Quality Reliability Technology

Road Vehicle Functional Safety in Ground-Level Radiation Environments

ASSIC KOREA 2018

SEPTEMBER 2018
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National Aeronautics and Space Administration
www.nasa.gov

Acronyms

Abbreviation	Definition
ADAS	Advanced driver assist systems
AIA	Atmospheric Imaging Assembly
AIEE	American Institute of Electrical Engineers
CME	Coronal mass ejection
COTS	Commercial-off-the-shelf
CTO	Chief Technology Officer
EEE	Electrical, electronic, and electromechanical
ESA	European Space Agency
EVE	Extreme Ultraviolet Variability Experiment
FIT	Failures in time
FMEDA	Failure modes, effects, and diagnostic analysis
FPGA	Field programmable gate array
GCR	Galactic cosmic ray(s)
GPU	Graphics processing unit
GSFC	Goddard Space Flight Center
HMI	Helioseismic and Magnetic Imager
IEEE	Institute of Electrical and Electronics Engineers
IRE	Institute of Radio Engineers
JEDEC	(independent semiconductor engineering trade organization)
LASCO	Large Angle and Spectrometric Coronagraph
MAPLD	Military and Aerospace Programmable Logic Devices (Workshop)
MBMA	Model-based mission assurance
MBSE	Model-based systems engineering

Abbreviation	Definition
MBU	Multiple-bit upset
MCU	Multiple-cell upset
NASA	National Aeronautics and Space Administration
NASEM	National Academies of Sciences, Engineering, and Medicine
NPSS	Nuclear and Plasma Sciences Society
NSREC	(IEEE) Nuclear and Space Radiation Effects Conference
QRT	Quality, Reliability, Technology (company)
SDO	Solar Dynamics Observatory
SEB	Single-event burnout
SEE	Single-event effect(s)
SEFI	Single-event functional interrupt
SEGR	Single-event gate rupture
SEL	Single-event latchup
SERESSA	School on the Effects of Radiation on Embedded Systems for Space Applications
SET	Single-event transient
SEU	Single-event upset
SiP	System-in-a-package
SoC	System-on-a-chip
SOHO	Solar and Heliospheric Observatory
SoM	System-on-module
SWaP	Size, weight, and power
TID	Total ionizing dose
TNID	Total non-ionizing dose

Acknowledgements

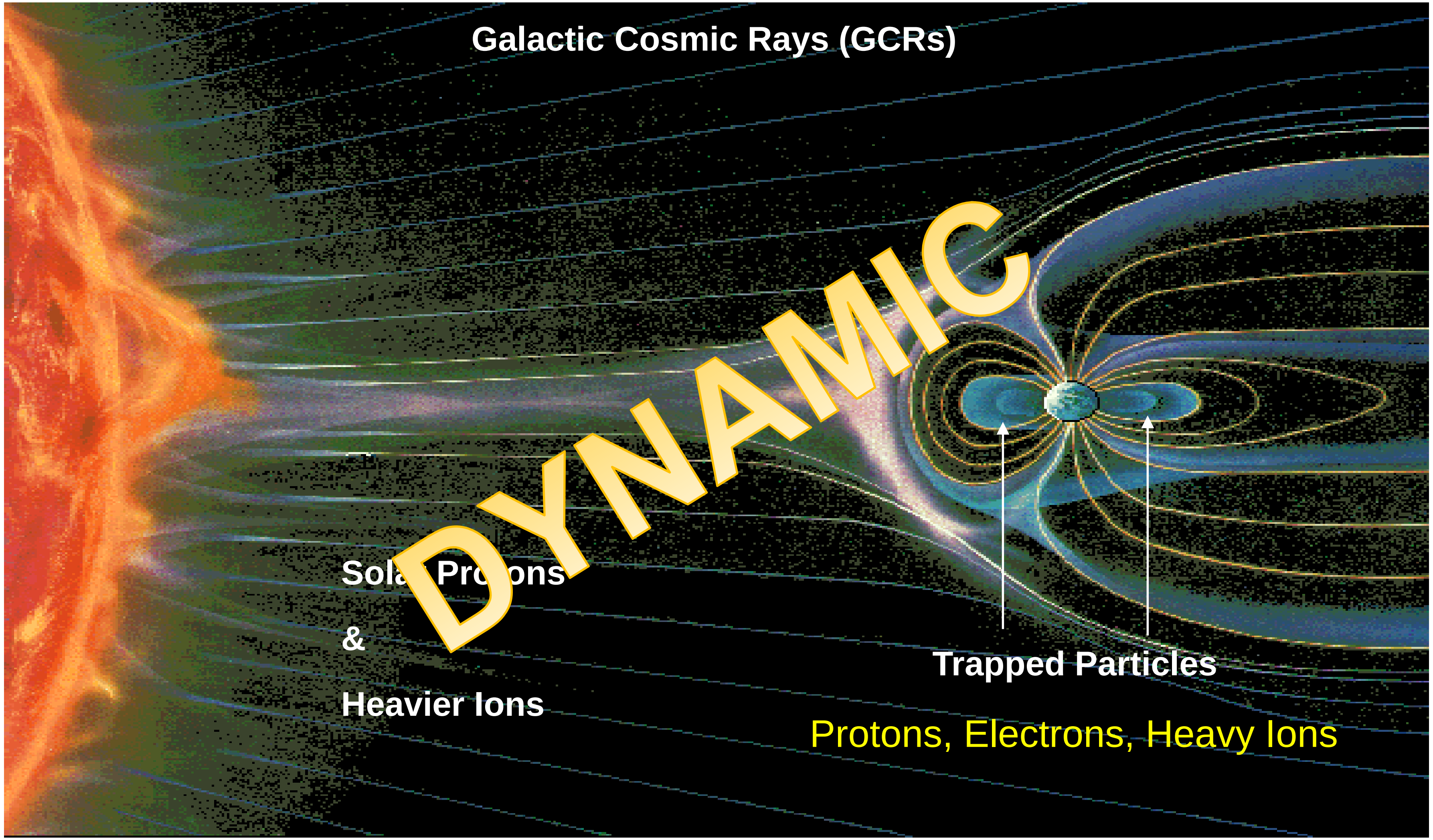
- Mr. Sung, CTO at QRT
- NASA Electronic Parts and Packaging (NEPP) Program
  - https://nepp.nasa.gov/
- Many additional contributors across academia, government, and industry

Outline

- Natural space radiation environment and linkage to ground-level environment
- Radiation effects in ground-based electronic systems
  - Focus on single-event effects (SEE)
  - Excludes cumulative effects like total ionizing and non-ionizing dose (TID, TNID)
- Current areas of focus for commercial-off-the-shelf (COTS) electronics in reliable systems
- Future needs for COTS electronics in reliable systems
- Conclusion / Question & Answer

