National Aeronautics and
Space Administration

# Radiation Effects & EEE Parts Selection

Michael Campola NASA GSFC

Radiation Effects and Analysis Group (Code 561)

National Aeronautics and Space Administration Small Satellite Learning from Experience, Achievements and Resolution Navigation Forum

# Agency level support

OSMA
OFFICE OF SAFETY & MISSION ASSURANCE

NEPP
NASA Electronic Parts and Packaging Program

**Contacts:**
Pete Majewicz – PM
Susana Douglas - Deputy

FLIGHT DATA SYSTEMS & RADIATION EFFECTS
Code 561 • NASA Goddard Space Flight Center

OCE
Office of the Chief Engineer

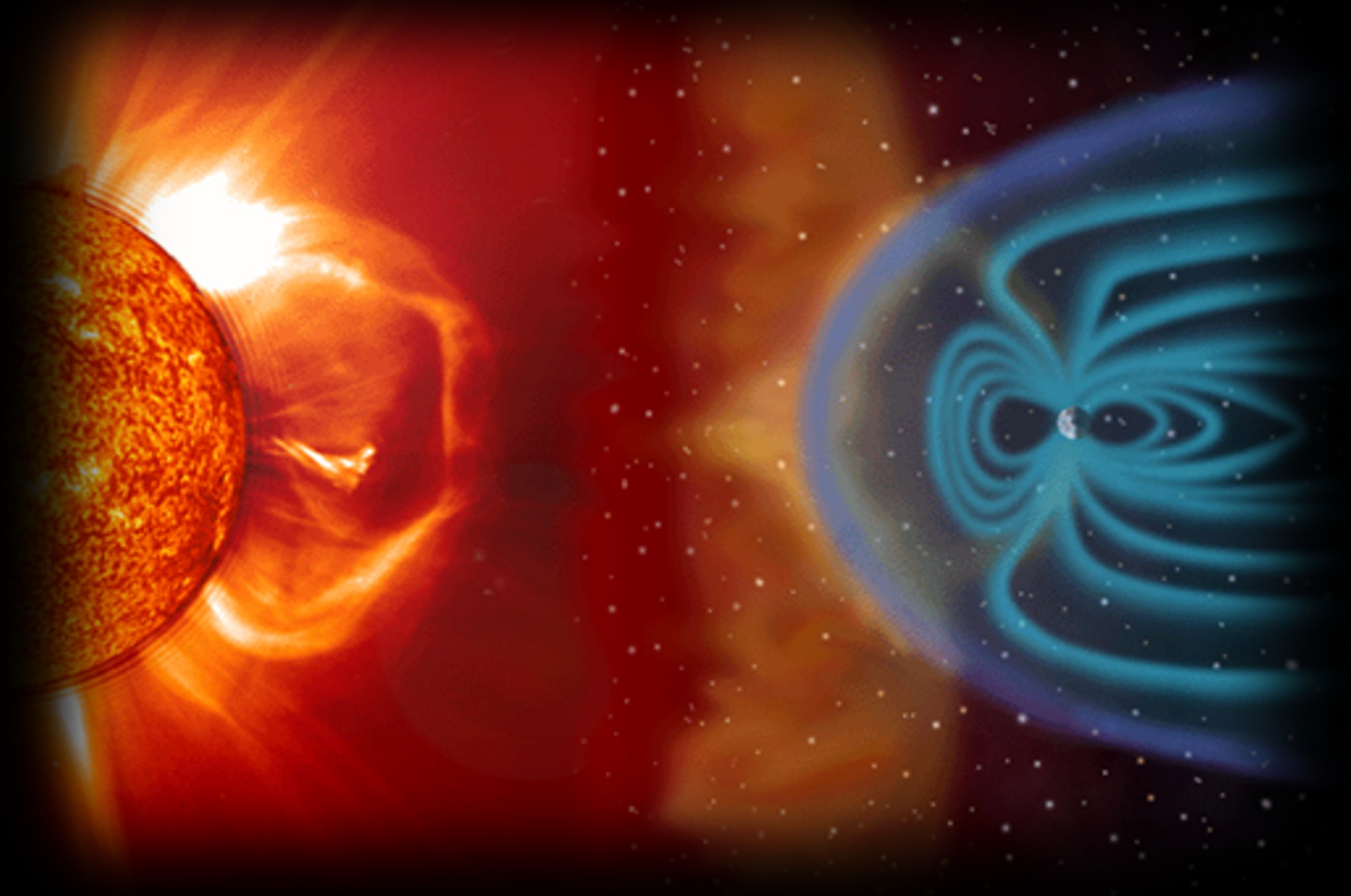
NASA Engineering and Safety Center

**Communities of Practice:**
Bob Hodson – Avionics
Ray Ladbury – Radiation
Yuan Chen – EEE Parts
Joe Minow – Space Environments

# Natural space radiation environment overview

This is a *dynamic* system governed by the heliomagnetosphere

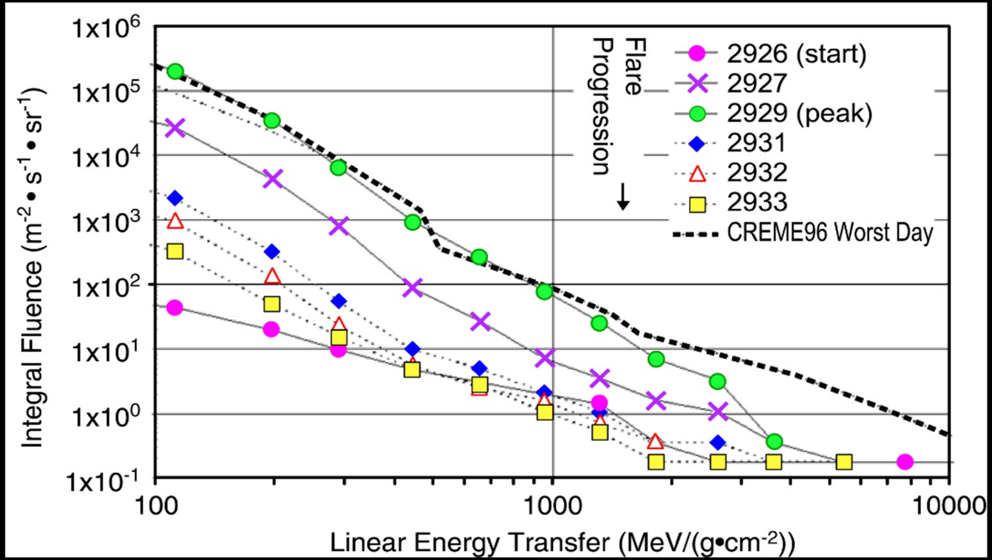
- Solar Maximum / Minimum
- Solar Flares
- Coronal Mass Ejections



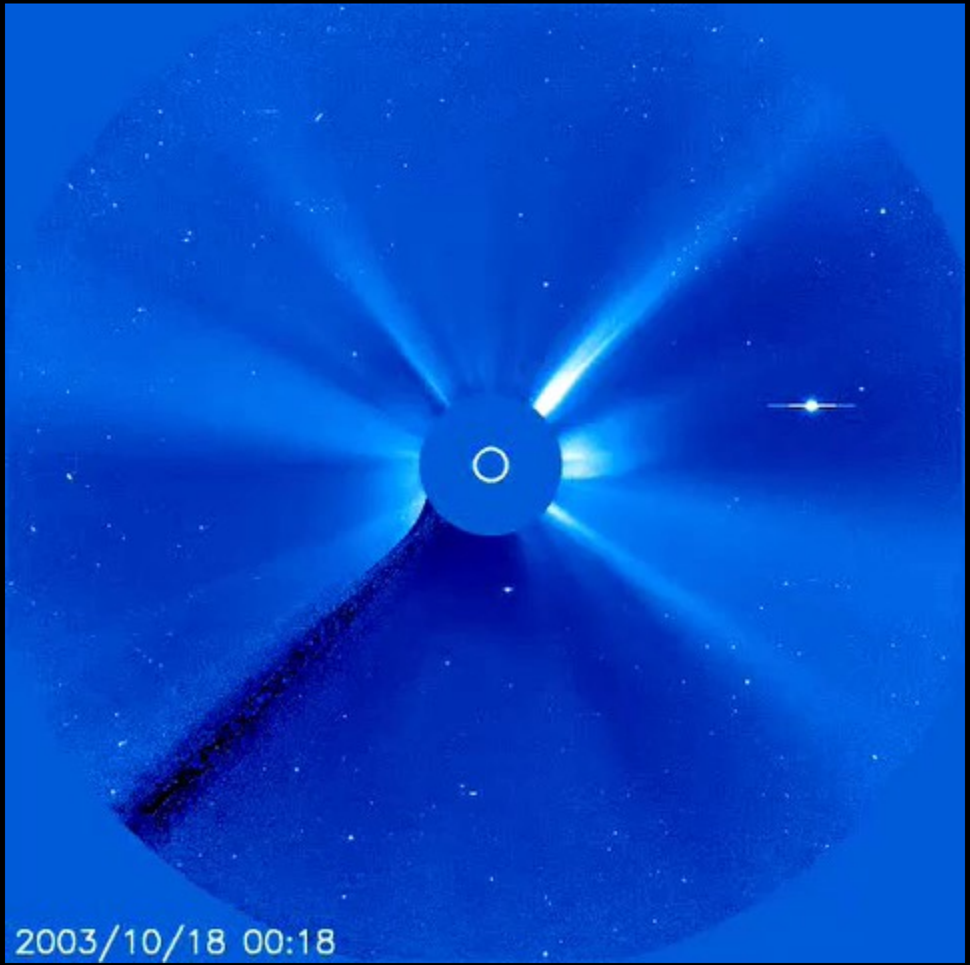
- Radiation Belts
- Geomagnetic Storms
- Galactic Cosmic Rays

# What a CME/Flare looks like when it shows up

- Halloween Storms (Oct. 18 - Nov. 7 2003)
  - Noise on detector
  - Lots of deposited charge
  - Lots of coverage, lots of secondaries



**C.S. Dyer et al., IEEE TNS, Dec. 2002**

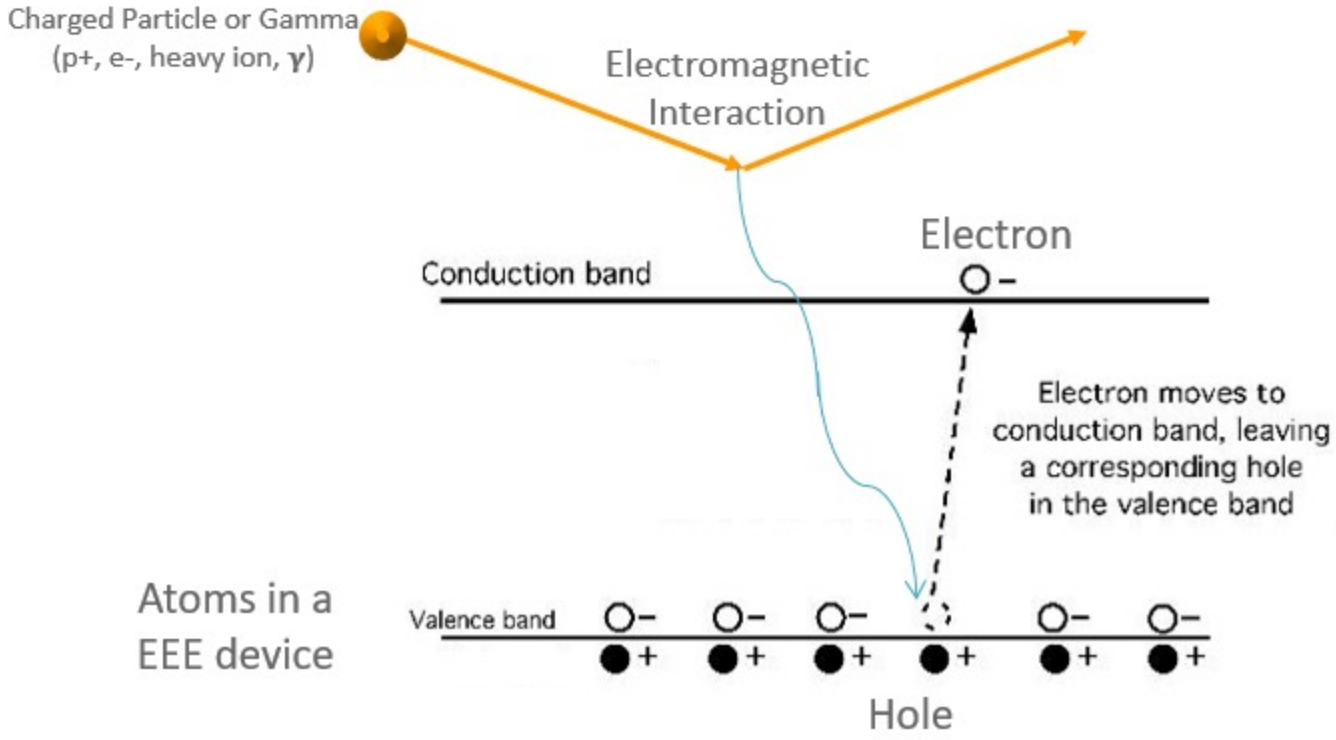


Courtesy of SOHO/LASCO consortium. SOHO is a project of international cooperation between ESA and NASA. (Mercury transit in background)

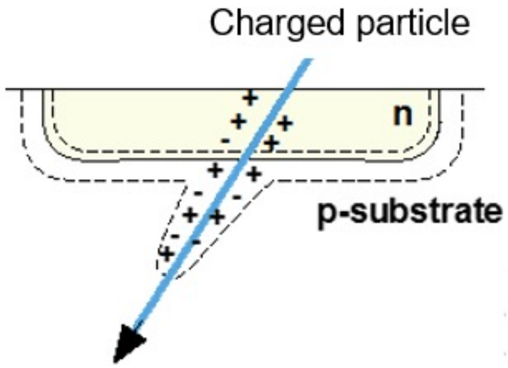
# Outline

- How radiation damage semiconductor devices
  - Cumulative effects: ionizing and non-ionizing dose
  - Single particle effects
  - Examples of failures
- Methods of analysis and test
  - Environment modelling and transport
  - Correllation
  - Radiation testing
- Key parameters to consider when selecting parts
  - Process / semiconductor layout / application
  - Ways system architecture can be used to help mitigate radiation effects
  - Part database resources and how to use them wisely
- Common pitfalls, lessons learned
- Radiation tools / resources / acronyms

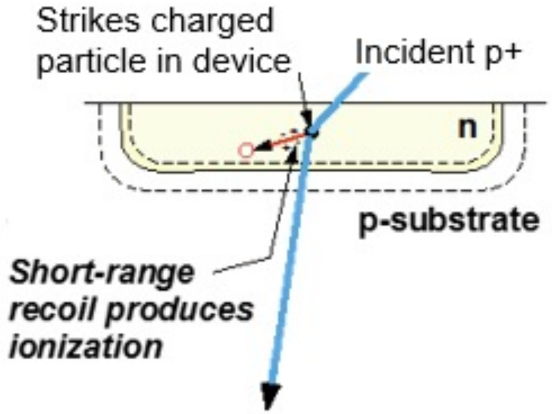
# Ionization Overview



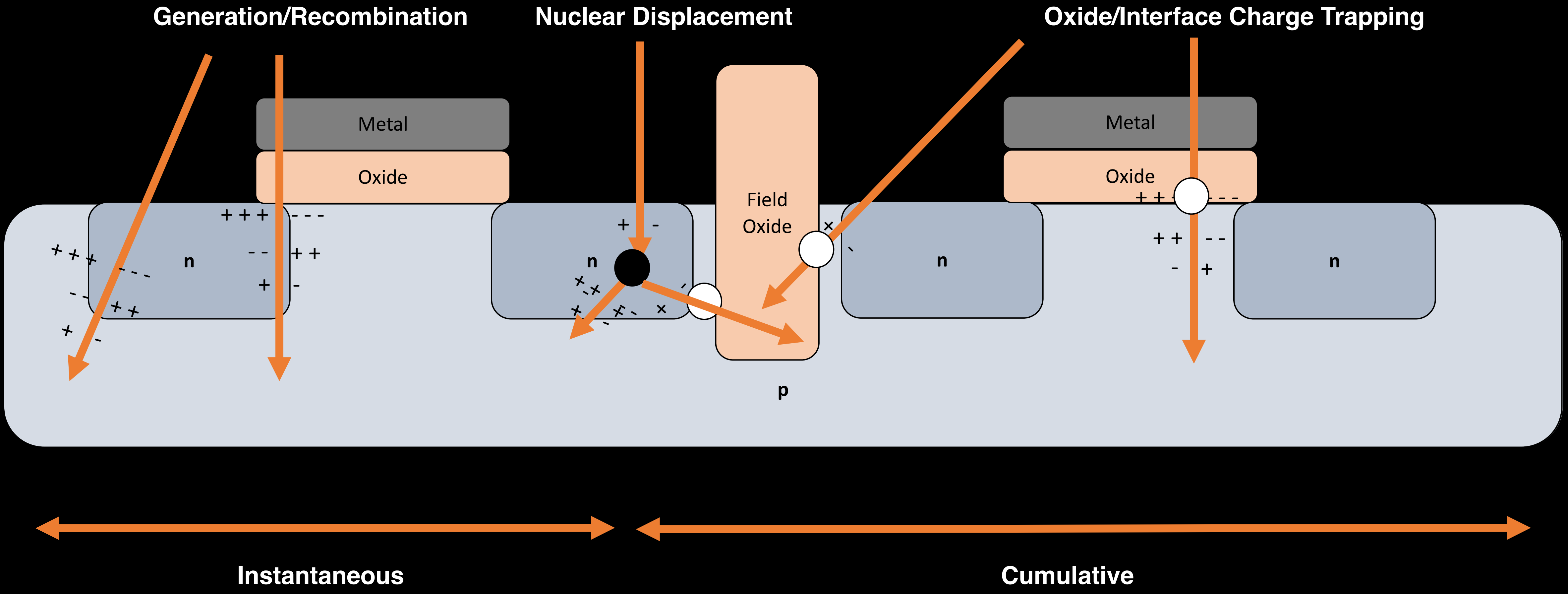
Direct Ionization



Indirect Ionization

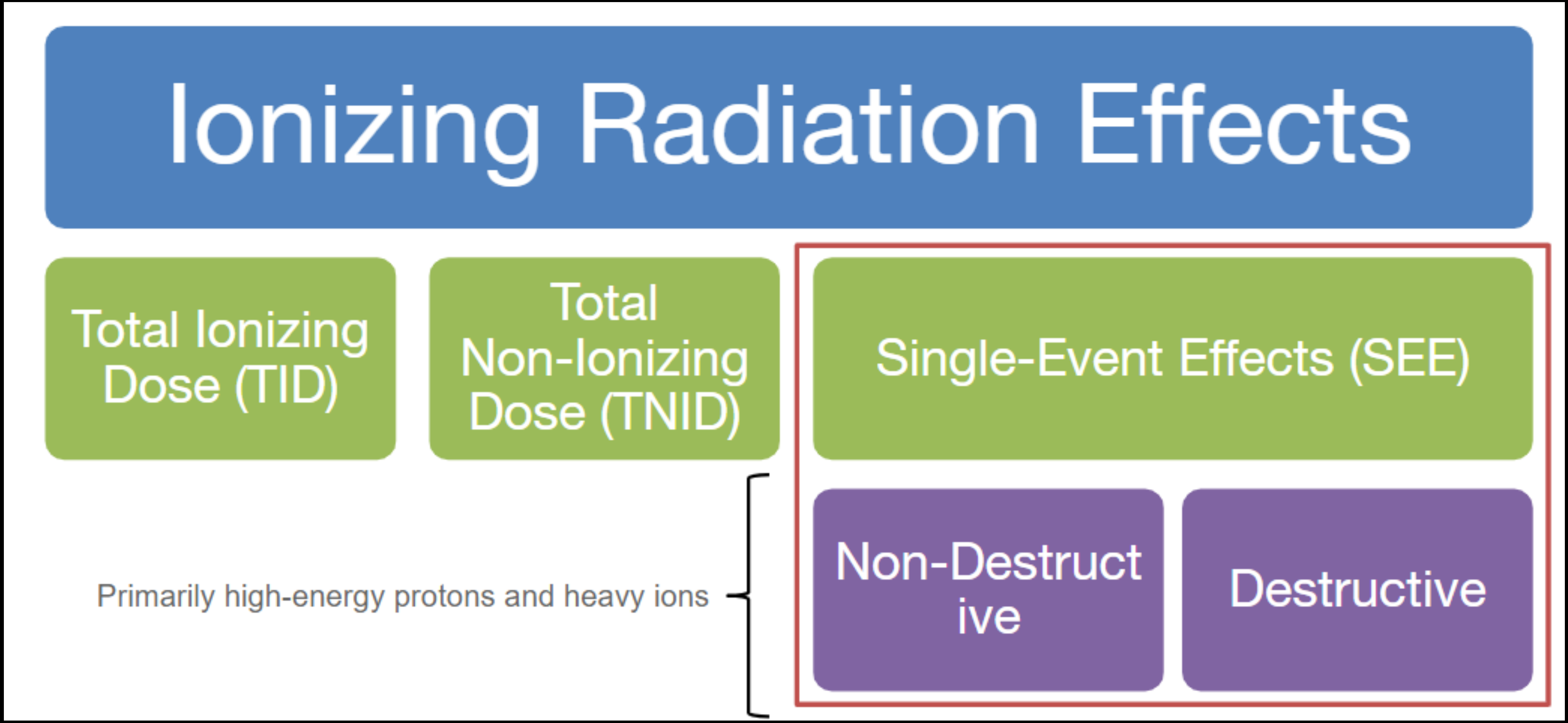


# Damage in parts overview – location matters



Brock J. LaMeres, Colin Delaney, Matt Johnson, Connor Julien, Kevin Zack, Ben Cunningham Todd Kaiser, Larry Springer, David Klumpar, "Next on the Pad: RadSat – A Radiation Tolerant Computer System," Proceedings of the 31st Annual AIAA/USU Conference on Small Satellites, Logan UT, USA, Aug. 5-10, 2017, paper: SSC17-III-11,
URL: http://digitalcommons.usu.edu/cgi/viewcontent.cgi?article=3618&context=smallsat

# Breaking down the different types of effects



Ionizing Radiation Effects

Total Ionizing Dose (TID)

Total Non-Ionizing Dose (TNID)

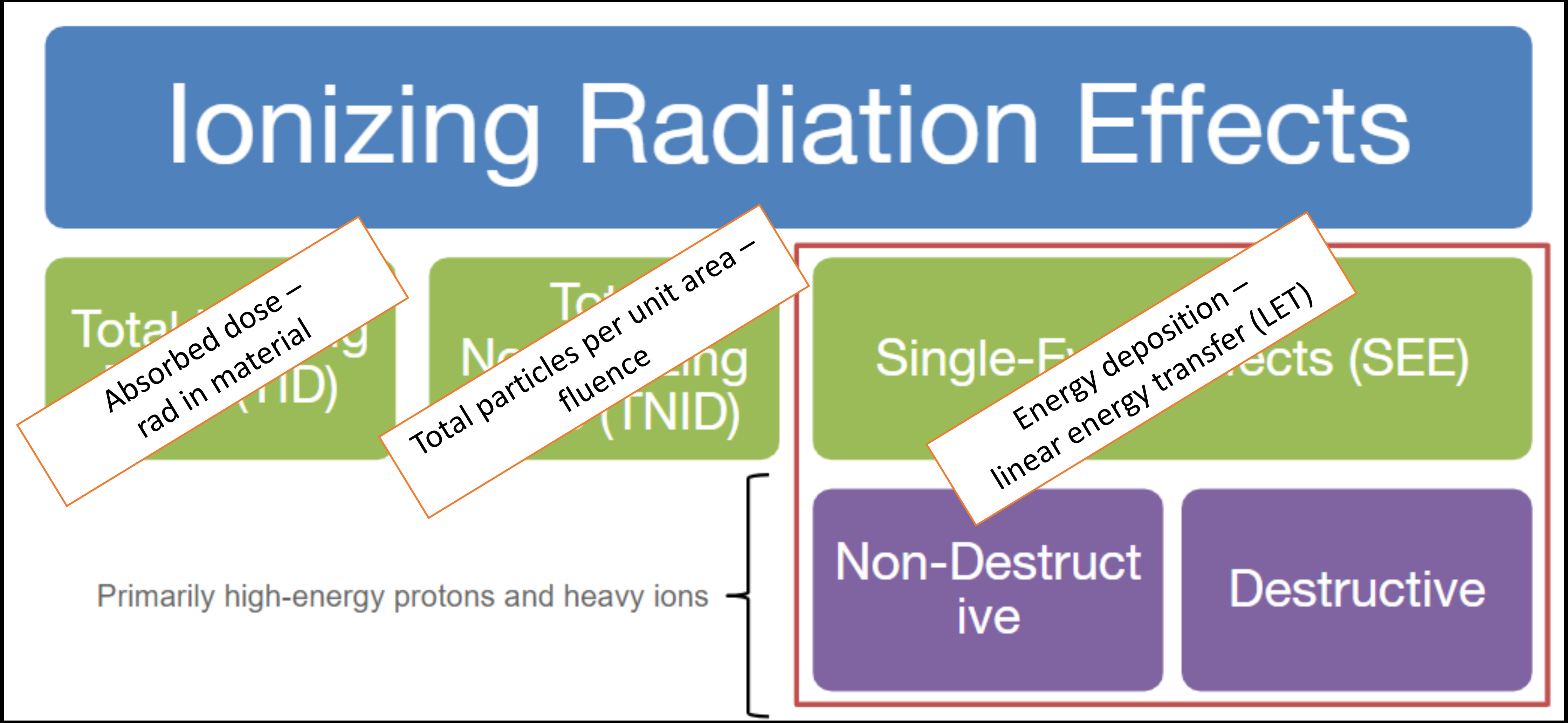
Single-Event Effects (SEE)

Non-Destructive

Destructive

Primarily high-energy protons and heavy ions

# Breaking down the different types of effects



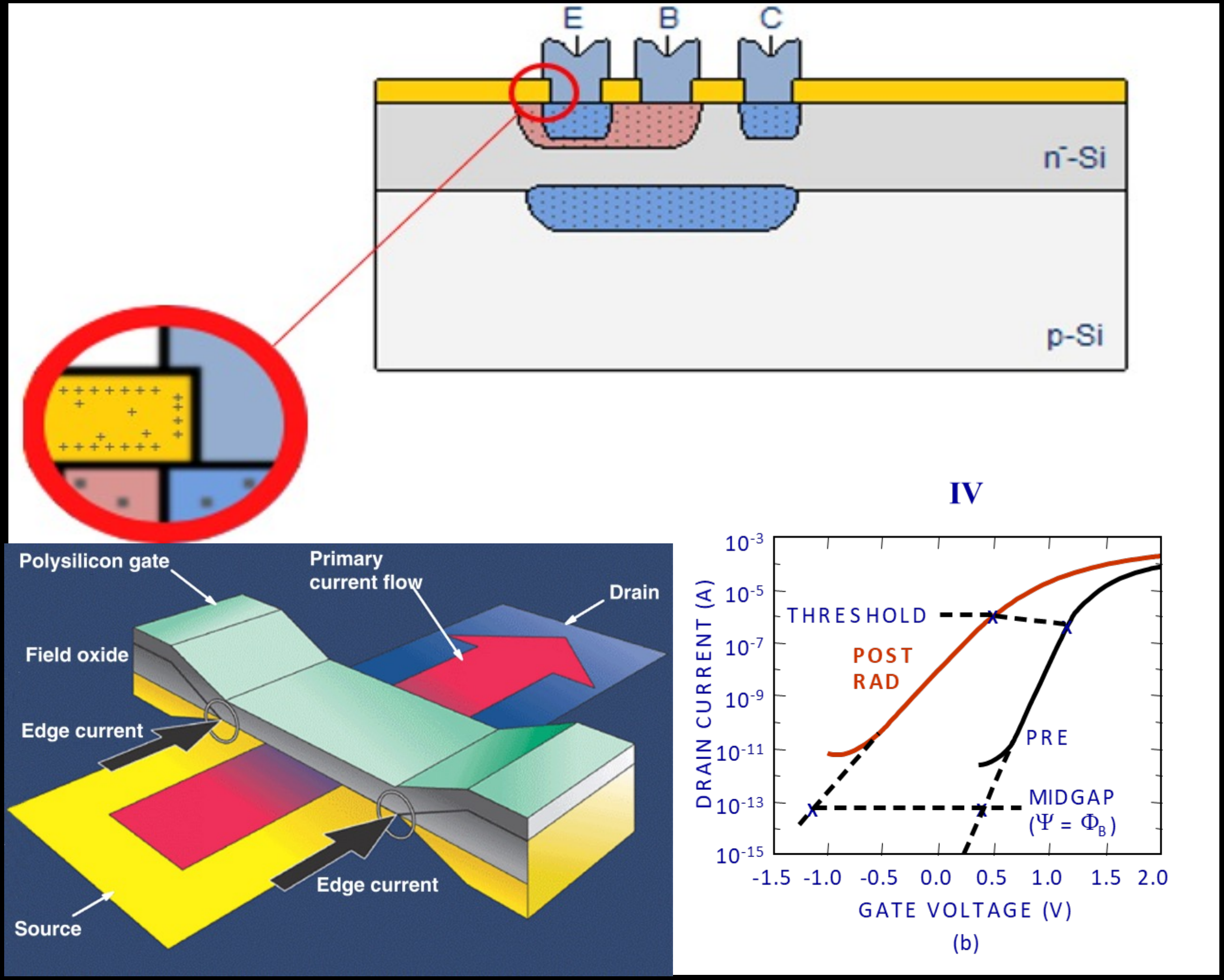
Absorbed dose – rad in material

Total particles per unit area – fluence

Energy deposition – linear energy transfer (LET)

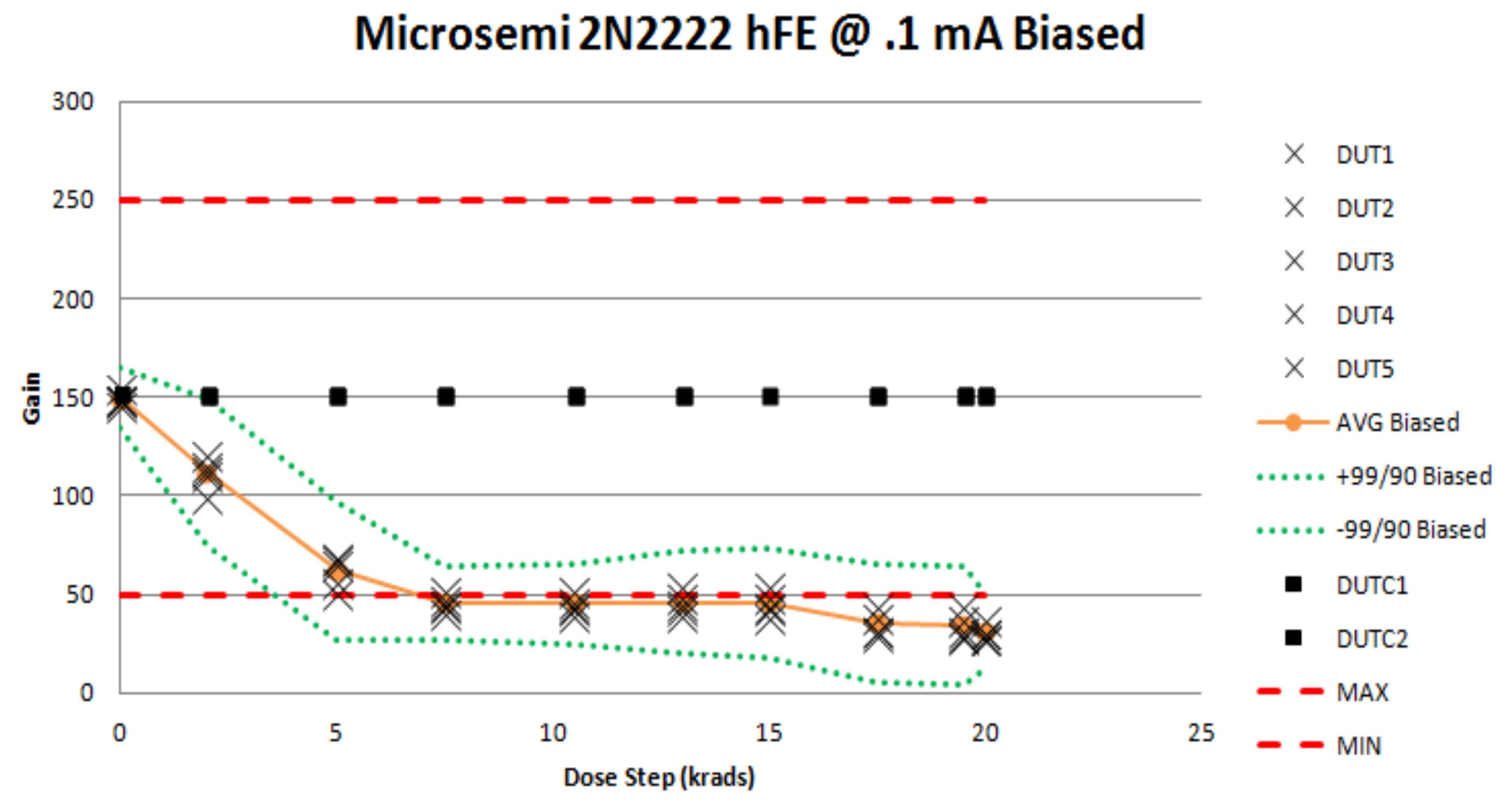
# Types of radiation effects – Total Ionizing Dose (TID)

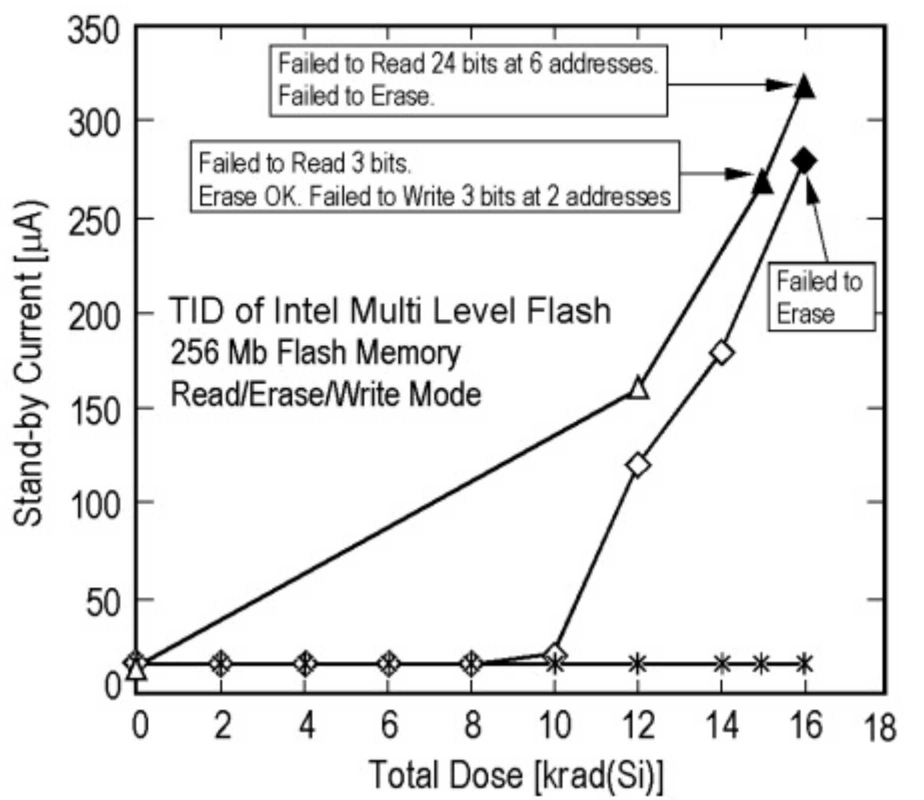
- Cumulative effect
    - Electron-hole pair creation and collection
    - Interface traps and oxide traps collect charge permanently
    - More imperfections result in easier charge trapping
    - Residual shift in static operation
    - Electric field impacts drift and diffusion
    - Oxide thickness and manufacturing plays a role in technology response
    - This is “TID damage”. Eventually the device will fail to operate.



