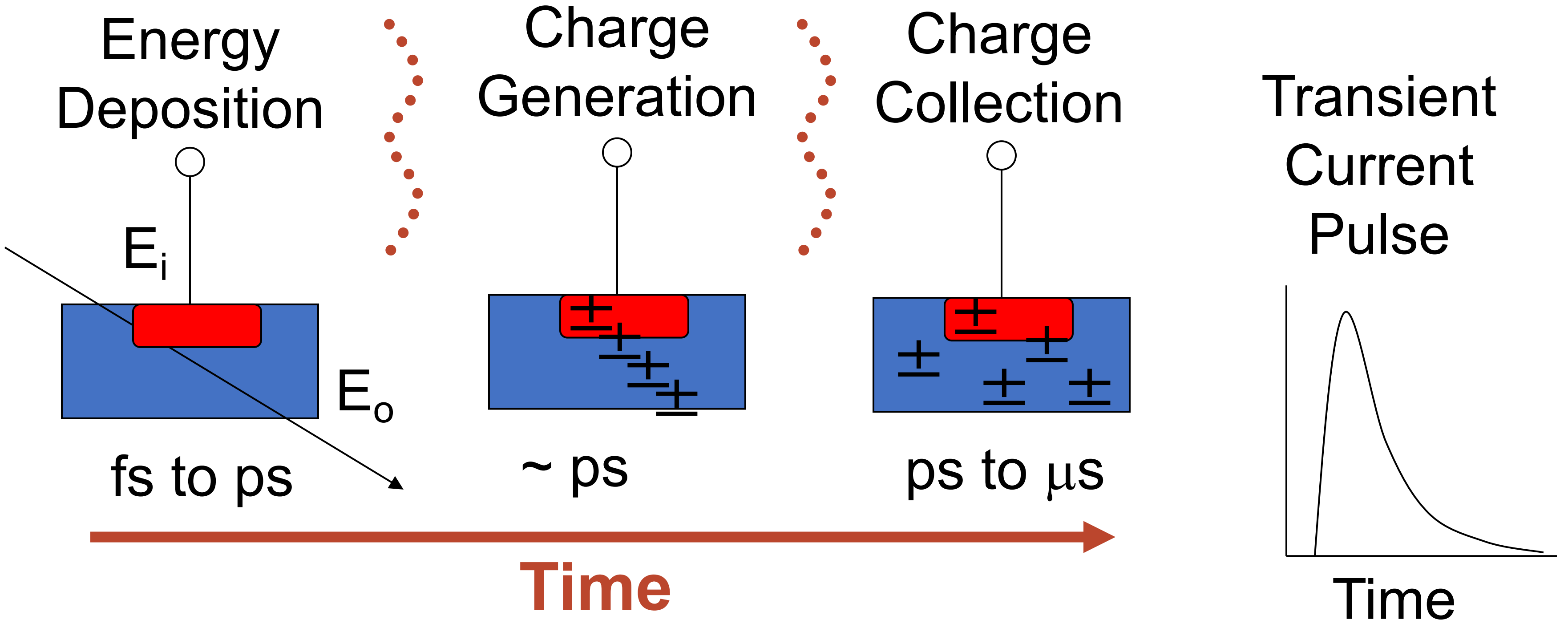
Radiation Effects with CRÈME96

Credit: Matthew Breeding, Vanderbilt University

Foundations in ionizing radiation

Mechanisms, units, and a review of basic calculations with SRIM

Energy deposition & charge generation



$E_{dep} \propto Q_{dep}$

Estimating deposition – energy in a box

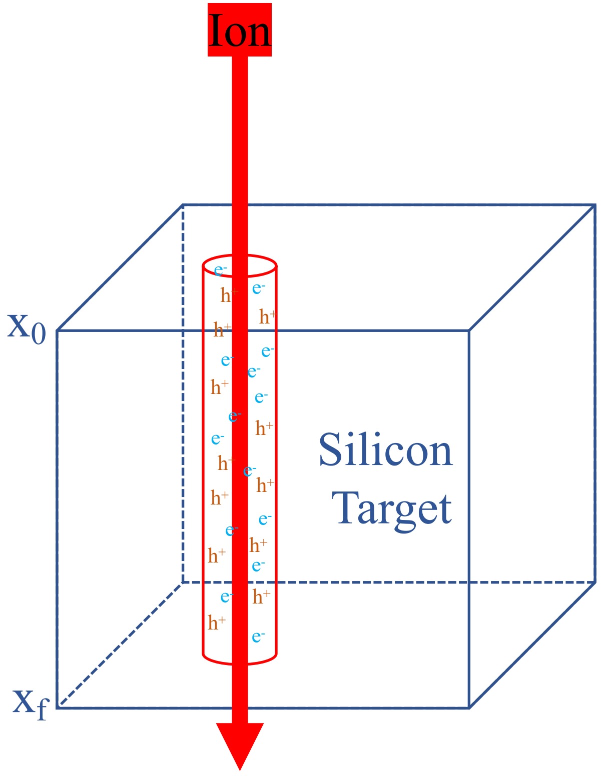
- LET is a differential quantity

$$LET = -\frac{1}{\rho}\frac{dE}{dx} \qquad [\text{MeV-cm}^2/\text{mg}]$$

- Integrating over a path length ($l = x_f - x_0$) gives the total energy deposited (or lost, depending on sign) by the particle for that interval:

$$Edep = \rho \int_{x_0}^{x_f} LET(x)\ dx$$

$$E_{dep} \approx \rho\left(x_f - x_0\right) LET$$



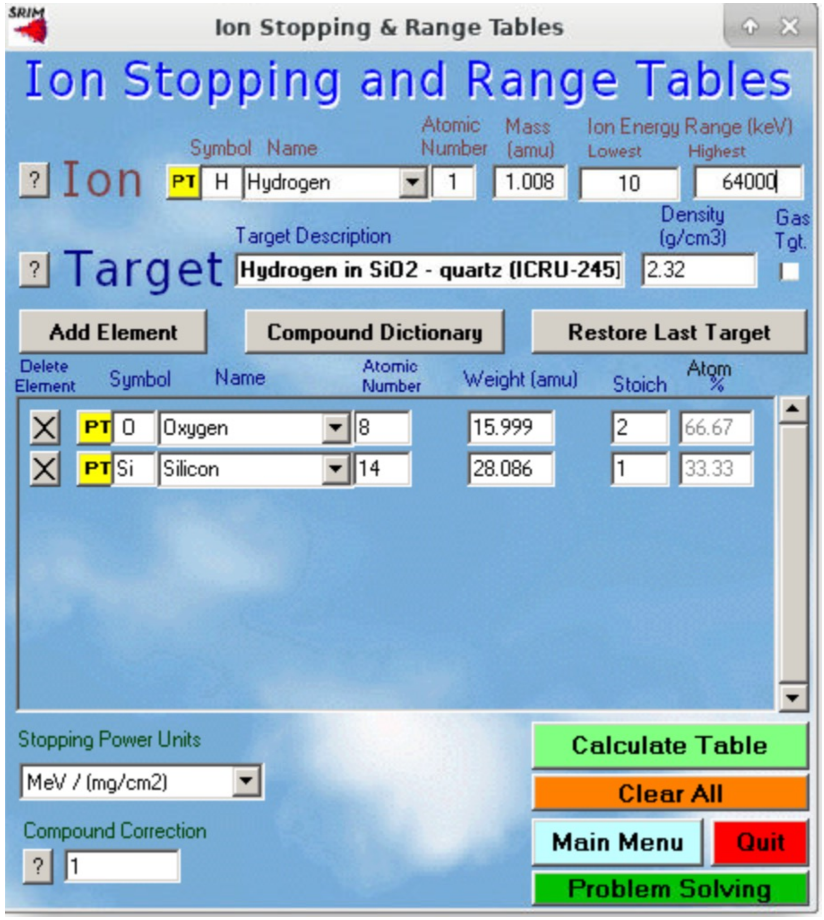
- NOTE – this assumes a constant LET– only valid for $x_f - x_0 \ll dx$

Quantifying ion stopping

- Assuming a constant LET (only valid for $x_f - x_0 \ll dx$):

$$E_{dep} \rightarrow \rho \left(x_f - x_0\right) LET$$

- SRIM (Stopping Range of Ions in Matter) gives LET values for a given (input) target material, a projectile ion, and a range of ion energies



SRIM output – range table

- Defaults to standard LET units
- Stopping split into electronic and nuclear components

$$LET_{tot} = LET_{nuc} + LET_{elec}$$

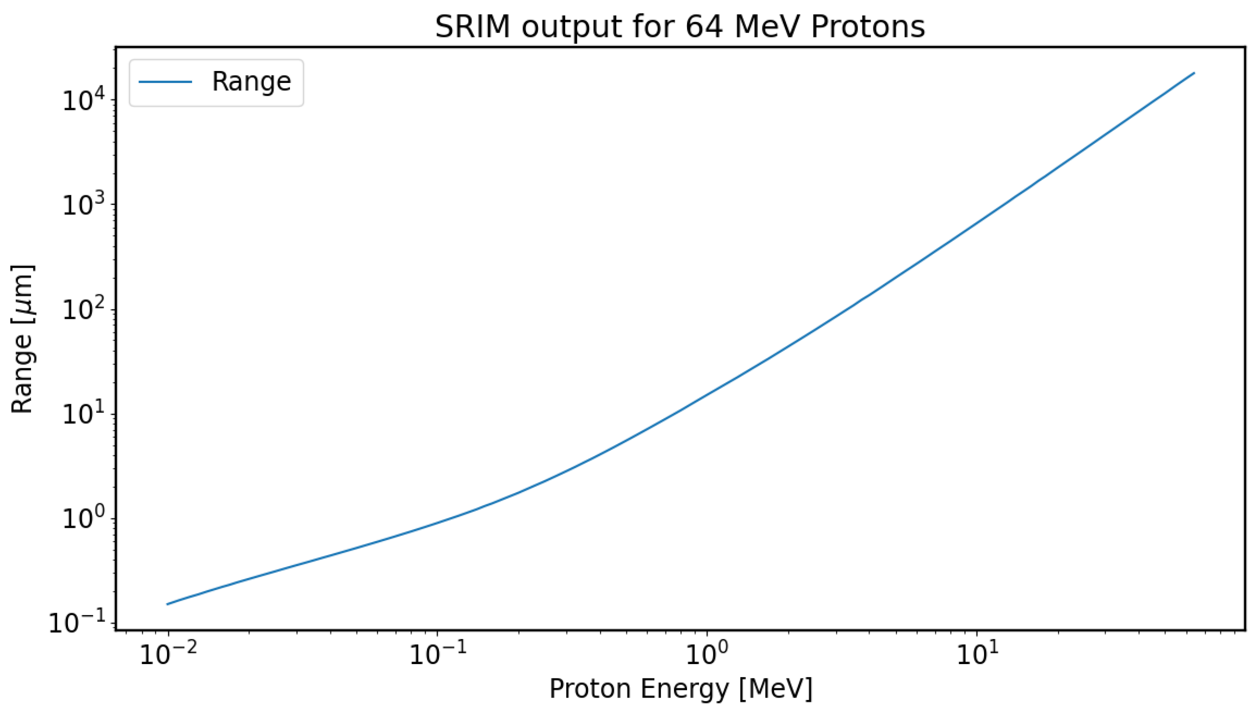
- LET density normalization implied (not just dE/dx)
- Range is also given as a function of energy

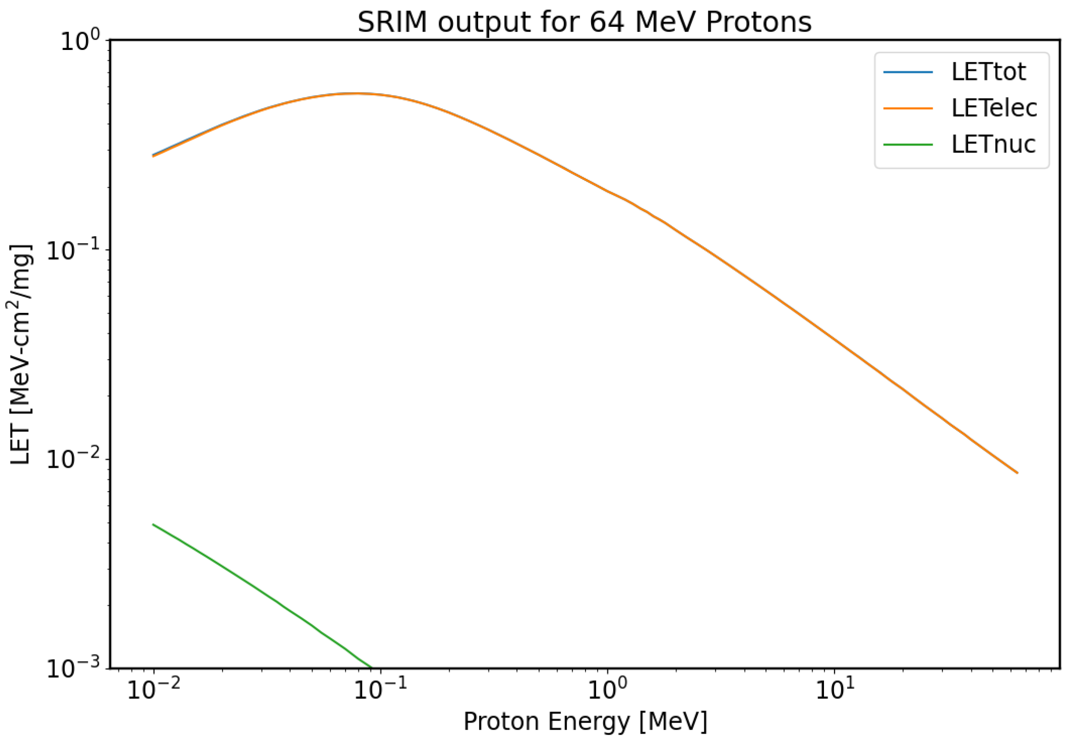
```
=========================================
Bragg Correction = 0.00%
Stopping Units =  MeV / (mg/cm2)
See bottom of Table for other Stopping units
```

