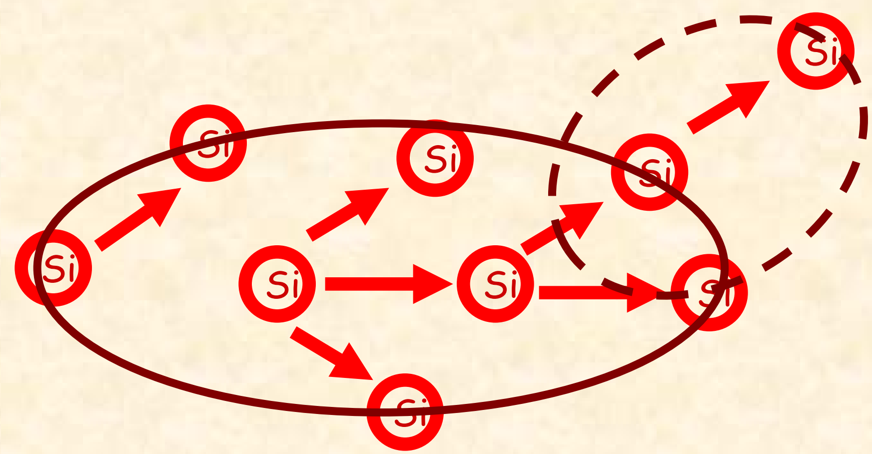
Effects of radiation (microscopic view)

IONIZATION



ATOMIC DISPLACEMENT
(bulk damage)

n, p, π+, π-…



Cascade of displacements → ***clusters***

overview

Effects of radiation in ELECTRONICS

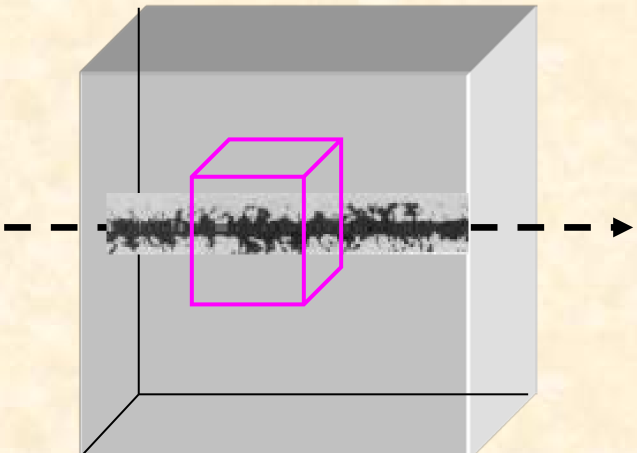
When a **quantum** strikes a device it can transfer energy to the medium both by atomic displacement and/or by ionization:

1. The particle ionizes the atoms of the medium. Noticeable effects in non-conductors after many particles: cumulative, Total Ionizing Dose effects (TID).
2. The particle transfers kinetic energy to the atoms and damages the structure of the medium (Non-Ionizing Energy Loss, NIEL). Displacement bulk damage presents noticeable effects after many particles: cumulative, Displace Damage Dose effects (DDD).

} Total Dose Effects

3. The particle releases enough ionization in a sensitive volume to induce a macroscopic device/system malfunction (single particle effect).

} Single Event Effects



overview

Effects of radiation in ELECTRONICS (macroscopic view; the time domain)

❑ cumulative (total dose) effects:

Effects that ***change with continuity (gradually) with increased exposure*** to radiation. Damage/deterioration can be monitored until it goes too far. **Predictable.**

• *tell tale concepts and words*:

- *small energy transfers,*
- *accumulation of effects,*
- *gradual parameter shifts (thresholds, leakage currents, type inversion,...)*
- *fluence*
- *Dose*
- ...

❑ Single Event Effects:

Effects that ***occur suddenly***, **not predictable on event to event basis (stochastic).**

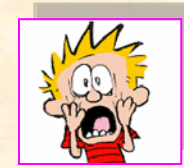
One speaks of **PROBABILITIES**

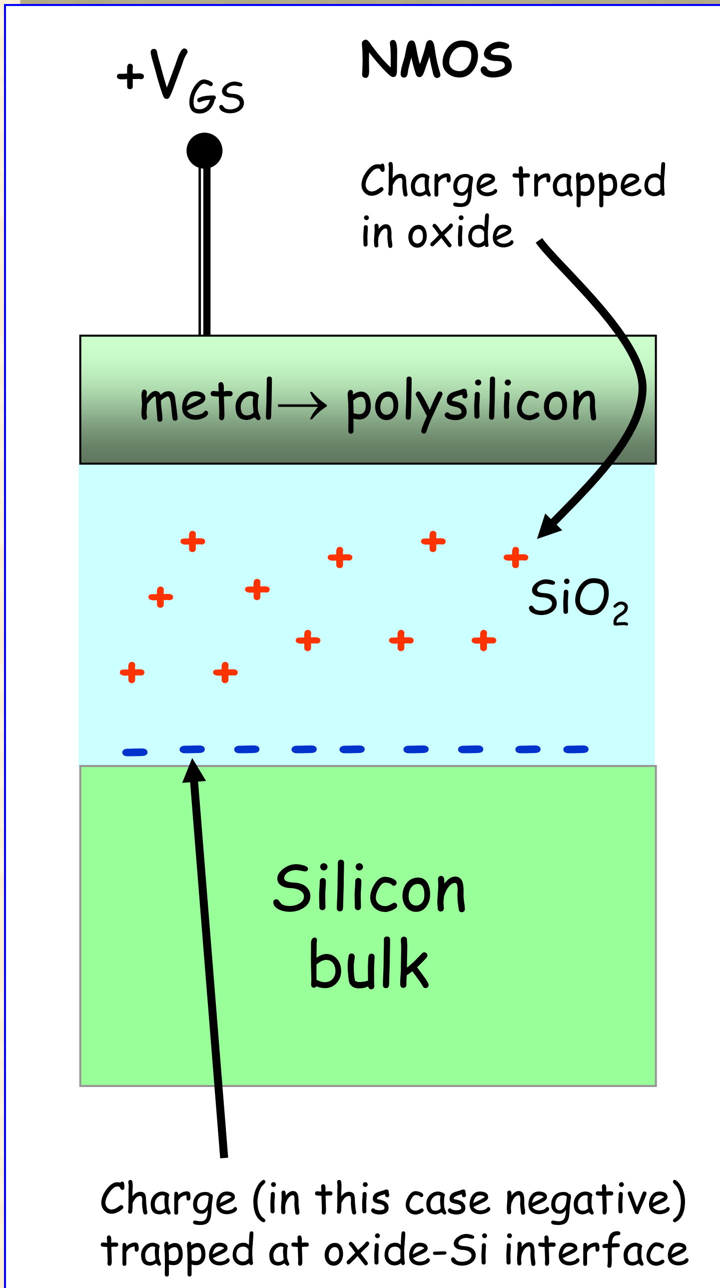
• *tell tale concepts and words: sudden anomalous signal; catastrophic consequences of a rare event; sooner or later; a matter of time;* ***stochastic****; probabilities;* ***cross-sections****;* ***flux*** *(luminosity); evaluation of risk; redundancy (backup); should have known better; bad luck; voodoo...*

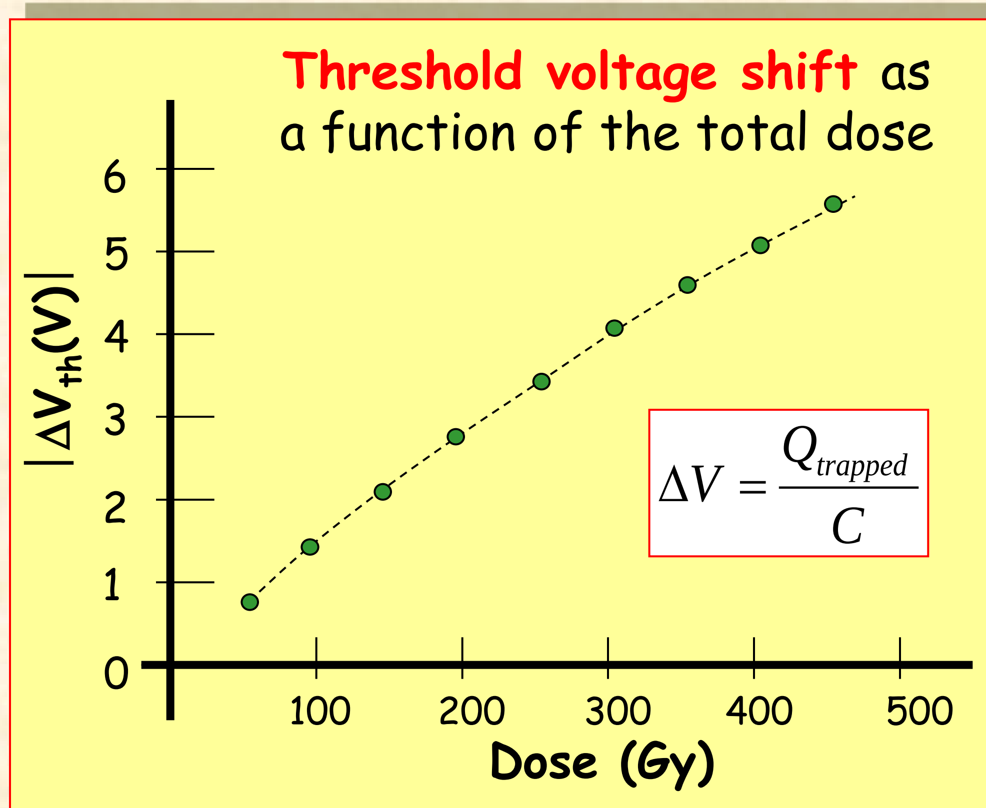
overview

TID

Charge trapping in oxide layer affects device operation







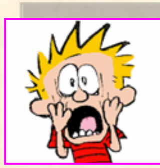
overview

Silicon detectors are used in practically all HEP experiments to provide precise coordinates for *tracking information*.

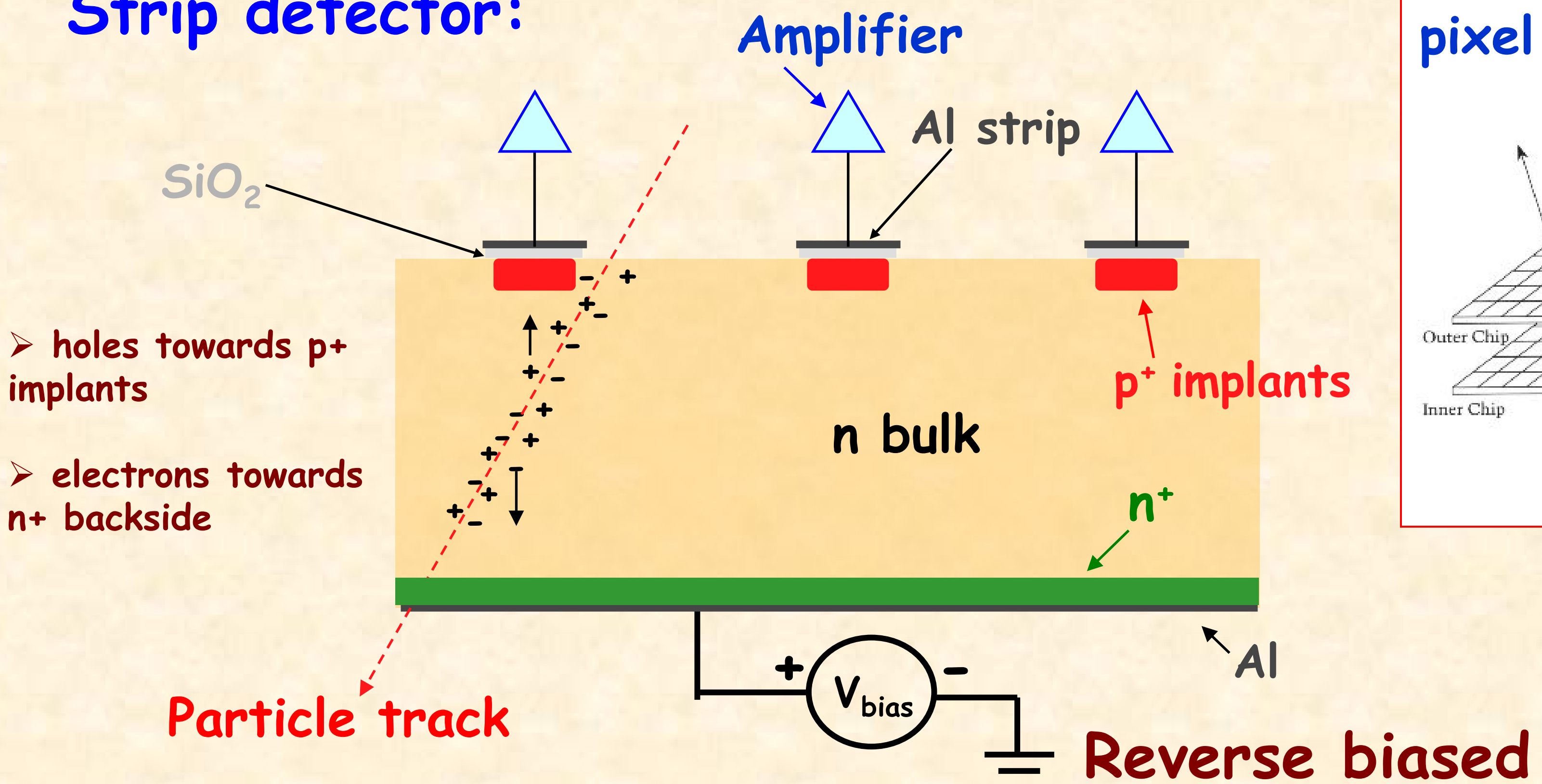
Displacment damage to the lattice

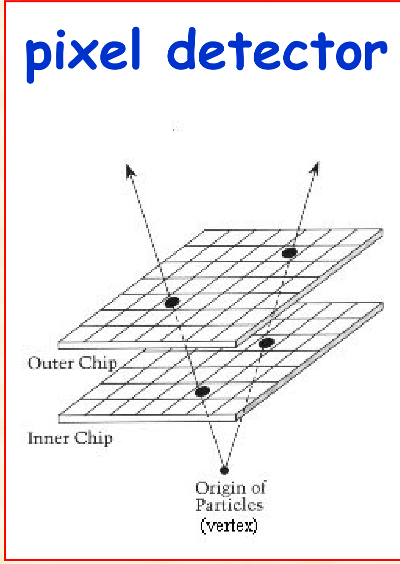
will interfere with the motion of the charge carriers and the detector will deteriorate!

DDD



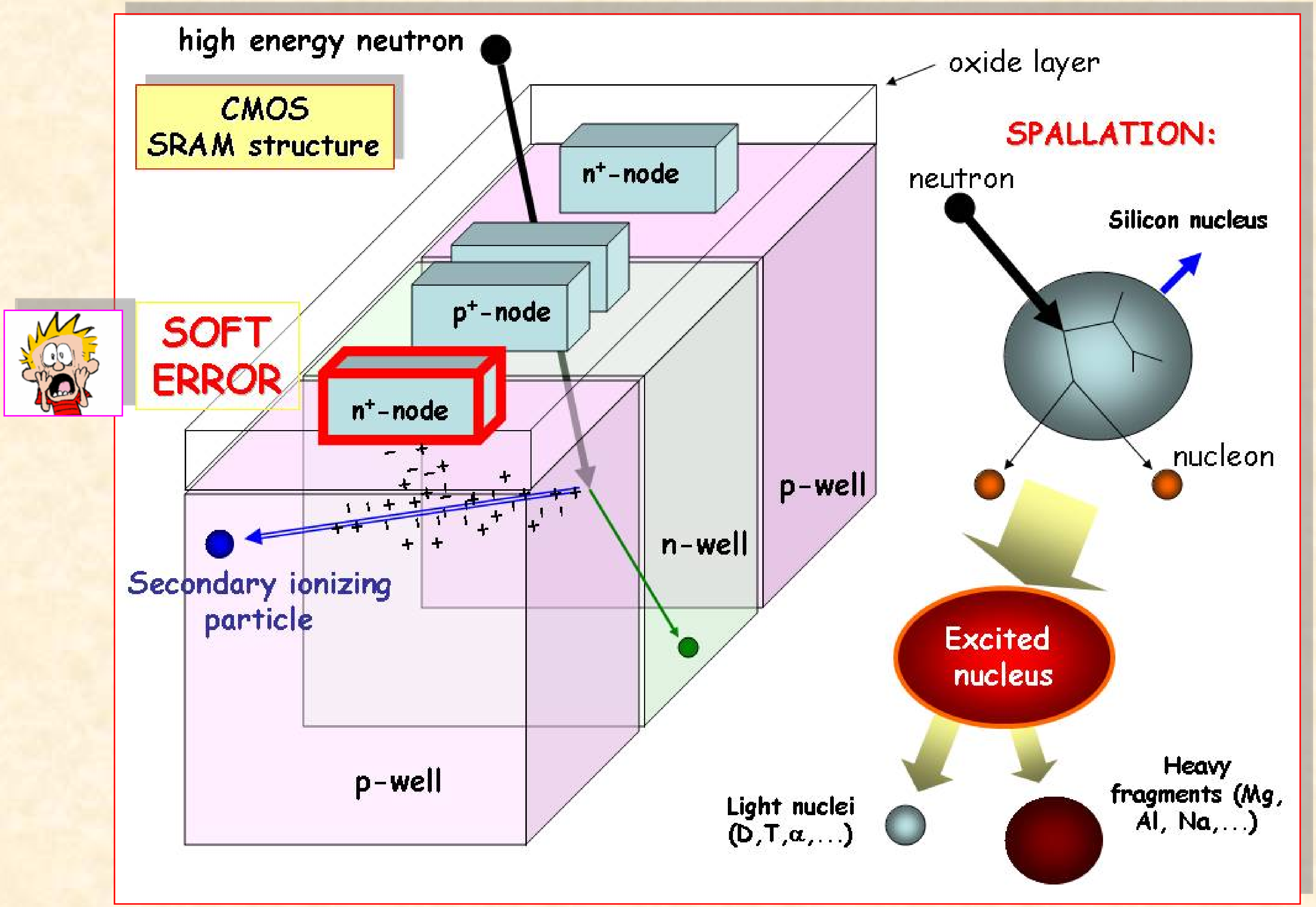
Strip detector:





overview

SEE



overview

Effects of radiation in SCIENTIFIC EQUIPMENT

Particle irradiation

Charging
- Biasing of instrument readings
- Pulsing
- Power drains
- Physical damage

Ionizing & Non-Ionizing Dose

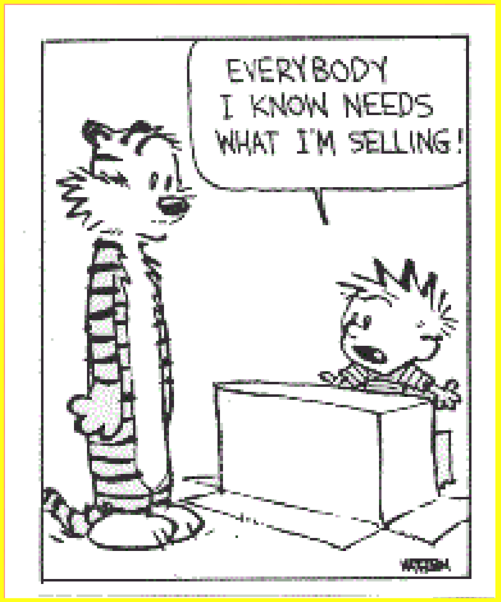
Degradation of:
- μ-electronics
- silicon sensors
- solar cells
- optical components

Single Event Effects
- Data corruption
- Noisy Images
- System shutdowns
- Circuit damage

material degradation

Degradation of:
- thermal, electrical, optical properties
- structural integrity

direct effects in electronics

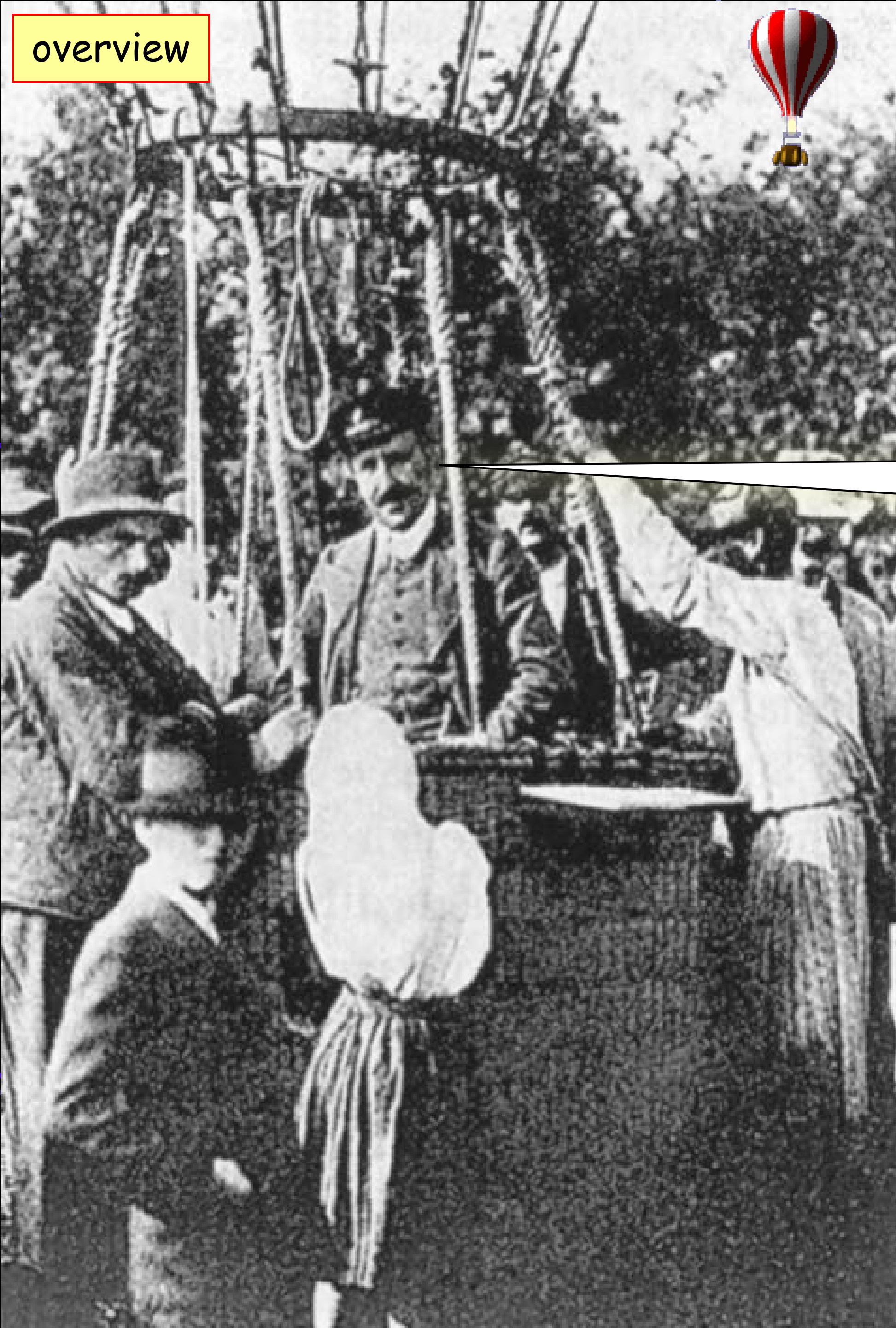


Radiation environments
(cultural overview)

- cosmic rays at flight altitudes and sea level
- accelerator-based experiments
- cosmic rays in outer-space

- **full circle**… cosmic rays at flight altitudes and sea level

overview



Victor Hess discovered “cosmic rays” in 1912 in balloon excursions using Wulf electroscopes

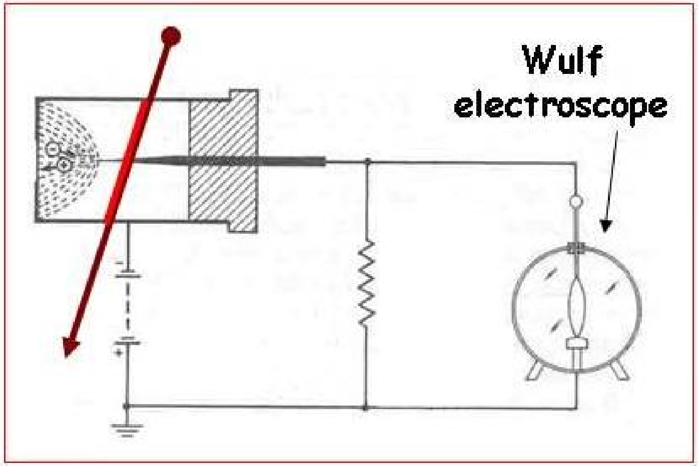
A dangerous discipline!
but full of treasures.

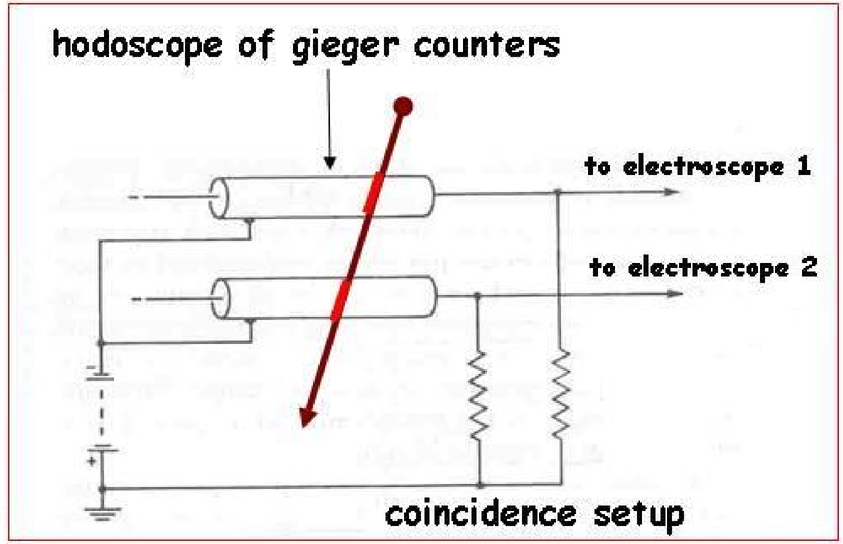
cosmic ray research played driving role in history “particle physics”

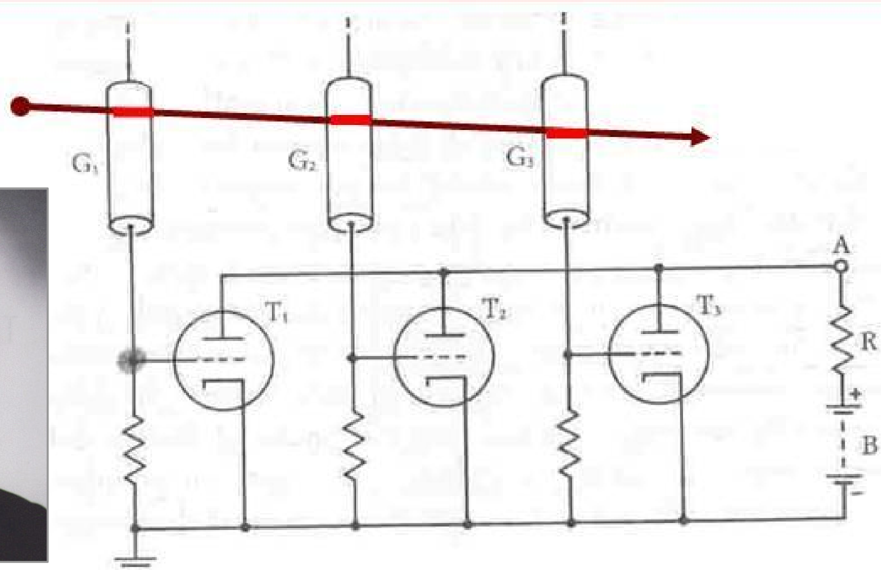
- *discoveries*
- *techniques*
- *theory*

fundamental role of cosmic ray research

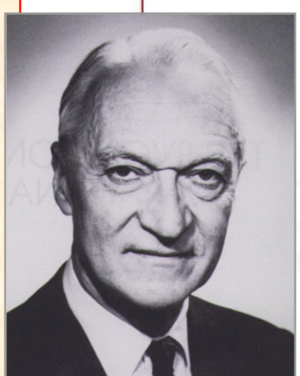
in history of techniques: ***counting experiments*** and *electronic triggers*

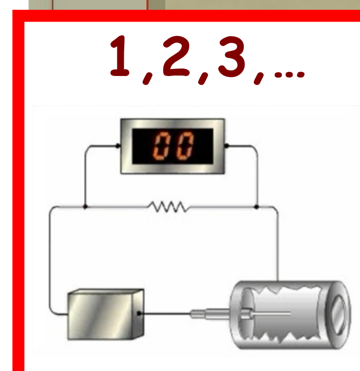






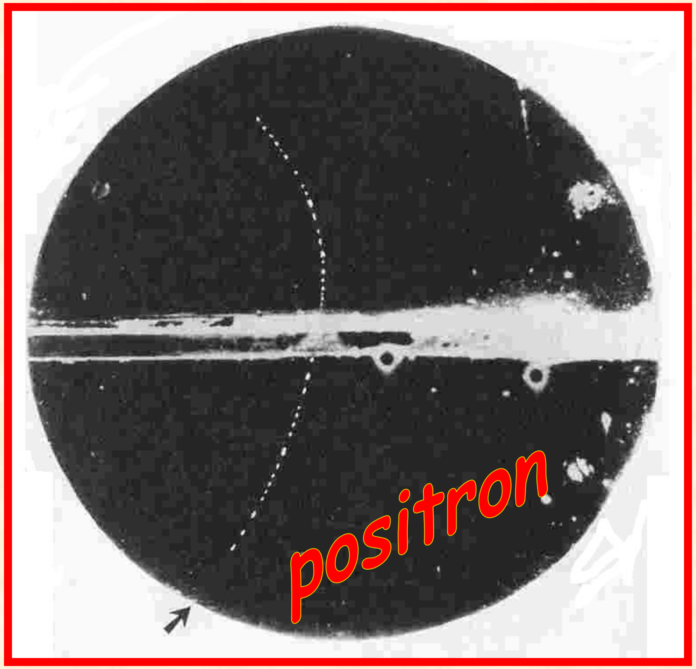
true modern electronic coincidence circuit (Bruno Rossi)

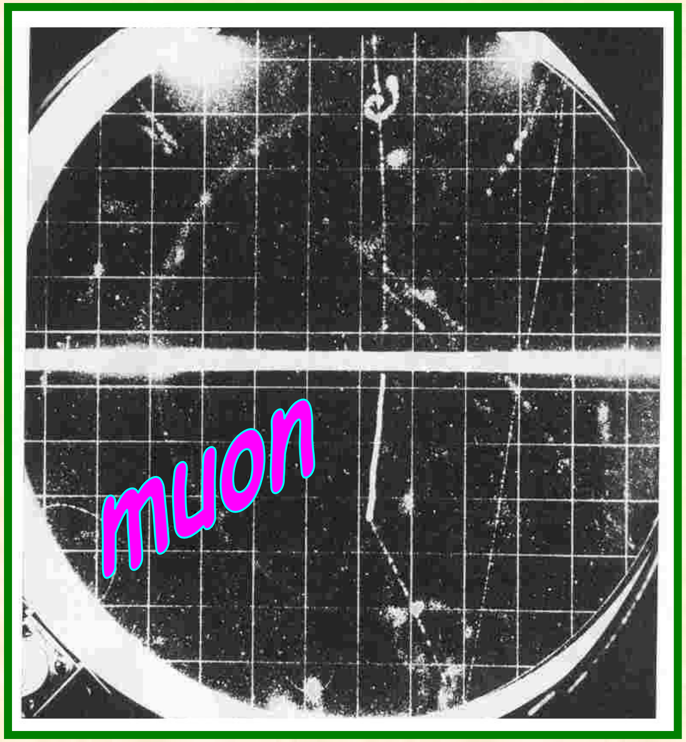


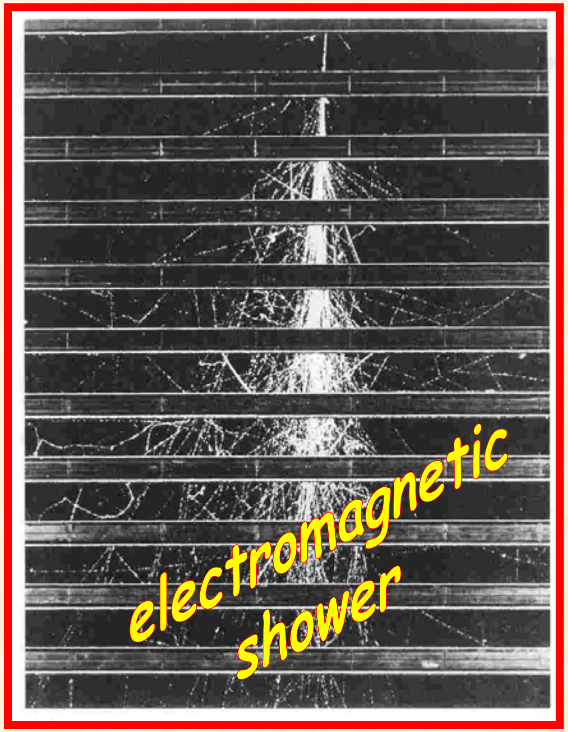


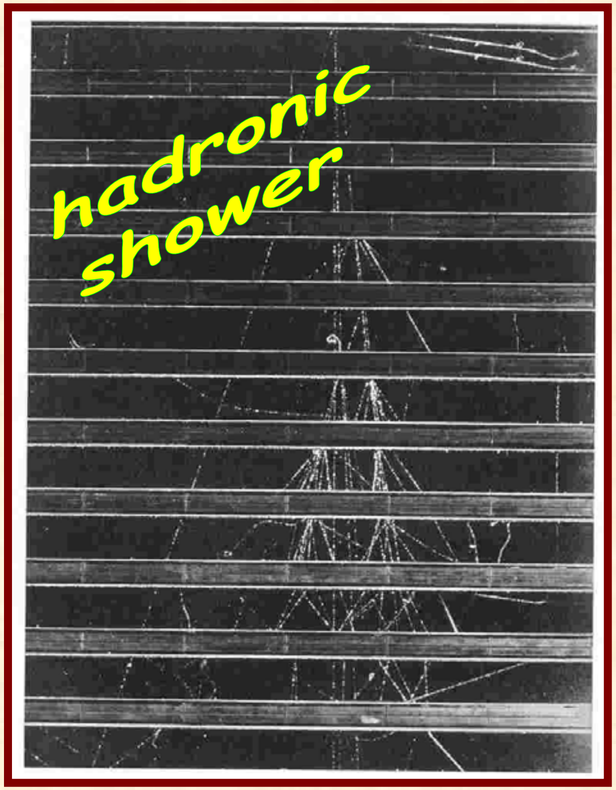
Cosmic ray research techniques, discoveries,…

e.g. cloud chambers triggered by geiger counters and Rossi electronics!







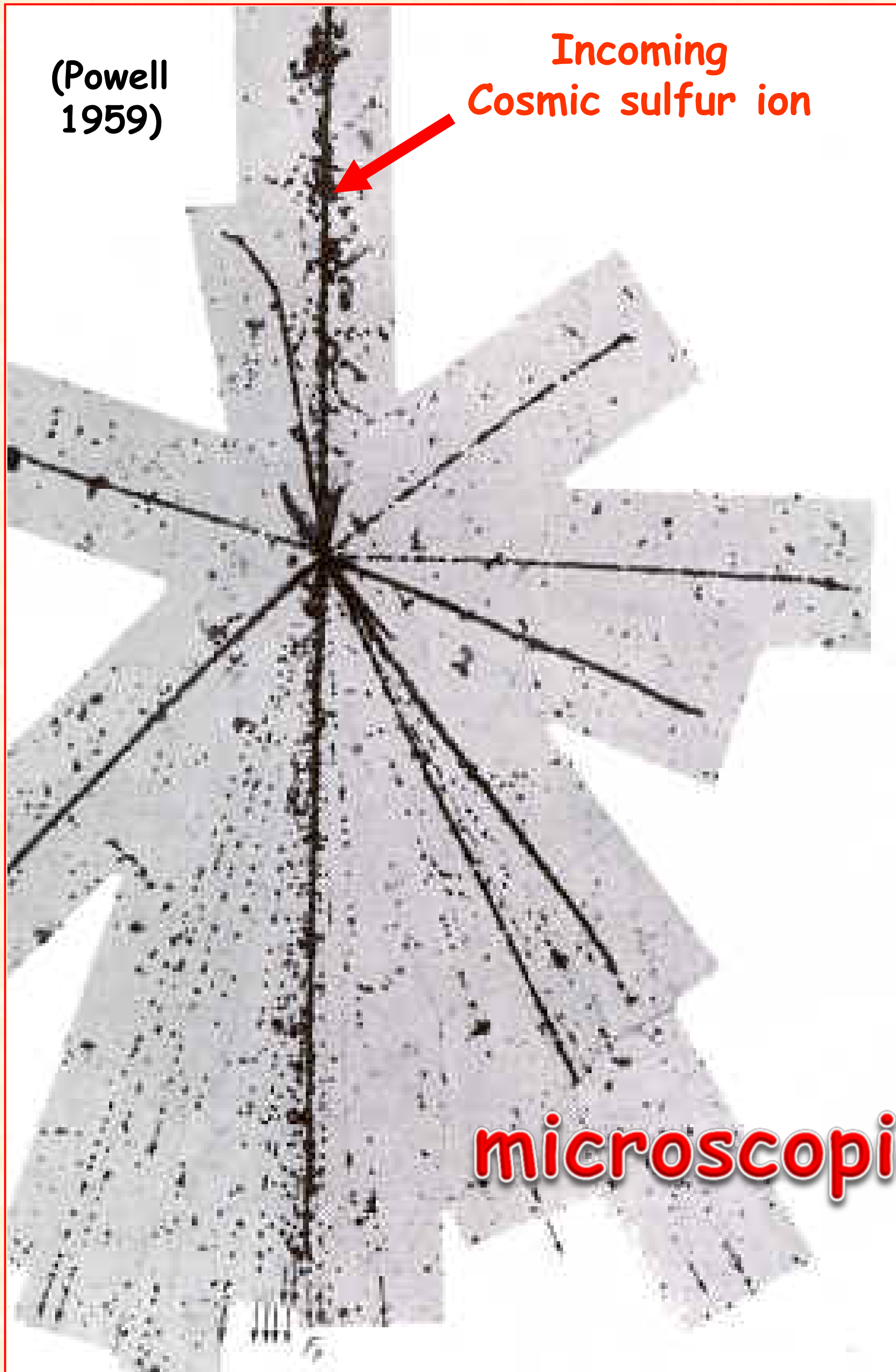


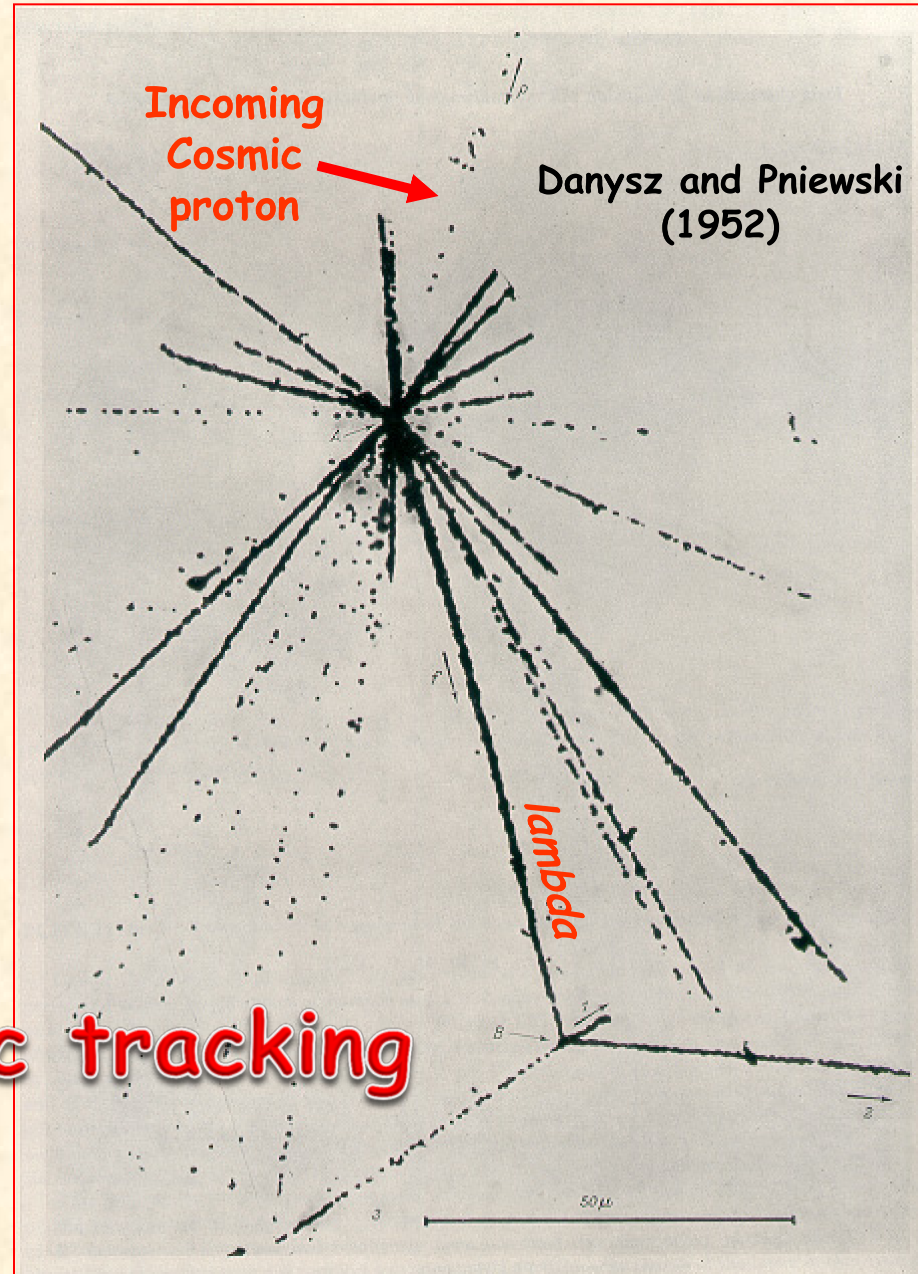
Particle identification

Nuclear emulsion

Cosmic rays

silver salt, usually bromide, embedded in gelatine

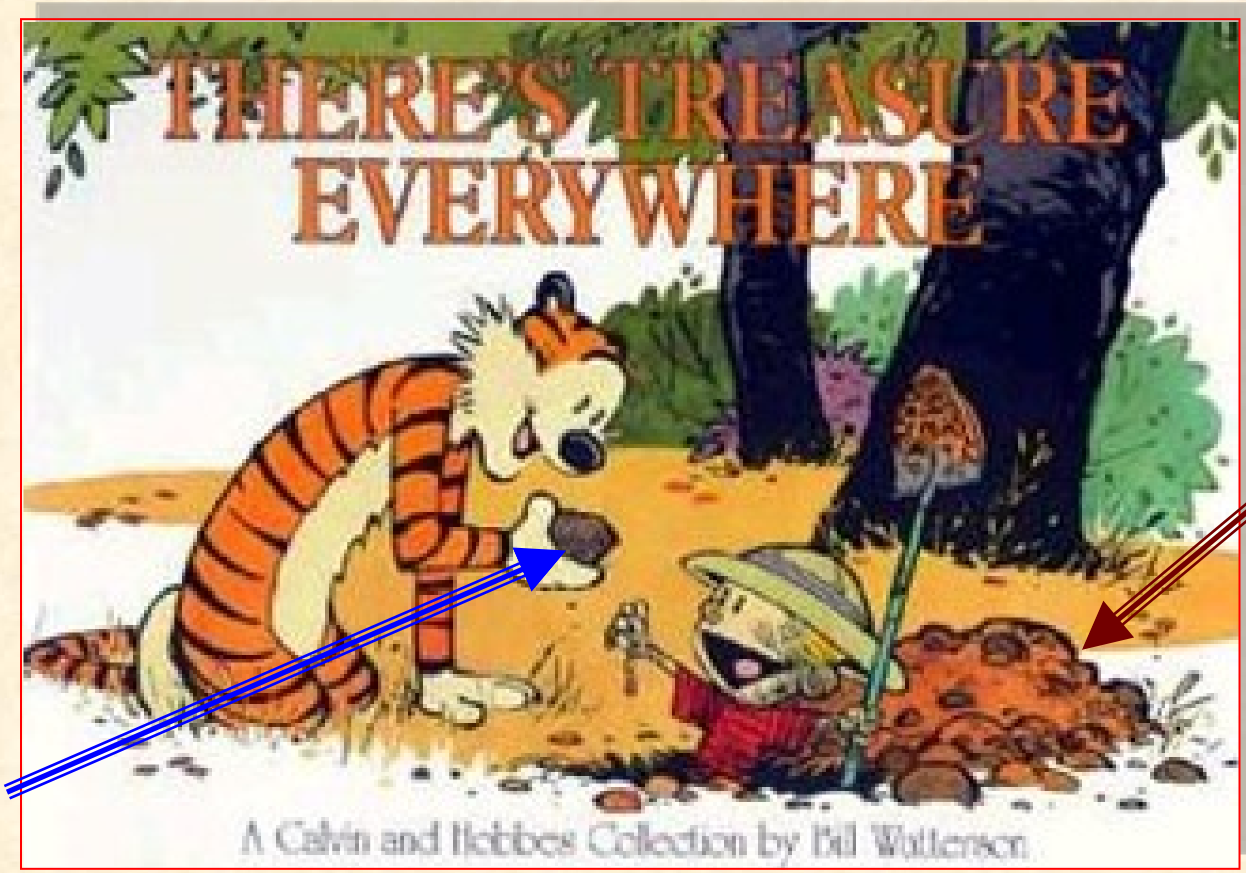




microscopic tracking

accelerators

High Energy Physicists at accelerators are after RARE hard-to-find events/particles.
They worry about radiation effects.

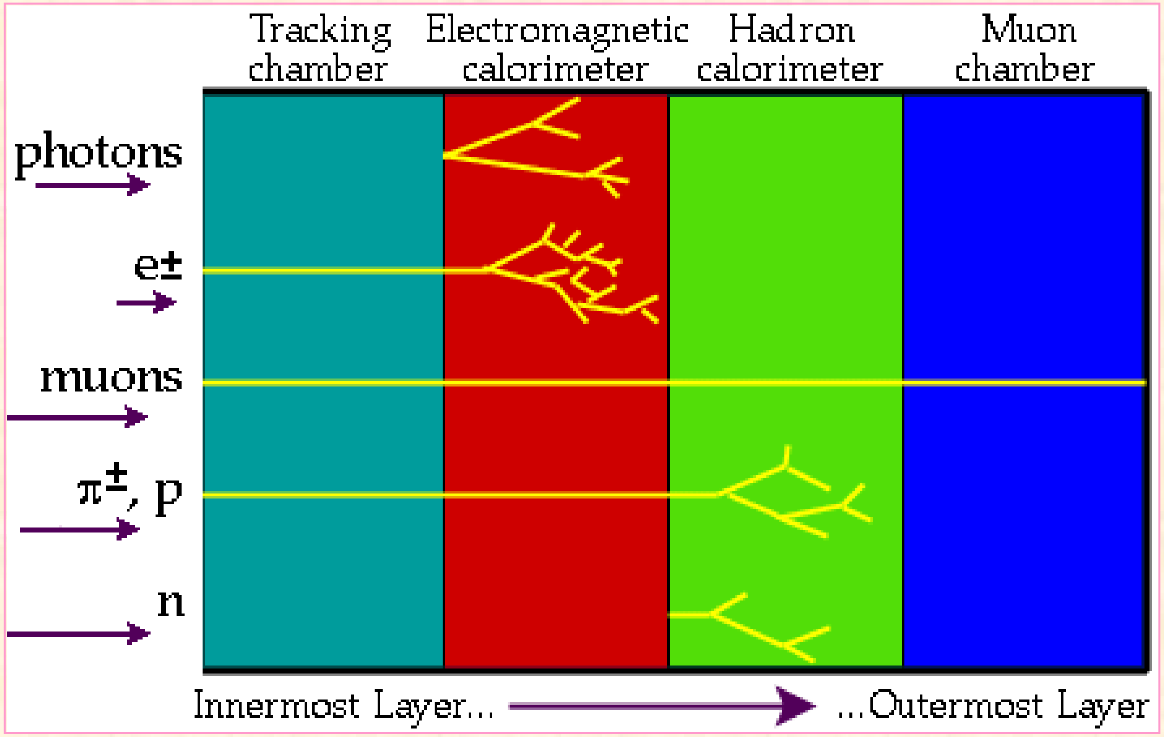


A lot of background radiation!!!

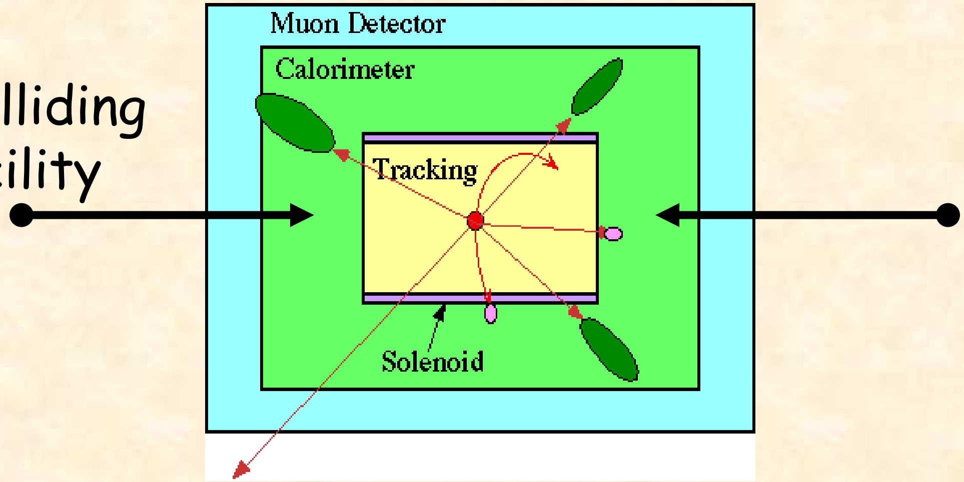
Signal?

detector cartoon

Typical modern detector system:
composed of dedicated (specialized) detectors and elements



e.g. at a colliding beam facility



accelerators

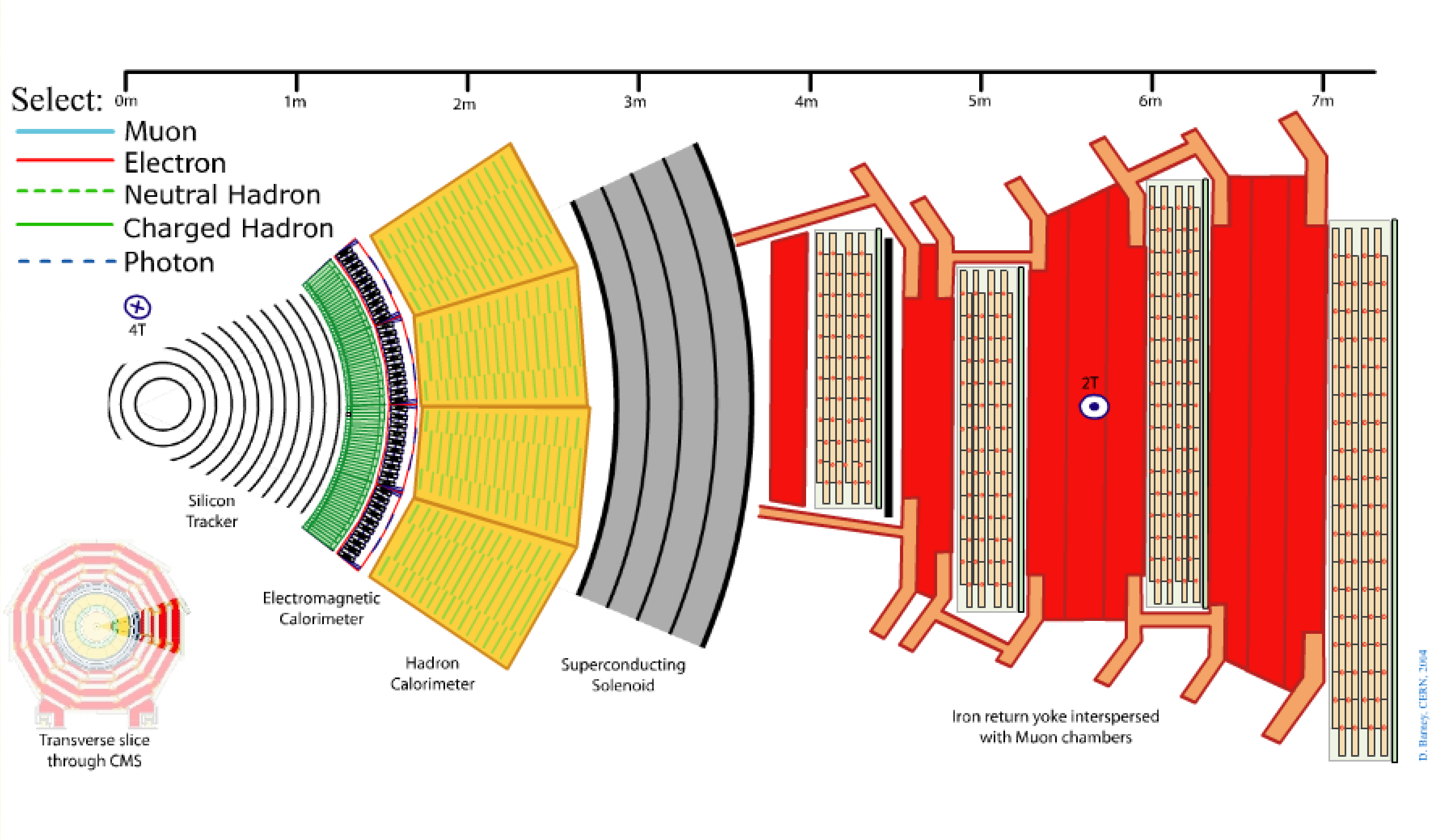
Inheritance, expansion

skip

Transverse slice through CMS detector

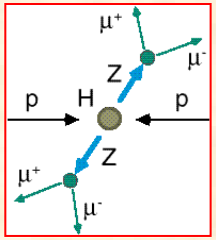
Click on a particle type to visualise the particle as it interacts in CMS.

Press “escape” to exit

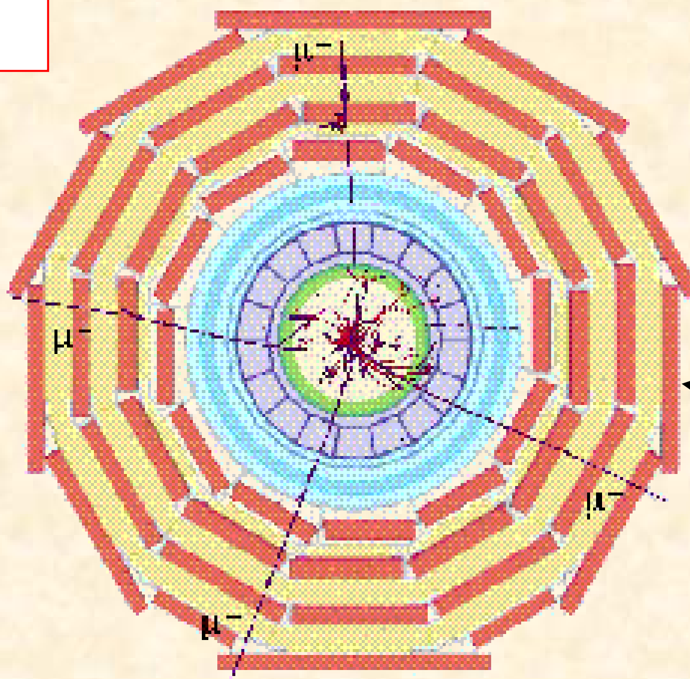


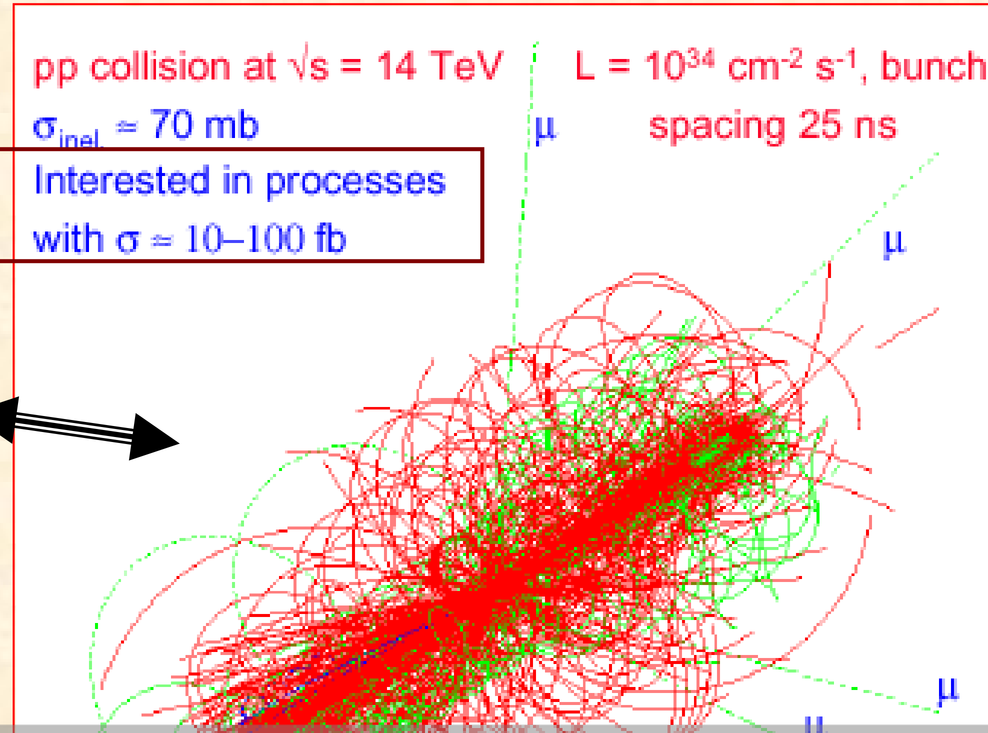
accelerators

RARE hard-to-find events/particles



ONE beam crossing "event" at CMS = **a lot of *soft physics stuff*** plus **very rare hard stuff** **(the rare event; in this case 4 stiff muons).**





After 10 years of operation will have produced just a few thousand of these rare **hard events** at

the very high price of producing ~ 10^{16} busy "events".

⇒ VERY RADIATION HOSTILE ENVIRONMNENT!

Space

Any scientist/engineer, in his/her right mind that sends instrumentation to *Outer Space,* worries…

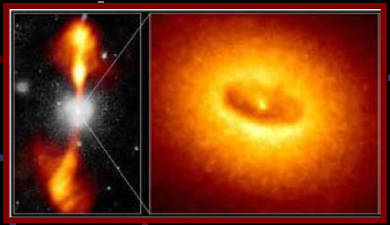
about radiation effects too!

Space

Energetic Space Radiation

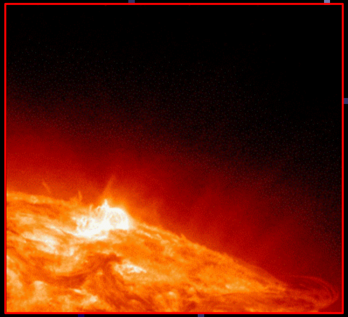
Heavy IONS

Galactic sources (1987a)

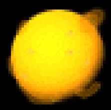


EXTRA-Galactic sources (NGC-4261)

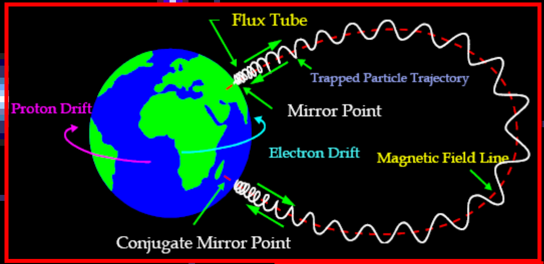
protons



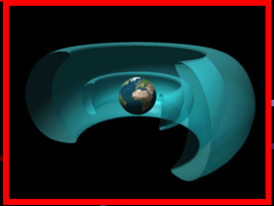
Solar flares



protons electrons



radiation belts

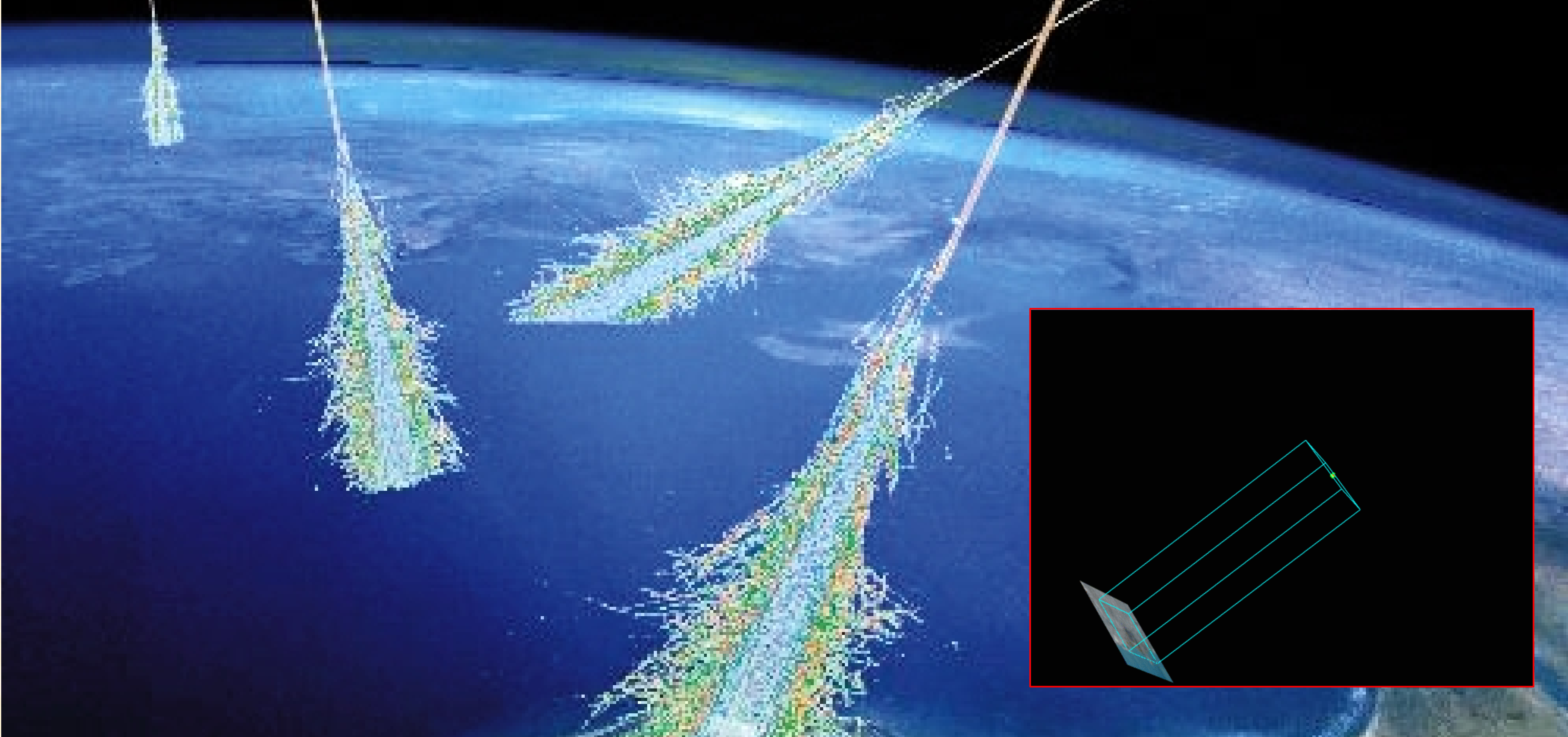


Cosmic ray air showers are with us all the time

Atmosphere "thickness" 1 kg/cm^2

Collisions are random. On average:

- protons collide after 1/14th ≈ 70 g/cm^2
- alphas collide after 1/40th ≈ 25 g/cm^2
- heavy ions collide in even less



Neutrons are widening problem for Industry

Air showers

Aviation

Yikes! Even normal human activities are not completely "safe"!

Automotive

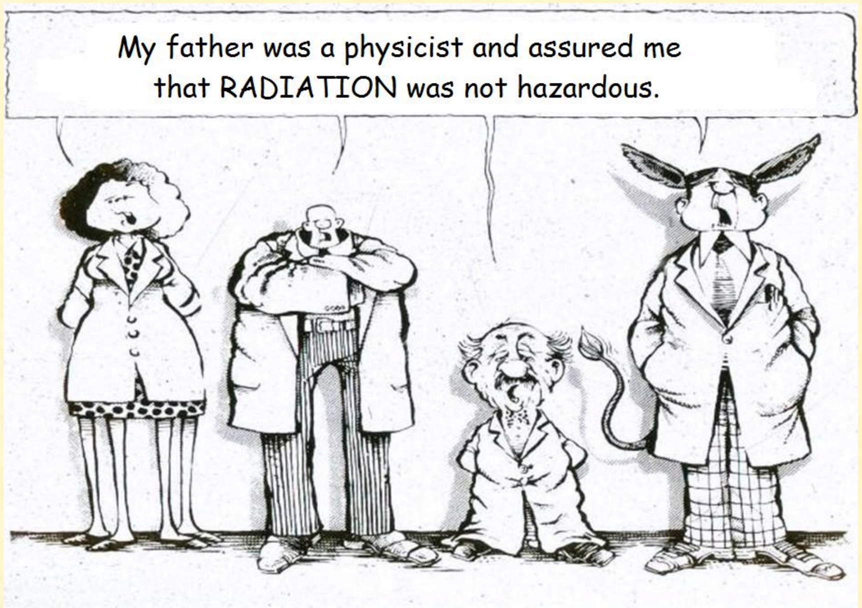
Trains

Infrastructure

"Radiation induced single events could be happening on everyone's PC, but instead everybody curses Microsoft."
Paul Dodd, Sandia National Laboratories

Medical

Now what?
What do you do?



- radiation Physics
- device Physics
- hazards
- assurance

When designing systems for radiation environments; e.g.

- *Accelerator based facilities* (HEP experiments, Radiation Therapy, in some cases even in Industry);
- *Space missions* (Astrophysics experiments, solar system exploration,Telecomunications satellites);
- *Nuclear Plants*
- *High Altitude Flight* (avionics)
- *Ground level critical/vital electronics* (e.g. computers, servers, pace-makers, electronic voting machines, power electronics,...)

"normal" activities

design issues

... MUST consider <u>all elements</u> (more or less vital) that may suffer from radiation effects (to high/lesser degree)

- **detectors (gas, silicon,...)**
- **semiconductor sensors (Si, GaAs, solar cells, ...)**
- **front-end electronics, CMOS, bipolar circuits, μ-processors**
- Infrared, X- and gamma-ray detectors
- LEDs, laser diodes
- Optocouplers, fibre-optic data links
- Insulators, cabling
- Optical materials
- Cryogenics
- ...
- **human beings** (Radio-Biology: astronauts, airplane crew, passengers, patients, personnel, scientists, ...*students*)

dealing with

Commercial Off The Shelf (COTS) approach to deal with radiation effects

knowledge and understand effects

- knowledge of environment
- understand microscopic effects
- understand system effects (simulations)

define, identify, test

- **define** requirements for parts/components
- **identify** candidate parts
- **test parts**
- engineer system
- **test system**

go for it! **Do experiment**

after F. Faccio
"COTS for the
LHC radiation environment:
the rules of the game"

dealing with

Evaluation of risks of effects in radiation environments

- to evaluate the risk of failure due to radiation in a given device or system (e.g. a HEP detector, SPACE detector, whatever ...) need

description of the radiation environment:

- **Make models** based on **experimental data** and tuned **Monte Carlo simulations** to calculate expected doses, particle types and fluences
- **Take results of experiments and simulations into account** when designing radiation tolerant/hard elements and systems for detectors
- **Allow for worse case scenarios** to account for unpredictable events (worst known solar storms and hope for less severe ones,...)
- ***Allow for safety margins!***

physical qualities and quantities

NEED TO understand/define

quality and quantity of radiation

- types of particles (p, e, γ, n, π, K, ions,...)
- energy of particles
- how many particles (flux/fluence)
- chances of certain effects occurring (cross-sections; thresholds)
- effects predictable (total dose) or stochastic (bad luck)
- sources predictable or stochastic

properties of target

- material (silicon, plastic, water...)
- active devices (memories, diodes,...., *living cells*)
- active volumes (different sensitivities, how many, where, ...)

physical qualities and quantities

NEED TO understand /define

- quality of radiation
  - particle type (p, e, γ, n, π, K, ions,...)
  - energy
  - flux/fluence (how many!); i.e. cross-sections
  - source predictable or stochastic

- properties of target
  - material (silicon, plastic, water...)
  - active devices (memories, diodes,...., *living cells*)
  - active volumes (different sensitivities, how many, where, ...)

- **Questions that need answers:**

after H. Sadrozinsky, Santa Cruz

- are the effects *predictable* or *stochastic* ?
- what is correct variable? How does effect scale?
  (dose, fluence, 1-MeV equivalent neutron fluence for NIEL; LET and fluence hadrons E > 20 MeV for SEE)
- any normalisation factors?
  (scaling, NIEL-hypothesis, quality factors, *radiobiological equivalents*)
- any role of microenvironment?
  (parasite structures such as latch-up in CMOS; *bystander effect*)
- ⇨ any relaxation effects?
  (annealing, *adaptive response*)
- are there dose rate/flux effects?
- are there low dose effects?

