Exposure to radiation damage: concepts, quantities

environments (no time)

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- ☐ Introduction (brief?)
- ☐ Part 1 (>1 hour ↑)
  - *"exposure" to concepts*
- ☐ Part 2 (<1 hour ↓)
  - *"exposure" to damage in electronics,*
  - *SEE,…*
- ☐ stuff I will not cover (no time)
  - *Will SKIP TID, DDD (leave to others)*
- ☐ summary slides (will not show)

Introduction

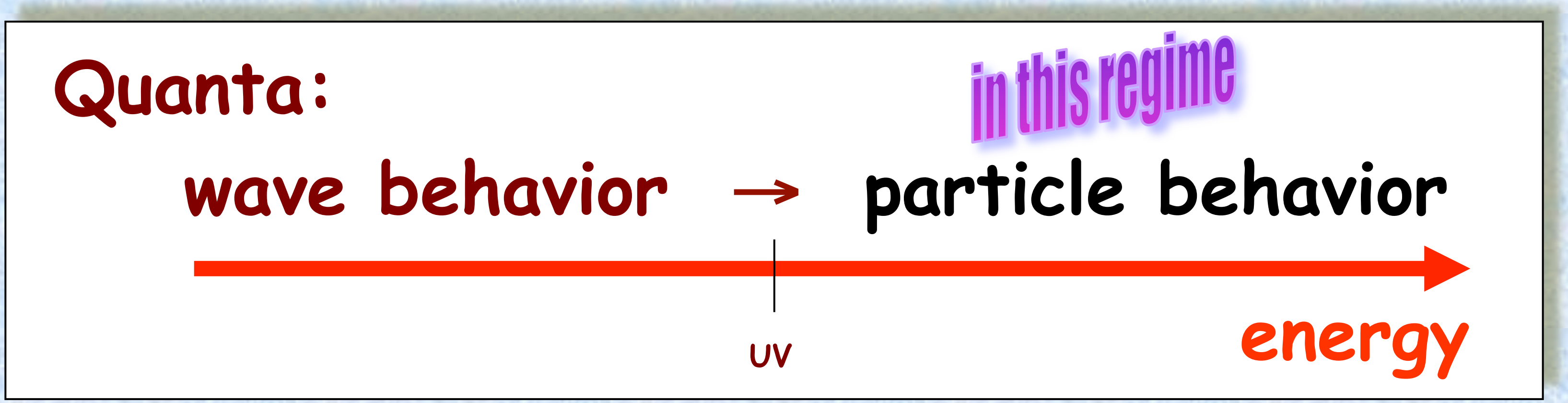
GLOSSARY

Radiation:

In the context of this talk on radiation effects,

"radiation: The transfer of energy by means of a **quantum** (particle or photon)."

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



Quanta:

in this regime

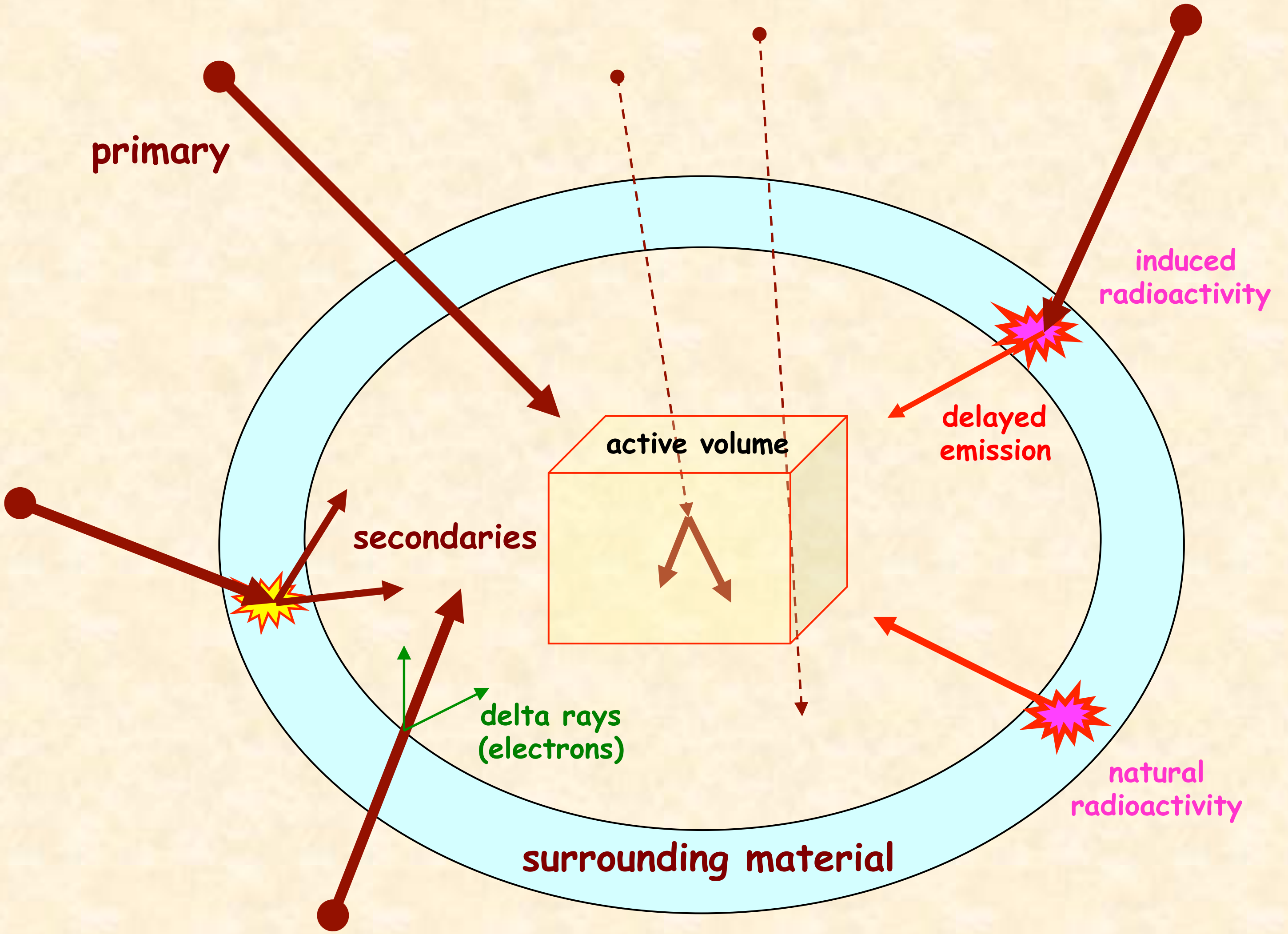
wave behavior → particle behavior

RADIATION: ubiquitous, problem, hazard, tool

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

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 • ...



primary

induced
radioactivity

delayed
emission

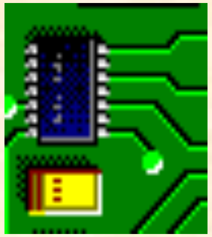
active volume

secondaries

delta rays
(electrons)

natural
radioactivity

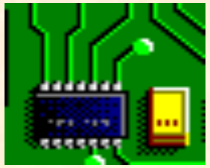
surrounding material



Radiation:

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

Radiation effects in electronics?



Who cares? Why worry?

Use of electronics:

- High Energy Physics
- Outer Space
- normal everyday life → all of us

Effects of radiation in SCIENTIFIC EQUIPMENT

after Barth

Particle radiation

Charging

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

Ionizing & Non-Ionizing effects

Degradation of:

- μ-electronics
- silicon sensors
- solar cells
- optical components

Single Event Effects

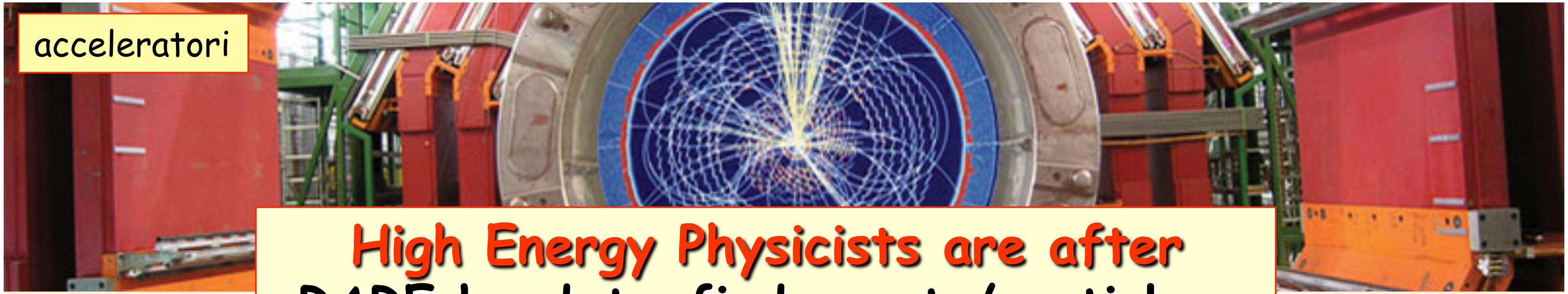
- Data corruption
- Noisy Images
- System shutdowns
- Circuit damage

material degradation

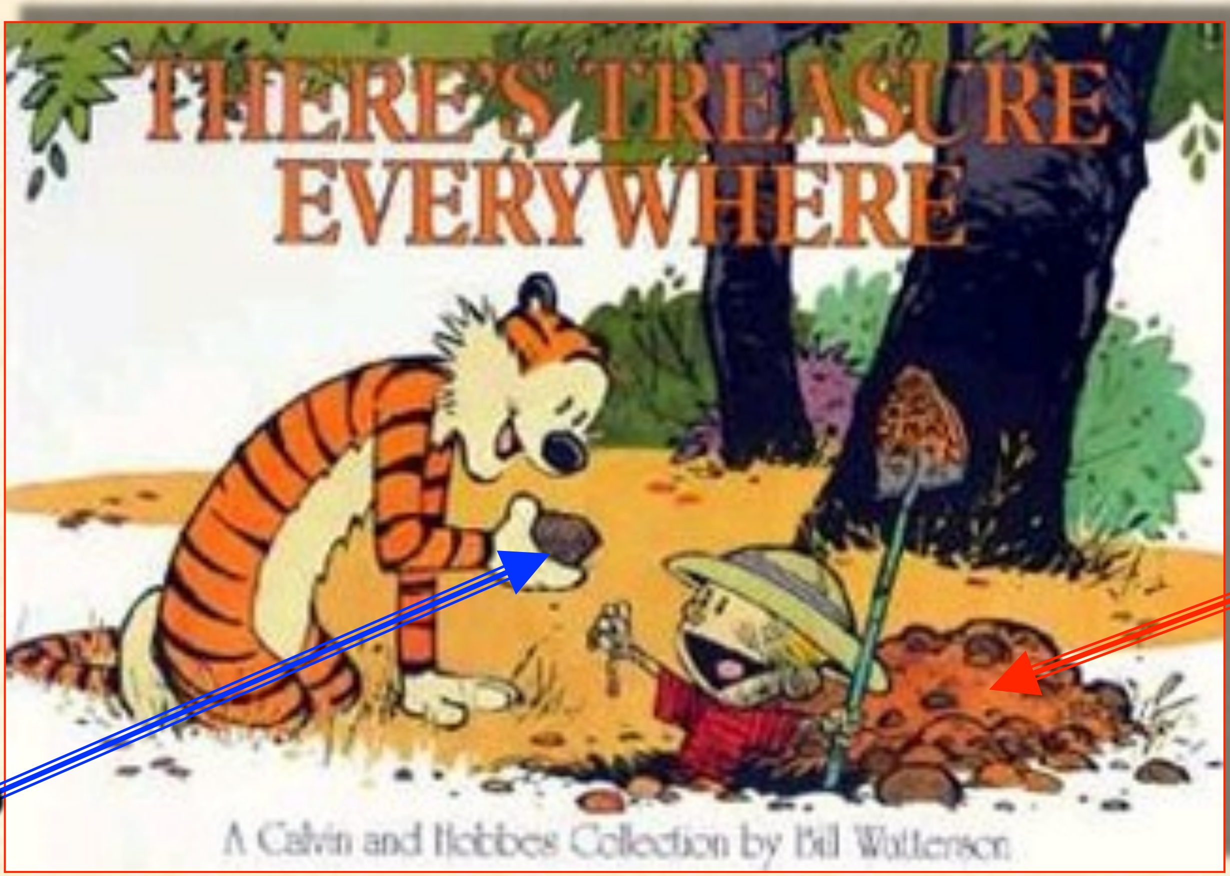
Degradation of:

- thermal, electrical, optical properties
- structural integrity

direct effects in electronics



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

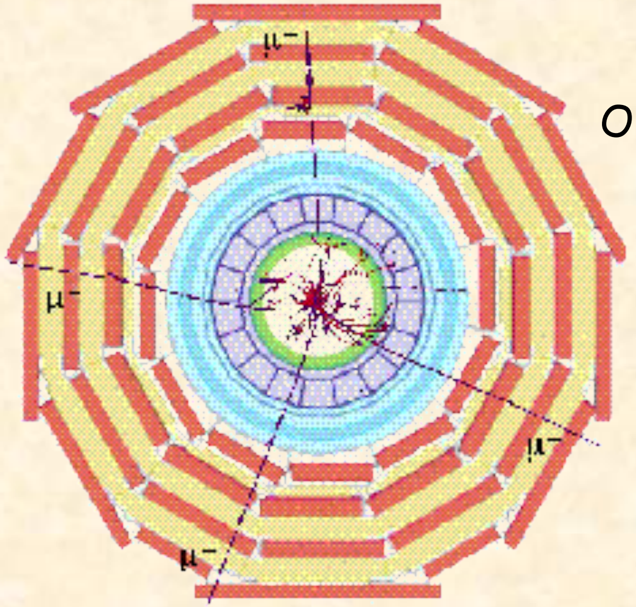


Signal?

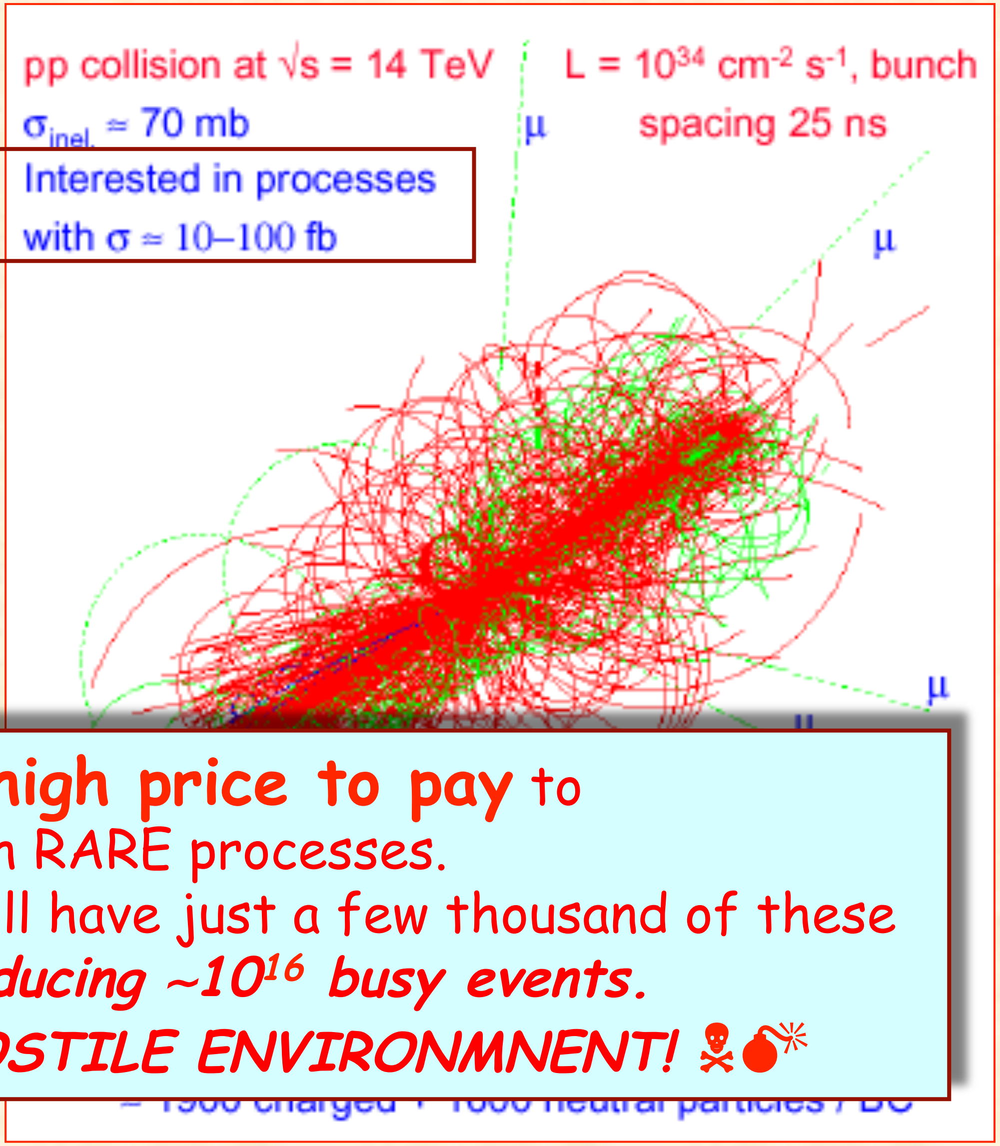
A lot of background radiation!!!

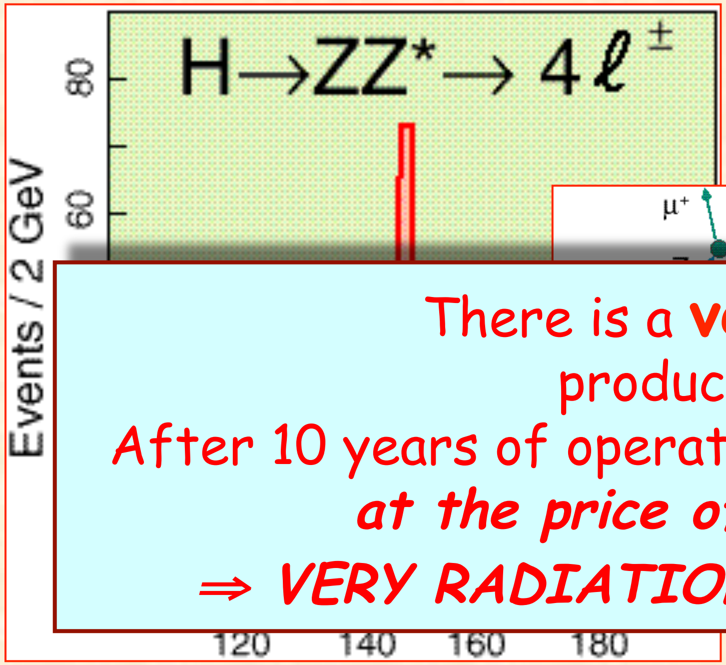
RARE hard-to-find events/particles

CMS/LHC Higgs signal



ONE simulated event at CMS





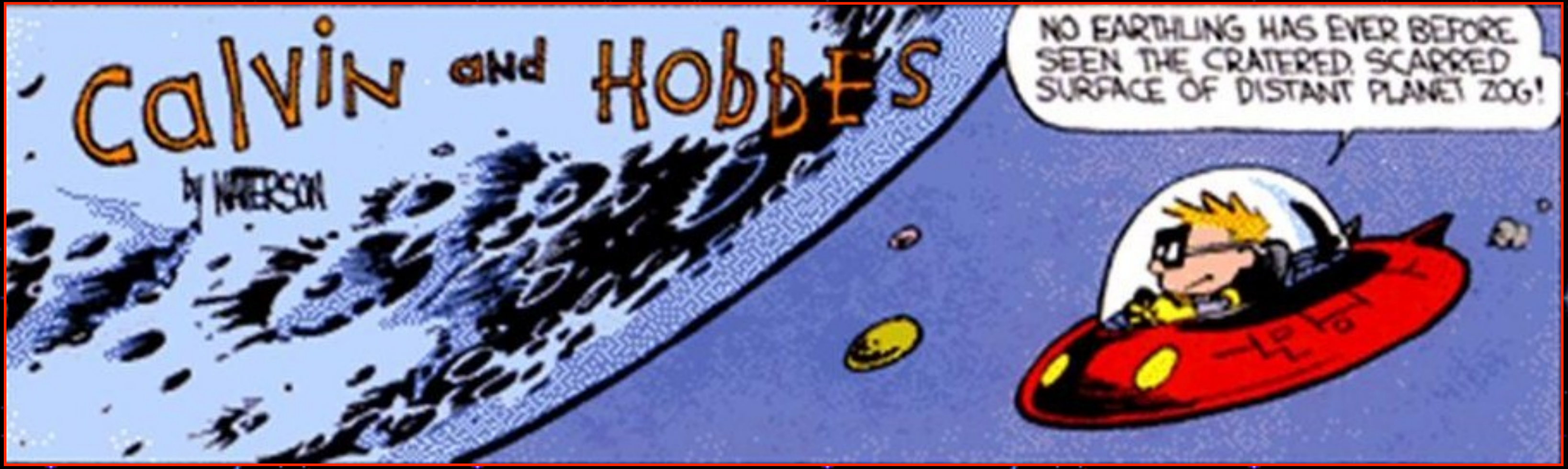
There is a **very high price to pay** to produce such RARE processes.

After 10 years of operation will have just a few thousand of these ***at the price of producing ~10^{16} busy events.***

⇒ ***VERY RADIATION HOSTILE ENVIRONMNENT!*** ☠💣

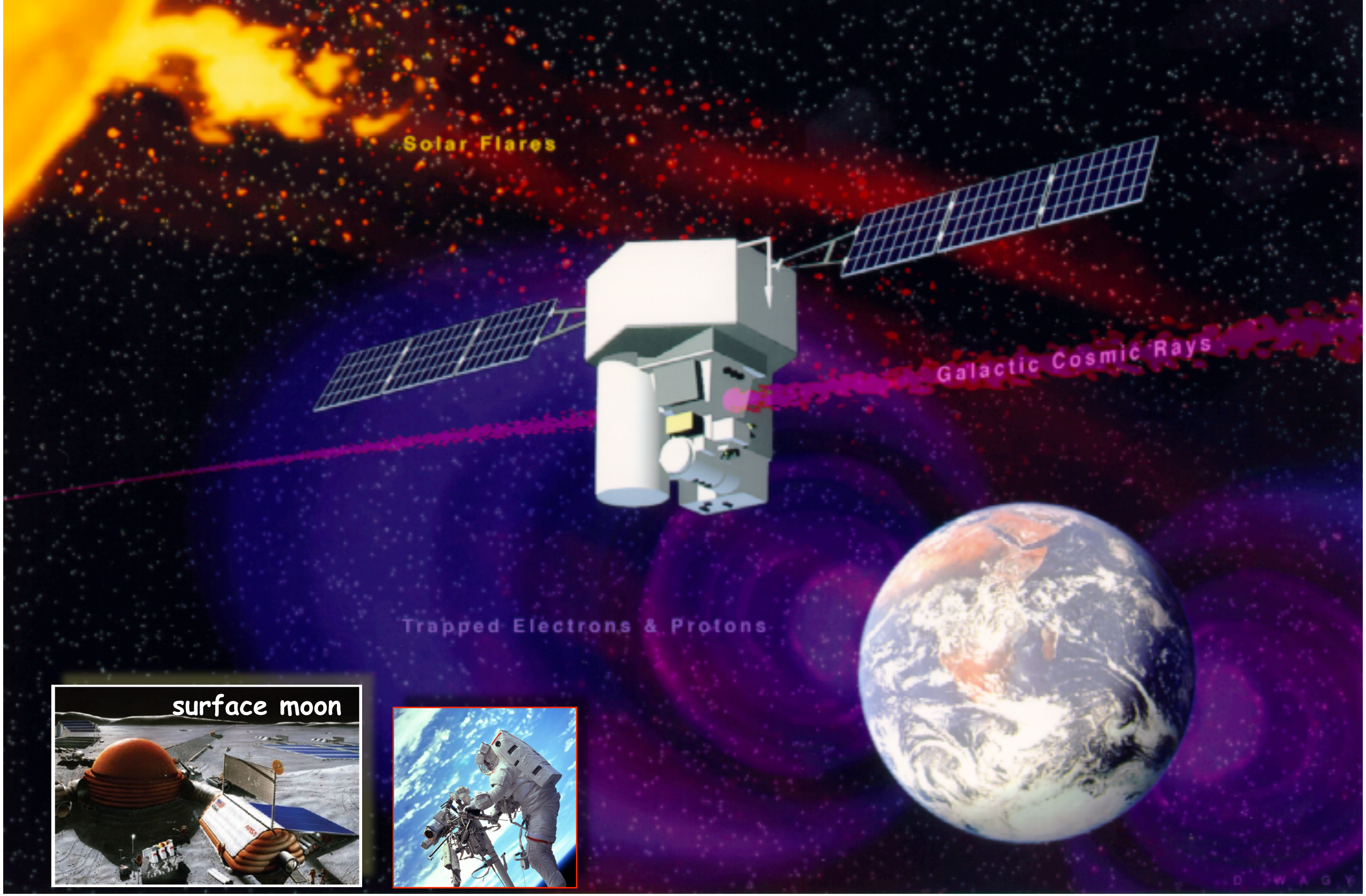
Space

Any scientist/engineer, in his/her right mind that sends instrumentation to *<u>Outer Space,</u>* worries about many things… radiation effects too!

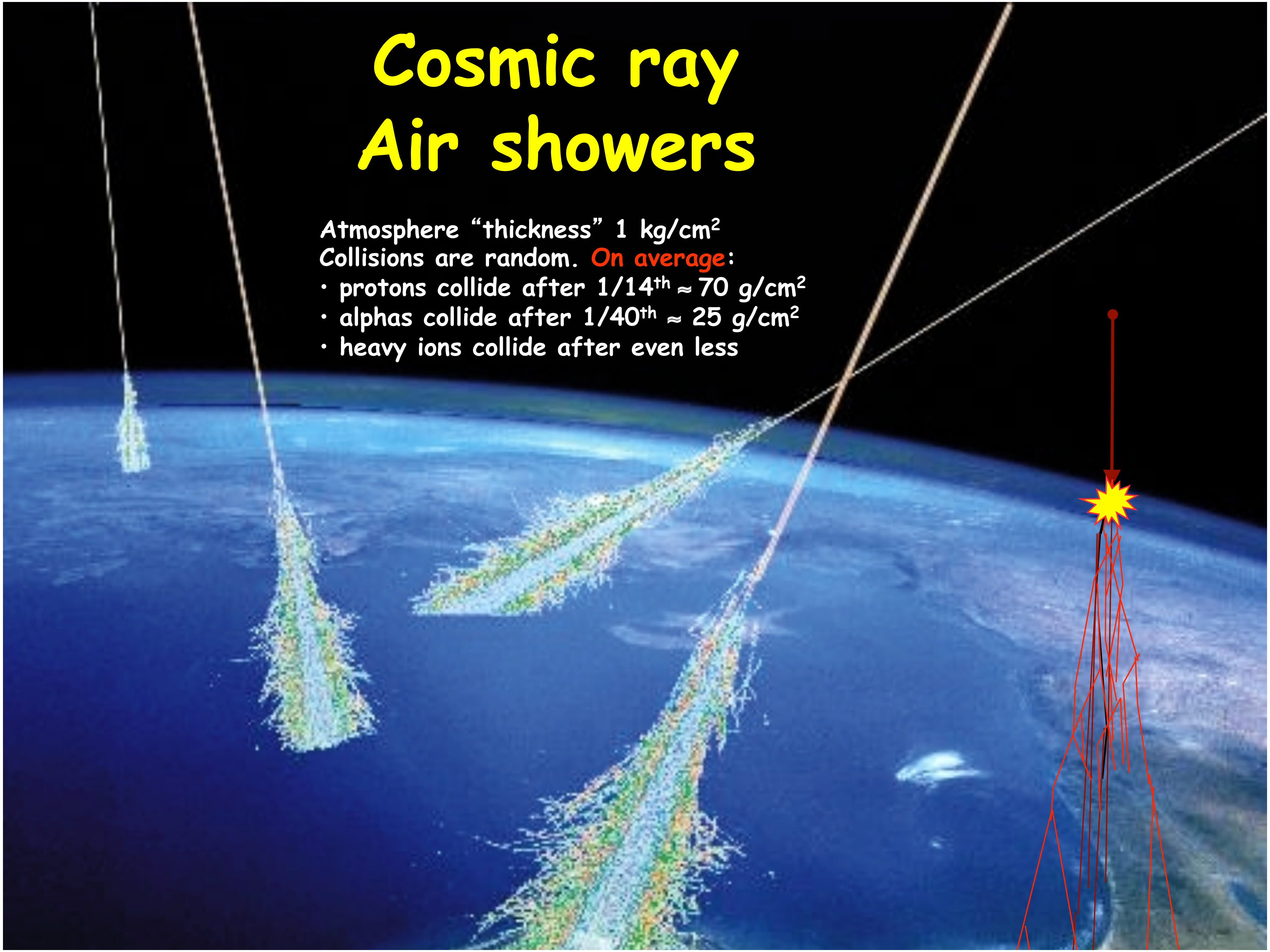


Space

Harsh Environment above Earth's Atmosphere



Cosmic ray
Air showers

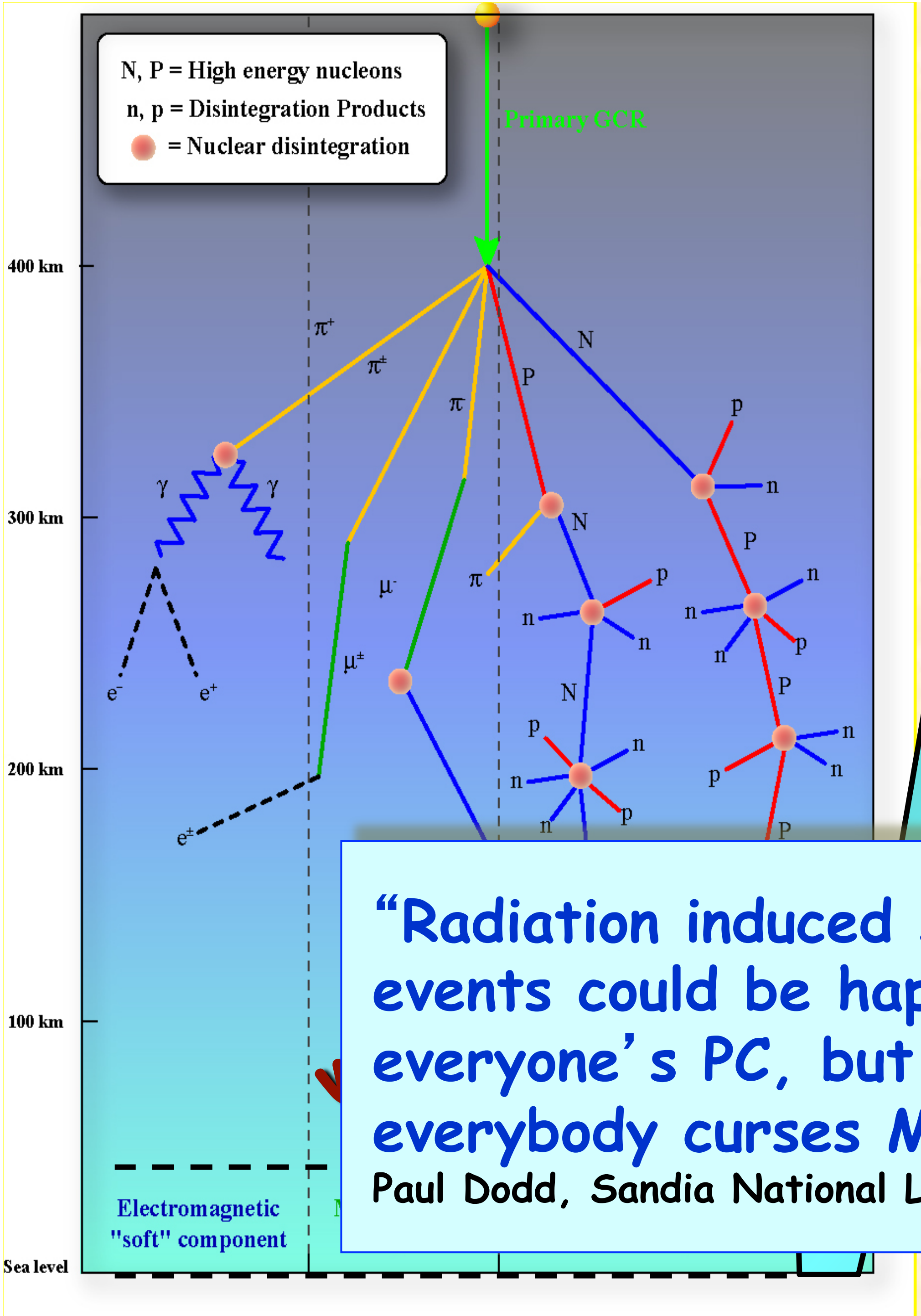


Atmosphere “thickness” 1 kg/cm^2

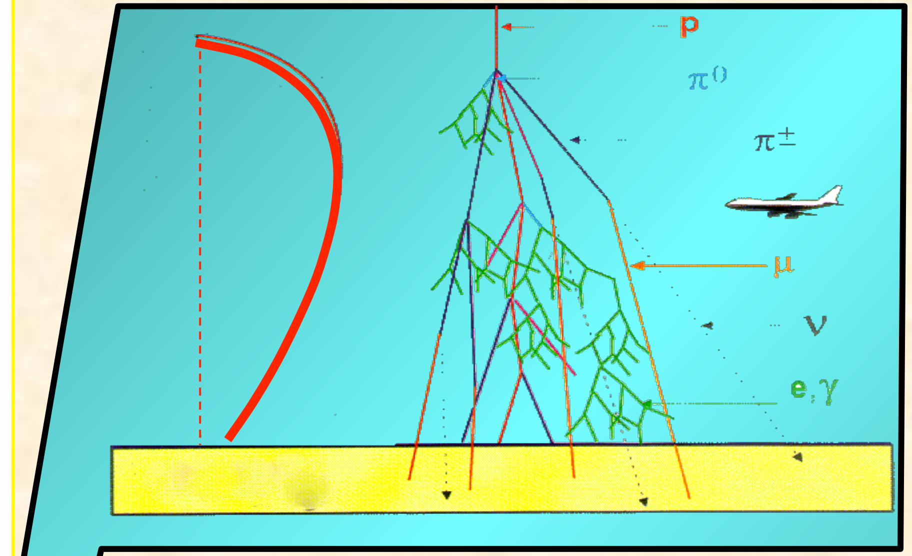
Collisions are random. On average:

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

Air showers



Shower maximum at ~18 km



Under 20 km altitude **neutrons**

ed **Single**

tems.

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a real

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s,…)

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

Paul Dodd, Sandia National Laboratories

Neutrons are widening problem for Industry

Air showers

Aviation

Automotive

Even normal human activities are not completely "safe"!

Trains

Infrastructure

Medical

Now what?
What do you do?

dealing with

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

- **detectors (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***)

Effects of radiation in ELECTRONICS

1) IONIZATION

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

2) ATOMIC DISPLACEMENT from lattice sites

accumulation of damage to lattice/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

dealing with

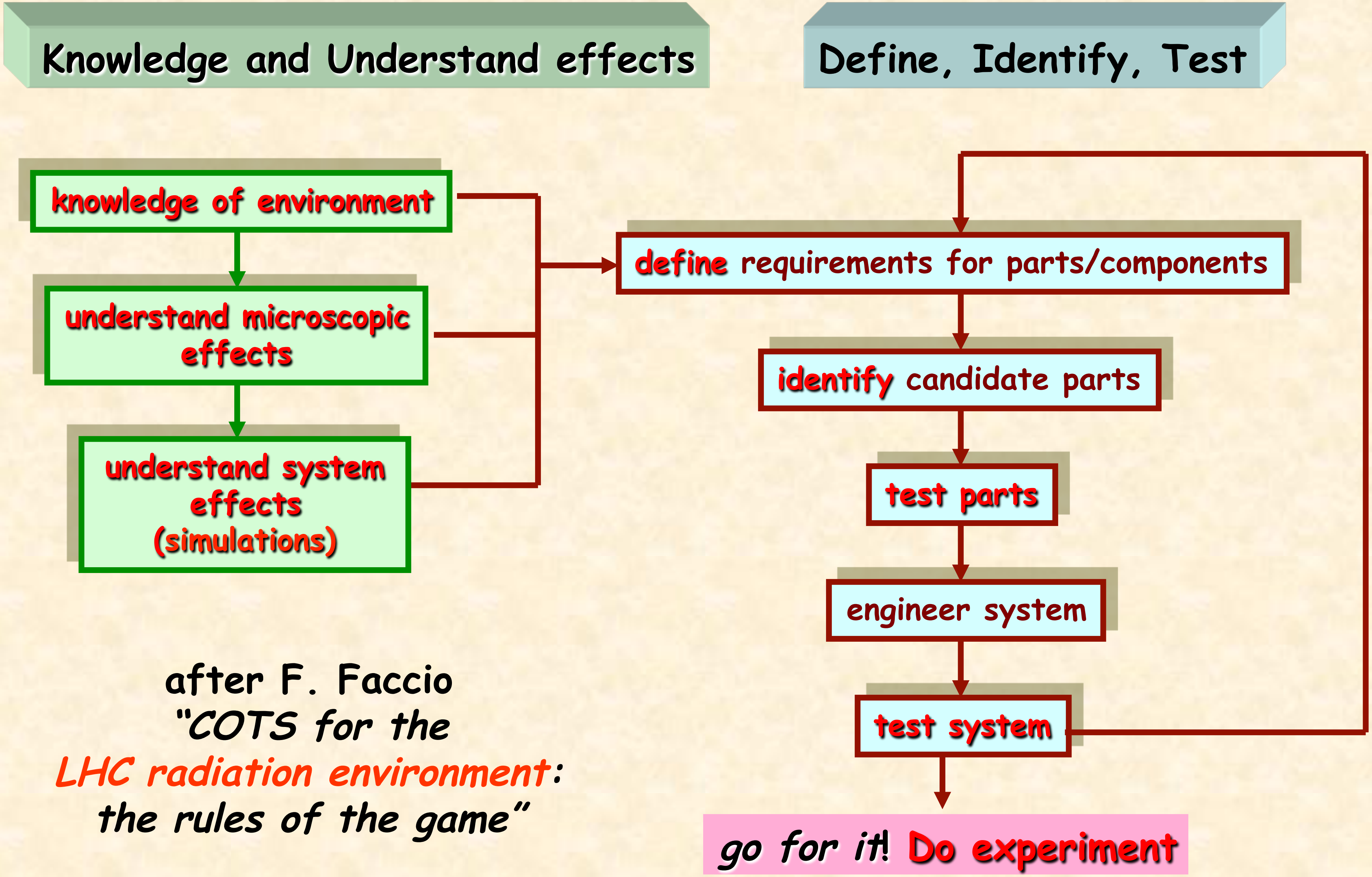
Evaluation of risks of effects in radiation environments

- 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 **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!***

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



Knowledge and Understand effects

Define, Identify, Test

knowledge of environment

understand microscopic effects

understand system effects (simulations)

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"

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, ...)

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 charged 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?

Words that need to be understood

- flux, fluence, exposure
- activity, luminosity
- dose
- stopping power = $(dE/dx)_{ele}$ + $(dE/dx)_{nucl}$
- LET
- NIEL
- Single Event Effect cross-section

PART 1:
radiation concepts

Radiation hazard symbol

Effects of radiation in matter

☞ Will discuss only standard electronic materials:

- silicon,
- its oxide.

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)

(*) coulomb barrier

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

Transfer of energy to matter

Energy loss in matter

1) Ionizing energy loss

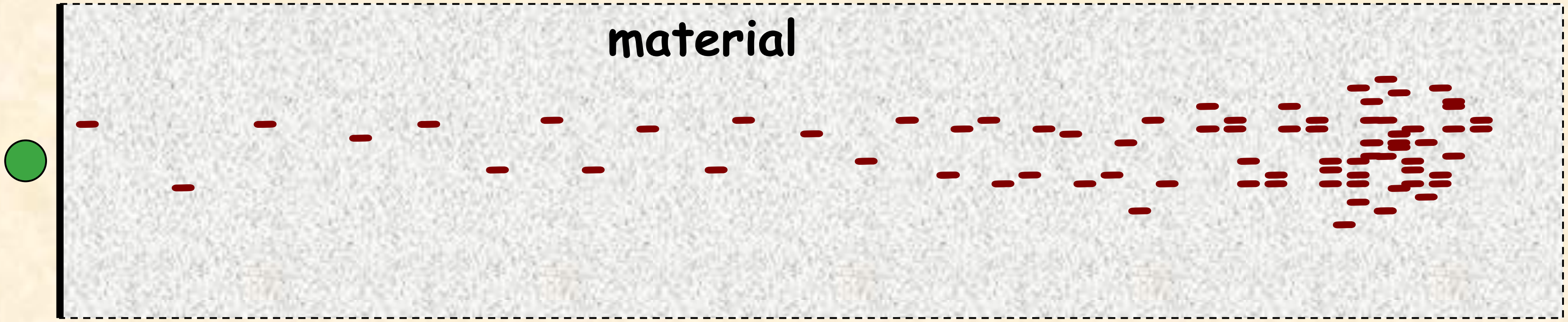
2) Non-ionizing energy loss

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

Particles (neutrons, pions, protons, ions, even electrons) can displace atoms from their usual lattice sites and damages the “bulk”.

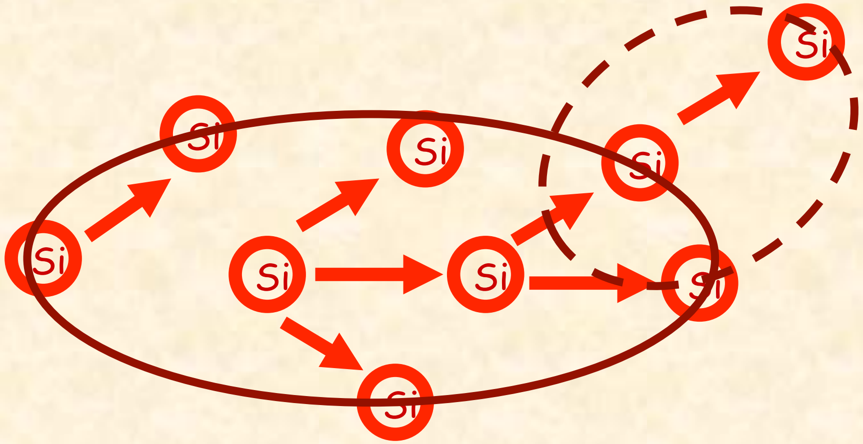
Effects of radiation (microscopic view)

IONIZATION (interaction with electrons of material)



ATOMIC DISPLACEMENT
(bulk damage)

n, p, π+, π-...



Cascade of displacements → ***clusters***

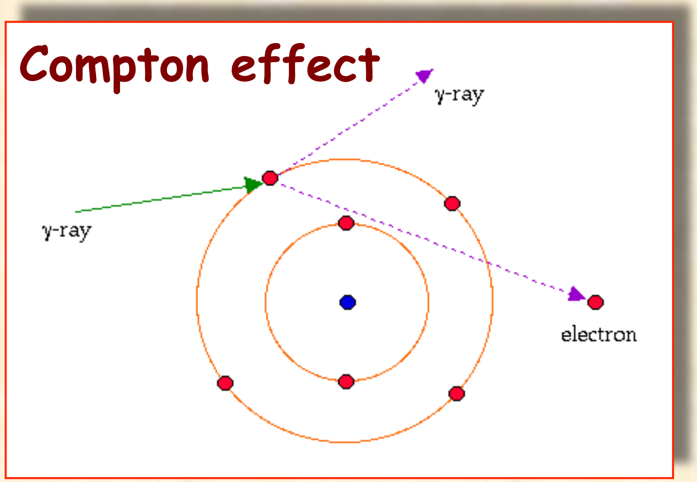
Effects of radiation (microscopic view)

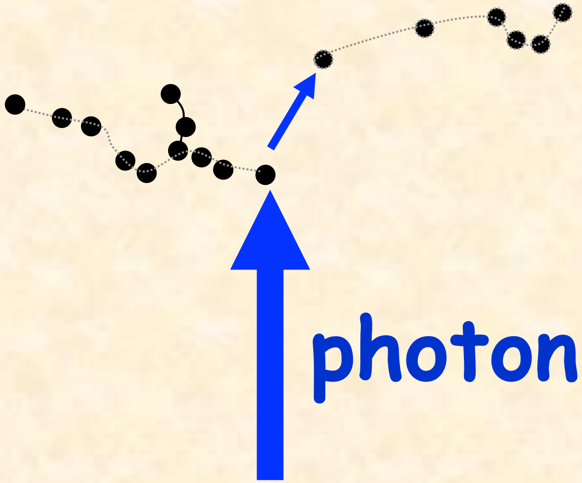
- electrons, photons (X-rays, gamma).