# Examples of TID device failures

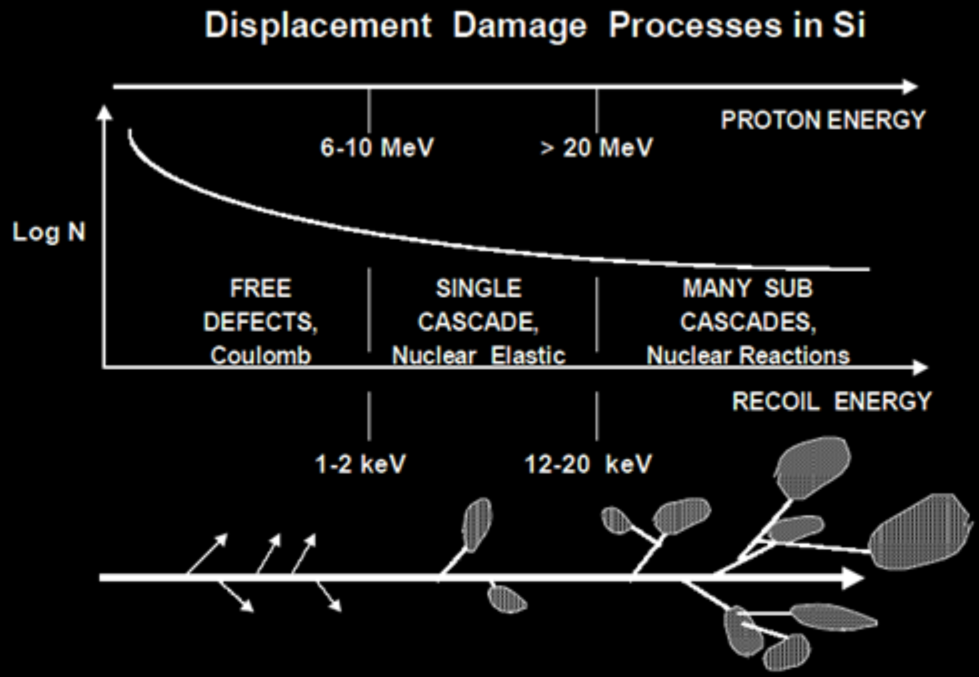
- Gain degradation, and drop of function… anything goes



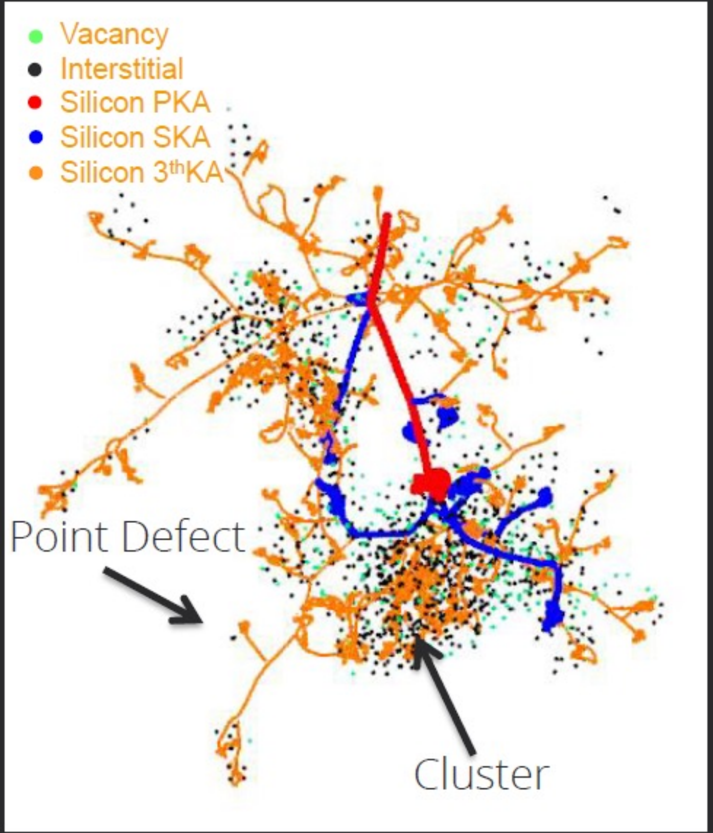


# Types of radiation effects – Total Non-Ionizing Dose (TNID)

- Cumulative effect
  - Primary knock-on atoms displace lattice and leave damage clusters
  - Changing fundamental properties like carrier mobility means that opto-electronics are the most susceptible
  - Some damage sites are so great that can lead to one hit failures within component functions (RTS, hot pixels, etc.)



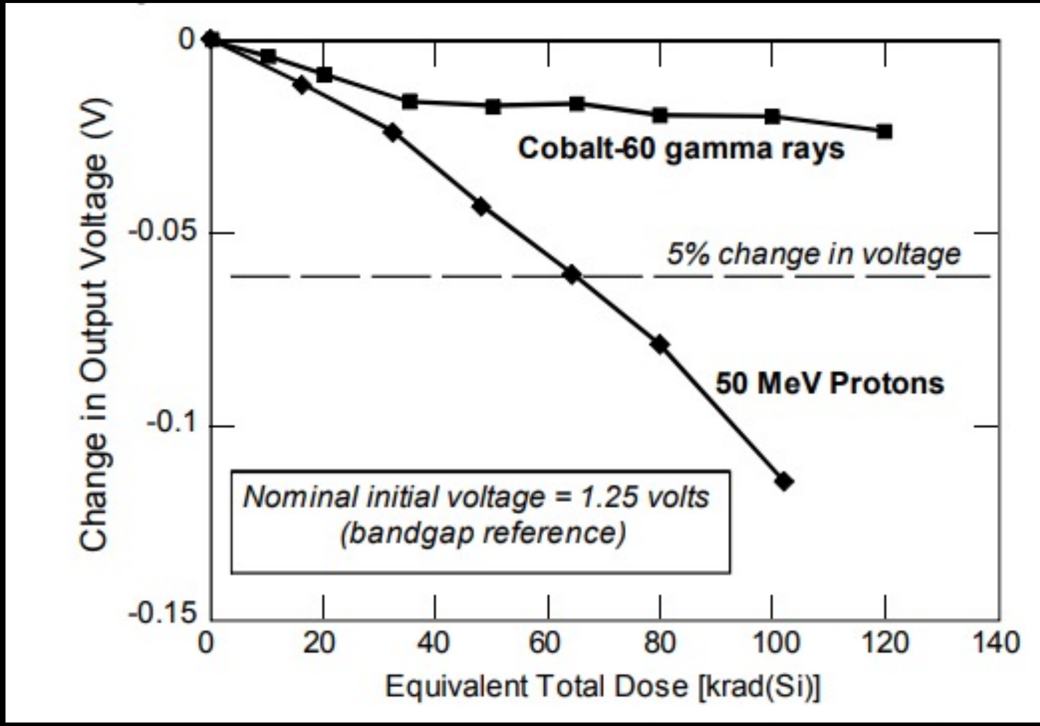
After C. J. Marshall, 1999 IEEE NSREC Short Course.



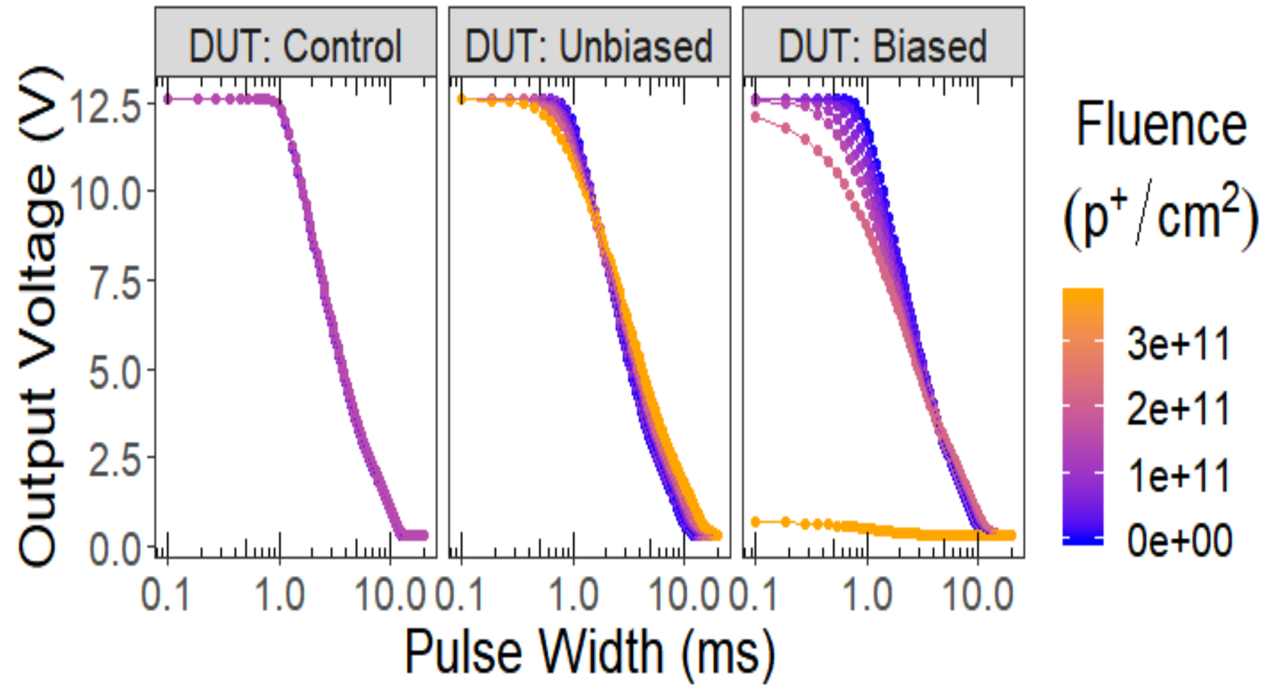
A. Jay et al., "Simulation of Single-Particle Displacement Damage in Silicon—Part III: First Principle Characterization of Defect Properties," in IEEE Transactions on Nuclear Science, vol. 65, no. 2, pp. 724-731, Feb. 2018, doi: 10.1109/TNS.2018.2790843.

# Examples of TNID device failures

- Loss of function, permanent damage – need experts for detectors/cryo



Linear Bipolars that depend on bulk properties



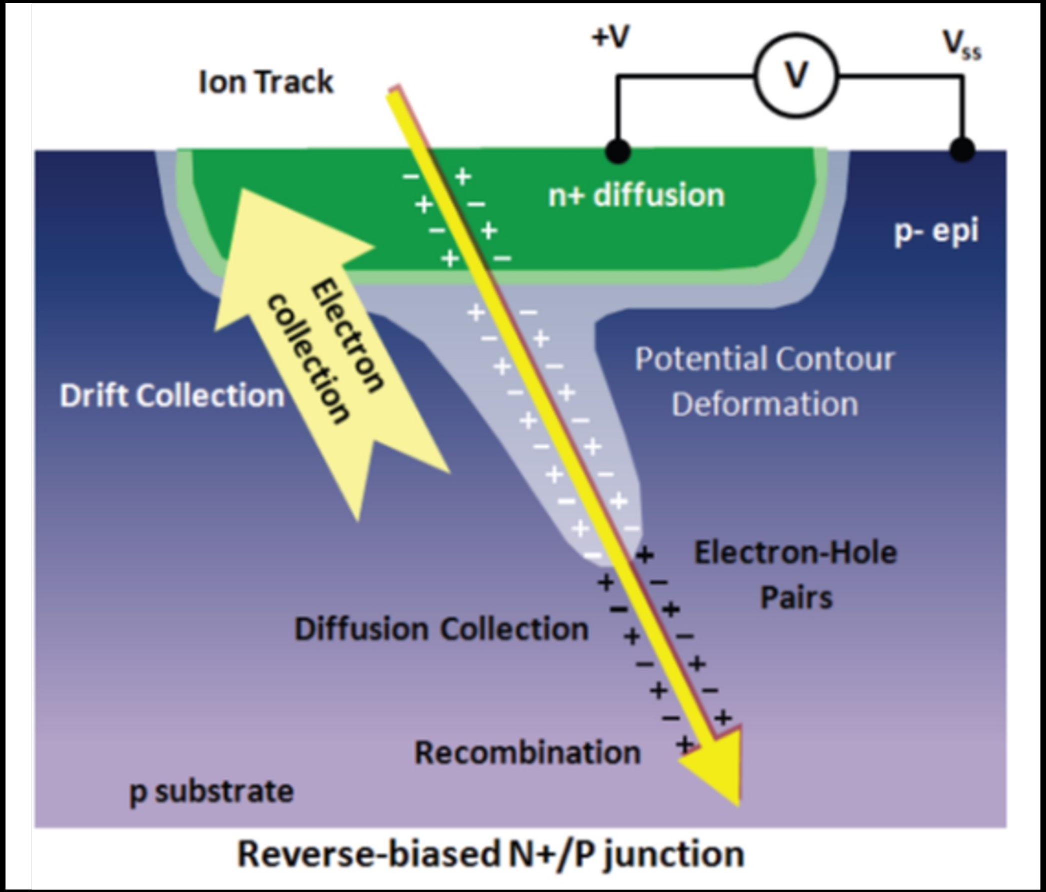
Optocouplers using highly efficient LEDs will be very soft

# Comparing TID to TNID

| (After Le Roch) | TID Vs TNID | |
|---|---|---|
| Dose threshold | TID threshold | One displacement = high degradation |
| Hardening | Hardening by design or process(1) | Limited hardening technic possible(2) |
| Shrinking electronic size | Thin oxide is less sensitive to TID(3) | More elementary functions impacted |
| Degradation uniformity | Almost uniform degradation | High nonuniformity: Poisson law |

# Single Event Effects in a p-n junction

- Single Incoming Particle
  - Ions traverse device, depositing energy along their path
  - Electron-hole pairs produced
  - Deformation of the depletion region if a junction is hit
  - Recombination dominates
  - Diffusion and drift driven by electrostatics within device
  - Dimensions and materials of device are crucial in signature response



R.C. Baumann, 2013 NSREC Short Course

# Types of radiation effects – Single Event Latchup (SEL)

- Instantaneously destructive
- SEL is a parasitic structure within the device being turned on, different than electrical latchup
- Even “non-destructive” has ramifications

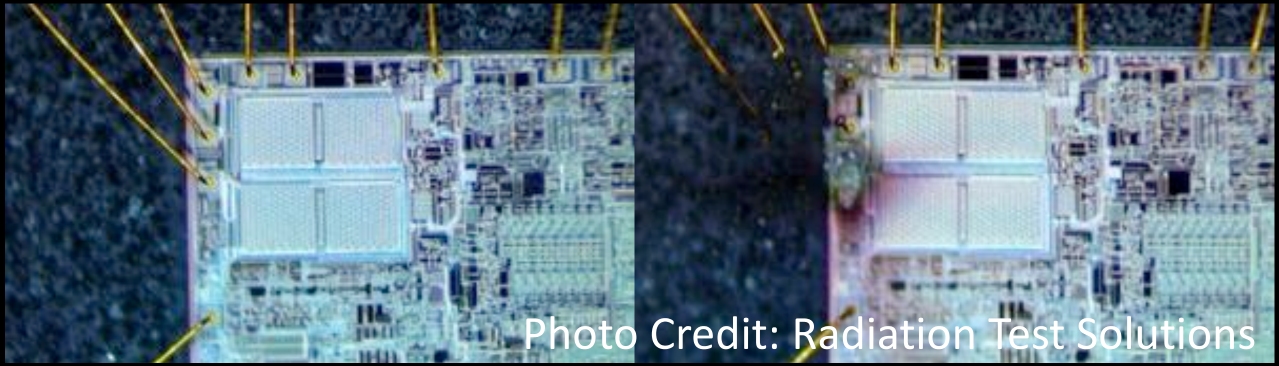
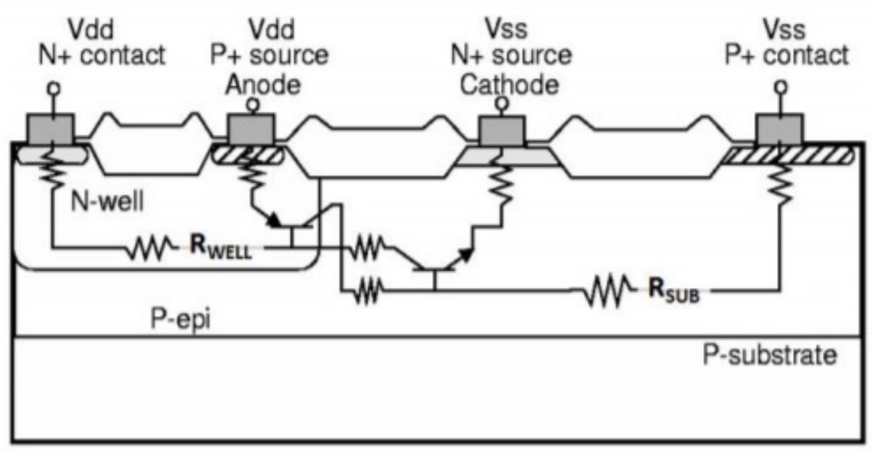
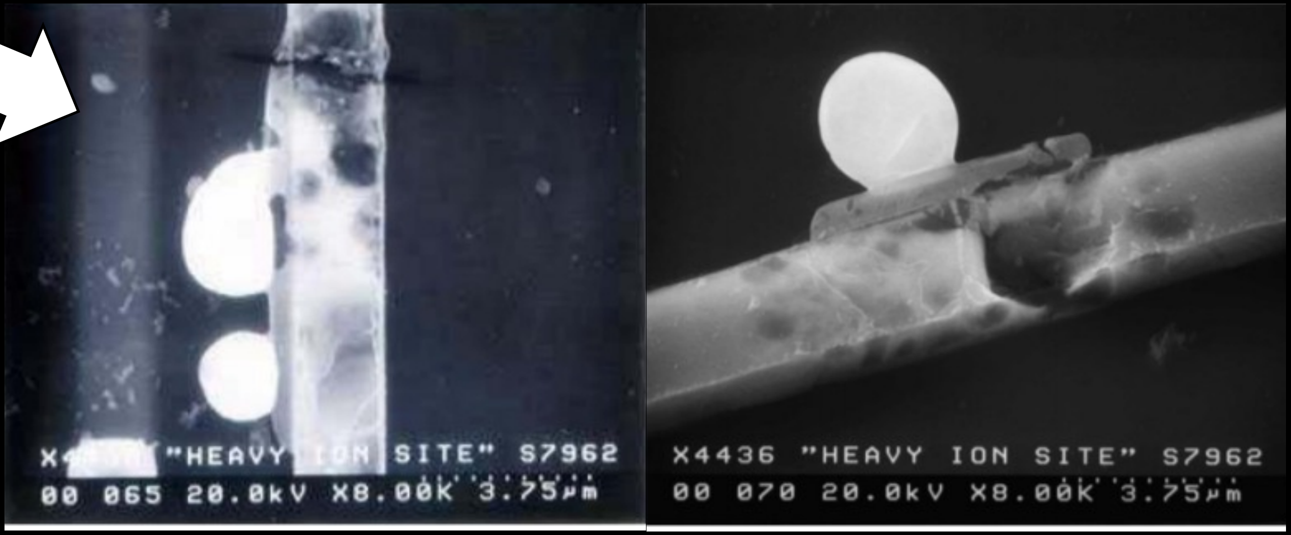


Photo Credit: Radiation Test Solutions

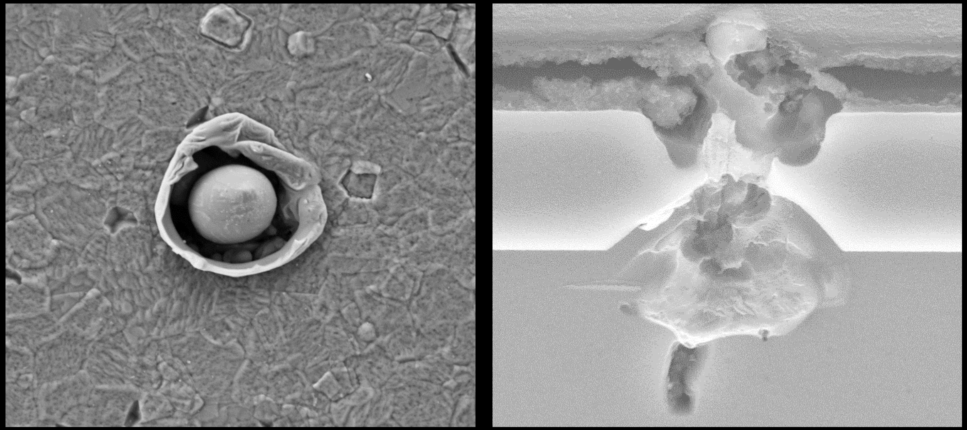


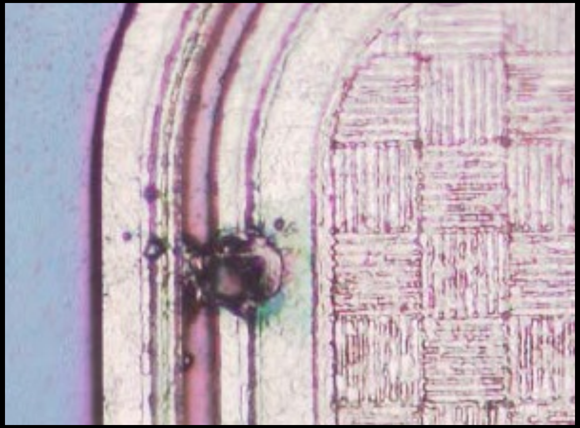


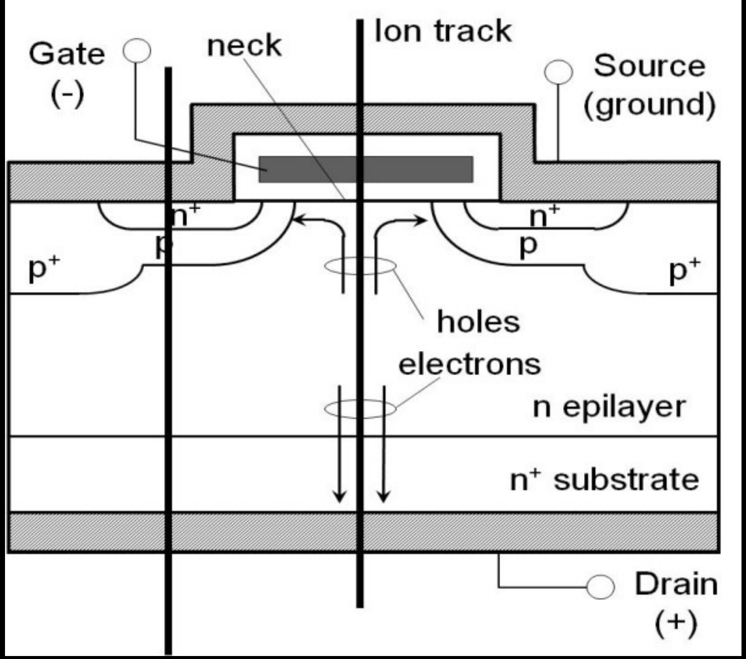
# Types of Radiation Effects - SEB/SEGR/SEDR

- Gate/Dielectric Rupture is charge overwhelming the oxide
- Burnout is current

  in the bulk mat'l.

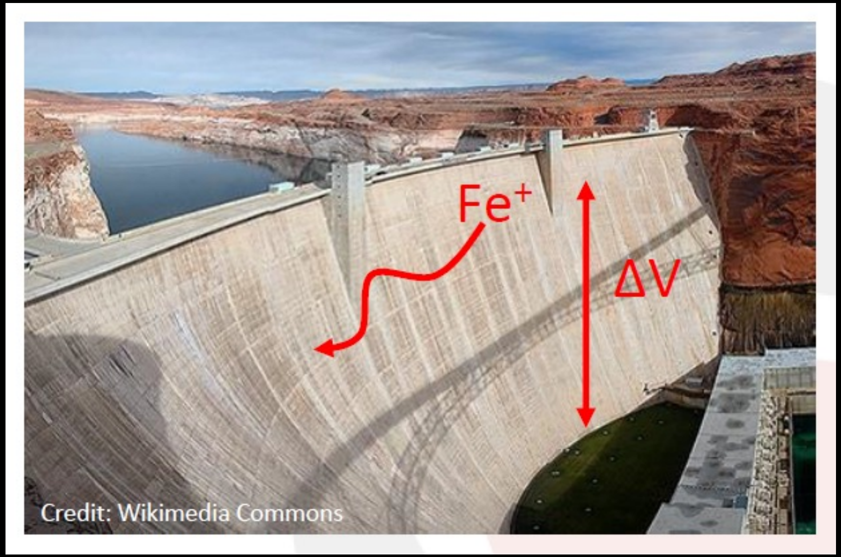






Single Event Burnout

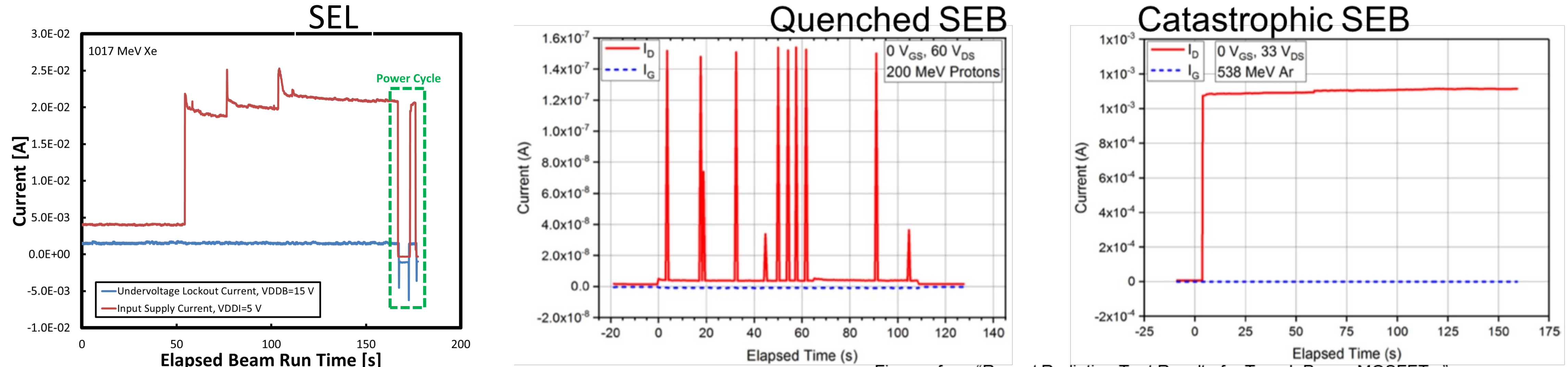
Single Event Gate Rupture



Credit: Wikimedia Commons

# Destructive effects, electrically speaking

- Current limiting is not foolproof, but can help in select applications



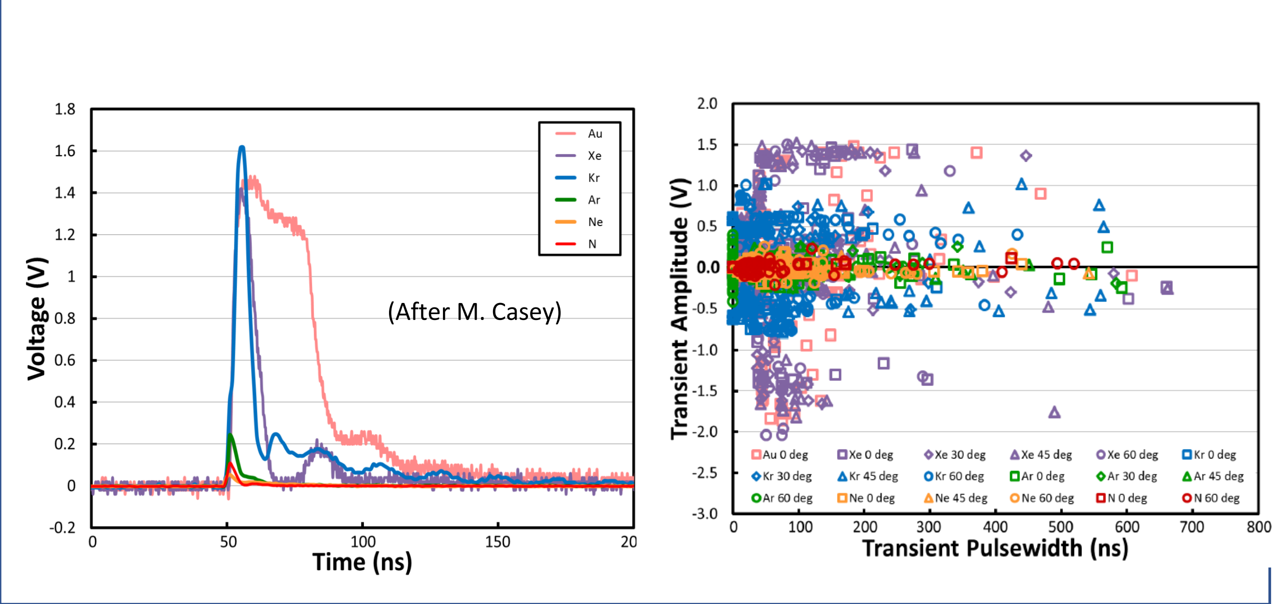
Figures from “Recent Radiation Test Results for Trench Power MOSFETs,”
https://nepp.nasa.gov/files/28959/2017-Lauenstein-NSREC-Paper-DW-MOSFETs-TN44382.pdf

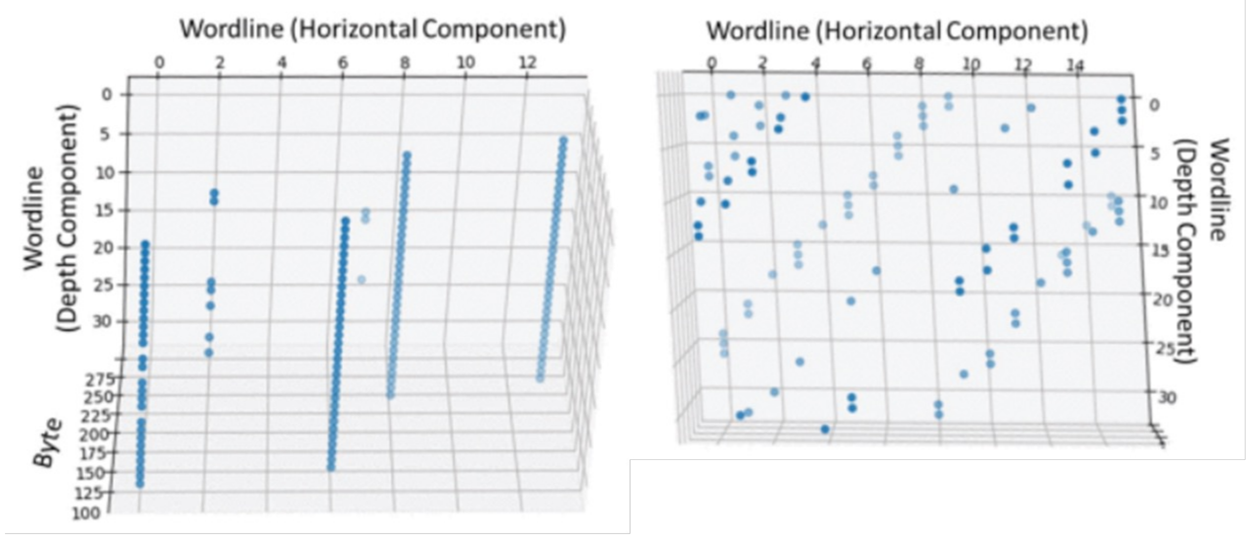
- Failure can depend on the mechanism, range of particle, and even the species

# Types of radiation effects – non-destructive SEE

- Individual errors persist and will accrue
- SET – happens in both analog/digital circuits
- SEU/MBU – feature size, physical layout
- Nuisances that must be planned for

https://ieeexplore.ieee.org/document/5994572/





E. P. Wilcox and M. J. Campola, "A TID and SEE Characterization of Multi-Terabit COTS 3D NAND Flash," 2019 IEEE Radiation Effects Data Workshop, San Antonio, TX, USA, 2019, pp. 1-7.

