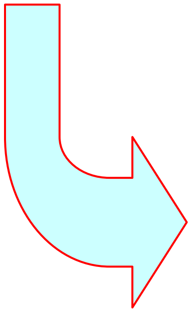
Legnaro (Padova)
April 4, 2005

Concepts, Physical Quantities, and Radiation Environments

Concetti, Grandezze Fisiche e ambienti di Radiazione

Prof. **Jeffery Wyss**
University of Cassino
INFN PISA

Original Title:
"Low Intensity Exposure to Radiation Concepts"

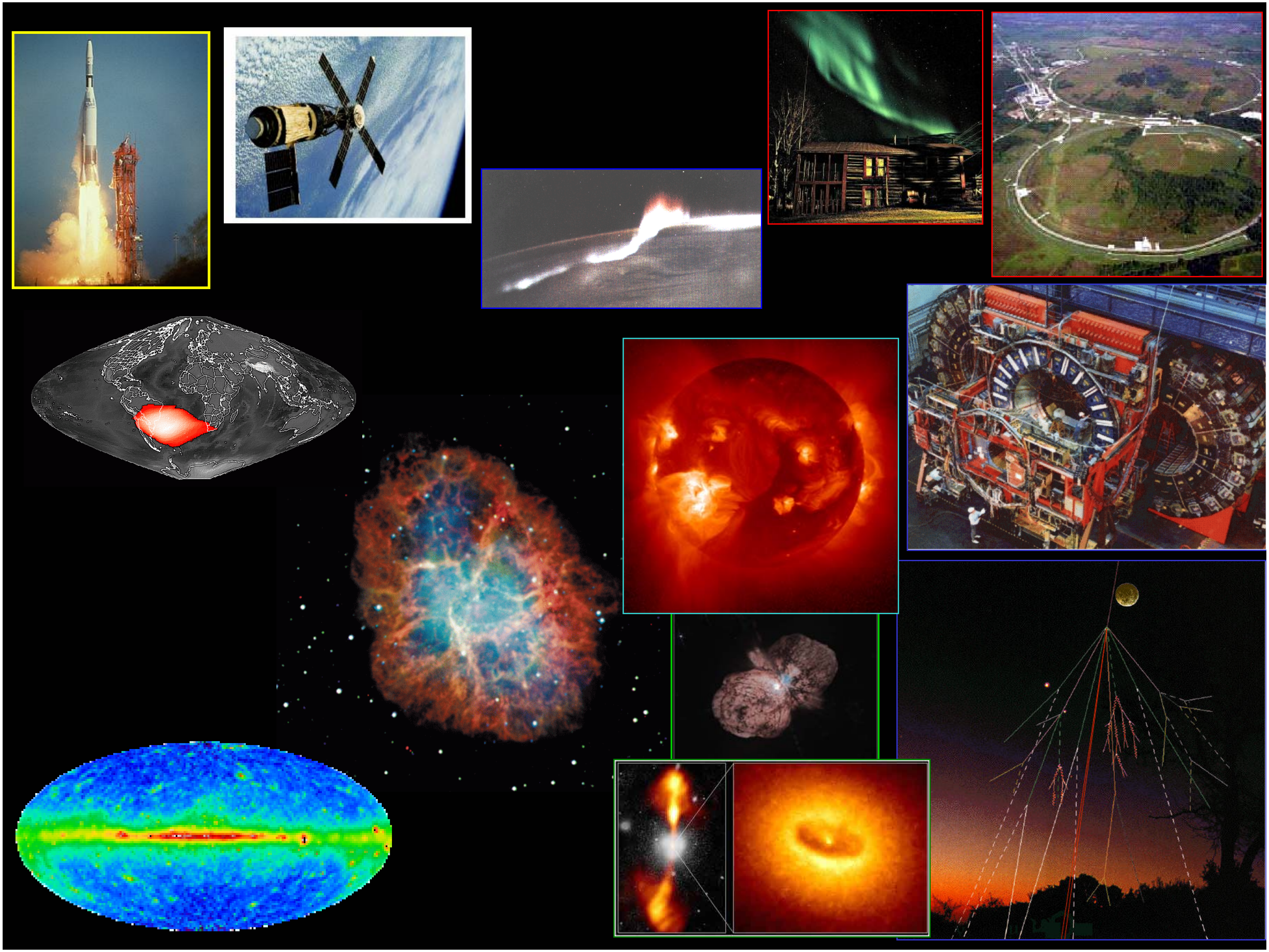


PART 1
OVERTURE (to relax)
+
pedestrian introduction
to
radiation concepts, quantities, environments

sore feet? blisters?

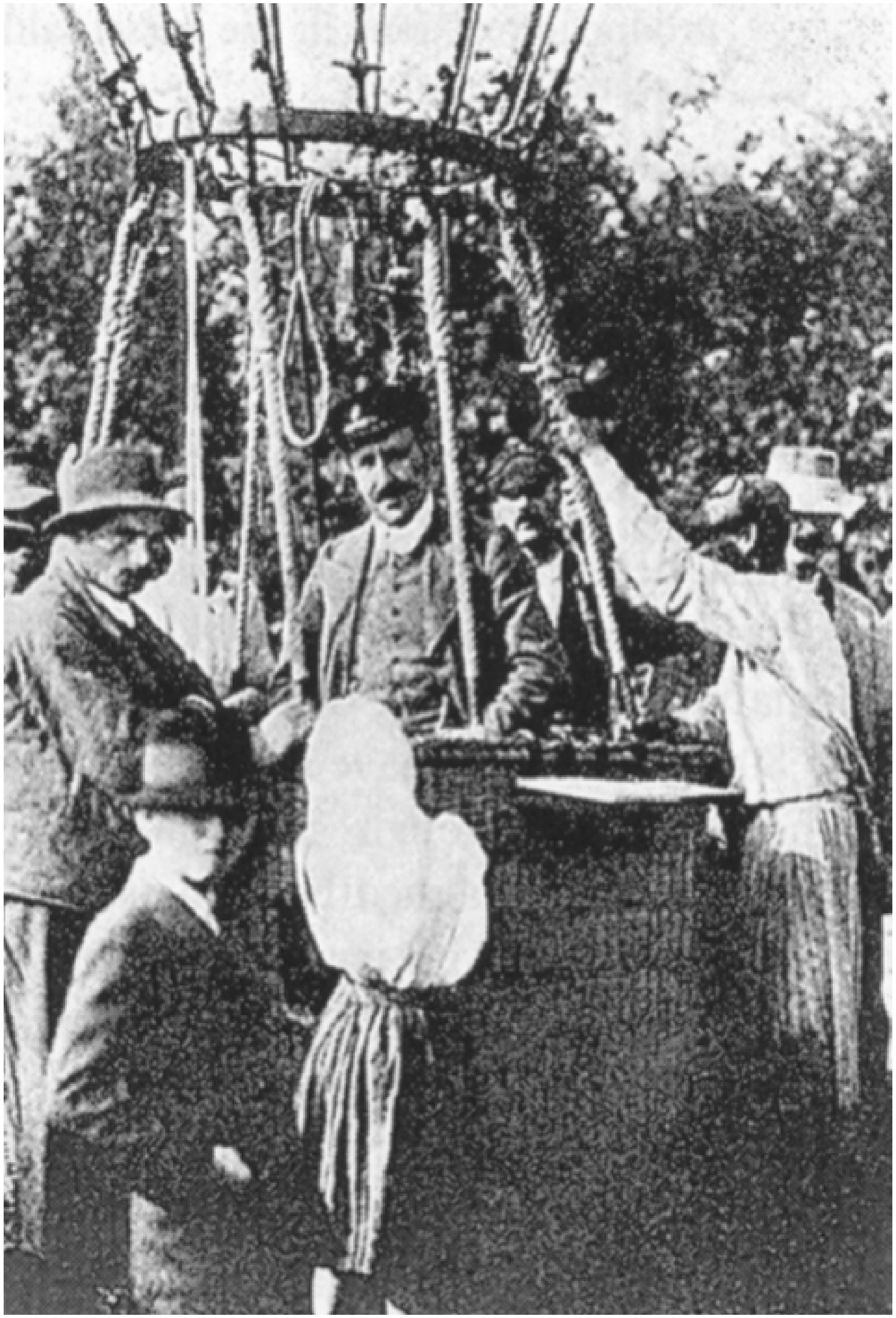
PART 2
overview of radiation issues and assurance of electronics

lighter, schematic more useful !?
Glance thru for rest of this school.



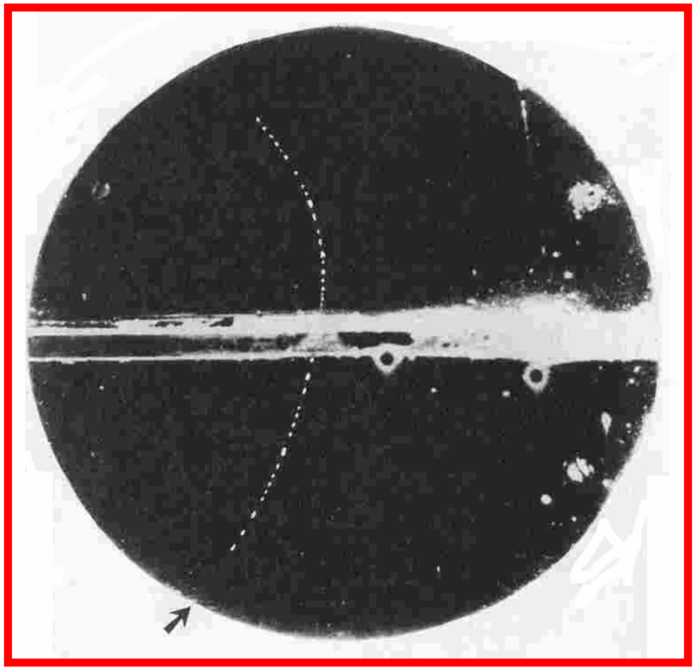
borealis: haunting beauty

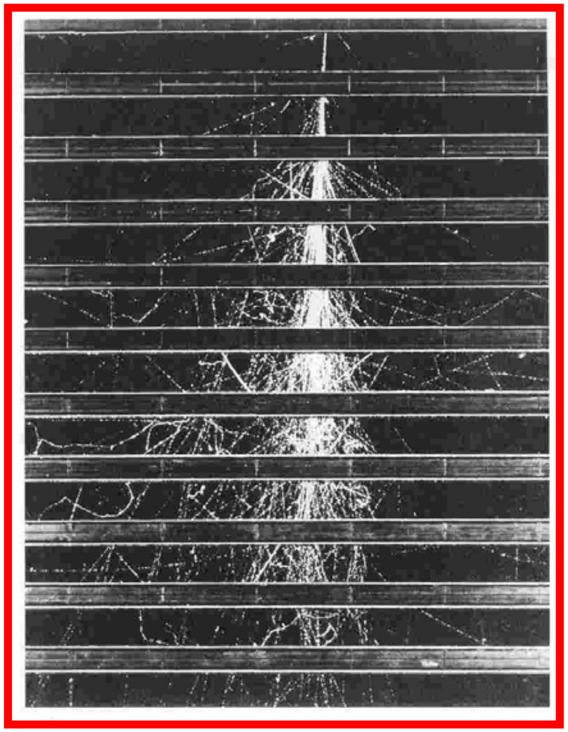
http://www.geo.mtu.edu/weather/aurora/images/



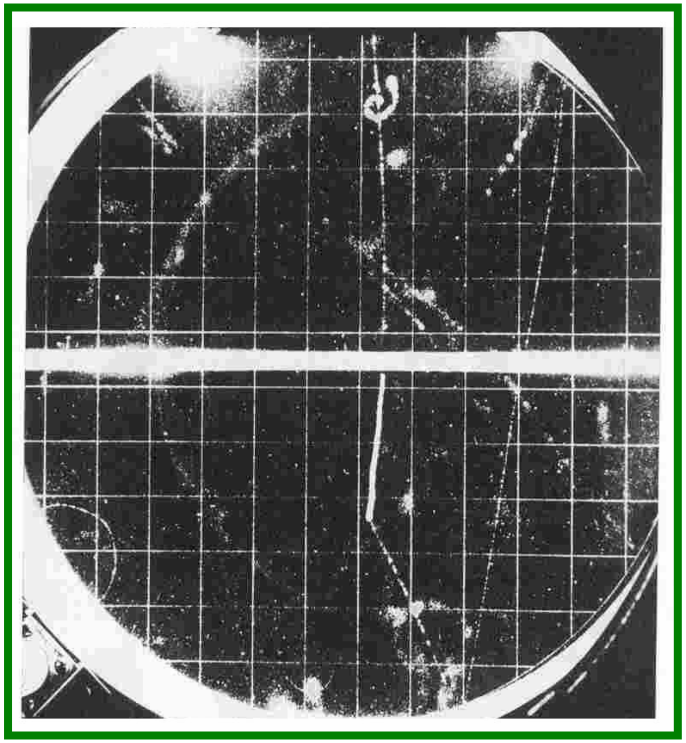
Victor Hess discovered
cosmic rays in 1912
in balloon

A dangerous discipline!
but full of treasures

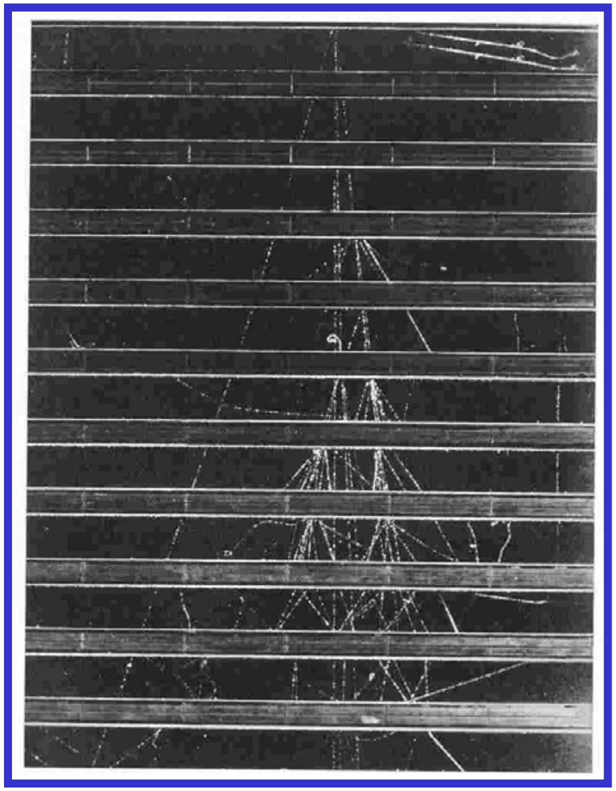




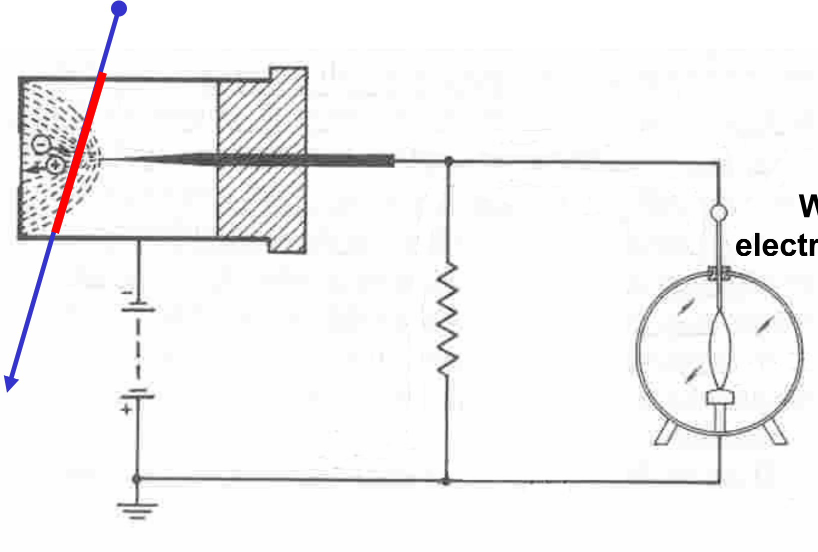
fundamental role of
cosmic ray research
in history
particle physics
theory (interactions)
and
techniques



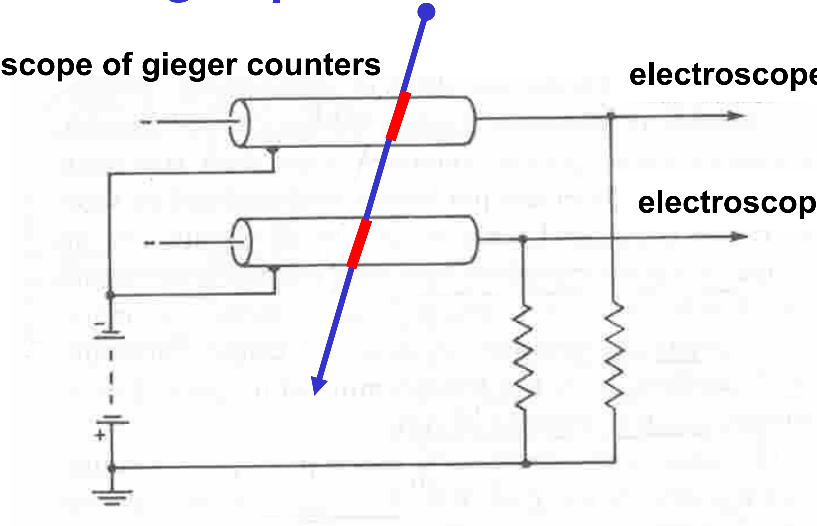
visual techniques
(need trigger!)



fundamental role of cosmic ray research
in history of techniques: *counting experiments*



Wulf electroscope

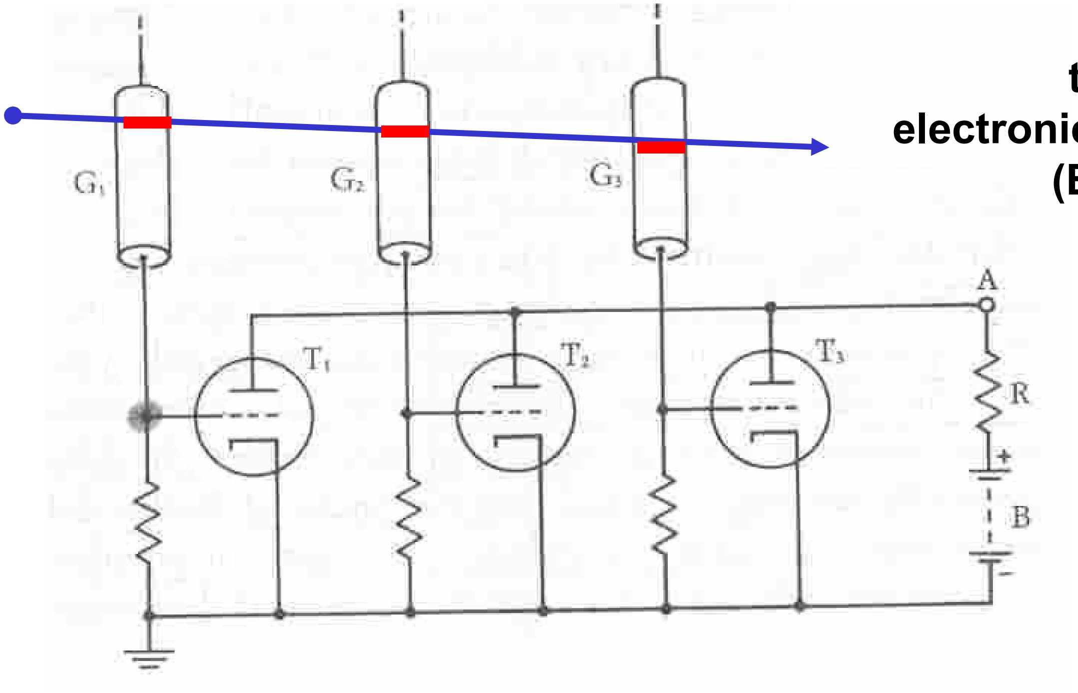


hodoscope of gieger counters

electroscope 1

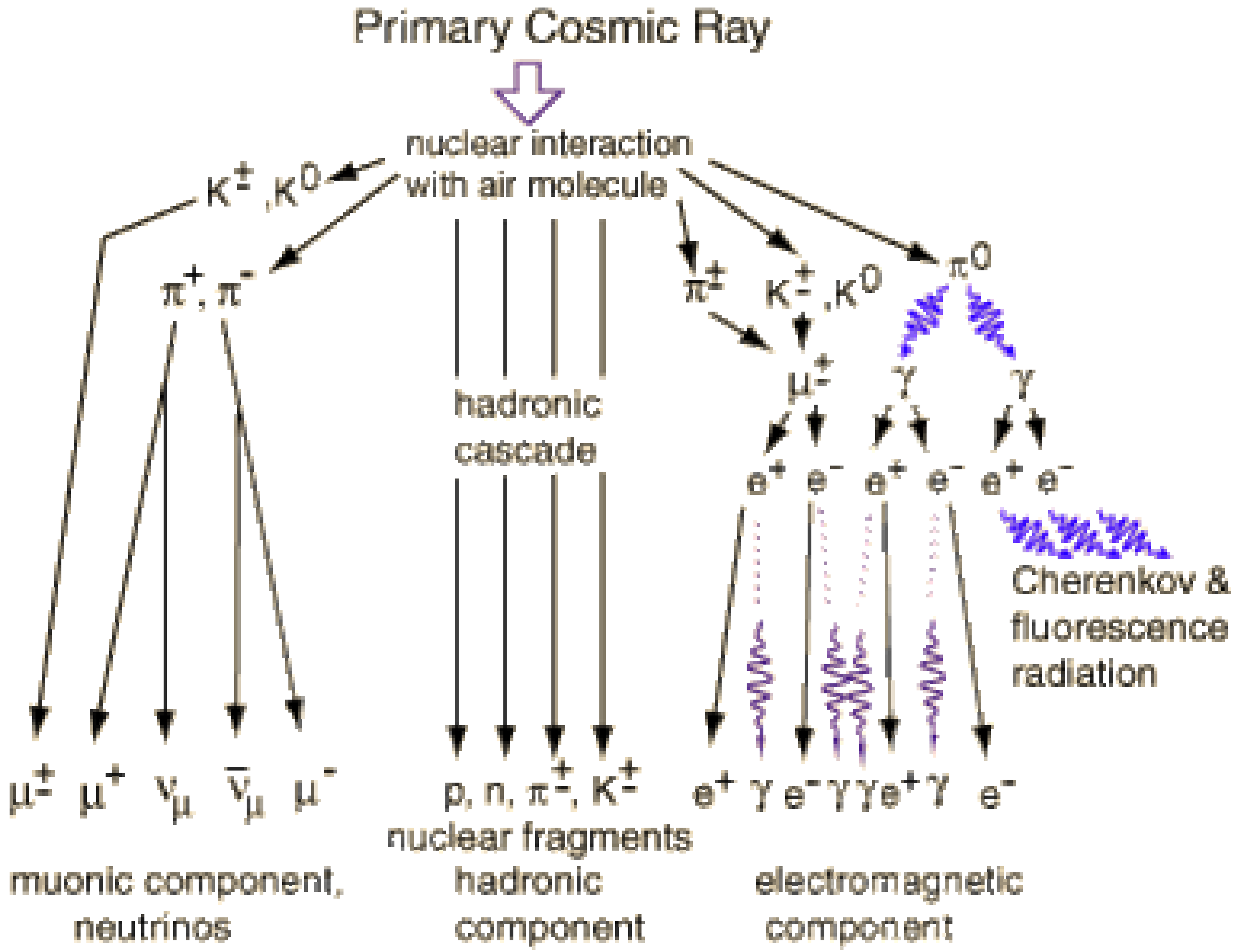
electroscope 2

coincidence setup



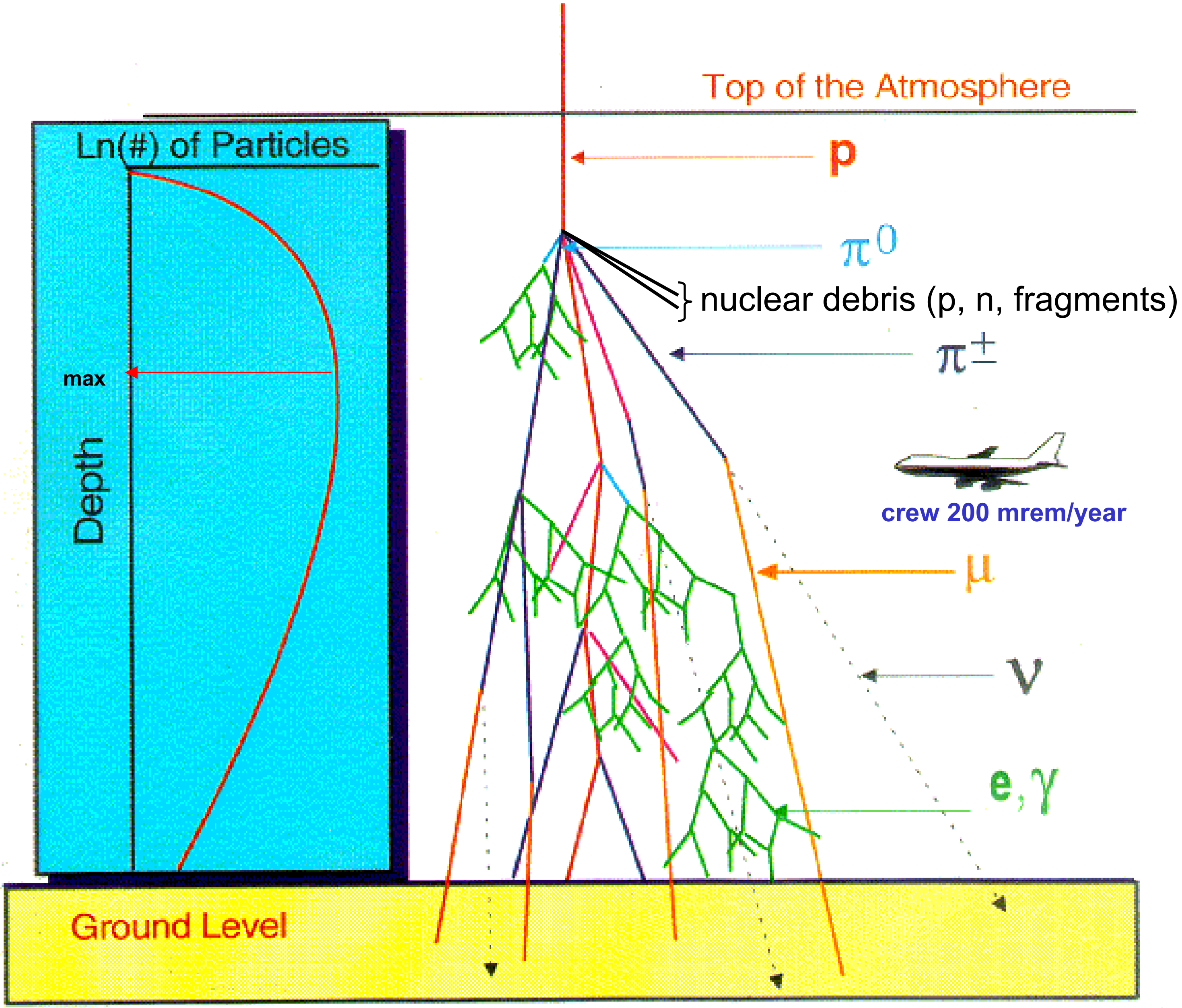
true modern electronic coincidence circuit (Bruno Rossi)

cosmic shower composition
(actors of elementary particle physics)



extensive hadronic air-showers

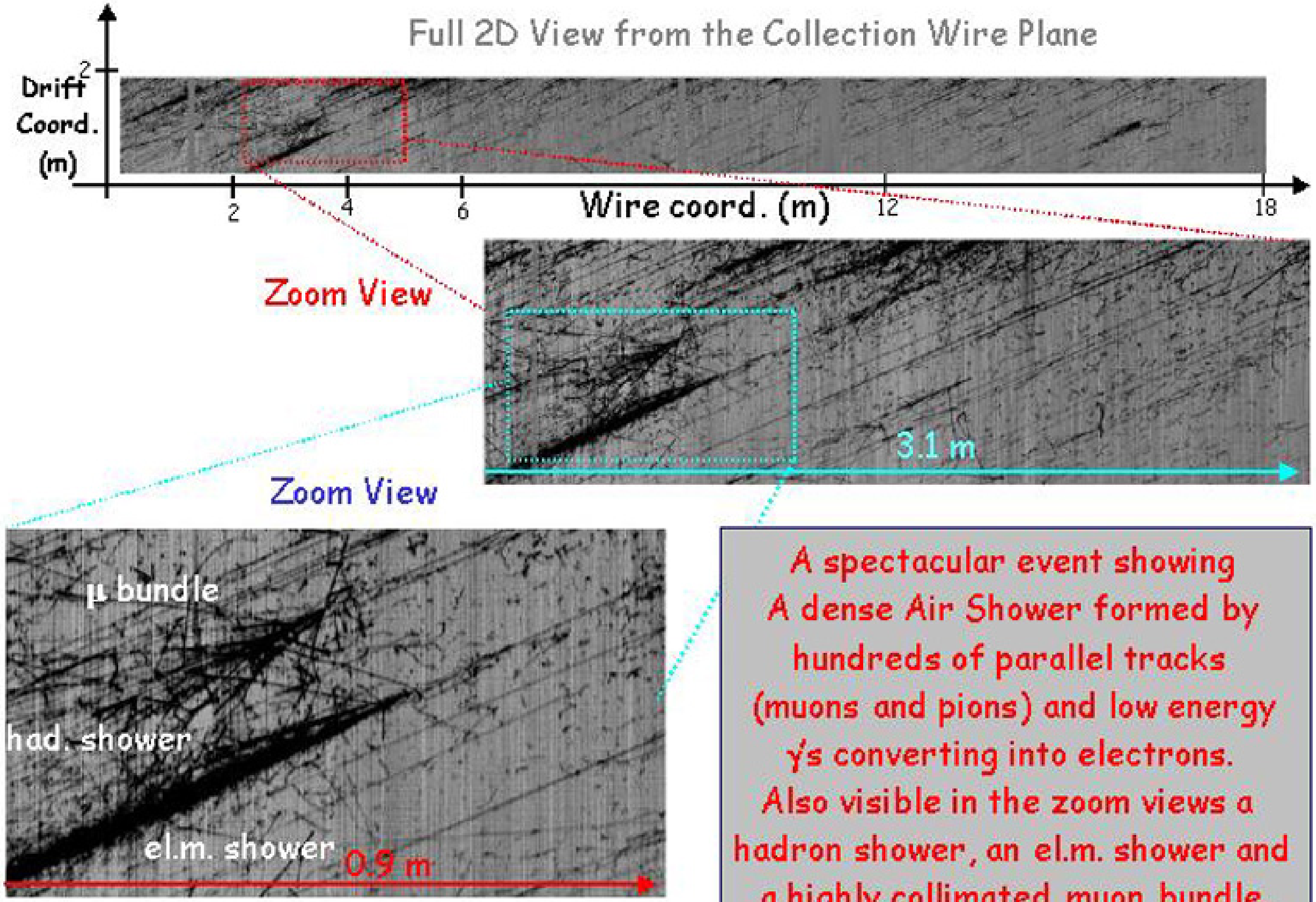
Pfotzer (1936)
discovered maximum
ionisation
at ~ 15 km altitude
⇒ thick atmosphere
sustains stable life
at sea level



NOTE: neutron flux
at sea (ground) level
10^5 neutrons/cm^2-year
with E>20 MeV
which may cause SEE

ICARUS (electronic with visual quality)

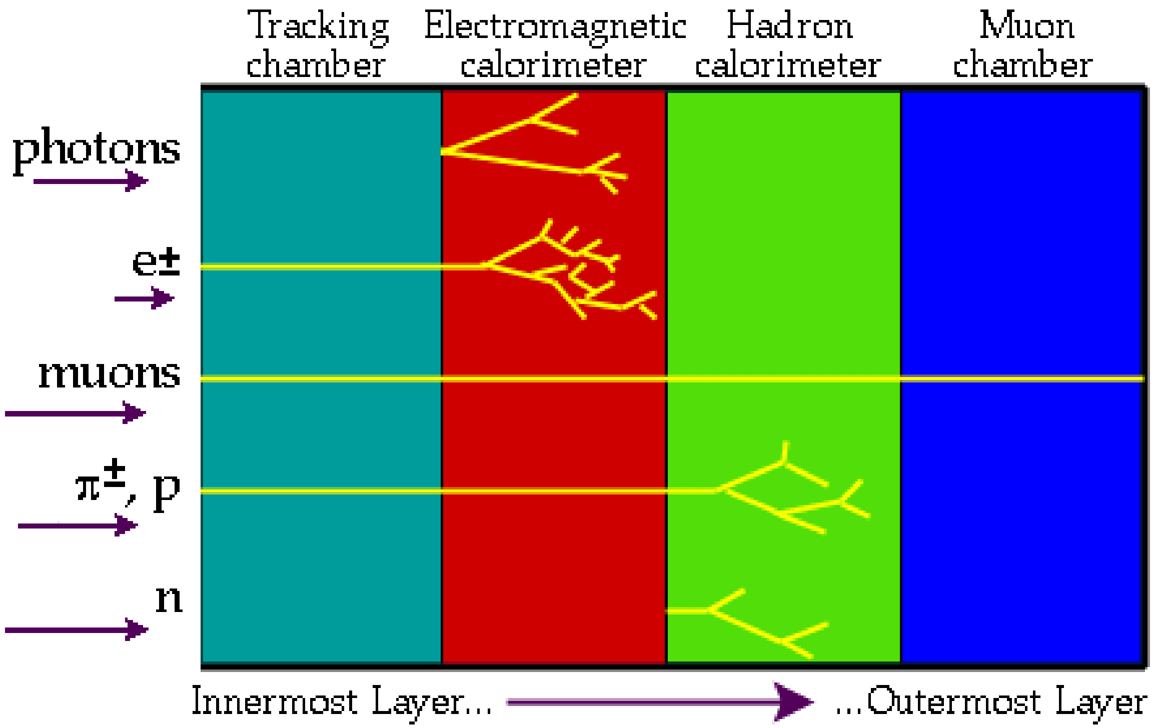
spectacular air-shower event



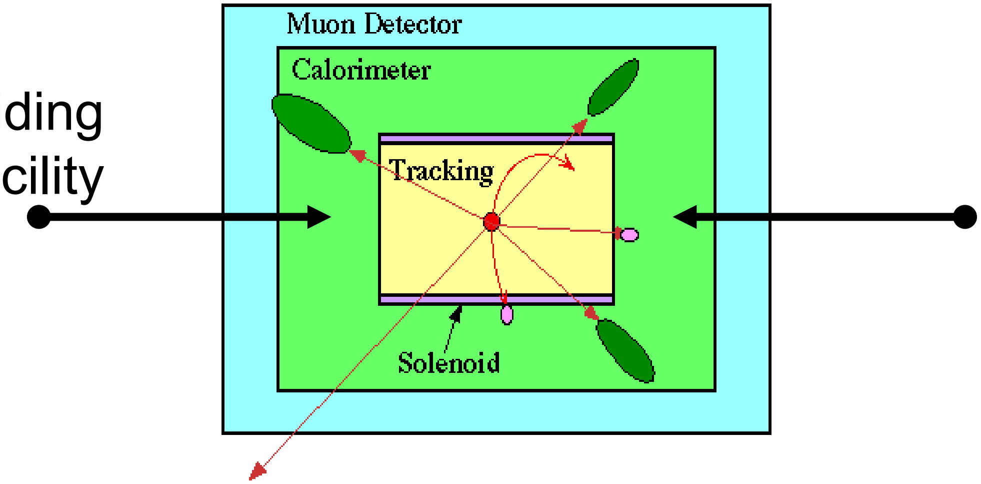
A spectacular event showing
A dense Air Shower formed by
hundreds of parallel tracks
(muons and pions) and low energy
γs converting into electrons.
Also visible in the zoom views a
hadron shower, an el.m. shower and
a highly collimated muon bundle.

