



Radiation Testing Electronics with Heavy Ions-The Best Way to Hit a Target Moving Ever Exponentially Faster

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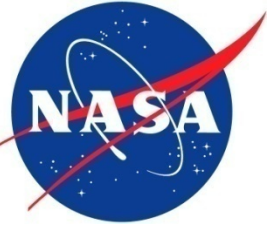
NASA Goddard Space Flight Center



Abbreviations

BNL—Brookhaven National Laboratory
CMOS—Complementary Metal-Oxide-Semiconductor
DRAM—Dynamic Random Access Memory
DUT—Device Under Test
E—Energy
 E_{dep} —Deposited Energy (by charge track)
eV—electron-Volt (also, GeV, MeV...)
GCR—Galactic Cosmic Rays
GEO—Geostationary Equatorial Orbit
GPU—Graphics Processing Unit
ISS—International Space Station
LBNL—Lawrence Berkeley National Laboratory
LEO—Low-Earth Orbit
LET—Linear Energy Transfer
MOSFET—Metal-Oxide-Semiconductor Field Effect Transistor

MSU—Michigan State University
NSCL—National Superconducting Cyclotron Lab.
NSRL—NASA Space Radiation Laboratory
SEE—Single-Event Effect
SEL—Single-Event Latchup
SIP—System In a Package
SPE—Solar Particle Event
SDRAM—Synchronous DRAM
SRAM—Synchronous Random Access Memory
SV—Sensitive Volume for a SEE
WC—Worst Case
WD—Worst Day
Z=Atomic # identifying element



Outline: Change Is Good; Change is Job Security

I. Basics of Single-Event Effects (SEE)

- A. Space Environments
- B. Mechanisms
- C. Testing And Hardness Assurance

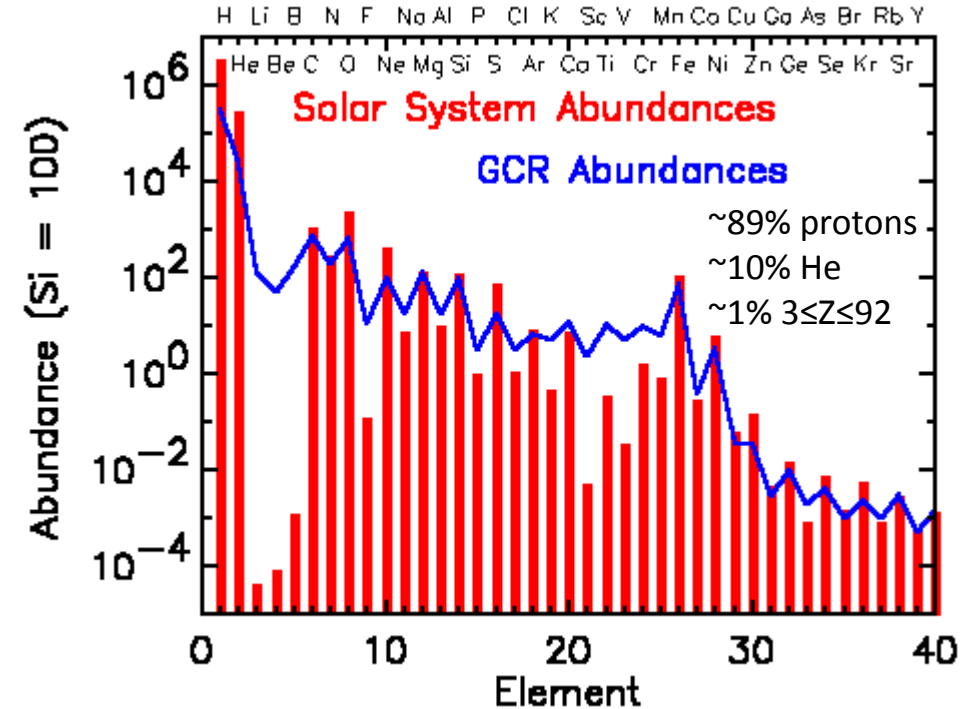
II. Microelectronics and Moore's Law

III. SEE Frontiers

- A. Technology Frontier
- B. Low-Energy Frontier
- C. High-Energy Frontier
- D. Cost and Accessibility Frontiers

IV. Other Developing Issues

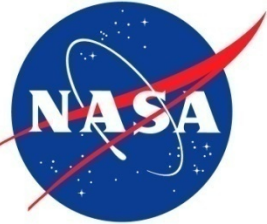
V. Conclusions



https://imagine.gsfc.nasa.gov/science/objects/cosmic_rays2.html

Above: Differences between elemental abundances in the Solar System and in Galactic Cosmic Rays (GCR) arise largely due to interactions between primary GCR ions and the interstellar plasma. This serves as an indicator of how far the GCR ions have traveled just to mess with your satellite.