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

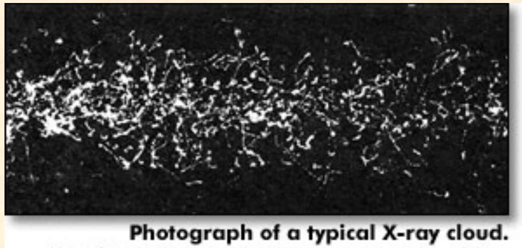
- n, p, $\pi^{\pm}$, K, α, heavy ions

- **Ionization: direct** when particle is charged in which case it is described by the **ionizing stopping power**. Ionization (indirect) 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 by **Non-Ionizing Energy Loss (NIEL) DOSE.**
- **Pattern of atomic displacement damage** depends on particle type and energy. Significant differences between ions, neutrons, protons and pions.
- **nuclear reactions**: nucleus breaks up into various **fragments**; point defects in silicon lattice by neutrons $n + {}^{30}Si \rightarrow {}^{31}P + e^{-} + \underline{\nu}$

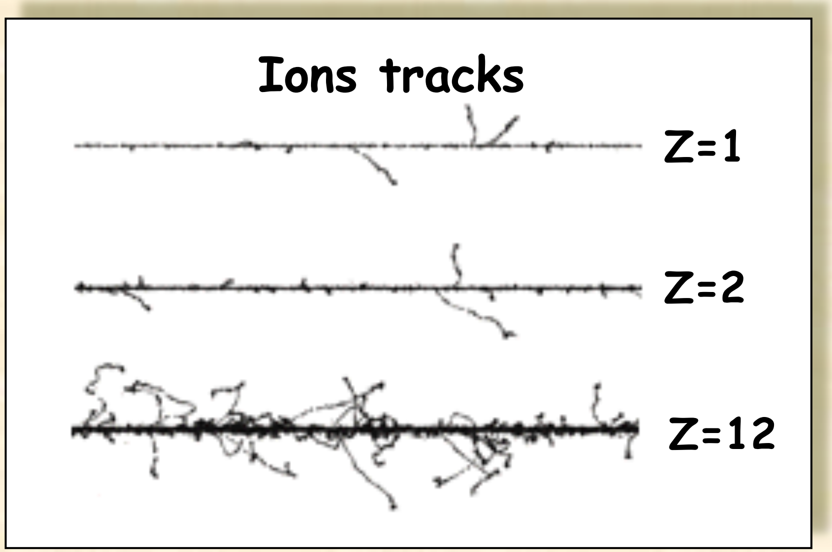




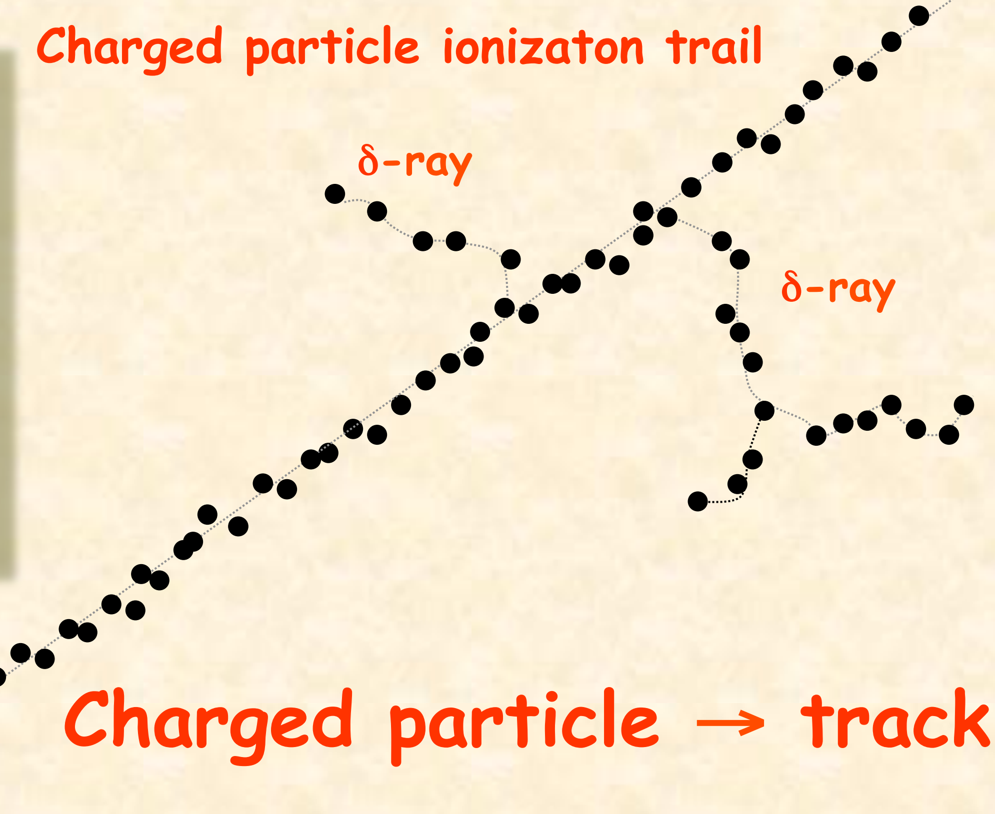
photon → no track



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



Charged particle ionizaton trail



Charged particle → track

Effects of radiation in ELECTRONICS (microscopic view)

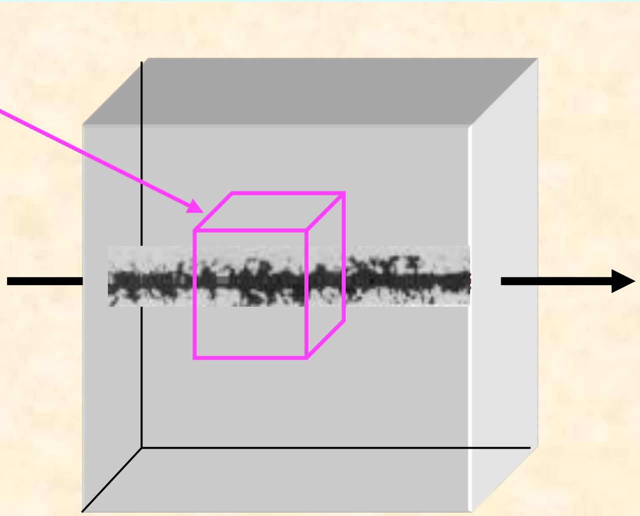
When a particle strikes a device it can transfer energy to the medium both by atomic displacement and/or by ionization:

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

}Total Dose Effects

3. The particle releases enough ionization in a sensitive volume to induce a device/system malfunction.

}Single Event Effects



Microscopic effects → Macroscopic effects

micro-effect			*macro-effect*
Accumulation of ΔE transfers to atomic nuclei (Coulomb, nuclear interactions)	protons, neutrons, high energy electrons	displacement damage of lattice	**bulk effects;** enhancement of TID Effects
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**
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**

Transfer of energy to matter

Dose = energy/mass

Doses:

- Total Ionization Energy Loss Dose (TID)
- Non-Ionization Energy Loss Dose (NIEL DOSE) also called **Displacement Damage Dose** (DDD)

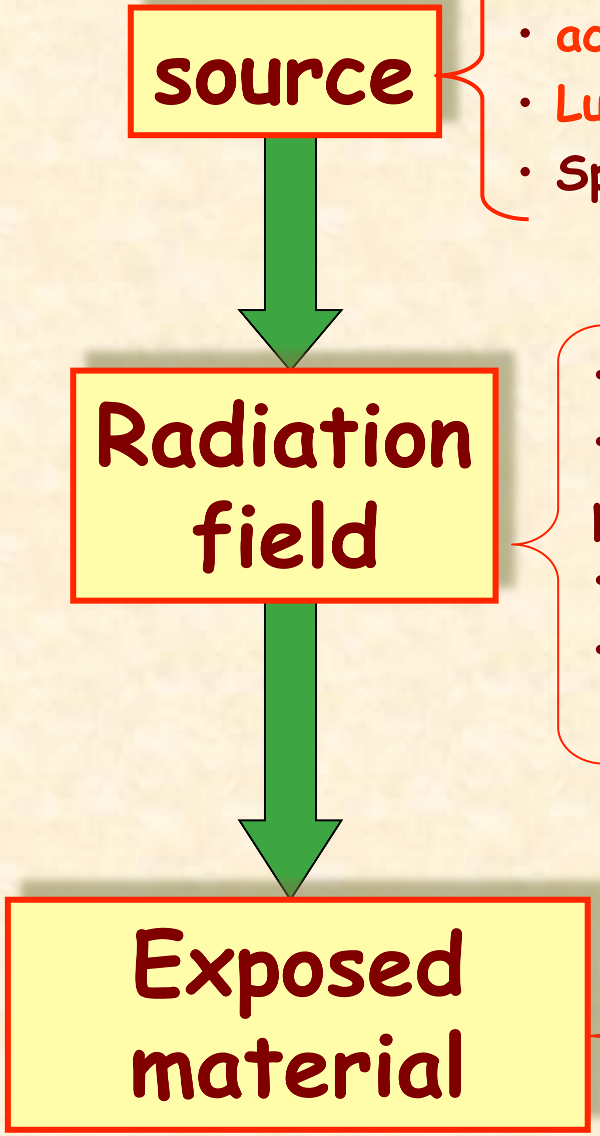
energy deposit variables: LET, TID, DDD

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

Macroscopic EFFECTS

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 (Upsets, Latchups, Burnout, Whatever…)	SEE cross-section. Ion LET spectra. SEE rates

Change gears



source

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

Radiation field

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

Exposed material

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

physical quantities

Very 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. See example.

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

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

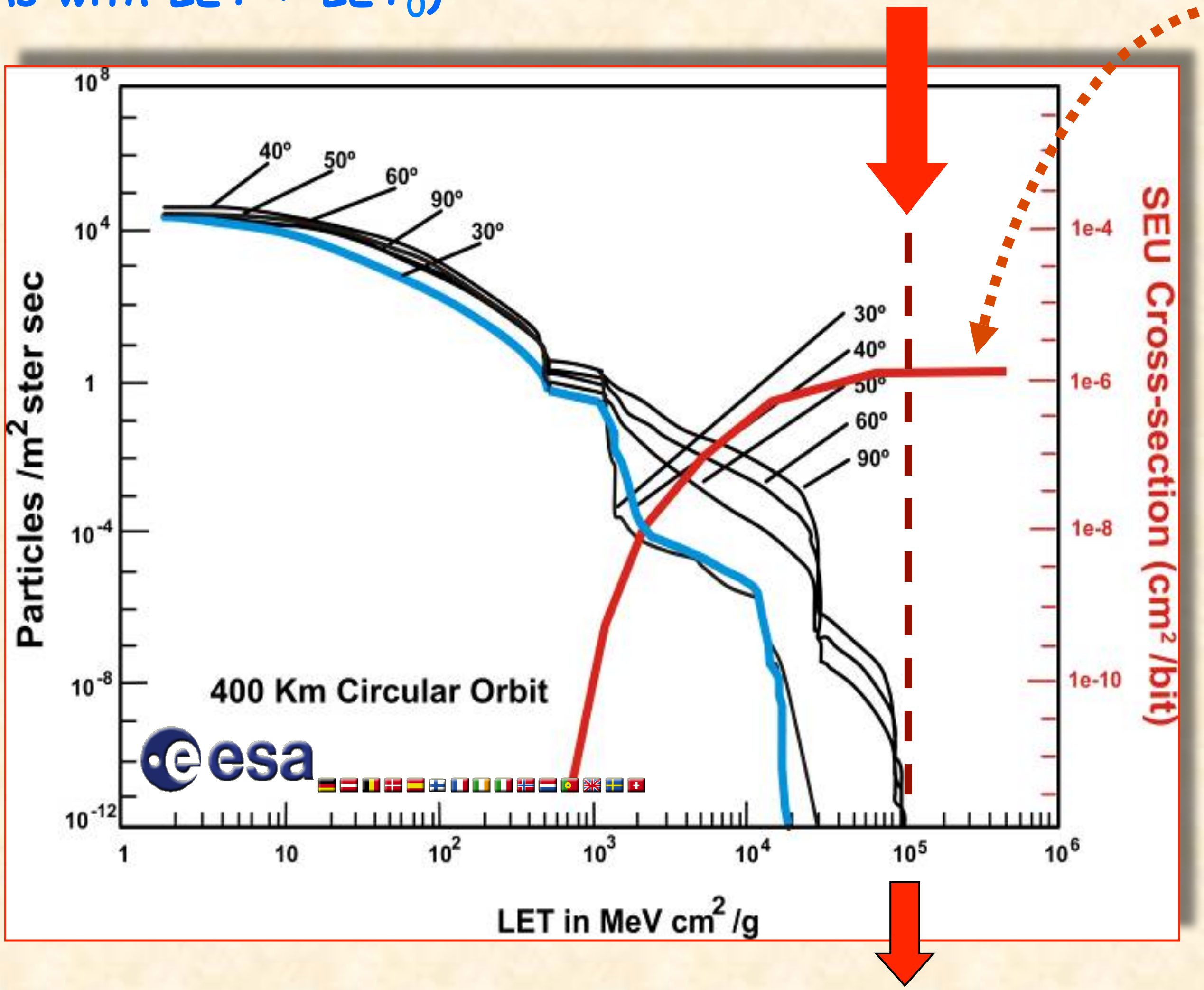
In some cases fluxes are also treated as differential with respect to Linear Energy Transfer.

SEE cross sections in SPACE

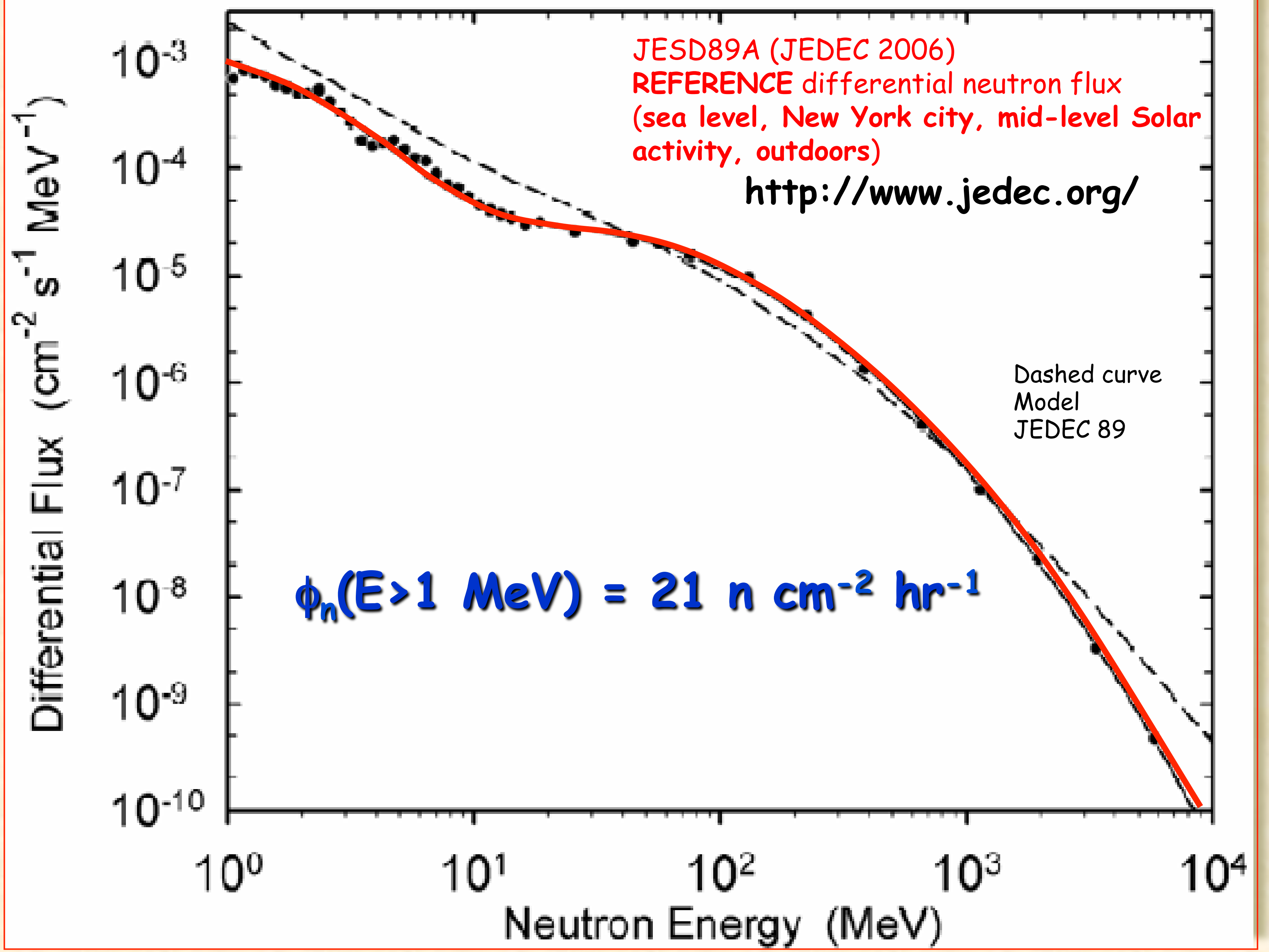
Integral distribution
(No. of ions with LET > LET_0)

natural cutoff

σ(LET) of
device



100 MeV cm^2/mg



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

$\phi_n(E>1\ \text{MeV}) = 21\ \text{n cm}^{-2}\ \text{hr}^{-1}$

❑ 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

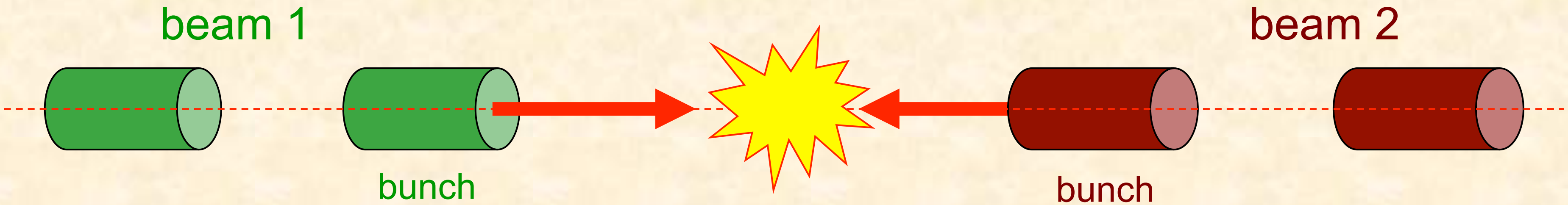
$$L = \frac{N_1 N_2}{A} \times \nu$$

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

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

R particle production rate = activity
σ_i cross-section of ith channel

HEP: colliding particle beams



N_1 , N_2 = particles per bunch

b = number of bunches/beam

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

A = cross-sectional area beams at intersection

interaction rate (events per second)

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

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

cross-section

cross-sections: CMS/LHC

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

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

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*

$$L = \int L(t)\,dt = 5 \times 10^{41}\ \text{cm}^{-2} = 5 \times 10^{5}\ \text{pb}^{-1} = 500\ \text{fb}^{-1}$$

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

Rate of ***inelastic events*** **(with host of protons, neutrons, pions, kaons, muons,….)**

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

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

Very high price to pay to produce RARE processes.
Example: with $\sigma_{rare} = 10^{-38}$ cm^2 = 10 fb
then after 10 years N = L • σ = 500 fb^{-1} × 10 fb = ***5000 events***

Radiation Field of Space and at sea level

Radiation field? Depends

Flux ϕ(particles/cm^2-s)

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}
heavy energetic ions 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}

Dose=energy/mass

Ionization dose

international units

1 Gy = 1 J/kg = 100 rad

= 6.25×10^{18} eV/kg

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.

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 <u>ionize air</u> 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 = 2.58×10^{-4} C/kg	**electonvolts (eV)** 1 eV = 1.6×10^{-19} J 1 keV 1 MeV 1 GeV 1 TeV

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 materials are altered.

Effects of typical Ionising Radiation Doses

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

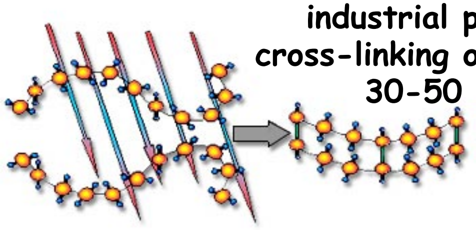
1 J/kg = 1 Gray (Gy) = 100 rad

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

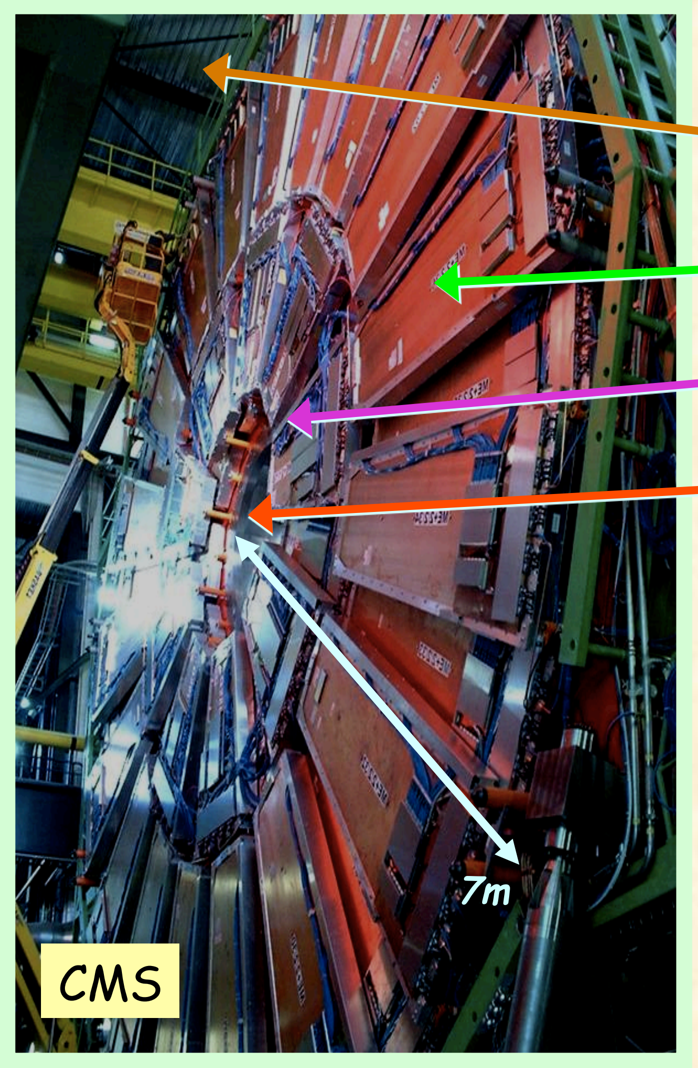
- < 1 kGy: Teflon structurally unstable
- 15-35 kGy: sterilization
- 20 kGy (2 Mrad): curing of polyester resins
- 100-200 kGy (10-20 Mrad): curing of epoxy resins
- 200 kGy: natural rubber unusable
- 1000 kGy (100 Mrad): polyvinylchloride (PVC) unusable
- 50-100 MGy: polyimide degraded significantly

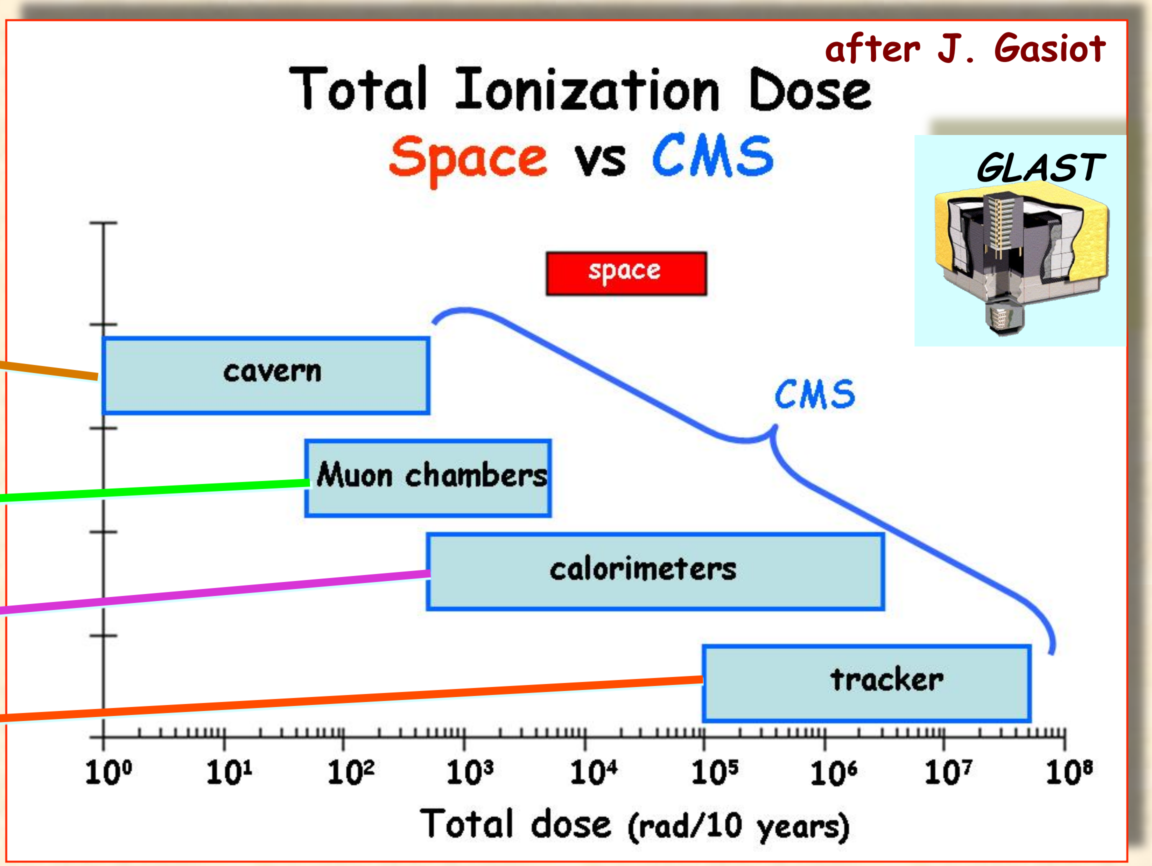


industrial process:
cross-linking of polymers
30-50 kGy

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 and give rise to total ionization damage. Hadrons (protons, pions and especially neutrons) cause displacement damage to the bulk and may also indirectly cause single event effects by creating heavily ionizing secondaries.

Dose

international units

$1\ \mathrm{Gy} = 1\ \mathrm{J/kg} = 6.25 \times 10^{18}\ \mathrm{eV/kg}$

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
$6.25 \times 10^{18} / 3.6 = 1.7 \times 10^{18}$ 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
$6.25 \times 10^{18} / 18 = 3.5 \times 10^{17}$ e-h pairs/kg
that is 8×10^{14} e-h pairs/cm^3

skip

international units

1 Gy = 1 J/kg = 6.25×10^{18} eV/kg

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

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)

- Total Ionization Energy Loss Dose
- Non-Ionization Energy Loss Dose (also called Displacement Damage Dose)

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) × fluence(length^{-2})

DOSES for particles (not photons)

TID, DDD ⇒ factors: LET, NIEL

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

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

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

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***.

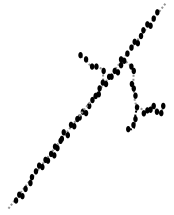
The fraction of the total energy absorption that results in damage to the lattice structure of solids through displacement of atoms is referred to as ***Non-Ionizing Energy Loss***.

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)

track



For a charged particle (makes 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**

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

density

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

GLOSSARY

Linear Energy Transfer (LET):

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

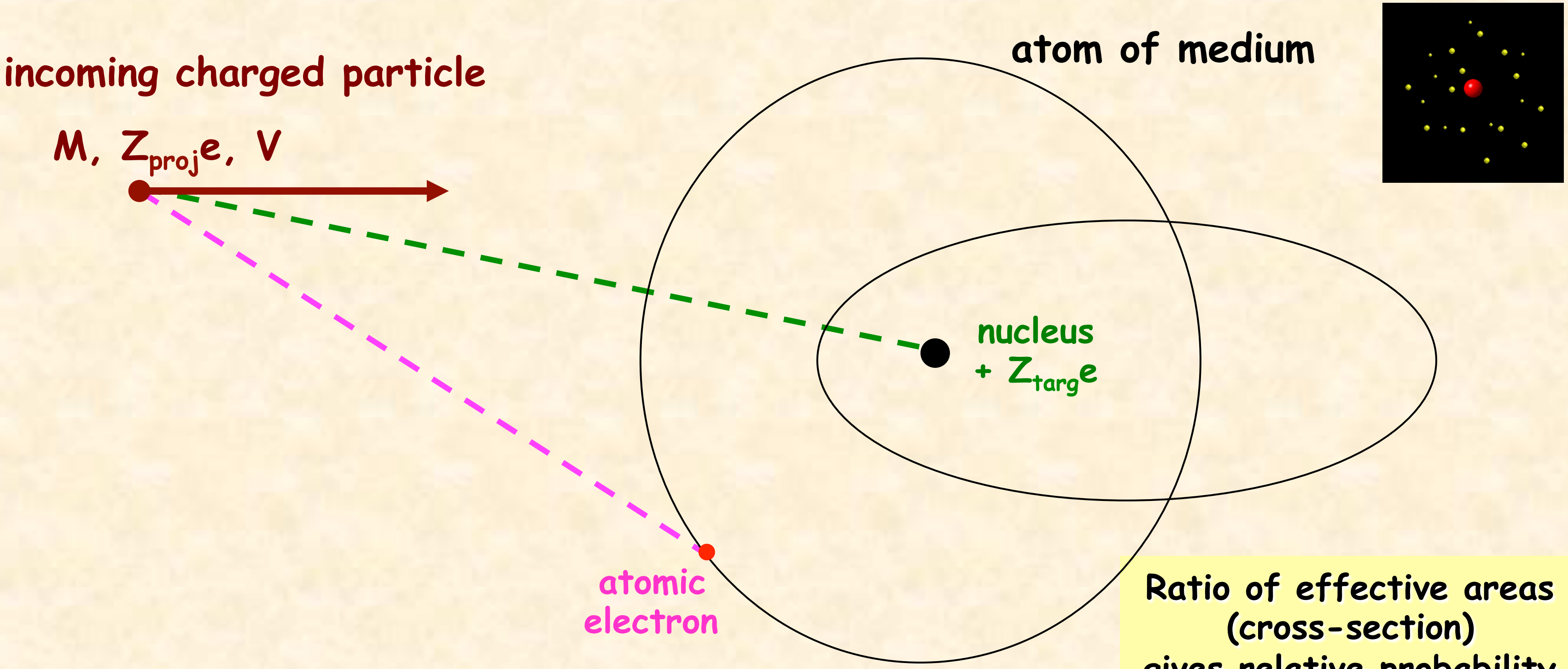
LET allows different ions to be considered together by simply representing the ion environment as the summation of the fluxes of all ions as functions of their LETs. This simplifies calculations of rates of Single Event Effects.

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

ionisation

A charged particle travelling thru a medium

Coulomb interaction with atomic electrons or with the nucleus:



the radius of nucleus $R_{nucleus}$ ~10^{-14} m

the radius of atom R_{atom} ~10^{-10} m

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

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

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

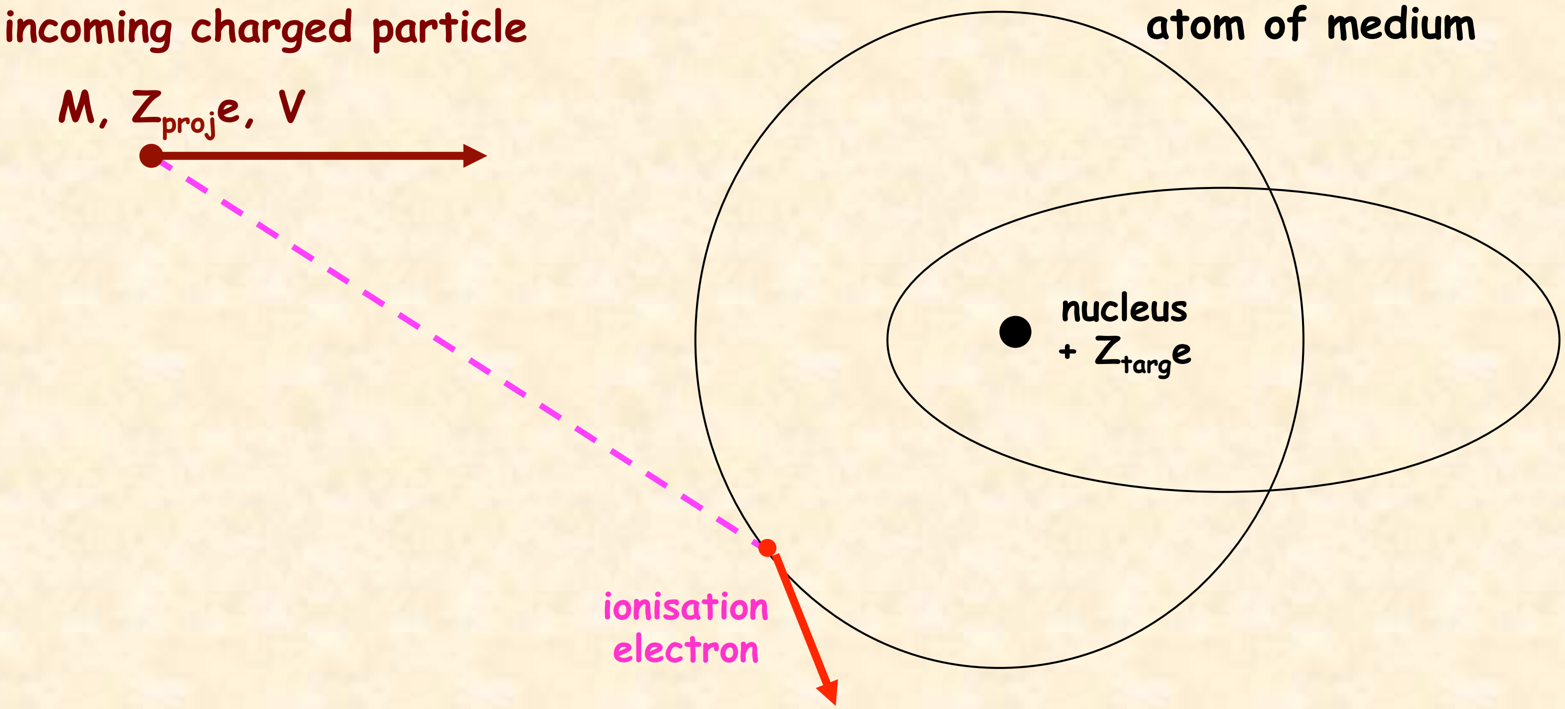
ionisation

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,…



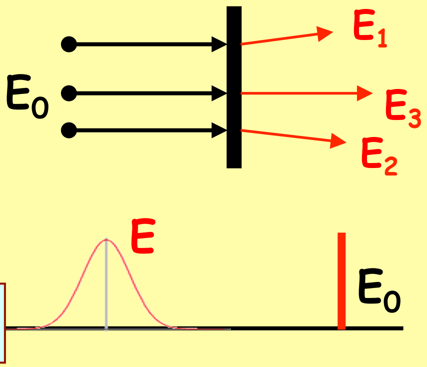
ionisation

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 particles get thru a macroscopic slab without interacting and losing some energy!



$\langle E\rangle - E_0 \equiv \Delta E \rightarrow 0$ as $\Delta x \rightarrow 0$

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

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

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

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!!!

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

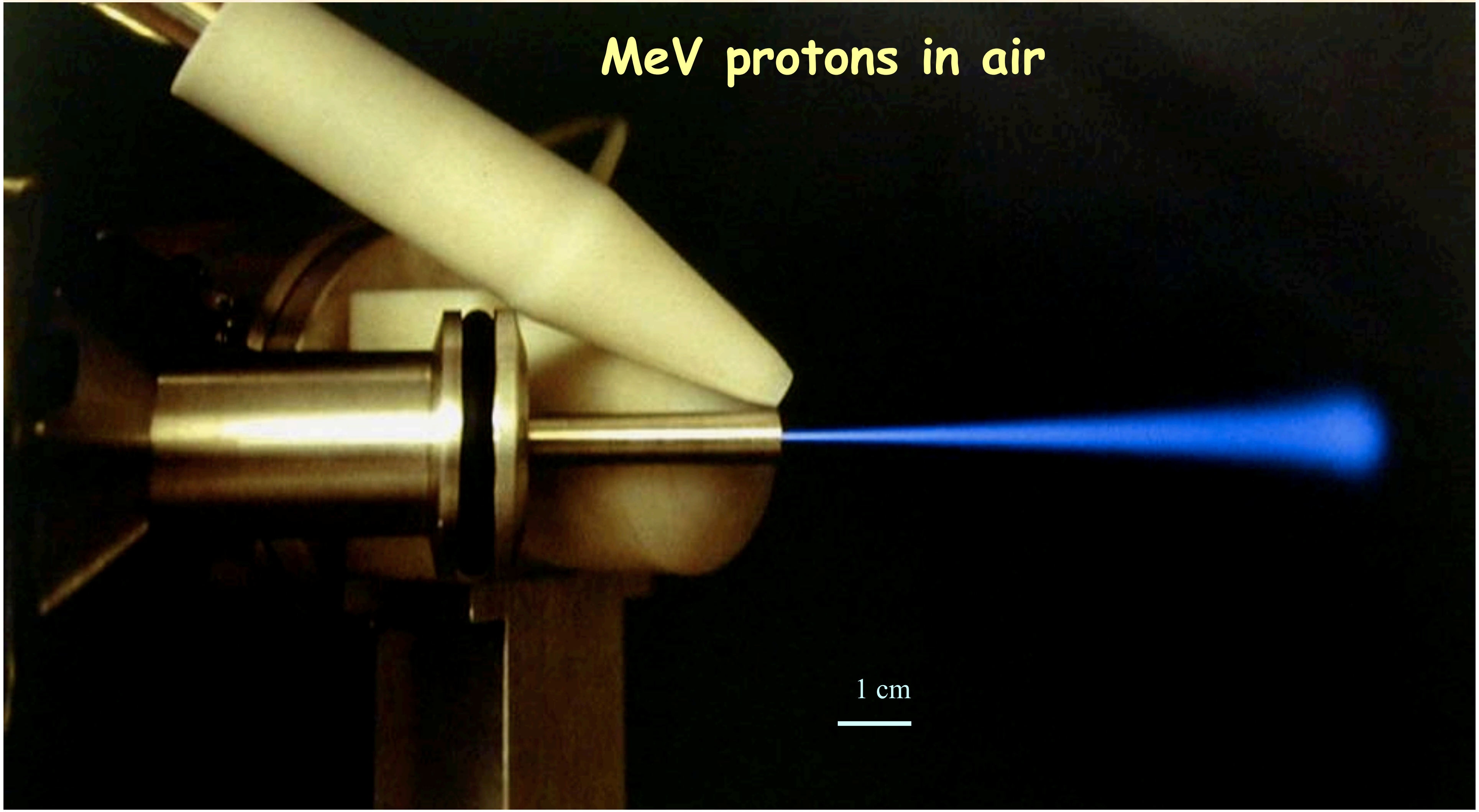
thickness of medium
for which kinetic energy of
incident particle is spent
WELL DEFINED

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:

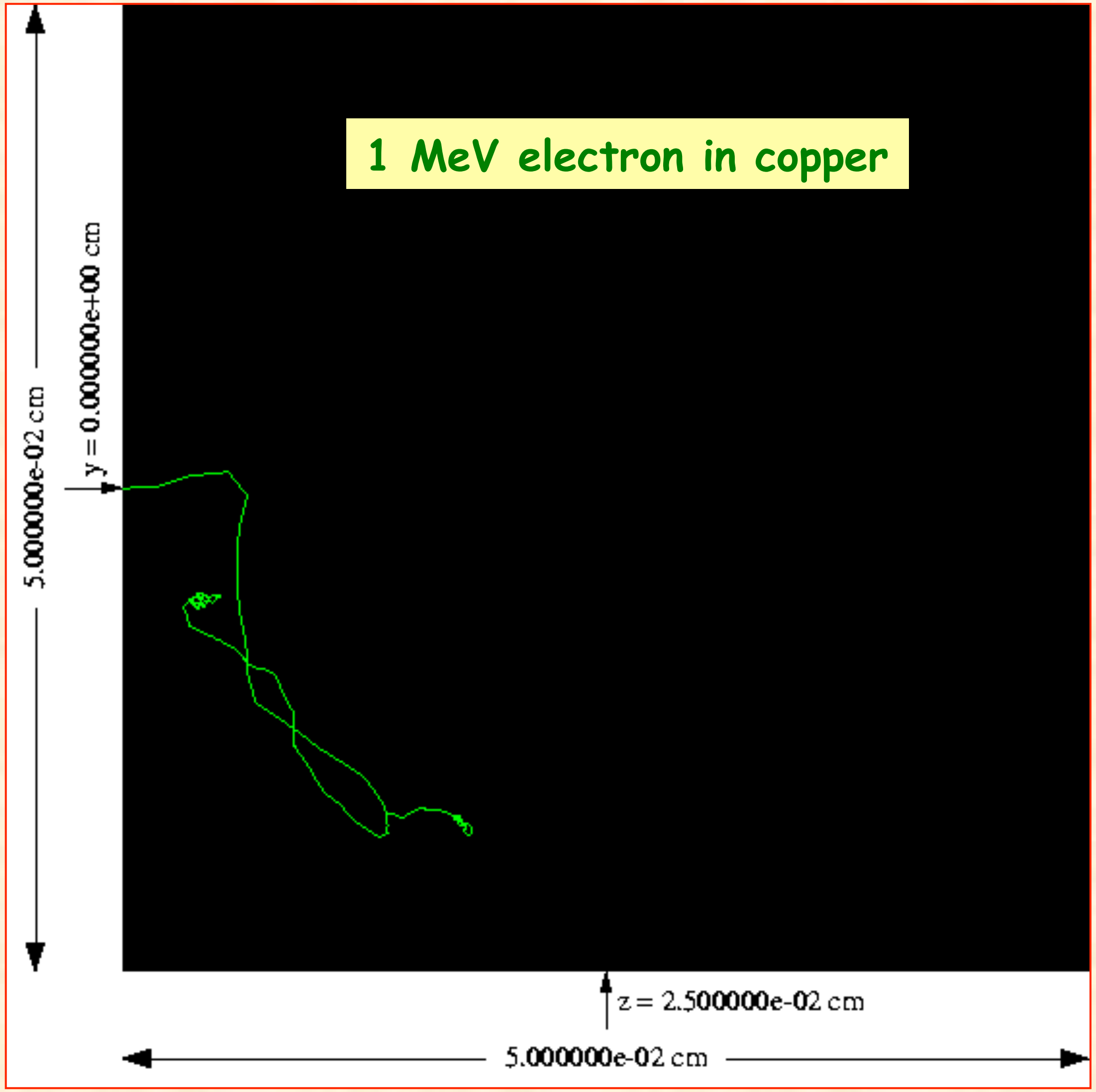
- may collide with an atomic electron and **lose ALL its energy in a single collision (billiard ball effect)!**

- **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://www2.slac.stanford.edu/vvc/egs/advtool.html

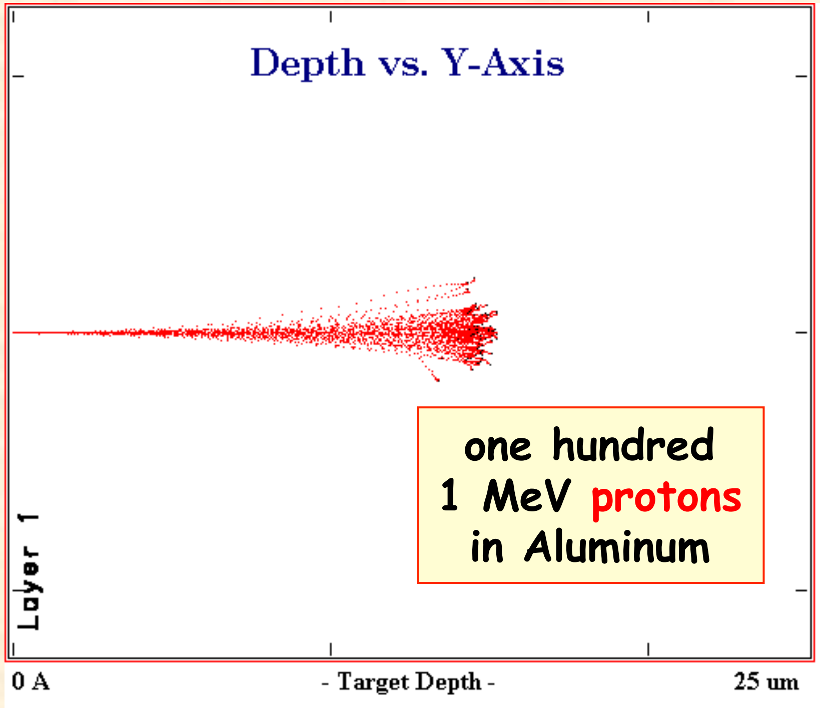

1 MeV electron in copper

path very zig-zag!