detectors: cartoon

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

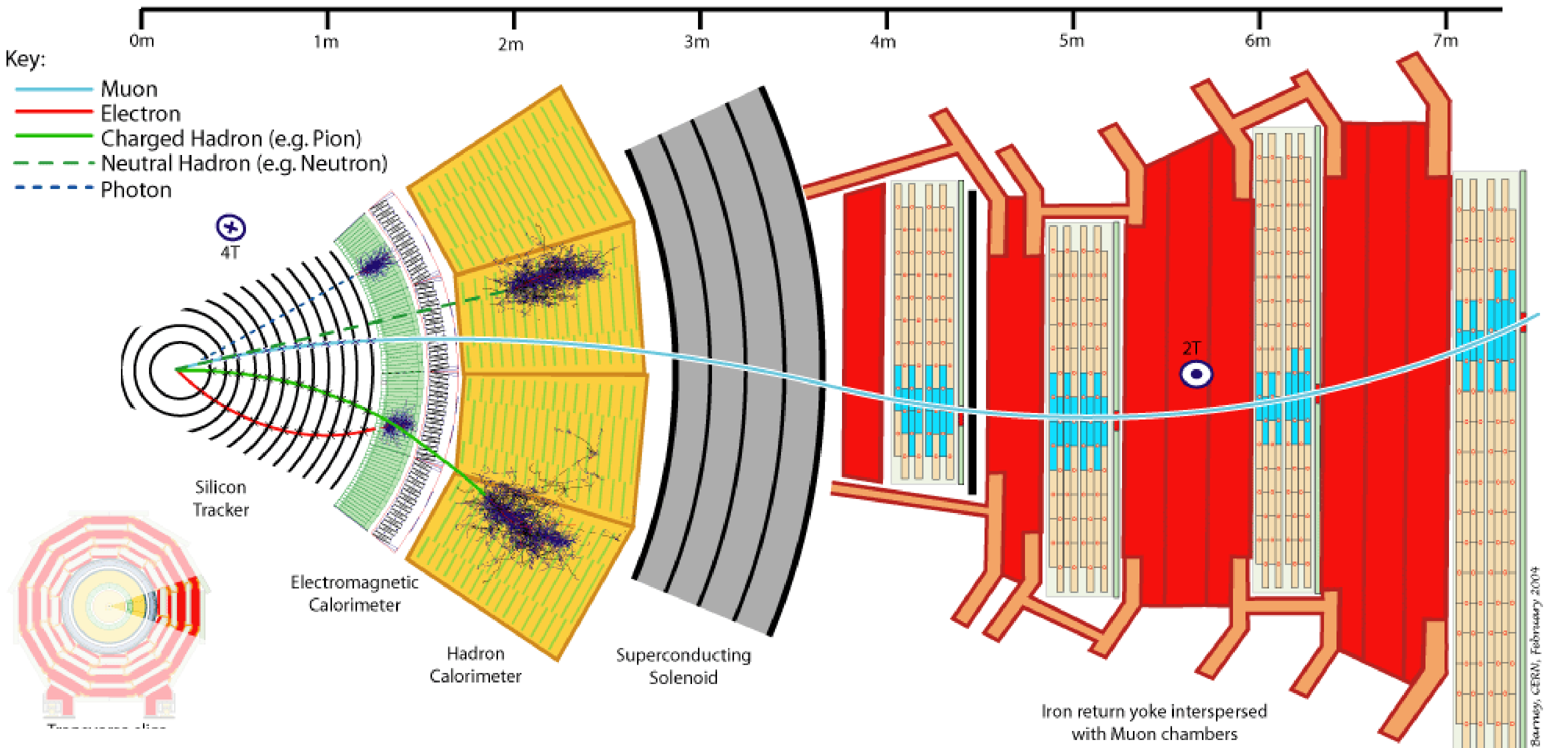


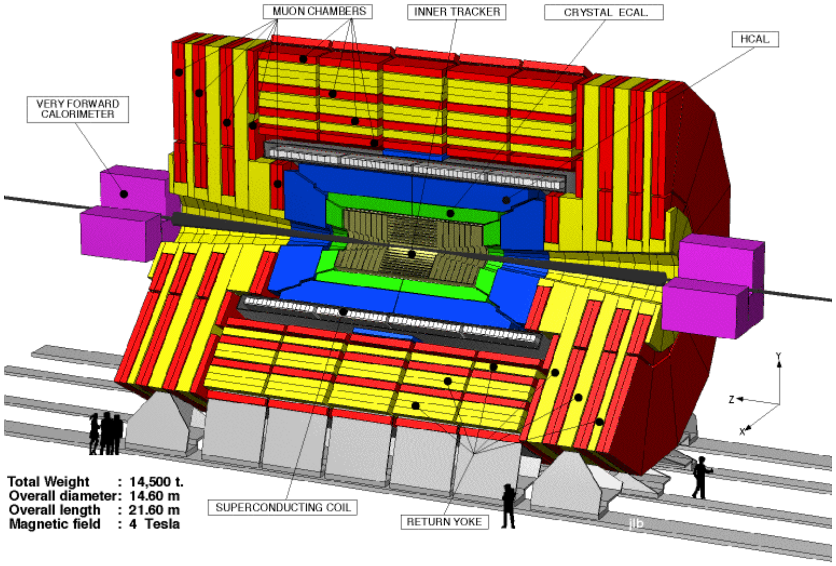
at a colliding beam facility

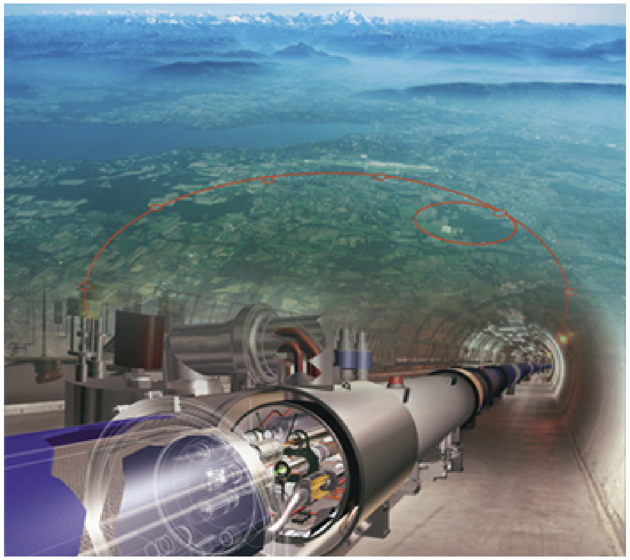


HEP detector

CMS at LHC







space detector

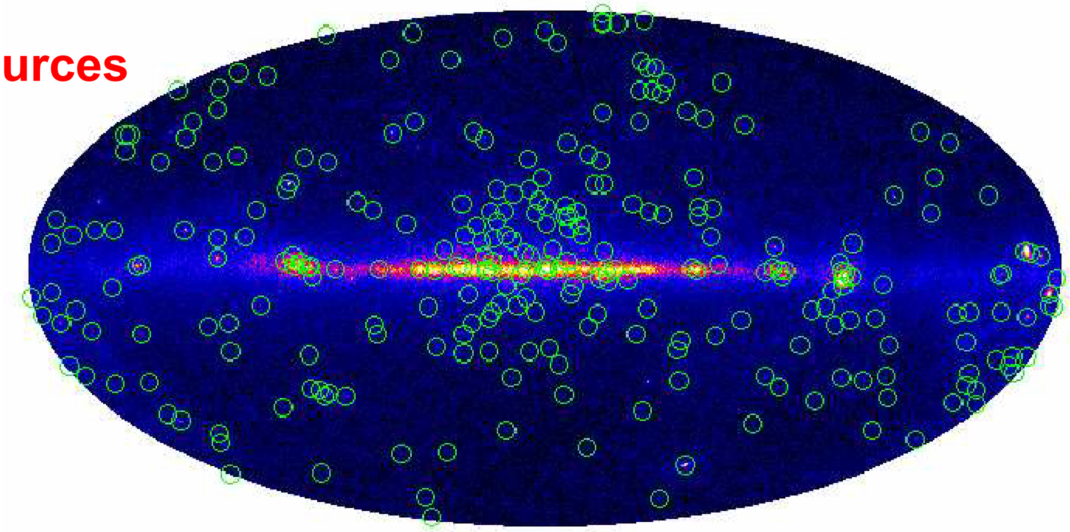
CGRO/EGRET gamma detection

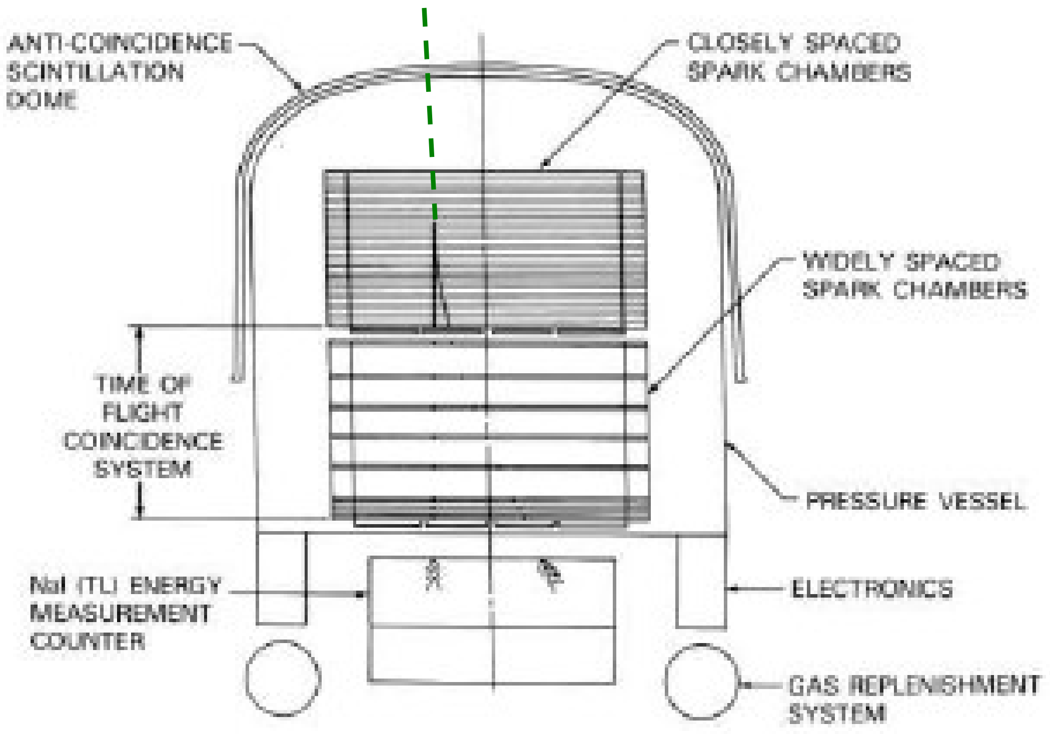
- 3EG catalogue, 271 point sources

  most blazars,

  5 pulsars,

  170 unidentified
- map of galactic background





- closely spaced spark chamber for tracking
- Widely spaced spark chamber for TOF
- NaI(Tl) electromagnetic calorimeter (7.7 X_0)
- Plastic scintillator anticoincidence dome
- Energy resolution ~10%
- Angular res. 10° (60 MeV) to 1° (10 GeV)
- Problems from backsplash from the CAL: the anticoincidence was too close

overview

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 •	• plastics • composite materials • ecology • semiconductors • …

Anticipation of conclusions!

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, ...)

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

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

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

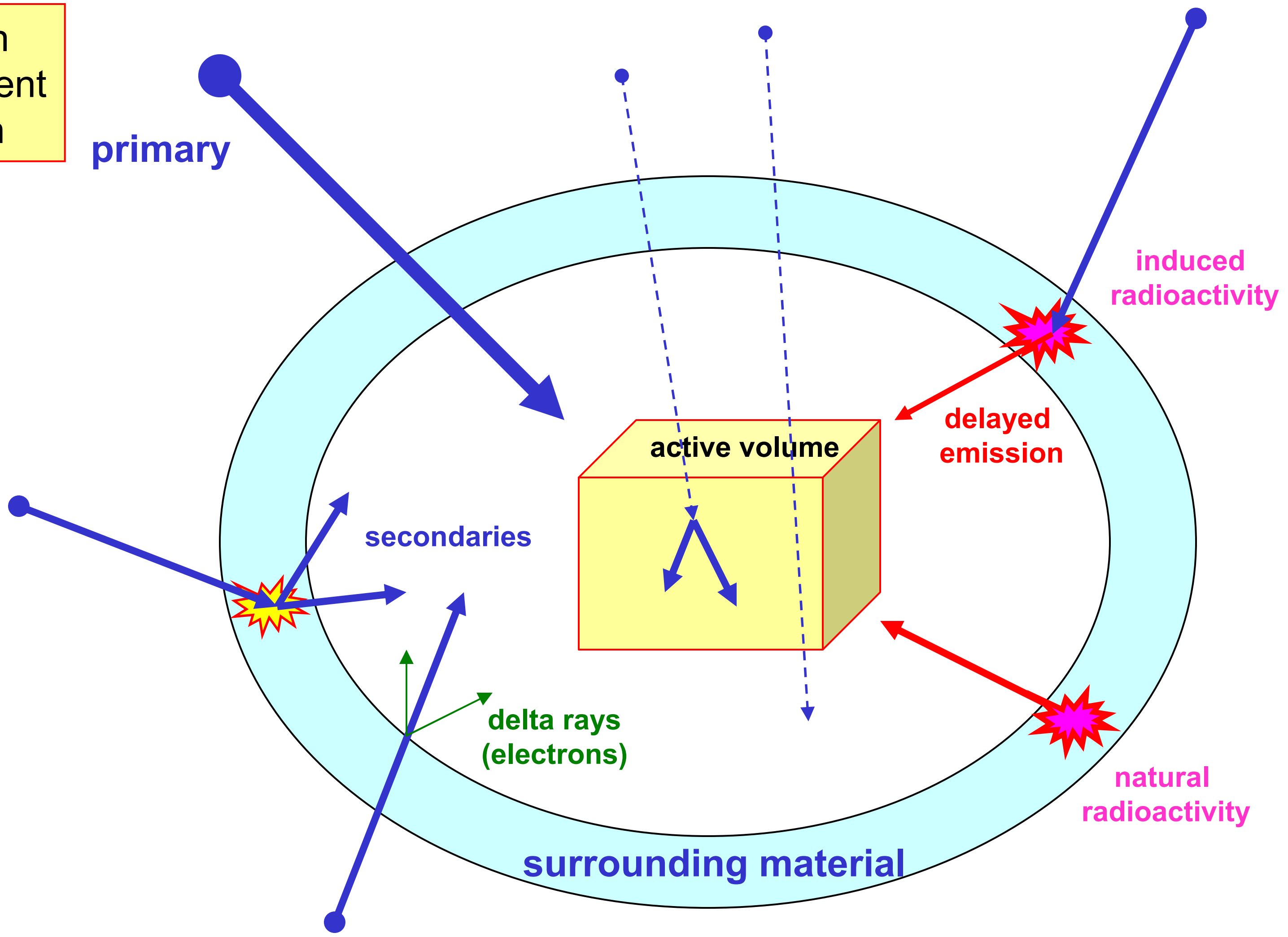
• any role of microenvironment?
(parasite structures such as latch-up in CMOS; *bystander effect*)

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

• are there dose rate/flux effects?

• are there low dose effects?

radiation
environment
cartoon



Radiation environment:

- **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)

basic particle interactions with matter

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

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

Photons:

- photoelectric effect
- Compton effect
- pair production

produce secondary electrons/positrons (extra slides)

Neutrons:

- Ionization cannot be induced but by secondary charged particles.
- Neutron capture/spallation/inelastic scattering: formation of excited composite nucleus followed by de-excitation and emission of γ-rays, particles (α, $\beta^{+/-}$, n, p), nuclear fragments
- Elastic scattering with nuclei ($\Rightarrow$ displacement damage)

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 by radiation per unit mass:

Formula	Measurement Unit
$D=E/M$	J/kg

Dose

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

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

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

proportionality

dose (energy/mass) = factor(energy-length^{2}/mass) × **fluence (length^{-2})**

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

- **ionising** energy loss → total ionising dose (TID)
- **non-ionising** energy loss (NIEL) → displacement damage dose (DDD)

physical quantities

Doses: TID, DDD ⇒ factors: LET, NIEL

dose (energy/mass) = factor(energy-length^2/mass) × fluence (length^{-2})

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

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

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

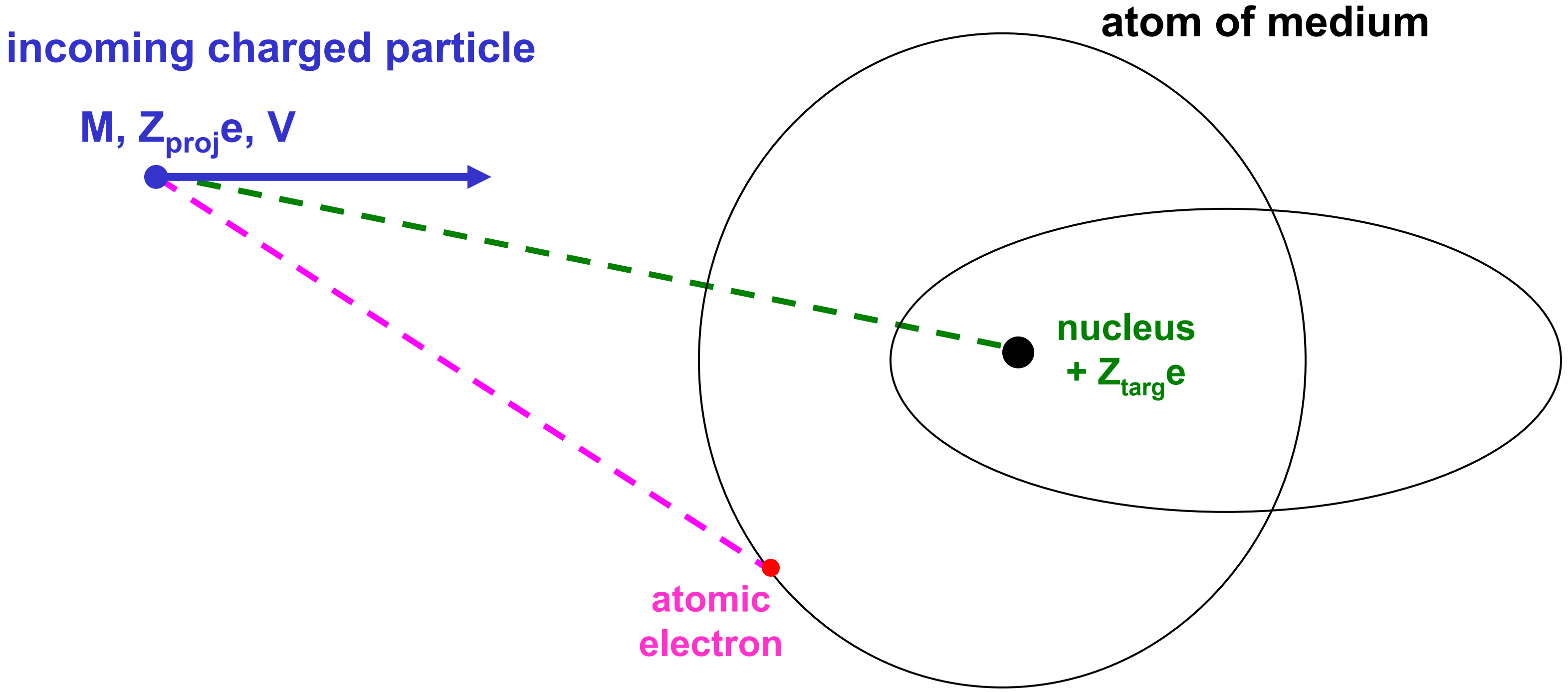
energy to ionisation(MeV) = **LET(MeV-cm^2/mg)** × **ϕ(cm^{-2})** × mass(g) × 10^3

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

ionisation

A charged particle travelling thru a medium

Coulomb interaction with atomic electrons or with the nucleus:



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

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

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

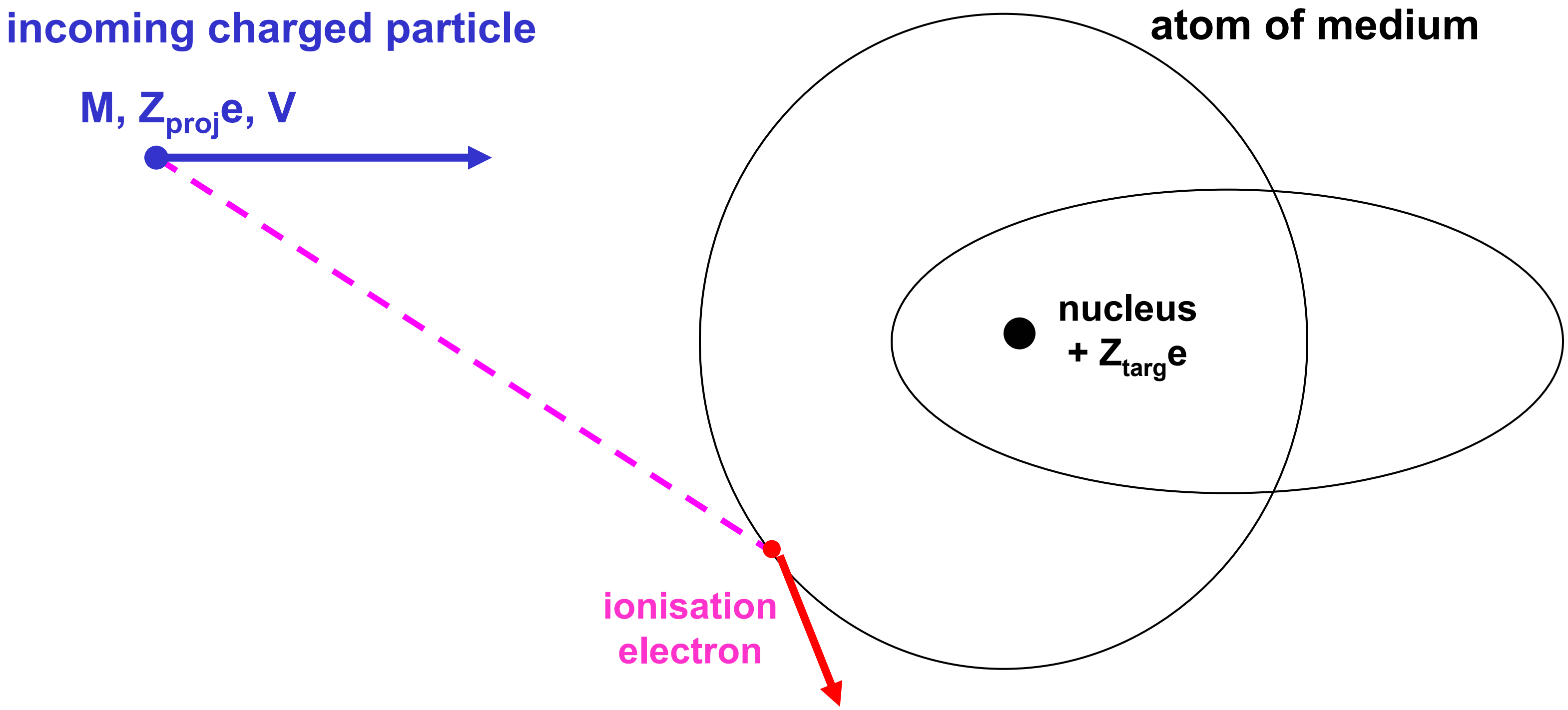
regards energy transfers coulomb collisions with electrons are much more important than with nuclei (except when very SLOW at end of range!)

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

transfer momentum and energy 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,…



incoming charged particle

M, Z_{proj}e, V

atom of medium

nucleus
+ Z_{targ}e

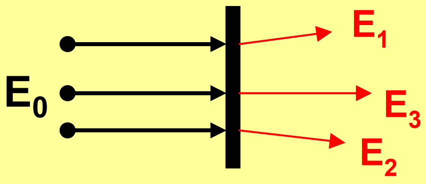
ionisation
electron

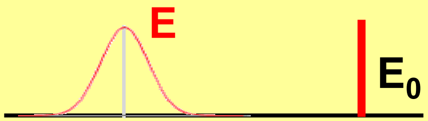
heavy charged particles (muon, p, α, ions,...)

Moving they exert **coulomb forces** on **many atoms simultaneously**

- **each atom has many electrons;**
- **the atomic electrons have different depths 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!**





$$\boxed{\langle E\rangle - E_0 \equiv \Delta E \rightarrow 0 \text{ as } \Delta x \rightarrow 0}$$

senseless/impossible to calculate energy loss by studying individual interactions

$\Rightarrow$ **calculate average energy loss of incident particle per unit distance travelled.**

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

ionisation

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

lose small amounts of energy per coulomb collision:

- **are hardly deflected by atomic electrons**
- **do get deflected by rare close-by interaction with nuclei (multiple scattering)**

BUT

the overall trajectory is almost a straight line!!!

$$\text{RANGE} = \int \left(\frac{dE}{dx} \right)^{-1} dE$$

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

TOTAL stopping power **dE/dx**

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

NOTE: both change along track as particle slows down to stop (thermal)

physical quantities

Bethe-Bloch heavy ions

$\beta = V/c$

$$\text{LET} = \left(\frac{dE}{dx}\right)_{\text{ioniz.}} \sim \left(\frac{Z_{eff}^{2}}{V^{2}}\right)_{\text{particle}} \times \left(\frac{z\rho}{A}\right)_{\text{target}} \times \left\{ ln\left(\frac{2\, m_e c^2 \beta^2}{I}\right) - ln\,(1-\beta^2) - \beta^2 - \delta \right\}$$

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

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

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

- for $V \approx v_{Bethe}$ and slower

  ion picks-up/retains 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

$$\text{LET}(Z,V) \sim \rho \times Z^2 \times F(V) = \rho \times \frac{Z^2}{\beta^2} \times f(V)$$

$$\frac{\text{LET}(Z,V)}{\rho} \sim \frac{Z^2}{\beta^2} \times f(V)$$

Silicon: ρ = 2.33 g/cm^3

physical quantities

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

$\mathrm{LET}(Z, V) = Z^2 \times \mathrm{LET}(\mathrm{proton}, V)$

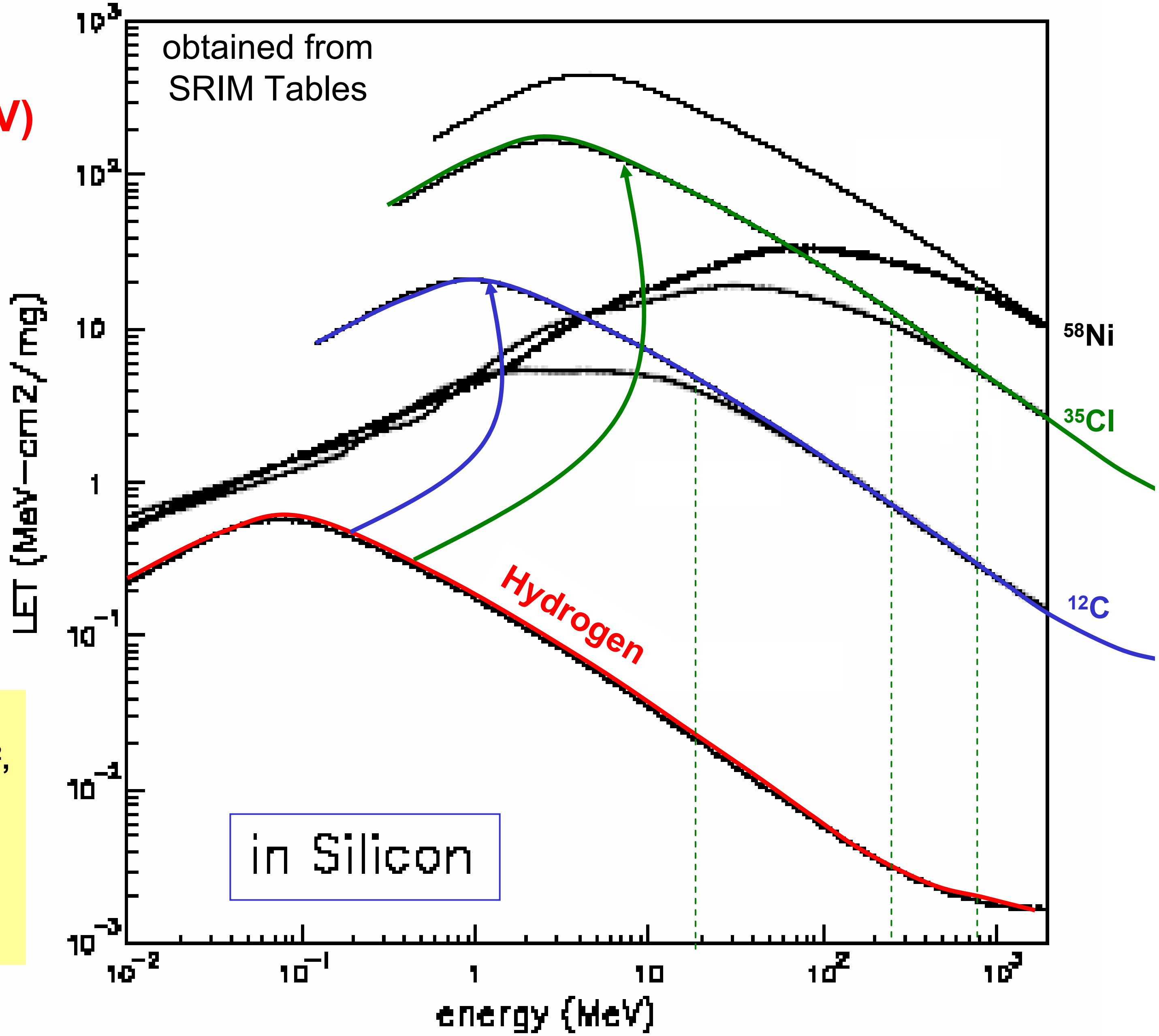
NOTE: for $V = Z^{2/3}/137$

$Z_{\mathrm{eff}} \approx 60\%$ of Z.

Dashed lines are

at kinetic energy E for

$Z_{\mathrm{eff}} \approx 90\%$ of Z.



Non-Relativistic approx.
kinetic energy $E = 1/2\, Mv^2$,
mass $M_{\mathrm{ion}} \approx A \times m_{\mathrm{proton}}$
$\Rightarrow$ ion has
same velocity of proton
for $E = A\, E_{\mathrm{proton}}$

physical quantities

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

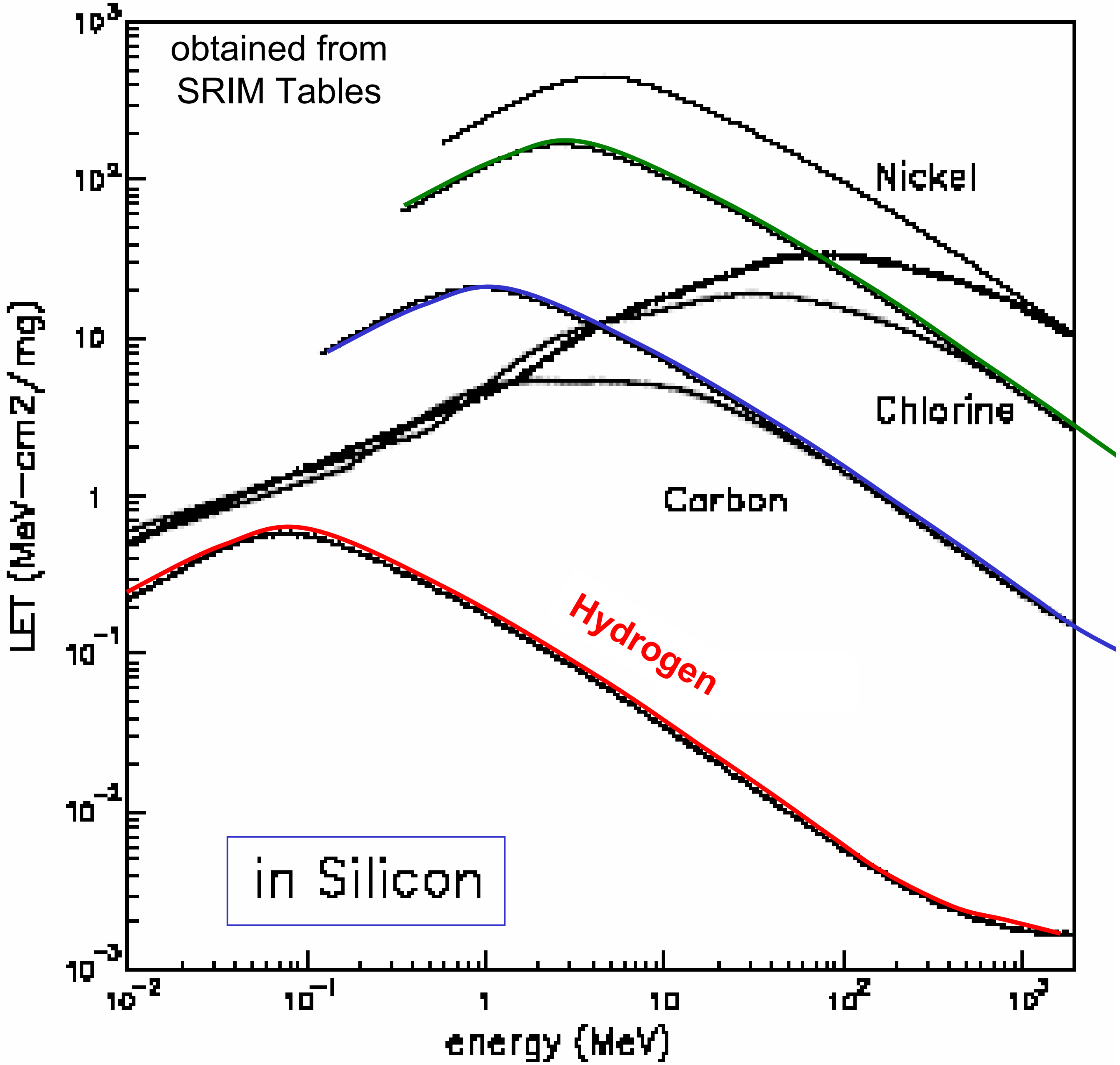
LET(Z, V) =
$Z^2 \times$ LET(proton, V)