Single-Event Effects (SEE): Why Do We Care?



- Two types of radiation effects
 - Cumulative (dose) effects result from long-term exposure to radiation environment
 - SEE occur promptly due to a **single particle** strike
- SEE are Poisson processes
 - Can occur any time in mission—first day to last
- Consequences limited to single part and range from
 - Self-recovering transient glitch
 - Correctable corruption of one or more bits of data
 - Uncorrectable corruption of data
 - Recoverable loss of partial or full device functionality
 - Catastrophic failure
 - Depends on part technology
- SEE can affect any mission
 - Any mission duration
 - Any environment (even terrestrial due to neutrons)

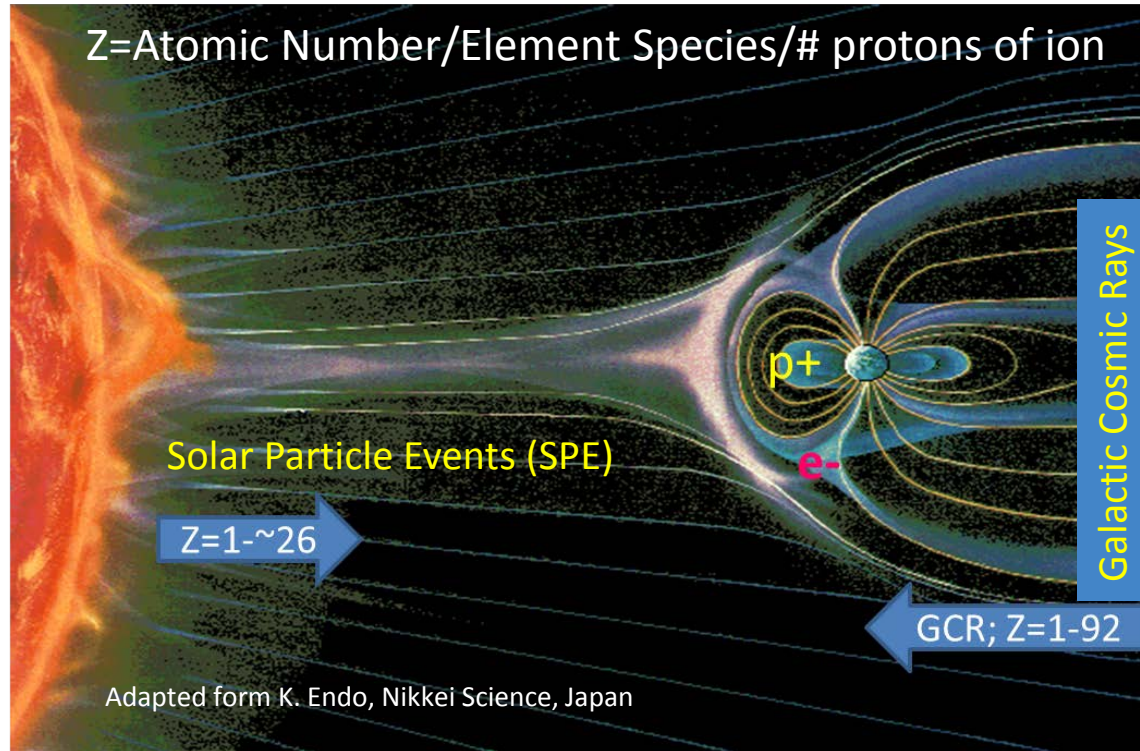
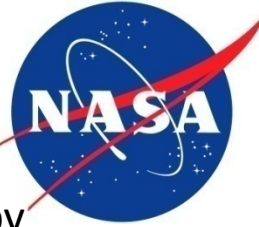


Adapted from H. Becker, IEEE Trans. Nucl. Sci. V. 49, p. 3009, 2002

Molten metal caused by high current from Single-Event Latchup (SEL).