01 Space and Ground-Level Radiation Environments

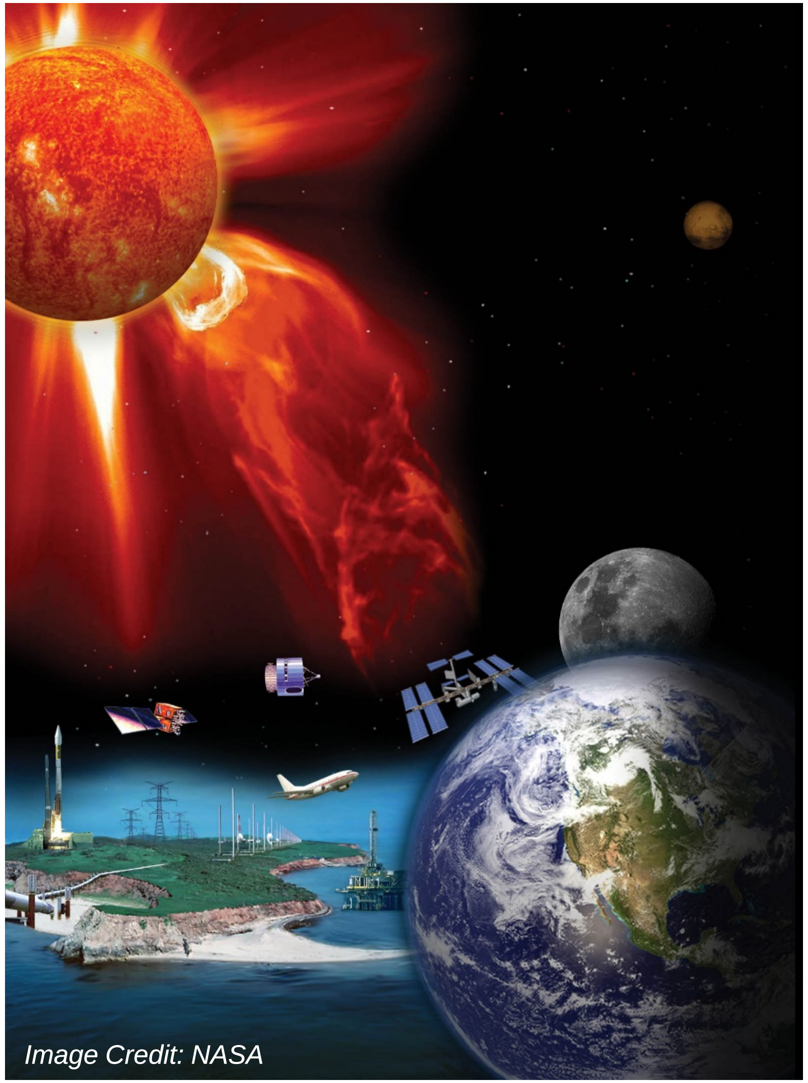
Natural Space Radiation Environment



After J. Barth, 1997 IEEE NSREC Short Course; K. Endo, Nikkei Science Inc. of Japan; and K. LaBel private communication.

Sun-Earth Connection

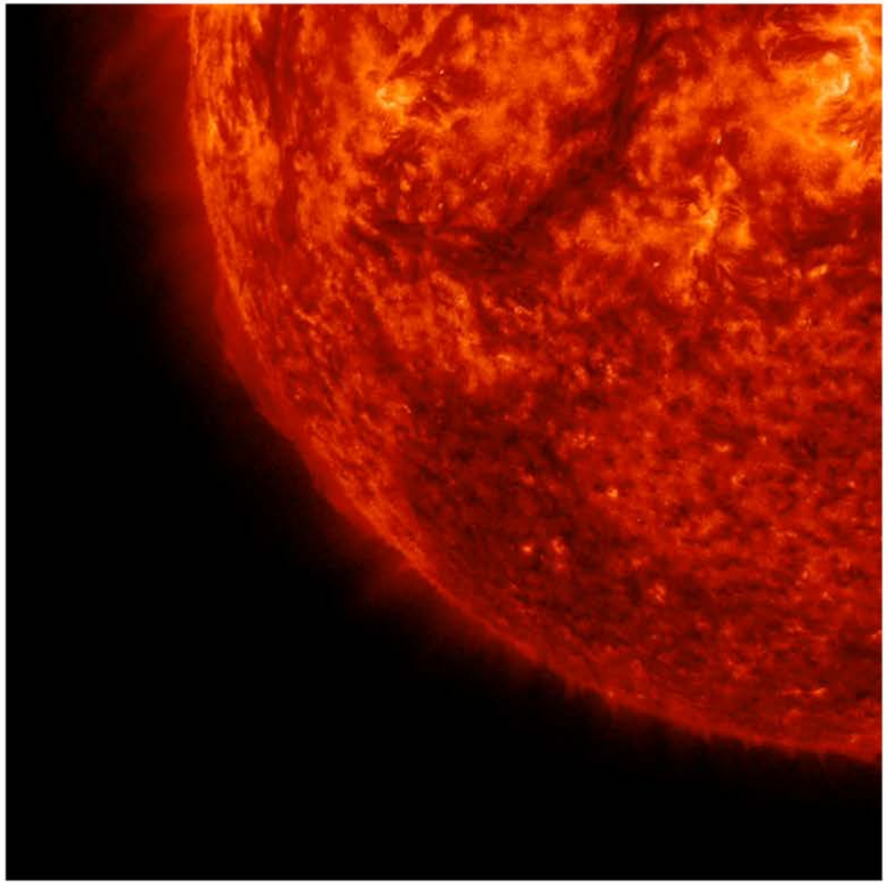
- Space weather is driven by changes in the Sun's magnetic field and by the consequences of that variability in Earth's magnetic field and upper atmosphere.
  - Space weather is generally mild but some times extreme.
  - Societal interest in space weather grows rapidly.
  - Space weather is an international challenge.
  - Mitigating against the impacts of space weather can be improved.
  - Existing observatories that cover much of the Sun–Earth system provide a unique starting point.



C. J. Schrijver, *et al.*, *Adv. Space Res.*, vol. 55, no. 12, pp. 2745-2807, 2015.

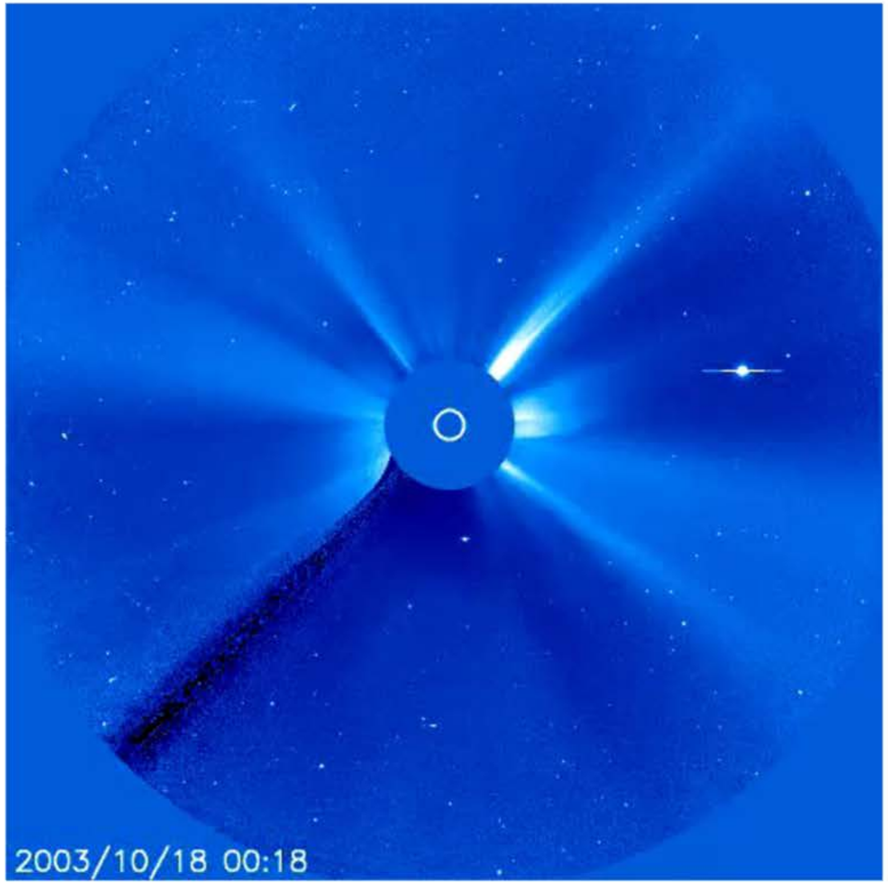
The Sun Controls Space Weather

Coronal Mass Ejection and Filament (24-Feb-2015)



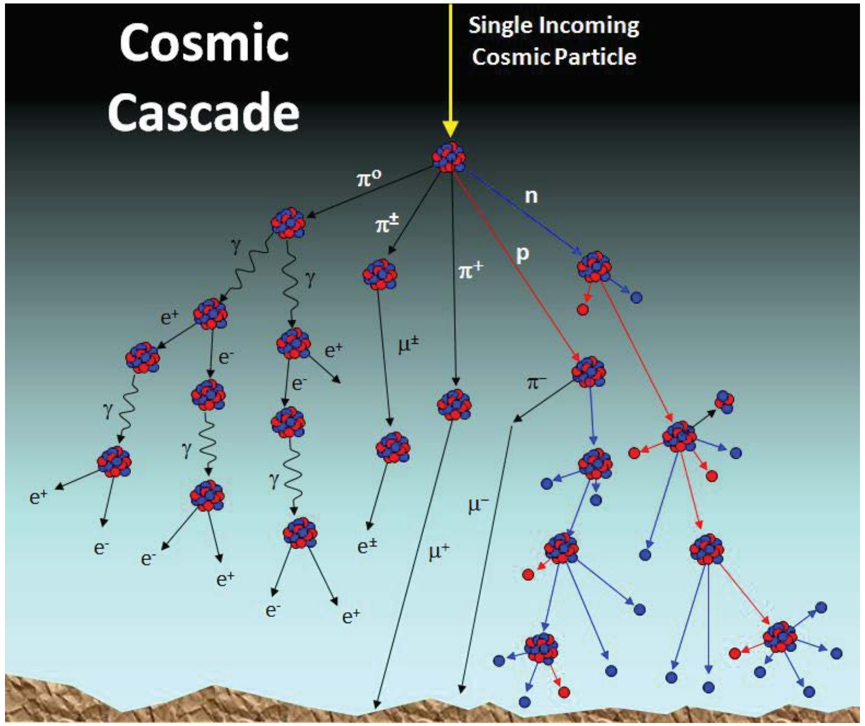
Courtesy of NASA/SDO and the AIA, EVE, and HMI science teams.

