ELISA
Enabling Linux in
Safety Applications

WORKSHOP

Test and Assurance of Non-Volatile Memory Devices for Space

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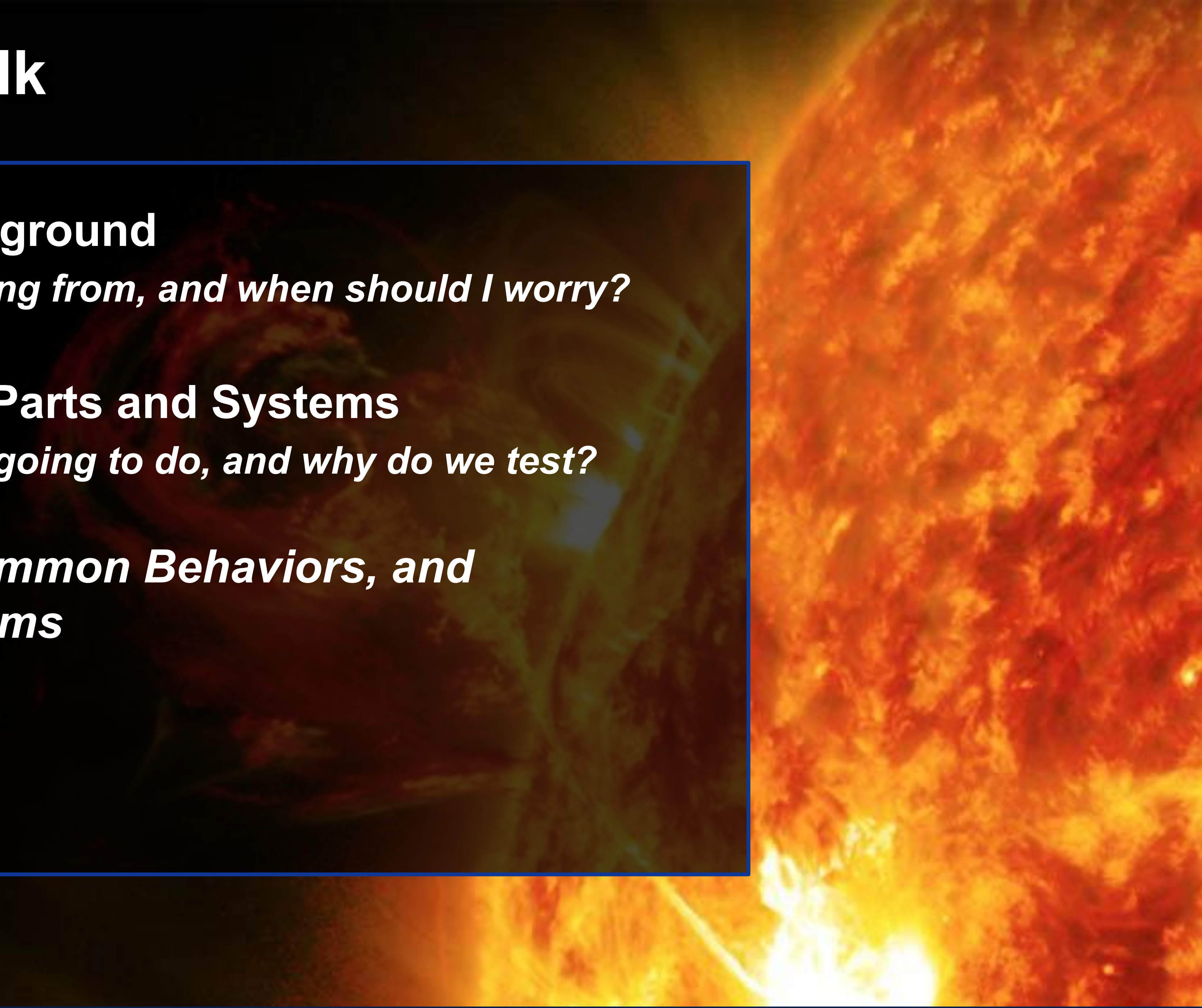
To be presented by Ted Wilcox at the ELISA: 12/11/24

Acronyms

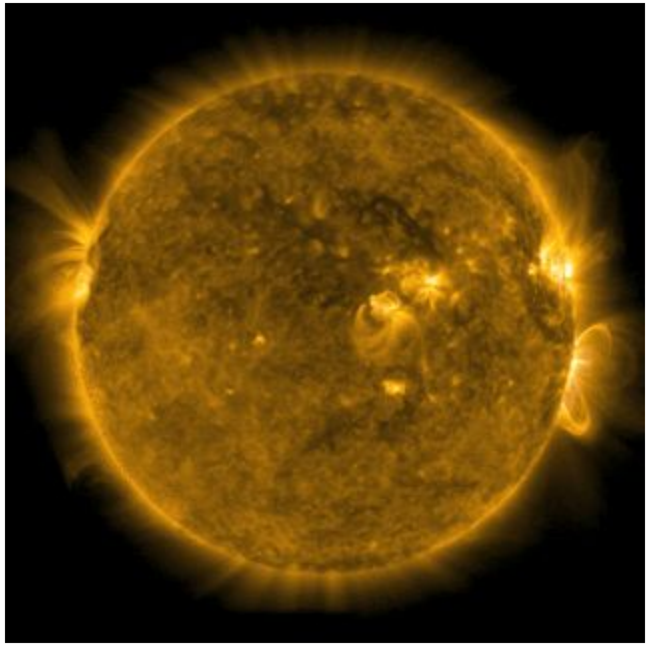
- CME – Coronal Mass Ejection
- CMOS – Complementary Metal Oxide Semiconductor
- COTS – Commercial Off The Shelf
- DDD – Displacement Damage Dose
- ECC – Error Correcting Code
- EDAC – Error Detection and Correction
- FPGA – Field Programmable Gate Array
- LEO – Low Earth Orbit
- LET – Linear Energy Transfer
- MEAL – Mission, Environment, Application, Lifetime
- MLC – Multi-Level Cell
- NVM – Non-Volatile Memory
- SEB – Single-Event Burnout
- SEE – Single-Event Effect
- SEFI – Single-Event Functional Interrupt
- SEGR – Single-Event Gate Rupture
- SEL – Single-Event Latchup
- SET – Single-Event Transient
- SEU – Single-Event Upset

Purpose of this talk



1. **Space Radiation Background**
   - *Where is this stuff coming from, and when should I worry?*
2. **Effects on Electronic Parts and Systems**
   - *What are my memories going to do, and why do we test?*
3. ***NVM Test Results, Common Behaviors, and Implications for Systems***

Three Primary Space Radiation Sources

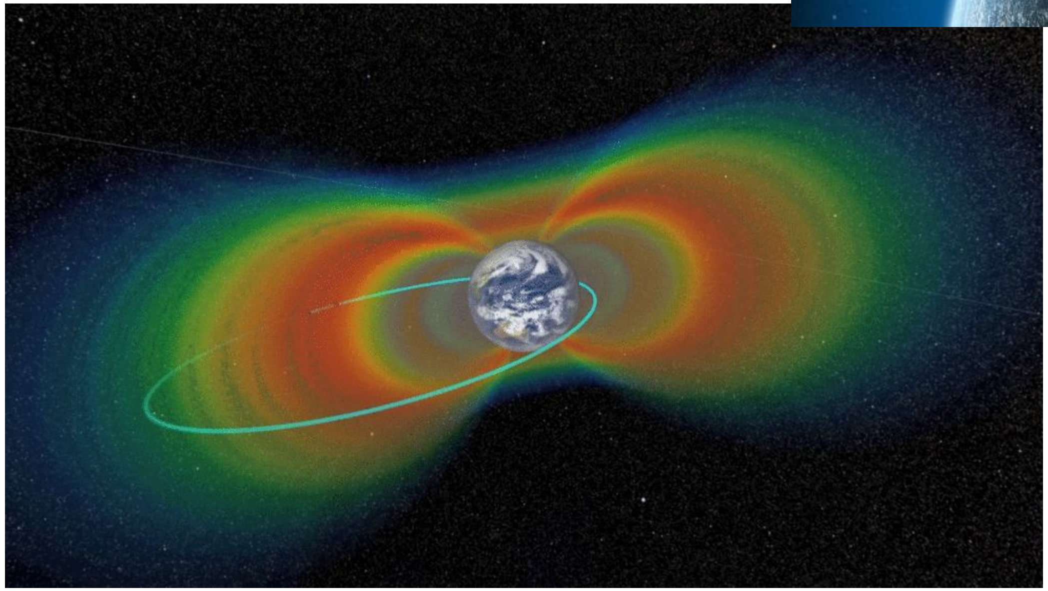


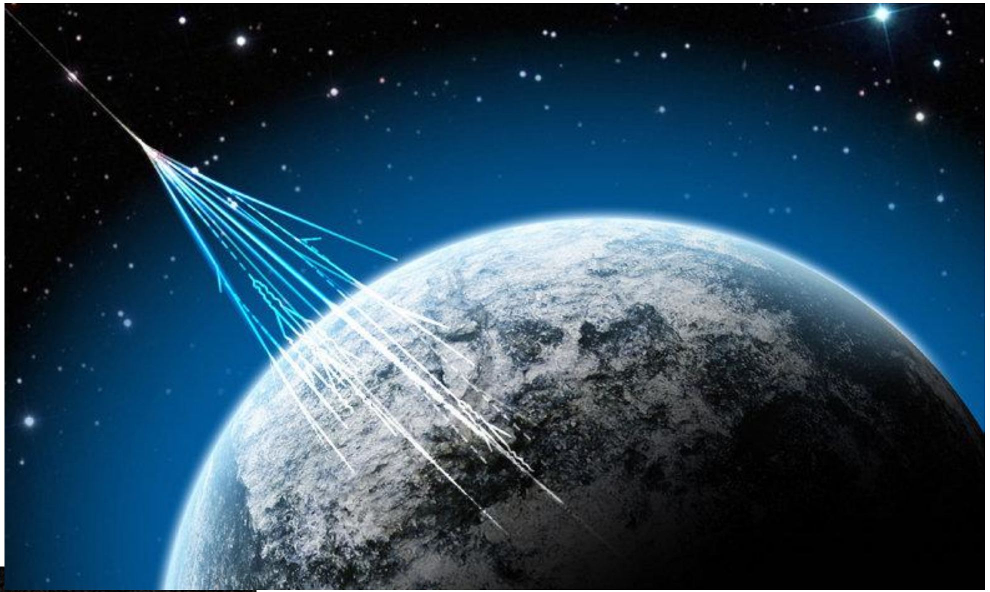
The Sun

LIVING WITH A STAR
LWS
NASA

Exploring the Extremes of Space Weather
Van Allen Probes

Earth's Van Allen Belts





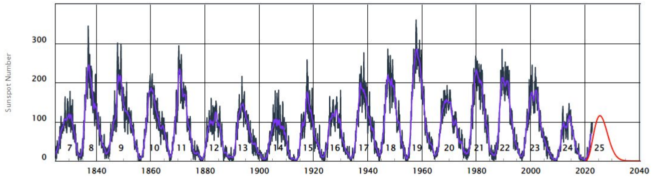
Galactic Cosmic Rays

VOYAGER

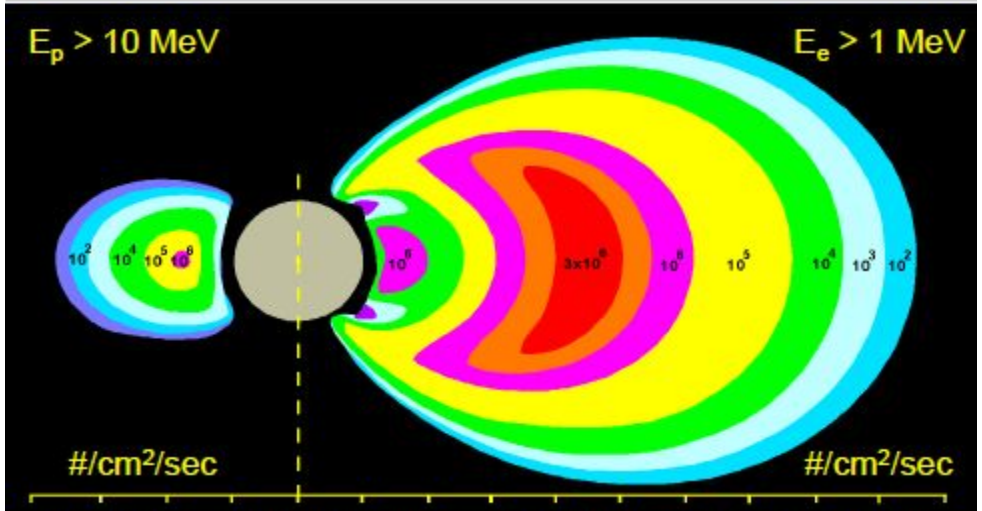
Three Primary Space Radiation Sources

Solar Activity

- Solar Wind
- CMEs (proton rich)
- Flares (heavy ion rich)