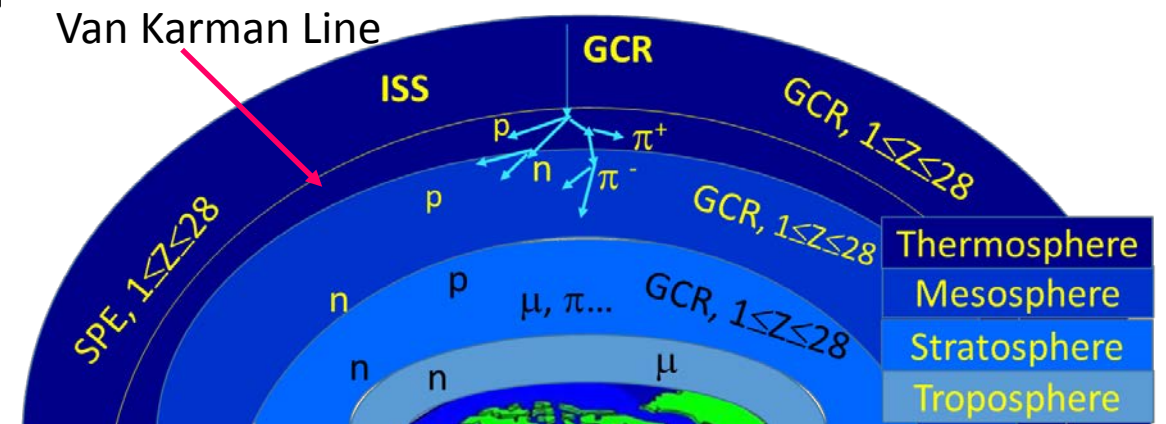
- Recent National Academies study: 25-50% of spacecraft anomalies due to SEE (depends on spacecraft orbits)
- SEE are often a significant barrier for use of state-of-the-art, high-performance parts and commercial systems
- SEE testing is often costly and challenging
 - Testing of a complex part (e.g. processor or other very complex part can take >1 year and cost >\$200K)
 - Assurance vs. cost is a continual trade-off w/ SEE testing