Halloween Storms (18-Oct – 7-Nov 2003)

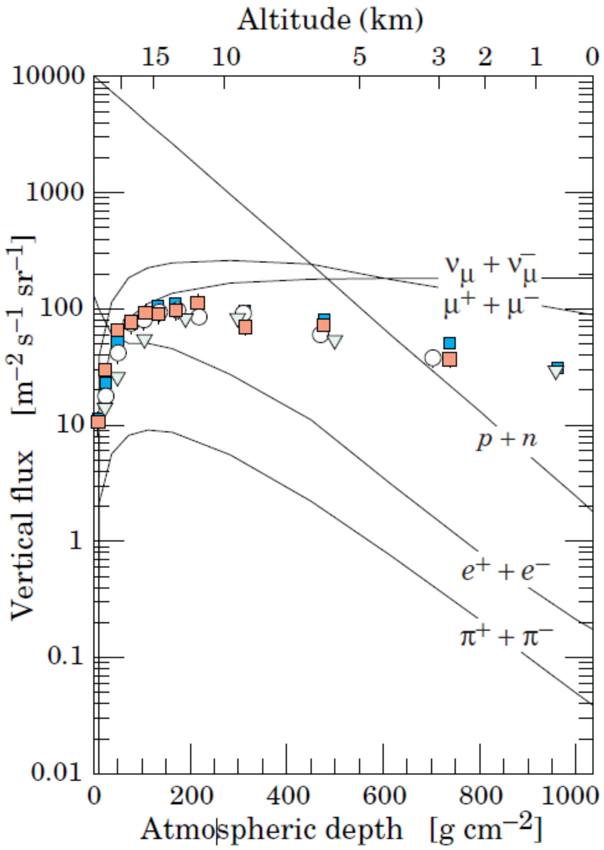


Courtesy of SOHO/LASCO consortium. SOHO is a project of international cooperation between ESA and NASA. (Mercury transit in background)

Energetic Particles in Earth's Atmosphere

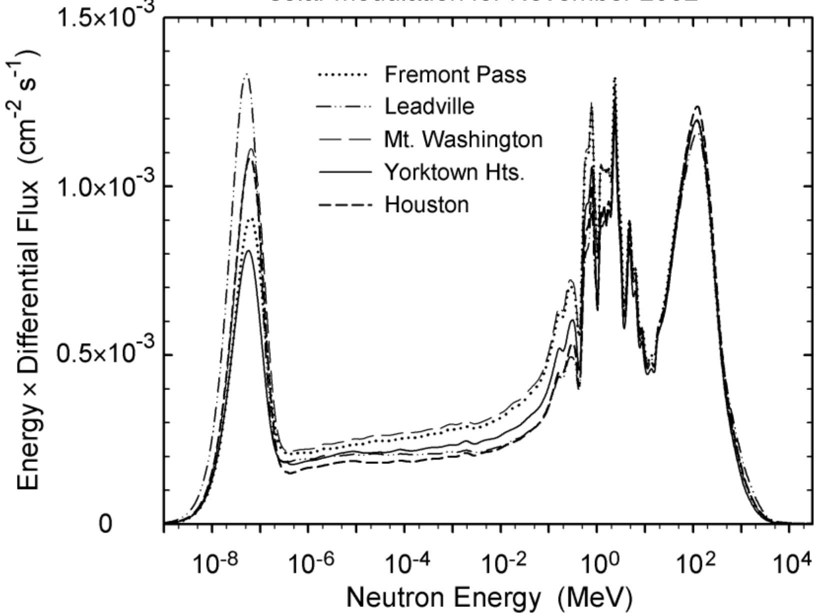


R. C. Baumann, *IEEE NSREC Short Course*, 2013.



M. Tanabashi *et al.* (Particle Data Group), *Phys. Rev. D*, 98, 030001, 2018.

Measured neutron spectra. Each spectrum has been scaled to sea level at the cutoff of New York City and solar modulation for November 2002

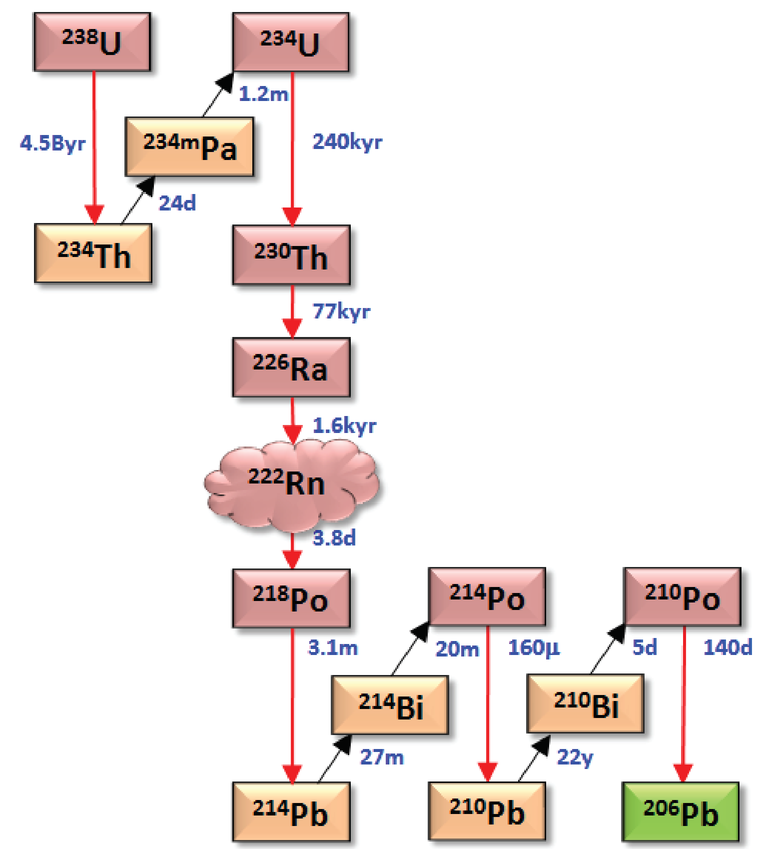


M. S. Gordon *et al.*, *IEEE Trans. Nucl. Sci.*, 2004.

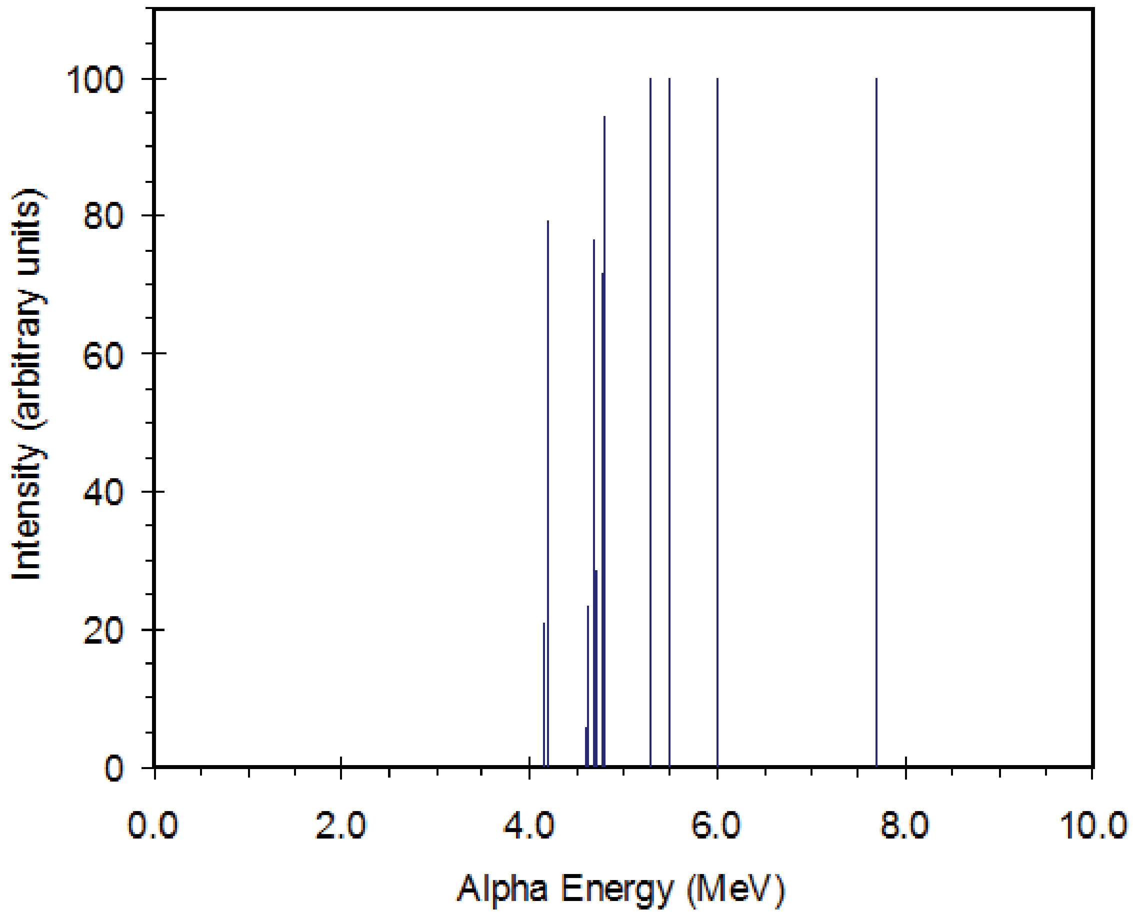
- High-energy particles impact Earth's atmosphere and create air showers, which generate a variety of particles that reach ground level -- anisotropic
- Depends on latitude/longitude, atmospheric depth, and solar activity