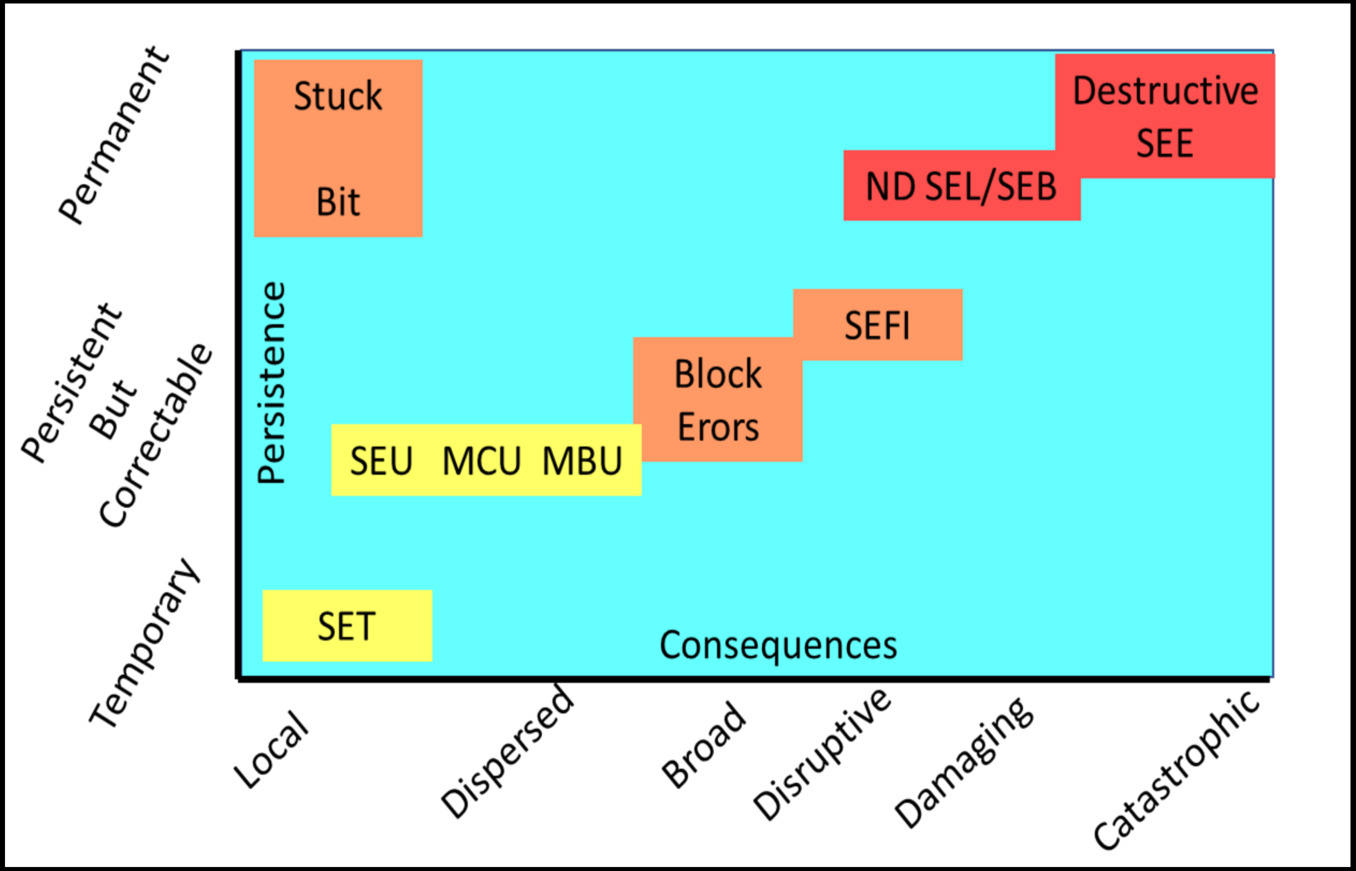
# Single Event Functional Interrupt (SEFI)

- A soft error that causes the component to reset, lock-up, or otherwise malfunction in a detectable way, but does not require power cycling of the device (off and back on) to restore operability, unlike single-event latch-up (SEL) or result in permanent damage as in single event burnout (SEB).

Figures from “Heavy Ion Test Report for the AD9364 RF Transceiver,”
https://nepp.nasa.gov/files/28554/NEPP TR 2016 Chen 15 071 AD9364 T031716 TN44752.pdf

# Types of radiation effects – Single Event Effects (SEE)

- Destructive
  - SEL - Latchup
  - SEB - Burnout
  - SEGR – Gate Rupture
  - SEDR – Dielectric Rupture
  - *SEU – Upsets can become stuck bits*
- Non-destructive
  - SET – Transients, can be analog and digital
  - SEU – Upsets, can happen in multiple bits/cells - MBU
  - SEFI – Functional Interrupts, for complex devices, typical category for response that needs refresh/reset/power-cycle to return to operation
  - Non-destructive does not mean non-disruptive



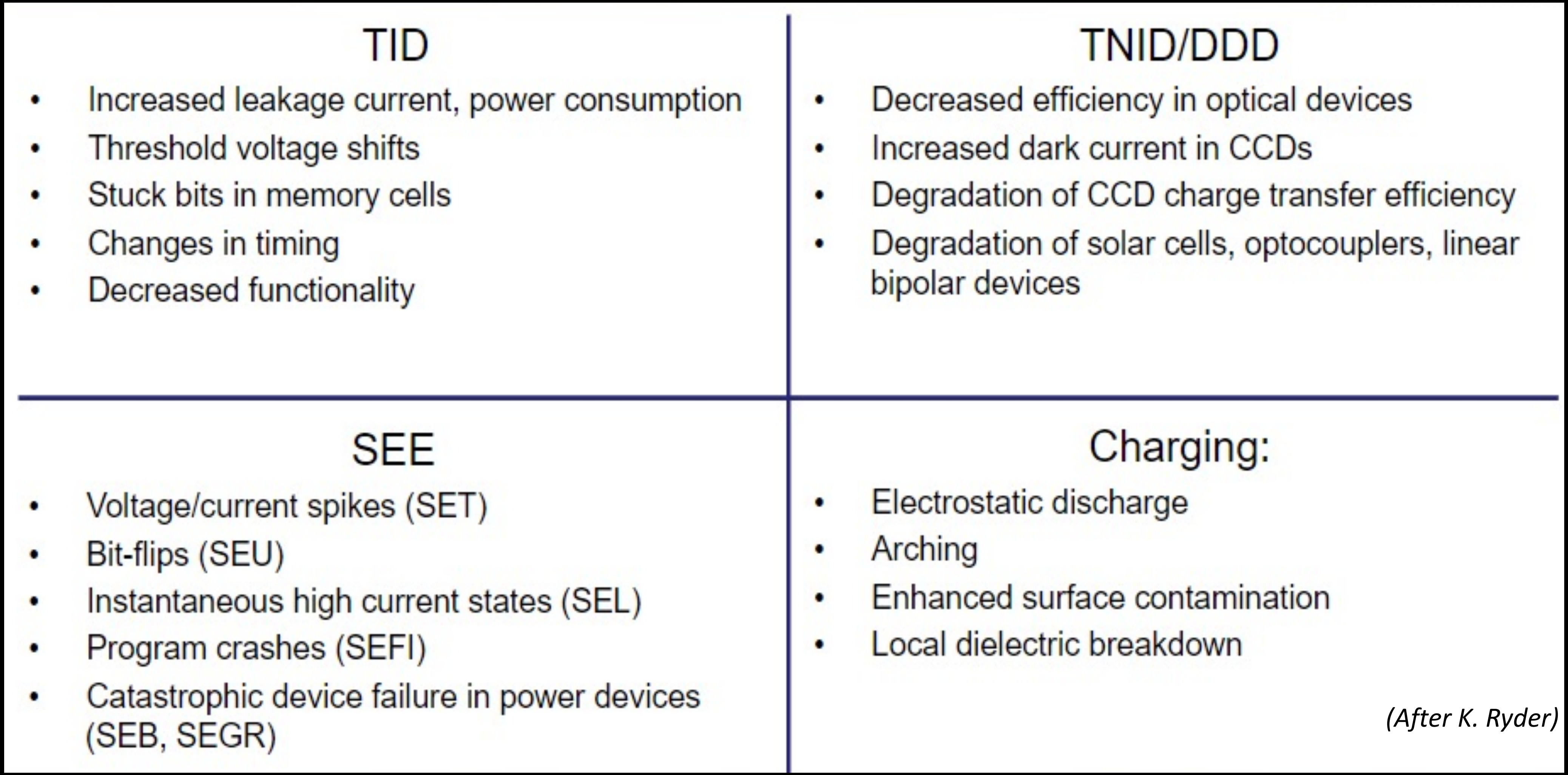
(After Ladbury)

# Which SEE?

- Concerns manifest differently by part type/technology
- This list is not exhaustive, and new technologies could fall into a family where new failure mechanisms are unknown
- Architecture and structures within are what create the threat

| | Non-destructive SEEs | | | Destructive SEEs | | | |
|---|---|---|---|---|---|---|---|
| | SET | SEU | SEFI | SEL | SEB | SEGR | SEDR |
| Memories | ✓ | ✓ | ✓ | ✓ | | | |
| Logic (Latches) | | ✓ | | | | | |
| Logic (Combinational) | ✓ | | ✓ | ✓ | | | |
| Microprocessors | | ✓ | ✓ | ✓ | | | |
| Analog or Mixed Signal Circuits | ✓ | | ✓ | ✓ | ✓ | | ✓ |
| Photonics | ✓ | | | | | | |
| FPGAs | | ✓ | ✓ | ✓ | | | ✓ |
| ASICs | | ✓ | ✓ | ✓ | | | |
| Power MOSFETs | | | | | ✓ | ✓ | |
| Other Power Devices | ✓ | | | ✓ | | | ✓ |
| Converters | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | |

# Summary of risks to electronic parts



### TID

- Increased leakage current, power consumption
- Threshold voltage shifts
- Stuck bits in memory cells
- Changes in timing
- Decreased functionality

### TNID/DDD

- Decreased efficiency in optical devices
- Increased dark current in CCDs
- Degradation of CCD charge transfer efficiency
- Degradation of solar cells, optocouplers, linear bipolar devices

### SEE

- Voltage/current spikes (SET)
- Bit-flips (SEU)
- Instantaneous high current states (SEL)
- Program crashes (SEFI)
- Catastrophic device failure in power devices (SEB, SEGR)

### Charging:

- Electrostatic discharge
- Arching
- Enhanced surface contamination
- Local dielectric breakdown

*(After K. Ryder)*

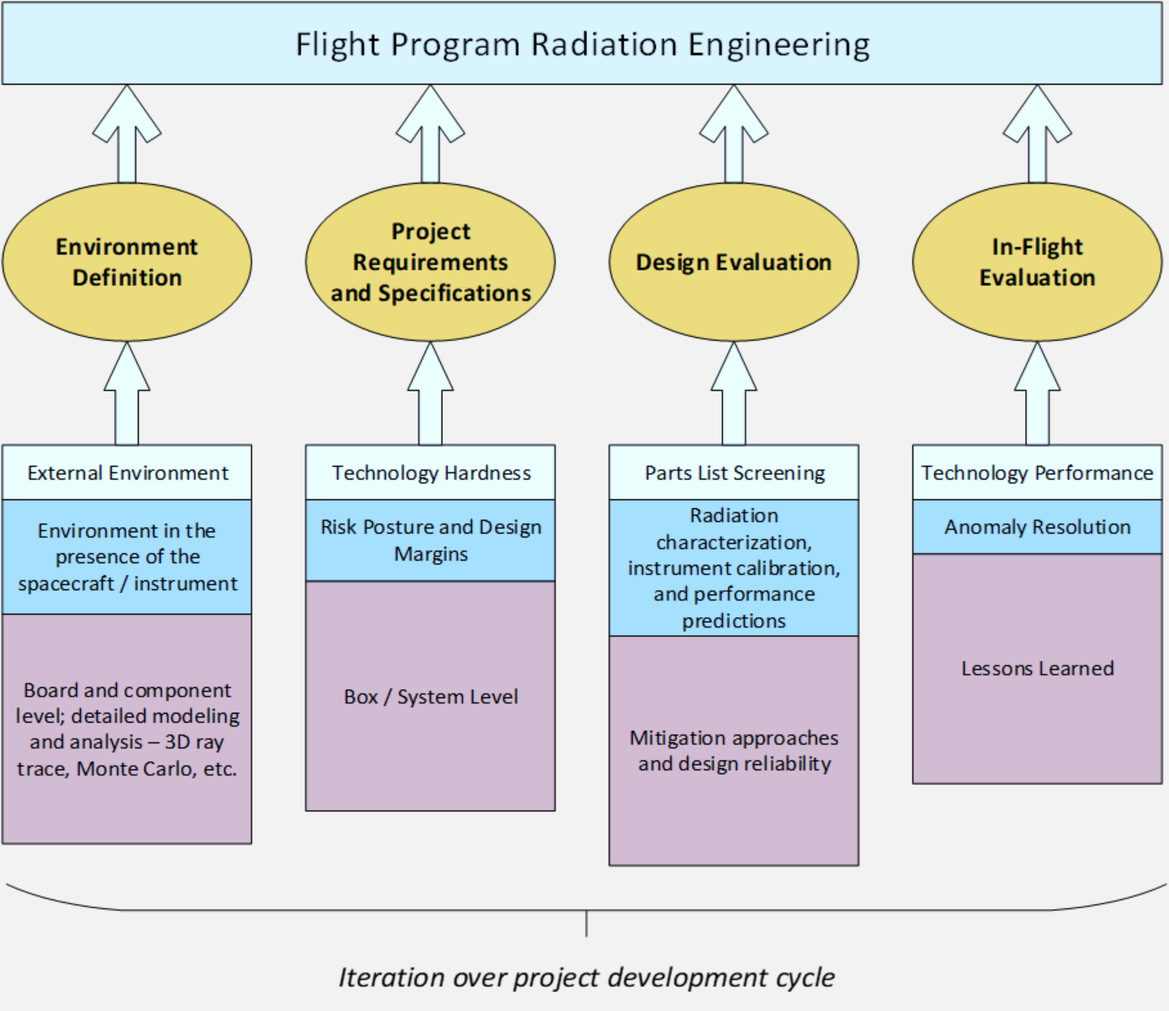
# Radiation Hardness Assurance (RHA) overview

RHA consists of all activities undertaken to ensure that the electronics and materials of a space system perform to their *design* specifications throughout exposure to the mission space environment

(After Poivey 2007) ↑

(After LaBel 2004) →

As we go beyond low earth orbit with our SmallSats it's important to note that the challenges are not unique to the platform



Flight Program Radiation Engineering

**Environment Definition**

**Project Requirements and Specifications**

**Design Evaluation**

**In-Flight Evaluation**

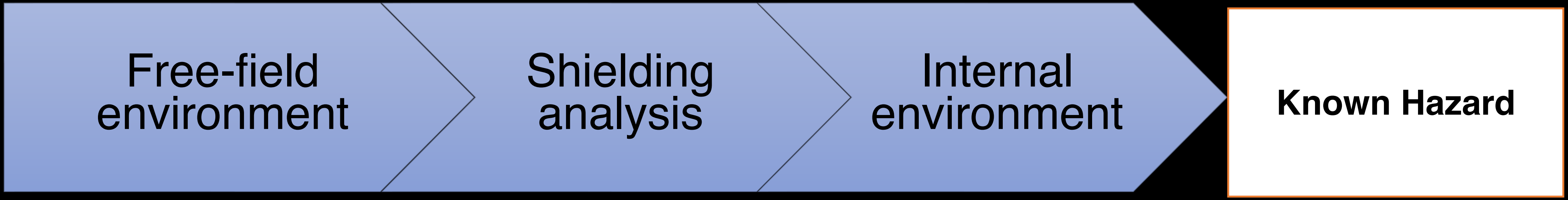
| External Environment | Technology Hardness | Parts List Screening | Technology Performance |
|---|---|---|---|
| Environment in the presence of the spacecraft / instrument | Risk Posture and Design Margins | Radiation characterization, instrument calibration, and performance predictions | Anomaly Resolution |
| Board and component level; detailed modeling and analysis – 3D ray trace, Monte Carlo, etc. | Box / System Level | Mitigation approaches and design reliability | Lessons Learned |

*Iteration over project development cycle*

# Methods of analysis

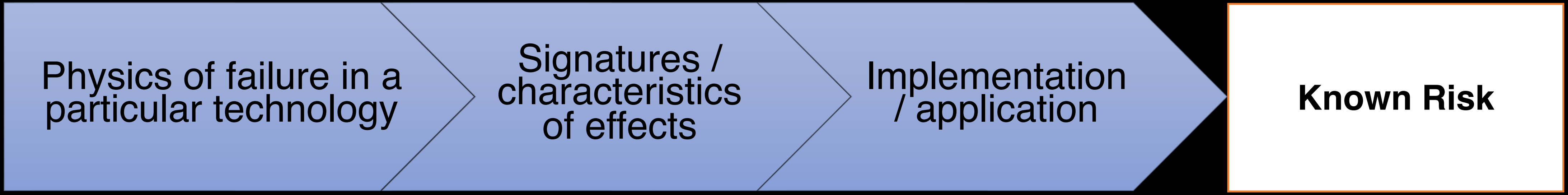
- Environment modelling and transport

  Considers all contributors based on mission environment and lifetime



Free-field environment → Shielding analysis → Internal environment → **Known Hazard**

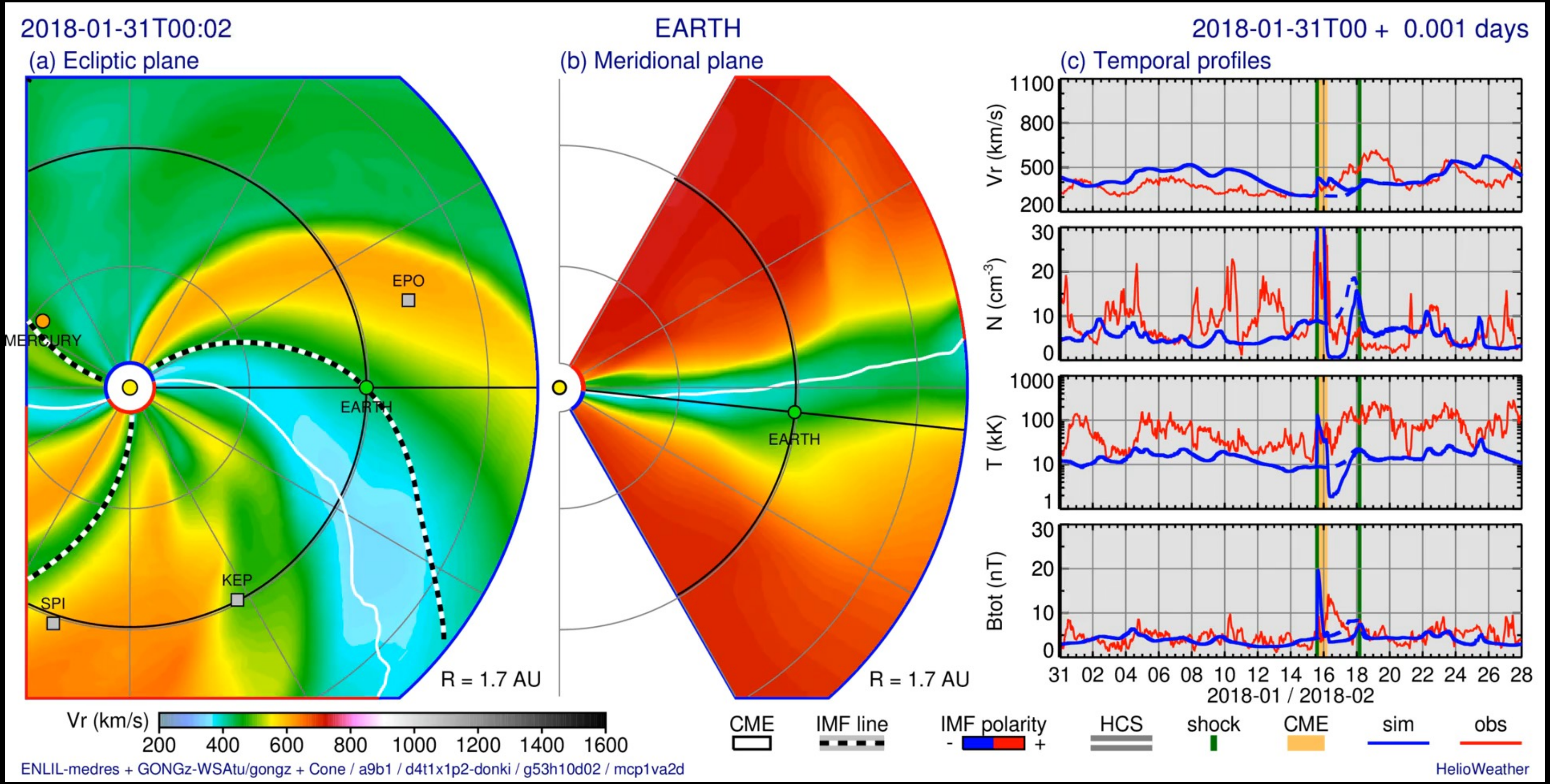
- Analysis and test correlation



Physics of failure in a particular technology → Signatures / characteristics of effects → Implementation / application → **Known Risk**

# Free-field environment

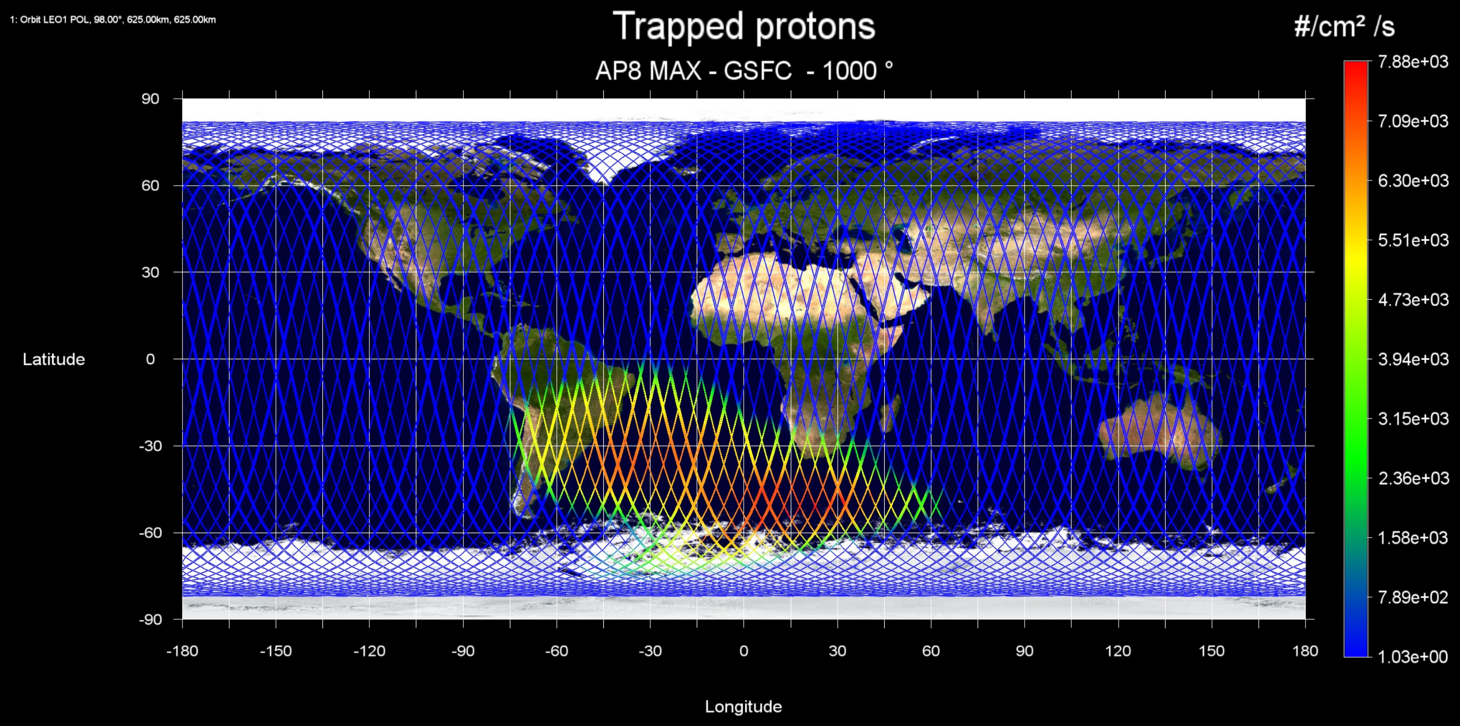
- Shielding and boxes also scatter the incoming particles
- CMEs/Flares present the worst case SEE environment and contribute to the dose of the mission

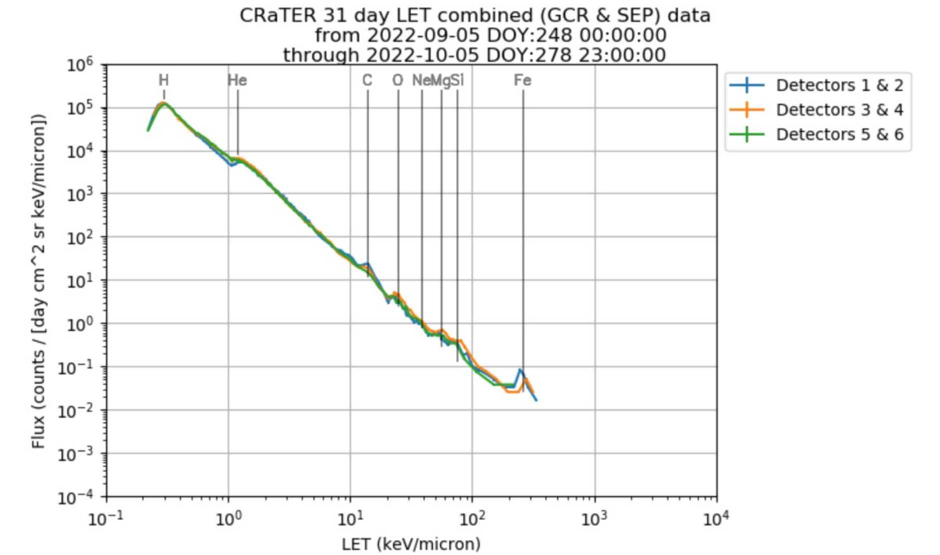


Space radiation is truly omnidirectional.

# On-orbit data products are used to create environment models

- We benefit from the science data products that come from calibrated instruments to map to environment conditions that inform our tests

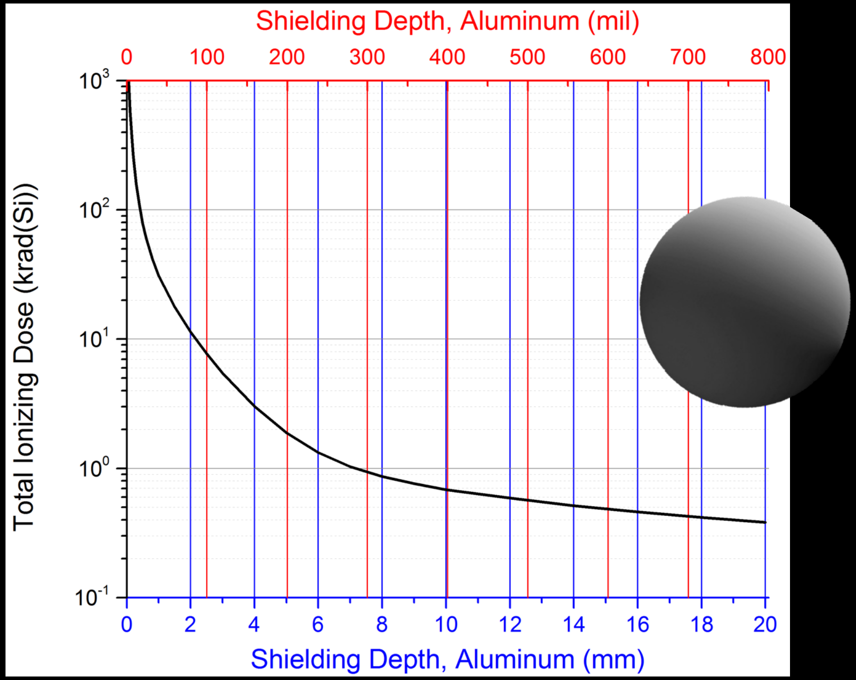




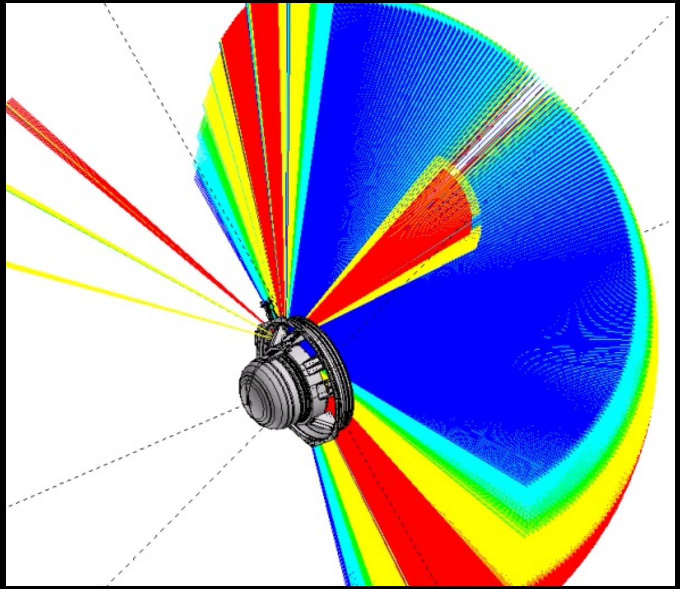
# Transport and deposition of dose

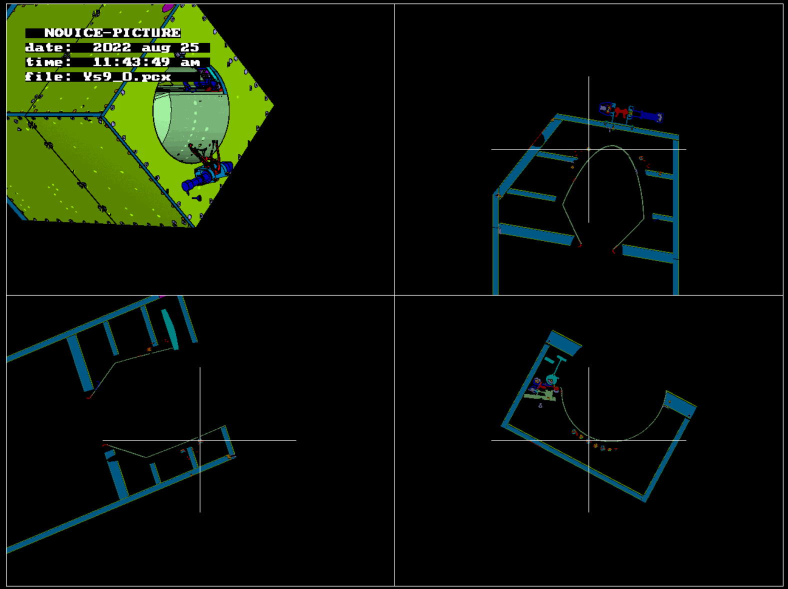
- Outside environment can get transported in several ways
- Shielding might not be as easy to increase on a SmallSat

## Simple (spheres)



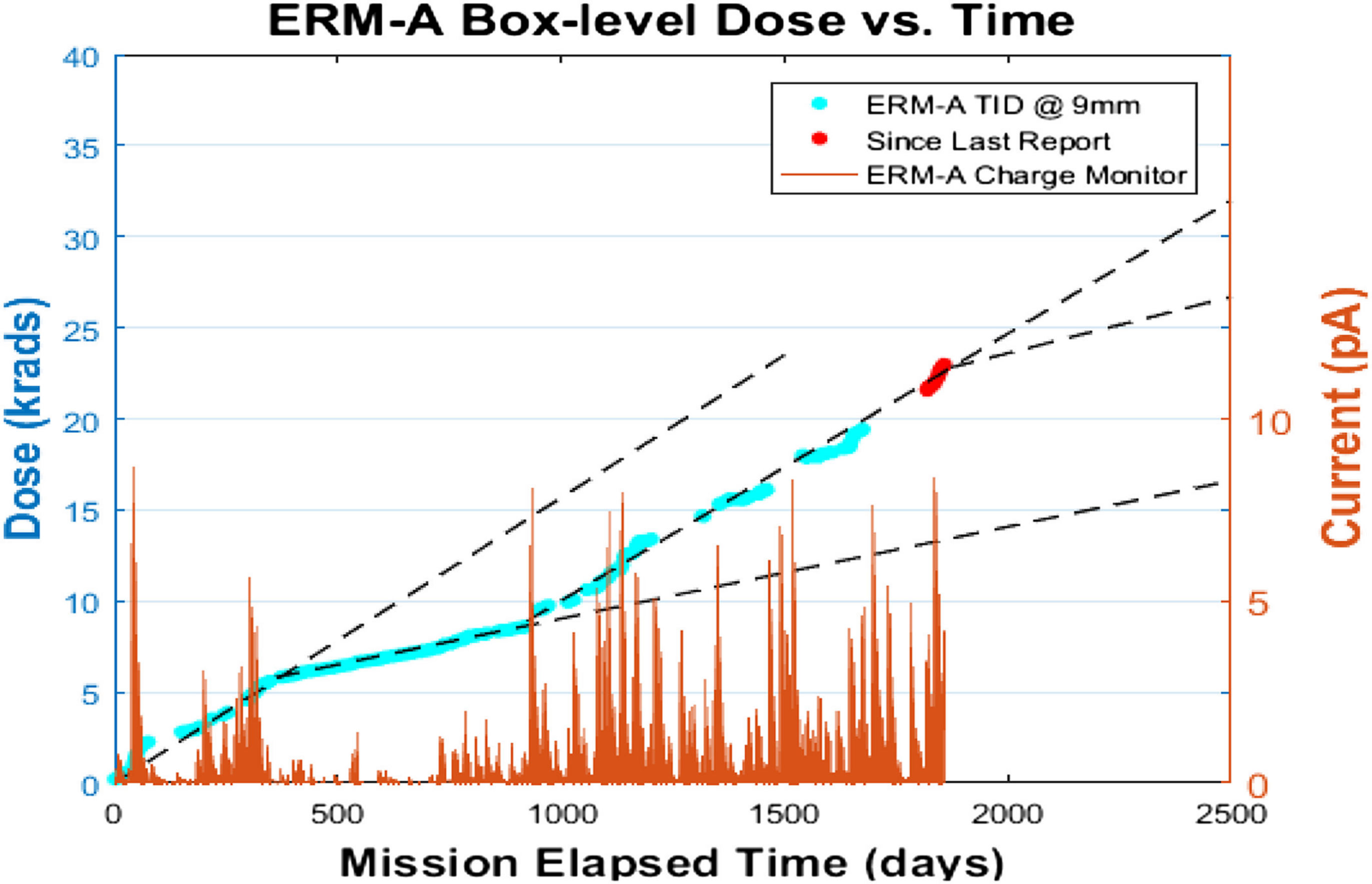
## Complex (CAD models)





# Environment correlation: Measured Dose

- On orbit dosimetry is straight forward: we have actual dose rates from dosimeters
- Ground based dose tests are accelerated life tests with special considerations: annealing, ELDRS, etc.