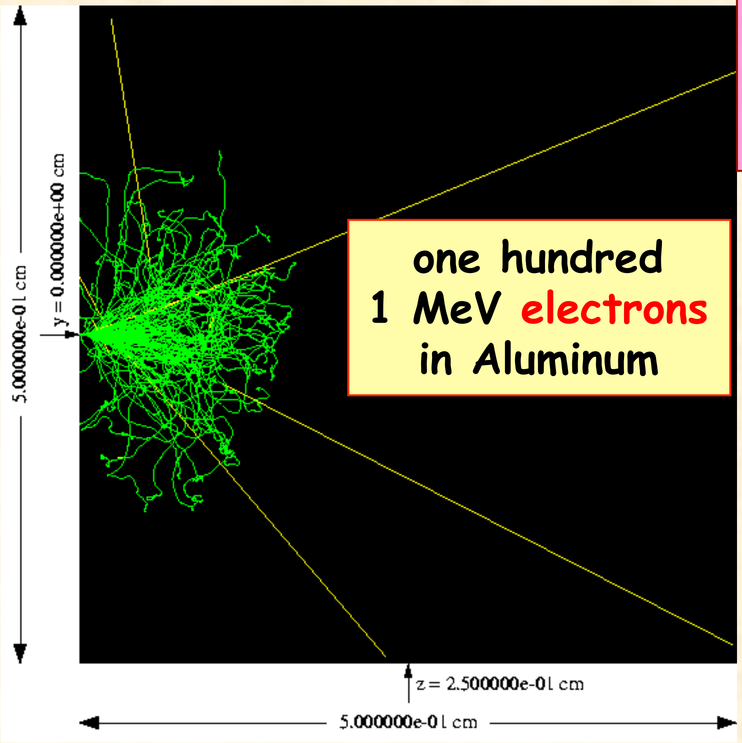
**0.5 mm
by
0.5 mm**

Range

range not well defined for electrons



one hundred
1 MeV protons
in Aluminum

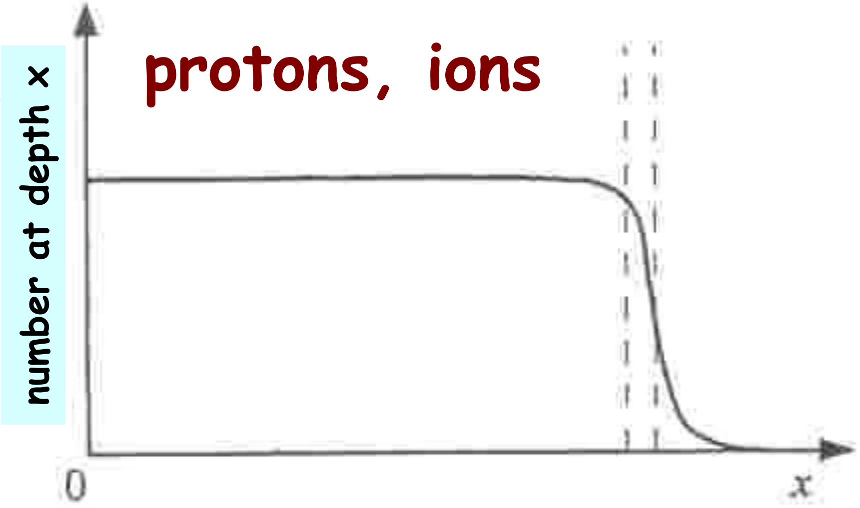


one hundred
1 MeV electrons
in Aluminum

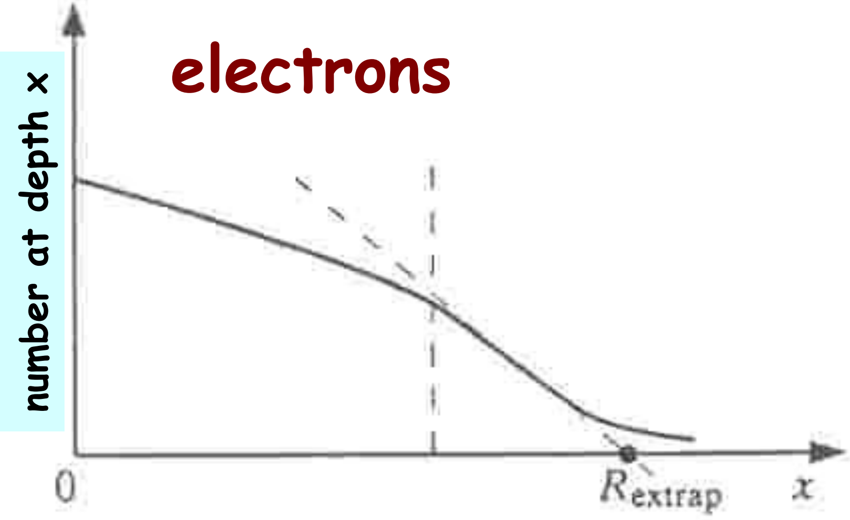
electrons in green

photons in yellow

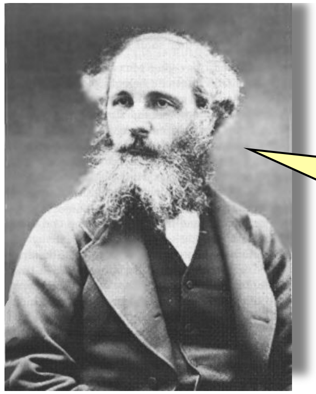
5 mm
by
5 mm



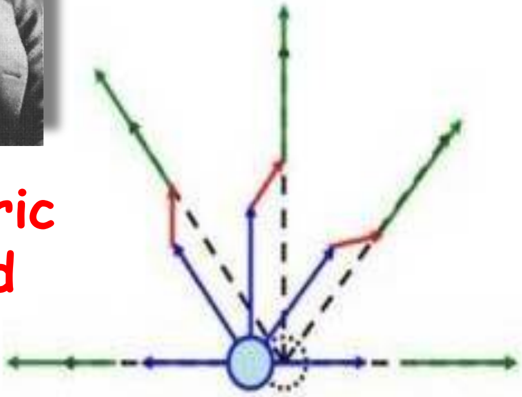
protons, ions



electrons



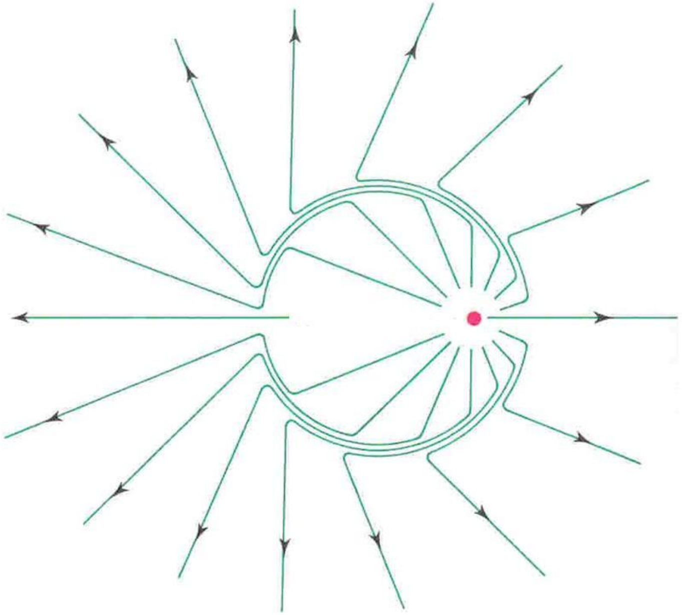
Take a charge .... and move it

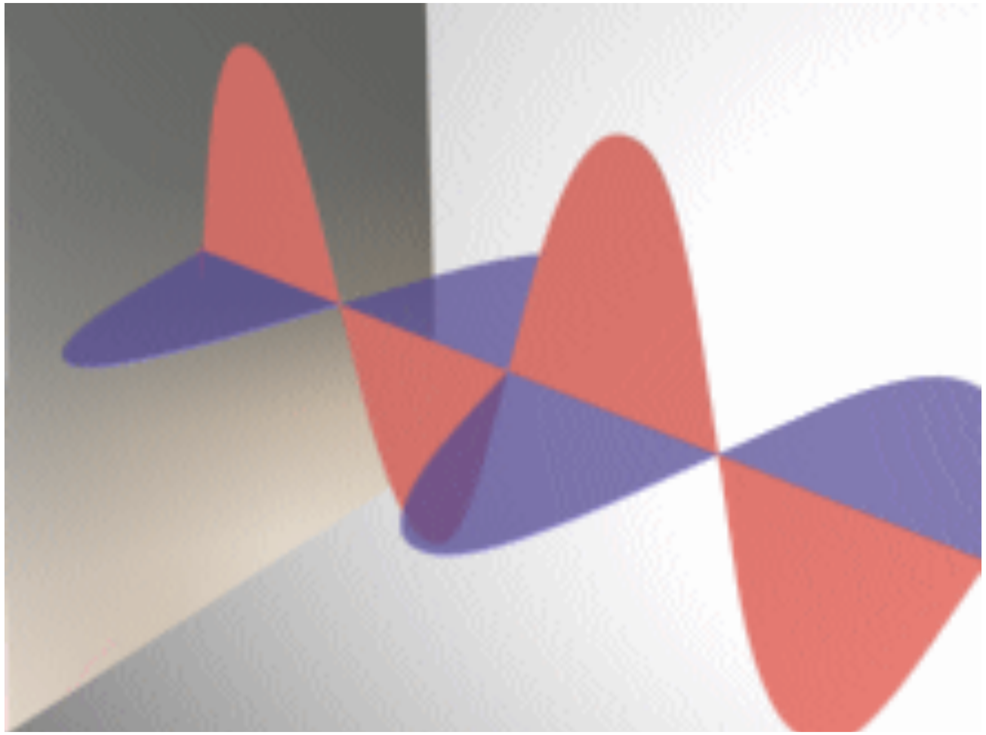


Electric field

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

Shake the charge back and forth

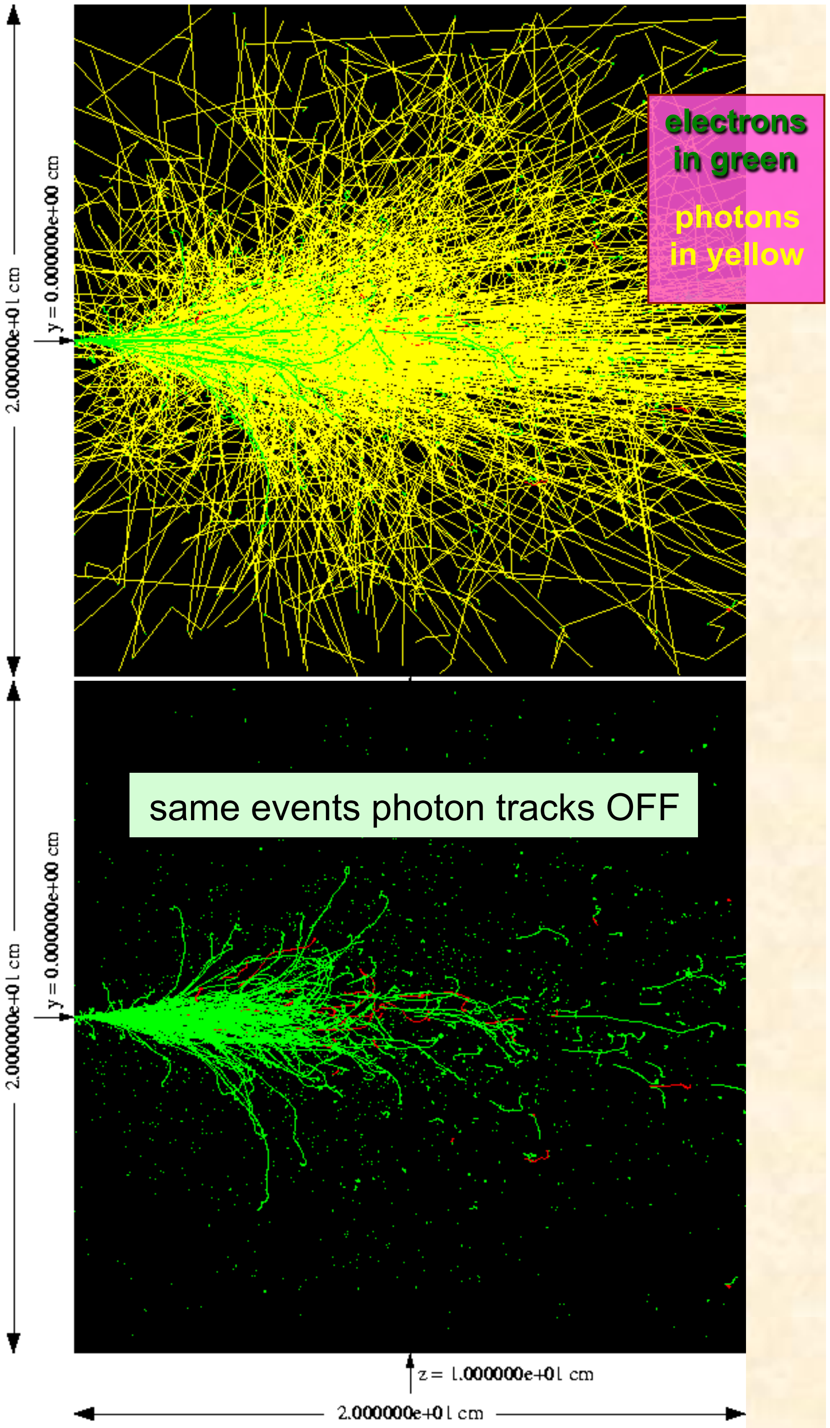




irradiation

Energetic electrons lose energy also by emitting photons

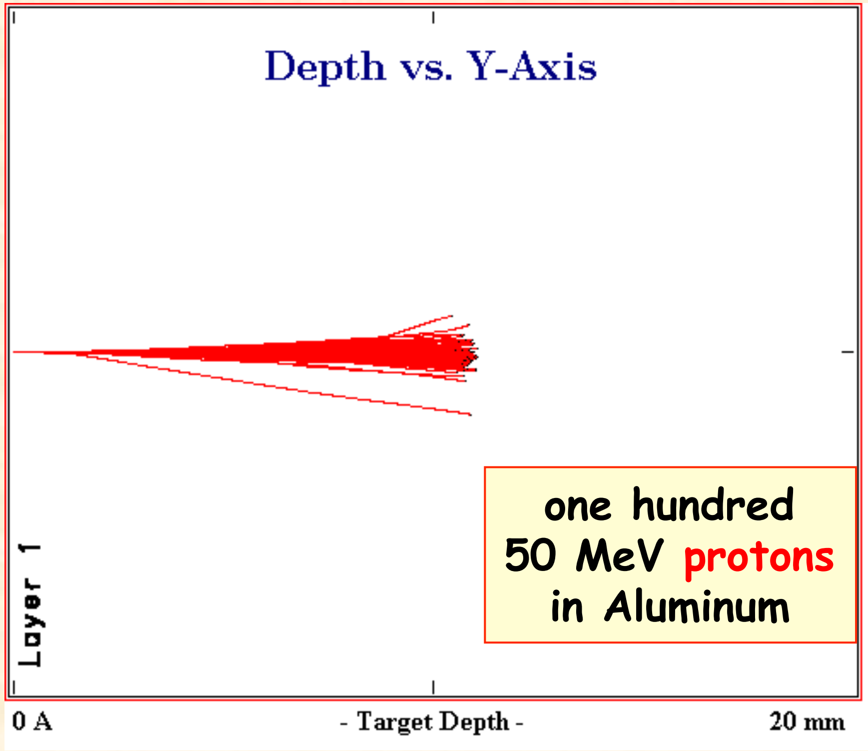
one hundred
50 MeV electrons
in Aluminum



electrons in green

photons in yellow

same events photon tracks OFF



one hundred
50 MeV protons
in Aluminum

GLOSSARY

Bremsstrahlung:

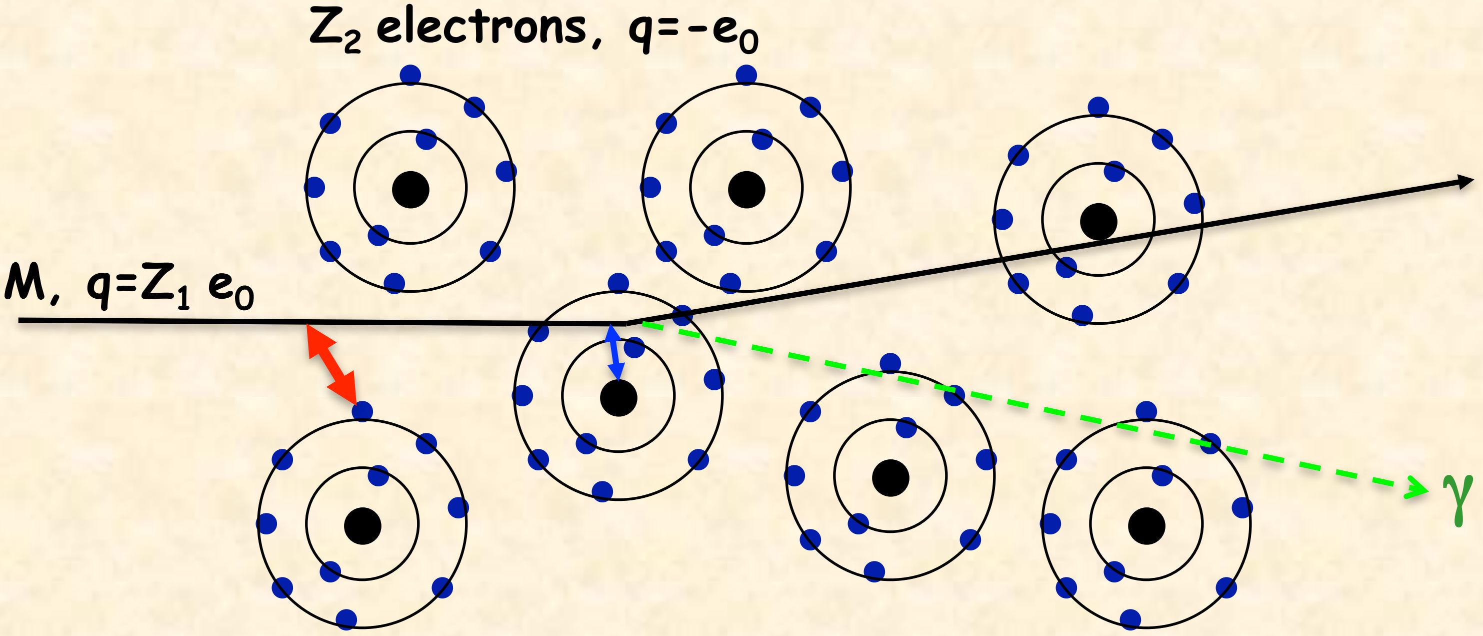
High-energy electromagnetic radiation in the X and *gamma* energy range that is emitted by charged particles as they slow down when they scatter off atomic nuclei.

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



Interaction with the atomic electrons. The incoming particle looses energy and the atoms are <u>excited</u> or <u>ionized.</u>

Interaction with the atomic nucleus. The particle is deflected by many soft scatterings (multiple scaterring) and occasional rare single hard rutherford scatterings.

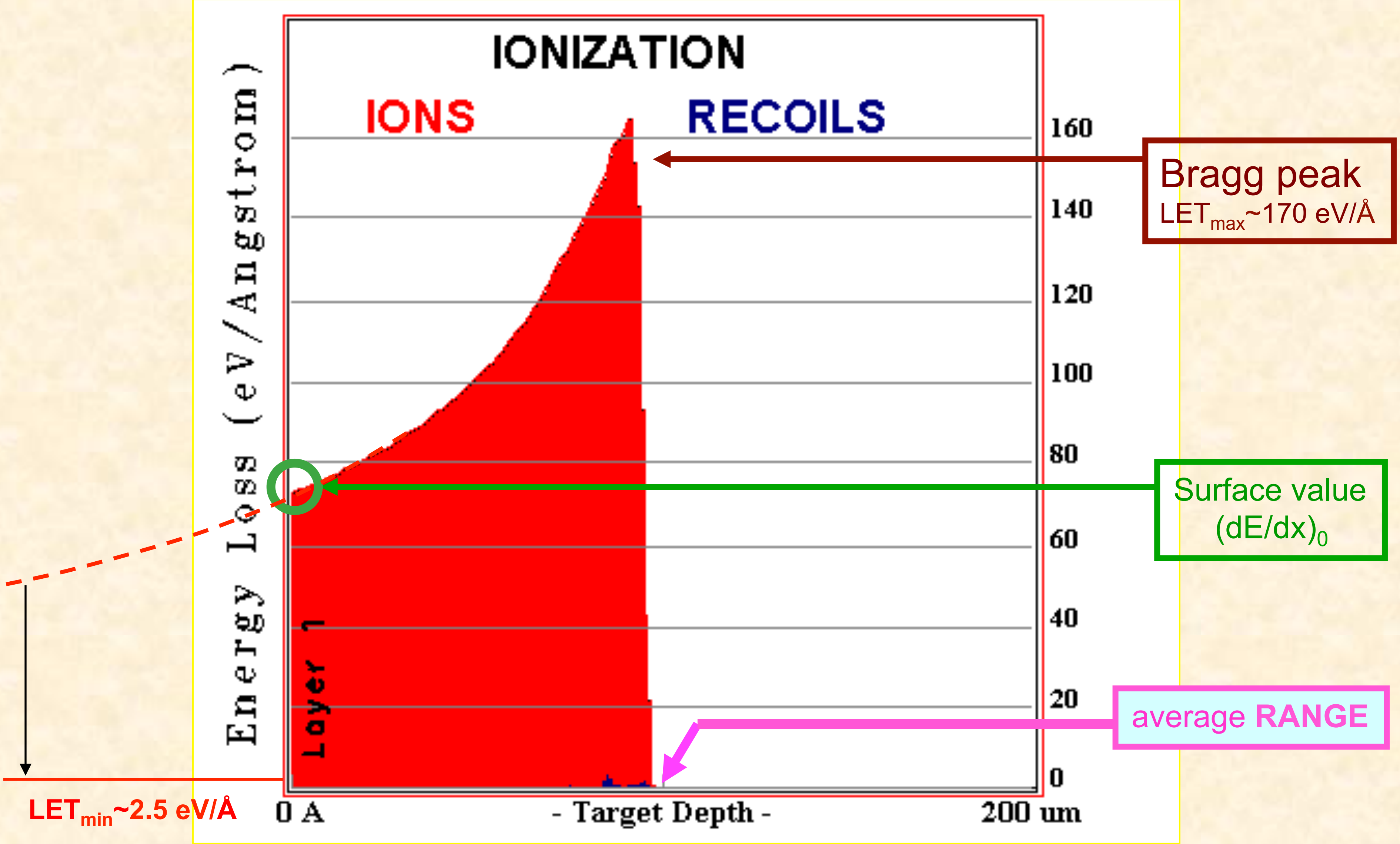
(If the incident particle is an electron then during these scattering events a <u>Bremsstrahlung</u> photons can be emitted.)

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

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



Bragg peak
LET_{max}~170 eV/Å

Surface value
$(dE/dx)_0$

average RANGE

LET_{min}~2.5 eV/Å

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

ionisation

Bethe-Bloch … for heavy ions

β = 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 >> $v_{Bethe} = v_0 Z^{2/3}$** **where $v_0 = c/137 = v_{Bohr}$**

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

- **for velocity of ion V ≈ v_{Bethe}** and slower

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

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

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

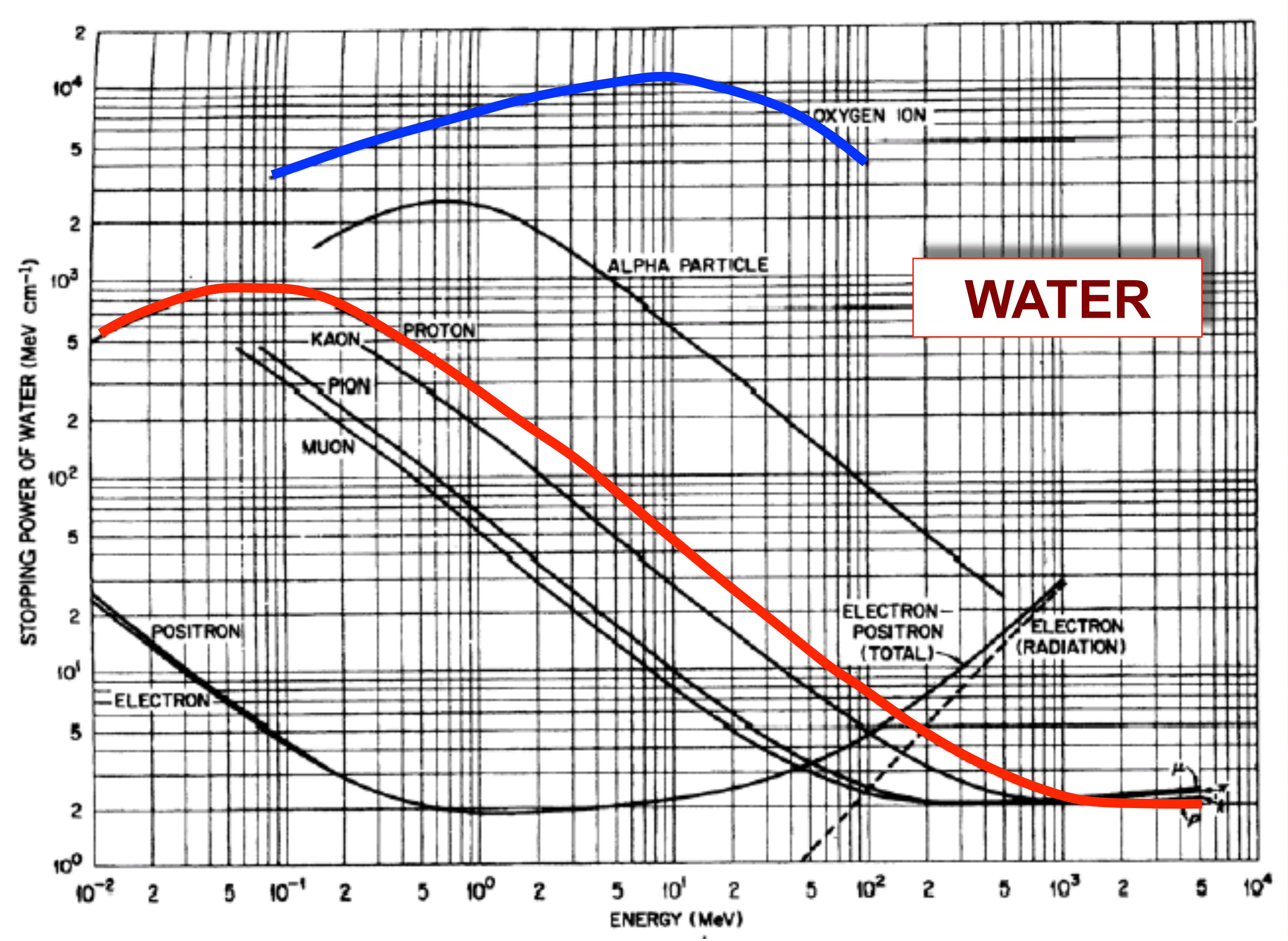
good to a few percent
A =1
B = 0.95

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

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

Silicon: ρ = 2.33 g/cm^3

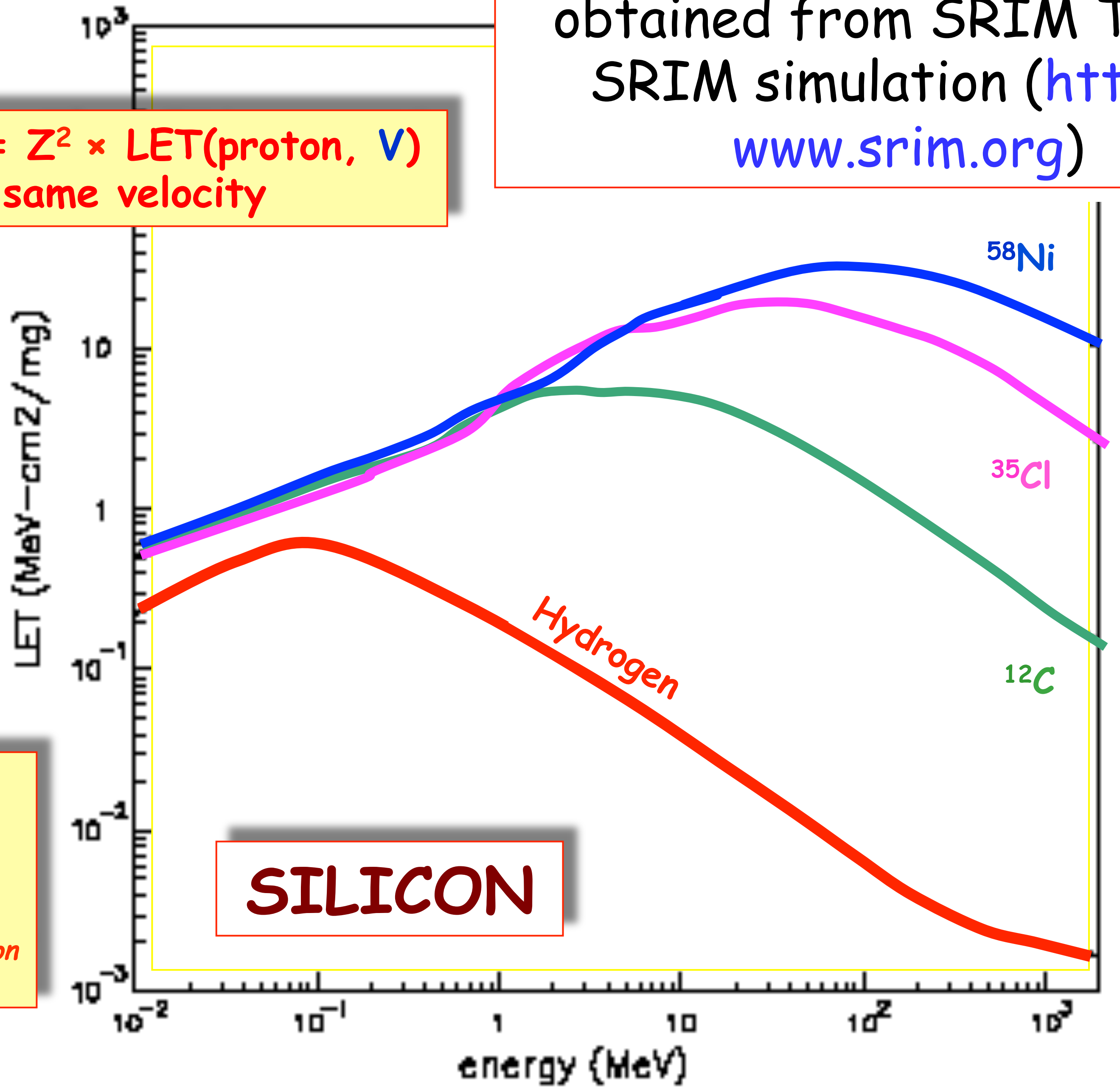
Ionizing stopping power $(dE/dx)_{ele}$ in MeV/cm



LET

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

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



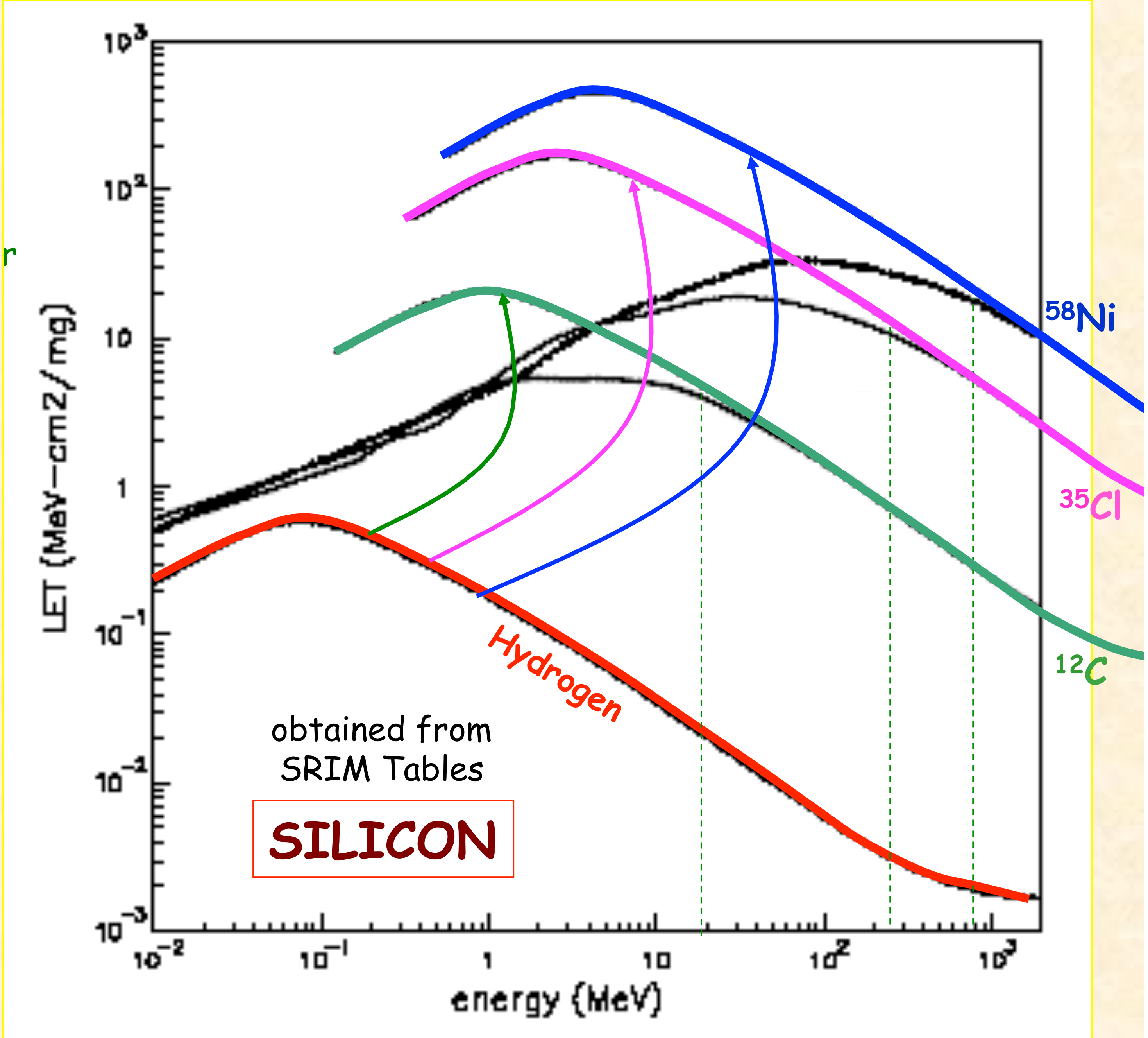
SILICON

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

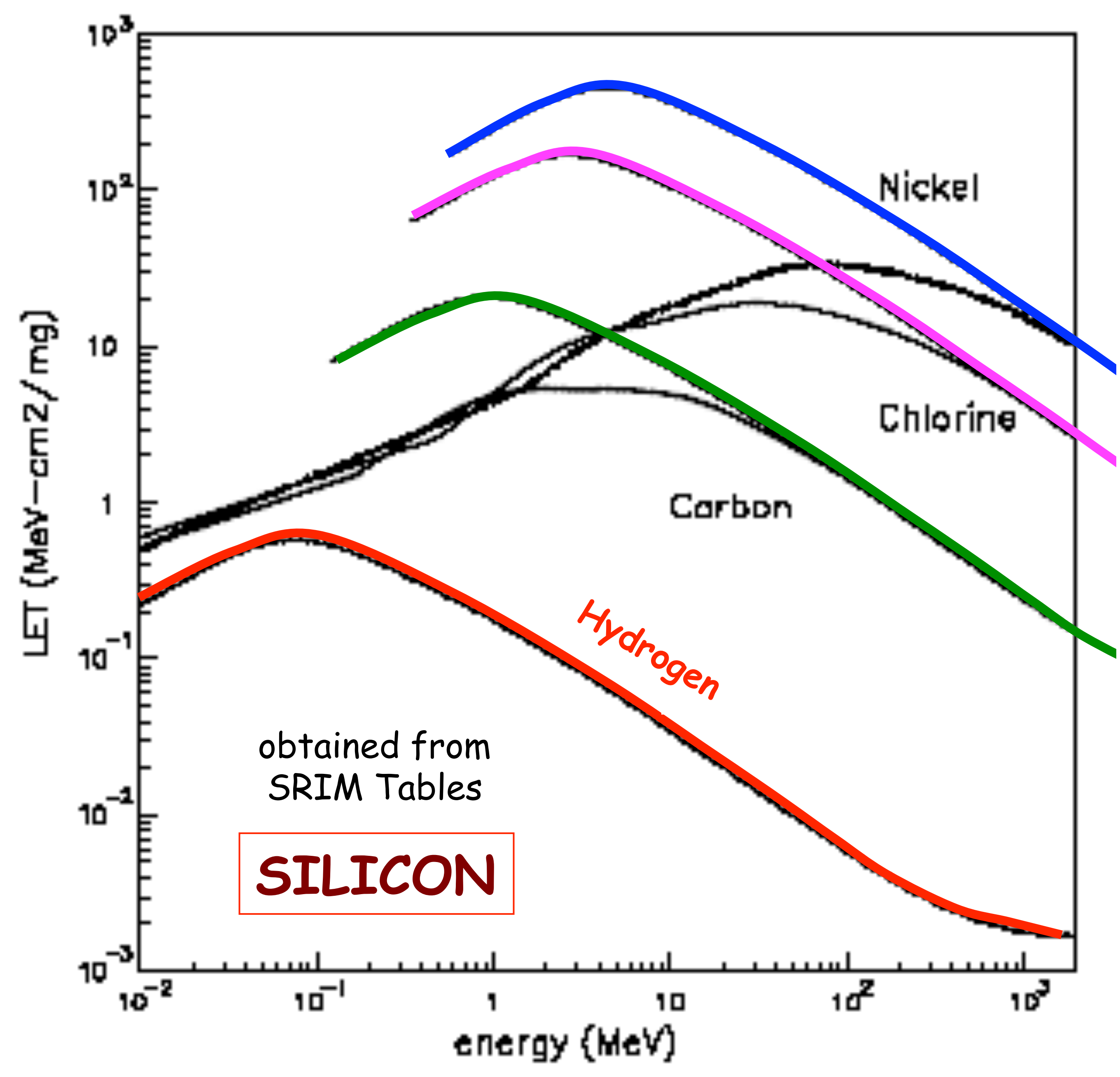
For **full stripping** (*naked nuclear charge Z)* can scale proton curve to any ion:

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-cm^2/mg =
= 0.0386 eV/Å

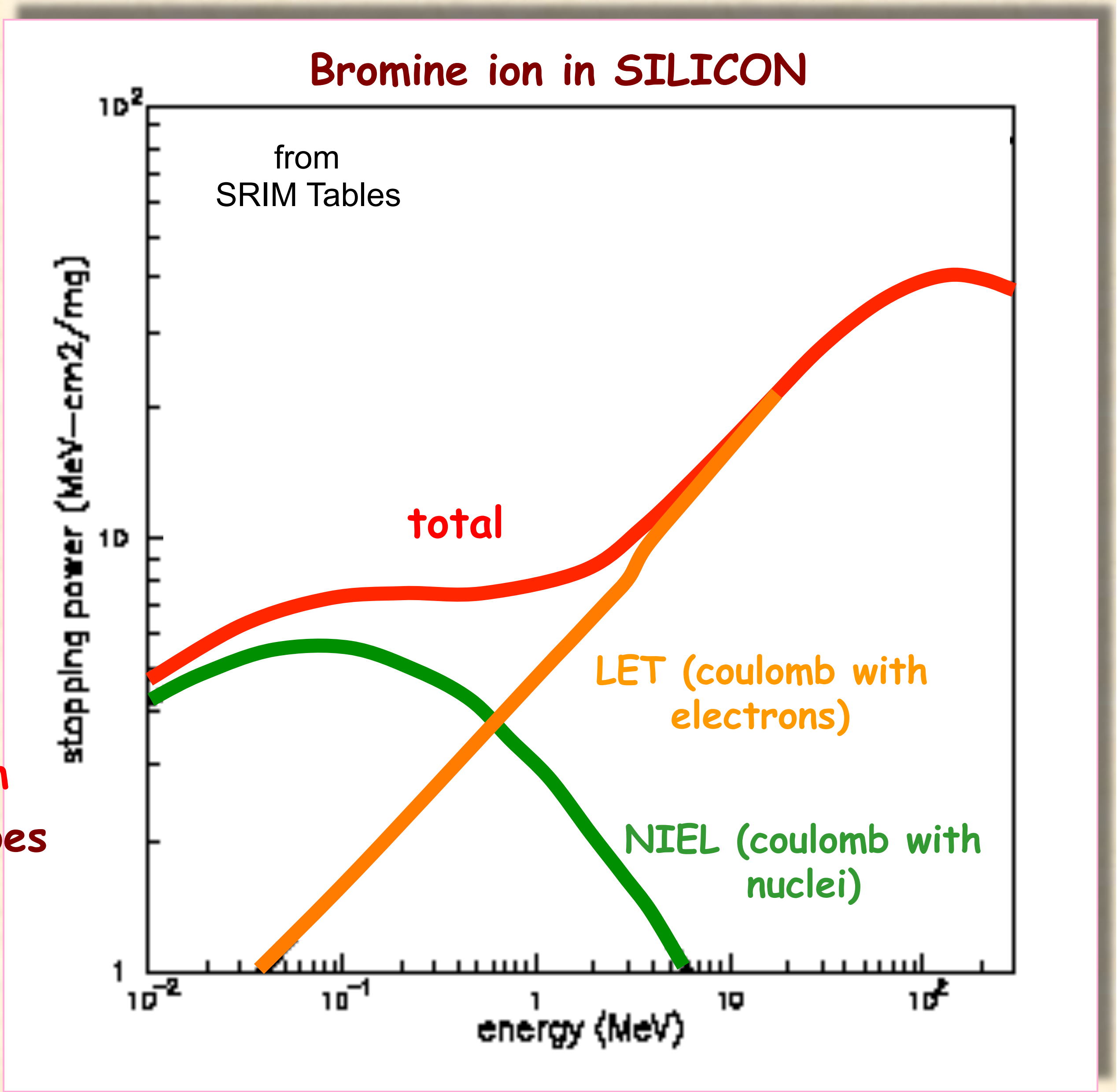
LET_{min}(Nickel, Z=28) =
1.3 MeV-cm^2/mg



Stopping power

total mass stopping power:
$(1/\rho)\ S = \mathrm{LET} + \mathrm{NIEL}_{coulombic}$

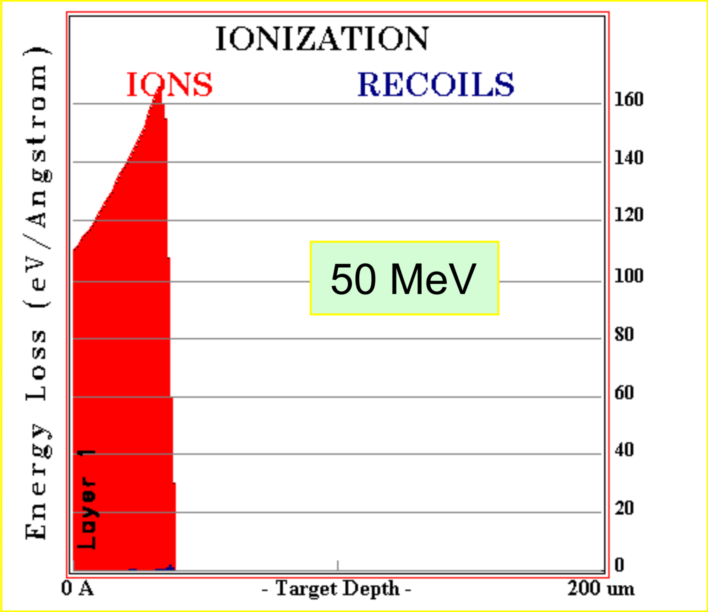
At low velocities ($V < v_0 Z^{2/3}$)
the specific energy loss
via elastic coulomb collisions
with nuclei (non-ionizing)
becomes important!

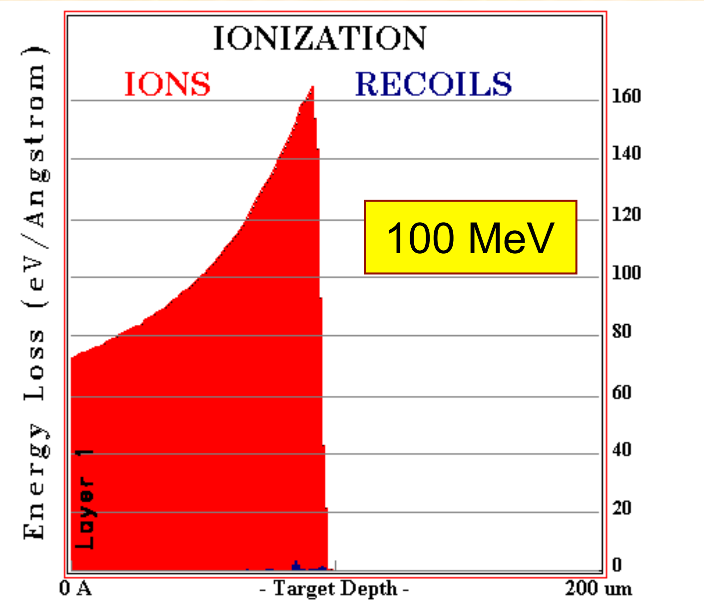


- LET goes thru a maximum
- nuclear stopping power goes through a maximum

range

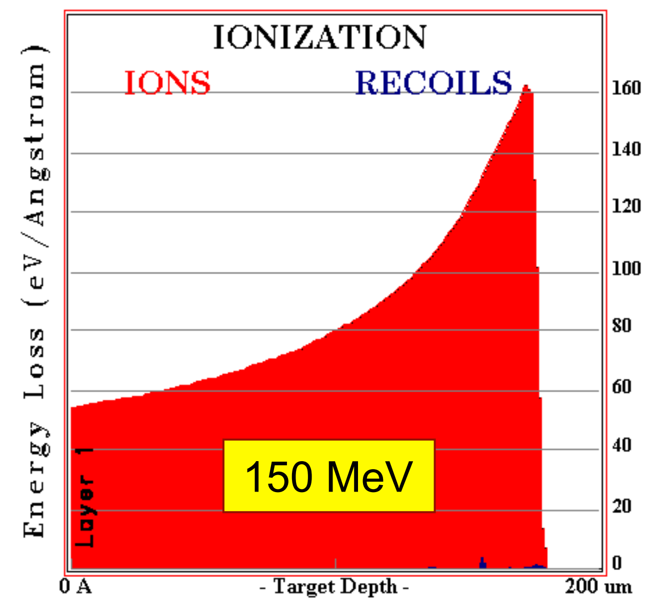
1 hundred O^{16} in silicon (SRIM 2003)





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

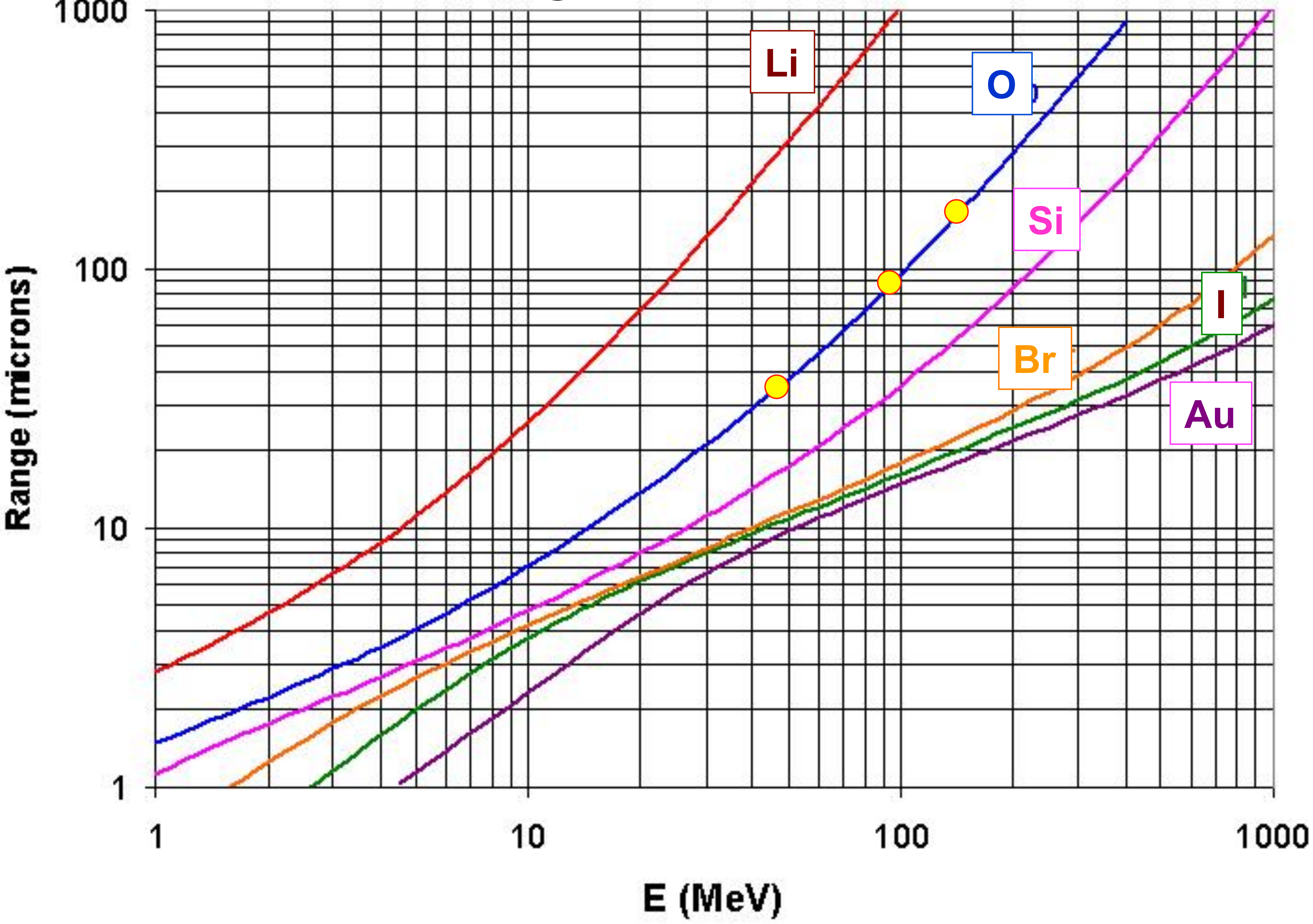


N.B. $(dE/dx)_0$ decreases monotonically with E!

range

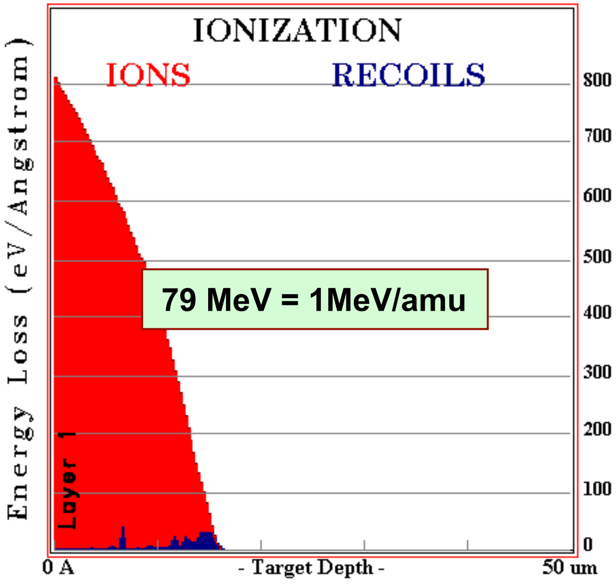
range in Silicon

from SRIM Tables

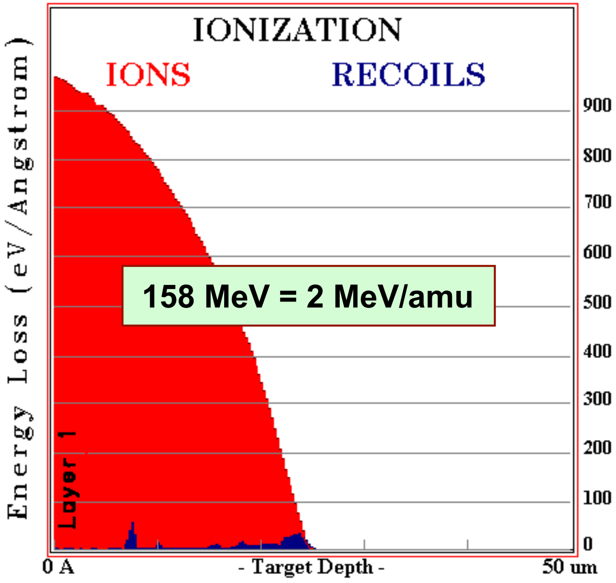


range

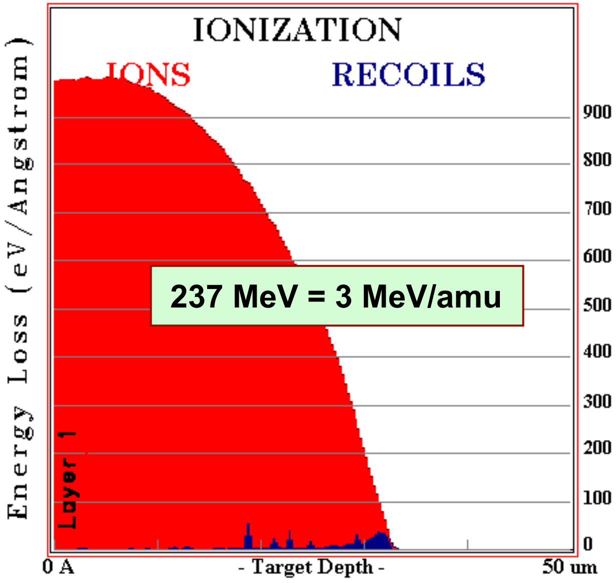
1 hundred Br^{79} in silicon (SRIM 2003)