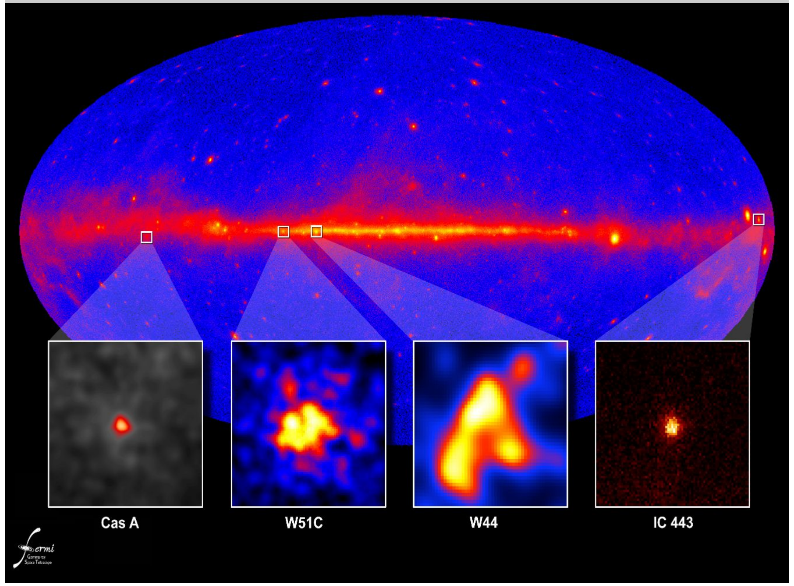
Trapped Particles in Planetary Magnetic Fields



A dip in the earth's dipole moment causes an asymmetry in the picture above: The South Atlantic Anomaly (SAA)

- Fluctuate with Solar Activity
- Not a perfect dipole
- Protons and Electrons trapped at different altitudes and energies

Galactic Cosmic Rays



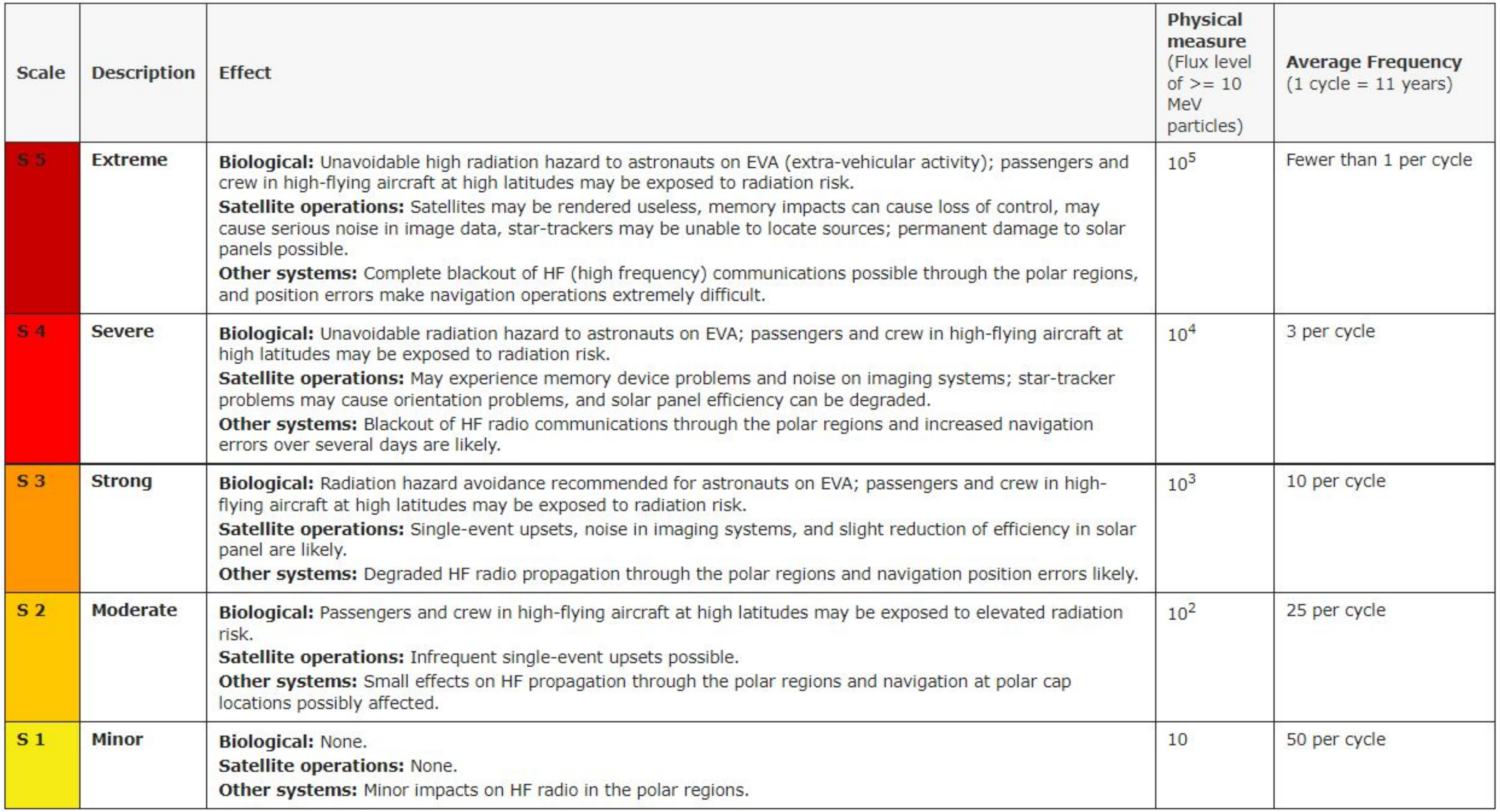
- Energetic supernovae remnants (~GeV, Z=1-92)
- Originate outside of our solar system

Images: NASA FERMI X-ray telescope, Solar Dynamics Observatory, Janet Barth (radhome.gsfc.nasa.gov)

Solar Particle Events (SPE)

By NOAA’s definition (broadest in terms of SPE classification)

- S1 (minor) SPE is in progress whenever the >10 MeV proton flux exceeds 10 proton flux units (PFUs, #/cm2/sr/s)

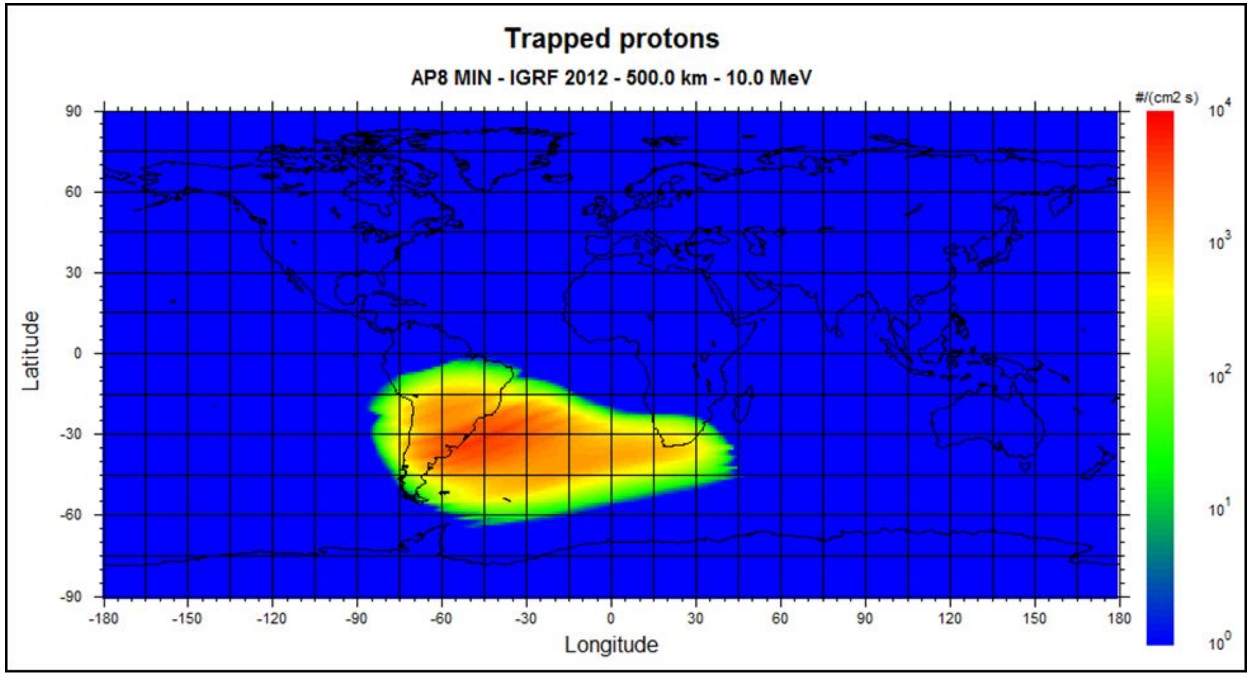


Scale	Description	Effect	**Physical measure** (Flux level of >= 10 MeV particles)	**Average Frequency** (1 cycle = 11 years)
S 5	Extreme	**Biological:** Unavoidable high radiation hazard to astronauts on EVA (extra-vehicular activity); passengers and crew in high-flying aircraft at high latitudes may be exposed to radiation risk. **Satellite operations:** Satellites may be rendered useless, memory impacts can cause loss of control, may cause serious noise in image data, star-trackers may be unable to locate sources; permanent damage to solar panels possible. **Other systems:** Complete blackout of HF (high frequency) communications possible through the polar regions, and position errors make navigation operations extremely difficult.	10^5	Fewer than 1 per cycle
S 4	Severe	**Biological:** Unavoidable radiation hazard to astronauts on EVA; passengers and crew in high-flying aircraft at high latitudes may be exposed to radiation risk. **Satellite operations:** May experience memory device problems and noise on imaging systems; star-tracker problems may cause orientation problems, and solar panel efficiency can be degraded. **Other systems:** Blackout of HF radio communications through the polar regions and increased navigation errors over several days are likely.	10^4	3 per cycle
S 3	Strong	**Biological:** Radiation hazard avoidance recommended for astronauts on EVA; passengers and crew in high-flying aircraft at high latitudes may be exposed to radiation risk. **Satellite operations:** Single-event upsets, noise in imaging systems, and slight reduction of efficiency in solar panel are likely. **Other systems:** Degraded HF radio propagation through the polar regions and navigation position errors likely.	10^3	10 per cycle
S 2	Moderate	**Biological:** Passengers and crew in high-flying aircraft at high latitudes may be exposed to elevated radiation risk. **Satellite operations:** Infrequent single-event upsets possible. **Other systems:** Small effects on HF propagation through the polar regions and navigation at polar cap locations possibly affected.	10^2	25 per cycle
S 1	Minor	**Biological:** None. **Satellite operations:** None. **Other systems:** Minor impacts on HF radio in the polar regions.	10	50 per cycle

NOAA

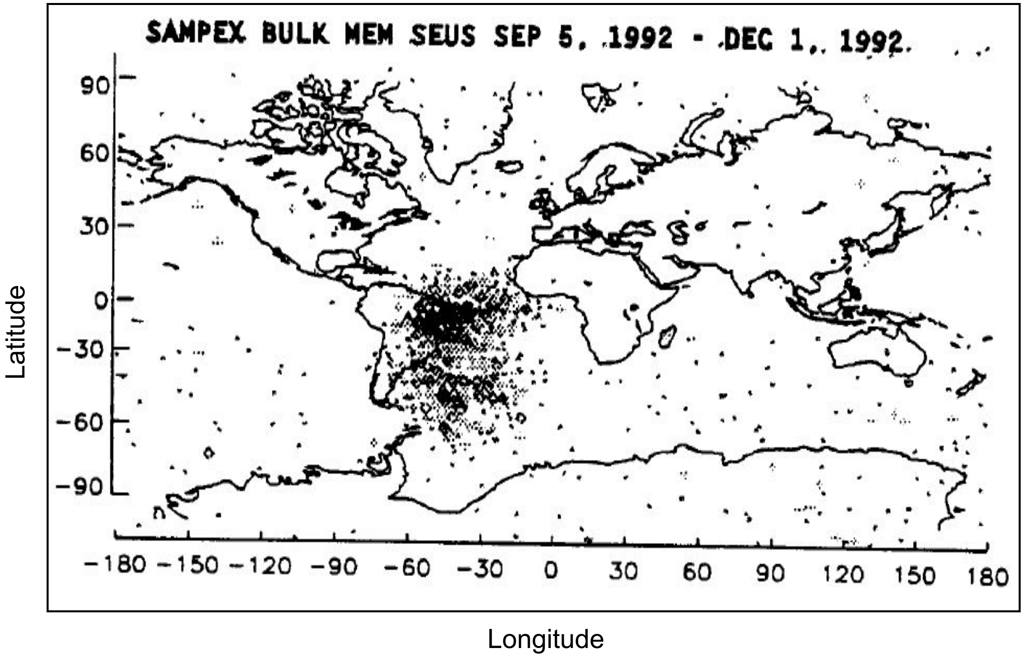
South Atlantic Anomaly

- Protons are present at lower altitudes over South America and the South Atlantic
- May require operational changes when entering South Atlantic Anomaly



OMERE v3.4

Solar Anomalous Magnetospheric Explorer (SAMPEX)