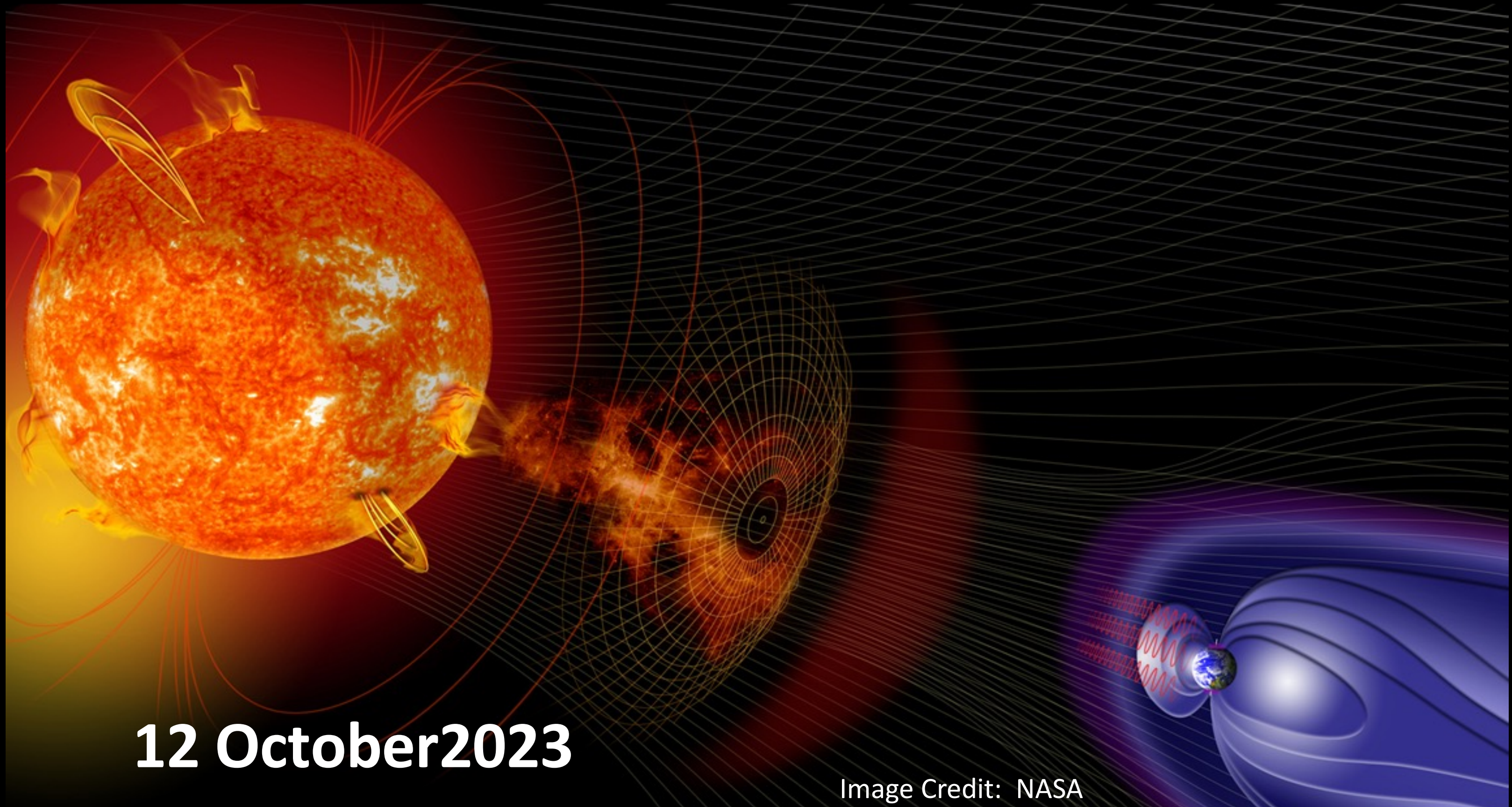
Space Weather, Volume: 16, Issue: 10, Pages: 1561-1569, First published: 24 September 2018, DOI: (10.1029/2018SW001910)

# Shielding Considerations for CubeSat Structures During Solar Maximum

**Larry Thomsen**
**NASA Langley Research Center**

**Tom Jordan and Larisa Milic**
**Experimental & Mathematical Physics Consultants (EMPC)**

**Bill Girard**
**Science & Technology Corporation (STC)**



12 October2023

Image Credit: NASA

# Reliability has a Price:  Enabling Missions, Return on Investment

- CubeSat Market: $0.5B-1B over 3 yr
- Over 1700 small satellites forecasted for 2017-2023 (www.spaceworksforecast.com)

- More than 500 over next 3 yr into polar low-Earth orbit (PLEO) (www.spaceworksforecast.com)

- Typical 6U CubeSat costs $6-9M (https://esto.nasa.gov/techval_space.html)

- CubeSat value at risk: $0.5-1B in the past 3 yr alone

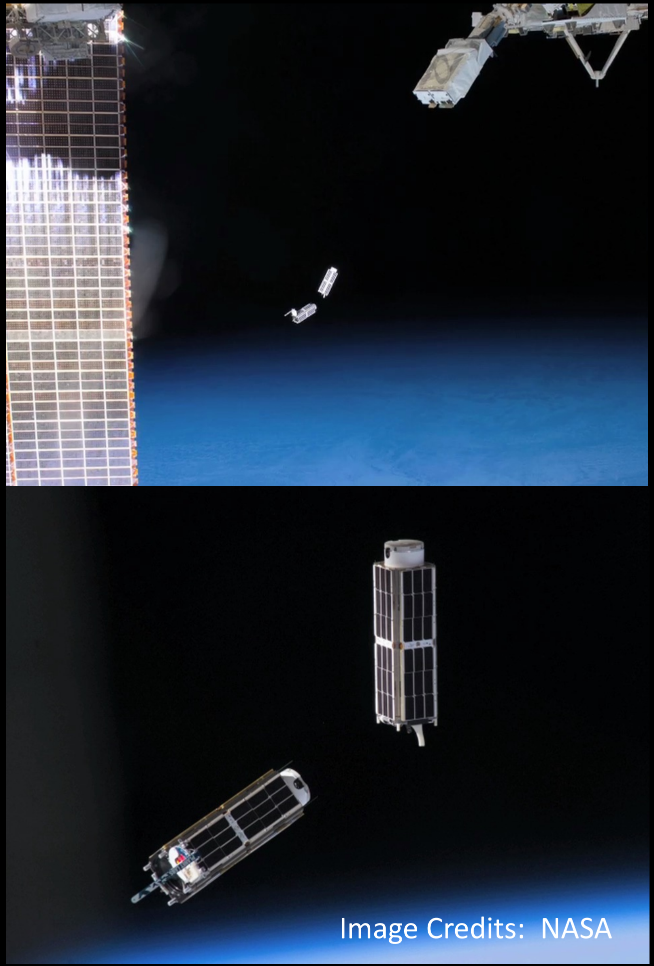


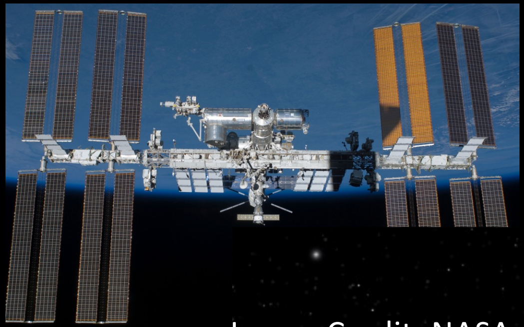
Image Credits:  NASA

ISS CubeSat Deployment, one of many space launch service methods

1 unit (U) = 10 cm x 10 cm x 10 cm

# Reliability Engineering for Mission Assurance

- **NASA Preferred Reliability Series, 1258, "Space Radiation Effects on Electronic Components in Low Earth Orbit," August 1996.**
  - **Typical Commercial parts hardness:**
    - Total Dose: 2 to 10 kRAD (typical)
    - SEU Threshold LET: 5 MeV/mg/cm2
    - SEU Error Rate: 10E-5 errors/bit-day (typical)
- **NASA Preferred Reliability Series, 1260, "Radiation Design Margin Requirement", May 1996.**
    - Radiation Design Margin 2 or 3
- **NASA Handbook 4002A, "Mitigating In-Space Charging Effects —a Guideline", 19 October 2017.**
    - 0.284-cm Aluminum equivalent minimum thickness to reduce internal discharge risk in Earth Orbit, upcoming revision.
- **NASA-STD-8729.1A, "NASA Reliability and Maintainability (R&M) Standard for Spaceflight and Support Systems", 13 June 2017.**



ISS

Image Credit: NASA

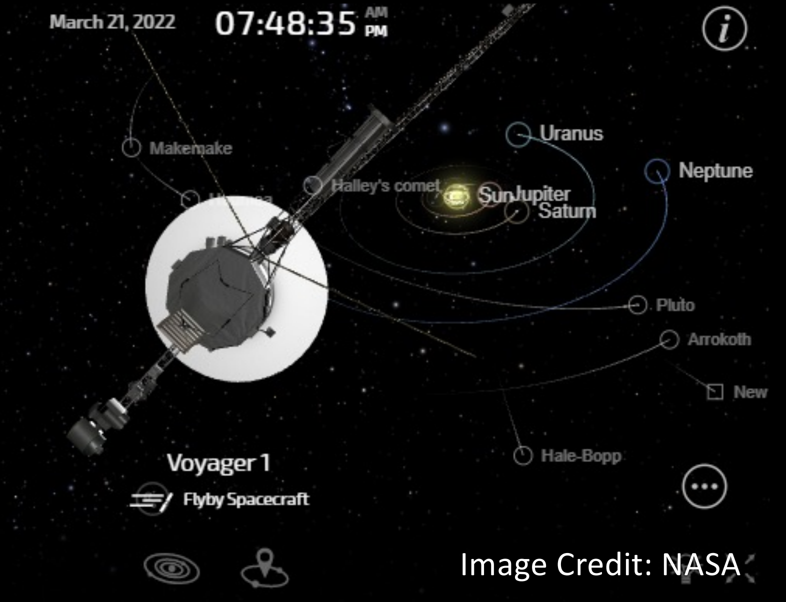


Image Credit: NASA

Voyager 1

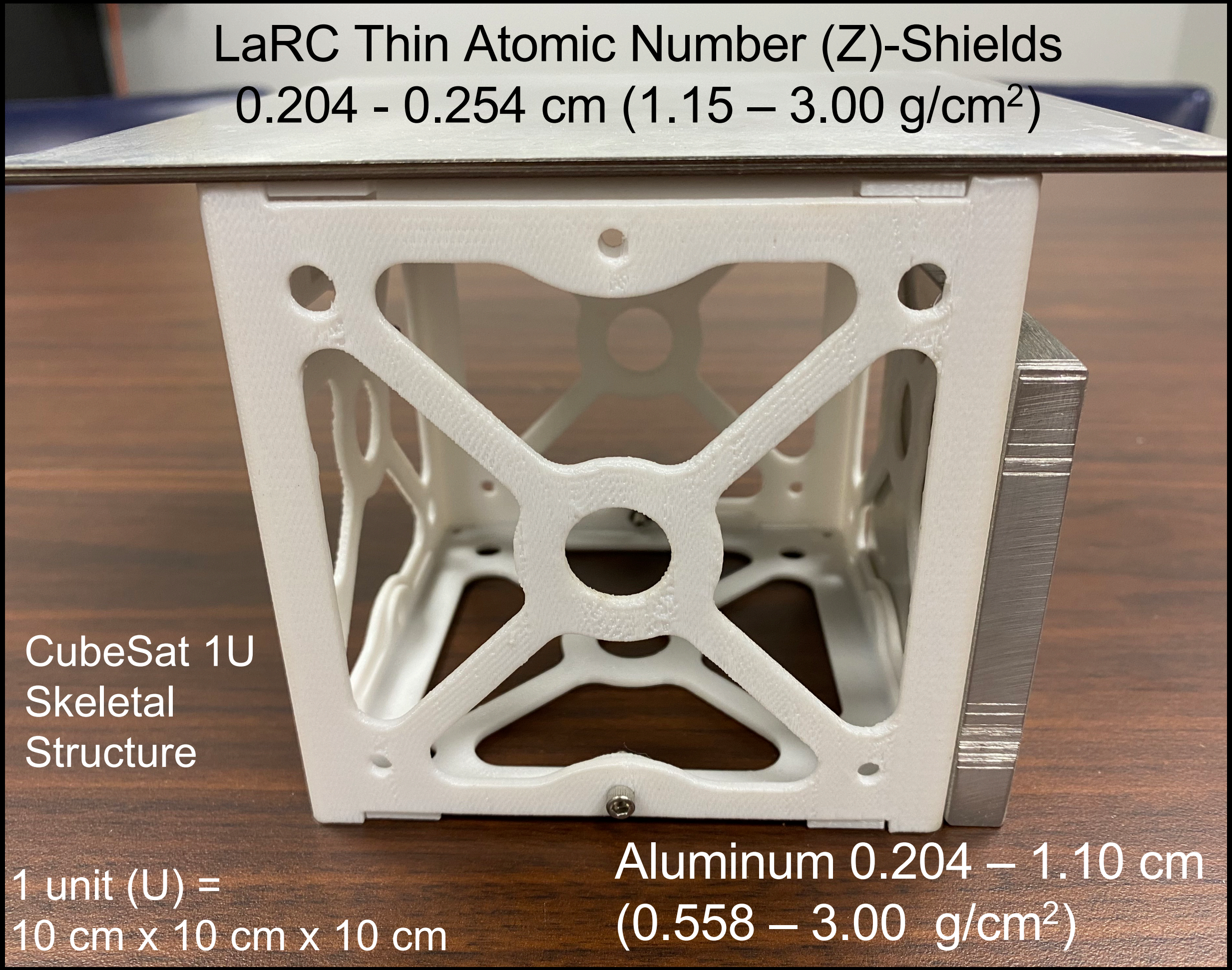
Image Credit: USAF

SCATHA (Spacecraft Charging at High Altitude)

*Standards, Design, Testing, and Guidelines Improve Reliability in the Radiation Environment*

Single Event Upset = SEU, LET = Linear Energy Transfer

# The Problem of Radiation Shielding of CubeSats is Putting Mass into the Walls of Thin Structures

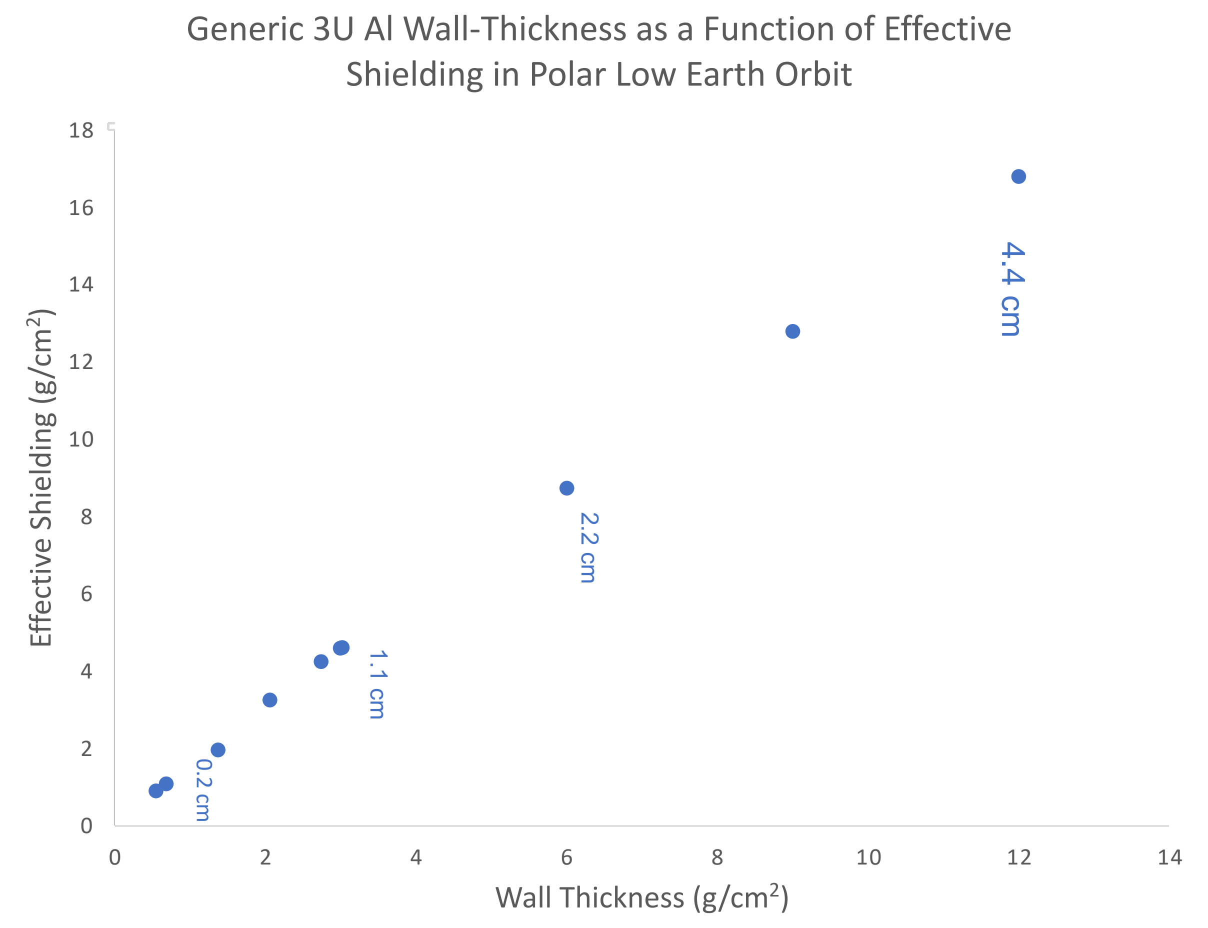


LaRC Thin Atomic Number (Z)-Shields
0.204 - 0.254 cm (1.15 – 3.00 g/cm$^2$)

CubeSat 1U
Skeletal
Structure

1 unit (U) =
10 cm x 10 cm x 10 cm

Aluminum 0.204 – 1.10 cm
(0.558 – 3.00 g/cm$^2$)

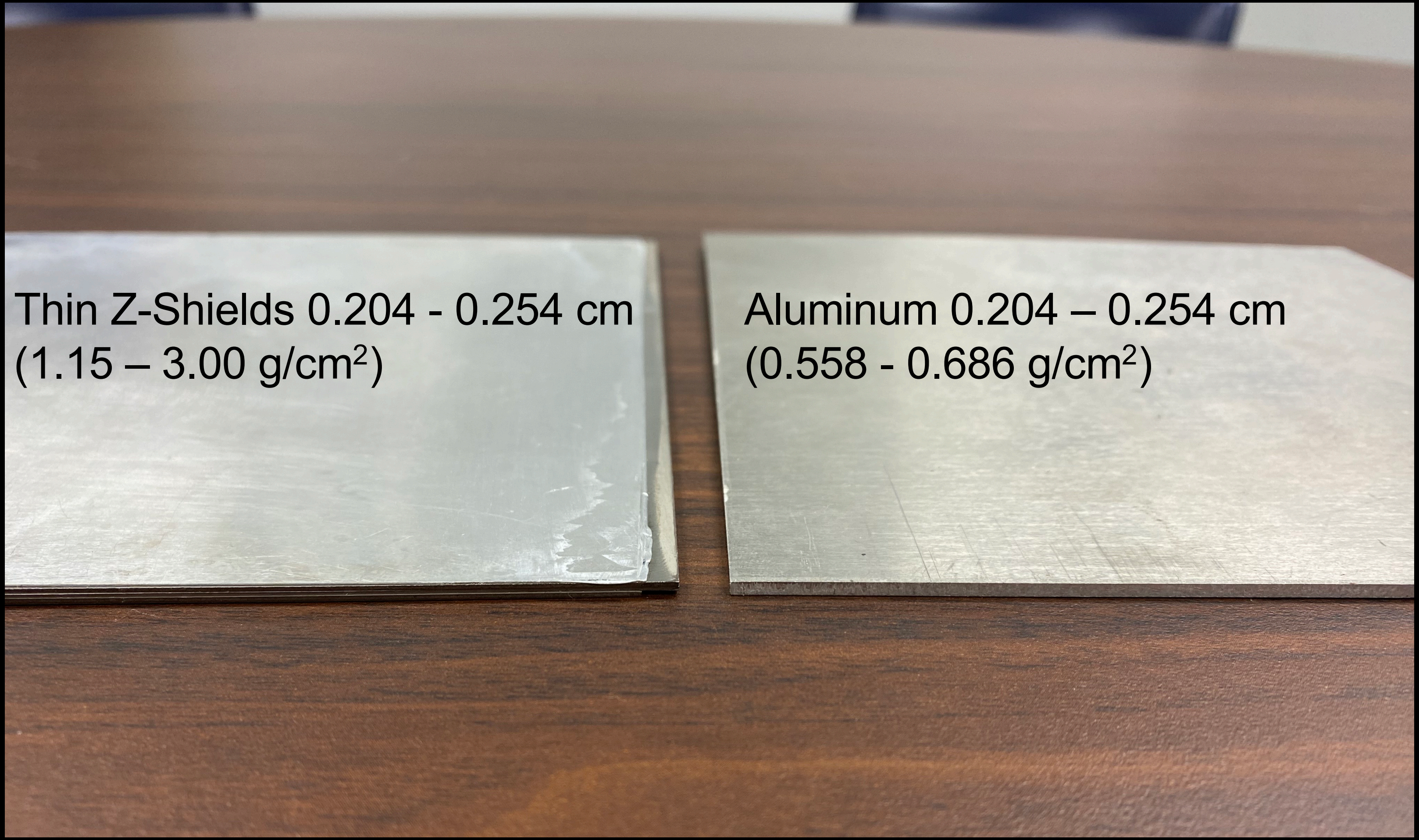


Generic 3U Al Wall-Thickness as a Function of Effective Shielding in Polar Low Earth Orbit

*Effective Shielding determined using NOVICE SIGMA, 3-D Ray Tracing Sector Analysis, Estimates with Aerospace Corporation Proton (AP)8 Solar Minimum Model for a 500-km altitude and 85$^o$ inclination orbit.*

# Aluminum CubeSat Structural Wall Thicknesses Limit Shielding

Shielding = mass thickness, areal density = g/cm$^2$ = thickness (cm) x density (g/cm$^3$)



Thin Z-Shields 0.204 - 0.254 cm (1.15 – 3.00 g/cm$^2$)

Aluminum 0.204 – 0.254 cm (0.558 - 0.686 g/cm$^2$)

# Total Ionizing Dose (TID) and Proton Single Event Effects (SEEs) Impact Mission Reliability Over Time

In most cases, shielding amounts reduce the dose rate, reduce particle fluence and energies

Image Credit: Microsoft Office Stock Image

Image Credit: Microsoft Office Stock Image

*Radiation Shielding: Like a wear rate, a 20,000 mile versus 100,000 mile tire tread life*
*If need new tires though no one available to change in space, yet……*

# Shields-1 (Z-Shield Vault): Performing over 4 Years in Polar Low-Earth Orbit

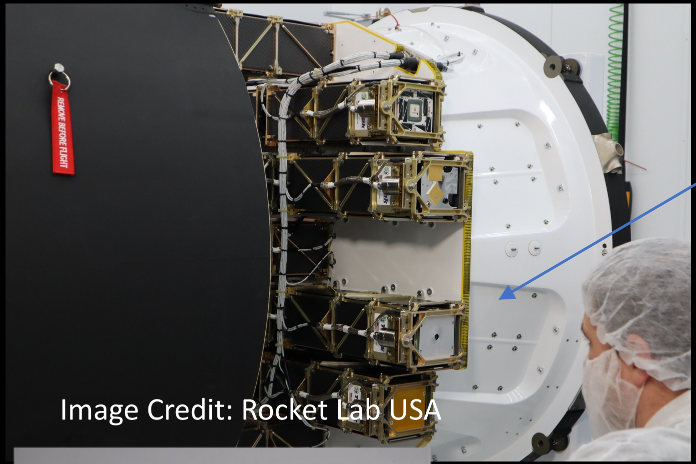
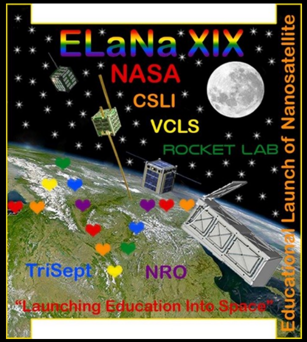
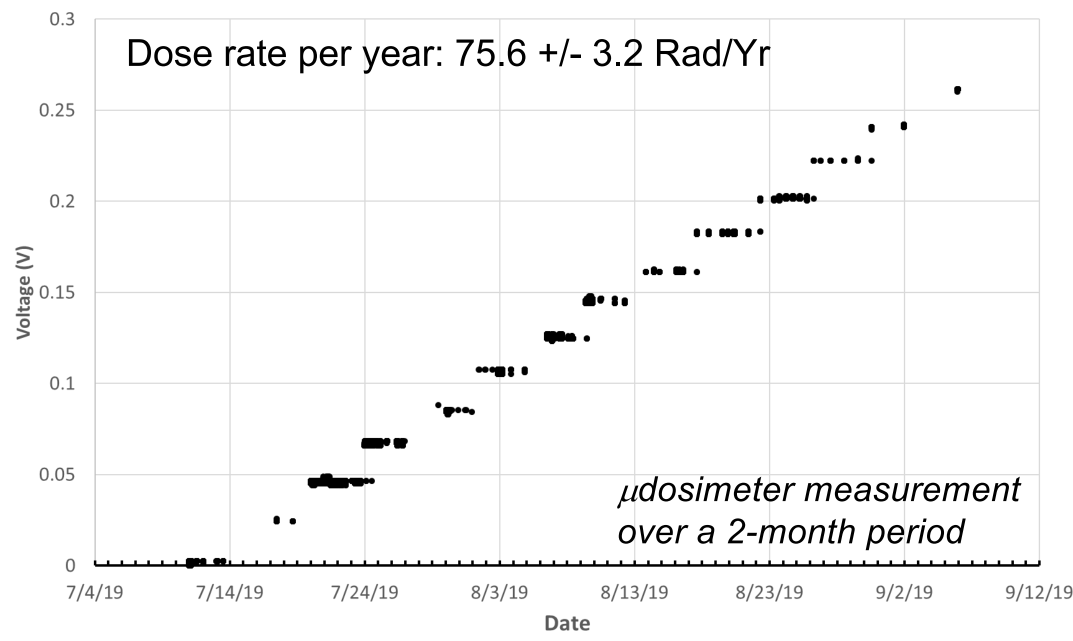


Image Credit: Rocket Lab USA

Shields-1 onboard Rocket Lab USA, Electron Rocket, NASA ELaNaXIX Mission, 16 December 2018 Launch



Z-Shield Vault Performance in Polar Low-Earth Orbit



*Space Heritage*
*NORAD ID 43850*

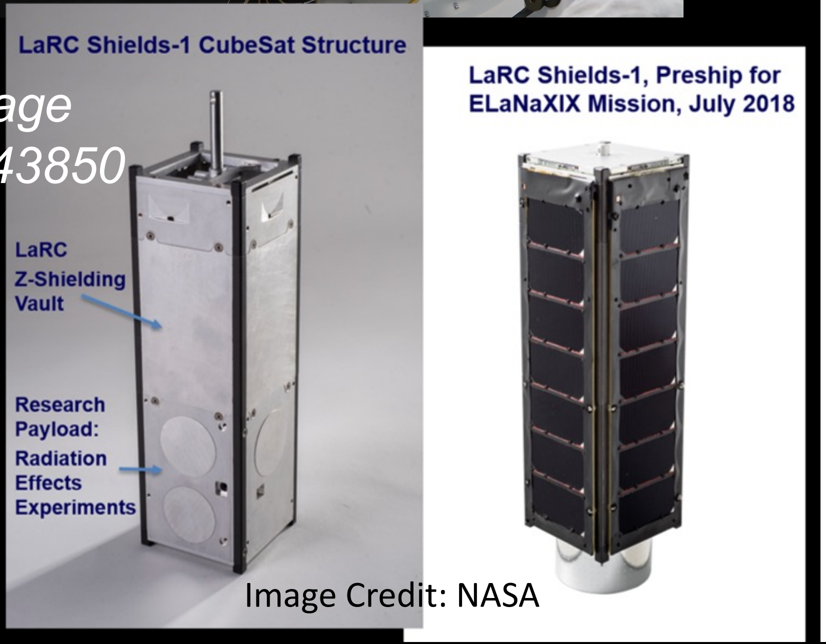


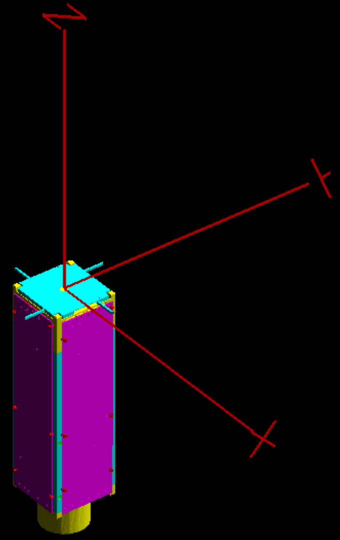
Image Credit: NASA

*North American Aerospace Defense Command = NORAD*

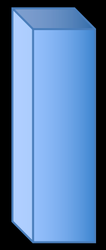
# TID, Effective Shielding, and Minimum Proton Threshold Approximations by NOVICE

- Polar Low-Earth Orbit (LEO):
  - $85^{o}$ Inclination
  - 500-km apogee/ perigee
- 1-yr mission, AP8 Radiation Belt Model, Solar Protons, SOLPRO (King) Model, 95% Confidence
- NOVICE ADJOINT Fluence and SIGMA Effective Shielding measurements at Shields-1 μDosimeter location in Electronics Enclosure (vault) and inside a generic 3U CubeSat containing four electronic boards
- *Minimum particle proton energy threshold for a detector is the minimum proton particle energy that transmits through spacecraft shielding to the detector.*
- *Minimum particle proton energy threshold for a detector is determined from the space environment integral fluence and the integral fluence at each detector.*

Shields-1 CAD Model



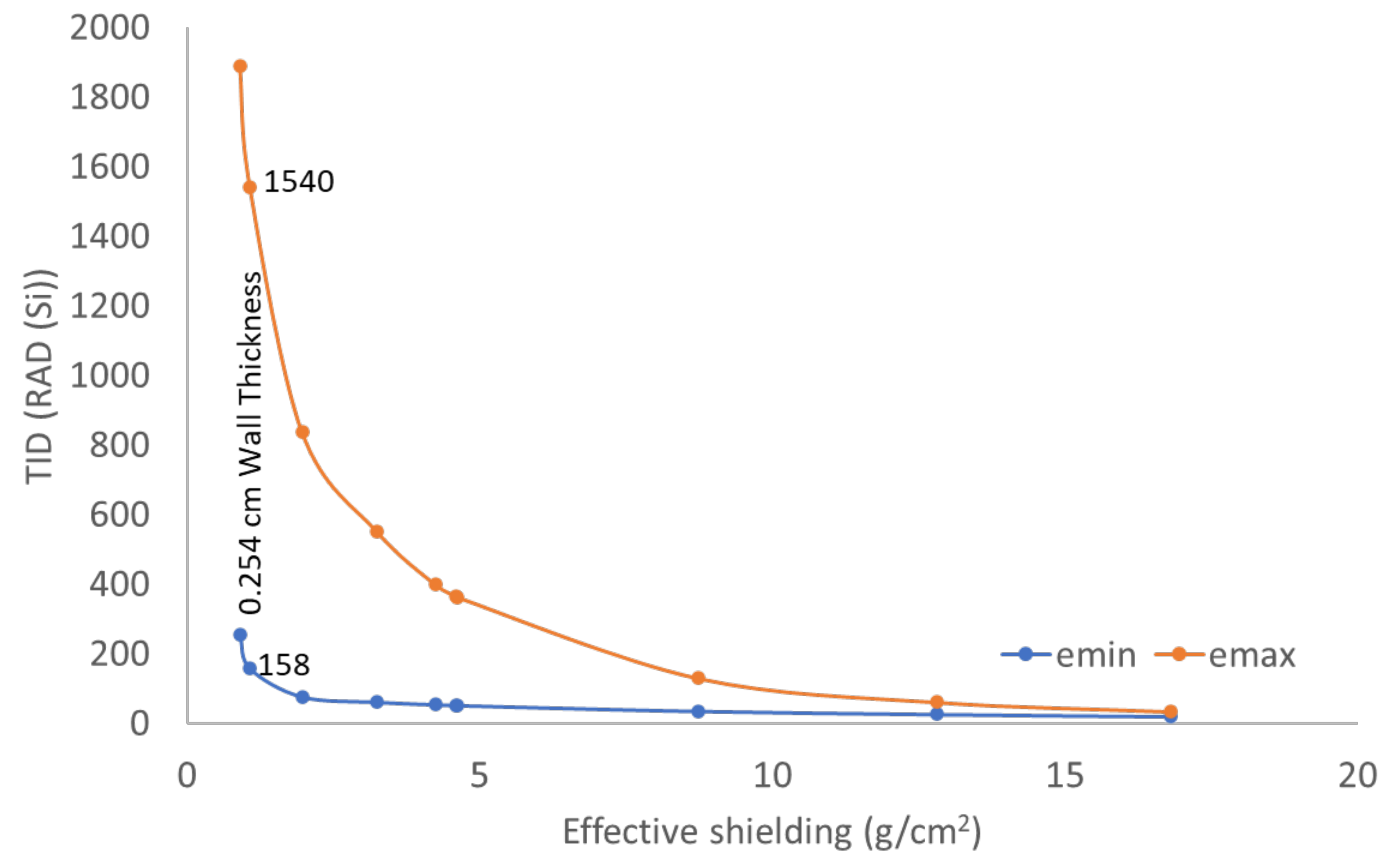
Thin-Walled (0.204 cm) Generic 3U CubeSat with Four Electronic Boards Inside



*Modeled CAD structures for this study*

NOVICE Software calculates and models radiation transport methods and effects. It uses ADJOINT Monte Carlo Code and SIGMA, a ray-tracing sector analysis tool. SOLPRO is a NASA developed code for estimated solar proton radiation effects.