SEE Radiation Environments

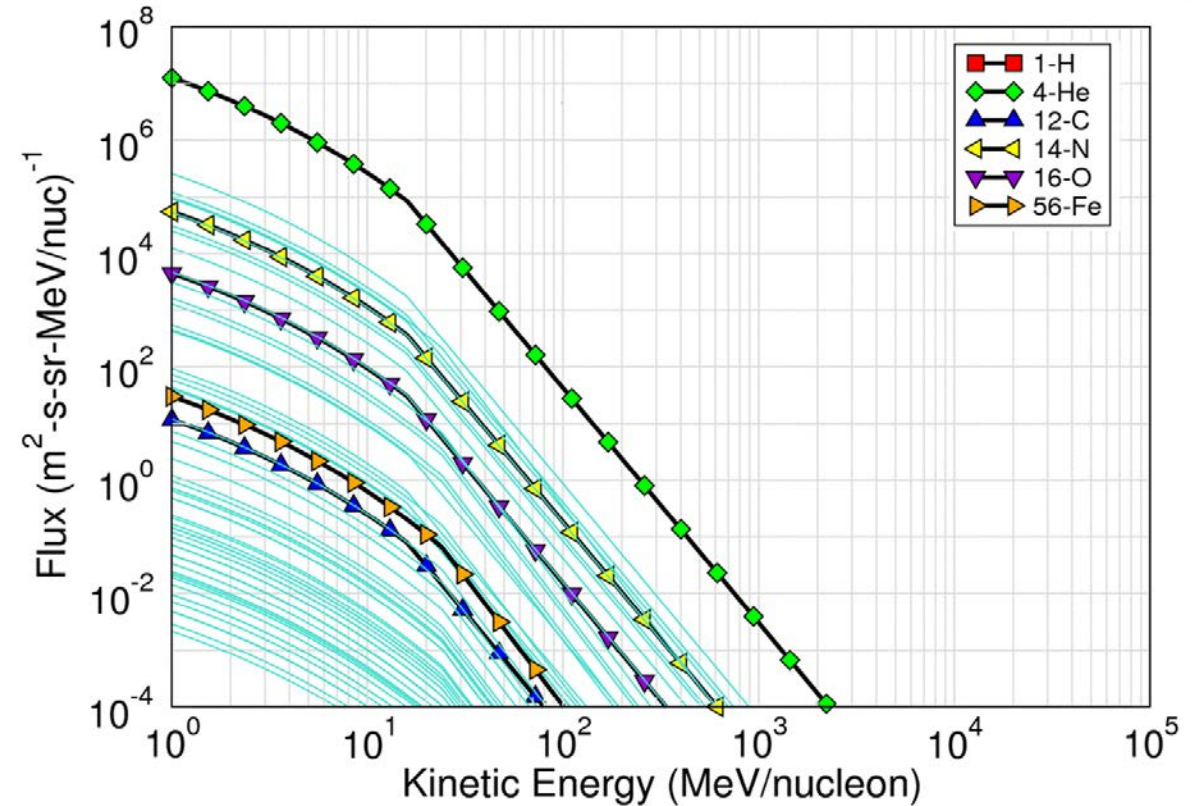
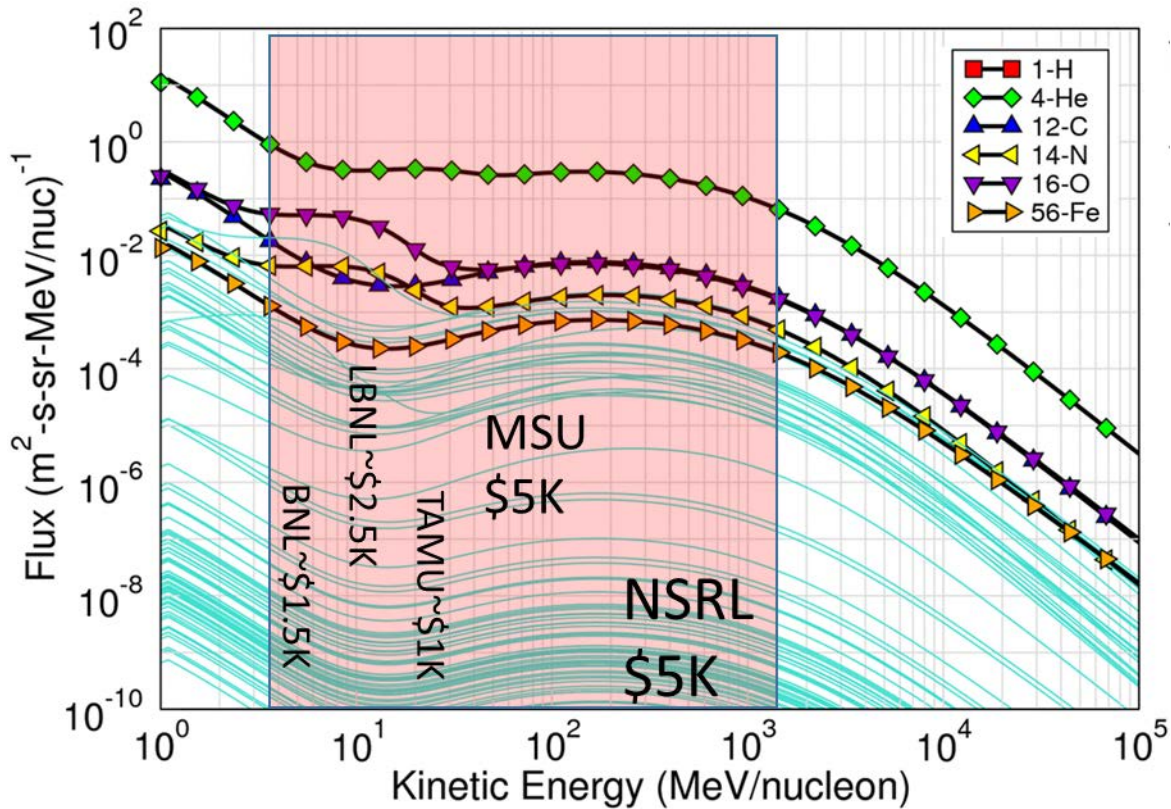


- Terrestrial radiation environment produced by interactions between GCR and SPE.
- Measurable GCR flux persists into the upper stratosphere
- In troposphere and at Earth's surface, mainly neutrons and muons (a few/cm²/s)
 - Flux worse near poles and at high altitude.
 - Neutrons cause SEE only by indirect ionization
 - Muons could cause SEE by indirect ionization, but low mass equates to low momentum transfer.
 - Not an issue yet at nominal supply voltages.