Ion Energy	dE/dx Elec.	dE/dx Nuclear	Projected Range	Longitudinal Straggling	Lateral Straggling
10.00 keV	2.785E-01	4.846E-03	1502 A	554 A	531 A
11.00 keV	2.918E-01	4.567E-03	1626 A	574 A	557 A
12.00 keV	3.046E-01	4.323E-03	1746 A	591 A	580 A
13.00 keV	3.170E-01	4.107E-03	1863 A	608 A	603 A
⋮	⋮	⋮	⋮	⋮	⋮
55.00 MeV	9.659E-03	3.991E-06	13.67 mm	588.91 um	470.89 um
60.00 MeV	9.028E-03	3.687E-06	15.98 mm	679.41 um	547.54 um
64.00 MeV	8.594E-03 +	3.476E-06	17.93 mm	739.14 um	612.22 um

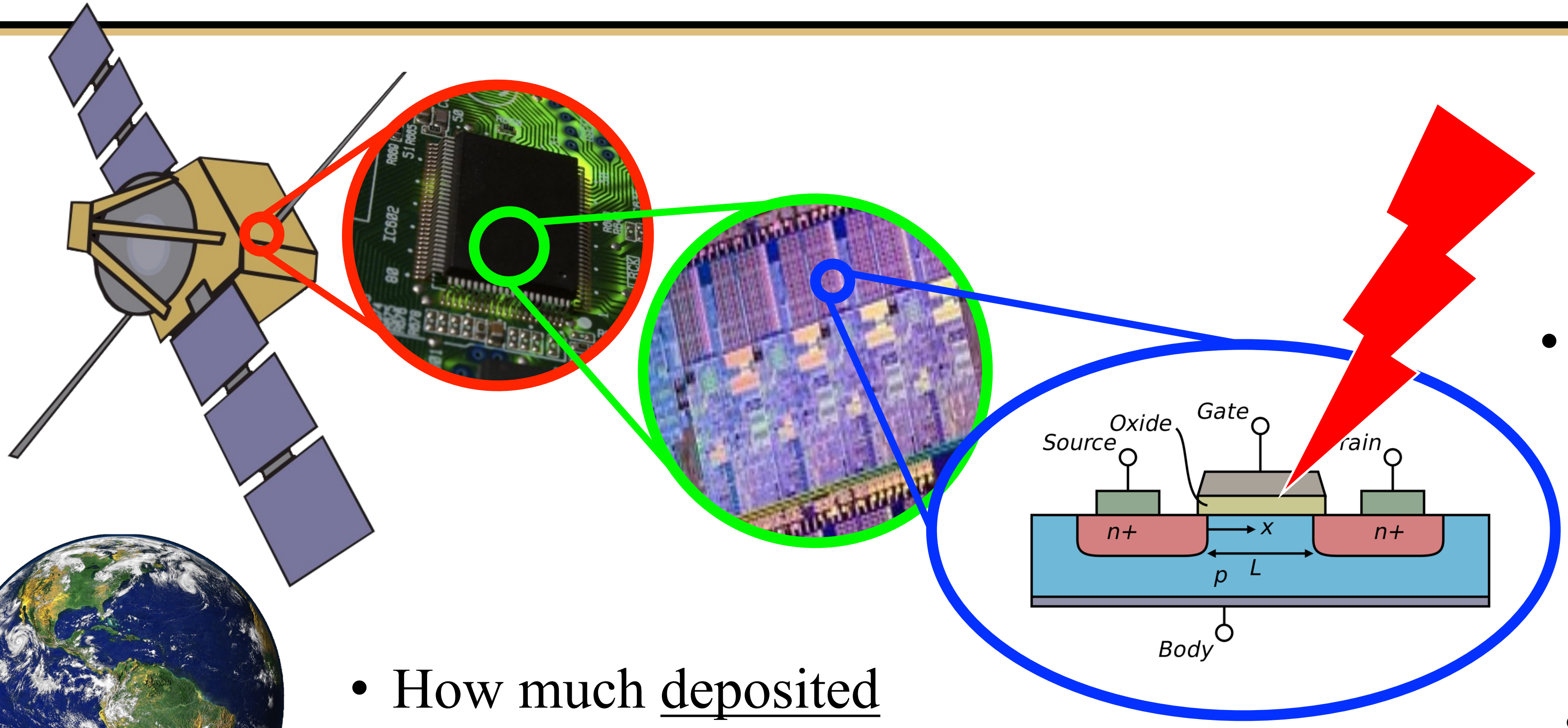
SRIM outputs

- Visualizing the relationship between range, LET, and kinetic energy





Refocus – what are we trying to do?



- How much deposited energy (charge generation) is required to cause an upset?

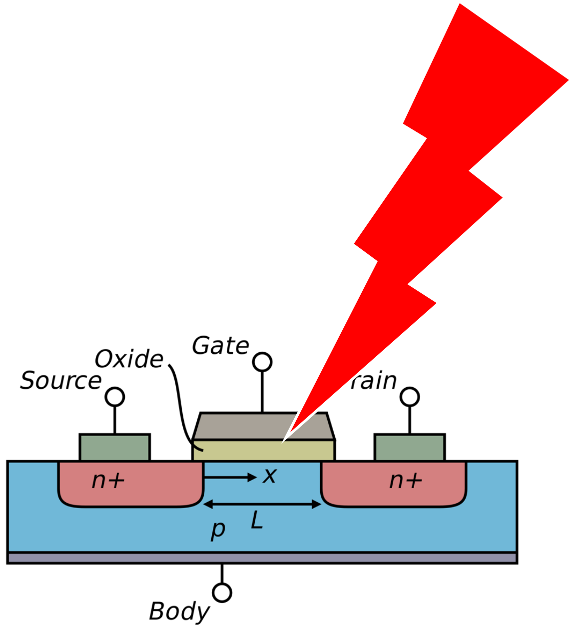
…01100~~1~~0100…
0

- Given a known radiation environment, how often does this happen?

→Event rate

- Can we do anything to reduce the event rate?

Summarizing so far



- Ionizing radiation deposits energy via several physical mechanisms
- The amount of energy deposited depends on the target material and the ion species & ion energy
- LET is how energy deposition is related between the rad. environment & circuit materials

…0110010100…
0

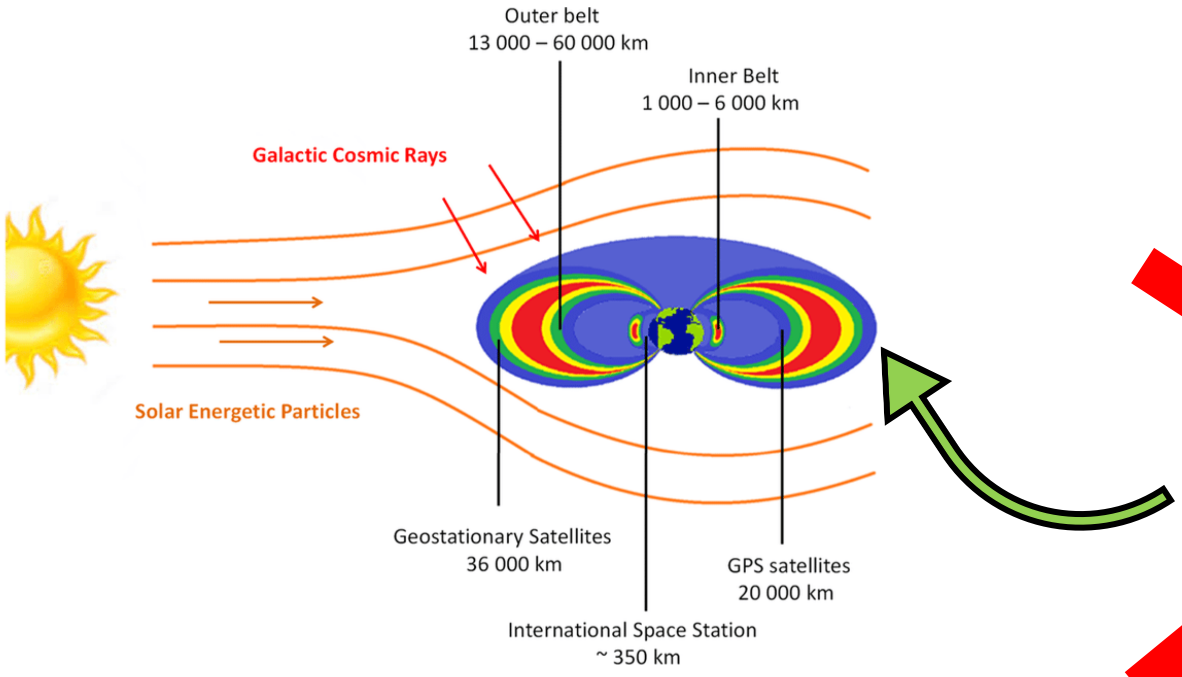
Next: radiation environments & applying these foundations

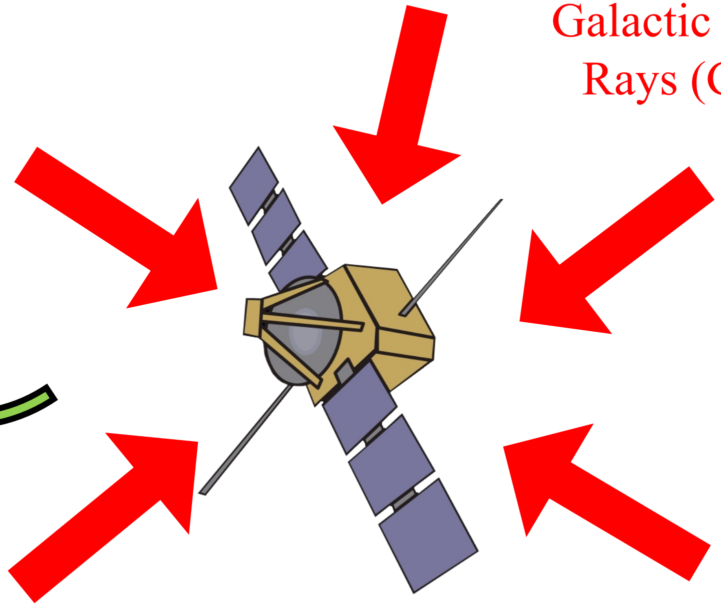
Radiation Environments & CRÈME96

Applying what we know about ionizing radiation to study environments and how they change

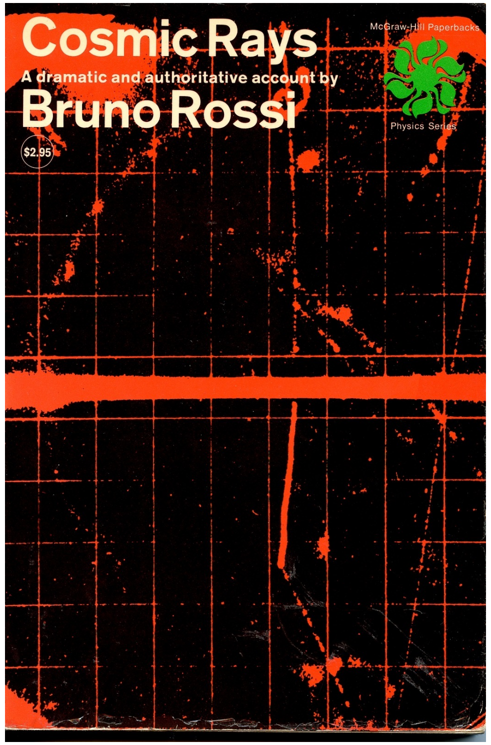
Radiation in space – GCRs

How is the radiation environment described (particles, energies?)
Can we shield the particles from the inside of the satellite?