PART 2:
radiation concepts

Radiation hazard symbol

source

- what kind is it (natural, reactor, accelerator)
- Space (Sun, Van Allen belts, galactic sources)
- activity
- Luminosity of accelerator

Radiation field

- where are you respect to source (and what surrounds you)
- exposure: what are you exposed to (types of particles at your location)
- Flux ϕ(particles/(cm^2-s))
- Fluence Φ(particles/cm^2)

Exposed material

- what are you made of (silicon, electronics)
- Dose, dose rate
- stopping power of particles (LET, NIEL)
- various effects (cumulative or sudden)

Radiation effect	Quantity, parameter
Electronic component degradation	Total ionization energy loss dose (TID)
Material degradation	Total ionization energy loss dose (TID)
Detector, sensor, CCD, degradation	Non-ionizing energy loss dose (NIEL) and equivalent fluence
Solar cell degradation	Non-ionizing energy loss dose (NIEL) and equivalent fluence
Single Event Effects (SEE): Upsets, Latchups, Burnout, Whatever…	SEE cross-section. Ion LET spectra. SEE rates

Words that need to be understood

- flux, fluence
- activity, luminosity
- cross-section (Single Event Effects)
- dose
- stopping power
- LET
- NIEL, equivalent fluence

basic radiation damage measurement quantities

- **Flux** (ϕ) is no. of particles per unit area and per unit time:

Formula	Measurement Unit
ϕ = Particles/(Area×Time)	Particles/(cm^2×s)

- **Fluence** (Φ) is no. of particles per unit area (time integral of the flux):

Formula	Measurement Unit
$\Phi = \int\phi\, dt$ = Particles/Area	Particles/cm^2

- **Dose** (D) is energy deposited by radiation per unit mass:

Formula	Measurement Unit
D=E/M	J/kg

GLOSSARY

Flux:

The amount of radiation crossing a surface per unit of time.

"integral" flux: particles per unit area per unit time (e.g. particles cm^{-2} s^{-1}) above a certain threshold energy.

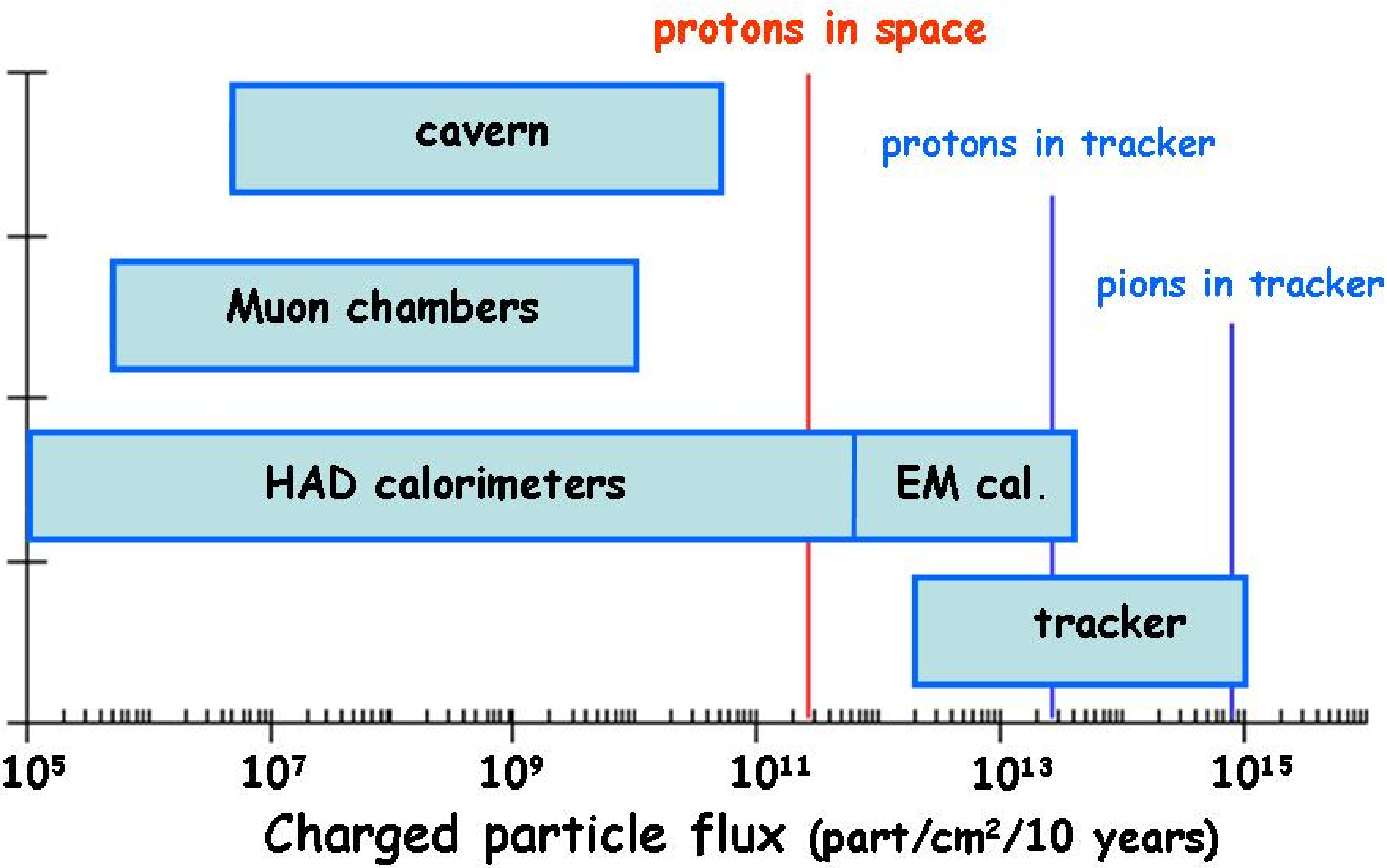
"differential" flux: is differential with respect to energy (e.g. particles MeV^{-1} cm^{-2} s^{-1}).

"directional" flux: is differential flux with respect to solid angle (e.g. particles cm^{-2} $steradian^{-1}$ s^{-1})

In some cases fluxes are reported with respect to Linear Energy Transfer (LET).

Charged hadron flux
Space vs CMS

after J. Gasiot



Radiation Field of Space and…

Radiation field

- integral flux of particles ϕ(particles/cm^2-s) with minimum energy

protons in space, Van Allen belts (E>10 MeV)	10^5 cm^{-2} s^{-1}
electrons in space, belts (E>1 MeV)	10^6 cm^{-2} s^{-1}
energetic heavy "energetic" in space (Geostationary orbit, 10 years)	10^6 cm^{-2} s^{-1}
Air shower neutrons at ground level E>2 MeV	18 cm^{-2} hr^{-1}

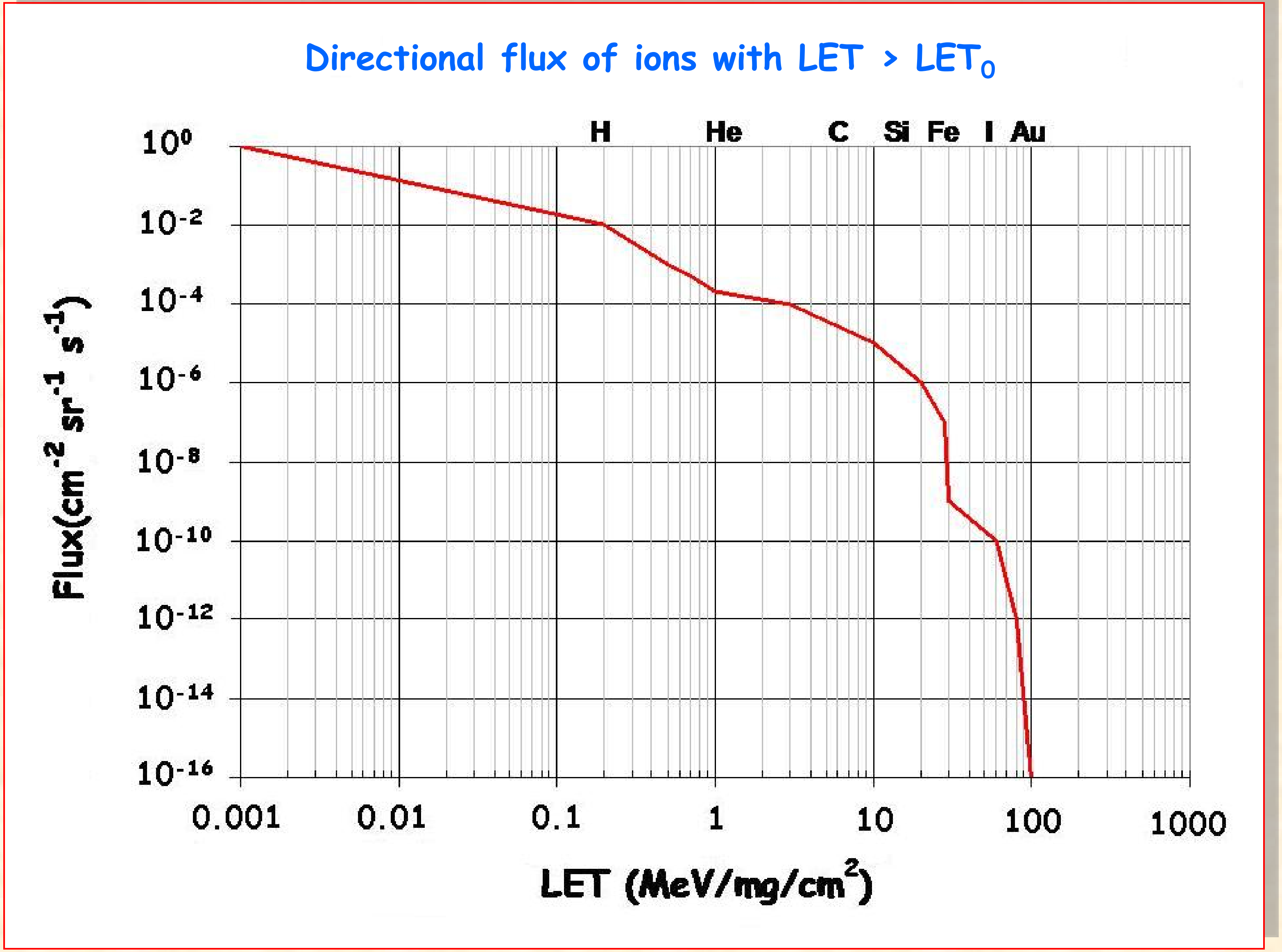
GLOSSARY

Energetic particle (space):

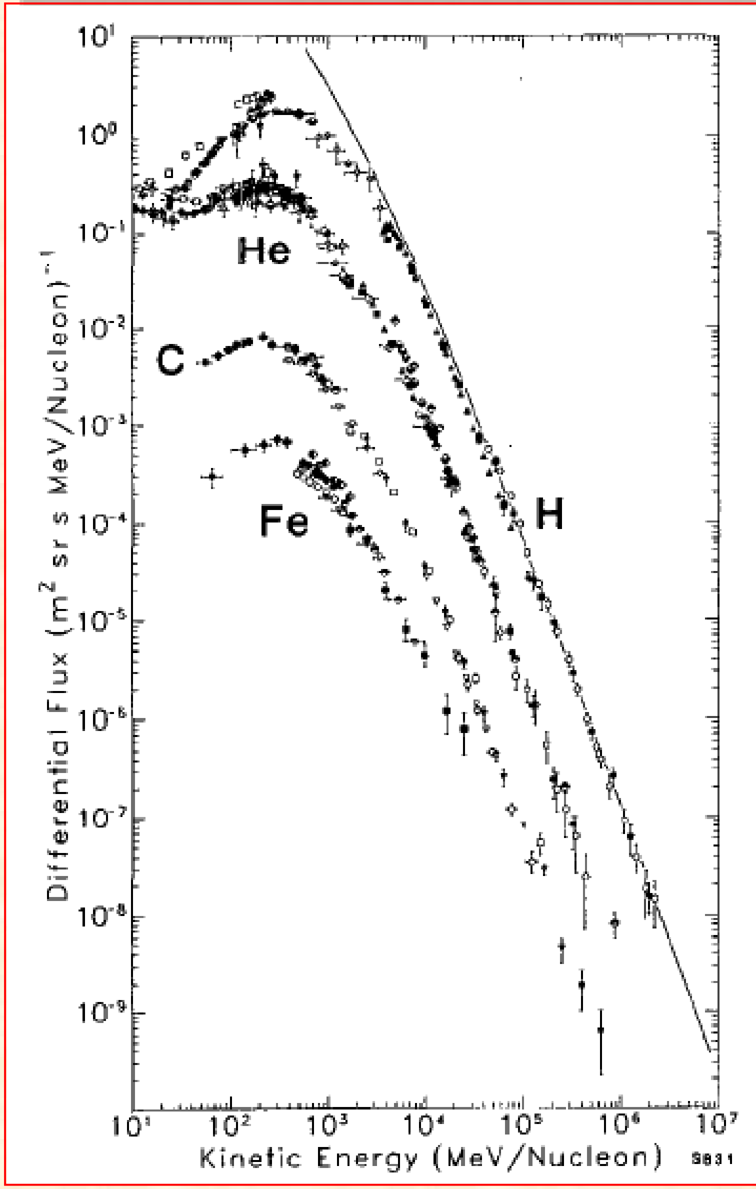
In the context of radiation effects in SPACE systems, “energetic particles” are those which can penetrate outer surfaces of a spacecraft.

For electrons, this is typically above 100 keV, while for protons this is above 1 MeV. Neutrons, gamma-rays and X-rays are also considered energetic particles. Heavy ions need greater energy to penetrate.

Cosmic ion flux in Space
directional integral spectrum vs LET

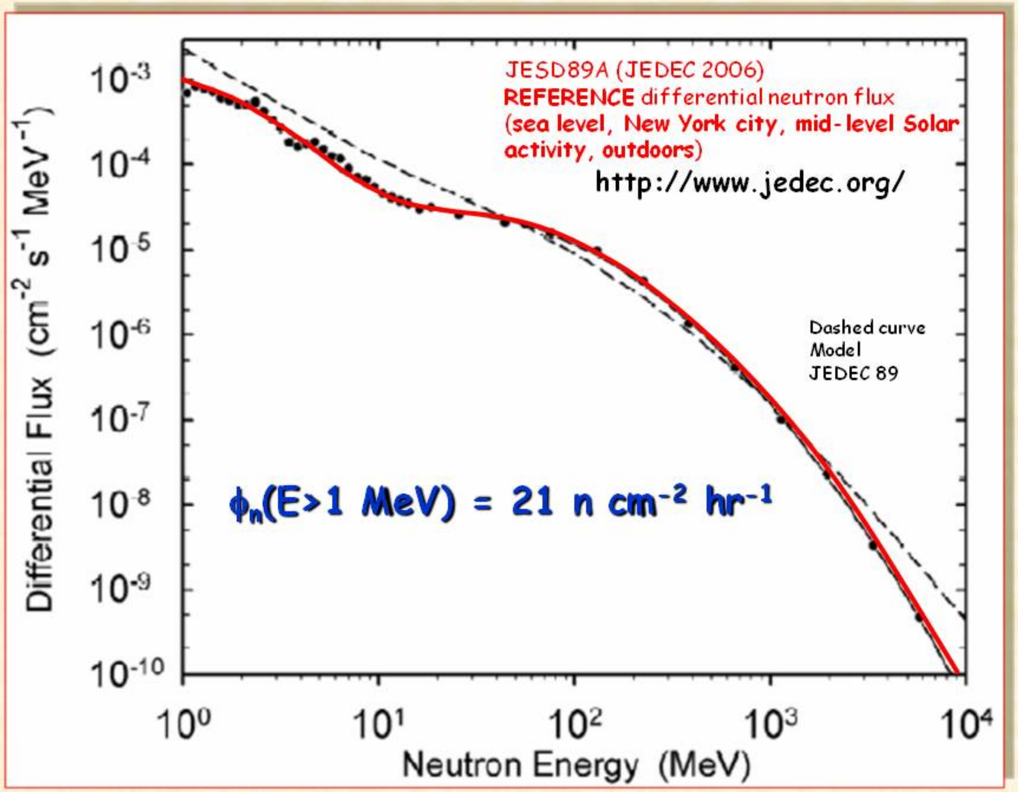


Differential Energy spectra of primary cosmic rays (galatic sources)

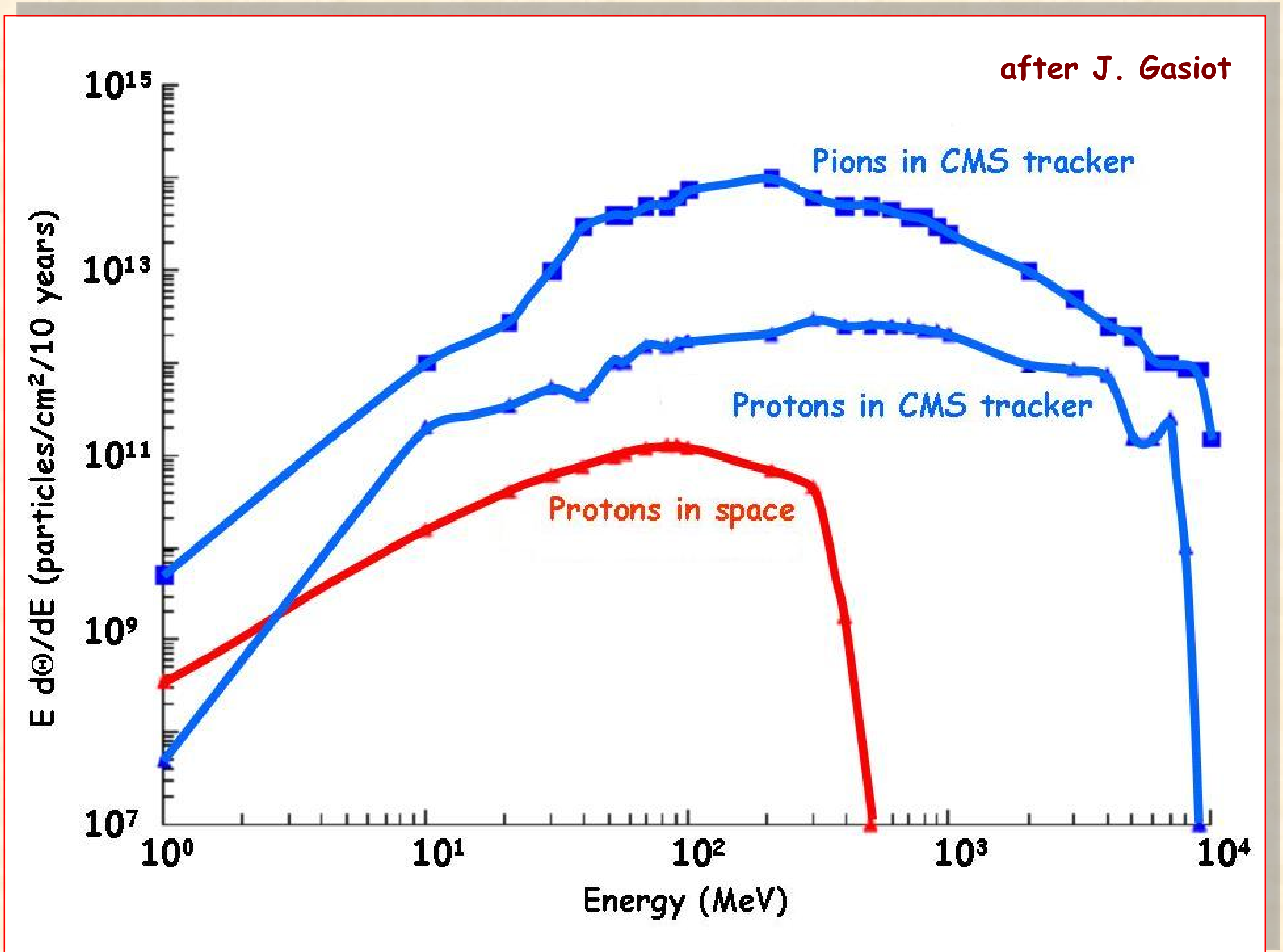


J.A.Simpson, Ann. Rev. Nucl. Part. Sci. 33 (1983) 323

Differential Energy spectra of air-shower neutrons at sea level

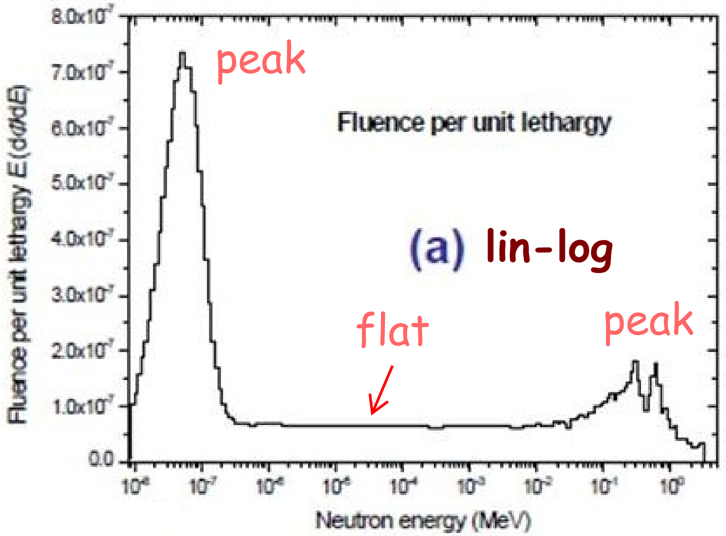


Differential flux: EdΘ/dE (lethargy representation)

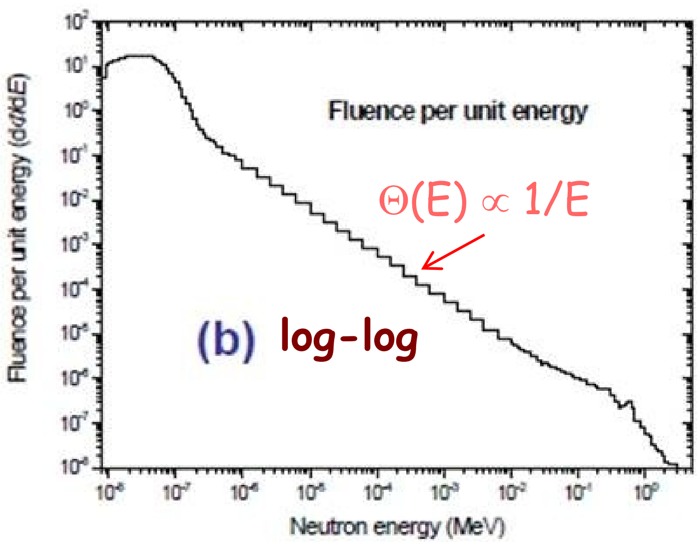


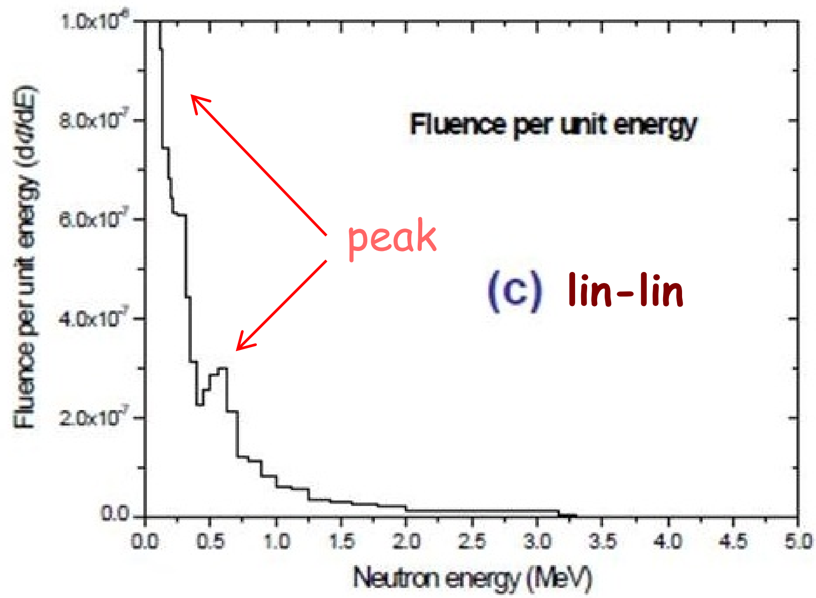
LETHARGY

The appearance of a neutron spectrum



"In the lethargy representation, equal areas under the energy spectrum in different energy regions represent equal energy-integrated fluxes."





❑ activity

Unit: 1 bequerel (Bq) = 1 disintegration/s
1 curie (Ci) = 3.7×10^{10} Bq
typical activity of Co^{60} source for radiotherapy ~ 1 kCi
geological sample activity ~ 0.1 Bq/s

❑ Luminosity ≡ flux

$$L = \frac{N_1 N_2}{A} \times \nu$$

$$R = \sum_i R_i = L \cdot \sum_i \sigma_i = L \cdot \sigma_{tot}$$

N_1, N_2 number of particles
A interaction area (size of beam)
ν collision frequency

R total particle production rate ≡ *activity*
σ_i cross-section of i[th] channel

GLOSSARY

parameter	radioactivity	Absorbed dose (D)	Dose equivalent (DE = D × *Quality*) Q=1 for photons; Q=20 for alpha	Exposure [in air] (for X-rays and gamma only)	energy
Definition	Rate of radiation emission (transformation or disintegration)	Energy delivered by radiation per unit mass of irradiated material	Dose in terms of biological effect	Expresses ability to ionize air and create charges that can be collected and measured	*"Capacity to do work"*
Common units symbol	curie (Ci) 1Ci = 37 GBq (a large amount)	Rad 1 rad = 100 erg/g 1 rad = 0.01 Gy	rem	roentgen (R)	joule (J)
International units (SI), symbol	becquerel (Bq) 1 Bq = 1 event of disintegration per second (a very small amount)	gray (Gy) 1 Gy = 100 rad 1 Gy = 1 J/kg	sievert (Sv) 1 Sv = 100 rem (a large dose) 1 Gy air dose equivalent = 0.7 Sv 1R ≅ 10 mSv of tissue dose	coulomb/kg $1\ R = 2.58 \times 10^{-4}$ C/kg	electonvolts (eV) $1\ eV = 1.6 \times 10^{-19}$ J 1 keV 1 MeV 1 GeV 1 TeV

dose

Effects of typical Ionising Radiation Doses

ionising dose = energy imparted by ionising radiation / mass of target

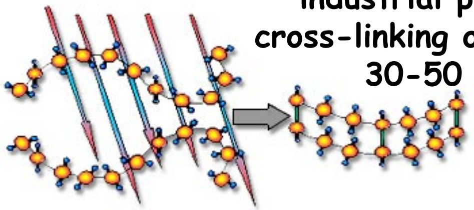
$$\text{ionising dose} = \frac{\text{energy imparted by ionising radiation}}{\text{mass of target}}$$

1 J/kg = 1 Gray (Gy) = 100 rad

- **radiobiological doses**
  - < 5 mGy: typical annual dose of human in *civilized* culture
  - 50 mGy: allowable annual dose for *radiation worker*
  - 1 Gy: common dose of X-ray treatment
  - 2.5 Gy: total-body lethal dose for humans and many mammals
  - 60 Gy: localized dose for full cancer therapy

- **technological/industrial doses**
  - < 1 kGy: Teflon structurally unstable
  - 15-35 kGy: sterilization
  - 20 kGy (2 Mrad): curing of polyester resins
  - 100-200 kGy (10-20 Mrad): curing of epoxy resins
  - 200 kGy: natural rubber unusable
  - 1000 kGy (100 Mrad): polyvinylchloride (PVC) unusable
  - 50-100 MGy: polyimide degraded significantly

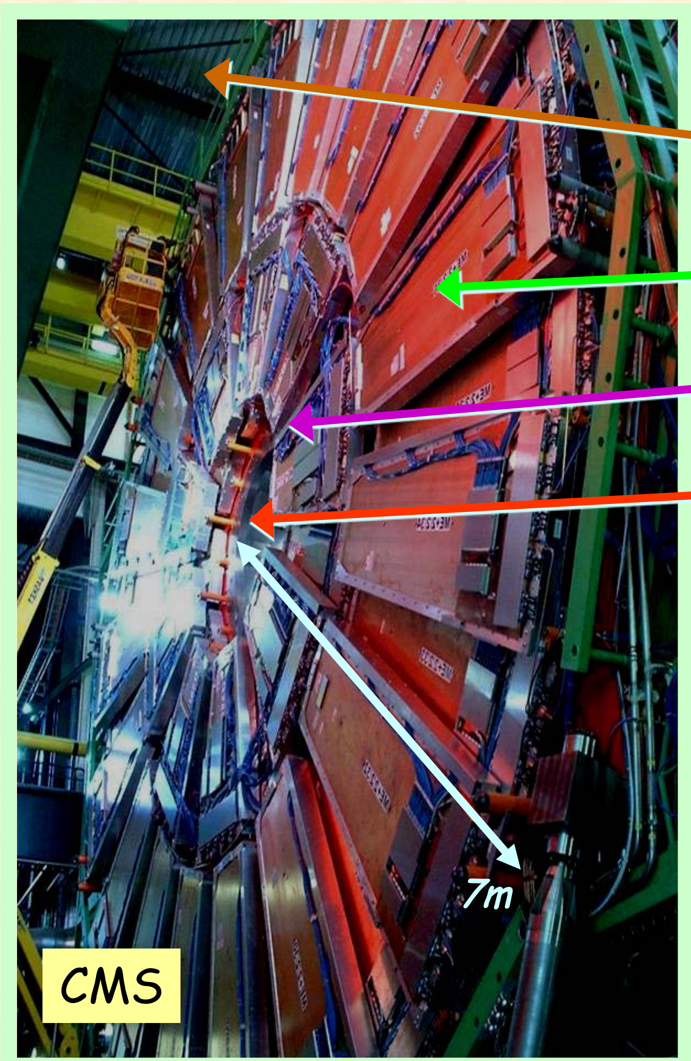
industrial process:
cross-linking of polymers
30-50 kGy

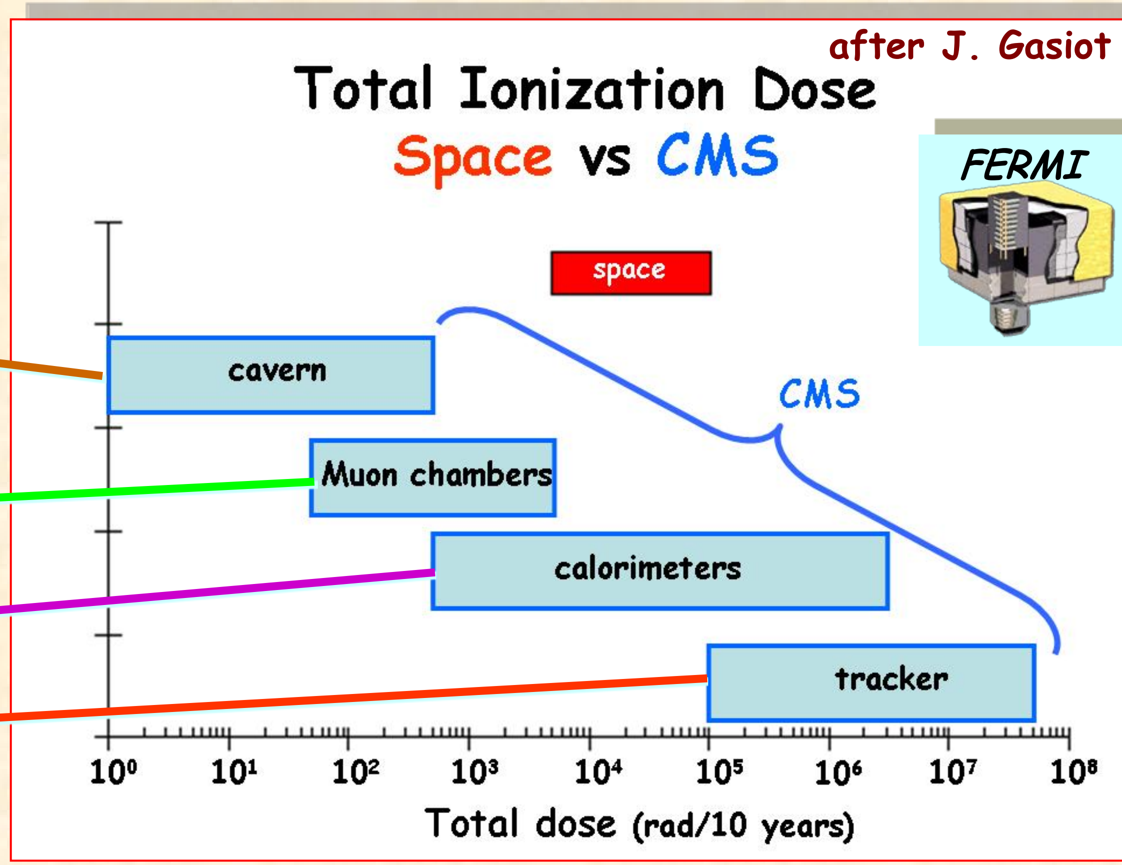


dose	Typical exposure	Number of electron-hole pairs and typical effect
1 mGy	Dose of 1 chest X-ray or 1 year of natural background	10^{12} e-h pairs/cm^3 • effects in insulators (charge trapping), • minor risks in biological cells,
4 Gy		4×10^{15} e-h pairs/cm^3 • transitory effects in semi-conductors, • 50% chance death after 1 month
10-20 Gy	delivered to tumor in radiotherapy	
10-100 Gy	Annual dose received by a satellite	
100 Gy	• Voltage shift induced in threshold of power MOSFET. • The current gain of a BJT may be cut down by a factor 10.	
1 MGy	Dose in sub-detectors of HEP experiments.	• Mechanical properties of some materials are altered.

High Energy Physics environment

Radiation environments of HEP experiments at accelerators are very hostile!





Very large number of particles are generated at every beam interaction. Charged particles ionize contribute TID. Hadrons (protons, pions and especially neutrons) contribute to DDD and may also indirectly cause SEE by creating heavily ionizing secondaries.

Radiation Levels in ATLAS

During the experiment lifetime (10 years)

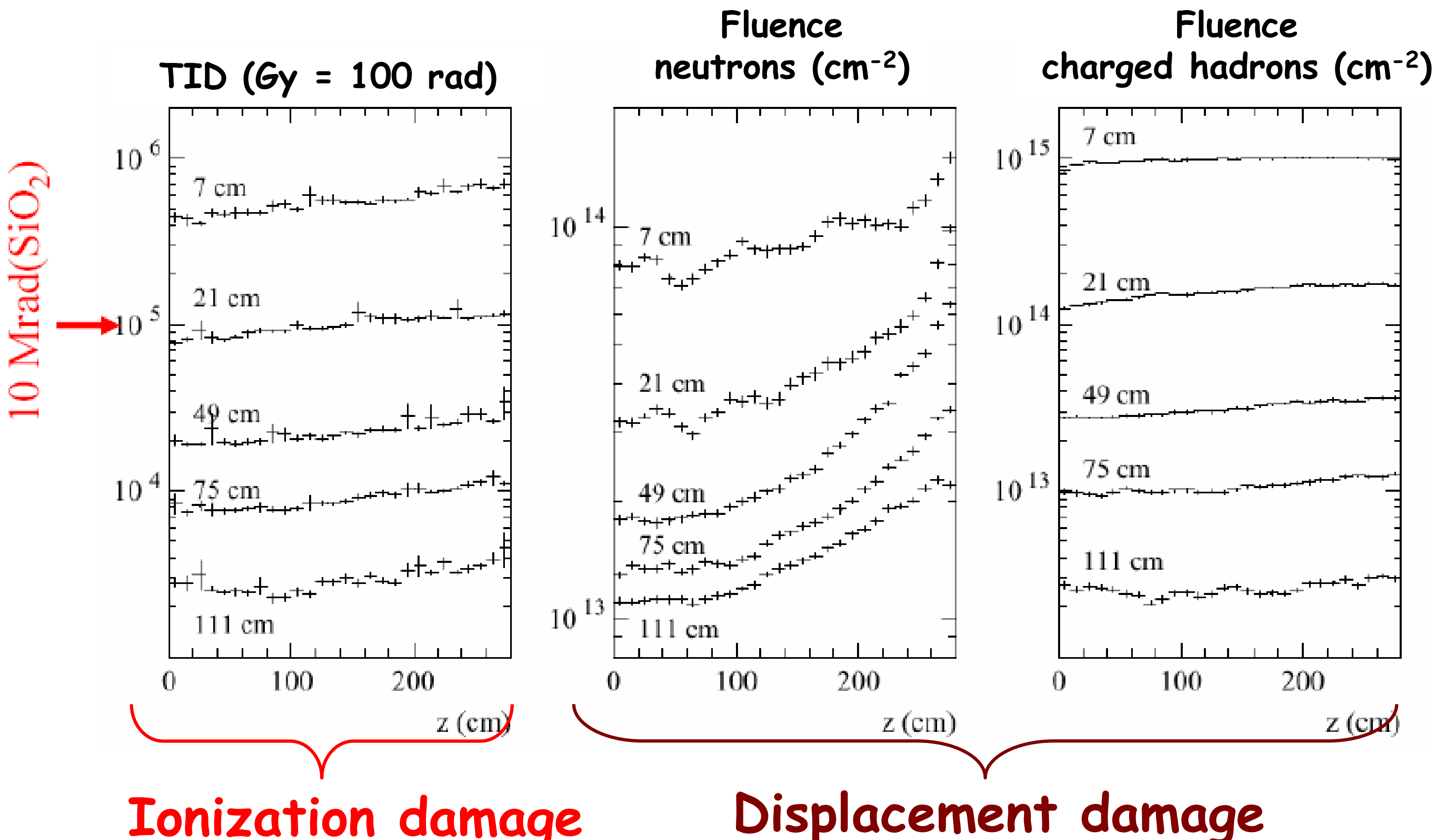
Detector zone	Total dose [rd]	Neutrons (1 MeV eq.) [n/cm^2]	Charged hadrons (> 21 MeV) [n/cm^2]
Pixels	112 M	$1.47\cdot10^{15}$	$2\cdot10^{15}$
SCT Barrel	7.9 M	$1.4\cdot10^{13}$	$1.1\cdot10^{14}$
ECAL (barrel)	5.1 k	$1.7\cdot10^{12}$	$3.6\cdot10^{11}$
HCAL	458	$2.5\cdot10^{11}$	$5.6\cdot10^{10}$
Muon det.	24.3 k	$3.8\cdot10^{12}$	$8.7\cdot10^{11}$

- TID = energy deposited via ionization per unit mass SI unit = Gy = 100 rd
- Neutron and Ch. Hadrons "intensities: are expressed in fluence = integral of flux over time (10 years in this case)
- Hadrons are particles subject to the strong interaction, mainly p and n (and pions) in our context

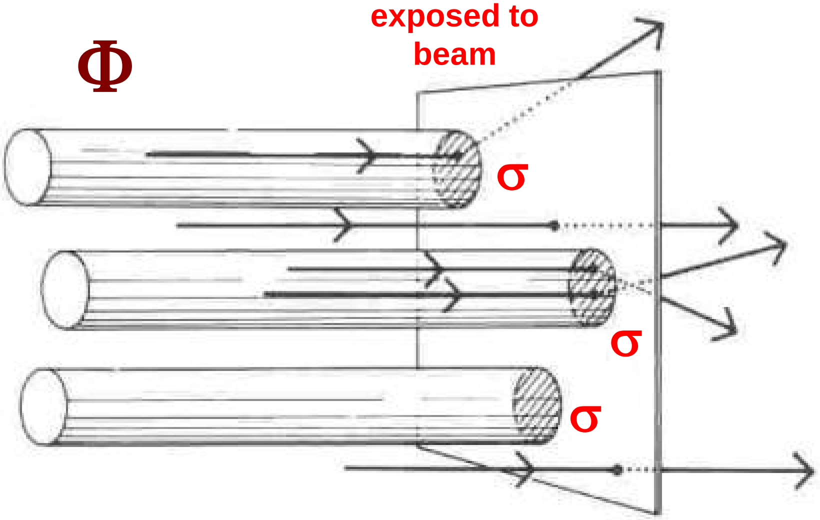
Radiation levels expected for the CMS Tracker

Microstrip detectors and APV25 chips:

25 cm<R<110 cm => 10^{13} cm^{-2} <Φ< 10^{14} cm^{-2}



cross section: a simple way to put it



N_s= number of scatterers in exposed area A

Rationale:

- **incident fluence $\Phi_{inc} = N_{inc}/A$**
  - **Interaction occurs if an incident particle strikes a scattering center**
- **area of each scattering center = σ**
- **total scattering area = $N_s \times \sigma$**

fraction of incident particles that INTERACT **n/N_{inc}**

is equal to the

fraction of exposed area that gives origin to SCATTERING

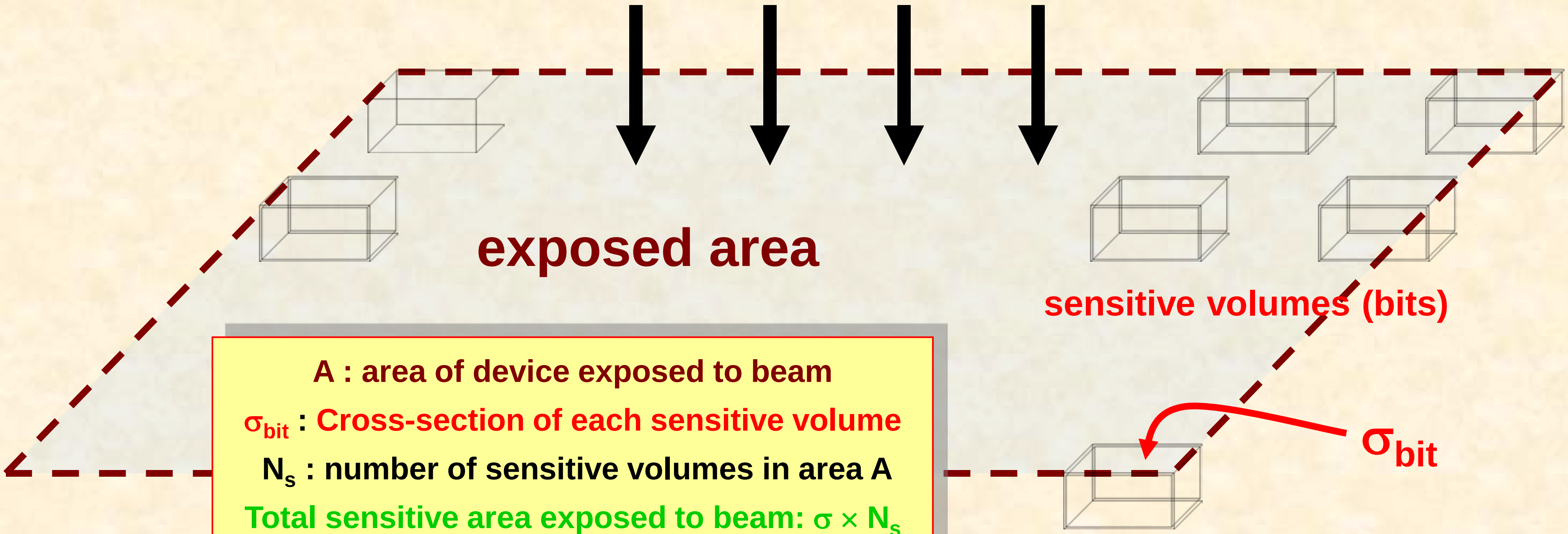
$$\frac{n}{N_{inc}} = \frac{N_s \cdot \sigma}{A} \Rightarrow \text{number of “events”} \quad n = N_s \frac{N_{inc}}{A}\sigma = N_s \cdot \sigma \cdot \Phi_{inc}$$

Experimentally:

$$\sigma = \frac{n}{N_S \cdot \Phi_{INC}}$$

cross-section: SEE

SEE experimental cross-section



A : area of device exposed to beam

σ_{bit} : Cross-section of each sensitive volume

N_s : number of sensitive volumes in area A

Total sensitive area exposed to beam: $\sigma \times N_s$

fraction of incident particles that cause SEE **N_{SEE}/N_{inc}**

is equal to the

fraction of exposed area that is sensitive

$$\frac{N_{SEE}}{N_{inc}} = \frac{N_s \cdot \sigma_{bit}}{A} \Rightarrow \text{number of events} \quad N_{SEE} = N_s \frac{N_{inc}}{A} \sigma_{bit} = N_s \cdot \sigma_{bit} \cdot \Phi_{inc}$$

Experimentally:

$$\sigma_{bit} = \frac{N_{SEE}}{N_S \cdot \Phi_{INC}} \qquad \sigma_{device} = N_s \cdot \sigma_{device} = \frac{N_{SEE}}{\Phi_{INC}}$$

PART 3:
Particle interactions

1) Ionizing energy loss

2) Non-ionizing energy loss

Ionizing radiation, such as x-rays, gammas, and all charged particles create free charge in materials, which affects properties and performance.

Particles (neutrons, pions, protons, ions, even electrons) can displace atoms from their usual lattice sites and produce "bulk" damage effects.

basic particle interactions with matter

Charged particles (protons, ions, electrons, muons, charged pions, kaons,...):

- COULOMB INTERACTIONS with electrons (ionization), and nuclei (atomic displacement)
- NUCLEAR INTERACTIONS (mainly for energetic hadrons: protons, pions, kaons).
- DECELERATION of CHARGED PARTICLE causes photon emission (Bremsstrahlung) with continuous spectra (mainly for electrons)

Neutrons:

- Neutron capture/spallation/inelastic scattering: formation of excited composite nucleus followed by de-excitation and emission of γ-rays, particles (α, $\beta^{+/-}$, n, p) and nuclear fragments
- Elastic scattering with nuclei (atomic displacement)
- ionization can be induced by secondary charged particles.

Photons:

- photoelectric effect
- Compton effect

} → produce secondary electrons/positrons

- pair production (see picture) → produces secondary electrons and positrons

Change of focus

- electrons, photons (X-rays, gamma).

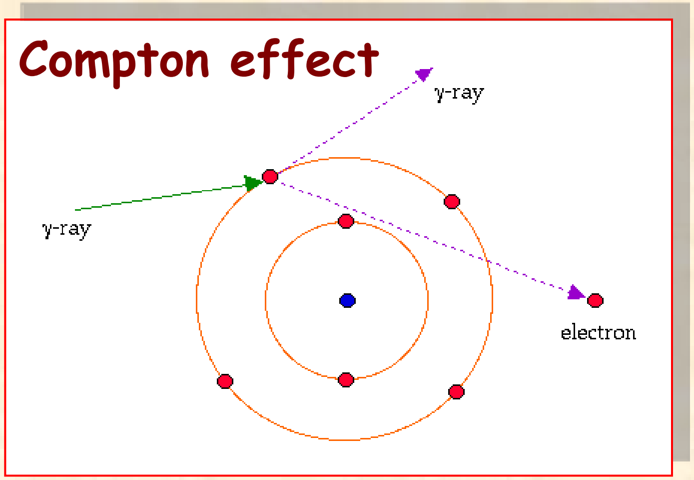
- **Ionization** (interaction with electrons of material). For photons it is described by dose, for electrons by ionizing stopping power.
- Note: high energy electrons also cause atomic displacement.
- gammas too… (1 MeV gammas create point-defects)

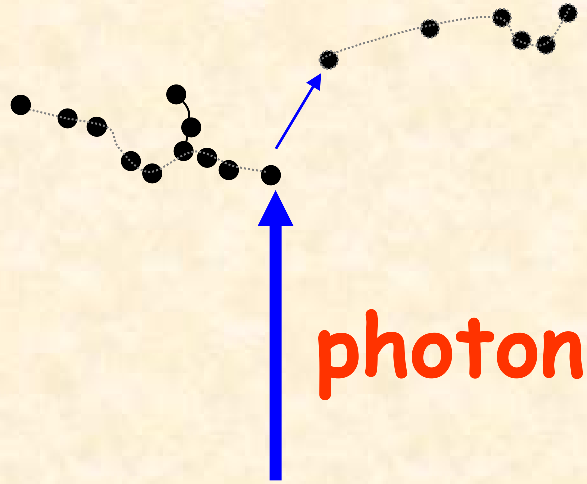
- n, p, $\pi^{\pm}$, K, α, heavy ions

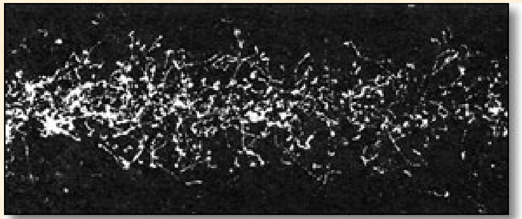
- **Ionization,** when primary is charged. It is described by the ionizing stopping power. Ionization also occurs when charged secondaries are produced by hard coulomb or nuclear interactions with nucleus.
- **atomic displacement** due to (coulombic, nuclear interactions) with atomic nuclei of material. Described **Non-Ionizing Energy Loss (NIEL)**
- **nuclear reactions**: nucleus breaks up into various fragments; point defects in silicon lattice by neutrons $n + {}^{30}Si \rightarrow {}^{31}P + e^- + \underline{\nu}$
- **Pattern of atomic displacement damage** depends on particle type and energy. Significant differences between ions, neutrons, protons and pions.

Ionization

Ionizing Radiation hazard sign

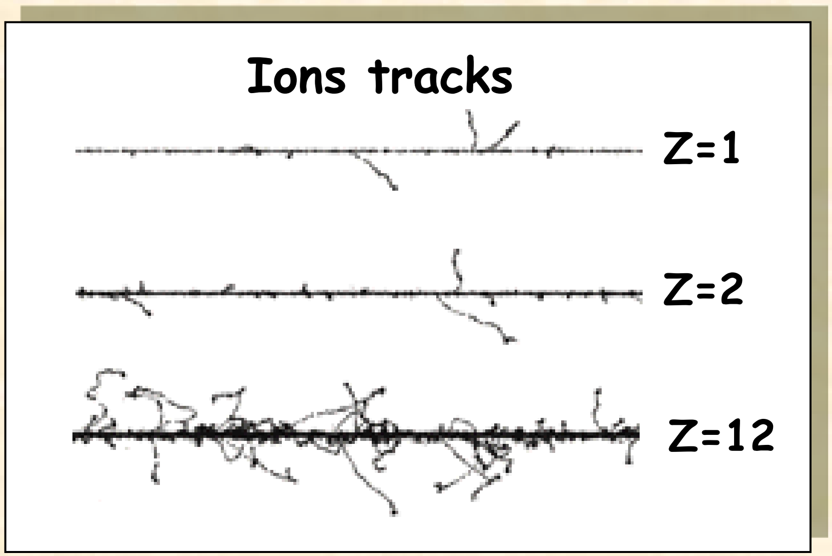




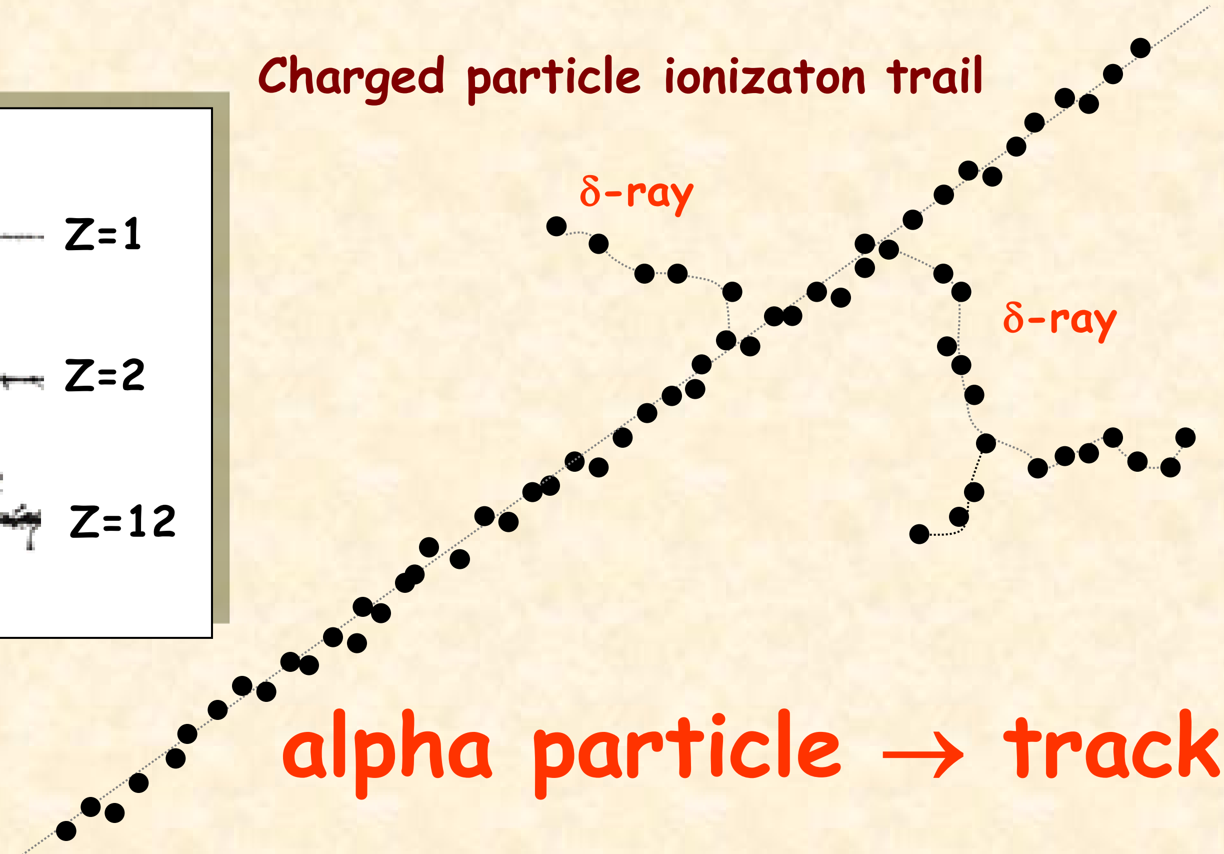


Photograph of a typical X-ray cloud. Condensation on the ions appears in white.

photon → no track



Charged particle ionizaton trail



alpha particle → track

Ionization …

… is ultimately associated with transfer of kinetic energy from incident particle to the bound electrons of the material substance.

- In the case of charged particles (electrons, protons, alfa, ions, muons, pions, …), ionization is caused DIRECTLY through the coulombic interaction with the electrons of the substance.

- In the case of neutral particles (photons, neutrons,…), ionization is mainly INDIRECT by the release of an energetic charged particle within the substance.

- photons: ionization is mainly the result of the transfer of photon energy to a bound electron providing sufficient kinetic energy to detach the electron from the atom. If the electron is energetic enough, it too can further ionize.

- neutrons: ionization is through a nuclear interaction event in which a recoiling nucleus of energetic charged particle nuclear reaction products are agents of ionization.

Dose=energy/mass

Ionization dose

international units

1 Gy = 1 J/kg = 100 rad

= 6.25×10^{18} eV/kg

Dose

international units

1 Gy = 1 J/kg = 6.25×10^{18} eV/kg

How many electron-hole pairs are produced?

In Silicon (ρ=2.33 g/cm^3, band gap = 1.125 eV) the average energy leading to creation of electron-hole pair 3.6 eV.

A dose of 1 Gy generates in silicon

6.25×10^{18}/ 3.6 = 1.7×10^{18} e-h pairs/kg

that is 4×10^{15} e-h pairs/cm^3

In SiO_2 (ρ=2.19 g/cm^3, band gap = 9 eV) the average energy leading to creation of electron-hole pair 17 eV.

A dose of 1 Gy generates in SiO_2

6.25×10^{18}/ 18 = 3.5×10^{17} e-h pairs/kg

that is 8×10^{14} e-h pairs/cm^3

Dose

international units

1 Gy = 1 J/kg = 6.25 × 10^{18} eV/kg

skip

$$\frac{\#\,pairs}{Gy-cm^3}=\left(\frac{\#\,pairs}{eV}\right)\left(\frac{1eV}{1.6\times10^{-19}\,J}\right)\left(\frac{1J}{Gy-kg}\right)\left(\rho(g/cm^3)\times\frac{1kg}{10^3\,g}\right)$$

Silicon:

$$\frac{1}{3.6}\times\frac{1}{1.6\times10^{-19}}\times\frac{2.33}{1000}=4\times10^{15}\,\frac{pairs}{cm^3-Gy}$$

SiO_2:

$$\frac{1}{17}\times\frac{1}{1.6\times10^{-19}}\times\frac{2.19}{1000}=8\times10^{14}\,\frac{pairs}{cm^3-Gy}$$

Dose for particles (not photons)

ways a particle can transfer (deposit) energy to medium:

1. ionising energy loss → total ionising dose (TID)
2. non-ionising energy loss (NIEL) → displacement damage dose (DDD)

Dose concept = energy deposited into a block of matter of a certain mass

- generic DOSE $= \dfrac{\text{energy imparted by radiation}}{\text{mass of target}}$
- dose scales with fluence ϕ

dose (energy/mass) $\propto$ fluence(length^{-2})

dose (energy/mass) = proportionality factor (energy-length^2/mass) $\times$ fluence(length^{-2})

DOSES for particles (not photons)

TID, DDD ⇒ factors: LET, NIEL

dose (energy/mass) = factor(energy-length²/mass) × fluence(length⁻²)

$$\text{dose (energy/mass)} = \text{factor}(\text{energy-length}^2/\text{mass}) \times \text{fluence}(\text{length}^{-2})$$

Total Ionising DOSE (TID) $= \dfrac{\text{energy to ionisation}}{\text{mass}} = \text{LET} \times \phi$

Displacement Damage DOSE (DDD) $= \dfrac{\text{energy to displacements}}{\text{mass}} = \text{NIEL} \times \phi$

Energy deposited into a block of matter of a certain mass:

energy to ionization = **LET(energy-length^2/mass)** × **fluence(length^{-2})** × **mass**

energy to displacements = **NIEL(energy-length^2/mass)** × **fluence(length^{-2})** × **mass**

N.B. Typically
LET and NIEL expressed in MeV-cm^2/mg

↓

Energy in MeV deposited into a block of matter of a certain mass in grams:

energy to ionisation (MeV) = **LET(MeV-cm^2/mg)** × **ϕ(cm^{-2})** × mass(g) × 10^3

energy to displacements (MeV) = **NIEL(MeV-cm^2/mg)** × **ϕ(cm^{-2})** × mass(g) × 10^3

GLOSSARY

Dose, absorbed dose, NIEL, dose equivalent:

Dose is a quantity of radiation delivered locally; i.e. at a given position. It usually refers to the energy absorbed locally per unit mass as a result of exposure to radiation.

The fraction of the total energy absorption that results in ionization and excitation is referred to as ***absorbed (ionization) dose***.

The fraction of the total energy absorption that results in damage to the lattice structure of solids through displacement of atoms is referred to as ***Non-Ionizing Energy Loss***.

Dose equivalent refers to a quantity applied to biological effects. It includes scaling factors to account for the more severe effects of certain kinds of radiation.

Stopping power

International Commission on Radiation Units and Measurements (ICRU)

For a charged particle (make tracks), the "**average energy loss**" is characterized by:

- **stopping power $S = dE/dx$ (keV/μm): the average energy loss per unit path length of particle in traversing a material**

Results from coulomb interactions (*):

1. with electrons $S_{ele} = (dE/dx)_{ele}$
2. with atomic nuclei $S_{nuc} = (dE/dx)_{nuc}$

Warning! Electrons also radiate photons!

- **mass stopping power**

$$(1/\rho)S = \text{LET} + \text{NIEL}_{\text{coulomb}(*)} \quad (\text{MeV-cm}^2/\text{mg})$$

density

(*) Note: rare nuclear (non-coulombic) interactions are not considered.

GLOSSARY

Linear Energy Transfer (LET):

The rate of energy deposit from a slowing energetic particle with distance travelled in matter, the energy being imparted to the material.

Normally used to describe the ionization track caused by passage of an ion. LET is material-dependent and is also a function of particle energy.

For ions of concern in space radiation effects, it increases with decreasing energy (it also increases at high energies, beyond the *minimum ionizing* energy).

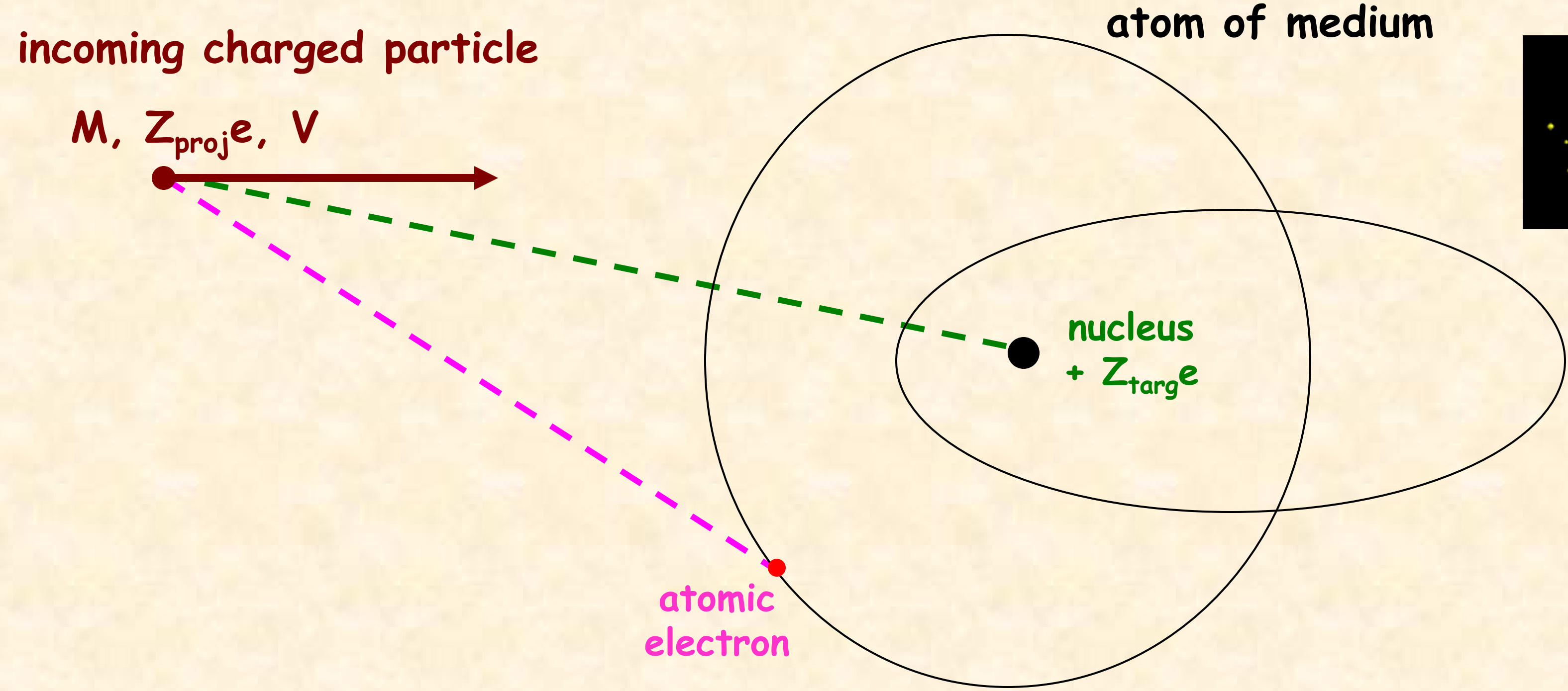
LET allows different ions to be considered together by simply representing the ion environment as the summation of the fluxes of all ions as functions of their LETs. This simplifies Single Event Effects calculations.

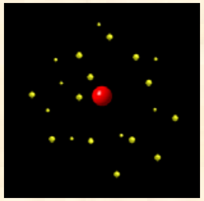
The total rate of energy loss of a particle, which also includes non-ionizing energy lass and emitted secondary radiation, is the *stopping power*.

ionisation

A charged particle travelling thru a medium

Coulomb interaction with atomic electrons or with the nucleus:





Ratio of effective areas (cross-sections) gives relative probability of interactions to occur.

- the radius of nucleus $R_{nucleus} \sim 10^{-14}$ m
- the radius of atom $R_{atom} \sim 10^{-10}$ m

$$\frac{\text{number of interactions with electrons}}{\text{number of interactions with nuclei}} = \frac{R_{atom}^2}{R_{nucleus}^2} \approx 10^8$$

Conclusion: regards energy transfers, coulomb collisions with electrons are much more important than with nuclei (except when very SLOW at end of range!)

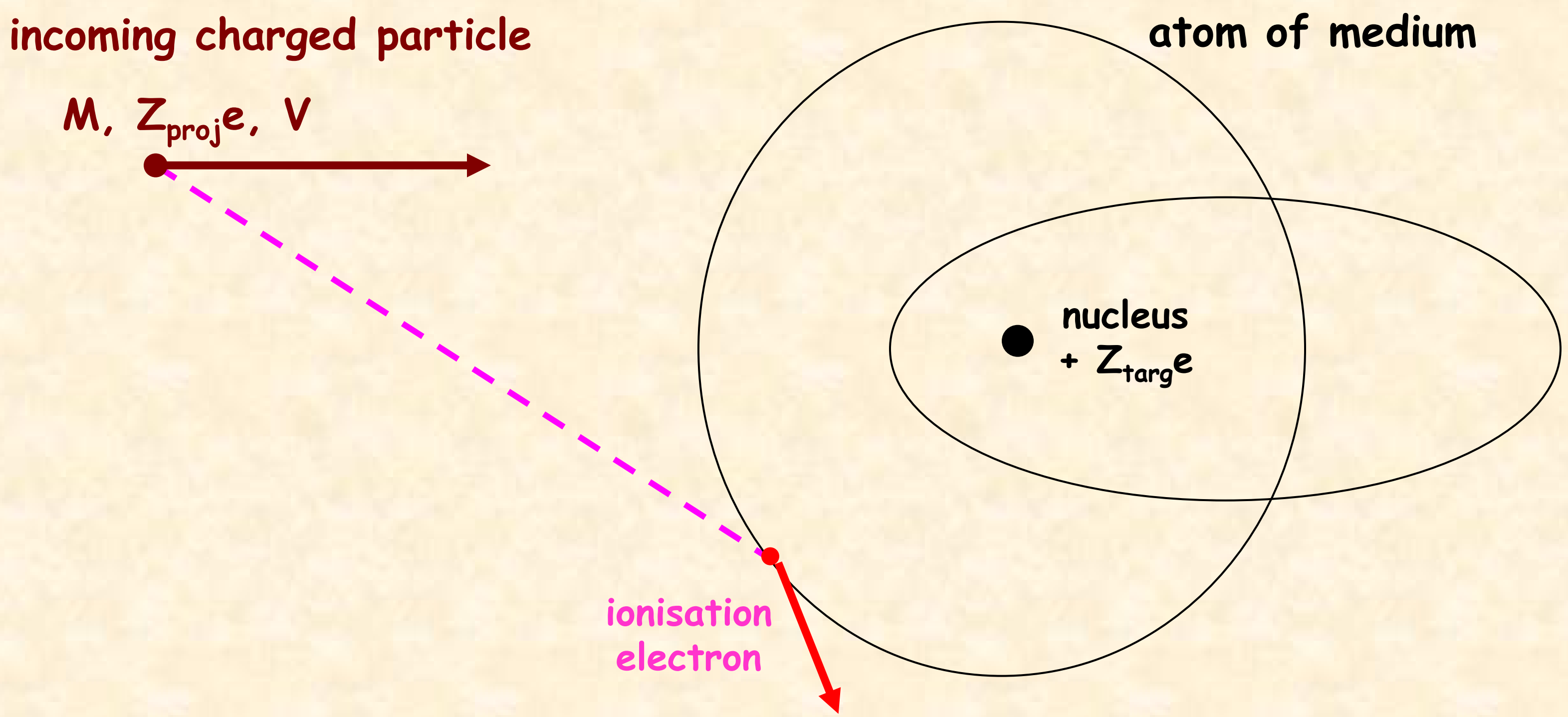
ionisation

Action of coulomb force, over a period of time (transit time)

transfer of momentum and energy to the bound electron
***might* result in ionisation or excitation (inelastic collisions).**
(in elastic collisions particle loses energy to conserve momentum and KE)

IONISATION: $KE_{electron}$ = energy given by particle - ionisation potential
The freed electron will also interact; i.e. it will ionise and excite, lose KE and stop.
Fast secondary electrons are called *delta-rays.*

EXCITATION: ... X-rays by de-excitation,…



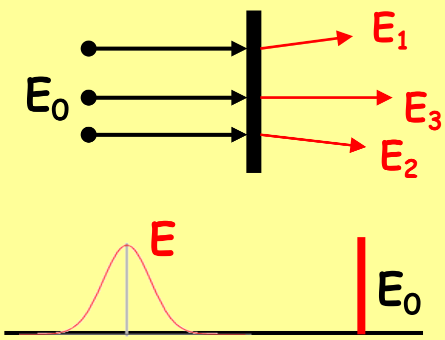
ionisation

HEAVY charged particles (muon, p, α, ions,...)

Moving thru medium they exert coulomb forces on many atoms simultaneously

- each atom of medium has many electrons;
- the atomic electrons have different depths inside atom hence different excitation and ionisation potentials;
- each interaction and associated energy transfer has own probability of occurrence

mean free path $\lambda \sim 1$ Å $\Rightarrow$ NO particle get thru a macroscopic slab without interacting and losing some energy!



Note: it is senseless/impossible to calculate energy loss by studying individual interactions

$\Rightarrow$ Must calculate mean residual energy of incident particle per unit distance travelled.

$$E = E_0 - \sum_i \Delta E_i = E_0 - \sum_i \left(\frac{\Delta E}{\Delta x}\right)_i \Delta x_i = E_0 - \int \left(\frac{dE}{dx}\right) dx$$

ionisation

HEAVY charged particles (muon, p, α, ions,...)