79 MeV = 1MeV/amu



158 MeV = 2 MeV/amu

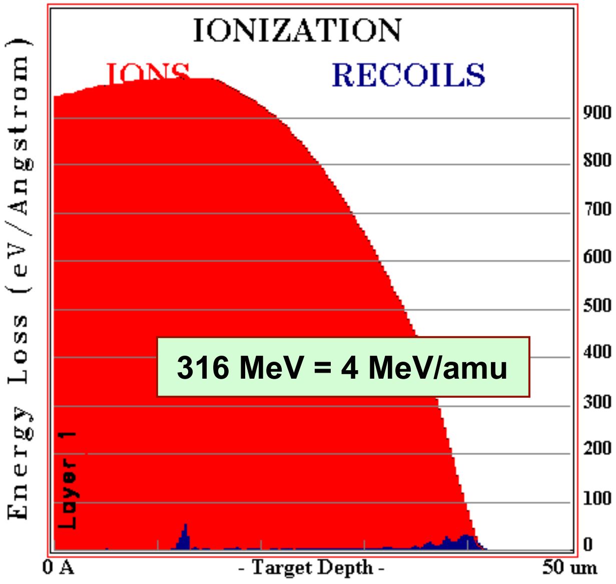


237 MeV = 3 MeV/amu

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

broad maximum

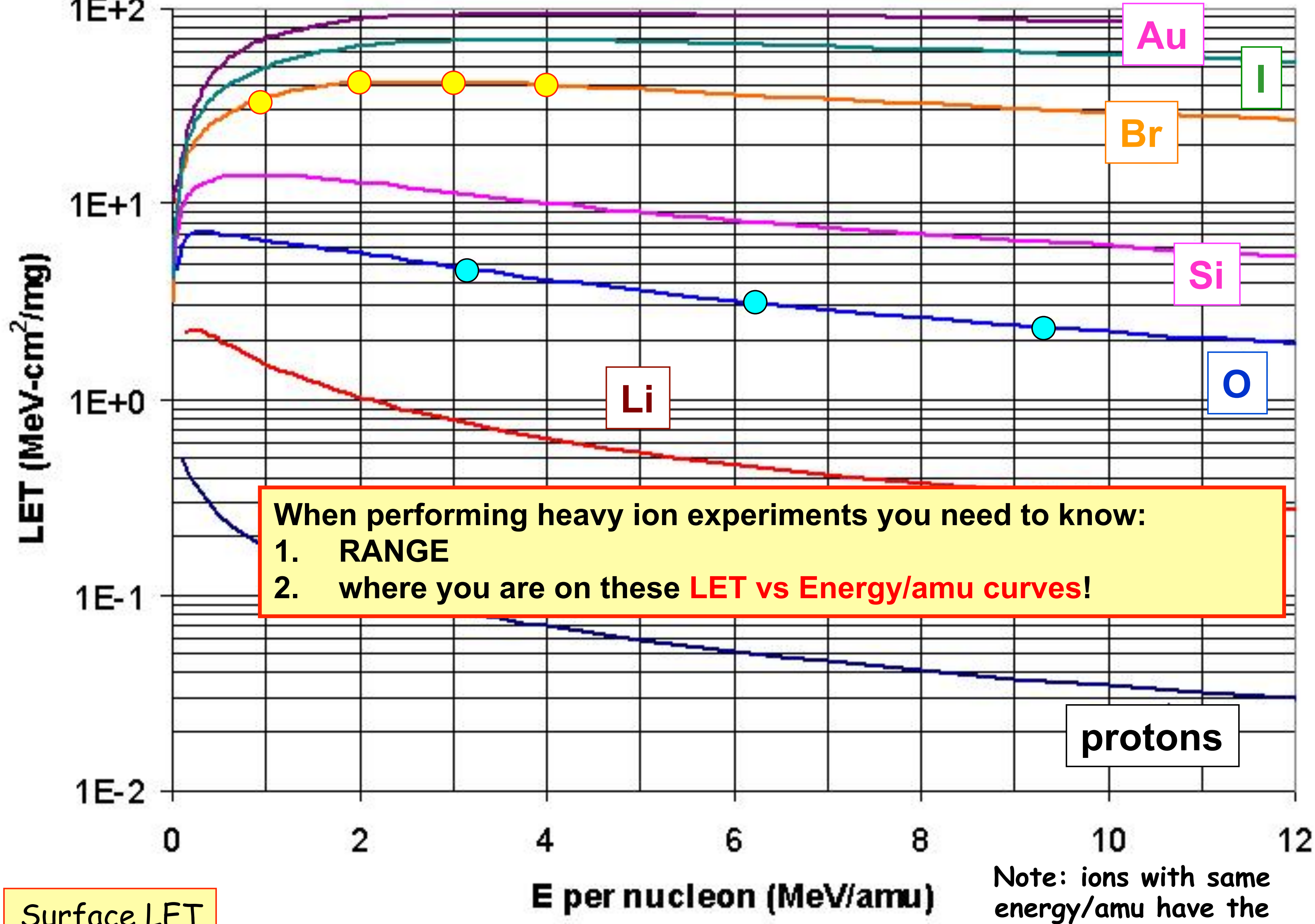
decrease!
beyond maximum



316 MeV = 4 MeV/amu

surface LET in Silicon

from SRIM Tables



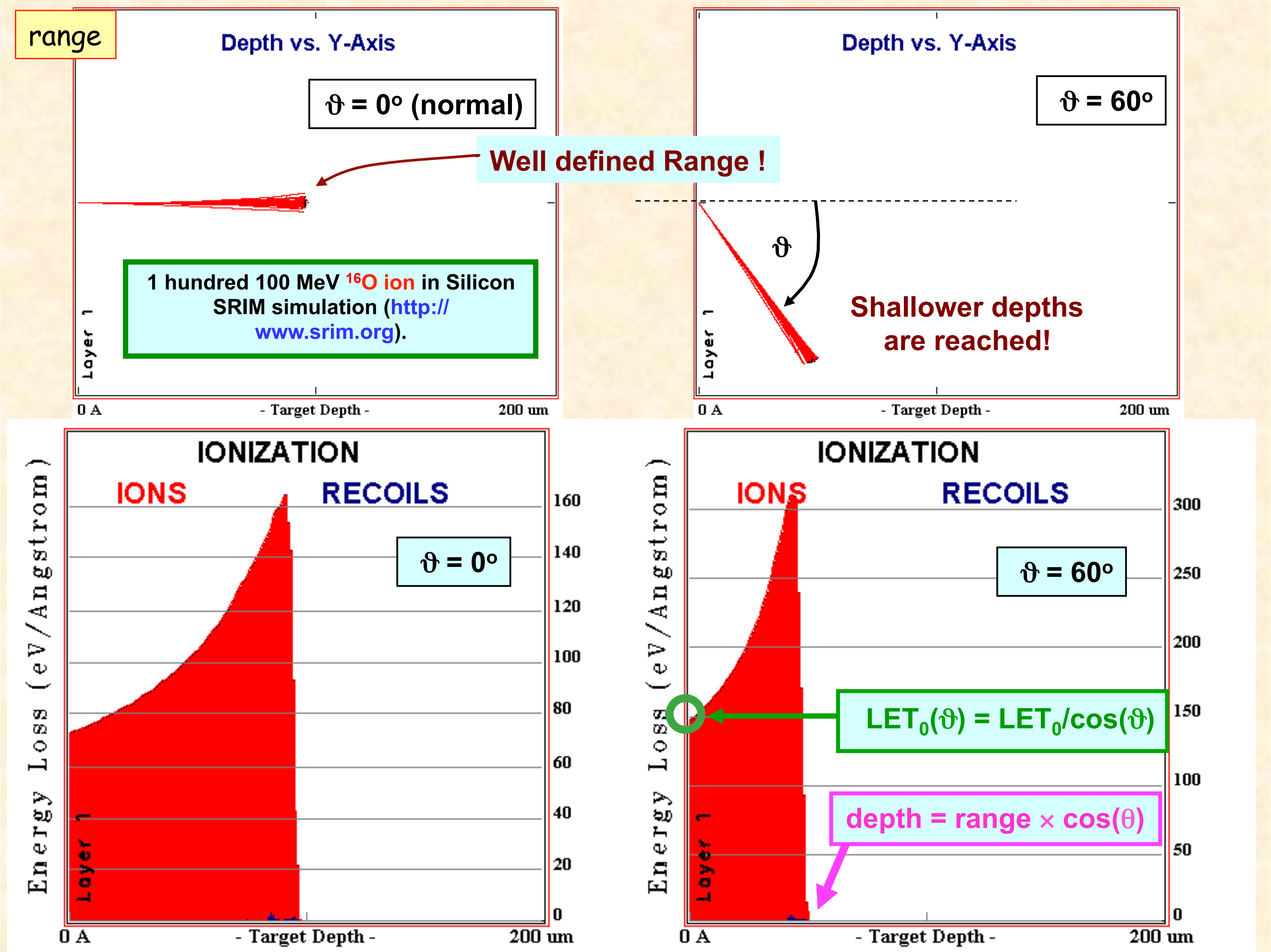
When performing heavy ion experiments you need to know:

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



ϑ = 0° (normal)

Well defined Range !

1 hundred 100 MeV ^{16}O ion in Silicon SRIM simulation (http://www.srim.org).

ϑ = 60°

Shallower depths are reached!

ϑ = 0°

ϑ = 60°

$LET_0(\vartheta) = LET_0/\cos(\vartheta)$

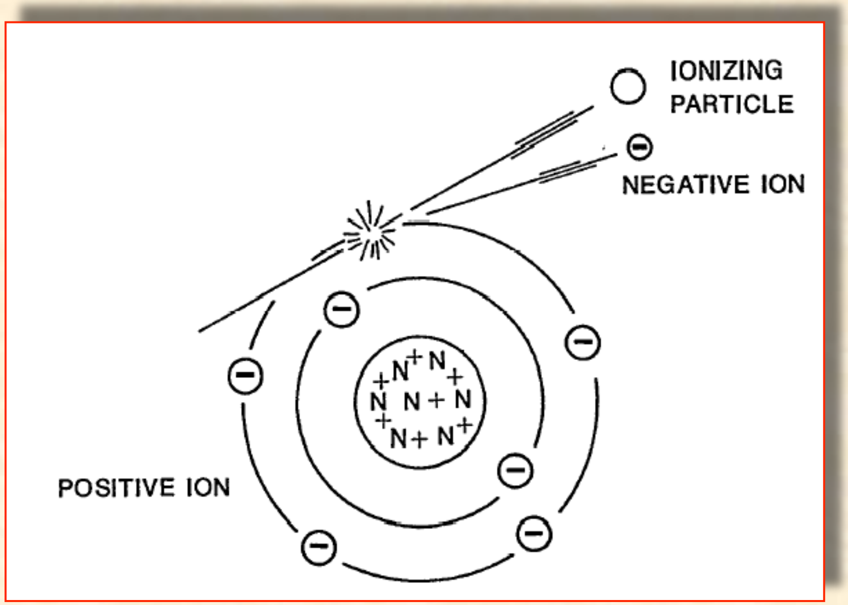
$\text{depth} = \text{range} \times \cos(\theta)$

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

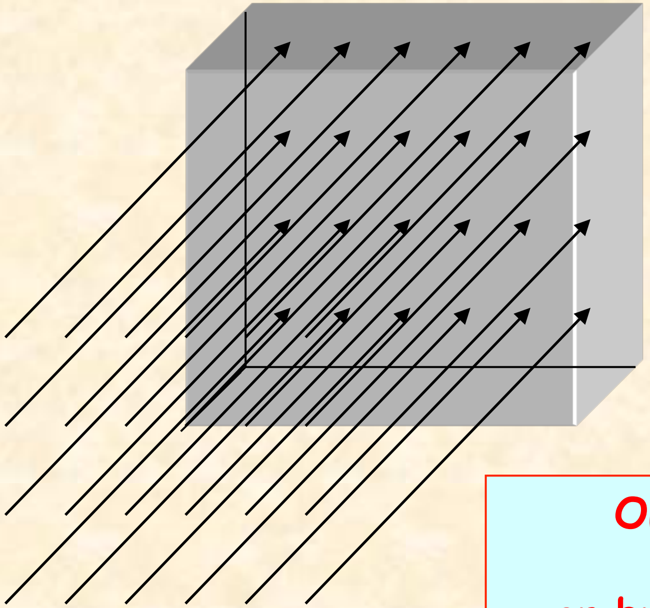
TID(rad) = 1.602 × 10^{-5} × fluence(cm^{-2}) × LET(MeV-cm^2/mg)

HOWEVER… caution!

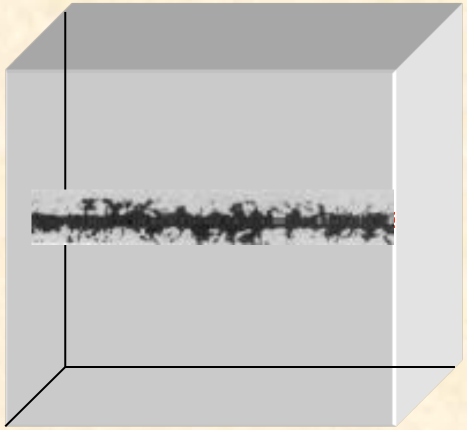
DOSE: energy absorbed per unit mass

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

X-rays and gamma radiation
deposit energy in uniform pattern



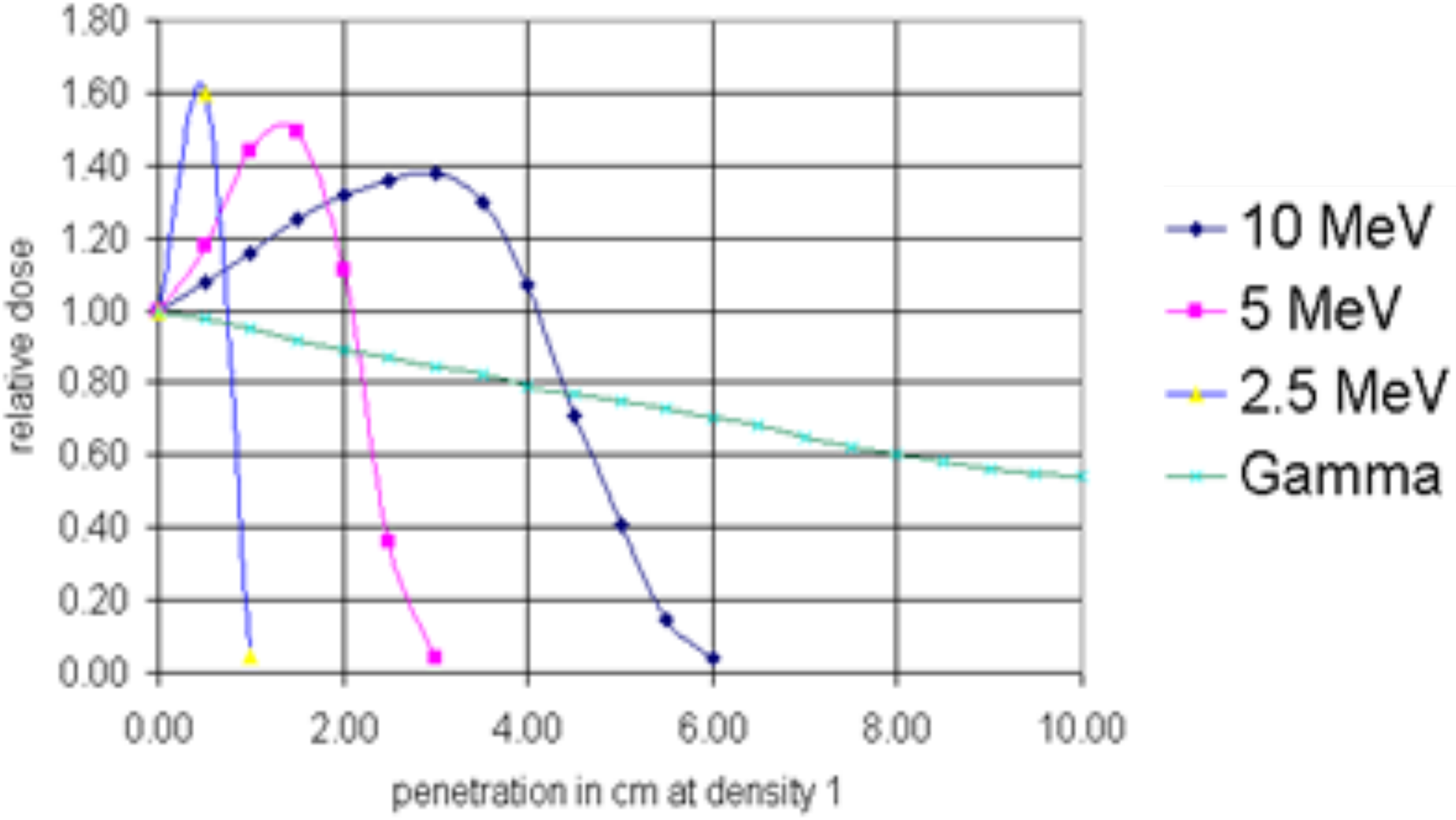
Ions deposit ionisation energy
in NON-uniform highly structured
pattern



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



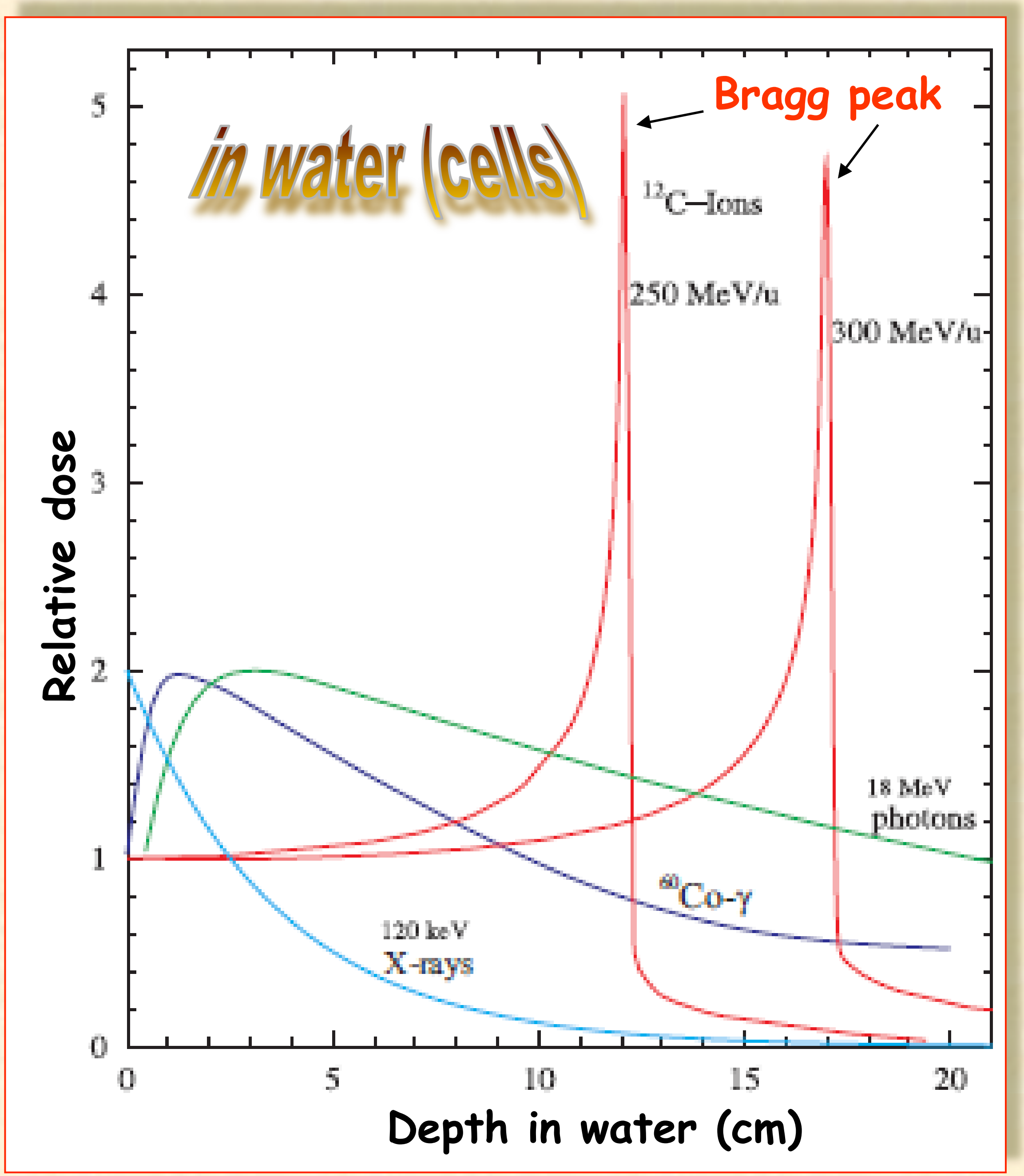
dose

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).



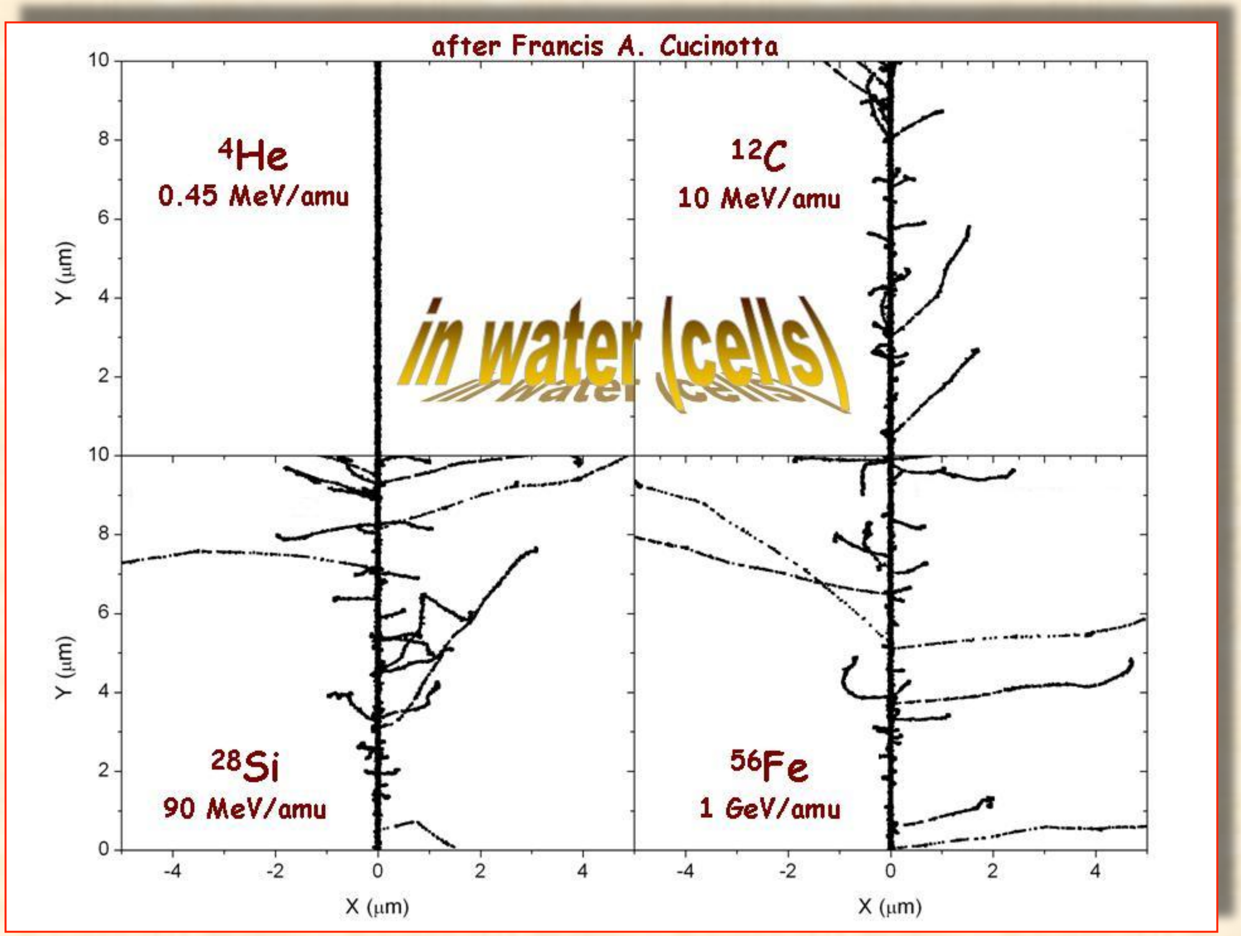
Note: ion dose peak in depth (Bragg peak)

track structure

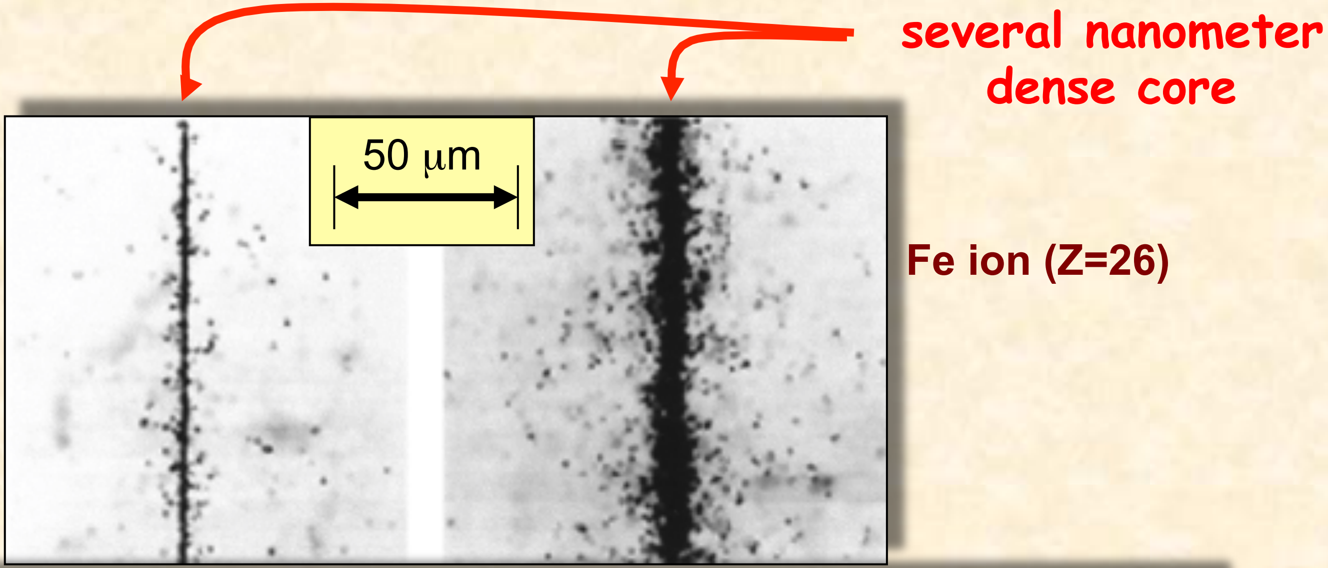
Track Structure

- **NOTE: LET does <u>not</u> adequately describe energy deposition at small scales**
- Full characterization of energetic heavy nuclei:
  - Charge, Z defines density of ionization along track (Z^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 **<u>same LET</u>** (~ 150 keV/micron)



track structure



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

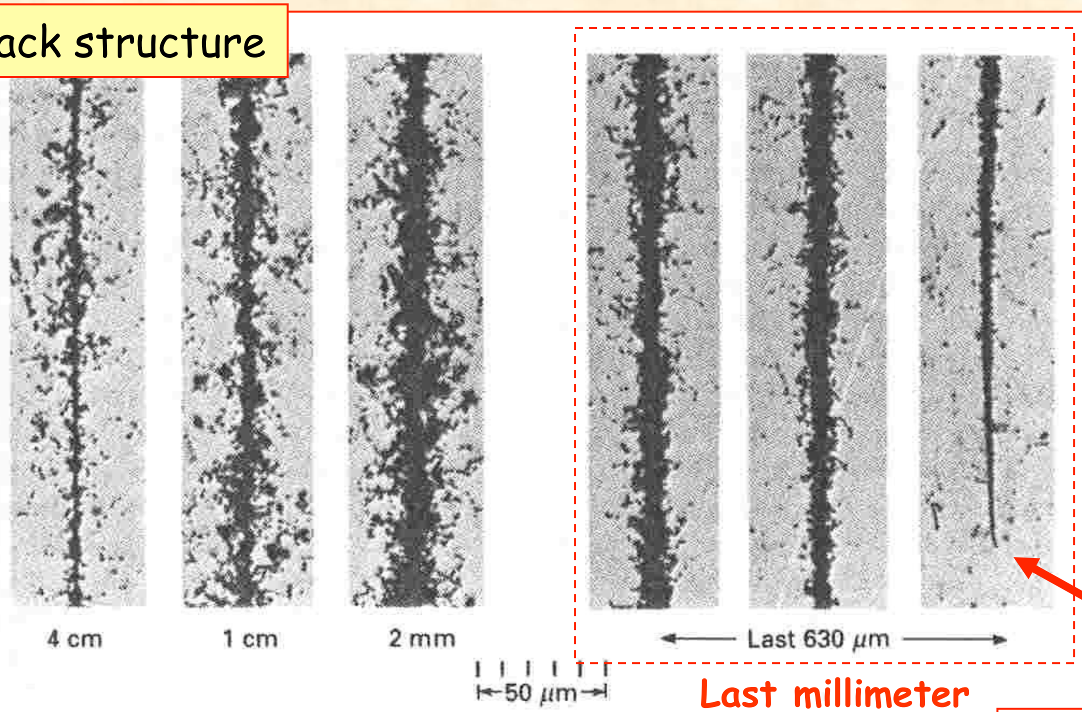
• exponential decrease of ionisation density with distance from track; radial extent of ionisation scales with the **velocity V of ion** (indeed the max energy transfer to electrons is $2m_eV^2$)

• height (intensity) of ionisation scales with velocity V of ion and with effective charge $Z_{effective}$ of ion (that changes and with velocity of ion)

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

track structure

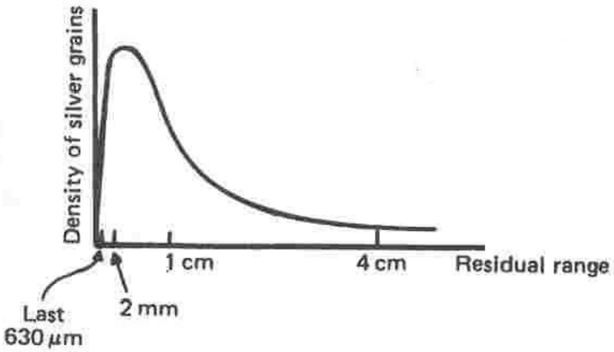
cosmic IRON nucleus



Last millimeter

Ion stopped!

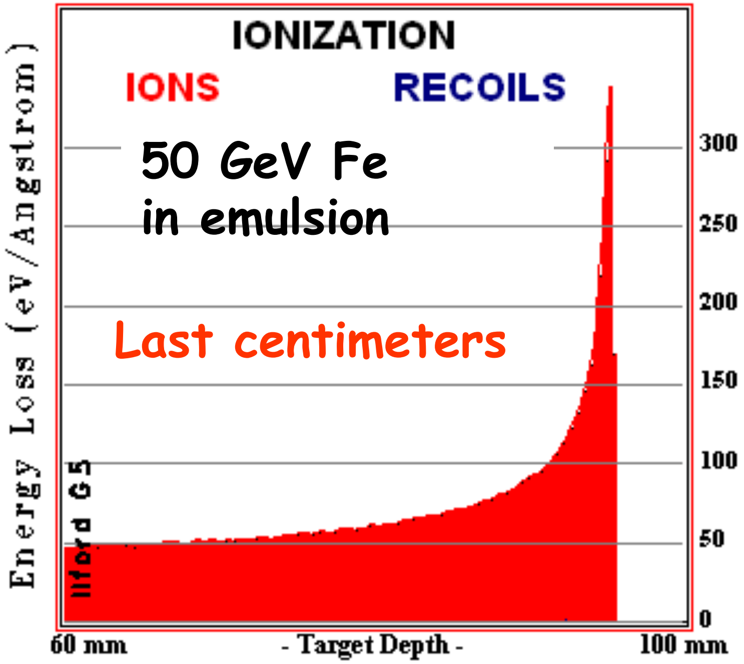
Nuclear emulsion tracks of a single cosmic Fe nucleus at various stages in its deceleration from relativistic velocities to REST. The distances are the residual ranges at which the ion track is observed.



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

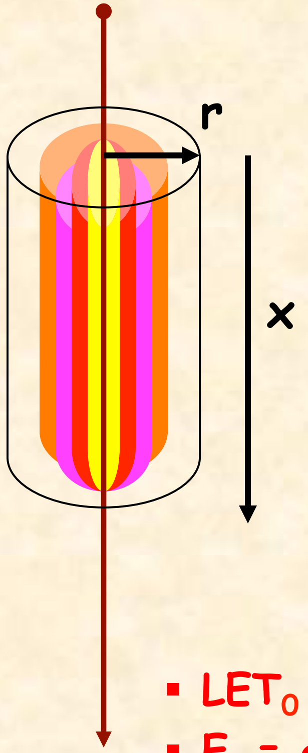
As ion slows
the **spatial extent**
of ionisation decreases (not enough energy to extract energetic deltas).

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



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):

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

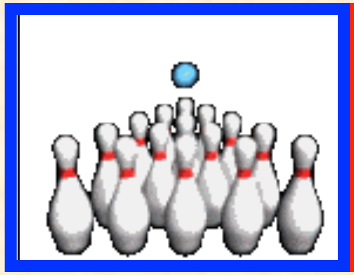
N.B. no x dependence ≡ shallow hypothesis

- 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

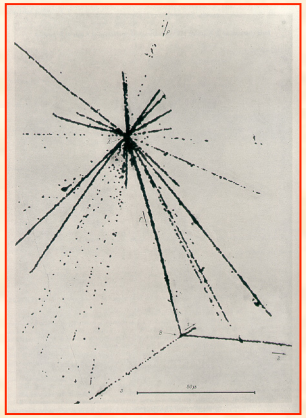
$$g(r,t) = 4.8 \times 10^{31}\ (\text{e-h/cm}^3\text{-s}) \times \exp(-r^2/r_0^2) \times \exp(-t^2/\tau^2)$$

Atomic displacement
(displacement damage)



elastic

anelastic



protons
ions
neutrons

neutrons
energetic protons
energetic ions

$\}$ Coulomb barrier

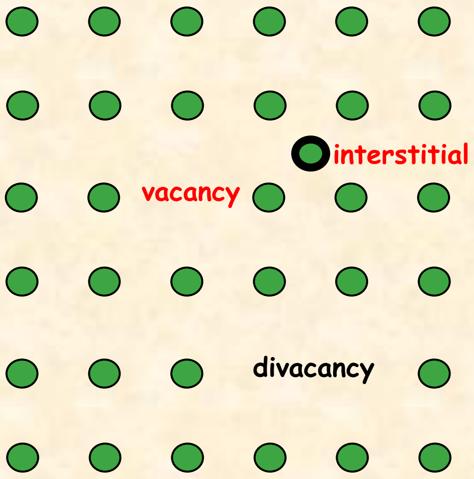
Particles can lose energy through non-ionizing interactions with materials, particularly through "displacement damage", or "bulk damage", where atoms are displaced from their original sites.

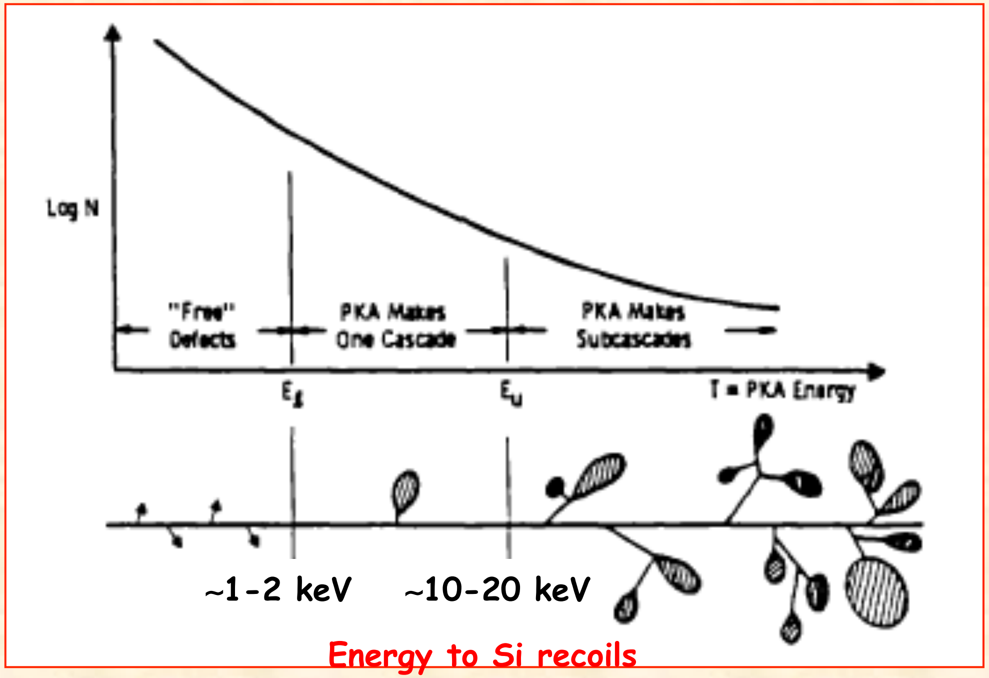
This can alter the electrical, optical and mechanical properties of materials and is an important damage mechanism for electro-optical components (solar cells, opto-couplers, etc.) and for detectors and sensors such as CCDs.

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).

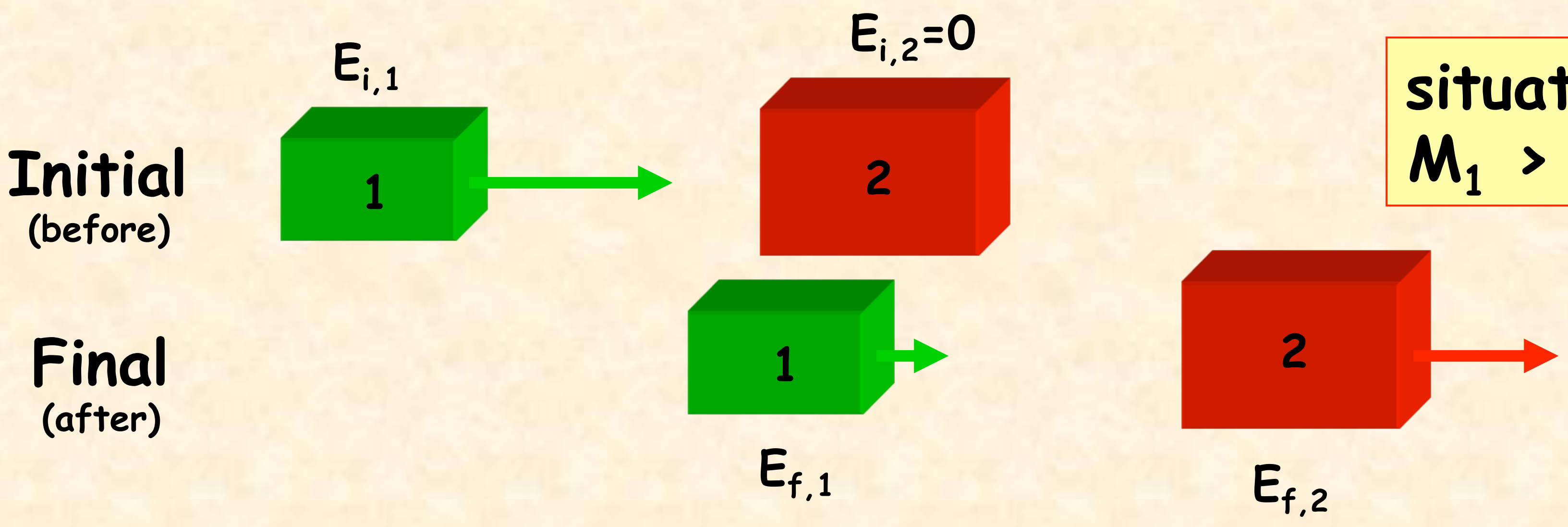
- pejorative mechanism: energetic PKA generates other point defects or even highly damaged regions (cascades, clusters), depending on energy transferred during the primary collision.





displacement

elastic collisions 1



situation $M_1 > M_2$

In elastic collisions $E_{f,1} + E_{f,2} = E_{i,1}$
hence the maximum transferable energy is

$$E_{f,2}^{\max} = E_{i,1} \times \frac{4M_1M_2}{(M_1+M_2)^2}$$ *(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 Frenkel pair
Silicon ion	25 eV (billiard ball effect)
neutron/proton	186 eV
electron	*319 keV (non-relativistic formula above)* **255 keV (relativistic)**

elastic collisions 3

MAXIMUM energy transferred to recoiling target atom

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

(non-relativistic)

e.g. incident neutrons in Silicon (recoiling Si)

incident energy	$E_{\text{max recoil}}$	comments assuming recoiling Silicon with maximum energy
35 keV	4.7 keV	range of recoiling Si ~ 200 Å, most of energy loss of Si recoil is <u>nuclear</u> (coulombic)
1 MeV	134 keV	range of recoil ~ 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 150 eV (isolated displacements, no clusters)

Displacement damage

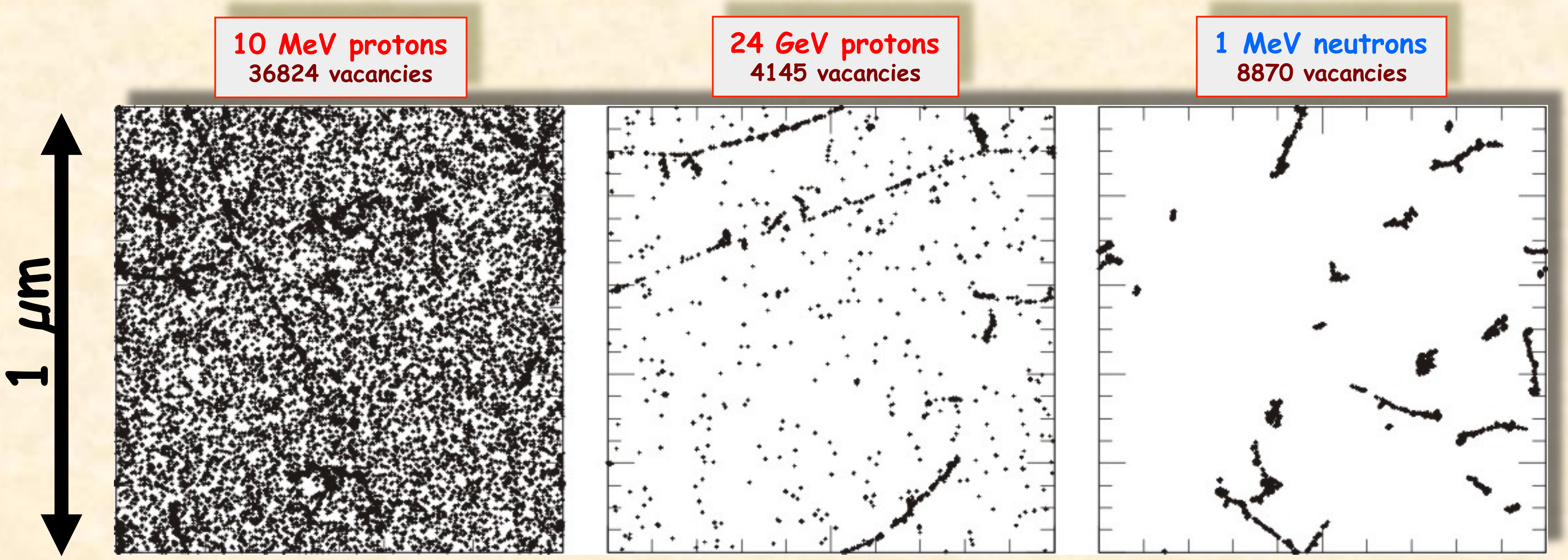
^{60}Co-gammas	Electrons	**Neutrons** (elastic scattering)
Max $E_\gamma \approx 1$ MeV Effective ionizing secondaries are *Compton* electrons. Point defects only. (No clusters!)	$E_e > 255$ keV for displacement $E_e > 8$ MeV for clusters	$E_n > 185$ eV for displacement $E_n > 35$ keV for clusters

More isolated defects ⟷ **More clusters**

By Mika Huthinen (ROSE)

by Mika Huhtinen ROSE TN/2001-02

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



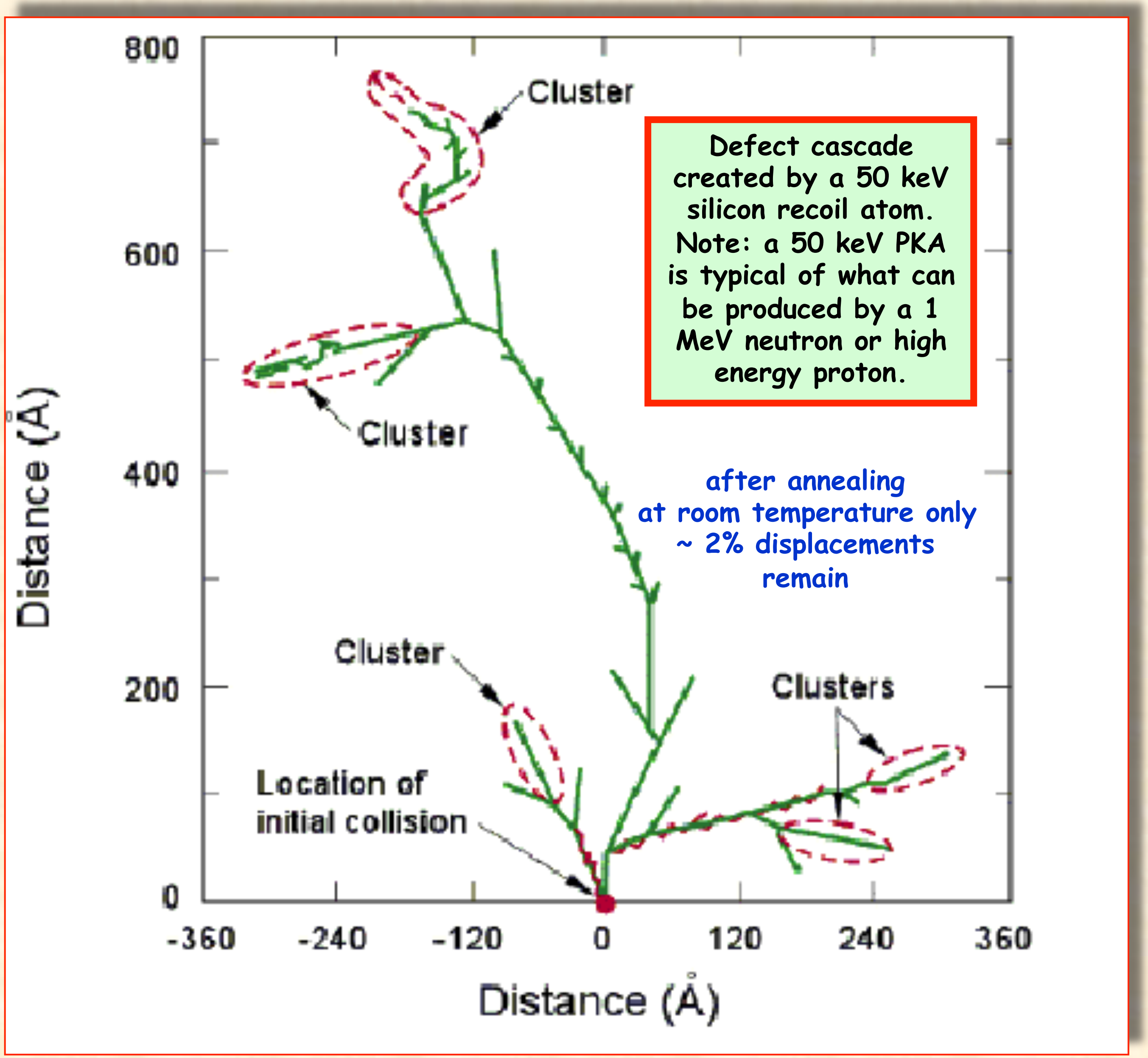
10 MeV protons
36824 vacancies

24 GeV protons
4145 vacancies

1 MeV neutrons
8870 vacancies

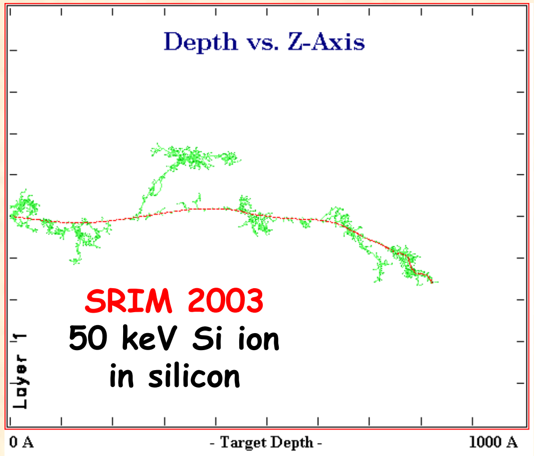
Ion displacement damage

adapted from V.A.J. Lint

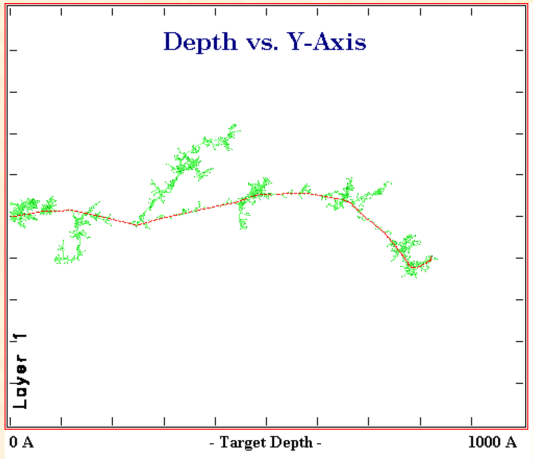


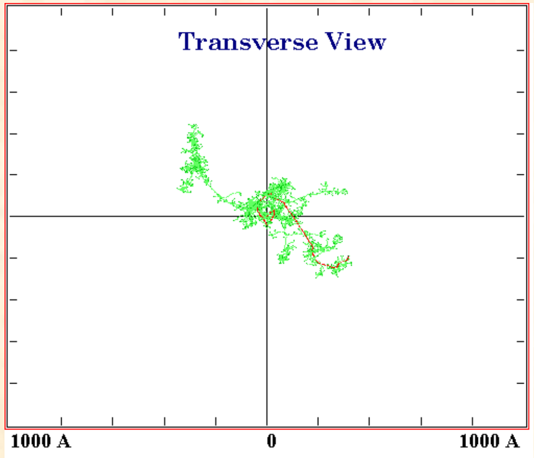
Defect cascade created by a 50 keV silicon recoil atom. Note: a 50 keV PKA is typical of what can be produced by a 1 MeV neutron or high energy proton.

after annealing at room temperature only ~ 2% displacements remain



SRIM 2003
50 keV Si ion
in silicon





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

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

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

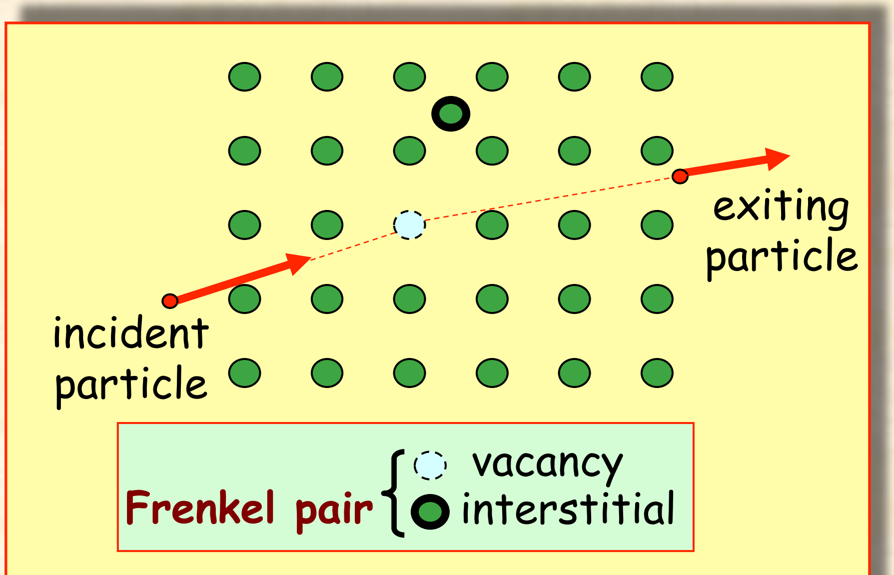
Measurement units

MeV/cm, also eV/μm

or

dividing by density

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



Interstitial and vacancy defect creation.