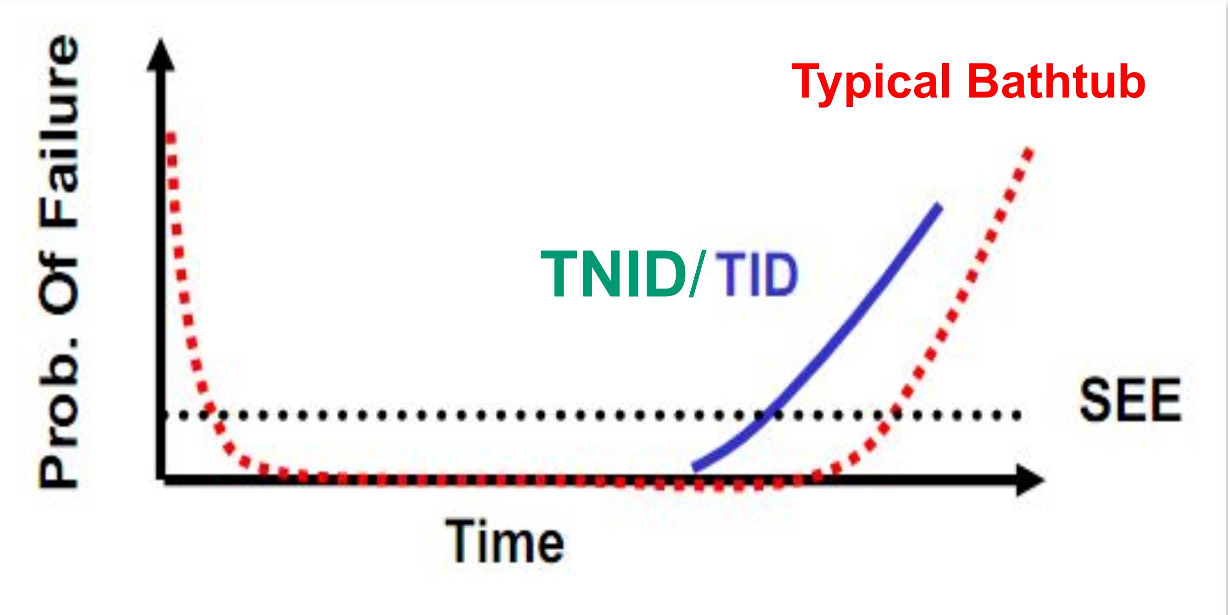


K. A. LaBel, et al., IEEE REDW, 1993.

EFFECTS ON ELECTRONIC PARTS

Broad Radiation Effects on EEEE Parts

- **Gradual Degradation**
  - Will it survive the mission length without failure?
  - Total Ionizing Dose (TID), Displacement Damage Dose (DDD/TNID)
- **Sudden Failure**
  - Could the part fail at any time?
  - Single-Event Latchup (SEL), Gate Rupture (SEGR), and Burnout (SEB)
- **Transient Anomalies**
  - Will the system tolerate glitches and potentially operate correctly through a solar storm?
  - Single-Event Upsets (SEU), Transients (SET), Functional Interrupts (SEFI)…



Total Ionizing Dose (TID)

- **First question we're asked:** "What are the krads for this mission?"
  - Measured in rad or gray, material specific
  - 1 gray = 100 rad
- Energetic photons or charged particles (e^-, p^+) interact with mass:

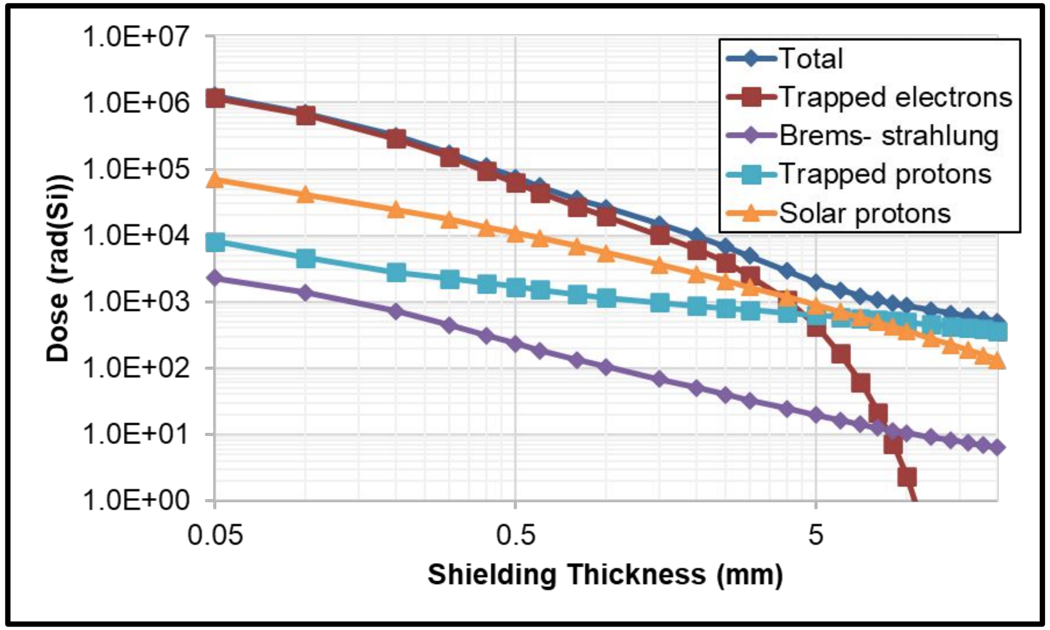
1. electron-hole pair generation
2. recombination of some electrons and holes
3. transport of remaining carriers by drift and diffusion
4. eventual trapping of holes in defects or interfaces

Long-term accumulated effect -> life-limiting

- ✔ Increased leakage current or power supply current
- ✔ Transistor or amplifier gains reduced
- ✔ Voltage regulators drifting from programmed output
- ✔ **Non-volatile memories unable to erase**
- ✔ High-speed CMOS logic slowed
- ✔ Data converter offsets
- ✔ Increased dark current in image sensors
- ✔ Frequency shifts in oscillators
- ✔ Coloring/darkening in optical materials
- ✔ Complex devices suddenly failing

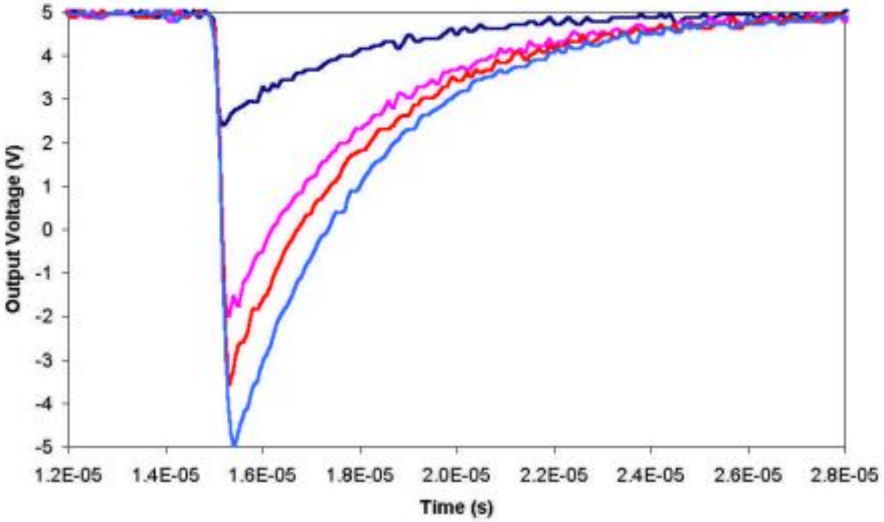
Mitigating TID in Electrical Systems

- Shield – either add more, or characterize what you already have
- Parts – find alternatives with better performance
- Design – tolerate larger parametric drift
- Operations – powering down during high-dose phases *may* help
- Sparing/Redundancy – only relevant if parts degrade slower when off



Single-Event Effects (SEE)

- Instantaneous and/or transient effects caused by a single particle striking a sensitive portion of an electronic device
- Electron-hole pairs are generated along an “ion track” through the device
  - Often caused by a “heavy ion” (direct ionization)
  - Or, a proton colliding into semiconductor material and generating fission fragments that indirectly ionize
- Result may be **destructive** or **non-destructive**. It may be mission-critical or irrelevant.

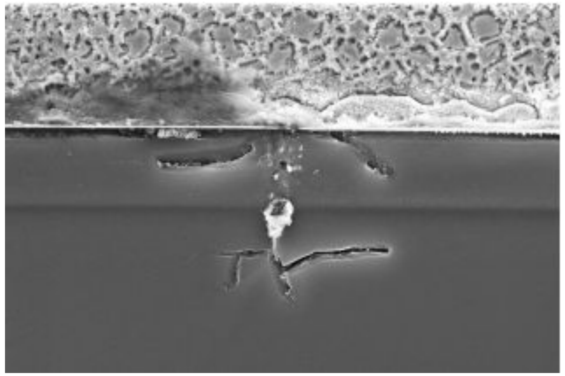


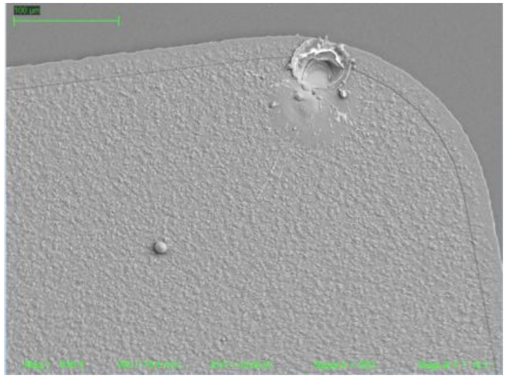
Single-event transients in an LM139 comparator

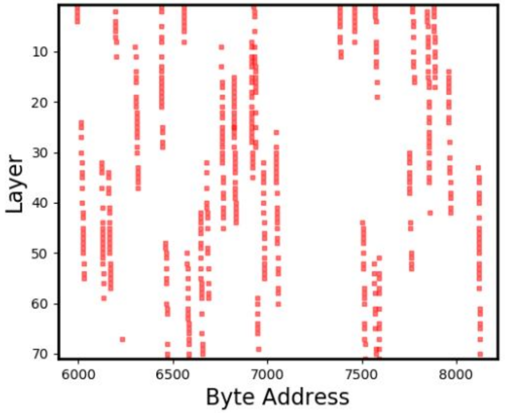
Consequences of SEE

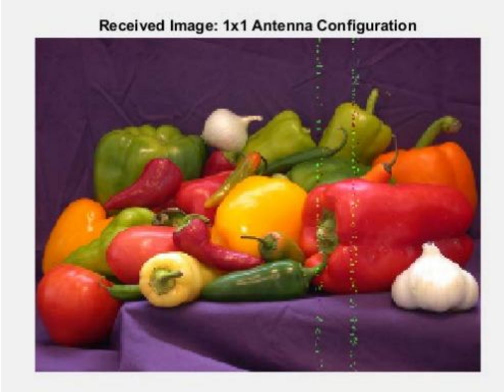
- **Destructive:** Random events capable of ending a mission on day 1 or day 1,000
  - **Single-event latchup** (SEL)
  - **Gate Rupture** (SEGR)
  - **Burnout** (SEB)
- **Avoid** this threat altogether by choosing immune technologies or testing for susceptibility
- **Difficult to predict** a priori

- **Non-Destructive**: Random data corruption, glitches, and resets.
- The most complex radiation effects at the design level; generally not solvable by parts selection alone
- Must **mitigate**, **tolerate**, or **ignore** based on MEAL
- Of particular concern with many computing systems!