Alpha (^{4}He) Particle Radiation

Decay chain for ^{238}U



Alpha (surface) emission spectrum from an infinitely thin sample



R. C. Baumann, *IEEE NSREC Short Course*, 2013.

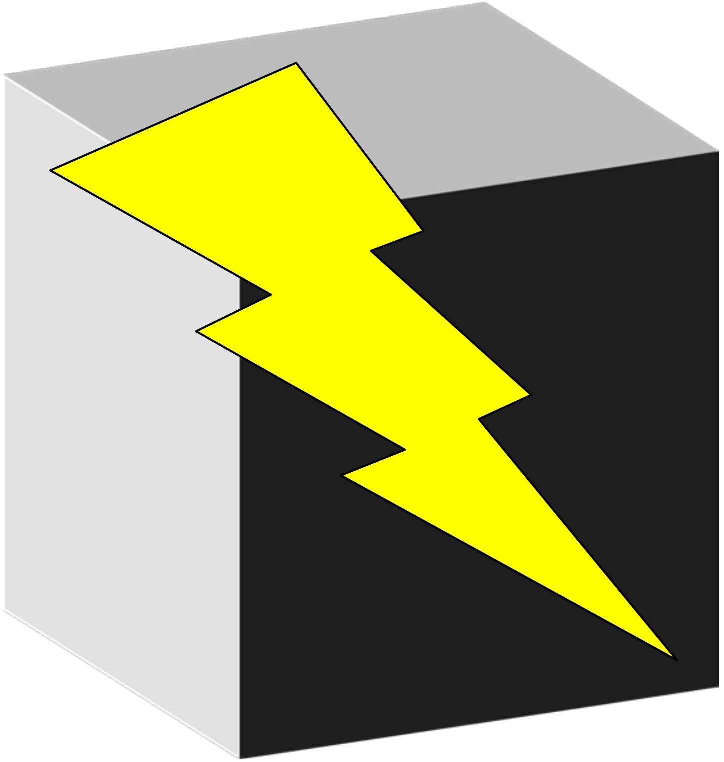
- ^{232}Th and $^{235/238}$U are relatively abundant in terrestrial materials used in electronics processing and active enough to be a radiation effects concern

02 Radiation Effects Overview

What Makes Radiation Effects So Challenging?

- Field is still evolving as are the technologies we want to use (e.g., process nodes, level of integration, etc.)
- A problem of dynamic range
  - Length: 10^{16} m → 10^{-15} m (1 light year → 1 fm)
  - Energy: 10^{19} eV → 1 eV (extreme energy cosmic ray → silicon bandgap)
  - Those are just two dimensions; there are many others.
    - Radiation sources, electronic process technologies (e.g., Si vs. GaN), etc.
- Variability and knowledge of the local radiation environment

What Are Radiation Effects?

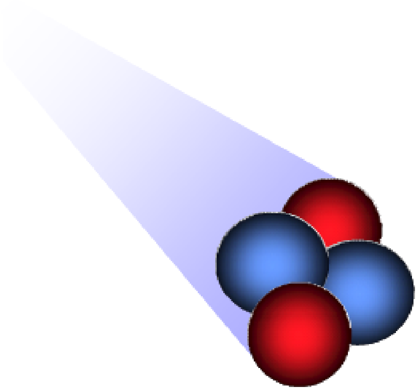


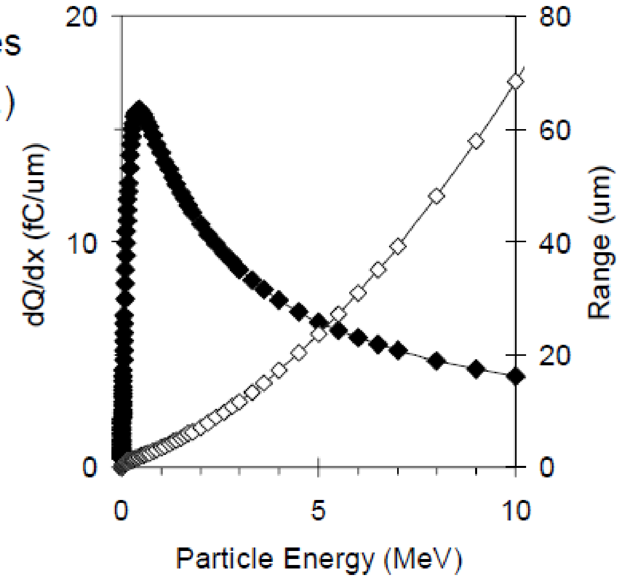
- Energy deposition rate in a “box”
- Source of energy and how it’s absorbed control the observed effects

Common Energy Deposition Processes at Ground-Level

- Direct and indirect ionization, examples

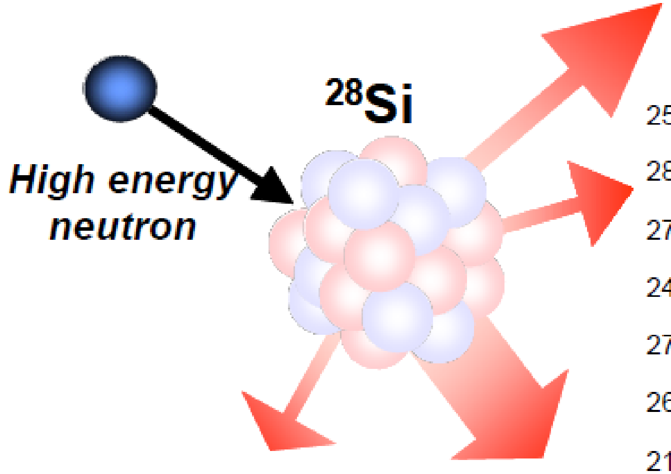
From radioactive impurities (^{232}Th, $^{238/235}U$, ^{210}Po, etc.)