NIEL

Non Ionizing Energy Loss (NIEL)

skip

NIEL = total energy that goes into displacements
PKA = Primary Knock-on Atom (e.g. silicon atom if a silicon lattice)
Frenkel pair = Interstitial-vacancy (I-V) pair

- **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!**

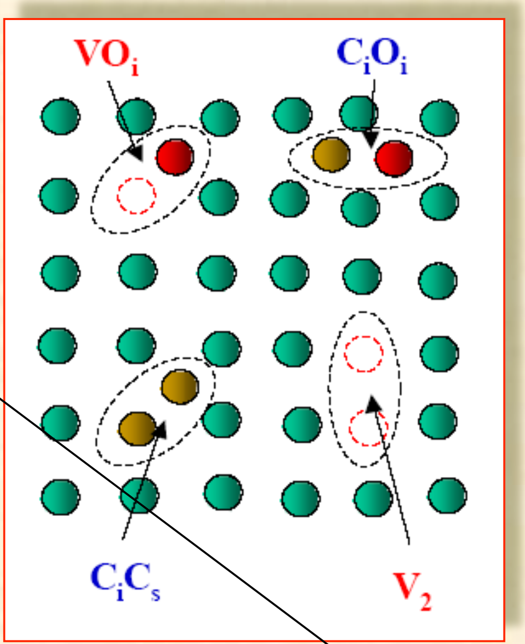
Displacement damage

Quasi-chemistry of defects

skip

complex kinetics

(time, concentration, and temperature dependences)



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

Various quasi-chemical reactions

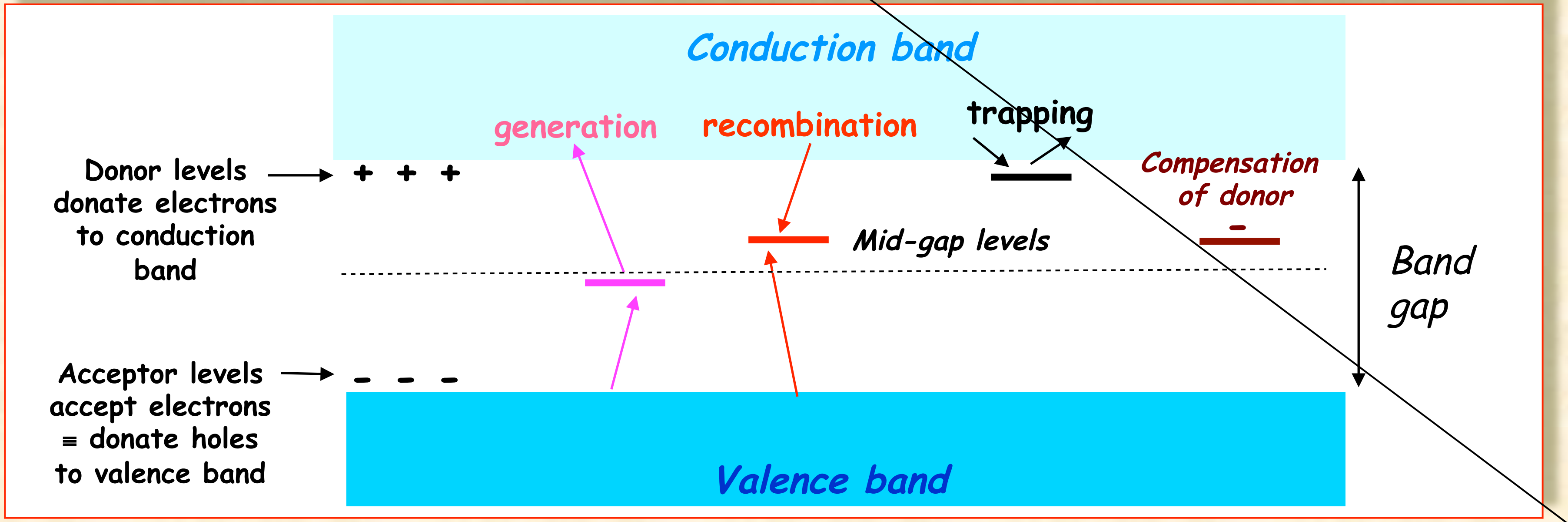
$$\begin{array}{llllll}
V+V \rightarrow V_2 & & V+V_2 \rightarrow V_3 & & & \\
V+O_i \rightarrow VO_i & \Rightarrow & V+VO_i \rightarrow V_2O_i & & V+V_2O_i \rightarrow V_3O_i & \\
V+P_s \rightarrow VP_s & & & & & \\
I+VP_s \rightarrow P_s & & I+V_2 \rightarrow V & & & \\
I+VO_i \rightarrow O_i & & I+V_2O_i \rightarrow VO_i & & I+V_3O_i \rightarrow V_2O_i & \\
I+C_s \rightarrow C_i & \Rightarrow & C_i+C_s \rightarrow C_iC_S & & & \\
 & & C_i+O_i \rightarrow C_iO_i & & &
\end{array}$$

Displacement damage

Damage → defects

skip

- 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



Conduction band

generation

recombination

trapping

Donor levels donate electrons to conduction band → + + +

Compensation of donor

Mid-gap levels

Band gap

Acceptor levels accept electrons ≡ donate holes to valence band → - - -

Valence band

NIEL

KERMA ≡ K.E. imparted by radiation into displacement
total <u>K</u>inetic <u>E</u>nergy <u>R</u>eleased in <u>MA</u>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 ⇒ “*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) =

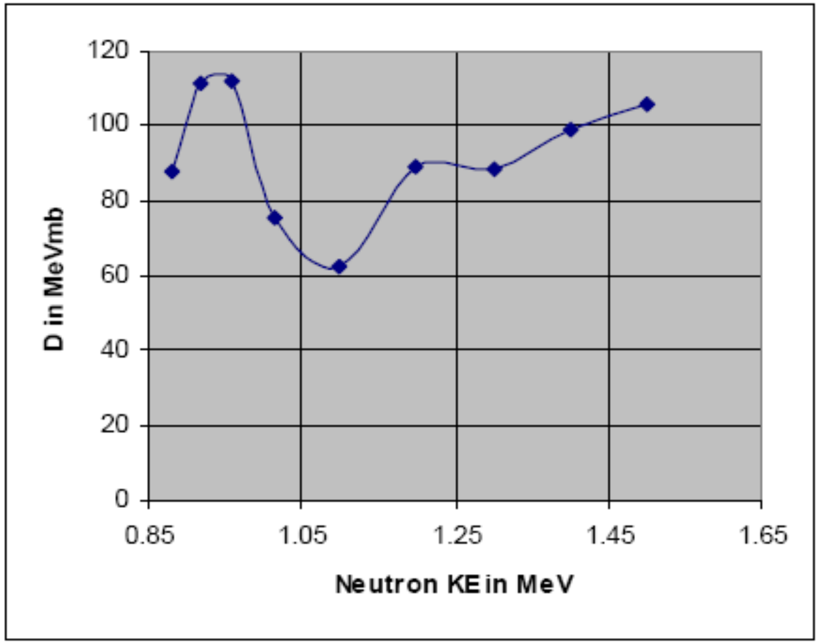
= 2.144 keV-cm^2/g

NIEL scaling 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)

NIEL scaling

“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 of leakage current

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

For a certain leakage current density value

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

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

$$\Rightarrow \quad \Phi_{equivalent} = \frac{\alpha_{delivered}}{\alpha_{std}} \cdot \Phi_{delivered} = K \cdot \Phi_{delivered} \quad \begin{cases} K > 1 \\ K < 1 \end{cases}$$

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

e.g. for K=2, $\Phi_{eq} = 2\Phi$

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.

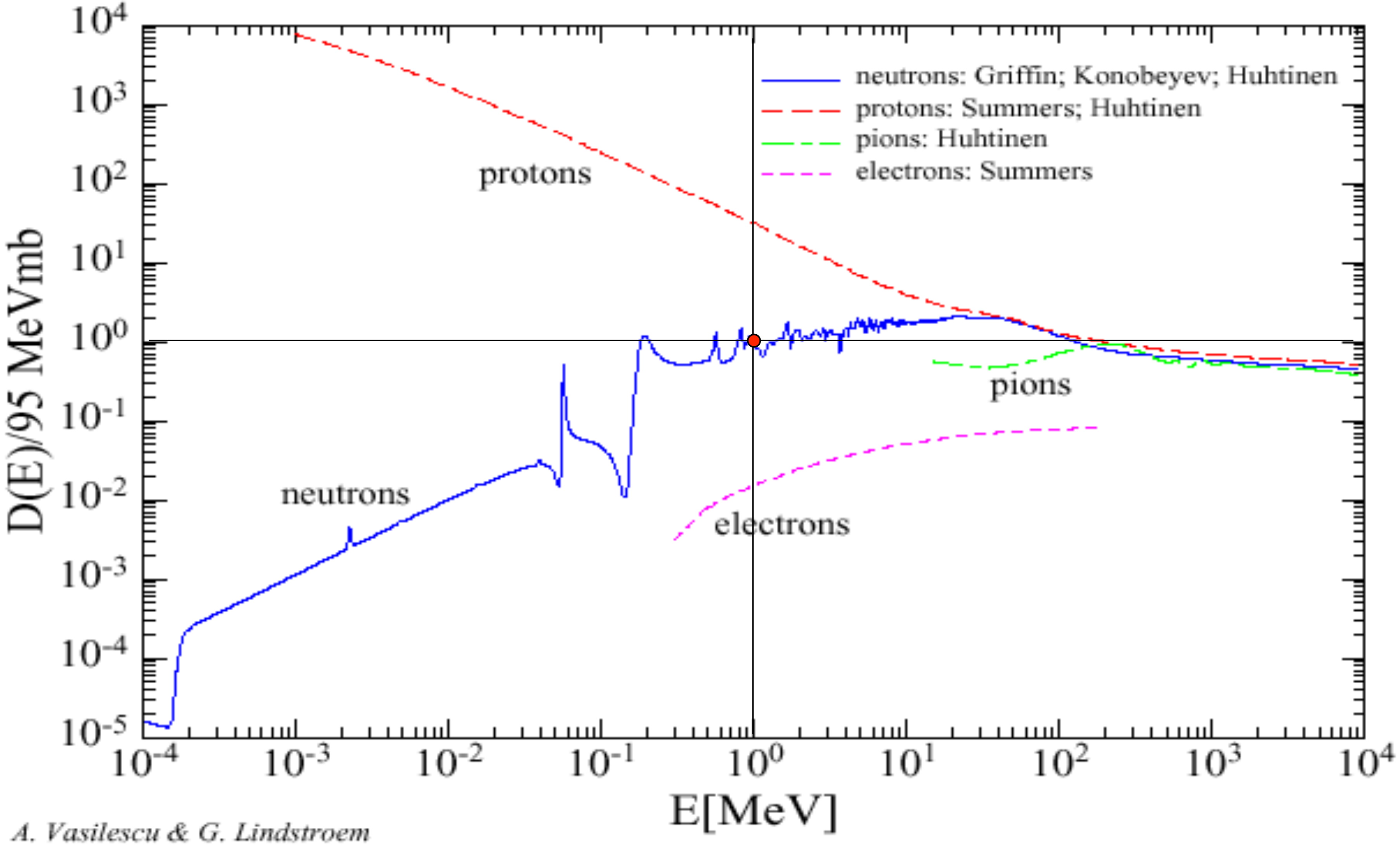
Hardness factors (also called damage coefficients) are used to scale the effect caused by particles to the damage caused by a standard particle type and energy.

In the context of non-ionizing energy loss effects, the standard particles are 1MeV neutrons. For example 1 hundred 50 MeV protons are equivalent to 226 1MeV neutrons.

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

NIEL scaling

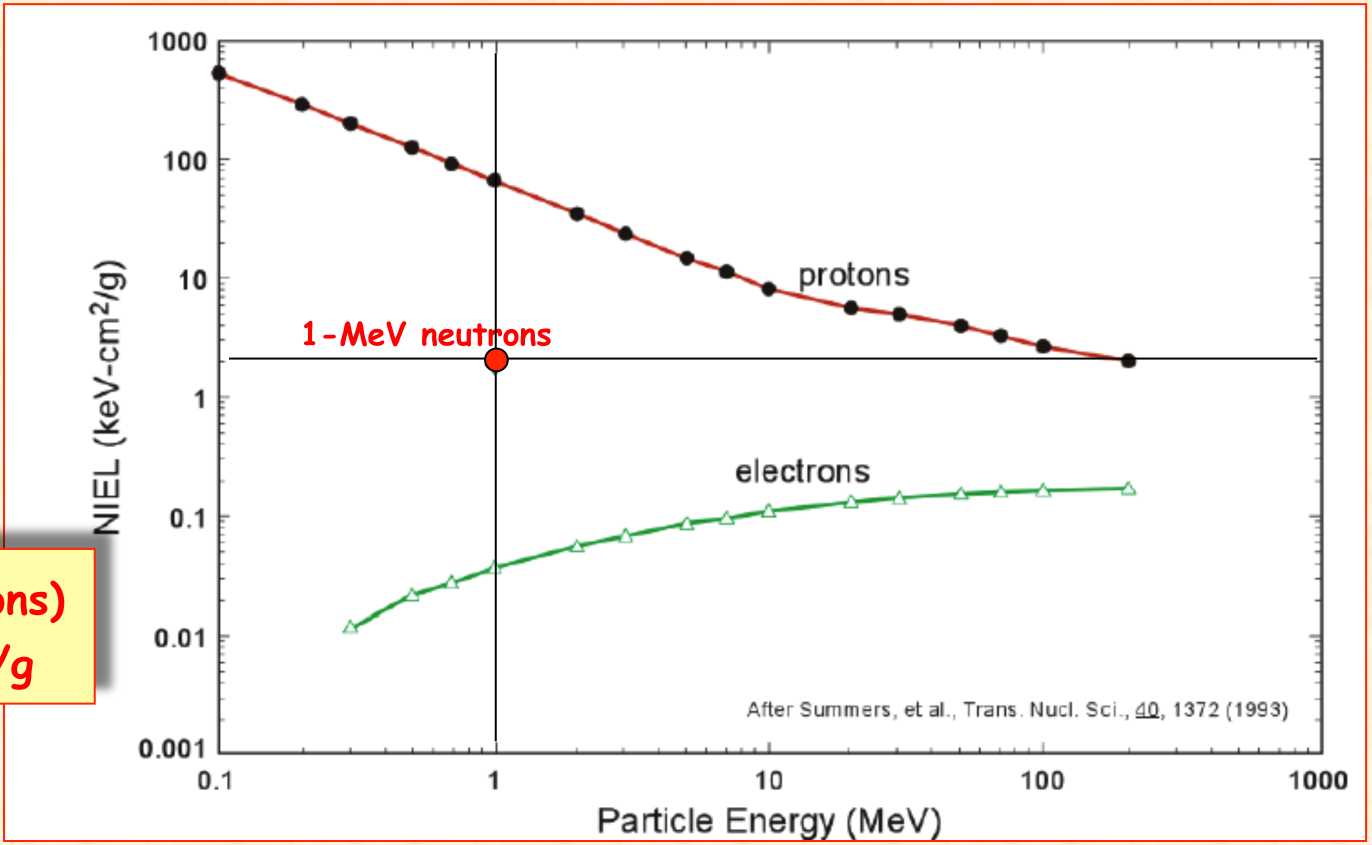
energy dependence of **Displacement damage cross-section D** in silicon for neutrons, protons, electrons and pions



A. Vasilescu & G. Lindstroem

NIEL scaling

energy dependence of **NIEL** in silicon



After Summers, et al., Trans. Nucl. Sci., 40, 1372 (1993)

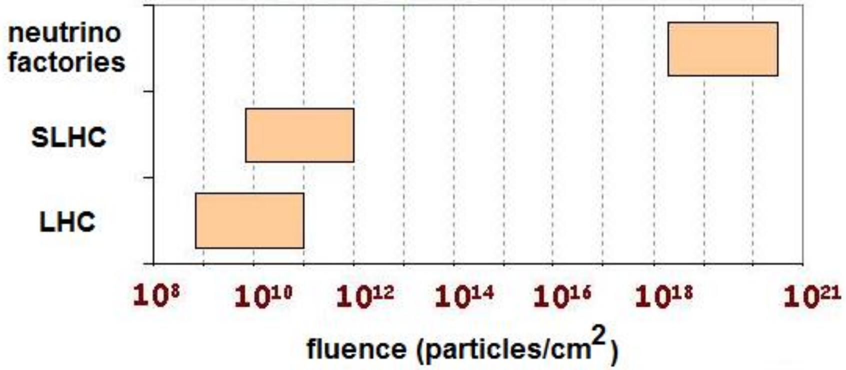
NIEL(1 MeV neutrons) = 2.037 keV-cm^2/g

particle	total dose [rad (Si)]	ϕ fluence (part/cm^2)	ϕ_{eq} equivalent neutron fluence (n/cm^2)	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

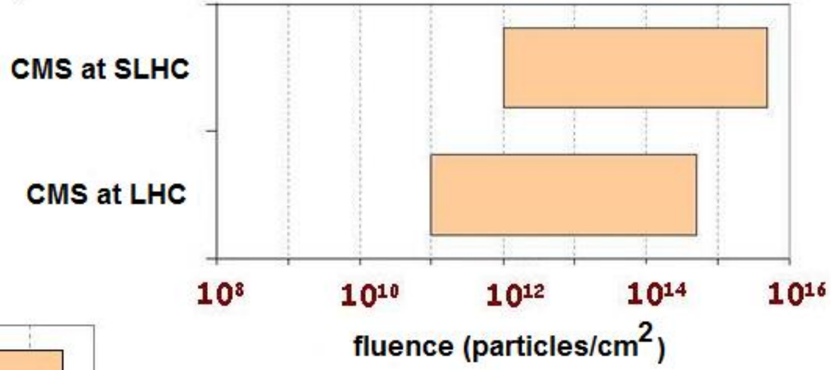
Non Ionizing Energy Loss
fluence expressed in *1MeV-equivalent neutrons*

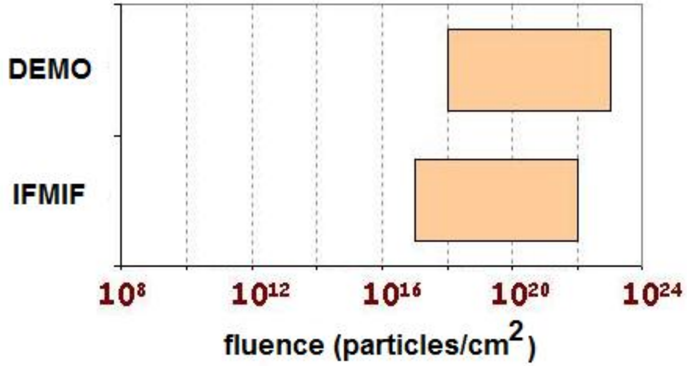
B. Camanzi and
A. G. Holmes-Siedle



Accelerators
caverns

Experiments at
accelerators





Nuclear fusion facilities

IFMIF International
fusion materials
irradiation facility

- Check time
- Check vital parameters

PART 2:

basic concepts of radiation damage in electronics

Electronics, because of the thin sensitive layer, tend to be most sensitive to ionization and the associated accumulation of charge in the material. High levels of localized ionization from a single particle 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.

Time domain

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 stochastically (suddenly).

Not predictable on event to event basis.

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 know better; bad luck; voodoo...*

macroscopic effects in electronic

3 MAIN GROUPS:

1)TID effects (total ionization dose effects) **skip**

2) DDD effects (displacement damage dose effects)

skip

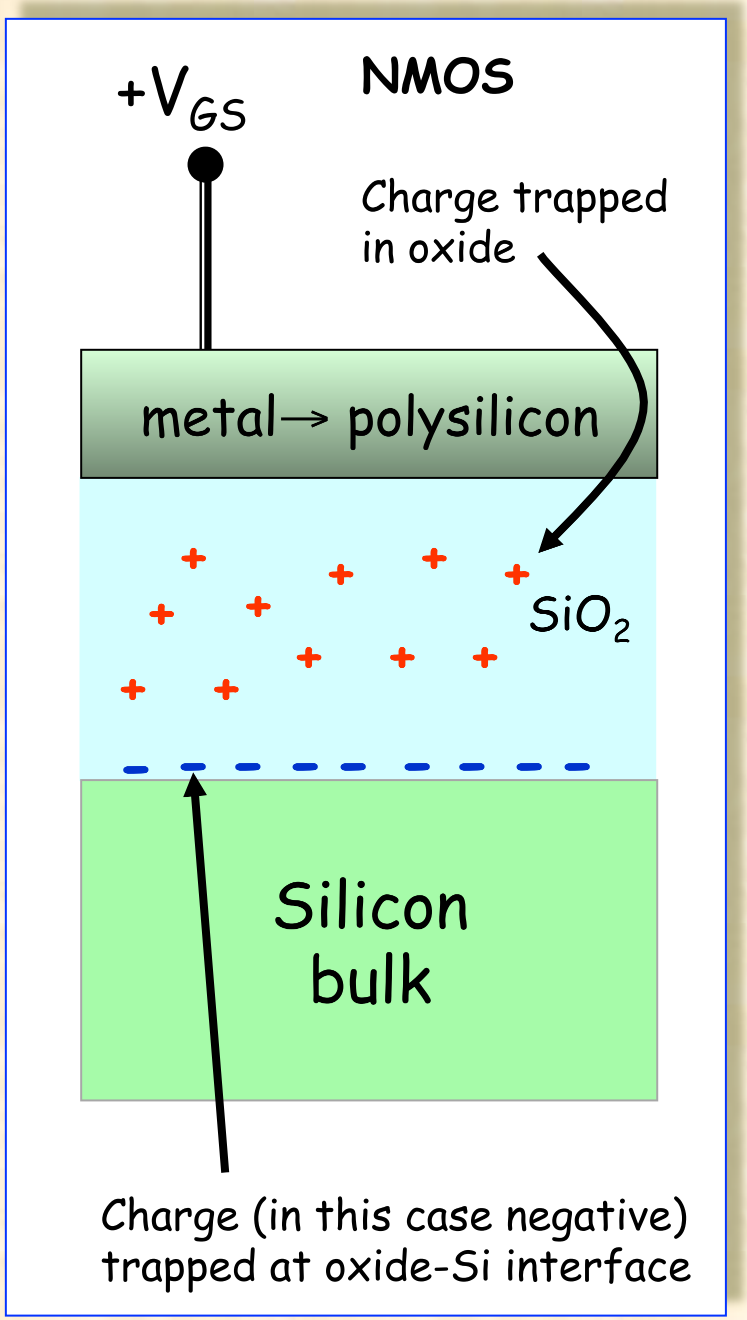
3) SEE (single event effects) **GO HERE**

TID effects

skip

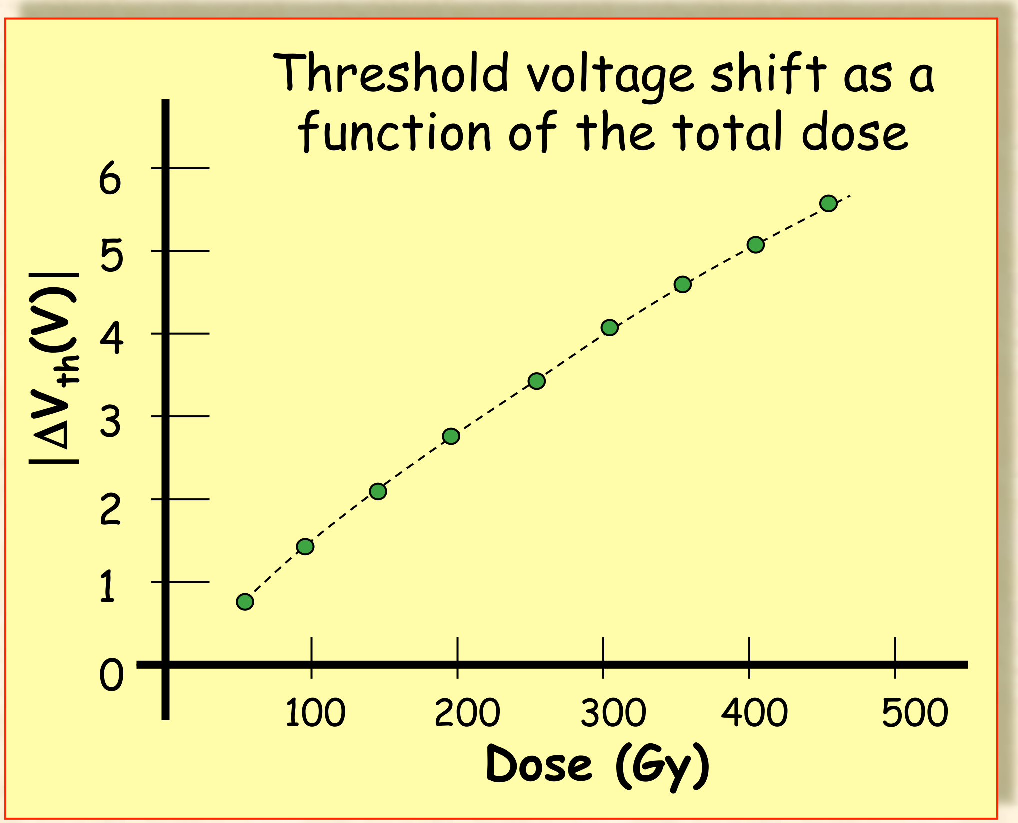
Charge trapping … affects device operation

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



Charge trapped in oxide

Charge (in this case negative) trapped at oxide-Si interface



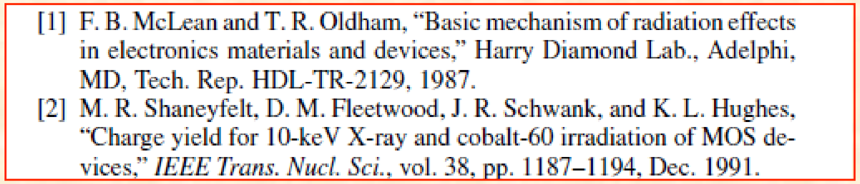
Threshold voltage shift as a function of the total dose

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 source and electric field across oxide (see figure)
3. electron and hole transport: time e ~ in picoseconds, h+ in milliseconds
4. Hole Trapping
5. Interface Trap Formation

How much charge is effectively trapped depends …

- **type of irradiation**
- **E-field**



[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.

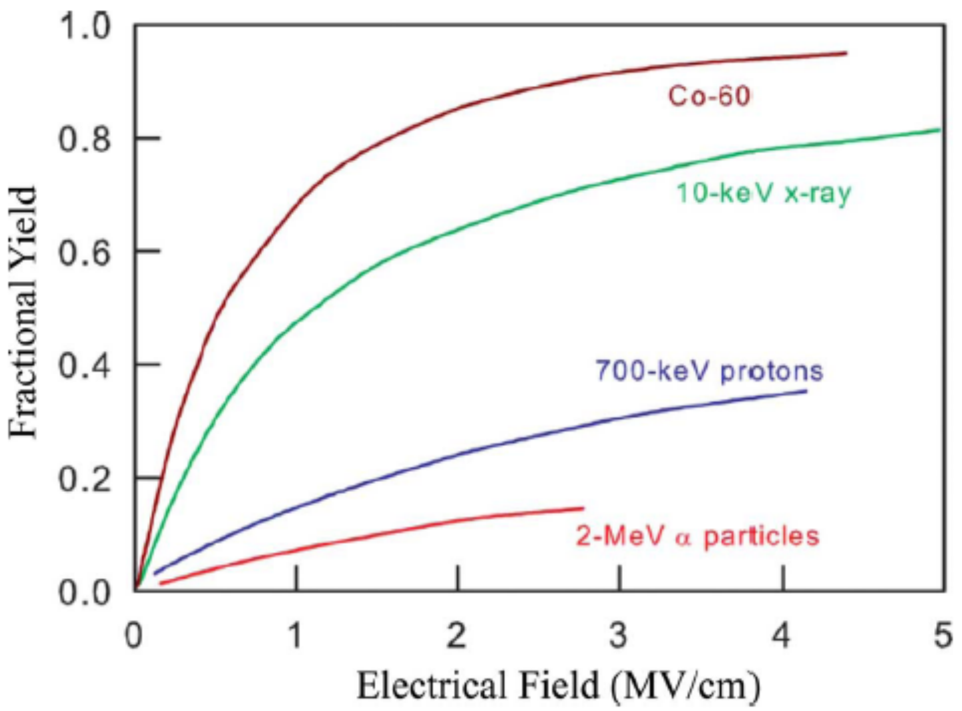
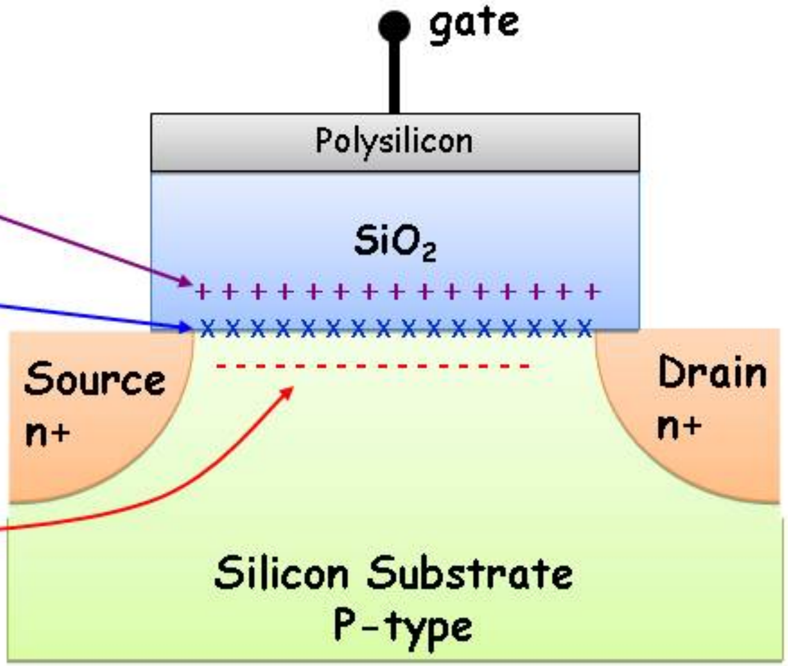


Fig. 1. Fractional yield as a function of the electrical field applied throughout the oxide and for different incident particles [1], [2].

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:

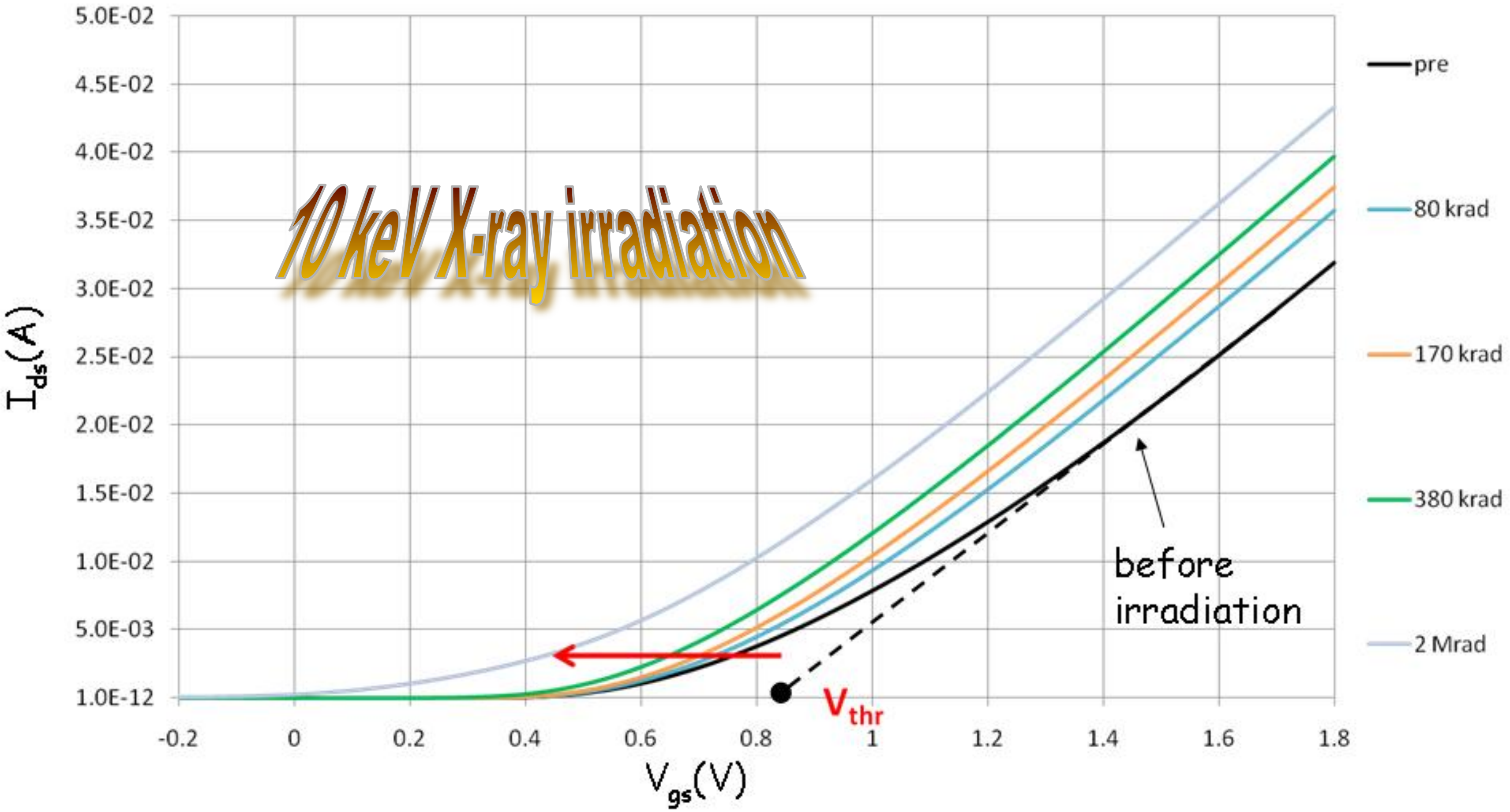
$$\Delta V_{IT} = -\frac{Q_{IT}}{C_{ox}} = \pm\frac{q \cdot N_{IT}}{C_{ox}}$$

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

EFFECTS of TID in MOS devices:

☐ Parasitic leakage current paths
☐ Mobility degradation
☐ Threshold voltage shift

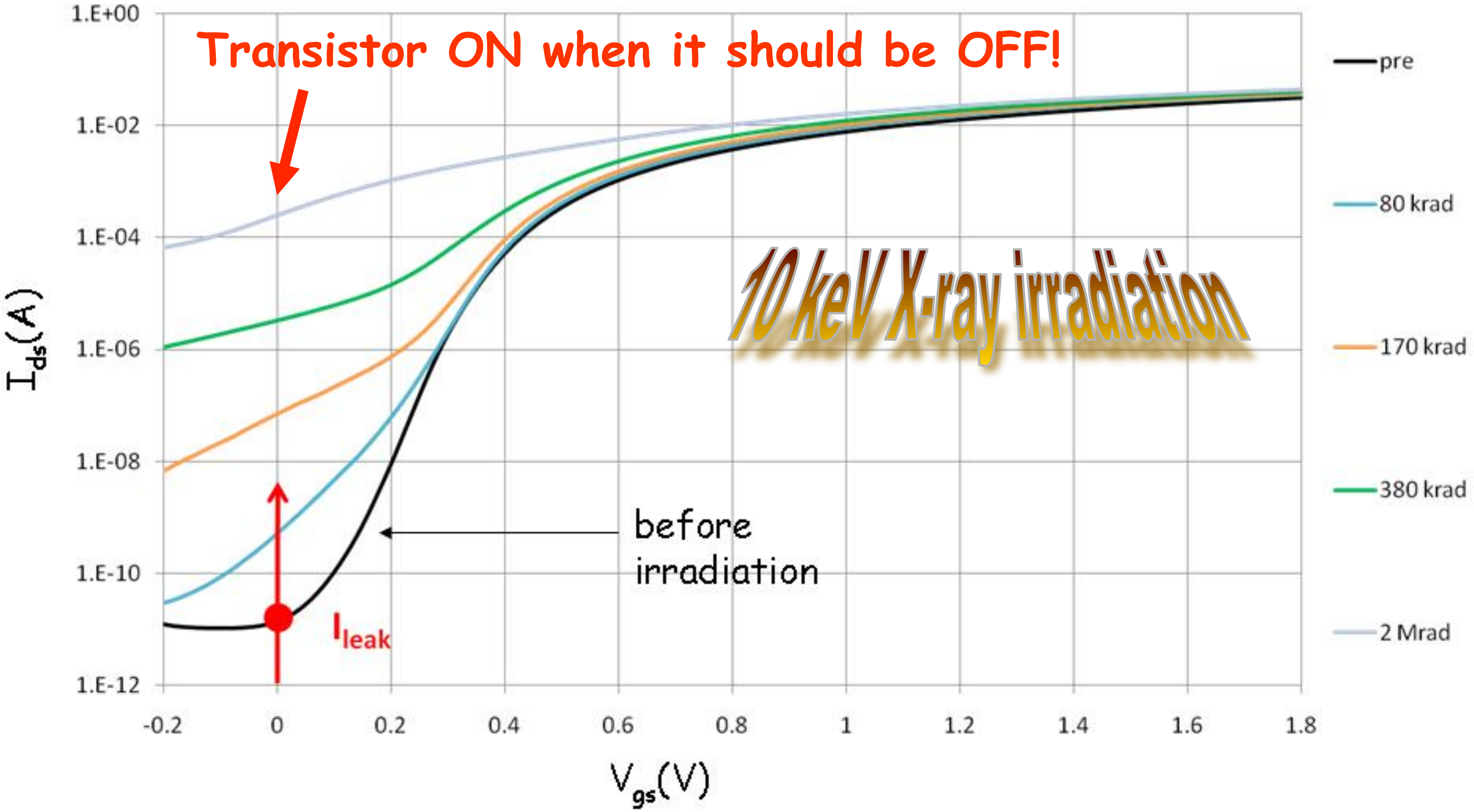
IV Characteristics
current drain-source I_{ds} vs voltage gate-source V_{gs}



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

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

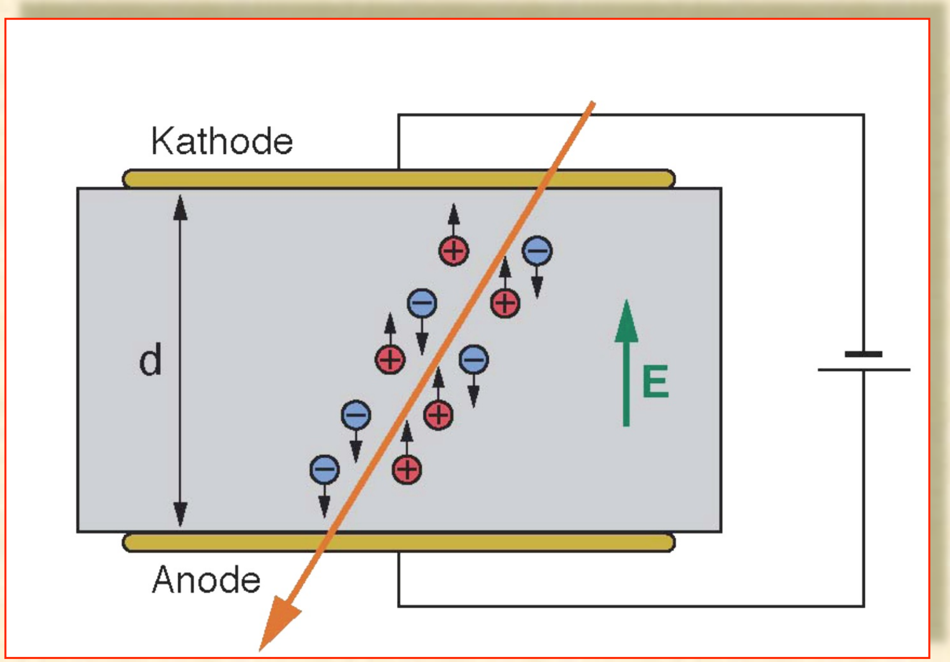
DDD effects

skip

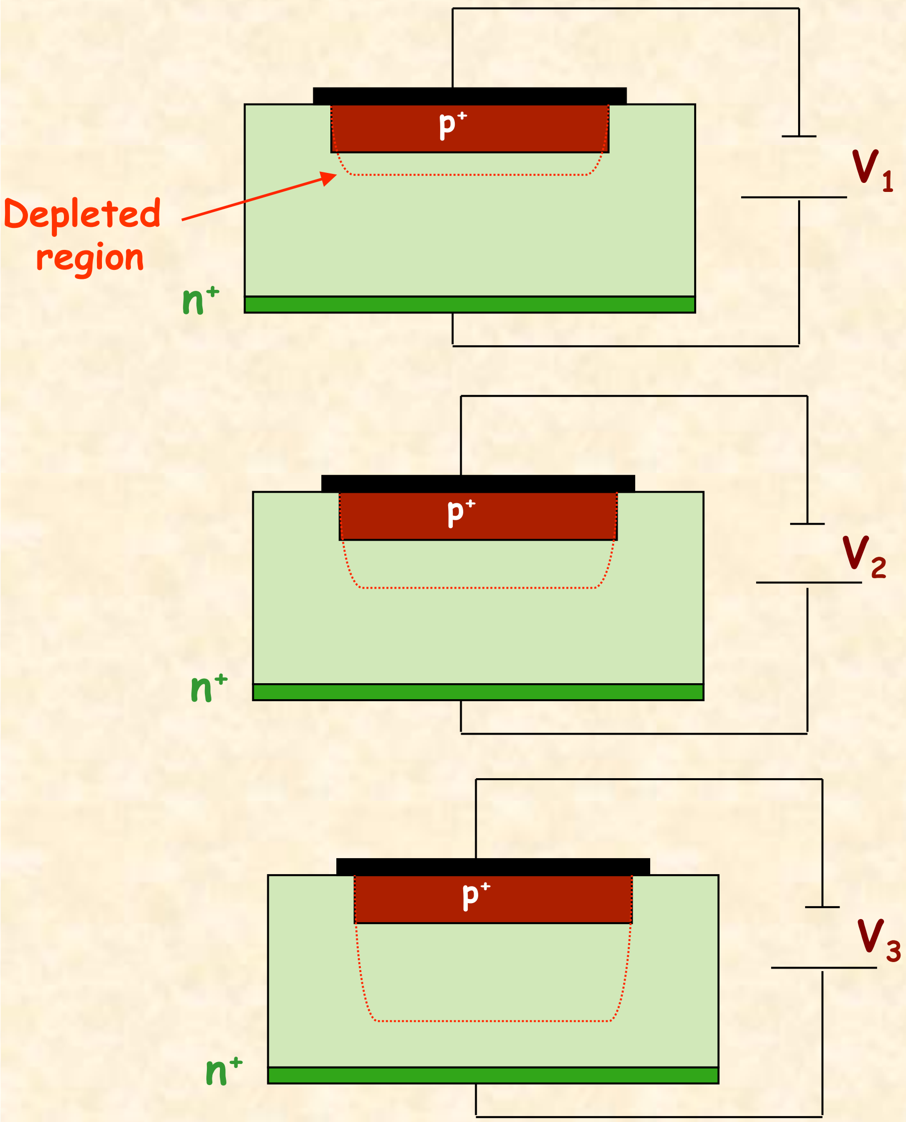
Silicon Detector – how it works

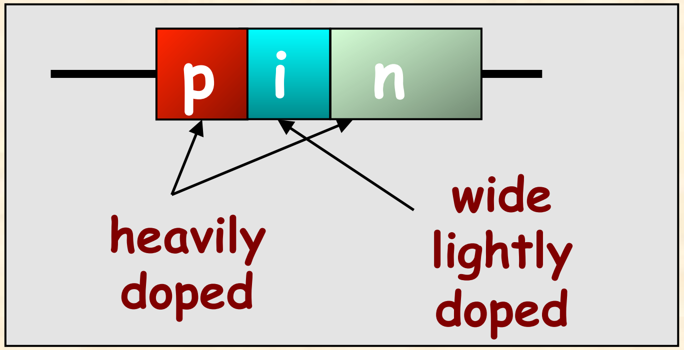
1. Take a piece of high resistivity silicon (not too thick, not to thin, typically about 300 μm)
2. produce two electrodes **(sounds easy. Its not!)**
3. Apply a voltage in order to create an internal electric field of some hundreds of volts across the device
4. charged particles crossing device will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