Will lose small amounts of energy per coulomb collision:

- are hardly deflected by atomic electrons
- do get slightly deflected by interactions with nuclei (multiple scattering)
- important deflections are very rare rutherford-like hard interactions

⇒ the overall trajectory is almost a straight line!!!

$$range = \int \left[\frac{dE}{dx} \right]_{total}^{-1} dE$$

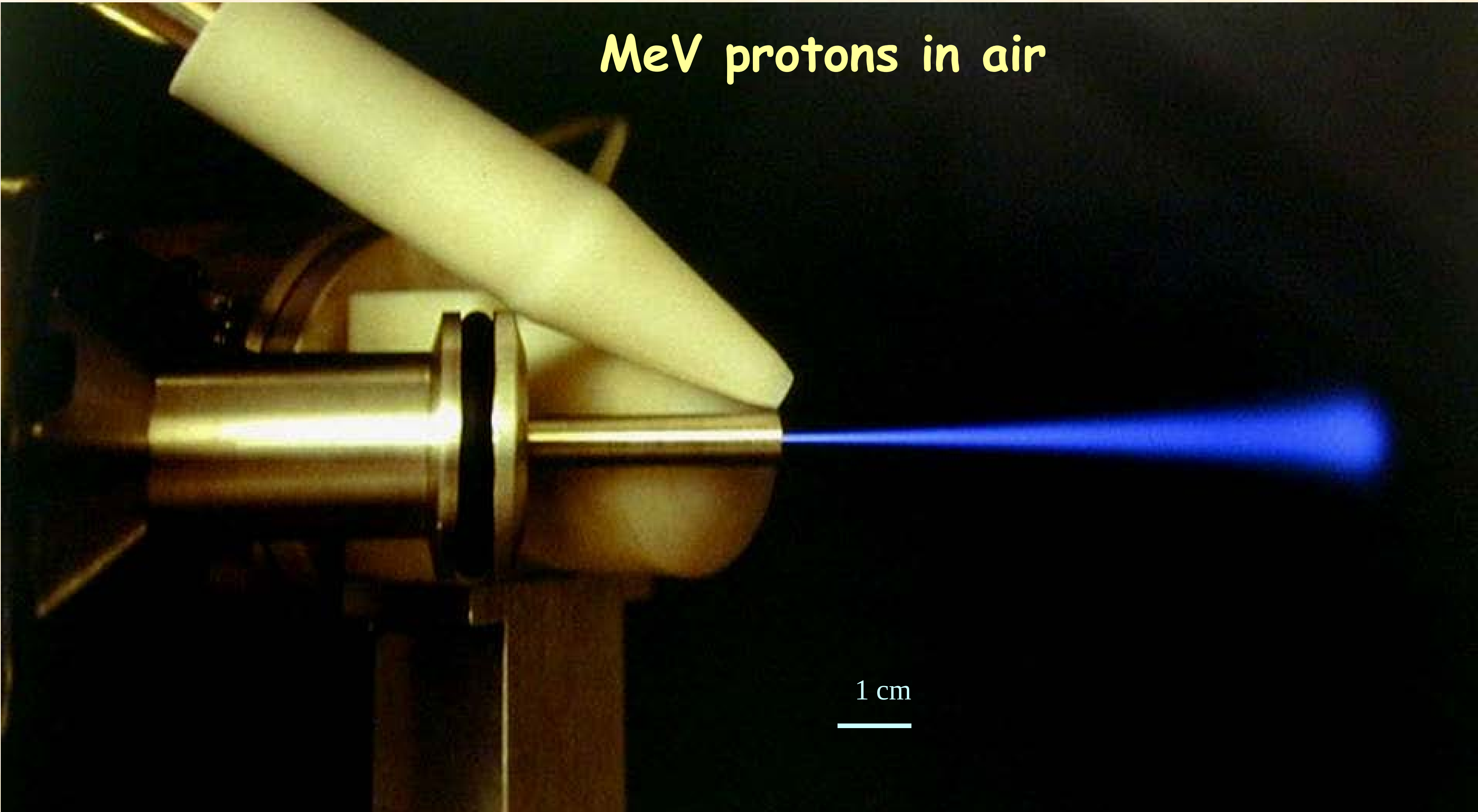
thickness of medium for which kinetic energy of incident particle is spent
WELL DEFINED

TOTAL stopping power **dE/dx**

$$dE/dx = dE/dx_{ionization} + dE/dx_{nuclear\ coulomb}$$

NOTE: both change along track as particle slows down till the ion is so slow as to be "harmless"

ionisation



WARNING

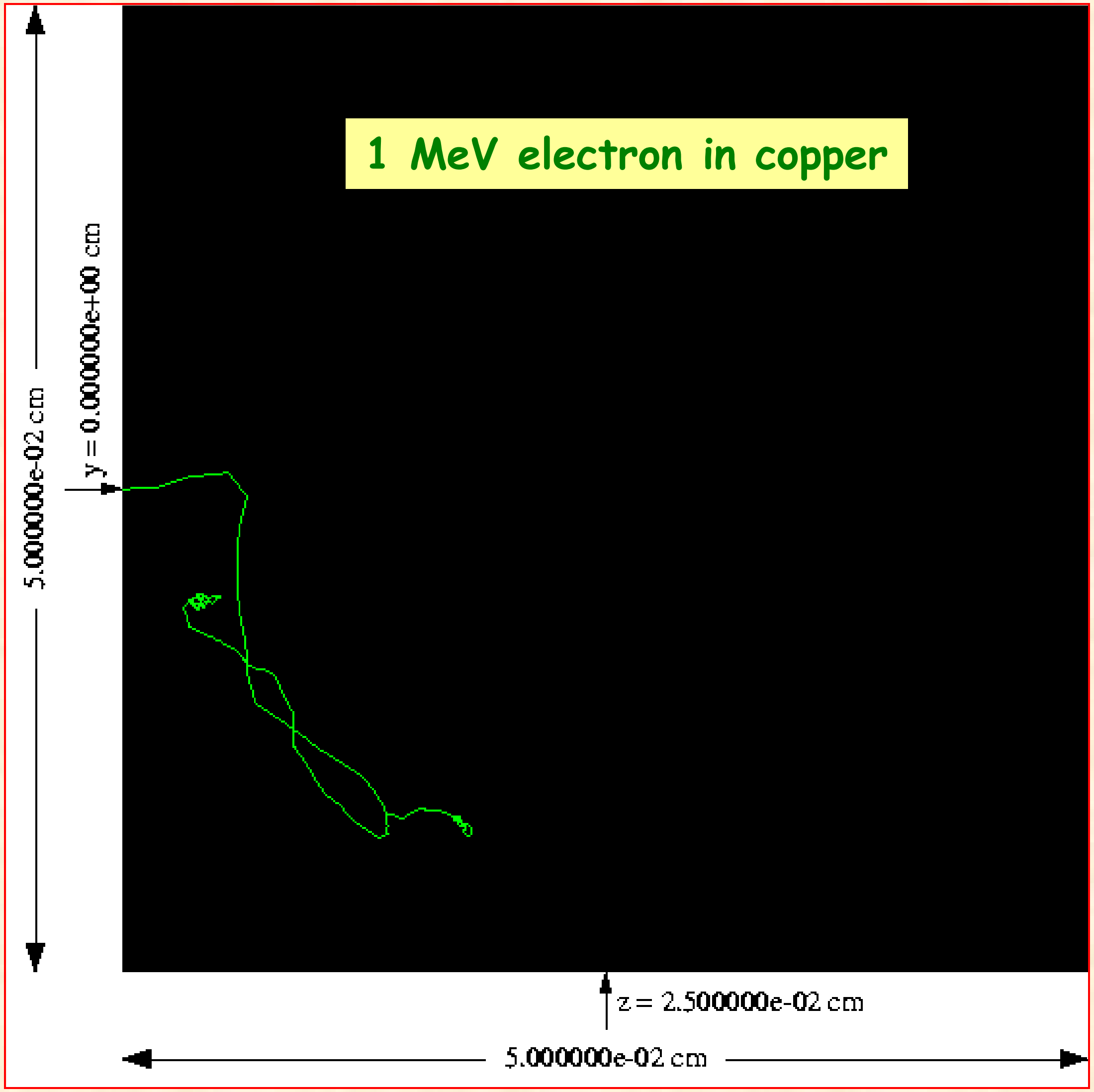
an electron (positron) projectile will behave quite differently:

- an incident electron may collide with an atomic electron and **lose ALL its energy in a single collision (billiard ball effect)!**
- **IN GENERAL: incident electrons and positrons may lose a large fraction of their kinetic energy in any one collision**
- are easily scattered to large angles hence their **trajectories are VERY ZIG-ZAG**

electron

EGS to order

http://www.slac.stanford.edu/~rfc/egs/basicsimtool.html

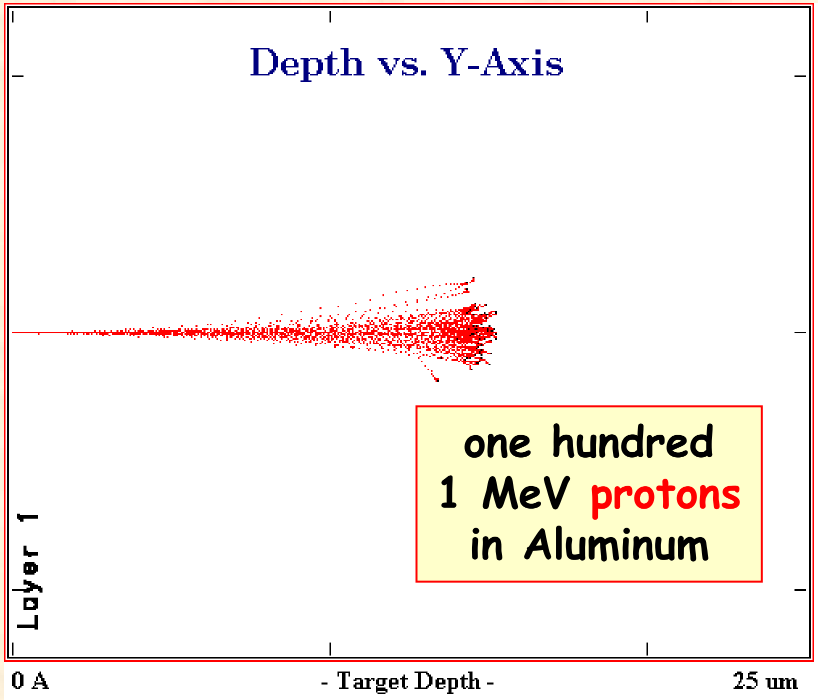


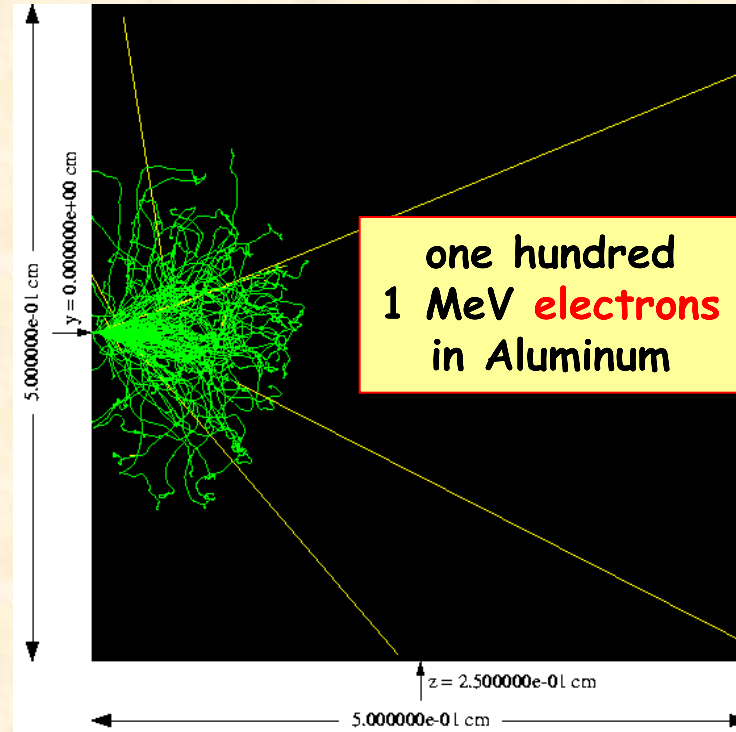
path very zig-zag!

0.5 mm by 0.5 mm

Range

range not well defined for electrons

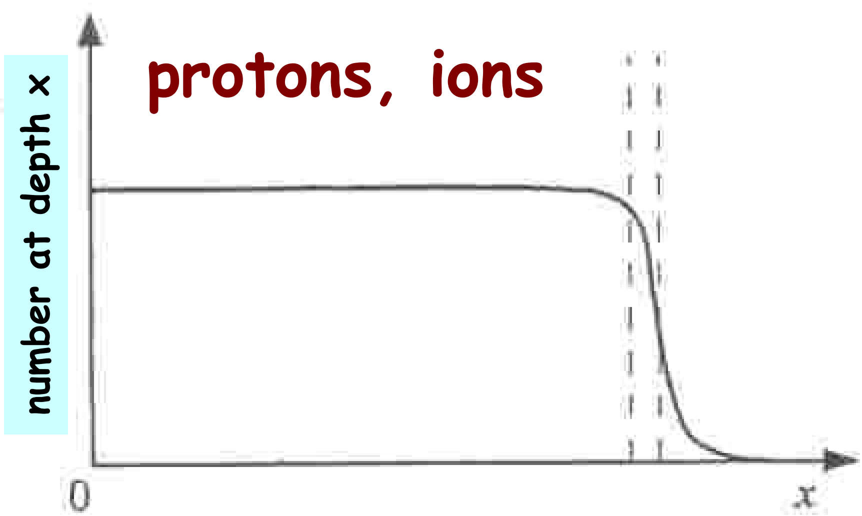


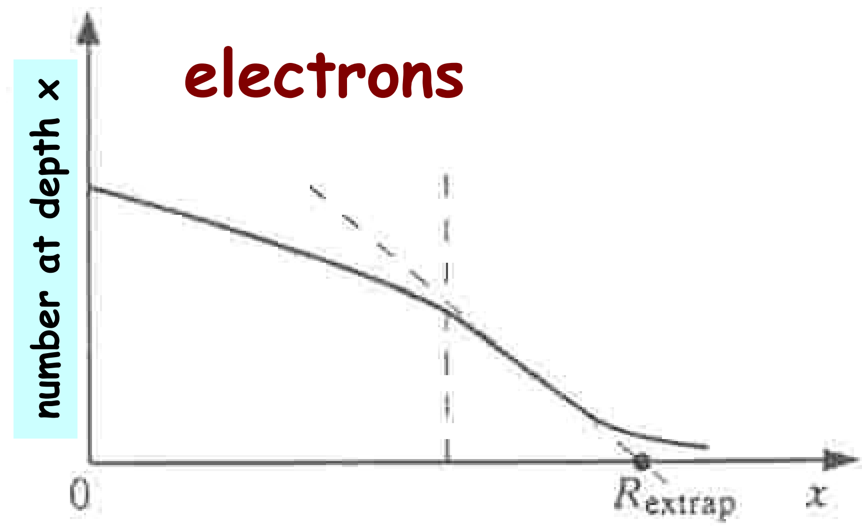


electrons in green

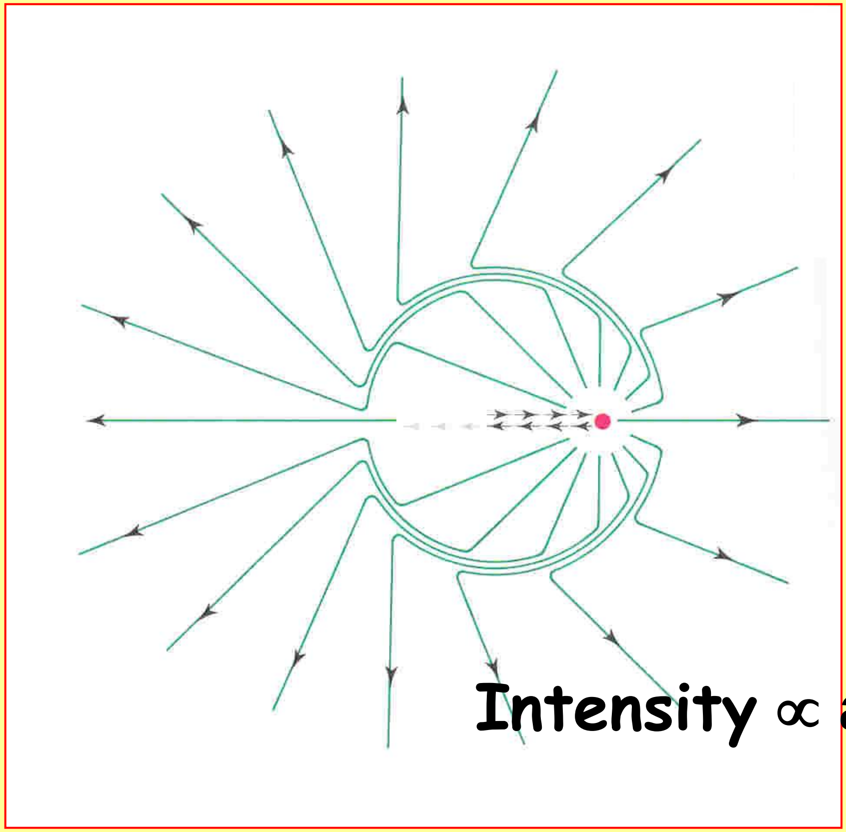
photons in yellow

5 mm by 5 mm





An accelerated charge will radiate!



classical EM theory
Intensity $\propto a^2$
Newton $\Rightarrow a = F/m$

$$\text{Intensity} \propto a^2 \sim \left\{ \frac{Z_{proj}\, Z_{targ}\, e^2}{M_{proj}} \right\}^2 \sim \frac{Z_{proj}^2\, Z_{targ}^2}{M_{proj}^2}$$

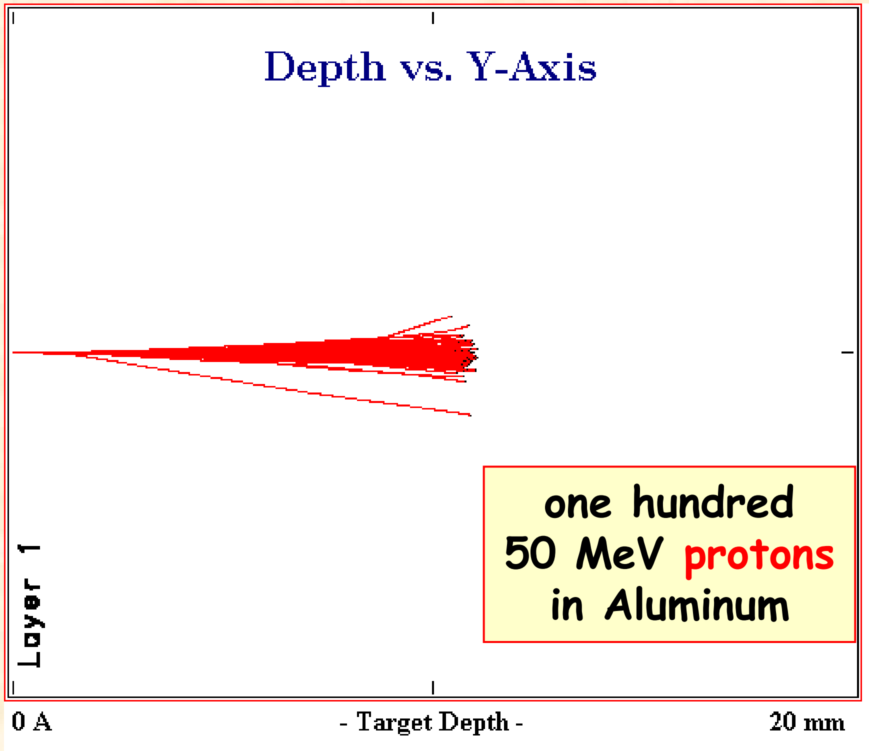
Non-relativistic

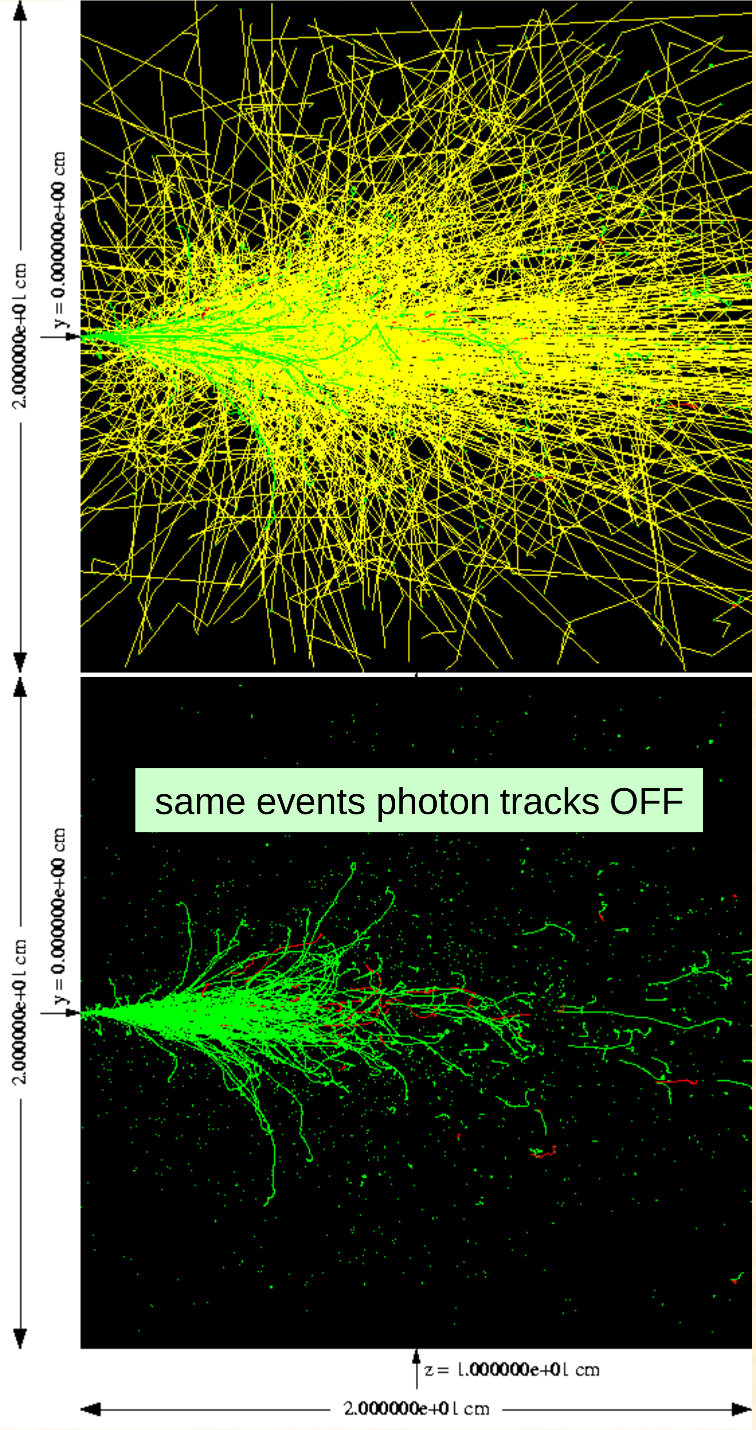
especially electrons!

irradiation

Energetic electrons lose energy also by emitting photons

one hundred
50 MeV electrons
in Aluminum





GLOSSARY

Bremsstrahlung:

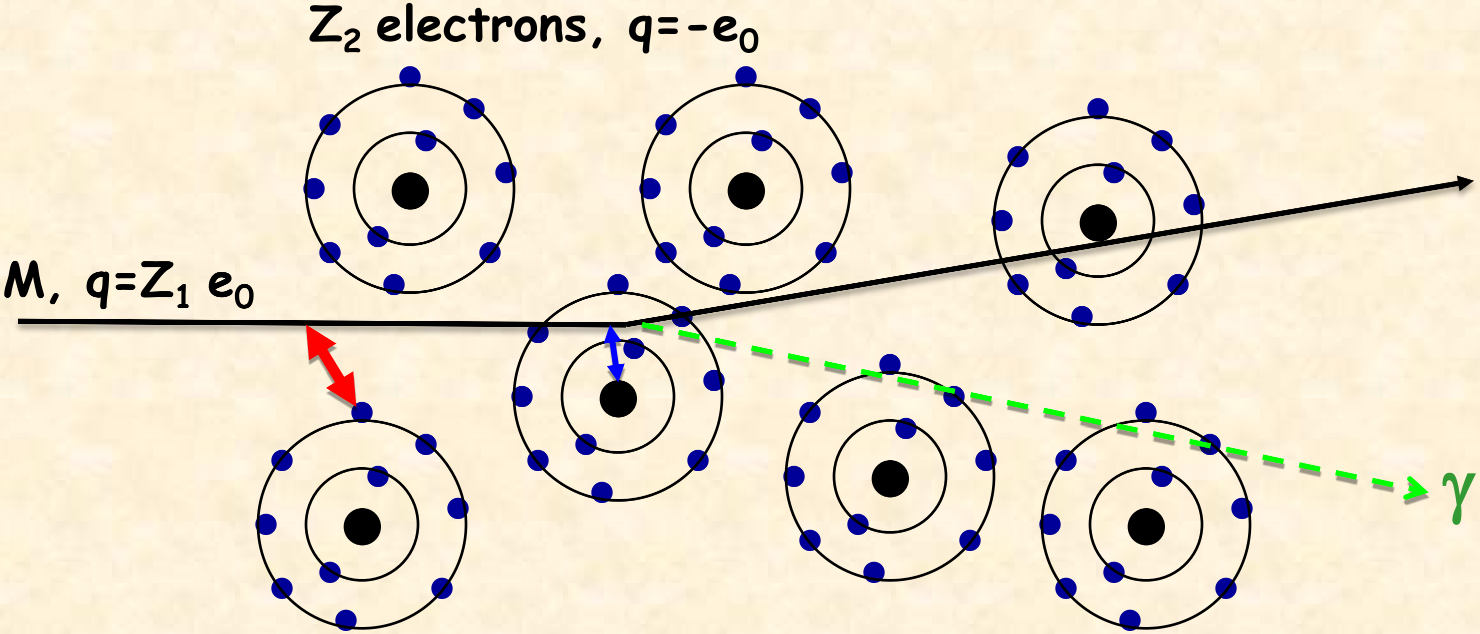
High-energy electromagnetic radiation in the X and *gamma* energy range that is emitted by charged particles as they slow down when they scatter off atomic nuclei.

Although the primary particle might ultimately be absorbed, the *bremsstrahlung* radiation can be highly penetrating.

The most common source of bremsstrahlung is electron scattering.

summary

Electromagnetic Interaction (coulombic) of Particles with Matter



Heavy charged particle:
Many interactions with the atomic electrons. The incoming "continuously" particle looses energy and the atoms are <u>excited</u> or <u>ionized.</u>

Interaction with the atomic nucleus. The particle is significantly deflected by numerous soft scatterings (multiple scattering) or and occasional rare single hard Rutherford scatterings.

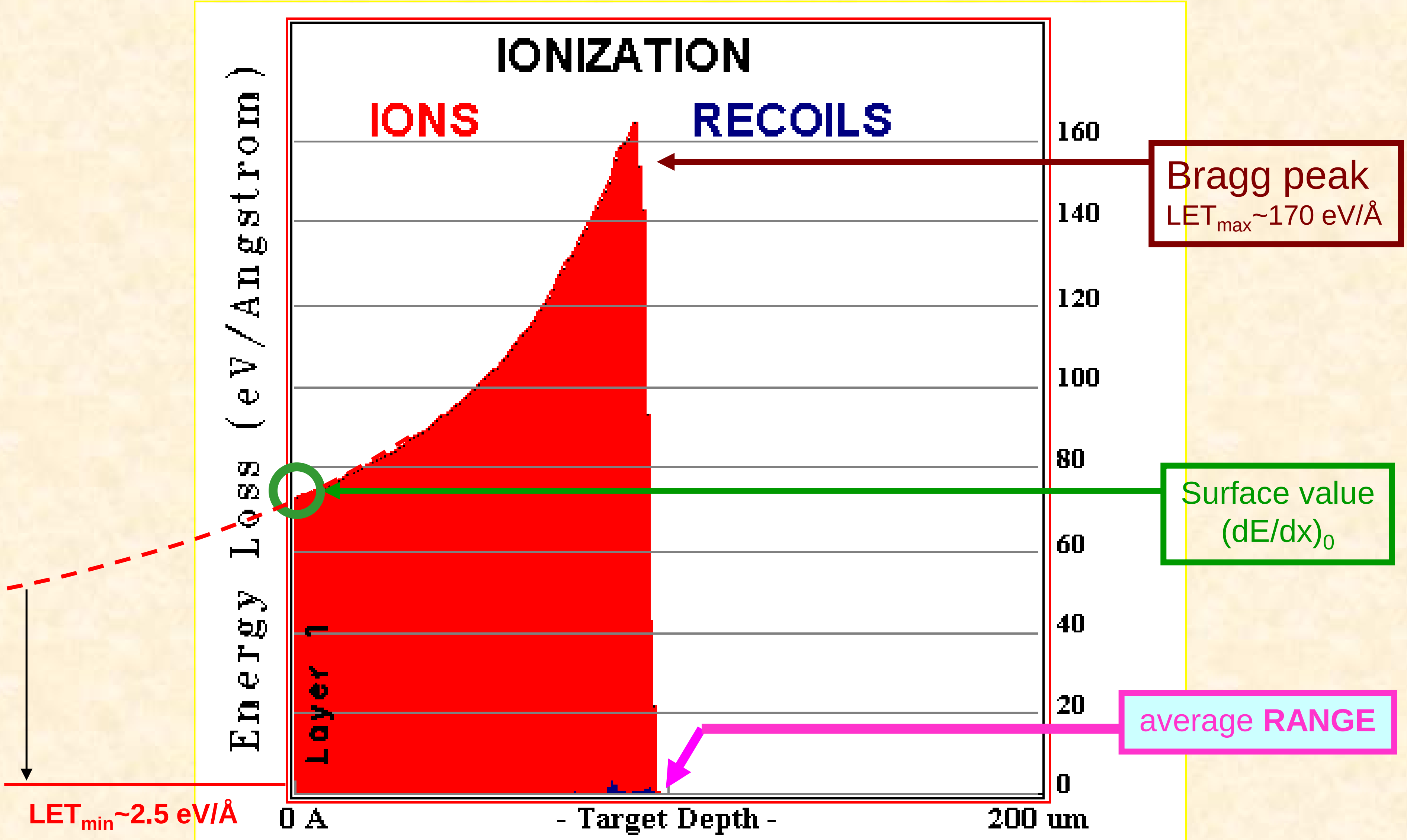
If the incident particle is an electron then the electron can lose a lot o energy in just one collision with an atomic electron or by emitting <u>Bremsstrahlung</u> photons.

Heavy particles (not electrons) … especially ions

- LET versus depth
- Surface LET
- Bragg peak
- Range
- Bethe-Bloch electronic stopping power for heavy ions
- stripping, effective charge

ionisation

$(dE/dx)_{ionization}$ vs depth of material

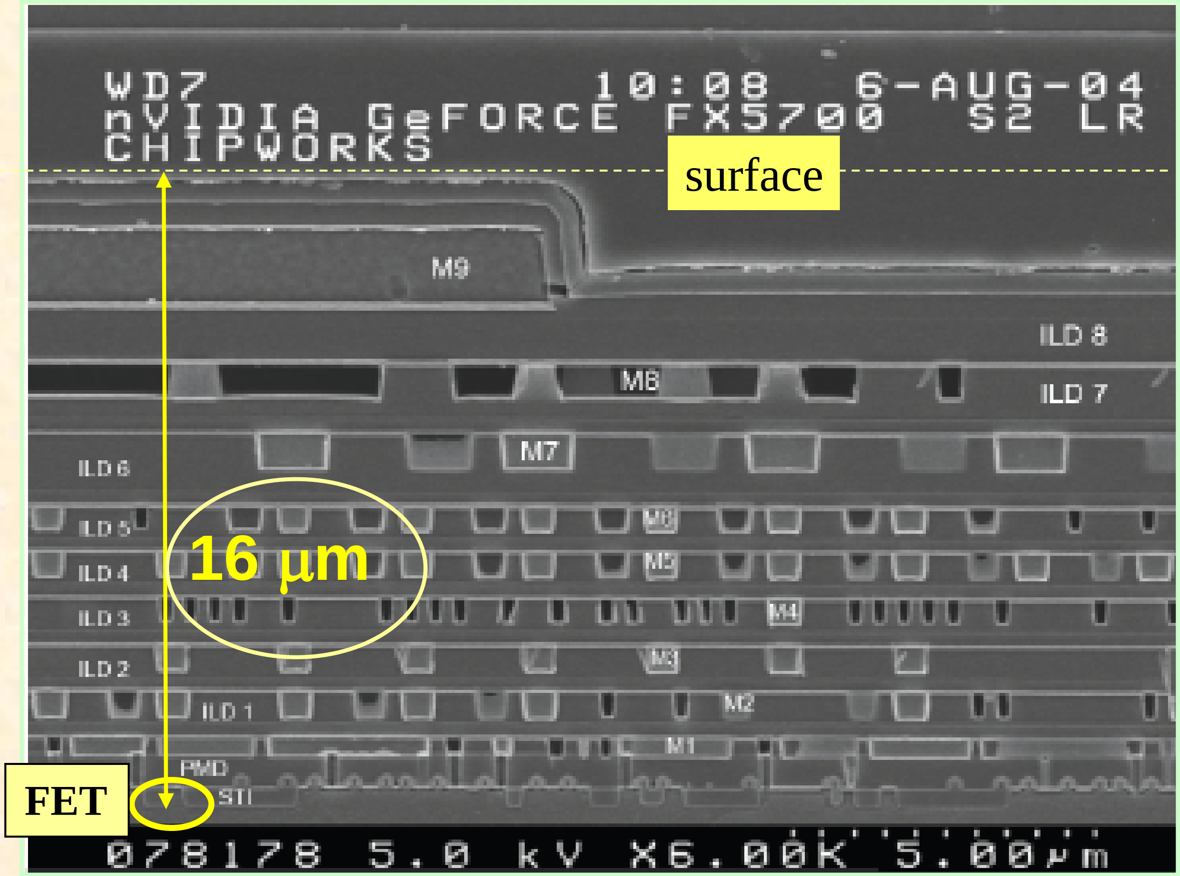


SRIM simulation (http://www.srim.org).

Dead superficial layers are an experimental problem for some types of devices.

- Ions must have sufficient energy to penetrate overlayers
- need to evaluate LET at the correct depth

Section of a chip (courtesy Doyle)



Sensitive volume is down here!

ionisation

Bethe-Bloch … for heavy ions

$\beta = V/c$

$$\left(\frac{dE}{dx}\right)_{ele} = \left(\frac{Z_{eff}^2}{V^2}\right)_{particle} \times \left(\frac{z\rho}{A}\right)_{material} \times \left\{ \ln\left(\frac{2m_e c^2 \beta^2}{I}\right) - \ln(1-\beta^2) - \beta^2 - \delta \right\}$$

I = mean excitation potential of target material; for Silicon I ≈ 170 eV

- **for velocity of ion $V \gg v_{Bethe} = v_0 Z^{2/3}$** **where $v_0 = c/137 = v_{Bohr}$**

  ion completely stripped of electrons, full nuclear charge, $Z_{eff} \sim Z$

- **for velocity of ion $V \approx v_{Bethe}$** and slower

  ion retains/picks-up electrons and charge decreases(!) as ion slows

$Z_{eff}(V) = \eta(V) \times Z$

$\eta(V) = 1 - A \exp(-B\, V/v_{Bethe})$

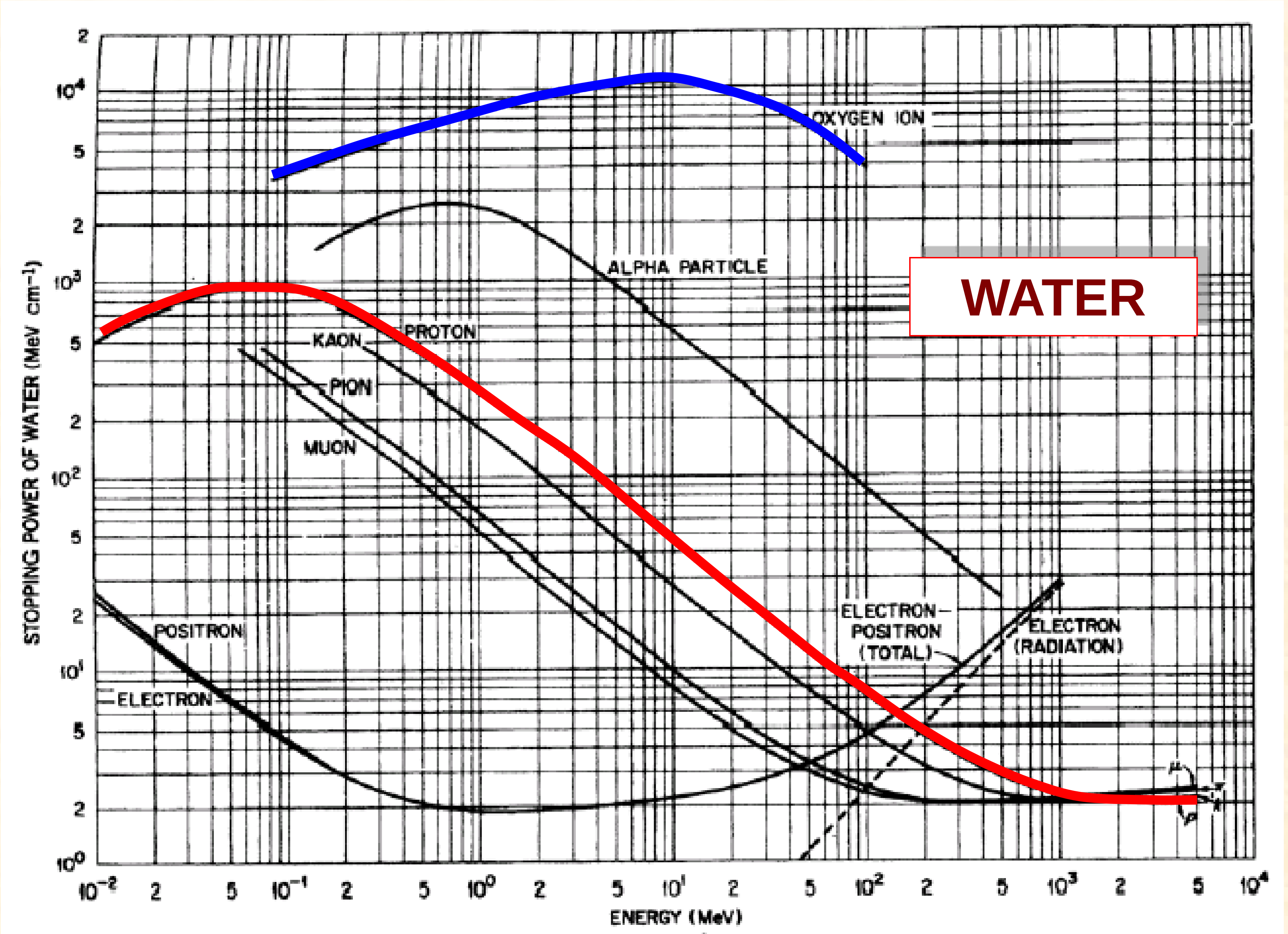
good to a few percent
A =1
B = 0.95

$$\left(\frac{dE}{dx}\right)_{ele} \approx \rho \times Z^2 \times F(V) = \rho \times \frac{Z^2}{\beta^2} \times f(V)$$

$$LET = \frac{\left(dE/dx\right)_{ele}}{\rho} \approx \frac{Z^2}{\beta^2} \times f(V)$$

Silicon: ρ = 2.33 g/cm³

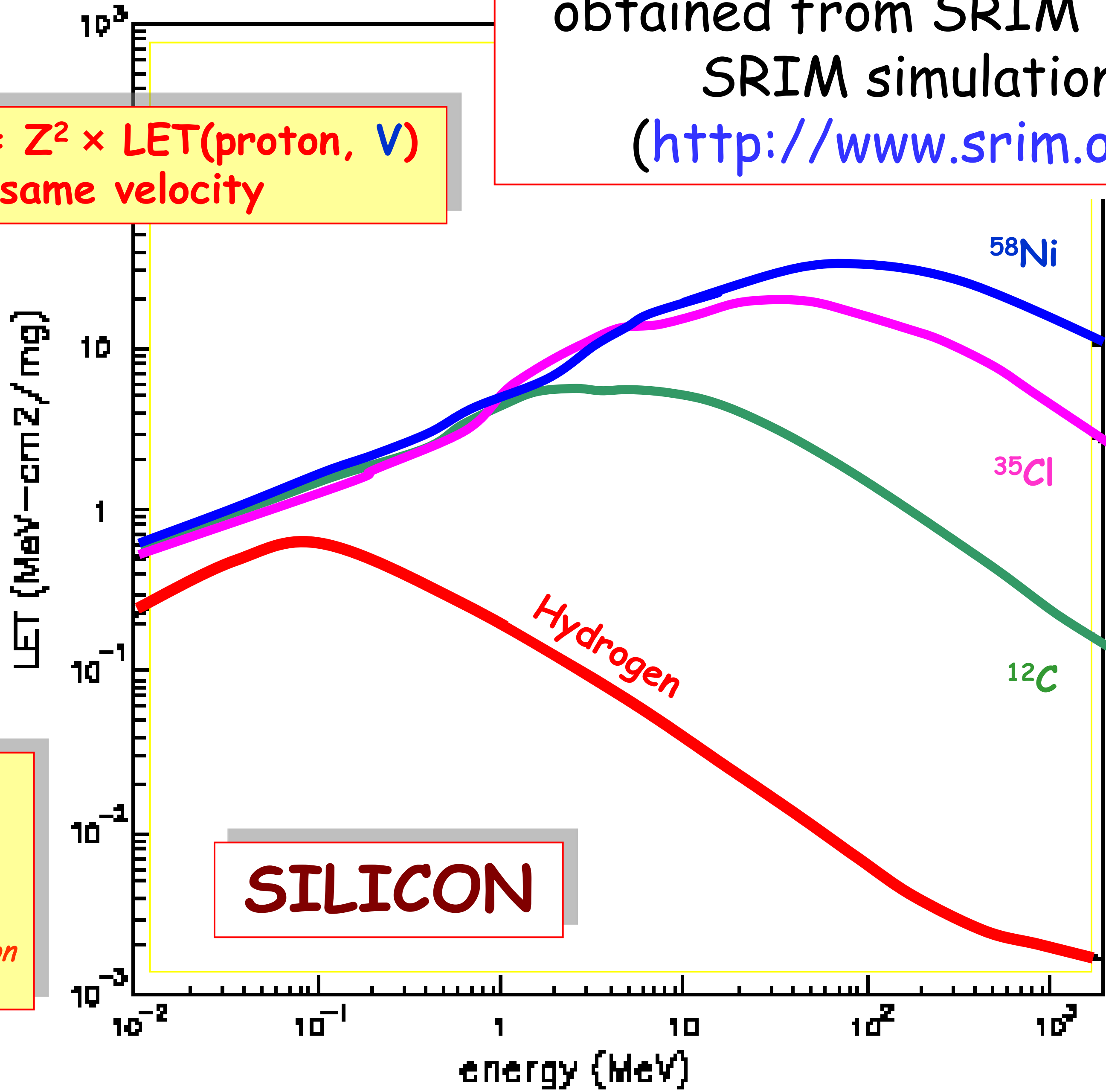
Ionizing stopping power $(dE/dx)_{ele}$ in MeV/cm



LET

LET(Z, V) = Z^2 × LET(proton, V)
for same velocity

obtained from SRIM Tables
SRIM simulation
(http://www.srim.org)

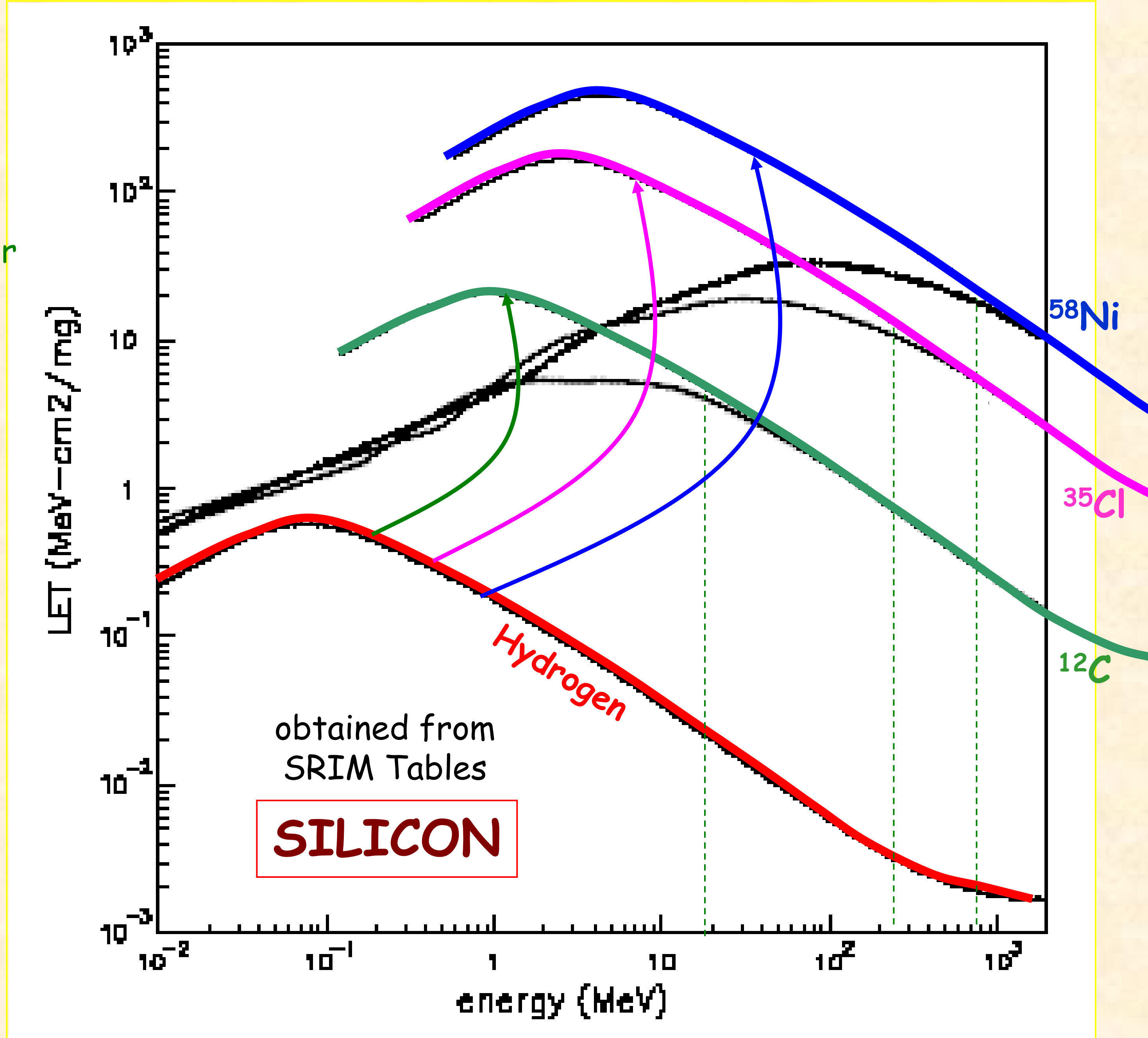


Non-Relativistic approx.
$K = 1/2\ Mv^2$,
$M_{ion} \approx A \times m_{proton}$
⇒ *ion has same V of a proton for* $K = A\ K_{proton}$

LET

For full stripping (*naked nuclear charge Z*) can scale proton curve to any ion:

NOTE:
for $V = v_0 Z^{2/3}$
$Z_{eff} \approx 60\%$ of Z.
Dashed lines are at kinetic energy E for $Z_{eff} \approx 90\%$ of Z.



LET

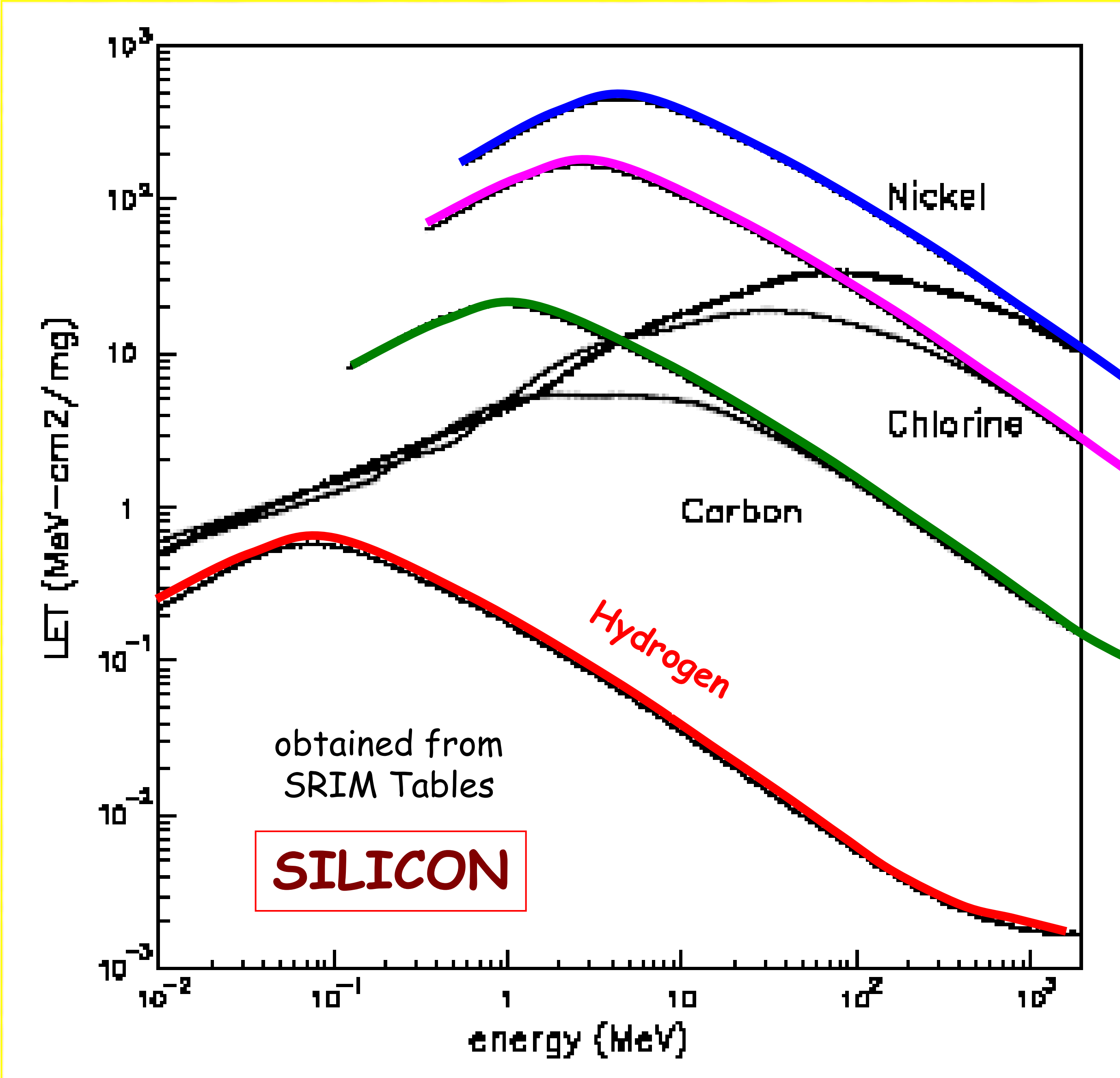
For **full stripping** (*naked nuclear charge Z)* can scale proton curve to any ion:

minimum of ionization
obtained for
$\beta\gamma \approx 3$ (Relativistic!),
i.e. for
$E_{min} \approx 2$ GeV/amu

$$\frac{LET_{min}(Z)}{LET_{min}(proton)} = Z^2$$

$LET_{min}(proton)$ =
1.665 × 10^{-3} MeV-cm²/mg =
= 0.0386 eV/Å

$LET_{min}(Nickel, Z=28)$ =
1.3 MeV-cm²/mg

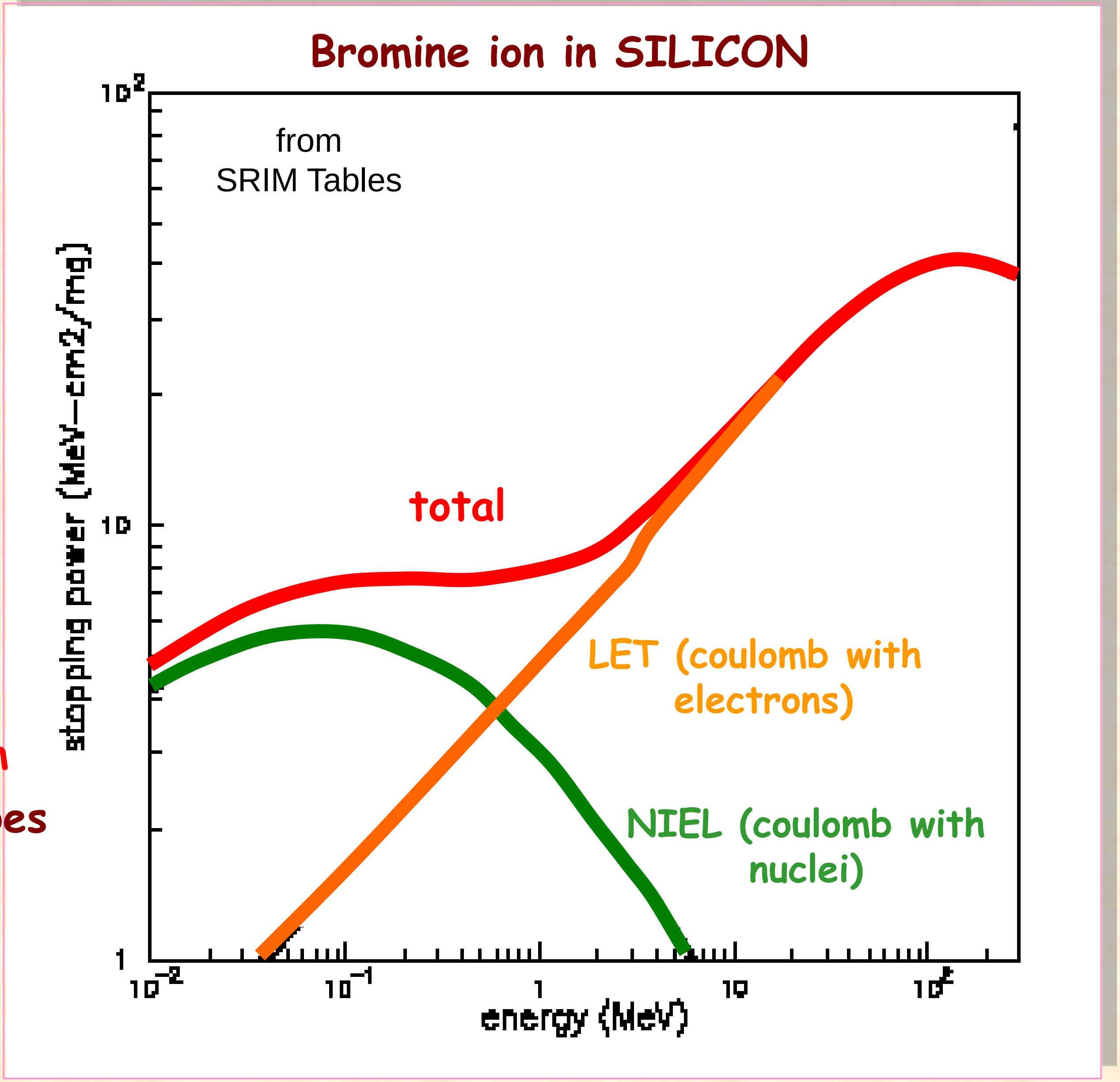


Stopping power

total mass stopping power:

$(1/\rho)\ S = \mathrm{LET} + \mathrm{NIEL}_{coulombic}$

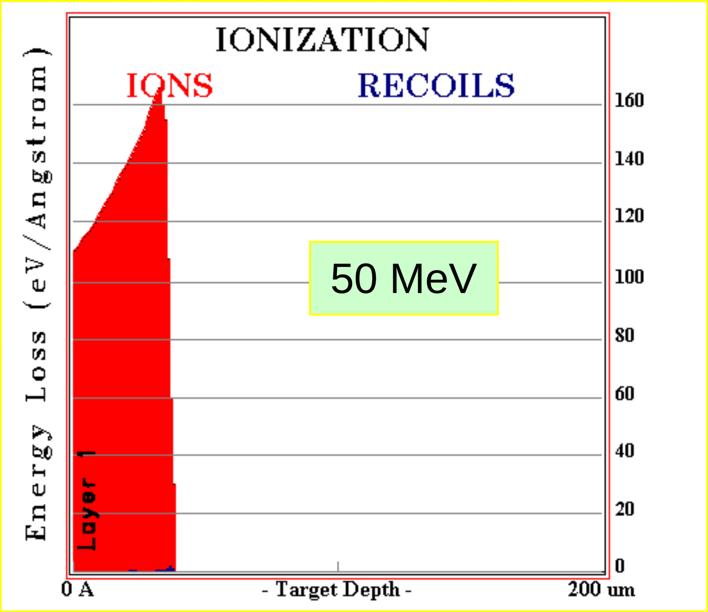
At low velocities ($V < v_0 Z^{2/3}$) the specific energy loss via elastic coulomb collisions with nuclei (non-ionizing) becomes important!

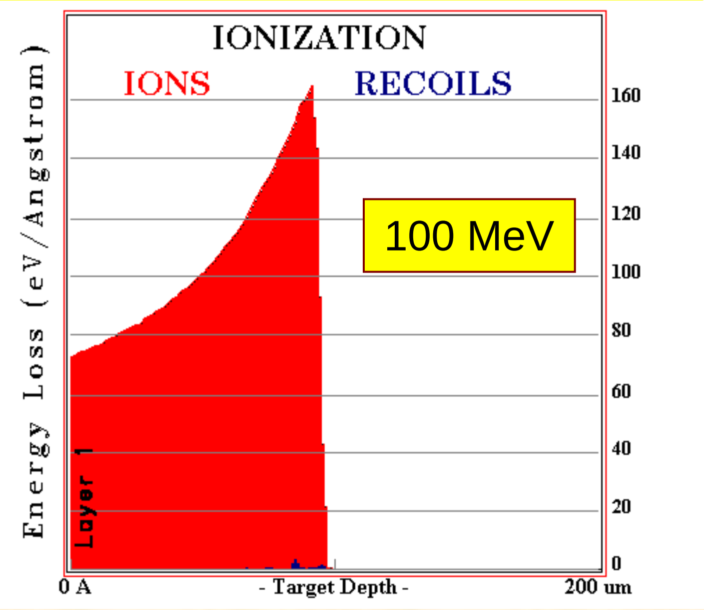


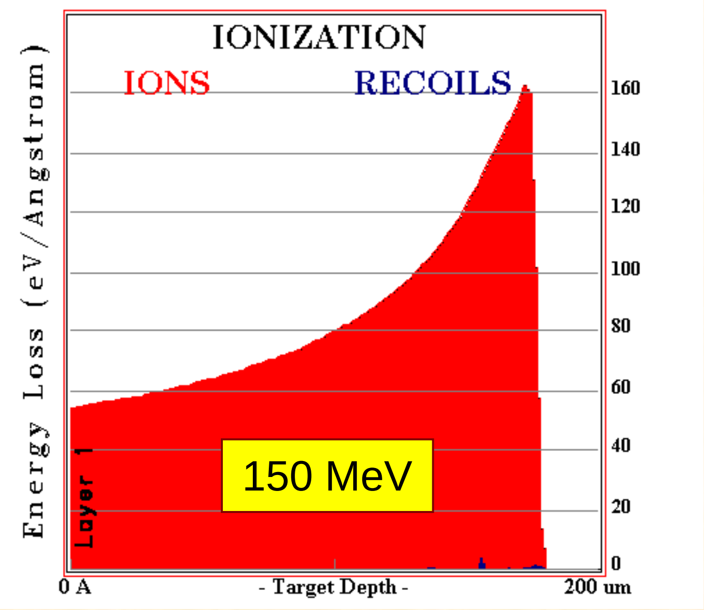
- LET goes thru a maximum
- nuclear stopping power goes through a maximum

range

1 hundred O^{16} in silicon (SRIM 2003)





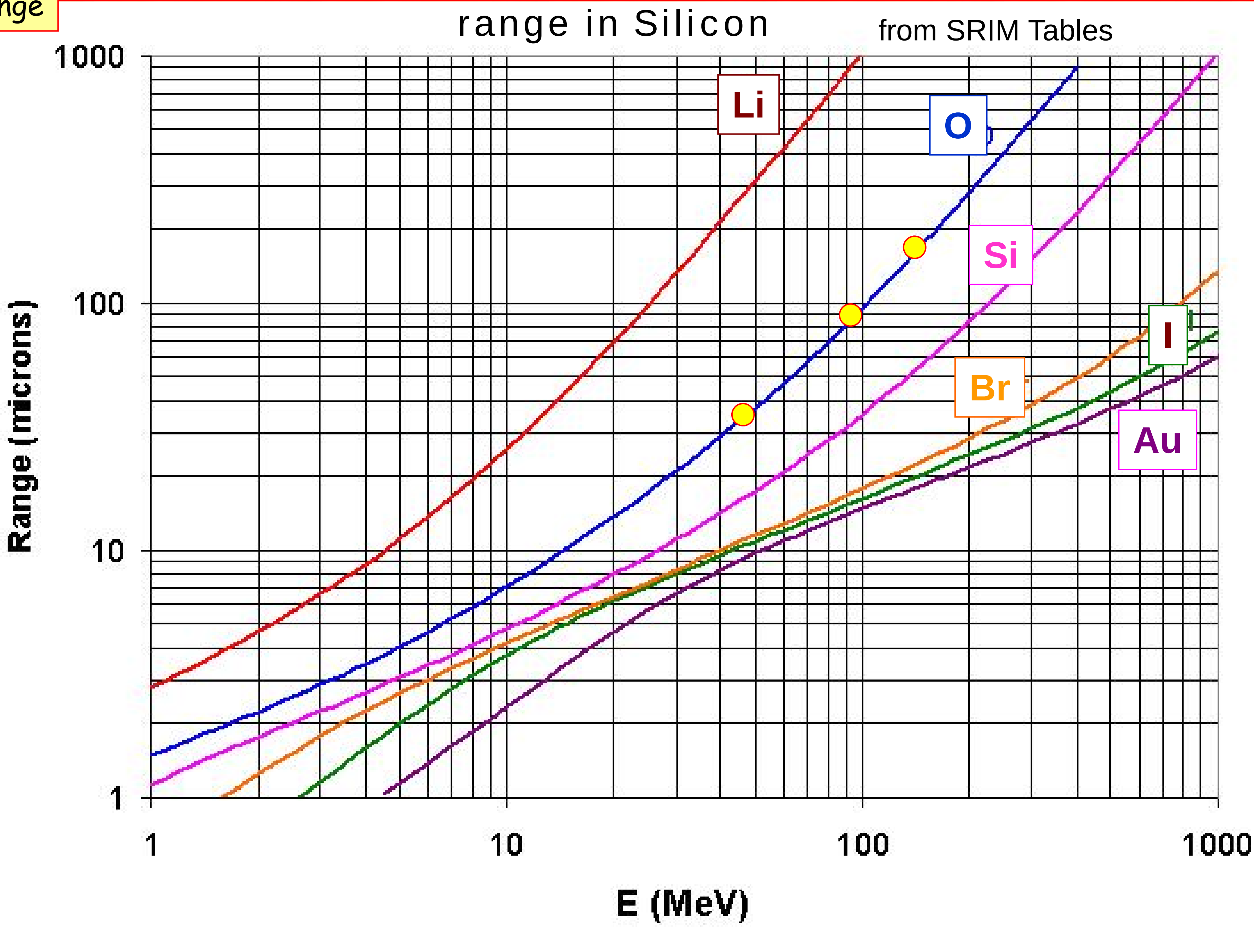


surface value of $(dEdx)_{ele}$ in silicon

energy (MeV)	range (microns)	$(dE/dx)_0$ (eV/Å)	$(dE/dx)_0$ (MeV-cm^2/mg)
50	37.65	108.16	4.66
100	95.23	72.12	3.107
150	176.23	53.97	2.325

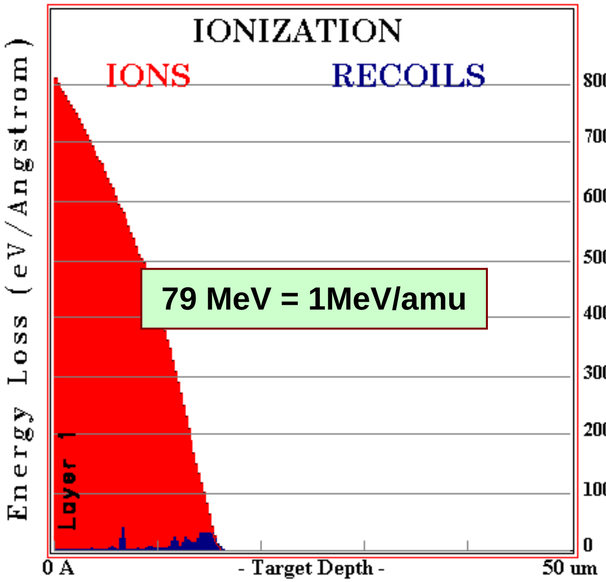
N.B. $(dE/dx)_0$ decreases monotonically with E!