- Space radiation environment has 2 ion sources/types
 - Galactic Cosmic Rays (GCR) have Atomic # $1 \leq Z \leq 92$ and energies ~ 100 s of MeV/nucleon (shielding ineffective)
 - Solar Particle Events (SPE) have $1 \leq Z \leq \sim 26$ and energies up to ~ 10 s of MeV/nucleon (shielding can be effective)
- Protons/electrons trapped by planetary magnetic fields to form radiation belts



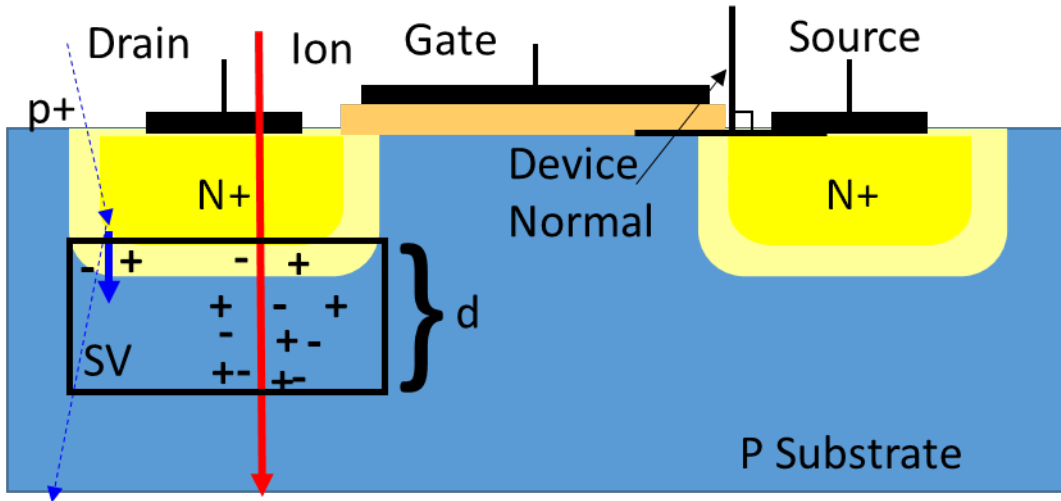
Heavy-Ion Environments: Space vs. Test



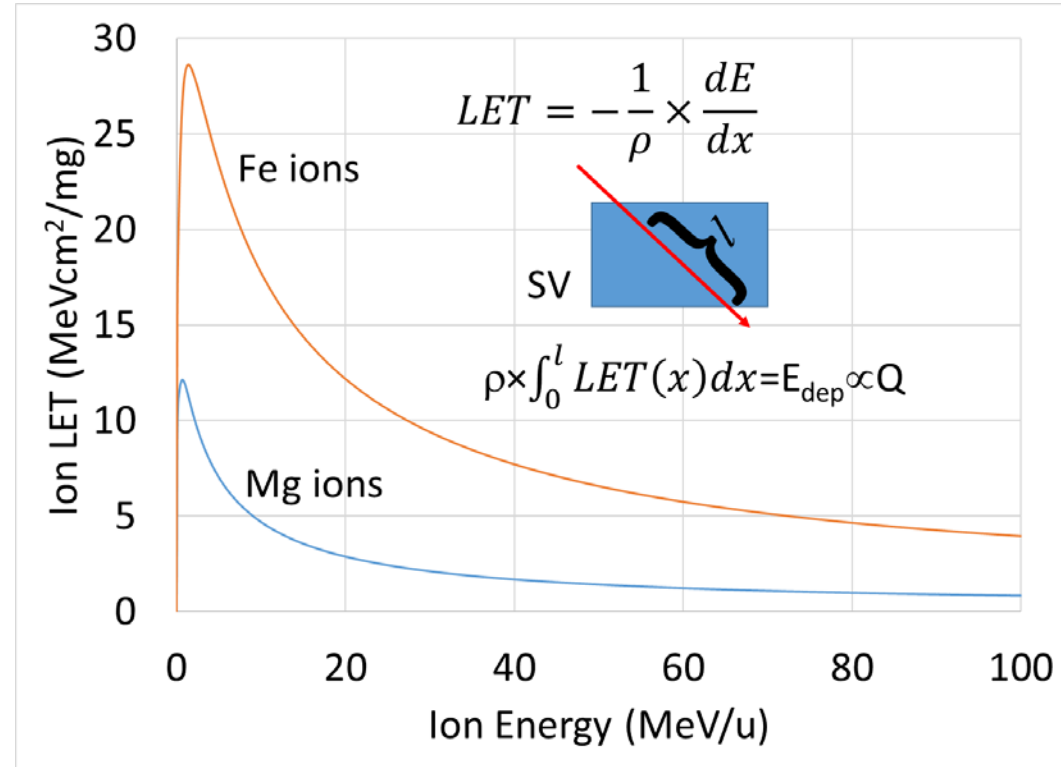
- Ideally, prefer test w/ ions characteristic of space
- GCR ions fairly flat out to >2 GeV/nucleon (min. ionizing)
- Difficult and expensive to achieve at accelerators