Galactic Cosmic Rays (GCRs)



Cottin, H., Kotler, J.M., Billi, D. *et al.* Space as a Tool for Astrobiology: Review and Recommendations for Experimentations in Earth Orbit and Beyond. *Space Sci Rev* **209,** 83–181 (2017).

CRÈME96 & CRÈME-MC @ Vanderbilt

Cosmic Ray Effects on Micro-Electronics
https://creme.isde.vanderbilt.edu/CREME-MC

VANDERBILT UNIVERSITY School of Engineering

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news

Patch to TRANS
Apr 15, 2020

Site Move
Jun 04, 2019

HUP "leaking" integration
Sep 01, 2016

Welcome to the CRÈME site

by Brian Sierawski — last modified Dec 20, 2011 11:47 AM
Contributors: Brian Sierawski, Marcus Mendenhall

It has been almost a decade since the introduction of CREME96, the current state-of
particle was much narrower than the minimum feature size in the microelectronic ci
transfer (LET) rate of the ionizing particle could then be measured and used to estin
no longer be ignored. This assumption in CREME96 has been shown to have signific
model that correctly accounts for the distribution of energy deposition about the tra

The need for a comprehensive and extensible complement to CREME96 that is widel
Geant4 Libraries, for the basic radiation-computation engine. This core Monte Ca

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Forgot your password?

New user?

creme96

TRP
GTRN
FLUX
TRANS
LETSPEC
HUP
PUP
DOSE

GCR Flux with CRÈME96

creme96

- TRP
- GTRN
- FLUX
- TRANS
- LETSPEC
- HUP
- PUP
- DOSE

CREME96/FLUX

External Space Ionizing-Radiation Environment: User-Supplied Parameters

1. **Atomic number of lightest species to be included:** 1
2. **Atomic number of heaviest species to be included:** 1
3. **Environment model:**

   a. GCR Version:

   - (•) CREME96 (valid 1950-1997)
   - ( ) CRÈME 2009 (Nymmik with extensions, valid 1760-present) (Note: this does not support trapped protons, and only

   b. Solar Conditions:

   Solar-quiet (no "flare") conditions:

   - (•) Solar Minimum (Cosmic-Ray Maximum)
   - ( ) Solar Maximum (Cosmic-Ray Minimum)
   - ( ) Enter year (eg. 1996.80)

   Solar-energetic particle ("flare") conditions:

   - ( ) Worst Week
   - ( ) Worst Day
   - ( ) Peak 5-minute-averaged fluxes

4. **Spacecraft location:**

   - (•) Near-Earth Interplanetary/Geosynchronous Orbit
   - ( ) Inside Earth's Magnetosphere

   a. **Name of GTRN file:** No file selected browse...

   b. **Name of trapped proton file:** No file selected browse... clear file (Optional)

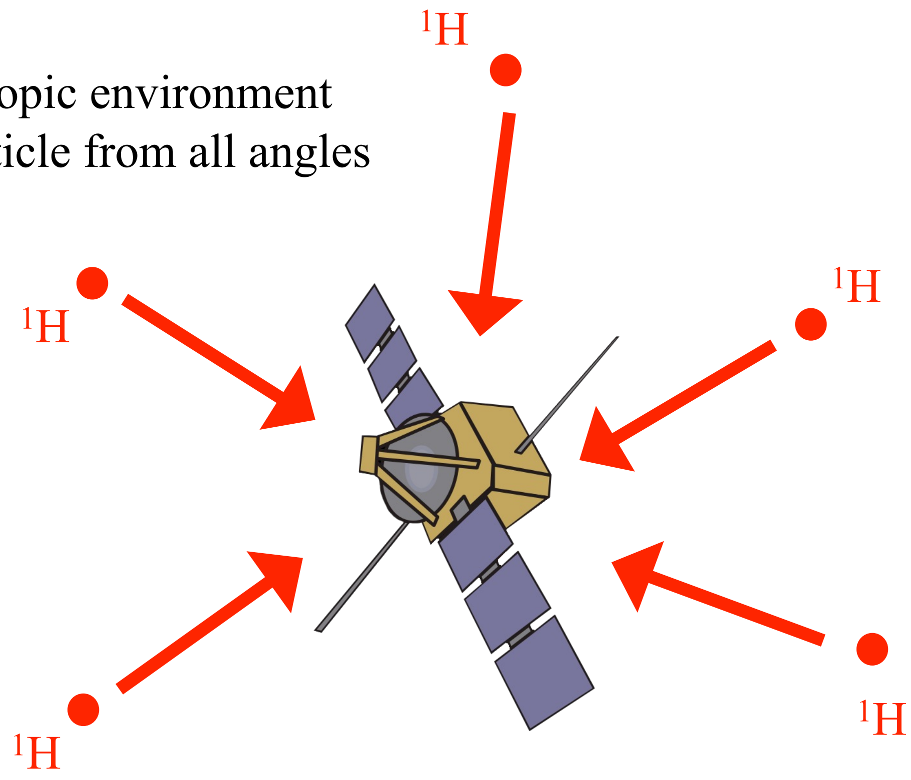
5. **Rootname for FLUX Output file:** ProtonsOnlySolarMinimum (.*flx* extension added automatically)

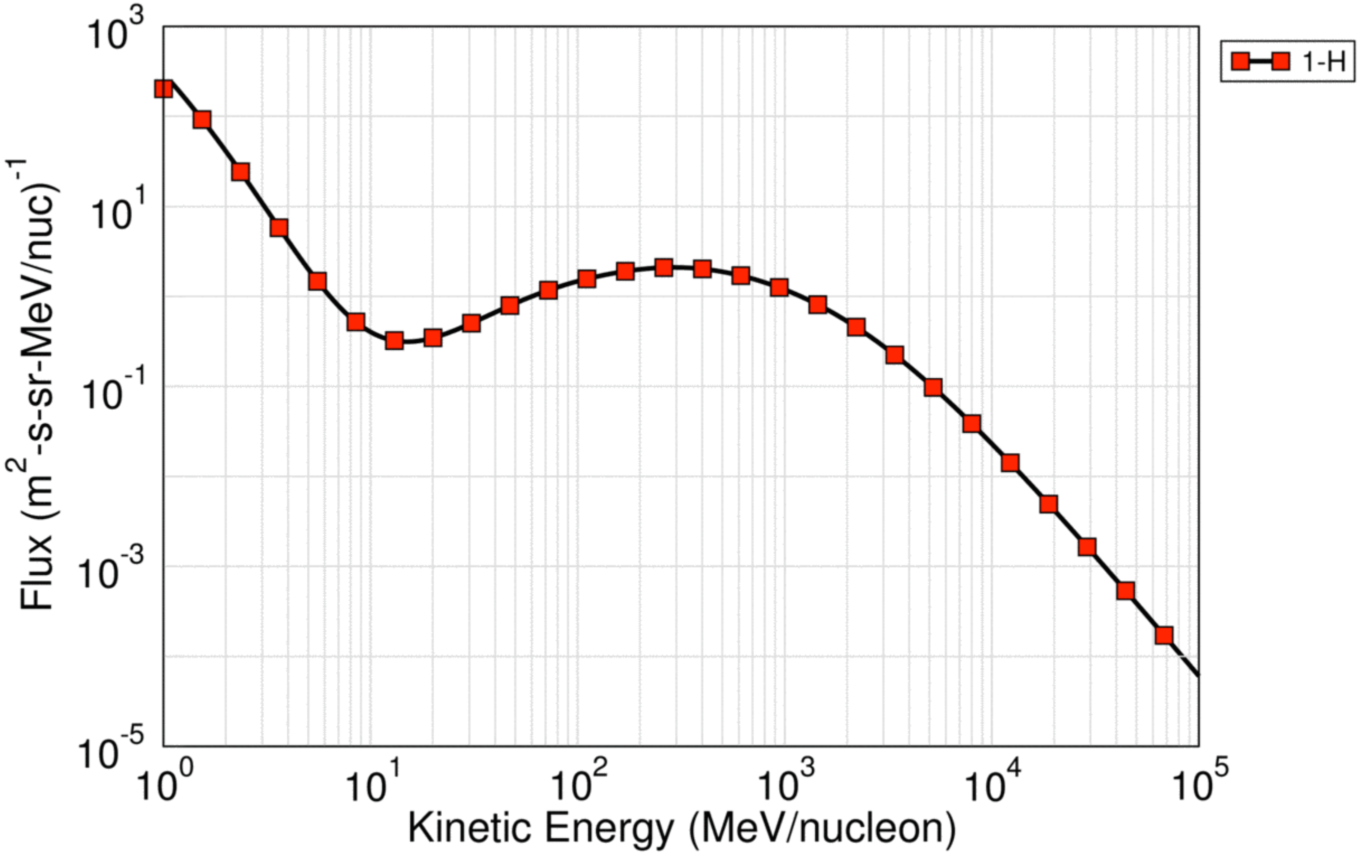
Submit Reset Help

Solar activity and GCRs are inversely proportional

Starting with just protons

Isotropic environment
→ particle from all angles





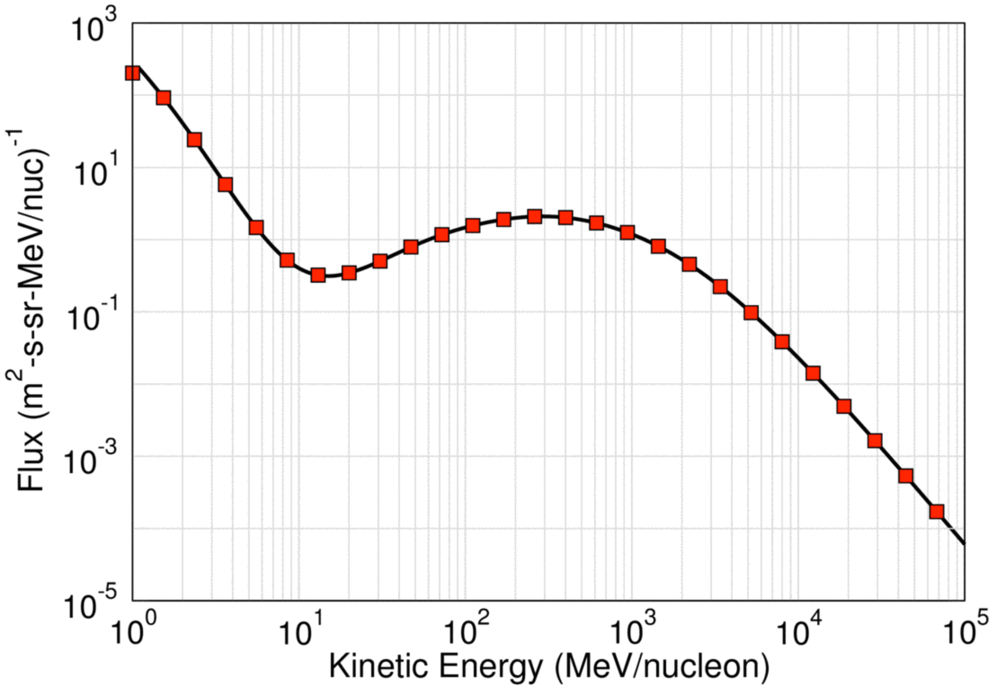
How many of these will deposit enough energy for an effect?

A quick note on units

- Flux ≠ Fluence!
- Flux is differential: $\left[\frac{\#}{cm^2\ s\ sr\ MeV/u}\right]$
- Integrating gives the fluence: $\left[\frac{\#}{cm^2}\right]$

Remember – we're interested in an event rate →
[# / device / day], [# / Mbit / year] etc.