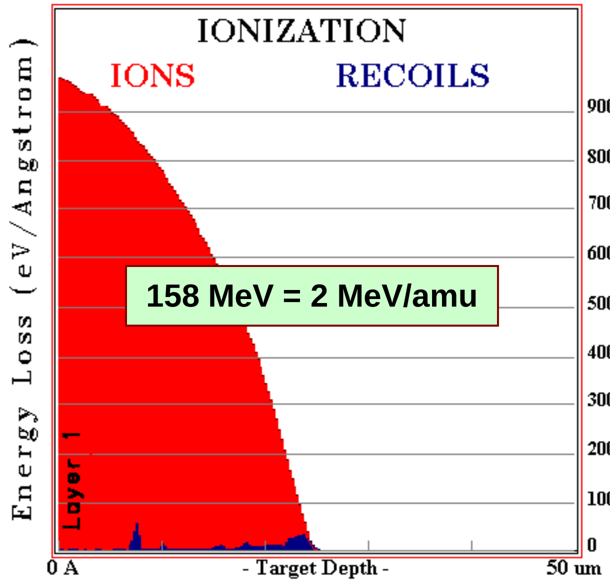
range

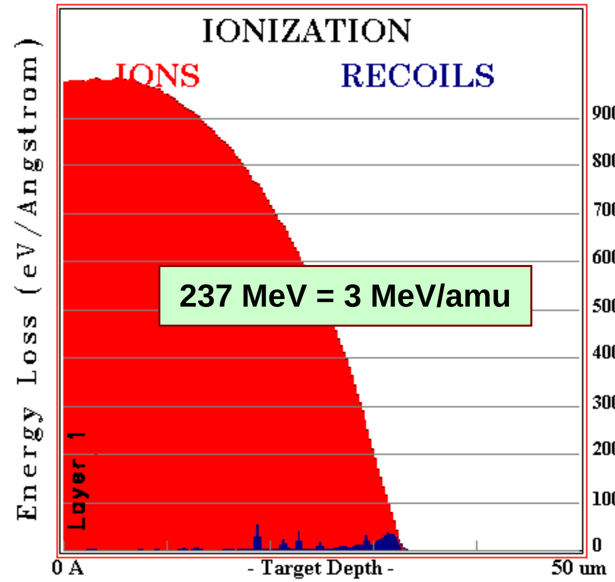

range in Silicon
from SRIM Tables
Range (microns)
1000
100
10
1
E (MeV)
1
10
100
1000
Li
O
Si
Br
I
Au

range

1 hundred Br^{79} in silicon (SRIM 2003)



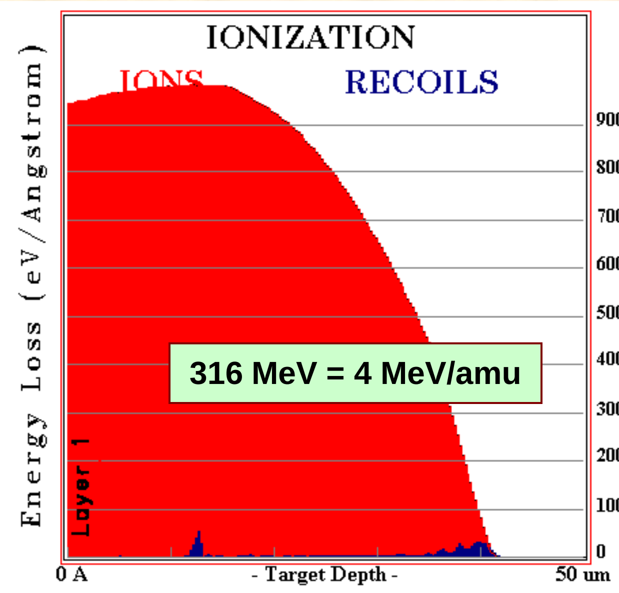


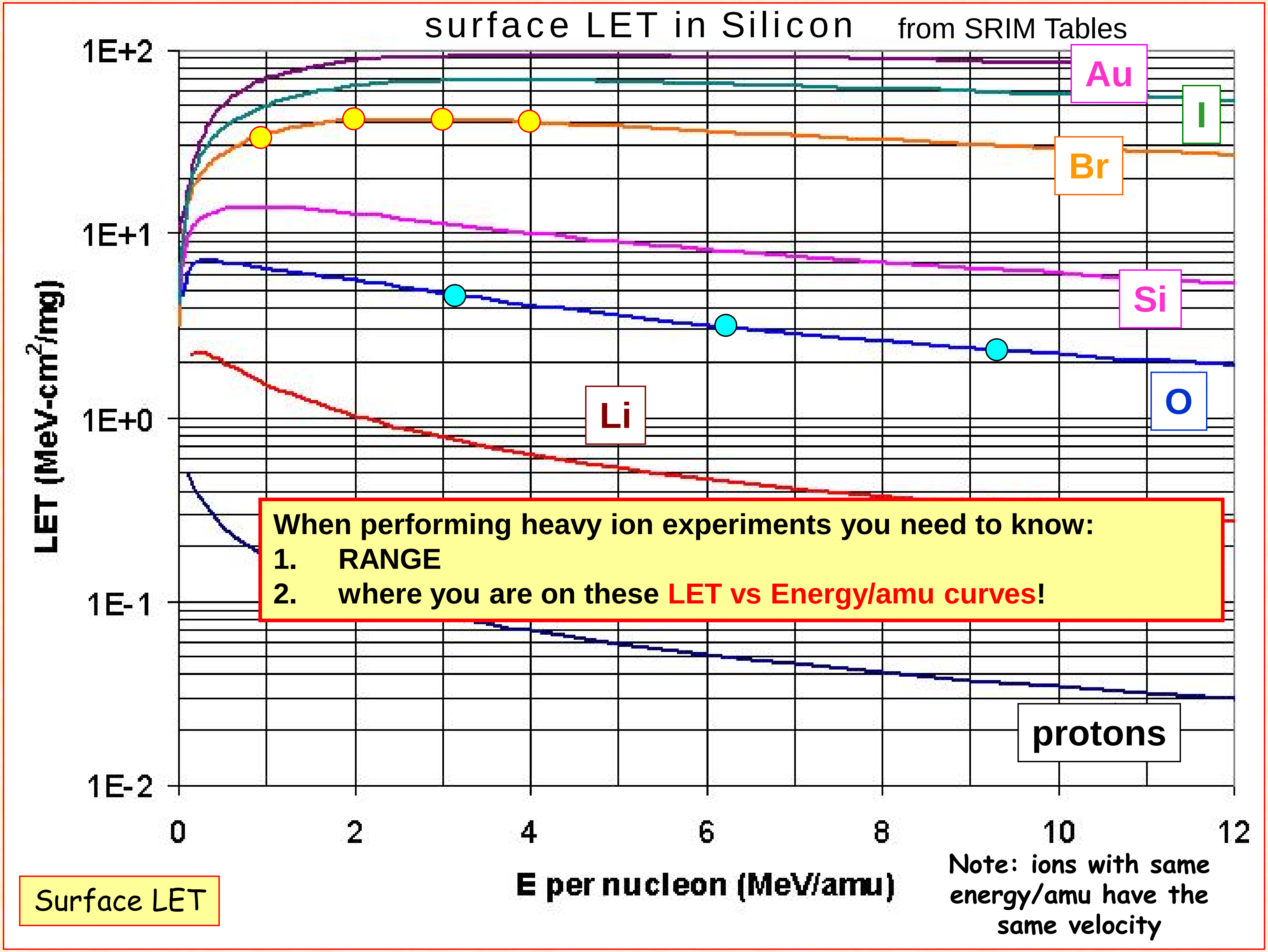


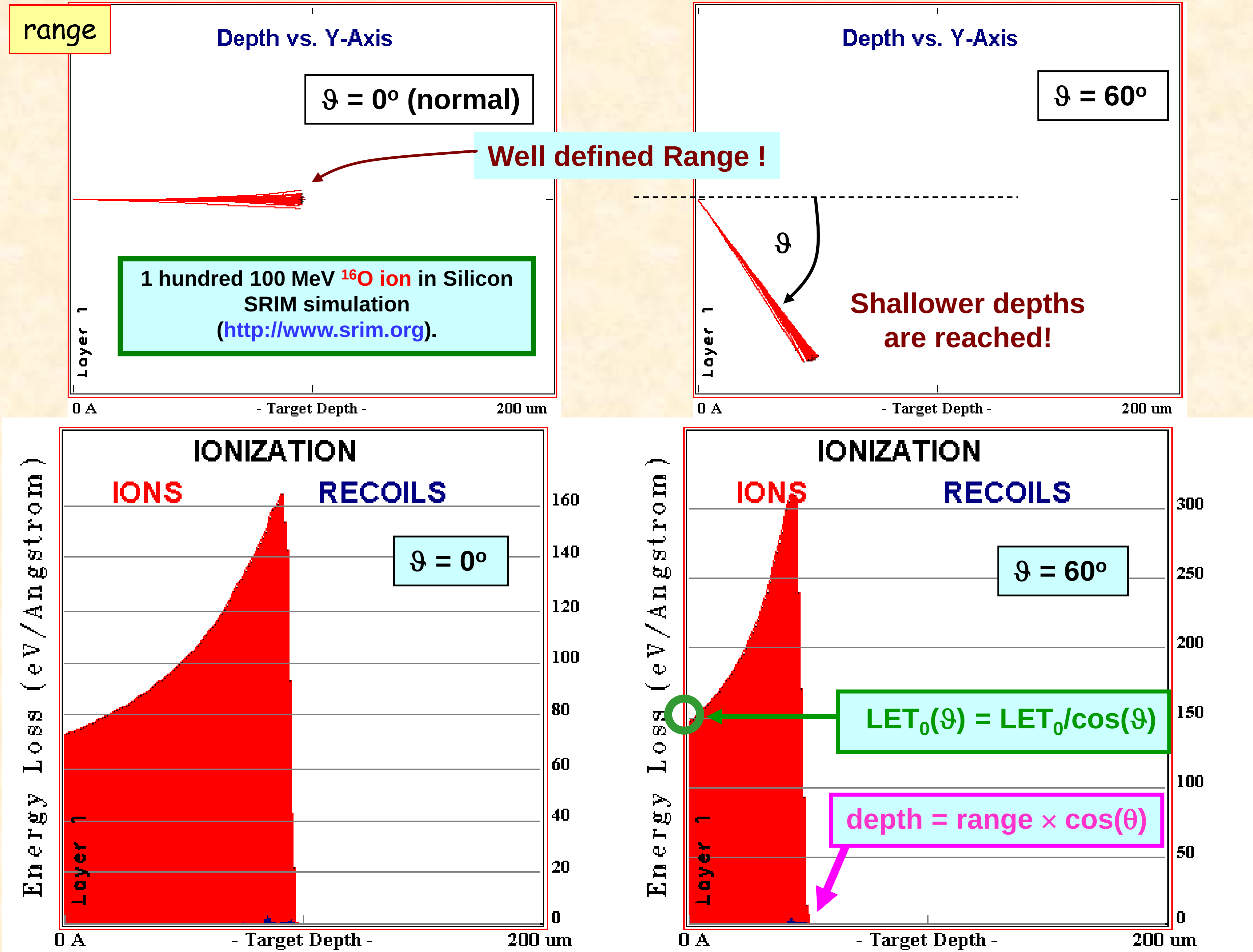
energy (MeV/amu)	LET(0) (eV/Å)	LET(0) (MeV-cm²/mg)
1	809	35.0
2	961	41.6
3	968	41.9
4	936	40.5

broad maximum

decrease! beyond maximum




surface LET in Silicon
from SRIM Tables
1E+2
1E+1
1E+0
1E-1
1E-2
LET (MeV-cm²/mg)
0
2
4
6
8
10
12
E per nucleon (MeV/amu)
Au
I
Br
Si
O
Li
protons
When performing heavy ion experiments you need to know:
1. RANGE
2. where you are on these LET vs Energy/amu curves!
Note: ions with same energy/amu have the same velocity
Surface LET


range
Depth vs. Y-Axis
ϑ = 0º (normal)
Well defined Range !
1 hundred 100 MeV 16O ion in Silicon SRIM simulation (http://www.srim.org).
Layer 1
0 A
- Target Depth -
200 um
Depth vs. Y-Axis
ϑ = 60º
ϑ
Shallower depths are reached!
Layer 1
0 A
- Target Depth -
200 um
IONIZATION
IONS
RECOILS
ϑ = 0º
Energy Loss (eV/Angstrom)
160
140
120
100
80
60
40
20
0
Layer 1
0 A
- Target Depth -
200 um
IONIZATION
IONS
RECOILS
ϑ = 60º
Energy Loss (eV/Angstrom)
LET0(ϑ) = LET0/cos(ϑ)
depth = range × cos(θ)
300
250
200
150
100
50
0
Layer 1
0 A
- Target Depth -
200 um

Caution ionization

Ionization energy loss = energy deposited per unit path length due to ionization resulting from the coulomb interaction of the impinging particle with the electrons of the material.

expression

$\Delta E_{ioniz}/\Delta x \rightarrow (dE/dx)_{ionization}$

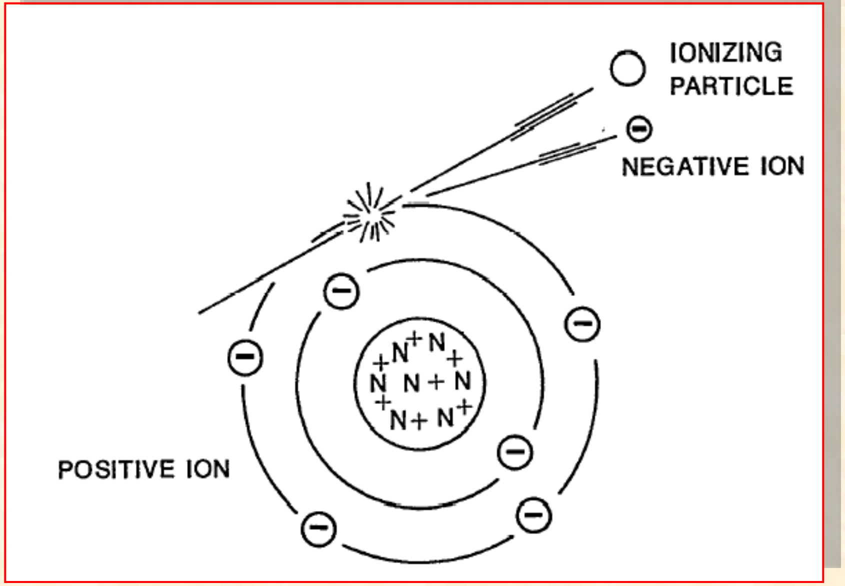
Measured in

MeV/cm (also keV/μm, eV/Å),

or dividing by density

($\rho_{Silicon}$ = 2.33 g/cm^3)

in MeV-cm^2/mg



LET, FLUENCE and Total Ionising DOSE (TID) are interrelated

$$TID(rad) = 1.602 \times 10^{-5} \times fluence(cm^{-2}) \times LET(MeV\text{-}cm^2/mg)$$

HOWEVER... caution!

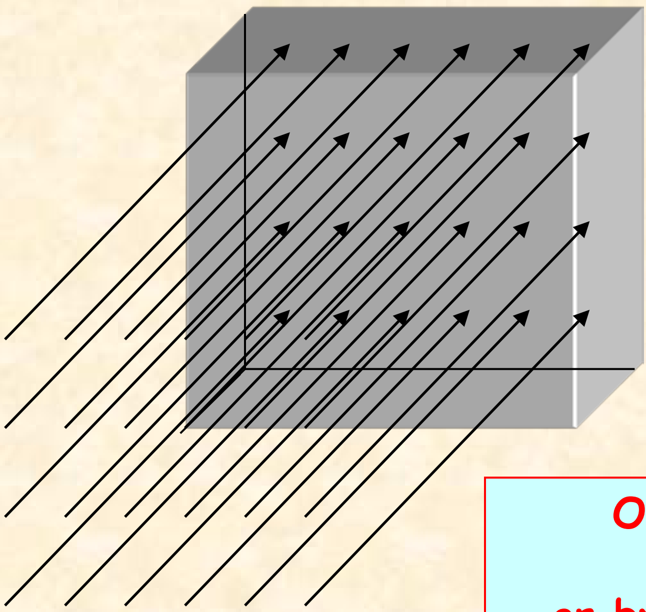
microdose

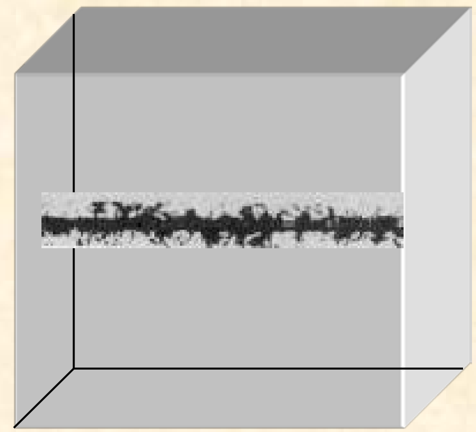
DOSE: energy absorbed per unit mass

WARNING: concept of DOSE does not define the spatial pattern of the energy absorption!

X-rays and gamma radiation deposit energy in uniform pattern

Ions deposit ionisation energy in NON-uniform highly structured pattern





One unit of dose can be deposited by many photons (left) or by a single ionizing particle track (right)

Common radiobiological X-ray doses (100 rad = 1 Gray) produce a uniform pattern of ionisation in target (cell, tissue, patient).
In the center of a SINGLE ION TRACK the local dose may be thousands of Gray but fall close to zero just just a few microns away!

dose

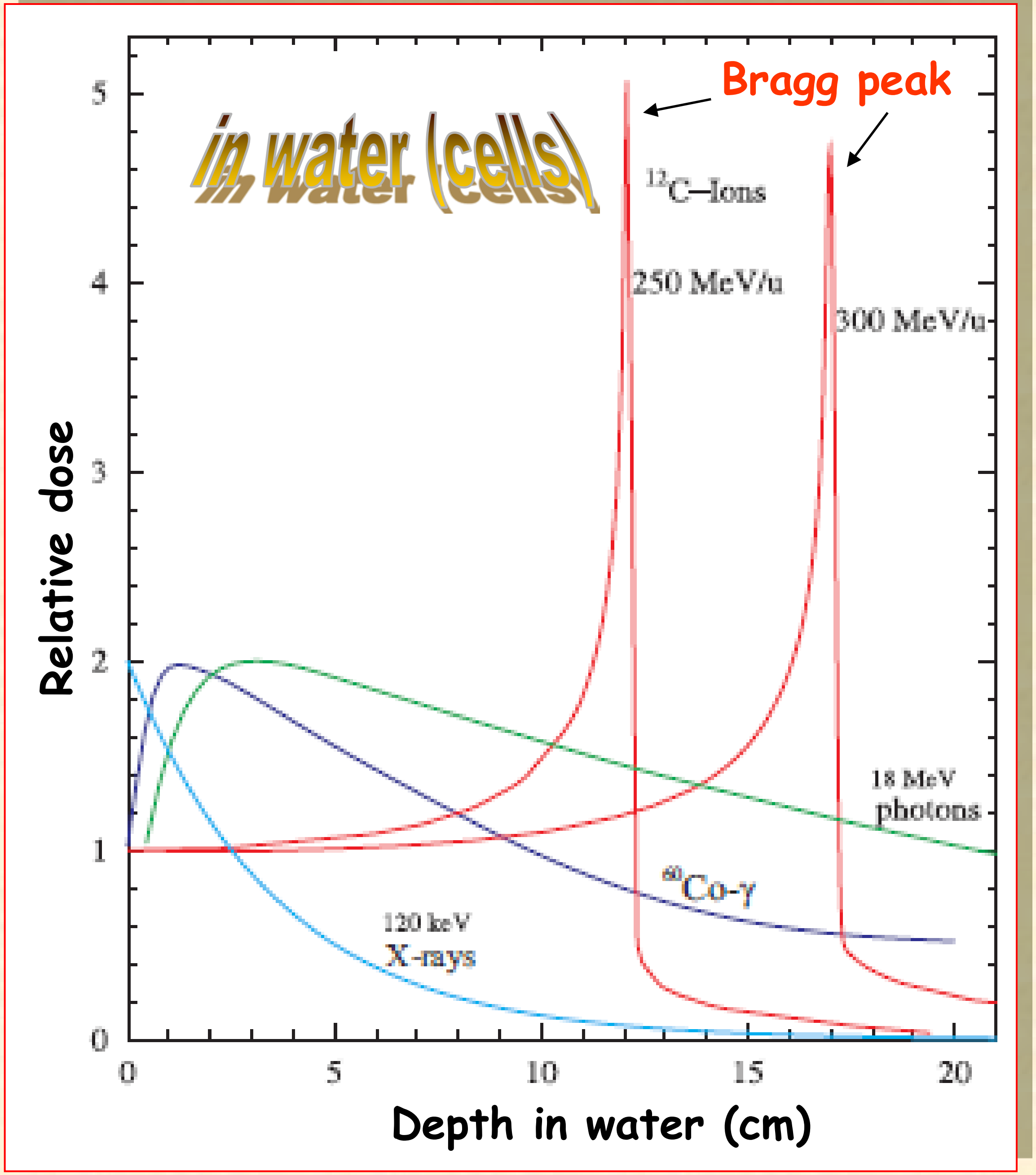
Comparative Depth Dose profiles

Depth dose profiles of photons:

- X-rays (light blue);
- gamma from ^{60}Co (blue);
- Bremsstrahlung from electron beam (green).

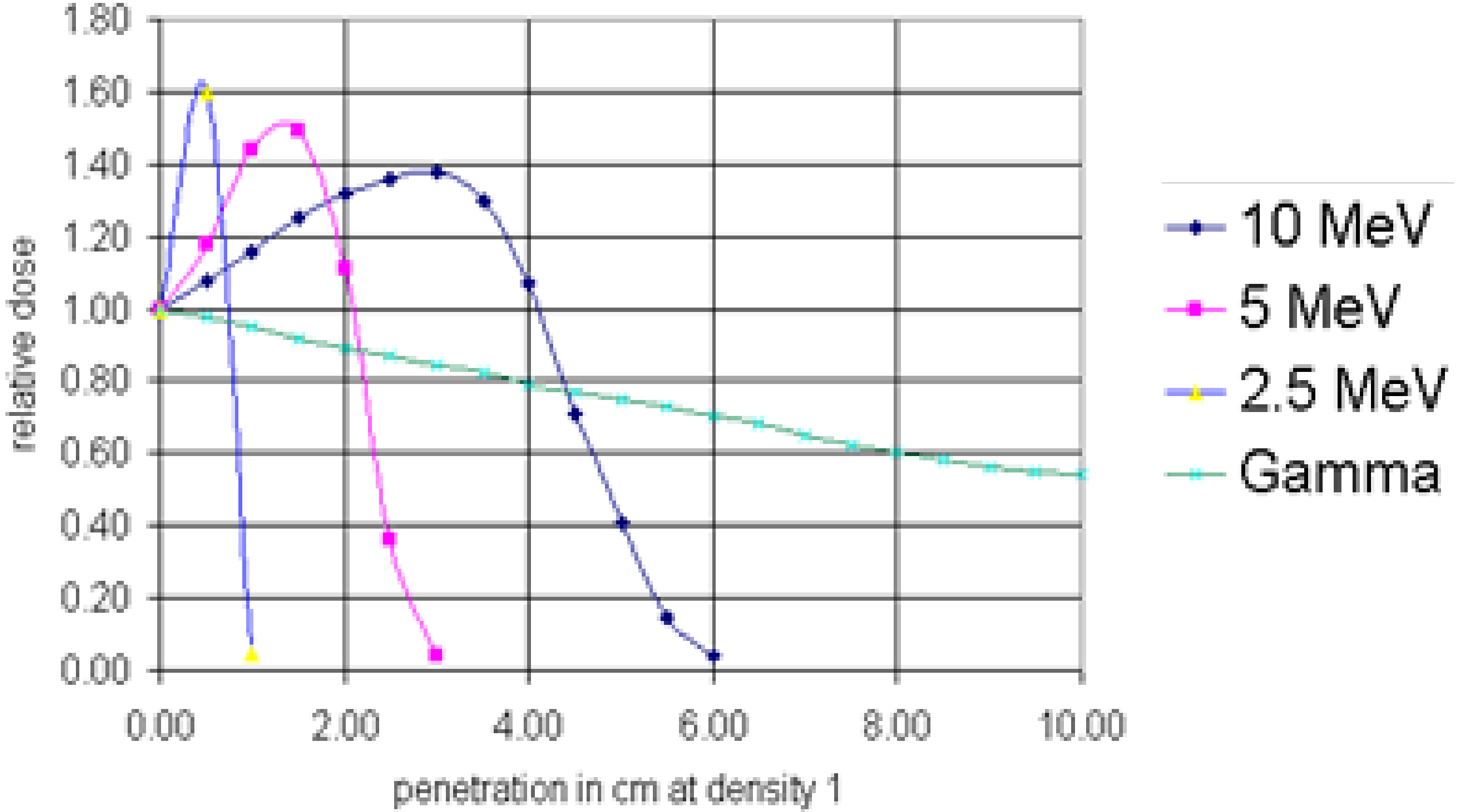
Depth dose profiles of carbon ion beams (red).

Note: ion dose peak in depth (Bragg peak)



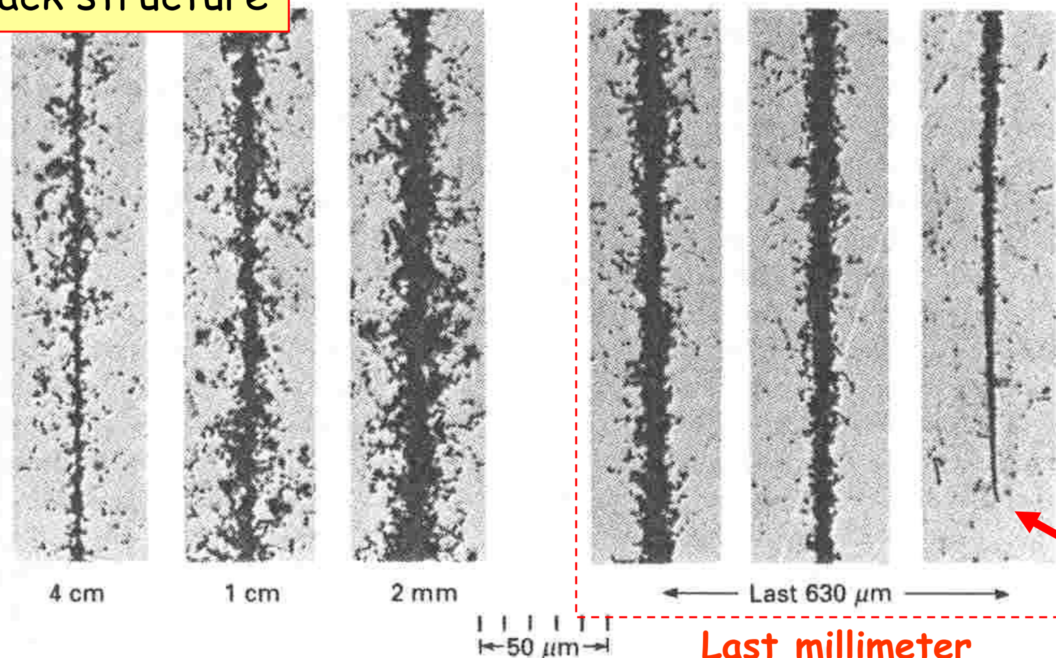
dose

dose depth distribution **electrons** (typical low energy LINACs) and gamma (CO^{60}) in water



track structure

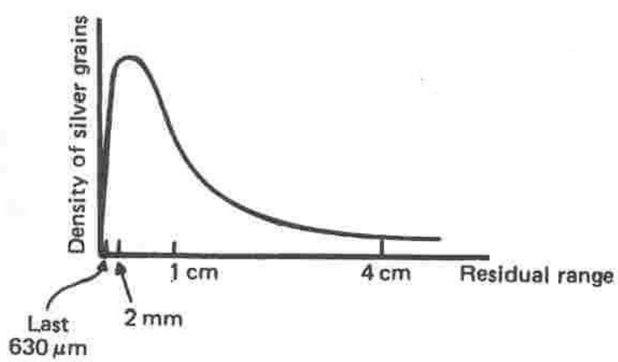
cosmic IRON nucleus



Last millimeter

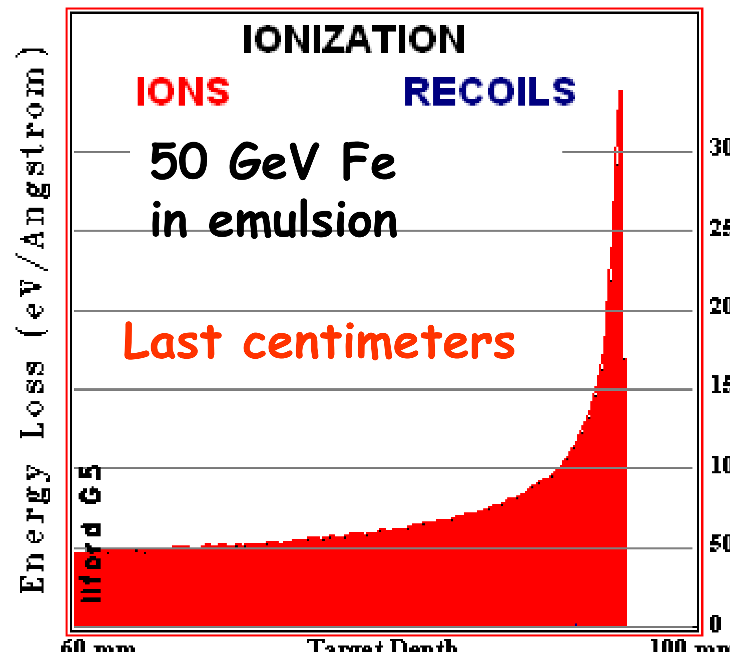
Ion stopped!

Nuclear emulsion tracks of a single cosmic Fe nucleus at various stages in its deceleration from relativistic velocities to REST. The distances are the residual ranges at which the ion track is observed.



As ion slows the **spatial extent** of ionisation decreases (not enough energy to extract energetic deltas).

The height of ionisation decreases as effective charge Z_{eff} of ion decreases.



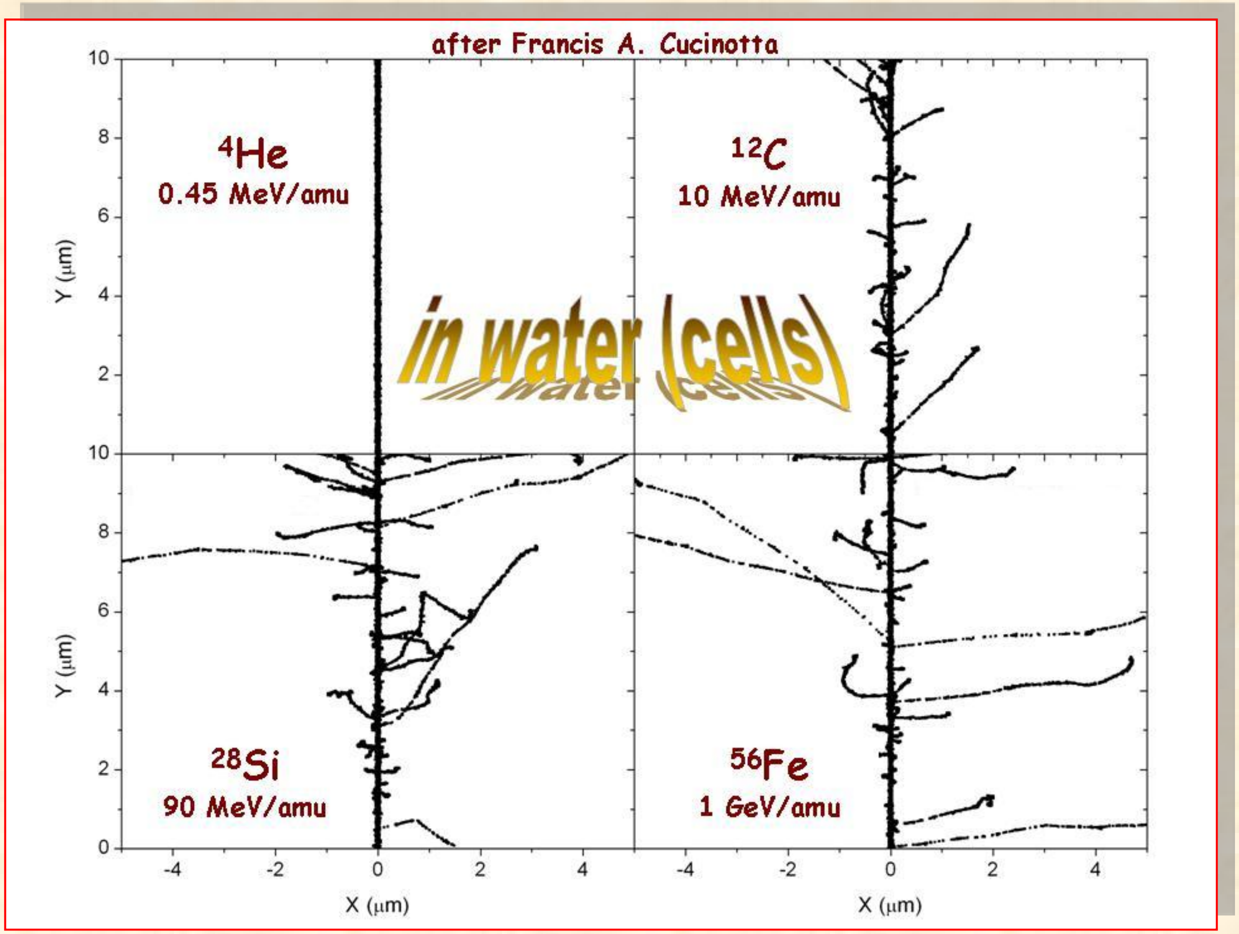
M. M. Shapiro, R. Silberberg (1970). *Ann. Rev. Nucl. Sci.*, **20**, 328

track structure

Track Structure

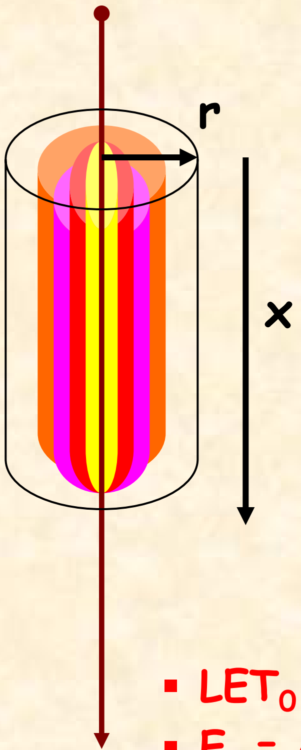
- **NOTE: LET does <u>not</u> adequately describe energy deposition at small scales**
- Full characterization of energetic heavy nuclei:
  - Charge, Q (Z) defines density of ionization along track (Q^2 dependence)
  - Kinetic energy of δ-rays defines width of track corresponding to maximum distance of energy deposition laterally from track

N.B. All four nuclei have about the **same LET** (~ 150 keV/micron)



track structure

simple track structure model



Model to describe heavy ion induced carrier (electron-hole pairs) generation rate density (number of e-h/cm^3-s):

spatial extent — time dependence

$$g(r,t) = \frac{1}{\pi^{3/2}\, r_0^2\, \tau}\, \frac{LET_0}{E_p} \times \exp(-r^2/r_0^2) \times \exp(-t^2/\tau^2)$$

N.B. no x dependence ≡ shallow hypothesis

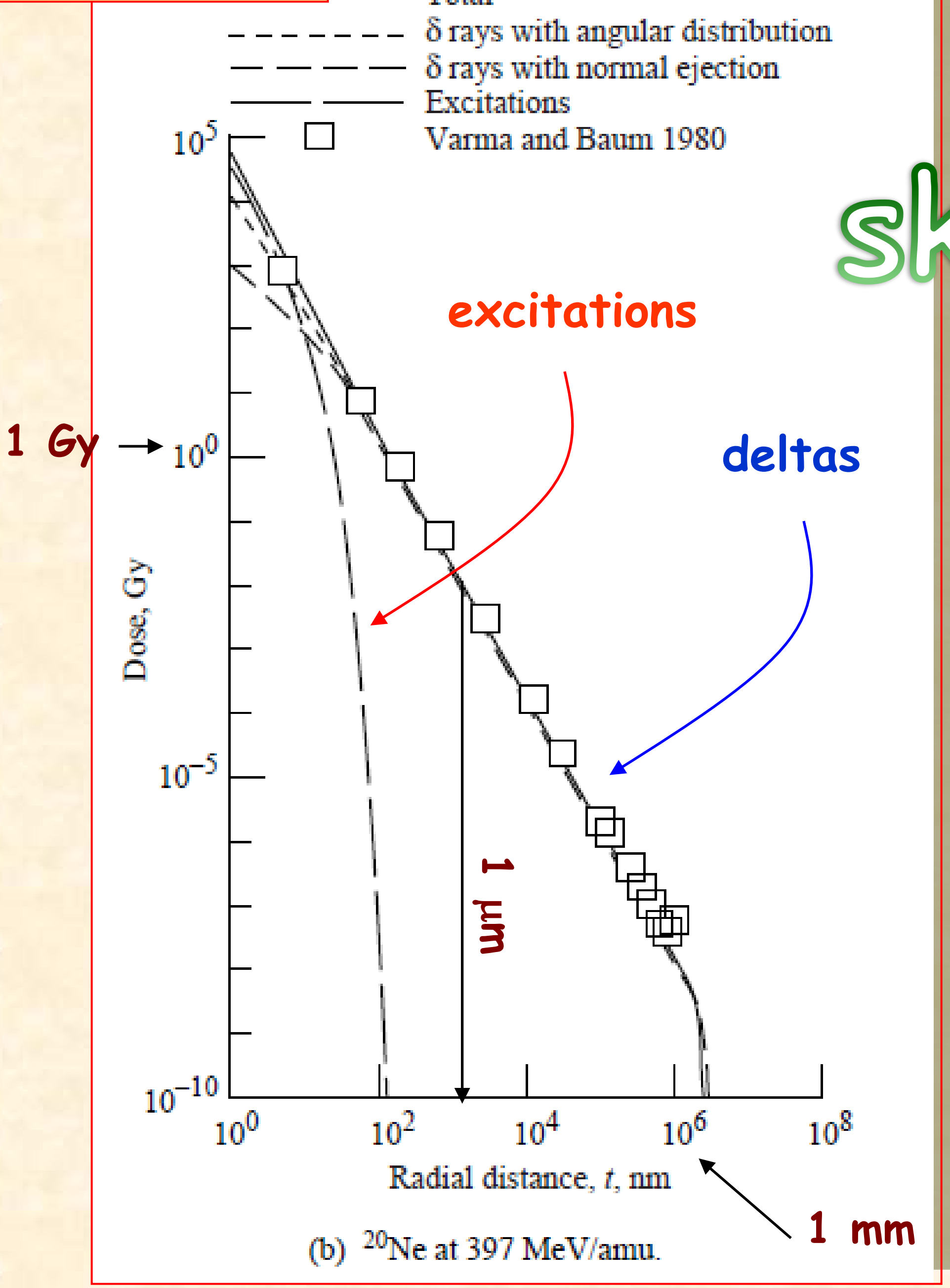
- LET_0 = initial surface LET (energy/length) value of impacting ion
- E_p = average energy to produce electron-hole pair (3.6 eV in Silicon)
- r_0 = length parameter arbitrarily and typically set at 100 nm (0.1 μm)
- τ = duration to describe temporal variation (gaussian) of generation rate; Includes the time of flight of the primary ion and the secondary electrons across the sensitive volume and the relaxation time of the generated carriers. Time of the order picoseconds (10^{-12} s).

example: for 158 MeV ^{79}Br

$$g(r,t) = 4.8 \times 10^{31}\ (\text{e-h/cm}^3\text{-s}) \times \exp(-r^2/r_0^2) \times \exp(-t^2/\tau^2)$$

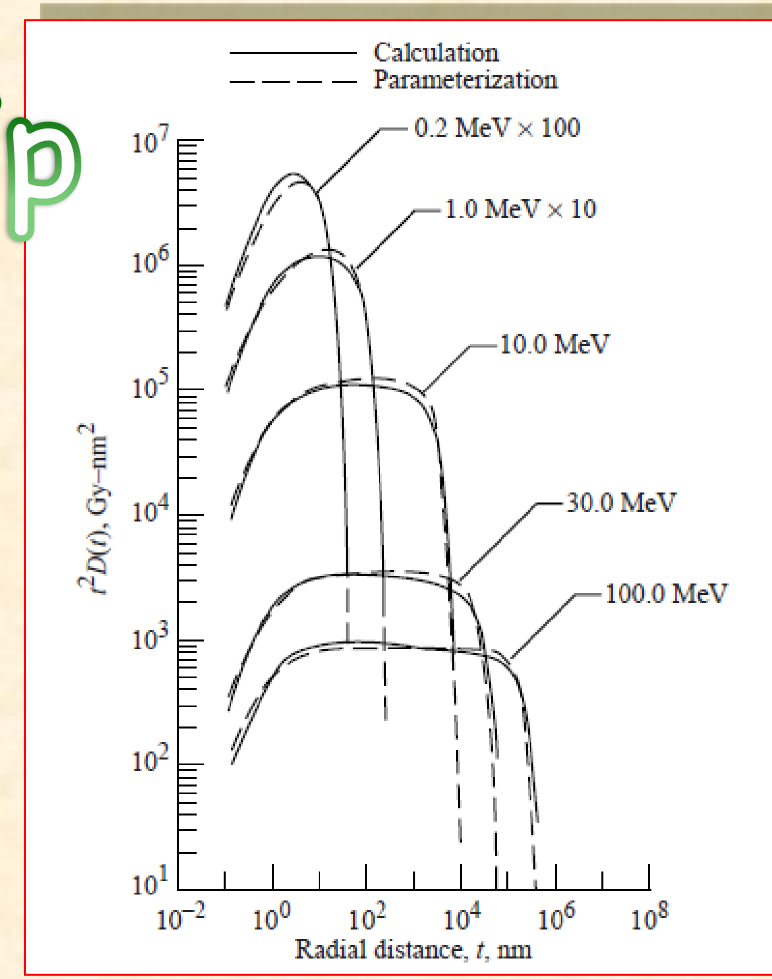
track structure

F. Cucinotta et al
NASA Technical Paper 3630



(b) ^{20}Ne at 397 MeV/amu.

skip



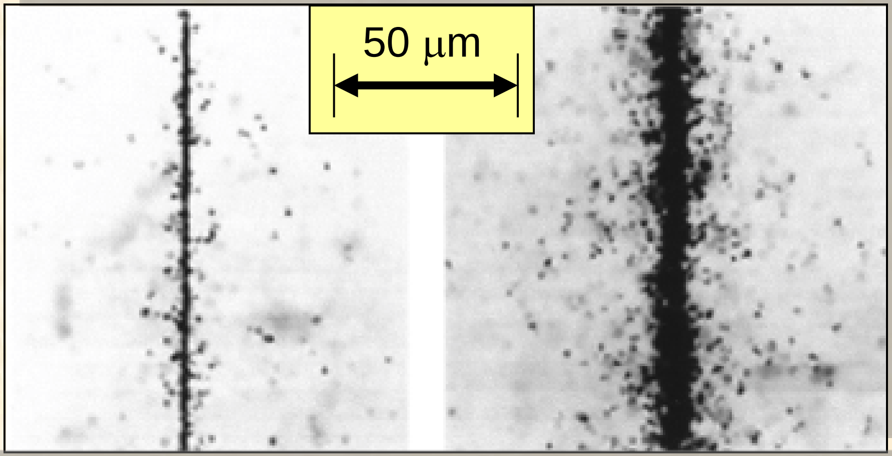
in water (cells)

track structure

skip

several nanometer dense core

ion with Z = 4 to 6



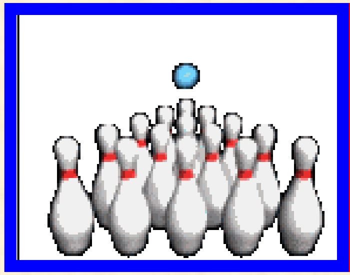
Fe ion (Z=26)

OUTSIDE CORE
the ionisation density is determined
by **energy** and **radial** distributions of secondary electrons

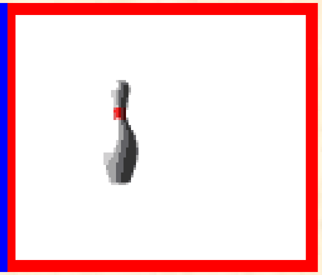
- exponential decrease of ionisation density with distance from track; radial extent of ionisation scales with the **velocity V of ion** (indeed the max energy transfer to electrons is $2m_eV^2$)
- ionisation scales with velocity V of ion and with effective charge $Z_{effective}$ of ion (that changes and with velocity of ion)

$$dE_{ion}/dx \propto Z_{eff}^2/V^2$$

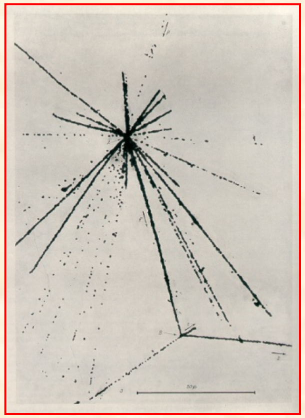
Atomic displacement
(displacement damage)



elastic



anelastic



elastic	anelastic
protons	neutrons
ions	energetic protons
neutrons	energetic ions

energetic protons, energetic ions } Coulomb barrier

Particles can lose energy through non-ionizing interactions with materials, particularly through "displacement damage", or "bulk damage", where atoms are displaced from their original sites.

This can alter the electrical, mechanical or optical properties of materials and is an important damage mechanism for electro-optical components (solar cells, opto-couplers, etc.) and for detectors, such as CCDs.

displacement

Non Ionizing Energy Loss (NIEL)

Non-ionization loss: the energy deposited per length unit due to non-ionizing interaction of the impinging particle with the nuclei of the lattice causing **displacement damage**. Interaction may be coulombic (electromagnetic) or *nuclear (strong force).*

expression

$\Delta E_{displacement}/\Delta x$

$\rightarrow$ **NIEL = $(dE/dx)_{displacement}$**

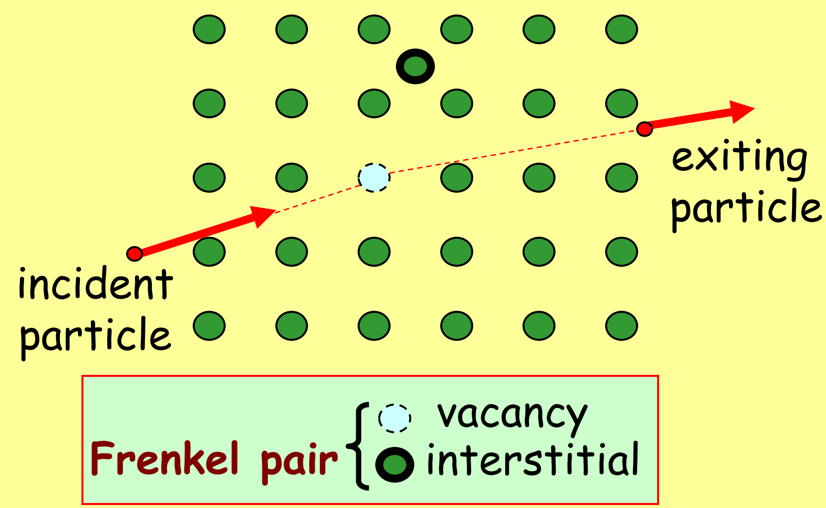
Measurement units

MeV/cm, also eV/μm

or

dividing by density

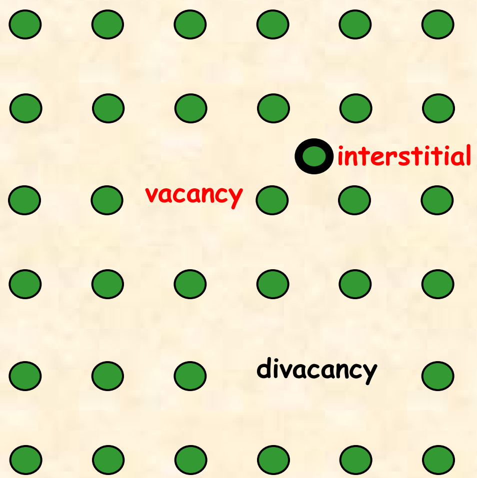
$MeV\text{-}cm^2/mg$

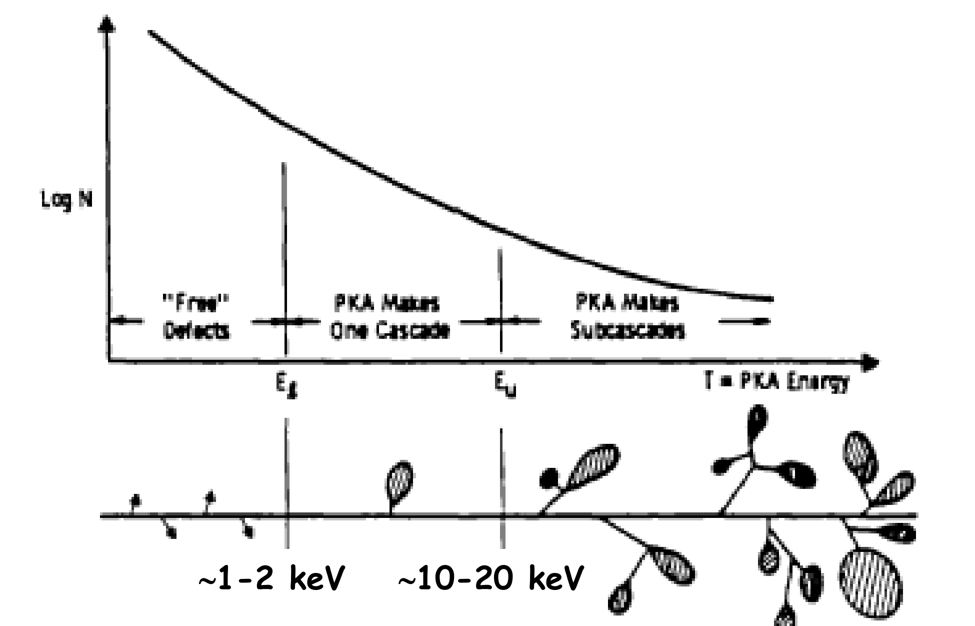


Interstitial and vacancy defect creation.

Displacement damage

- caused by: p, n, ions, electrons, γ-rays
- result of: transfer of non-ionizing energy (NIEL) to lattice **NUCLEI** causing structural damage to lattice (defects).
- basic mechanism: collision between incoming particle and a lattice nucleus (called Primary Knock-on Atom, i.e. PKA) displaces atom from original lattice position generating point defects (vacancies and interstitials).
- pejorative mechanism: energetic PKA generates other point defects or even highly damaged regions (cascades, clusters), depending on energy transferred during the primary collision.

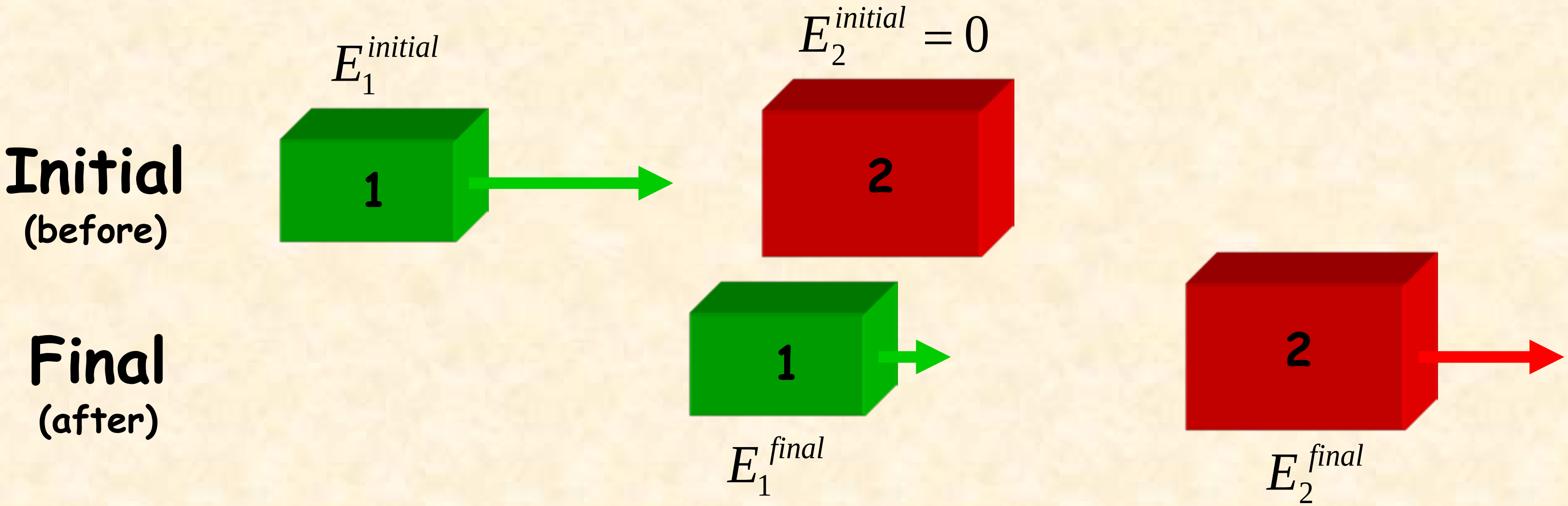




Energy to Si recoils

displacement

elastic collisions 1



In elastic collisions kinetic energy is conserved $E_1^{final} + E_2^{final} = E_1^{initial}$
hence the maximum transferable energy for a given incident energy is

$$E_{2,\max}^{final} = E_1^{initial} \times \frac{4M_1M_2}{(M_1+M_2)^2}$$ *(non-relativistic)*

MINIMUM energy of incident particle to give target particle a minimum (threshold) energy

$$E_{incident}^{\min} = E_{threshold} \times \frac{(M_{inc}+M_{tar})^2}{4M_{inc}M_{tar}}$$ *(non-relativistic)*

elastic collisions 2

MINIMUM energy for displacement

$$E_{incident}^{min} = E_{threshold} \times \frac{(M_{inc} + M_{tar})^2}{4M_{inc}M_{tar}}$$

(non-relativistic)

Displacement damage threshold energies			
diamond	germanium	silicon	GaAs
35±5 eV	27.5 eV	25 eV	7-11 eV

in Silicon

incident particle	E_{min} for creation of a displacement (Frenkel pair)
Silicon ion	25 eV (billiard ball effect)
neutron/proton	186 eV
electron	~~319 keV (above non-relativistic formula)~~ 255 keV (relativistic)

displacement

elastic collisions 3

MAXIMUM energy transferred to recoiling target atom

$$E_{recoil}^{\max} = E_{inc} \times \frac{4M_{inc}M_{tar}}{(M_{inc} + M_{tar})^2}$$

(non-relativistic)

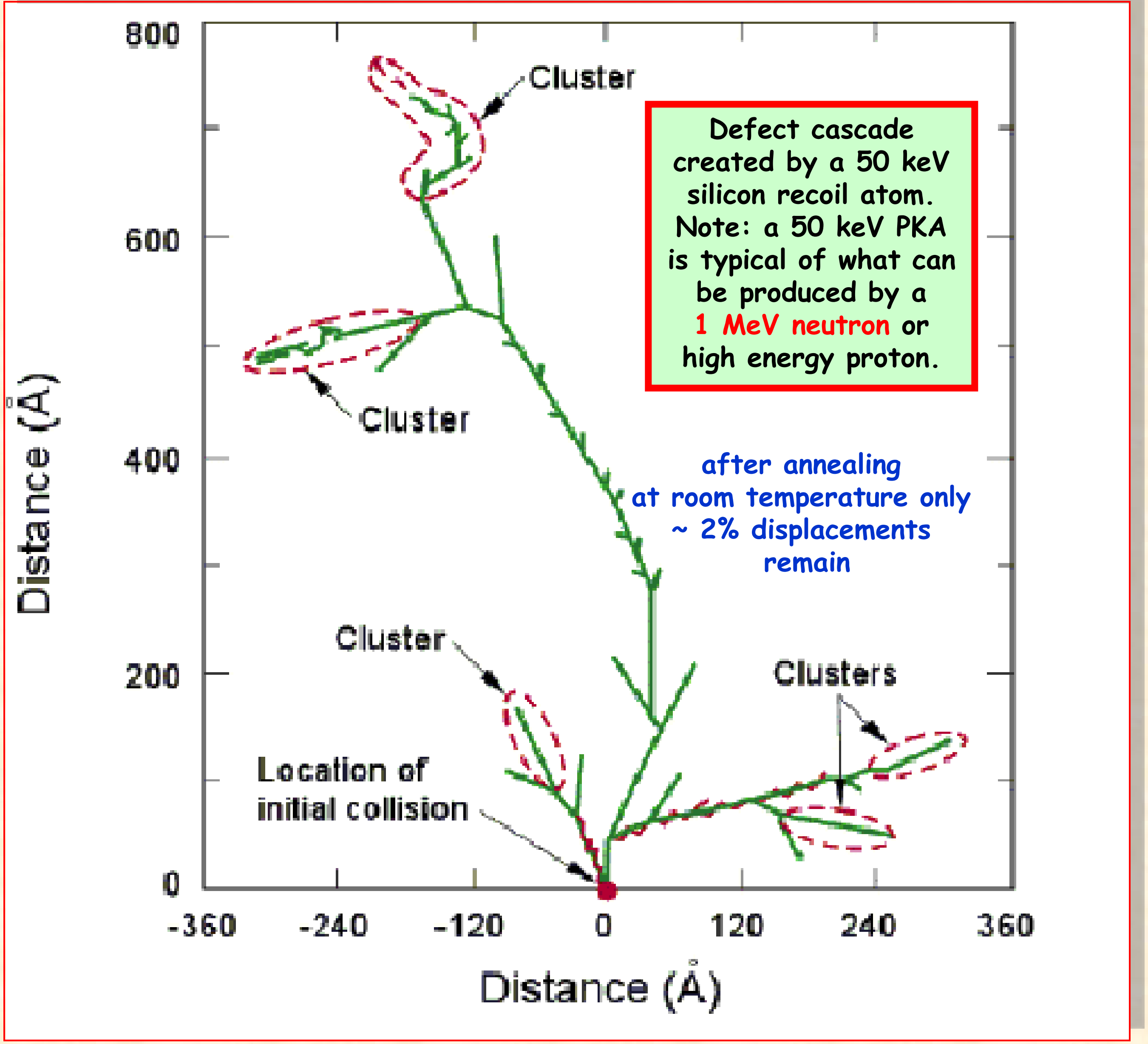
e.g. incident NEUTRONS in Silicon

incident energy of neutron	$E_{recoil}^{\max}$	Comments assuming recoiling Silicon with maximum energy
35 keV	4.7 keV	range of recoiling Si is ~ 200 Å, most of energy loss of slow recoiling Si is nuclear $(dE/dx)_{nucl}$
1 MeV	134 keV	range of faster recoiling Si is ~ 6000 Å, ~ 50% of energy loss of Si recoil is nuclear → 2700 displacements ~ 60% recombine within 100 picoseconds → leaving 1000 displacements followed by further long term annealing

NOTE: max E_{recoil} from Co-60 is only 150 eV (isolated displacements, no clusters)

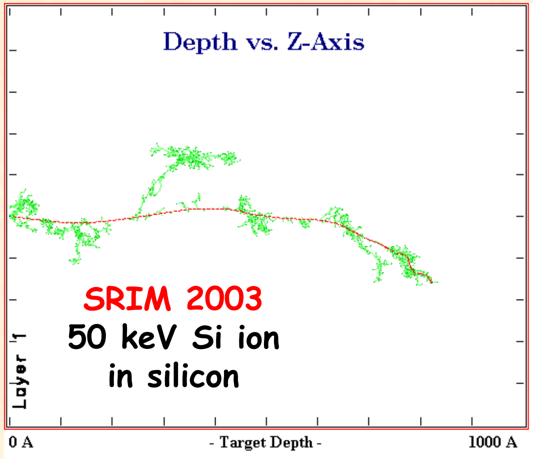
Ion displacement damage

adapted from V. A. J. Lint

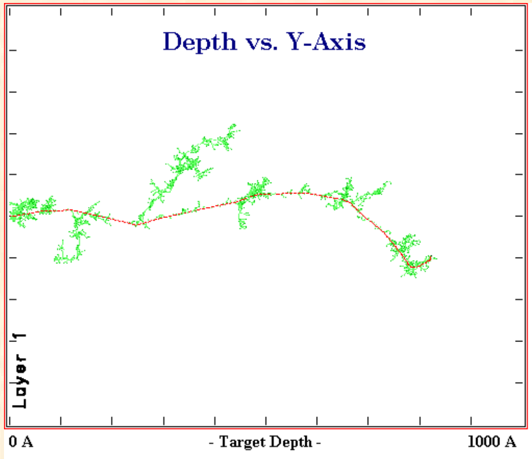


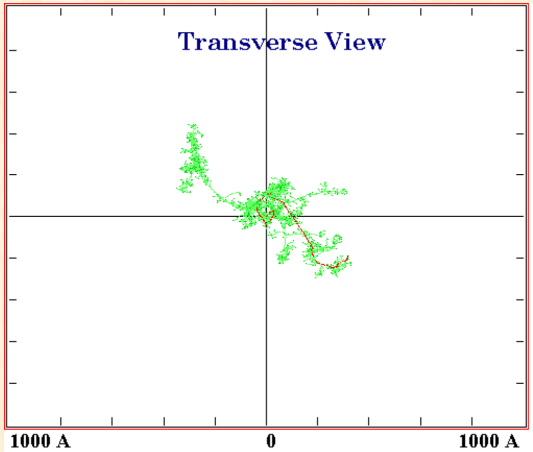
Defect cascade created by a 50 keV silicon recoil atom. Note: a 50 keV PKA is typical of what can be produced by a 1 MeV neutron or high energy proton.

after annealing at room temperature only ~ 2% displacements remain



SRIM 2003
50 keV Si ion in silicon





Displacement damage

Vacancies in Silicon

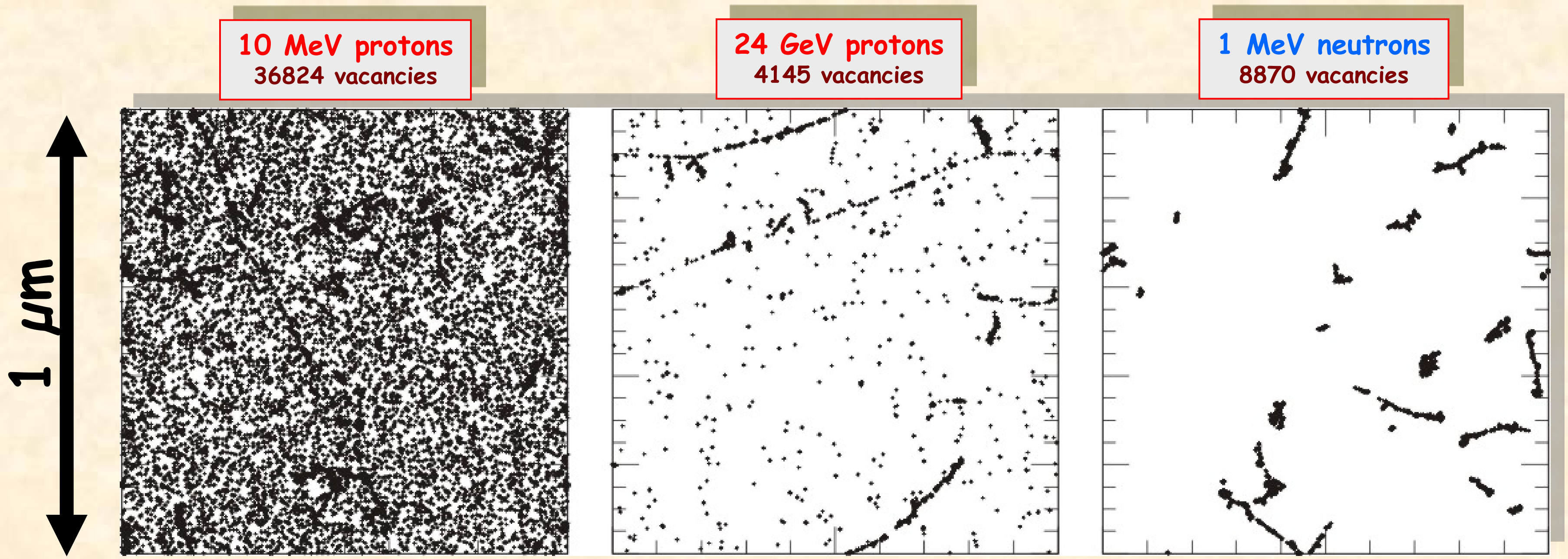
^{60}Co-gammas	Electrons	Neutrons (elastic scattering)
Max $E_\gamma \approx$ 1 MeV Effective particles are *Compton* electrons. Point defects only. (No clusters!)	E_e > 255 keV for displacement E_e > 8 MeV for cluster	E_n > 186 eV for displacement E_n > 35 keV for cluster

More isolated defects ⟷ More clusters

By Mika Huthinen (ROSE)

by Mika Huhtinen ROSE TN/2001-02

INITIAL distribution of vacancies in (1μm)^3 after fluence of 10^{14} particles/cm^2



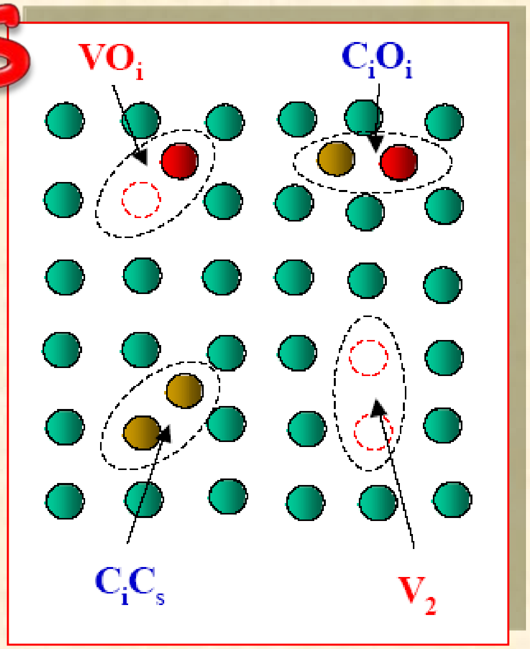
Displacement damage

Quasi-chemistry of defects

Next talks

complex kinetics

(time, concentration, and temperature dependences)



I = interstitial
V = vacancy
S = substitutive
O = Oxygen
C = Carbon
P = Phosphorus

Various quasi-chemical reactions

$V+V \rightarrow V_2$ $V+V_2 \rightarrow V_3$

$V+O_i \rightarrow VO_i \Rightarrow$ $V+VO_i \rightarrow V_2O_i$ $V+V_2O_i \rightarrow V_3O_i$

$V+P_s \rightarrow VP_s$

$I+VP_s \rightarrow P_s$ $I+V_2 \rightarrow V$

$I+VO_i \rightarrow O_i$ $I+V_2O_i \rightarrow VO_i$ $I+V_3O_i \rightarrow V_2O_i$

$I+C_s \rightarrow C_i \Rightarrow$ $C_i+C_s \rightarrow C_iC_S$

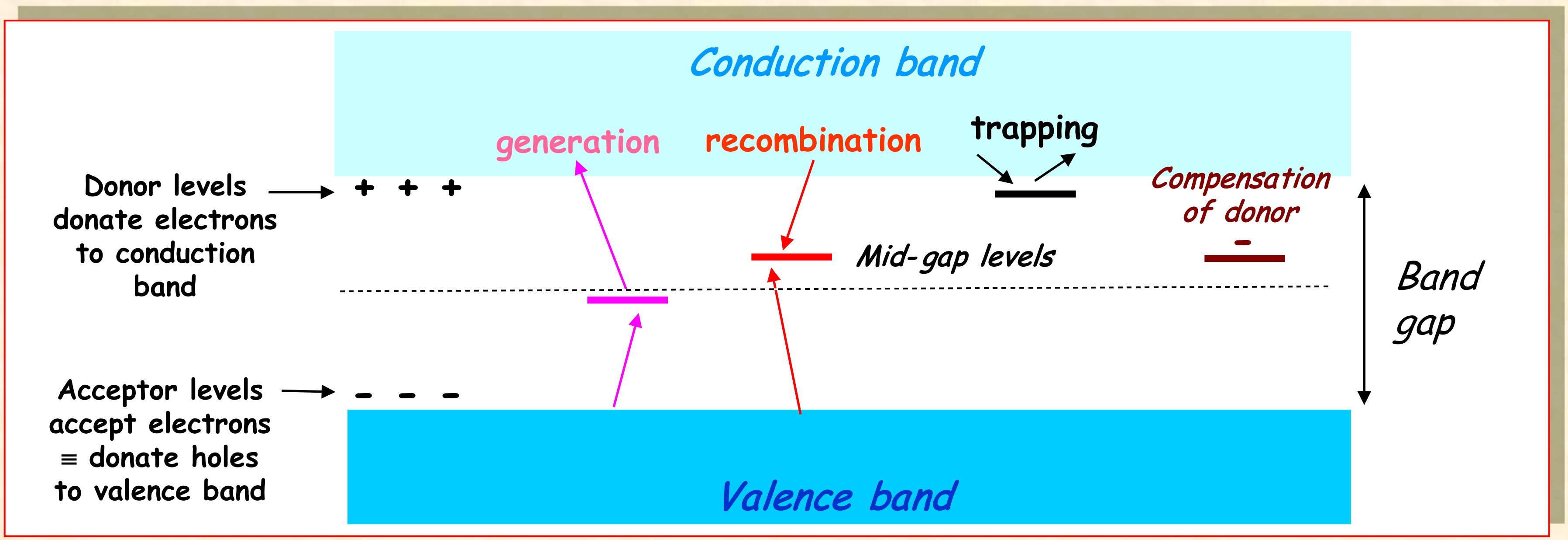
$C_i+O_i \rightarrow C_iO_i$

Displacement damage

Damage → defects

Next talks

- n-type Si: V-P, V-O, V-V are stable defects.
- p-type Si: V-O, V-V are stable defects.
- **Defects can be electrically active** (energy levels in the bad gap) and capture and release electrons and holes from the conduction and valence bands
  - → Defects can be charged
  - → can be generation centers ⇒ leakage current
  - → can be **recombination centers ⇒ minority carrier lifetime**
  - → can be **trapping centers ⇒ carrier removal**
  - → compensation ⇒ **type inversion (n- to p-type) & increase in depletion voltage**
  - → Scattering by defects ⇒ carrier mobility at high fluence



NIEL

Non Ionizing Energy Loss (NIEL)

skip

NIEL = energy/m^3 per unit fluence that goes into displacements

PKA = Primary Knock-on Atom (e.g. silicon atom if a silicon lattice)

Frenkel pair = Interstitial-vacancy (I-V) pair

Reasonably:

- The number N of displacements (I-V pairs) is proportional to the energy of the PKA
- $N=E_{PKA}/2E_{th}$ (according to Kinchin-Pease), where E_{PKA} is the kinetic energy of the PKA, E_{th} is the threshold energy to create a Frenkel pair
- in cascade regime the "*nature*" of the damage is independent of the energy of the PKA; one just gets more cascades!

NIEL

KERMA ≡ K.E. imparted by radiation into displacement
total **K**inetic **E**nergy **R**eleased in **MA**tter (silicon)

"BULK DAMAGE is proportional to total kinetic energy (K.E.) that goes into DISPLACING atoms (silicon); i.e.

- damage ∝ Kinetic Energy gone to DISPLACEMENT (KERMA)
- damage scales with particle fluence ϕ

$$\text{displacement damage dose (DDD)} = \frac{\text{KERMA}}{\text{mass}} \propto \phi$$

$$\text{DDD} = \frac{\text{KERMA}}{\text{mass}} = \text{NIEL} \times \phi$$

units: $\text{NIEL}(\text{MeV-cm}^2/\text{mg}) = \text{NIEL}(\text{keV-cm}^2/\text{g}) \times 10^3$

$$\text{KERMA (keV)} = \text{NIEL}(\text{keV-cm}^2/\text{g}) \times \phi(\text{cm}^{-2}) \times \text{mass(g)}$$

$$\text{KERMA (MeV)} = \text{NIEL}(\text{MeV-cm}^2/\text{mg}) \times \phi(\text{cm}^{-2}) \times \text{mass(g)} \times 10^3$$

NIEL

NIEL ⇒ "*Damage function*" *D*

The quantity NIEL is often given in terms of the
Displace Damage cross-section D
(also called damage function, or displacement kerma function)

KERMA = D × the incident fluence × number of irradiated silicon atoms
(KE released in matter)

remembering definition of a barn = 10^{-24} *cm*^{2}

KERMA(MeV) = D(MeV-mb) × ϕ(cm^{-2}) × (# Si atoms) × (10^{-27} cm^2/mb)

WARNING: sometimes D is called NIEL.

conversion factor for converting D → NIEL:

100 MeV-mb = 100 MeV-mb × (10^3 keV/MeV) × (10^{-27} cm^2/mb) × (mole Silicon/28.086 g) × (6.022×10^{23}/mole) =

= 2.144 keV-cm^2/g

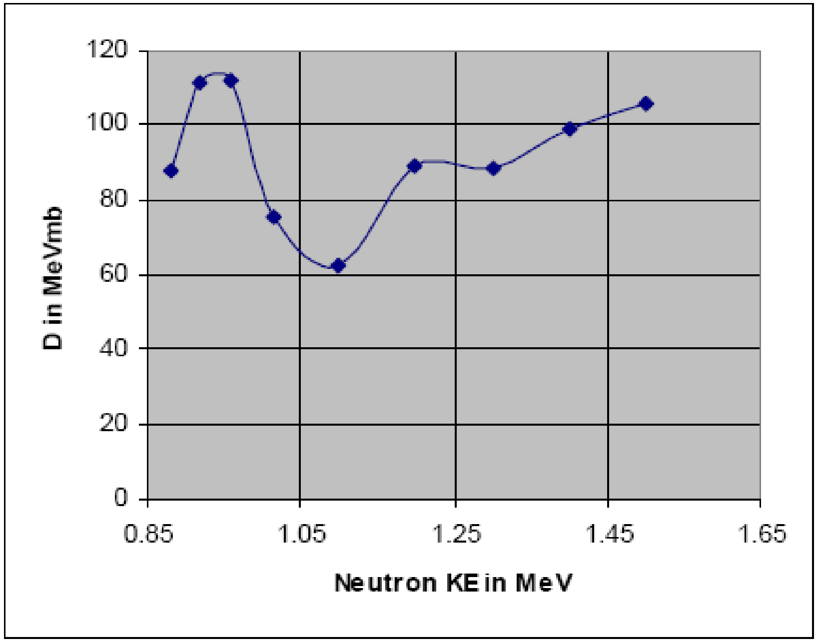
NIEL scaling

NIEL scaling hypothesis 1

Observation: degradation of silicon devices (detectors) is *roughly* proportional to *amount of displacement damage*
(i.e. to the kinetic energy imparted to the silicon atoms)

HYPOTHESIS: Displacement Damage is due to non-ionising energy transfers to lattice and can be expressed in terms of the damage caused by a certain flux of mono-energetic neutrons (equivalent damage)

Unfortunately the displacement damage by neutrons has a strong energy dependence.