Direct ionization characterized by stopping power, dE/dx

High-energy neutrons (>1 MeV)



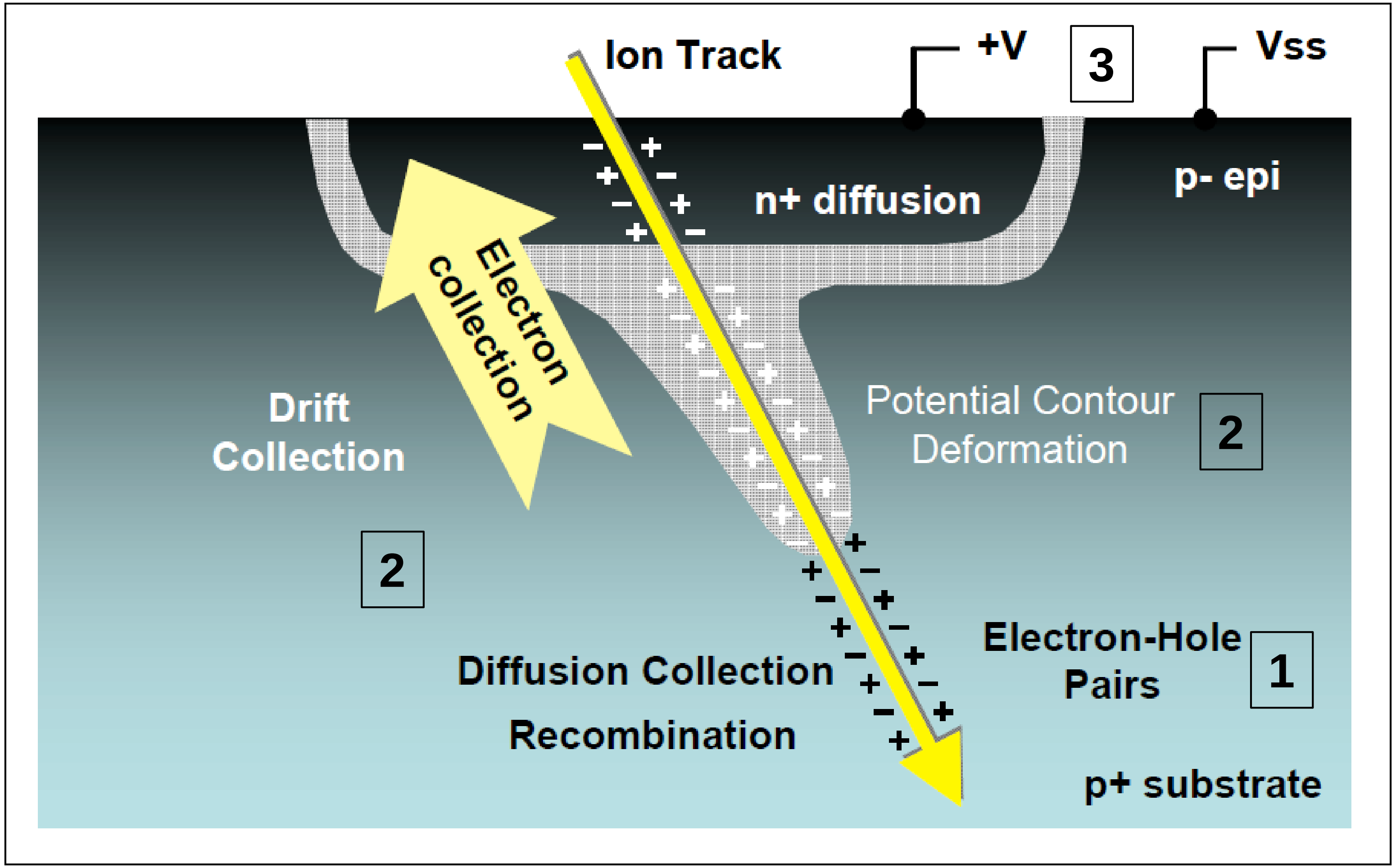
$^{25}Mg + \alpha$	2.75 MeV
$^{28}Al + p$	4.00 MeV
$^{27}Al + d$	9.70 MeV
$^{24}Mg + n + \alpha$	10.34 MeV
$^{27}Al + n + p$	12.00 MeV
$^{26}Mg + {}^{3}He$	12.58 MeV
$^{21}Ne + 2\alpha$	12.99 MeV

n + ^{28}Si reaction showing some of the reaction pathways and associated threshold energies

R. C. Baumann, *IEEE NSREC Short Course*, 2005.

- Not covering effects due to low-energy/thermal neutrons, which can be an issue for technologies that contain ^{10}B

Energy Deposition in Silicon



R. Baumann, *IEEE NSREC Short Course*, 2005.

What Are Single-Event Effects (SEE)?

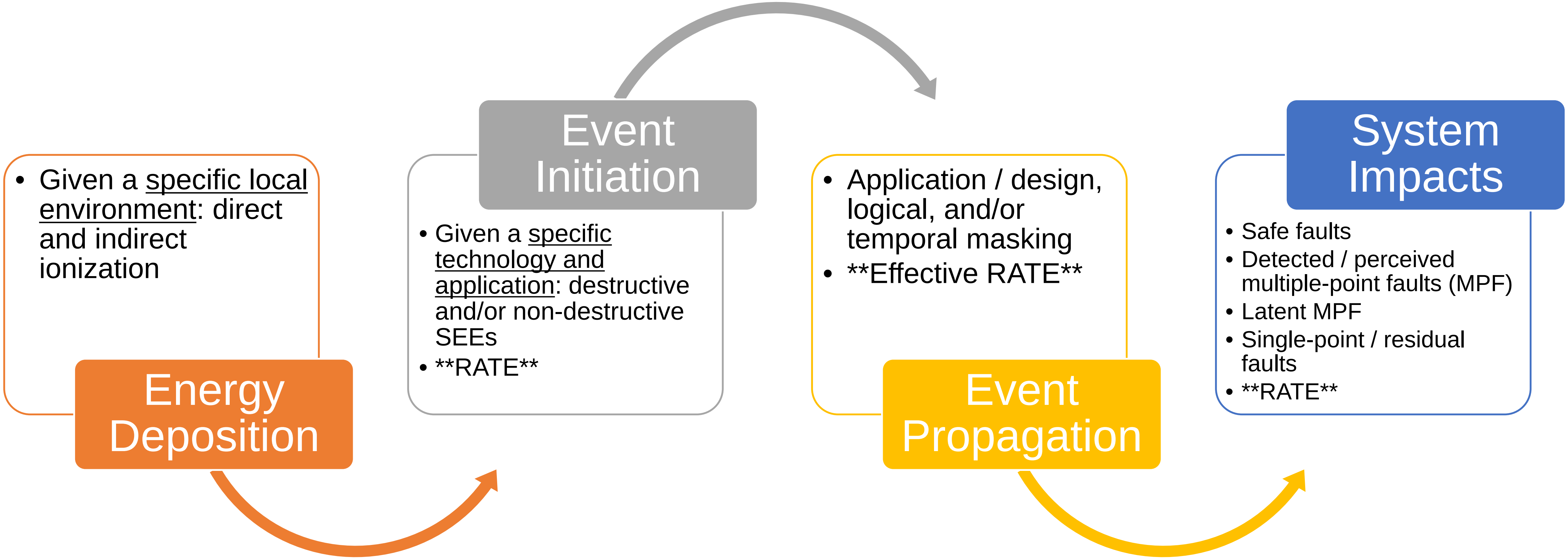
- A single-event effect is a disturbance to the normal operation of a circuit caused by the passage of a single ion (*e.g.*, alpha particle or neutron inelastic reaction product) through or near a sensitive node in a circuit
- SEEs can be either destructive or non-destructive

Several Representative SEE Types

Non-Destructive	Destructive
Single-Event Upset (SEU)	Single-Event Latchup (SEL)
Multiple-Bit Upset (MBU) Multiple-Cell Upset (MCU)	Single-Event Burnout (SEB)
Single-Event Transient (SET)	Single-Event Gate Rupture (SEGR)
Single-Event Functional Interrupt (SEFI)	

After S. Buchner, *SERESSA 2011 Course*, Toulouse, France

SEE – From Component to System



- Knowledge (via validated simulation results and/or experimental measurements) of the SEE event rate at the component level and/or the realized fault probability at the (sub-)system level is essential

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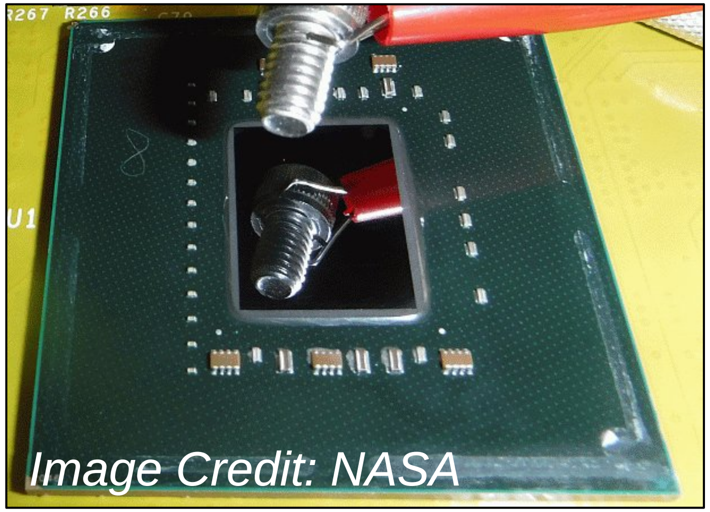
03 Current Focus Areas for COTS Electronics in Reliable Systems