Mitigating SEE

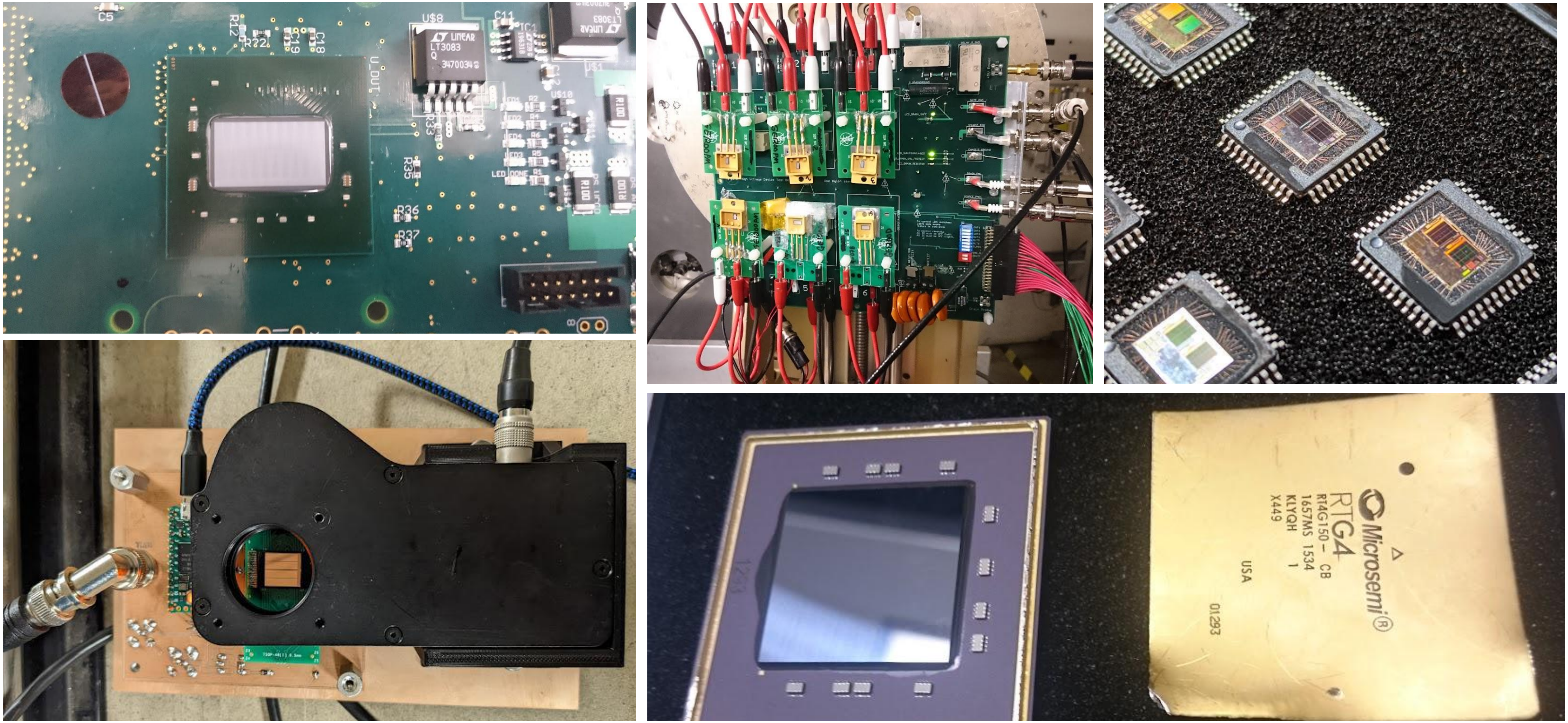
- **Avoid destructive SEE at all cost**
  - Highest consequences of all radiation effects hazards
  - Derate within a tested safe operating area if possible
  - Avoid unknown, untested parts
  - SEL *may* be mitigated with current-limiting and power-cycling, but the risk is non-zero

Primarily, a parts selection concern

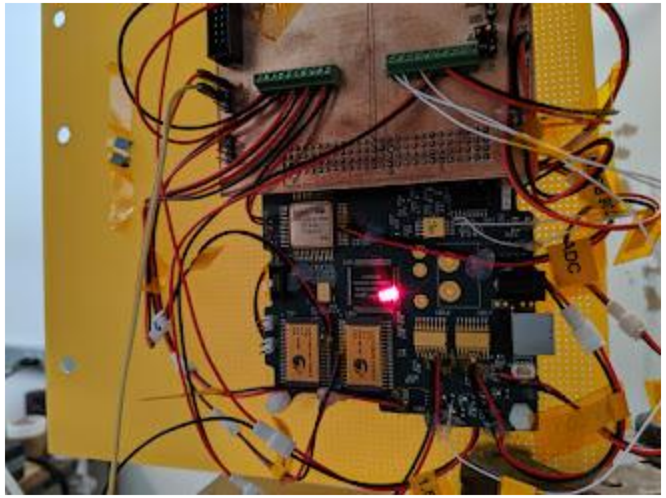
- **Characterize and mitigate non-destructive SEE**
  - Filtered power supplies
  - Redundant computers, hardened FPGA designs
  - EDAC on memories
  - Watchdog timers and autonomous resets
  - Power limiting to susceptible devices
  - Independent power cycling/reset for subsystems
  - Identify the risks, explore the possible consequences

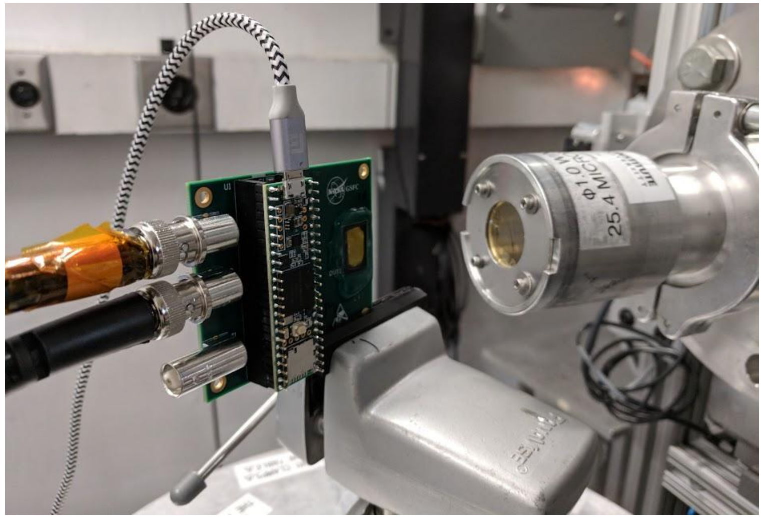
Primarily, an electrical circuit/system design concern

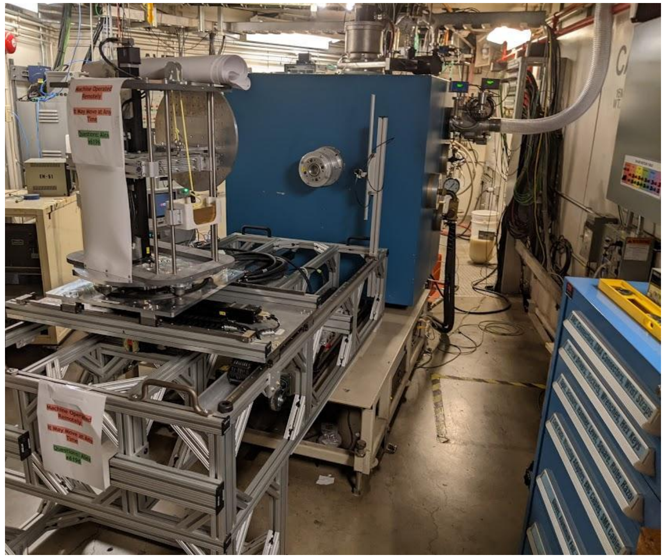
SEE Testing Photos



SEE Facilities

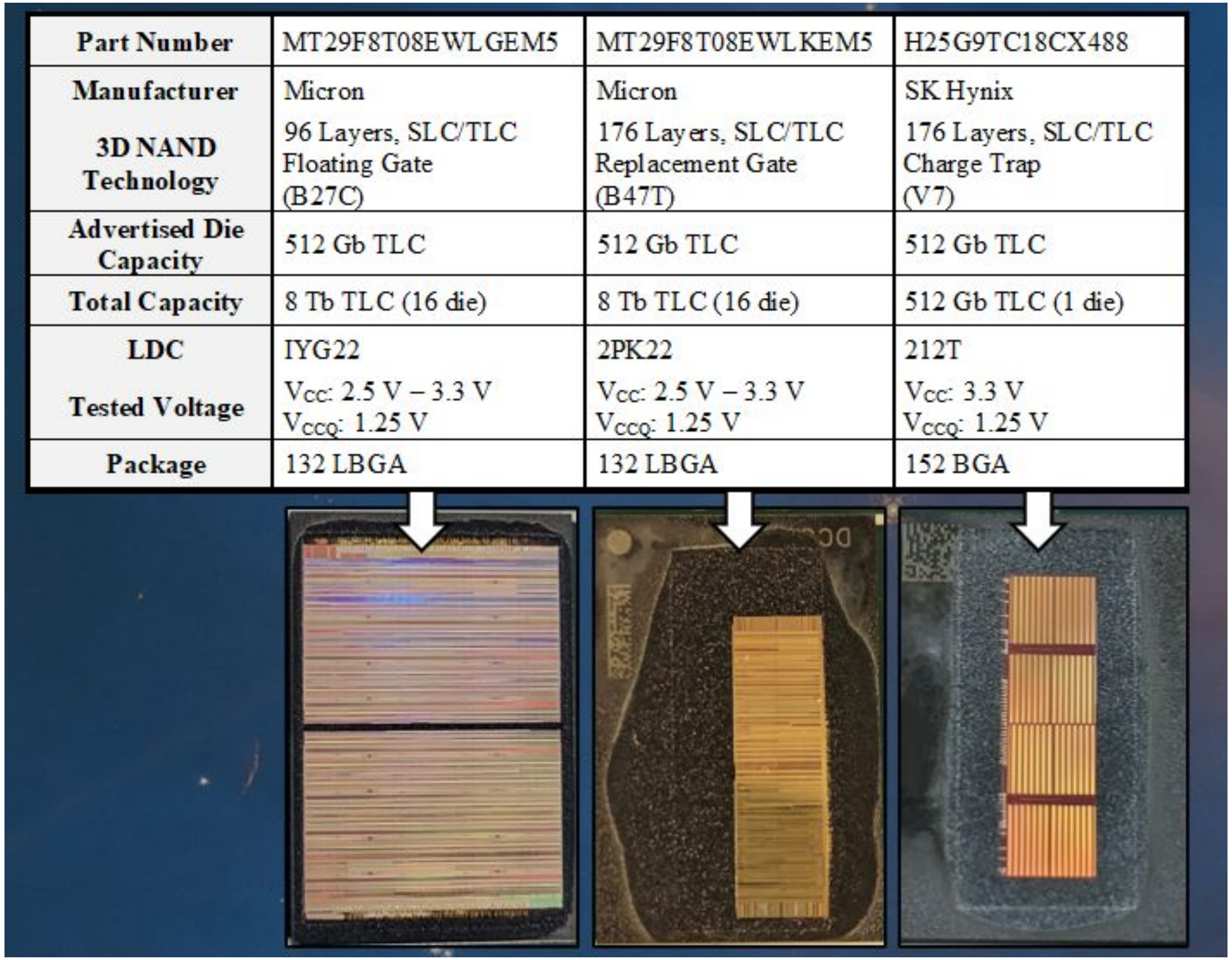






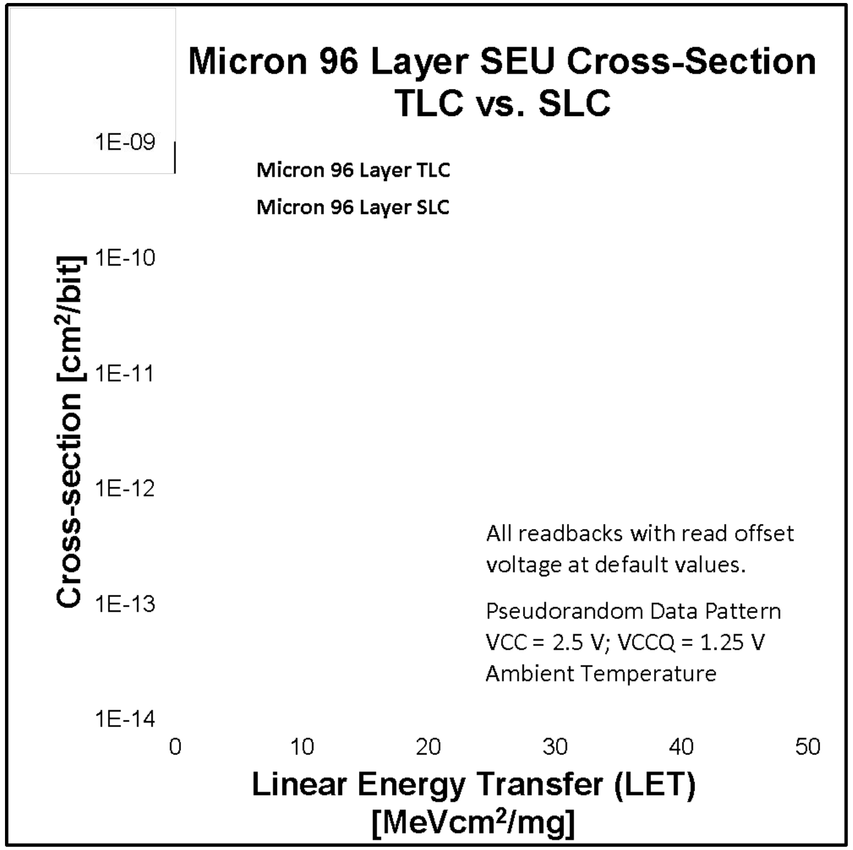
NVM TEST RESULTS, COMMON BEHAVIORS, AND IMPLICATIONS FOR SYSTEMS

Low-Level Characterization of Non-Volatile Memory



Part Number	MT29F8T08EWLGEM5	MT29F8T08EWLKEM5	H25G9TC18CX488
Manufacturer	Micron	Micron	SK Hynix
3D NAND Technology	96 Layers, SLC/TLC Floating Gate (B27C)	176 Layers, SLC/TLC Replacement Gate (B47T)	176 Layers, SLC/TLC Charge Trap (V7)
Advertised Die Capacity	512 Gb TLC	512 Gb TLC	512 Gb TLC
Total Capacity	8 Tb TLC (16 die)	8 Tb TLC (16 die)	512 Gb TLC (1 die)
LDC	IYG22	2PK22	212T
Tested Voltage	V_{CC}: 2.5 V – 3.3 V V_{CCQ}: 1.25 V	V_{CC}: 2.5 V – 3.3 V V_{CCQ}: 1.25 V	V_{CC}: 3.3 V V_{CCQ}: 1.25 V
Package	132 LBGA	132 LBGA	152 BGA

Wilcox, IEEE NSREC 2023 Dataworkshop



All readbacks with read offset voltage at default values.