Neutron displacement damage as a function of energy, from E 722-94 (1998 Annual Book of ASTM Standards)

"Standard" Bulk Damage

NIEL-hypothesis: "A particle fluence ϕ can be reduced to an equivalent 1 MeV neutron fluence ϕ_{eq} to produce the nearly the same bulk damage."

In silicon the *reference values* are:

D(1 MeV neutrons) = 95 MeV-mb

NIEL(1 MeV neutrons) = 2.037 keV-cm^2/g

These are chosen as STANDARD reference values when calculating the equivalent 1 MeV neutron fluence values for irradiations using:

- neutrons of another energy;
- other particle types (electrons, protons, pions, ions...)

NIEL scaling using "hardness factors"

"Damage parameters induced by different particles scale with NIEL!"
"To scale the effects of one radiation type to another, use the hardness factor K."

A generic damage parameter α (e.g. leakage current) measured with one type of radiation (X) should compare with the same parameter measured using another type of radiation (Y) scale according to:

$$\frac{\alpha(X)}{\alpha(Y)} = \frac{k(X)}{k(Y)}$$

always true?

α(X) and α(Y) are the generic damage parameters using radiations X and Y,

and

K(X) and K(X) are the hardness factors of radiation X and Y, respectively.

NIEL scaling

NIEL scaling of leakage current

skip

Use the hardness factor K to scale the fluence ϕ of a generic particle type and energy to an equivalent fluence ϕ_{eq} of a standard particle at standard energy.

leakage current density $\propto \phi$

$$\Delta j = \frac{\Delta I_{leak}}{Vol} = \alpha_X \cdot \Phi_X = \alpha_Y \cdot \Phi_Y$$

$$\Phi_Y = \frac{\alpha_X}{\alpha_Y} \cdot \Phi_X = K_{YX} \cdot \Phi_X$$

$$\Rightarrow \quad \Phi_{equivalent} = \frac{\alpha_{delivered}}{\alpha_{std}} \cdot \Phi_{delivered} = K \cdot \Phi_{delivered}$$

K>1

K<1

$$K = \frac{\Phi_{equivalent}}{\Phi_{delivered}}$$

e.g. for K=2, $\Phi_{eq} = 2\times\Phi$, hence 5×10^{13} particles/cm^2 make bulk damage equivalent to 10^{14} standard-ones/cm^2

GLOSSARY

Equivalent Fluence:

A quantity which attempts to represent the damage at different energies and from different particle types.

Hardness factors (also called damage coefficients) are used to scale the effect caused by particles to the damage caused by a standard particle type and energy.

In the context of non-ionizing energy loss effects, the standard particles are 1MeV neutrons.

For example: one hundred 50 MeV protons are "equivalent" to 226 1-MeV neutrons.

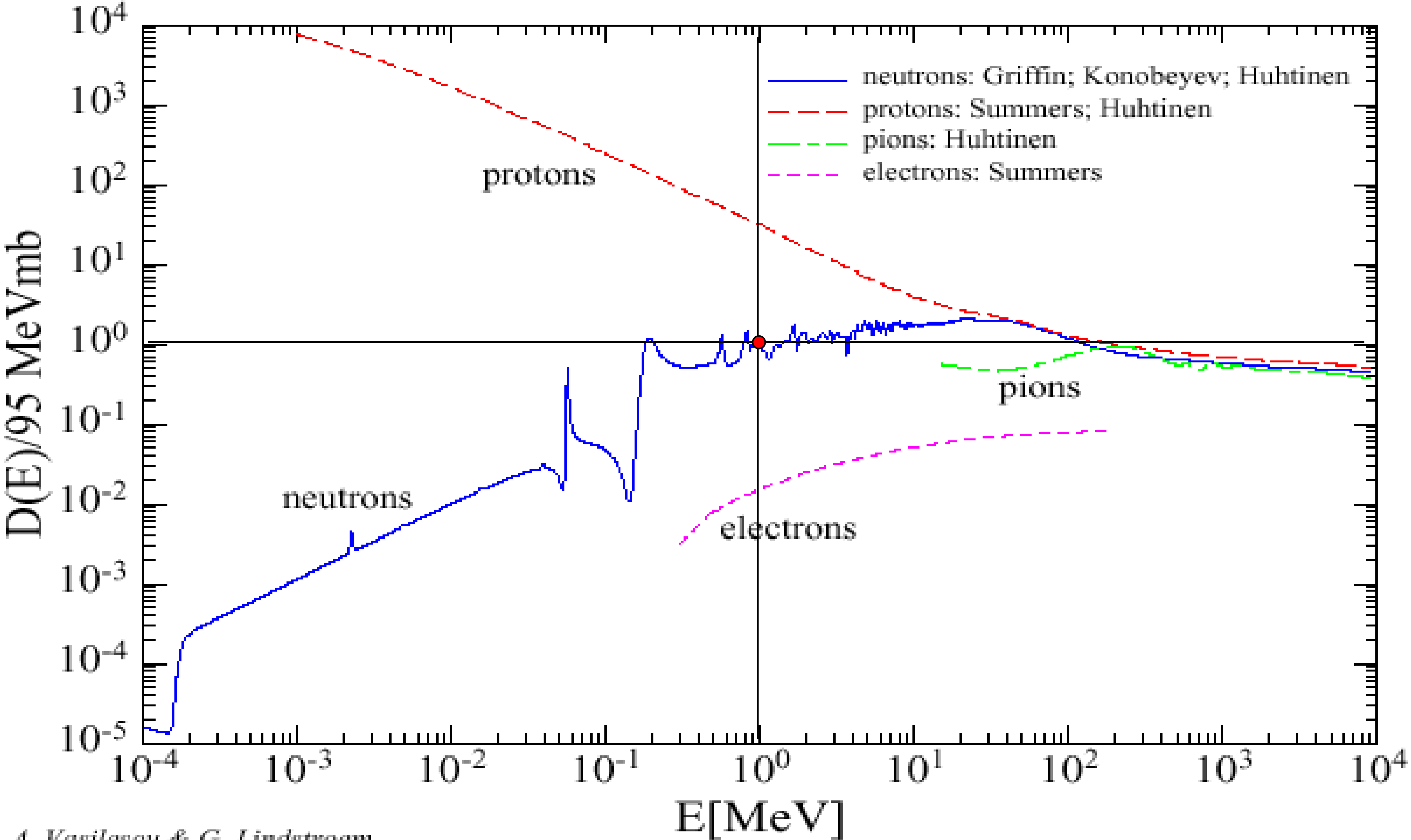
For solar cell degradation the standard particle is often taken to be 1MeV electrons. For example one 10-MeV proton is "equivalent" to 3000 1MeV electrons.

NIEL scaling

energy dependence of

Displacement damage cross-section D in silicon

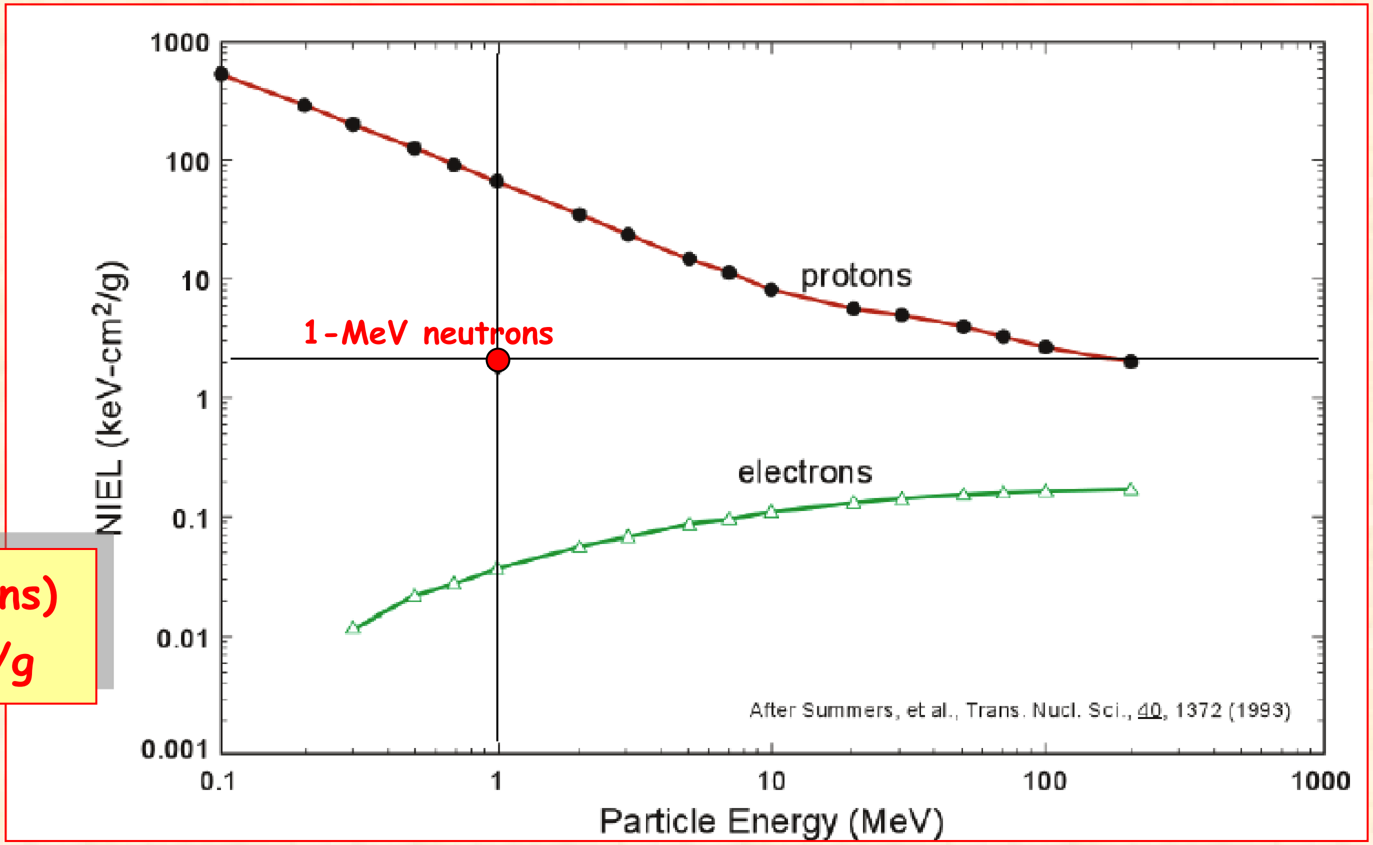
for neutrons, protons, electrons and pions



A. Vasilescu & G. Lindstroem

NIEL scaling

energy dependence of **NIEL** in silicon



NIEL(1 MeV neutrons) = 2.037 keV-cm²/g

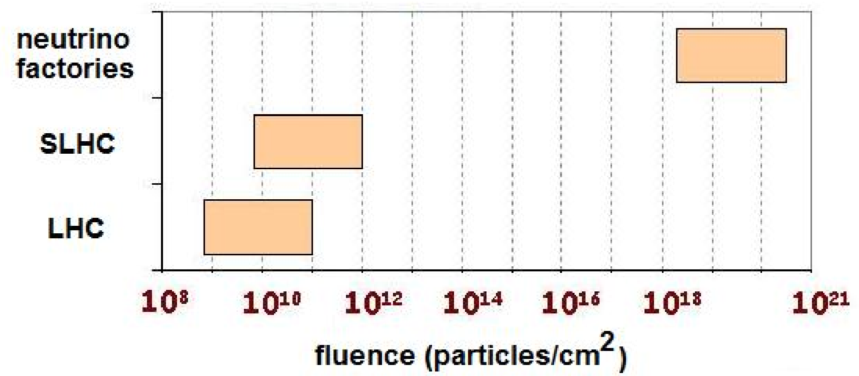
particle	total dose [rad(Si)]	ϕ fluence (part/cm²)	ϕ_{eq} equivalent neutron fluence (n/cm2)	hardness factor $K = NIEL/NIEL_0 = \phi_{eq}/\phi$
electrons (100 MeV)	100k	3.3×10^{12}	3.8×10^{11}	0.12
electrons (2 MeV)	100k	4.1×10^{12}	8.6×10^{10}	0.02
protons (50 MeV)	100k	6.2×10^{11}	1.4×10^{12}	2.26

Standard fluences

Non Ionizing Energy Loss

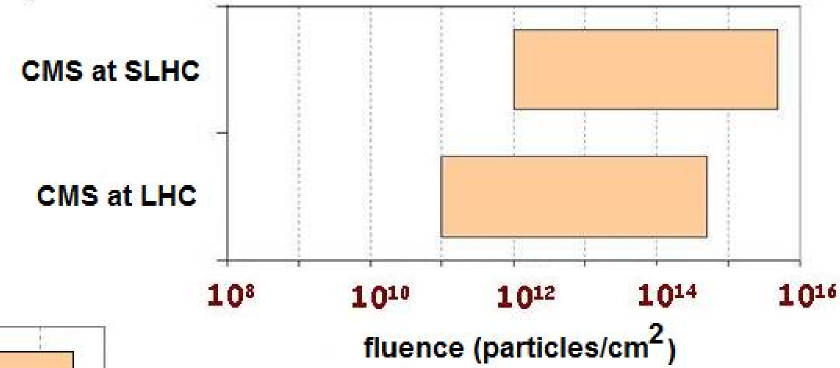
fluence expressed in *1MeV-equivalent neutrons*

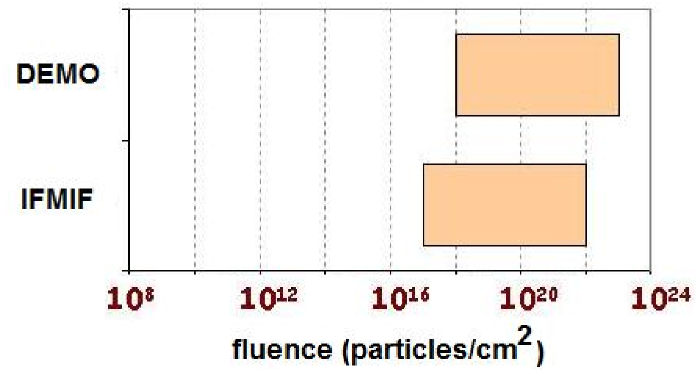
B. Camanzi and
A. G. Holmes-Siedle



Accelerators caverns

Experiments at accelerators





Nuclear fusion facilities

IFMIF
International fusion materials irradiation facility

PART 4: basic concepts of radiation damage in electronics

- Electronics, because of the thin sensitive layer, tends to be most sensitive to ionization and the associated accumulation of charge in the material.
- High levels of localized ionization can also affect the behavior of electronics.
- Detectors and sensors are sensitive to both ionization and displacement damage effects, with the most important damage often coming from bulk effect.

Effects of radiation in ELECTRONICS

❑ IONIZATION

- affects all ELECTRONICS
  - Charge build-up in insulating layers (*cumulative effect)*
  - Charge injection into sensitive nodes (*single effect*)

❑ ATOMIC DISPLACEMENT from lattice sites

*accumulation of damage to bulk (**cumulative effects**)*

- affects SENSORS and DETECTORS
  - Crystal structure damage
  - Introduction of traps
  - Introduction of mid-band states

radiation damage of electronics, detectors and sensors depends on device type and technology

Microscopic effects → physical quantities

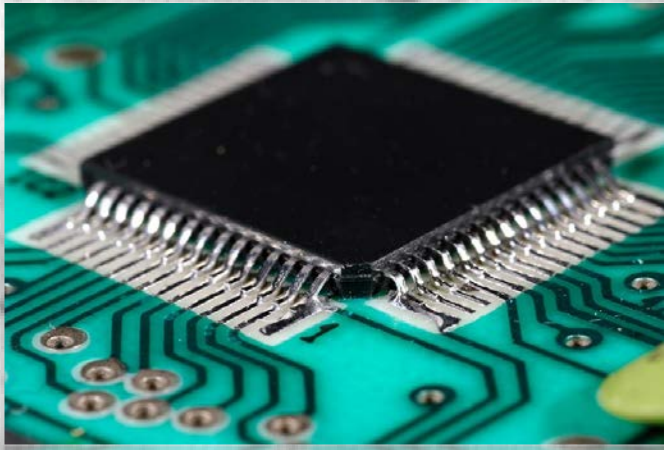
energy deposit variables: LET, TID, DDD

Particle type	*energy deposit*	*quality of measurable effect*	*variable*
heavy particles (primary and secondary): slow protons, α, ions, nuclear fragments	strong ionisation	highly structured tracks, Single Event Effects, Stochastic	Linear Energy Transfer (LET) of single ion
electrons (primary and secondary: compton, photo-electric), muons, m.i.p.	slight ionisation	less structured tracks → uniform; effect by accumulation of charges; predictable	integrated total ionising dose (TID)
neutrons, VERY slow ions (end of range)	non-ionising energy loss	effect by accumulation of displacement damage (*lattice disorder*); uniform (clusters); predictable	integrated displacement damage dose (DDD)

Radiation: Microscopic effects → macroscopic effects

		micro-effect	*macro-effect*
Light charged particles electrons, photons (indirect), muons, pions,...	Direct or secondary ionization	<u>Small</u> $\Delta E_{ionization}$ deposited uniformily and delivered over a long time.	**Total Integrated Ionizing Dose (TID) Effects**
heavy charged particles protons, alfa, **ions**	Direct ionization	<u>Sudden large</u> $\Delta E_{ionization}$ deposited in the '*wrong place at the wrong time*'.	**Single Event Effects**
protons, neutrons, high energy electrons, very slow ions	displacement damage of lattice	<u>Accumulation</u> of small ΔE transfers to atomic nuclei (Coulomb, nuclear interactions).	**DDD bulk effects:** enhancement of TID
Energetic heavy particles (protons, neutrons, energetic ions)	Secondary ionization by recoil atoms and nuclear fragments	<u>Sudden</u> high ΔE transfer to a single nucleus at the '*wrong place and time*'.	**Single Event Effects**

SEE effects



"Single Event Effects" (SEE) are becoming more and more important!

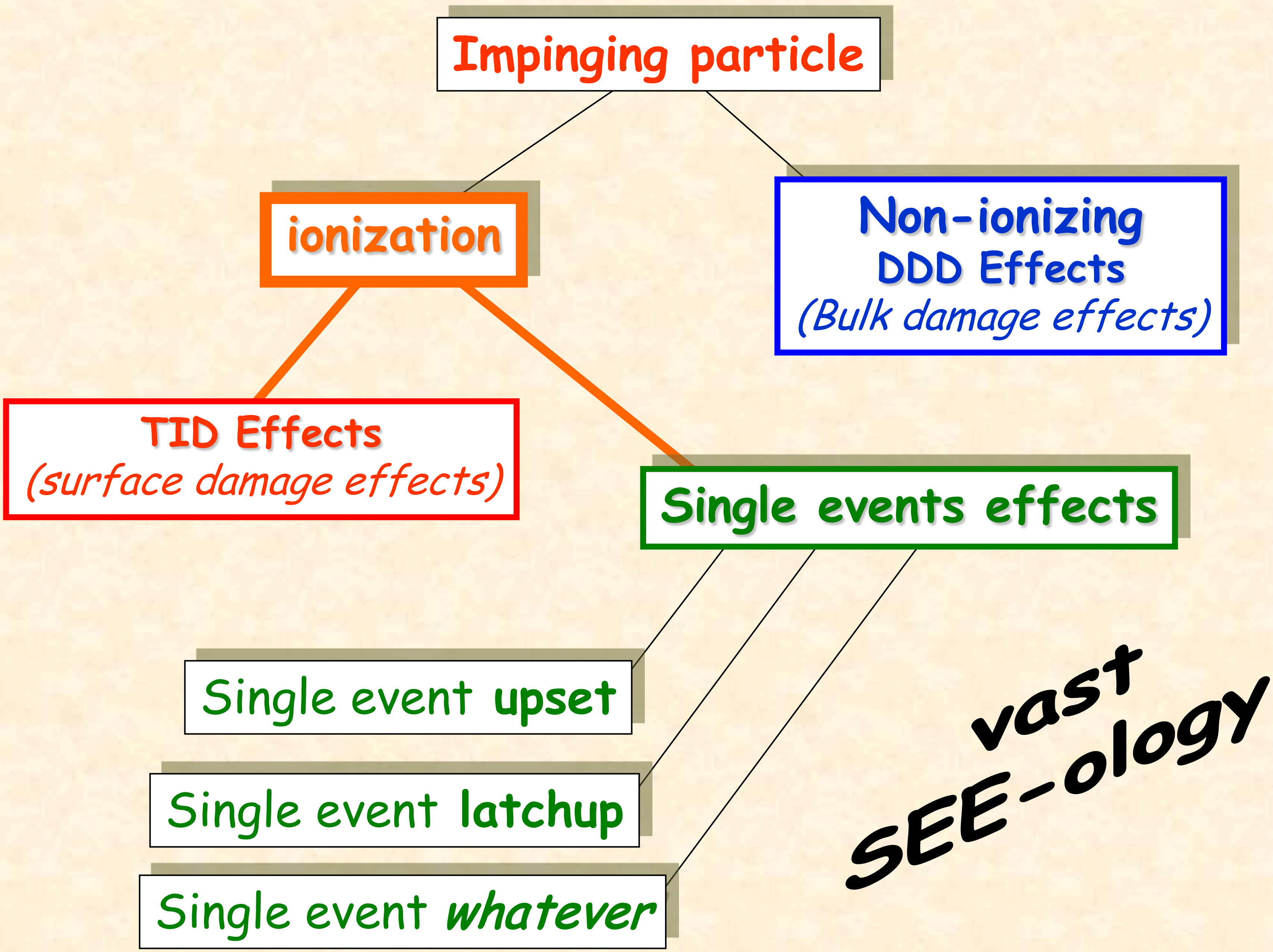
This is due to:

- technology evolution (electronics everywhere!)
- increased sensitivity hence stricter requirements for new applications outside of traditional fields
- growing complexity of whole systems (computers, servers,…)

Single Event Effects (SEE)

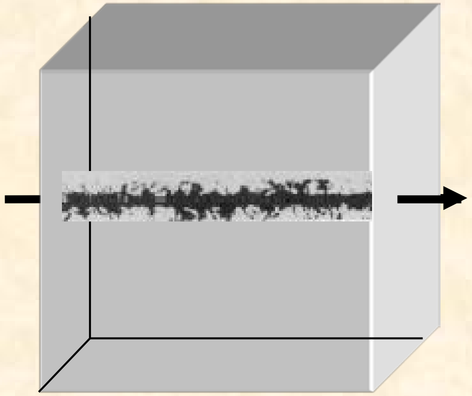
1. In space applications electronic devices may receive direct impacts of galactic and extra-galactic heavy energetic ions (HZE) cosmic rays during operational lifetime of a spaceflight.
2. Energetic neutrons and protons may produce secondary highly ionizing ions may be produced in nuclear interactions.
3. Highly ionizing ions are produced indirectly (secondaries) in the experimental halls of High Energy Physics experiments such as LHC where huge quantities of hadrons are produced.
4. Neutrons are a problem in avionics and at sea level.

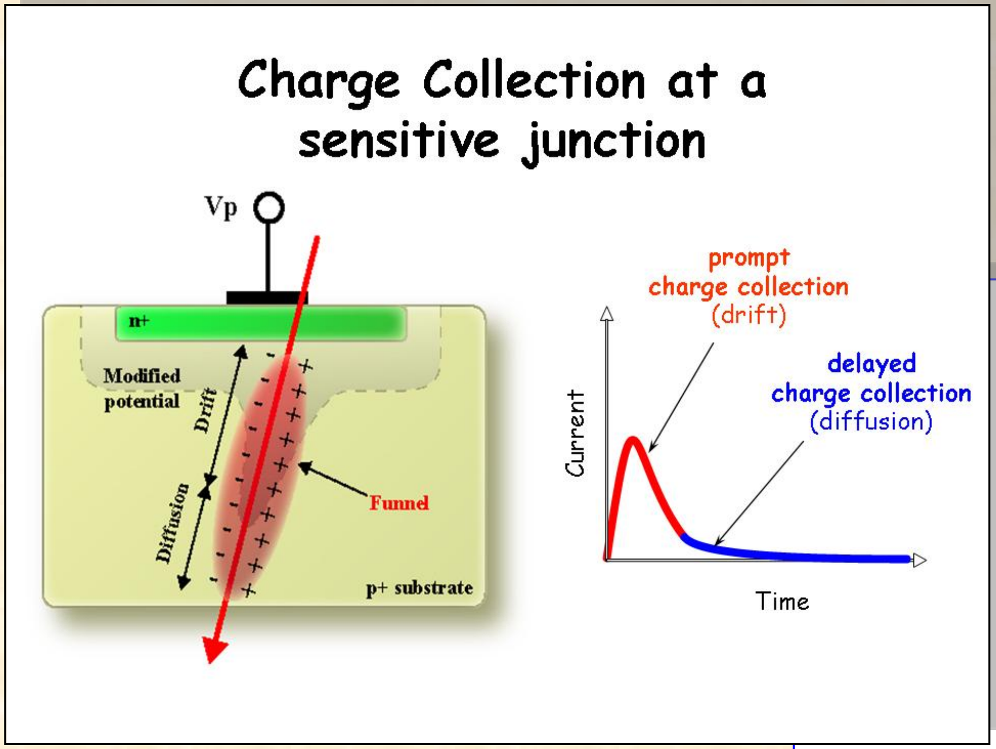
Radiation Damage on Semiconductor Devices

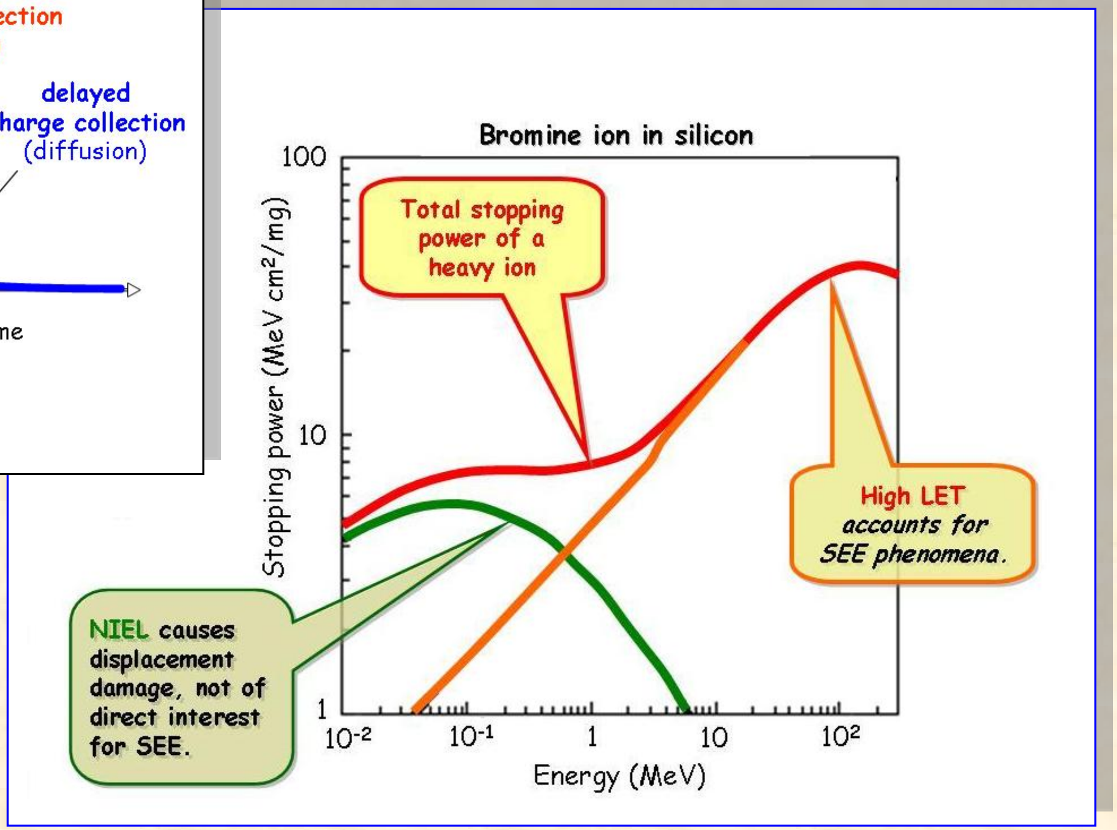


When an heavily ionizing particle (e.g. a heavy ion) interacts with a device it leaves an ionization trail that perturbs the device.

Ions deposit ionization energy in highly structured pattern

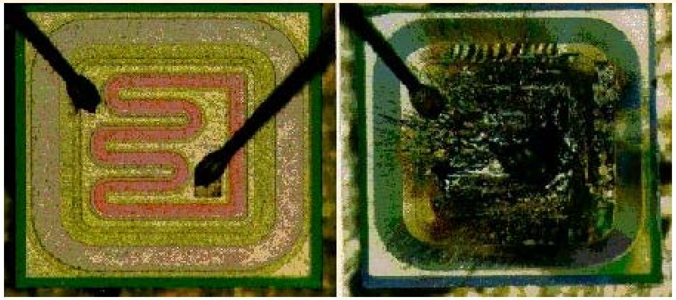


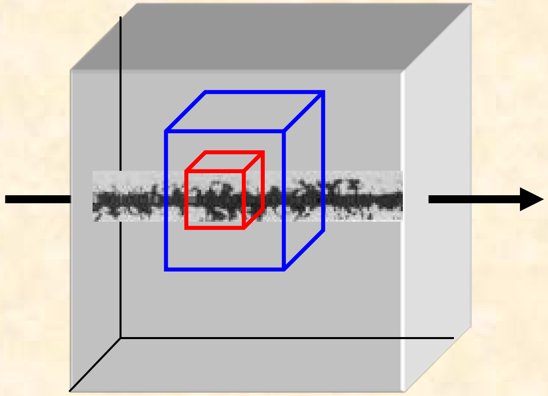




Depending on circumstances the ionization induced perturbation may cause negative effects:

- a transient in the device output
- a bit flip
- a destructive latch-up
- burn-out, especially in high-power transistors etc. etc.





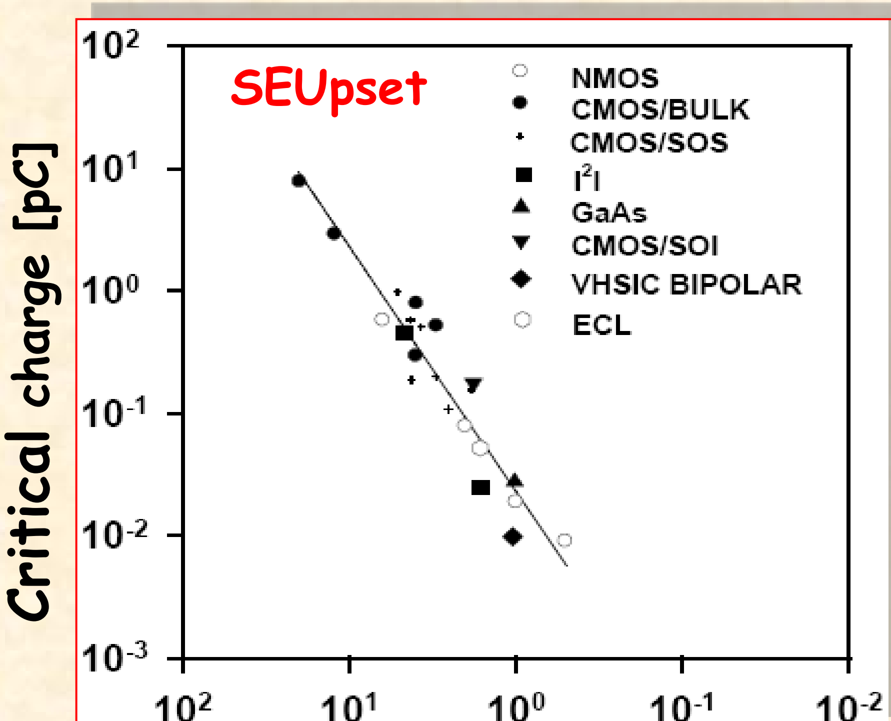
A SEE occurs if an **ionizing particle** deposits in a **sensitive volume** a charge higher than some *threshold value*.

For a given radiation environment the mechanism of an SEE and the chance of it occurring depend on the device and the technology.

For a given device the rate of SEE is proportional to the flux of particles with sufficient LET.

Experimental concepts:

- threshold charge ⇒ LET,
  cross-section σ as a function of LET.



Feature size [μm] (size of technological process)

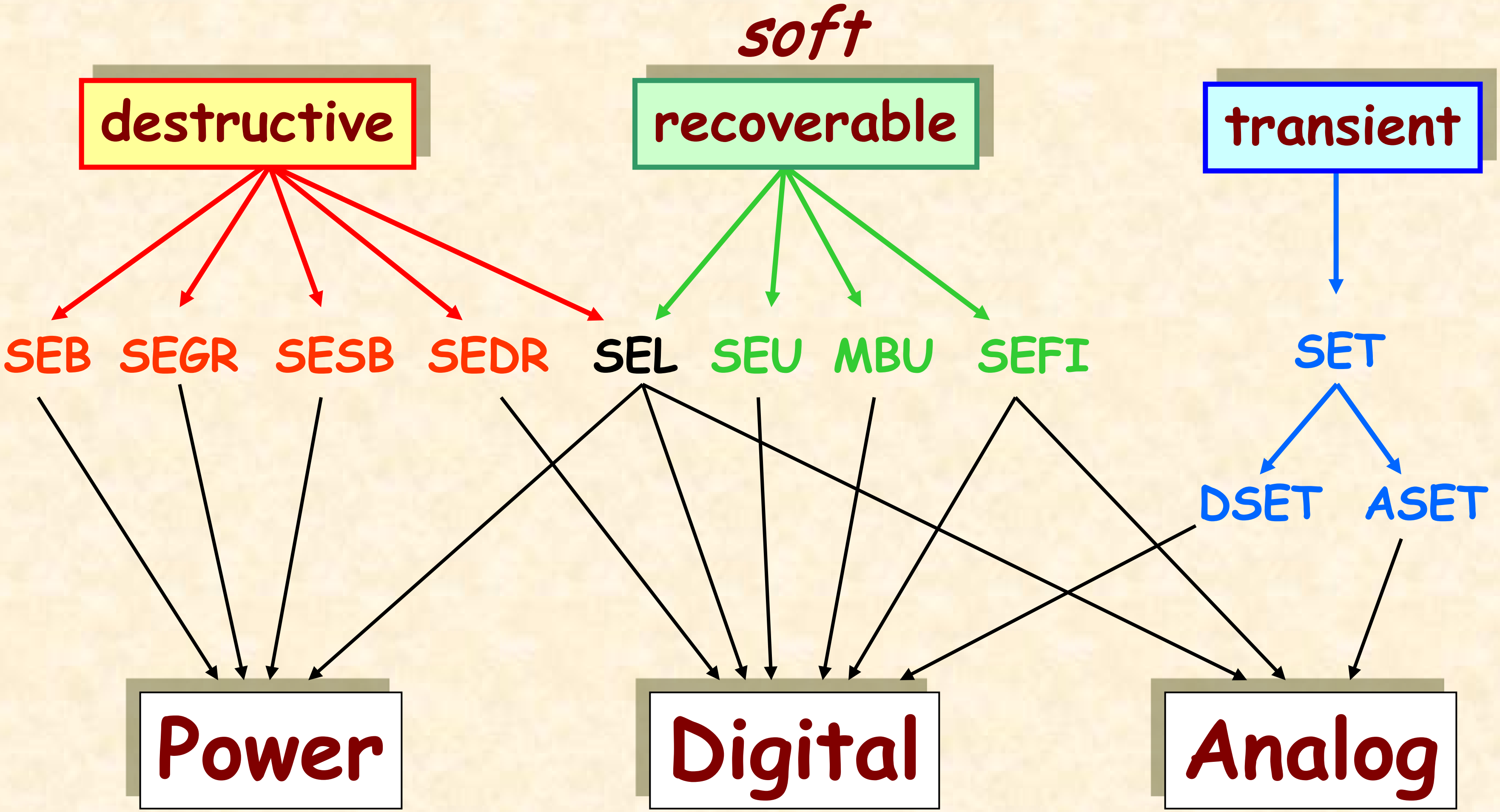
Component technology evolution

Parameters affecting SEE:

- **critical charge** (amount needed to change the logic state of a cell)
- **sensitive geometry** (the volume in which the deposited charge is effective to generate a perturbation in the device)
- number of elements (complexity)

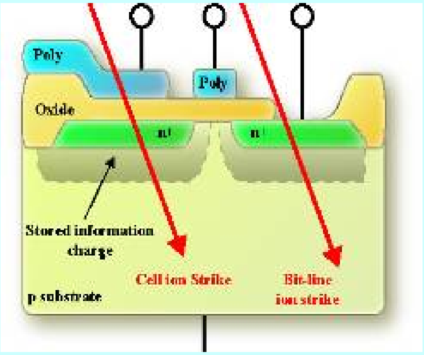
Technology node (nm)	Sensitive volume of Si (μm^3)	Critical charge in Si (fC)
250	0.245	8
130	0.025	2.5
90	0.02	1.2
65	0.0035	0.8

SEE

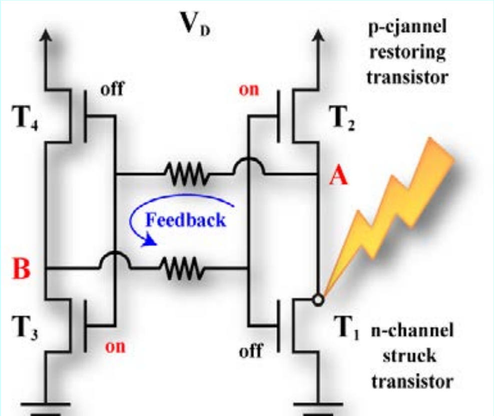

soft
destructive
recoverable
transient
SEB
SEGR
SESB
SEDR
SEL
SEU
MBU
SEFI
SET
DSET
ASET
Power
Digital
Analog

Soft (non-destructive) vs Hard (destructive)

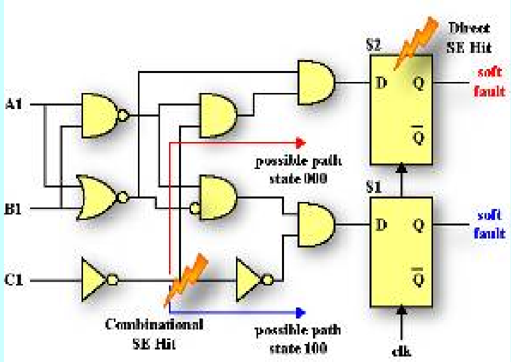
Soft errors



DRAM cell flip

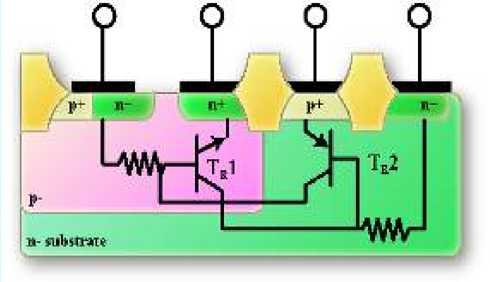


SRAM cell flip

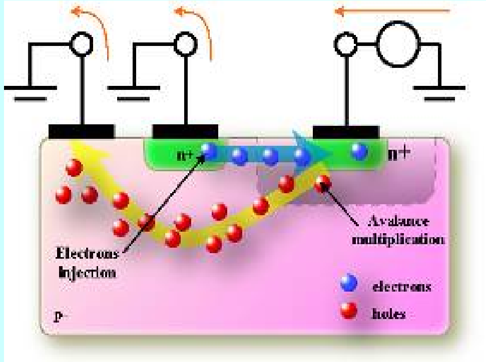


Propagation in logic

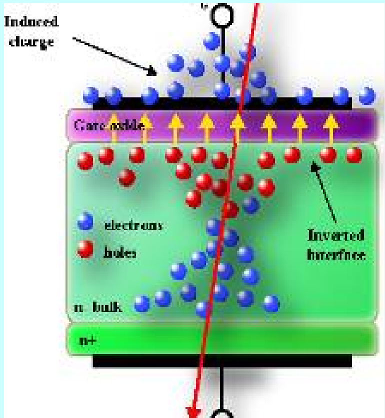
Hard errors



SE Latchup in pnpn CMOS structure



SE Snap-back in n-MOS transistor



SE Gate rupture

Single Event Effects (SEE)

- ❑ **Upset (SEU): change in logic state, e.g. SRAM memory**
  - **temporary loss in equipment functionality**
  - **temporary modification to system behaviour**
  - **functionality returns without power cycle**

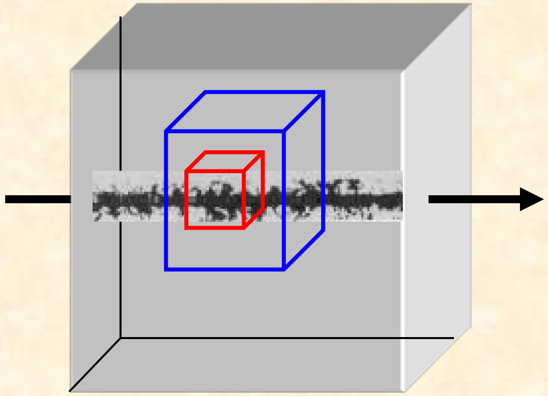
- ❑ **Latch Up (SEL): creation of low-impedance short circuit that triggers a *parasitic PNPN structure* that stops proper functioning**
  - **Requires power cycle to correct; may be destructive**

- ❑ **Single Event Burnout (SEB):** an ion induced current flow turns on the parasitic npn transistor below the source that leading to device destruction if sufficient short-circuit energy is available.

- ❑ **Single Event Gate Destruction/Rupture (SEGD/R):** an ion through the gate (but avoiding the p-regions), generates a plasma filament through the n-epi layer that applies the drain potential to the gate oxide, ***damaging*** (increased gate leakage) or ***rupturing*** the gate oxide insulation (device destruction).
  - **permanent damage to power transistors or other high voltage devices**

GLOSSARY

	Description	Affected devices
SEU **upset**	Corruption of information	Memories, latches in logic devices
MBU **multiple bit upset**	Several momeory elements corrupted by single ion	Memories, latches in logic devices
SEFI **functional interrupt**	Loss of normal operation	Complex devices with built in state/control sections
SET **transient**	Pulse response of certain amplitude and duration	Analog, mixed signal devices
SED **disturb**	Momentary corruption of info in a but	Combinatorial logic, latches in logic devices
SHE **hard error**	Unalterable change of state of a memory cell	Memories, latched in logic devices
SEL **latchup**	Generation of unexpected high current	CMOS, BiCMOS
SESB **snap back**	Generation of unexpected high current	N-channel power MOSFETs, SOI
SEB **burnout**	Destructive burn-out	BJT, etc.
SEGR **gate rupture**	Rupture of gate dielectric	Power MOSFETs
SEDR **dielectric rupture**	Rupture of dielectric layer	Non-volatile NMOS, FPGA, linear devices



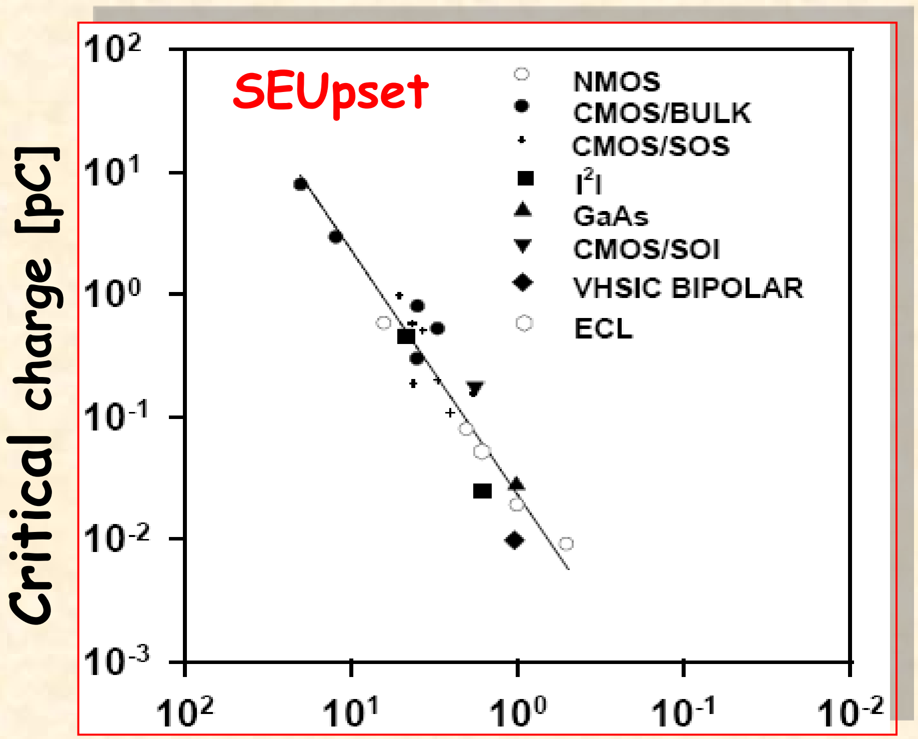
A SEE occurs if an **ionizing particle** deposits in a **sensitive volume** a charge higher than some *threshold value*.

For a given radiation environment the mechanism of an SEE and the chance of it occurring depend on the device and the technology.

For a given device the rate of SEE is proportional to the flux of particles with sufficient LET.

Experimental concepts:

- **threshold charge ⇒ LET, cross-section σ as a function of LET.**



Feature size [µm] (size of technological process)

SEE rates

- ❑ **determine sensitivity volume**

  Difficult to determine!
  - must make assumptions about device geometry
  - the sensitive volume smaller than physical geometry
  - the sensitive volume is different for different ions

- ❑ **measure the cross-section vs LET**
- ❑ **determine the LET effective spectrum**

  Depends on radiation environment (e.g. orbit), shielding,...

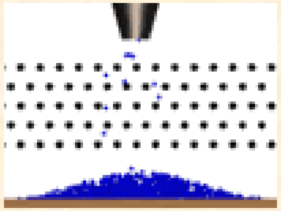
May calculate rate.

What is a SEE cross-section?

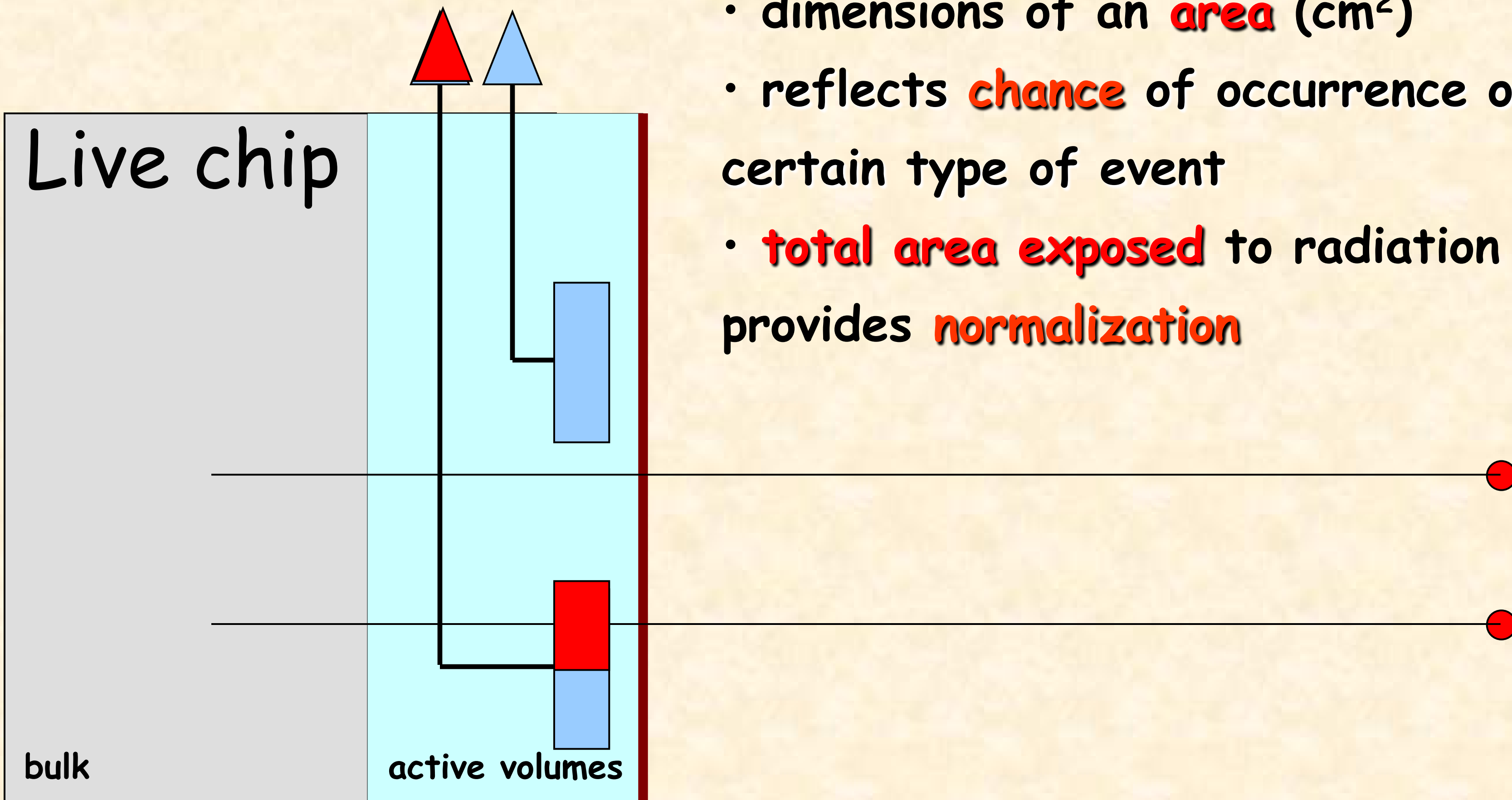
cross-section: SEE

Single Event Effects
The cross-section concept

σ

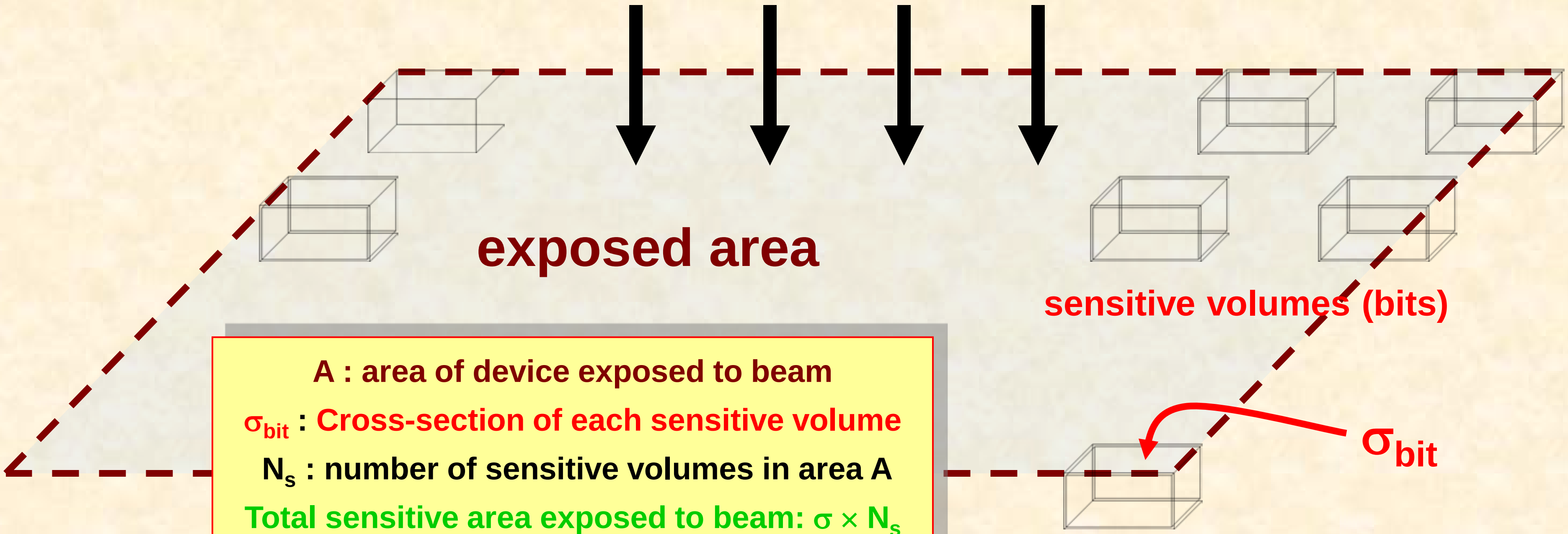


- useful and pervasive concept in radiation (examples from HEP, SEE)
- dimensions of an **area** (cm^2)
- reflects **chance** of occurrence of a certain type of event
- **total area exposed** to radiation provides **normalization**



cross-section: SEE

SEE experimental cross-section



A : area of device exposed to beam

σ_{bit} : Cross-section of each sensitive volume

N_s : number of sensitive volumes in area A

Total sensitive area exposed to beam: $\sigma \times N_s$

fraction of incident particles that cause SEE **N_{SEE}/N_{inc}**

is equal to the

fraction of exposed area that is sensitive

$$\frac{N_{SEE}}{N_{inc}} = \frac{N_s \cdot \sigma_{bit}}{A} \Rightarrow \text{number of events} \quad N_{SEE} = N_s \frac{N_{inc}}{A} \sigma_{bit} = N_s \cdot \sigma_{bit} \cdot \Phi_{inc}$$

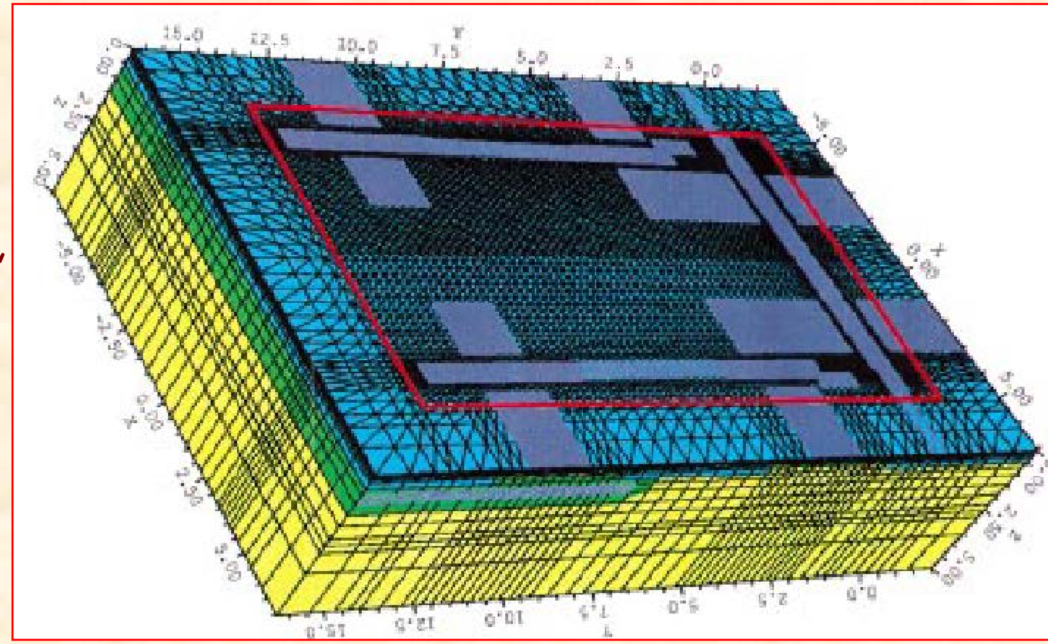
Experimentally: $\sigma_{bit} = \dfrac{N_{SEE}}{N_S \cdot \Phi_{INC}}$ $\qquad \sigma_{device} = N_s \cdot \sigma_{device} = \dfrac{N_{SEE}}{\Phi_{INC}}$

SEE

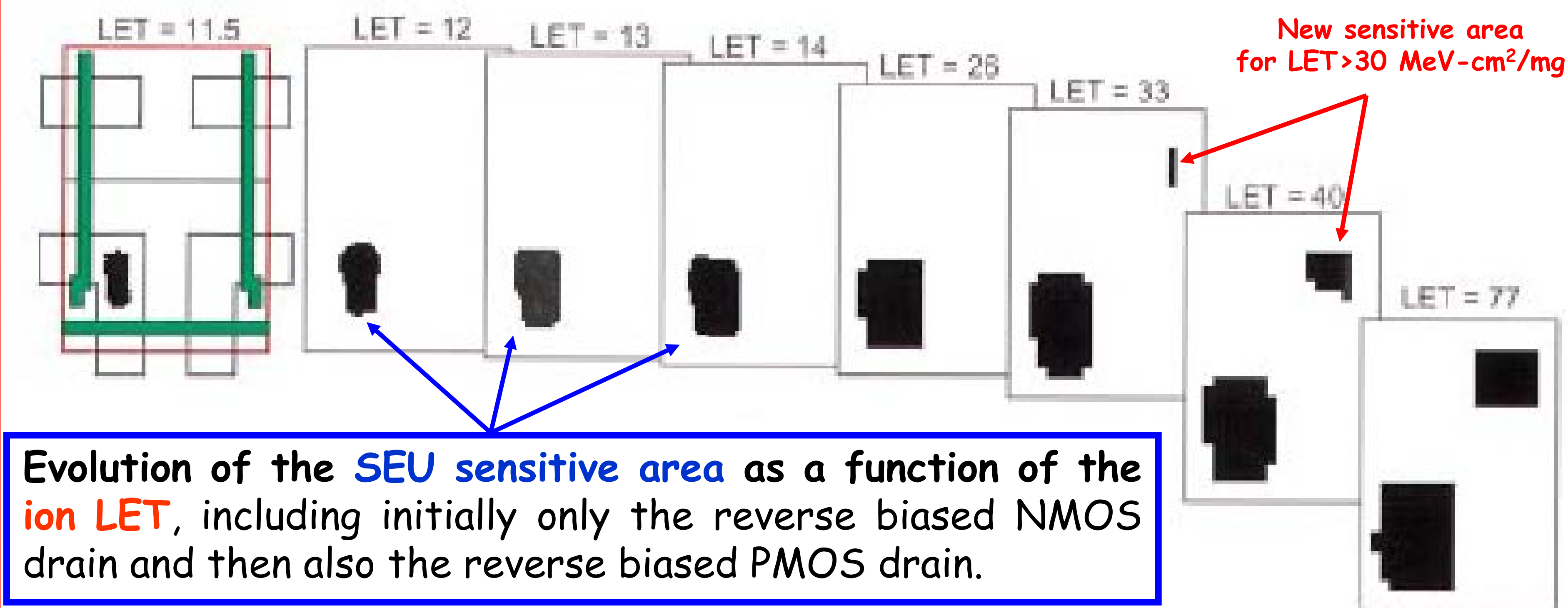
sensitivity micro-map

CMOS 256K SRAM
unit cell SEU *simulation*

Davinci 3D-simulation, P.E.Dodd et al., IEEE Trans.Nucl.Sci. Vol 48 pp1893-1903, Dec. 2001



Simulations performed for ion strikes incident every 0.5 μm throughout the unit cell.



Evolution of the SEU sensitive area as a function of the ion LET, including initially only the reverse biased NMOS drain and then also the reverse biased PMOS drain.

broad beam SEE experiments

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

(*) In silicon a LET of 97 MeV-cm^2/mg corresponds to *charge deposition per unit path length* of 1pC/μm. NOTE factor ~100: it is handy for conversion.

WEIBULL FIT of threshold curve

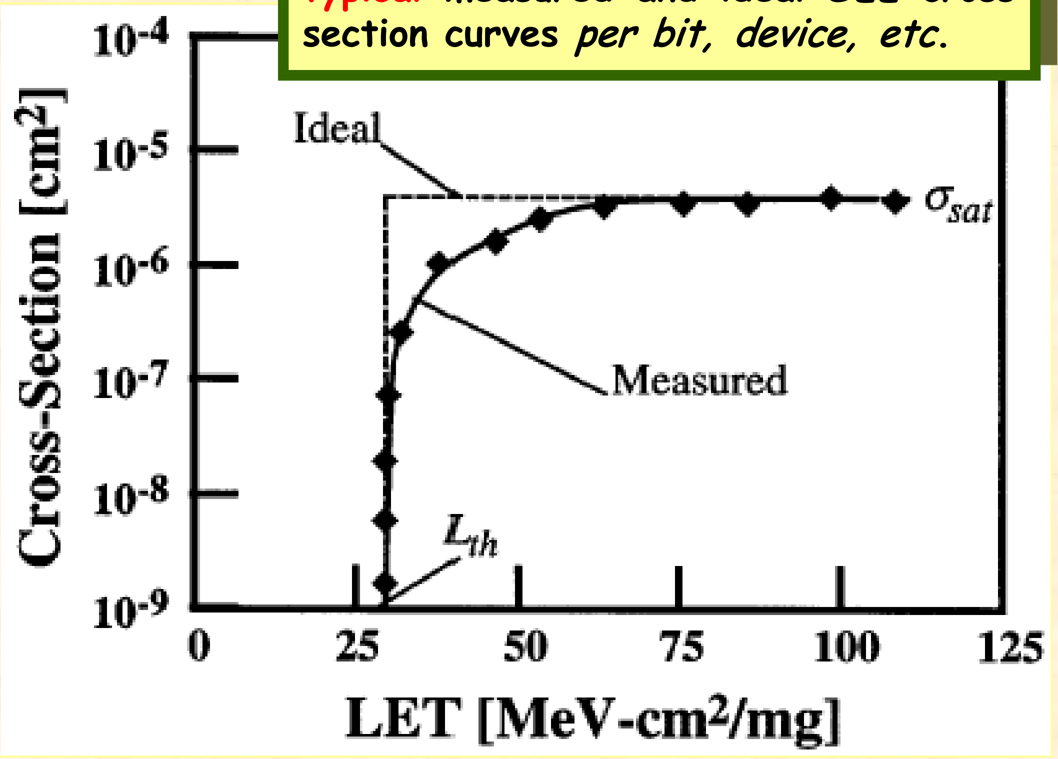
$$\sigma = \sigma_{sat} \times \{1-\exp[-(L-L_{th})/W]^S\}$$

σ_{sat}: saturation value

L_{th}: threshold LET value

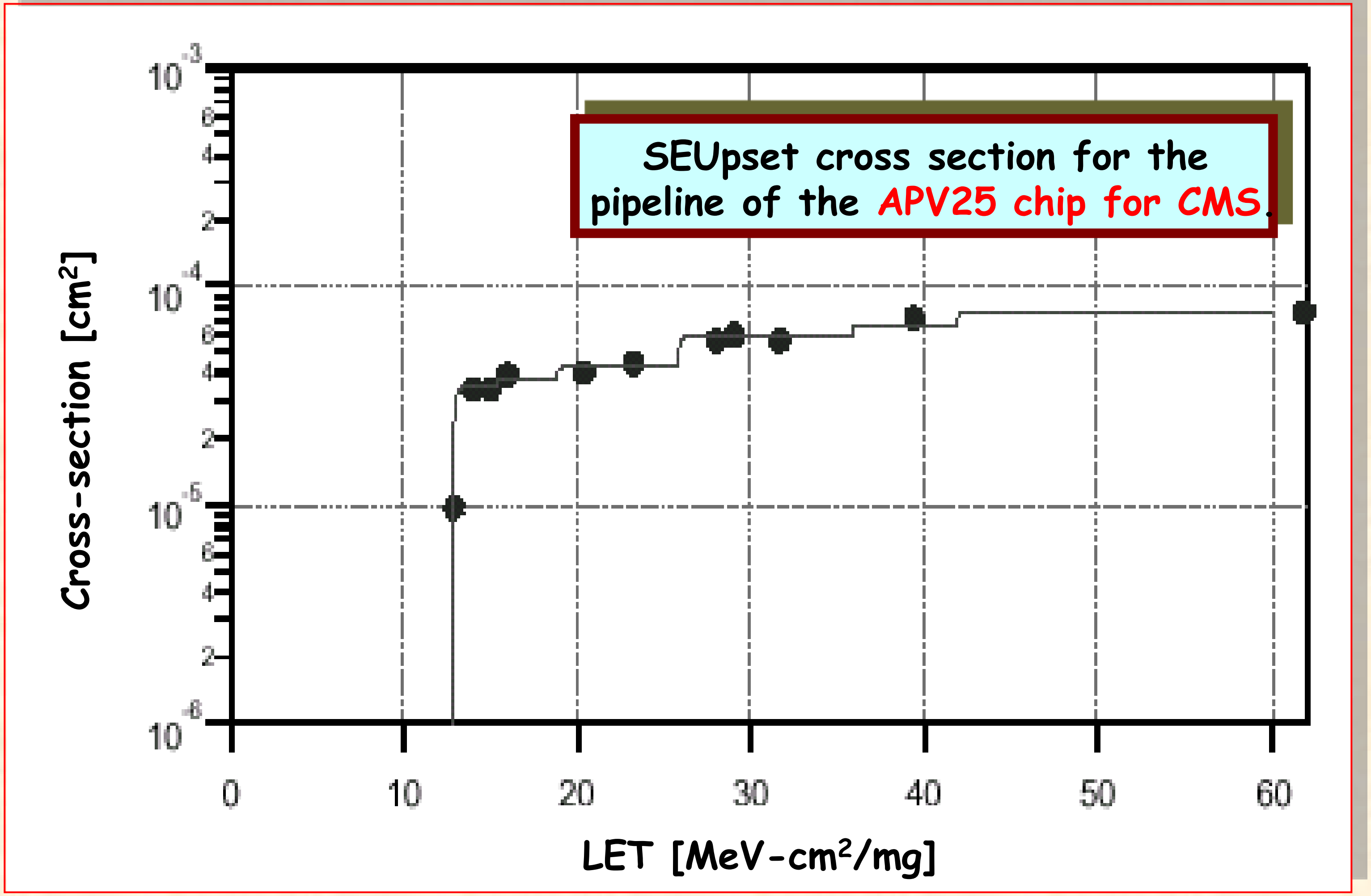
W and s are fitting parameters

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



SEE

SEE effects in Application Specific-ICs at SIRAD (LNL)



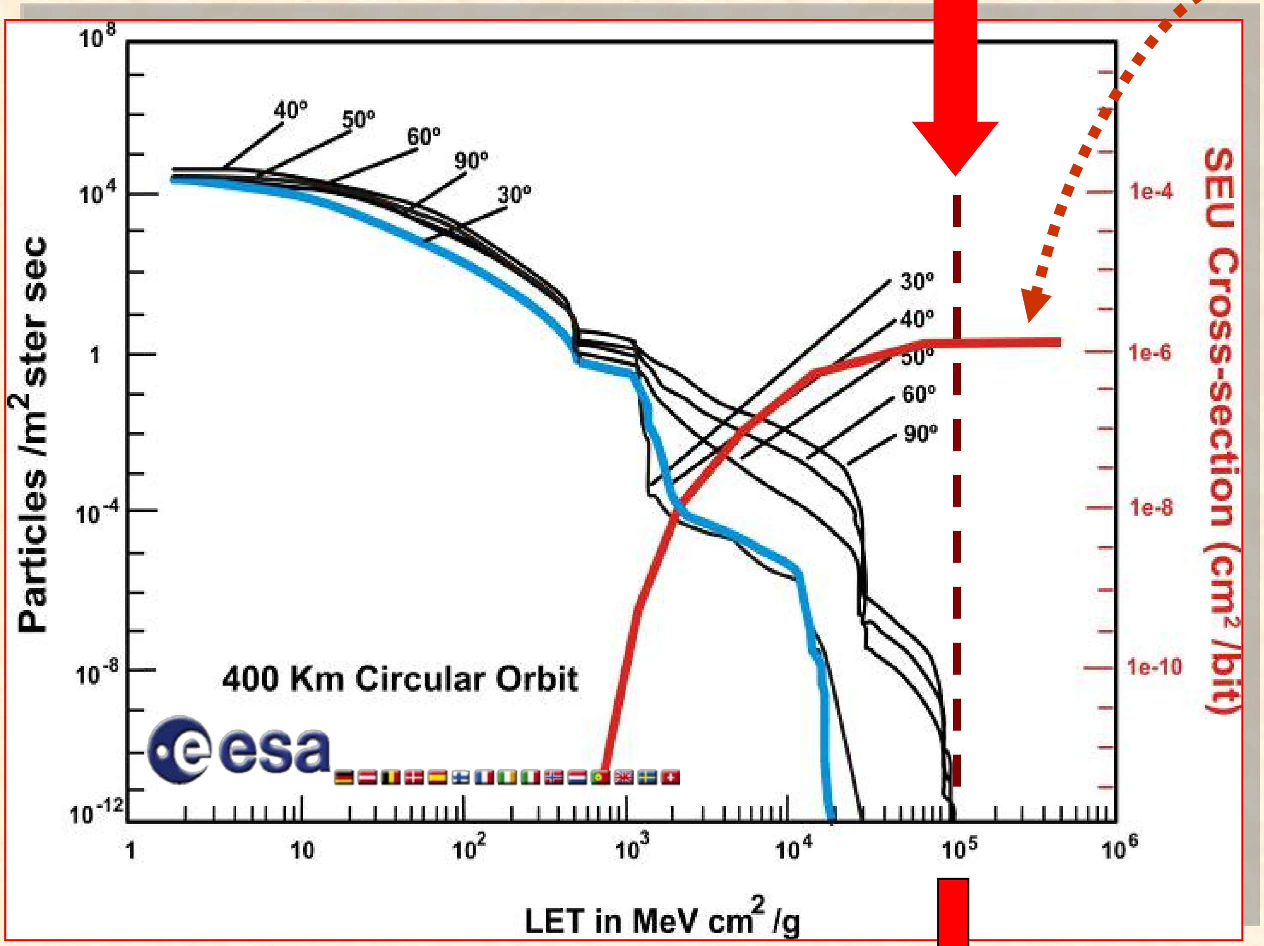
Solid line is a multiple Weibull fit based on simulations

Ion induced SEE cross sections in real contexts

Integral distribution
(No. of ions with LET > LET_0)

natural cutoff

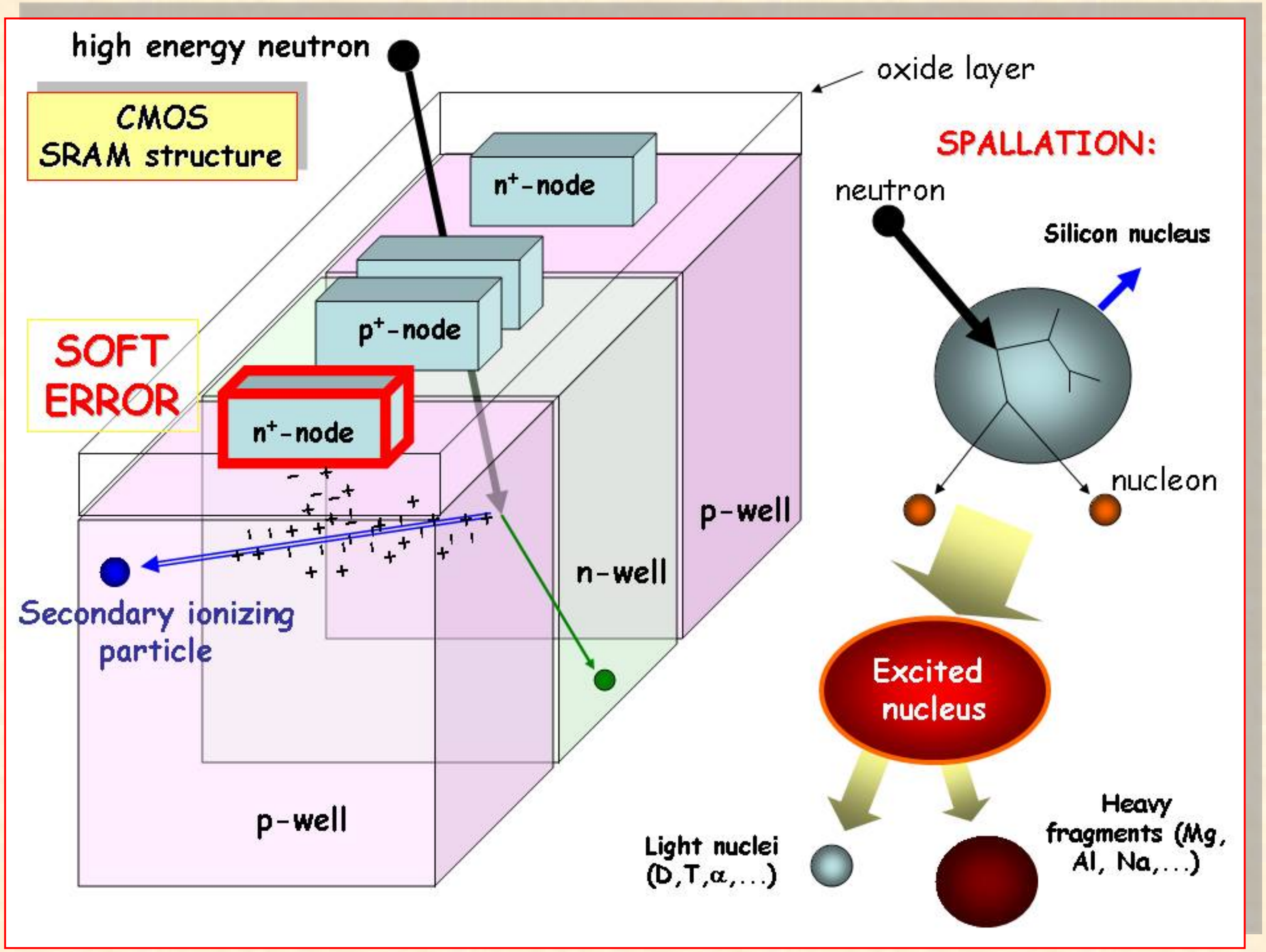
σ(LET) of device



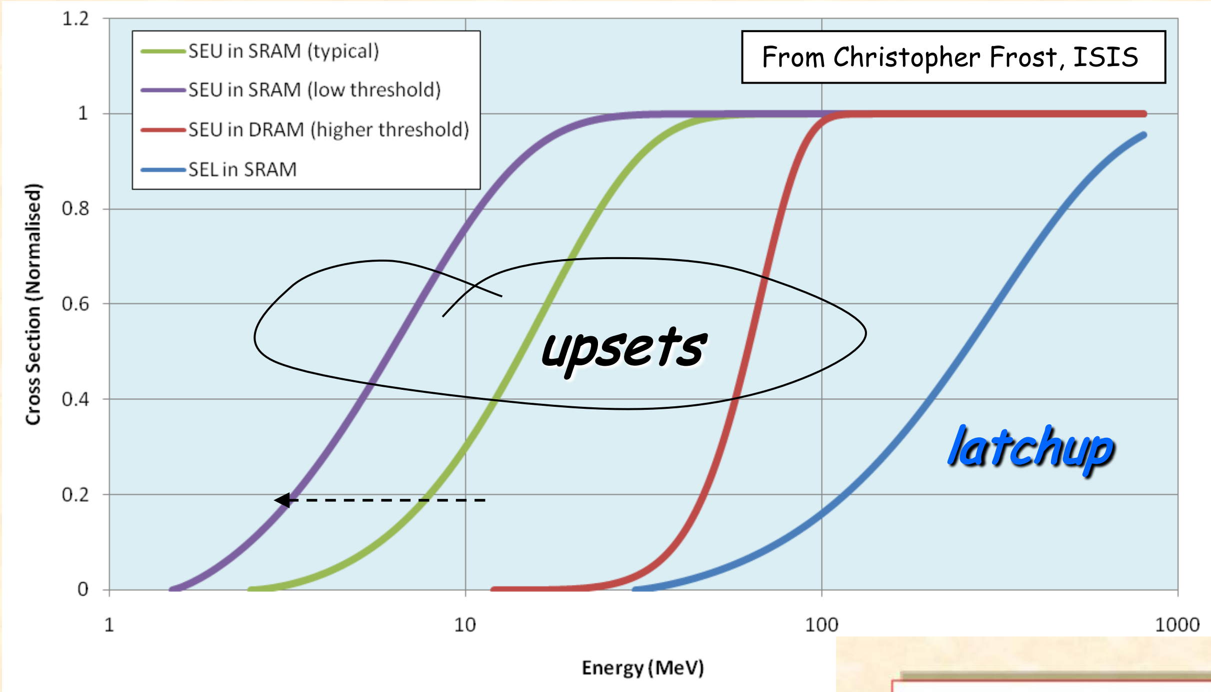
100 MeV cm^2/mg

Hadron induced Single Event Effects (SEE)

a fast neutron (E > few MeV) interacts with a nucleus
to produce a heavily ionizing secondary that then
causes an anomalous macroscopic effect in an electronic device.