Important Distinction Between Aerospace & Automotive

- Spacecraft and payloads are still largely custom-built
- Touch labor and significant testing for validation
- Traditionally, little to no economy of scale

Important Distinction Between Aerospace & Automotive →*What are COTS parts?*

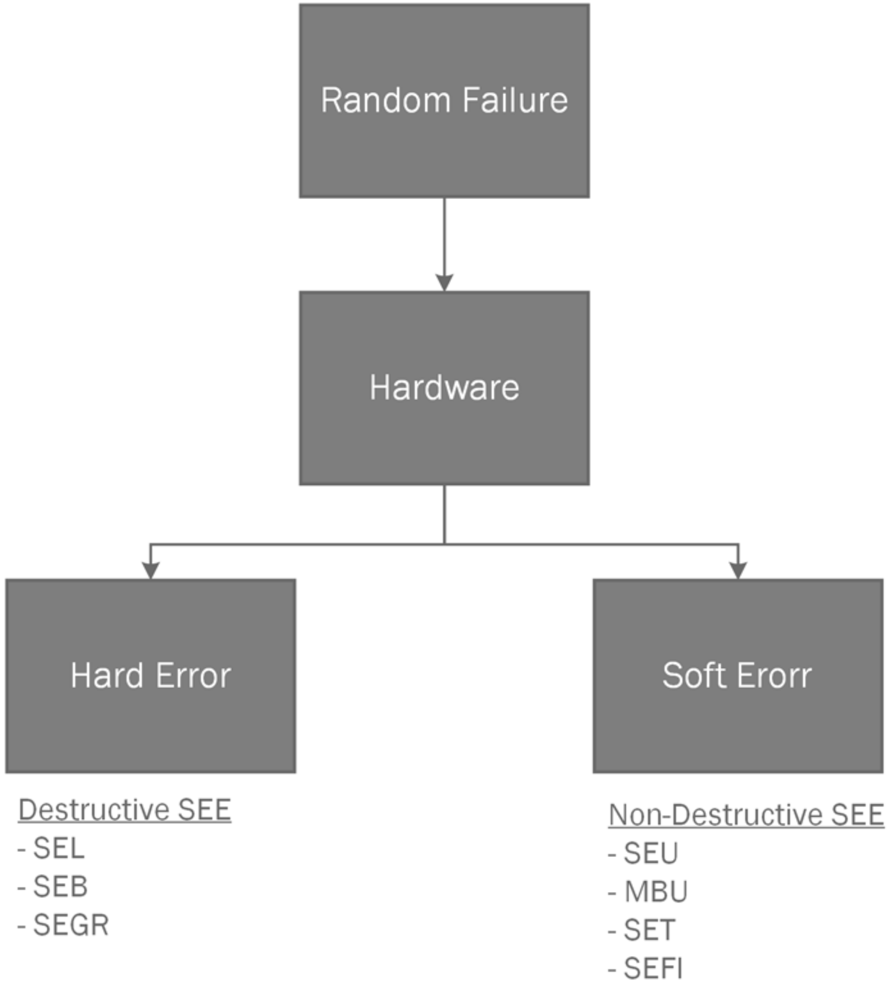
- Space users' perspective
  - Parts designed for applications where the specifications, materials, etc. are established solely by the manufacturer / vendor pursuant to market forces
  - Parts not explicitly designed for space applications
    - May have additional requirements imposed by users or external organizations
  - Automotive-grade parts are a type of COTS hardware, but fall into a unique category



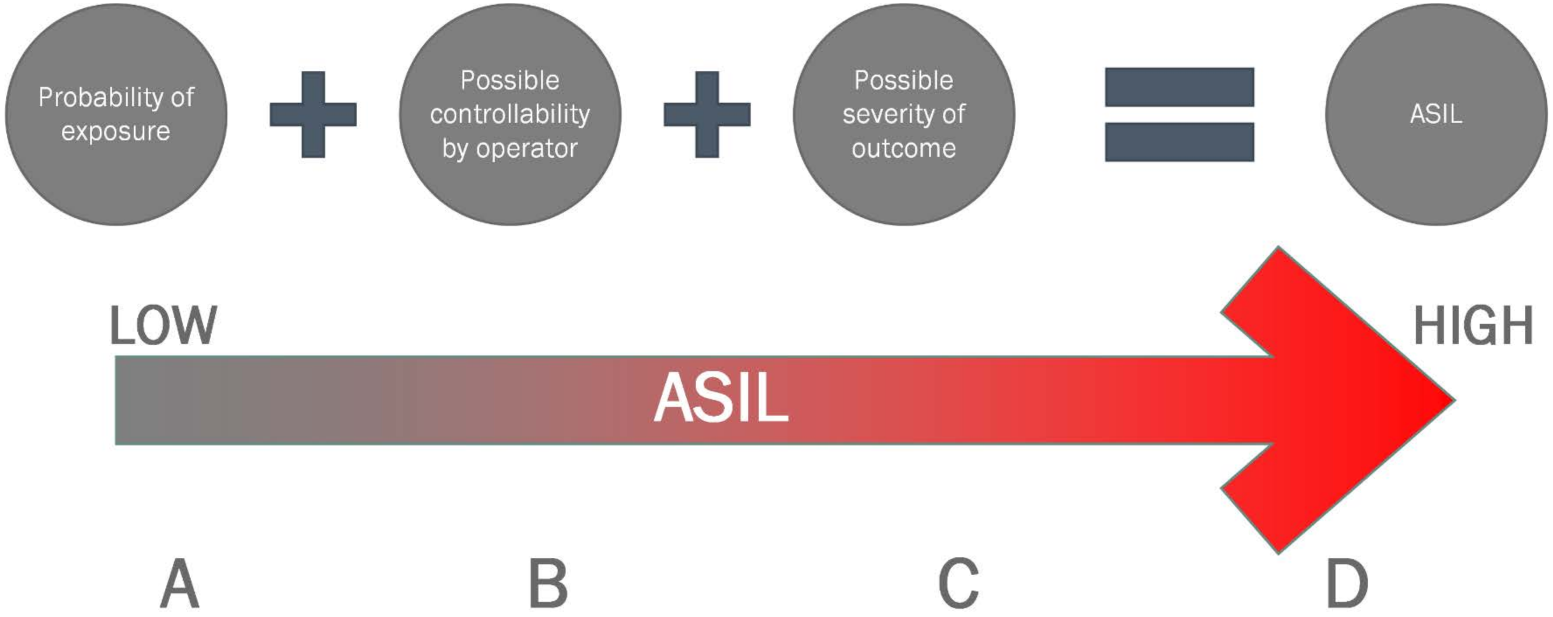
Xilinx Virtex-7 FPGA prepared for radiation testing

Road Vehicle Functional Safety – Radiation Perspective

- SEEs show up as random hardware failures
    - Stochastic failure that can occur during the lifetime of a component
- SEEs follow a probability distribution that may or may not be known
    - Constant with time, state-dependent, etc.
- Can impact both availability and reliability



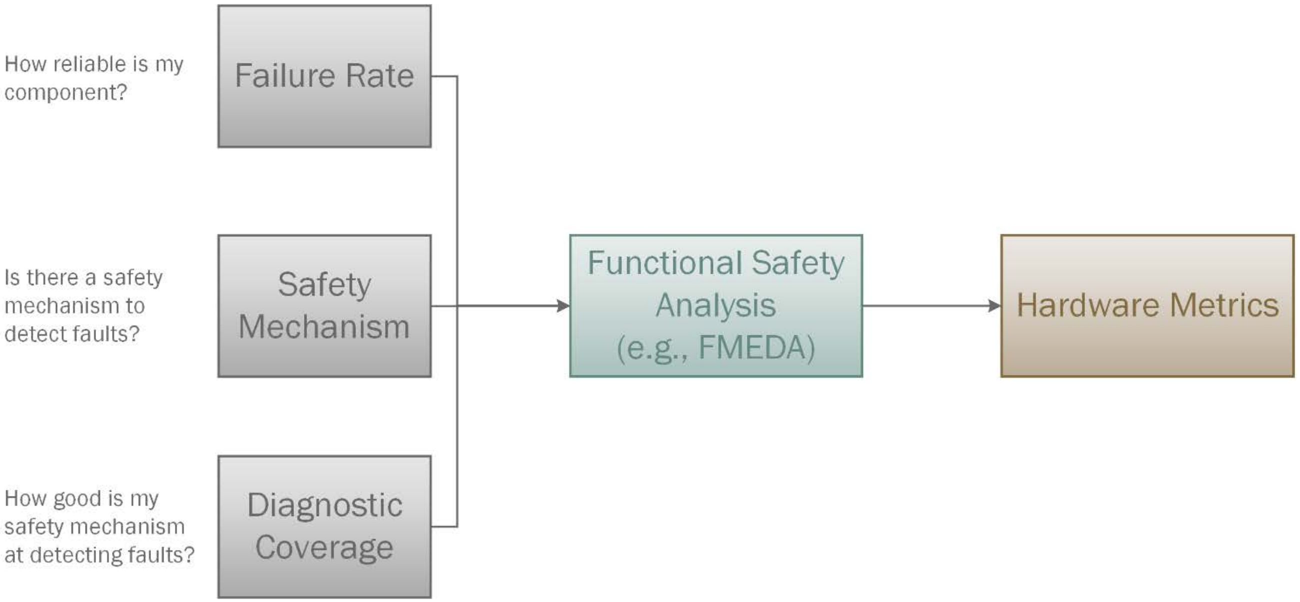
ISO 26262 Automotive Safety Integrity Levels (ASIL)