Pseudorandom Data Pattern
VCC = 2.5 V; VCCQ = 1.25 V
Ambient Temperature

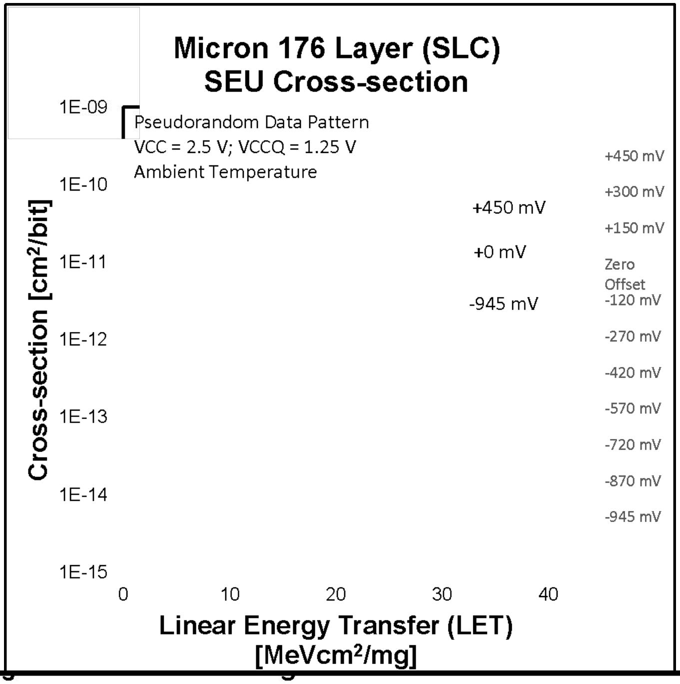
Prediction of N bit upsets (SEU) per year per device in a particular environment.

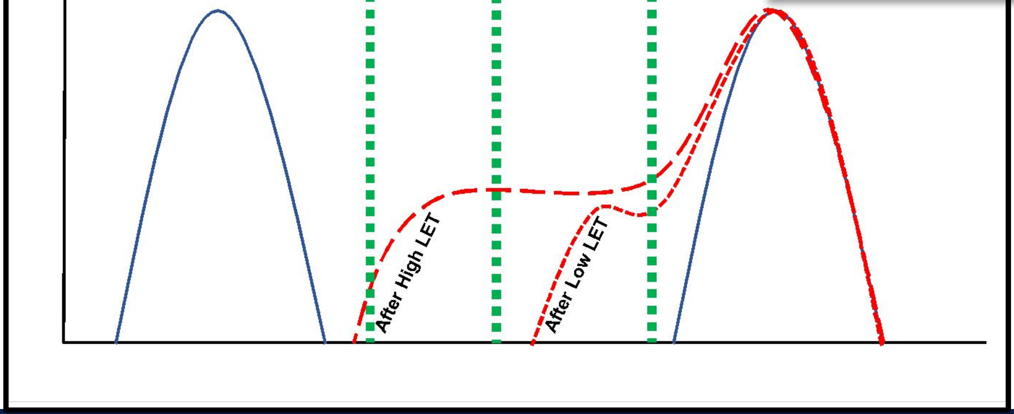
Error Signatures of Piece Part Memories

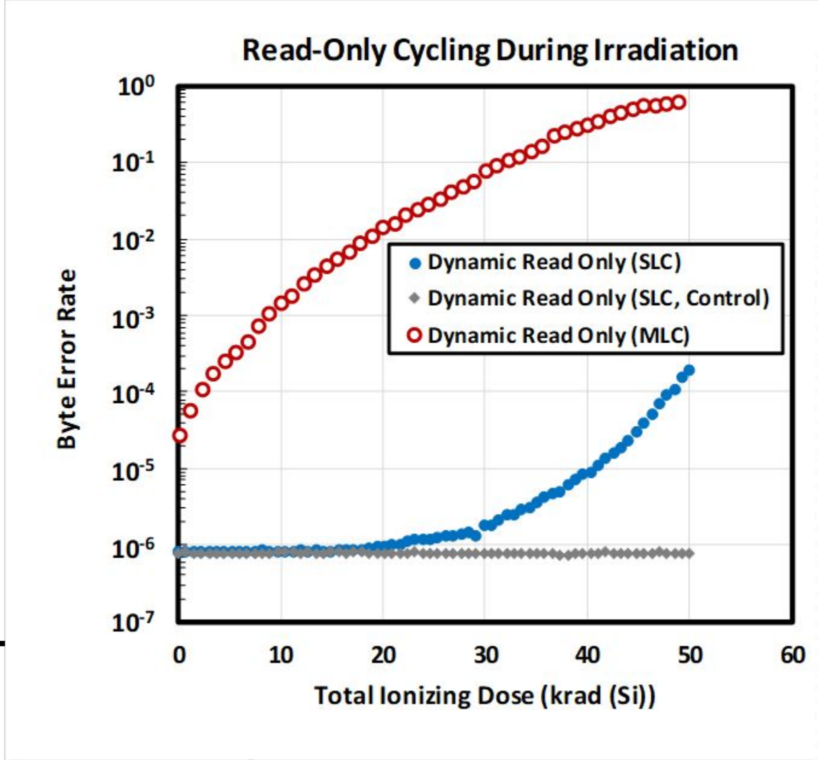
- **Single Event Effects** (totally random over time, higher with solar activity):
  - Individual random bits are changed.*
  - Isolated blocks are inaccessible.
  - Sequential or repetitive data errors (every N bytes, every N pages, etc.).
  - Sudden supply current changes (potentially destructive).
  - Reads, programs, or erases fail or take longer to complete.
  - Devices are suddenly unresponsive.
- **Total Ionizing Dose** (cumulative)
  - Long term data corruption if not refreshed periodically.*
  - Erase failures at moderate dose levels (usually the first to go)*
  - Long term increases in supply current
  - Eventual complete failure of device

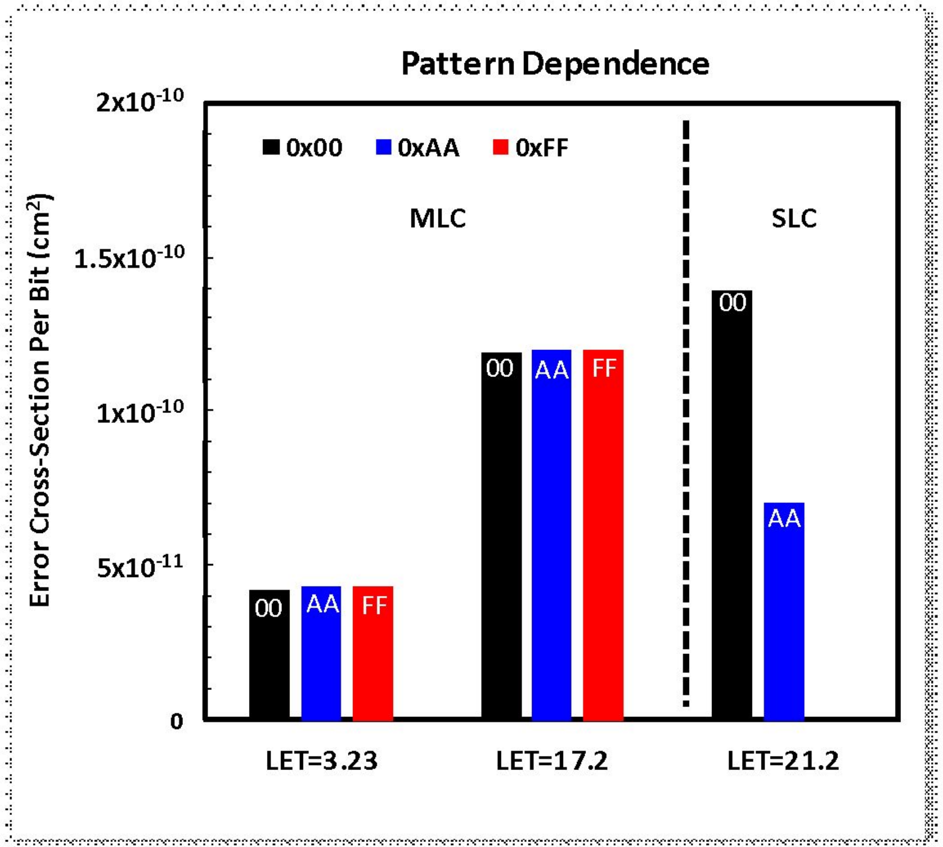
***Non-charge based (MRAM, FRAM, ReRAM, etc) are not as prone to bit cell errors or erase circuitry charge pump failures.**

Informative to System (HW/FW) Design



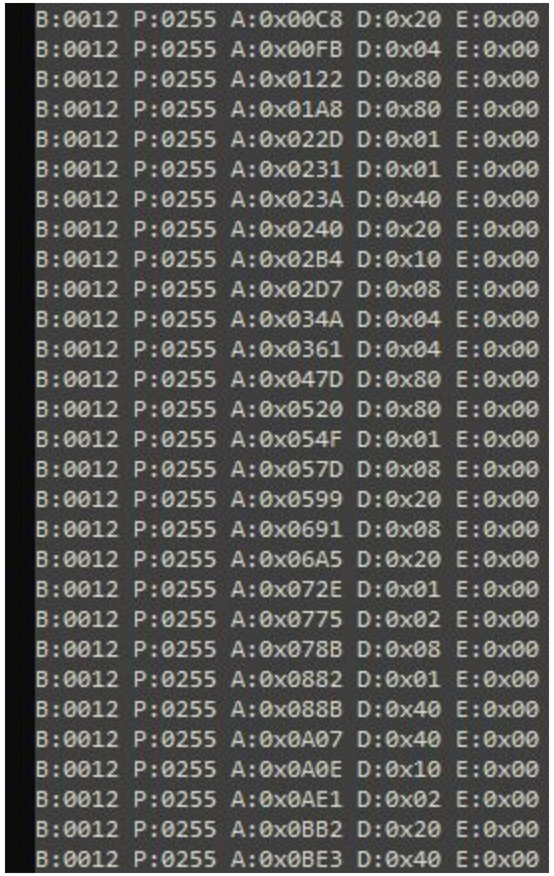






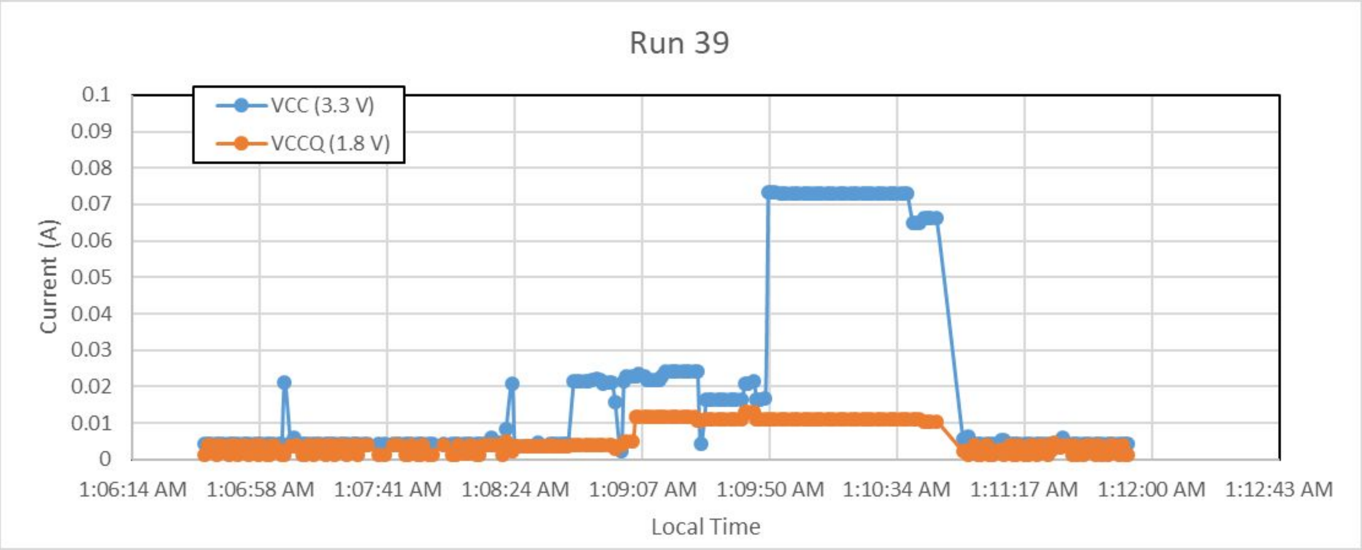
Result: Optimization of a hardware storage system for fewer bit errors

High-Level Effects (Where ECC Fails)