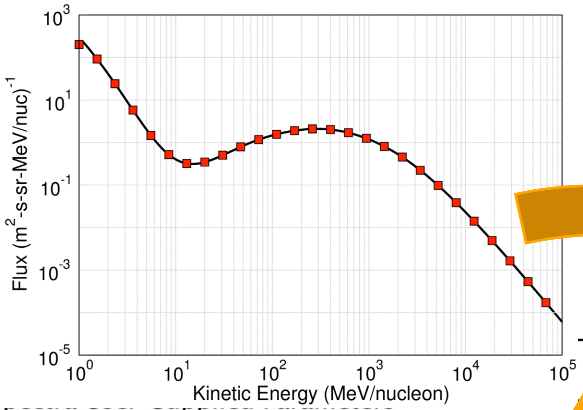
- Will need to account for the size of the devices/circuit
- Need to map kinetic energy to LET



Getting to energy deposition – LETSPEC

creme96

- TRP
- GTRN
- FLUX
- TRANS
- LETSPEC
- HUP
- PUP
- DOSE

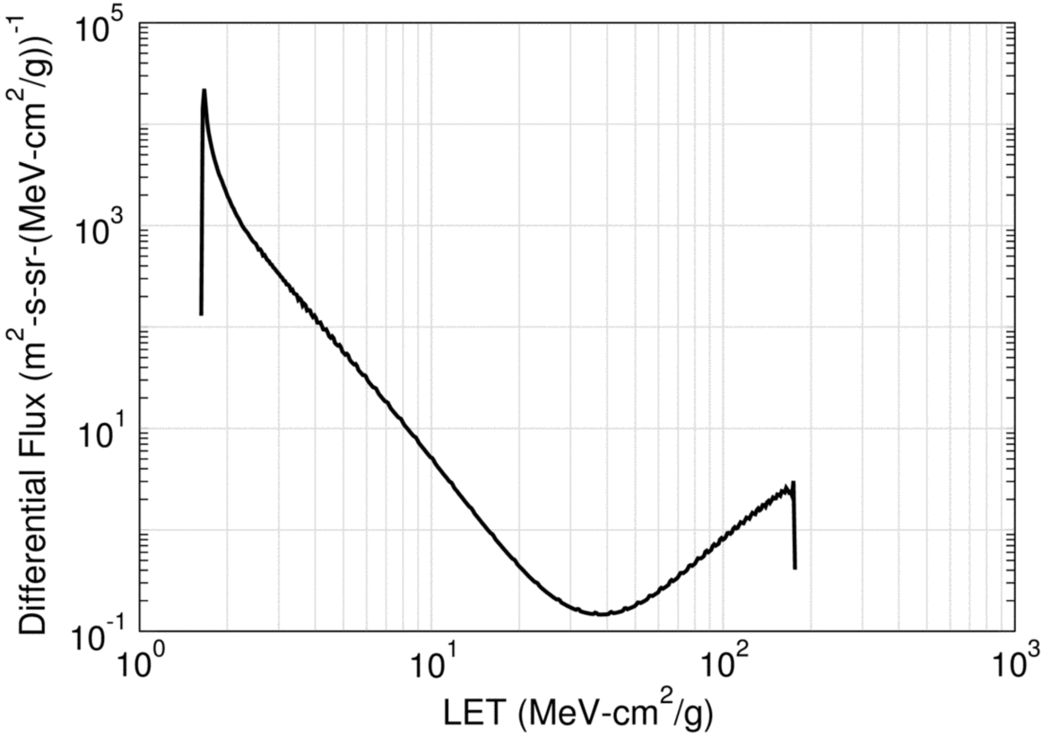


CREME96/LETSPEC

Linear Energy Transfer (LET) S

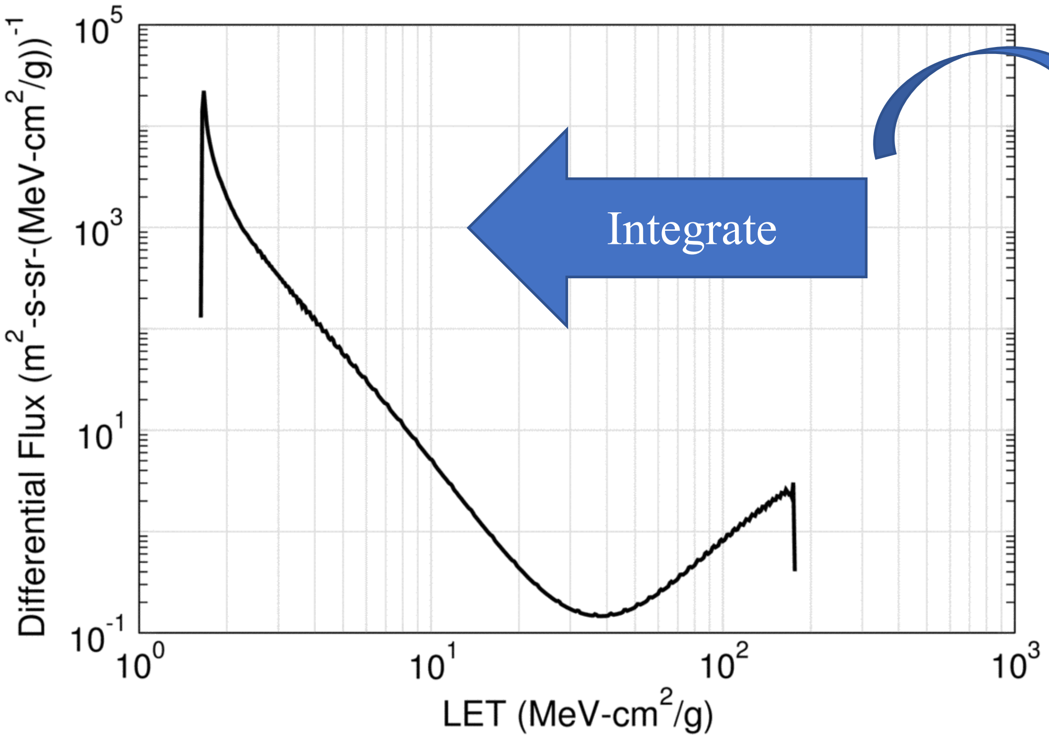
1. **Name of flux file:** ProtonsOnlySolarMinimum (CREME96 flux/environm browse...
2. **Atomic number of lightest species to be included:** 1
3. **Atomic number of heaviest species to be included:** 1
4. **Minimum Energy value:** 0.1 MeV/nuc
5. **Device material:** silicon
6. **Do you want a differential LET spectrum too?** ☑
7. **Rootname for LETSPEC output file:** ProtonsOnlySolarMinimum (*.let* extension

Submit Reset Help



Getting to energy deposition

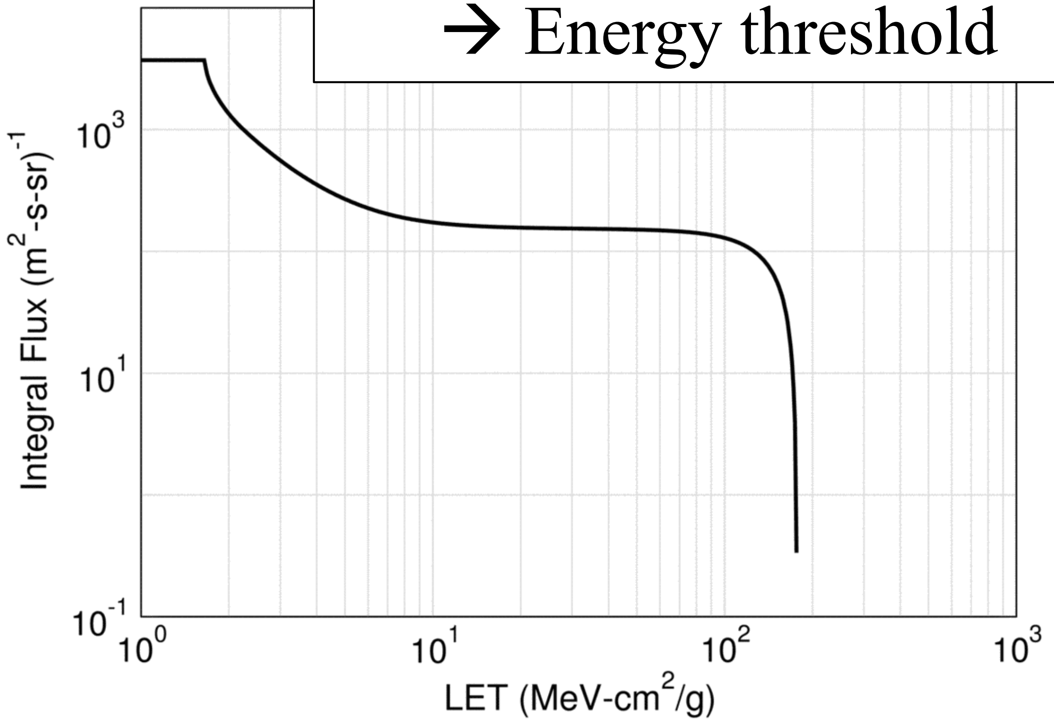
- Then integrate from high to low LET



$$E_{dep} \approx \rho\left(x_f - x_0\right) LET$$

(assuming small path)

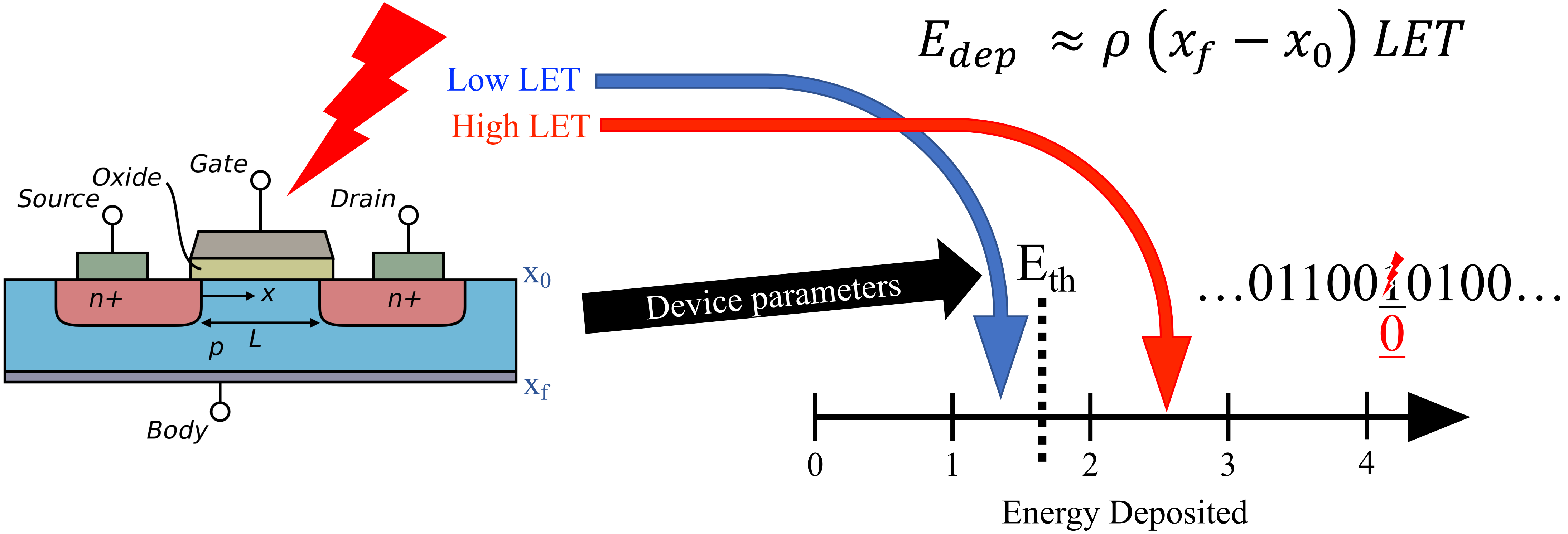
→ Energy threshold



Introduction of energy threshold

- Our "box" ideally corresponds to something physically meaningful
  - →A transistor that can upset

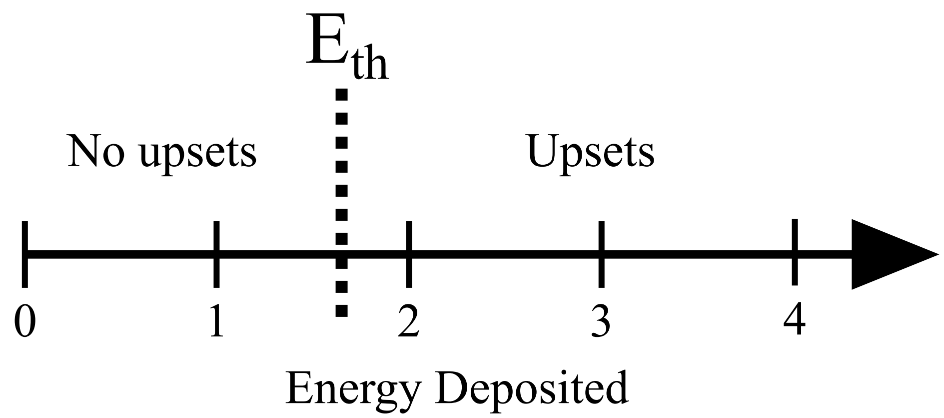
$$E_{dep} \approx \rho\left(x_f - x_0\right) LET$$