Adapted from National Instruments white paper, “What is the ISO 26262 Functional Safety Standard?,” http://www.ni.com/white-paper/13647/en/

Level	Associated Severity Class
ASIL A	No injuries
ASIL B	Light and moderate injuries
ASIL C	Severe and life-threatening injuries (survival probable)
ASIL D	Life-threatening injuries (survival uncertain), fatal injuries

Functional Safety Analysis Implications for Radiation Effects



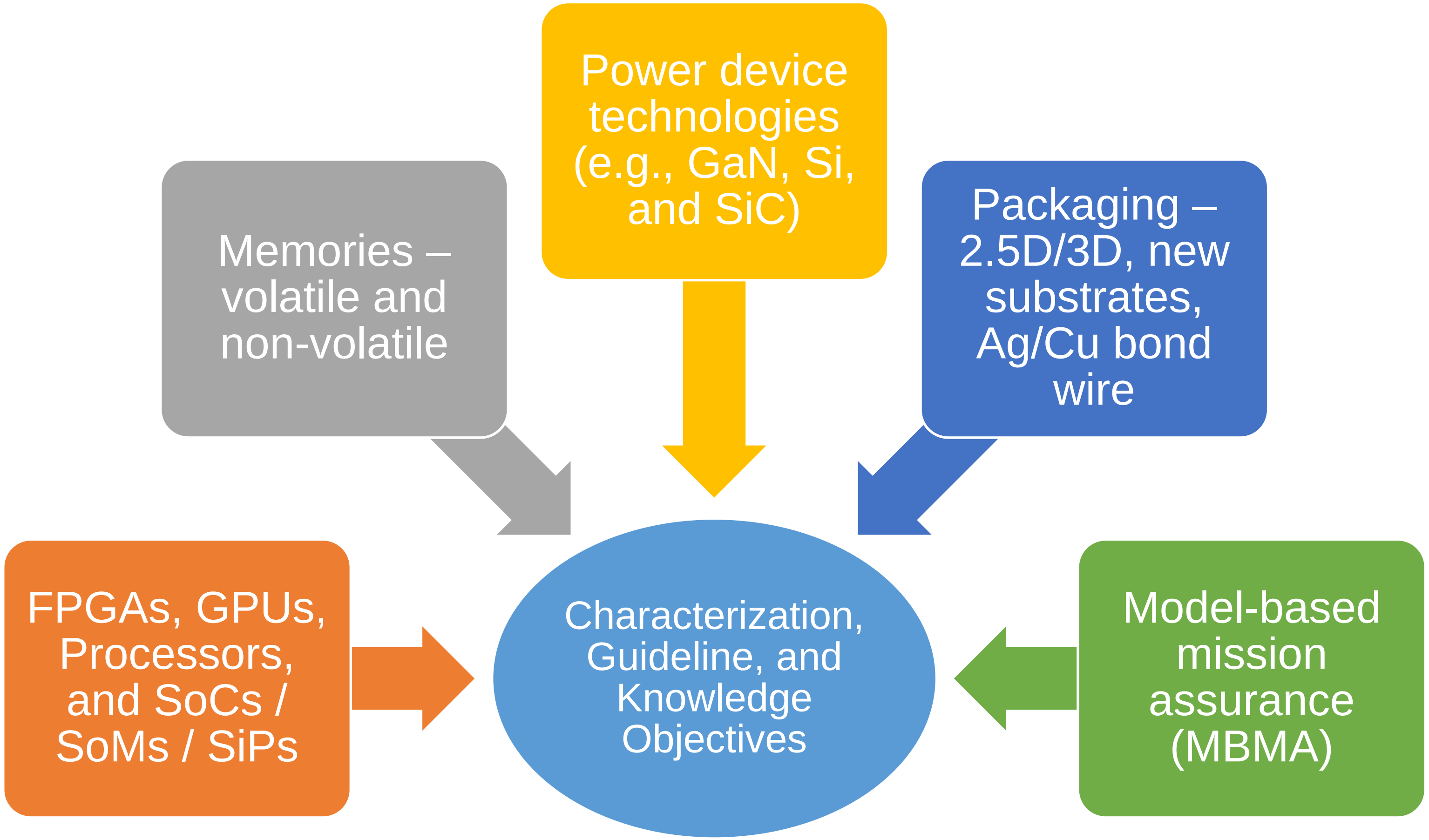
ASIL	Failure Rate	Single Point Failure Metric (SPFM)	Latent Failure Metric (LFM)
A	< 1000 FIT	Not relevant	Not relevant
B	< 100 FIT	≥ 90%	≥ 60%
C	< 100 FIT	≥ 97%	≥ 80%
D	< 10 FIT	≥ 99%	≥ 90%

1 FIT = 1 failure in 10^9 device-hours

Adapted from A. Keffer, "Functional Safety Verification," *SEE Symposium/MAPLD Workshop*, La Jolla, CA, May 2018.

- Produces a range of implications for component-level radiation response knowledge, efficacy of validation practices, and ultimate system visibility

Current Hardware Assurance Focus Areas



- Spans both component- and packaging-levels
  - Workmanship and board-level issues are separate; still critical

Observed Trends and Challenges

Potential threats to safety / reliability

- Current and emerging programs continue to pose new technological challenges – size, weight, and power (SWaP)
- Finite budgets and truncated schedules force designers and management to push technologies to their physical limits
- Budget and schedule pressures challenge how technologies and products are verified
- Need a clear understanding of the different verification processes to ensure proper verification of the technology
- Capabilities, advantages, and limitations of the testing and inspection performed at each level are different, and the risk incurred by omitting verification steps depends on the level of integration as well as the application, (radiation) environment, and lifetime

Adapted from “Guidelines for Verification Strategies to Minimize Risk Based On Mission, Environment, Application, and Lifetime,” NASA/TM-2018-220074

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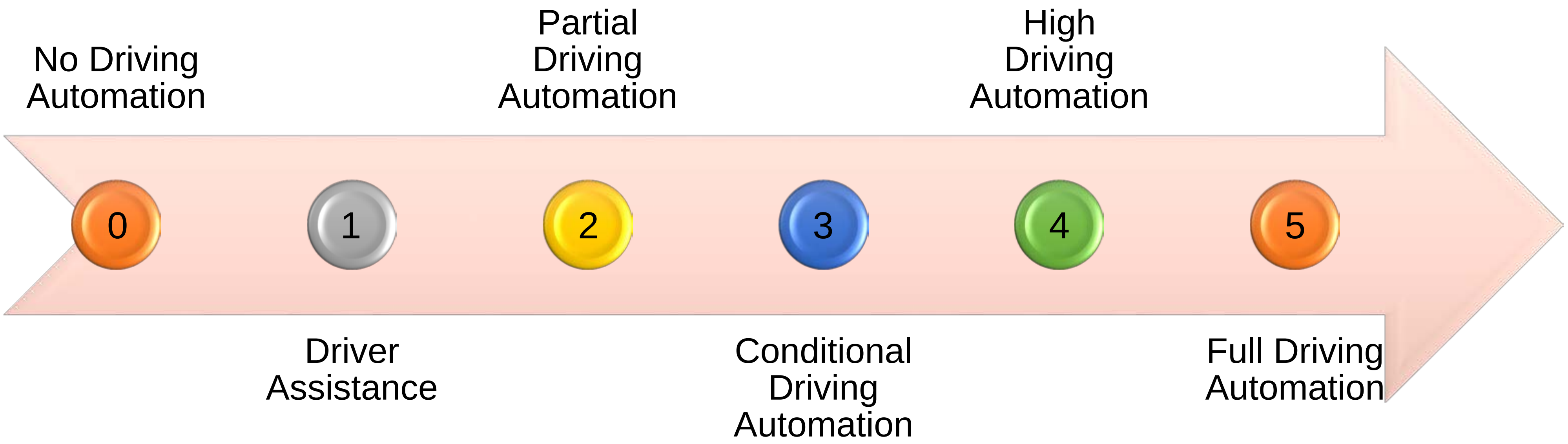
04 Future Needs for COTS Electronics in Reliable Systems