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

$$\frac{\mathrm{LET}_{min}(Z)}{\mathrm{LET}_{min}(\mathrm{proton})} = Z^2$$

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



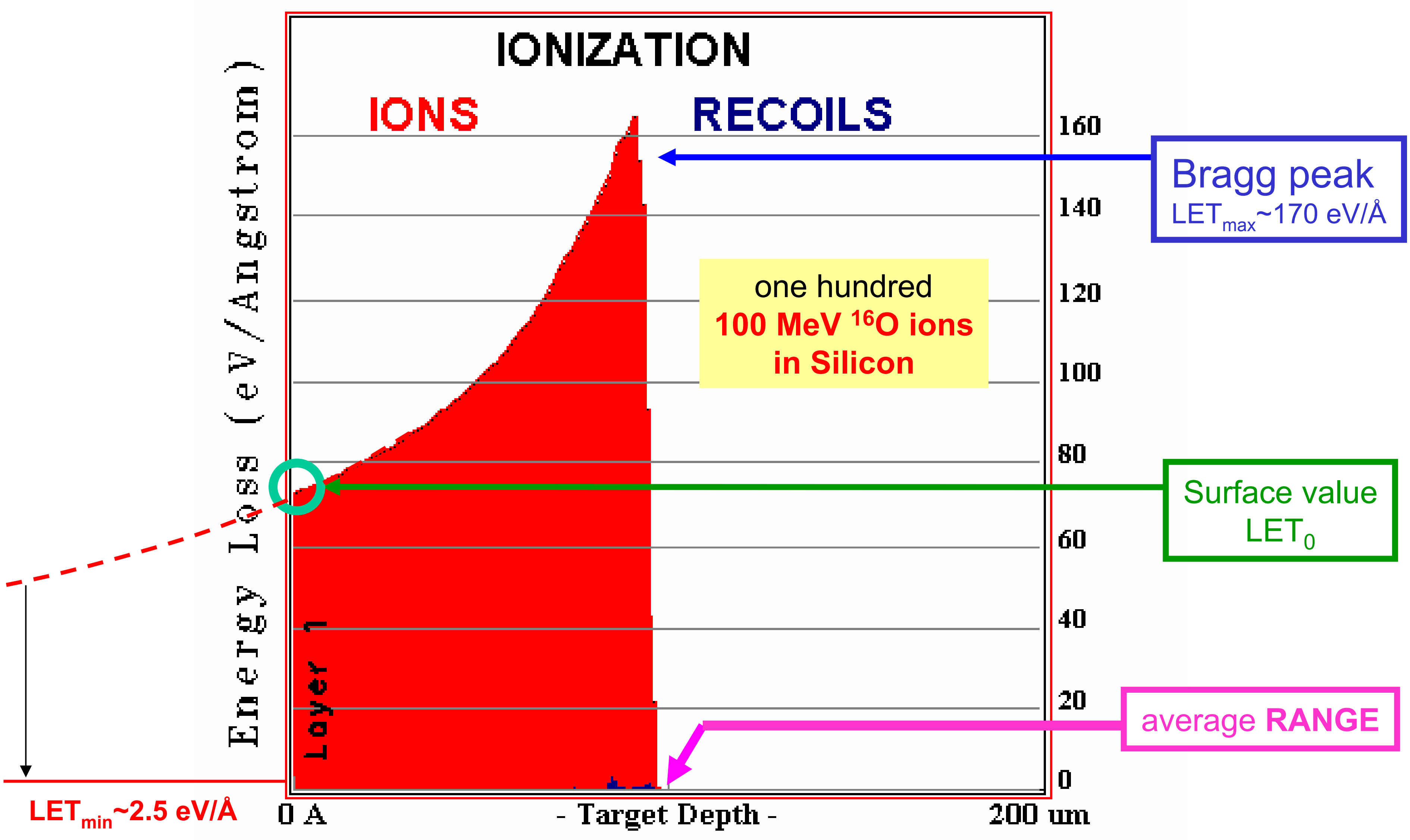
max LET does not simply scale

ion	LET_{Min} ($MeV\text{-}cm^2/mg$)	LET_{Max} ($MeV\text{-}cm^2/mg$)	E_{Max} (MeV)	Range at E_{max} (μm)
H	1.665×10^{-3}	**0.53**	0.08	0.92
α	6.67×10^{-3}	**1.57**	0.47	2.21
$^{12}C_6$	0.06	**5.38**	2.42	3.06
$^{16}O_8$	0.11	**7.46**	5.54	4.98
$^{25}Mg_{12}$	0.24	**12.18**	16.74	7.52
$^{28}Si_{14}$	0.33	**14.57**	22.46	8.45
$^{35}Cl_{17}$	0.48	**18.13**	33.4	10.13
$^{58}Ni_{28}$	1.3	**31**	87.8	15.73

elastic nucleon-Silicon	$n + {}^{28}Si \rightarrow n + {}^{28}Si$ *with high LET recoiling Silicon*
inelastic nucleon-Silicon	$n + {}^{28}Si \rightarrow \alpha + {}^{25}Mg$ $Q = -2.6\ MeV$ $p + {}^{28}Si \rightarrow \alpha + {}^{25}Al$ $Q = -7.7\ MeV$ *reactions with high LET fragments*

physical quantities

LET = $(dE/dx)_{ionization}$ vs depth



one hundred
100 MeV ^{16}O ions in Silicon

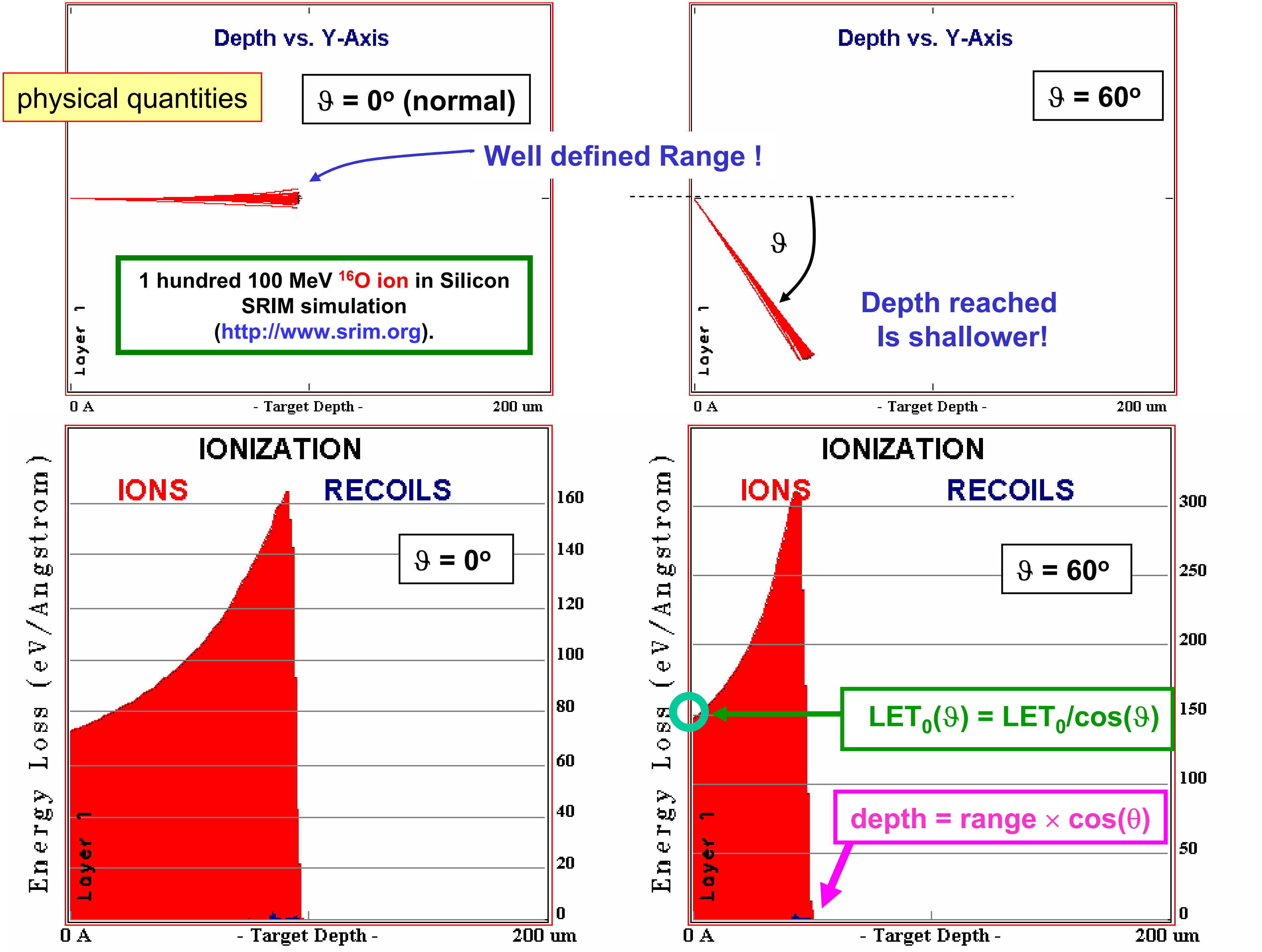
Bragg peak
LET_{max}~170 eV/Å

Surface value
LET_0

average **RANGE**

LET_{min}~2.5 eV/Å

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



physical quantities

$\vartheta = 0°$ (normal)

Well defined Range !

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

$\vartheta = 60°$

Depth reached
Is shallower!

$\vartheta = 0°$

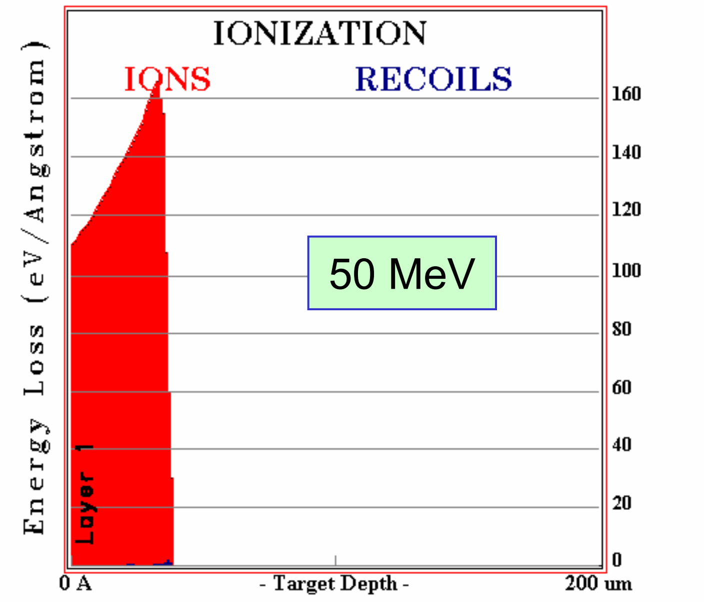
$\vartheta = 60°$

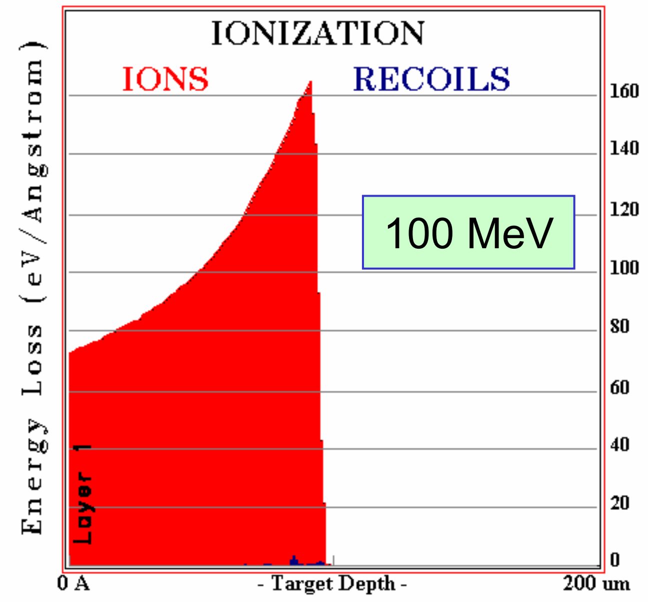
$LET_0(\vartheta) = LET_0/\cos(\vartheta)$

depth = range $\times$ cos(θ)

physical quantities

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

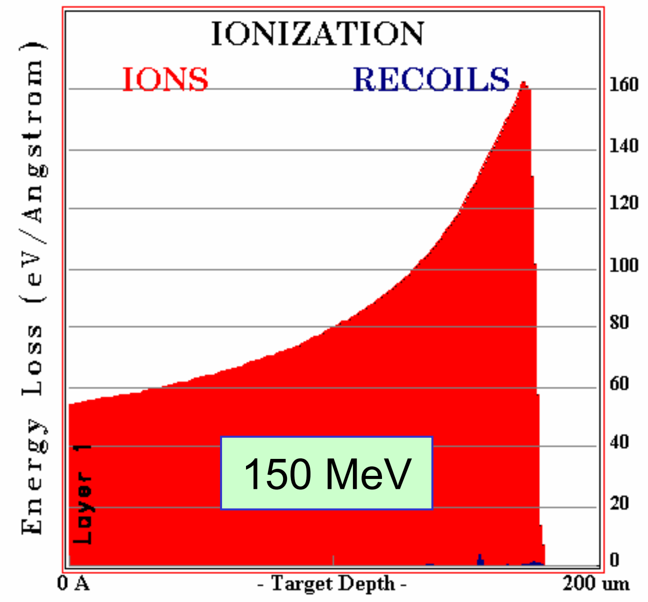




surface LET in silicon

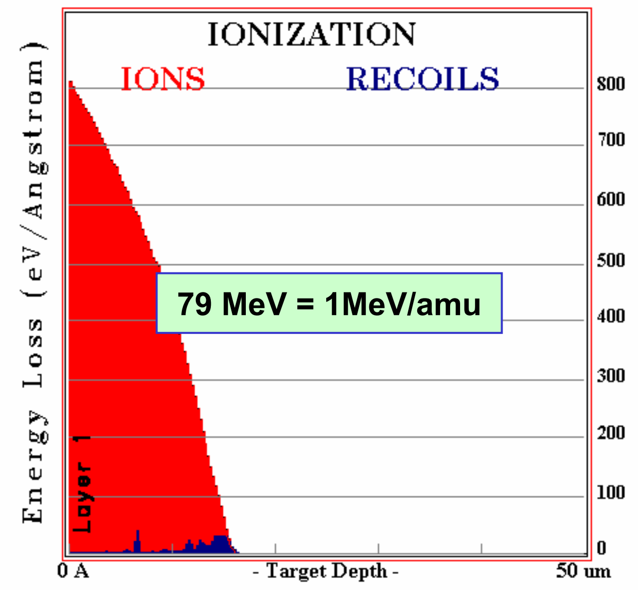
energy (MeV)	range (microns)	LET(0) (eV/Å)	LET(0) (MeV-cm^2/mg)
50	37.65	108.16	4.66
100	95.23	72.12	3.107
150	176.23	53.97	2.325

LET(0) decreases monotonically with E!

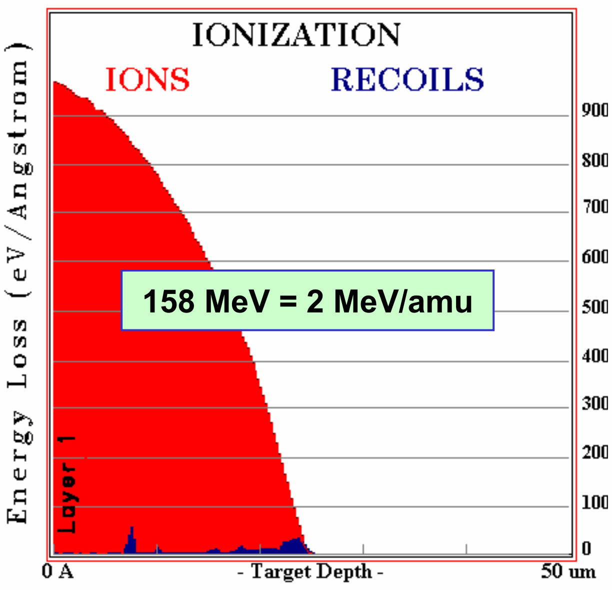


physical quantities

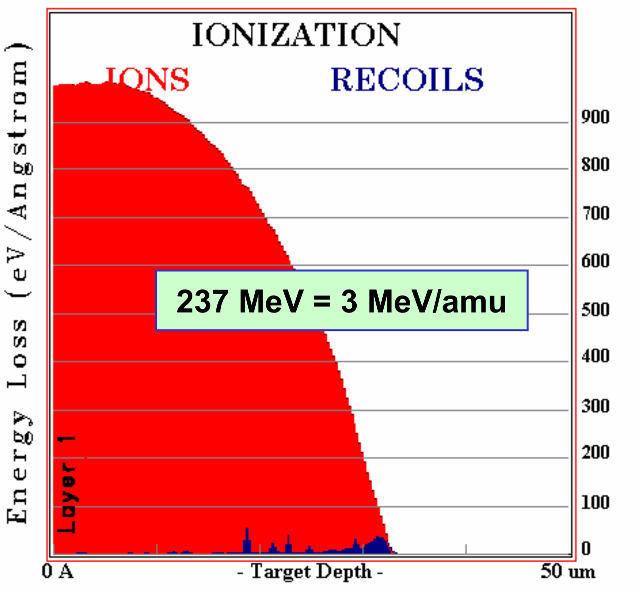
1 hundred Br^{79} in silicon (SRIM 2003)



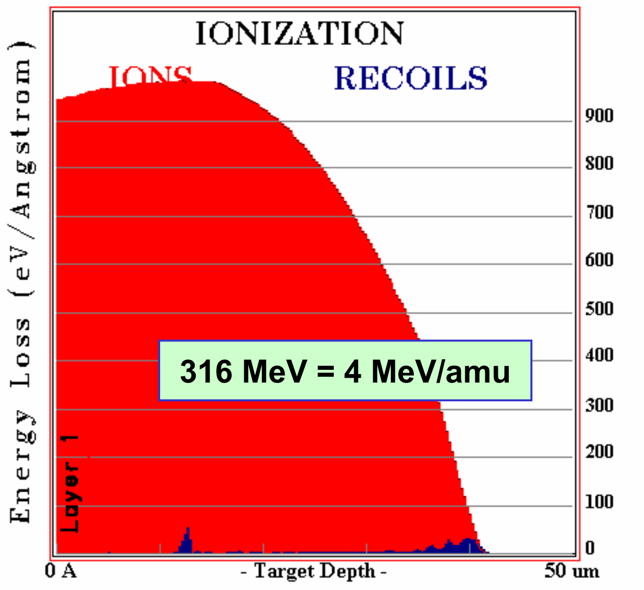
79 MeV = 1MeV/amu



158 MeV = 2 MeV/amu



237 MeV = 3 MeV/amu



316 MeV = 4 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

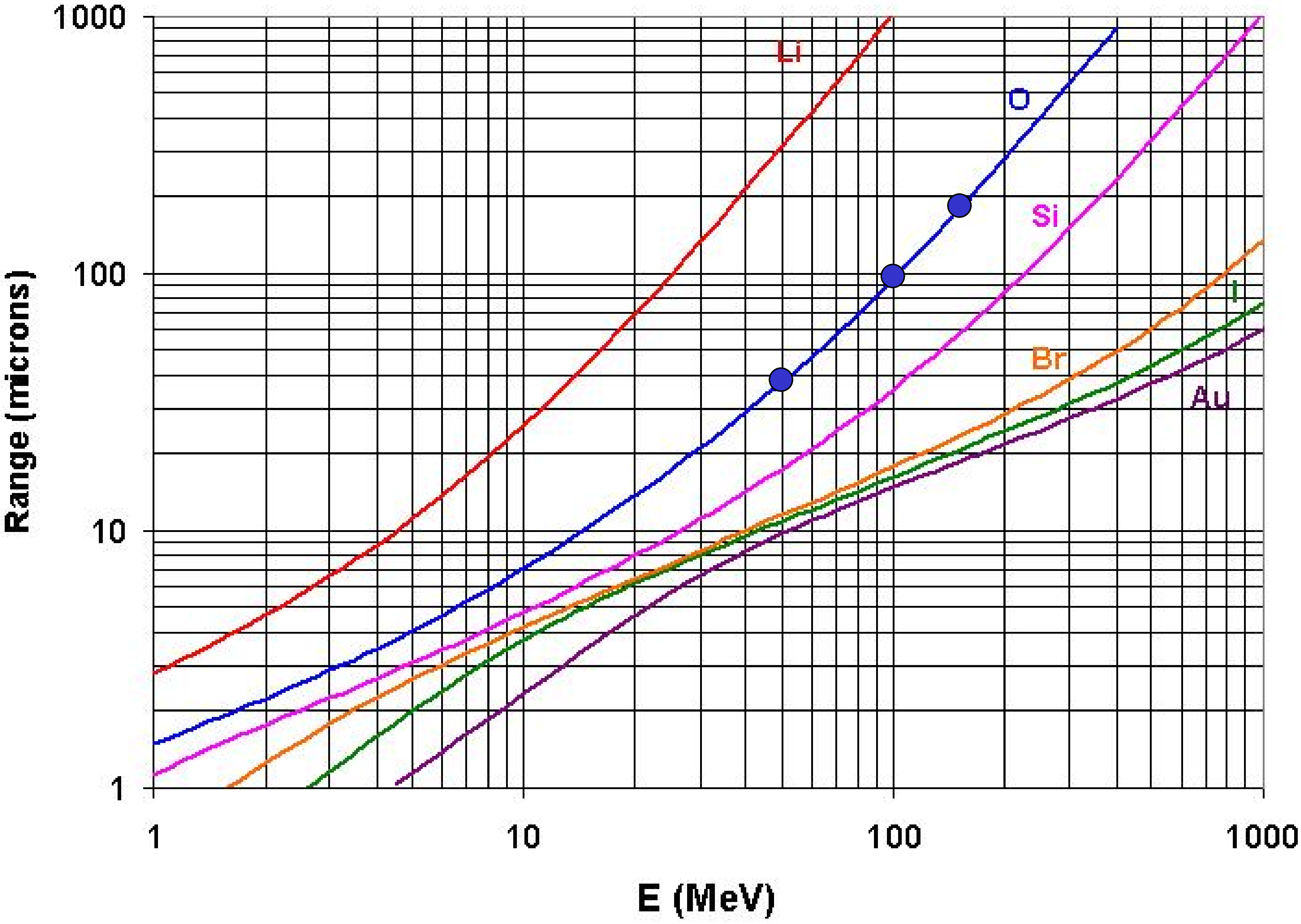
broad maximum

decrease!
beyond maximum

physical quantities

range in Silicon

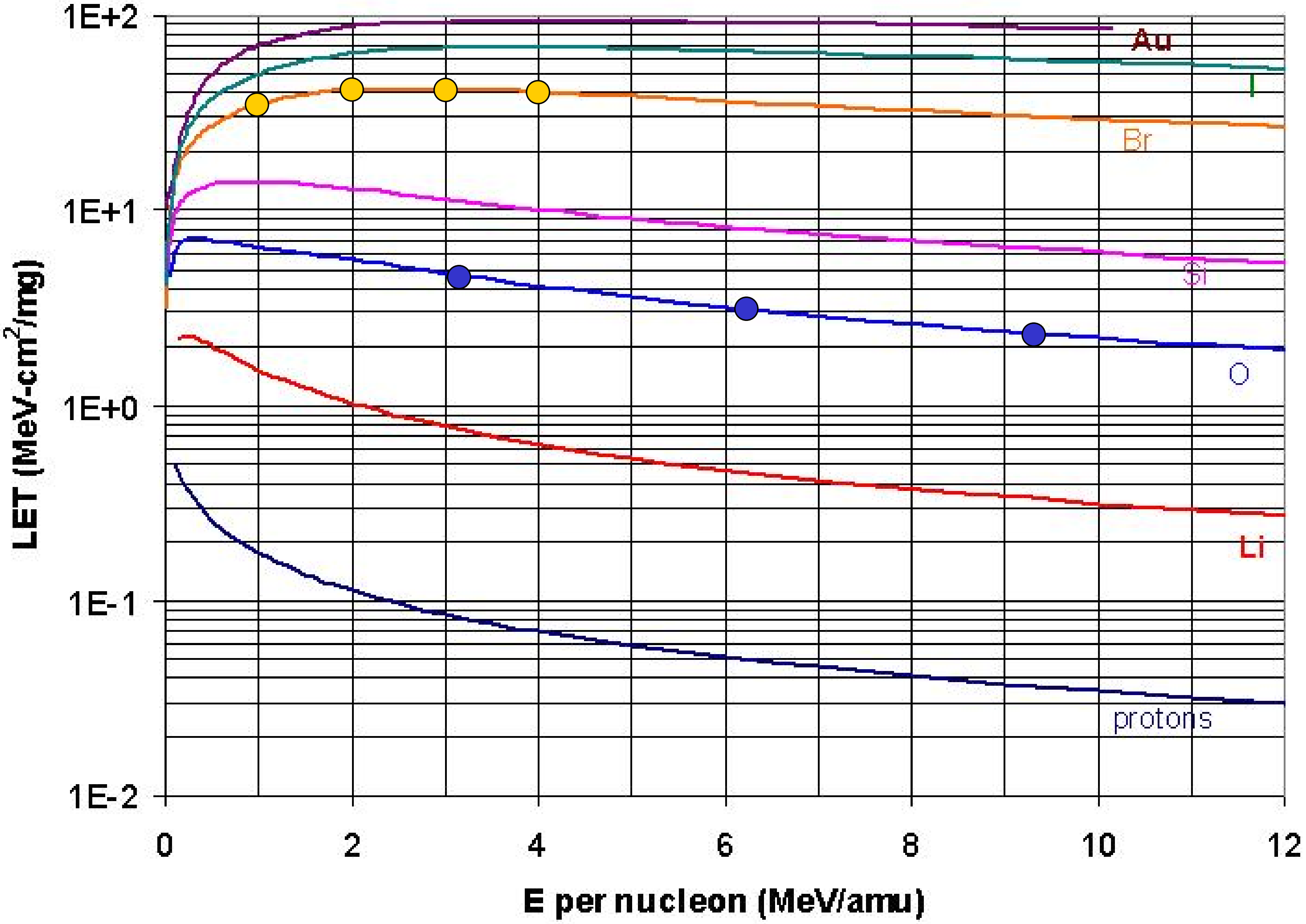
obtained from
SRIM Tables



physical quantities

surface LET in Silicon

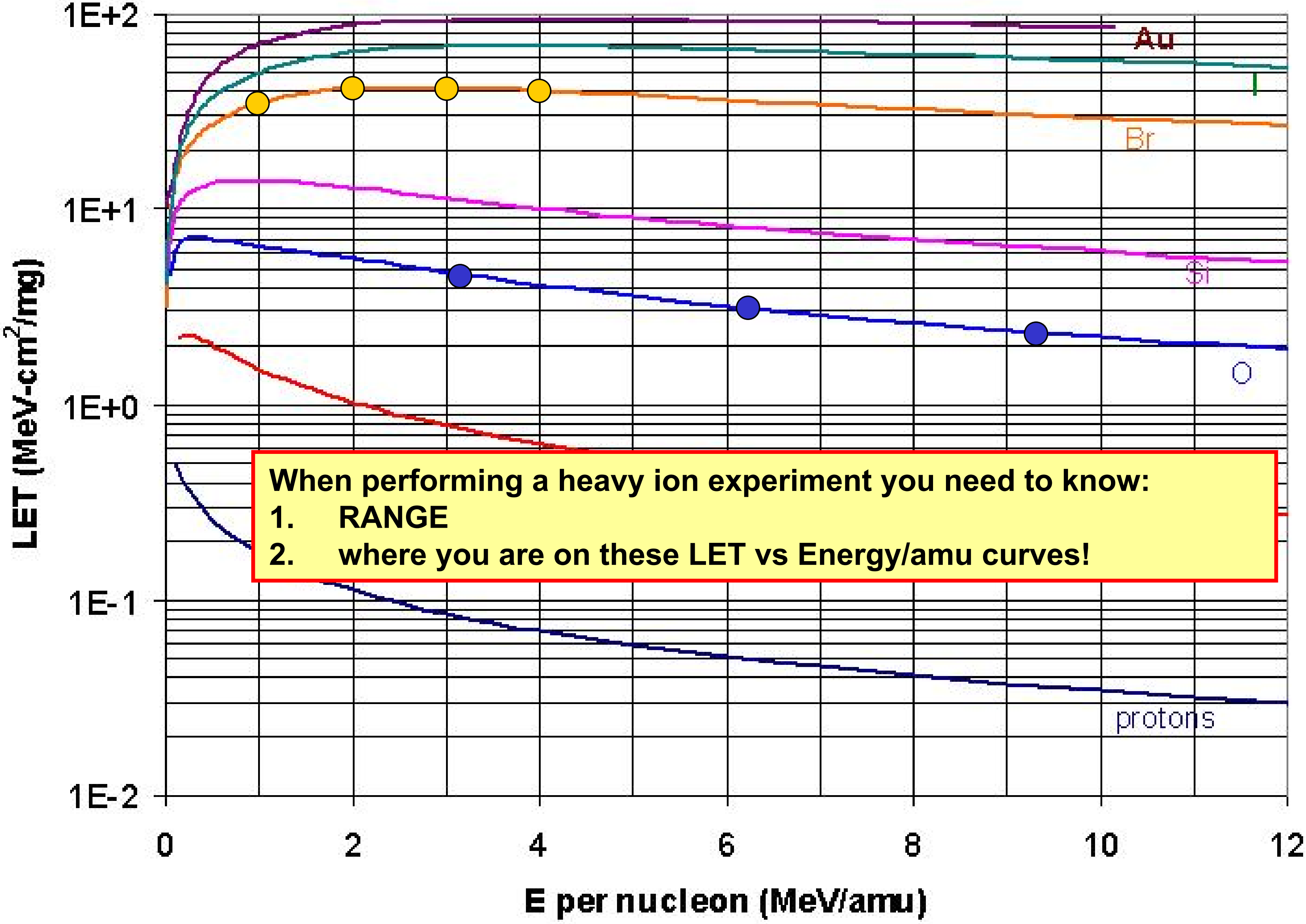
obtained from
SRIM Tables



physical quantities

surface LET in Silicon

obtained from SRIM Tables



When performing a heavy ion experiment you need to know:

1. **RANGE**
2. **where you are on these LET vs Energy/amu curves!**

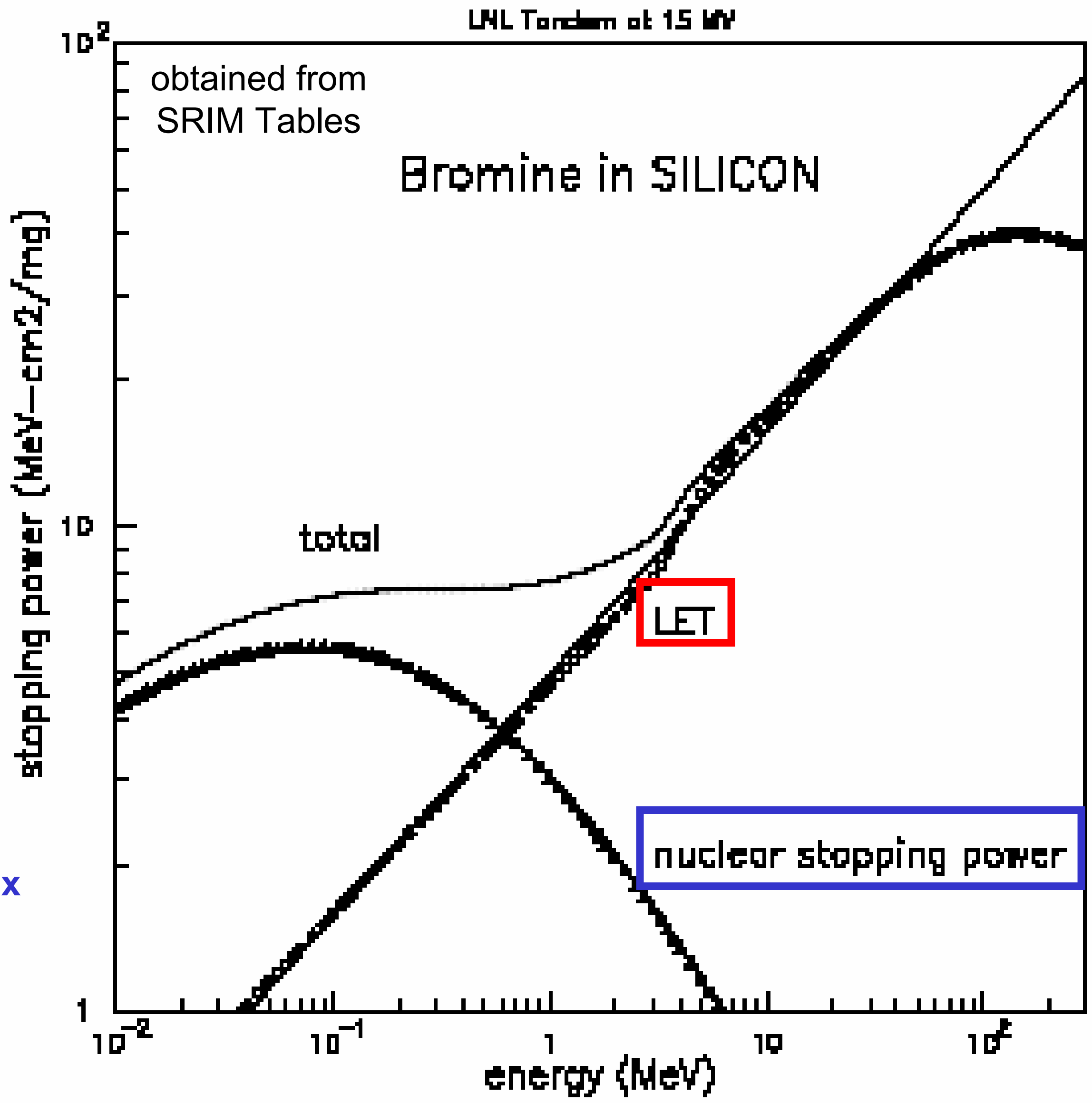
physical quantities

total stopping power of a heavy ion:

$$dE/dx = (dE/dx)_{\text{ionization}} + (dE/dx)_{\text{nuclear coulomb}} = \text{LET} + \text{NIEL}$$

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

- **LET decreases monotonically**
- **nuclear stopping power goes thru max**



obtained from
SRIM Tables

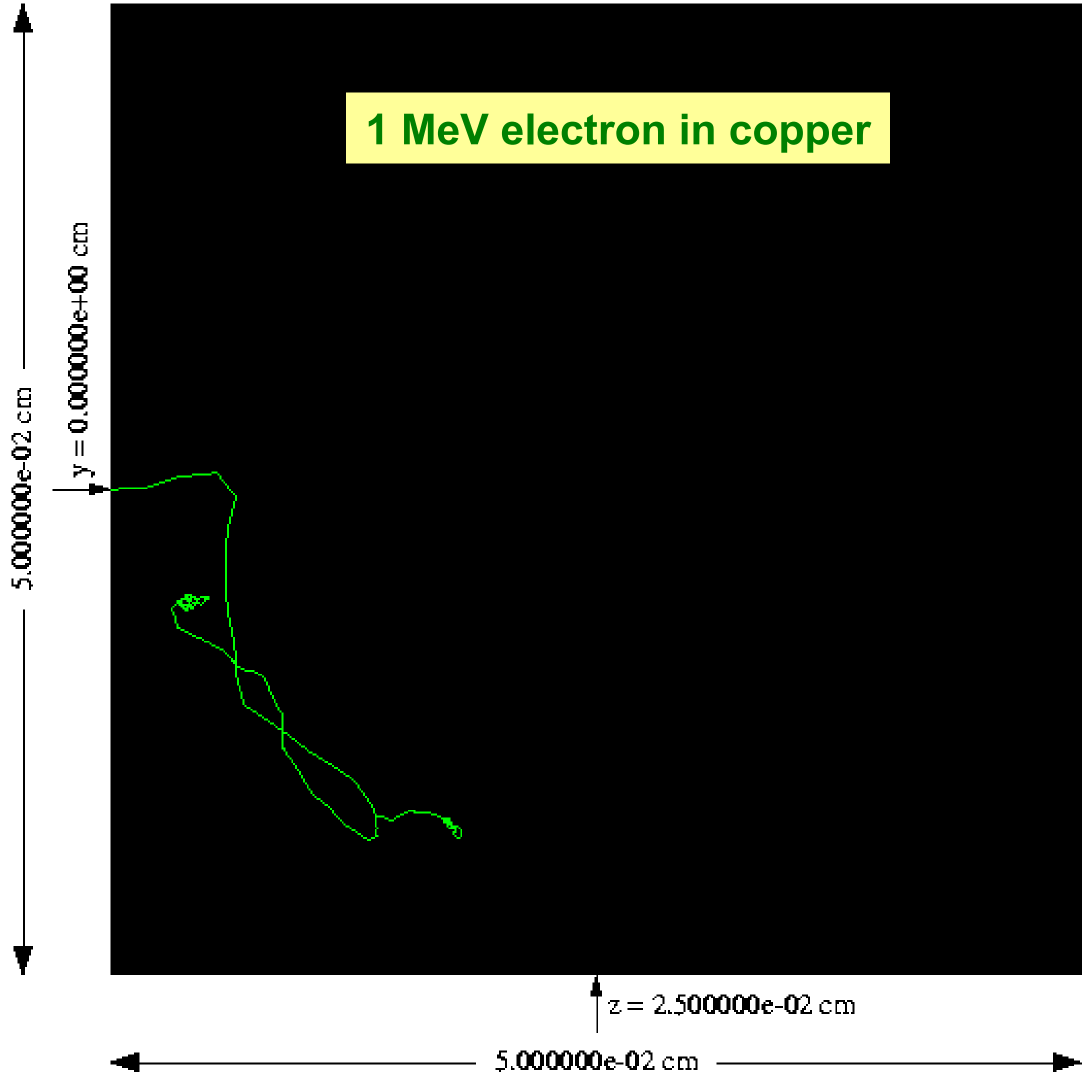
ionisation

WARNING: an electron (positron) projectile behaves quite differently:

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

EGS to order

http://www2.slac.stanford.edu/vvc/egs/advtool.html

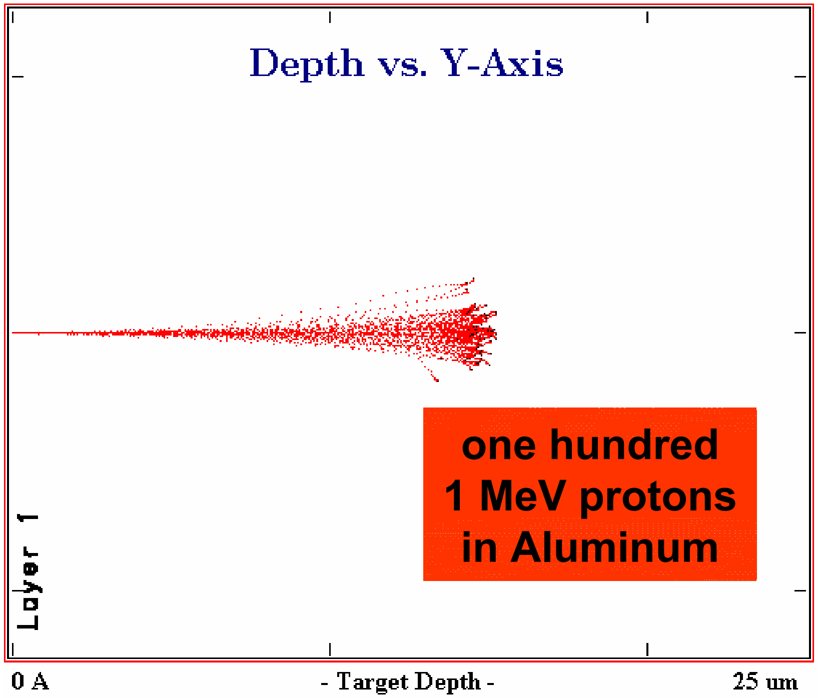


1 MeV electron in copper

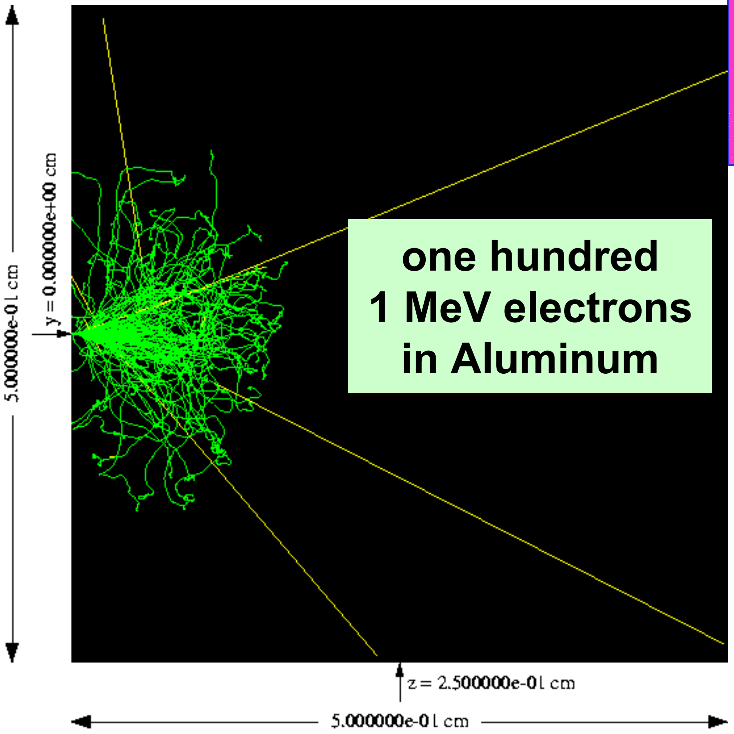
path very zig-zag!