Energy threshold and LETSPEC

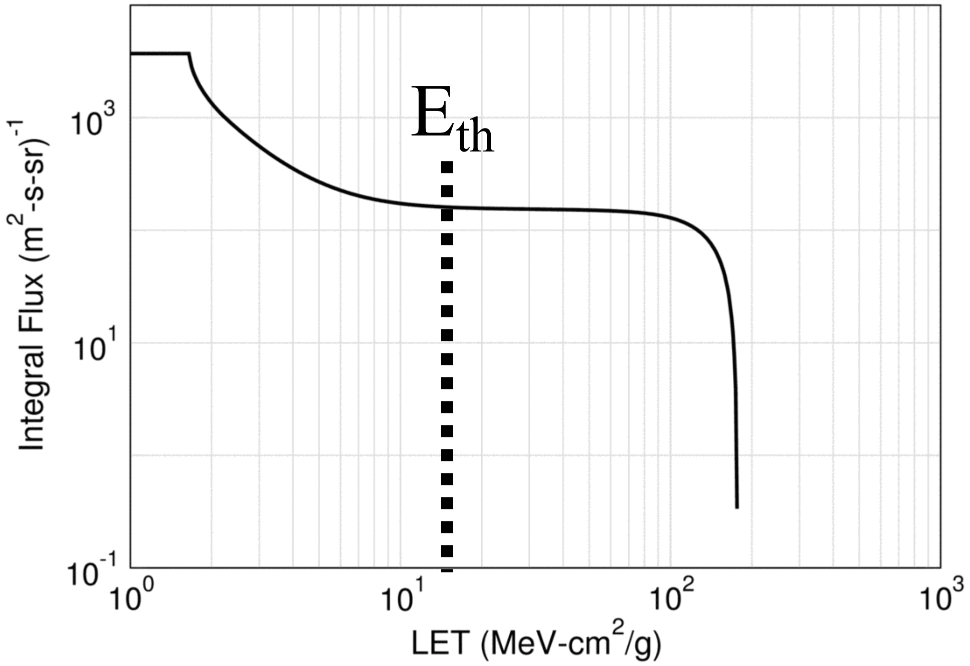
- Two ways to change E_{dep} -- path length & LET

$$E_{dep} \approx \rho \left(x_f - x_0\right) LET$$



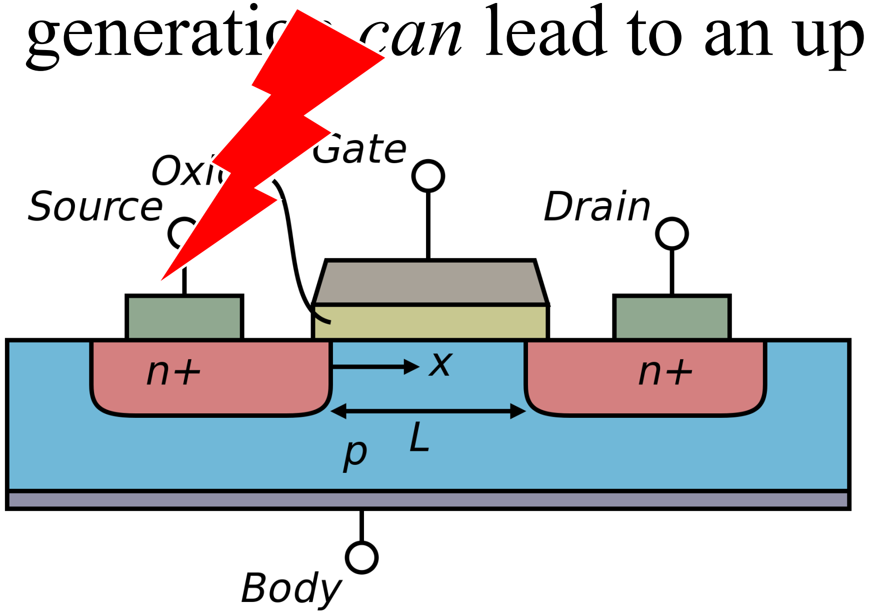
If we assume constant path length, *only* LET determines if an error occurs

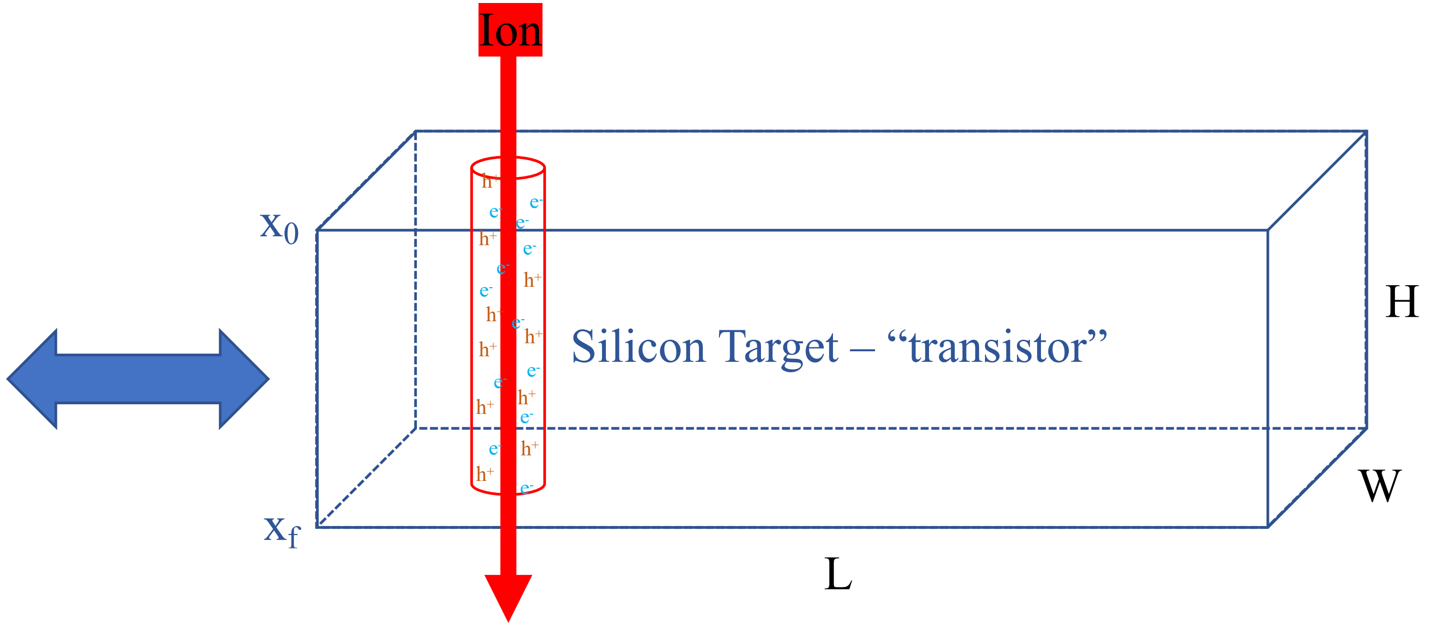
→ This is why the flux is integrated with LETSPEC



Expanding on "energy in a box"

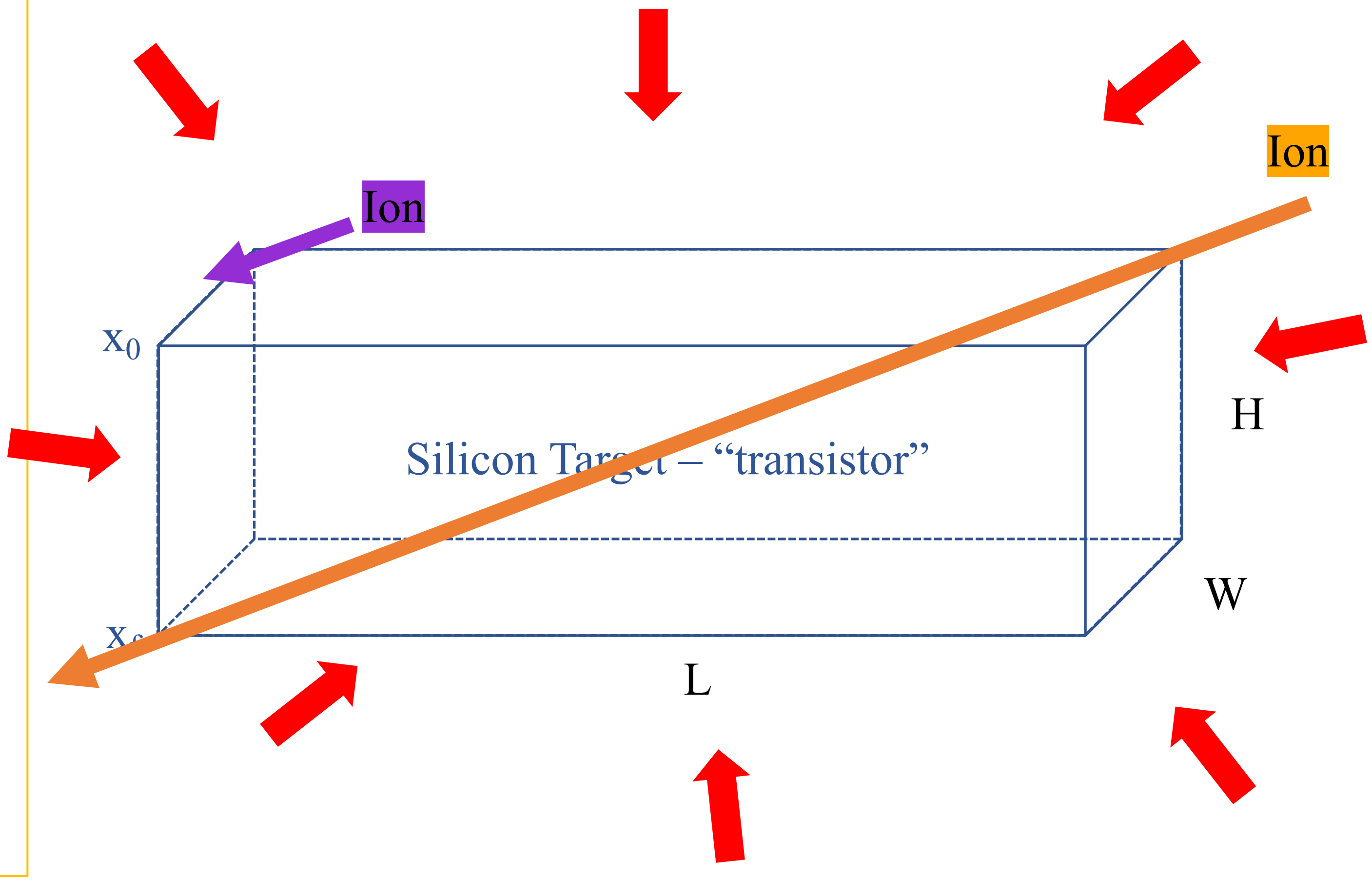
- Path lengths are not constant in the real world
- Approximate the transistor as an RPP inside of which charge generation *can* lead to an upset



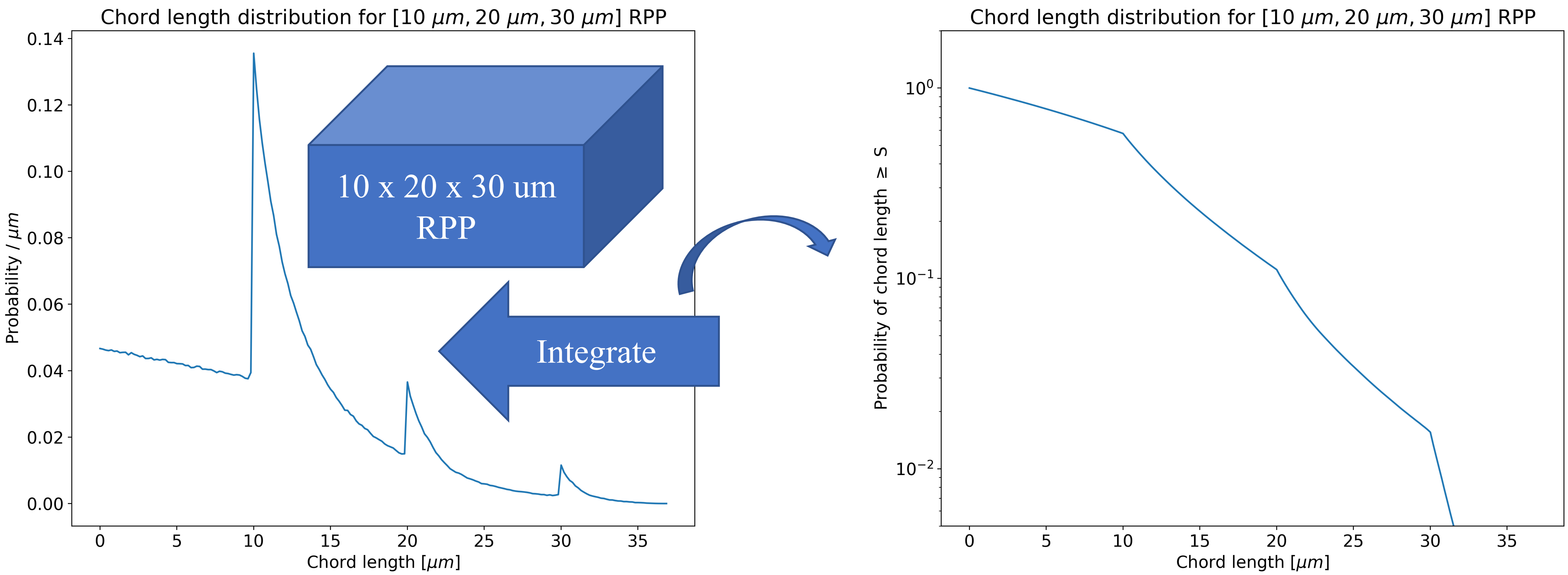


Chord lengths

- The heavy ion environment in space is *isotropic** – particles come from all directions
- The path lengths are not as simple here – multiple possible *chords*
  - Longest: from corner to corner
  - Shortest: infinitesimally small (e.g. path clips a corner)