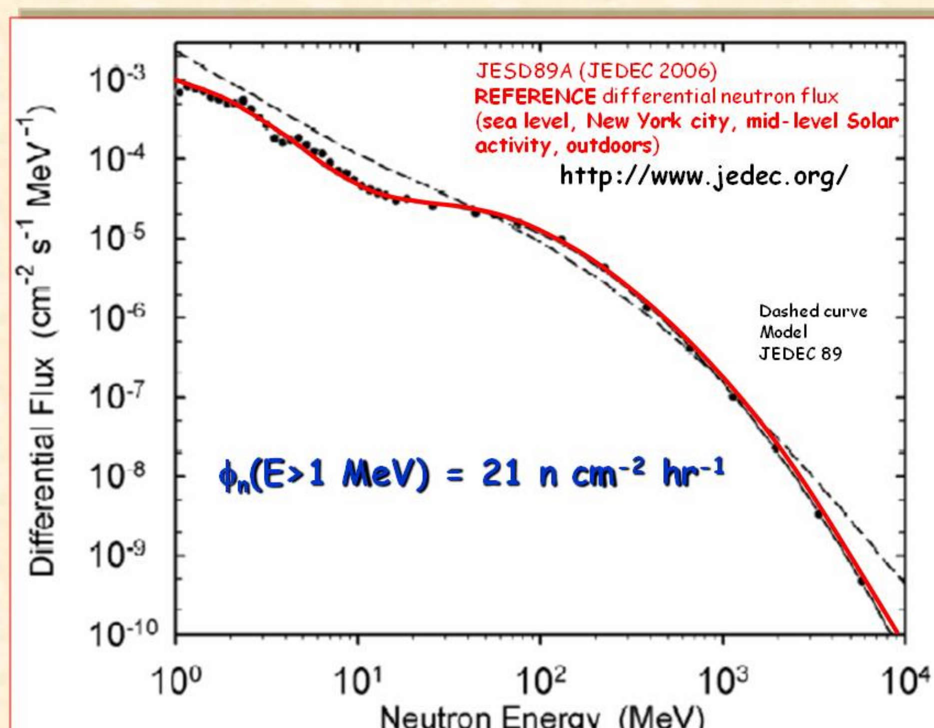


Note: to fragment a nucleus and cause a SEE, a **charged hadron** (proton, pion, kaon,...) needs to overcome coulomb barrier.



SEE Cross Sections induced by fast neutrons (E_n > 1 MeV)

Reference neutron differential energy spectrum



Rate of SEE in device with N_{bits}

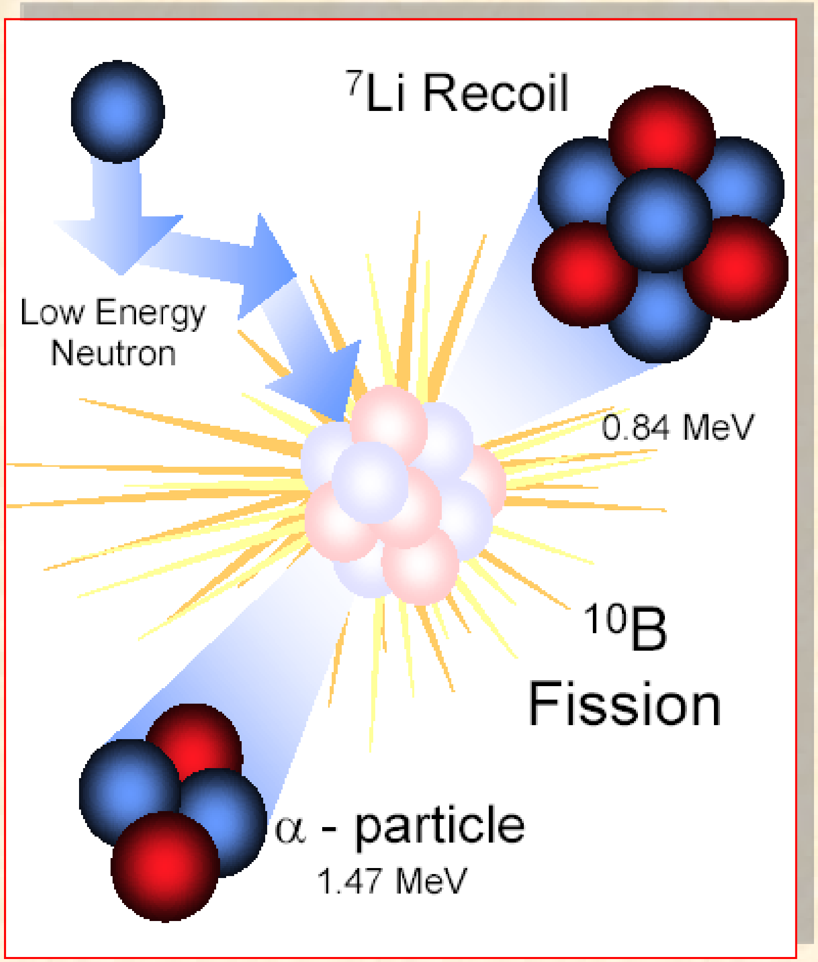
$$Rate_{SEE} = N_{bits} \times \int_{E_0}^{E_{max}} \sigma_{dev}(E)\varphi_{NY}(E)dE$$

Slow thermal neutrons too

The SEE problem with low energy neutrons too due to use of Boron-10 in the <u>cover glass layer of some microchips</u> (*Borophosphosilicate glass - BPSG). BPSG was used as for a polishing technique. It has been replaced with a Chemical Mechanical Polishing (CMP) technique.*

Boron-10 has a high cross-section for emission of an alpha particle when struck by a **thermal neutron** (a neutron slowed to be in thermal equilibrium with its environment)

N.B. Thermal neutron may induce SEE when Boron concentration becomes extremely high (e.g. PMOSFETS)



SEE

Single Event Effects (SEE)

- single ionizing particle deposits enough ionization in a sensitive volume to cause spontaneous damage in live device. Note: it requires a minimum amount of ionization!
- due to:
  - heavy ions (e.g. primary galactic high charge and energy cosmic rays)
  - neutrons
  - protons, pions

  (neutrons, protons, pions) ⇒ Ionizing nuclear fragments
- effects in live electronics depend greatly on technology and design:
  - permanent HARD SEE (may be destructive)
    - SEL (CMOS, CPUs, PLC,...
    - SEB (MOSFETs, power devices,...)
    - SEGR (power MOSFETS)
    - ...
  - static SOFT SEE (data corruption)
    - SEU (RAM, PLC,...)
    - SEFI
  - transient SEE (spurious signal)
    - combinatorial logic
    - operational amplifiers

physical quantities of interest:

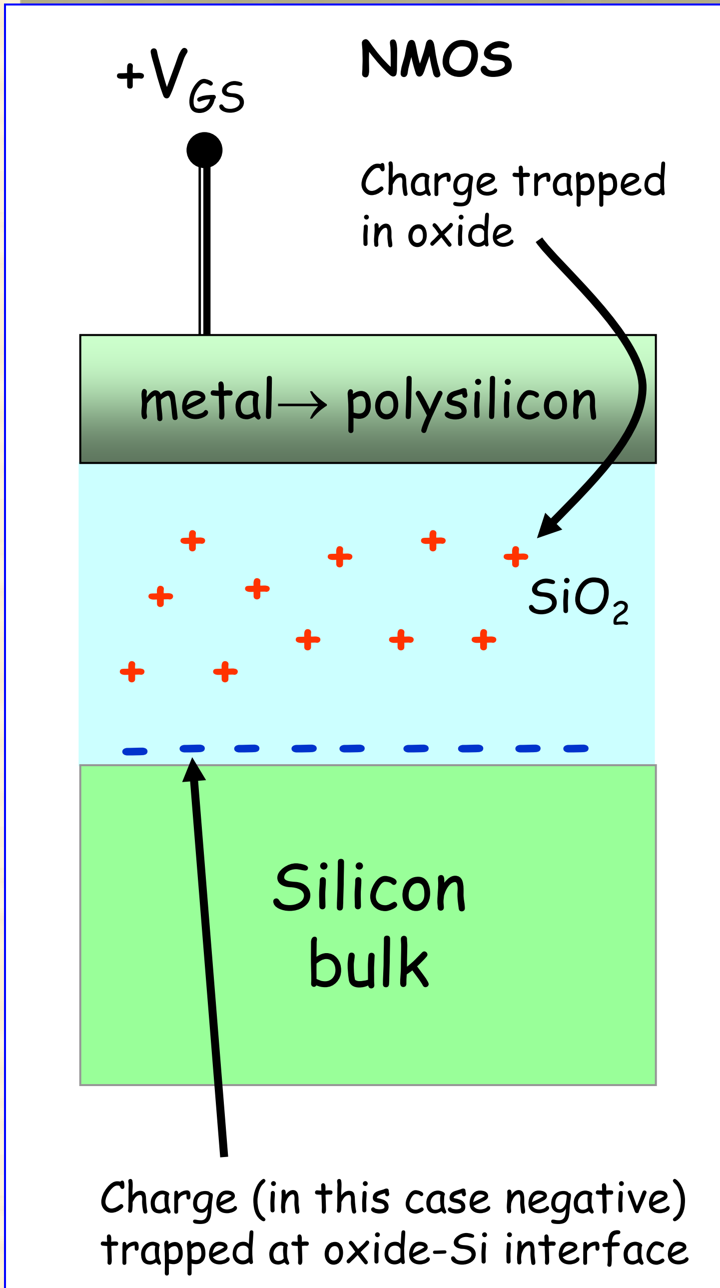
- particle fluence Φ(#/cm^2)
- Linear Energy Transfer (LET) (keV-cm^2/g)
- hadron energy
- cross-section $\sigma(cm^2) = N_{SEE} / \Phi$
- σ *versus* LET (ions) or energy E (hadron) (threshold and plateau values)

- rate of effects scale with particle flux
- tolerance of devices expressed in cross-section(cm^2) = N_{SEE}/fluence
- depends on specific ionization power of culprit LET > $LET_{threshold}$
- in hadron environment SEE rates proportional to hadron flux E > 20 MeV $E_{neutrons}$> 2 MeV

SEE testing

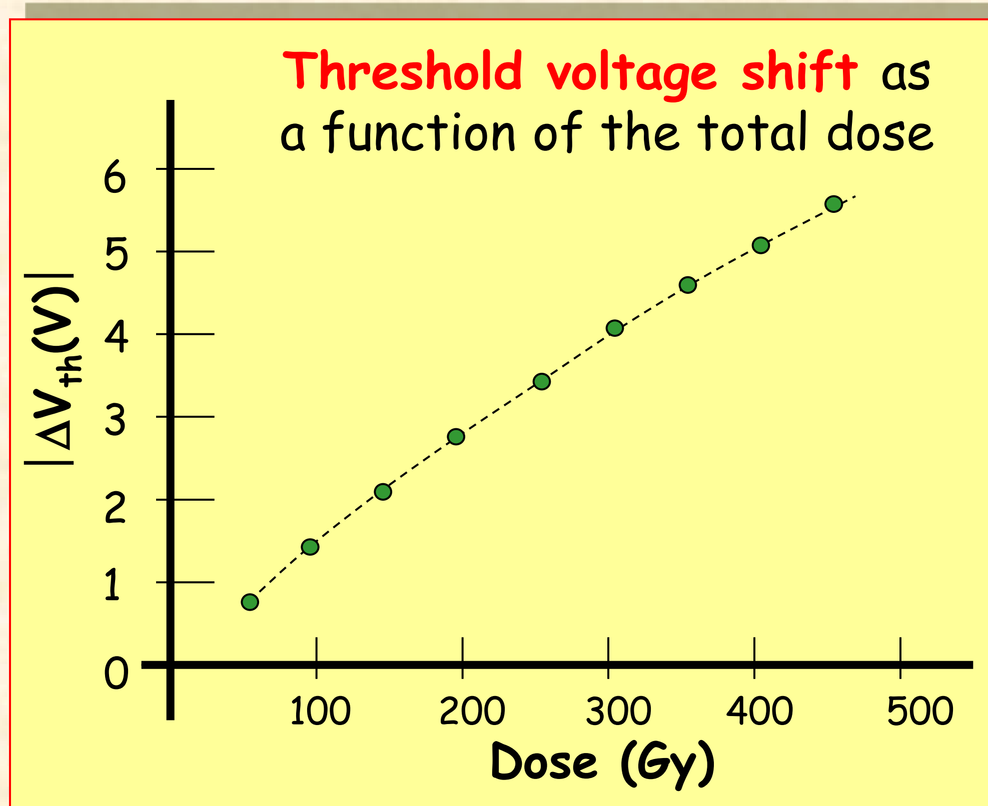
	name	method	Merit/demerit
proton	Proton accelerator test	Irradiate DUT with mono-energetic protons	• Many facilities • Equality with neutron? (also ionization; TID may accelerate SEE)
neutron	Field tests	Keep number of devices at a certain location	• Costly, time consuming • Reliable • Corrections necessary
neutron	Quasi-monoenergetic neutrons	Irradiated DUTs with quasi mono-energetic neutrons	• facilities Limited • Versatile • Correction necessary (quasi monoenergtic)
neutron	Spallation neutrons	Irradiated DUTs with neutrons of broad energy range similar to atmospheric neutronb spectrum	• High flux • Facilities limited • White spectrum similar to atmospheric one • Uncertain in selectrion of energy range
neutron	Thermal neutrons	Irradiated DUTs with thermal neutrons from experimental reactor	• Facilities limited • Estimation of SER in field is difficult do to great difference in neutron spectrums
Heavy ion	Heavy ions SEE test	Irradiated DUTs with mono-energetic heavy ions	• Suitable to understand basic SEE mechanism • No immediate correlation with neutron induced SEE
laser	Focused laser beam test	Pulsed laser beam is focused at a specific spot on the DUT	• Easy access • Pre-treatment of DUT • Equality with neutron SEU

Total Ionization Dose effects



Charge trapping … affects device operation

$$\Delta V = \frac{Q_{trapped}}{C}$$



BASIC MECHANISMS in oxide layer:

1. Electron-Hole Pair Generation in SiO_2: ~ 17 eV/pair
2. Pair Recombination. N.B. "fractional yield" depends on **type of radiation** and on the electric field (MV/cm) across the oxide (see figure)
3. electron and hole transport: e^- ~ in picosec, **h^+ in millisecond**
4. **Hole Trapping**
5. Interface Trap Formation

How much charge is trapped depends ….

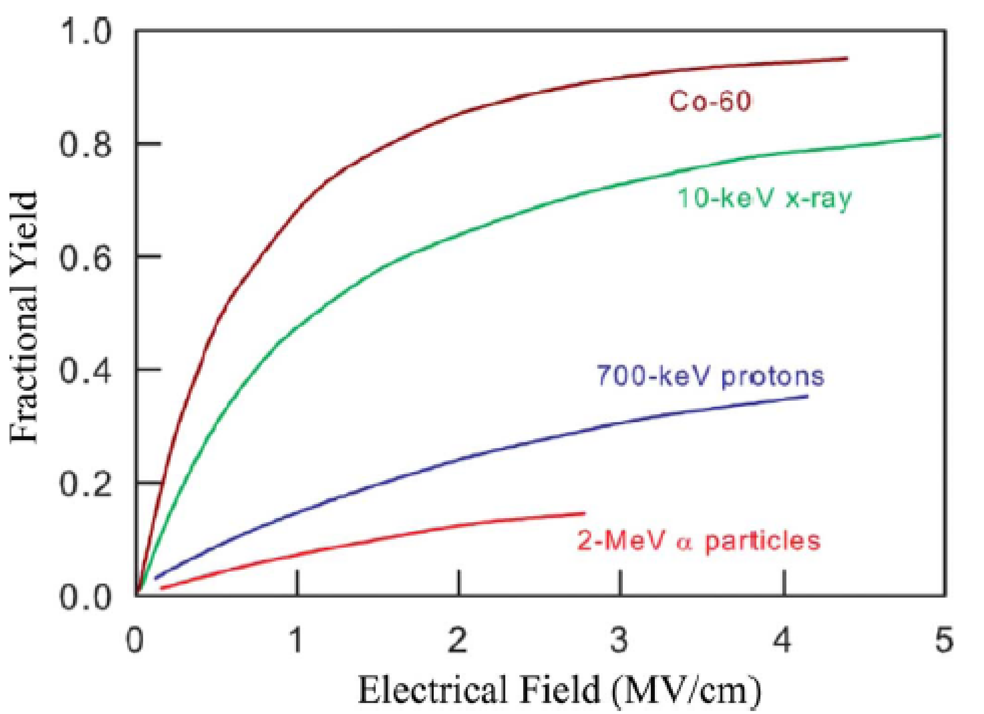


Fig. 1. Fractional yield as a function of the electrical field applied throughout the oxide and for different incident particles [1], [2].

[1] F. B. McLean and T. R. Oldham, "Basic mechanism of radiation effects in electronics materials and devices," Harry Diamond Lab., Adelphi, MD, Tech. Rep. HDL-TR-2129, 1987.

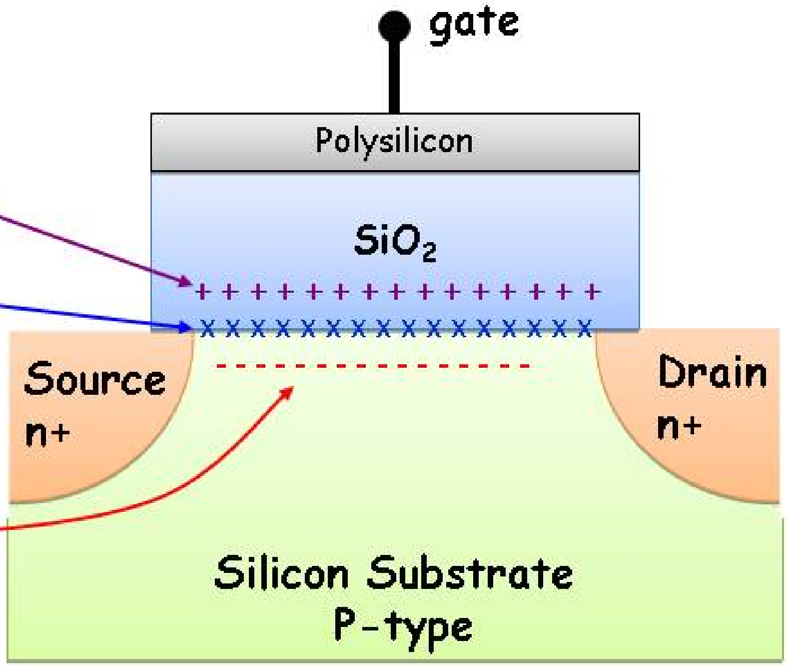
[2] M. R. Shaneyfelt, D. M. Fleetwood, J. R. Schwank, and K. L. Hughes, "Charge yield for 10-keV X-ray and cobalt-60 irradiation of MOS devices," *IEEE Trans. Nucl. Sci.*, vol. 38, pp. 1187–1194, Dec. 1991.

Charge trapping inside oxide and at Si/SiO2 interface

1. **Oxide Trapping**
   Number trapped N_{OT}

2. **Interface Trapping**
   Number trapped N_{IT}

3. Accumulation of positive charge in oxide (N_{OT}) creates parasitic channel for leakage current



Resultant voltage shifts due to trapped charges:

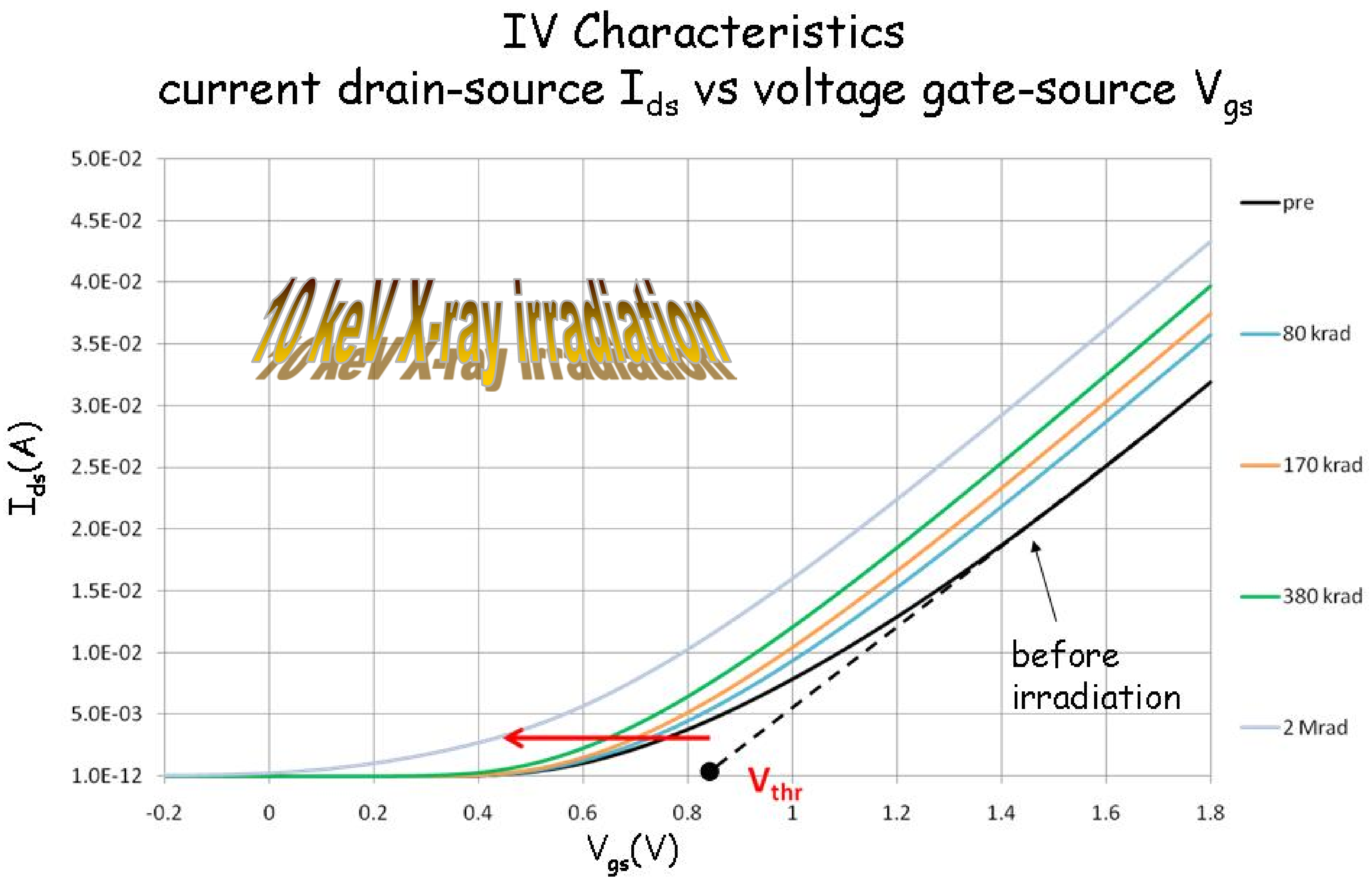
$$\Delta V_{IT} = -\frac{Q_{IT}}{C_{ox}} = \pm\frac{q \cdot N_{IT}}{C_{ox}}$$

$$\Delta V_{OT} = -\frac{Q_{OT}}{C_{ox}} = -\frac{q \cdot N_{OT}}{C_{ox}}$$

EFFECTS of TID in MOS devices:

- ❑ Parasitic leakage current paths
- ❑ Mobility degradation
- ❑ Threshold voltage shift

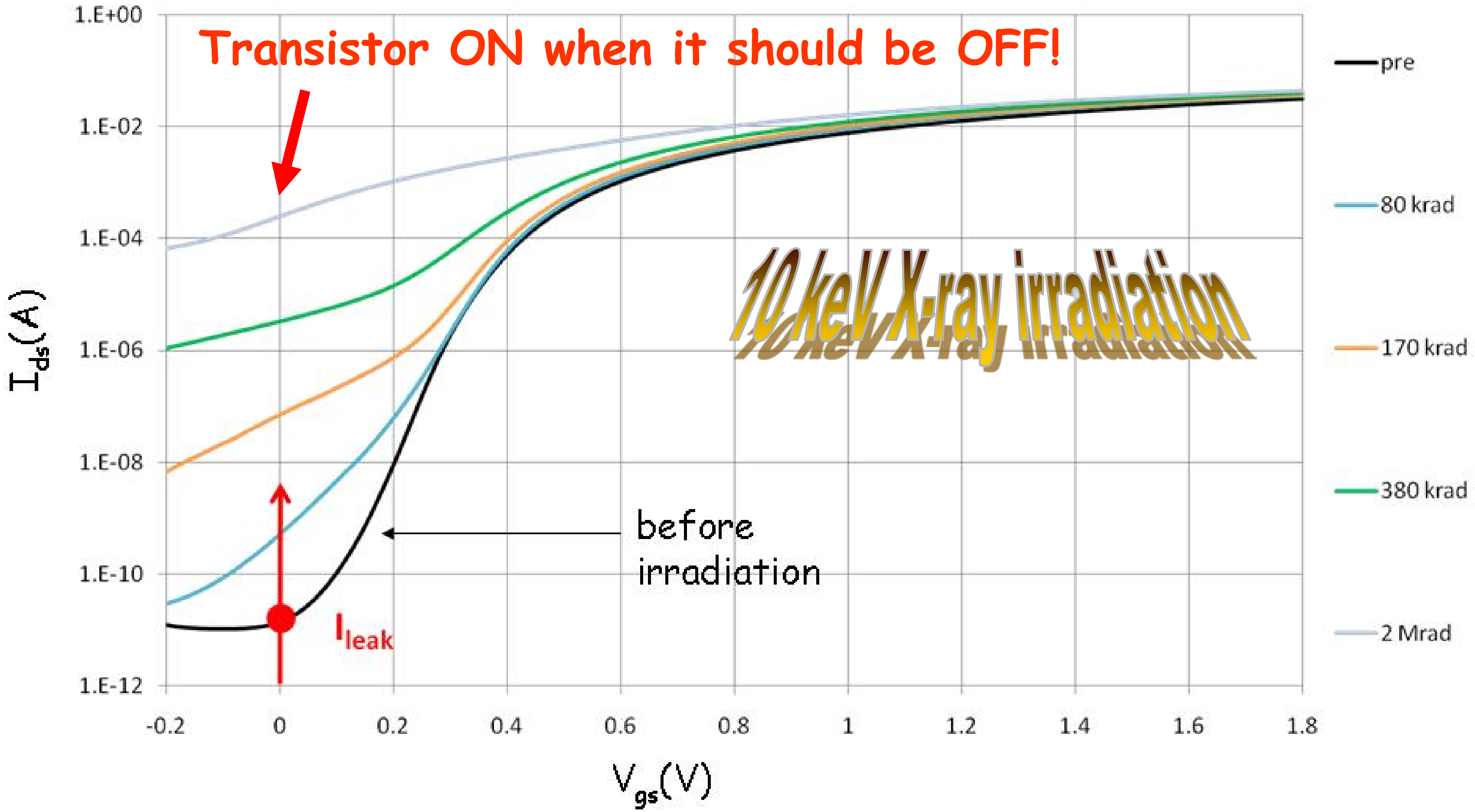
Voltage shifts



N.B. $V_{theshold}$ is given by linear extrapolation (dashed line)

Same IV Characteristics *but in log scale*

current drain-source I_{ds} vs voltage gate-source V_{gs}



N.B. $I_{leakage}$ is given current for zero voltage on gate

TID

steps to long term effects in electronics: surface damage

skip

Several step process:

a) Ionization produced along track of ionizing particle; i.e. creation of electrons and holes with a certain distribution. (Note: if produced in great quantities (e.g. highly ionizing ions, nuclear fragments,...) there is risk of SEE).

b) Initially many electron-hole pairs recombine before moving too much. Recombination takes place between electrons and holes produced in the same and in different events.

c) Surviving electrons diffuse or drift away. Some electrons end up on traps, others escape from the dielectric.

d) Carriers trapped on levels with low ionization energies get thermally re-excited into the conduction or valence band and, subject to further drift or diffusion, escape the dielectric or are captured on deep trap levels (production of permanently trapped charges).

e) In addition, in the energy gap new oxide-silicon interface levels are induced and occupied by electrons or holes (depending on position of Fermi level at the interface).

f) **NET EFFECT: induced charges in the oxide changes the electric field in the semiconductor, in the region of the interface.**

old units still in use

1 Gy = 100 rad

Typical electronic-part tolerance

COTS ("commercial off the shelf"): 5-20 krad

Rad Tolerant : 100 krad

Rad Hard : 1 Mrad

TID

TID, Ionization Damage

- **Cumulative damage** **as in insulators wherein electrons and holes produced by ionization are fixed and charged regions are induced; i.e. material does not return to its initial state.**

  In context of silicon devices (wherein there are oxide layers and Si-SiO_2 interfaces) also called surface damage.
- **due to energy deposition in form of ionization:**
  - **electrons**
  - **gamma and X-rays (⇒ electrons via photoelectric, Compton and pair-production)**
  - **pions, protons, ions**
- **damages all types of semiconductor electronics (CMOS and bipolar)**
  - **Threshold Shifts (transistors)**
  - **Leakage Current**
  - **Timing Changes**
  - **Startup Transient Current**
  - **Functional Failures**

physical quantities of interest:

- **Linear Energy Transfer LET (MeV-cm^2/mg)**
- **Total Ionizing Dose (TID) 100 rad = 1 Gray**
- **for protons and ions: TID = LET × Fluence**

- **effects scale with total dose**
- **tolerance of devices expressed in TID (Gray or Rad; 1 Gy = 100 rd = 1 J/kg)**
- *modern CMOS COTS usually can withstand 10-20 krad (good for* ***low(*) orbits****)*
- **shielding may *partially* mitigate**
  - **Low energy protons**
  - **Electrons**

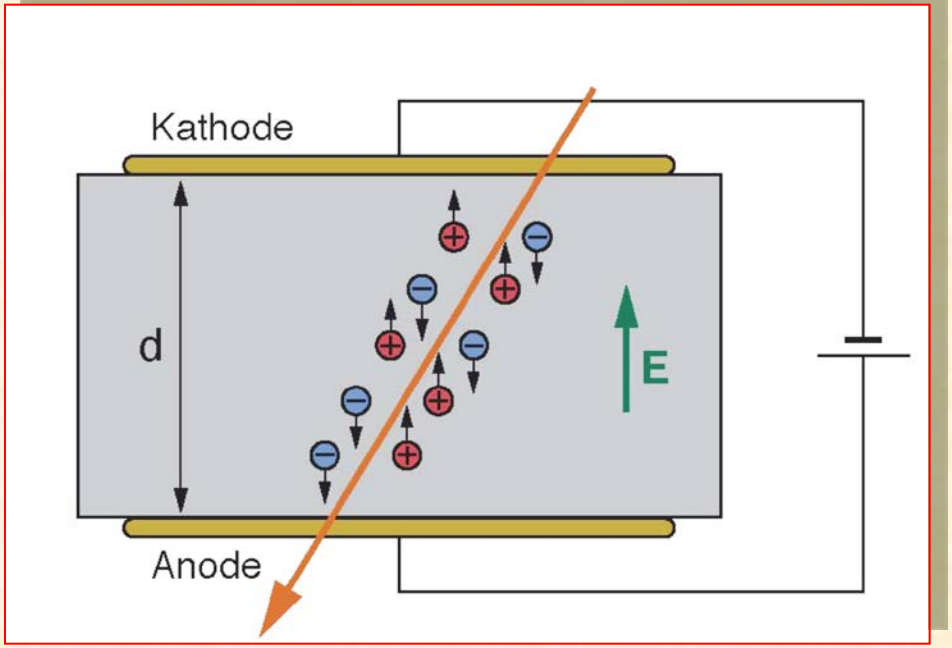
(*) below Van Allen

DDD effects

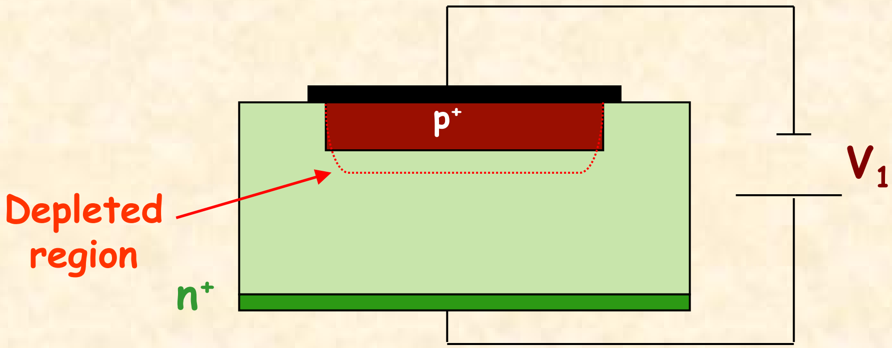
Silicon Detector – how it works

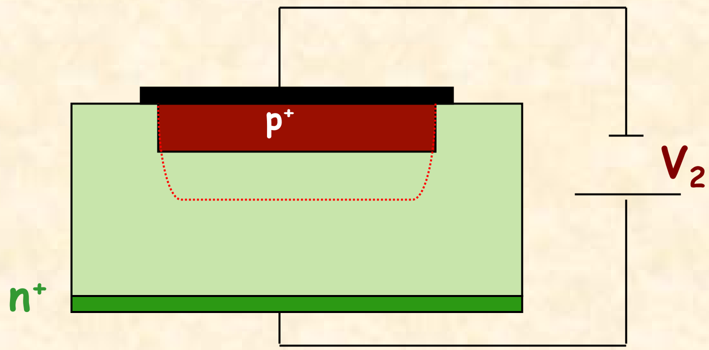
1. Take a piece of high resistivity silicon (not too thick, not to thin, typically about 300 μm)
2. produce two electrodes **(sounds easy. Its not!)**
3. Apply a voltage in order to create an internal electric field of some hundreds of volts across the device
4. charged particles crossing device will produce electron-hole pairs
5. The moving electrons and holes will create a signal in the electric circuit.

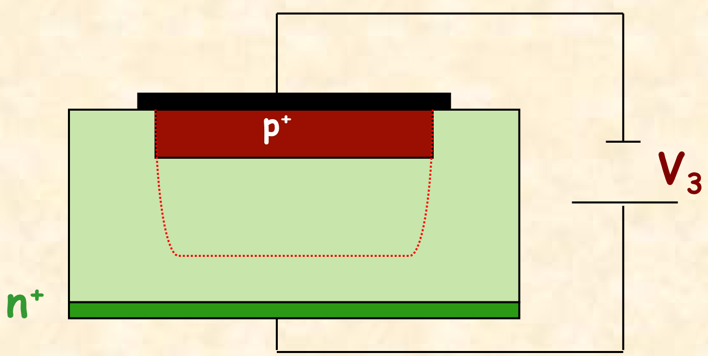
Radiation damage affects detector performance and Charge Collection Efficiency **(depending on detector, geometry and readout electronics!)**



pin-diode detector



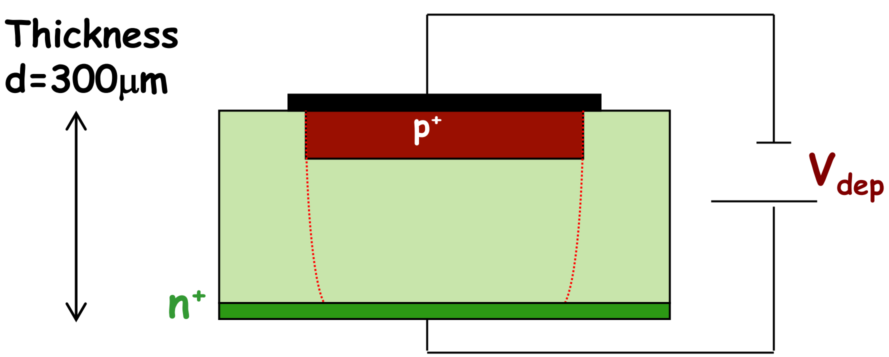




If the detector is under-depleted:

- Charge loss → inefficiency
- Charge spread → loss resolution

To fully deplete apply V_{dep}



Radiation Damage in Silicon detectors

The two types of radiation damage to detector materials:

1) **TID ("surface damage") due to ionization energy loss and trapping of charges in oxide layers and interfaces. It affects**
    - interstrip capacitance (noise factor)
    - breakdown behavior,
2) **DDD ("bulk damage") due to non-ionizing energy loss and build up of crystal defects. It leads to**

   i. Changes in **effective doping concentration** (higher depletion voltage)

   ii. **Increase** ↑ of **leakage current** (increase of shot noise, thermal runaway!)

   iii. **Increase** ↑ of **charge carrier trapping** and hence loss of collected charge.

Detectors can fail from radiation damage! ⇒ Signal/noise ratio is the quality factor to "keep and eye on"

Collected Charge for a Minimum Ionizing Particle (MIP) in a silicon detector

- **Mean energy loss**

  S_{ele} = dE/dx (Si) = 3.88 MeV/cm

  ⇒ 116 keV for d= 300μm thickness

- **Most probable energy loss**

  ≈ 0.7 ×mean

  ⇒ 81 keV

- **3.6 eV to create an e-h pair**

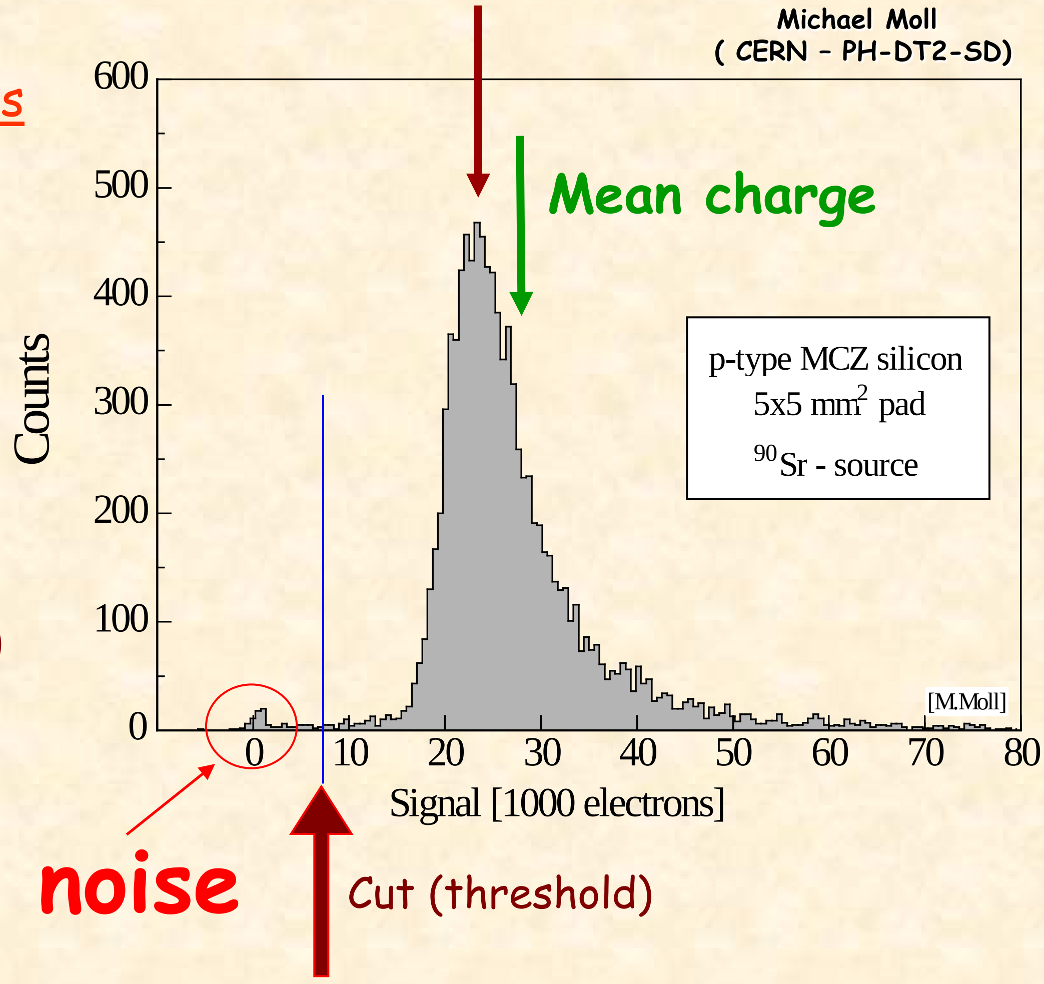
  ⇒ 72 e-h / μm (mean)

  ⇒ 108 e-h / μm (most probable)

- **Most probable charge** (300 μm)

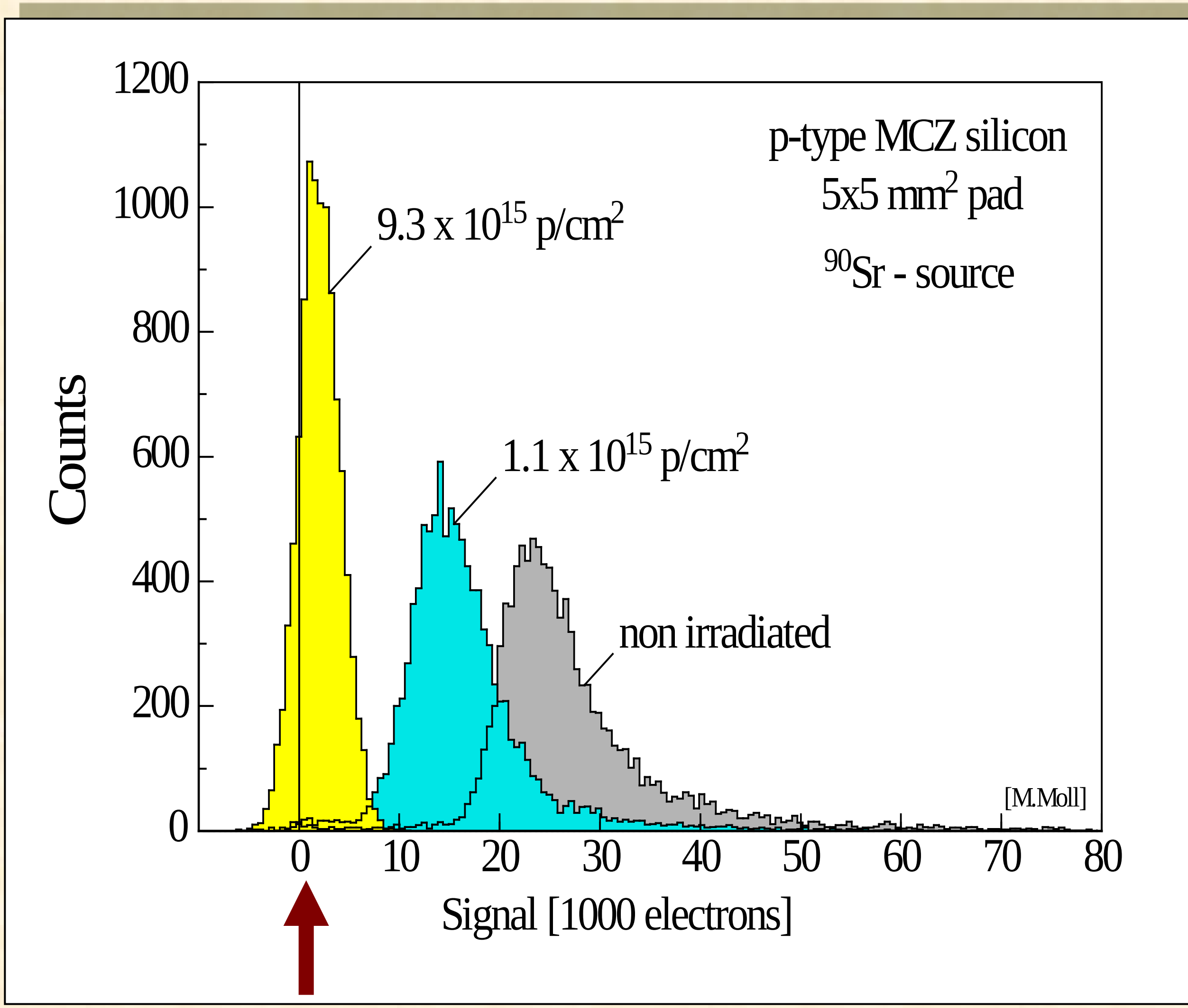
  ≈ 22500 e ≈ 3.6 fC

Most probable charge ≈ 0.7× mean



DDD effects

Figure of Merit of detectors: Signal-to-Noise Ratio S/N



MCZ = Czochralski (CZ) crystal growth in an axial magnetic field

High fluence proton irradiation causes so severe bulk damage that S/N degrades too much.

Michael Moll
(CERN – PH-DT2-SD)

What is signal and what is noise? Any bets?

Leakage current effect

Defects act as recombination-generation centers: an increase in overall leakage current with fluence is an almost universal effect (caused most efficiently by mid-gap states created by damaging the bulk lattice).

It does not seem to depend on:

- the details of doping,
- impurities,
- processing.

Exemplifies NIEL scaling hypothesis

It is parameterized by:

$$I_{leakage} = I_0 + \alpha \cdot Vol \cdot \Phi_{eq}$$

$$\alpha \approx 4 \times 10^{-17} \, A/cm$$

$$I_{leakage} = I_0 + \alpha \cdot Vol \cdot \Phi_{eq}$$

Damage parameter

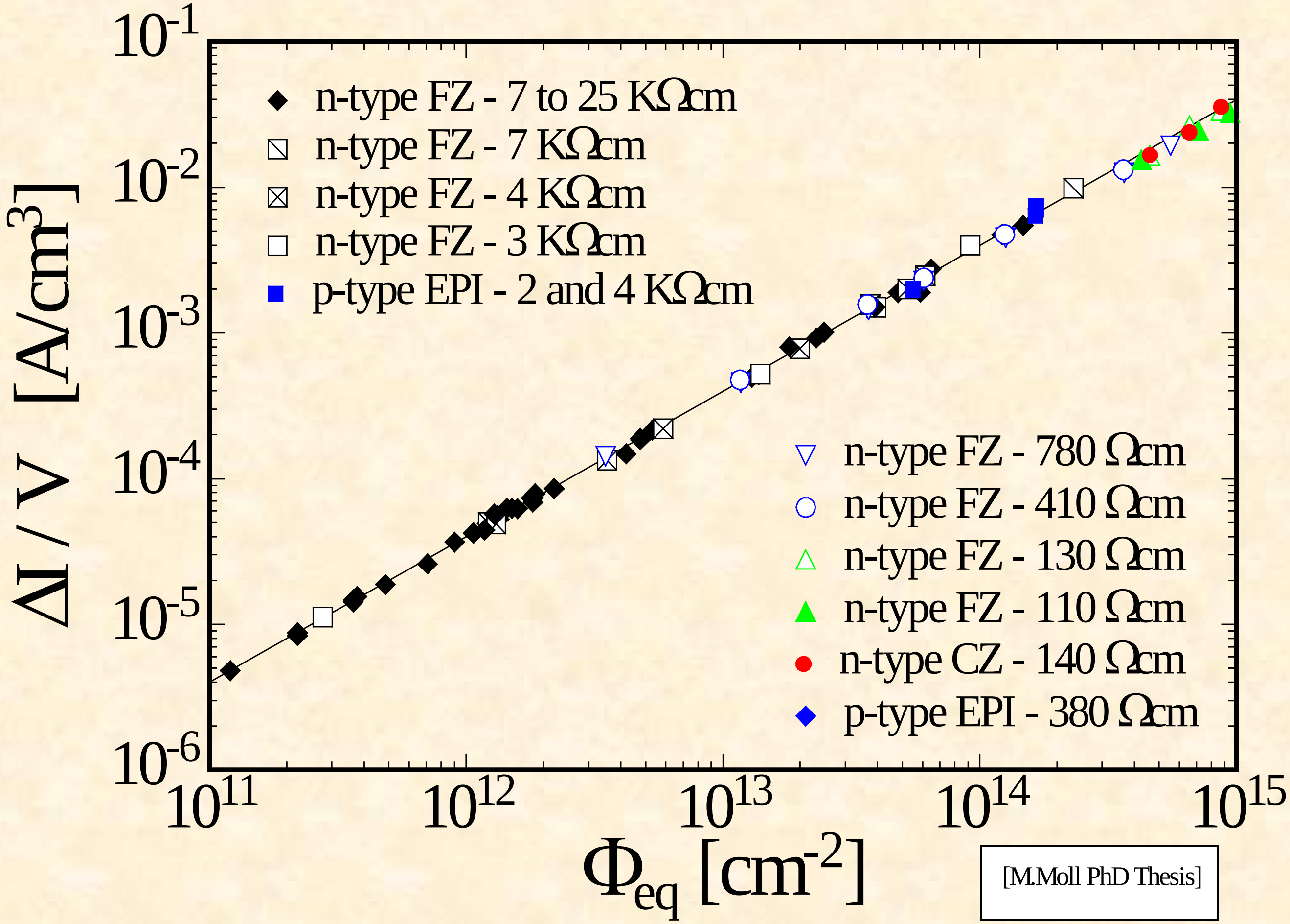
The leakage current per unit volume **grows linearly** with equivalent fluence Φ_{eq}

The α damage parameter is constant over several orders of equivalent fluence and independent of impurity concentrations in Si.

Leakage current per unit volume

$$\frac{\Delta I_{leak}}{V} = \alpha \cdot \Phi_{eq}$$

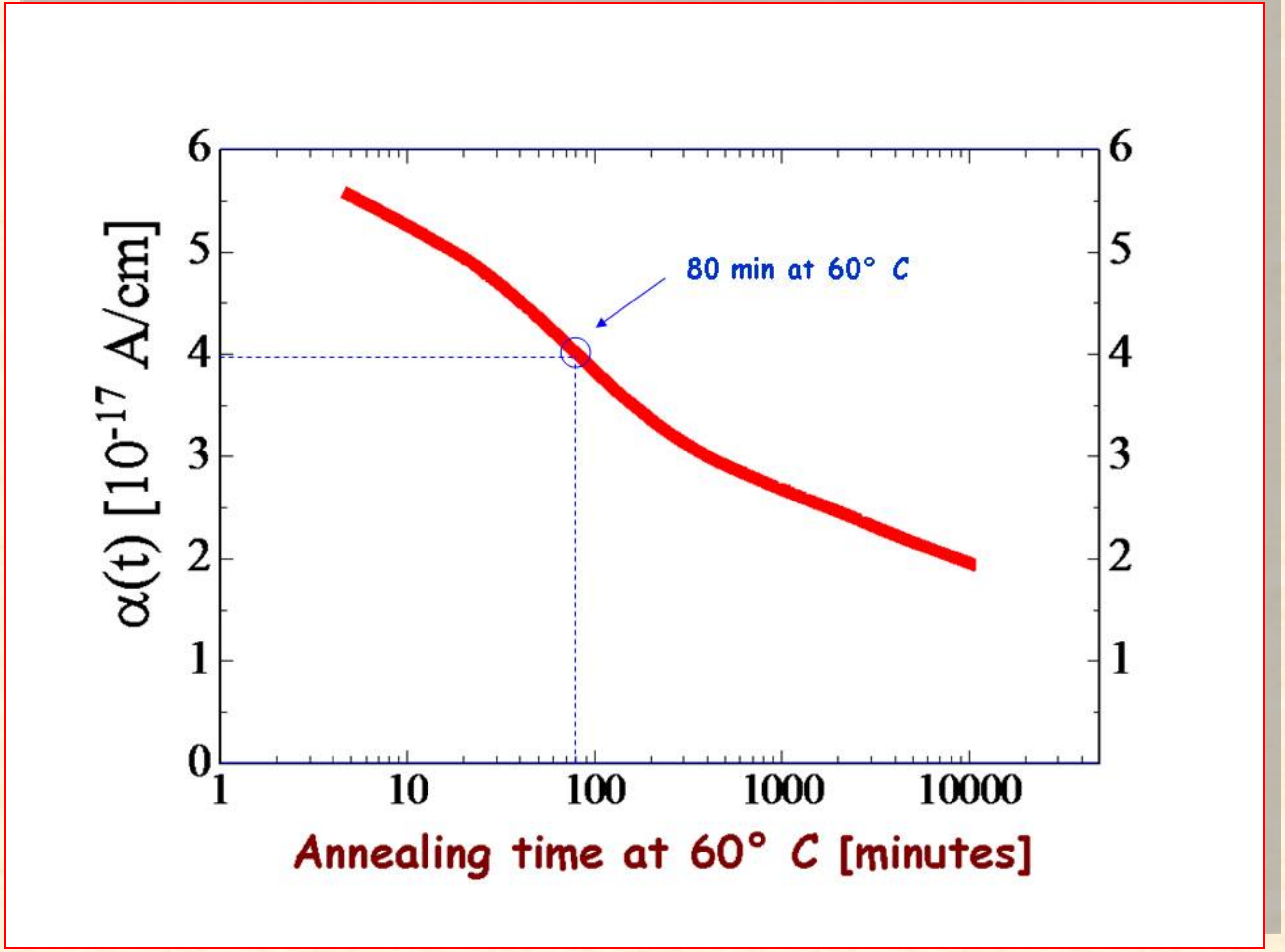
I_{leak} measured 80 min at 60° C



Question: What α constant? Answer: the "standard one".

- Leakage current decreases in time (depending on temperature)
- Strong temperature dependence

$$I \propto \exp\left(-E_g / 2k_B T\right)$$



Cool idea! Cool detectors during operation!

Example: I(-10°C) ~1/16 I(20°C)

- **"Type inversion"** : with increasing equivalent fluence, donors become more compensated.

The material seems to change from n-type to p-type (type inversion): the effective doping concentration $N_{eff} = N_D - N_A$ changes from positive to negative (space charge inversion)

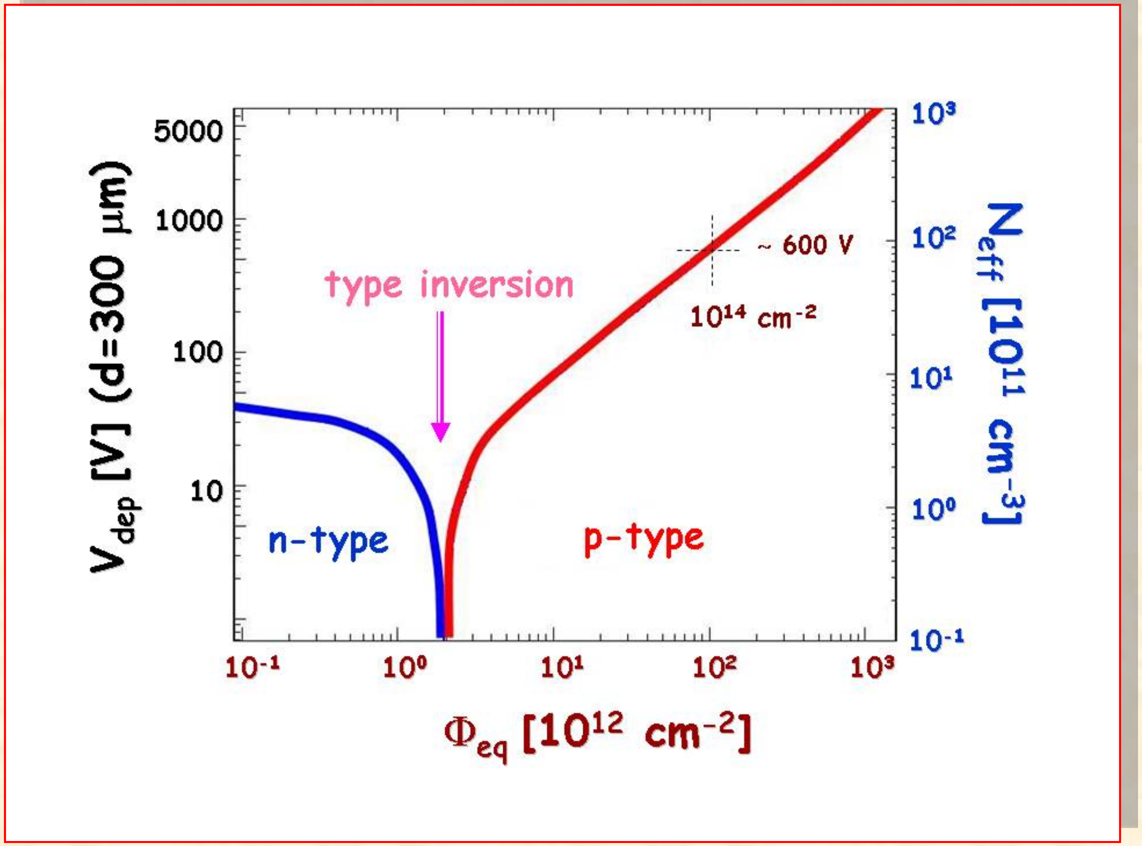
⇒ **increase of depletion voltage**

$$V_{depletion} = \frac{e N_{eff} d^2}{2 \varepsilon_0 \varepsilon_{Silicon}}$$

$$N_{eff} = \frac{2 \varepsilon_0 \varepsilon_{Si} V_{dep}}{e d^2}$$

d = 300 μm

ε_{Si} = 11.7



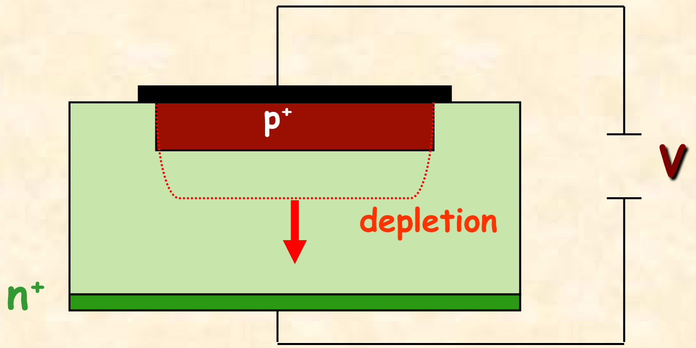
Depletion Voltage

For a non-irradiated diode and before type inversion, the depletion region grows from the p-n junction side; i.e. from the p^+ implant for p-intrinsic-n detectors.

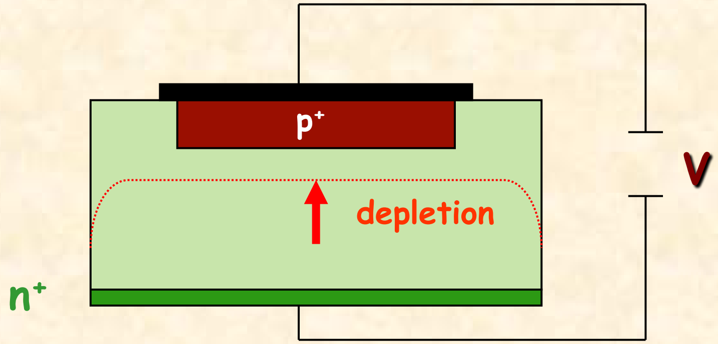
With Type-Inversion, the n-type bulk starts to behave like p-type bulk and the depletion grows from the backside of the diode.

If the detector is under-depleted:
⇒ Charge spread
⇒ Charge loss

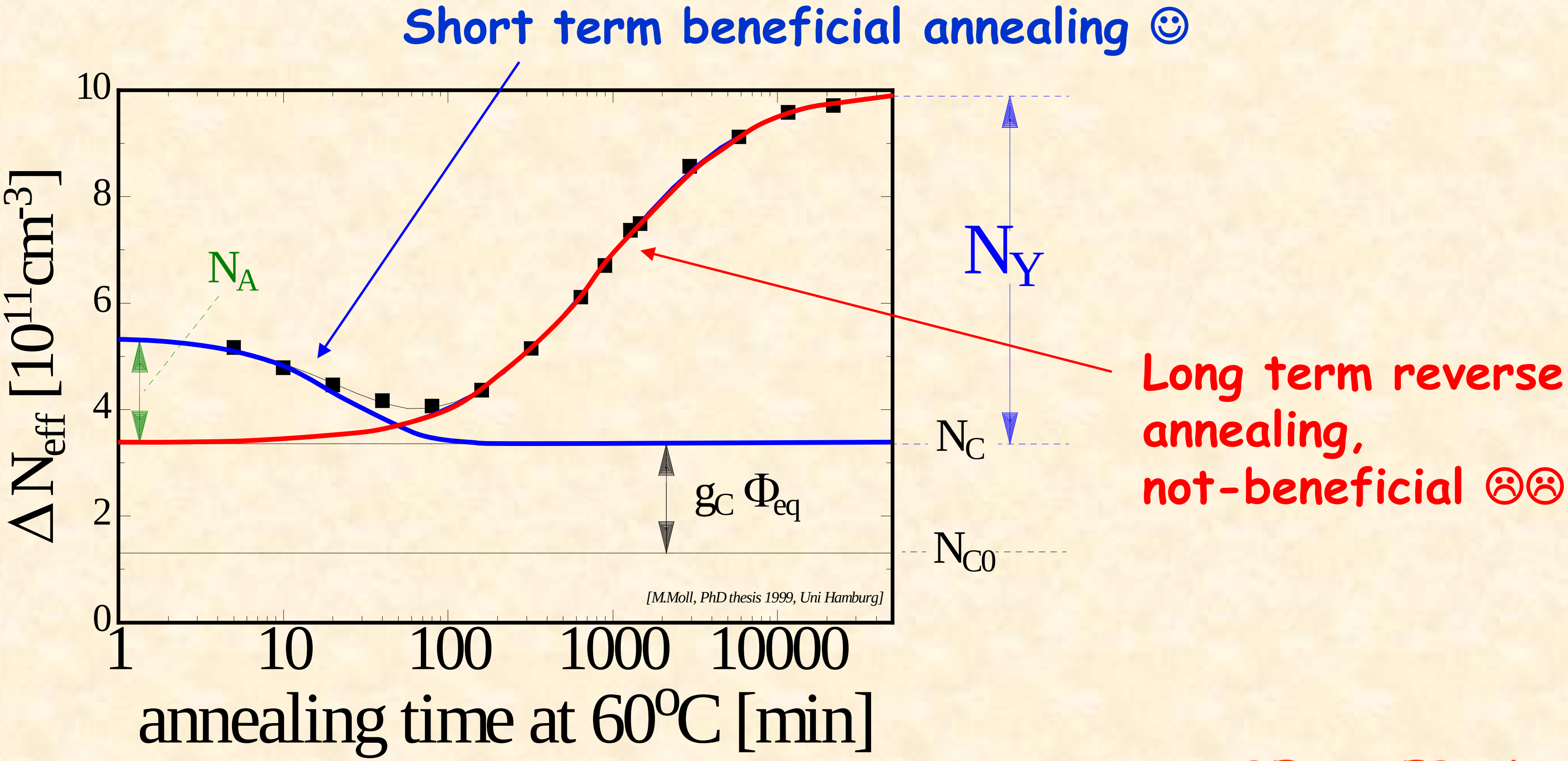
Before type inversion:



After type inversion:



Question: What effective doping concentration N_{eff}?



- WARNING: time constant depends on temperature:
  - ~ 500 years (-10°C)
  - ~ 500 days (20°C)
  - ~ 21 hours (60°C)

BE CAREFUL!
Keep detectors cool even when the experiment is not running!