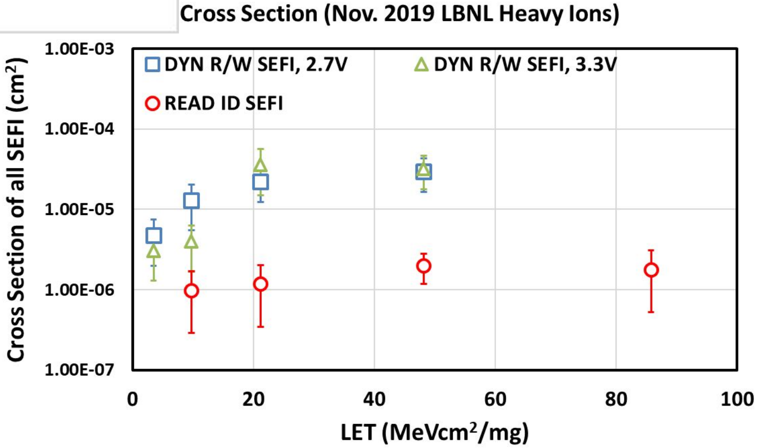
```
B:0012 P:0255 A:0x00C8 D:0x20 E:0x00
B:0012 P:0255 A:0x00FB D:0x04 E:0x00
B:0012 P:0255 A:0x0122 D:0x80 E:0x00
B:0012 P:0255 A:0x01A8 D:0x80 E:0x00
B:0012 P:0255 A:0x022D D:0x01 E:0x00
B:0012 P:0255 A:0x0231 D:0x01 E:0x00
B:0012 P:0255 A:0x023A D:0x40 E:0x00
B:0012 P:0255 A:0x0240 D:0x20 E:0x00
B:0012 P:0255 A:0x02B4 D:0x10 E:0x00
B:0012 P:0255 A:0x02D7 D:0x08 E:0x00
B:0012 P:0255 A:0x034A D:0x04 E:0x00
B:0012 P:0255 A:0x0361 D:0x04 E:0x00
B:0012 P:0255 A:0x047D D:0x80 E:0x00
B:0012 P:0255 A:0x0520 D:0x80 E:0x00
B:0012 P:0255 A:0x054F D:0x01 E:0x00
B:0012 P:0255 A:0x057D D:0x08 E:0x00
B:0012 P:0255 A:0x0599 D:0x20 E:0x00
B:0012 P:0255 A:0x0691 D:0x08 E:0x00
B:0012 P:0255 A:0x06A5 D:0x20 E:0x00
B:0012 P:0255 A:0x072E D:0x01 E:0x00
B:0012 P:0255 A:0x0775 D:0x02 E:0x00
B:0012 P:0255 A:0x078B D:0x08 E:0x00
B:0012 P:0255 A:0x0882 D:0x01 E:0x00
B:0012 P:0255 A:0x088B D:0x40 E:0x00
B:0012 P:0255 A:0x0A07 D:0x40 E:0x00
B:0012 P:0255 A:0x0A0E D:0x10 E:0x00
B:0012 P:0255 A:0x0AE1 D:0x02 E:0x00
B:0012 P:0255 A:0x0BB2 D:0x20 E:0x00
B:0012 P:0255 A:0x0BE3 D:0x40 E:0x00
```

Large portions of blocks and pages zero'd out



Static devices that start drawing current

Read/write operations that fail to complete; devices that fail to respond entirely



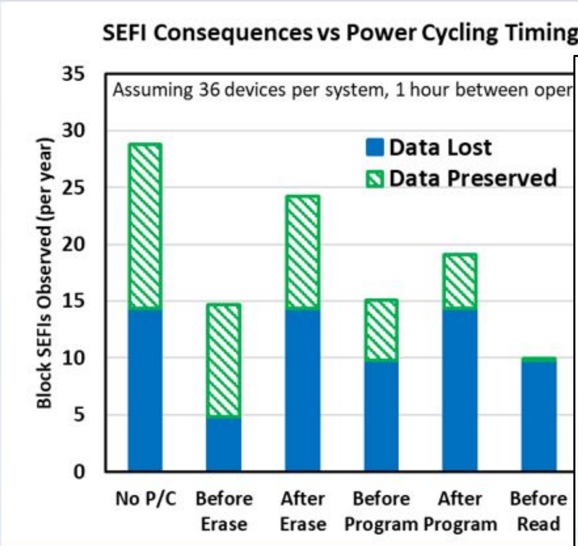
ECC built for terrestrial applications may handle upsets from ionizing radiation in space – But has no chance against block-level failures and other SEFI unique to ionizing radiation environment

Informative to Operations

The Application Matters for Mitigation

Notional Application: E | IDLE | P | IDLE | R | IDLE

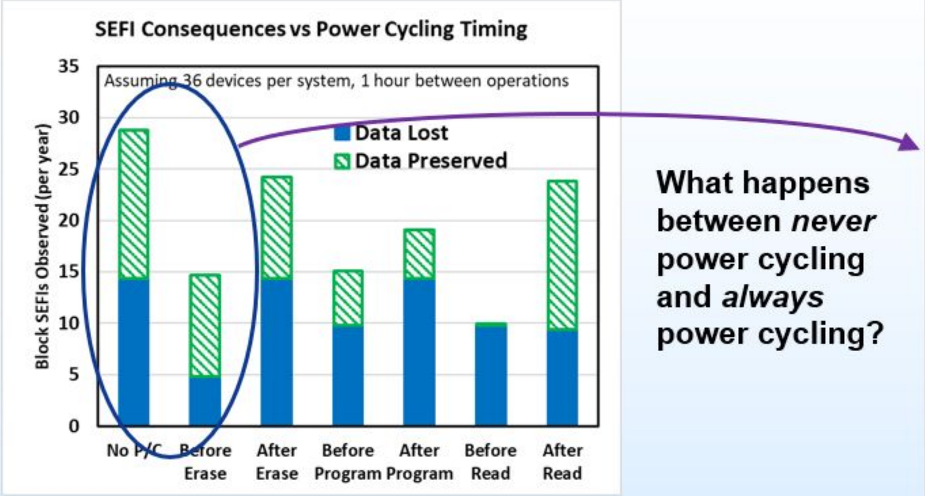
Possible Power Cycling Locations



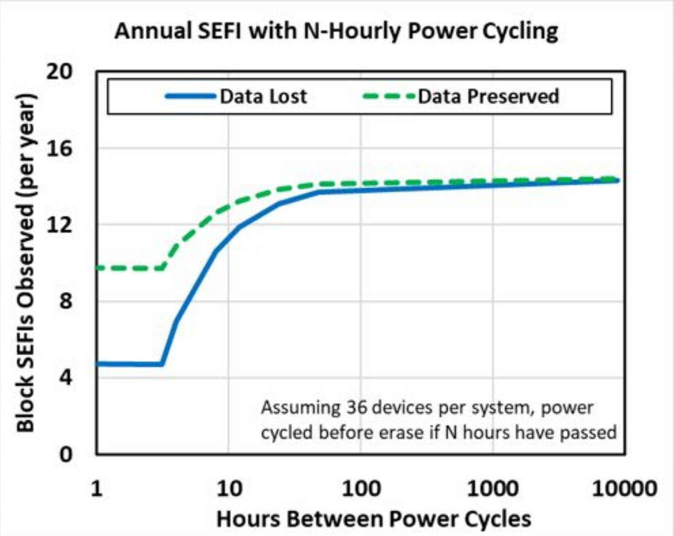
SEFI Consequences vs Power Cycling Timing

Minimizing data loss requires consid
of individual SEFI consequence

Mitigation by N-Hourly Power Cycling



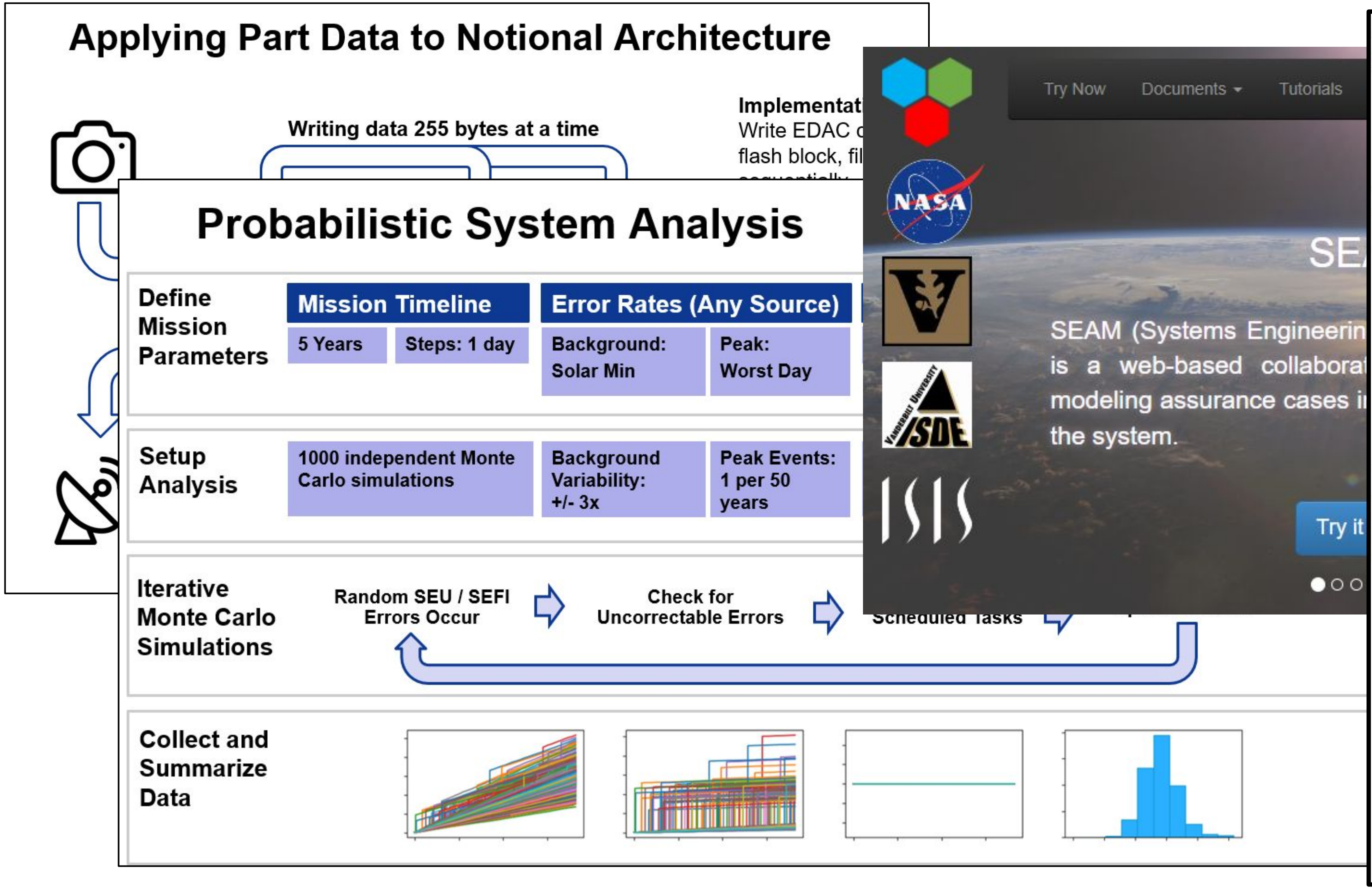
What happens between *never* power cycling and *always* power cycling?



- Power cycling daily, weekly, once-per-orbit is common suggestion → won't *eliminate* SEFIs

Wilcox, Single Event Effects Symposium, 2022

… and Architectures



Applying Part Data to Notional Architecture

Probabilistic System Analysis

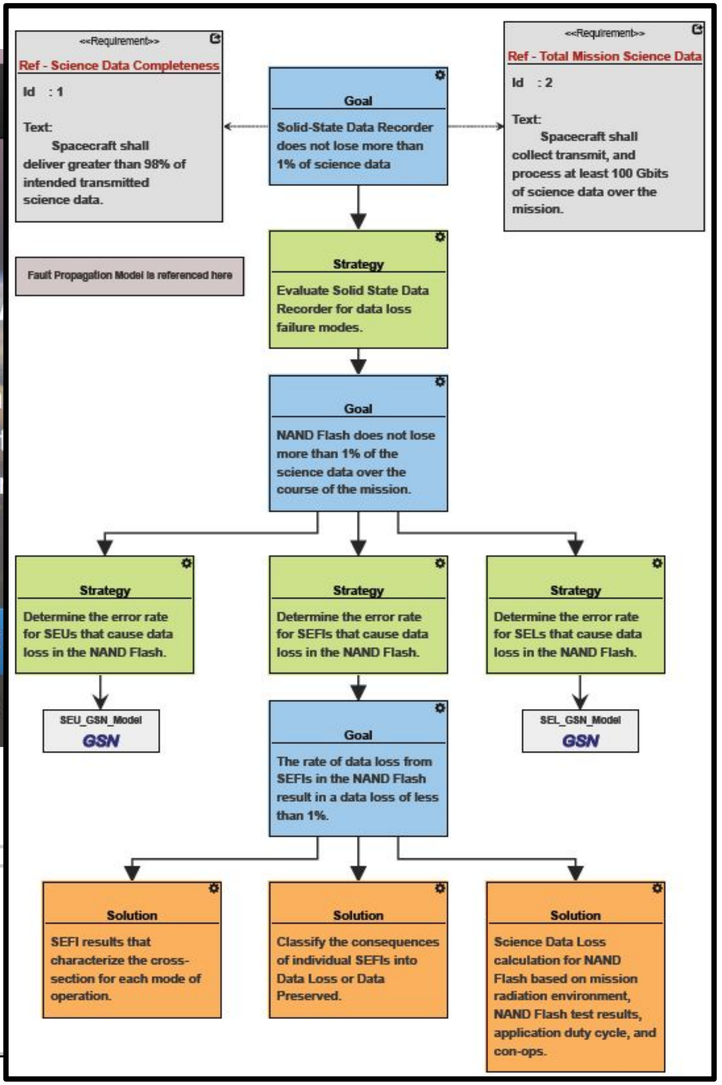
Define Mission Parameters
- **Mission Timeline**: 5 Years; Steps: 1 day
- **Error Rates (Any Source)**: Background: Solar Min; Peak: Worst Day

Setup Analysis
- 1000 independent Monte Carlo simulations
- Background Variability: +/- 3x
- Peak Events: 1 per 50 years

Iterative Monte Carlo Simulations
- Random SEU / SEFI Errors Occur
- Check for Uncorrectable Errors
- Scheduled Tasks

Collect and Summarize Data

SEAM (Systems Engineerin
is a web-based collaborat
modeling assurance cases i
the system.