**0.5 mm
by
0.5 mm**

range not well defined for electrons



one hundred
1 MeV protons
in Aluminum

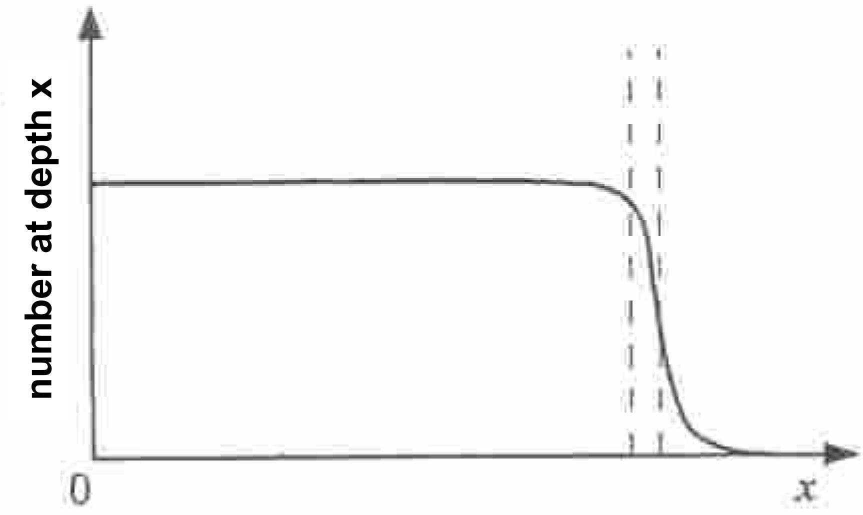


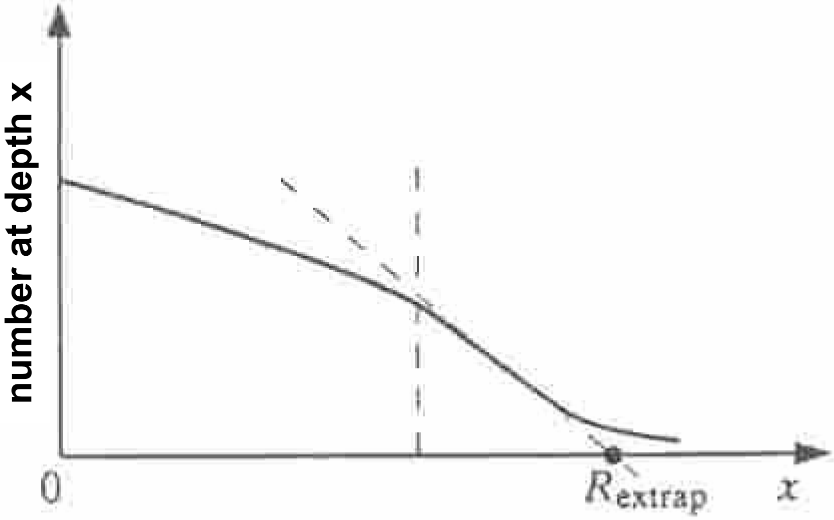
one hundred
1 MeV electrons
in Aluminum

electrons
in green

photons
in yellow

5 mm
by
5 mm

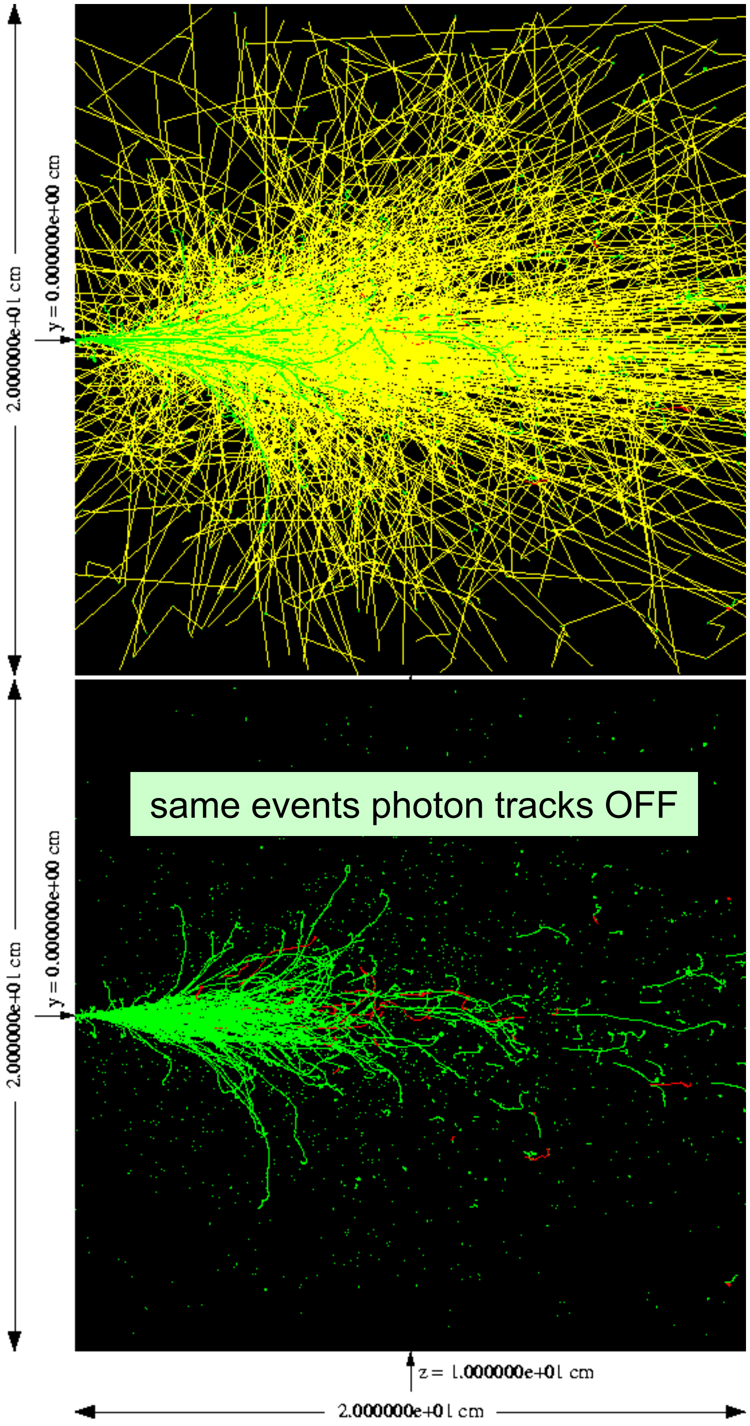




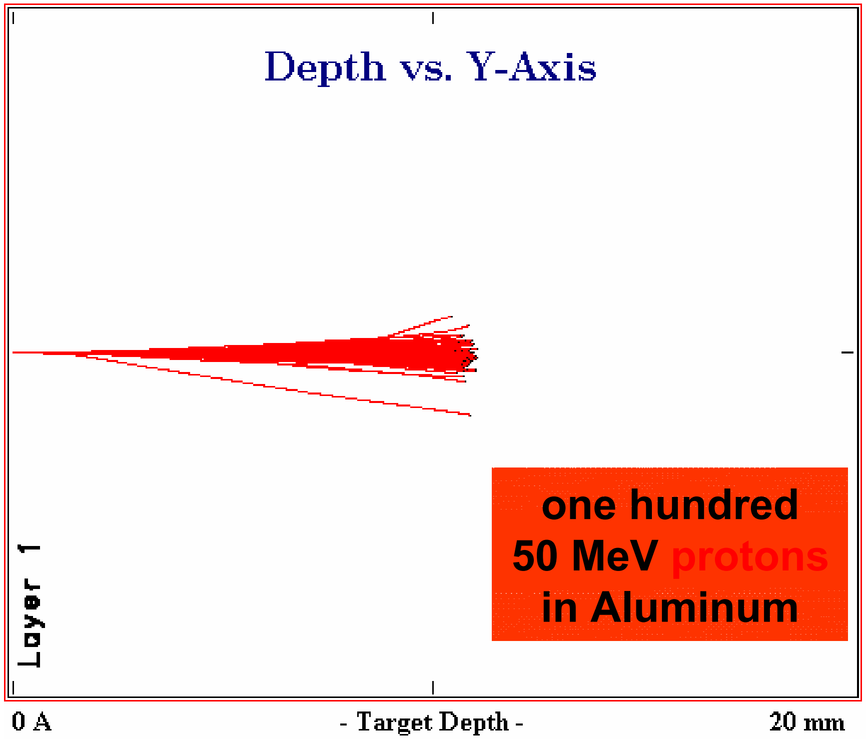
radiation

electrons lose energy also by radiation

one hundred
50 MeV electrons
in Aluminum



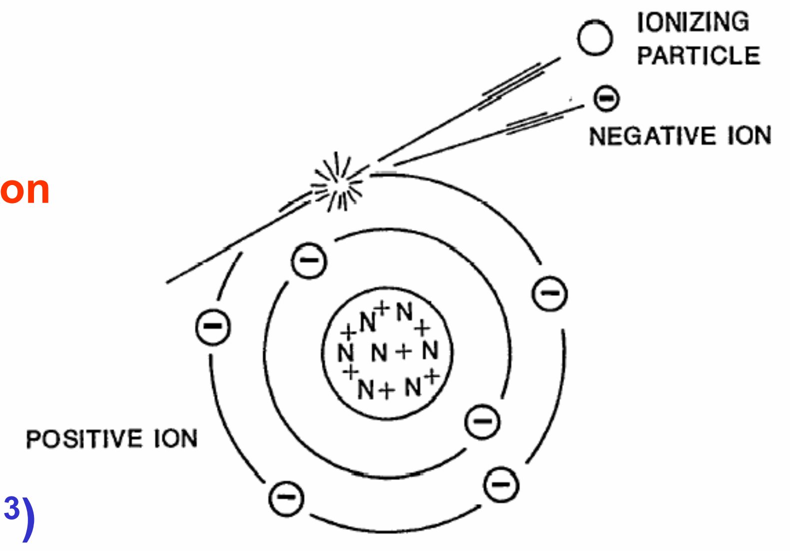
same events photon tracks OFF



one hundred
50 MeV protons
in Aluminum

summary: Linear Energy Transfer (LET)

energy deposited per unit path length due to ionization;
i.e. the coulomb interaction of the impinging particle with the electrons of the material causing ionization.



expression

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

Measurement units

MeV/cm, also eV/μm

or dividing by density ($\rho_{Silicon}$ = 2.33 g/cm^3)

MeV-cm^2/mg

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

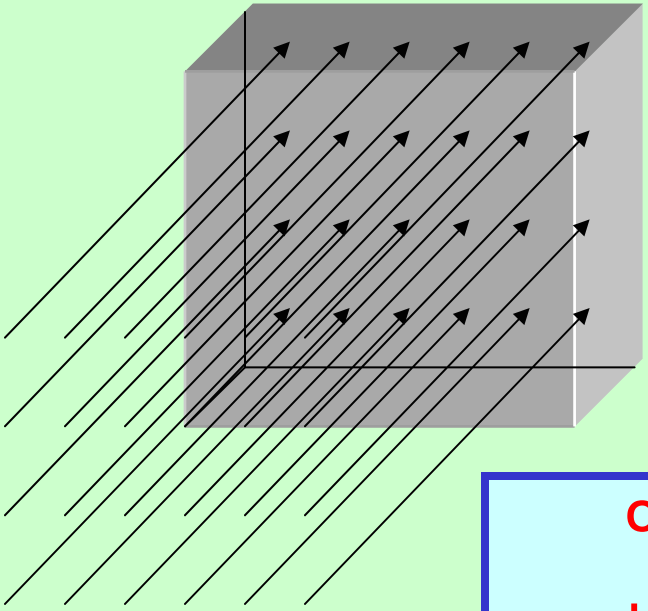
$$TID(rad) = 1.602 \times 10^{-5} \times fluence(\#/cm^2) \times LET(MeV\text{-}cm^2/mg)$$

HOWEVER... caution!

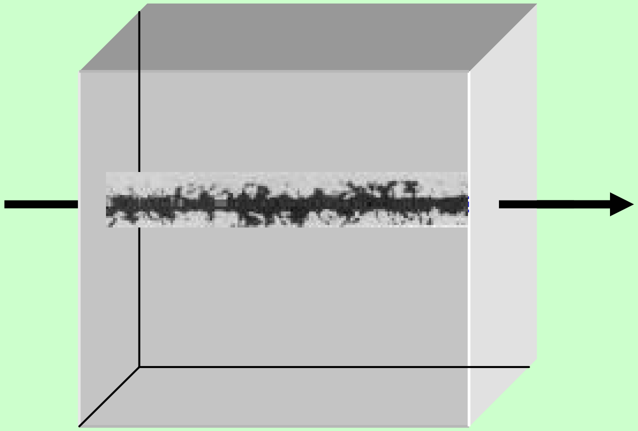
DOSE: energy absorbed per unit mass

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

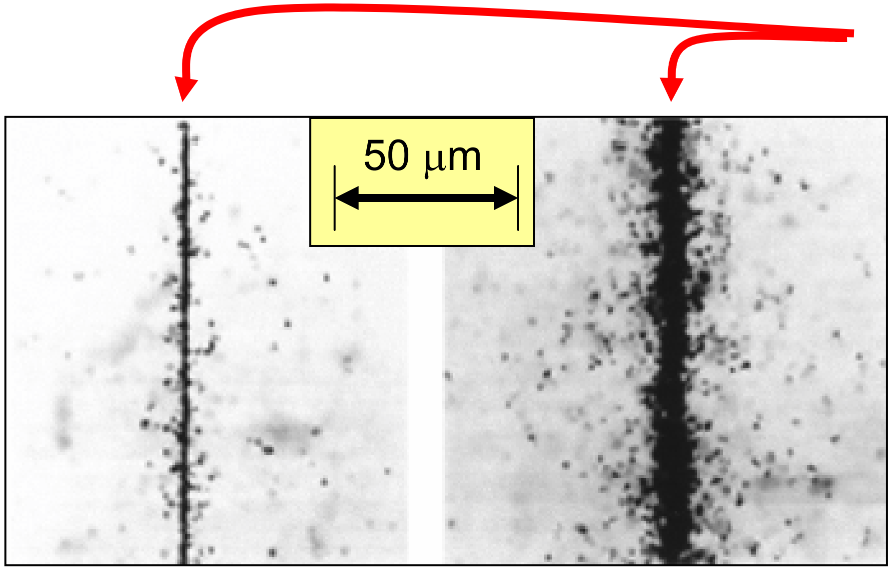


One unit of dose can be deposited by many photons (left) or by a single ionizing particle track (right)

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!

track structure



several nanometer dense core

ion with Z = 4 to 6

Fe ion (Z=26)

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

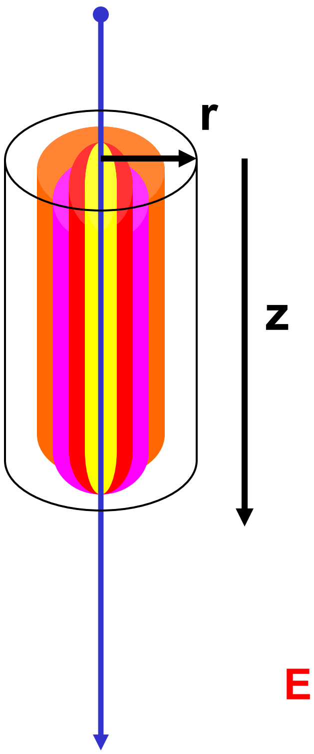
- exponential decrease of ionisation density with distance from track; radial extent of ionisation scales with the **velocity V of ion** (indeed the max energy transfer to electrons is $2m_eV^2$)

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

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

track structure

simple track structure model



Model to describe heavy ion induced carrier (electron-hole pairs) generation rate density (number of e-h/cm³-s):

spatial extent

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

N.B. no z 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)

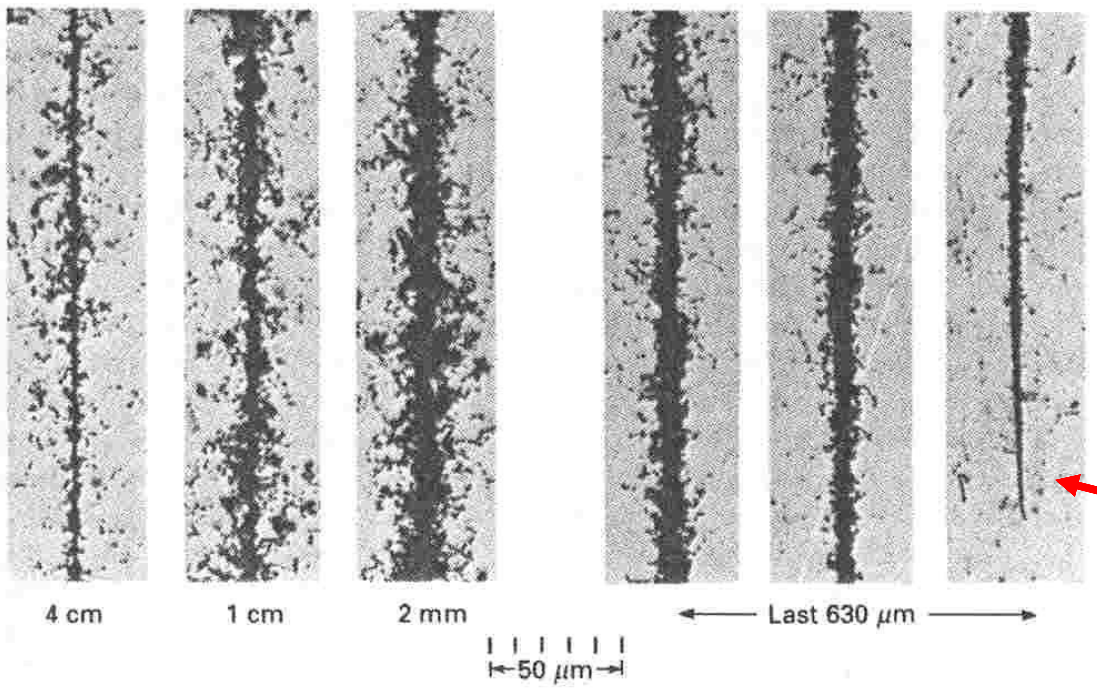
r_0 = length parameter arbitrarily and typically set at 100 nm (0.1 μm)

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 carrierers. Of the order 10^{-12} s

example: for 158 MeV ^{79}Br $g(r,z,t) = \boxed{4.8 \times 10^{31}\ \text{(e-h/cm}^3\text{-s)}} \times \exp(-r^2/r_0^2) \times \exp(-t^2/\tau^2)$

track structure

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

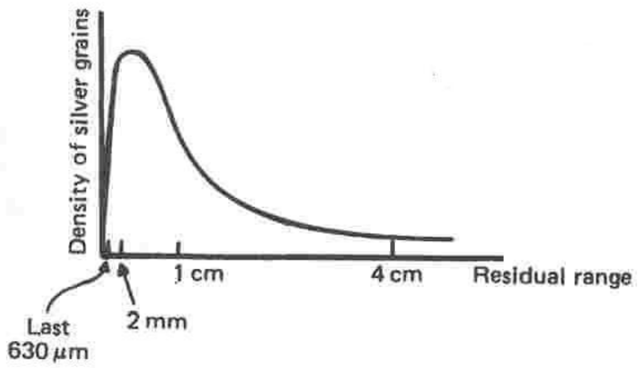


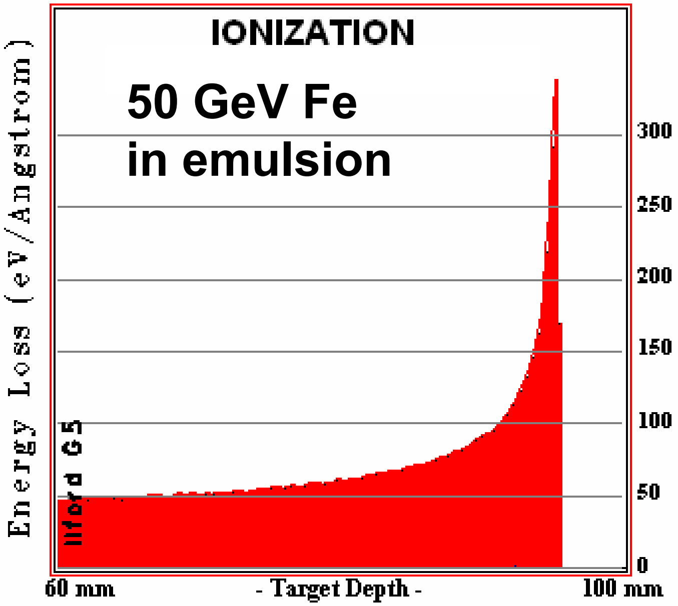
Ion stopped

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

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

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





physical quantities

Effects of typical Ionising Radiation Doses

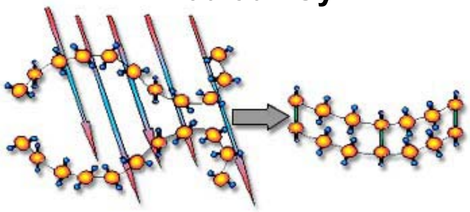
$$\text{ionising dose} = \frac{\text{energy imparted by ionising radiation}}{\text{mass of target}}$$

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



Life in space

its a tough life in space

- Skylab mission 2500 mrad = 0.025 Gy
- orbits 250-300 km at 65^{o} (resp. equator) 10 mrad/day
- pass thru Van Allen 0.1-0.2 Gy/hr (passage lasts10-20 min)

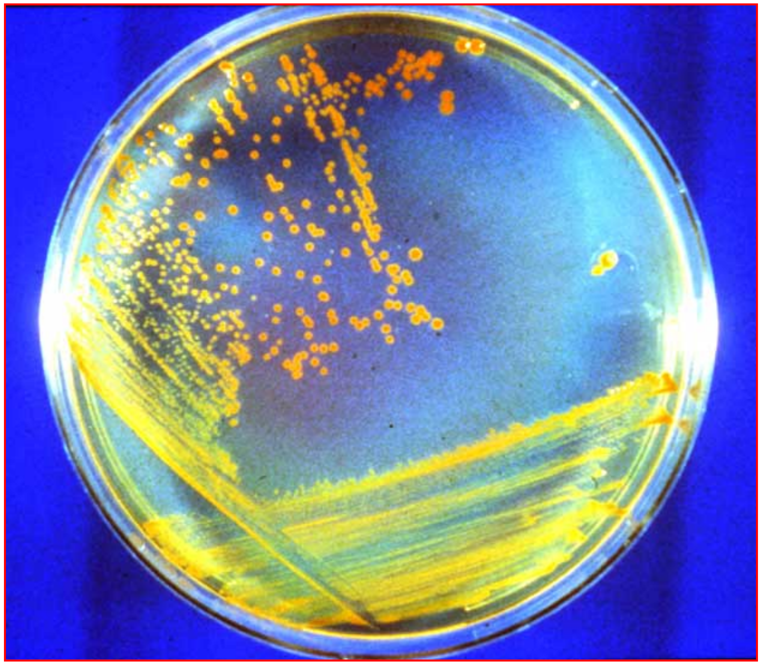
- Shuttle ~ 433 mrem/mission average skin dose
- Shuttle 7864 mrem highest skin dose
- CT scan 700 mrem/event
- X-ray diagnostic 100-200 mrem/event
- human natural sources (cosmic, radioactivity) 80 mrem/yr

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

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

rad-hard bacteria

deinococcus radiodurans



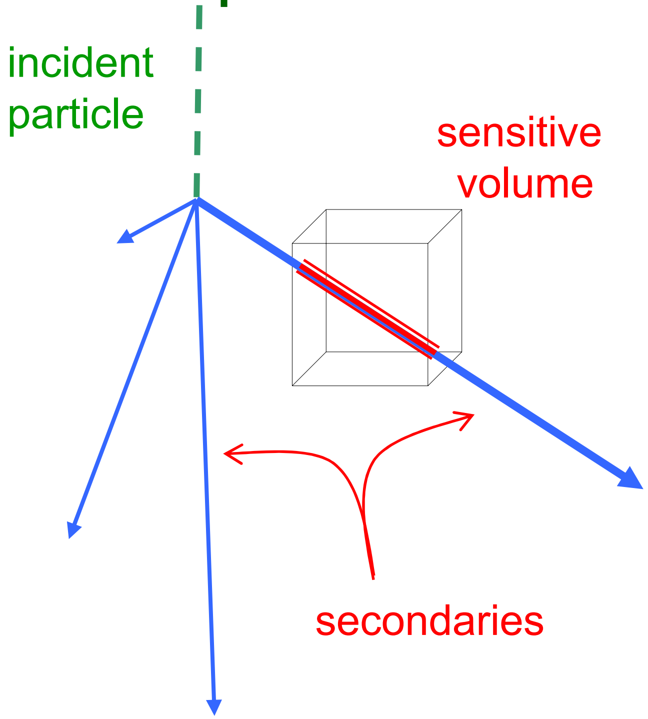
Single Event Effects (SEE)

A single particle produces enough ionisation (directly or indirectly) causing a macroscopic (anomalous) effect in a polarized device. Threshold effect: requires a large energy deposition in a sensitive part of a chip:

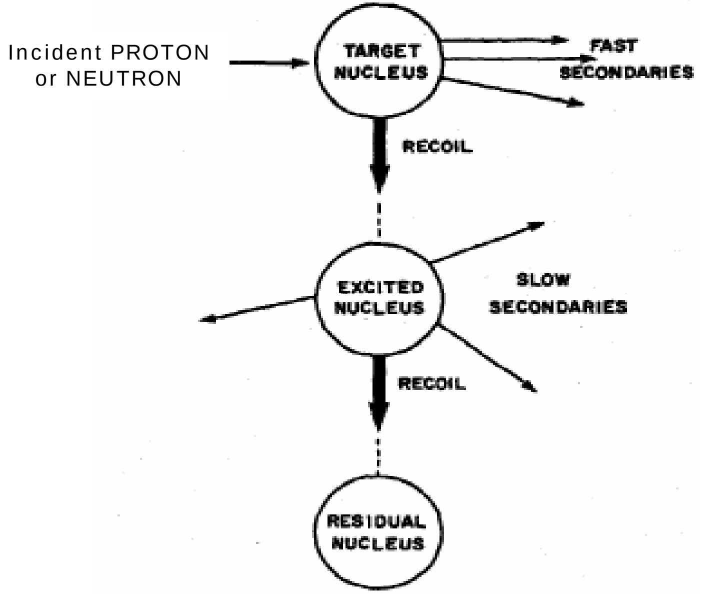
- ***passage of heavy ion (in Space, not at LHC)***
- ***energetic recoiling nucleus or fragment***

At LHC possible nuclear reactions:

- ***hadron-Si scattering at high energy (E>20 MeV)***
- ***low-energy (E< 20 MeV) neutron-Si scattering***
- ***thermal neutron capture on boron $^{10}B(n,\alpha)^{7}Li$***



Inelastic scattering:



nuclear spallation reaction induced by protons/ neutrons.

- **cascade stage** (top): fast secondaries emerge in the forward direction.
- **evaporation stage** (middle): secondary protons, neutrons, deuterons and alphas particles emerge isotropically.
- **recoil stage** (bottom): residual fragment of the target nucleus emerges with the momentum gained in the earlier stage.

strong ionization effects: SEE

SEE-OLOGY

**For a given radiation environment
the mechanisms of an SEE and the PROBABILITY of it occurring
are *device and technology dependent*.**

destructive events

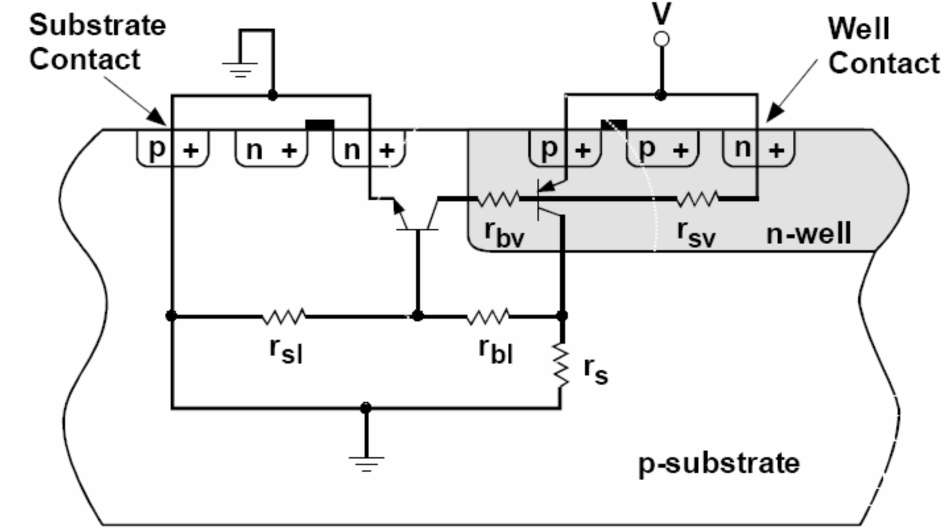
- **Single Event Burnout (SEB) in power DMOS transistor**
- **Single Event Snapback (SES) in MOSFET**
- **Single Event Gate Rupture (SEGR) in DMOS transistor**
- **Single Event Latch-up (SEL) in CMOS technologies**

NON-destructive events

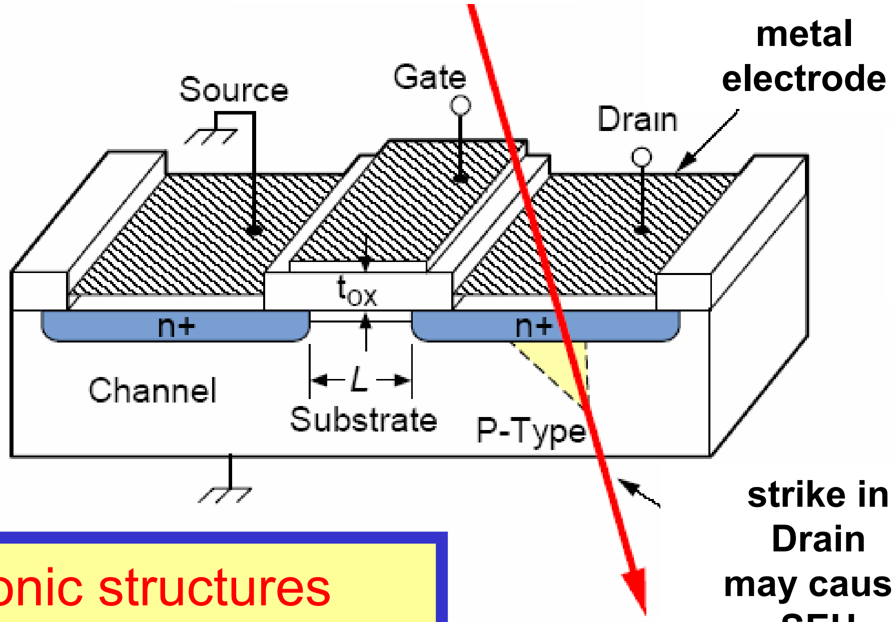
- **Single Event Drain Current Collapse (SEDC^2)**
- **Single Event Upset (SEU)**
- **Single Event Disturb (SED)**
- **Single Event Transient (SET)**
- **Single Event Functional Interrupt (SEFI)**

NOTE: SEE rates are proportional to flux of particles with sufficient LET

SEL path in CMOS structure

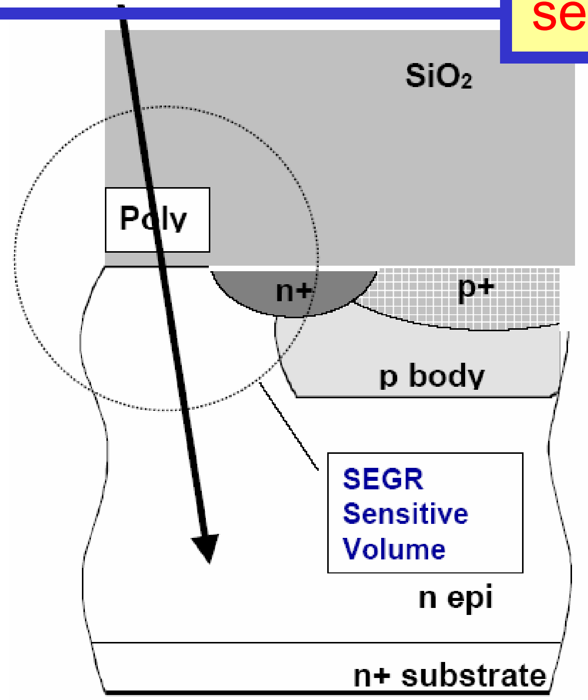


SEU in a DRAM



strike in Drain may cause SEU

various electronic structures sensitive to ionising impacts (SEE)