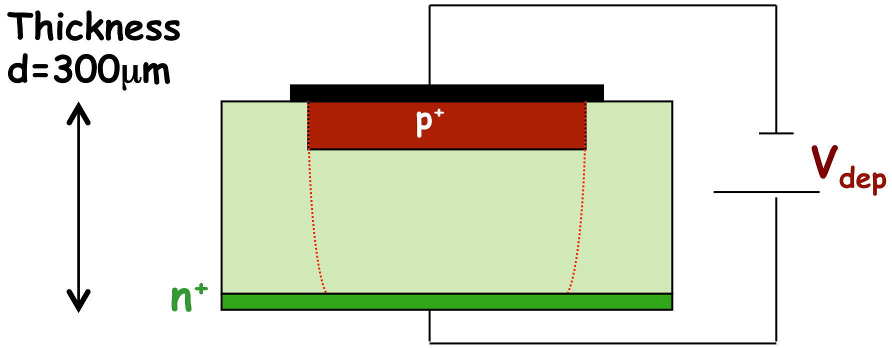




N.B. If the detector is under-depleted:

- 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= <u>300μm thickness</u>

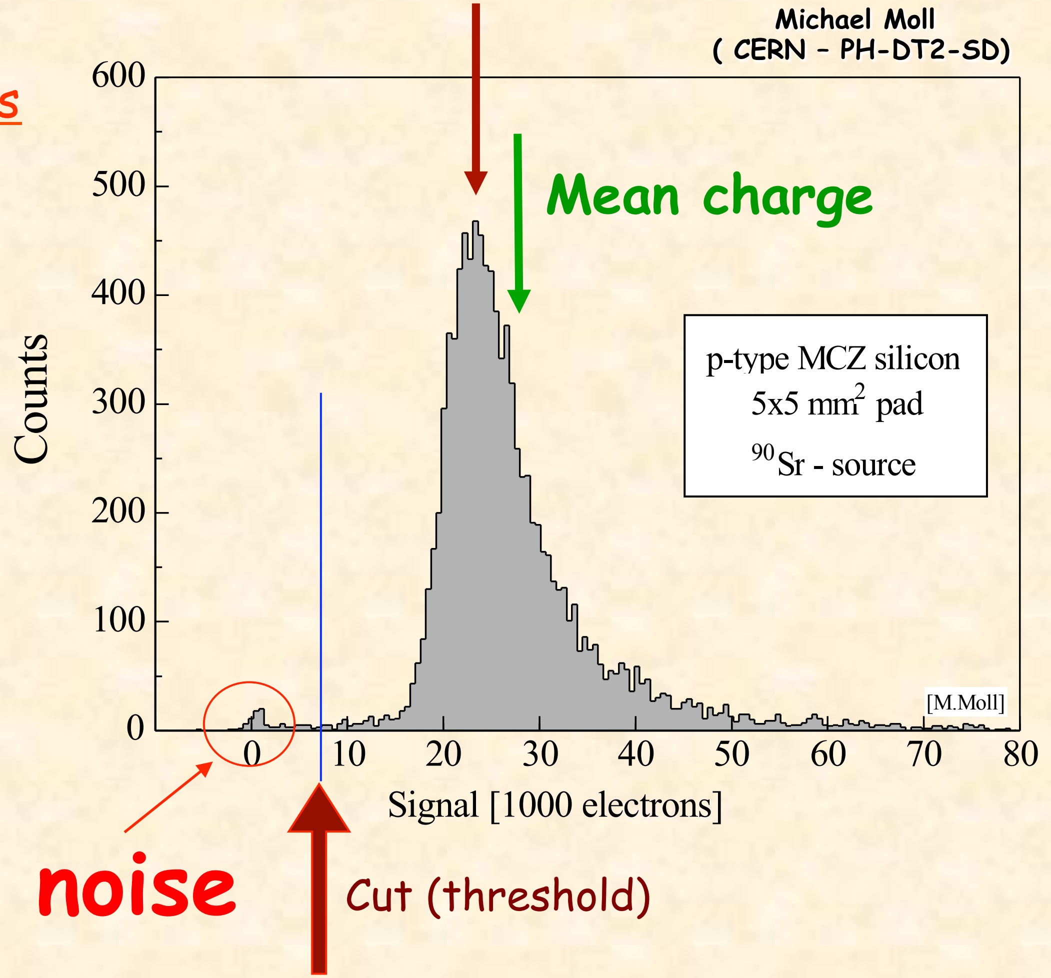
- **Most probable energy loss**
  ≈ 0.7 ×mean
  ⇒ 81 keV

- **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)

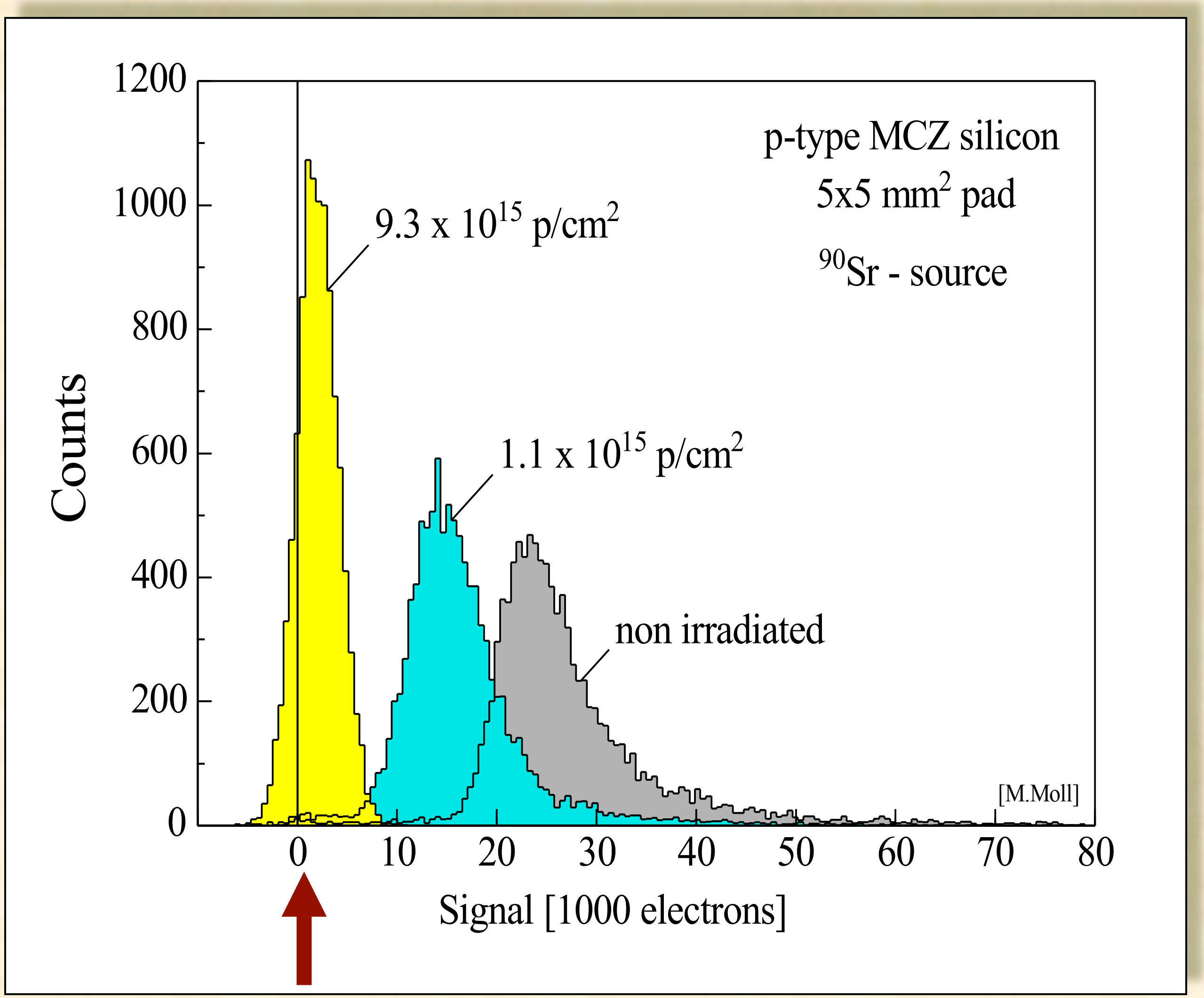
≈ 22500 e ≈ 3.6 fC

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:

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

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

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

Damage parameter

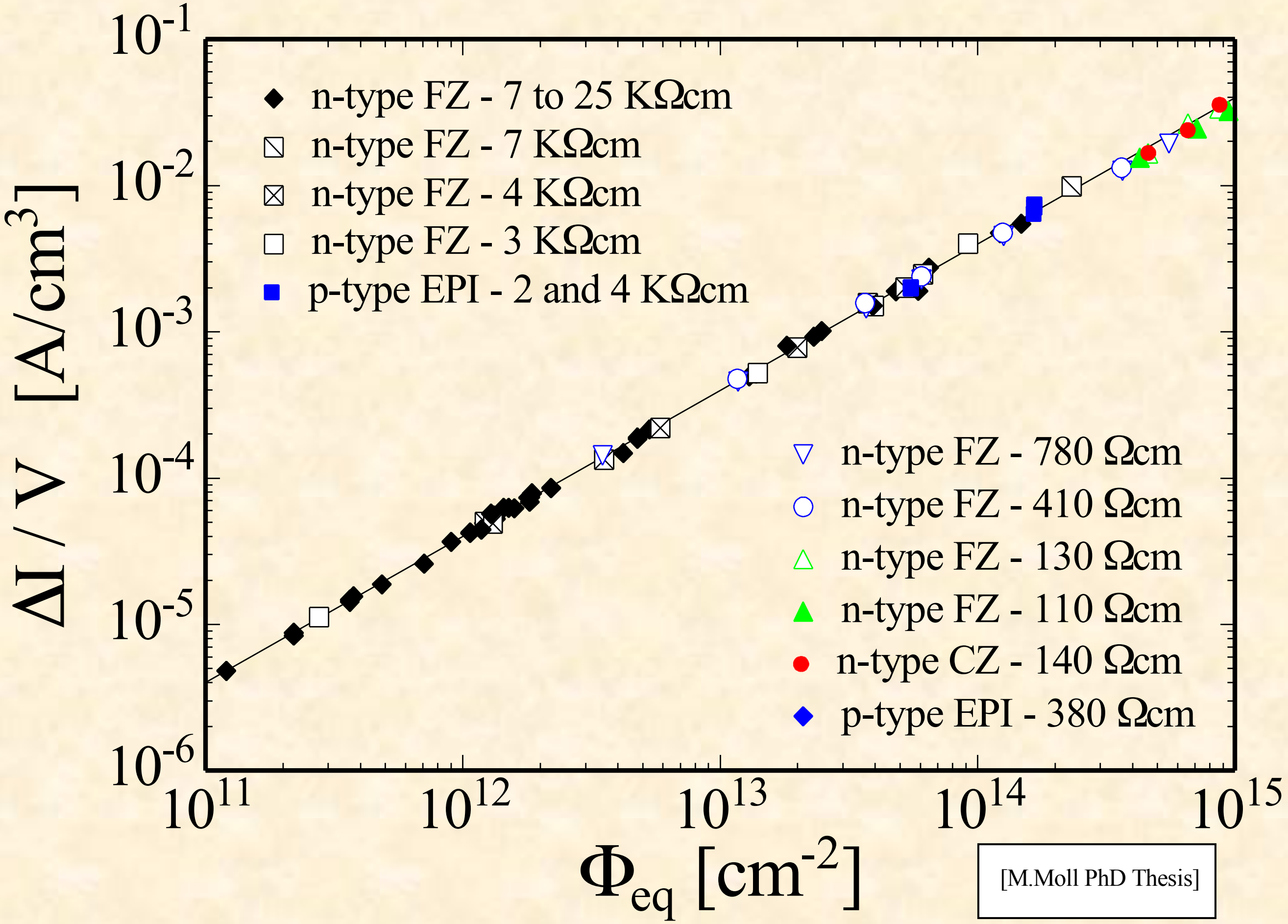
The leakage current per unit volume **grows linearly** with equivalent fluence Φ_{eq}

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

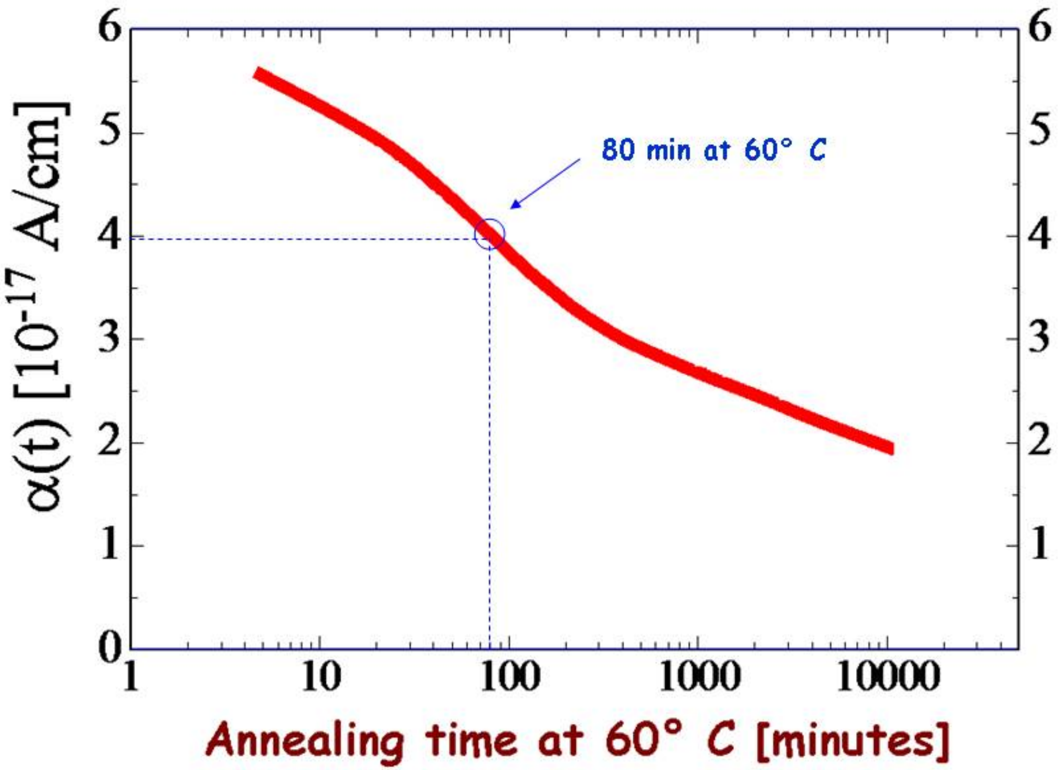


[M.Moll PhD Thesis]

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

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

$$I \propto \exp\left(-\frac{E_g}{2k_BT}\right)$$



Cool idea! Cool detectors during operation!
Example: $I(-10°C) \sim 1/16\ I(20°C)$

- **"Type inversion"** : with increasing 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)

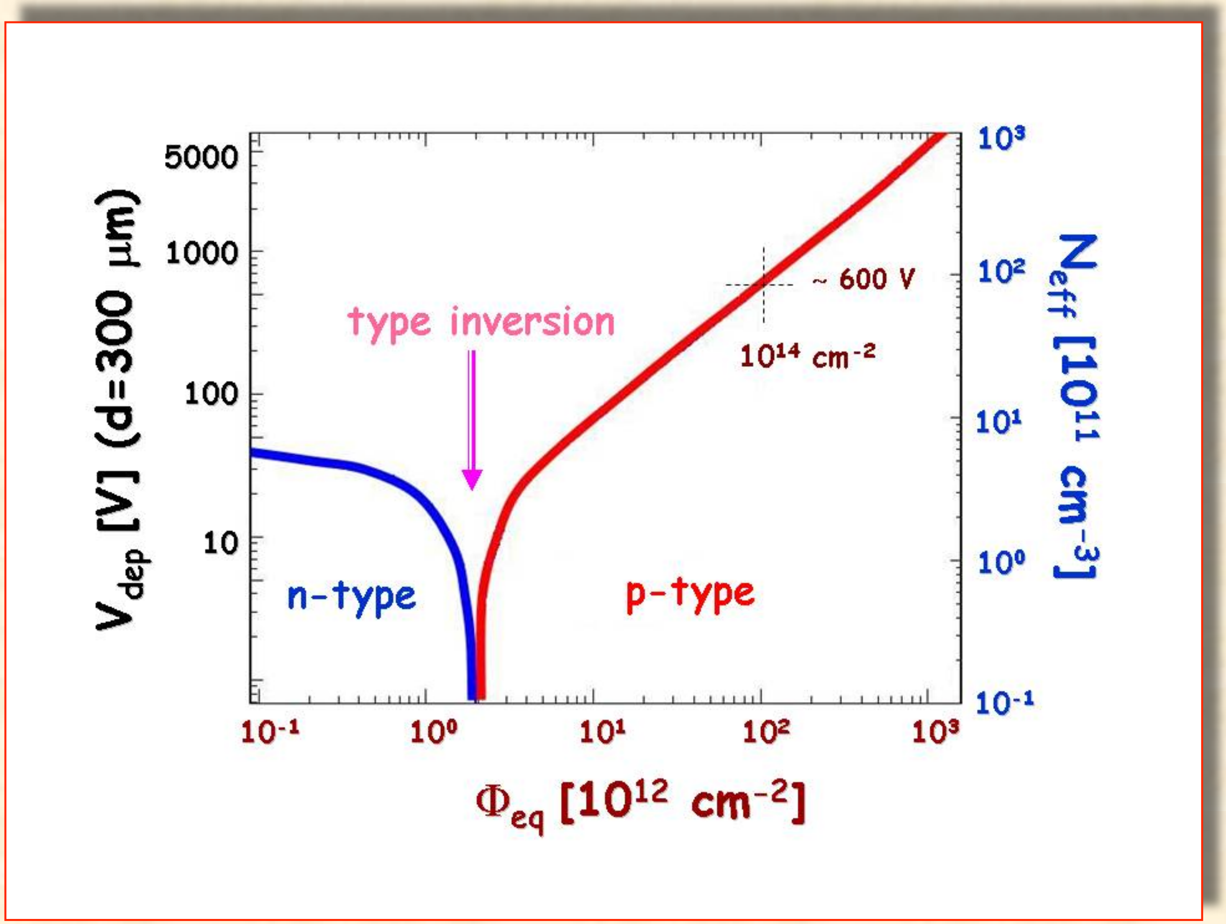
⇒ **increase of depletion voltage**

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

$$\boxed{N_{eff} = \frac{2\varepsilon_0\varepsilon_{Si}V_{dep}}{ed^2}}$$

$d = 300\ \mu m$

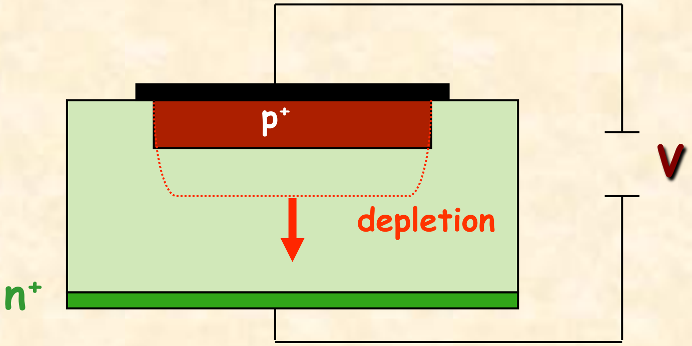
$\varepsilon_{Si} = 11.7$



Depletion Voltage

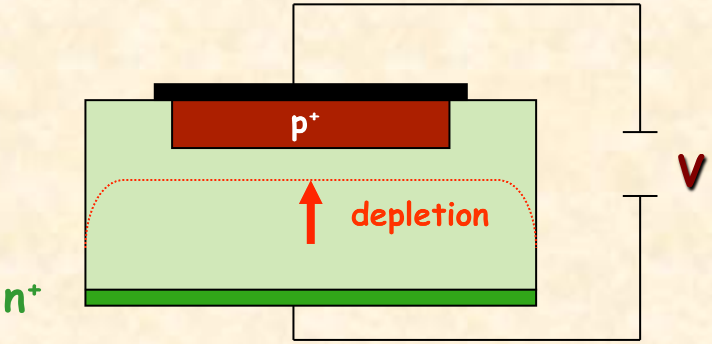
For a non-irradiated diode and before type inversion, the depletion region grows from the p-n junction side; i.e. from the p^+ implant for p-intrinsic-n detectors.

Before type inversion:



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

After type inversion:



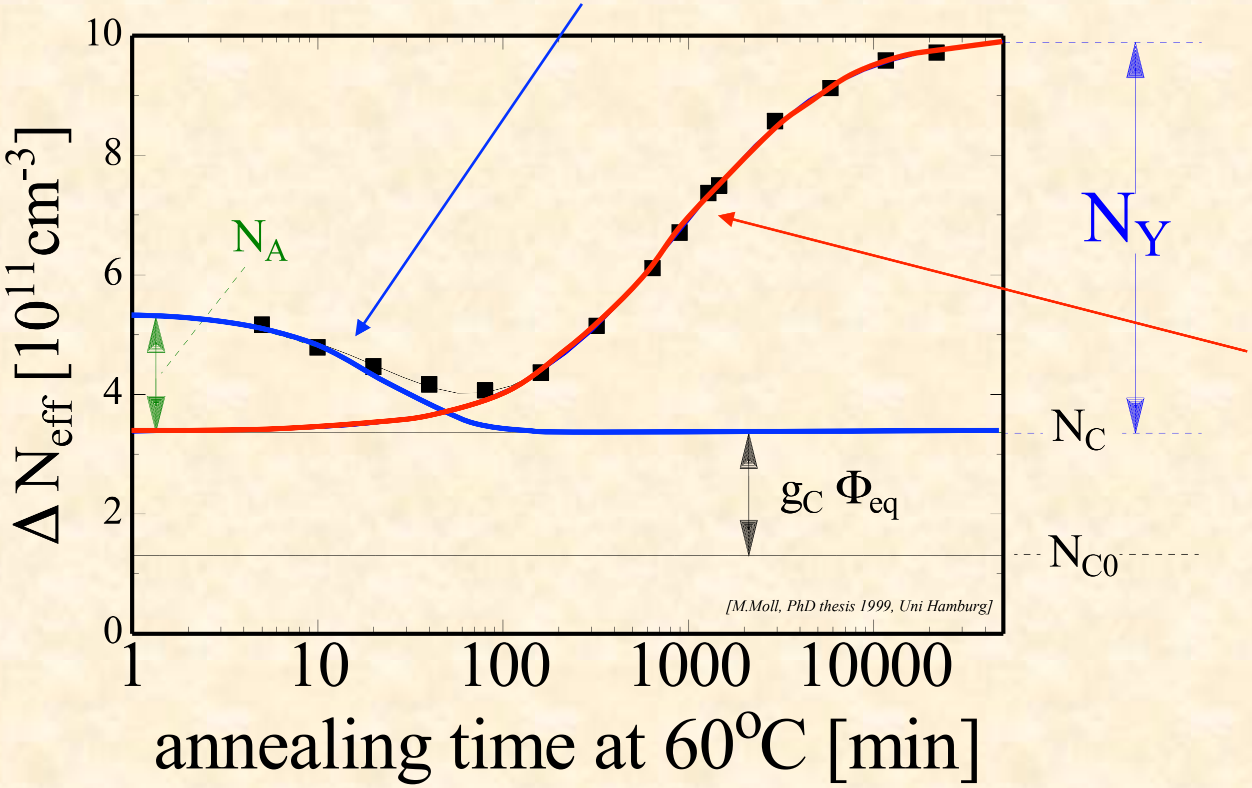
If the detector is under-depleted:

⇒ Charge spread

⇒ Charge loss

Question: What effective doping concentration N_{eff}?

Short term beneficial annealing ☺



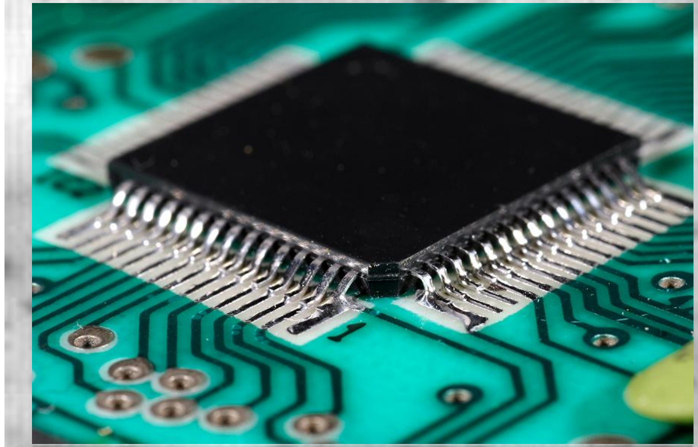
[M.Moll, PhD thesis 1999, Uni Hamburg]

Long term reverse annealing, not-beneficial ☹☹

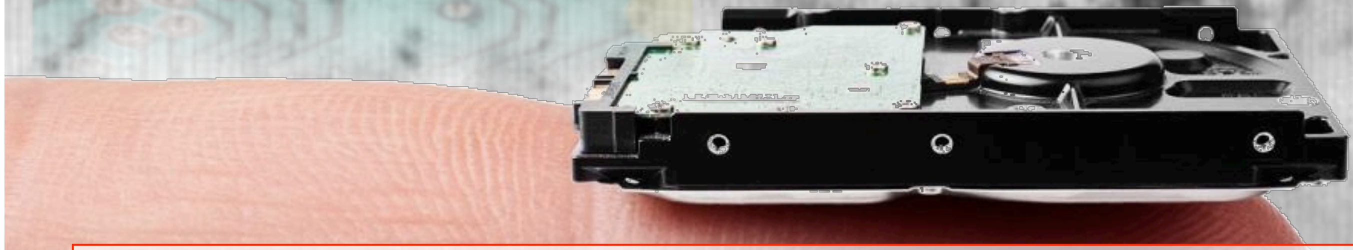
- WARNING: time constant depends on temperature:

~ 500 years (-10°C)
~ 500 days (20°C)
~ 21 hours (60°C)

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



SEE effects

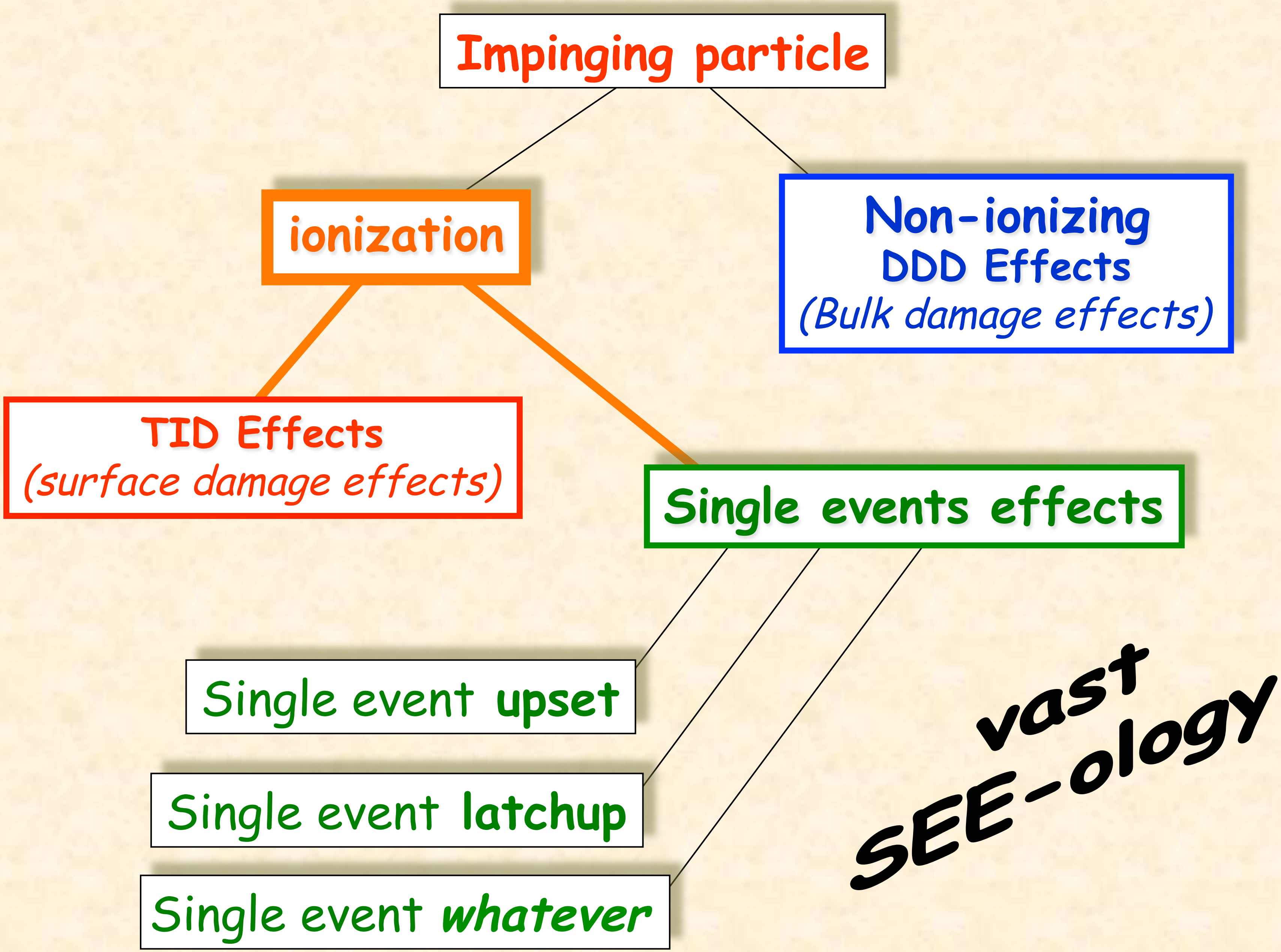


"Single Event Effects" (SEE) are becoming more and more important!

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,…)

Radiation Damage on Semiconductor Devices



Impinging particle

ionization

Non-ionizing
DDD Effects
(Bulk damage effects)

TID Effects
(surface damage effects)

Single events effects

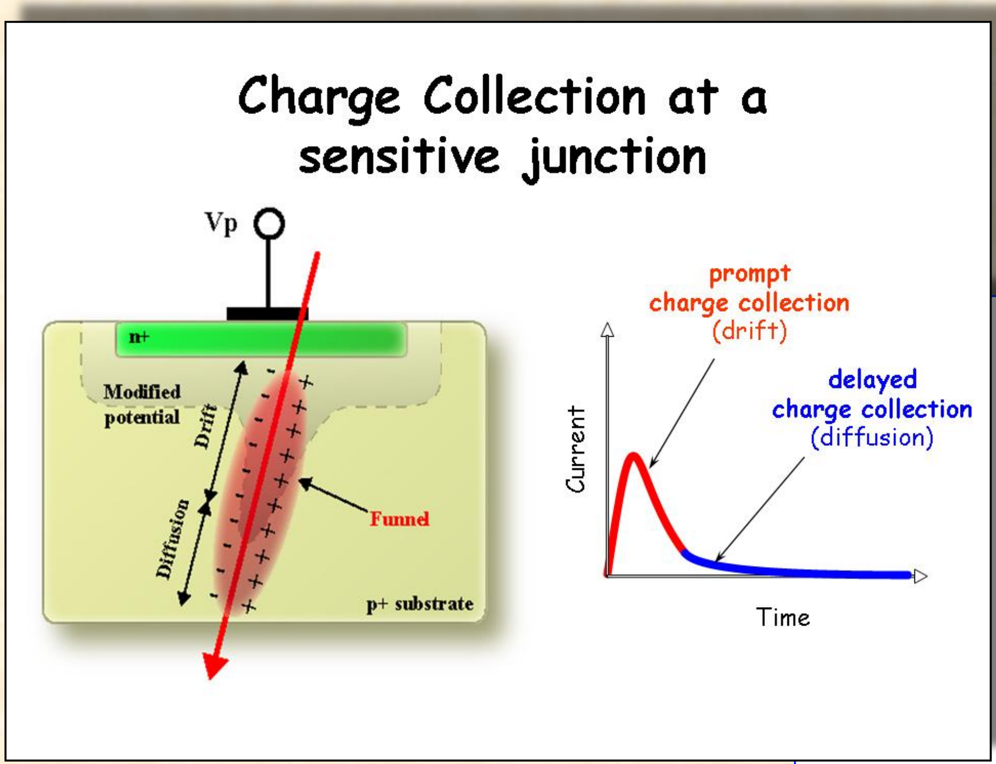
Single event **upset**

Single event **latchup**

Single event ***whatever***

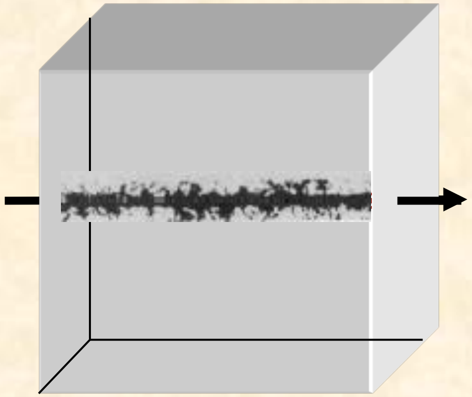
vast
SEE-ology

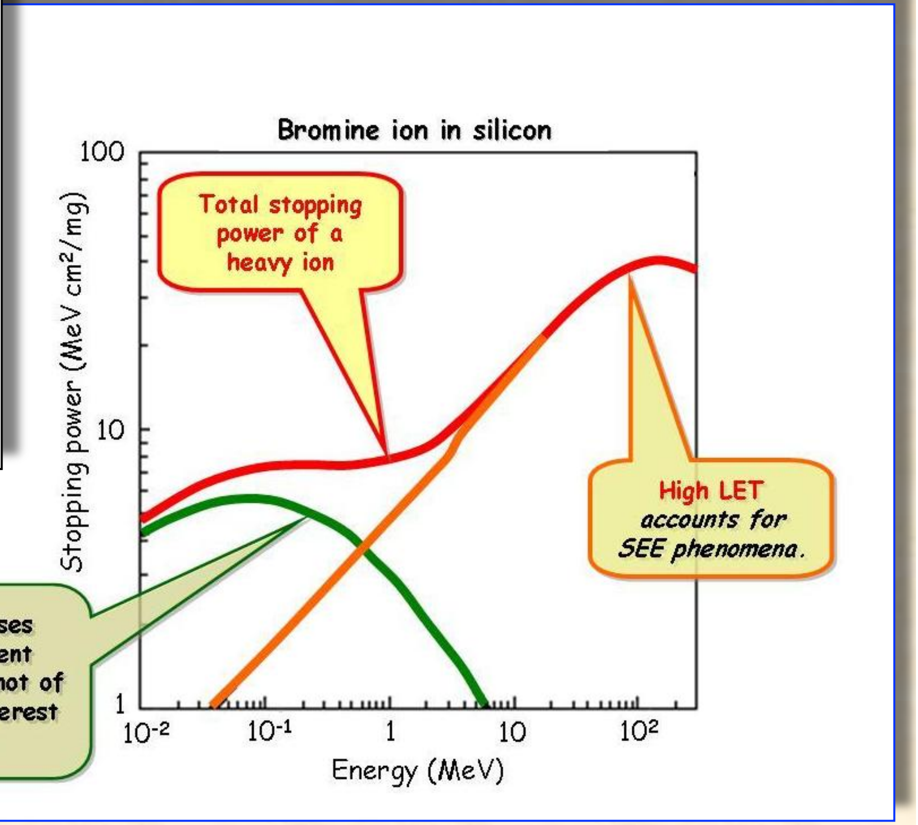
When an heavily ionizing particle (e.g. a heavy ion) interacts with a device it leaves an ionization trail that perturbs the device.



Charge Collection at a sensitive junction

Ions deposit ionization energy in highly structured pattern

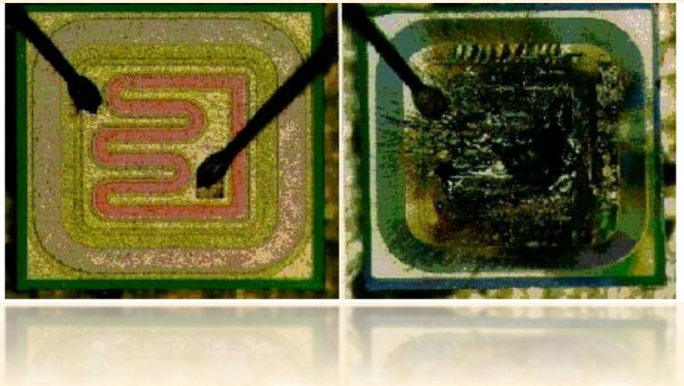


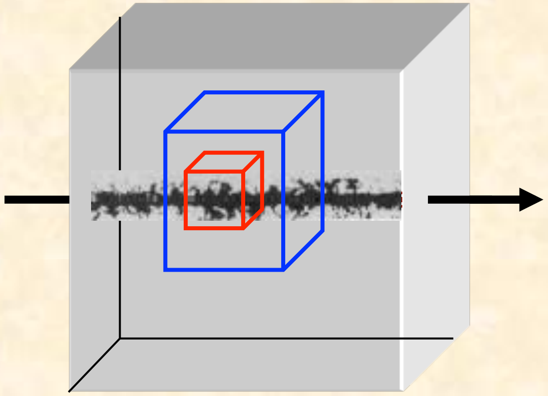


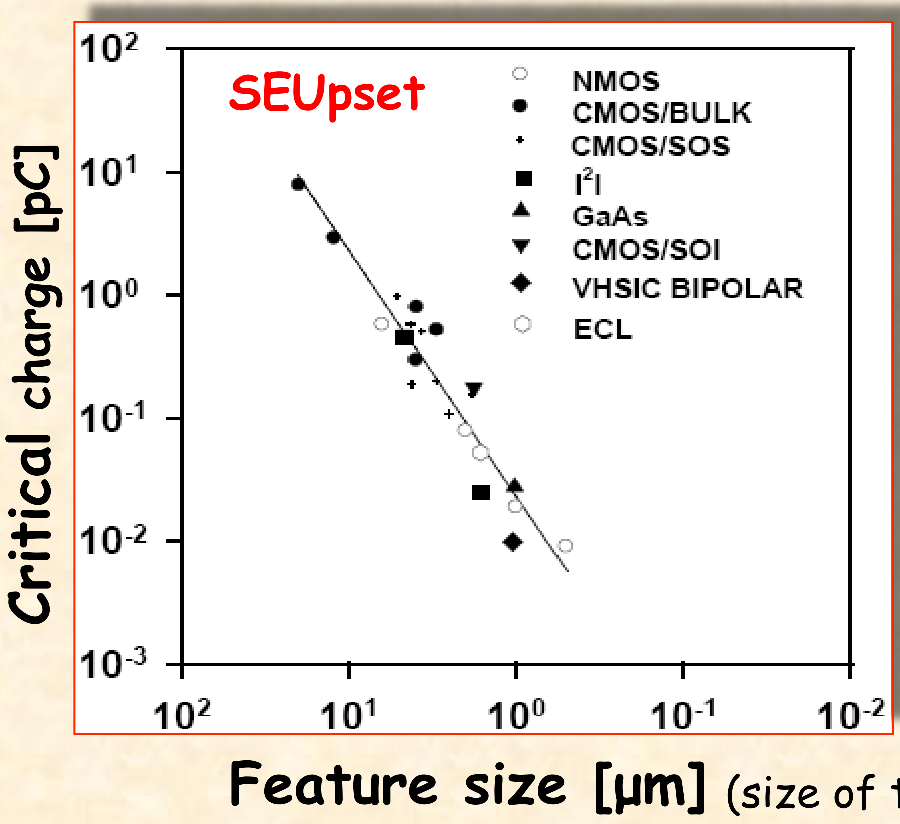
Depending on circumstances the ionization induced perturbation may cause negative effects:

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

etc.







(size of technological process)

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.

Component technology evolution

Parameters affecting SEE:

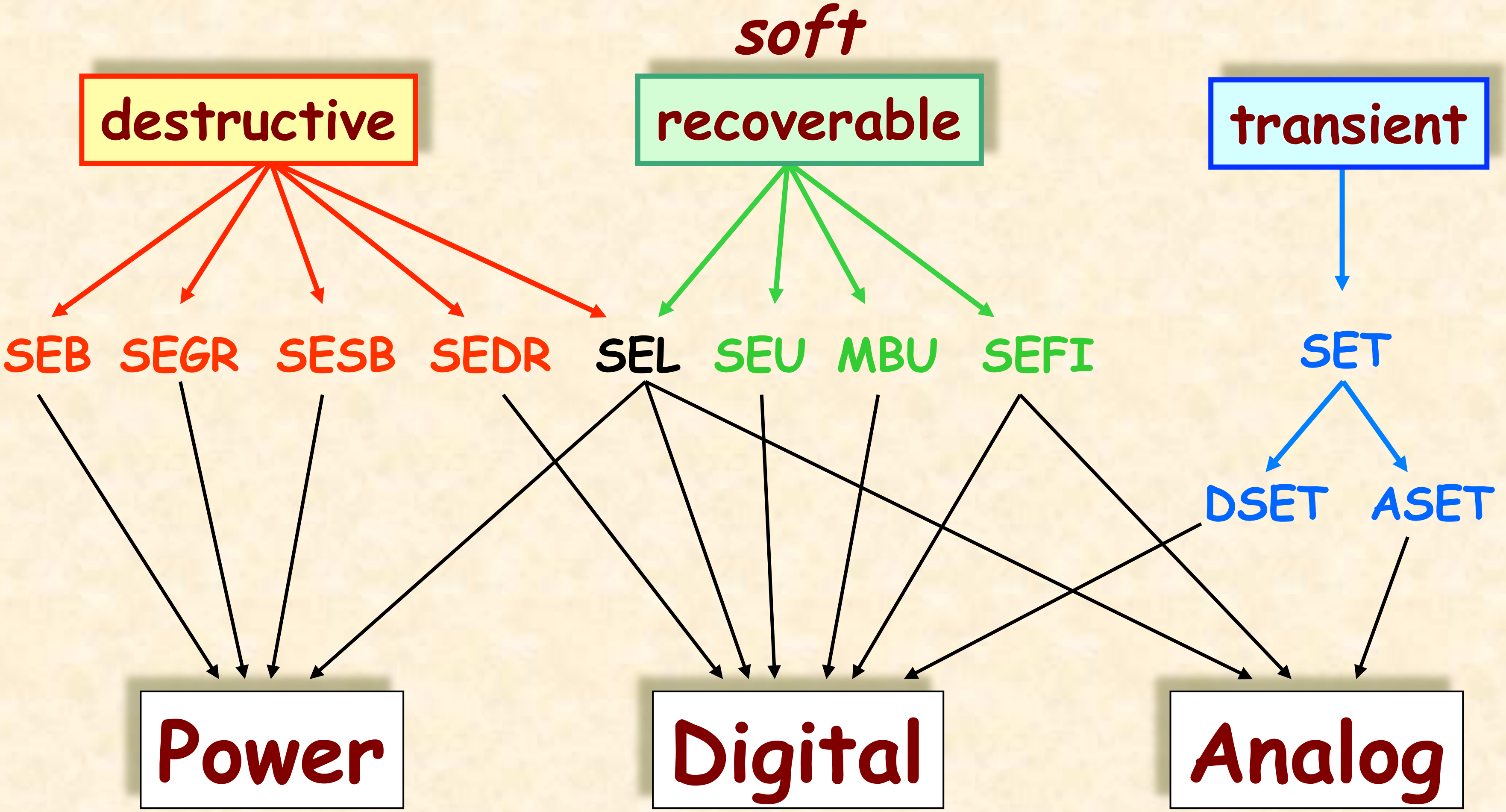
☐ **critical charge** (amount needed to change the logic state of a cell)

☐ **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

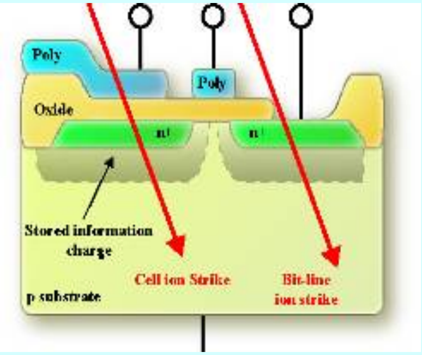
Power

Digital

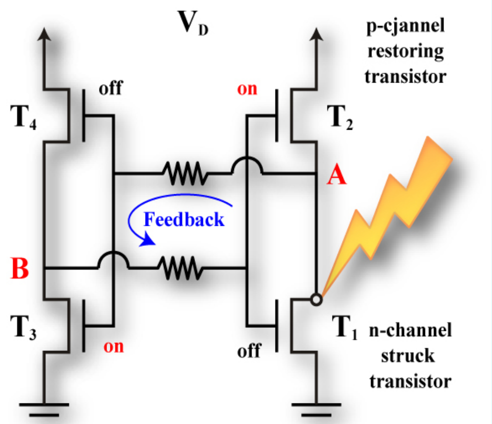
Analog

Soft (non-destructive) vs Hard (destructive)

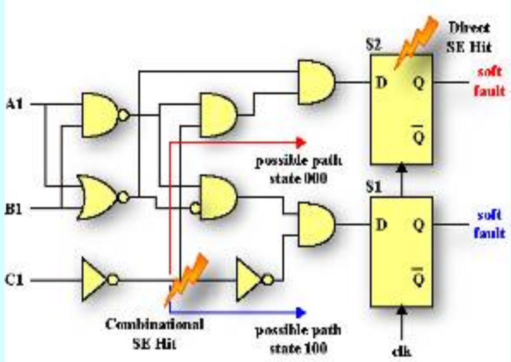
Soft errors



DRAM cell flip

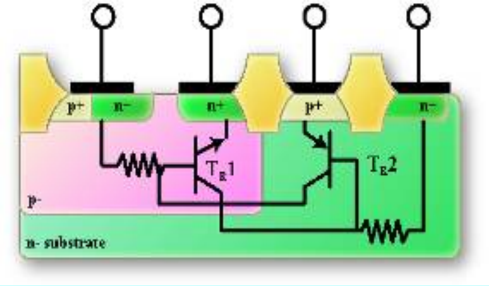


SRAM cell flip

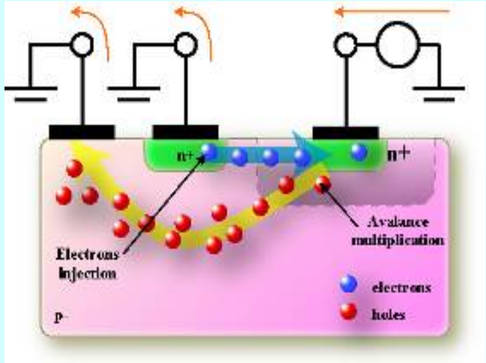


Propagation in logic

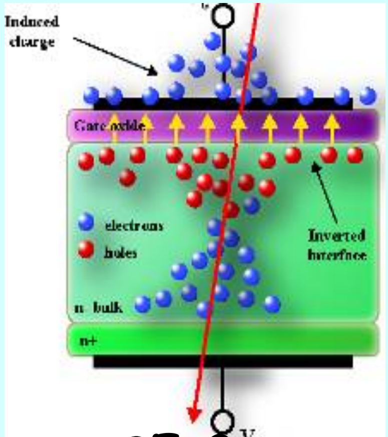
Hard errors



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

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**

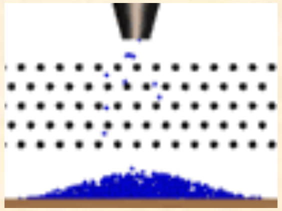
Depends on radiation environment (e.g. orbit), shielding,…

May calculate rate.