<<Requirement>>
Ref - Science Data Completeness
Id : 1
Text: Spacecraft shall deliver greater than 98% of intended transmitted science data.

Goal: Solid-State Data Recorder does not lose more than 1% of science data

<<Requirement>>
Ref - Total Mission Science Data
Id : 2
Text: Spacecraft shall collect transmit, and process at least 100 Gbits of science data over the mission.

Fault Propagation Model is referenced here

Strategy: Evaluate Solid State Data Recorder for data loss failure modes.

Goal: NAND Flash does not lose more than 1% of the science data over the course of the mission.

Strategy: Determine the error rate for SEUs that cause data loss in the NAND Flash.

Strategy: Determine the error rate for SEFIs that cause data loss in the NAND Flash.

Strategy: Determine the error rate for SELs that cause data loss in the NAND Flash.

SEU_GSN_Model GSN

SEL_GSN_Model GSN

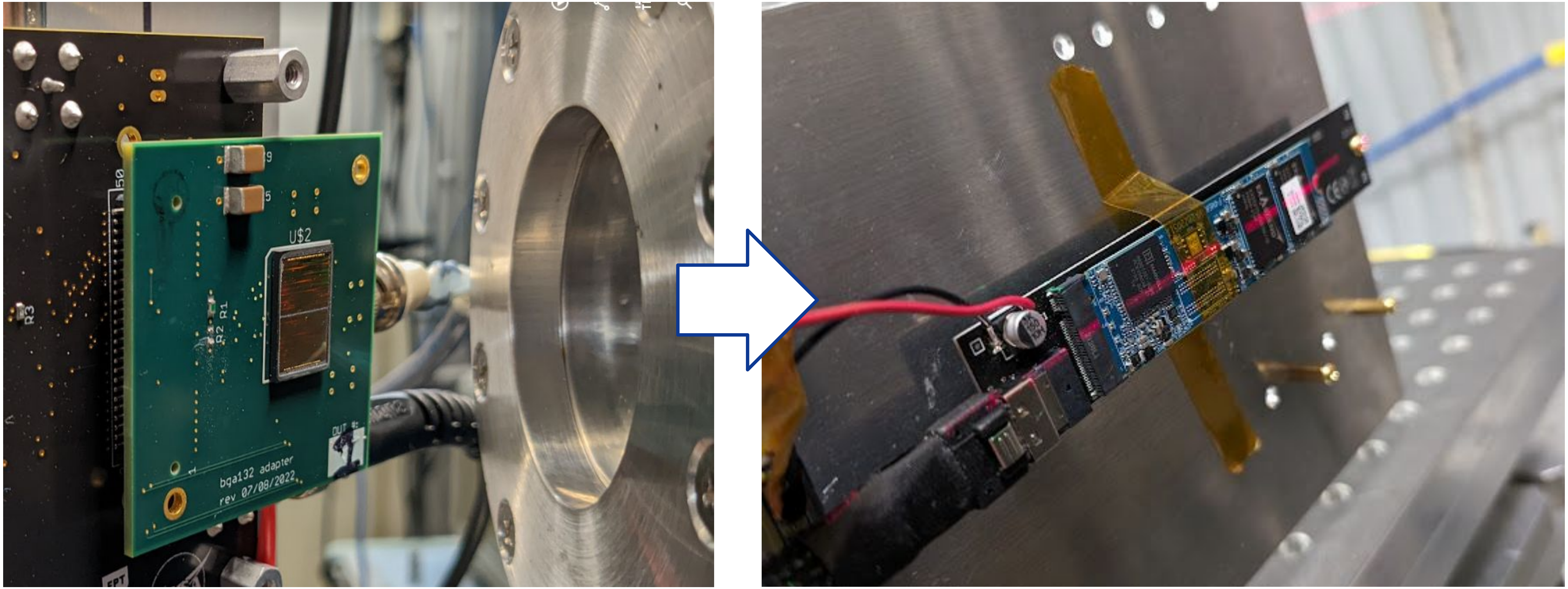
Goal: The rate of data loss from SEFIs in the NAND Flash result in a data loss of less than 1%.

Solution: SEFI results that characterize the cross-section for each mode of operation.

Solution: Classify the consequences of individual SEFIs into Data Loss or Data Preserved.

Solution: Science Data Loss calculation for NAND Flash based on mission radiation environment, NAND Flash test results, application duty cycle, and con-ops.

Tackling the problem from the system first…



How do individual bits behave under irradiation?

How does the system react when it is under irradiation?

Very High-Level SEE Testing

Power On

Initiate Active R/W

Beam On

No

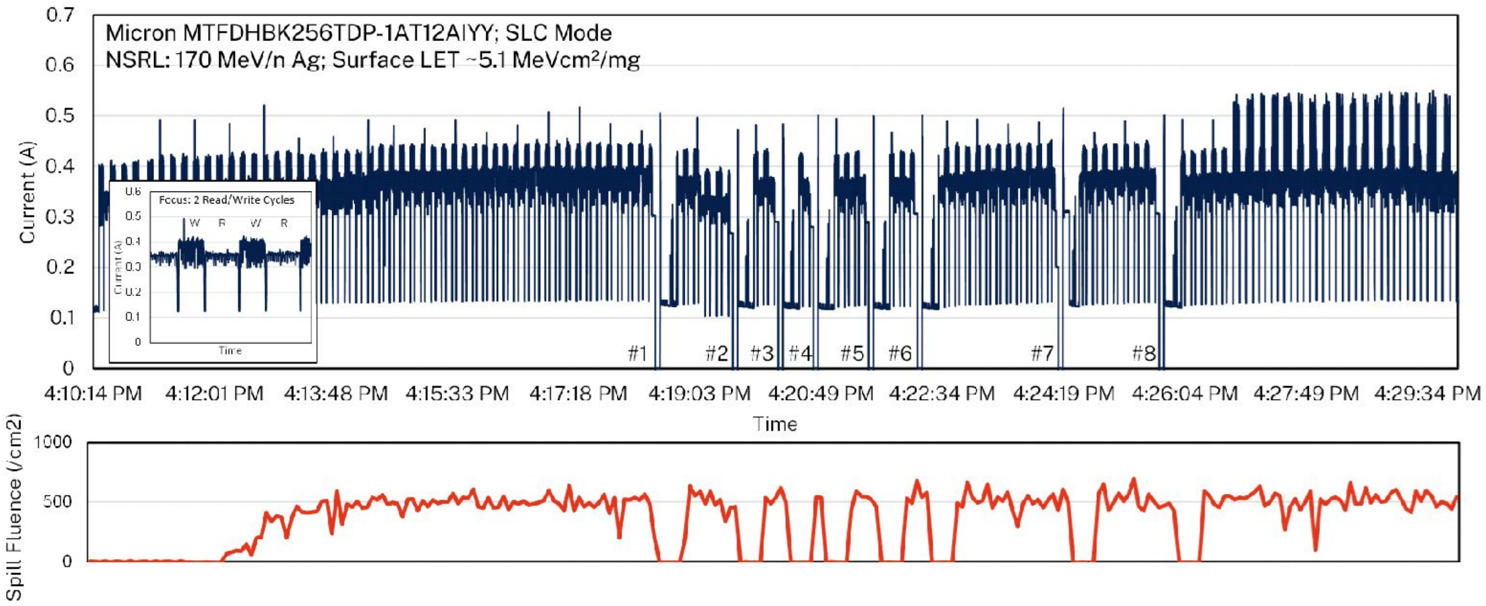
Error?

Yes

Wait

Beam Inhibit

Power Off



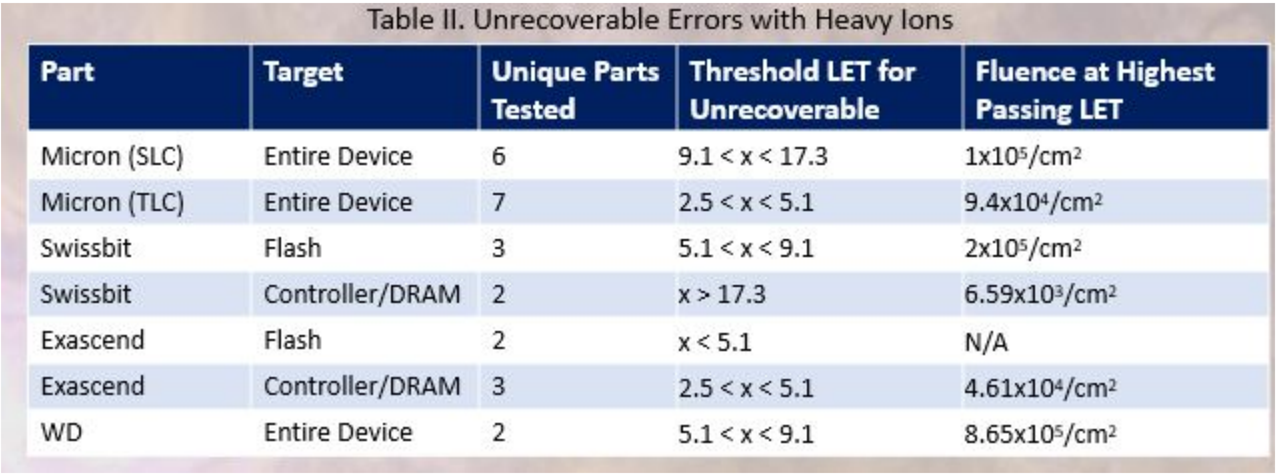
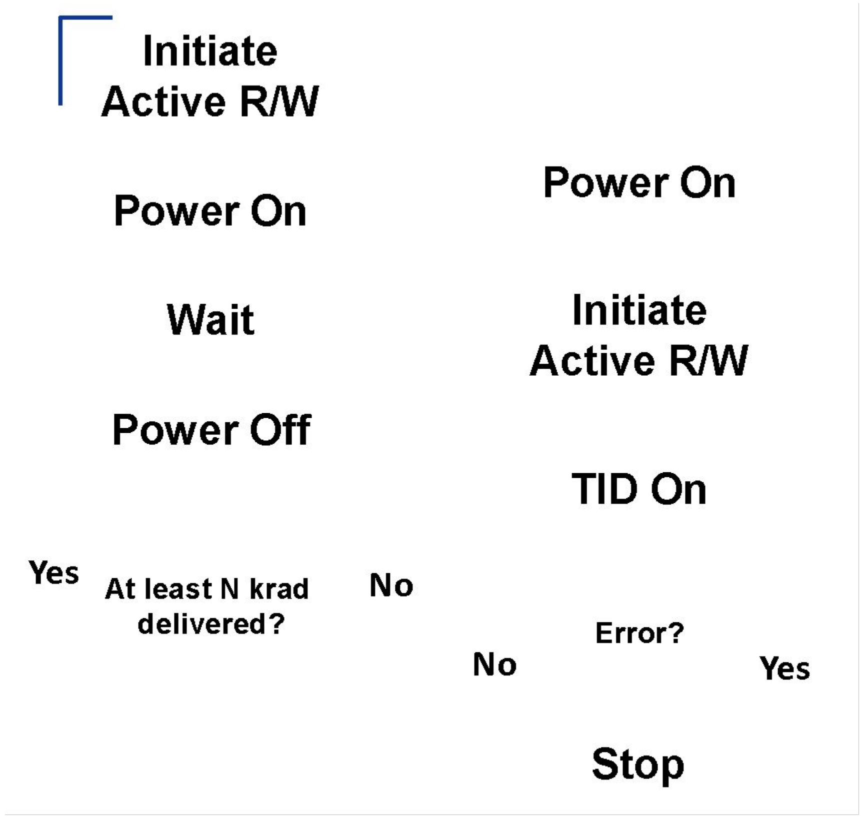


Table II. Unrecoverable Errors with Heavy Ions

Part	Target	Unique Parts Tested	Threshold LET for Unrecoverable	Fluence at Highest Passing LET
Micron (SLC)	Entire Device	6	9.1 < x < 17.3	1x10^5/cm^2
Micron (TLC)	Entire Device	7	2.5 < x < 5.1	9.4x10^4/cm^2
Swissbit	Flash	3	5.1 < x < 9.1	2x10^5/cm^2
Swissbit	Controller/DRAM	2	x > 17.3	6.59x10^3/cm^2
Exascend	Flash	2	x < 5.1	N/A
Exascend	Controller/DRAM	3	2.5 < x < 5.1	4.61x10^4/cm^2
WD	Entire Device	2	5.1 < x < 9.1	8.65x10^5/cm^2

Wilcox, NSREC 2024

Very High-Level TID Testing



Initiate Active R/W

Power On

Wait

Power Off

Yes

At least N krad delivered?