DDD

NIEL, Displacement Damage (DD)

- **Cumulative bulk damage; e.g. a less ordered lattice produces long term effects on semiconductor properties**
- **due to energy deposition in non-ionizing interactions:**
  - **neutrons**
  - **protons, ions (especially slow ones near end of range)**
  - **energetic electrons**
- **effects in electronics:**
  - **Production of defects which results in progressive device degradation**
  - **May be similar to TID effects**
- **sensitive devices (NOTE: CMOS, not bulk sensitive, is practically unaffected)**
  - **silicon detectors**
  - **laser diodes, LED, opto-couplers**
  - **solar cells**
  - **CCDs**
  - **linear bipolar devices**

physical quantities of interest:

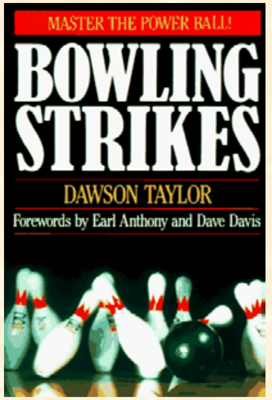
- **particle fluence Φ(#/cm^2)**
- **Non-Ionizing Energy Loss (NIEL) (keV-cm^2/g)**
- **DDDose = NIEL $\times$ Φ**

- **effects scale with particle fluence**
- **tolerance of devices expressed in fluence of 1-MeV neutron equivalents**
- **risk begins at fluence > 10^{11-12} 1-MeV neutrons/cm^2**

- **shielding has some effect:**
  - **depends on location of device**
  - **may reduce significant electron and some proton damage**

DDD

steps to long term effects in electronics: displacement damage



four step process:

1) Primary particle <u>hits</u> atom in lattice, transferring enough energy to displace it. Creation of interstitials and vacancies (Frenkel defects). For high energy primaries, nuclear reactions can occur and produce several fragments.

1) The recoil atom or its fragments (secondaries) migrate through lattice causing further displacements. The *mean free path* between successive collisions decreases towards end of the range, so that defects are produced close and interact (general; i.e. true for primary and secondaries, tertiariares...).

2) Thermal motion causes rearrangement of the lattice defects. Annealing at room temperature. Some rearrangements are influenced by presence of impurities in initial material.

3) Thermally stable defects influence the semiconductor properties; e.g. increase of capture, generation and recombination rates of non-equilibrium charge carriers.

NET Effects of displacements in **detectors (reverse biased pn-junctions)** cause:

a) <u>changes of the internal electric field</u>, due to modified doping concentrations,
b) eventually leading to <u>inverting the conduction type for very high irradiations</u>;
c) <u>increase of the leakage current</u>;
d) <u>changes in capacitance and resistivity</u>;
e) <u>charge collection losses</u>.

Summary slides

Summary TID, NIEL, SEE

1. **Total Ionization Dose (TID), for electronics also called surface damage:**
   - **Effects caused by long term exposure to *ionizing radiation*.**
   - Induces changes in the mechanical and electrical properties of materials that may cause them to operate incorrectly or even fail.
   - An important effect for **insulators** (charge build-up), cabling, electronics (surface charge effects), optical elements (lenses, filters) and cryogenics.

2. **Displacement Damage Dose (DDD)** also called **NIEL**:
   - **Effects due to long term exposure to interactions with *non-ionizing energy transfers*.**
   - Originates displacement defects in semiconductor materials (introduction of deep band-gap levels, traps,...)
   - Important effect in all semiconductor **bulk-based devices.**

3. **Single Event Effects (SEE):**
   - **Effect due to a single interaction, wherein a *large ionization* gives a temporary or permanent damage to many electronically live devices or systems.**
   - Important effect for digital circuits such as memories or microprocessors.
   - Induces errors, undesired latch-ups and may lead to system failure.

Radiation: Microscopic effects → macroscopic effects

micro-effect			*macro-effect*
Small $\Delta E_{ionization}$ deposited uniformily and delivered over a long time.	charged particles	Direct or secondary ionization	**Total Integrated Ionizing Dose (TID) Effects**
Sudden large $\Delta E_{ionization}$ deposited in the '*wrong place at the wrong time*'.	heavy charged particles (protons, **ions**)	Direct ionization	**Single Event Effects**
Accumulation of small ΔE transfers to atomic nuclei (Coulomb, nuclear interactions).	protons, neutrons, high energy electrons	displacement damage of lattice	**bulk effects; enhancement of TID Effects**
Sudden high ΔE transfer to a single nucleus at the '*wrong place and time*'.	Energetic heavy particles (protons, neutrons, energetic ions)	Secondary ionization by recoil atoms and nuclear fragments	**Single Event Effects**

CONCLUSIONS: studying radiation effects NEED TO define

- **quality of radiation**
  - particle type (p, e, γ, n, ions,...)
  - energy
  - flux/fluence (how many!); i.e. cross-sections
  - source predictable or stochastic

- **properties of target**
  - material (silicon, plastic, water...)
  - active devices (memories, diodes,..., *living cells*)
  - active volumes (different sensitivities, how many, where, ...)

Questions that need answers:

after
H. Sadrozinsky,
Santa Cruz

• are there *predictable* or *stochastic* effects?

• what is correct variable?
(dose, fluence, 1-MeV equivalent neutron fluence for NIEL;
LET and fluence hadrons E > 20 MeV for SEE)

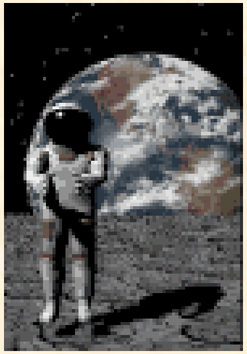
• any normalisation factors?
(scaling, NIEL-hypothesis, quality factors, *radiobiological equivalents*)

• any role of microenvironment?
(parasite structures such as latch-up in CMOS; *bystander effect*)

⇨ • any relaxation effects?
(annealing, *adaptive response*)

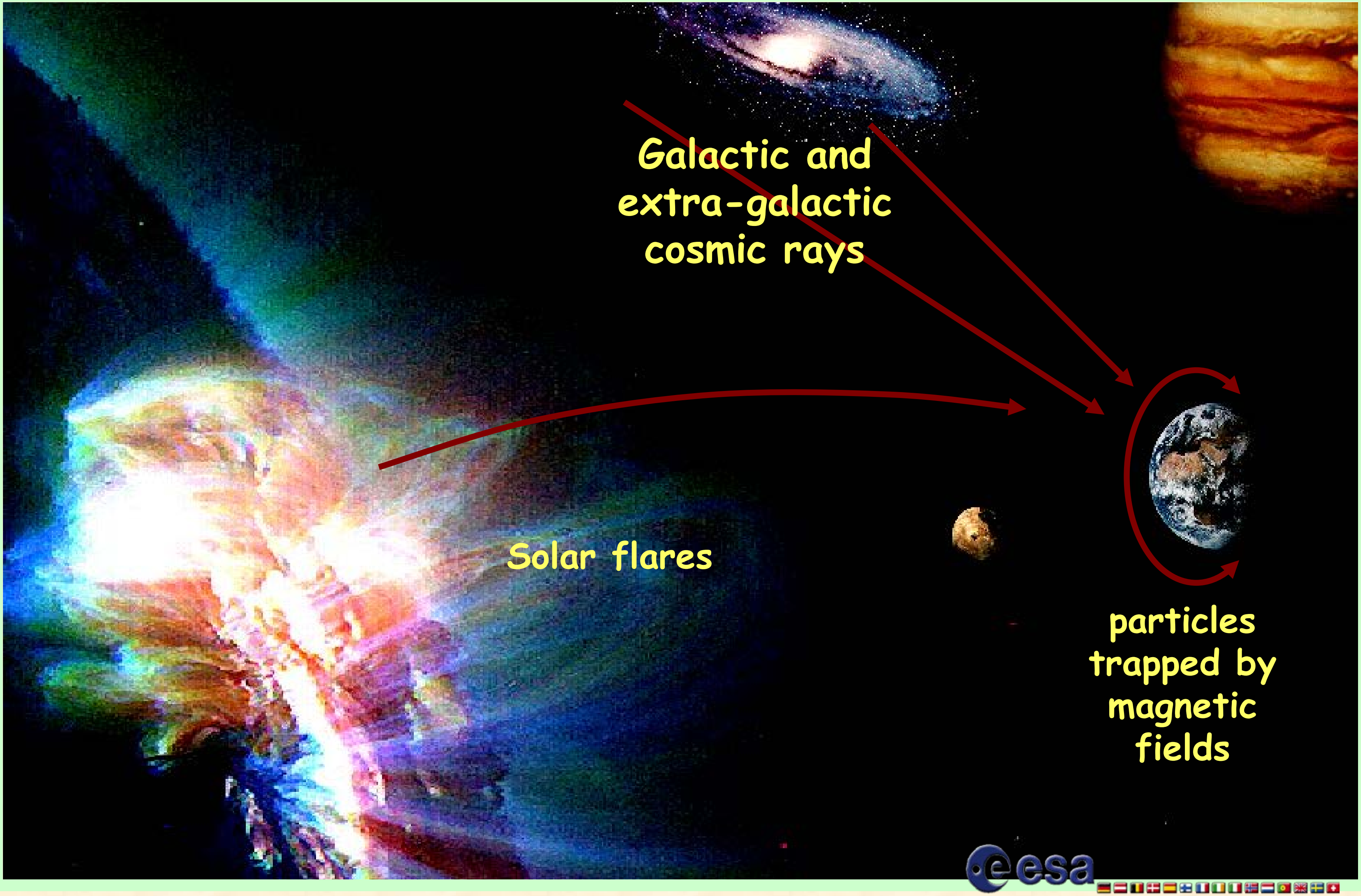
• are there dose rate/flux effects?

• are there low dose effects?

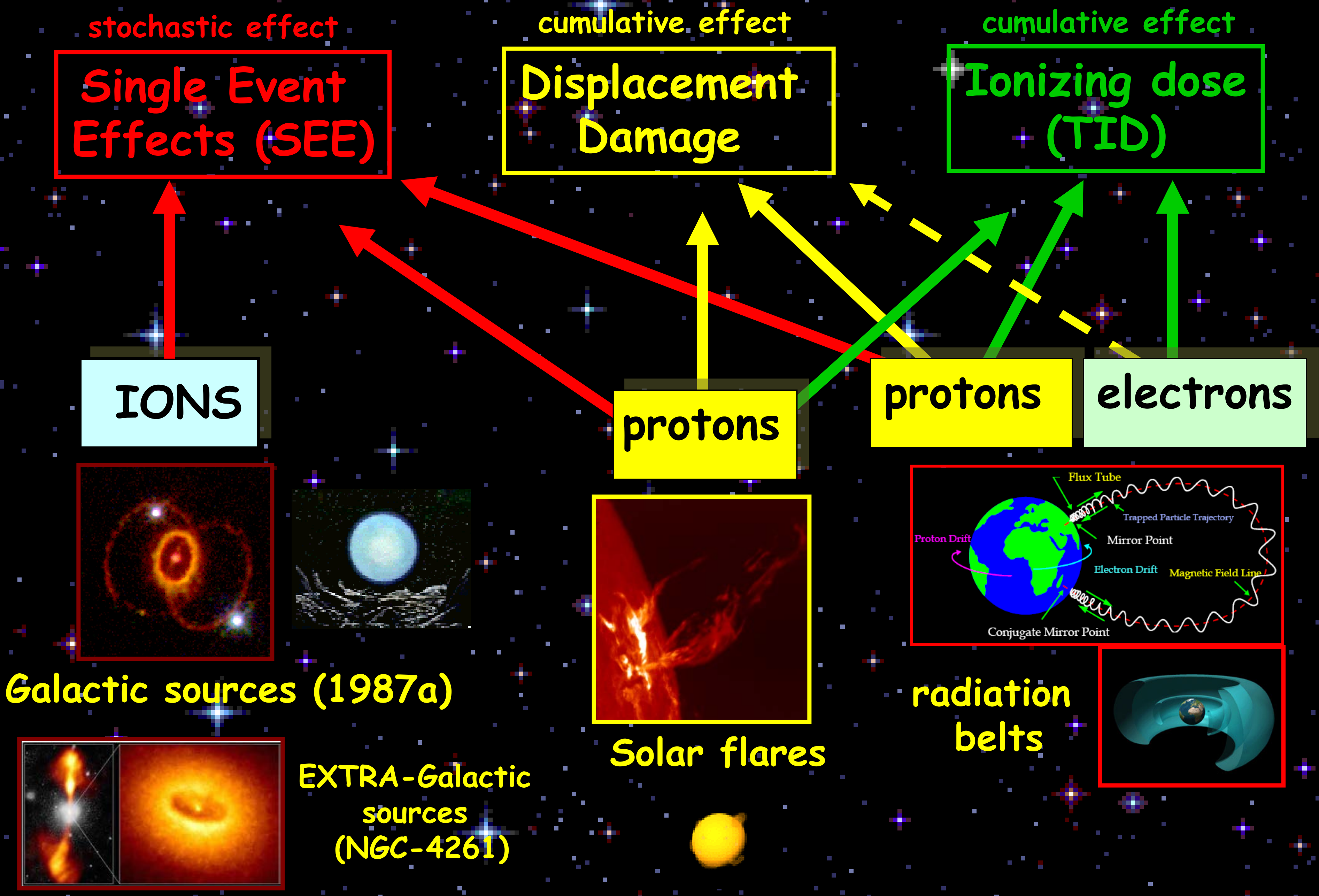


PART 5:
Environments

The space environment is full of energetic particles

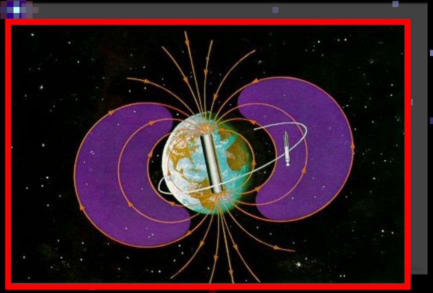


Space Radiation and effects on electronics



Space radiation environment 1

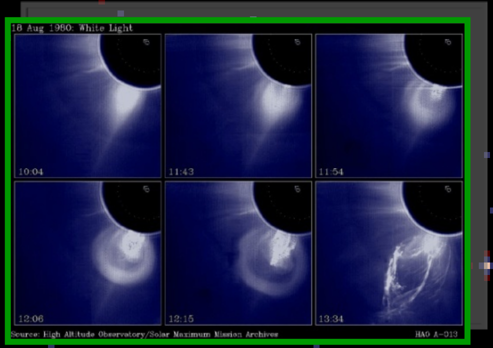
Radiation belts (Van Allen): depends on Solar activity



protons keV ÷ 500 MeV

electrons eV ÷ 10 MeV

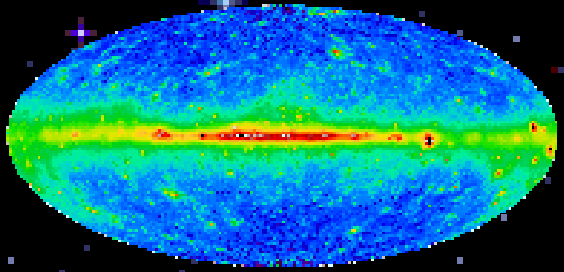
Solar wind and flares: depends on Solar activity



protons keV ÷ 500 MeV

ions 1 ÷ few 10 MeV/n

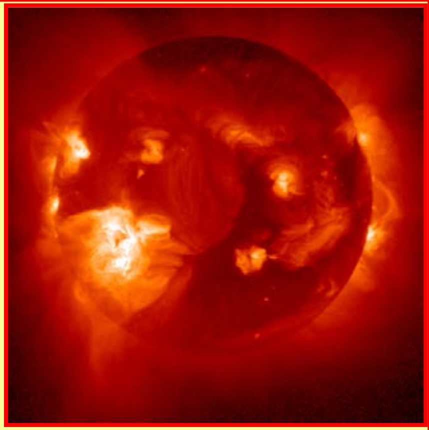
Galactic Cosmic Rays (GCR, *HZE*): ~ constant background



Protons and HZE ions *(high charge Z and energy E)*

Flux maximum at ~ 300 MeV/n

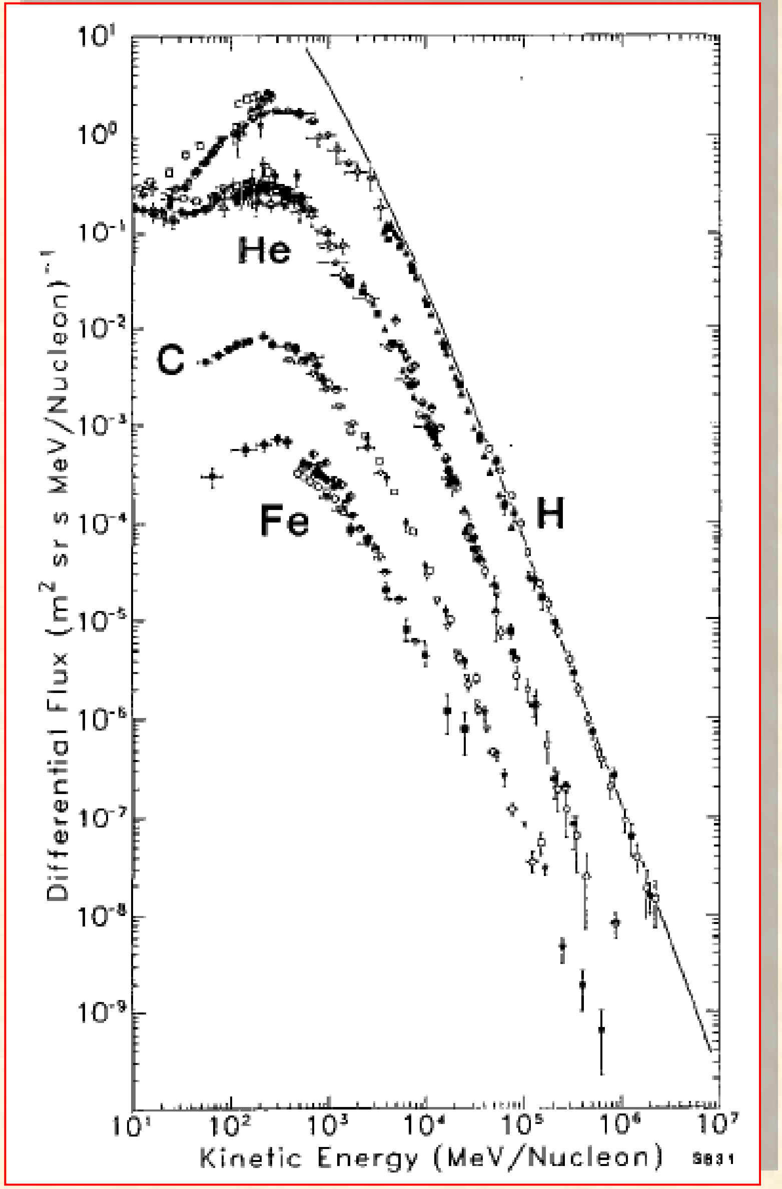
Space radiation environment 2



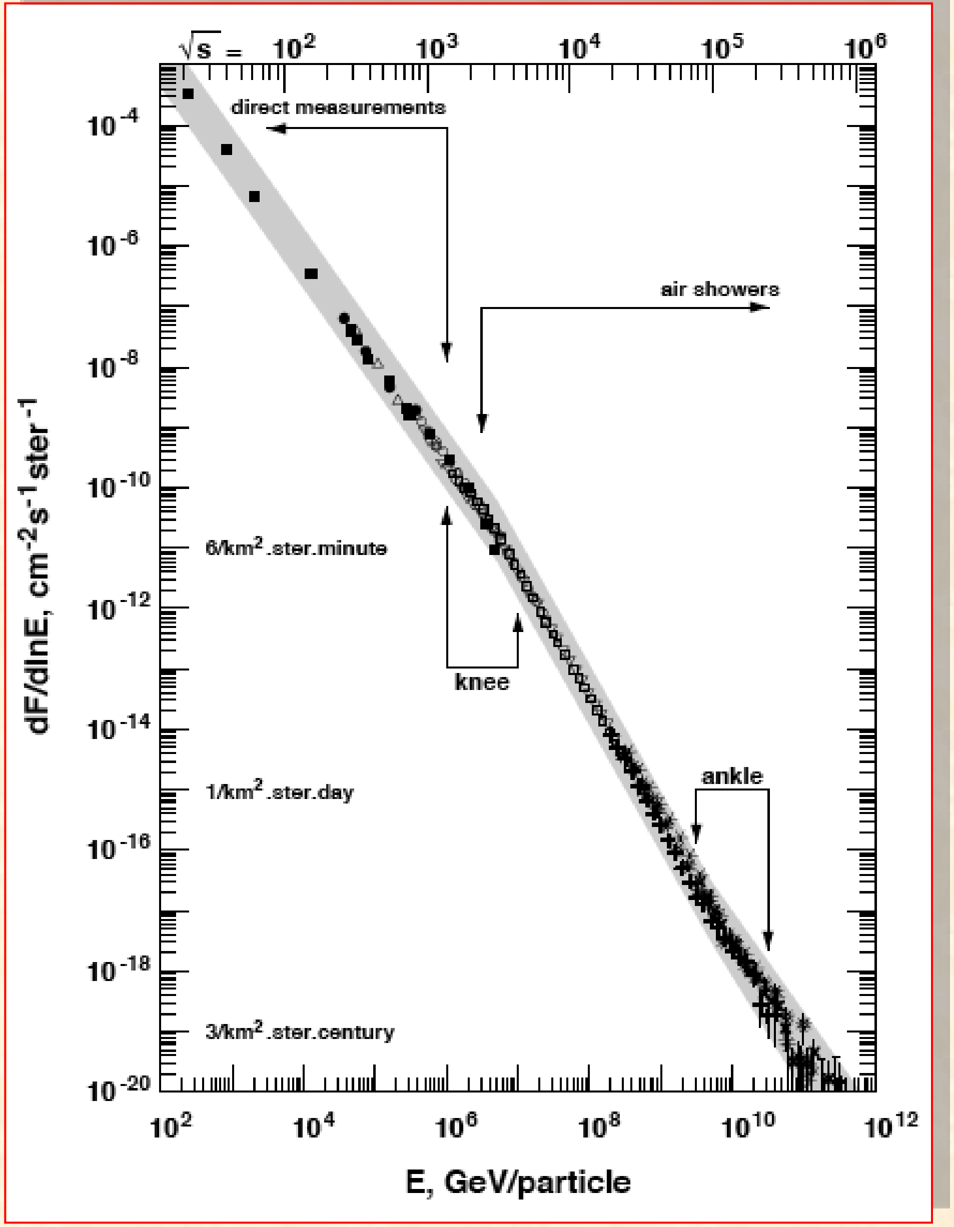
- **Solar particle events**: give rise to solar cosmic rays
- Solar activity: 11-year cycle:
  - ➢ 7 years of high activity (*solar maximum*)
  - ➢ 4 years of low activity (*solar minimum*)
- composition: mostly protons, α, heavy nuclei
- *Flares*: at Earth surface fluxes up to 10^6 p/(cm^{2}s) [1972], spectra highly variable

- **Galactic Cosmic Rays**: diffuse galactic background
- composition: ~85% protons, ~14% α, ~1% heavy nuclei (HZE)
- most up to 10 GeV/amu. Rarely up to up to 10^{20} eV (10^{11} GeV) = **16 joules**!
- anti-correlated with solar activity: solar flux scatters incoming charged particles

Energy spectra of primary cosmic rays

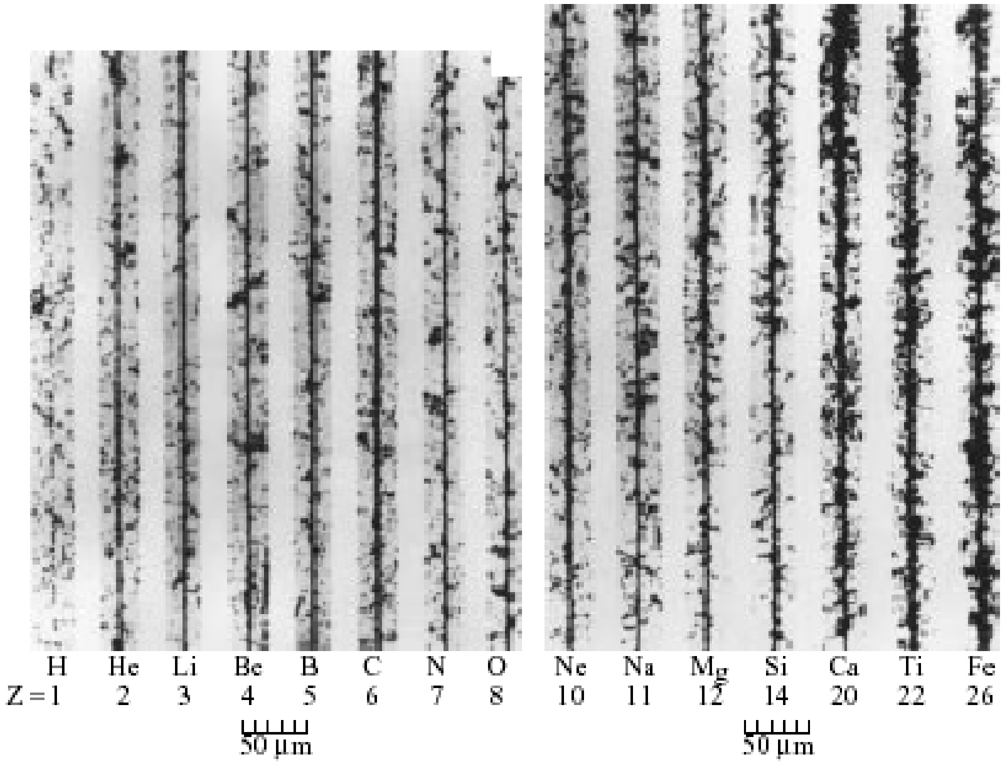


J.A.Simpson, Ann. Rev. Nucl. Part. Sci. 33 (1983) 323

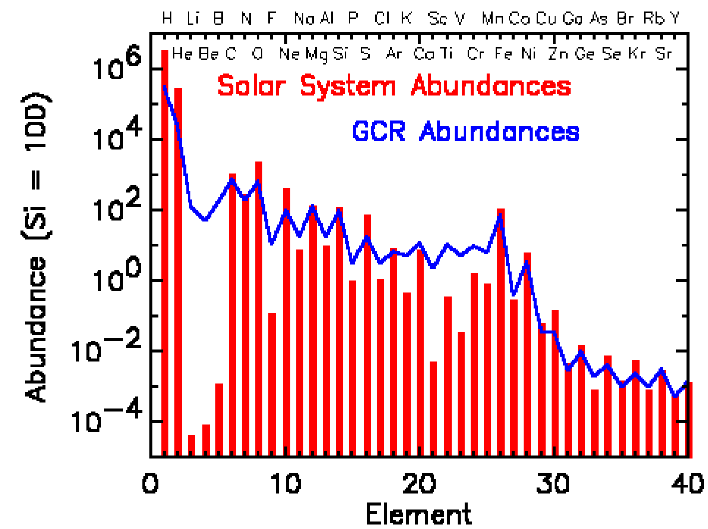


T. Stanev, SLAC Summer Institute, 2004; astro-ph/0411113.

Galactic High Charge and Energy (HZE) ions



McDonald F. B. (1965). “Review of Galactic and Solar Cosmic Rays”, *Second Symposium on Protection Against Radiations in Space* (Reetz A., editor), NASA SP-71: 19-29



HZE are a direct cause of Single Event Effects

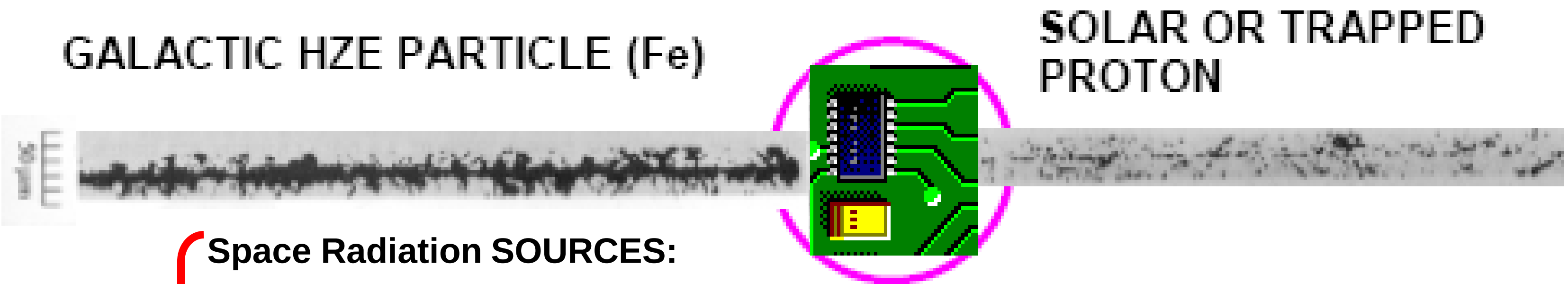
Simulating the radiation environment

- CREME (models cosmic-ray environment and effects) . The standard model for cosmic ray environment assessment, and standard tool to investigate radiation induced effects.
- Provides comprehensive set of cosmic ray and flare ion energy spectra
- Includes treatment of geomagnetic shielding and material shielding
- Worst case scenarios: worst day, worst week, peak 5 minutes, solar maximum, solar minimum

- PURPOSE: Calculate electron/proton/ion fluxes, and energy released in device

⇒ failure rates of device can be estimated

paradigm in SPACE electronics



Space Radiation SOURCES:

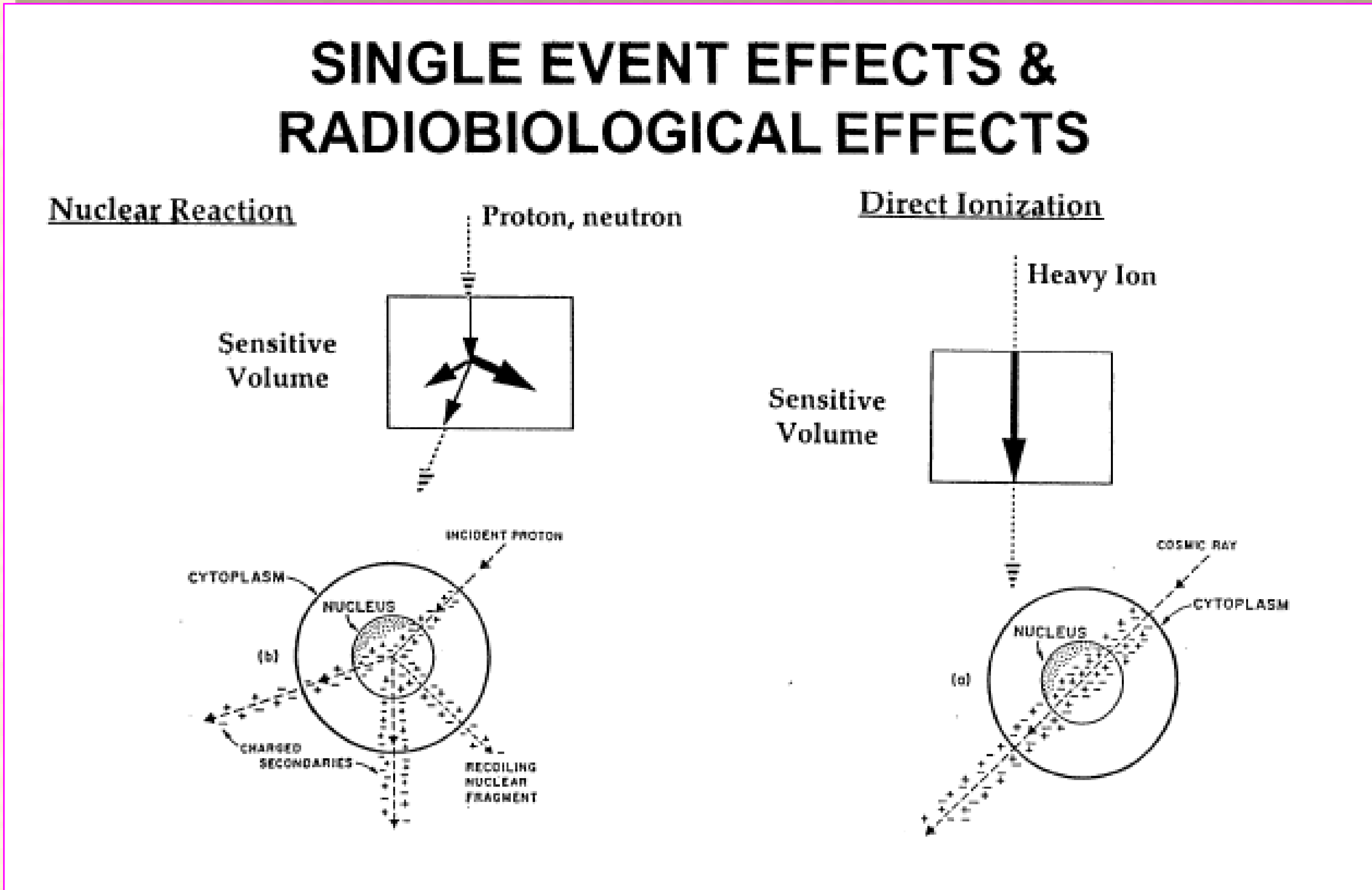
- **predictable**: trapped protons and electrons, galactic cosmic rays
- **stochastic (unpredictable):** protons from solar event (storm, flare)

electronic RESPONSES (effects):

- **predictable effects** (continuous Dose→ parameter shifts): thresholds; leakage currents…
- **stochastic effects** (unpredictable Single Event Effects): SEE

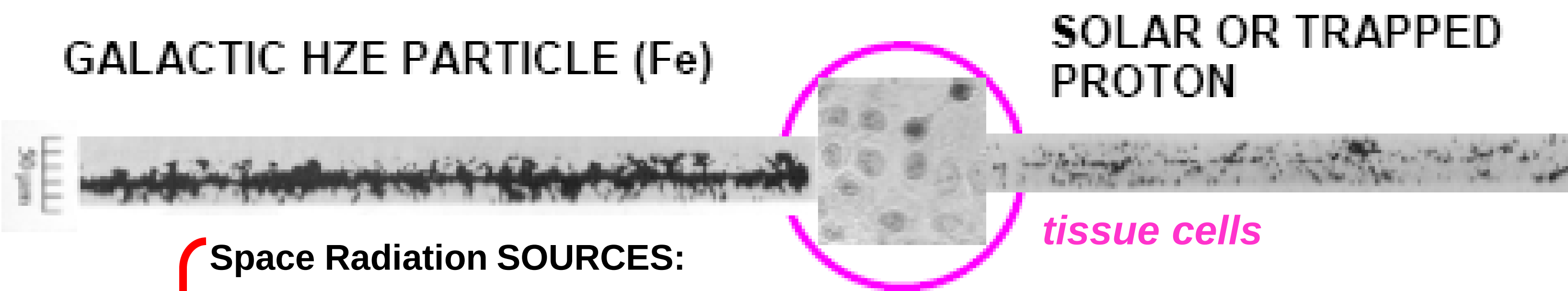
	device/system 1	device/systen 2	device/system 3
trapped particles	dose predictable effect stochastic	dose predictable *effect negligible*	dose predictable *effect negligible*
solar storm protons	dose stochastic effect stochastic	dose stochastic effect predictable	dose stochastic *effect negligible*
galactic cosmic rays (HZE)	dose predictable effect stochastic	dose predictable *effect negligible*	dose predictable effect predictable

SEE in biology



New paradigm in SPACE RADIOBIOLOGY

adapted from P.Todd: **Space Radiation Health: a brief primer**
Gravitational and Space Biology Bulletin 16(2) June 2003



Space Radiation SOURCES:

- **predictable**: trapped protons and electrons, galactic cosmic rays
- **stochastic (unpredictable):** protons from solar event (storm, flare)

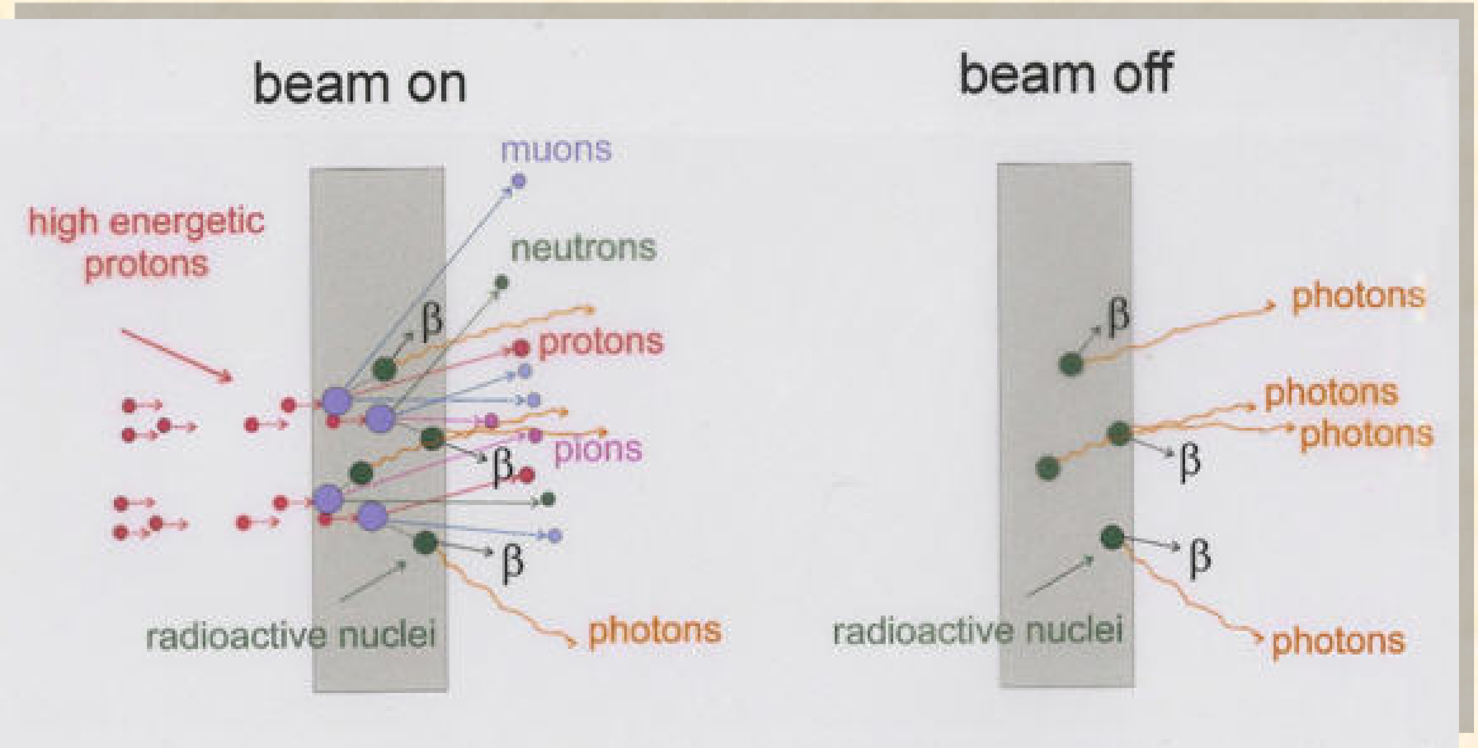
Biological RESPONSES (effects):

- **predictable effects** (continuous Dose→Response curves): blood, immune system
- **stochastic effects** (unpredictable Single Event Effects): cancer

	cancer	immune	neurological
trapped particles	dose predictable effect stochastic	dose predictable *effect negligible*	dose predictable *effect negligible*
solar storm protons	dose stochastic effect stochastic	dose stochastic effect predictable	dose stochastic *effect negligible*
galactic cosmic rays (HZE)	dose predictable effect stochastic	dose predictable *effect negligible*	dose predictable effect predictable

accelerators

Radiation at accelerators



PROMPT radiation

INDUCED radioactivity

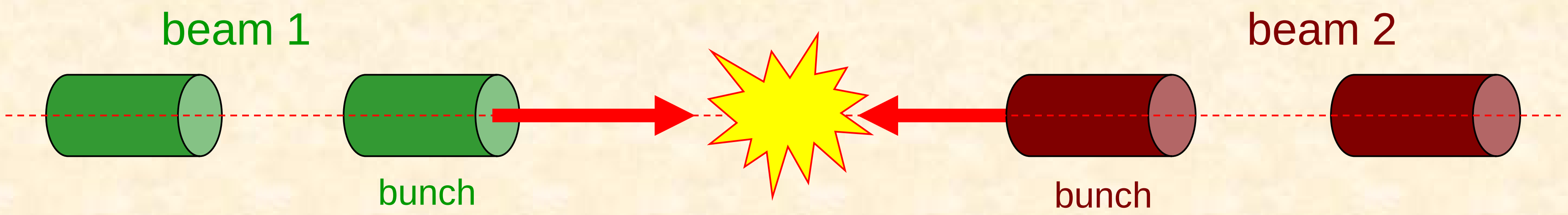
RF cavities

Klystrons

Radioactive sources α,β,γ

cross section

HEP: colliding particle beams



N_1 , N_2 = particles per bunch

b = number of bunches/beam

f = revolution frequency; i.e. bunches per second cross

A = cross-sectional area beams at intersection

interaction rate (events per second)

$$R_{int} \propto \underbrace{f \cdot b \cdot \mathbf{N_1} \cdot \mathbf{N_2} / \mathbf{A}}_{\text{L luminosity (cm}^{-2}\text{ s}^{-1})}$$

total interaction rate: $R_{int} = L \cdot \sigma_{tot}$

cross-section

cross-sections: CMS/LHC

"...big as a barn..."

cross-section of 1 *barn* = 10^{-24} cm^2 = 10^{-12} cm on a side

1 *inverse picobarn* = 1 pb^{-1} = (10^{-36} cm^2)$^{-1}$ = 10^{36} cm^{-2} = 10^{-3} fb^{-1}

LHC luminosity L(t) = 10^{34} cm^{-2} s^{-1} = 10^{-2} pb^{-1} s^{-1}

upgrade 35

time integrated luminosity *in 10 LHC physics years*

L = ∫ L(t) dt = 5 × 10^{41} cm^{-2} = 5 × 10^5 pb^{-1} = 500 fb^{-1}

$\sigma_{inelastic}$ = 80 mb = 8 × 10^{-26} cm^2

Rate of ***inelastic events***

$R_{elastic}(t) = L(t) \cdot \sigma_{inelastic} = 8 \times 10^8$ events/s

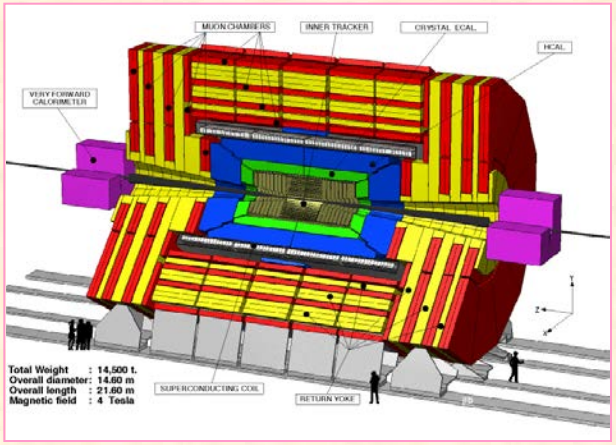
after 10 years $N_{elastic}$ = 4 × 10^{16} events

Consider a RARE process with $\sigma_{rare} = 10^{-38}$ cm^2 = 10 fb

After 10 years N = L • σ = 500 fb^{-1} × 10 fb = ***5000 events***

Extremely hostile radiation environment!!!

Radiation @ LHC



❑ Instantaneous effects (due to presence of beam):

- **detector occupancy** (pattern recognition, detector saturation and pileup, trigger rates)
- **Single Event Effects** (data corruption, loss of control or timing,…): neutrons (E > few MeV) and charged hadrons with E>21 MeV (coulomb barrier)

❑ Cumulative effects due to long duration of experiment:

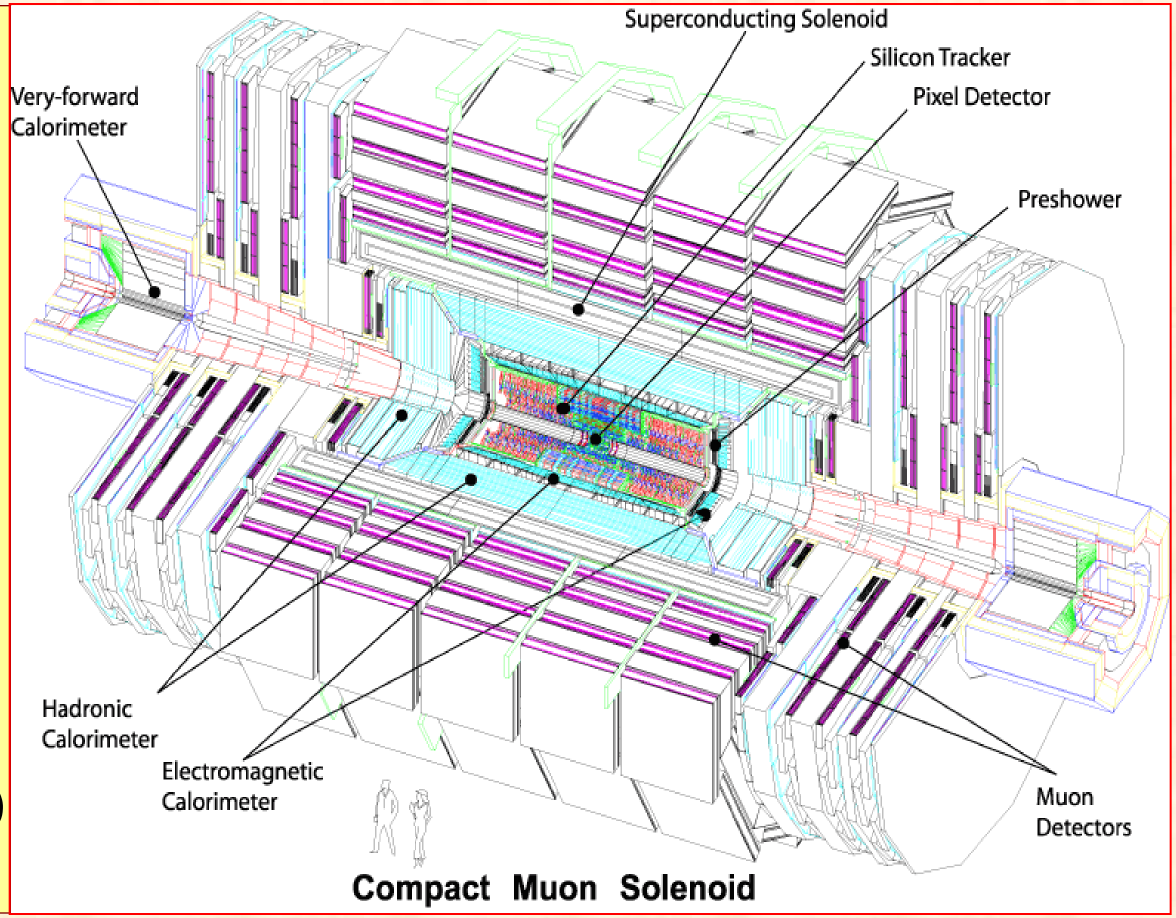
- **bulk (displacement) damage** to Silicon-detectors: neutrons > 20 keV, charged hadrons
- **surface (Ionization) damage** to electronics (degrade of S/N,…)
- Light loss in scintillators/fibers
- activation of detectors and materials (problems for maintenance)
- damage to materials (insulators)

Normalized Radiation levels @ CMS

lowest/highest levels integrated over 10 years:

- **Total Ionization Doses**
  - 5 Gy (Cavern)
  - 8 MGy (Pixels)
- **Displacement Damage fluences**
  - 2×10^{10} equivalent 1 MeV neutrons/cm^2 (Cavern)
  - 2.5×10^{15} equivalent 1 MeV neutrons/cm^2 (Pixels)
- ***Hadron fluences (SEE risk)***
  - 2×10^{9} hadrons/cm^2 (Cavern)
  - 3×10^{13} hadrons/cm$^{/2}$ (Pixels)

  $E_{charged\ hadrons}$ > 21 MeV



Obtained from simulation tools (Fluka, …)

- uncertainties due to: physics models; detector model, …
- uncertainties with electronics (COTS, dose rate effects, …)

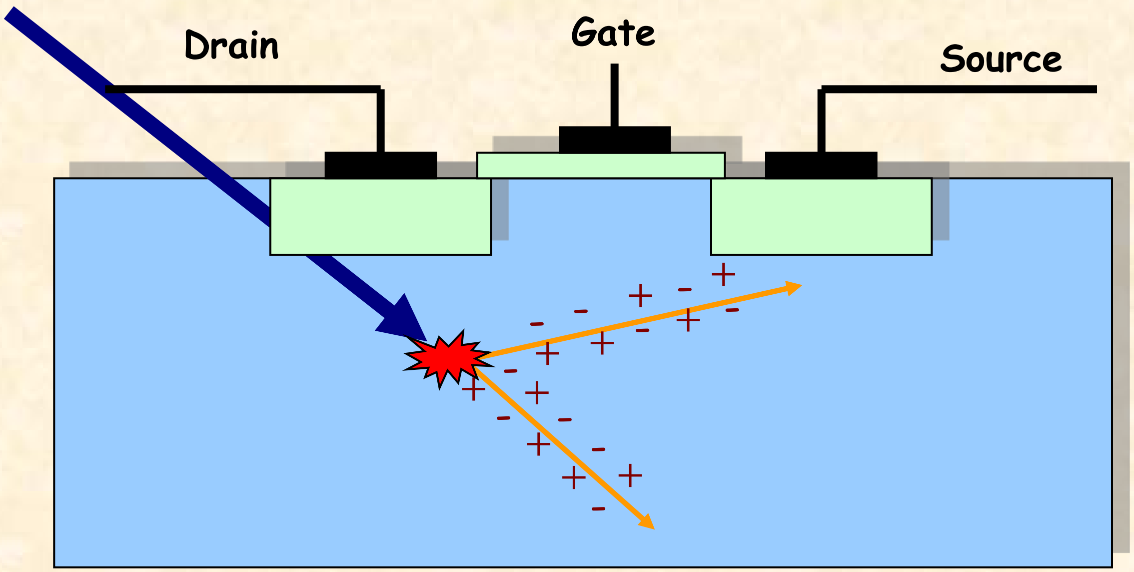
→ **Safety Factors**

Physics of hadron-induced SEE

Interdisciplinary approach is required to understand SEEs

(1) Primary hadron
(accelerator, cosmic-ray physics)

(4) Charge transport in device
(device physics)



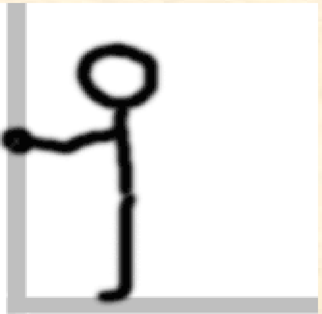
(2) hadron-nucleus reactions with production of ionizing seondaries (Nuclear Physics)

(3) Generation of electron-hole pairs
(radiation physics and solid-state physics)

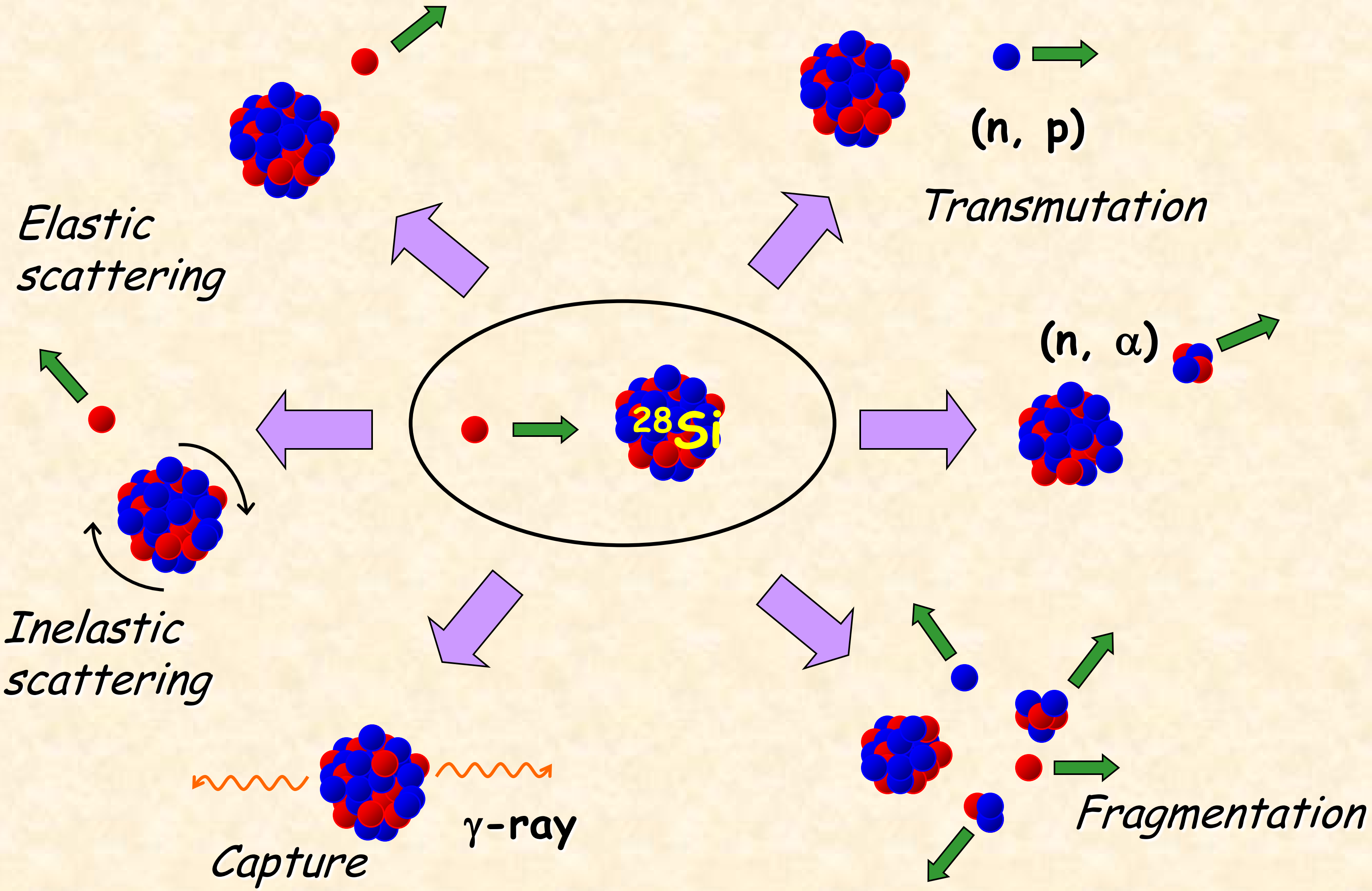
Neutron induced SEE

Neutron induced SEE is:

- an increasing, real and current problem;
- increasing use of complex microchip technologies in wider commercial and economic activity;
- no single technological solution in near future.



neutron-induced reactions on ^{28}Si



thresholds

n + Si→ p + Al
E_{thresh} = 3.85 MeV

n + Si→ α + Mg
E_{thresh} = 2.65 MeV

THRESHOLD ENERGIES OF NEUTRON REACTIONS WITH SILICON AND OXYGEN ATOMS

Reaction	Neutron Threshold Energy (MeV)
Si elastic	0
Si inelastic	1.78
Si(n,α)	2.76
Si(n,p)	4
Si(n,d)	9.70
Si(n,n-α)	10.35
O elastic	0
O inelastic	6.05
O(n,α)	2.35
O(n,n-α)	7.61
O(n,p)	10.24
O(n,d)	10.52

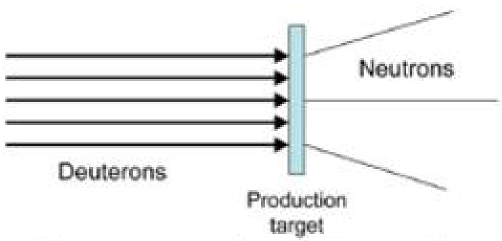
As active volumes of devices become smaller, SEE occur for E_n closer to threshold values.

BAGGIO *et al.*: SINGLE EVENT UPSETS INDUCED BY 1–10 MEV NEUTRONS IN STATIC-RAMS USING MONO-ENERGETIC NEUTRON SOURCES

IEEE TRANSACTIONS ON NUCLEAR SCIENCE, VOL. 54, NO. 6, DECEMBER 2007

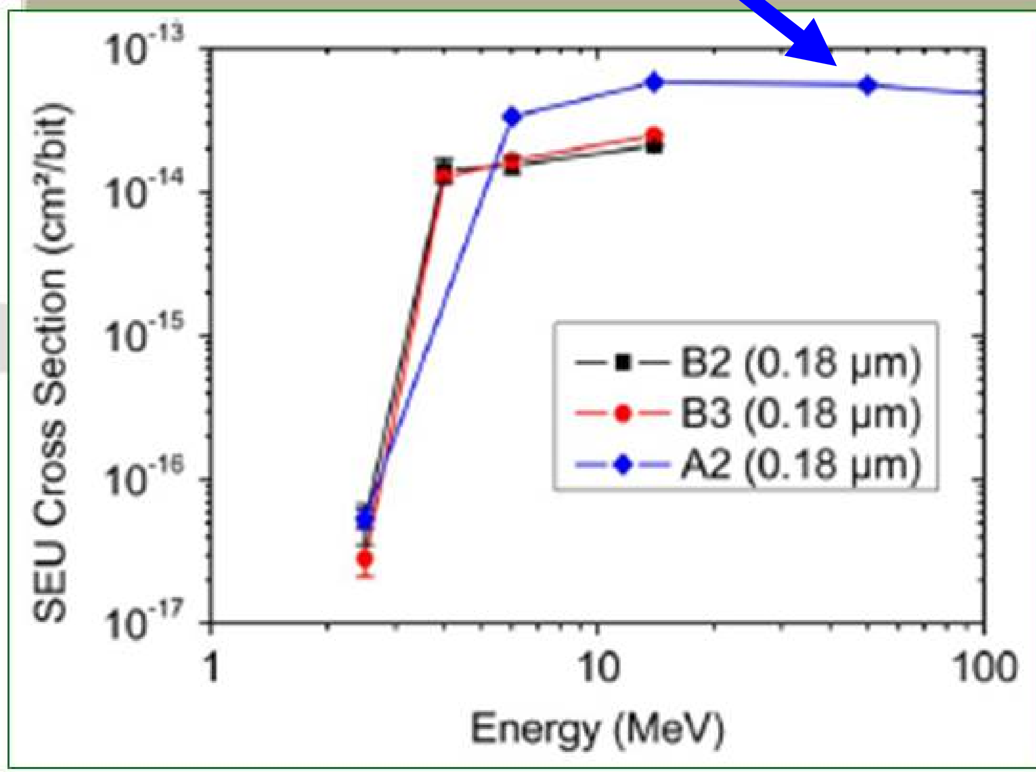
***Abstract*—The neutron-induced SEU sensitivity in the 1–10 MeV energy range is investigated using monoenergetic neutron beams at 2.5, 4, 6, and 14 MeV. Below the 0.25 μm technology node, bulk technologies exhibit a relatively high sensitivity to neutrons between 4 and 6 MeV which is explained by the contribution of alpha particles coming from (n, α) reactions. In the terrestrial environment, the contribution to SER of neutrons in this energy range exceeds 10%.**

Depending on the ion current and the reaction efficiency, the neutron fluxes are ranging from 3×10^4 n/cm^2/s at 4 MeV, up to 10^9 n/cm^2/s at 14 MeV.



Deuteron Energy	Target	Reaction	Neutron Energy
180 keV	Ti/D	D(d,n)^{3}He	2.5 MeV
1.06 MeV	Ti/D	D(d,n)^{3}He	4 MeV
3.2 MeV	Ti/D	D(d,n)^{3}He	6 MeV
180 keV	Ti/T	T(d,n)^{4}He	14 MeV

50 MeV proton data point



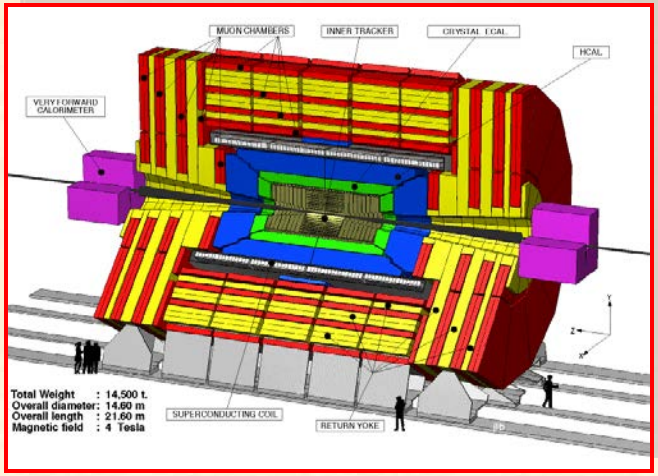
Neutrons, neutrons, yet more neutrons

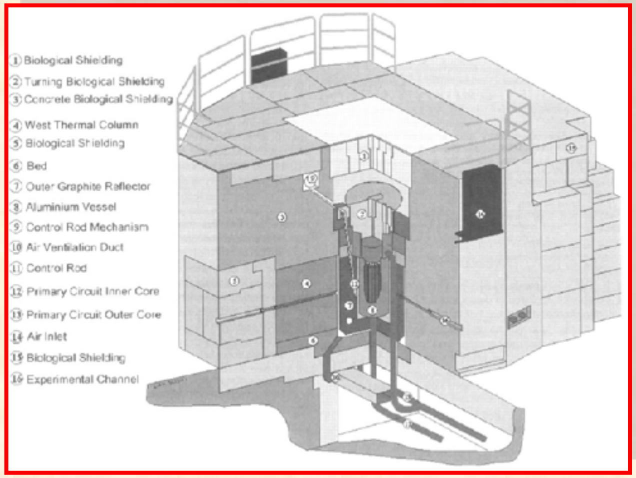
Energetic neutrons:

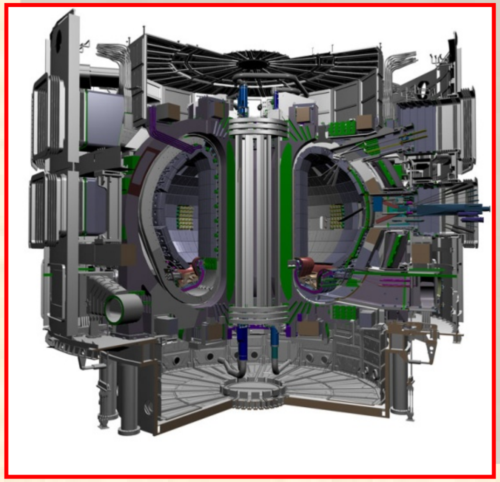
- High energy collisions (e.g. LHC)
- thermonuclear fusion reactors (ITER)
- nuclear power plants

} a GREAT many neutrons

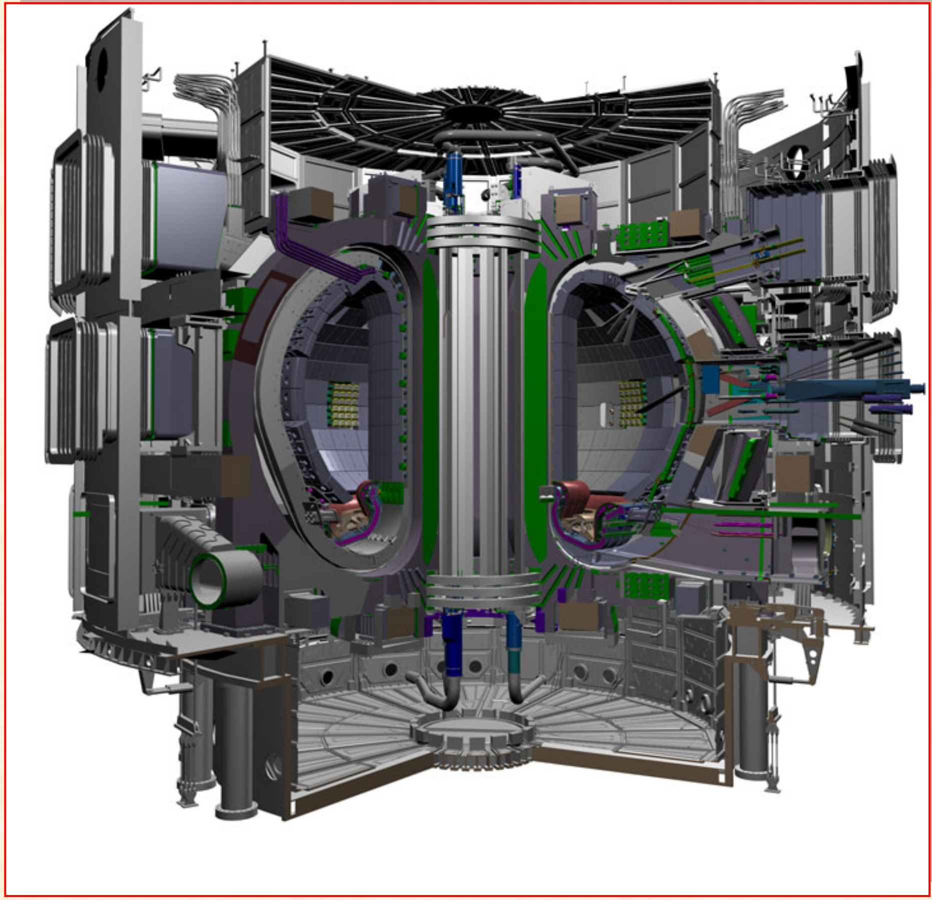
- cosmic ray atmospheric showers (avionics and SEA LEVEL electronics). (more than enough neutrons to cause trouble)







ITER
(International Thermonuclear Experimental Reactor)

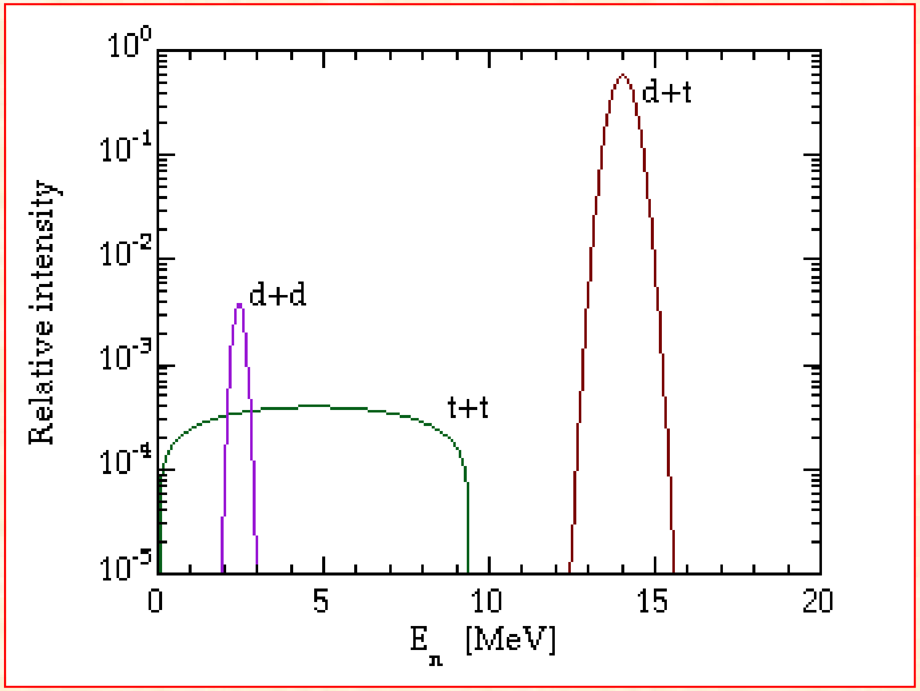


Initial D-D phase

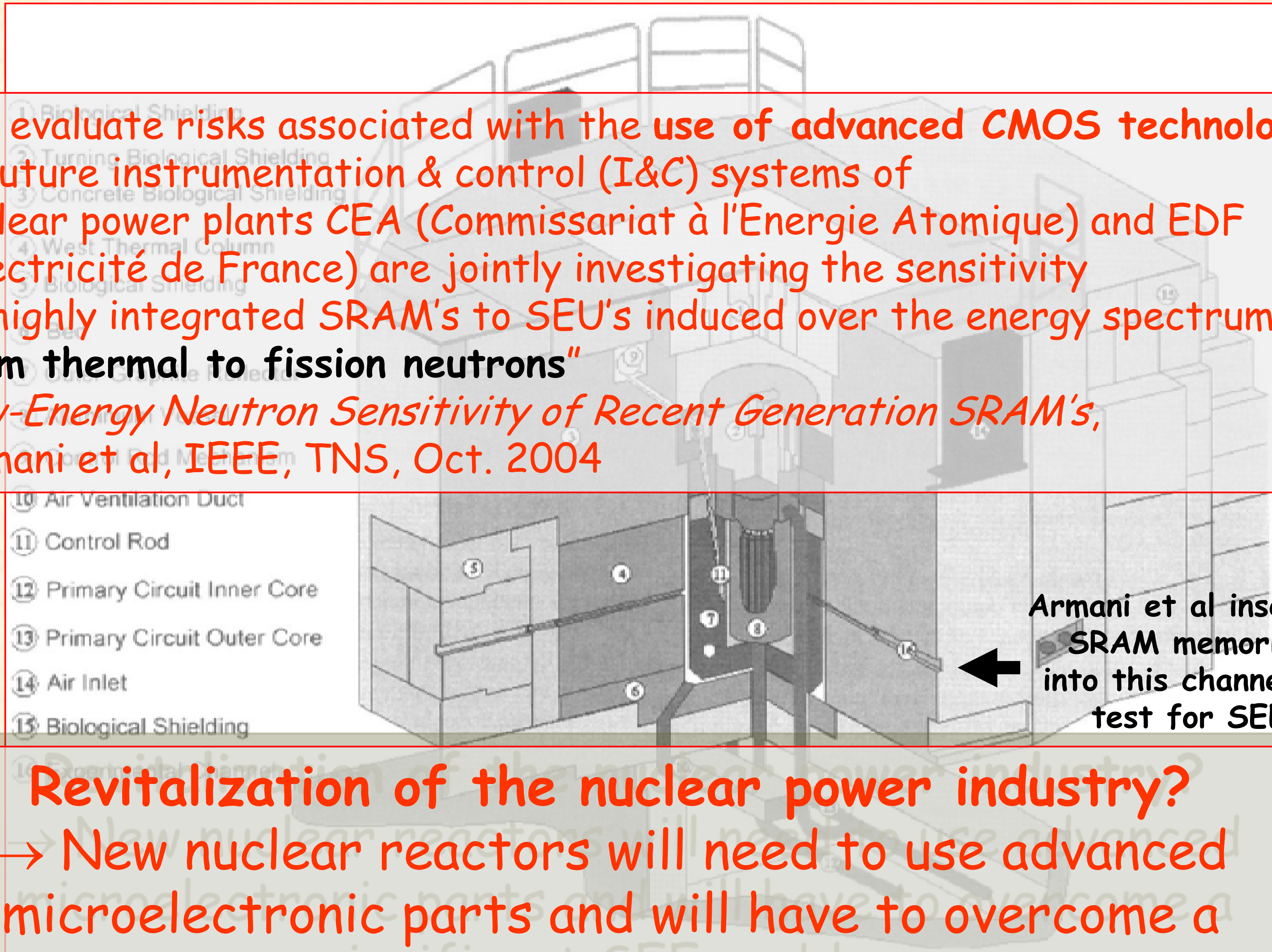
$^{2}H_{1}$ + $^{2}H_{1}$ → $^{3}He_{2}$ (0.82 MeV) + n (2.45 MeV)

Fusion D-T

$^{2}H_{1}$ + $^{3}H_{1}$ → $^{4}He_{2}$ (3.5 MeV) + n (14.1 MeV)



SEE in the nuclear power research and industry



"To evaluate risks associated with the **use of advanced CMOS technology** in future instrumentation & control (I&C) systems of nuclear power plants CEA (Commissariat à l'Energie Atomique) and EDF (Electricité de France) are jointly investigating the sensitivity of highly integrated SRAM's to SEU's induced over the energy spectrum **from thermal to fission neutrons**"

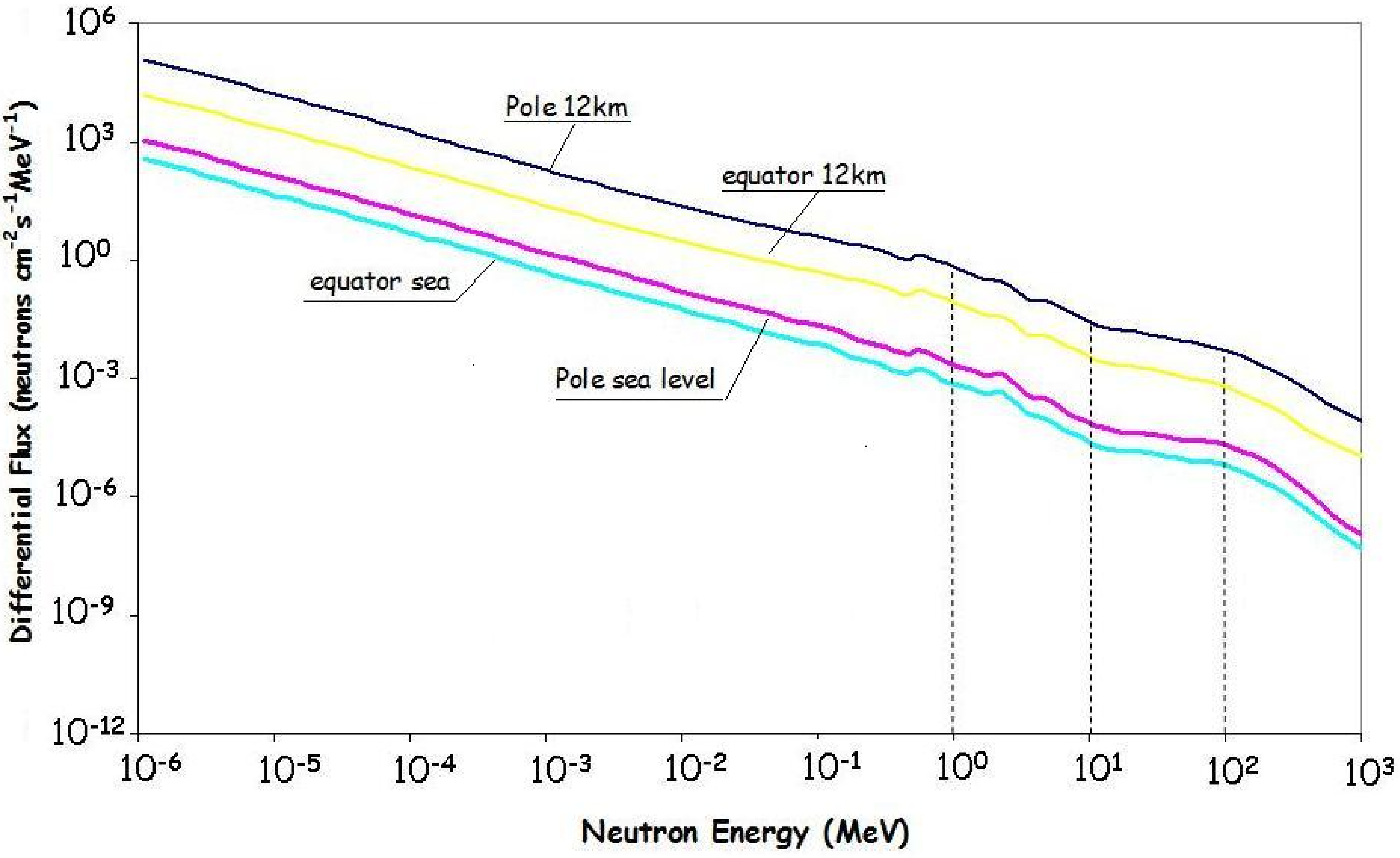
Low-Energy Neutron Sensitivity of Recent Generation SRAM's, Armani et al, IEEE, TNS, Oct. 2004

Armani et al inserted SRAM memories into this channel to test for SEE

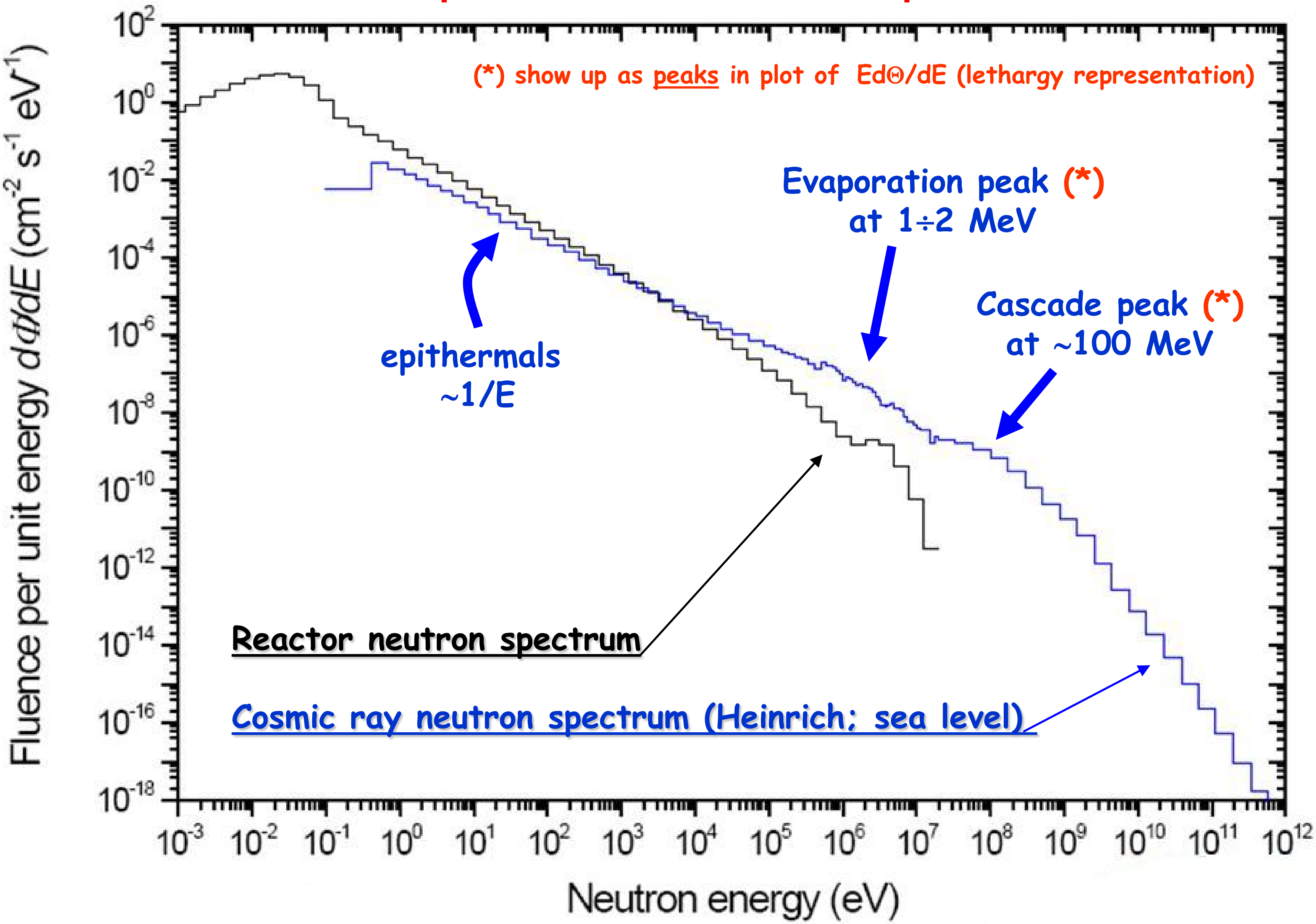
Revitalization of the nuclear power industry?