# TID Increases during Solar Maximum for Thin-Walled Shielding



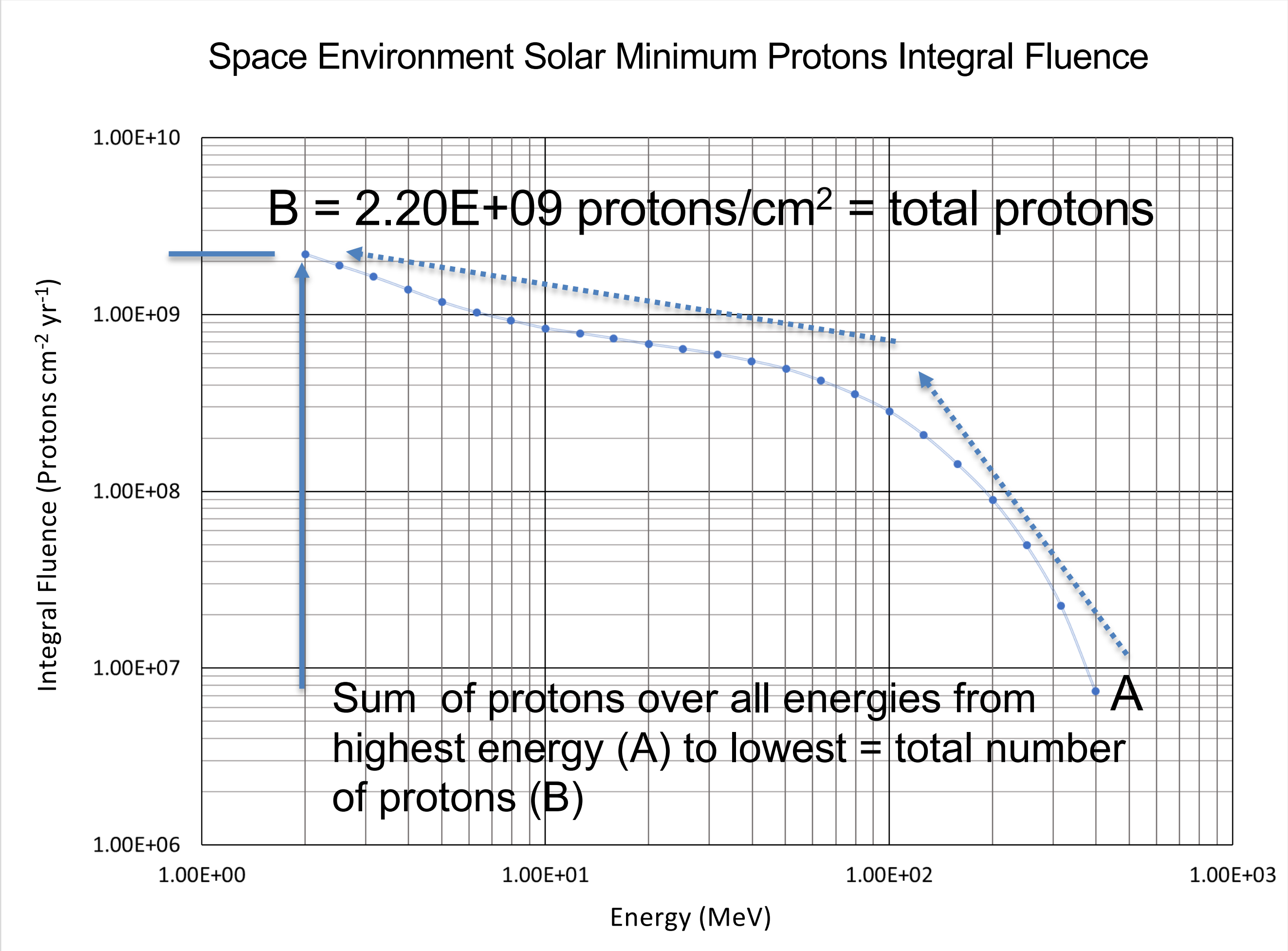
- For thin-walled shielding, TID 10x difference solar minimum to solar maximum
- With a Radiation Design Margin (RDM) of 2 or 3, ( 3 kRAD or 4.5 kRAD), at limits of commercial part hardness range of 2 to 10 kRAD.

*solar minimum = emin, solar maximum = emax*

*NASA Preferred Reliability Series, 1260, "Radiation Design Margin Requirement", May 1996.*

*NASA Preferred Reliability Series, 1258, “Space Radiation Effects on Electronic Components in Low Earth Orbit,” August 1996.*

# Shields-1 NOVICE Model Fluence (Solar minimum)



B = 2.20E+09 protons/cm$^2$ = total protons

Sum of protons over all energies from highest energy (A) to lowest = total number of protons (B)

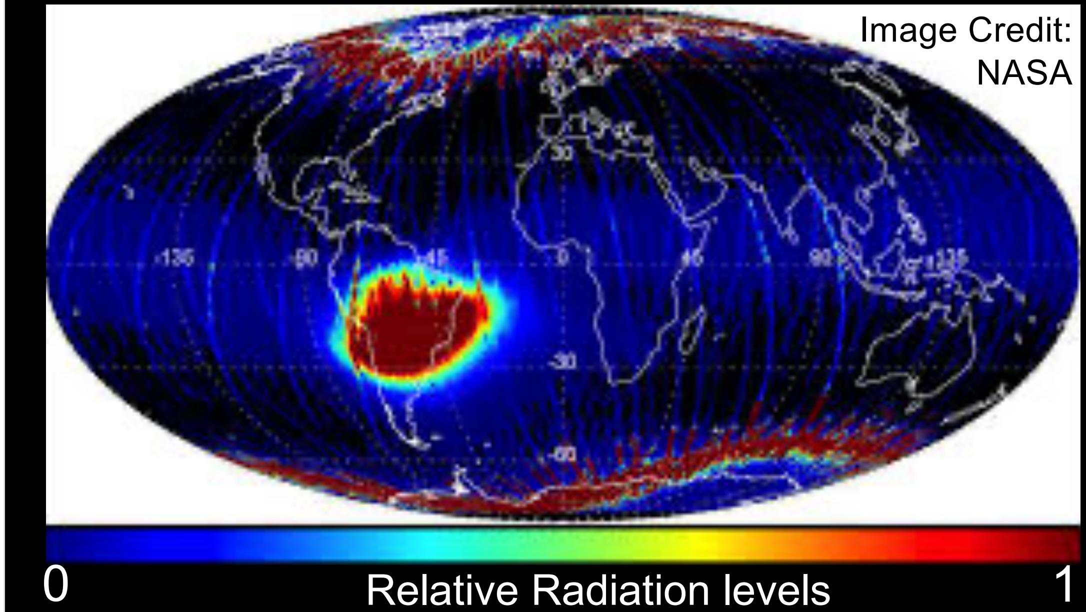
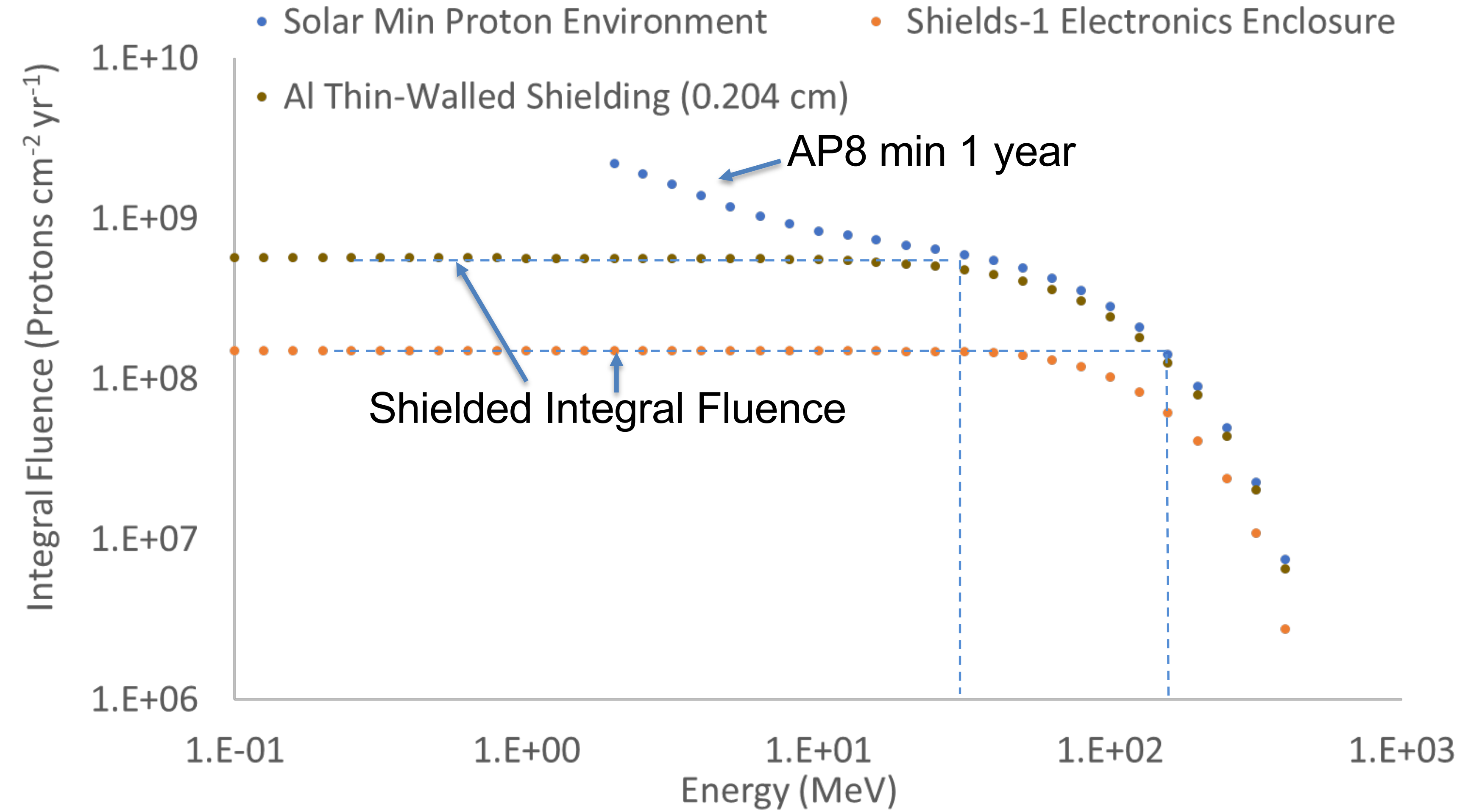


Image Credit: NASA

South Atlantic Anomaly (SAA) dominates the polar low-Earth orbit proton flux/fluence

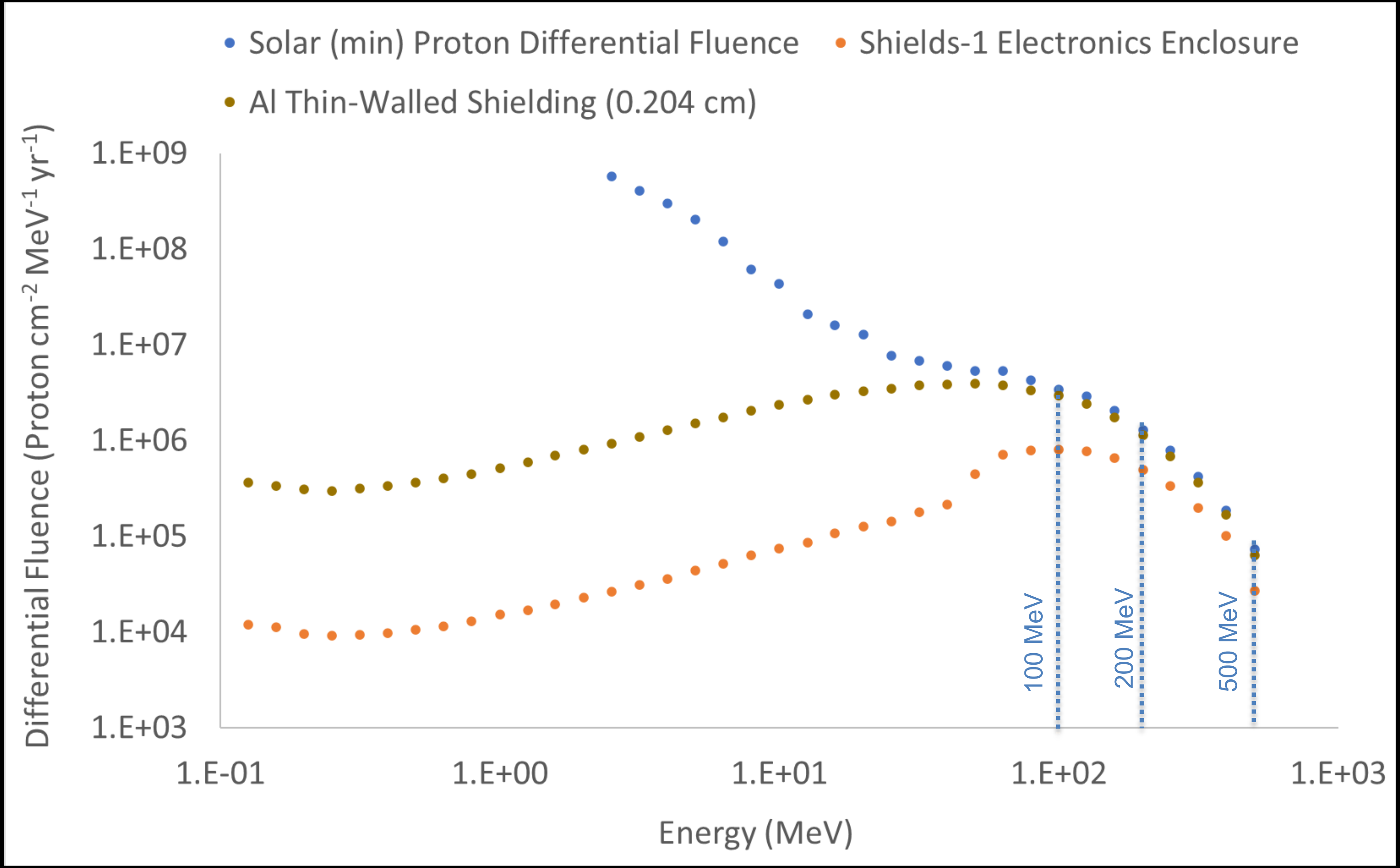
# Minimum Proton Energy Thresholds, Influence Proton SEE



| Name | Material | Wall Areal Density (g/cm$^2$) | Total Proton Integral Fluence (protons/cm$^2$) | Proton Minimum Threshold Energy (MeV) | Effective Shielding (g/cm$^2$) | % Particles Remaining |
|---|---|---|---|---|---|---|
| Shields-1 Electronic Enclosure | AlTiTa | 3.02 | 1.52E+08 | 151 | 21.3 | 6.90 |
| Generic CubeSat (3U) | Al | 0.550 | 5.68E+08 | 36.2 | 0.907 | 25.8 |

Solar Minimum Total Proton fluence = 2.20E+09 (protons/cm$^2$). *Extrapolated Proton Minimum Threshold Energy, assumes spherical shielding from Adjoint Model.*

# Shielding Contributes to Attenuation of Energetic Protons



| Name | Proton Attenuation (%) | | |
|---|---|---|---|
| | 100 MeV | 200 MeV | 500 MeV |
| Shields-1 Electronic Enclosure | 76.5 | 61.7 | 63.0 |
| Generic CubeSat (3U) | 13.7 | 12.4 | 12.6 |

# Spacecraft of All Shielding Levels Influenced by Proton SEE

- NOAA Space Weather Prediction Center (SWPC) Solar Radiation Storm Severity Scales
  - magnitude flux levels above 10-MeV proton energies from 1-5, and correspond to historical occurrence rates for a 11-year solar cycle.

  - Typically 50 minor, 25 moderate, 10 strong, 3 severe, and less than 1 extreme solar particle event (SPE). SEE events have increased probability of occurrence from moderate to extreme severity.
  - Many SPEs last several days and longer with increased flux over a short amount of time.

- In terms of reliability: Increased shielding reduces the effects of proton SEE by increasing minimum proton energy thresholds.

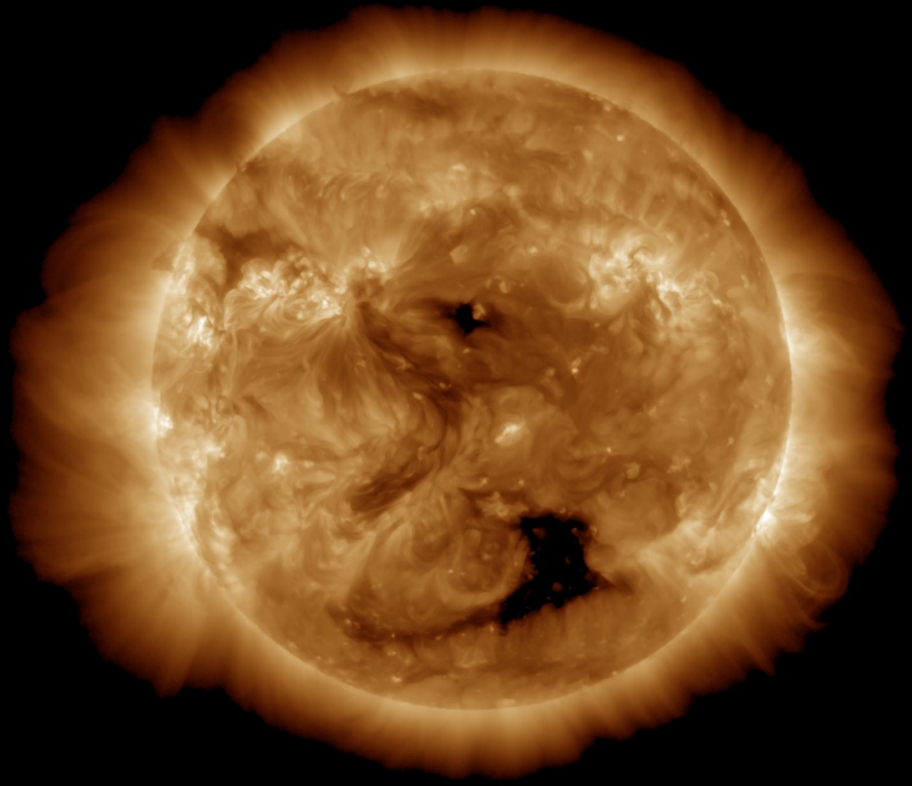


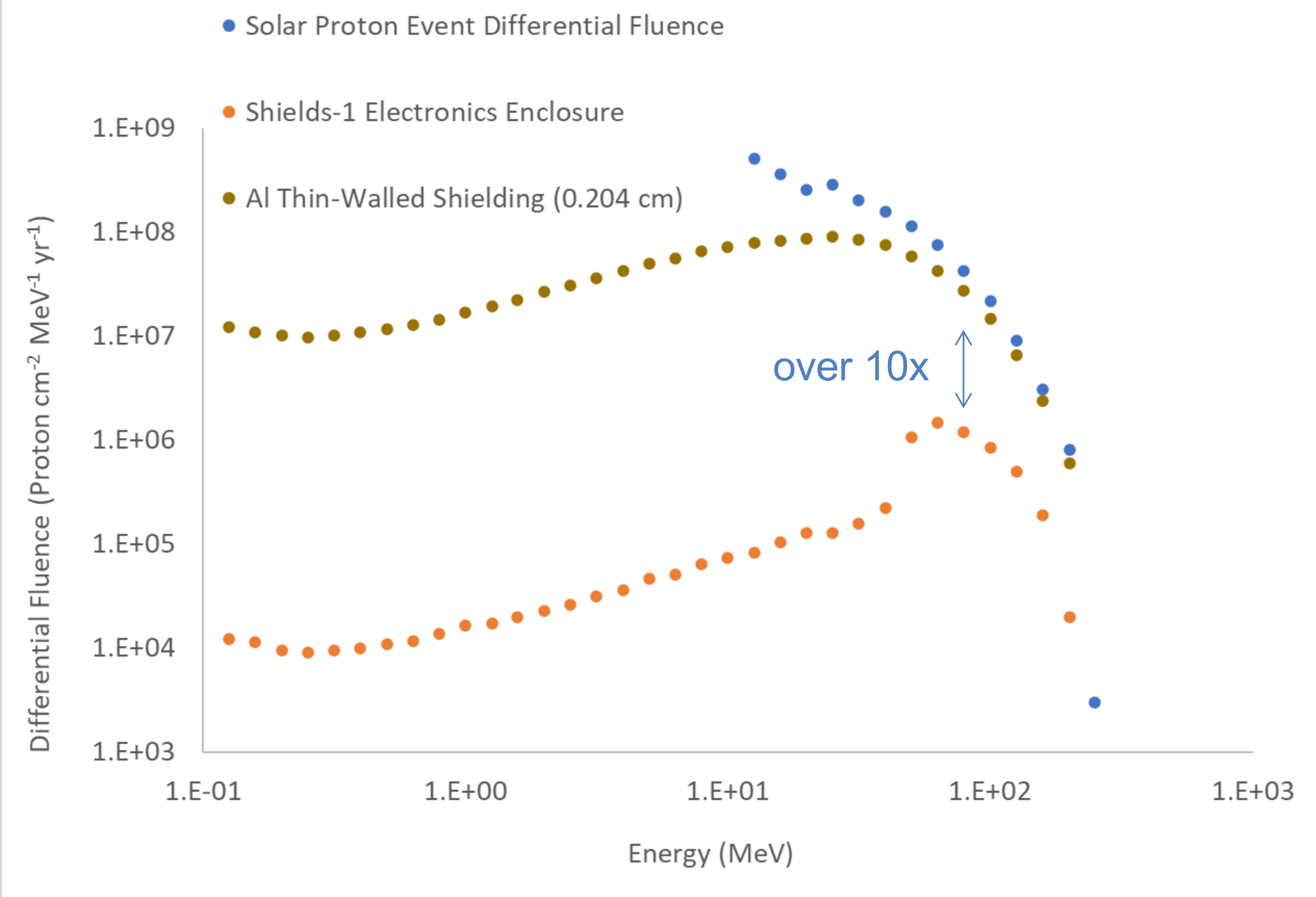
Image credit: NOAA

GOES-18 SUVI Composite 195 Angstroms 2023-05-04 13:20:07

https://www.swpc.noaa.gov/noaa-scales-explanation

National Oceanic and Atmospheric Administration = NOAA

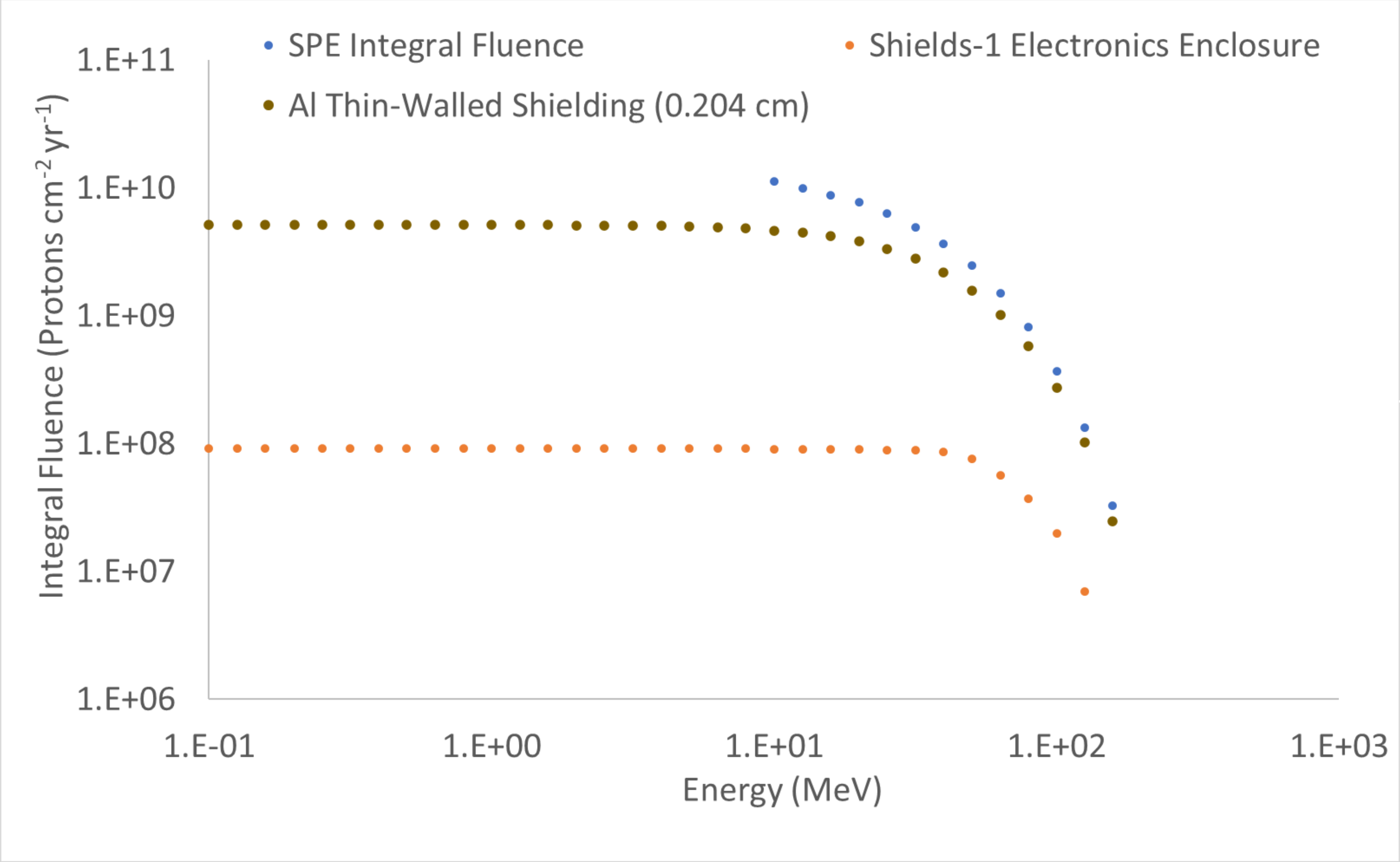
# Attenuation of SPE Protons a Magnitude Lower with Z-Shielding



*SPE worst-case over 1-yr mission, 95% Confidence Level without geomagnetic shielding, SOLPRO (1972 King) Model*

*CubeSats in polar low-Earth orbit exposed to solar activity over the poles*

# Worst-Case SPE Protons Penetrate Al Thin-Walled Structure



| Name | Total Proton Integral Fluence (protons/cm$^2$) | % Particles Remaining |
|---|---|---|
| Shields-1 Electronic Enclosure | 9.14E+07 | 0.809 |
| Generic CubeSat (3U) | 5.15E+09 | 45.6 |

SPE Proton Integral Fluence 1.13E+10

# Conclusions

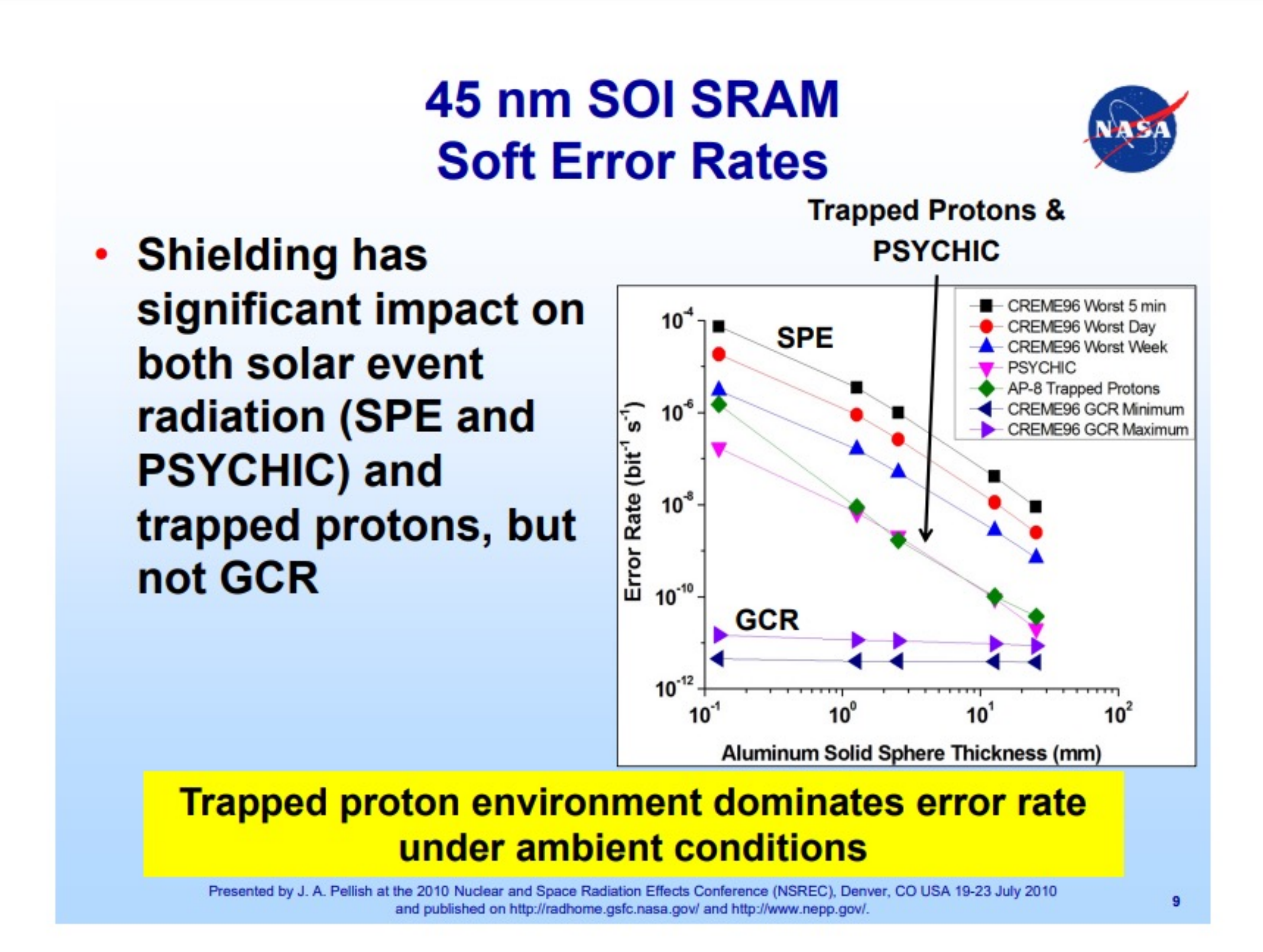
- Shielding provides a system level mitigation for proton SEE and total ionizing dose.
- CubeSats have limited volume and wall thickness constraints using aluminum.
- TID increases behind Al Thin-Walled Shielding during solar maximum.
- Thin Z-Shields offer increased mass and therefore shielding for thin-walled structures (i.e., CubeSats).
- Minimum proton thresholds increase with shielding areal density, which reduces the number of energetic protons available for TID and SEE in SAA and during SPEs.
- Increased minimum proton thresholds with shielding reduces proton radiation effects from increased SPE severities.
- Energetic proton attenuation reduces TID and SEE for commercial, radiation-tolerant, and radiation-hardened parts.