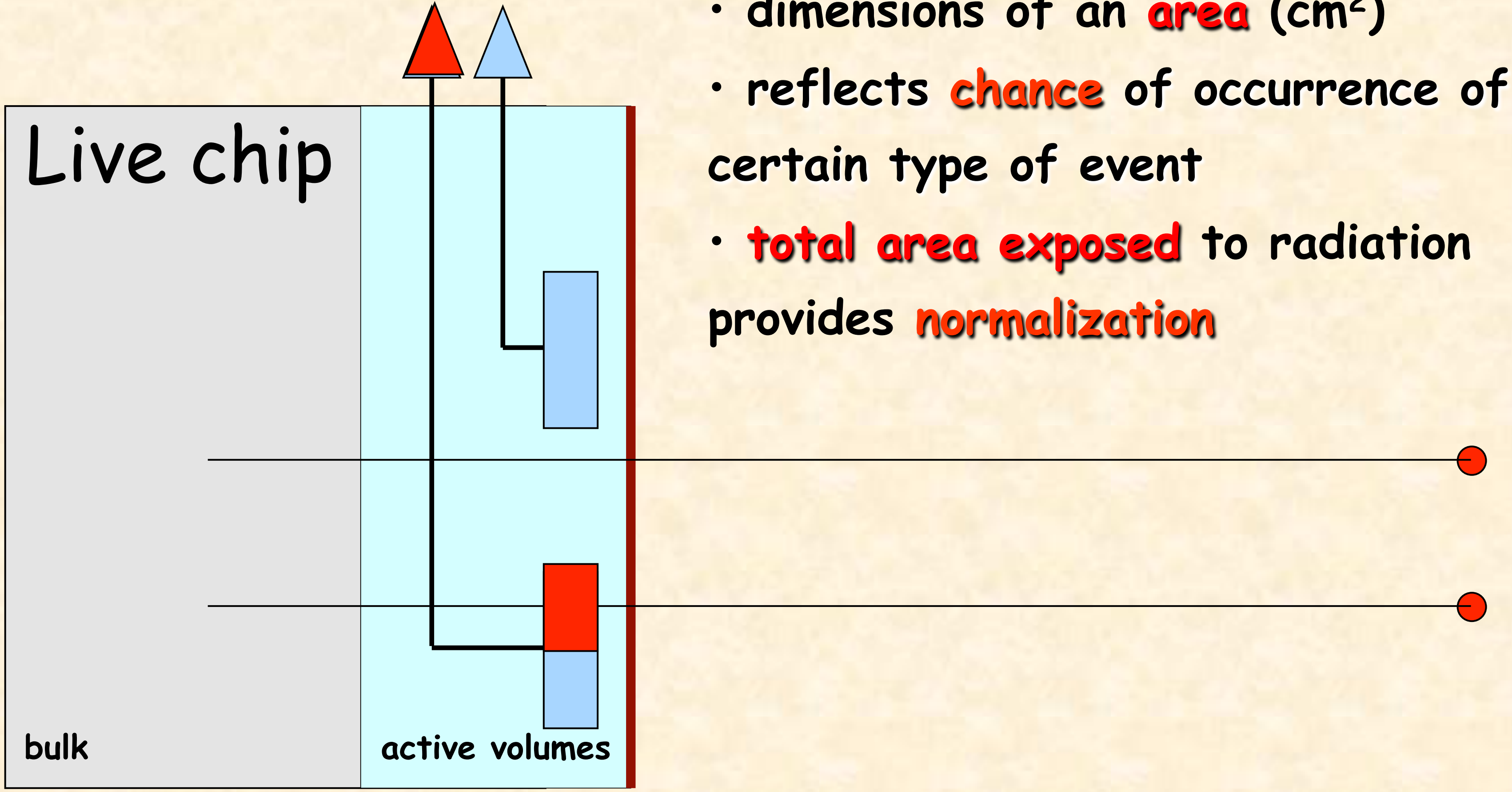
What is a SEE cross-section?

Single Event Effects
The cross-section concept

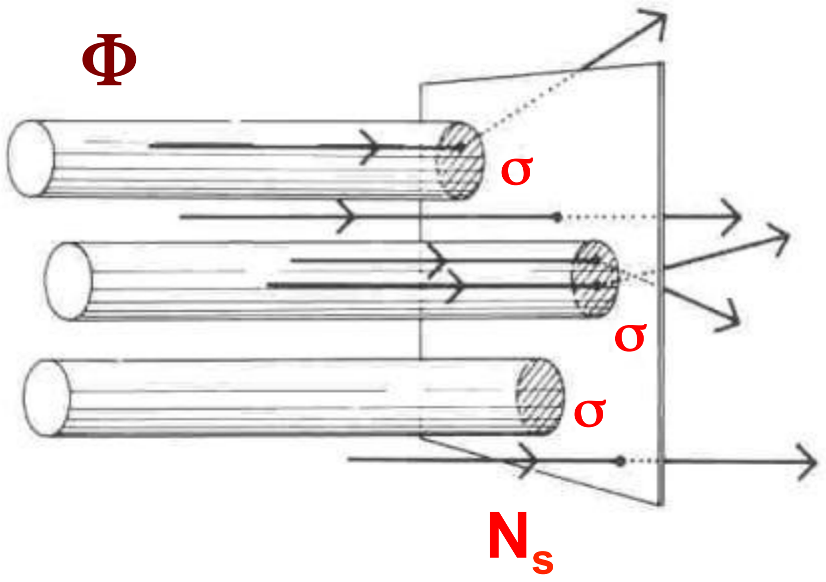
σ



- **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 sections: a simple way to put it



Rationale:

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

fraction of incident particles that INTERACT

=

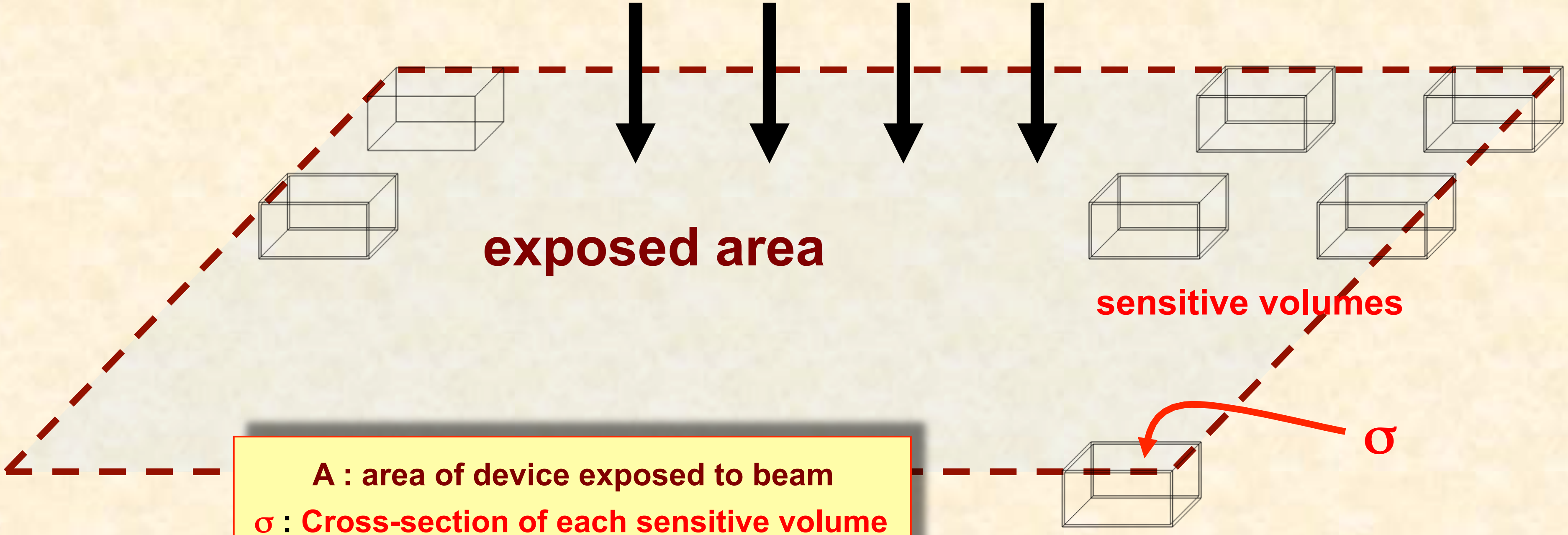
fraction of exposed area that give origin to SCATTERING

$$\frac{n}{N_{inc}} = \frac{N_s \times \sigma}{A} = n_s\ \sigma$$

area density of scattering centers

cross-section: SEE

SEE experimental cross-section



A : area of device exposed to beam

σ : Cross-section of each sensitive volume

n : number of sensitive volumes in area A

Total sensitive area exposed to beam: σ × n

<u>fraction</u> of incoming particles that cause SEE

=

<u>fraction</u> of exposed area that is sensitive

$$\frac{N_{SEE}}{N_{INC}} = \frac{n \times \sigma}{A}$$

Per sensitive Volume (e.g. per bit)

$$\sigma = \frac{N_{SEE}}{n} \times \frac{A}{N_{INC}} = \frac{N_{SEE}}{n \times \phi_{INC}}$$

$$\left(\sigma_{device} = \frac{N_{SEE}}{\phi_{INC}} \right)$$

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-cm²/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

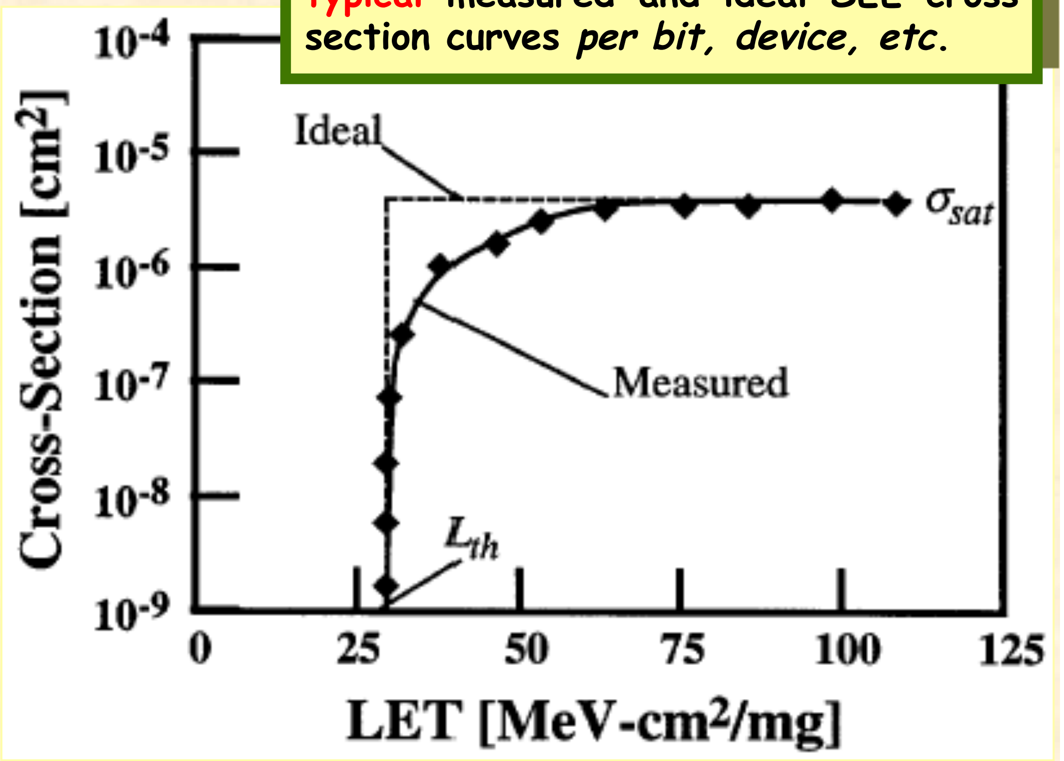
$\sigma = \sigma_{sat} \times \{1-\exp[-(L-L_{th})/W]^{s}\}$

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.*

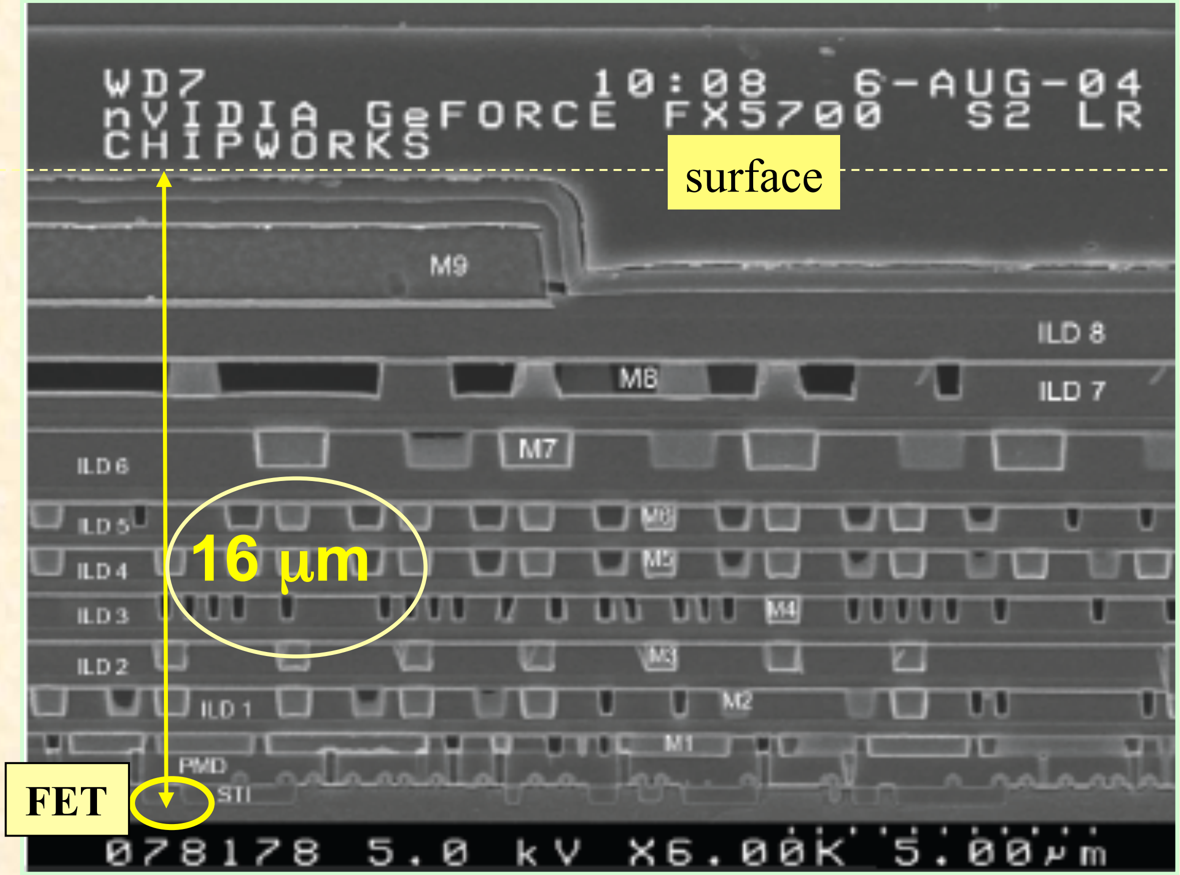


SEE testing

Dead superficial layers are an experimental problem for <u>some types of devices</u>.

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

ection of a chip
ourtesy Doyle)



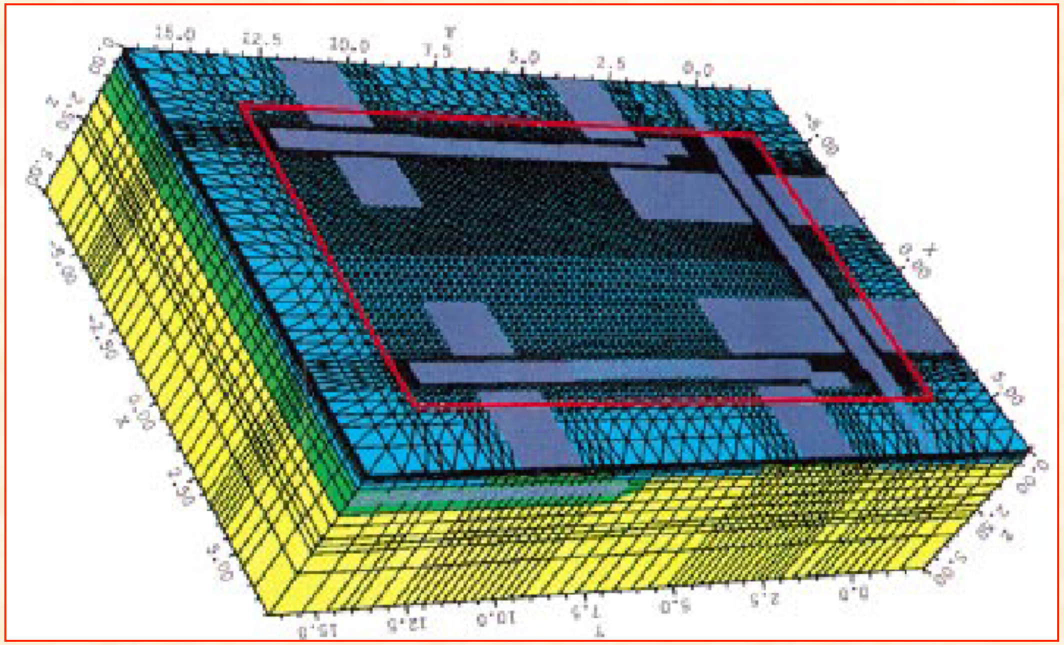
Sensitive volume is down here!

SEE

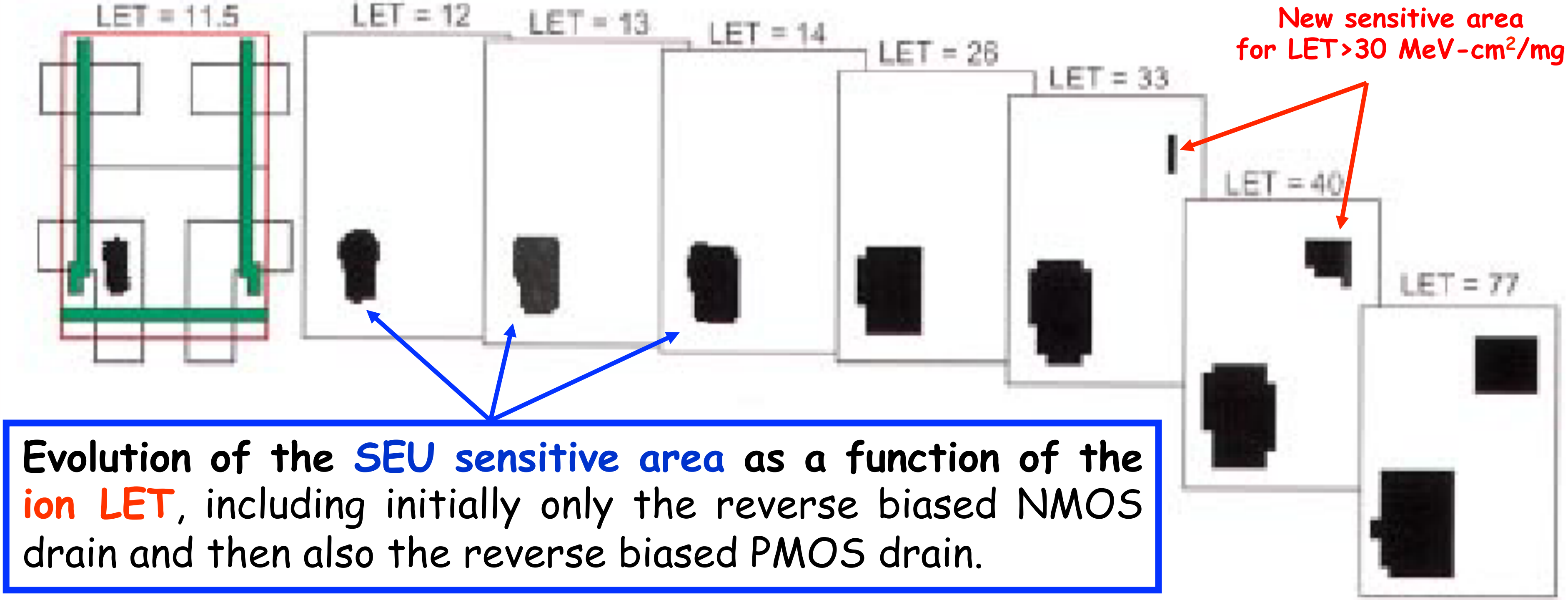
sensitivity micro-map

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.

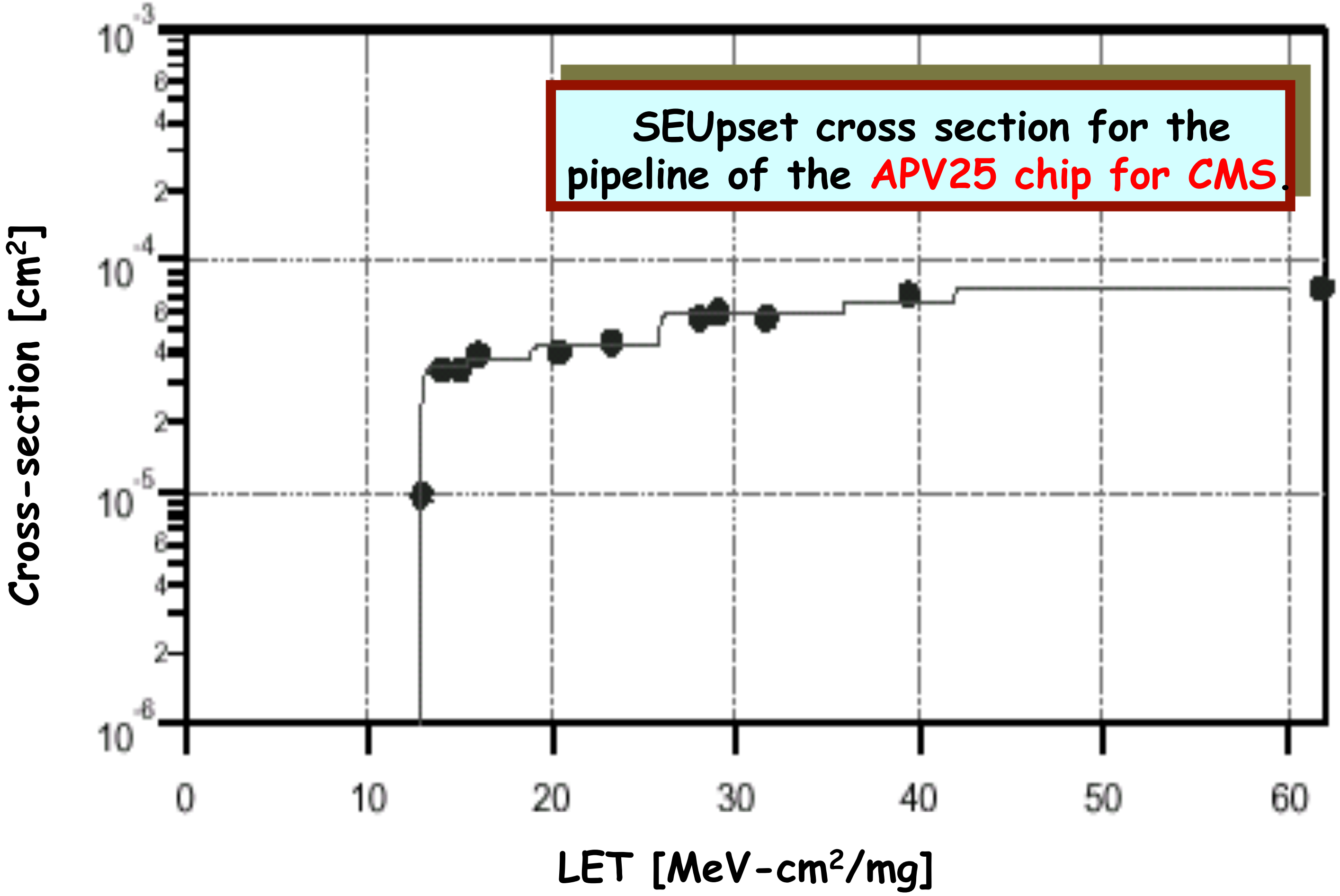


New sensitive area
for LET>30 MeV-cm^2/mg

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.

SEE

SEE effects in an Application Specific-IC used at LHC

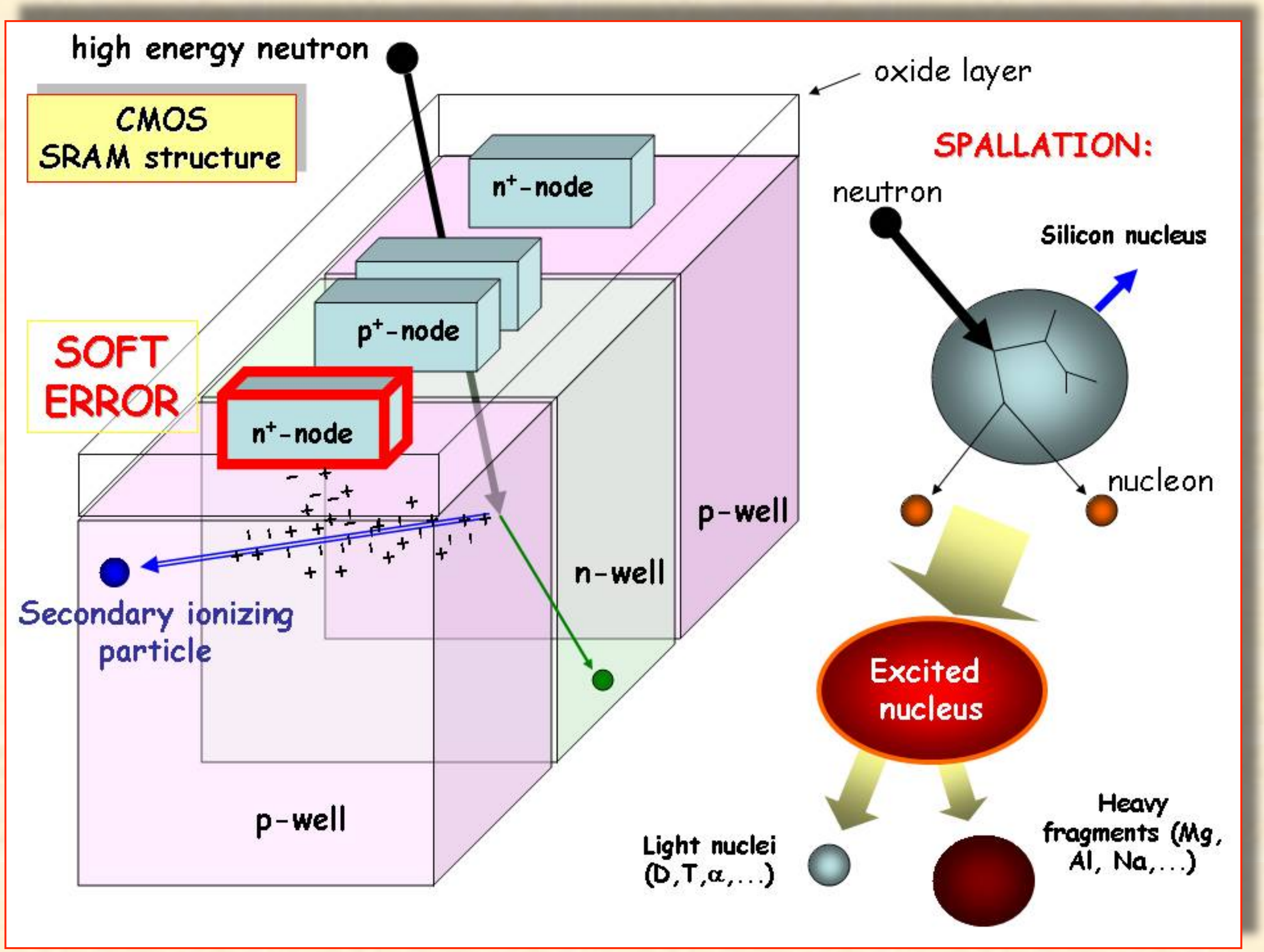


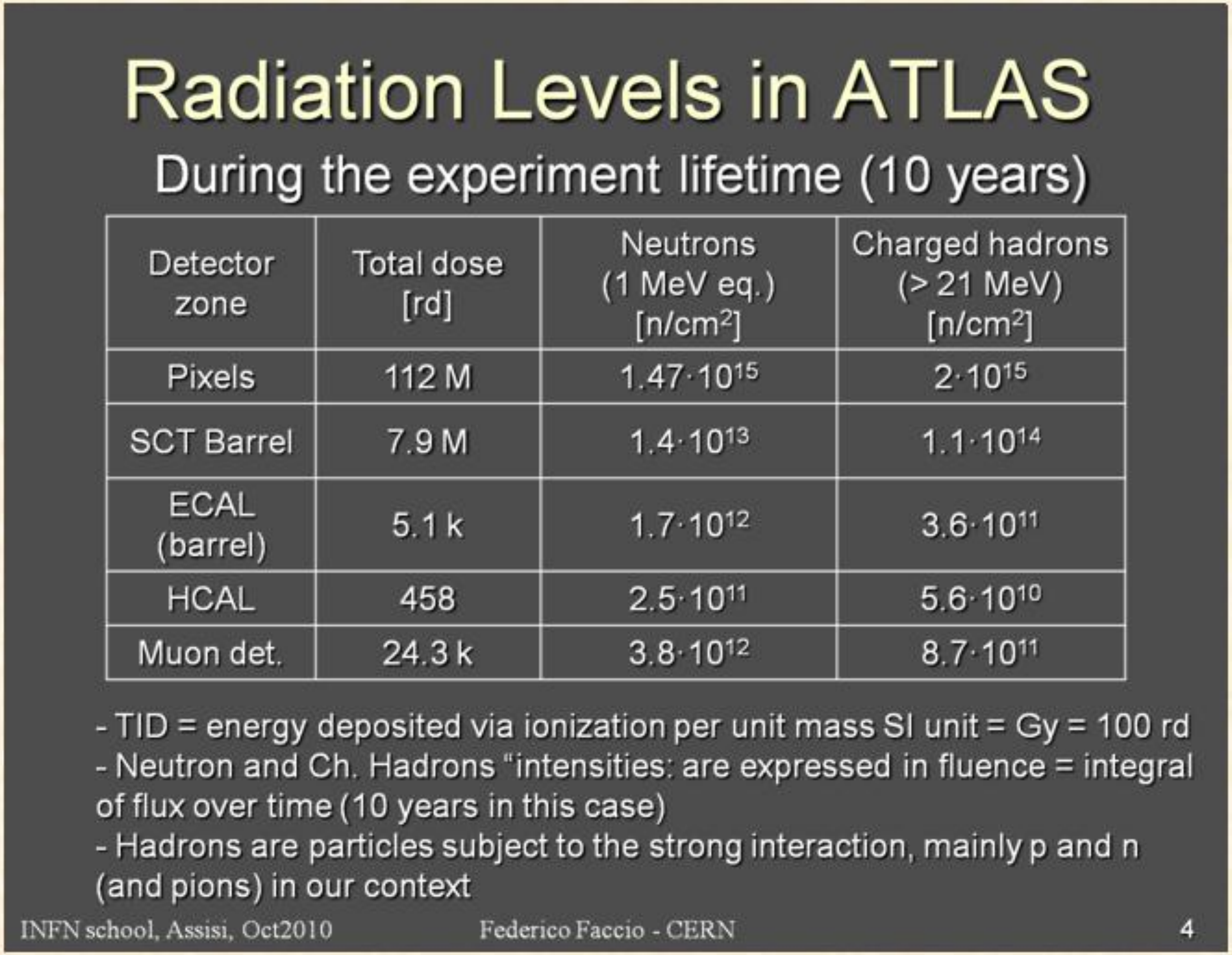
Solid line is a multiple Weibull fit based on simulations, but direct microscopic evidence would be more compelling.

Ions at CMS?
What ions?

Hadrons!
They can induced SEE.

A hadron (neutron, proton, pion,…) can interact with a nucleus to produce a heavily ionizing secondary ion that then causes an anomalous macroscopic effect in an electronic device.





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	$1.47 \cdot 10^{15}$	$2 \cdot 10^{15}$
SCT Barrel	7.9 M	$1.4 \cdot 10^{13}$	$1.1 \cdot 10^{14}$
ECAL (barrel)	5.1 k	$1.7 \cdot 10^{12}$	$3.6 \cdot 10^{11}$
HCAL	458	$2.5 \cdot 10^{11}$	$5.6 \cdot 10^{10}$
Muon det.	24.3 k	$3.8 \cdot 10^{12}$	$8.7 \cdot 10^{11}$

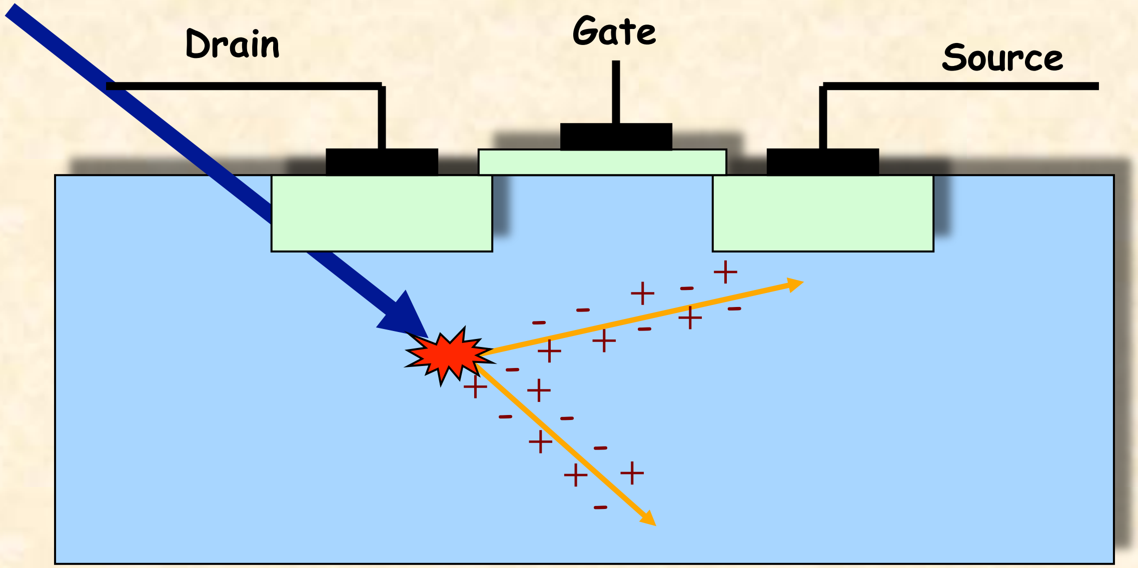
- TID = energy deposited via ionization per unit mass SI unit = Gy = 100 rd
- Neutron and Ch. Hadrons "intensities: are expressed in fluence = integral of flux over time (10 years in this case)
- Hadrons are particles subject to the strong interaction, mainly p and n (and pions) in our context

Physics of **hadron-induced SEE**

Interdisciplinary approach is required to understand SEEs

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

(4) Charge transport in device
(device physics)



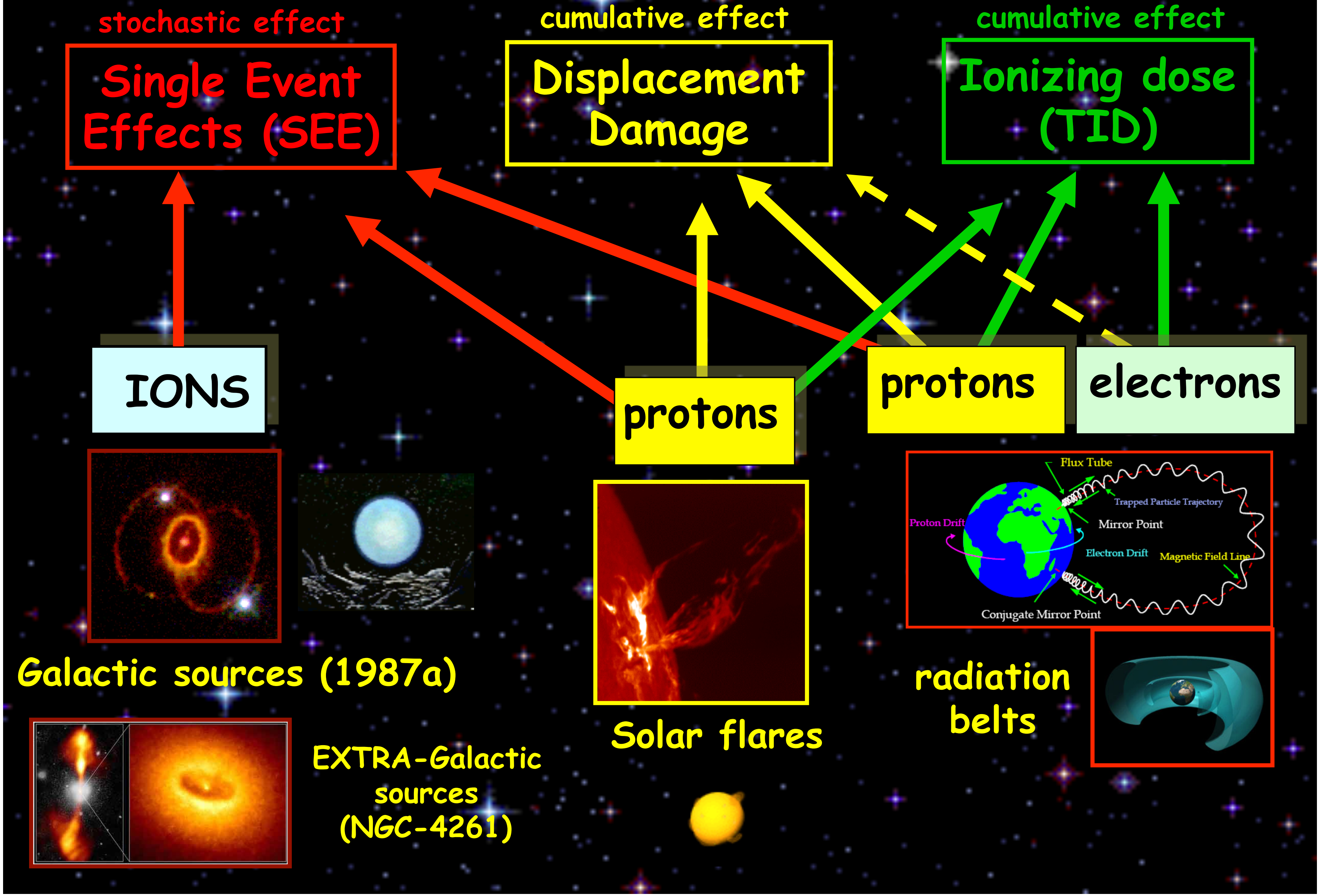
(2) neutron-nucleus reactions
with production of ionizing seondaries (Nuclear Physics)

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

Single Event Effects (SEE)

1. Energetic neutrons and protons may produce secondary highly ionizing ions in nuclear interactions.
2. 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.
3. Neutrons are a problem in avionics and at sea level.
4. 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.

Space Radiation and effects on electronics



stochastic effect

Single Event Effects (SEE)

cumulative effect

Displacement Damage

cumulative effect

Ionizing dose (TID)

IONS

protons

protons

electrons

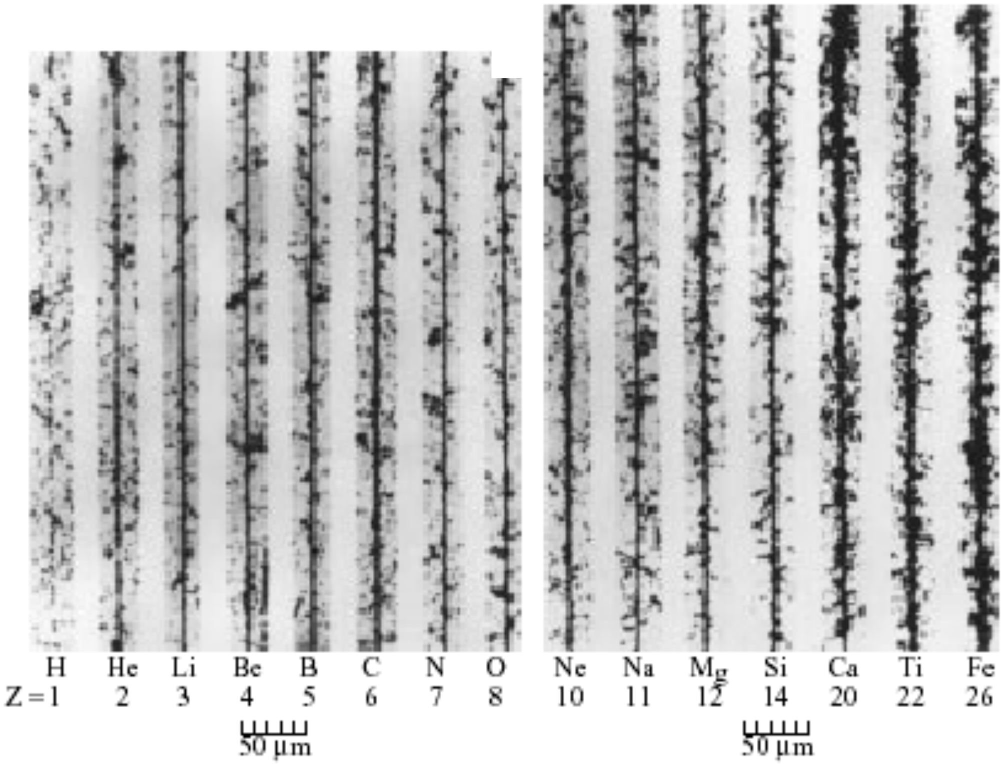
Galactic sources (1987a)

EXTRA-Galactic sources (NGC-4261)

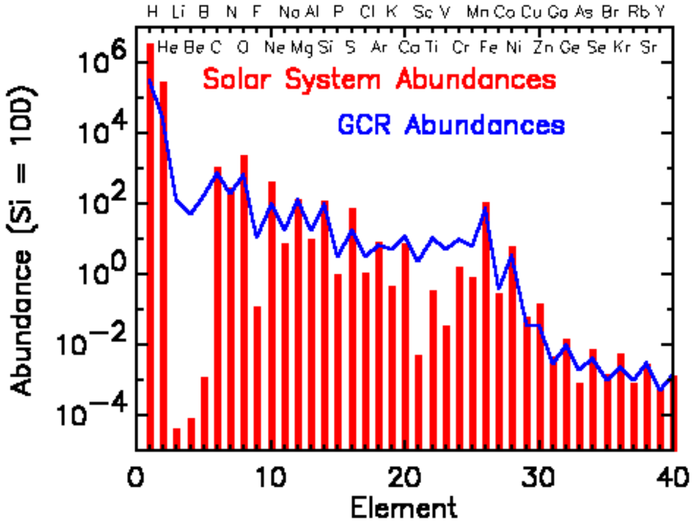
Solar flares

radiation belts

Galactic High Charge and Energy (HZE) ions



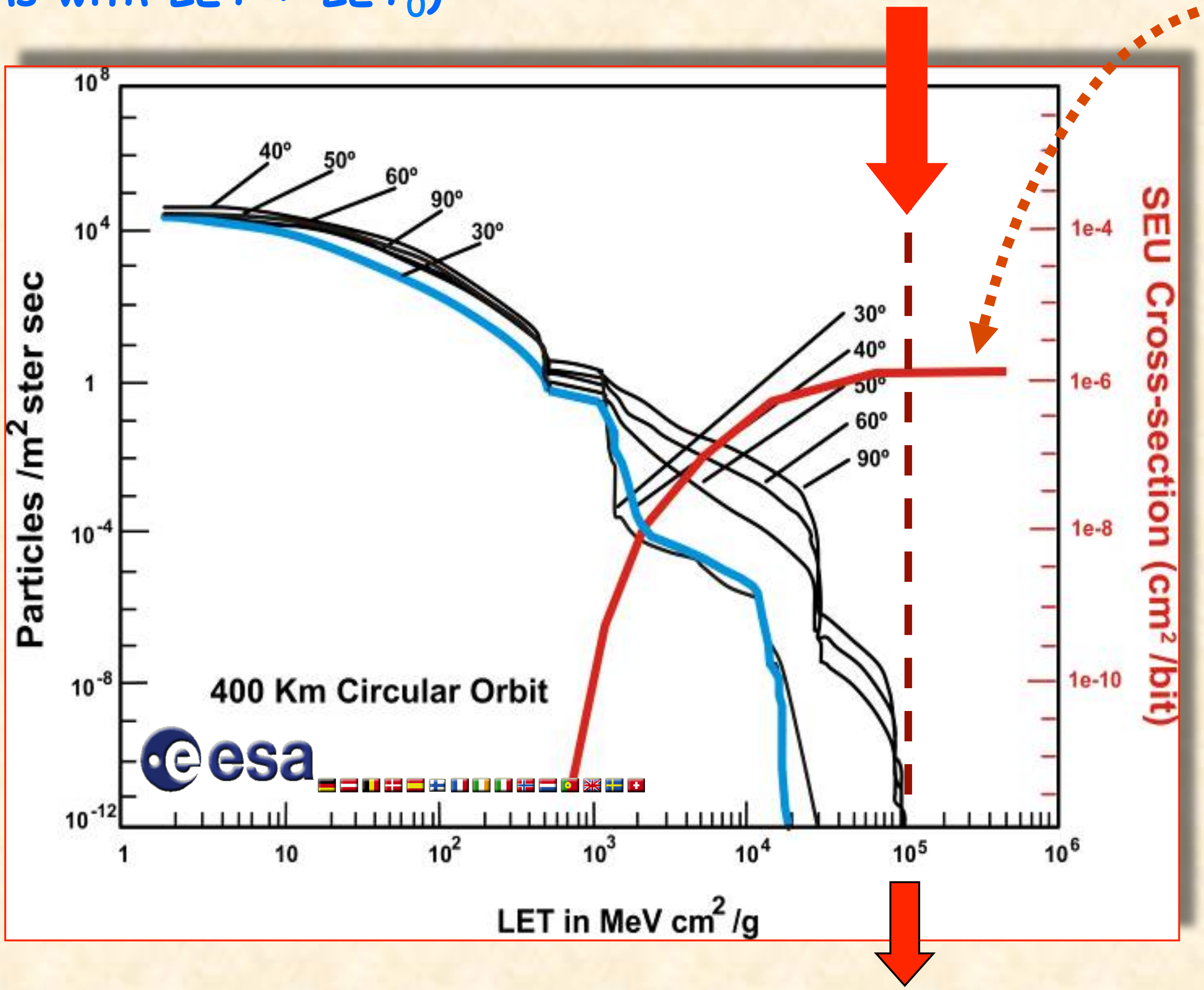
McDonald F. B. (1965). "Review of Galactic and Solar Cosmic Rays", *Second Symposium on Protection Against Radiations in Space* (Reetz A., editor), NASA SP-71: 19-29



HZE are a direct cause of Single Event Effects

SEE cross sections in SPACE

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



100 MeV cm^2/mg

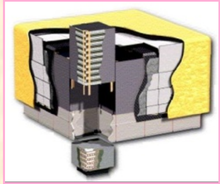
Simulating the radiation environment

- **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

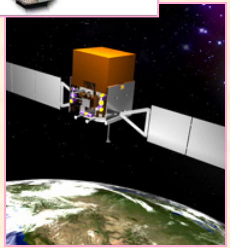
⇒ failure rates of device can be estimated

LET spectra and dose for FERMI *(GLAST)*

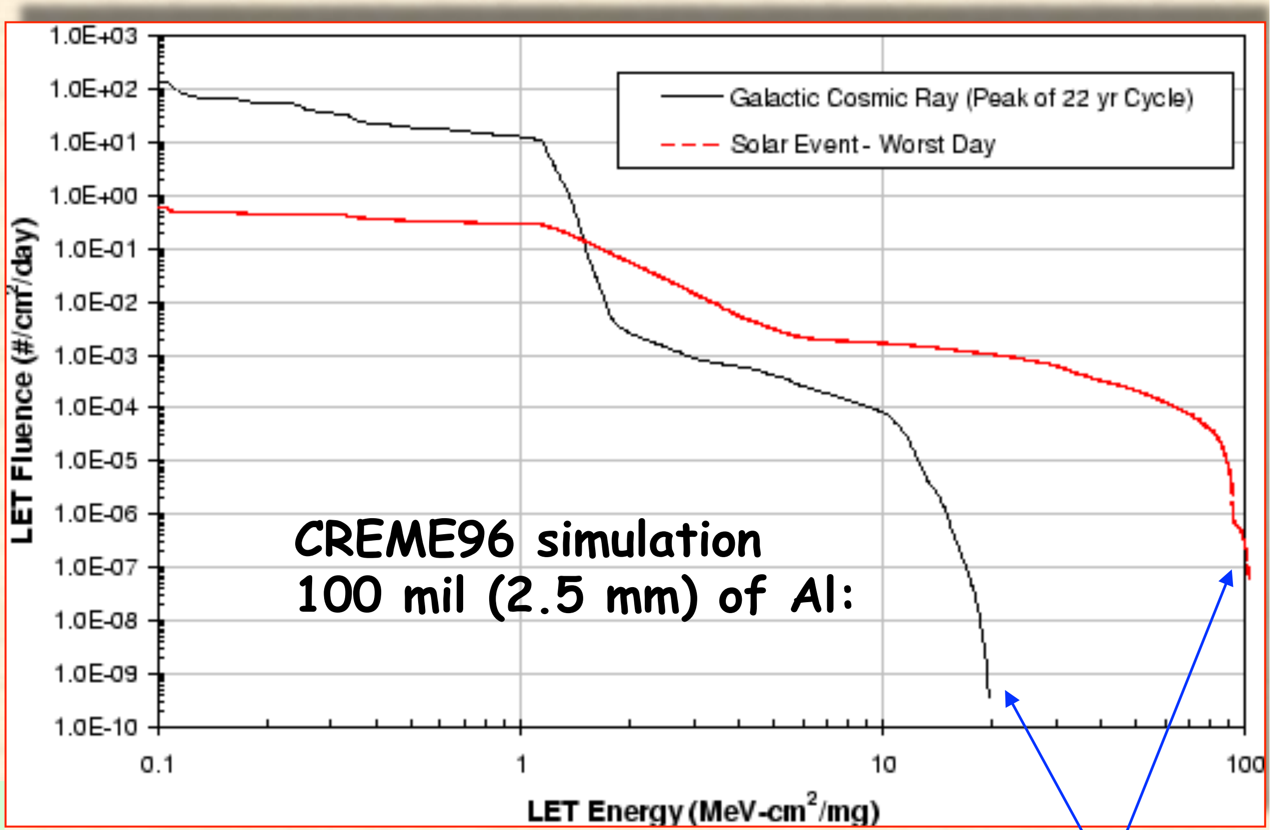


- GLAST orbital parameters:
  - ➢ 565 km asl, circular orbit
  - ➢ 28.5° inclination, ~1.6 hr orbital period
  - ➢ 5 year mission

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/cm^2 (5 yrs)



CREME96 simulation
100 mil (2.5 mm) of Al:

upper cutoffs

FERMI estimate

10 krad, 1 ion event/cm^2 (5 years)

Summary slides

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**

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.