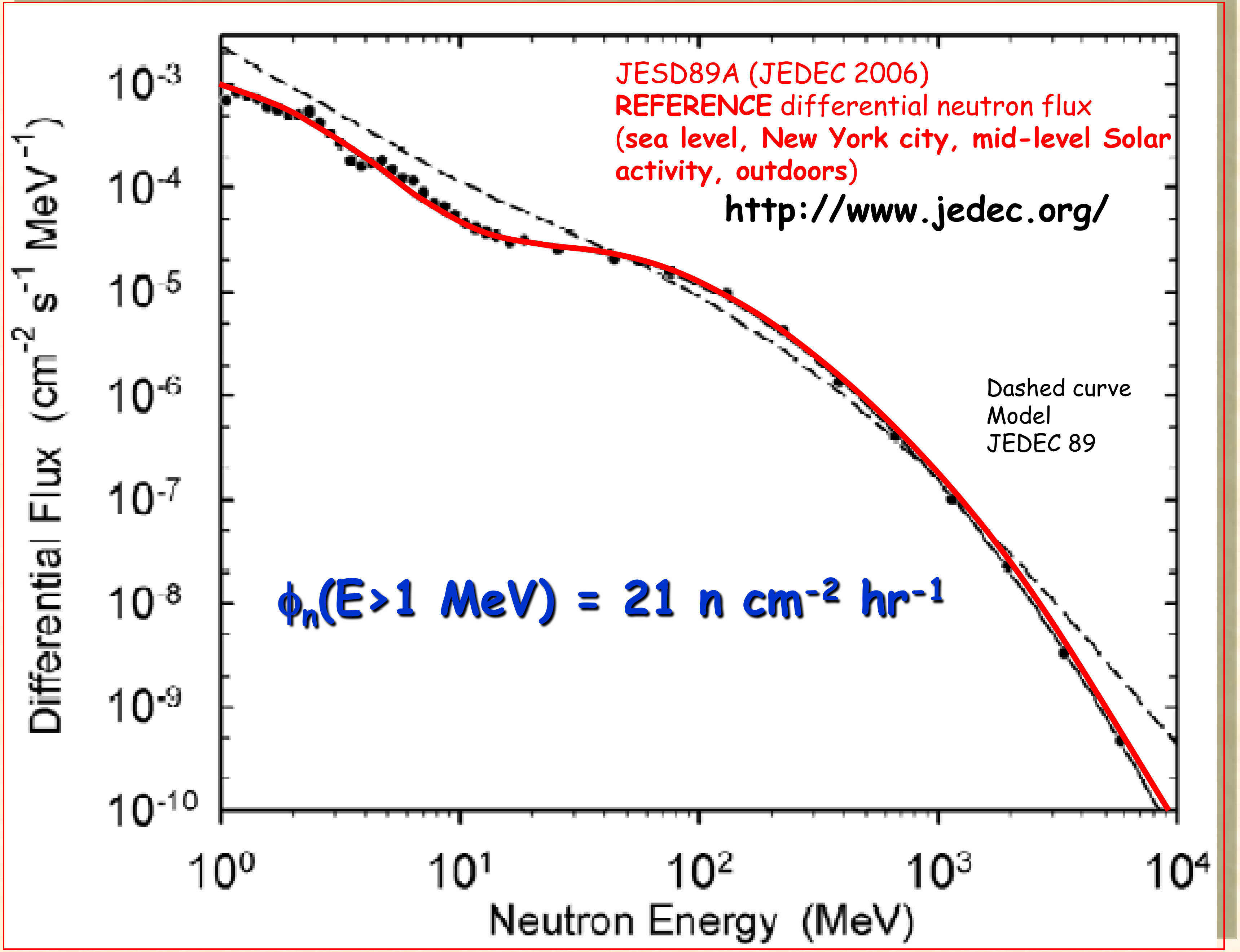
→ New nuclear reactors will need to use advanced microelectronic parts and will have to overcome a significant SEE problem.

Continuous ("white") atmospheric neutron spectra



"white" spectra: reactor vs atmospheric one




JESD89A (JEDEC 2006)
REFERENCE differential neutron flux
(sea level, New York city, mid-level Solar activity, outdoors)
http://www.jedec.org/
Dashed curve
Model
JEDEC 89
φn(E>1 MeV) = 21 n cm-2 hr-1
Differential Flux (cm-2 s-1 MeV-1)
Neutron Energy (MeV)
10-3
10-4
10-5
10-6
10-7
10-8
10-9
10-10
10^0
10^1
10^2
10^3
10^4

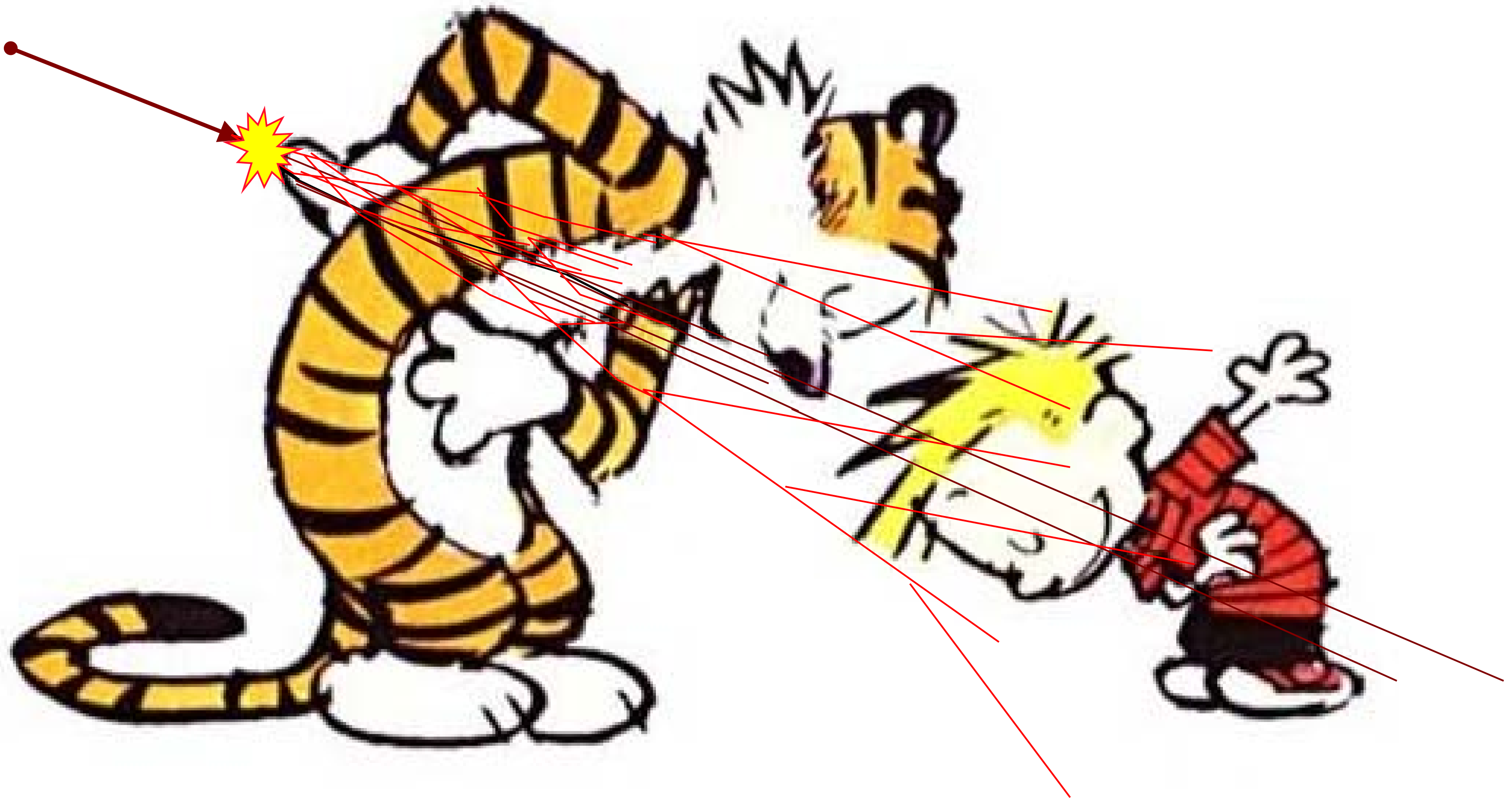
Systems complex and error prone to atmospheric neutrons

- ❑ **electronic systems are more complex as feature sizes decrease increasing likelihood of SEE causing a system failure and increases the probability of a neutron defeating error correction mechanisms (multiple bit upsets).**

- ❑ SEE threat also from low energy "thermal" neutrons through a reaction of boron present as dopant in semiconductors. Thermal neutrons are generated within moderating materials (concrete in buildings; fuel in aircraft;…)

- ❑ **Developments towards smaller faster devices at lower bias voltages have increased SEE susceptibility in the 1÷10 MeV range making soft errors more likely as they are then sensitive to the greater proportion (~40%) of atmospheric neutron flux.**

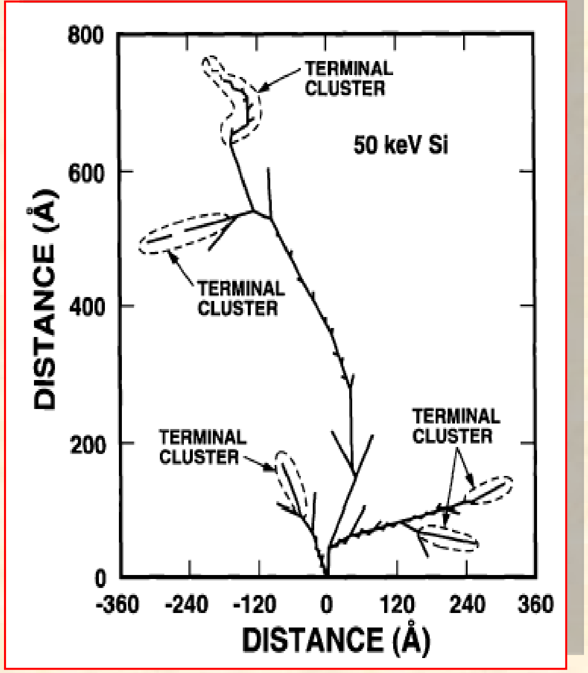
END



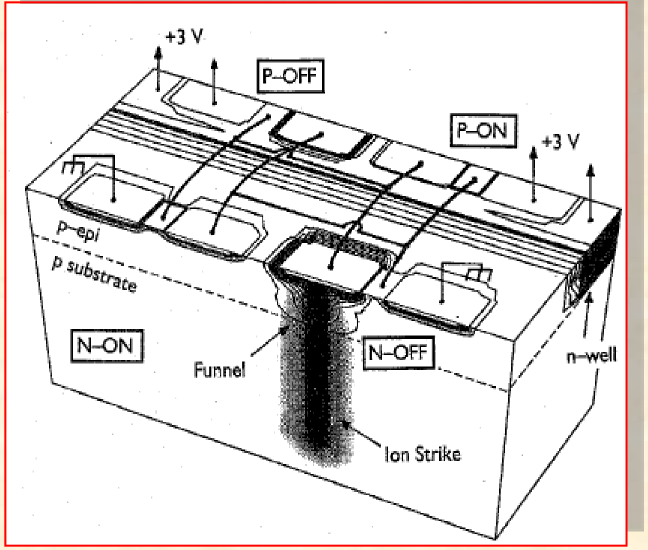
Extra slides

History of the SIRAD irradiation facilities at 15MV Tandem accelerator of LNL (protons, heavy ions)

The facility was created from scratch in 1996-7 and in 1998 started running bulk damage studies in silicon detectors for High Energy Physics applications (in the framework of the RD48 CERN Collaboration, R&D for CMS) using 30 MeV protons and 70 MeV lithium ions.



In 2000 the facility began studies of heavy ion induced Single Event Effects (SEE) in microelectronics devices for HEP and space applications.



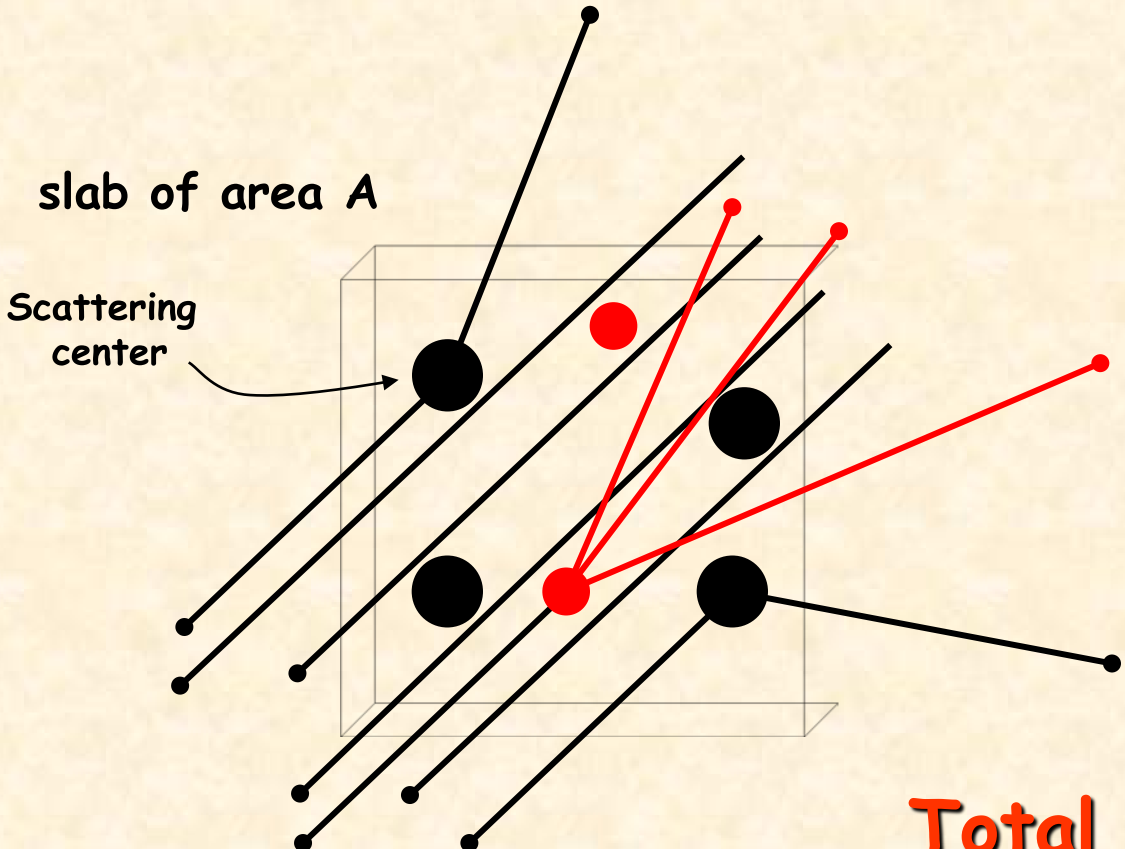
Presently SEE studies are the main activity.

- **"global" (broad beam) irradiation**
- **Ion Electron Emission Microscopy**
- **TID studies with X-ray machine**
- **Future:** neutron-induced SEE at the SPES 70 MeV 500μA cyclotron

cross section

Total event rate $n(t) = \phi \cdot N_s \cdot \sigma_{tot} = L(t) \times \sigma_{tot}$

flux



- fluence $\Phi = \int \phi(t)dt$
- integrated luminosity

$$L = \int L(t)dt$$

- N_s = number of scattering centers in slab of area A each with cross-section σ_{tot}

ϕ number of incident particles per area A and per unit time (a *flux*)

Total cross section

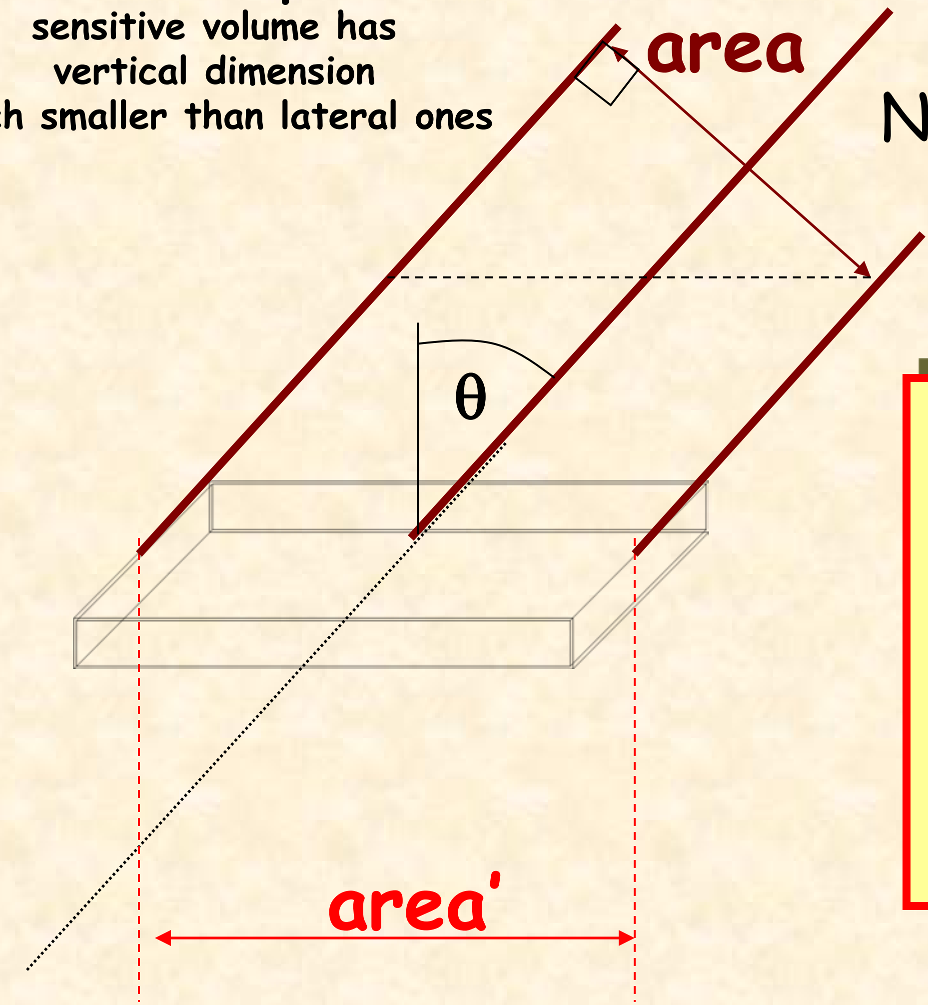
$$\sigma_{tot} = \sigma_{elastic} + \sigma_{inelastic}$$

$$\sigma_{tot} = \sum_k \sigma_k$$

total cross-section is sum of cross-sections of all possible modalities (channels)

inclined SEE exposure

SEE assumption:
sensitive volume has
vertical dimension
much smaller than lateral ones



Beam fluence ϕ

NOTE: **area** = **area'** cos(θ)

$$LET(\theta) = LET(0^o)/\cos(\theta)$$

AND

$$\sigma(LET,\theta) = \frac{N_{SEE}}{\phi \cos(\theta)}$$

NOTE: cos(θ) enters twice!

1. LET(θ)
2. σ(θ)

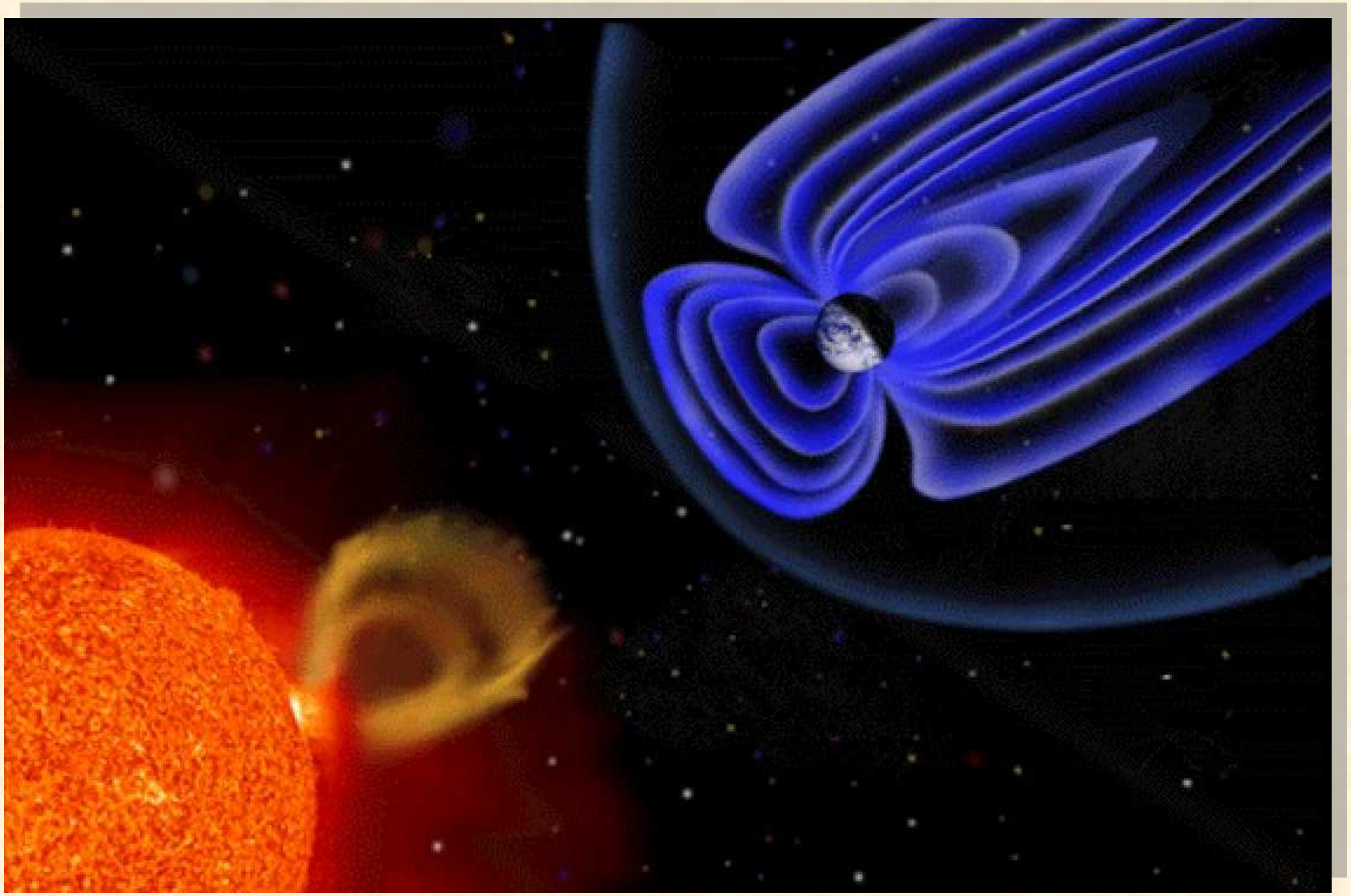
borealis: haunting beauty

http://www.geo.mtu.edu/weather/aurora/images/

Space radiation environment

Space is full of energetic particles with damaging potential (TID,DDD,SEE):

- from the SUN: *normal* solar wind and solar events (storms, flares)
- from outside the solar system (galactic cosmic rays)

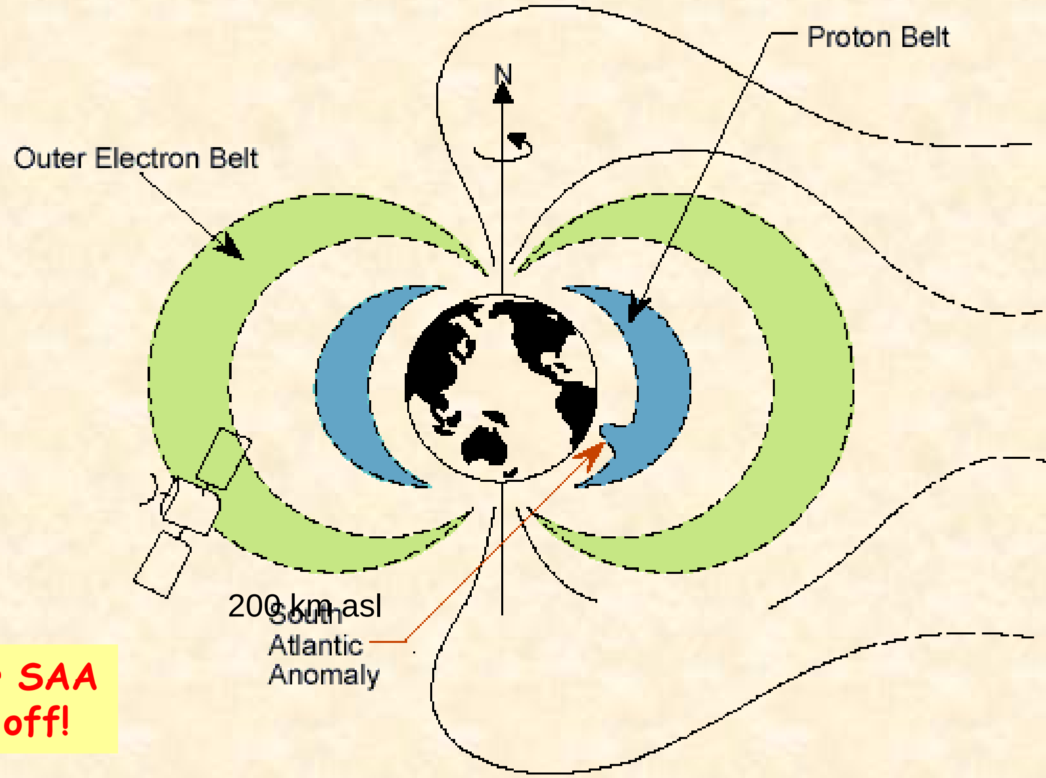


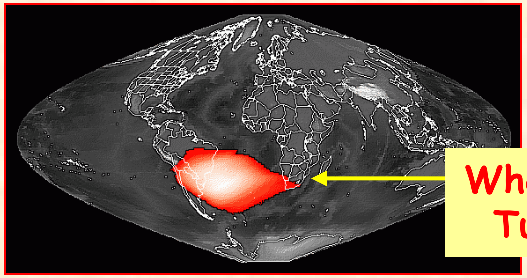
- Some are deflected when their magnetic rigidity is small enough, others are magnetically trapped in Van Allen belts.

trapped particles

- The Earth's dipole is slightly off-axis (320 km from the planet axis) and inclined at 11.5°
- In some points the magnetic field intensity is smaller
- Lowest magnetic intensities are above Brazil, the so called South Atlantic Anomaly (SAA)

- For instruments in Low Earth Orbit (below 1500 km) the SAA gives the highest contribution to radiation exposure
- Electrons: up to 7 MeV in *inner* & *outer zone*
- Protons: up to 100s MeV
- Current models: AE8 & AP8, with data from 43 satellites, 55 space instruments, 1630 channel-months of data

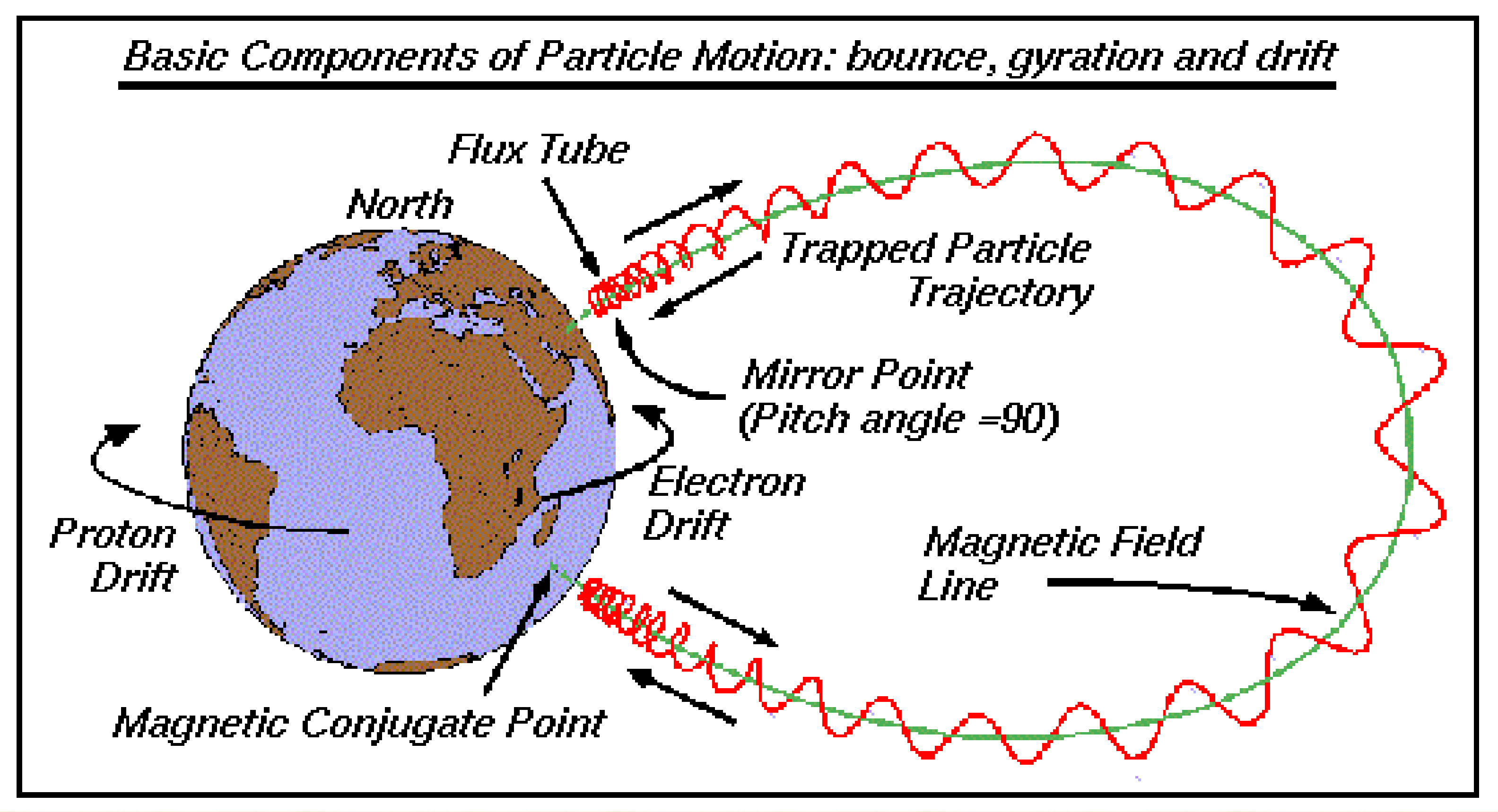




When passing over SAA
Turn electronics off!

trapped particles (extra slide)

- Passing charged particles interact with Earth magnetic dipole field
- Some particles are trapped in Van Allen belts
- At poles particle may bounce (magnetic mirroring), and drift around the Earth depending on their charge
- Particles are trapped if the mirror point is high enough

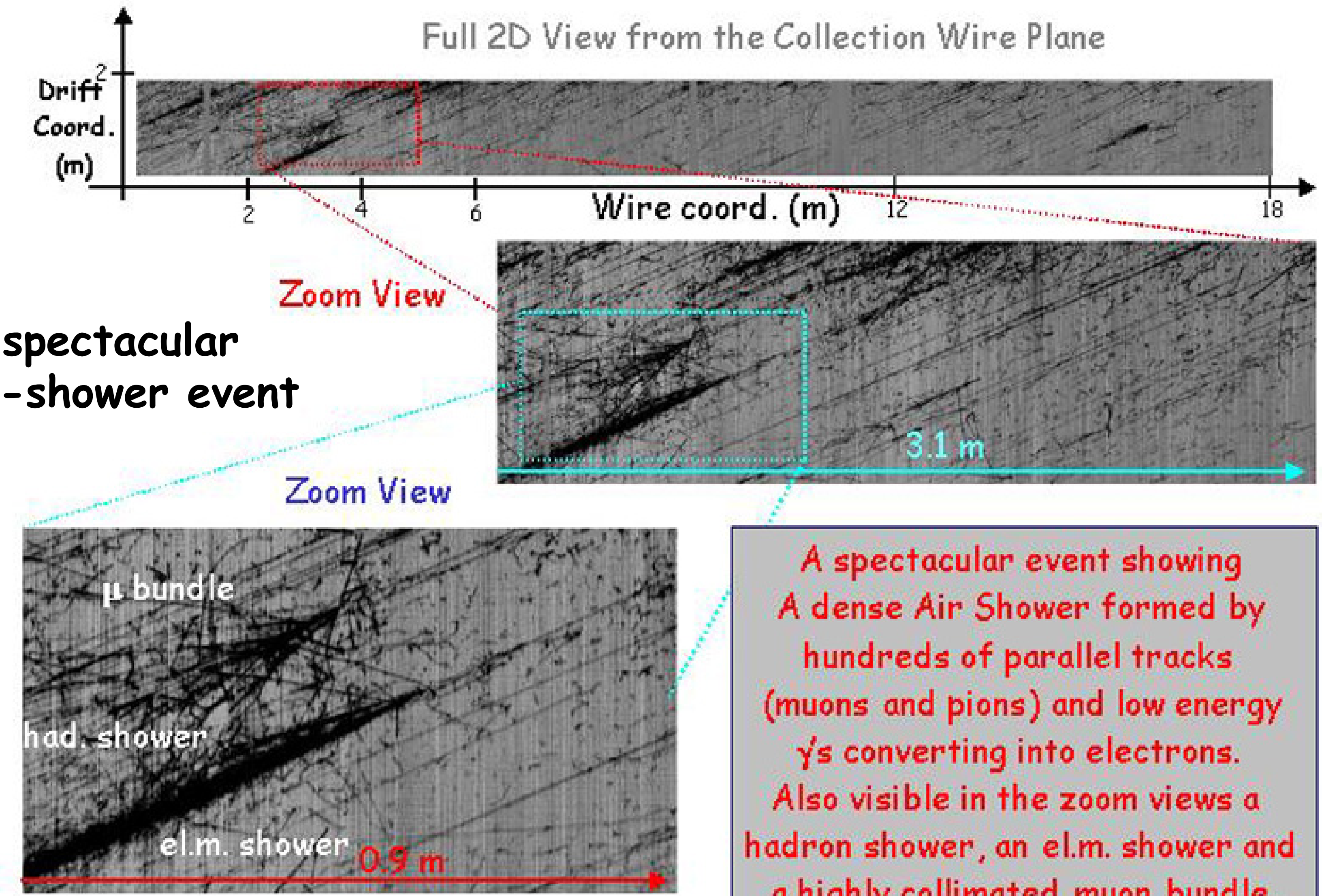


ICARUS (liquid argon time projection chamber)

Cosmic rays

electronic but with visual quality!

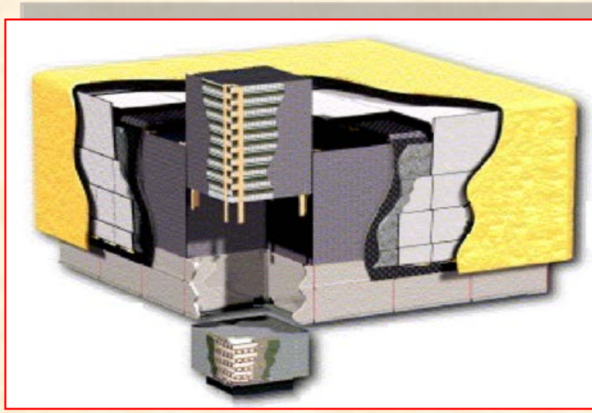
spectacular air-shower event

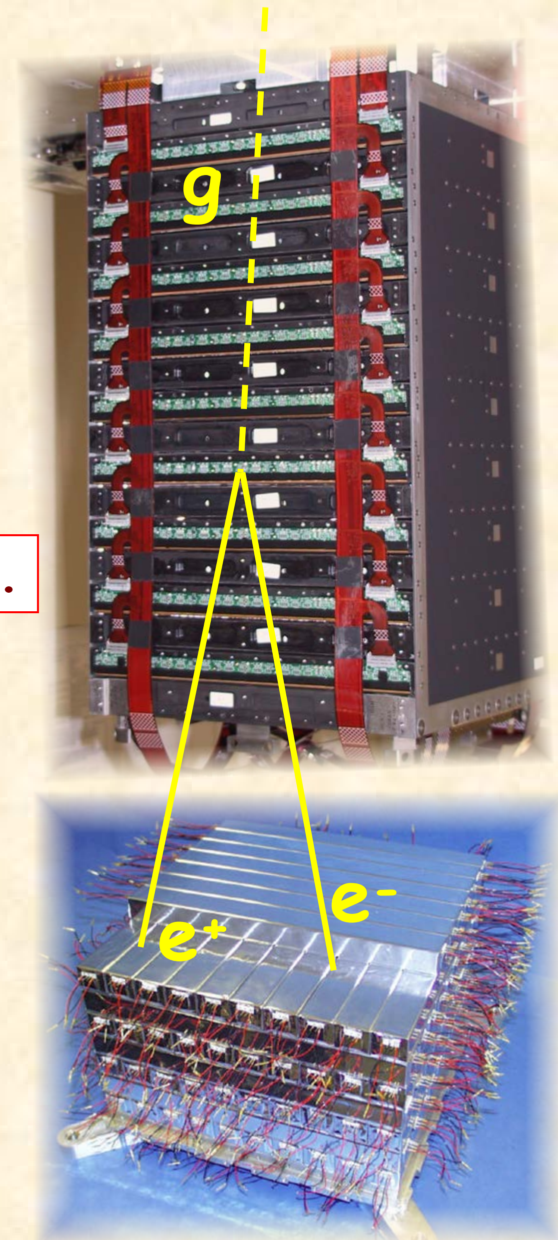


A spectacular event showing A dense Air Shower formed by hundreds of parallel tracks (muons and pions) and low energy γ's converting into electrons. Also visible in the zoom views a hadron shower, an el.m. shower and a highly collimated muon bundle.

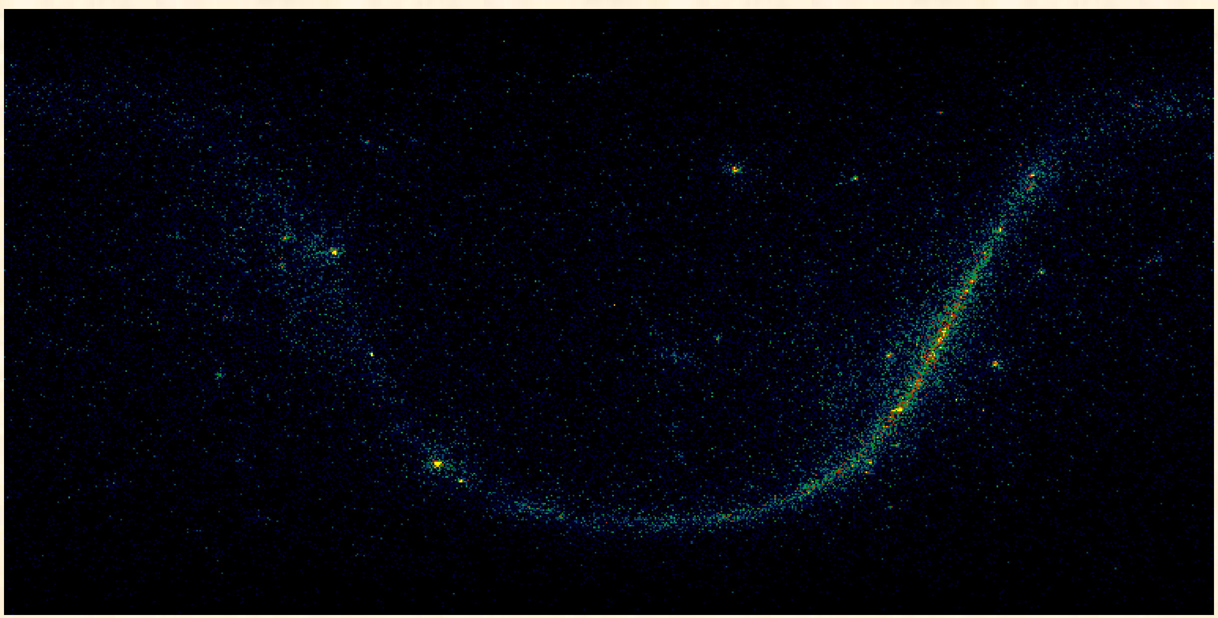
Fermi Gamma-ray Space Telescope (ex-GLAST)

detector in space





A lot of silicon (less than CMS but more that Atlas!).



Space

Harsh Environment above Earth's Atmosphere

Space

Space Environment Effects complete picture

after Barth

Source	Effect	Consequences
Plasma	Charging	❑ Biasing of instrument readings ❑ Pulsing ❑ Power drains ❑ Physical damage
Particle radiation	Charging; Ionizing & Non-Ionizing Dose; Single Event Effects; material degradation	
	Ionizing & Non-Ionizing Dose	Degradation of: ❑ μ-electronics ❑ silicon sensors ❑ solar cells ❑ optical components
	Single Event Effects	❑ Data corruption ❑ Noisy Images ❑ System shutdowns ❑ Circuit damage
Neutral *gas particles*	Drag; material degradation	❑ Torques ❑ Orbital decay
Ultraviolet & X-ray	material degradation	Degradation of: ❑ thermal, electrical, optical properties ❑ structural integrity
Micro-meteors & orbital debris	material degradation; Impacts	❑ Structural damage ❑ Decompression

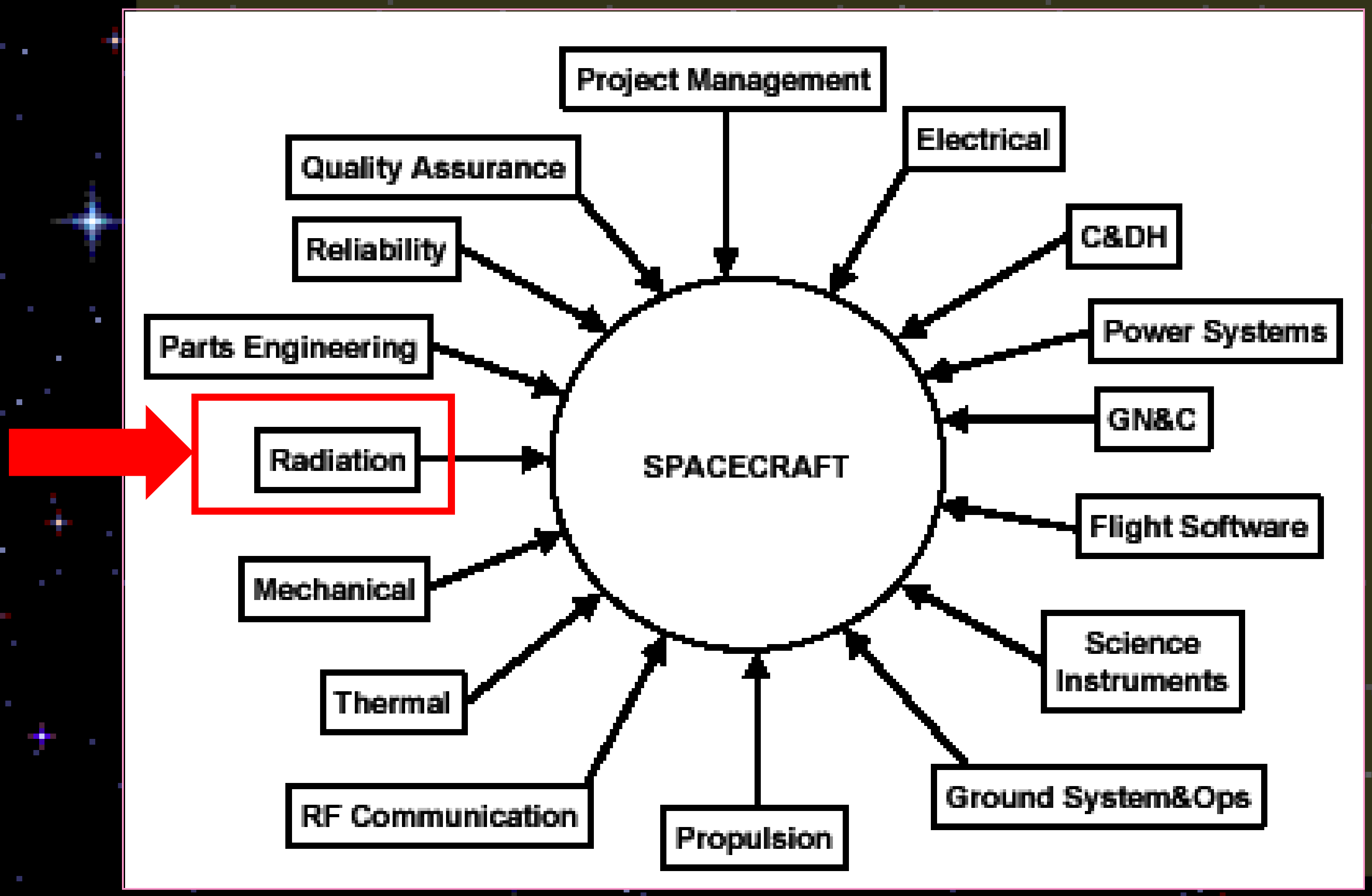
Radiation Effects (Ionizing & Non-Ionizing Dose, Single Event Effects)

Vacuum, shock, and thermal cycles also important

Space

Spacecraft design team

A typical spacecraft design team:
the radiation group is only one part of the team.



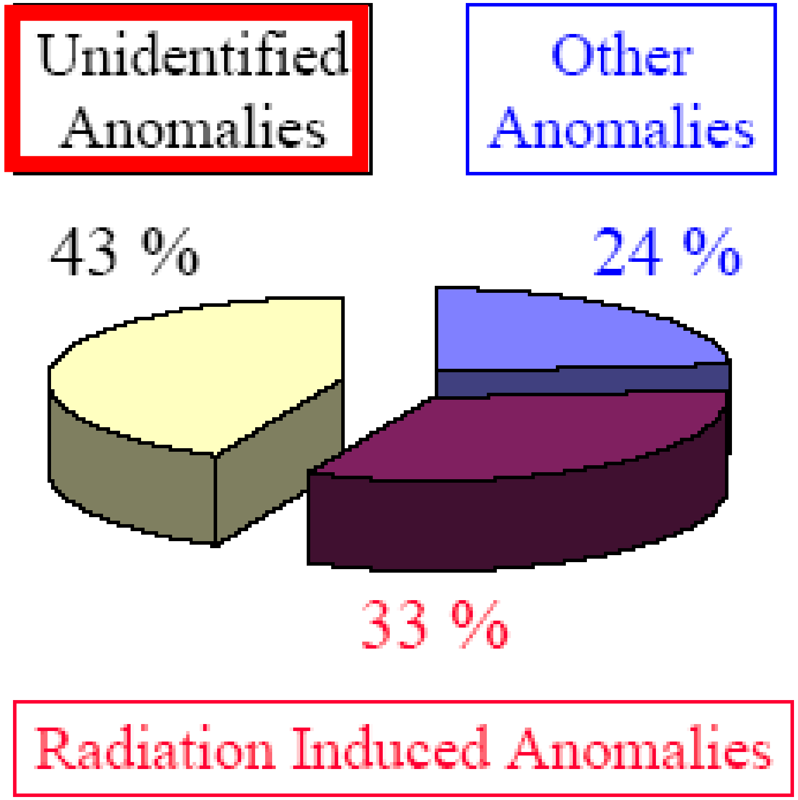
Space

In context

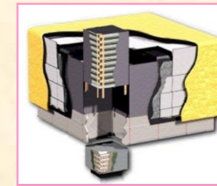
J. Gasiot

«Electronique et Rayonnement»

Université de Montpellier II, FRANCE



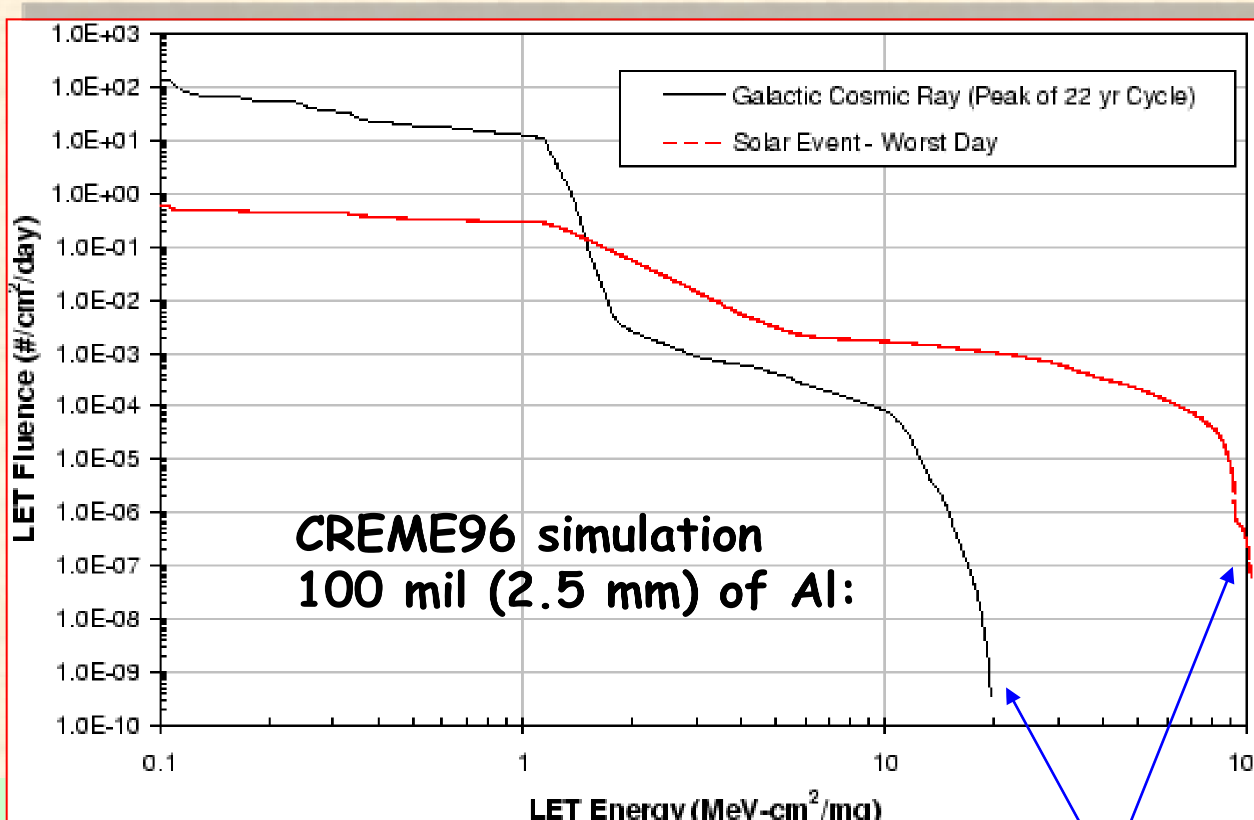
LET spectra and dose for FERMI *(GLAST)*



- GLAST orbital parameters:
  - 565 km asl, circular orbit
  - 28.5° inclination, ~1.6 hr orbital period
  - 5 year mission

Courtesy of Riccardo Rando, FERMI collabortion

- Biggest contribution to dose is passage into South Atlantic Anomaly
- Maximum total dose is 0.8 krad in most exposed devices in a 5 year mission
- 5X engineering limit, another 2X safety margin
- Galactic Cosmic Rays + Solar Particle Events < 0.3 ions/cm² (5 yrs)



FERMI estimate

10 krad, 1 ion event/cm² (5 years)

Biological radiation QUALITY weighting factors

1 Sv = 1 Gy × RBE = 100 rad × RBE = 100 rem

skip

Radiation type	***R**elative **B**iological **E**ffectiveness*
photons, electrons and muons	1
protons > 2 MeV (except recoil protons)	5
alpha particles and heavy ions (Z>2)	20
neutrons < 10 keV	5
10 keV <100 keV	10
100 kev < 2 MeV	20
2 MeV < 20 MeV	10
> 20 MeV	5

Rolf Sievert

1 Sv = 1 Gy × RBE = 100 rad × RBE = 100 rem

1 mSv = 100 mrem

skip

- 3 mSv/yr = average exposure of a person in one year

- 0.2 μSv/hr …. at 4000 m above sea level
- 5 μSv/hr …. at 12000 m above sea level
- 13 μSv/hr …. at 20000 m above sea level
- 50 μSv …. flight London → New York

- X-ray …. 1mSv
- CAT scan …. 3÷4 mSv
- total body scan (scintigrafia), PET …. 20 mSv
- radiotherapy ….tens of Sv

its a tough LIFE in space

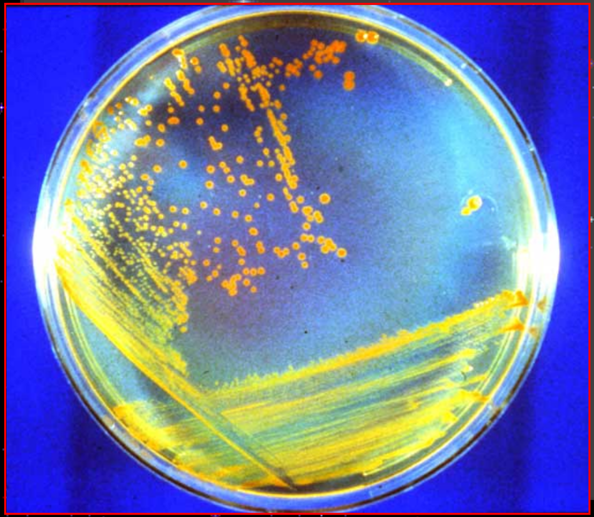
skip

• active Sun (every 11 yrs) may expel intense clouds of protons that deliver doses of 0.3-3 Gy/3 days (Townsend, Shinn, Wilson, *Radiation Research 126:108-110*);

• NOTE: ~ 1/2 of cells of crew members of round trip to Mars will be traversed by at least one galactic cosmic rays with high charge and energy (HZE) (Setlow, *Mutation Research 430:169-175*)

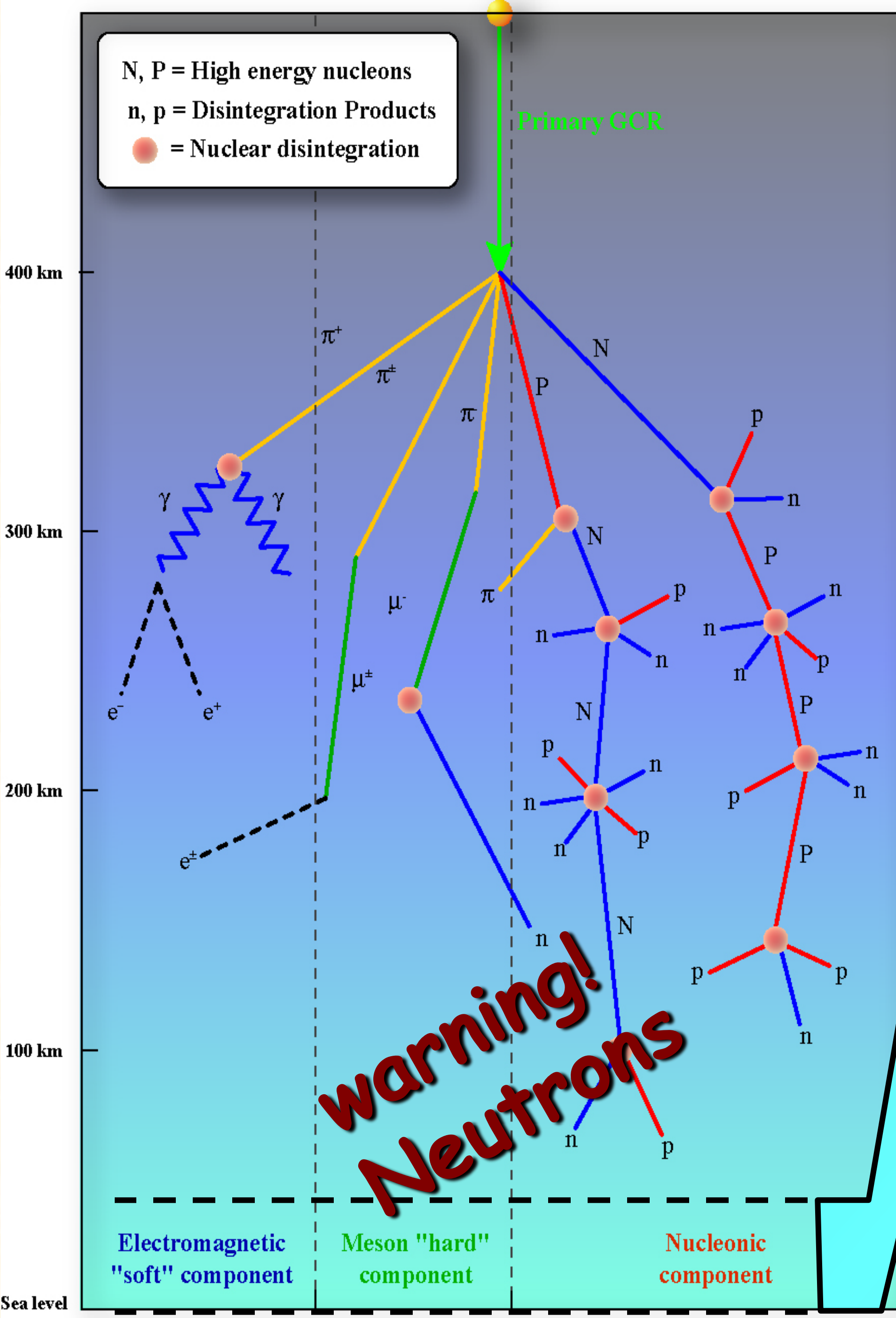
rad-hard bacteria

deinococcus radiodurans



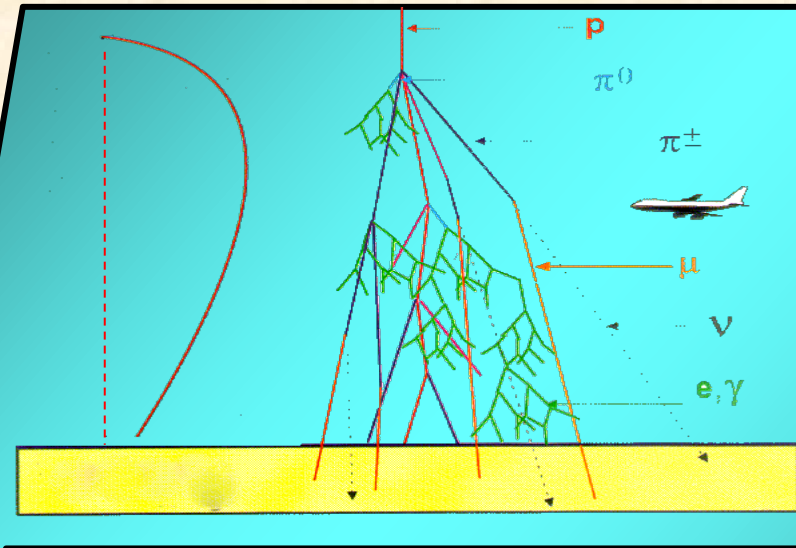
- Skylab mission 2500 mrad = 0.025 Gy
- orbits 250-300 km at 65º (resp. equator) 10 mrad/day
- pass thru Van Allen 0.1-0.2 Gy/hr (passage lasts 10-20 min)

- Shuttle ~ 433 mrem/mission average skin dose
- Shuttle 7864 mrem highest skin dose



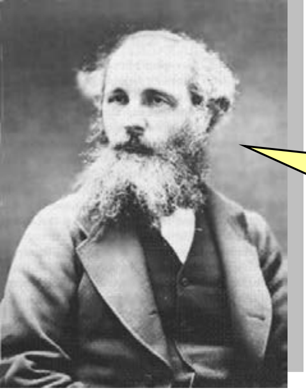
Air showers

Shower maximum at ~18 km

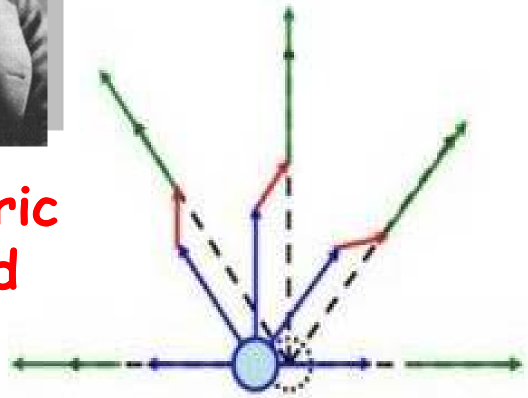


Under 20 km altitude **neutrons** dominate as cause of so called **Single Event Effects** in avionic systems.

In mountains and <u>at sea level</u> there are enough of them to be a real concern for ground-based electronics that play vital roles (e.g. in computers, pace makers, cars, voting machines…, power devices in locomotives,…)



Take a charge .... and move it



Electric field

There will be **kinks** in the electric field and they will **propagate**

Shake the charge back and forth and…