No

Power On

Initiate Active R/W

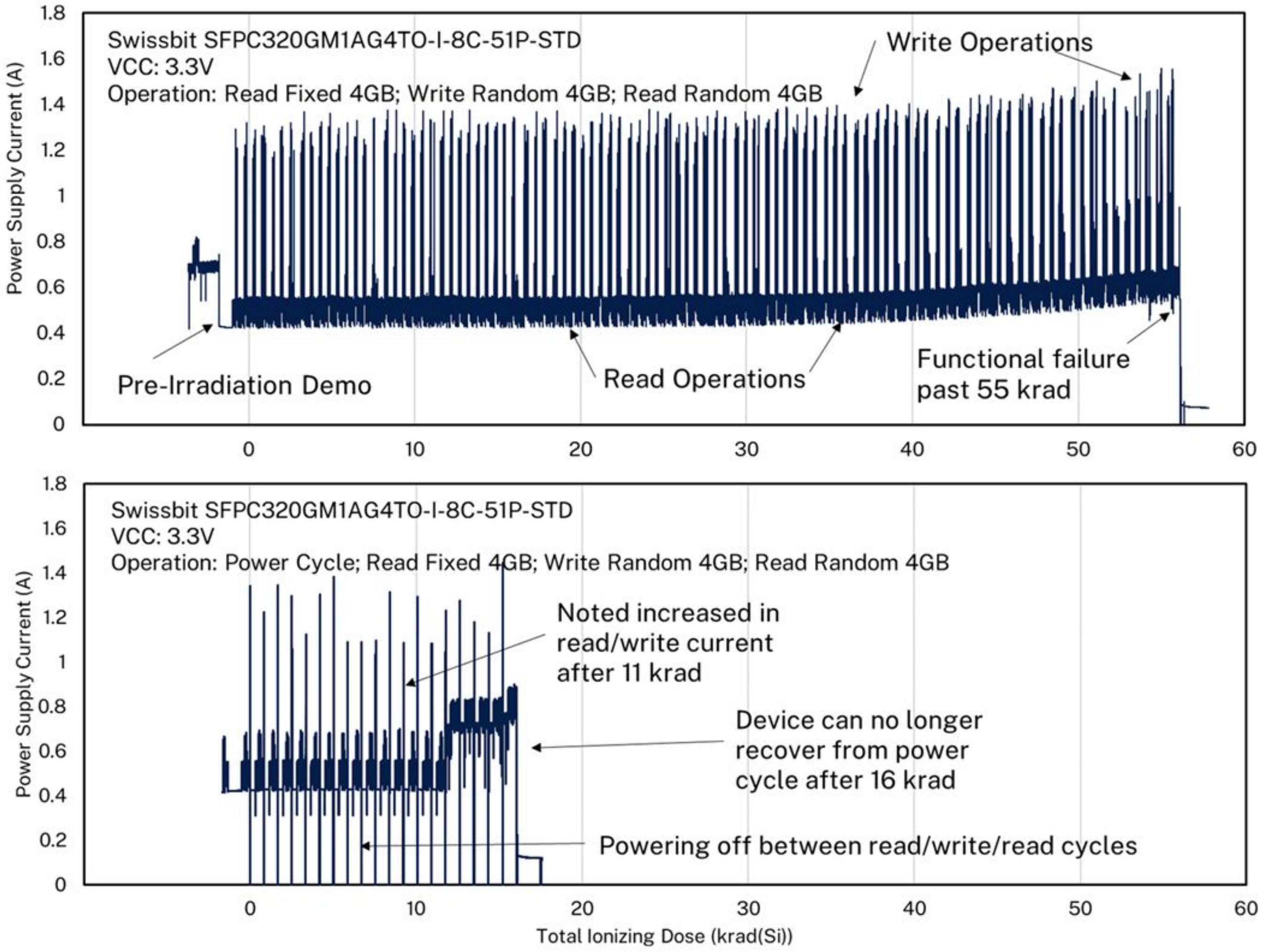
TID On

No

Error?

Yes

Stop



Error Signatures at the Drive Level

- **Single-Event Effects**
  - Suddenly unresponsive to any command.
  - Locked into read-only mode.
  - Visible to system but incapable of any reads or writes.
  - Sudden supply current changes
  - Marked decrease in read or write speeds.
  - Changes in device ID and other meta data.
- **Total Ionizing Dose**
  - Degraded read/write speeds
  - Long-term data corruption
  - Slow increase supply current
  - Failure to boot
  - Eventual failure to operate

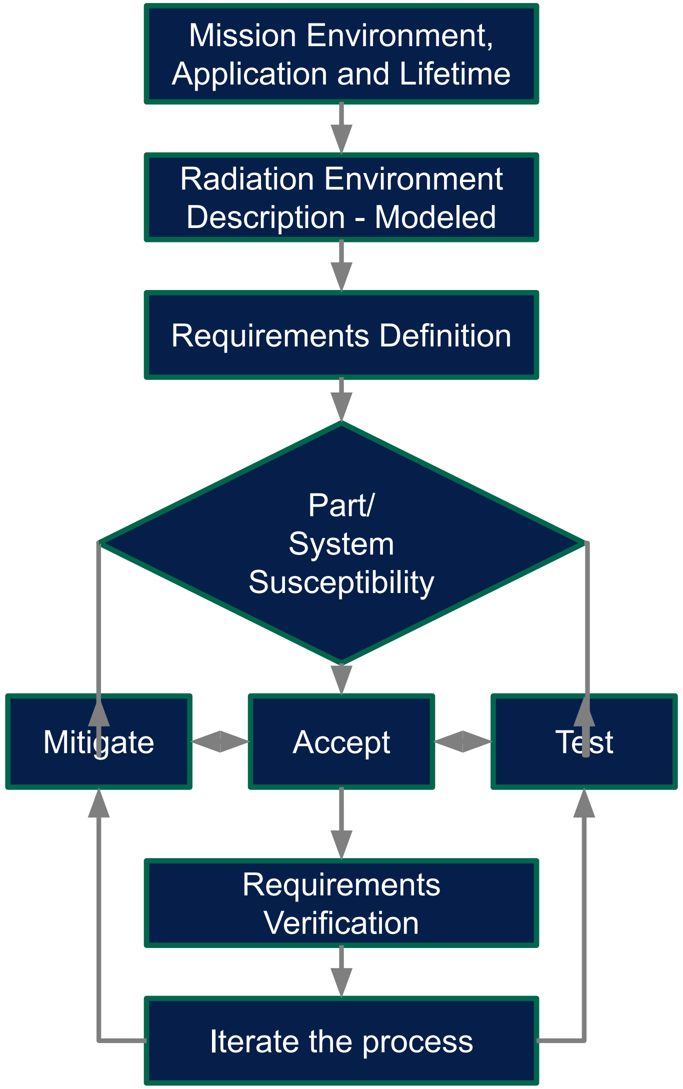
None of these are expected by a normal consumer OS or firmware and may be poorly handled.

Operational Effects As a Result

- FPGA- or Microcontroller-based tests of piece parts can be crafted to detect, characterize, and recover virtually any effect observed in a discrete memory.
- With our OS-based testers using commercial solid-state drives, we observe
  - Operating system crashes when directly tied to bu
  - Unmounted drives tha
  - Los
  - Une ed or high latency
  - Inab failure (the drive firmware itself)
  - Unintended activation while sleeping
  - Test challenges due to black box activities within drive (re-mapping, rebuilding)
  - Essentially no flipped bits at user level
  - Lack of transparency re: operations that failed during beam or when failure occurred
  - Odd device-specific behavior, like capacity changes or device lockdown

Robust software will expect memory failures that are not relevant to automotive or datacenter applications.

Classical Radiation Hardness Assurance



Mission Environment, Application and Lifetime

Radiation Environment Description - Modeled

Requirements Definition

Part/ System Susceptibility

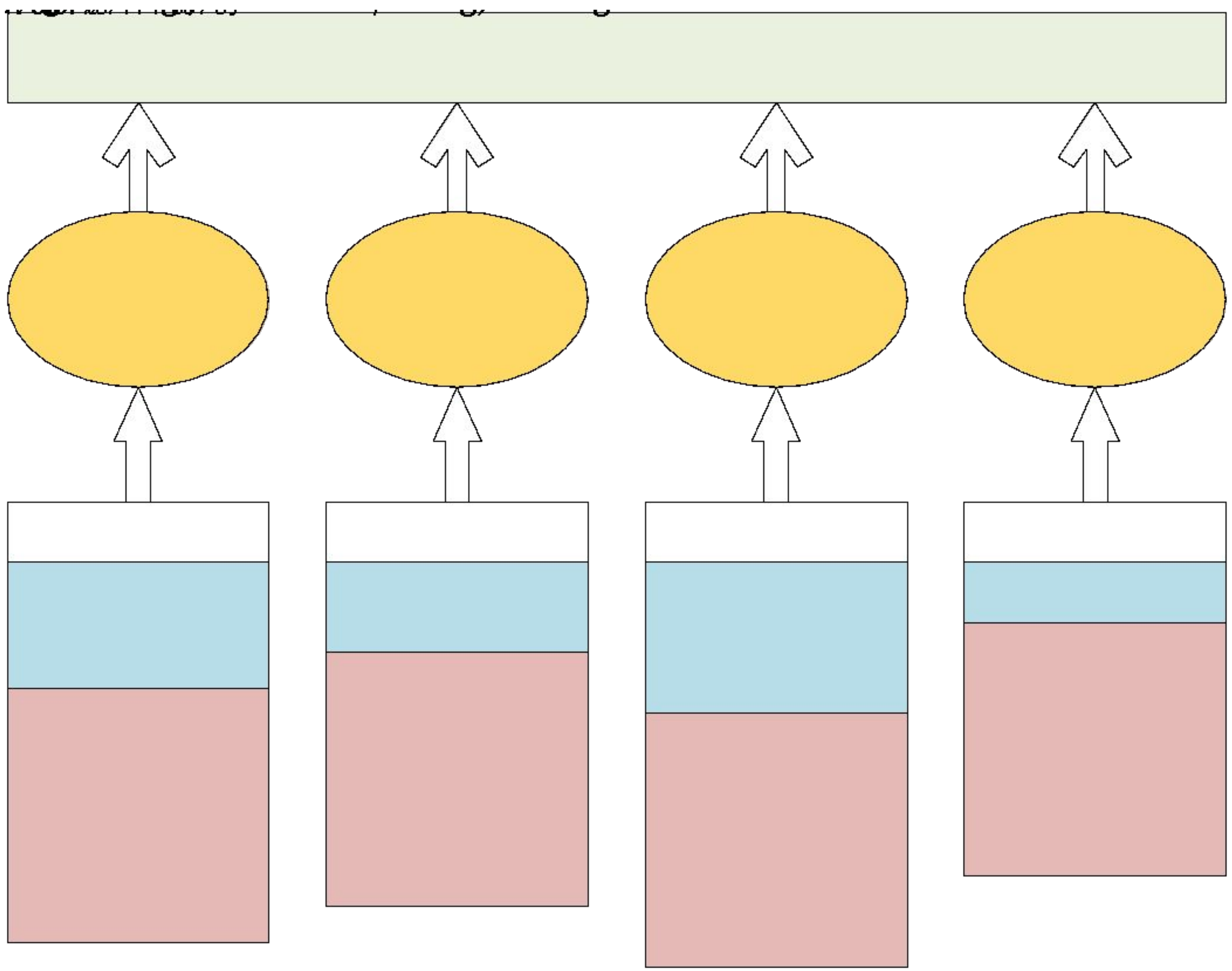
Mitigate

Accept

Test

Requirements Verification

Iterate the process



All predicated upon up-front knowledge of parts, testing of part performance, and system adjustments to compensate

Challenges faced in a world of systems

Survivability

- Must survive until needed
- Entire mission?
- Screening for early failures in components

Availability

- Must perform when necessary
- Subset of time on orbit
- Operational modes
- Environmental response

Criticality

- Impact to the system
- Part or subsystem function
- Mission objectives

Reliability

- Resultant of all
- Many aspects and disciplines
- Known unknowns

- **We are working complex interactions of hardware and software**
- **To be clear: radiation is not fixable with software or fault-tolerant design, but they are part of the solution.**
- **There are always transistor-level failure modes that may exist**
- **May be masked by relatively benign (in the classical sense) errors that are not handled by a system not design for radiation effects.**

Final Thoughts

- Zero trust of unknown hardware systems (e.g., a datacenter SSD) operating in unplanned environments (e.g., LEO)
- Verify, retry, recover, or restart when needed with minimal overhead
- I expect a reduction in confidence in test data at the system/block level; significant unknown unknowns are hard to find. However, parts level testing is of lesser value if the system is a black box.
- Intrinsically radiation-tolerant solid state drives do not appear to exist
- Memories have memory – consider that effects may persist and yet be recoverable
- Certain memories may accumulate errors when turned off; consider implications of 8 year interplanetary cruise on a COTS flash array