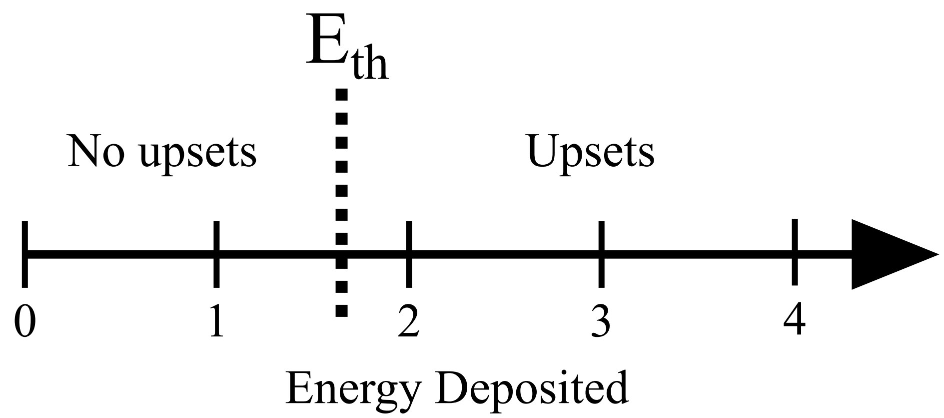
Chord length distribution



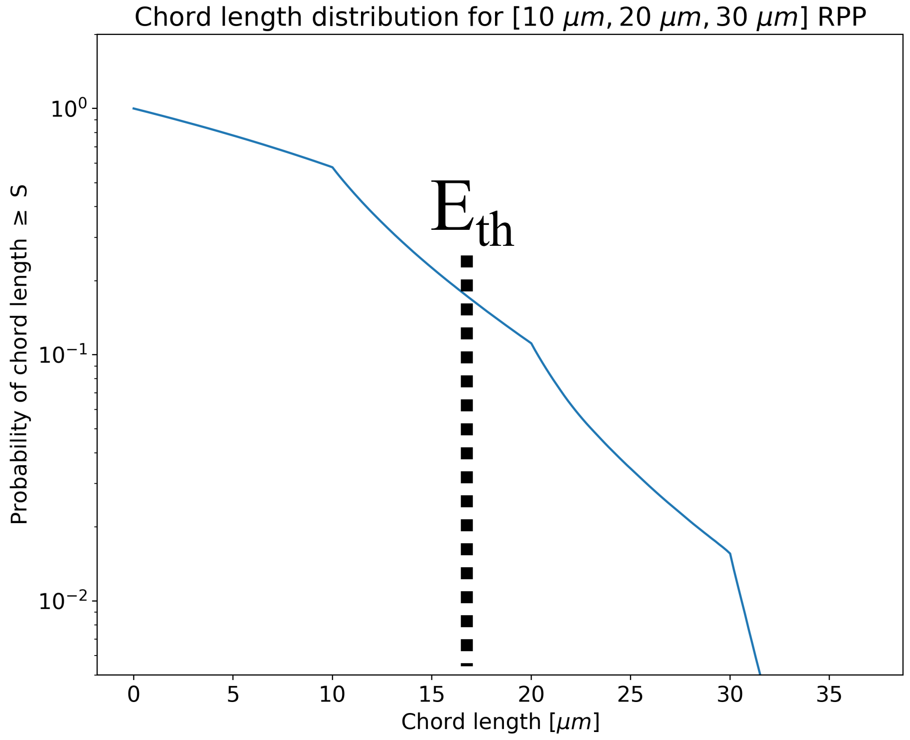
Energy threshold and chord distributions

- Two ways to change E_{dep} -- path length & LET

$$E_{dep} \approx \rho \left(x_f - x_0\right) LET$$



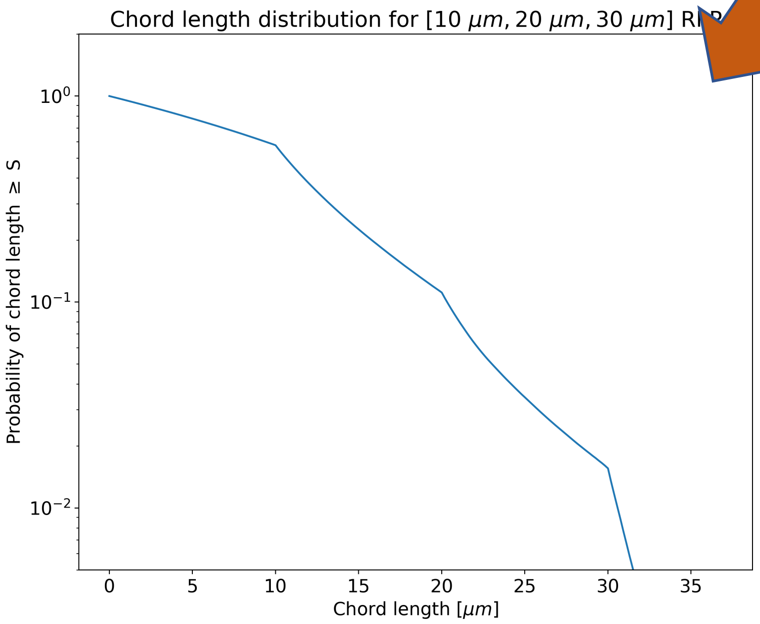
If we assume constant LET, *only* path length determines if an error occurs

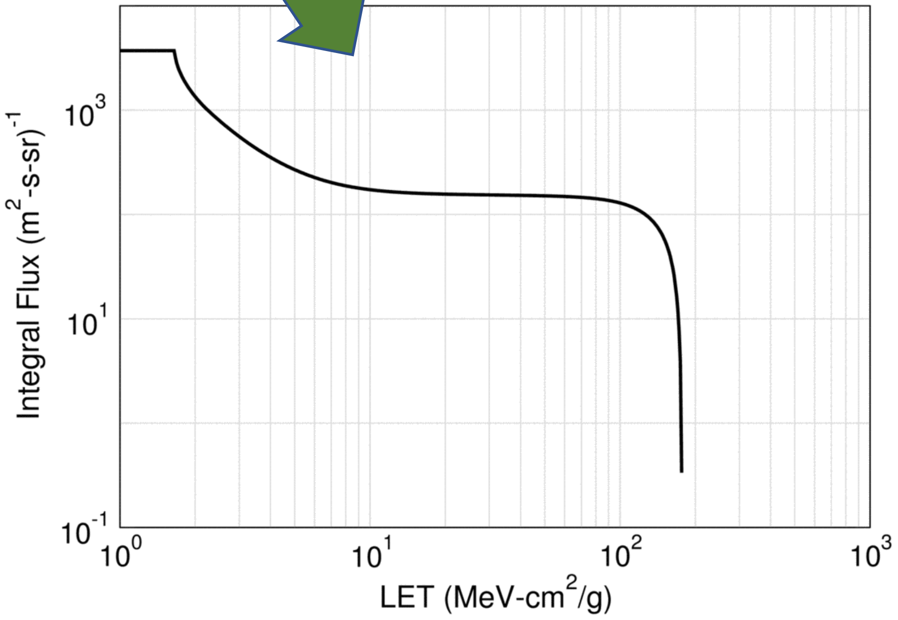


CRÈME96 handles chord and LET dist.

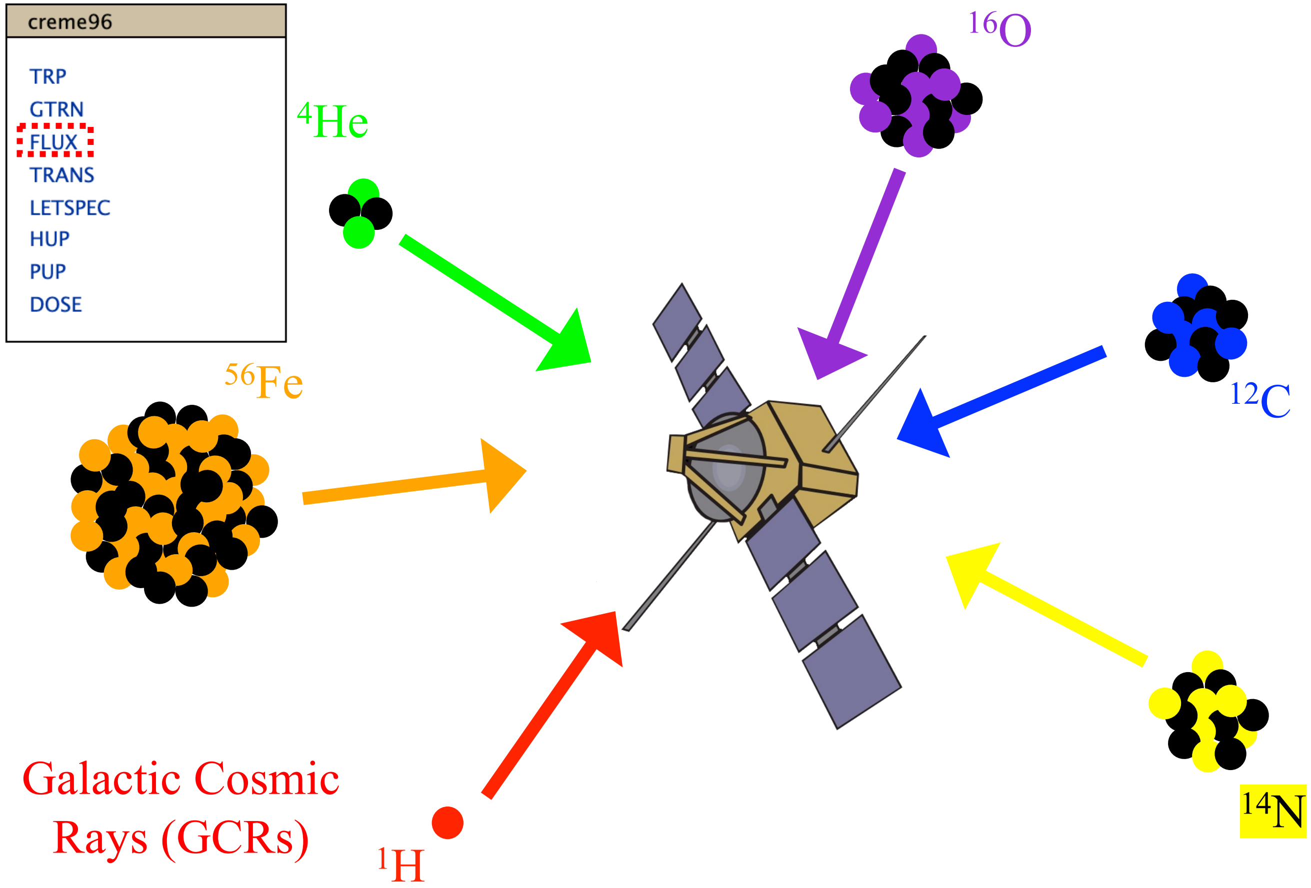
- CRÈME96 calculates energy deposition in RPP by accounting for both

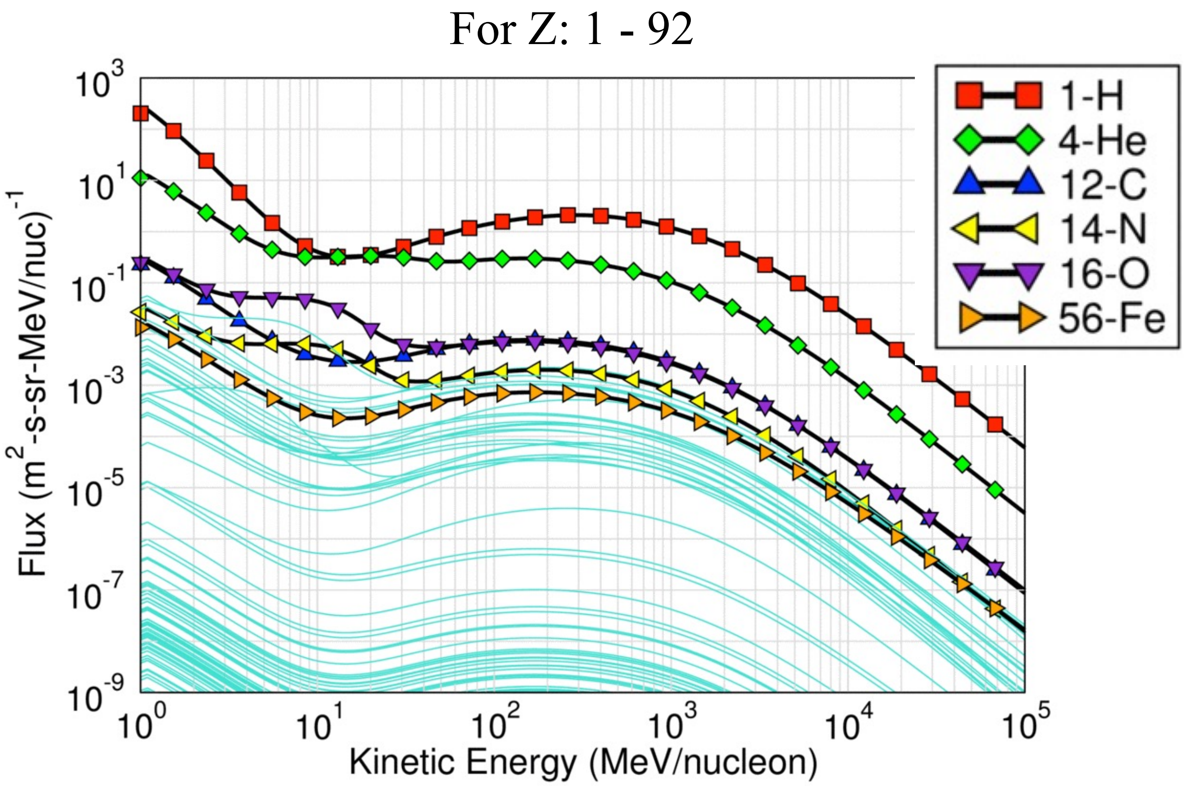
$$E_{dep} \approx \rho\,(x_f - x_0)\,LET$$