# Acknowledgements

- R. Bryant (LaRC)
- M. Jones
- R. Lueg
- K. Somervill
- T. Burns
- C. Rhoades
- M. Cooney
- N. Miller
- B. Seufzer
- V. Stewart
- H. Soto
- S. Thibeault
- A. Thornton
- S. Gayle
- C. Fay
- M. Banchy
- D. Keck
- J. Applin
- J. Alexa (AMA)
- S. Sankaran (AMA)
- J. Cutler (UMich)
- W. Kim (JPL)
- I. Jun (JPL)
- J. Minow (MSFC)
- B. Blake (Aerospace Corp.)
- B. Crain (Aerospace Corp.)
- A. Goff (Luna Innovations)
- S. Princiotto (Teledyne)
- M. Wrosch (Vanguard Space)

- ELaNaXIX Mission NASA CubeSat Launch Initiative
- NASA Wallops Flight Facility CubeSat Ground Operations

# Transport and SEE



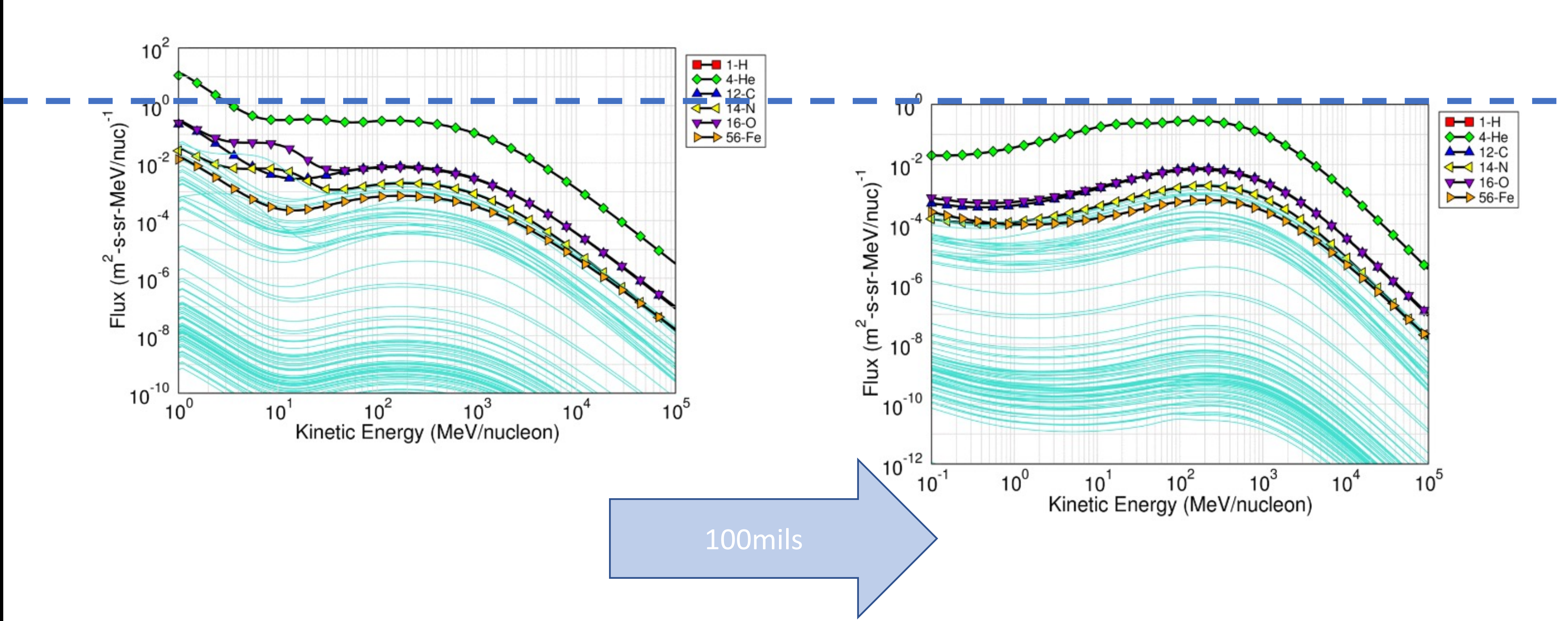
## 45 nm SOI SRAM Soft Error Rates

- **Shielding has significant impact on both solar event radiation (SPE and PSYCHIC) and trapped protons, but not GCR**

**Trapped proton environment dominates error rate under ambient conditions**

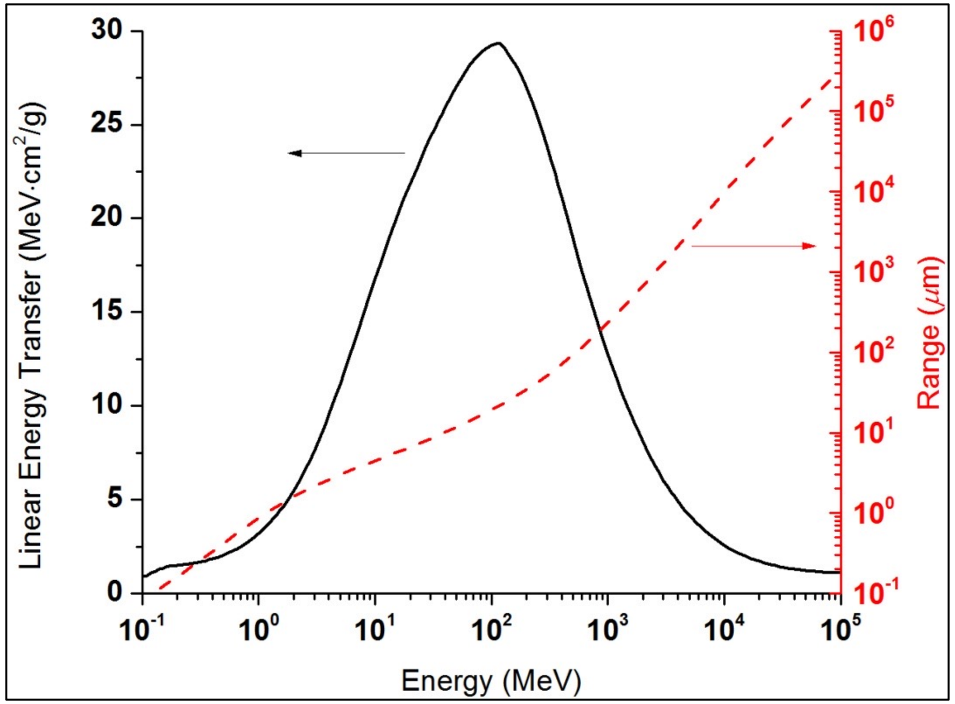
Presented by J. A. Pellish at the 2010 Nuclear and Space Radiation Effects Conference (NSREC), Denver, CO USA 19-23 July 2010 and published on http://radhome.gsfc.nasa.gov/ and http://www.nepp.gov/.

# Transport and SEE



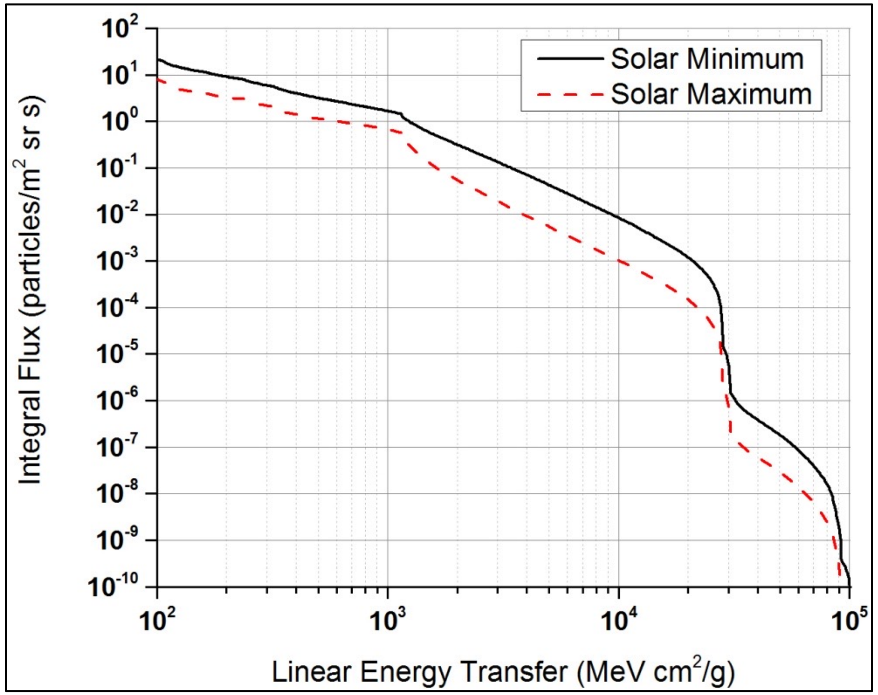
# Using the Linear Energy Transfer (LET) metric

Iron in Silicon



Generated with SRIM-2008

LET Spectrum behind 2.5 mm of Aluminum

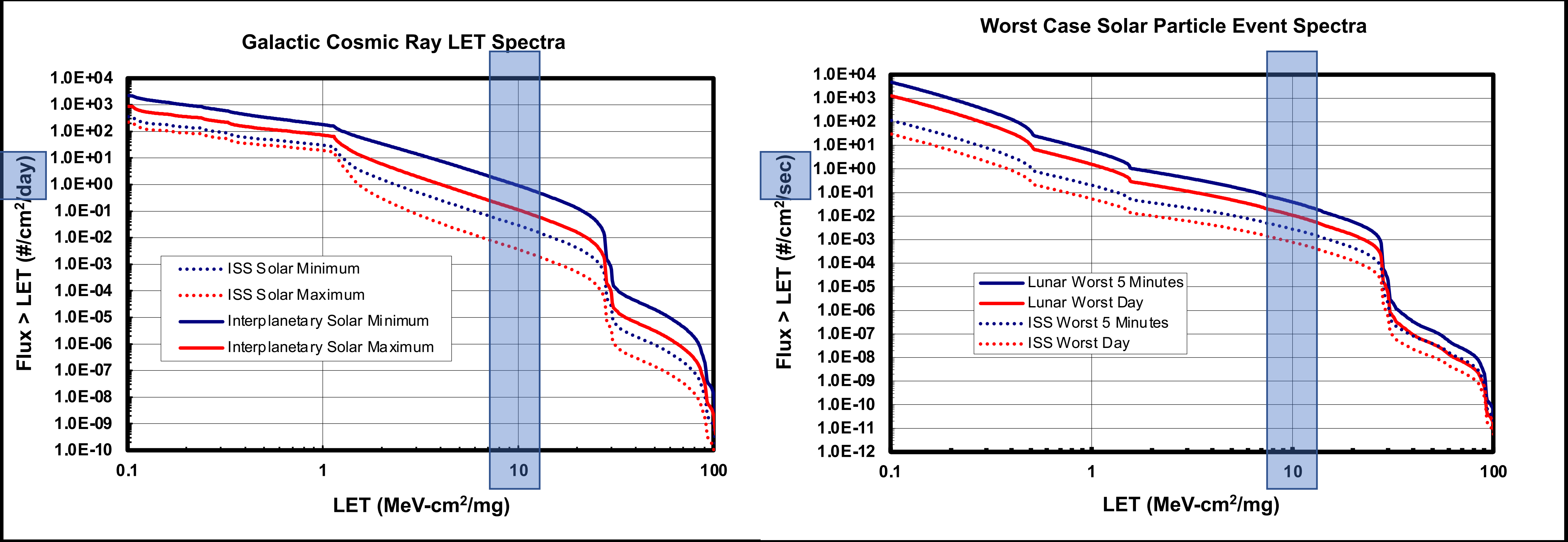


Generated with CREME96

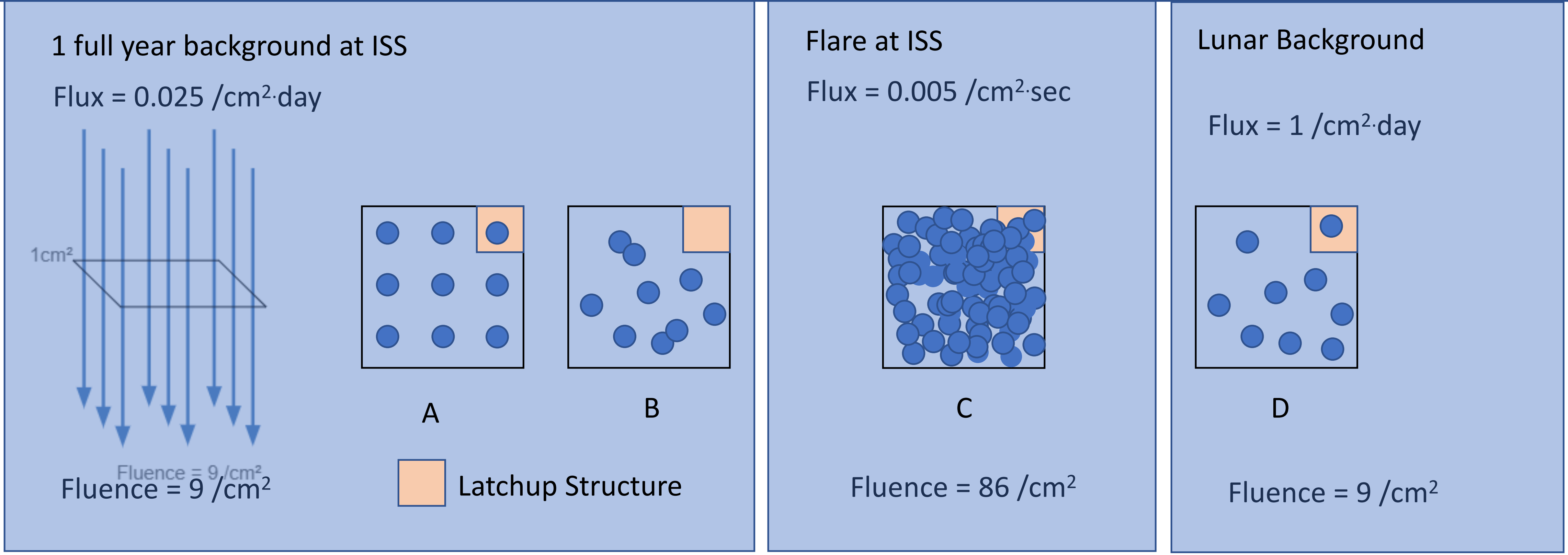
$$S = -\frac{dE}{dx} \Rightarrow \mathrm{LET} = -\frac{1}{\rho}\frac{dE}{dx}$$

Stopping power (S), depends on target material; LET does not

# Considering the different environments



# Just LET = 10 MeV·cm$^2$/mg



1 full year background at ISS

Flux = 0.025 /cm$^2$·day

Fluence = 9 /cm$^2$

🟧 Latchup Structure

Flare at ISS

Flux = 0.005 /cm$^2$·sec

Fluence = 86 /cm$^2$

Lunar Background

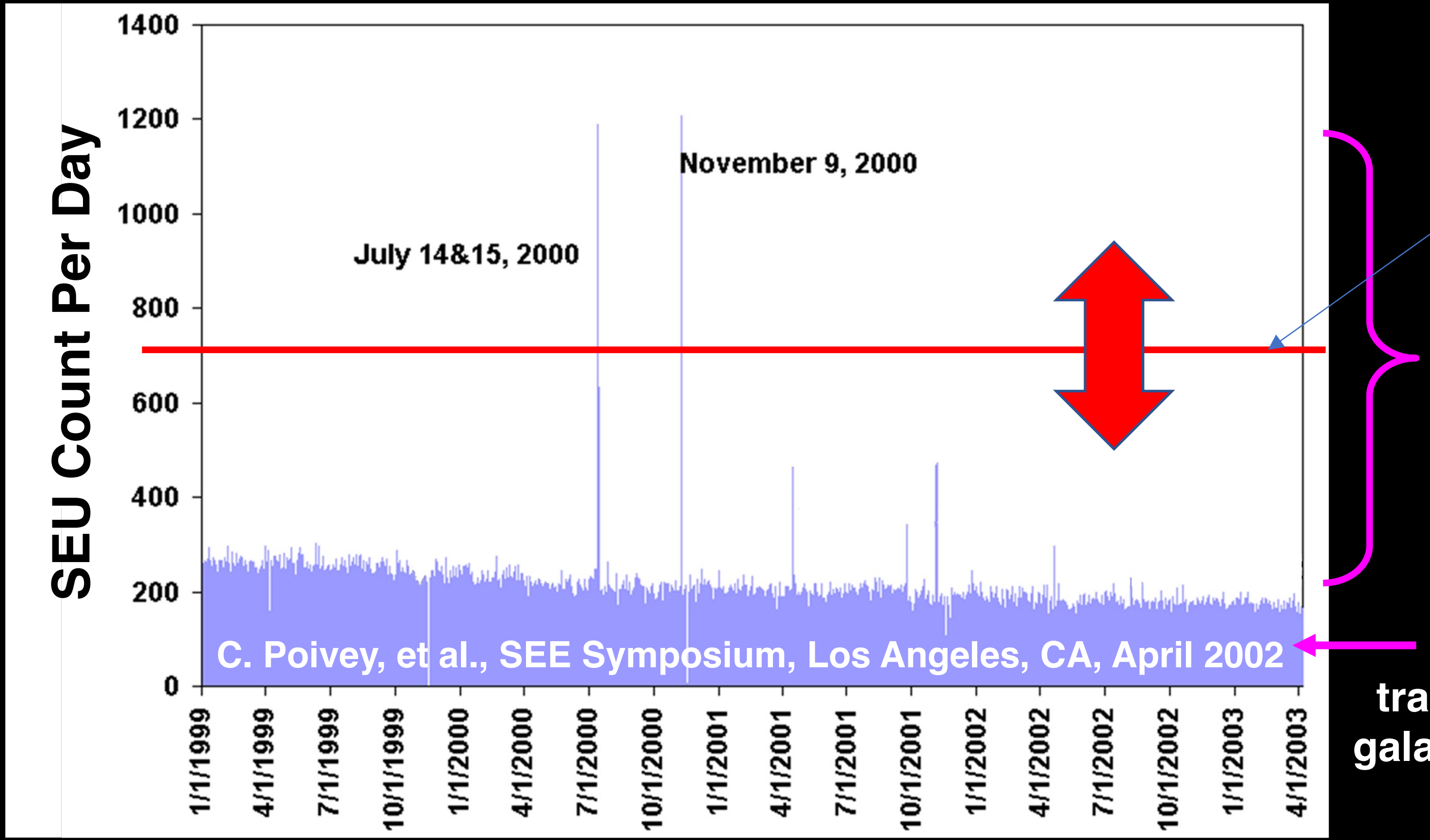
Flux = 1 /cm$^2$·day

Fluence = 9 /cm$^2$

Mission A – Device latches up catastrophically
Mission B – Same duration as mission A, but no effect seen
Mission C – 1 day solar flare
Mission D – Lunar orbit for 9 days

This is for one LET, and ignores directional effects and is meant to be a simple example of why on-orbit heritage does not work for DSEE

# Environment Correlation: Measured Single Event Upsets



C. Poivey, et al., SEE Symposium, Los Angeles, CA, April 2002

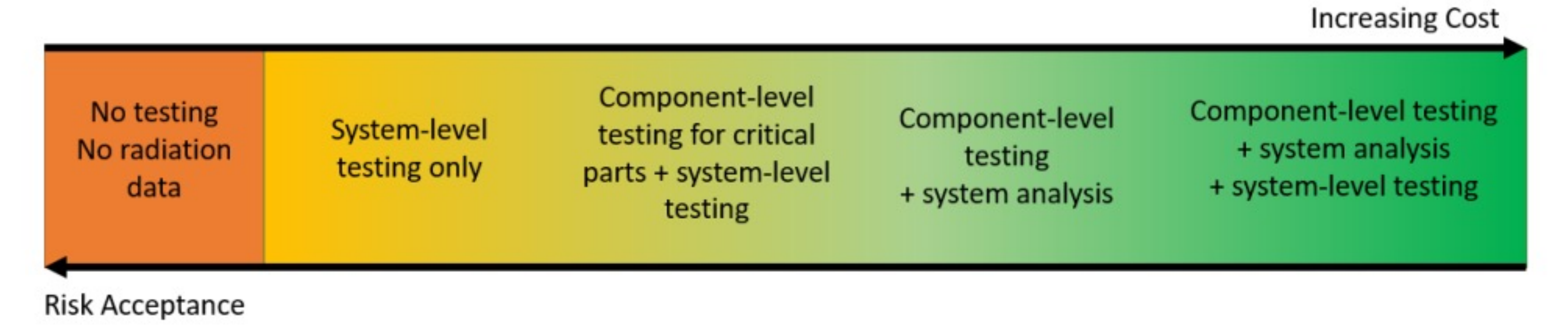
**System upset or mitigation overwhelmed?**

**Worst Case: solar particle events**

**Quiet Time: trapped protons & galactic cosmic rays**

**Without testing the flight design, we don't know if we are in or out of bounds**

# Radiation Testing

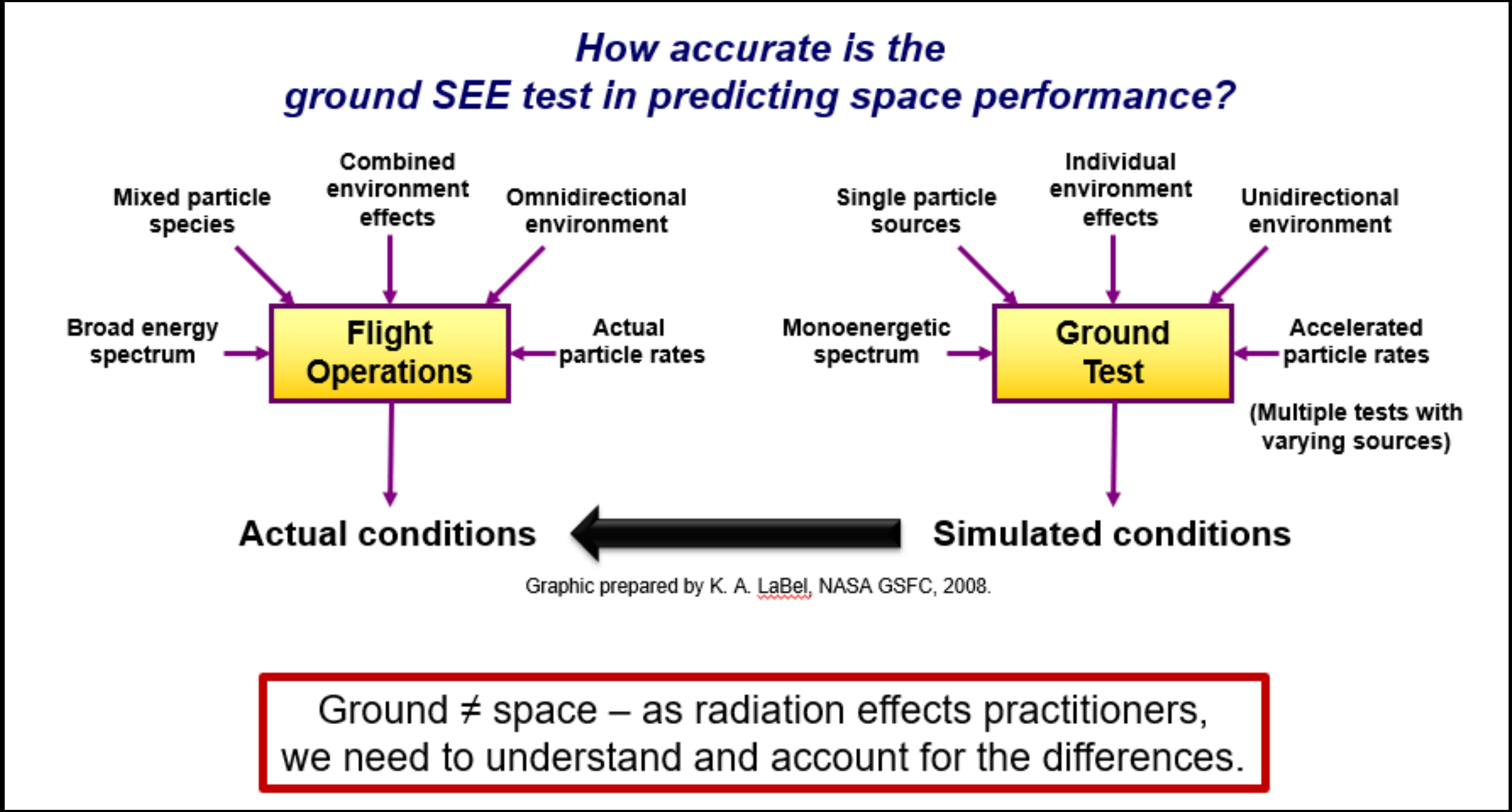


(After A. Coronetti)

- For TID we use energetic photons, typically gamma rays
  - They can be imparted uniformly and have good charge yield
- For TNID we use energetic protons or neutrons avoiding coulombic interactions
  - Can use mono-energetic fluences to represent full damage predicted in environment if the material follows NIEL principles
- For SEE we use heavy ions, protons (mostly secondaries), secondaries of neutrons, and sometimes pulsed laser
  - We try to know the amount of charge creation, so that we can estimate rates on-orbit

# Radiation Testing

- Testing is tailored to characterizing mechanism for analysis in any environment
- Most times it takes multiple tests to okay a part for a given environment



***How accurate is the ground SEE test in predicting space performance?***

Mixed particle species

Combined environment effects

Omnidirectional environment

Broad energy spectrum

**Flight Operations**

Actual particle rates

Actual conditions

Single particle sources

Individual environment effects

Unidirectional environment

Monoenergetic spectrum

**Ground Test**

Accelerated particle rates

(Multiple tests with varying sources)

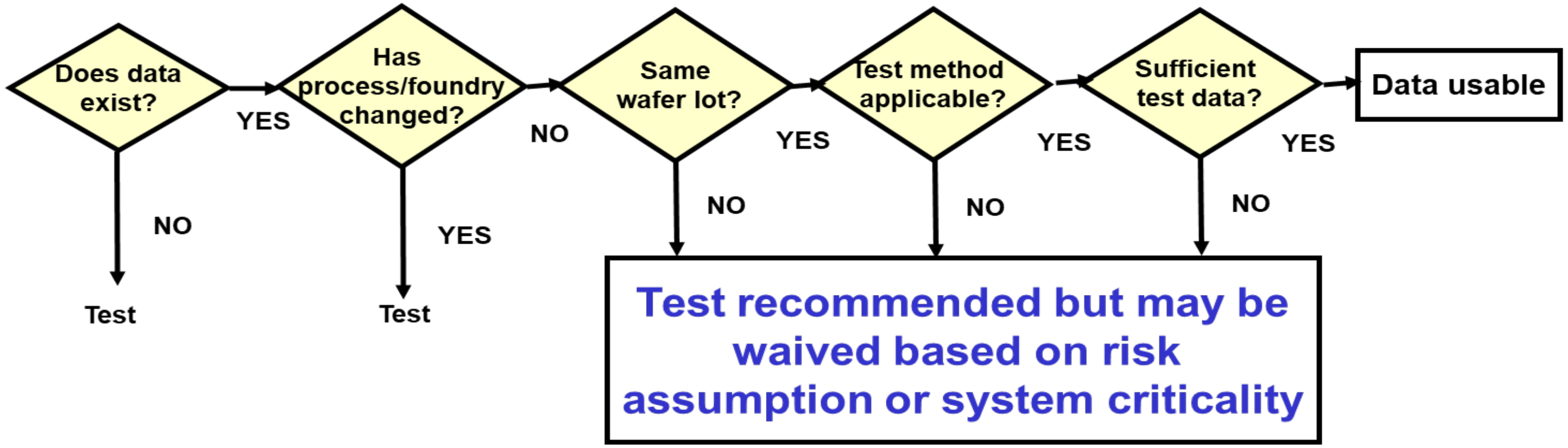
Simulated conditions

Graphic prepared by K. A. LaBel, NASA GSFC, 2008.

Ground ≠ space – as radiation effects practitioners, we need to understand and account for the differences.

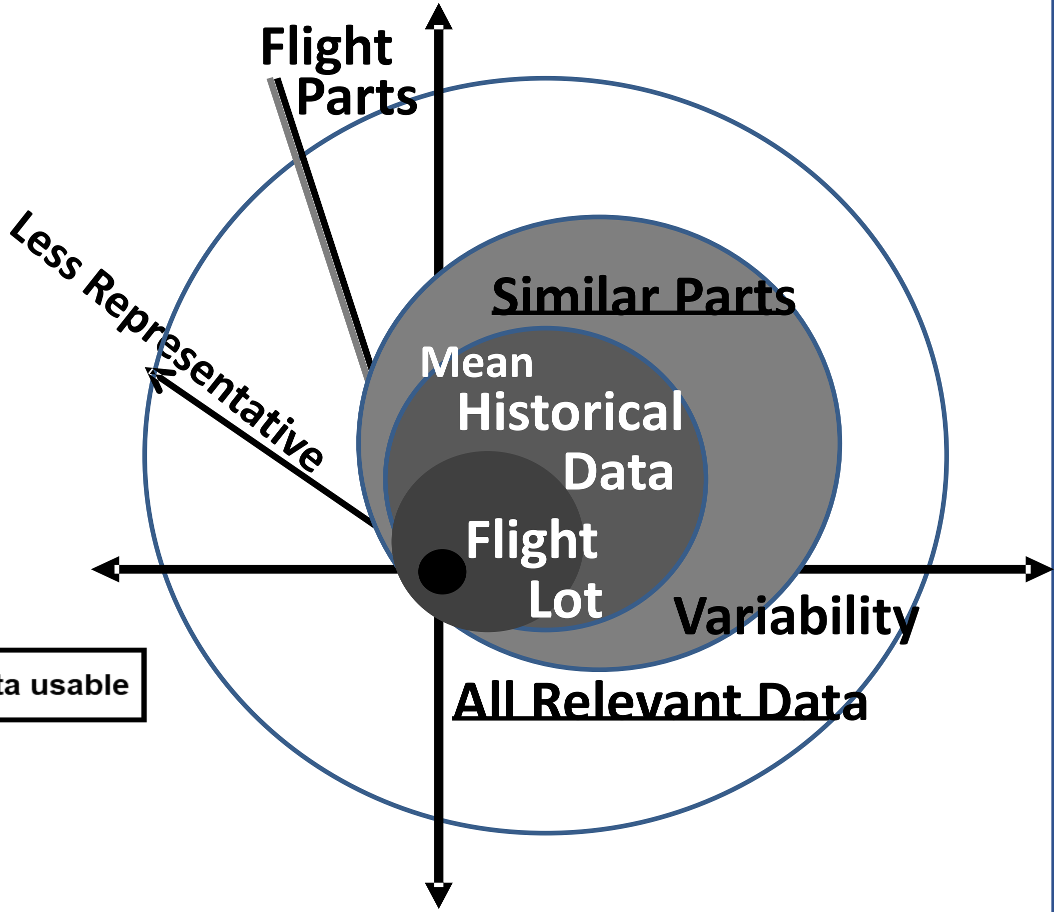
# Data worthiness

- Focus on application driven risks
- Mil-Aero vs. COTS vs. something else
- Is the data applicable?
  - Has the part changed? New foundry, new layout / tape-out / passivation?
  - Does the test condition address your application?
  - Is the source used sufficient to close all risks for your environment?