Single Event Effects (SEE)

- single ionizing particle deposits enough ionization in a sensitive volume to cause <u>spontaneous damage</u> 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 } ⇒ slow highly ionizing recoil nucleus, 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
- rate of effects <u>scale with particle flux</u>
- 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

physical quantities of interest:

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

DDD

NIEL, Displacement Damage (DD)

- Cumulative <u>bulk damage</u>; 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:

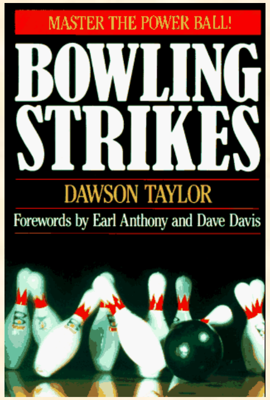
- particle fluence Φ(#/cm^2)
- Non-Ionizing Energy Loss (NIEL) (keV-cm^2/g)
- DDDose = NIEL × Φ

- effects <u>scale with particle fluence</u>
- tolerance of devices expressed in fluence of 1-MeV neutron equivalents
- risk begins at fluence $> 10^{11\text{-}12}$ 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 hits 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) changes of the internal electric field, due to modified doping concentrations,
b) eventually leading to inverting the conduction type for very high irradiations;
c) increase of the leakage current;
d) changes in capacitance and resistivity;
e) charge collection losses.

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

TID

steps to long term effects in electronics: surface damage

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.

CONCLUSIONS: studying radiation effects NEED TO define

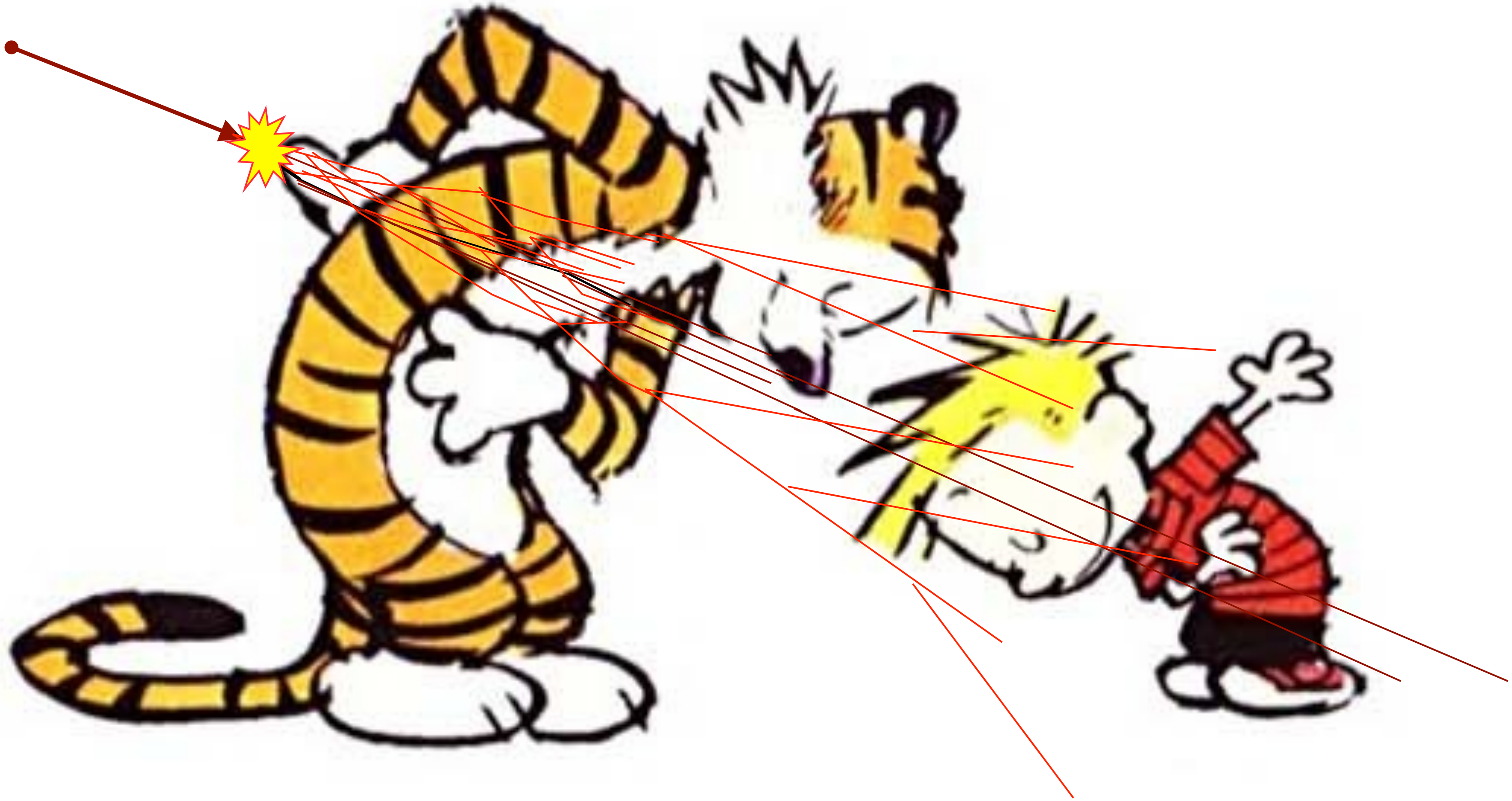
- quality of radiation
  - particle type (p, e, γ, n, ions,...)
  - energy
  - flux/fluence (how many!); i.e. cross-sections
  - source predictable or stochastic
- properties of target
  - material (silicon, plastic, water...)
  - active devices (memories, diodes,..., *living cells*)
  - active volumes (different sensitivities, how many, where, ...)

Questions that need answers:

after
H. Sadrozinsky,
Santa Cruz

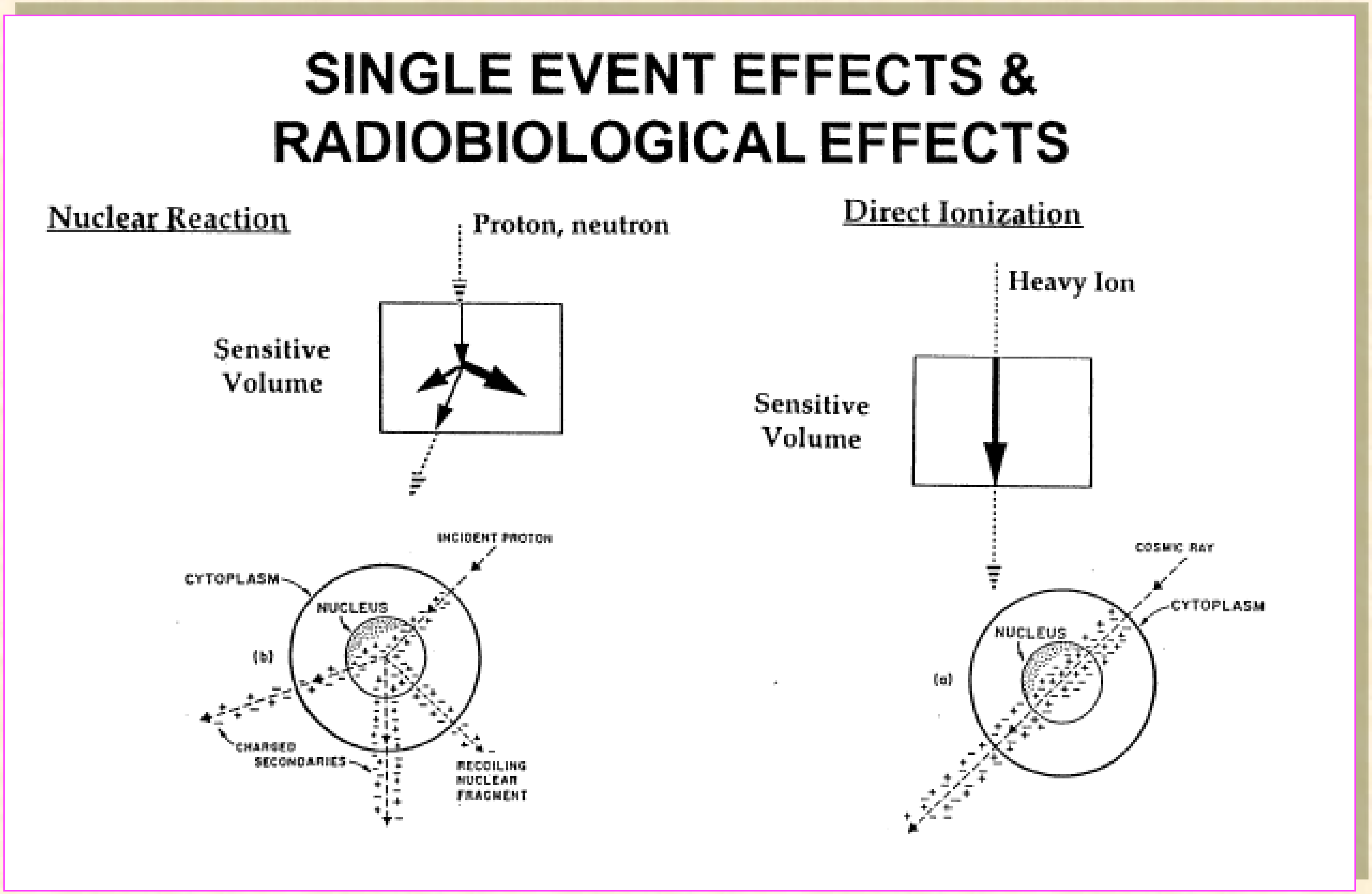
- are there *predictable* or *stochastic* effects?
- what is correct variable?
  (dose, fluence, 1-MeV equivalent neutron fluence for NIEL;
  LET and fluence hadrons E > 20 MeV for SEE)
- any normalisation factors?
  (scaling, NIEL-hypothesis, quality factors, *radiobiological equivalents*)
- any role 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?

END



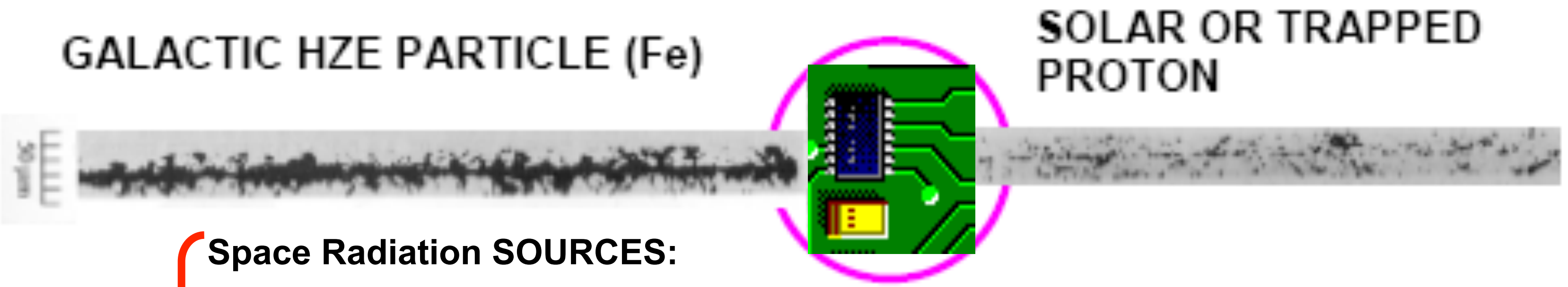
Extra slides

SEE in biology



SINGLE EVENT EFFECTS & RADIOBIOLOGICAL EFFECTS

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

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:

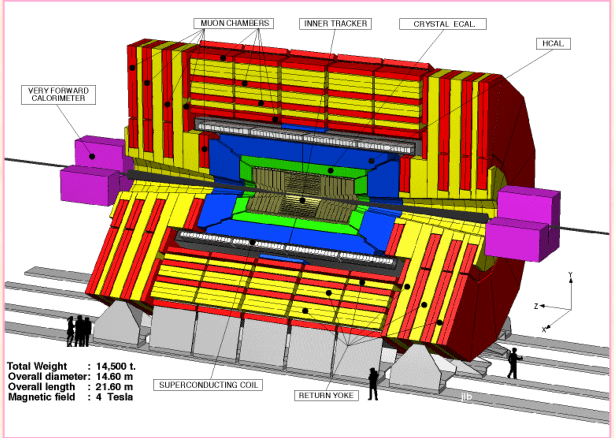
- **predictable**: trapped protons and electrons, galactic cosmic rays
- **stochastic (unpredictable):** protons from solar event (storm, flare)

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

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

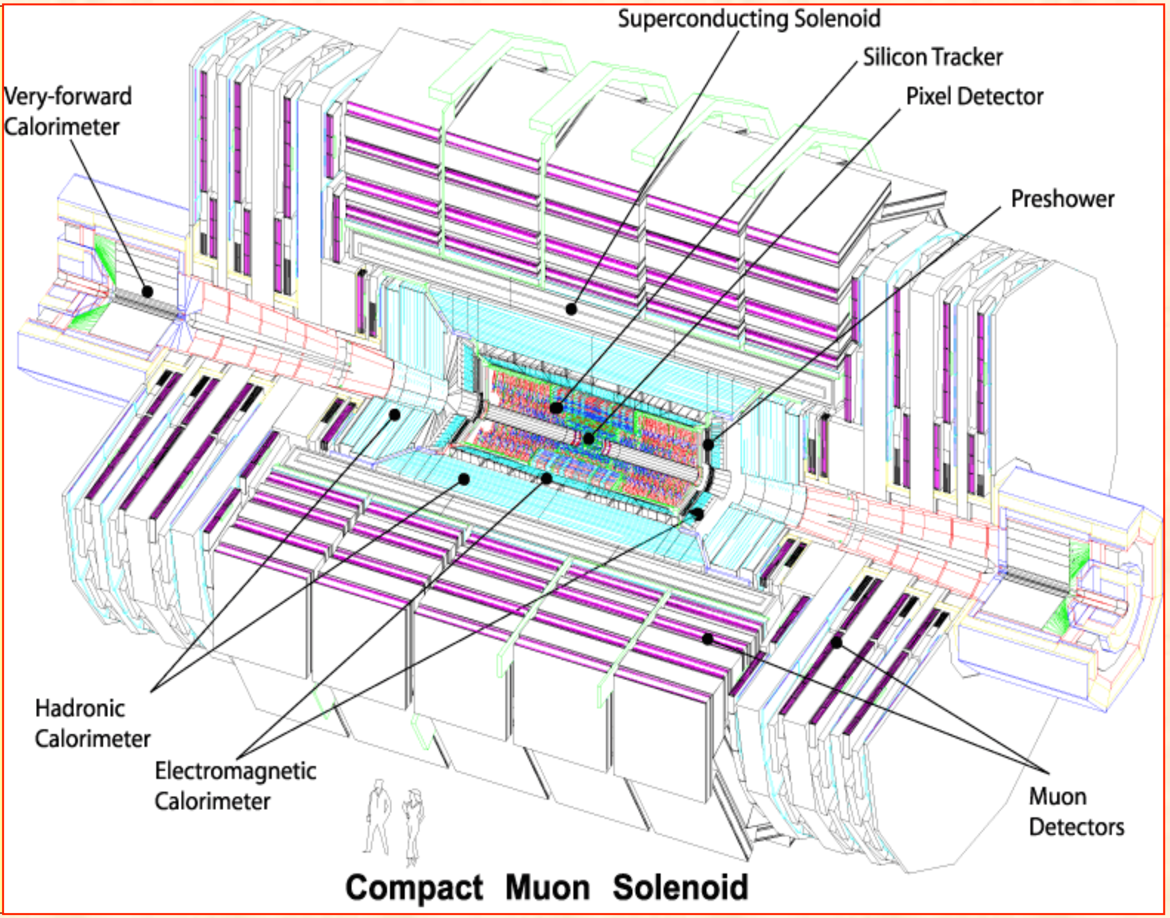
lowest/highest levels integrated over 10 years:

- **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)

- ***SEE fluences***
  - 2×10^{9} hadrons/cm^2 (Cavern)
  - 3×10^{13} hadrons/cm$^{/2}$ (Pixels)

  $E_{\text{charged hadrons}} > 21$ MeV



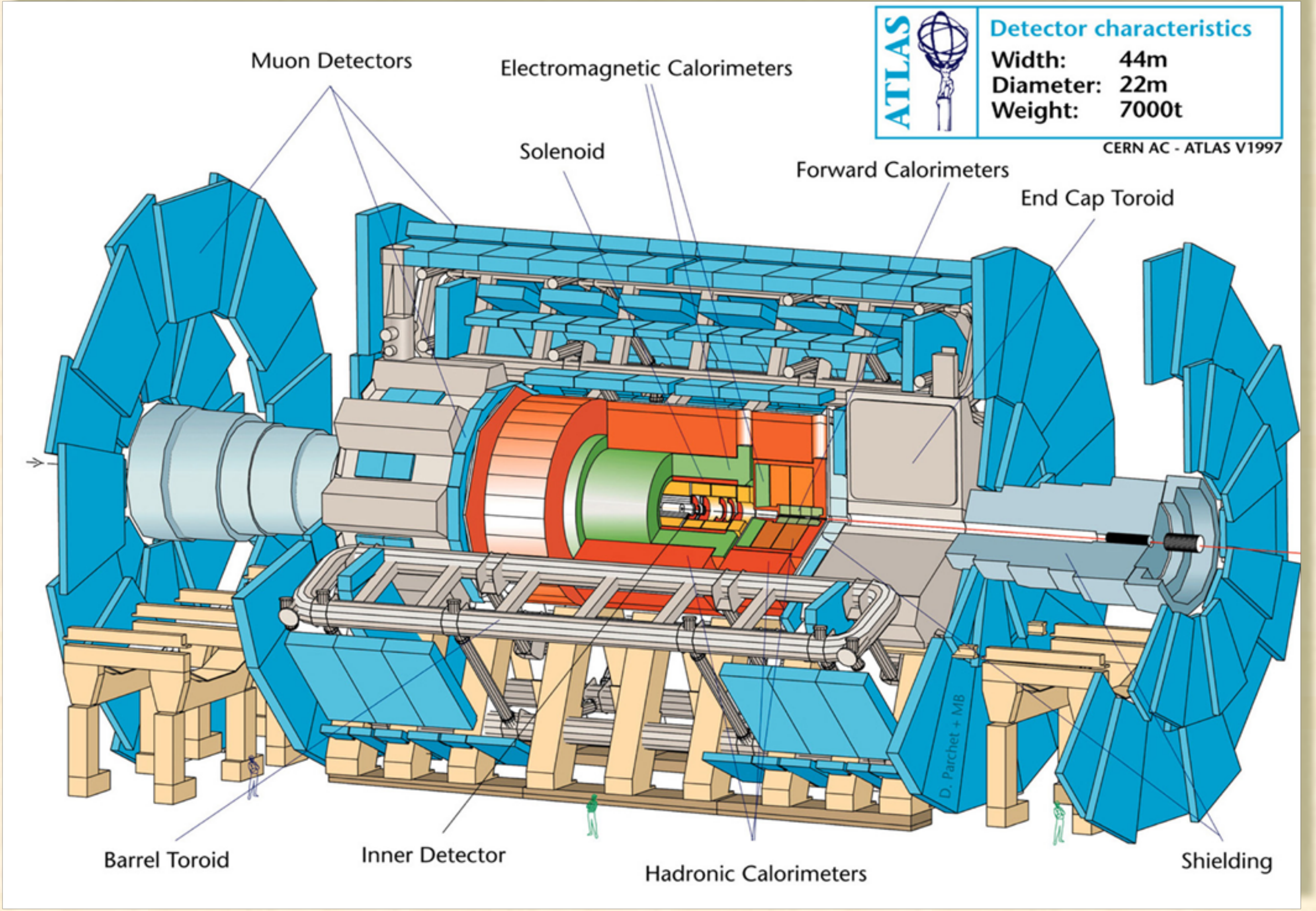
Compact Muon Solenoid

Obtained from simulation tools (Fluka, …)

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

→ **Safety Factors**

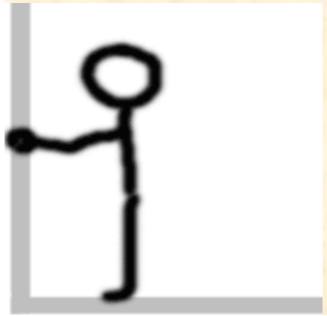
ATLAS


ATLAS
Detector characteristics
Width: 44m
Diameter: 22m
Weight: 7000t
CERN AC - ATLAS V1997
Muon Detectors
Electromagnetic Calorimeters
Solenoid
Forward Calorimeters
End Cap Toroid
Barrel Toroid
Inner Detector
Hadronic Calorimeters
Shielding
D. Parchet + MB

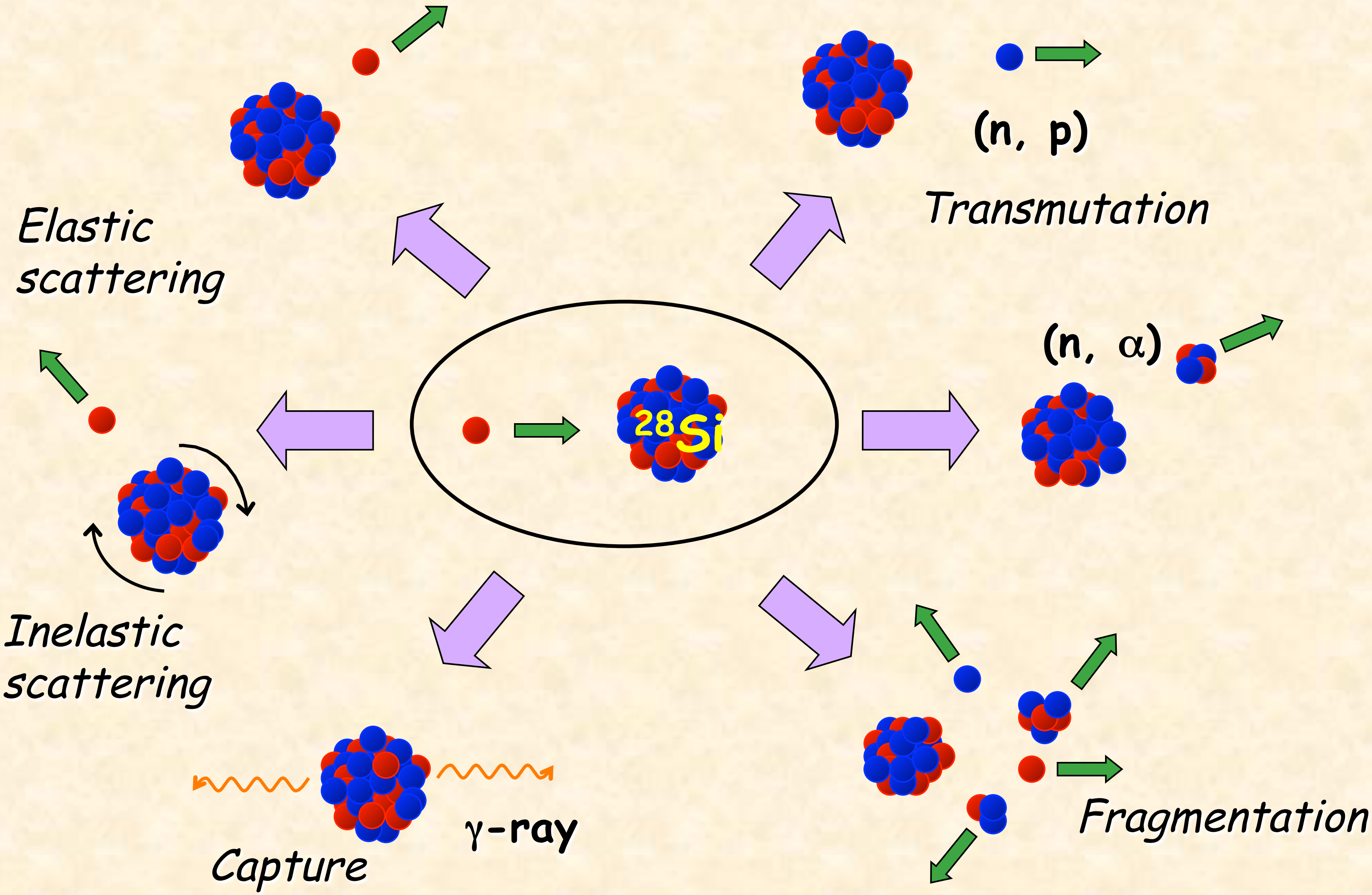
Neutron induced SEE

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



Elastic scattering

Inelastic scattering

Capture

γ-ray

(n, p)

Transmutation

(n, α)

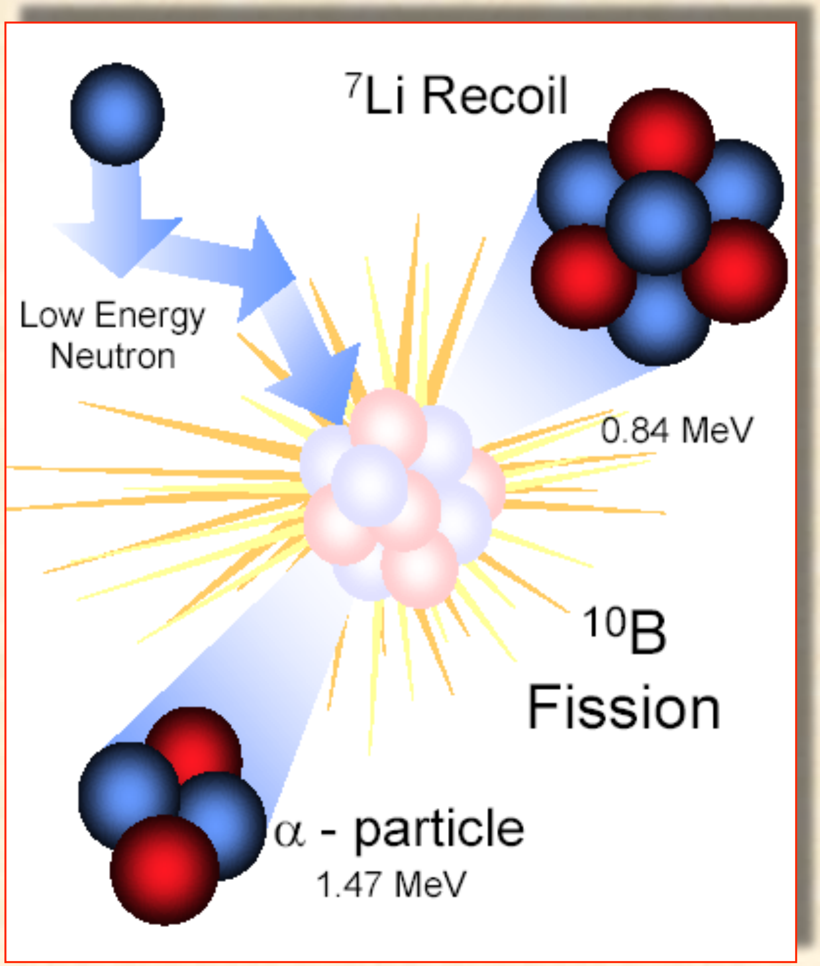
Fragmentation

thermal neutrons too (lesson learned!)

The SEE problem with low energy neutrons too due to use of Boron-10 in the cover glass layer of some microchips (*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)

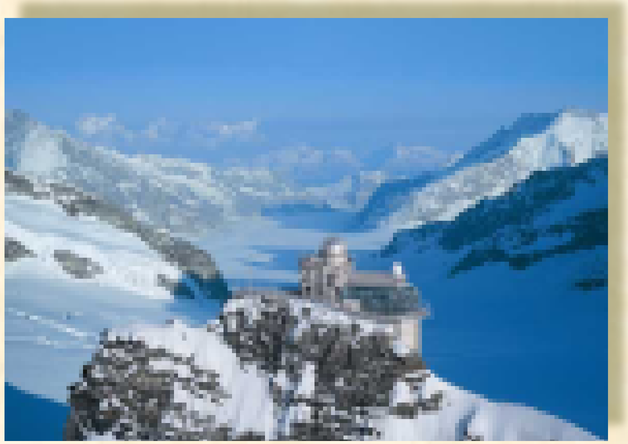


SEE testing

- SEE tests are performed to evaluate the expected error/failure rate of component and whole systems for specific environment (Space, HEP, Avionic, Sea level,…) by using:
  - PROTON & Ion beams from accelerators
  - Neutron beams
  - Alpha sources
  - Lasers
  - Neutron sensitivity field tests: a *large number* of devices can be operated under low intensity radiation at diverse atmospheric locations (sea level, then mountains at various altitudes)

"accelerated" (faster than natural rate)

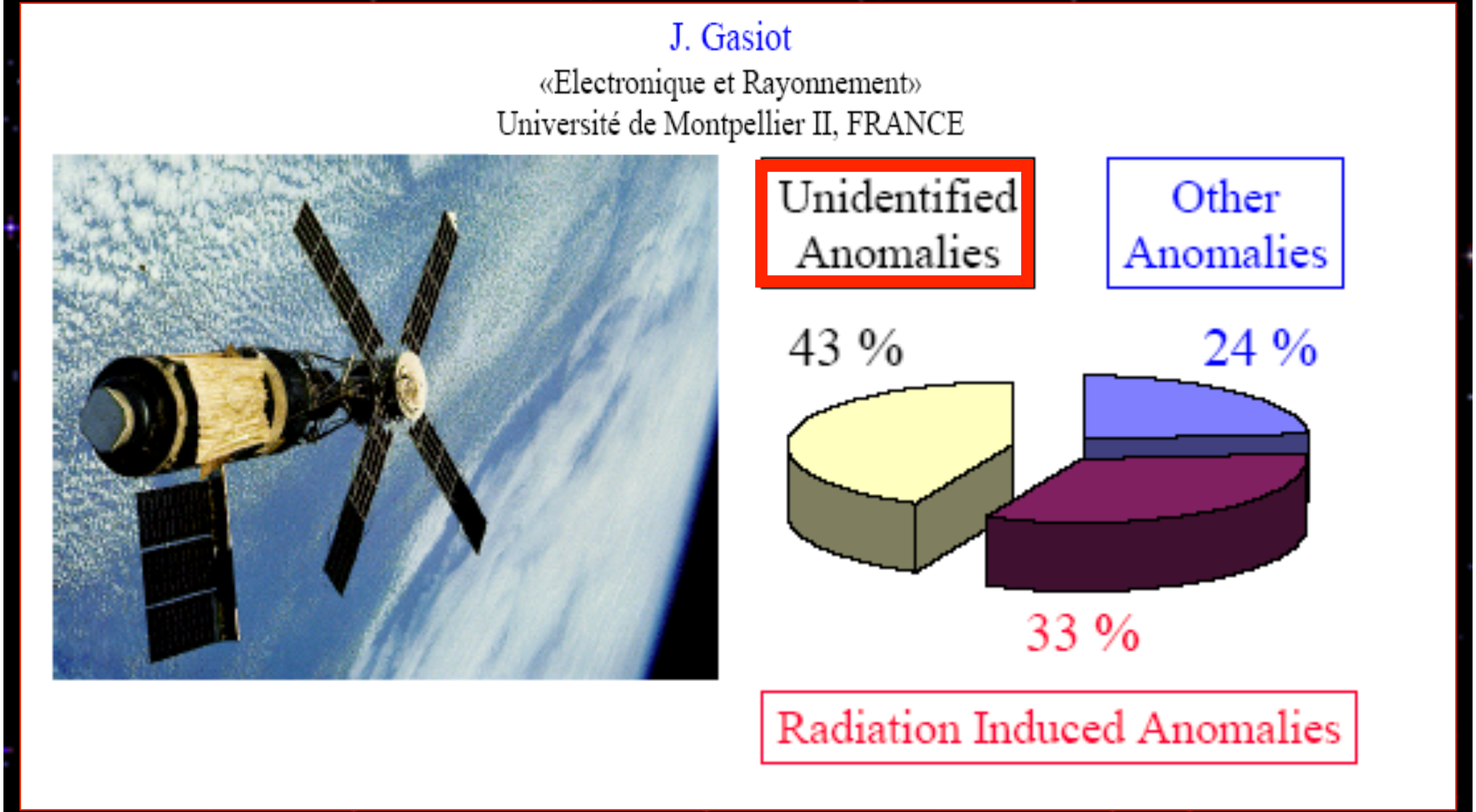
High Altitude Research Station Jungfraujoch, CH, 3580m (46.5^0 N, 8^0 E)



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**
	Quasi-monoenergetic neutrons	**Irradiated DUTs with quasi mono-energetic neutrons**	**· facilities Limited** **· Versatile** **· Correction necessary (quasi monoenergtic)**
	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**
	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**

Space in context



J. Gasiot
«Electronique et Rayonnement»
Université de Montpellier II, FRANCE

Unidentified Anomalies

Other Anomalies

43 %

24 %

33 %

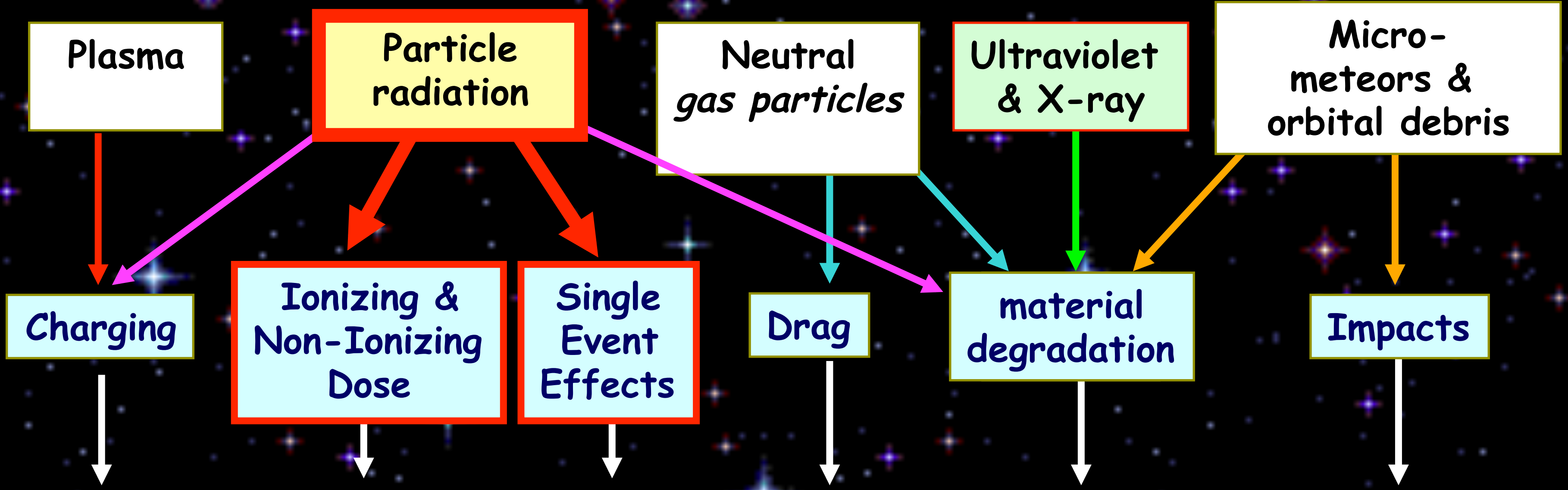
Radiation Induced Anomalies

Unidentified Anomalies?

Space

Space Environment Effects complete picture

after Barth



Plasma

Particle radiation

Neutral *gas particles*

Ultraviolet & X-ray

Micro-meteors & orbital debris

Charging

Ionizing & Non-Ionizing Dose

Single Event Effects

Drag

material degradation

Impacts

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

Radiation Effects

Drag:

☐ Torques

☐ Orbital decay

Material degradation:

Degradation of:

☐ thermal, electrical, optical properties

☐ structural integrity

Impacts:

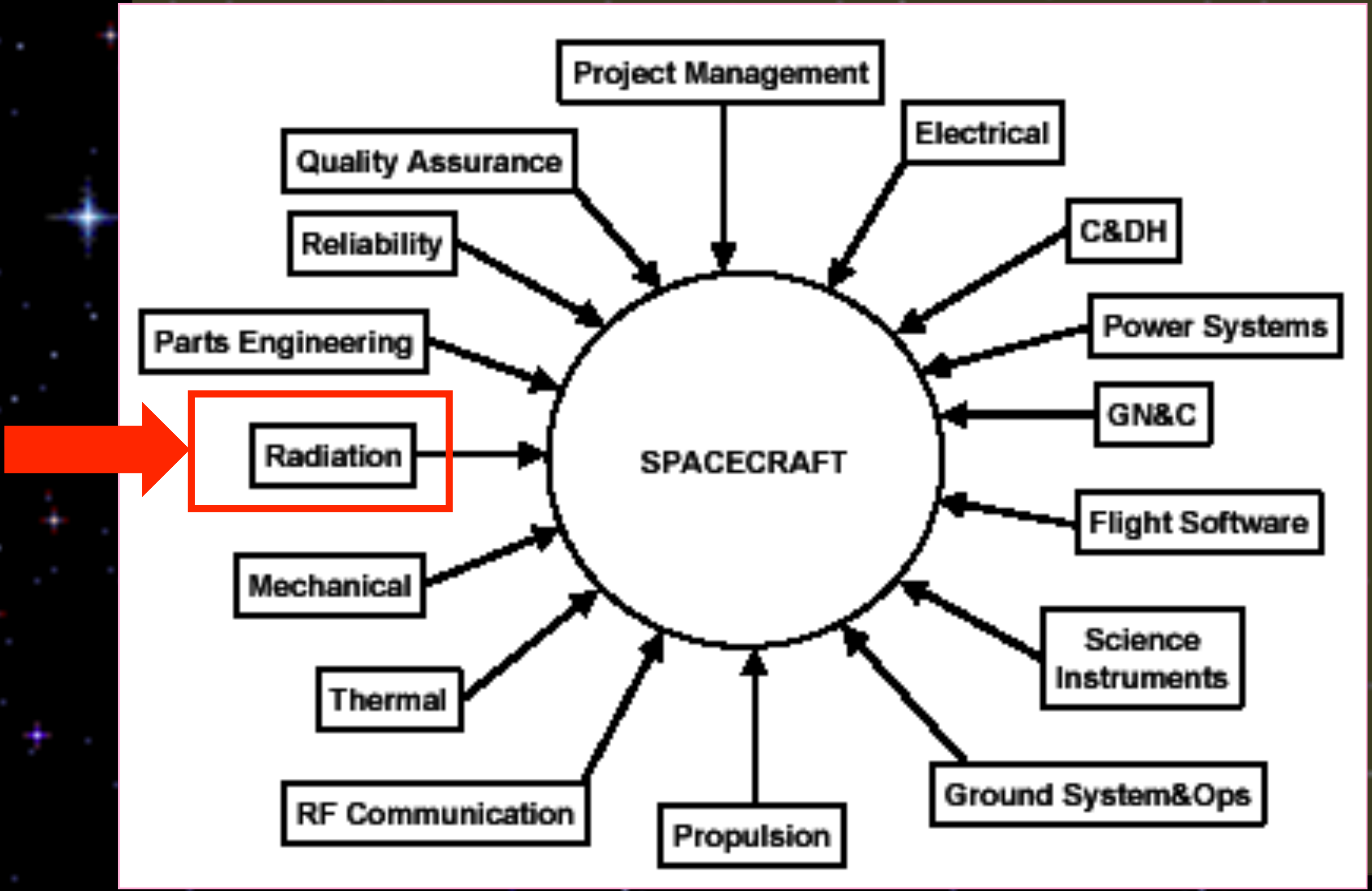
☐ Structural damage

☐ Decompression

Vacuum, shock, and thermal cycles also important

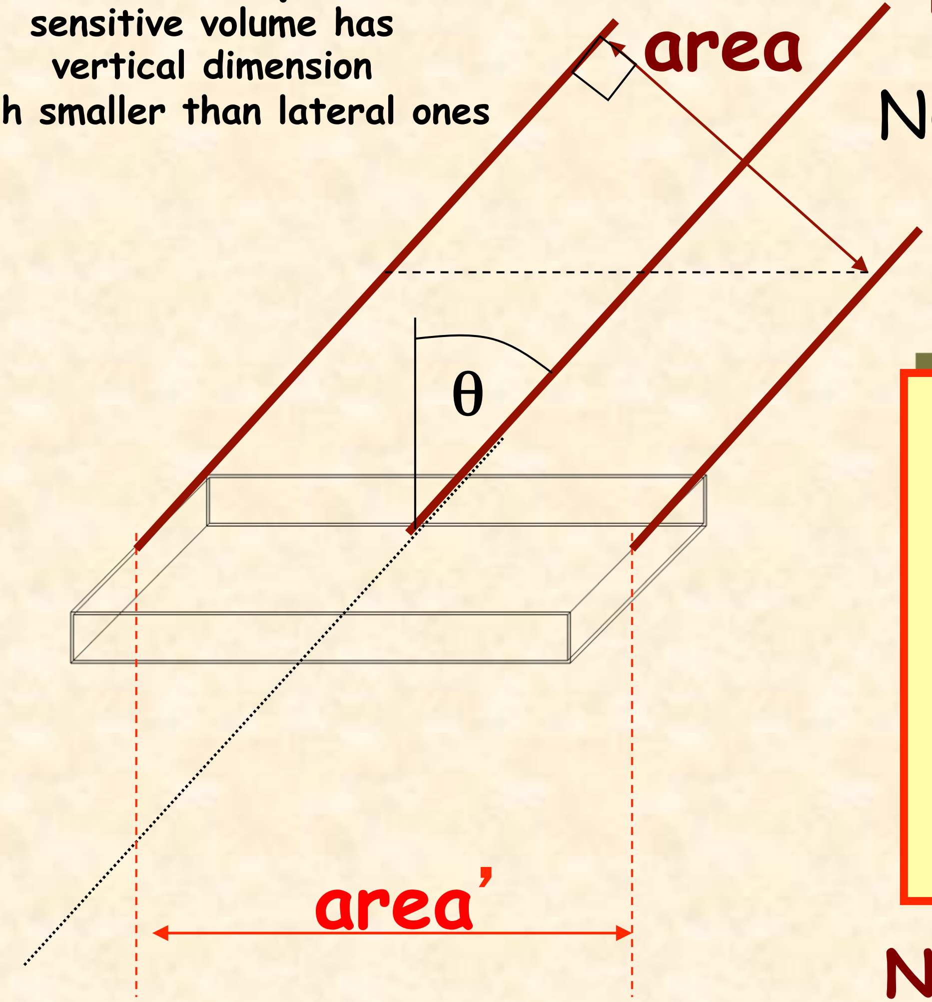
Spacecraft design team

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



inclined SEE exposure

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



Beam fluence φ

NOTE: **area** = **area'** cos(θ)

$$LET(\theta) = LET(0^{\circ})/\cos(\theta)$$

AND

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

NOTE: cos(θ) enters twice!