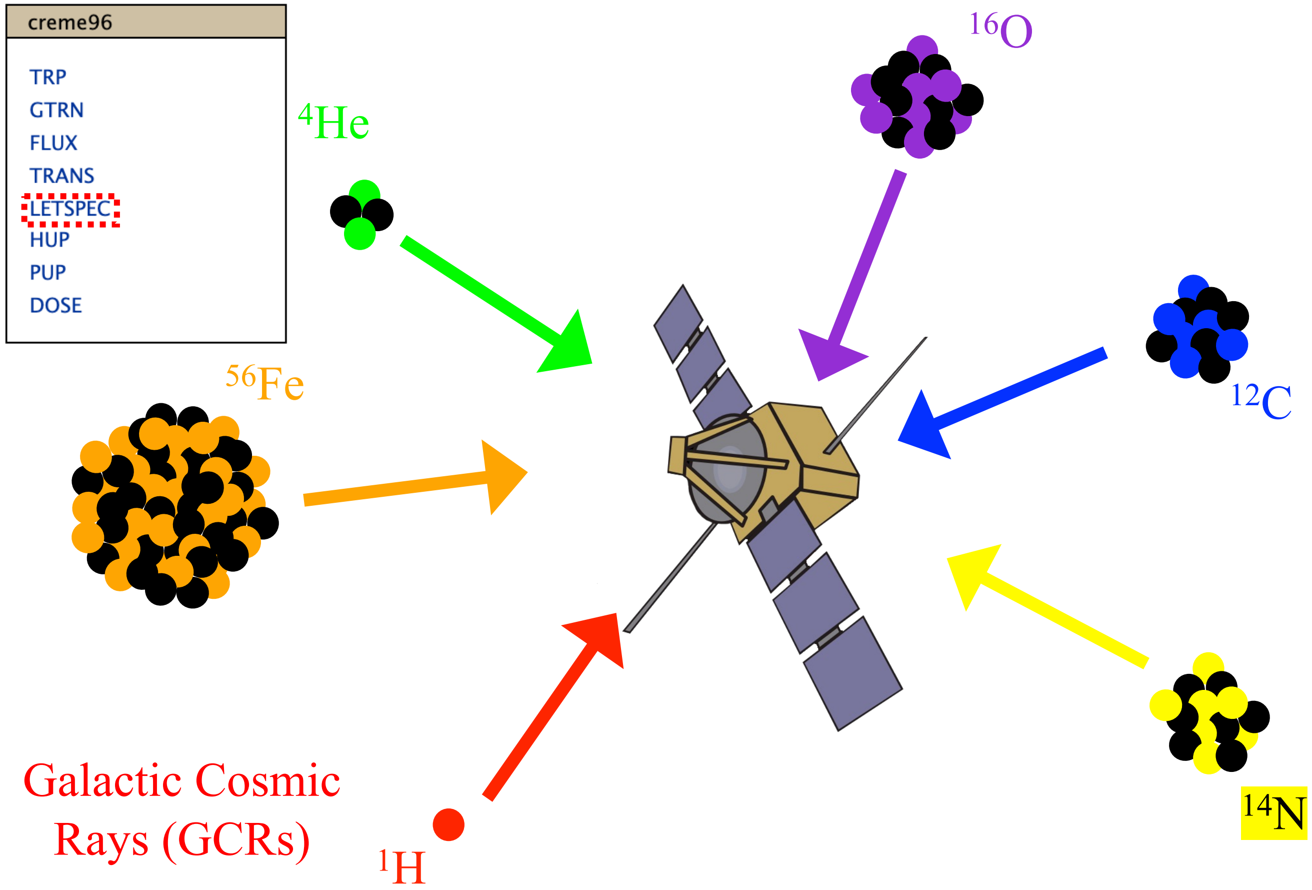


Real GCR environment – FLUX

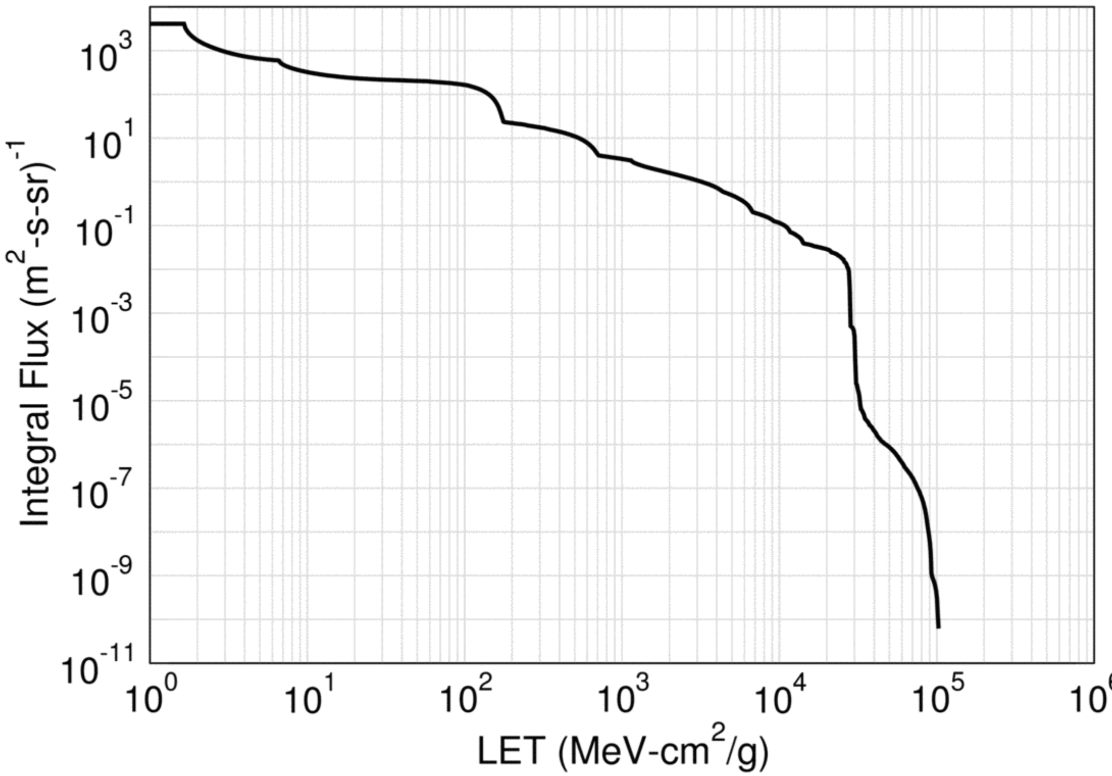




Real GCR environment – LETSPEC

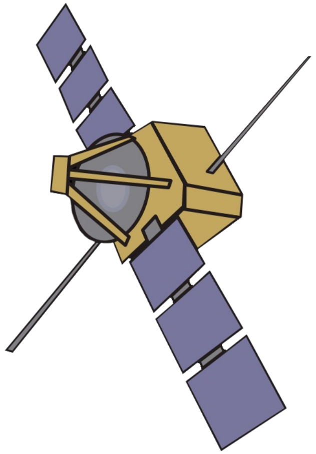


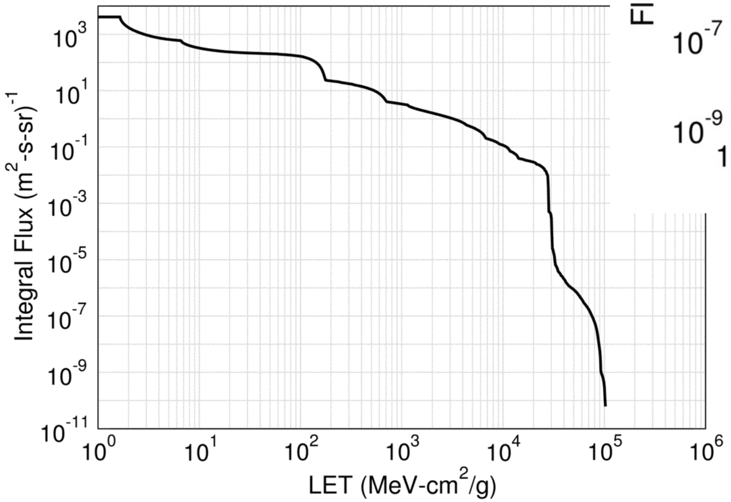
(Integrated over all particle species)

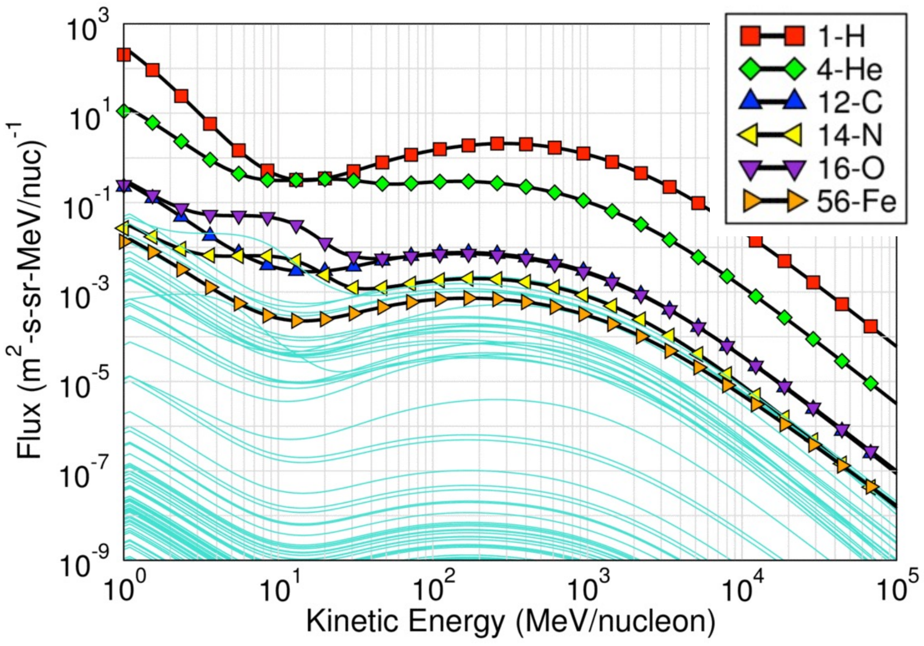


Next steps

The FLUX / LETSPEC calculations so far only describe the radiation environment **<u>outside</u>** the satellite







What about the environment *inside*?
What if we include <u>shielding</u>?