Does data exist?
YES → Has process/foundry changed? · NO → Test
Has process/foundry changed?
NO → Same wafer lot? · YES → Test
Same wafer lot?
YES → Test method applicable? · NO
Test method applicable?
YES → Sufficient test data? · NO
Sufficient test data?
YES → Data usable · NO

Test recommended but may be waived based on risk assumption or system criticality

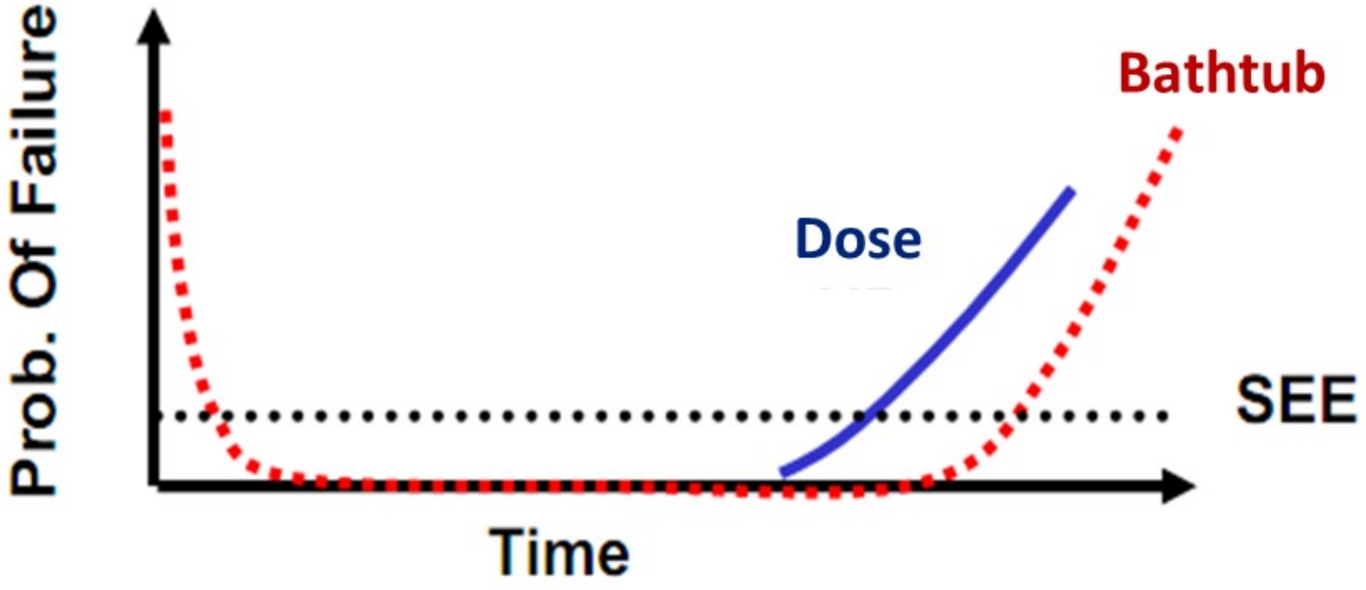


Ray Ladbury, NSREC2017 SC,

https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20170006865.pdf

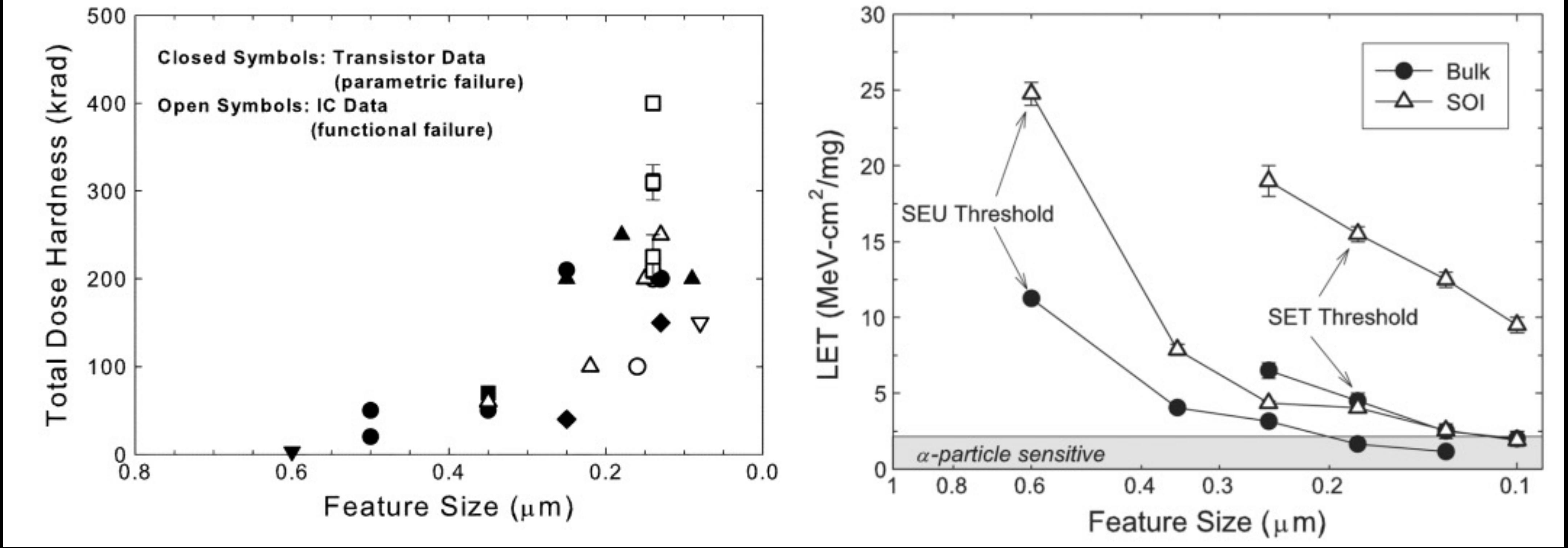
# Damage is a two-fold problem

- Dose shows up as you'd expect: wear-out mechanism (cumulative) – many damage sites or trapped charges accrue over time
- Single events show up as random failures-in-time (instantaneous) – one particle with sufficient energy deposition in the right location



# CMOS Technology Trends

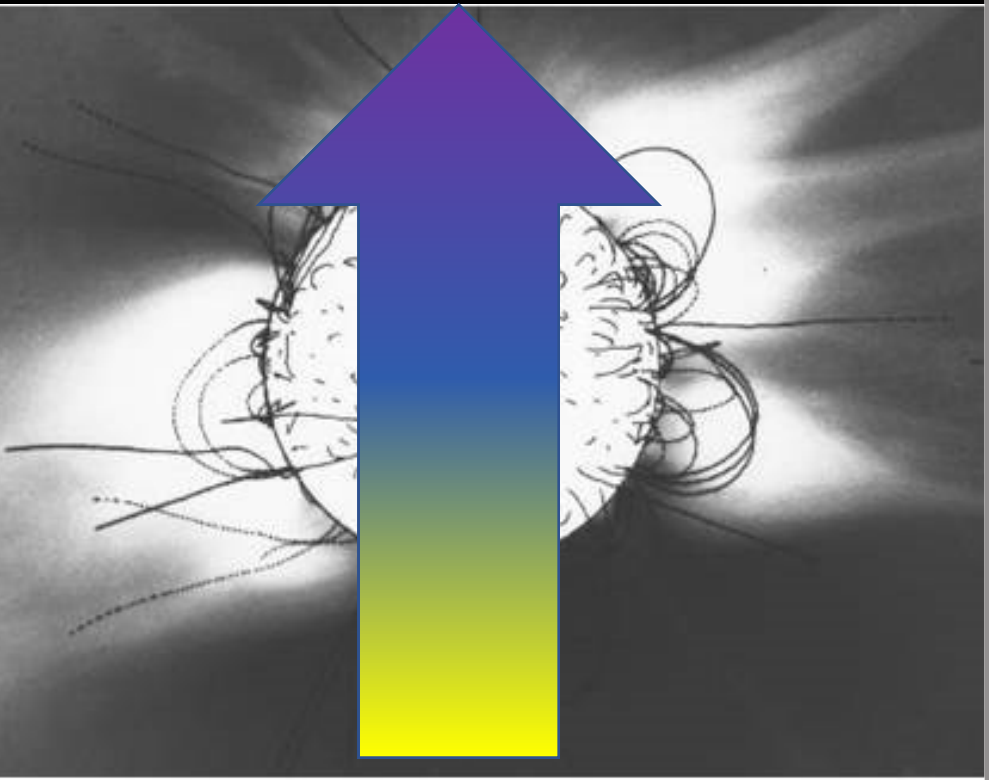
For CMOS in general, the scaling of feature size is increasing resilience with respect to dose and **increasing the susceptibility** to single event effects.



P. E. Dodd, M. R. Shaneyfelt, J. R. Schwank and J. A. Felix, "Current and Future Challenges in Radiation Effects on CMOS Electronics," in IEEE Transactions on Nuclear Science, vol. 57, no. 4, pp. 1747-1763, Aug. 2010, doi: 10.1109/TNS.2010.2042613.

# Notional dose factors to keep in mind for parts

Inherently difficult to expect nominal operation in radiation environment

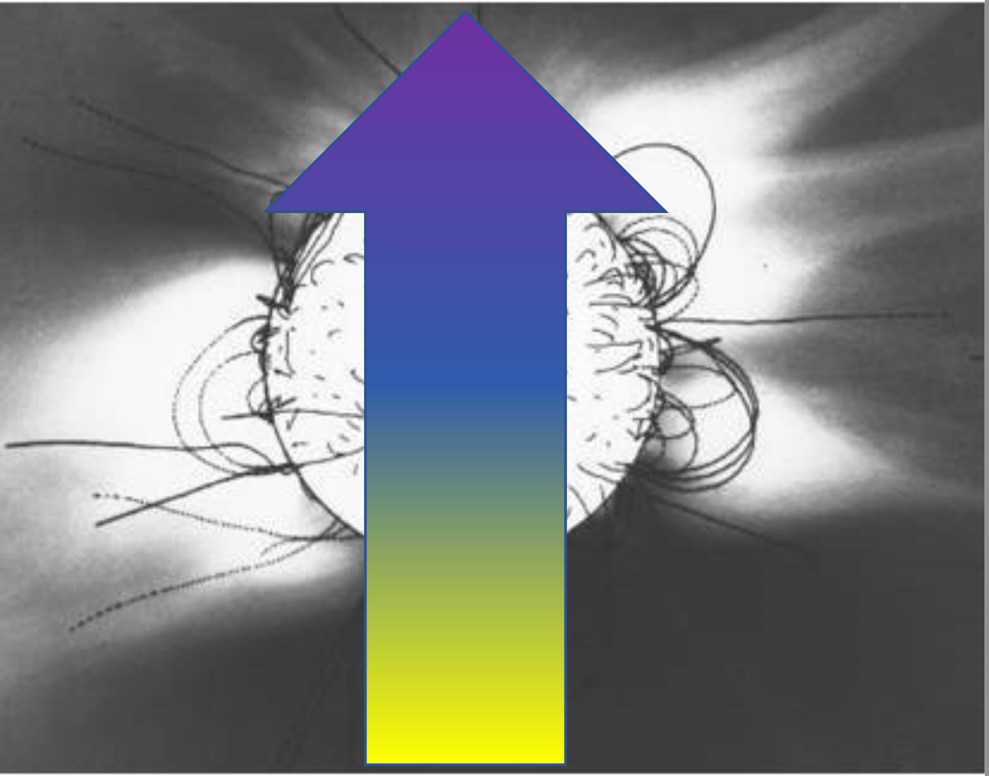


Dose signature predictable

| *Environment Contributors* | Technology | Device Complexity |
|---|---|---|
| *Long Mission, Radiation Belts, High inclination* | Bipolar, Power, Hybrid, Multi-process, opto-electronics | Memories, Processors, FPGAs |
| *Solar Wind / Particle Events* | CMOS (to an extent) | ICs, FETs |
| *Galactic Cosmic Rays* | Hardened Devices | Discrete |

# Notional SEE risk factors to keep in mind

Inherently difficult to expect nominal operation in radiation environment



SEE signature less disruptive to functions

| SEE Types | SEE in Technology | Device Complexity |
|---|---|---|
| Destructive SEE, Non-destructive SEL/SEB | Highly Scaled, Hybrid, Multi-process | Memories, Processors, FPGAs |
| Stuck bits, block errors, SEFI, MBU | Power, CMOS | ICs, FETs |
| SET, SEU | Bipolar, Hardened Devices | Discrete |

# Parts Selection Questions

- What technology – semiconductor materials – make up your part?
- What functions do you need it to provide? How Critical?
- Could there be destructive SEE? Is there evidence to suggest that there aren’t?
- Could non-destructive SEE interrupt your critical operations? Does the system have a way to accommodate them or return to safe operation?
- Will the parts survive the full mission when considering dose? Both Ionizing and Non-Ionizing?

# Part guidance diatribe: “IT DEPENDS”

- Power is always critical
  - Derating vs. Efficiency
- Process trends
  - CMOS shrinking
    - FinFETs
    - Gate All Around (GAA)FETs
  - GaN, SiC, $GaO_x$ for Power
  - 3D Memory stacks
- Mixed Signal and System on a Chip
  - Always going to be performance driven usage of new components
- FPGA types
  - Flash
  - SRAM
  - Antifuse
- Memories
  - Flash, MRAM, FRAM, SDRAM

# Mitigation techniques

| Mitigation Techniques | TID | DDD | SEE | Charging |
|---|---|---|---|---|
| **Part Selection** | X | X | X | |
| **Material Selection** | | | | X |
| **Shielding** | X | X | (X) | X |
| **Operating Parameters** | X | X | (X) | |
| **CONOPS** | X | X | X | X |
| **Circuit Design** | X | X | X | |
| **EMI Design** | | | | X |
| **TMR** | | | X | |
| **EDAC** | | | X | |
| **Watchdog** | | | X | |
| **Cold Spare** | (X) | (X) | (X) | |

Adoption of mitigation techniques occur throughout the lifetime of the satellite

# Deciding if you need to mitigate at all

## Error-Functional

- High number of SEE signature allowable
- Design may inherently be indifferent to SEE signature with mitigation in place or robust design practices
- Nuisance or manageable function impacts (e.g. filtered transients, error detection and correction on memories) beyond part responses
- No action needed

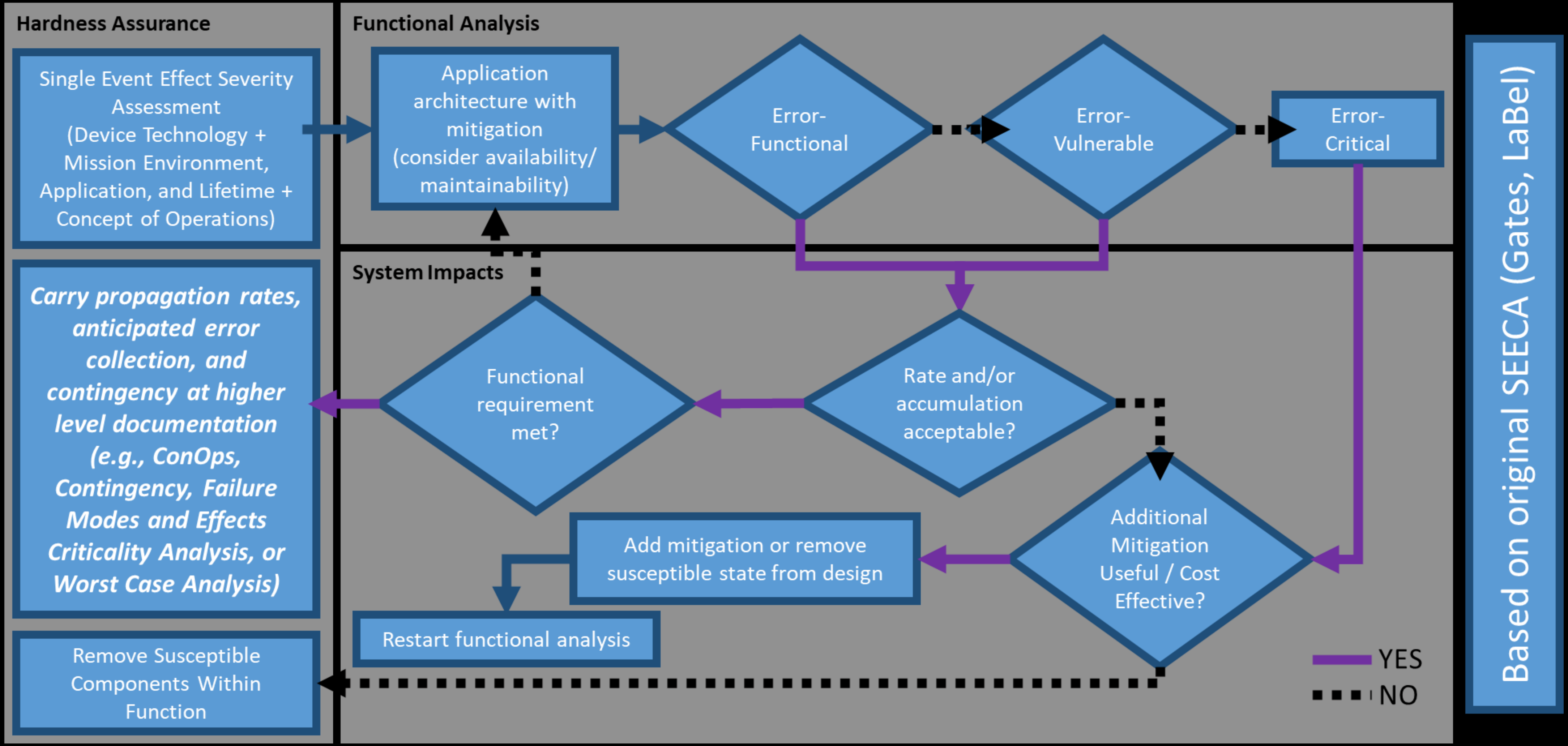
## Error-Vulnerable

- Low number of SEE signature tolerable
- Design may require function for small window of availability or spend very little time in the susceptible state
- Mitigation needed in order to be reclassified as error-functional (e.g. SEFI of Flash, Multi-bit upsets)
- Ground or autonomous operations must be anticipated

## **Error-Critical**

- SEE signature not allowable
- Disruption of function identified as single point of failure or design cannot continue to perform after SEE
- Mitigation needed in order to be reclassified as error-vulnerable (e.g. destructive SEL, many error accumulation, boot image corrupted due to error accumulation, SEFI that requires ground intervention or box level reset waiting on ground)
- Anomaly review needed or loss of mission

# Mitigating with system architecture



**Hardness Assurance**

Single Event Effect Severity Assessment (Device Technology + Mission Environment, Application, and Lifetime + Concept of Operations)

**Functional Analysis**

Application architecture with mitigation (consider availability/ maintainability)

Error-Functional

Error-Vulnerable

Error-Critical

**System Impacts**

Rate and/or accumulation acceptable?

Functional requirement met?

***Carry propagation rates, anticipated error collection, and contingency at higher level documentation (e.g., ConOps, Contingency, Failure Modes and Effects Criticality Analysis, or Worst Case Analysis)***

Additional Mitigation Useful / Cost Effective?

Add mitigation or remove susceptible state from design

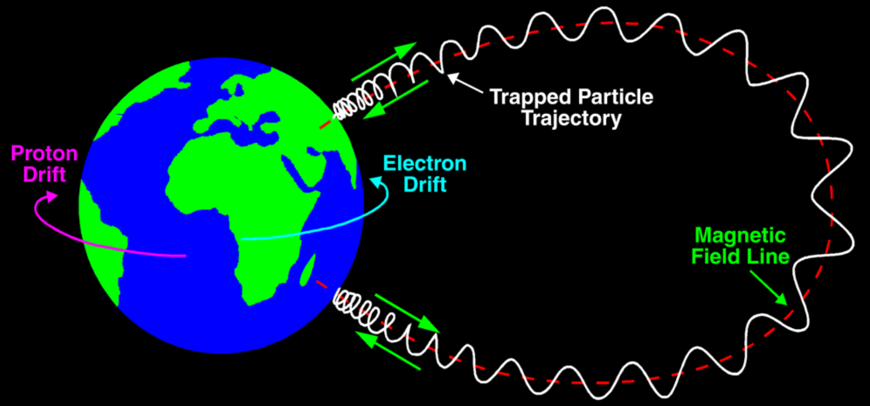
Restart functional analysis

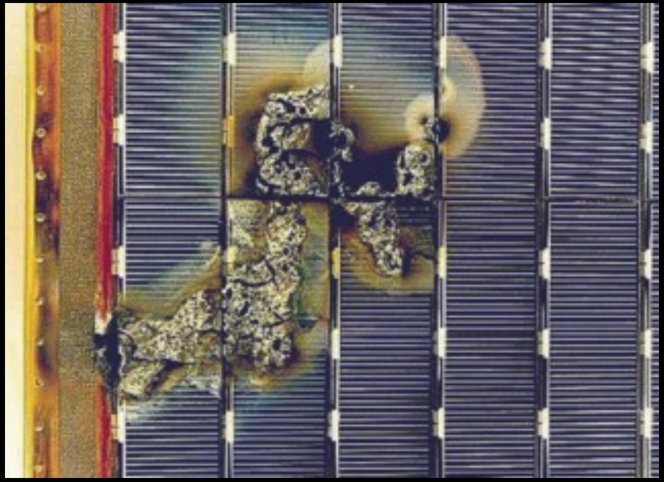
Remove Susceptible Components Within Function

Based on original SEECA (Gates, LaBel)

# Common pitfalls, lessons learned

- Thinking radiation is one number to meet
  - Dose profile behind different amounts of shielding also depends on the type of incident radiation
  - SEE that have low LET susceptibilities can benefit from some shielding, higher LET will always be present
- Tight tolerance in application
  - Not considering the dynamic environmental conditions
  - Derating is your friend
- Overly complex mitigation doesn't solve the problem
  - Verification of mitigation very well could require testing, and $$$
  - Additional susceptibilities introduced into reliability overall
- Don't forget about other environment driven failures
  - Charging / Corrosion
  - Temperature
- Heritage? What heritage?
  - Part to part variation, lot to lot variation
  - Better predictor for dose performance if you have part fidelity




ESA EURECA satellite solar array sustained arc damage.
***Credits: ESA***

# Big Takeaways

- Model your environment, it’s free doesn’t take a lot of effort and the simple approach is conservative as a starting point
- A little bit of shielding goes a long way! Not joking, Reynolds wrap if you have to
- Telemetry like dosimeters or memory upset counts can help with anomaly resolution
- If nothing else, due diligence is necessary for destructive SEE, either have evidence that they are not in your design, do a test, or design as if they exist

# Radiation tools out there (free)

- SmallSat / System Architecture
  - R-Gentic – https://vanguard.isde.vanderbilt.edu/RGentic/
  - SEAM – https://modelbasedassurance.org/
- Environments and Transport
  - Spenvis – https://www.spenvis.oma.be/
  - OMERE – http://www.trad.fr/en/space/omere-software/
  - OLTARIS – https://oltaris.nasa.gov
  - SRIM – http://www.srim.org/
  - JPL NSET - NSE Tools (nasa.gov)
- Rate Calculations
  - CRÈME – https://creme.isde.vanderbilt.edu/

# Databases and information

- Radhome – radhome.gsfc.nasa.gov – radiation test reports for flight projects and NEPP
- PMPedia – pmpedia.space – part data and reports
- NEPP – nepp.nasa.gov – publications/reports on technology trends
- S3VI – s3vi.ndc.nasa.gov
- NTRS – ntrs.nasa.gov – all REAG publications and presentations that are cleared for public consumption
- IEEE Xplore – one stop shop for radiation peer reviewed journal entries (TNS), data workshops, emerging methodologies, etc.
- CCMC - Home | CCMC (nasa.gov)
- Others to come ESA, JPL, SRHEC/DoD

# Recent NASA Guidelines

- *Avionics Radiation Hardness Assurance (RHA) Best Practices (NESC-RP-19-01489)*
  - Covers TID, TNID, and SEE
  - Development of new NASA technical standard for RHA to be released

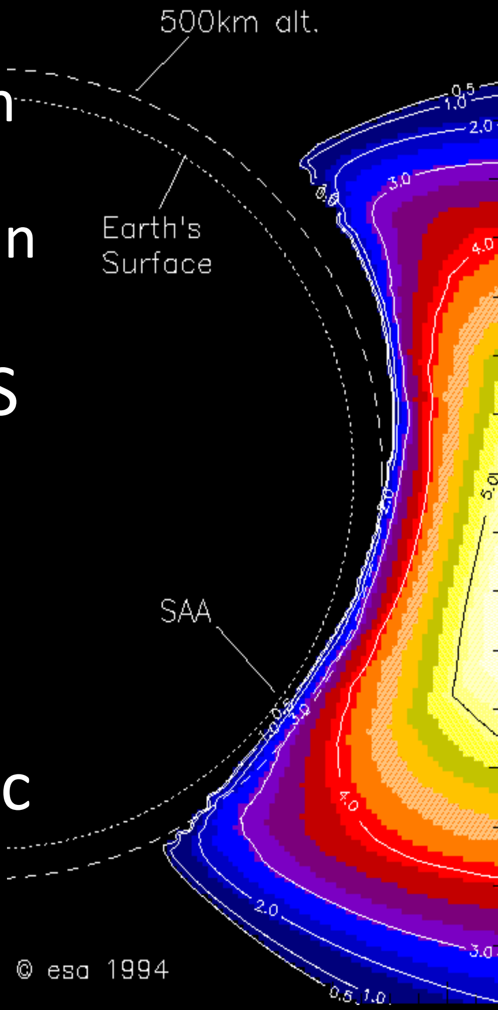
- Application to COTS Electronics
  - Radiation effects issues with COTS parts are the same as with others
  - Guidance on robust methods to handle unit-to-unit variability
  - Guidance on test and evaluation to help address COTS testing challenges
  - Single-Event Effects Criticality Analysis

# NASA Guidelines/Standards in the works

- *Radiation Hardness Assurance Standard*
- Radiation Handbook

# Attribution for stolen content ☺

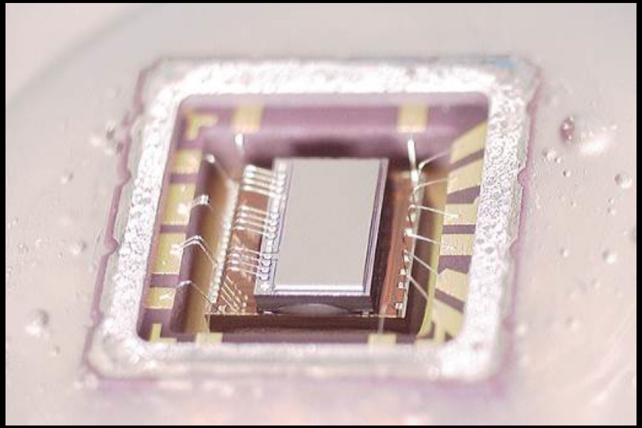
- A lot of this content has been previously put together
  - Radiation Effects & Analysis Group (REAG) members: Megan Casey, Ken Ladbury, Jonny Pellish, Ted Wilcox, Mike Xapsos, and others
  - Outside help: Jet Propulsion Lab (JPL), Radiation Test Solutions (RTS), Un Chattanooga (UTC), and others
- You can find those resources readily in NASA Technical Reports S by searching for:
  - Texas A&M University (TAMU) Cyclotron Facility Bootcamp
  - NASA Space Radiation Lab (NSRL) Radiation Test Workshop
  - NASA Electronic Parts and Packaging Electronics Technology Workshop
- NASA Engineering & Safety Center (NESC) Academy – has video c radiation 101

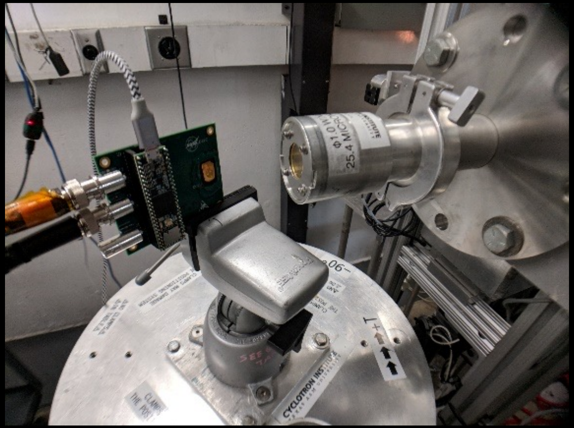


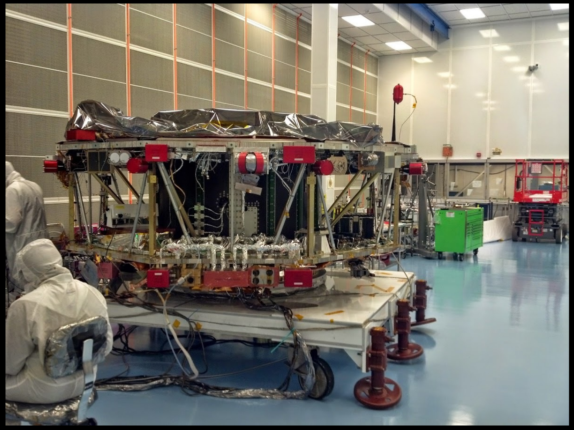
© esa 1994

# THANK YOU

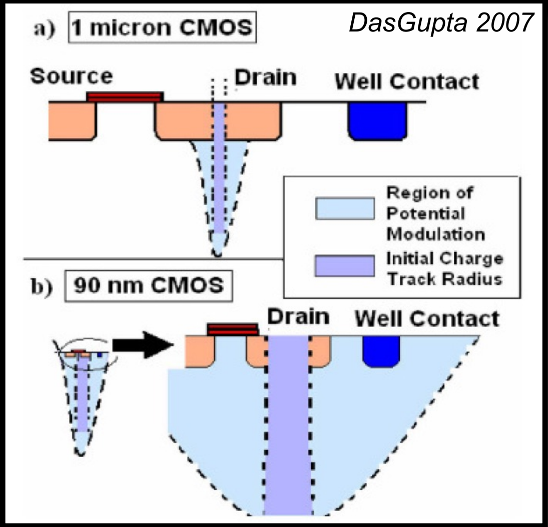
michael.j.campola@nasa.gov

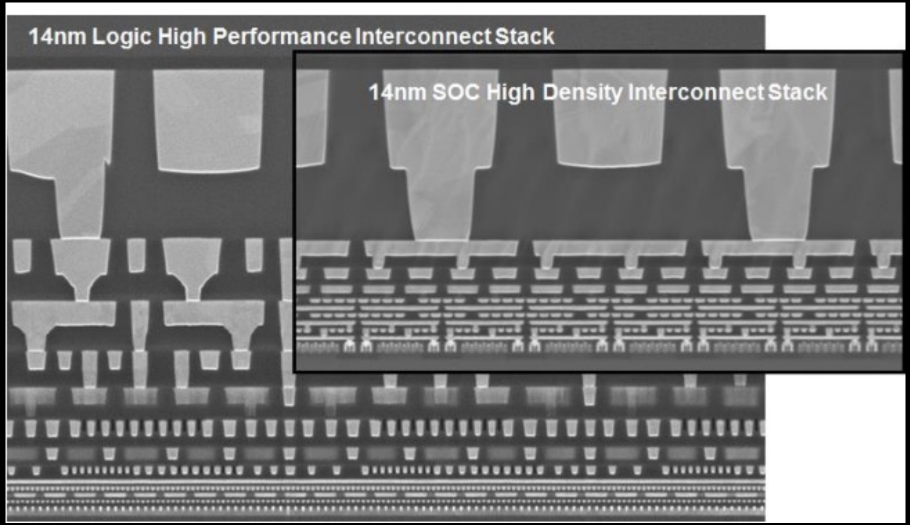


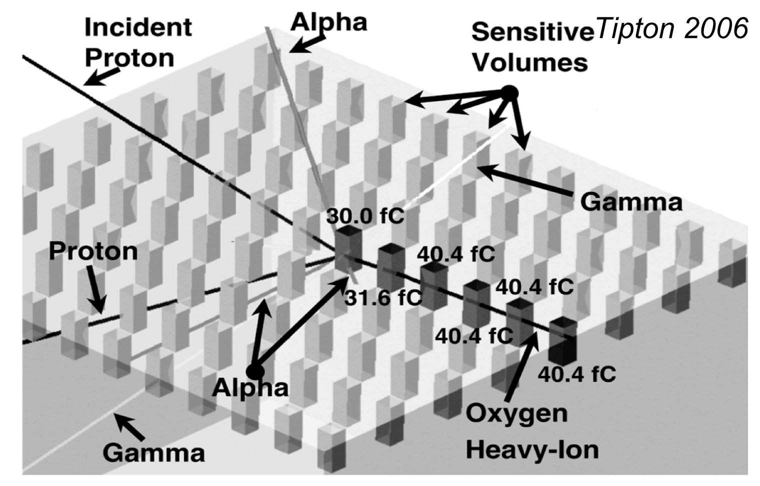




# Scaling and sensitive volumes







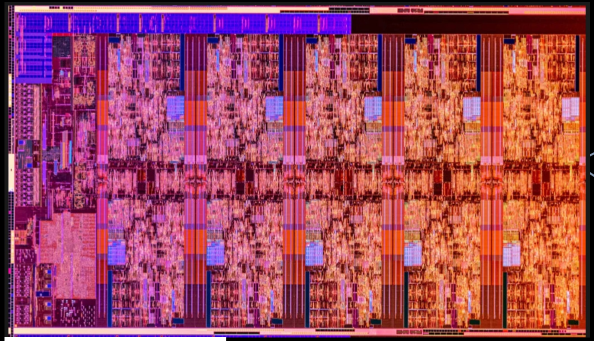
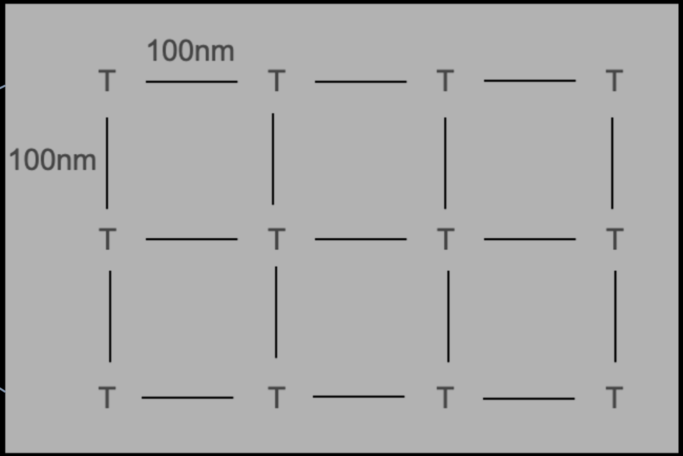
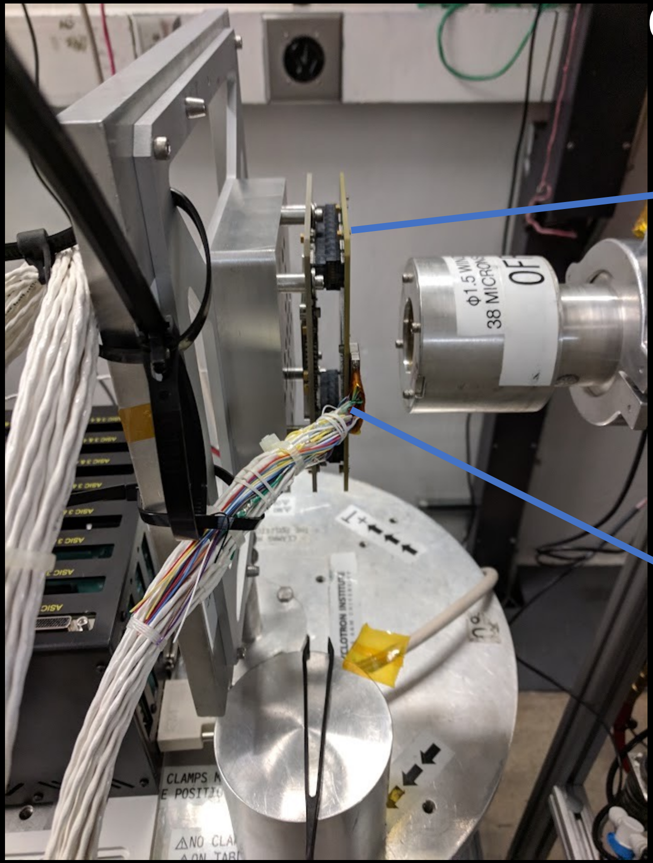