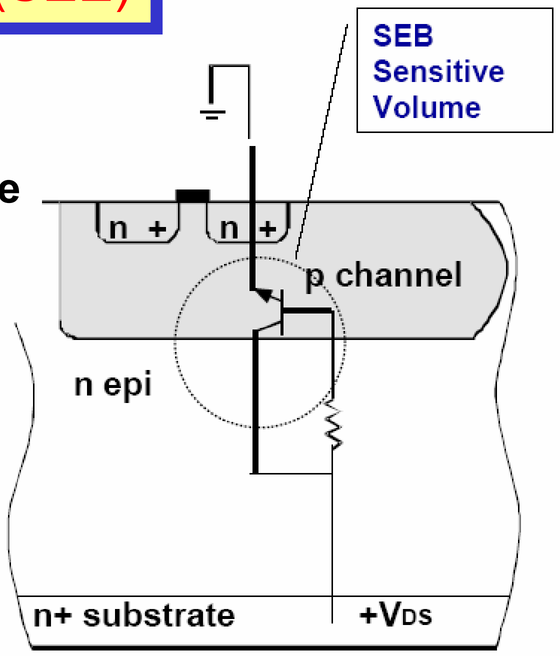


MOSFET

destructive SEGR

HEXFET

destructive SEB



Non Ionizing Energy Loss (NIEL)

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 coulomb or nuclear (strong).

expression

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

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

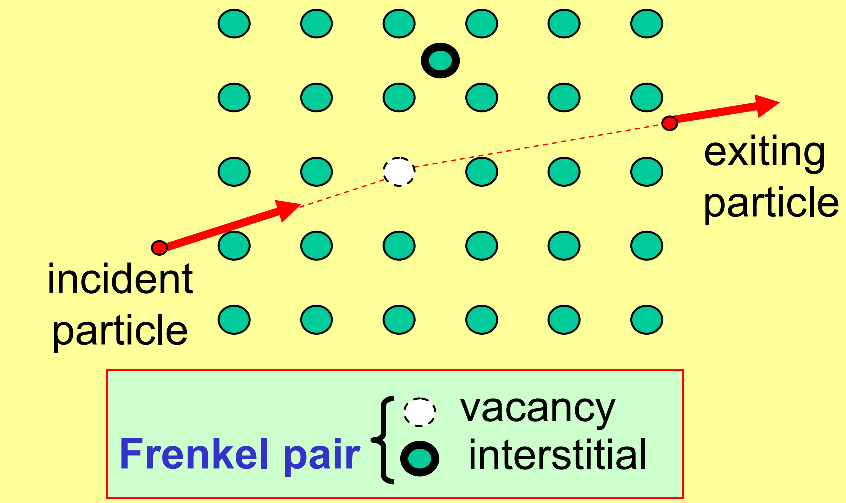
Measurement units

MeV/cm, also eV/μm

or

dividing by density

MeV-cm^2/mg



Interstitial and vacancy defect creation.

physical quantities

Non Ionising Energy Loss (NIEL)

BULK DAMAGE is proportional to total kinetic energy (K.E.) into DISPLACING atoms (silicon)

- **damage ∝ Kinetic Energy gone to DISPLACEMENT**
- **damage scales with particle fluence ϕ**

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

KERMA ≡ K.E. imparted by radiation into displacement

total Kinetic Energy Released in MAtter (silicon)

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

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

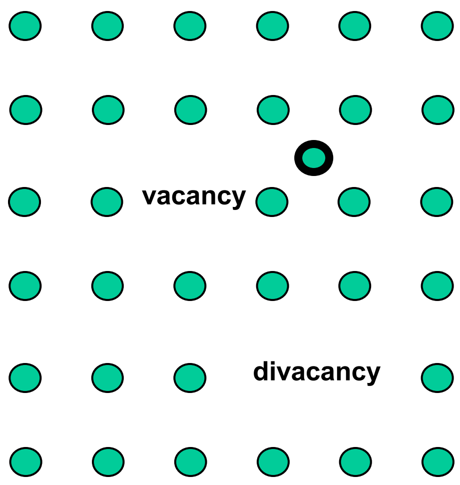
$\text{KERMA (keV)} = \text{NIEL(keV-cm}^2\text{/g)} \times \phi(\text{cm}^{-2}) \times \text{mass(g)}$

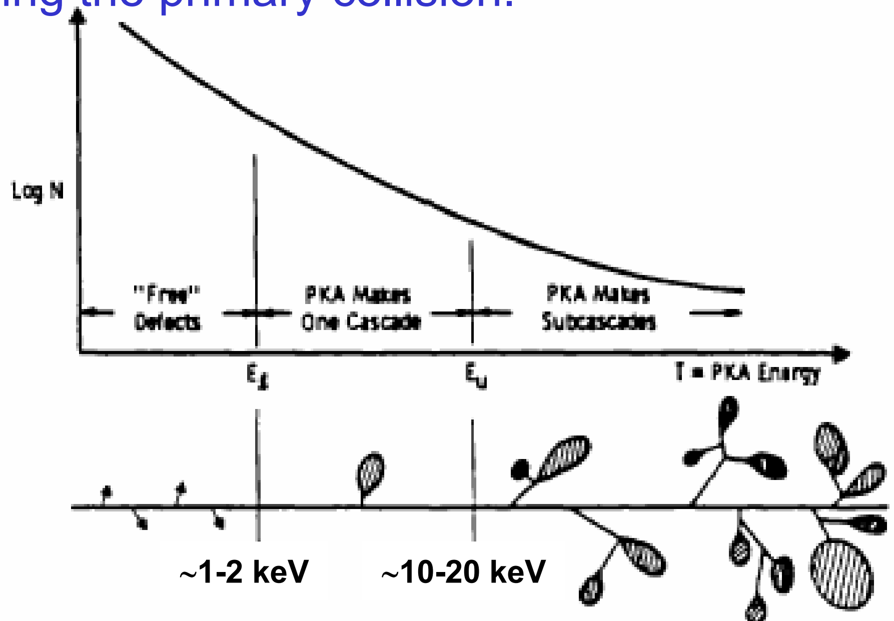
$\text{KERMA (MeV)} = \text{NIEL(MeV-cm}^2\text{/mg)} \times \phi(\text{cm}^{-2}) \times \text{mass(g)} \times 10^3$

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 primary knock-on atoms generate other point defects or even highly damaged regions (cascades, clusters), depending on energy transferred during the primary collision.



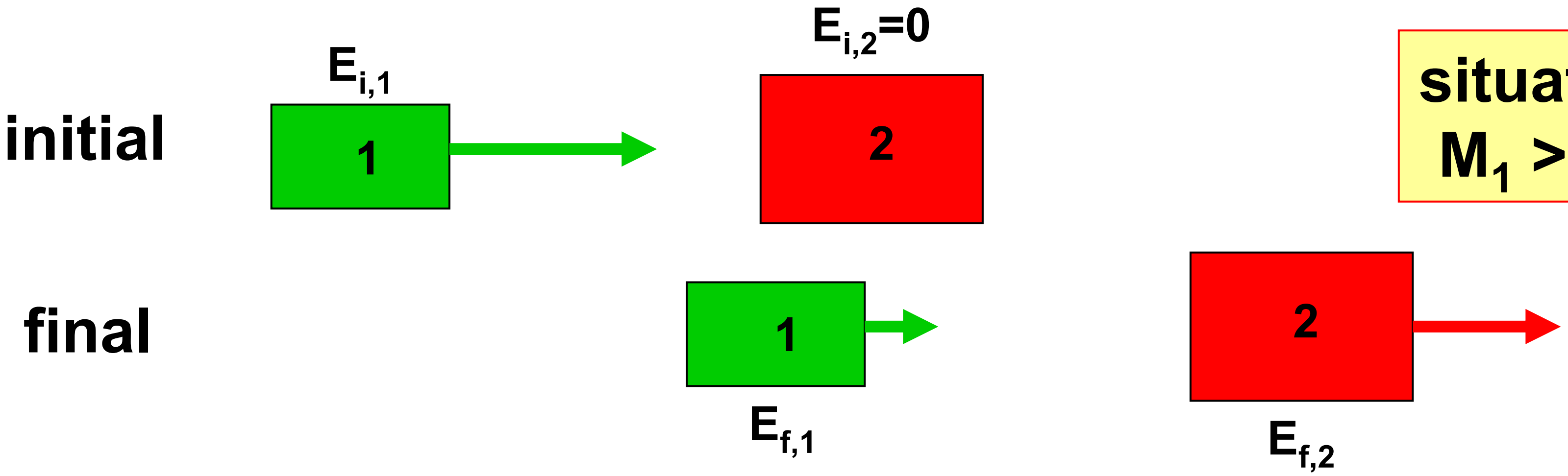


Energy to Si recoils

physical quantities

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

$$E_{f,2}^{max} = 4\, E_{i,1} \times \frac{M_1 M_2}{(M_1 + M_2)^2}$$

(non-relativistic)

minimum energy for displacement

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

(non-relativistic)

elastic collisions 2

minimum energy for displacement

$$E_{inc}^{min} = E_{threshold} \times \frac{(M_{incident} + M_{target})^2}{4\, M_{incident}\, M_{target}}$$ **(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} (eV) for creation Frenkel pair**
Silicon ion	25 (billiard ball effect)
neutron/proton	186
electron	*319 (non-relativistic formula above)* 255 (correct relativistic)

physical quantities

elastic collisions 3

maximum energy
to recoiling target
atom

$$E_{\text{max recoil}} = E_{\text{inc}} \times \frac{4\,M_{\text{incident}}\,M_{\text{target}}}{(M_{\text{incident}} + M_{\text{target}})^2}$$

(non-relativistic)

neutrons in Silicon

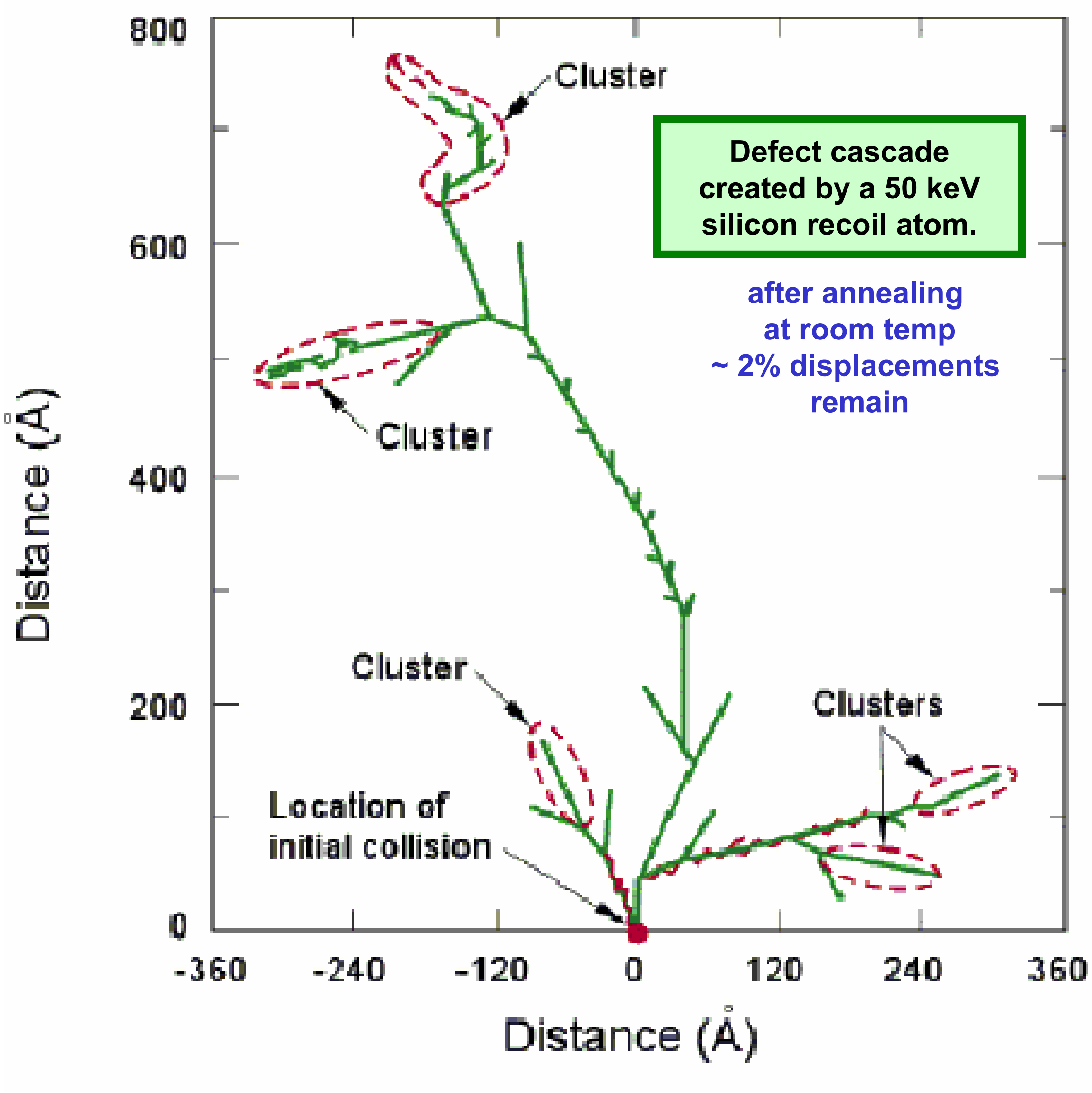
incident energy	$E_{\text{max recoil}}$	comments assuming max energy recoiling Silicon
35 keV	4.7 keV	range of recoil ~ 200 Å, most of energy loss of Si recoil is nuclear
1 MeV	134 keV	range of recoil ~ 6000 Å, ~ 50% of energy loss of Si recoil is nuclear → 2700 displacements ~ 60% recombine within 100 ps → leaving 1000 displacements followed by further long term annealing

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

physical quantities

Ion displacement damage

adapted from V.A.J. Lint

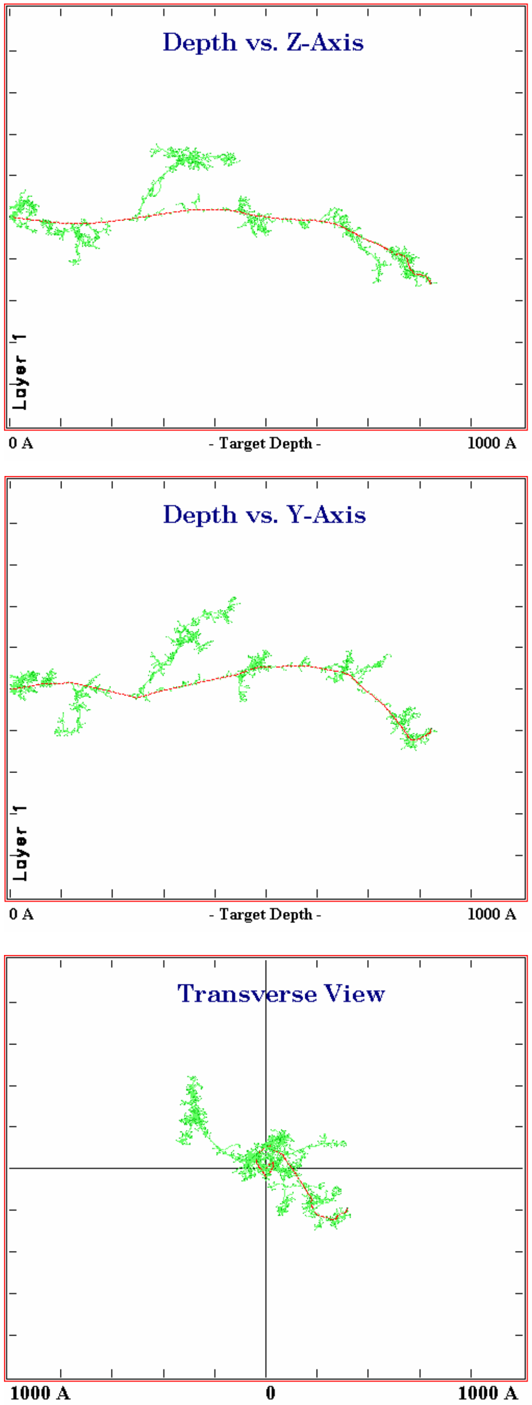


Defect cascade created by a 50 keV silicon recoil atom.

after annealing at room temp ~ 2% displacements remain

SRIM 2003

50 keV Si ion in silicon



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

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 D to 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) =

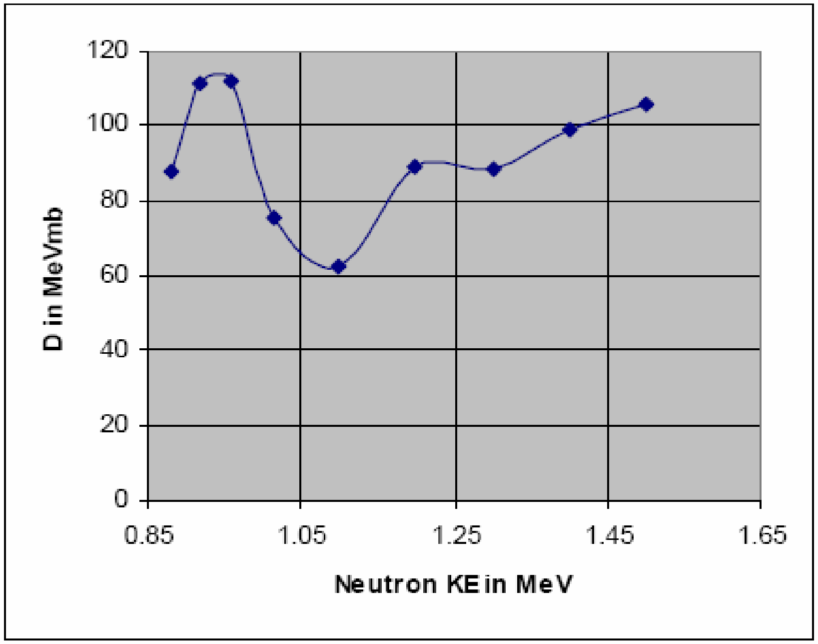
= 2.144 keV-cm^2/g

NIEL scaling hypothesis 1

Observation: degradation of silicon devices (detectors) is *roughly* proportional to amount of displacement damage measured in terms of 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 that caused by a certain flux of mono-energetic neutrons.

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



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

Standard 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:

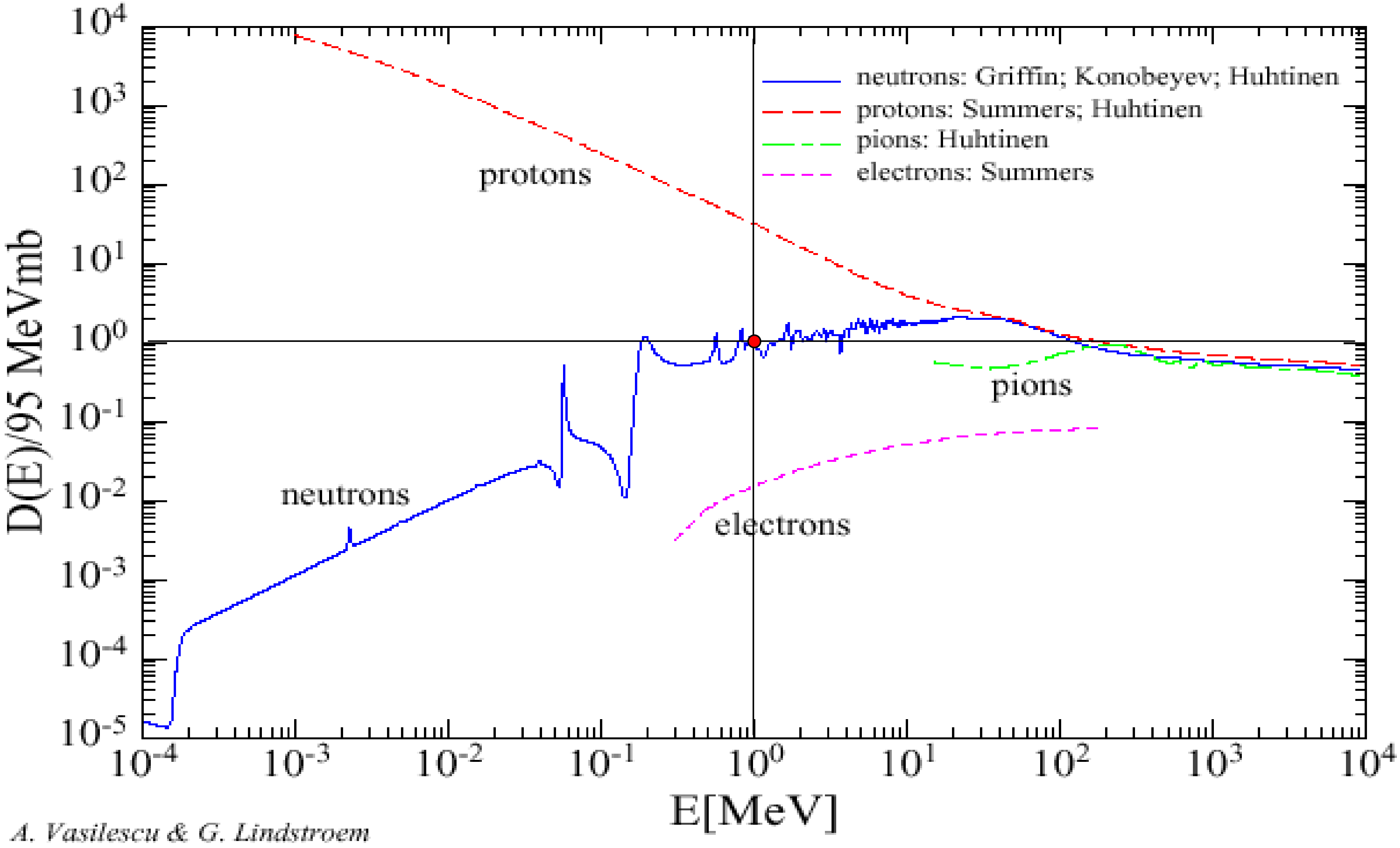
D(1 MeV neutrons) = 95 MeV-mb

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

chosen as STANDARD reference values when calculating the equivalent 1 MeV neutron fluence values for irradiations using neutrons of another energy, or other particle types (electrons, protons, pions, ions...)

physical quantities

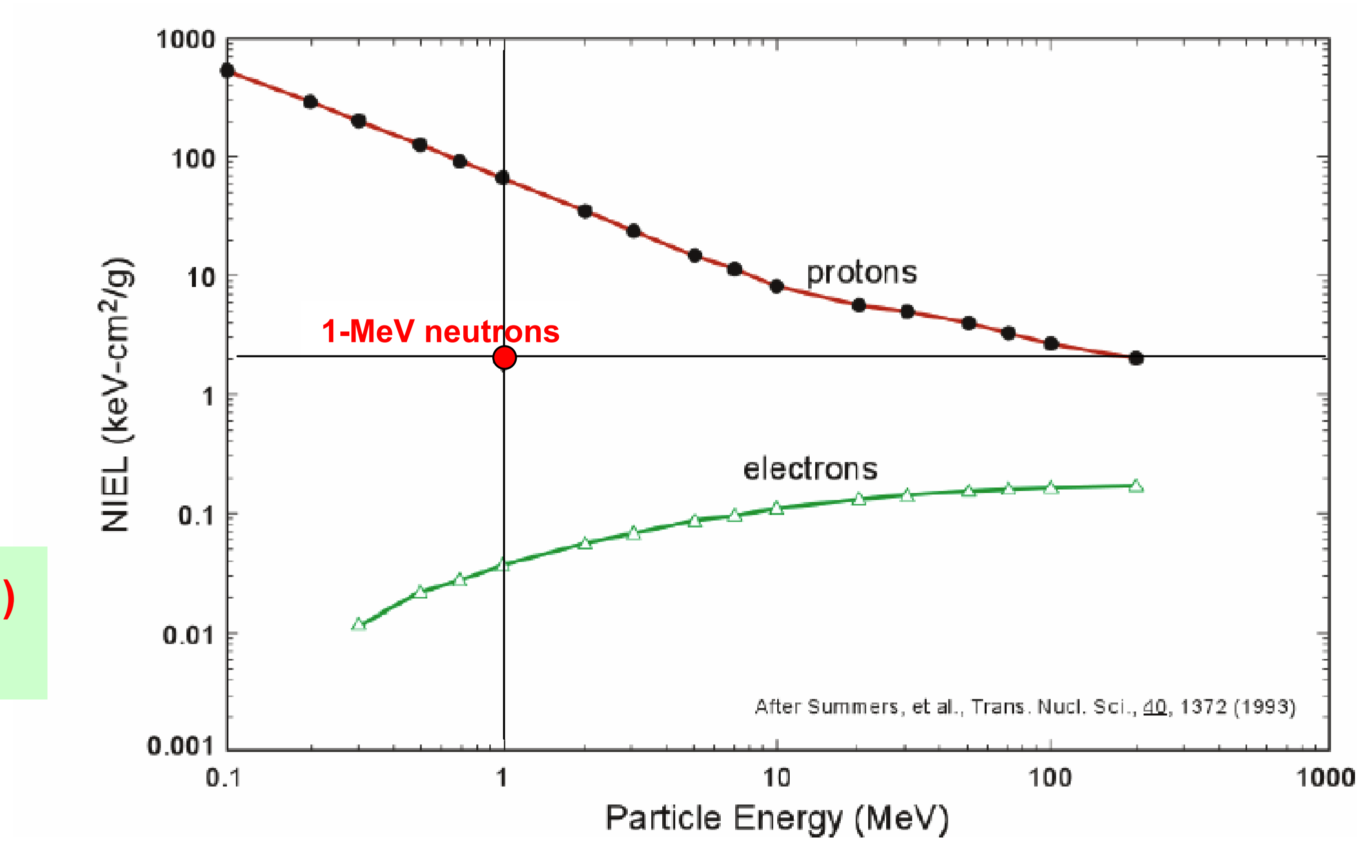
energy dependence of Displacement damage cross-section D in silicon for neutrons, protons, electrons and pions



physical quantities

energy dependence of NIEL in silicon

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



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

particle	total dose [rad(Si)]	ϕ fluence (part/cm^2)	ϕ_{eq} equivalent neutron fluence (n/cm2)	hardness factor $k = \phi_{eq}/\phi$
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

physical quantities

NIEL scaling based hardness factor

The damage parameters induced by different particles scale with NIEL (!?)

Accordingly the **generic damage parameter** α should scale with the **hardness factor K**:

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

always true?

$\alpha(X)$ and $\alpha(Y)$ are the generic damage parameters of radiation X and Y,

and

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

physical quantities

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, VERY slow ions (end of range)	integrated displacement damage dose (DDD)

cross-section: a basic concept

$$\boxed{\sigma}$$

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

mean free path = average distance travelled by a particle without interacting

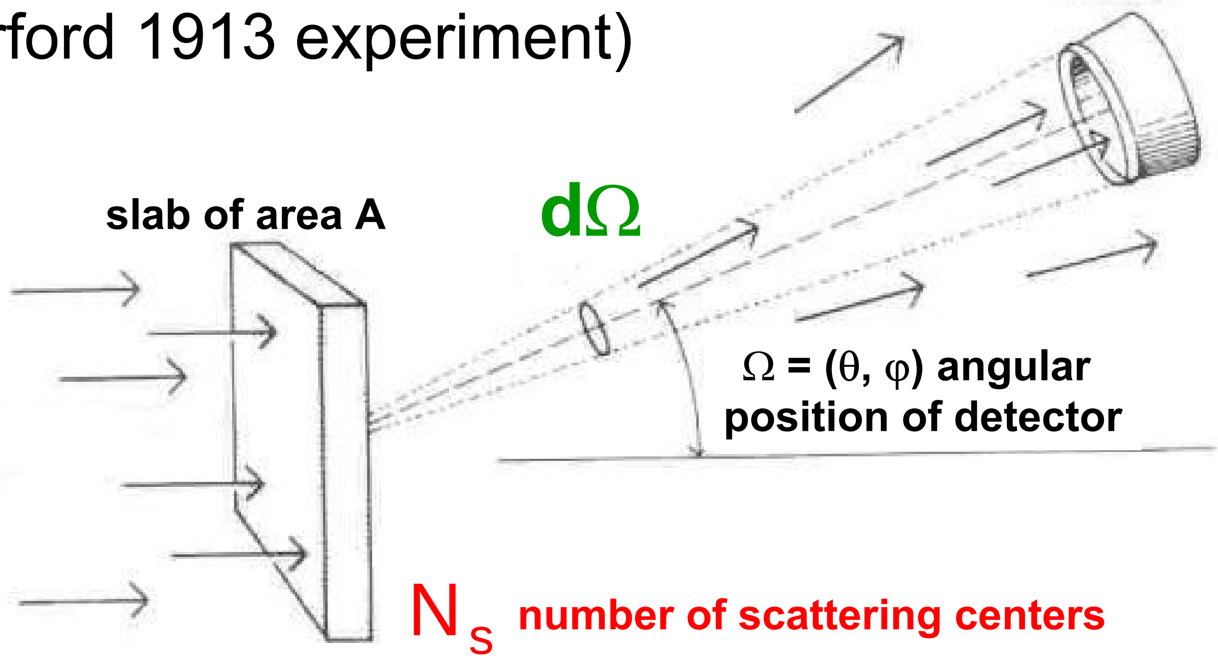
$$\lambda = \frac{1}{n_s \sigma}$$

n_s (cm^{-3}): number density of scattering centers

cross section

differential cross-section

(Rutherford 1913 experiment)



Small detector opening
$d\Omega = d(\cos\theta)\, d\varphi$

slab of area A

$d\Omega$

$\Omega = (\theta, \varphi)$ angular position of detector

Φ = number N_{inc} of incident particles per area A (a *fluence*)

N_s **number of scattering centers**

- **target *small compared to distances of experiment***
- **number of particles into detector opening $\propto d\Omega$**
- **thin target; i.e. at most one scatter**

an area!!!

no. of detected particles $\mathbf{dn} \propto N_s\, \Phi\, d\Omega \Rightarrow \mathbf{dn} = \chi(\Omega)\, N_s\, \Phi\, d\Omega$

differential cross-section $\chi(\Omega) \equiv \dfrac{d\sigma}{d\Omega}$

$\xrightarrow{}$ **azimuth symmetry**

$$\frac{d\sigma}{d\theta} \equiv \int \chi(\Omega)\, d\varphi$$

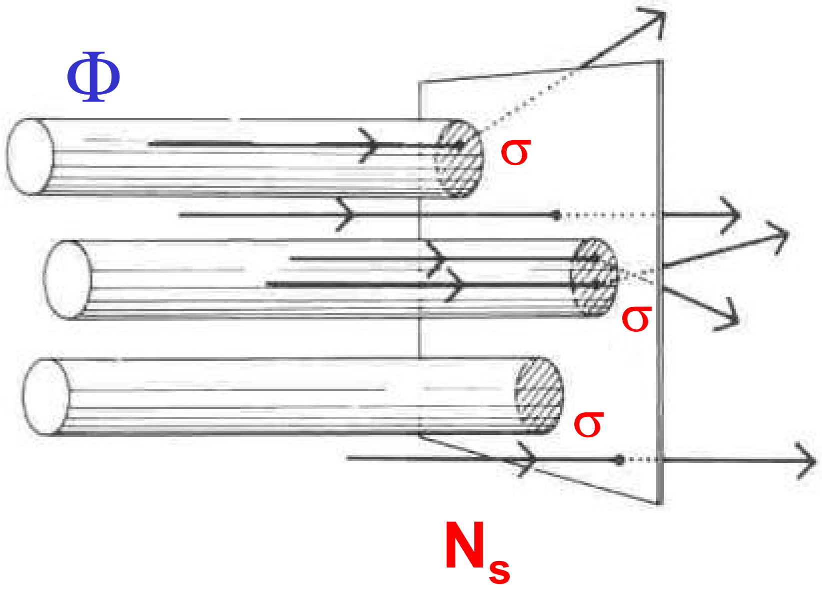
cross section

"effective cross section" of scattering

total number of particles removed from beam

$$n = \int dn = N_s\, \Phi \underbrace{\int \chi(\Omega)\, d\Omega}_{} = N_s\, \Phi\, \sigma$$

"effective cross-section of the scattering"



Rationale:

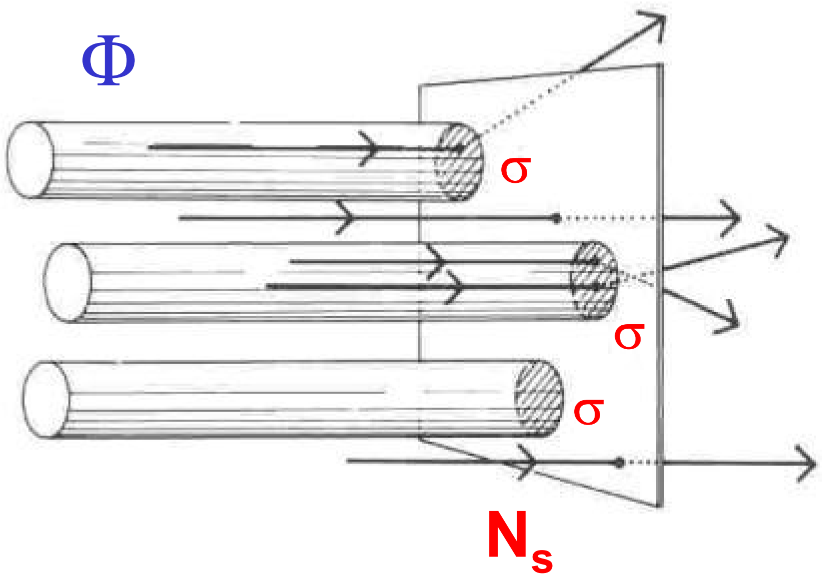
- **area of each scattering center =** σ
  - **total area of scatterers =** $N_s\ \sigma$

number of scatters ≡ fluence × total area that scatters

$$n = \underbrace{\Phi \times N_s}_{\text{integrated Luminosity (cm}^{-2})}\ \sigma$$

cross section

cross sections: another way to put it



Rationale:

- **area of each scattering center =** σ
- **total area of scatterers =** $N_s\ \sigma$
- **flux** $\Phi = N_{inc}/A$

area density of scattering centers

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

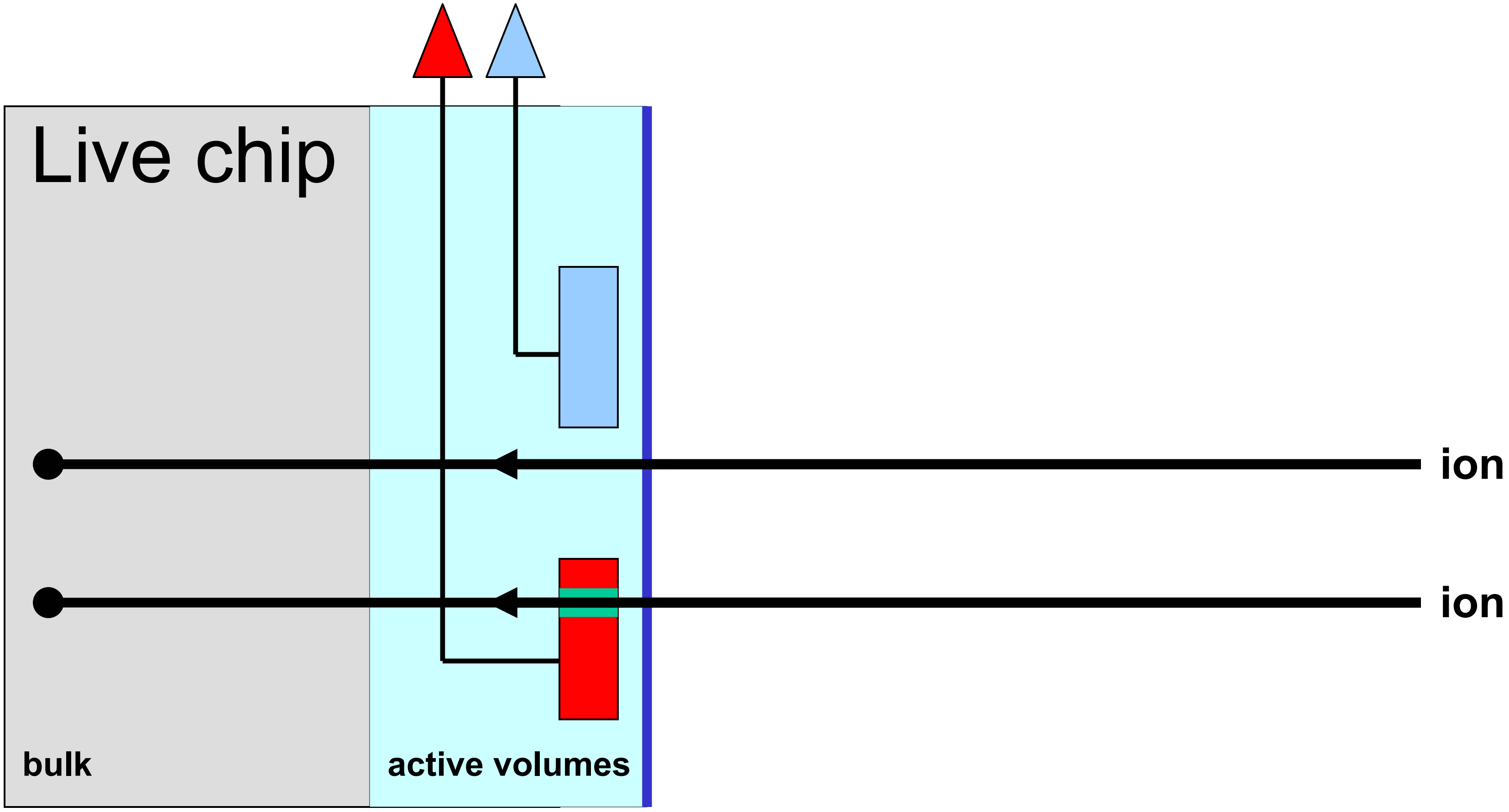
fraction of incident particles that interacted

=

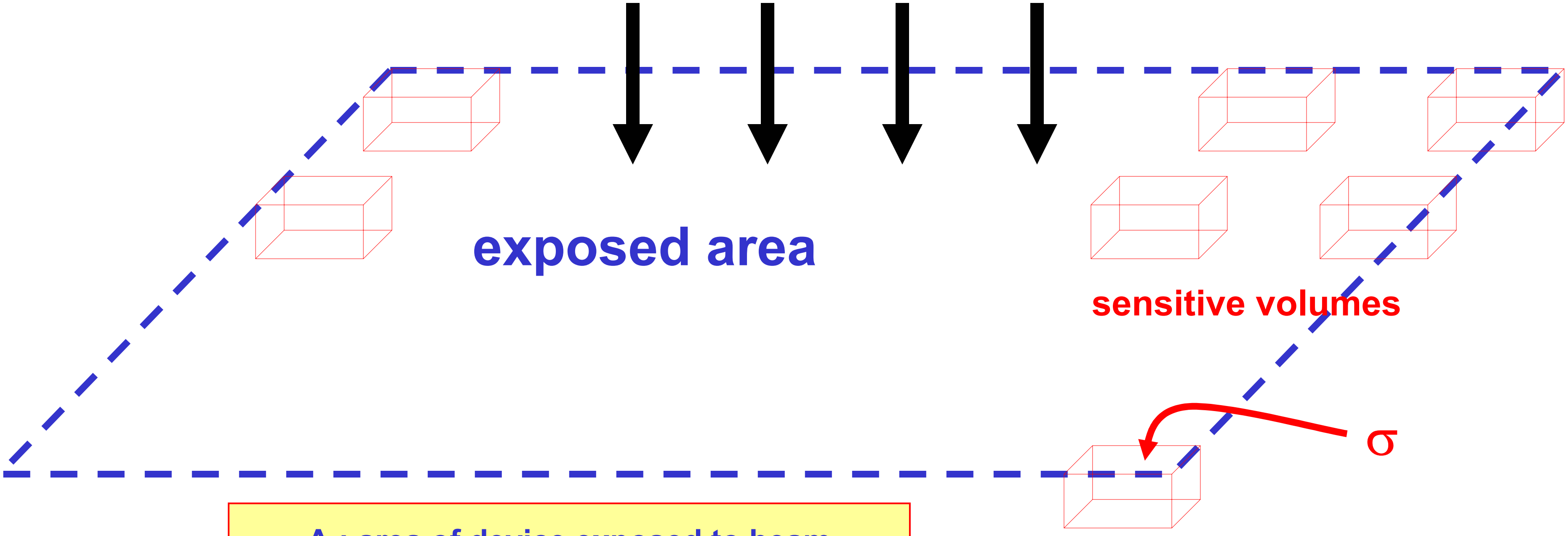
fraction of exposed area that gives origin to scattering

SEE cross-section

anticipation



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

fraction of incoming particles that cause SEE
is equal to
fraction of exposed area that is sensitive

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

Per sensitive Volume (e.g. per bit)

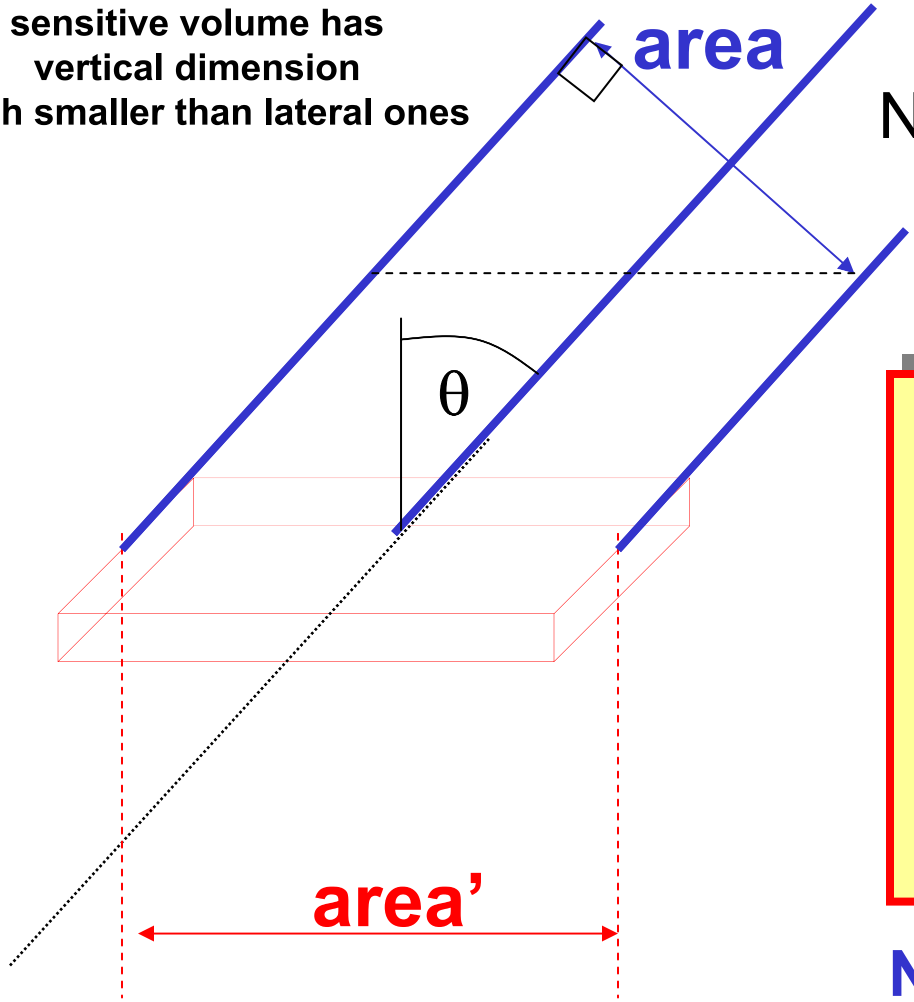
$$\sigma = \frac{N_{SEE}}{n} \times \frac{A}{N_{INC}} = \frac{N_{SEE}}{n \times \phi_{INC}}$$

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

inclined SEE exposure

SEE assumption:

sensitive volume has
vertical dimension
much smaller than lateral ones



Beam fluence ϕ

NOTE: **area** = **area'** cos(θ)

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

AND

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

NOTE: cos(θ) enters twice!

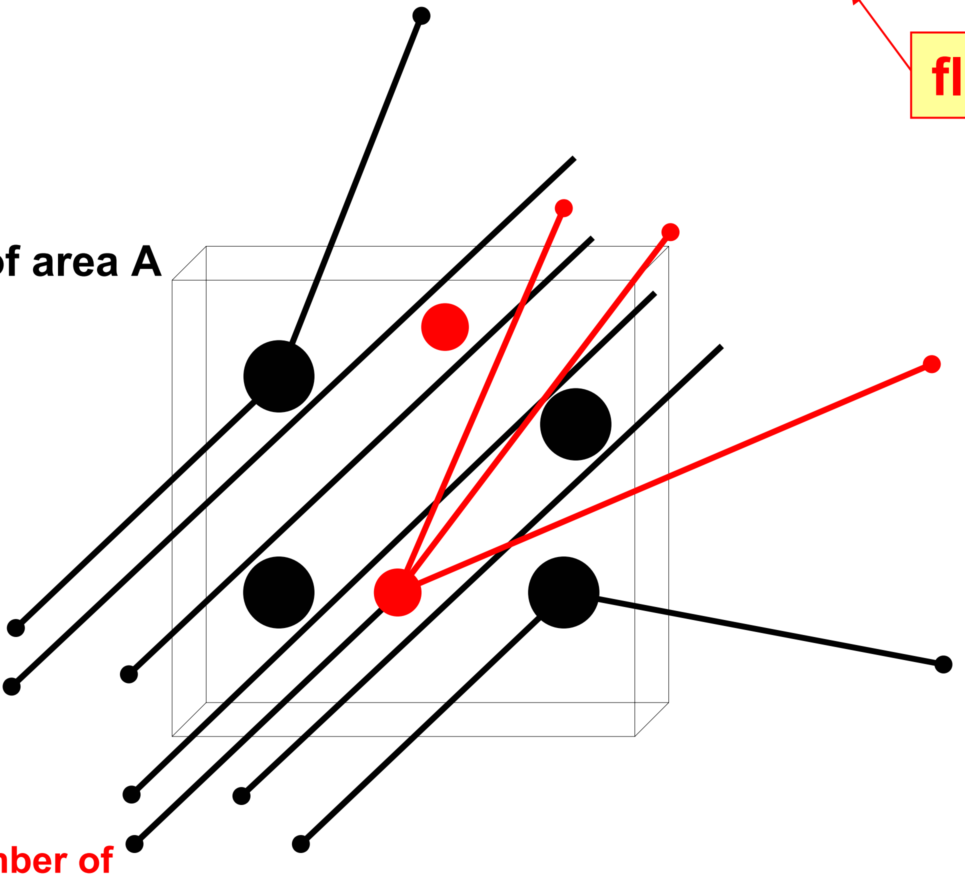
cross section

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

flux

fluence $\Phi = \int \phi \, dt$

integrated luminosity
$\mathcal{L} = \int L(t) \, dt$



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

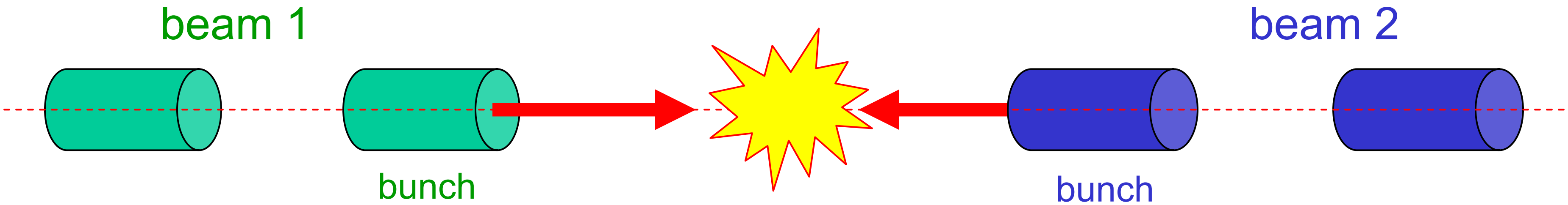
$$\text{cross section } \sigma_{tot} = \sigma_{elastic} + \sigma_{inelastic}$$

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

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

cross section

colliding particle beams



N_1 , N_2 = particles per bunch

b = number of bunches/beam

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

A = cross-sectional area beams at intersection

interaction rate (events per second)

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

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

interaction rate of type k: $R_k = L \bullet \sigma_{\mathbf{k}}$

cross-sections: CMS/LHC

“...big as a barn...”

1 barn = 10^{-24} cm^2 = 10^{-12} cm on a side

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

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

upgrade 35

time integrated luminosity *in 10 LHC physics years*

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

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

Rate of inelastic events

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

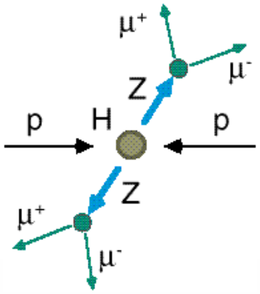
after 10 years N_{elastic} = 4 × 10^{16} events

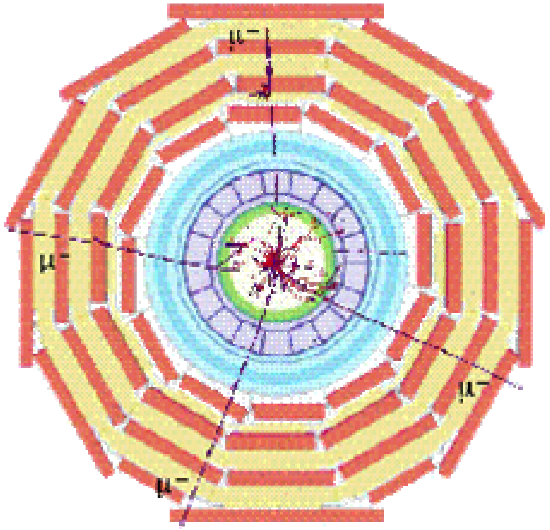
Consider a RARE process with σ_{rare} = 10^{-38} cm^2 = 10 fb

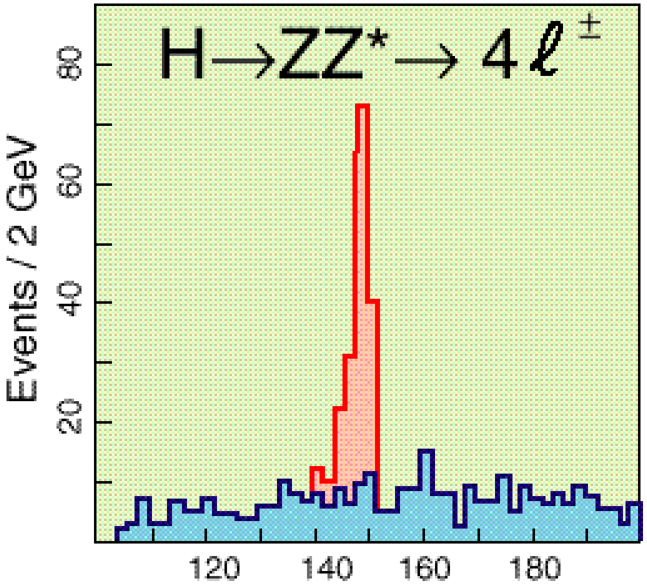
After 10 years N = L • σ = 500 fb^{-1} × 10 fb = 5000 events

Extremely hostile radiation environment!!!

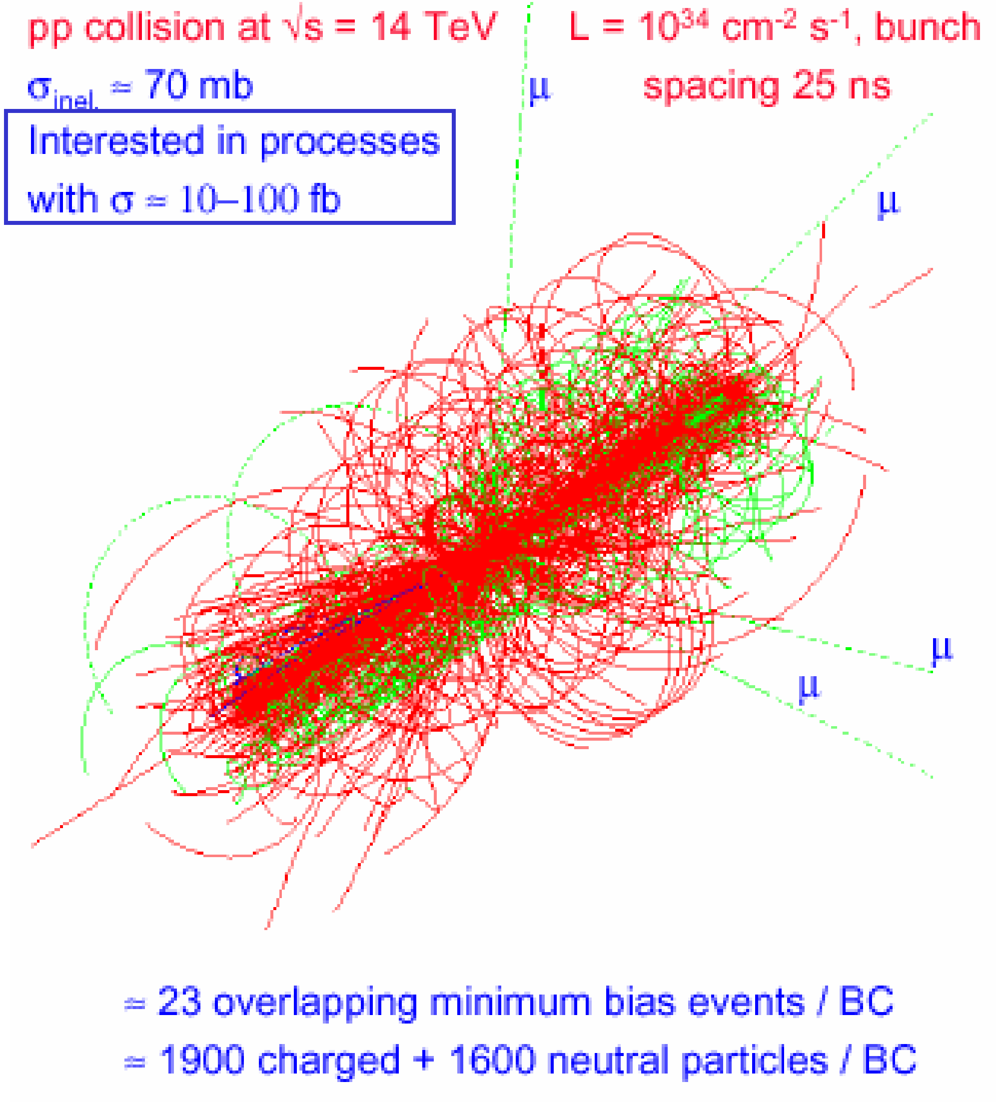
HE-Physicists are after
RARE hard-to-find events







simulated event at CMS:



pp collision at $\sqrt{s}$ = 14 TeV

$L = 10^{34}$ cm^{-2} s^{-1}, bunch spacing 25 ns

$\sigma_{inel.} \simeq 70$ mb

Interested in processes with $\sigma \simeq 10$–100 fb

$\simeq$ 23 overlapping minimum bias events / BC

$\simeq$ 1900 charged + 1600 neutral particles / BC

Radiation levels @ 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>2 MeV, charged hadrons E>20 MeV, ……… In Space galactic HZE

➢ Cumulative effects due to long exposure to radiation:

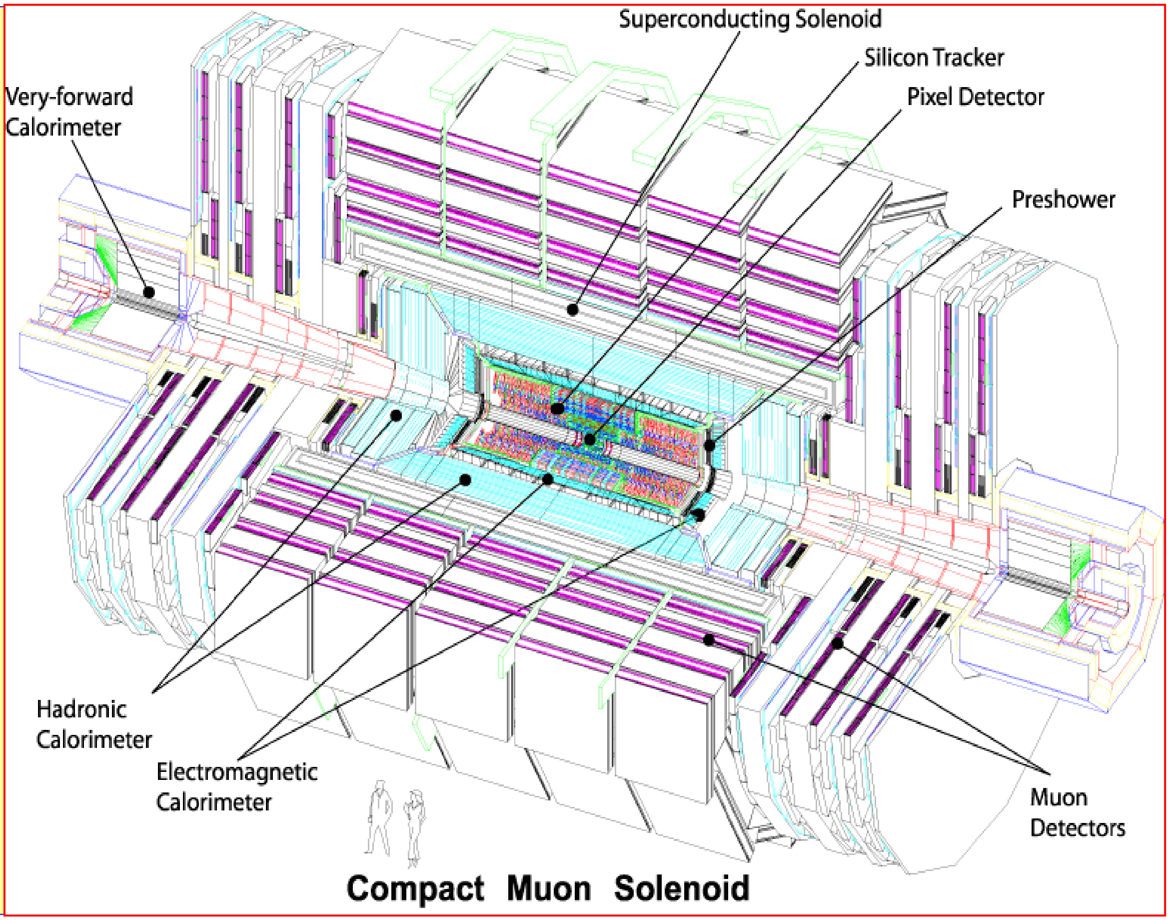
- **bulk (displacement) damage** to Silicon-detectors:
  neutrons > 20 keV, charged hadrons
- **surface (Ionization) damage** to electronics (degrade of S/N,…)
- Light loss in scintillators/fibers
- activation of detectors and materials (problems for maintenance)
- damage to materials (insulators)

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)

  for $E_{\text{hadrons}} > 20$ MeV



Obtained from simulation tools (Fluka, …)

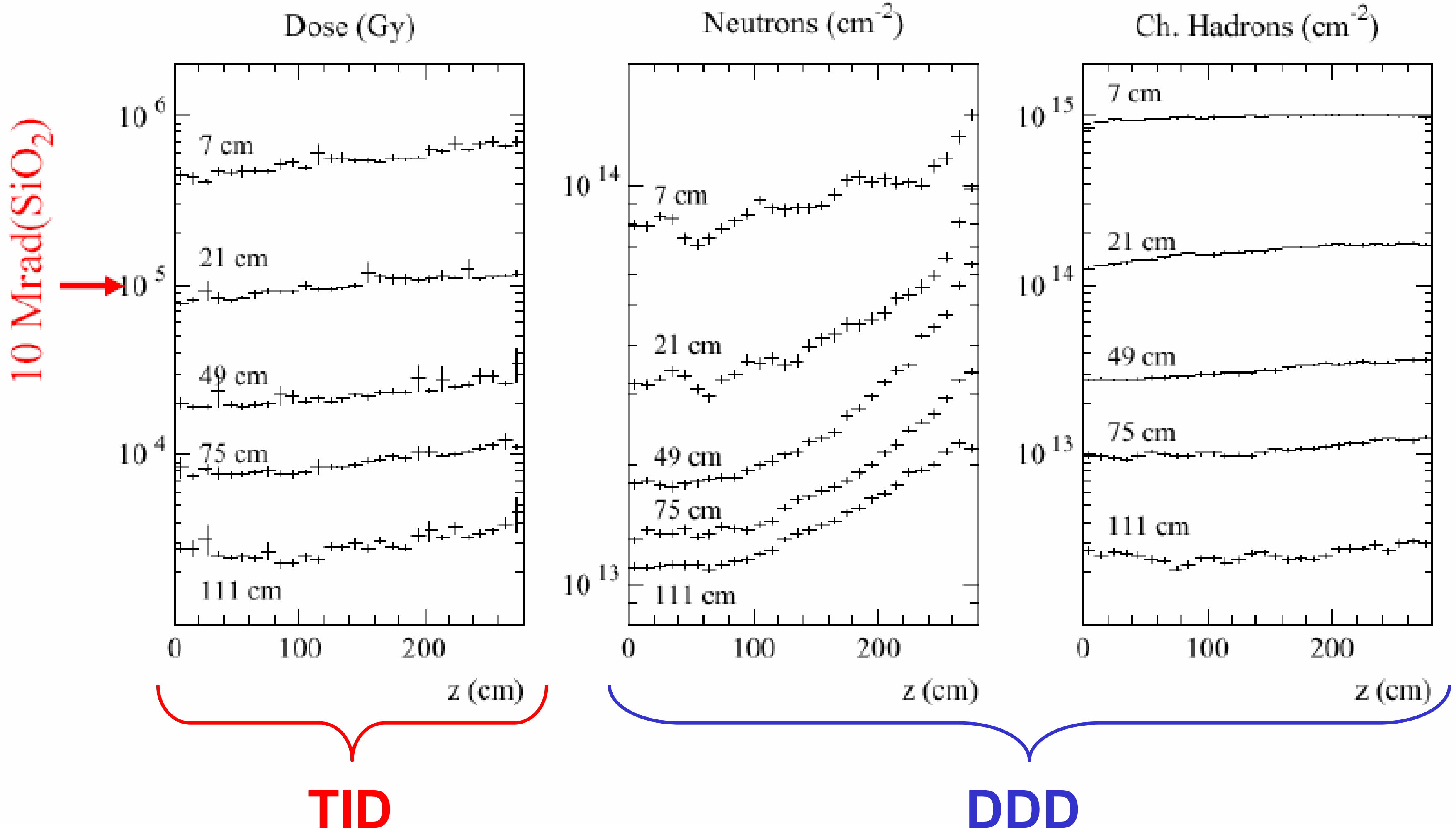
- uncertainties due to: physics models; detector model, …
- uncertainties with electronics (COTS, dose rate effects, …)

→ **Safety Factors**

Radiation levels expected for the CMS Tracker

Microstrip detectors and APV25 chips:

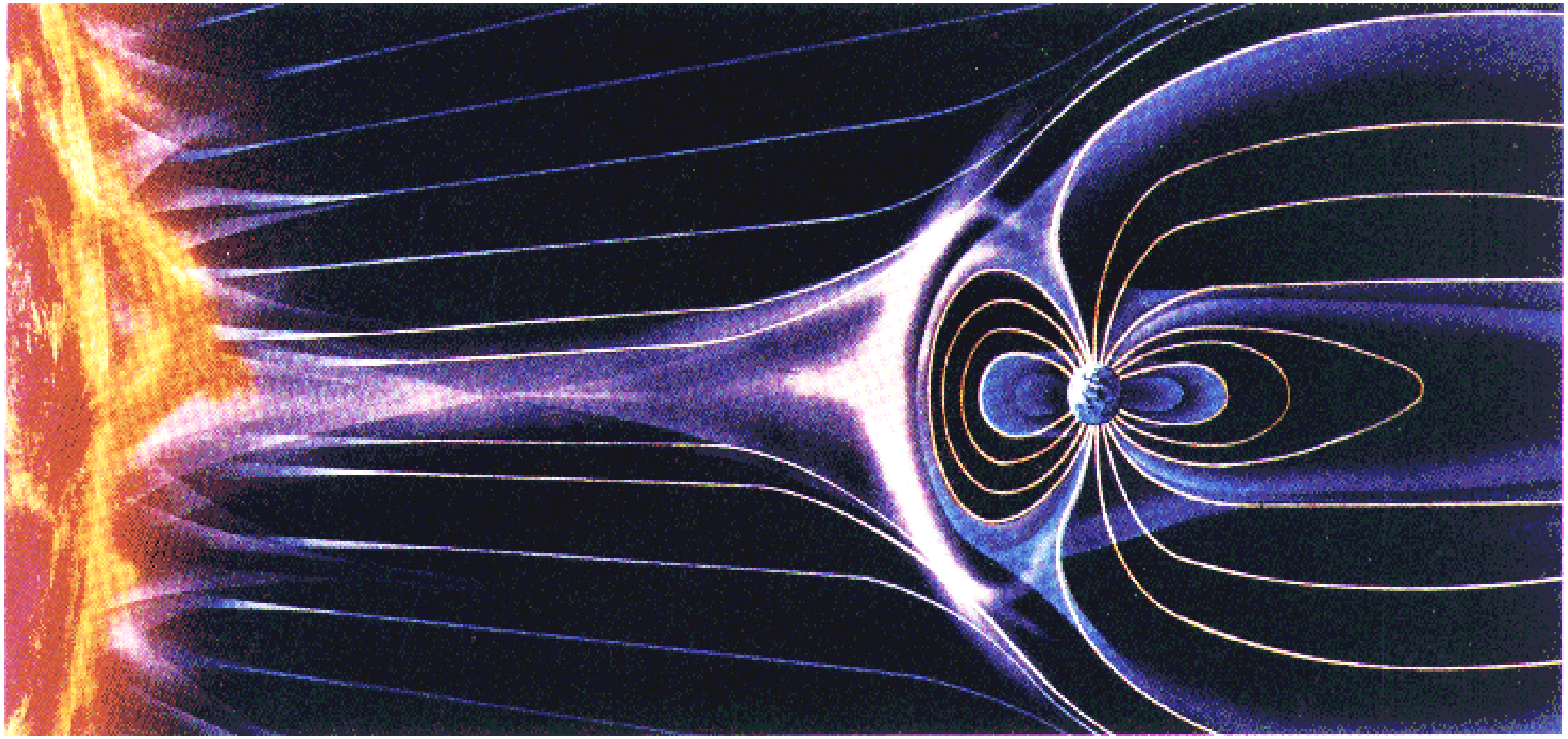
25 cm<R<110 cm => 10^{13} cm^{-2} <Φ< 10^{14} cm^{-2}



Space radiation environment 1

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

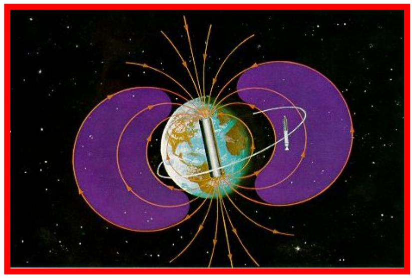
- from the SUN: normal solar wind and solar events (storms, flares)
- from outside the solar system (galactic cosmic rays)



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

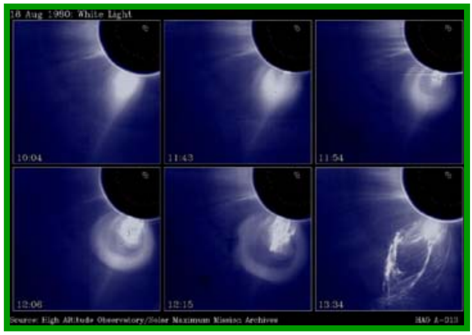
Space radiation environment 2

Radiation belts (Van Allen): depends on Solar activity



protons	keV ÷ 500 MeV
electrons	eV ÷ 10 MeV

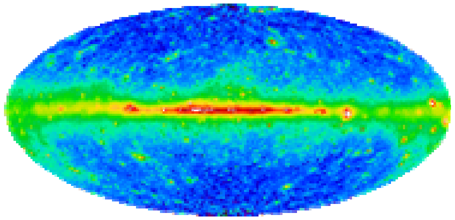
Solar wind and flares: depends on Solar activity



Source: High Altitude Observatory/Solar Maximum Mission Archives

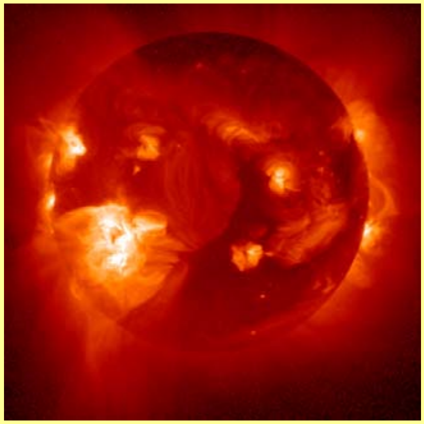
protons	keV ÷ 500 MeV
ions	1 ÷ few 10 MeV/n

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



Protons and ions ***(high charge Z and energy E)***	Flux maximum at ~ 300 MeV/n

Space radiation environment 3

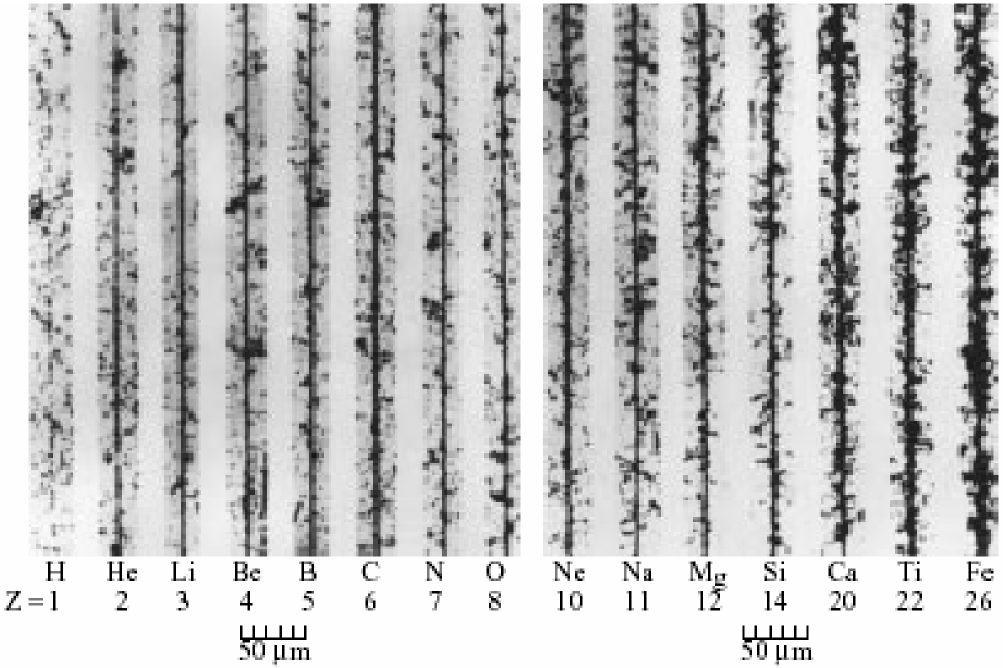


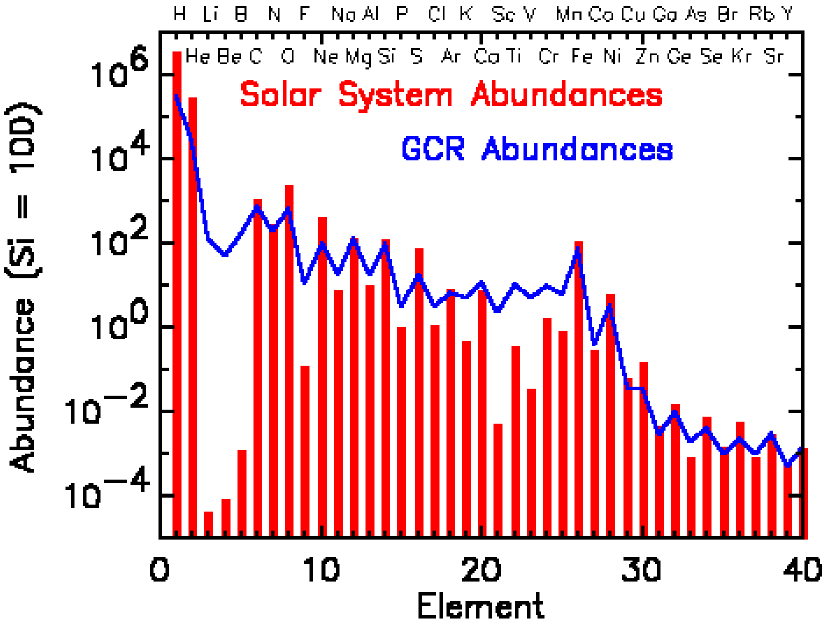
- **Solar particle events**: give rise to solar cosmic rays
- Solar activity: 11-year cycle:
  - □ 7 years of high activity (*solar maximum*)
  - □ 4 years of low activity (*solar minimum*)
- composition: mostly protons, α, heavy nuclei
- *Flares*: at Earth surface fluxes up to 10^6 p/(cm^{2}s) [1972],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