Climbing the Autonomy Ladder



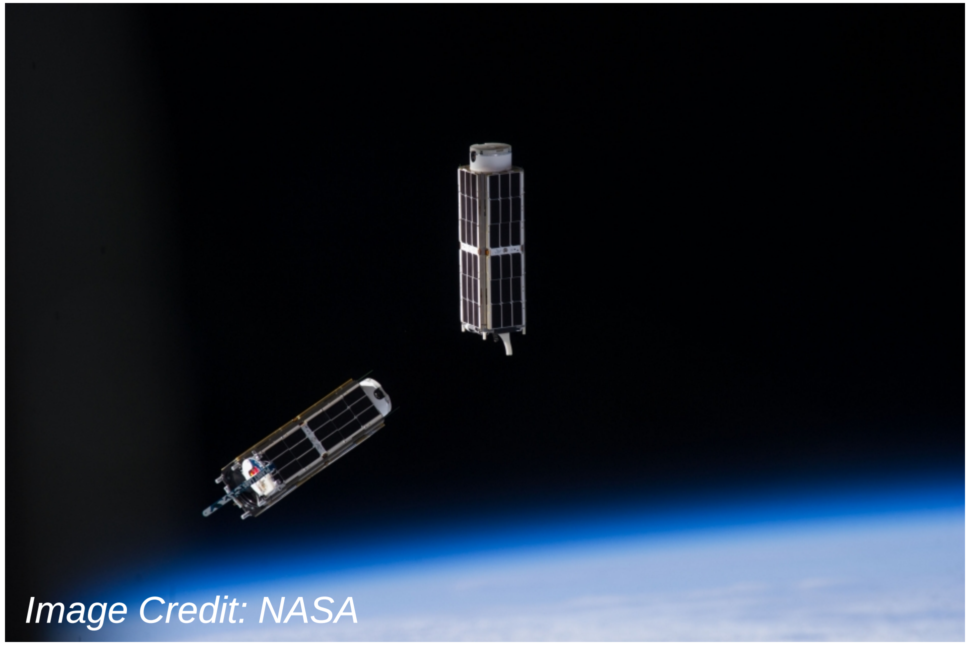
Adapted from SAE J3016, "Surface Vehicle Recommended Practice"

- Climbing to Level 3+ requires massive computing power and levels of real-time ADAS integration that will necessitate a shift in testing and verification methodologies
- What will "adequate" state space coverage look like for a system guaranteed to experience random failures from radiation events?

Adapting to the COTS Assembly

- Increasing the integration level of fundamental elements may speed technology insertion and adaptability
  - Confounds current evaluation approaches
- Physics of failure requires deep insight – not always available
- Given a modular architecture, what will happen if hardware is intentionally refreshed periodically?
  - Adapt to security risks & customer demands
  - Mitigate impact of process defect ceiling constraints
  - How will this impact the supply chain and functional safety verification processes?

Set of NanoRacks CubeSats is photographed by an Expedition 38 crew member after the deployment by the NanoRacks Launcher attached to the end of the Japanese robotic arm



Radiation Engineering & Testing Infrastructure

Testing at the Speed of Light **– The State of U.S. Electronic Parts Radiation Testing Infrastructure**

Committee on Space Radiation Effects Testing Infrastructure for the U.S. Space Program

National Materials and Manufacturing Board
Division on Engineering and Physical Sciences

The National Academies Press
Washington, DC
www.nap.edu

- Even with sophisticated modeling, radiation testing remains essential to characterize, qualify, and validate
- Radiation testing facilities are often unique and the required engineering expertise is highly-specialized and takes time to develop
- NASEM report provides:
  - Background on space environment and its effects on electronics
  - Current state of single-event effects hardness assurance and infrastructure
  - Future infrastructure needs and a path forward

https://www.nap.edu/catalog/24993/testing-at-the-speed-of-light-the-state-of-us

Additional Thoughts for Consideration

- *Normal Accidents: Living with High-Risk Technologies*, Charles Perrow, Princeton University Press, 1999.
  - Analyzes the social side of technological risk
  - Examines complex vs. linear interactions and tight vs. loose coupling
  - Argues that conventional engineering approaches to ensuring safety fail because systems complexity makes failure inevitable
    - Pessimistic view, but worth considering
- R. Kwasnick *et al*., "Telemetry for reliability," *IEEE Int. Reliability Physics Symp.*, Monterey, CA, 2017.
  - Presents a multi-stage framework for establishing accurate use conditions inputs for product reliability modeling
  - Discusses knowledge-based qualification of integrated circuit products, which includes predicting product failure in the field over time for failure mechanisms

Partnering is Critical for Success

- Radiation effects is one of the most challenging areas for reliable system design
  - Cross-cutting, multi-disciplinary
- NASA partners with:
  - Academia
  - Industry
  - International
  - Other government agencies
- Encourage expansion internal to and external from automotive electronics community

Proton Radiation Test at
the University of California, Davis

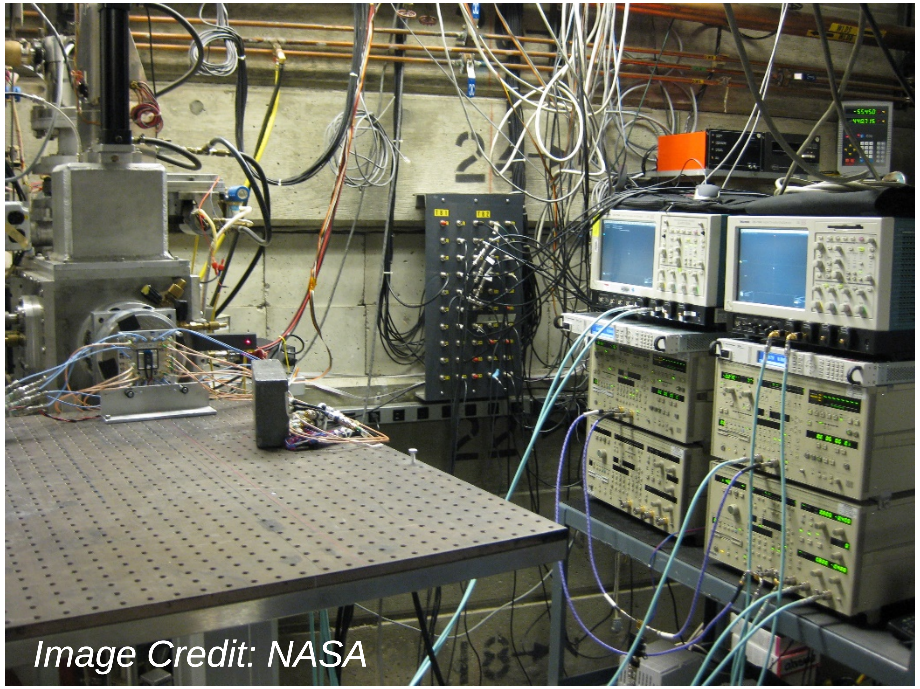


Image Credit: NASA

Summary

- Space radiation, and modulation due to space weather, affects the terrestrial radiation environment (e.g., neutrons et al.) -- alpha particles are an additional environment
- SEE are initiated by the ground-level radiation environment and can produce failures that propagate through systems
- Performance requirements in combination with size, weight, power, and cost constraints will challenge verification methodologies, including potential radiation testing
- Adapting radiation engineering processes at the assembly level will be a paradigm-shifting challenge
- Partnering and knowledge sharing is always beneficial and will become essential to meeting and overcoming challenges

Thank you for your attention!
Question & Answer

Image credit: NASA
International Space Station is seen in this twenty-second exposure as it flies over the Washington National Cathedral, 29-Nov-2017