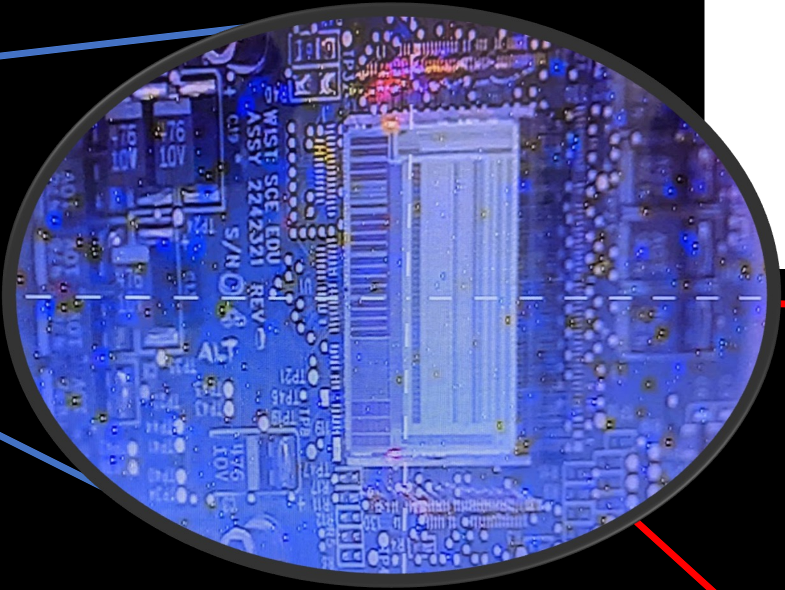
Image: Intel

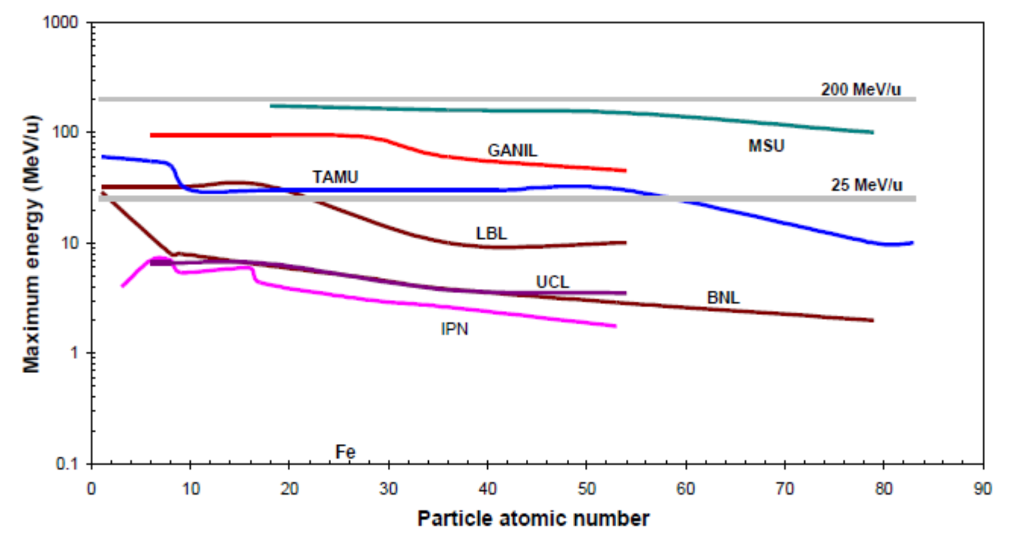


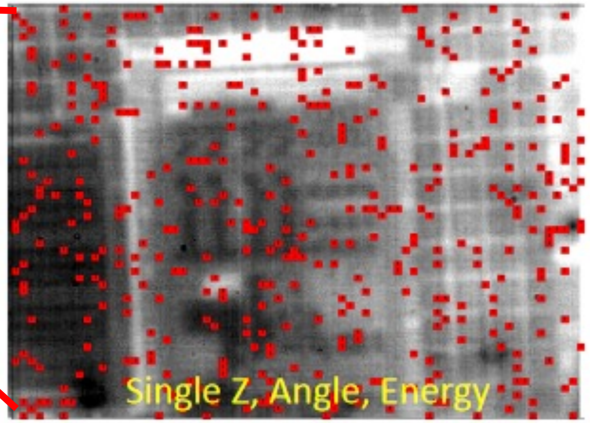
# SEE - Heavy Ions

- LET and coverage at facilities – careful considerations





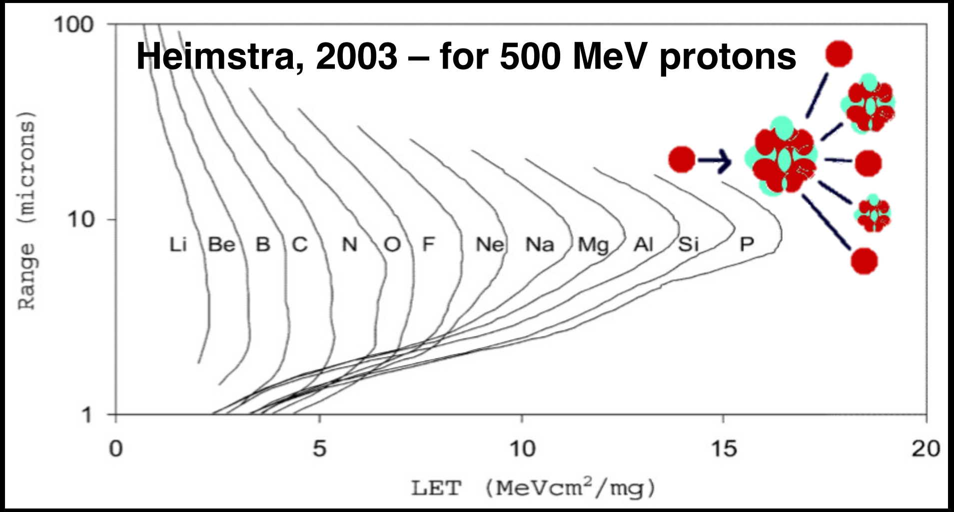


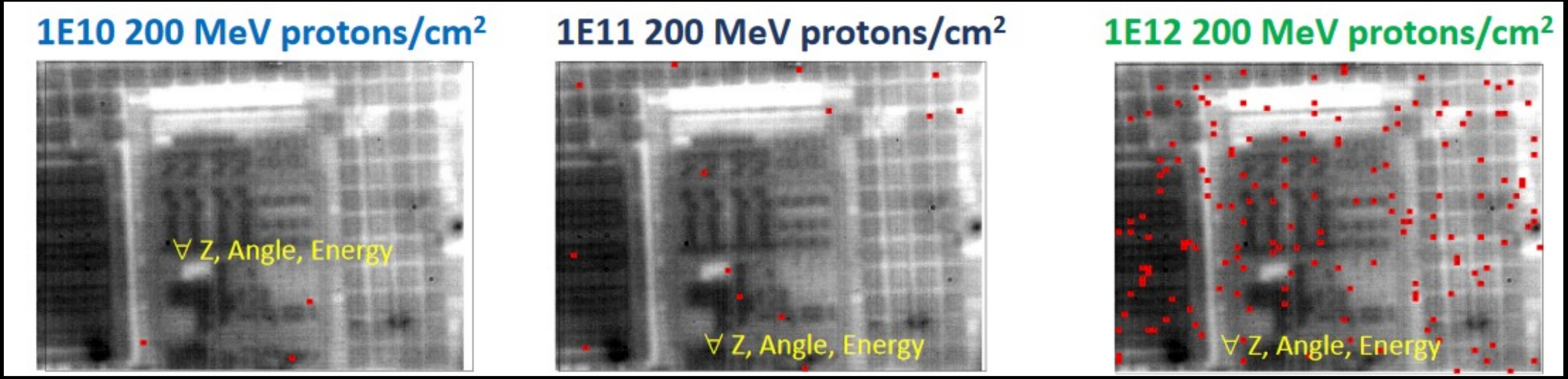


Coverage from 1E7 ions/cm$^2$

# SEE Testing with energetic protons

- Protons are not that great for SEE, especially the destructive effects
- Have to go to high fluences and then you are competing with dose effects during tests

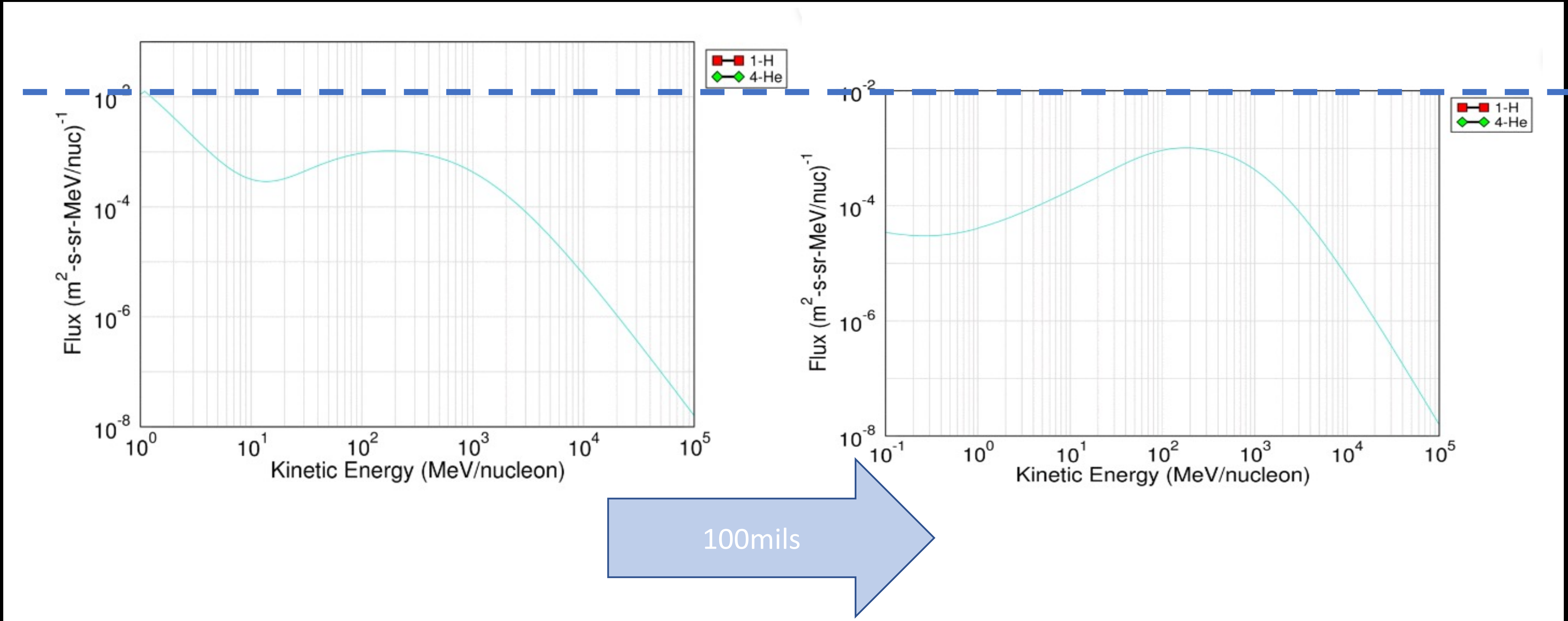

Heimstra, 2003 – for 500 MeV protons


1E10 200 MeV protons/cm²

1E11 200 MeV protons/cm²

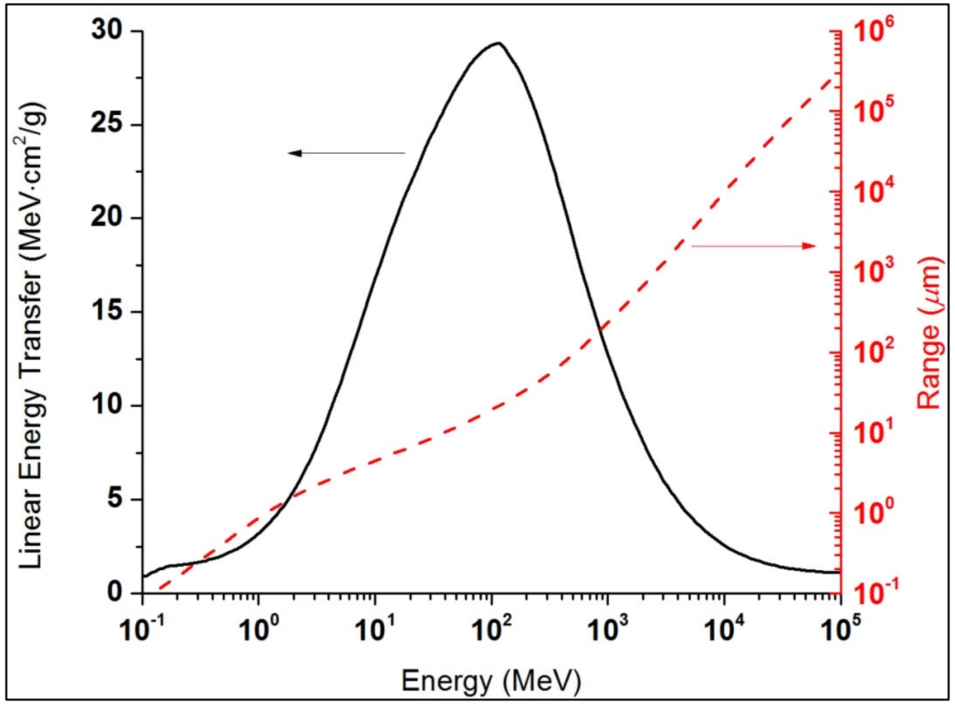
1E12 200 MeV protons/cm²

# Transport and SEE



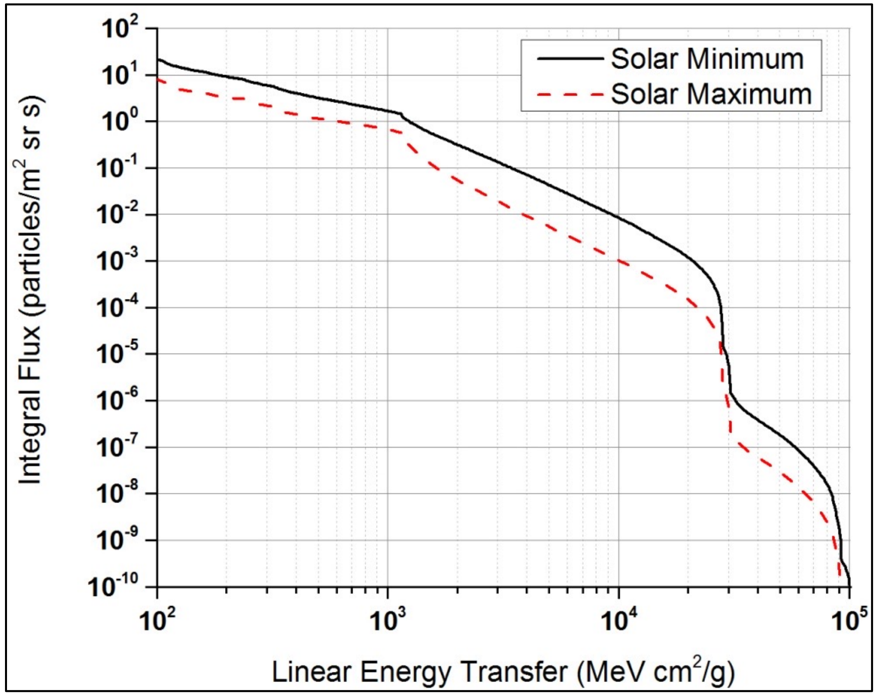
# Using the Linear Energy Transfer (LET) metric

Iron in Silicon



Generated with SRIM-2008

LET Spectrum behind 2.5 mm of Aluminum



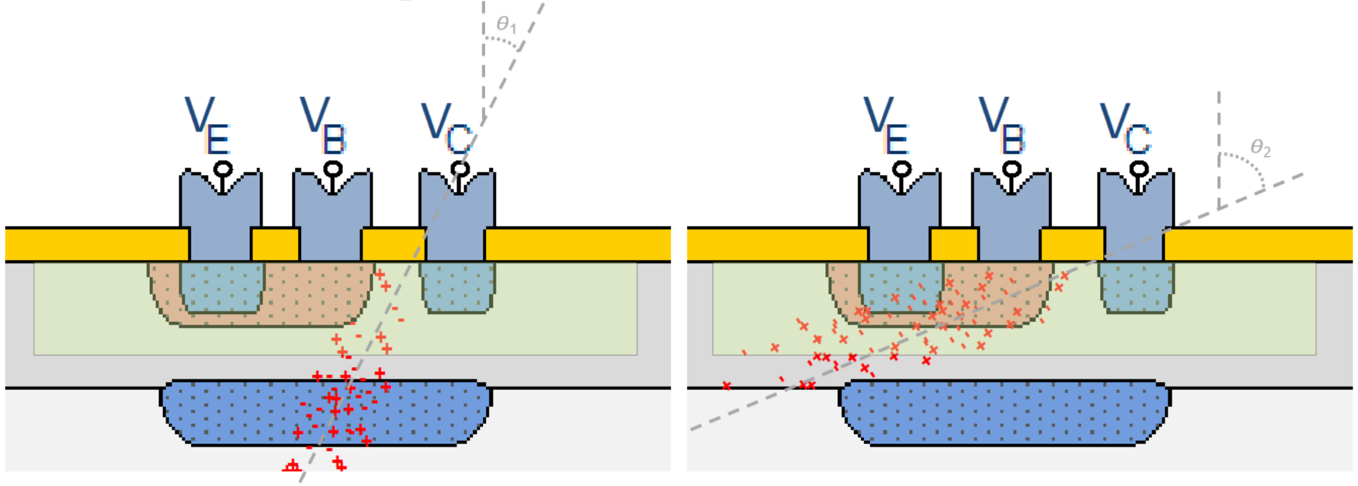
Generated with CREME96

$$S = -\frac{dE}{dx} \Rightarrow \mathrm{LET} = -\frac{1}{\rho}\frac{dE}{dx}$$

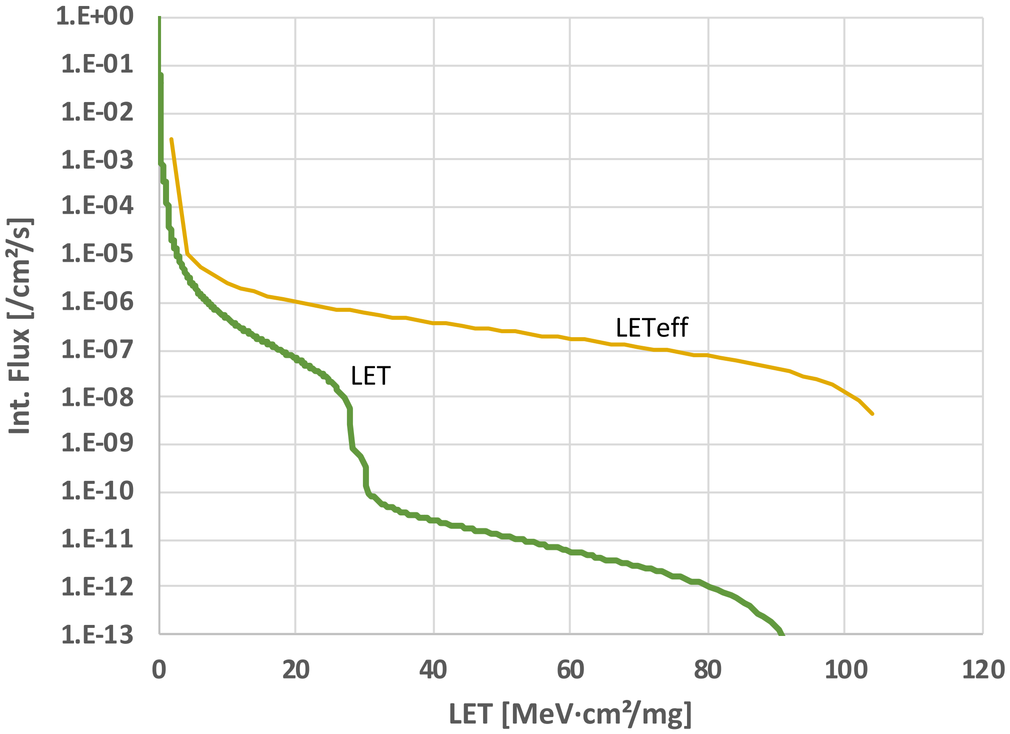
Stopping power (S), depends on target material; LET does not

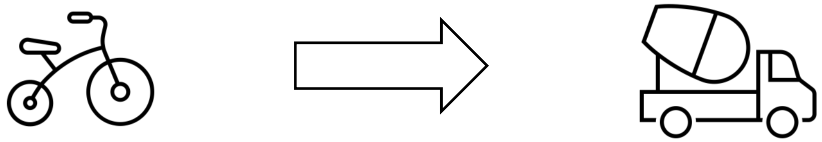
# Omni-directional problem set

## Influence of Angle of Incidence

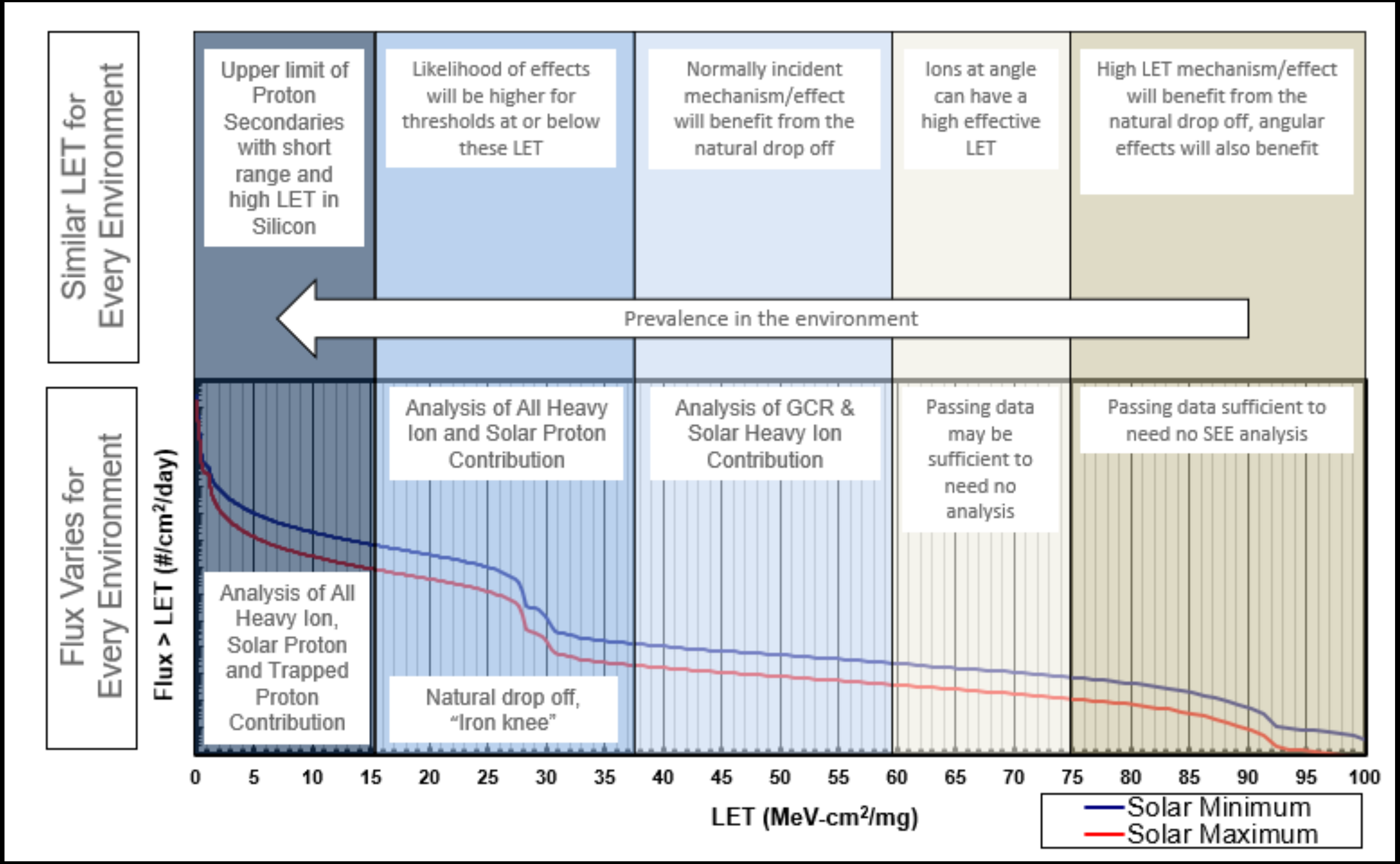


- Larger angle of incidence deposits greater charge in SV
- Comparable to being hit with a higher LET ion
- Effective LET: $LET_{eff} = LET / \cos(\theta)$



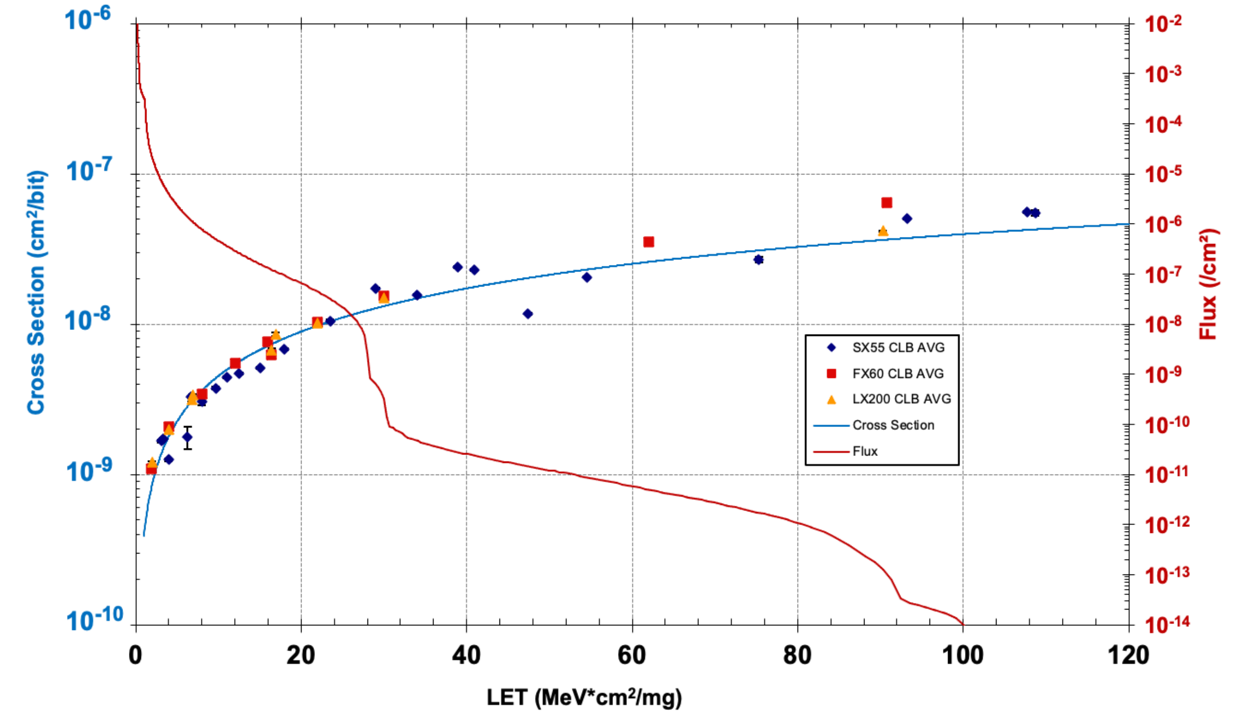


# Which LET is okay to use?



# Predicting on-orbit rates

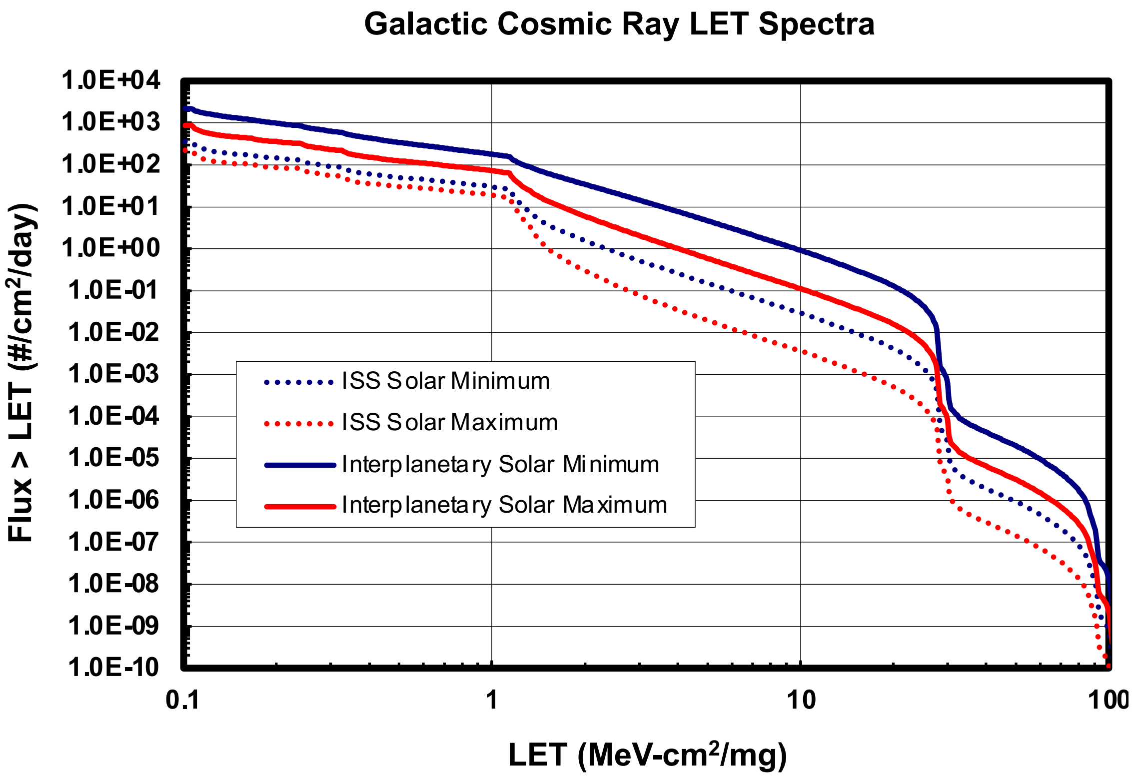
- There will be different rates for different environmental conditions
- There are more than one ways to get a rate estimation – FOM, RPP, IRPP, MC, etc.
- All are similar in that you have to consider the environment <u>and</u> part sensitivity
- Calculation is forgiving

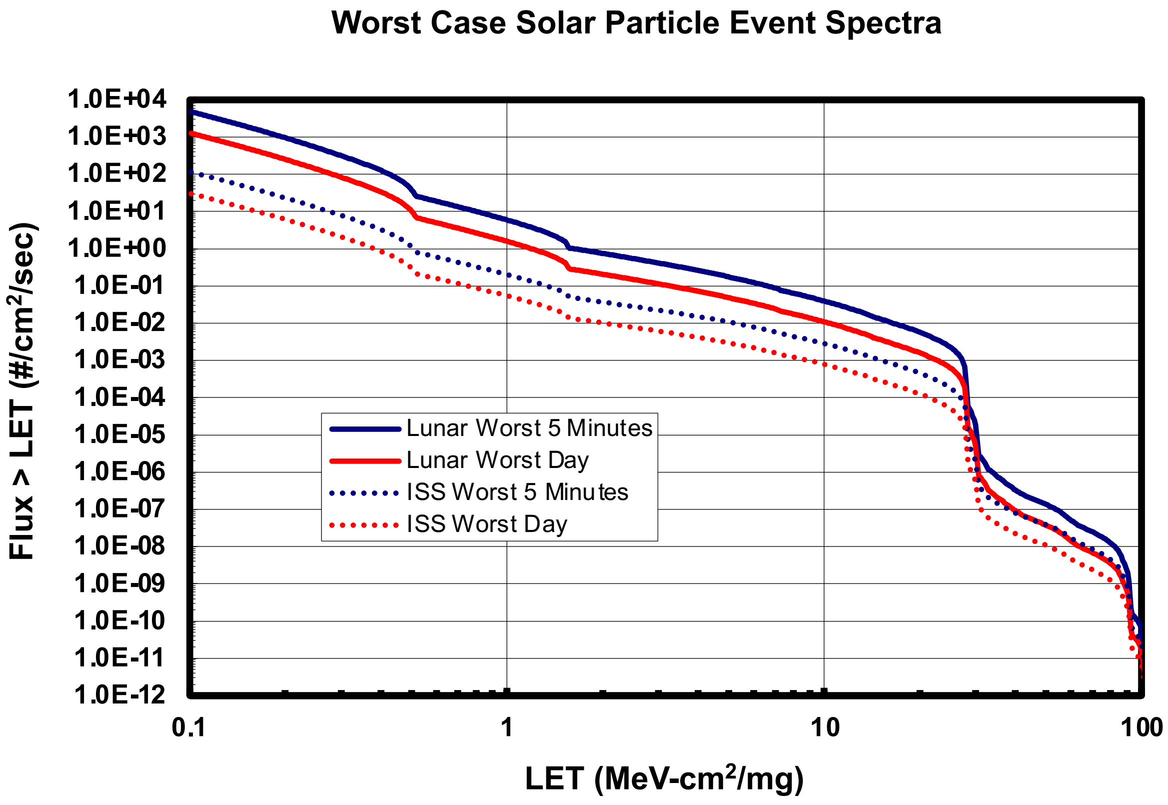


$$Rate = \int \underbrace{\frac{dflux(LET,\theta)}{dLET}}_{\text{environment}} \cdot \underbrace{\sigma(LET,\theta)}_{\text{device response}}\, d\theta\, dLET$$

# Different spectra for different environment conditions

LET is not energy – rate of energy loss in a material, think charge deposition





# Solar Particle Event Models