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

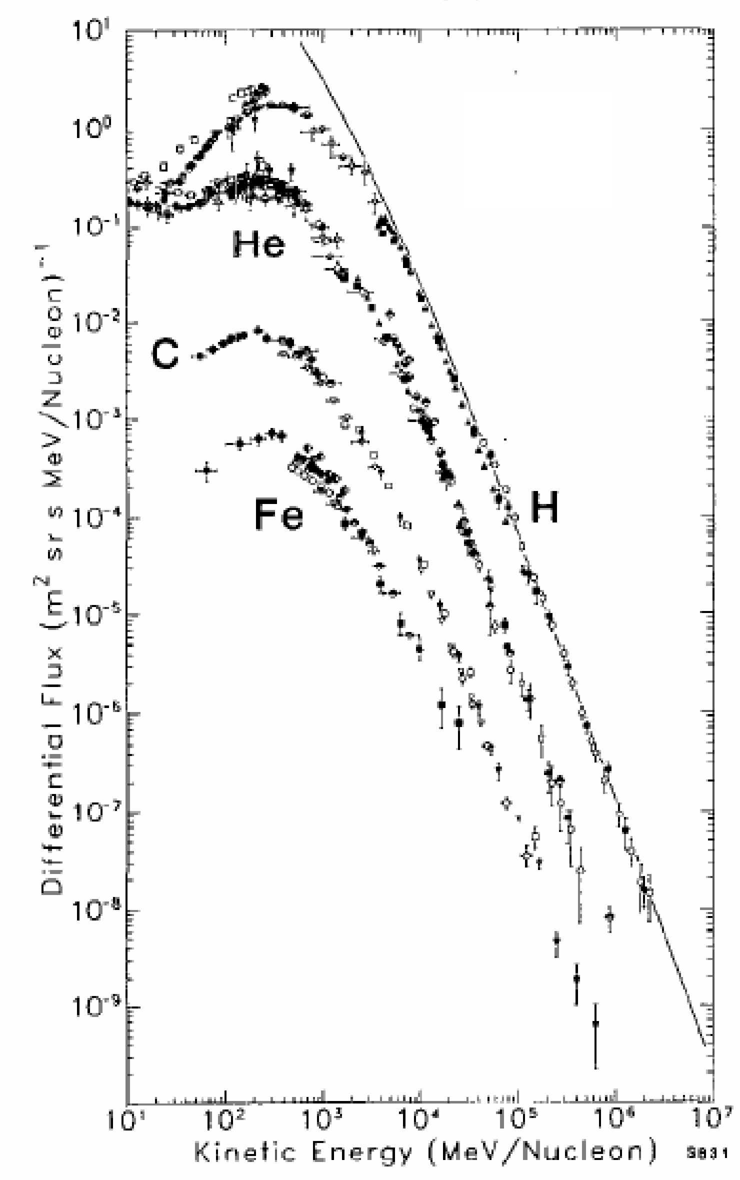
High Charge and Energy (HZE)
cosmic-ray tracks in nuclear emulsion

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

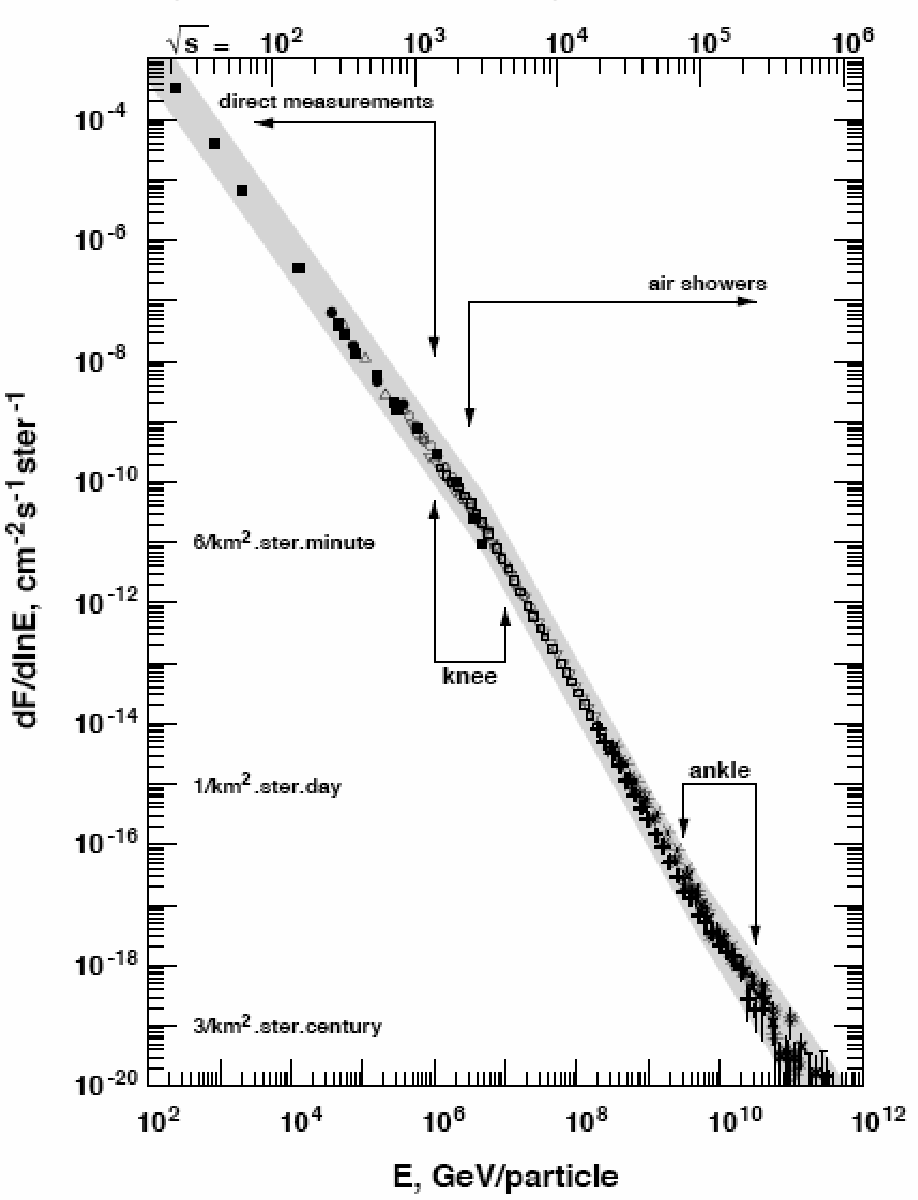




Energy spectra of primary cosmic rays



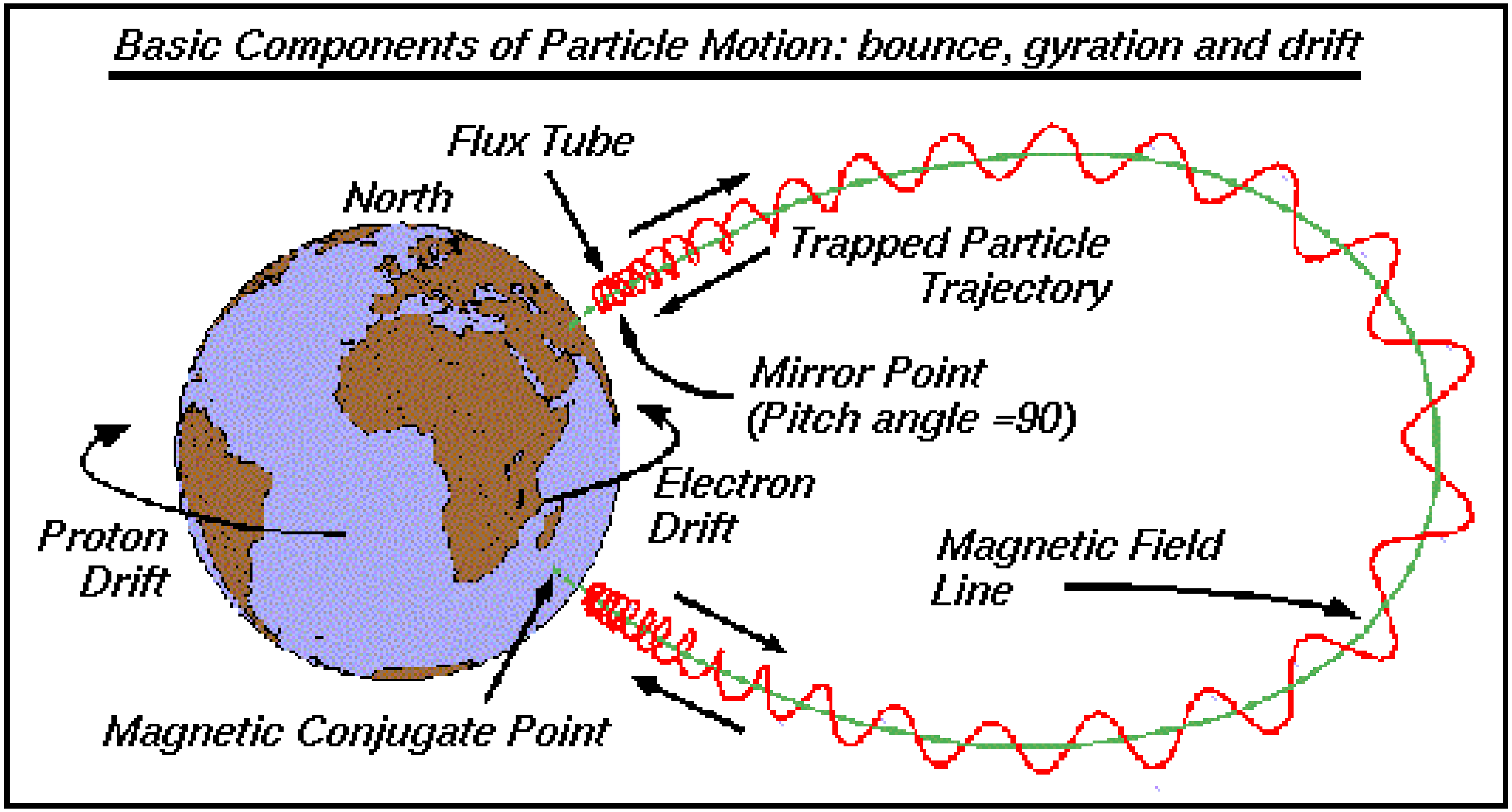
J.A.Simpson, Ann. Rev. Nucl. Part. Sci.
33 (1983) 323



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

trapped particles (extra slide)

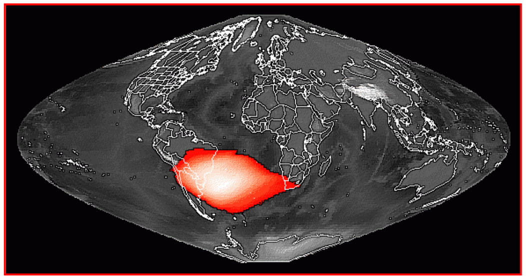
- Passing charged particles interact with Earth magnetic dipole field
- Some particles are trapped in Van Allen belts
- At poles particle may bounce (magnetic mirroring), and drift around the Earth depending on their charge
- Particles are trapped if the mirror point is high enough

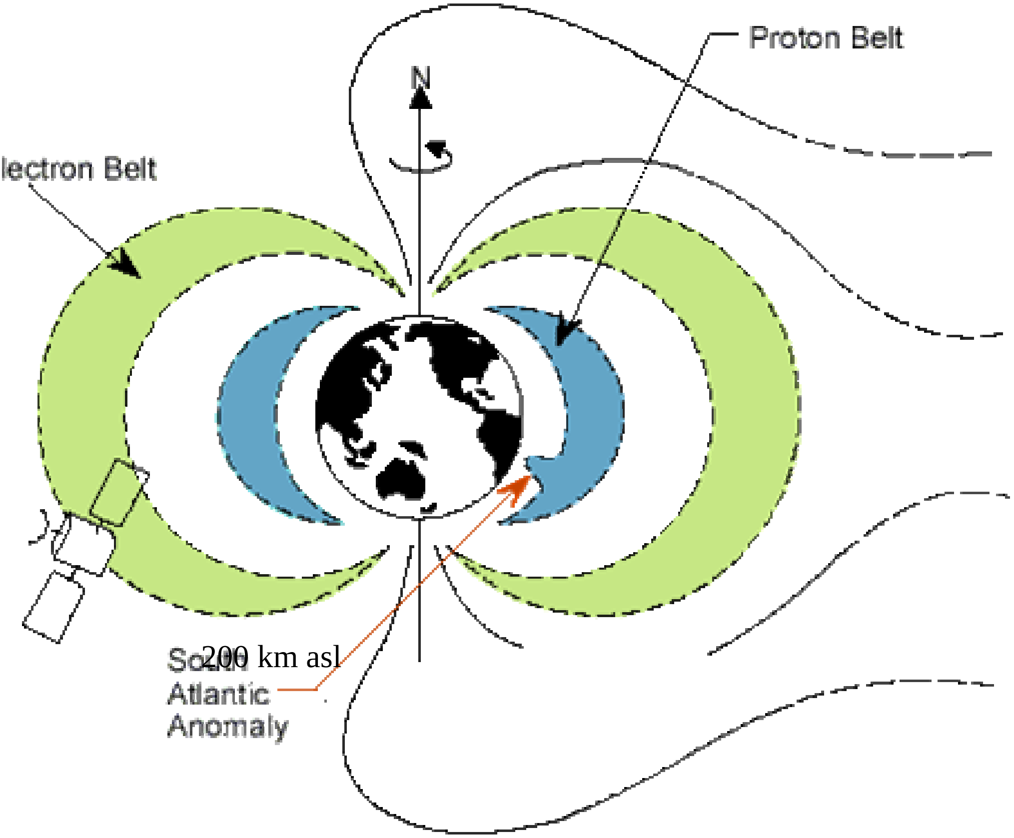


trapped particles

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

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





space detectors

detector systems for space missions

- **An “astrophyscis detector” on board a spacecraft is also composed of a number of dedicated detectors and elements, each subsystem subject to fail from radiation in a higher or lesser degree.**

Each spacecraft is exposed to different levels of radiation depending on the type of mission (type of orbit, where, how long,...)

Simulating the radiation environment

- CREME96 (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

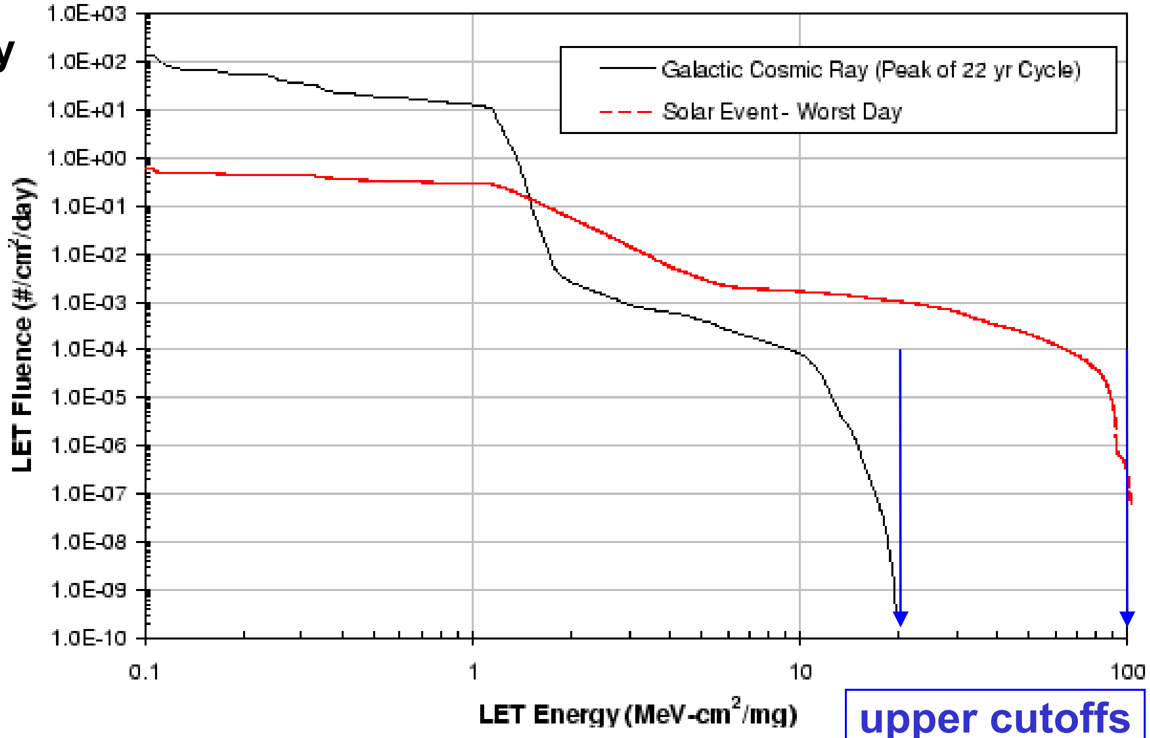
LET spectra and dose for GLAST

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

Courtesy of
Riccardo Rando,
GLAST collabortion

CREME96 simulation RESULTS 100 mil (2.5 mm)Al:

- **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)**



upper cutoffs

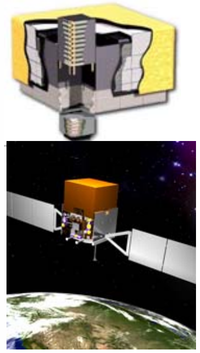
GLAST estimate

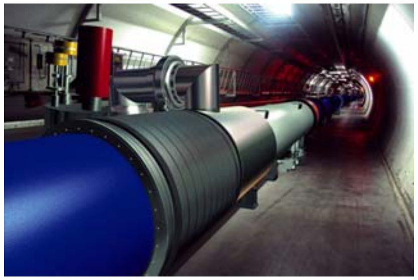
10 krad, 1 ion event/cm^2 (5 years)

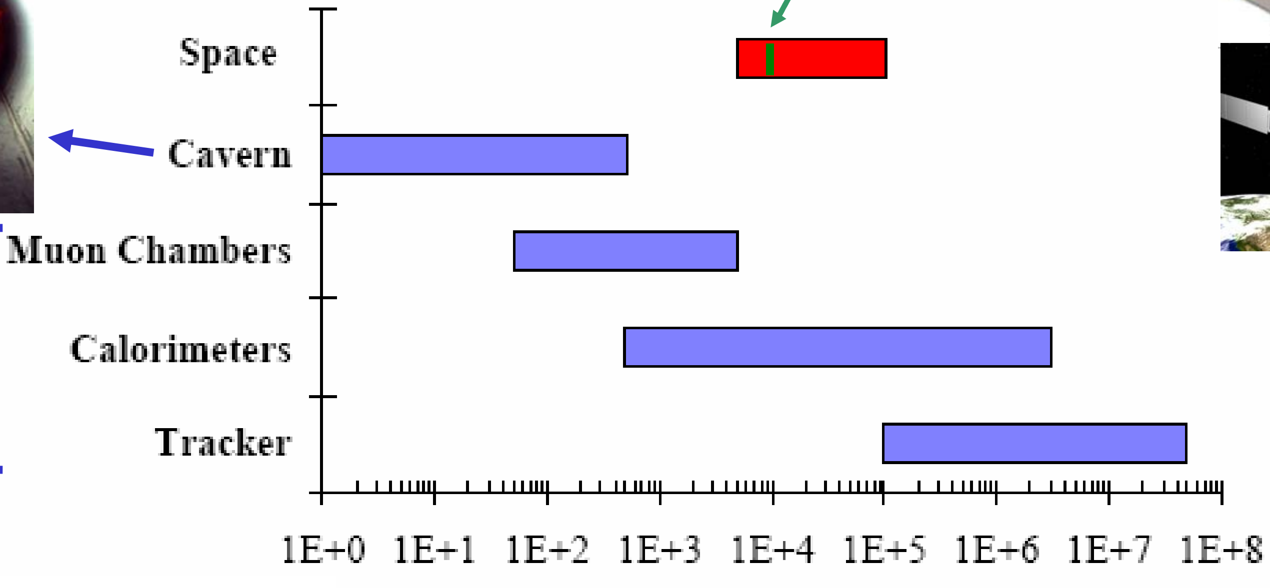
Comparison HEP (CMS@LHC) with Space Environment

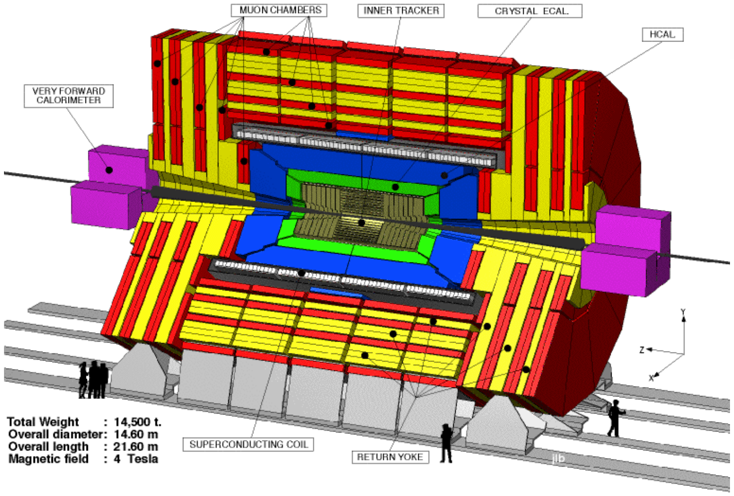
Total Ionisation Dose in Space and CMS

GLAST
10 krad/5 years









PART 2

overview of radiation issues and assurance of electronics

design issues

In designing systems for radiation environments

for

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

design issues

In designing systems for radiation environments

must

consider elements that may fail from radiation

(to higher/lesser degree)

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

TID,DDD,SEE

In general

radiation damage of electronics depends on technology used

Depending on ***particle type*** *and* ***energy***, in a given detector or system,

macroscopic effects of radiation

can be classified into ***THREE MAIN GROUPS***:

- **cumulative effects**
  - **TID (surface damage)**
  - **DDD (NIEL, bulk damage)**
- **transient effects**
  - **SEE**

TID,DDD,SEE

Summary (from part 1) radiation 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**

TID,DDD,SEE

time domain of effects: cumulative *versus* transient

cumulative effects:

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

- *tell tale concepts and words: small energy transfers, accumulation of effects, gradual parameter shifts (thresholds, leakage currents, type inversion,...)*

transient, single event effects:

effects that occur stochastically (suddenly).
Not predictable on event to event basis.

- *tell tale concepts and words: signal; sudden, large or high energy deposits; out of the blue, catastrophic event; redundancy (backup); sooner or later; evaluation of risk;*
should have known better; bad luck, voodoo...

TID,DDD,SEE

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.

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

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.

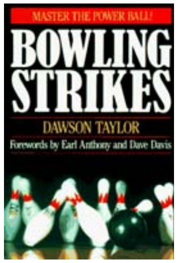
d) Carriers trapped on levels with low ionization energies get thermally re-excited into the conduction or valence band and, subject to further drift or diffusion, escape the dielectric or are captured on deep trap levels (production of permanently trapped charges).

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.

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.

2) 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...).

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

4) 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.

DDD

NIEL, Displacement Damage (DD)

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

physical quantities of interest:

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

- effects scale with particle fluence
- 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

Single Event Effects (SEE)

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

physical quantities of interest:

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

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

broad beam SEE experiments

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

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

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

- **practical flux set by dead-time of DUT (typical few $10 \div 10^4$ ions cm^{-2}s^{-1})**
- **Statistical Error improves with Fluence**
- *however* **Fluence Limited by Total Dose**

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

WEIBULL FIT of threshold curve

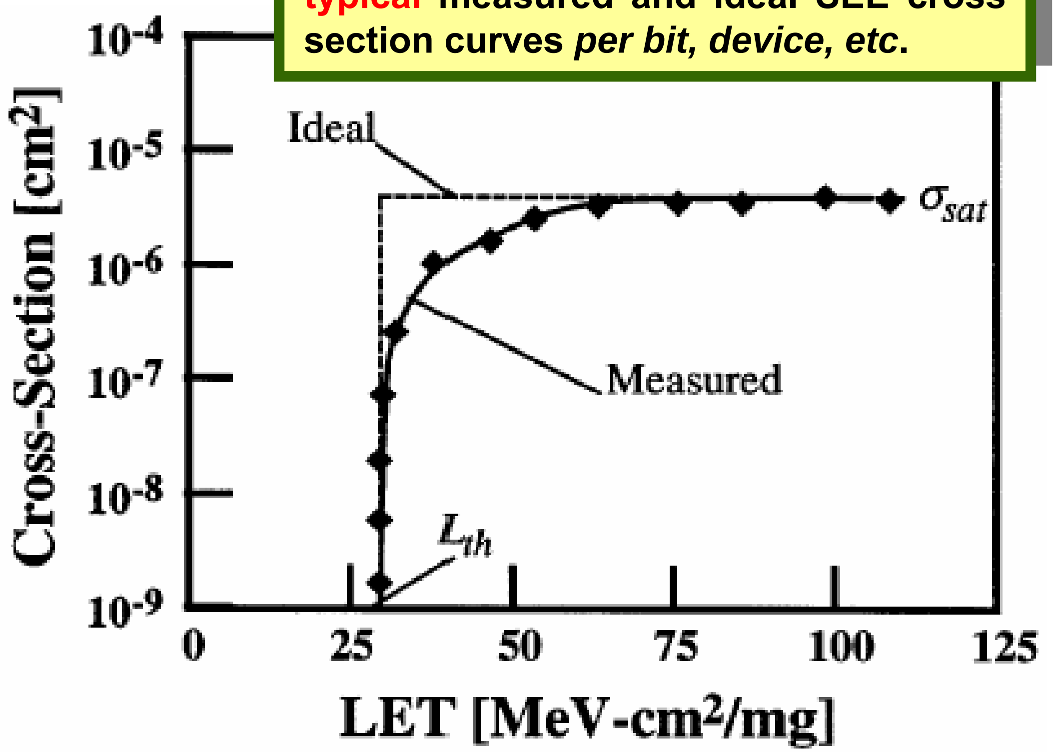
$\sigma = \sigma_{sat} \times \{1-\exp[-(L-L_{th})/W]^S\}$

σ_{sat}: saturation value

L_{th}: threshold LET value

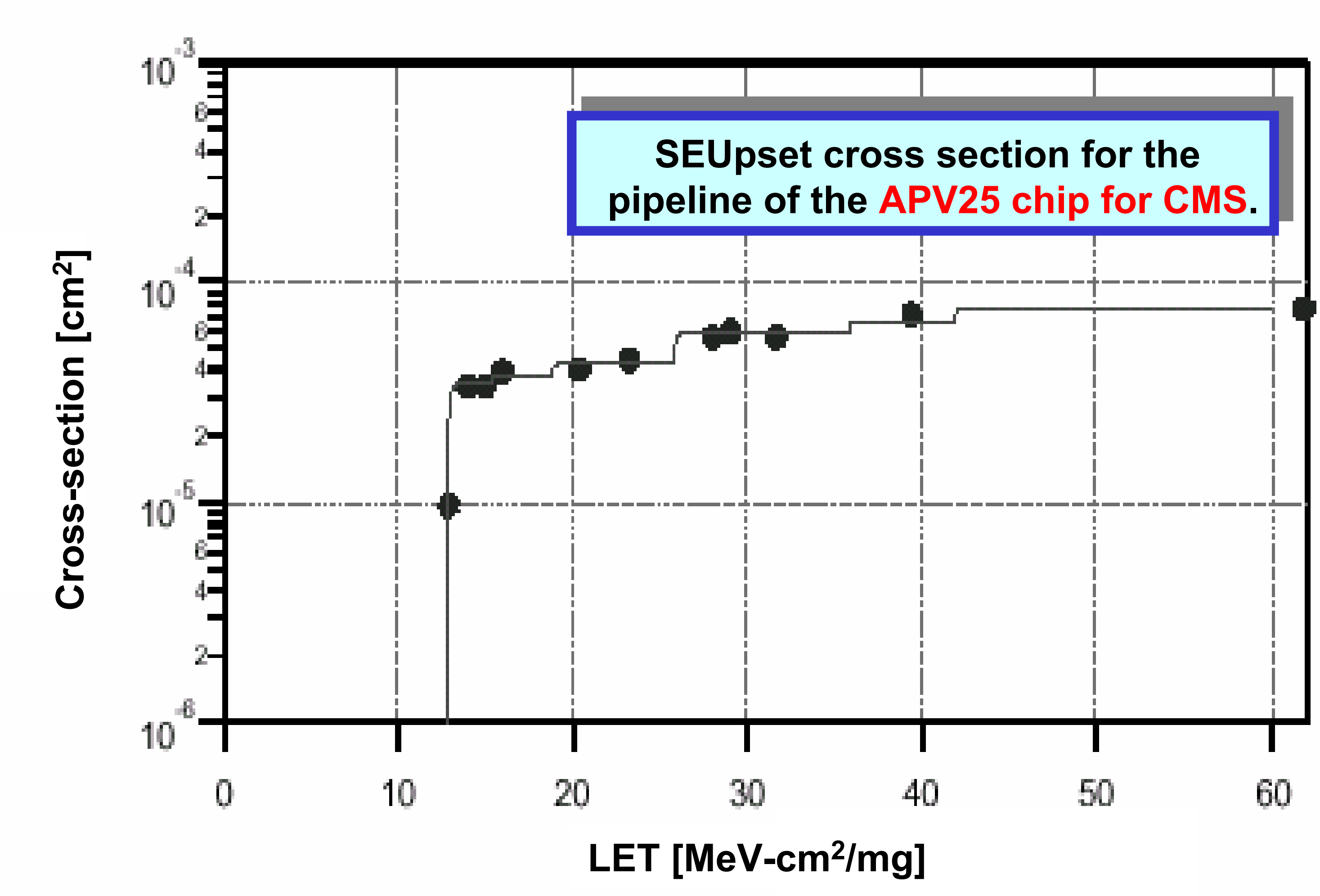
W and s are fitting parameters

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



SEE

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



SEUpset cross section for the pipeline of the **APV25 chip for CMS**.

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

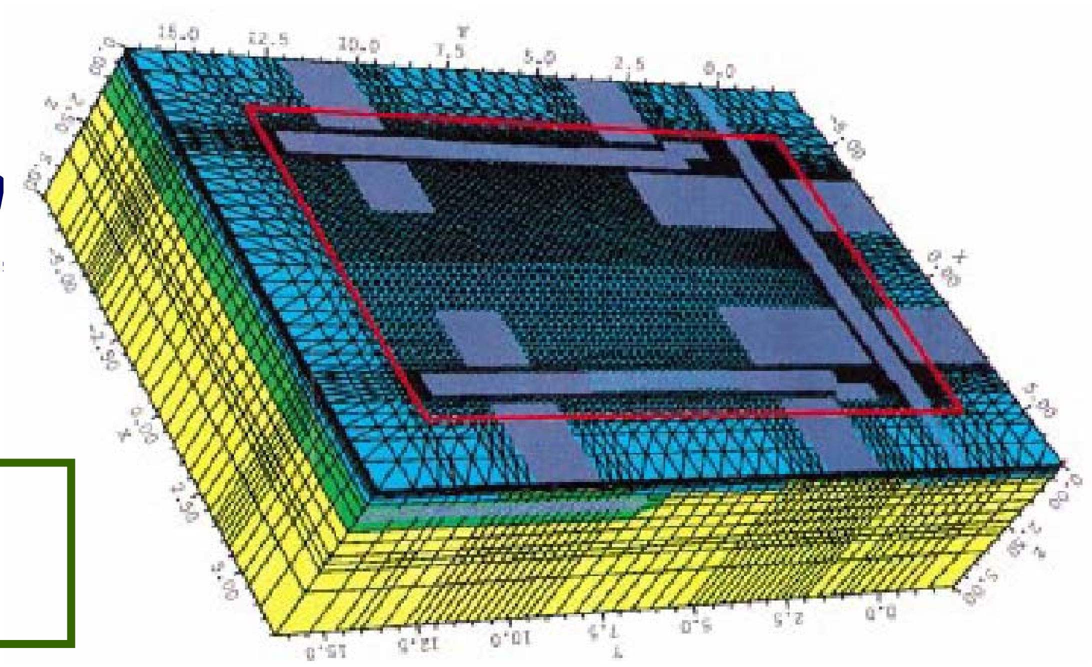
SEE

sensitivity micro-map

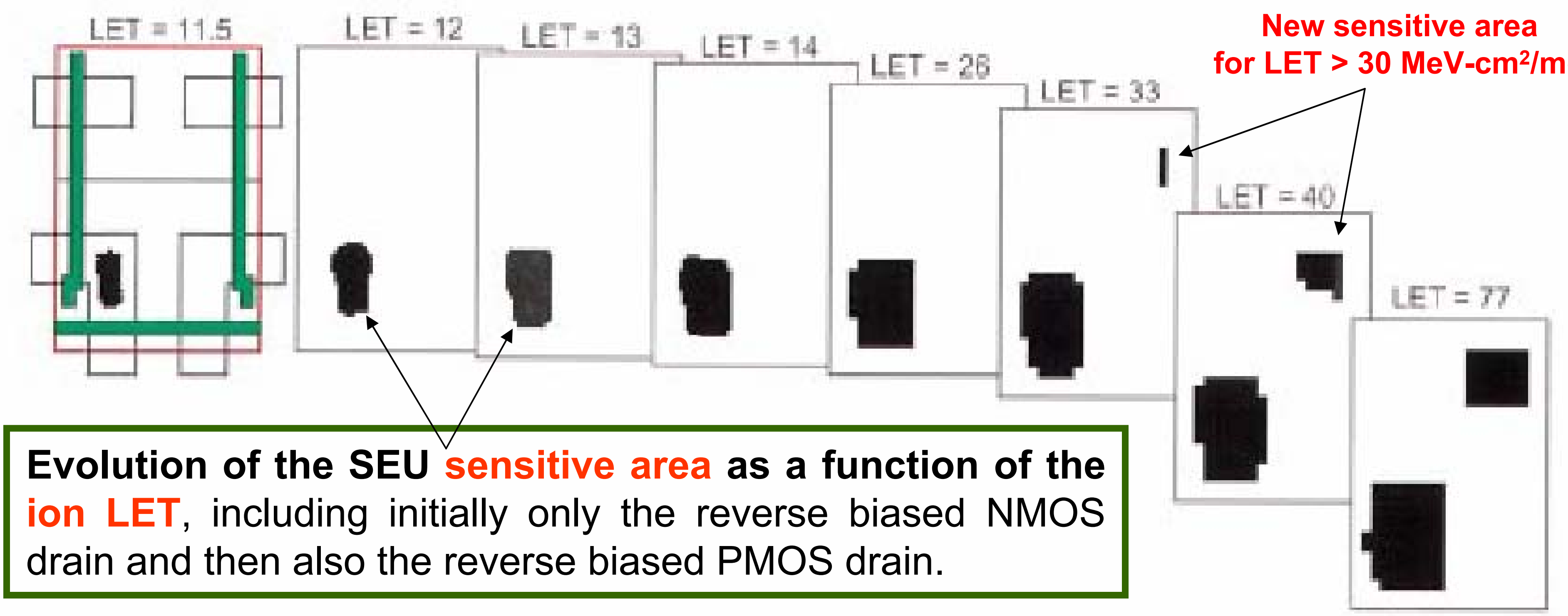
CMOS 256K SRAM

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.