Shielding with CRÈME96 – TRANS

creme96

- TRP
- GTRN
- FLUX
- TRANS
- LETSPEC
- HUP
- PUP
- DOSE

NOTE – need to generate LETSPEC again for internal environment

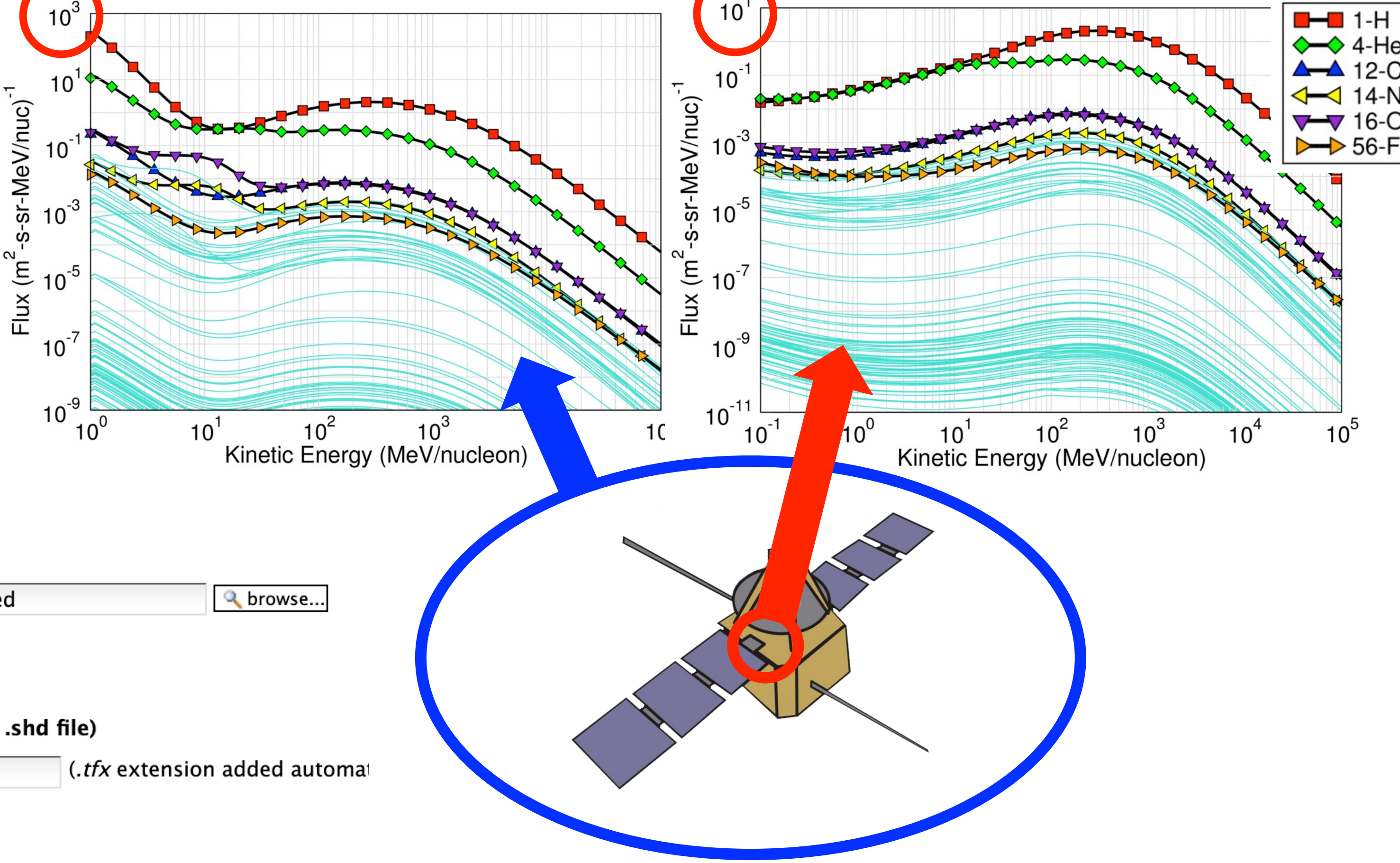
CREME96/TRANS

Nuclear Transport Module User-Supplied Parameters

1. **Name of flux file:** No file selected
2. **Shielding material:** aluminum
3. **Shield Thickness:**
   - **Specify single value:** 100 mils
   - **Use an existing distribution file:** No file selected browse...
4. **Transport Code:**
   - **Creme96 TRANS/UPROP**
   - **HZETRN1995/Nucfrg2 (warning: beta code, and cannot use a .shd file)**
5. **Rootname for TRANS Output file:** (*.tfx* extension added automat

Submit Reset Help

Before shielding (external env.) After shielding (internal env.)

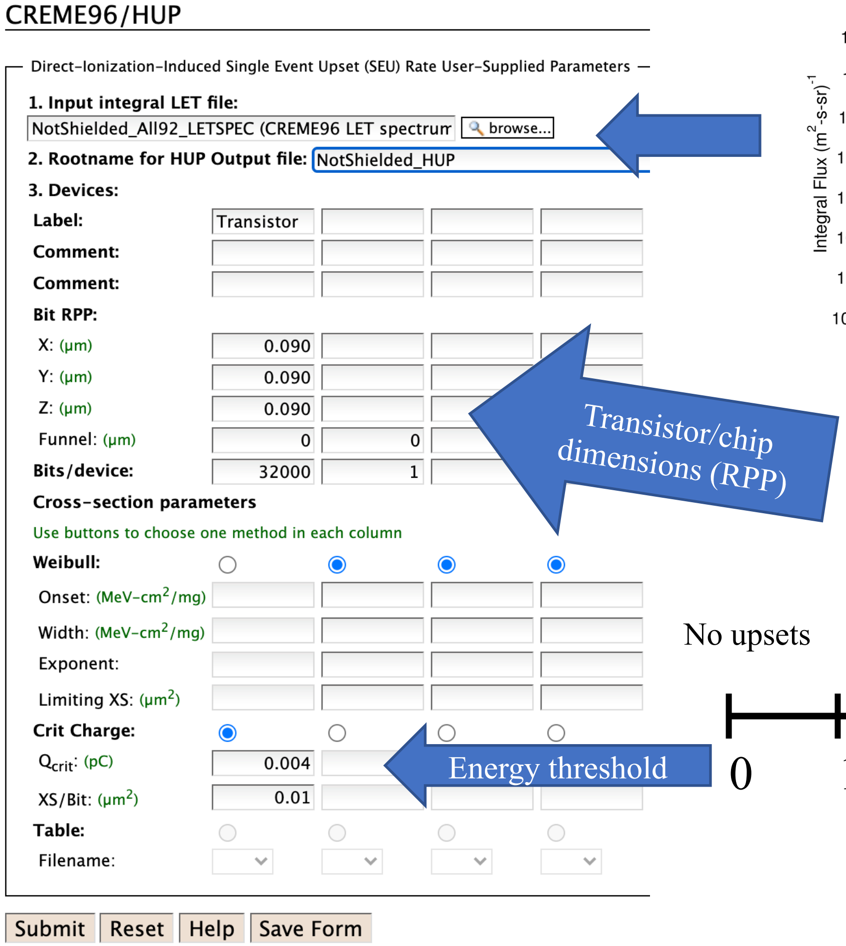


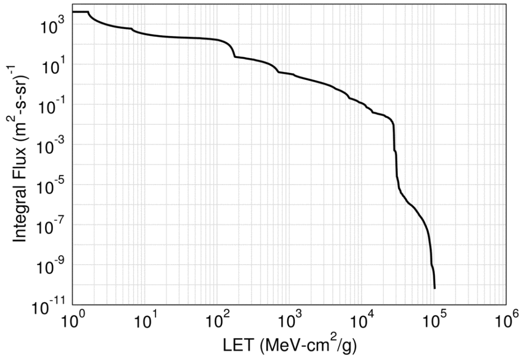
From LETSPEC to Upsets

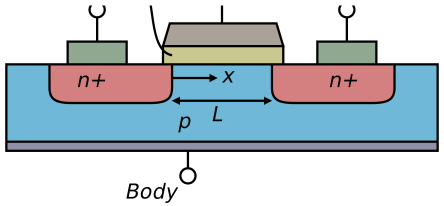
- Heavy-ion-induced Upsets (HUP)

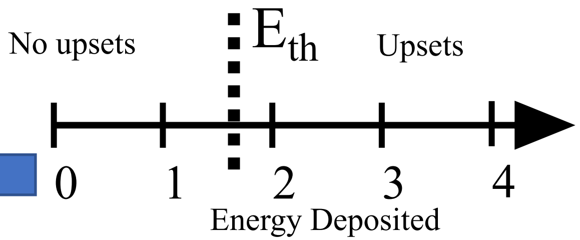
creme96

- TRP
- GTRN
- FLUX
- TRANS
- LETSPEC
- HUP
- PUP
- DOSE

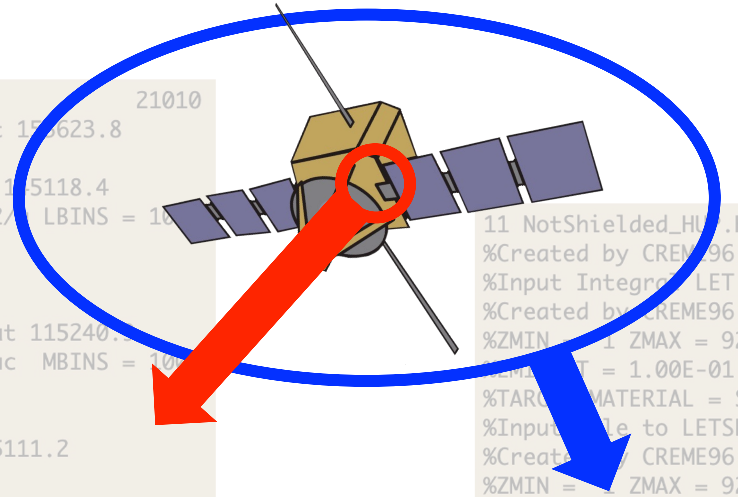








Heavy ion induced event rates



```
15 Shielded_HUP.HUP                                                          21010
%Created by CREME96:HI_UPSET_DRIVER Version  210 on  20210204 at 15623.8
%Input Integral LET Spectrum File: Shielded_All92_LETSPEC.let
%Created by CREME96:LETSPEC_DRIVER Version  210 on  20210204 at 15118.4
%ZMIN =  1 ZMAX = 92 LETMIN = 1.00E+00 LETMAX = 1.10E+05 MeV-cm2/  LBINS = 10
%EMINCUT = 1.00E-01 MeV/nuc
%TARGET MATERIAL = SILICON
%Input File to LETSPEC_DRIVER: TRANS_92.tfx
%Created by CREME96:TRANSPORT_DRIVER Version  210 on  20210203 at 115240.
%ZMIN =  1 ZMAX = 92  EMIN = 1.0000E-01 EMAX = 1.0000E+05 MeV/nuc  MBINS = 10
%Thickness =   100.0000 mils       ALUMINUM
%Input File to TRANSPORT_DRIVER: FLUX_example92.flx
%Created by CREME96:FLUX_DRIVER Version  210 on  20210203 at 115111.2
%ZMIN =  1 ZMAX = 92
%IMODE  =   0 SOLAR-QUIET MODE: YEAR =  1977.0000
%ITRANS =   0 GEOSYNCH/NEAR-EARTH INTERPLANETARY FLUXES

 REPORT NO.    1:   Transistor T O D O
 RPP Dimensions: X =     0.09000  Y =     0.09000  Z =     0.09000 microns.
 Funnel length =    0.00000 microns.
 CROSS-SECTION INPUT    5
     Critical charge =   4.00000E-03 picocoloumbs
     Cross-Section    =   1.00000E-02 square microns/bit
 Rates:       SEEs/bit/second     /bit/day    /device/second    /device/day
 *****    1    6.57845E-15     5.68378E-10    2.10510E-10     1.81881E-05
```

```
11 NotShielded_HU .HUP                                                          21010
%Created by CRE 96:HI_UPSET_DRIVER Version  210 on  20210204 at 153545.5
%Input Integr  LET Spectrum File: NotShielded_All92_LETSPEC.let
%Created by  REME96:LETSPEC_DRIVER Version  210 on  20210204 at 145338.1
%ZMIN    1 ZMAX = 92 LETMIN = 1.00E+00 LETMAX = 1.10E+05 MeV-cm2/g LBINS = 1002
        T = 1.00E-01 MeV/nuc
%TAR    MATERIAL = SILICON
%Inpu    le to LETSPEC_DRIVER: FLUX_example92.flx
%Creat    CREME96:FLUX_DRIVER Version  210 on  20210203 at 115111.2
%ZMIN =    ZMAX = 92
%IMODE  =   0 SOLAR-QUIET MODE: YEAR =  1977.0000
%ITRANS =   0 GEOSYNCH/NEAR-EARTH INTERPLANETARY FLUXES

 REPORT NO.    1:   Transistor T O D O
 RPP Dimensions: X =     0.09000  Y =     0.09000  Z =     0.09000 microns.
 Funnel length =    0.00000 microns.
 CROSS-SECTION INPUT    5
     Critical charge =   4.00000E-03 picocoloumbs
     Cross-Section    =   1.00000E-02 square microns/bit
 Number of bits =   3.20000E+04
 Rates:       SEEs/bit/second     /bit/day    /device/second    /device/day
 *****    1    6.82001E-14     5.89249E-09    2.18240E-09     1.88560E-04
```

Conclusion

- CRÈME96 and SRIM are useful tools to begin exploring radiation effects
- We can use SRIM to learn about the range and stopping power of ions in various material systems at different energies
- CRÈME96 provides a way of characterizing the radiation environment in space with and without shielding; includes module for estimating error rates in actual devices

Additional resources

- CRÈME96 guide included at: https://creme.isde.vanderbilt.edu/CREME-MC/help/how-to-run-creme96
- CRÈME96 & CRÈME-MC help pages at:

  https://creme.isde.vanderbilt.edu/CREME-MC/help
- Official SRIM tutorial included at: SRIM.org