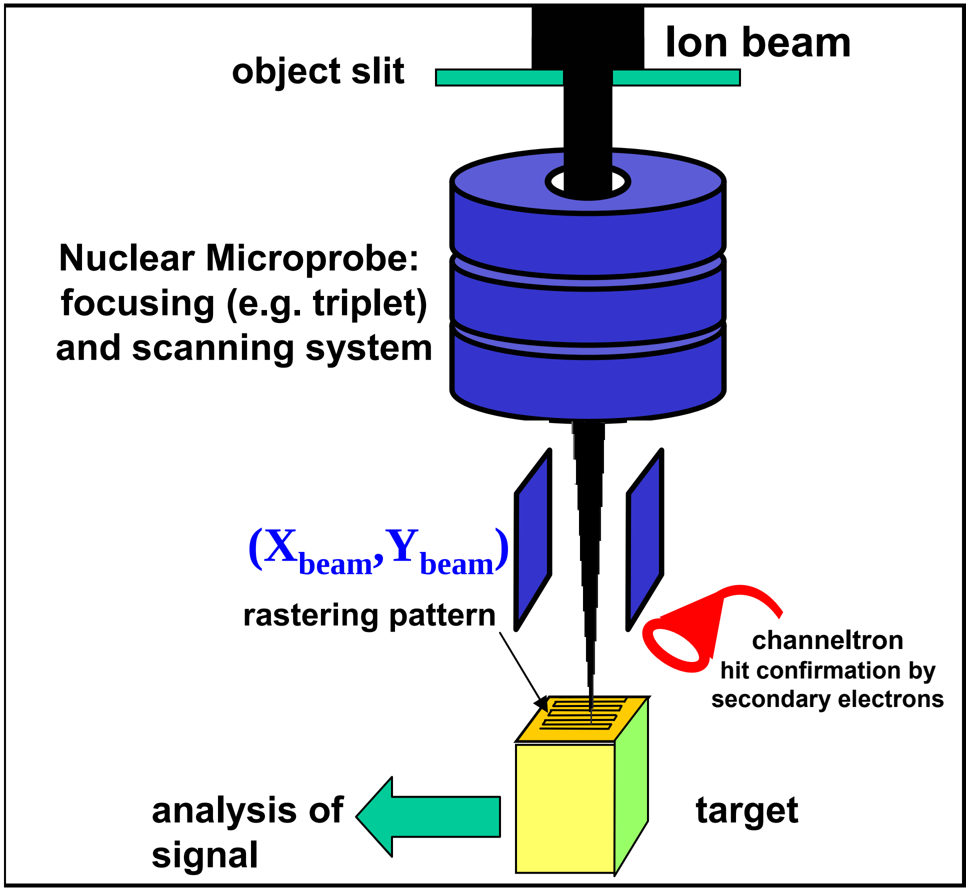
New sensitive area for LET > 30 MeV-cm^2/mg

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

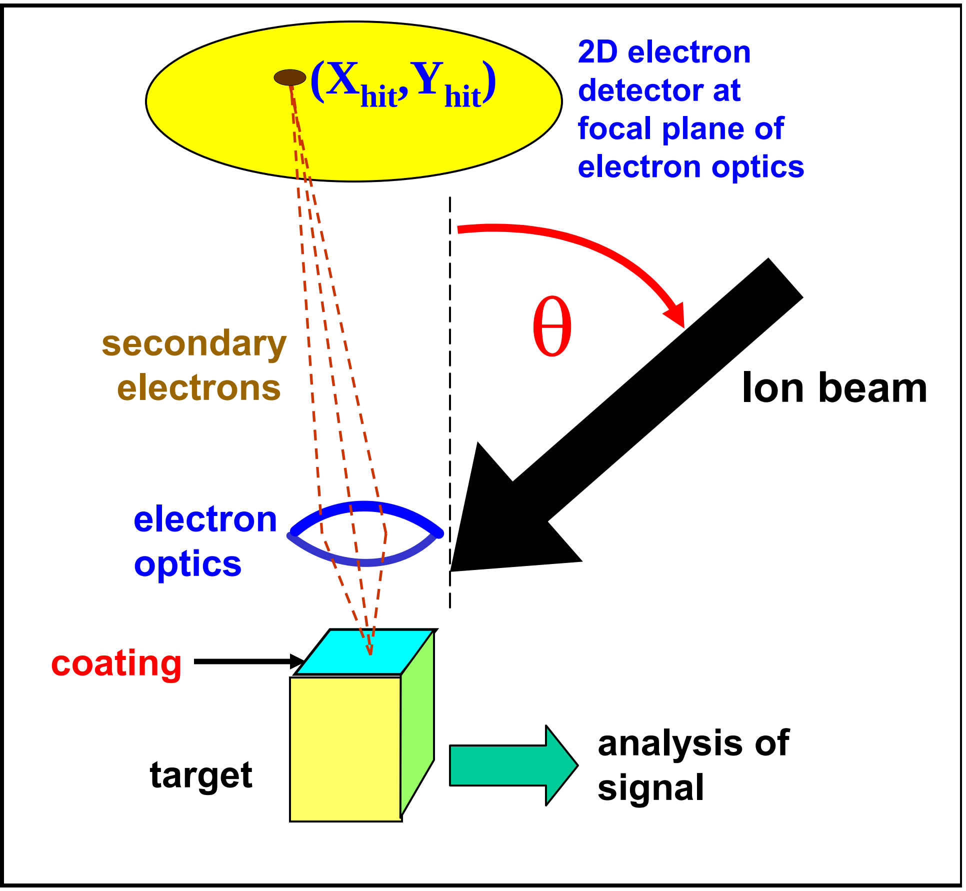
nuclear microprobe *VS* IEEM

Nuclear Microprobe Analysis



Resolution on target determined by beam optics: spot size and positioning. Difficult to micro-focus heavy energetic ions; e.g. rigidity of a 300 MeV Au^{+25} ion is 1.40 T-m, 1.7 times more than 95 MeV C^{+6} ion.

Ion Electron Emission Microscopy

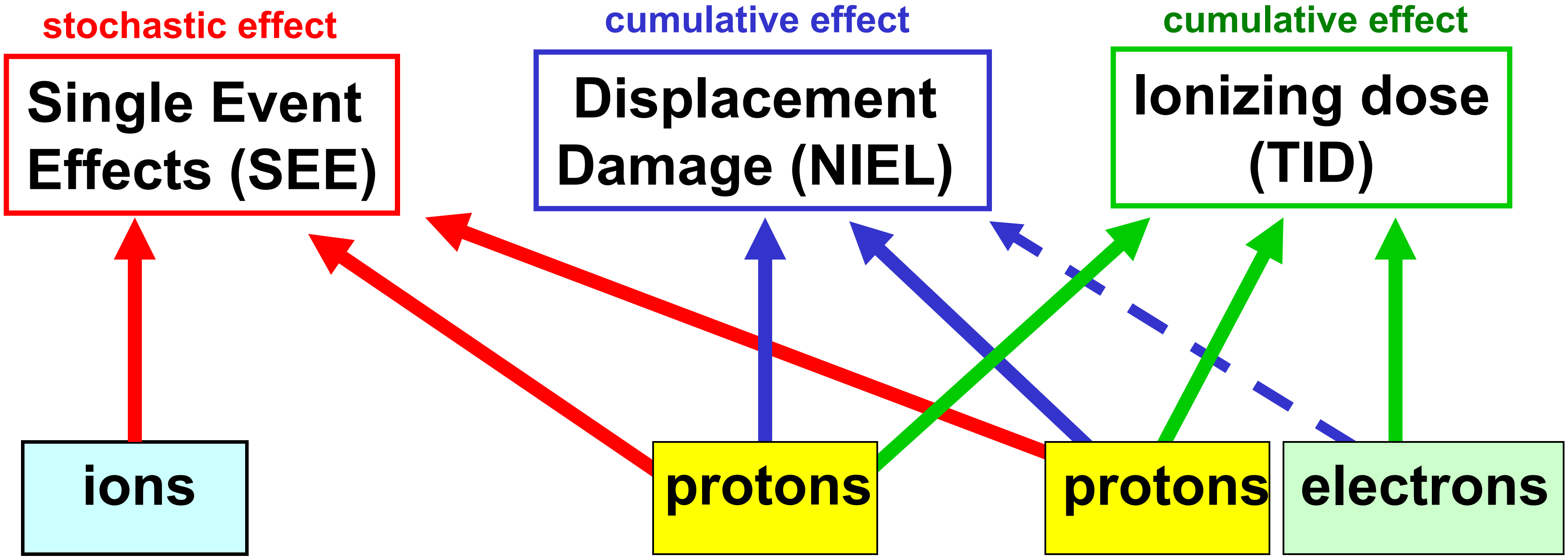


Resolution on target: lateral size of field of view divided by linear line pair resolution of sensor.

analysis: SEE mapping, Ion Beam Induced Charge Collection, Time Resolved IBICC,…

TID,NIEL,SEE

Space Radiation and effects on electronics



stochastic effect

Single Event Effects (SEE)

cumulative effect

Displacement Damage (NIEL)

cumulative effect

Ionizing dose (TID)

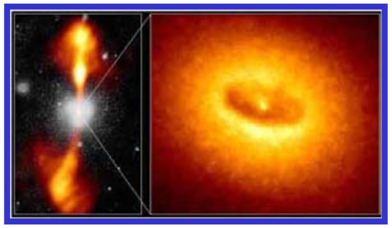
ions

protons

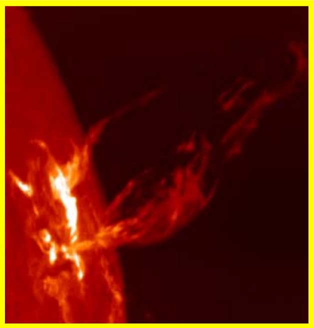
protons

electrons

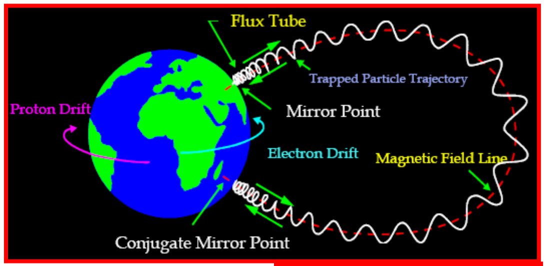
Galactic sources (1987a)

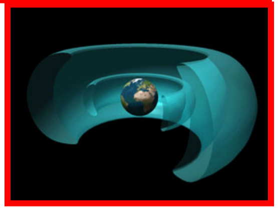


extra-Galactic sources (NGC-4261)



Solar flares

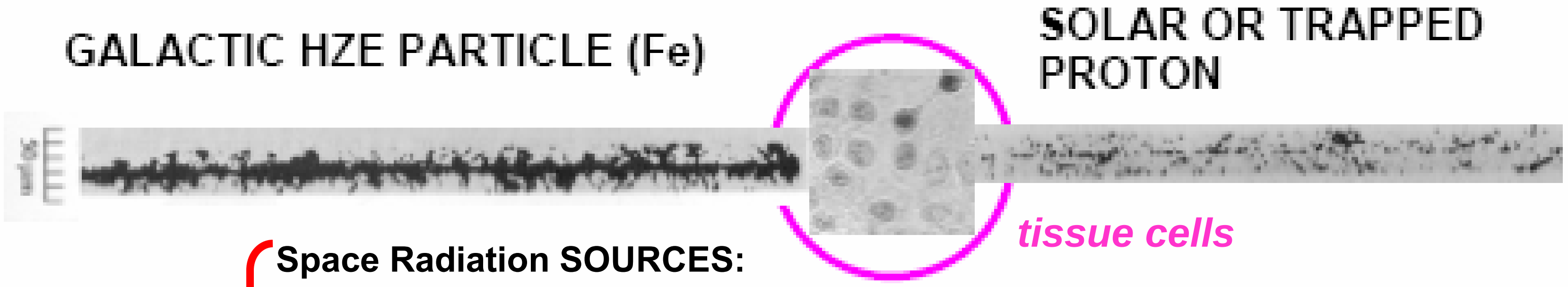




radiation belts

paradigm also adopted 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)**

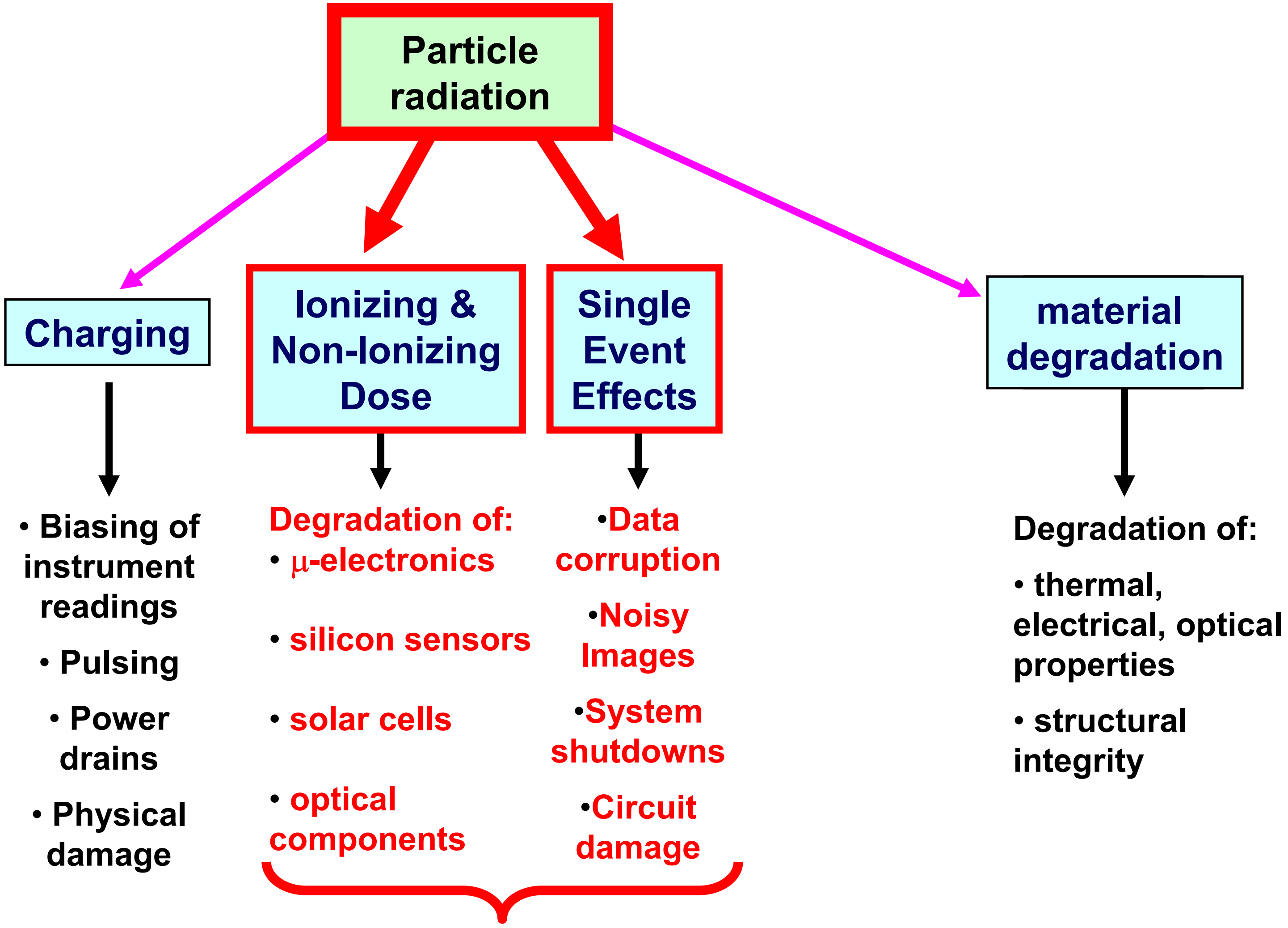
Biological RESPONSES (effects):

- **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	**dose predictable** **effect stochastic**	**dose predictable** *effect negligible*	**dose predictable** **effect predictable**

in perspective

Particle Radiation Effects in Scientific Equipment



Particle radiation

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

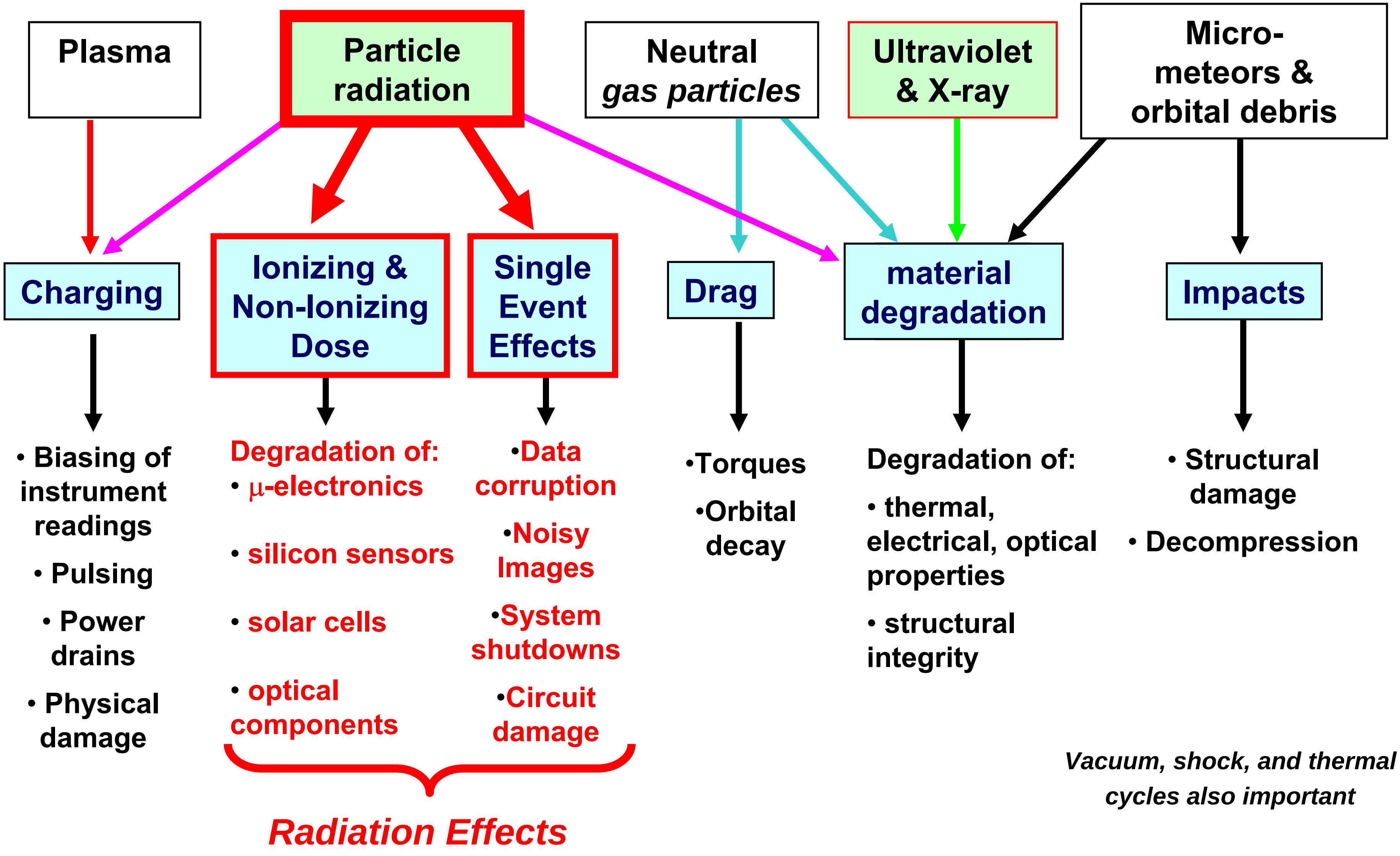
direct effects in electronics

material degradation

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

in perspective

Space Environment Effects
more complete picture



Plasma

Particle radiation

Neutral *gas particles*

Ultraviolet & X-ray

Micro-meteors & orbital debris

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

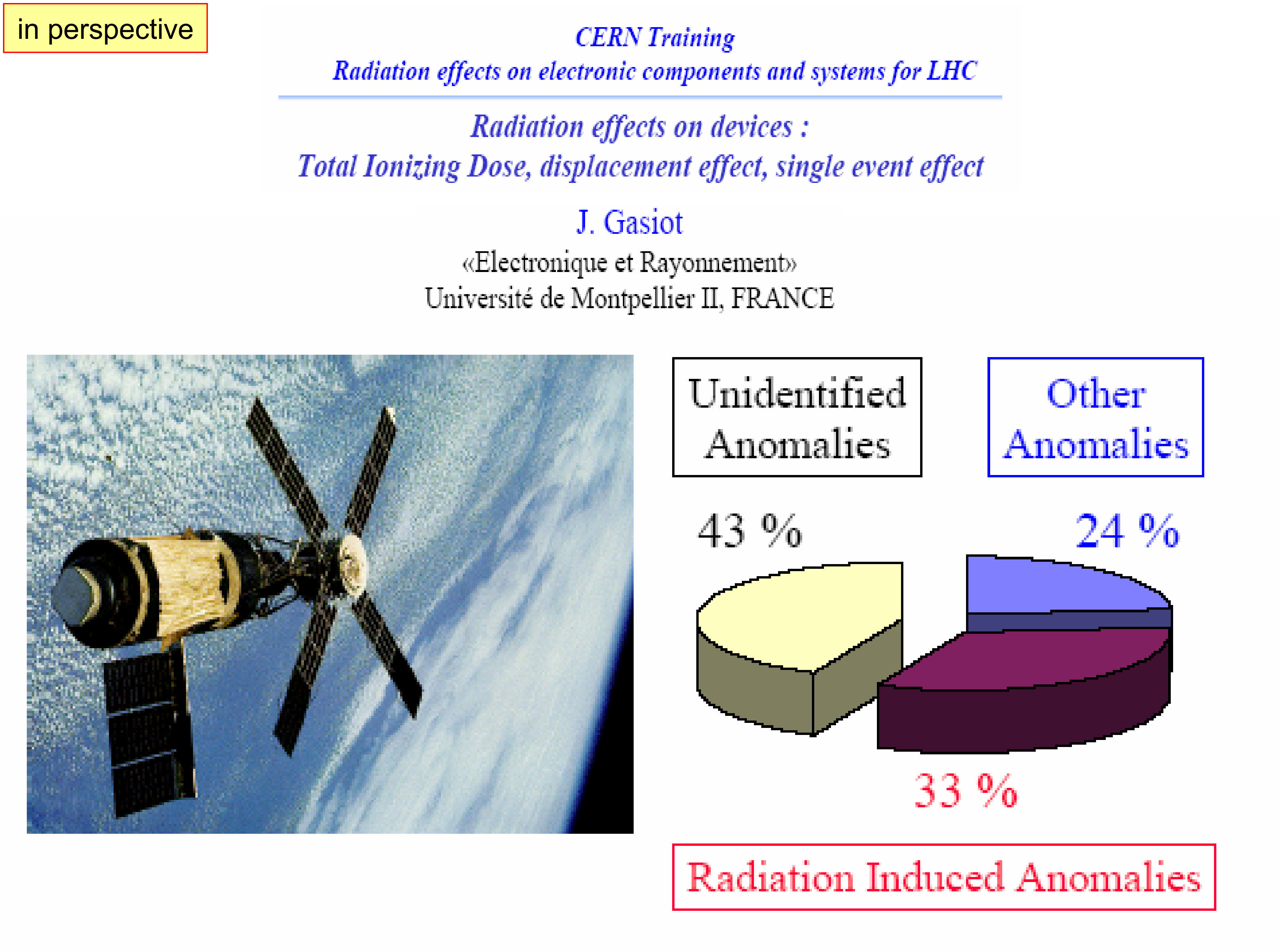
Degradation of:
- thermal, electrical, optical properties
- structural integrity

Impacts

- Structural damage
- Decompression

Vacuum, shock, and thermal cycles also important

in perspective



CERN Training
Radiation effects on electronic components and systems for LHC

Radiation effects on devices :
Total Ionizing Dose, displacement effect, single event effect

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

Unidentified Anomalies

Other Anomalies

43 %

24 %

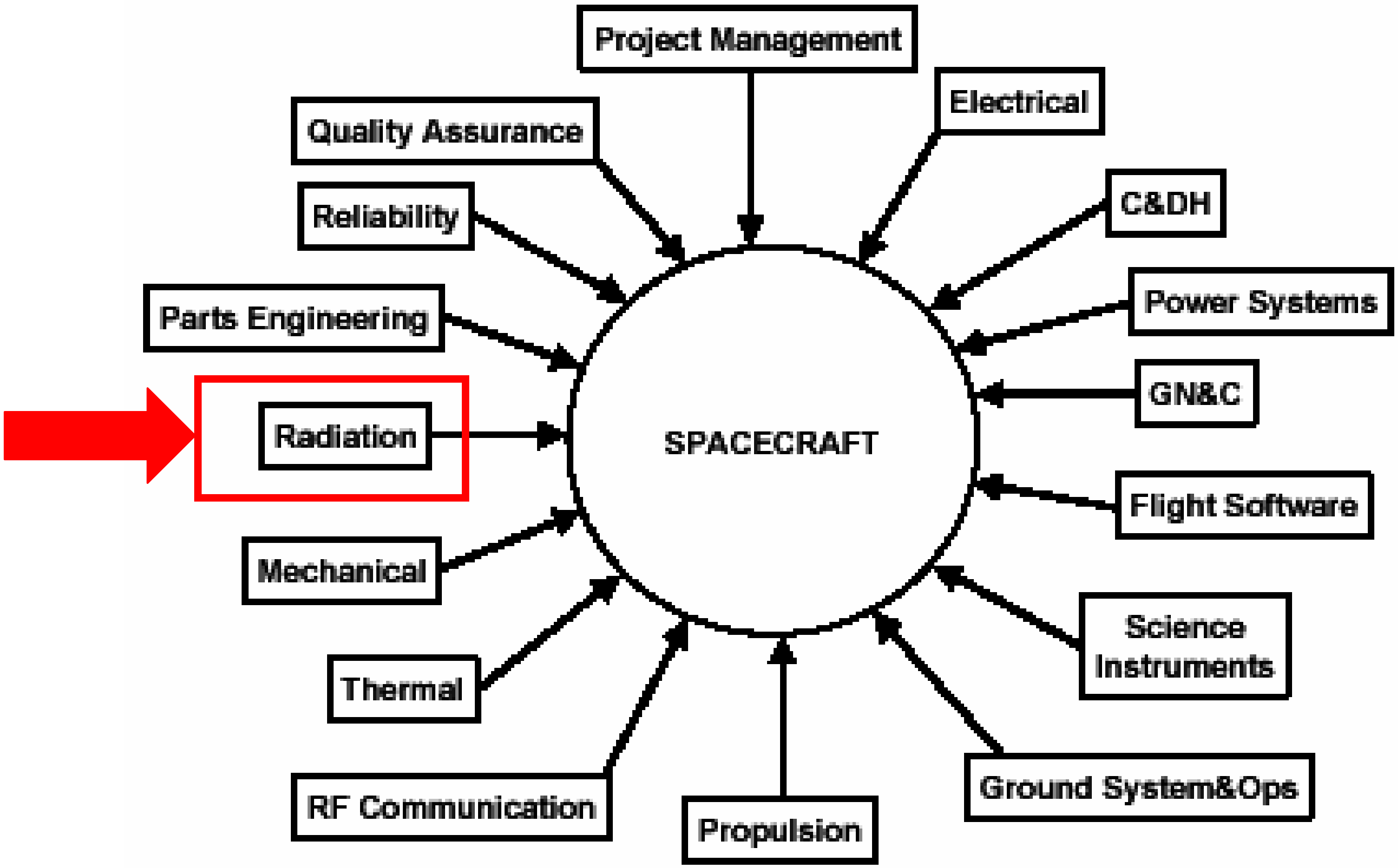
33 %

Radiation Induced Anomalies

in perspective

Spacecraft design team

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



dealing with

In approaching radiation effects

What do I do?

1. need a CLUE
2. tell people (engineers) what to do
3. when ready, perform experiment

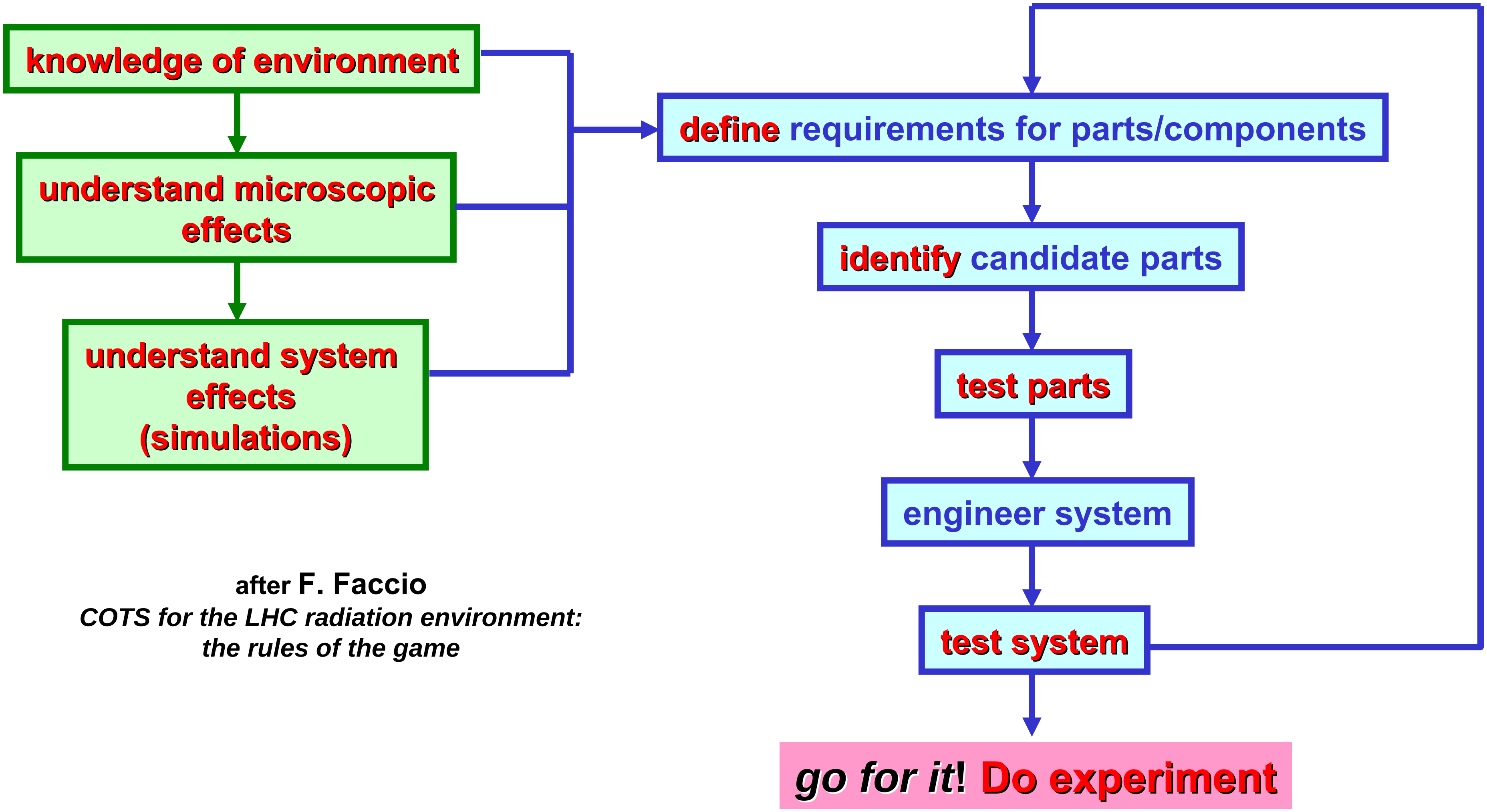
empirical approach

dealing with

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

dealing with

Simulate radiation environment and effects

- to evaluate the risk of failure due to radiation in a given **HEP detector, space detector,...**

  need **description of the radiation environment: i.e.**

  - **Make models** based on **experimental data** and **Monte Carlo simulations** to calculate expected doses, particle types and fluences
  - **Take results of simulation 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**

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, ...)**

• 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?

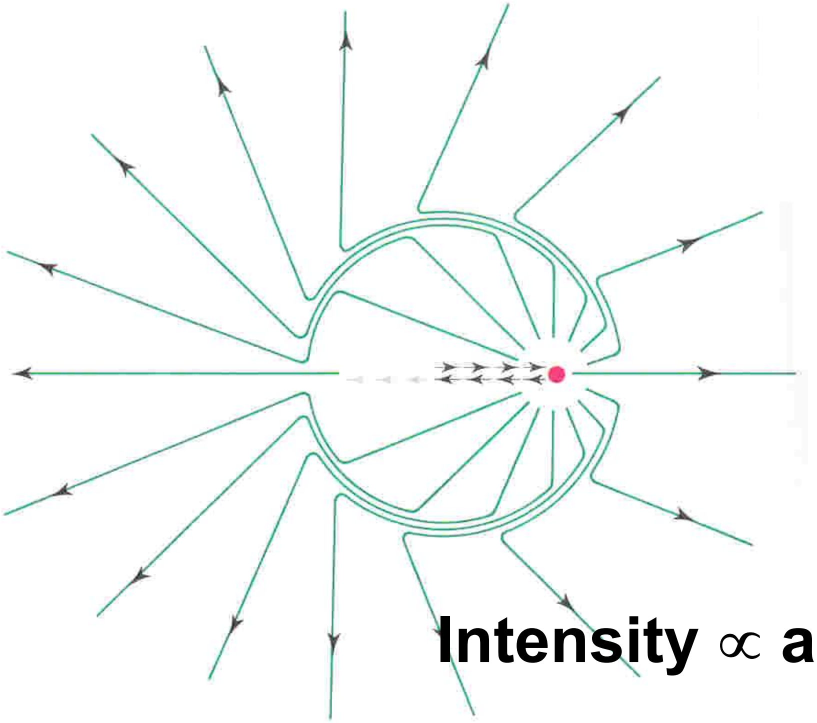
• are there low dose effects?

extra slides

radiation

expanding EM kink

Shake a charge and it will radiate! (classical) ⇒ it will emit photons (quanta)



(classical EM theory) Intensity $\propto a^2$

Newton ⇒ $a = F/m$

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

relativistic treatment ....

radiation

bremsstrahlung (radiation)

- **for two particles in the same medium, the lighter particle emits a greater amount of bremsstrahlung (*other things being equal*)**

electrons (positrons) are *lightest charged particles* and it is easiest to make them shake off photons

$m_{muon} \approx 200\ m_e$

$m_{proton} \approx 1840\ m_e$

$m_{proton} \approx 4(1840)\ m_e$

- **more bremsstrahlung is emitted if a particle travels in a dense medium with a dense high atomic number Z_{targ} than in one with a low atomic number**

electrons have two main energy loss channels: ionisation and bremsstrahlung

$$\left(\frac{dE}{dx}\right)_{rad} = \frac{Z\ E(MeV)}{750}\left(\frac{dE}{dx}\right)_{ionization}$$

$$\frac{dE}{dx} = \left\{1 + \frac{Z\ E(MeV)}{750}\right\}\left(\frac{dE}{dx}\right)_{ionization}$$

enhancement factor due to radiation

enhancement factor due to radiation

E(MeV)	Al	Pb
0.5	1.009	1.05
1	1.02	1.11
5	1.09	1.55
10	1.17	2.09
50	1.87	6.47

dose depth distribution electrons (typical low energy LINACs) and gamma (C0^{60}) in water