- SPE ions closer to accelerator energies
 - Lower energy (higher LET) drives rates for lightly shielded devices
 - Moderate shielding significantly decreases SPE rates
- Heavy-ion content highly variable event to event

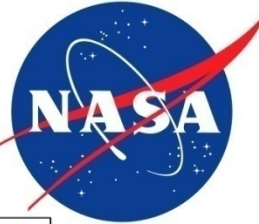
SEE Mechanisms and Consequences



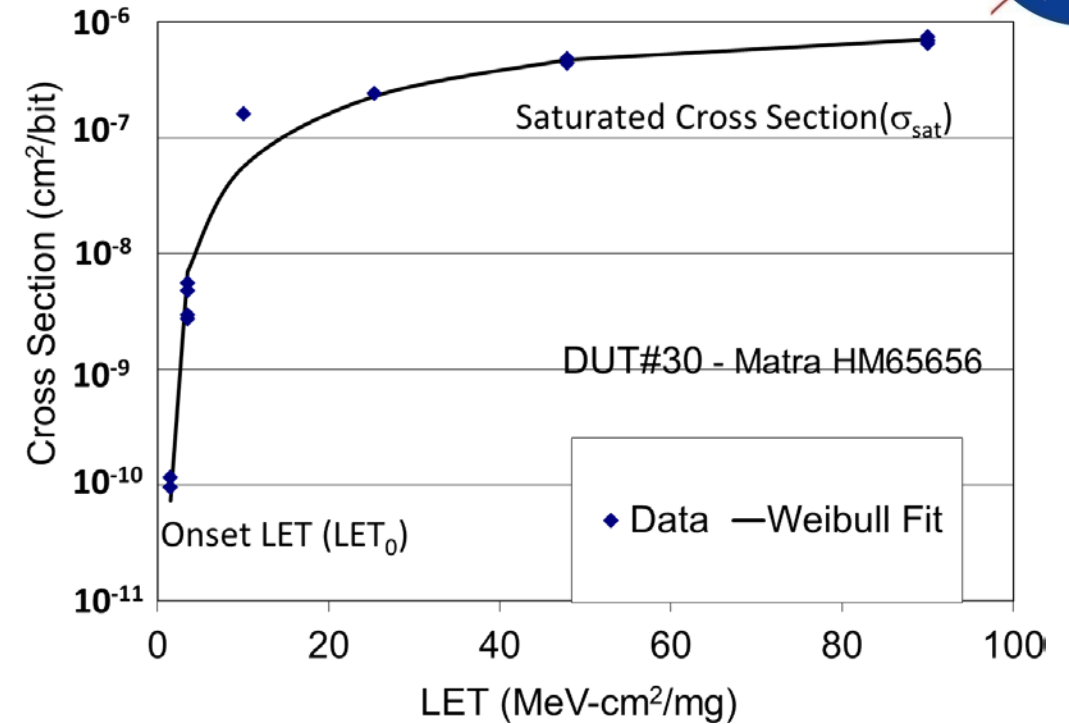
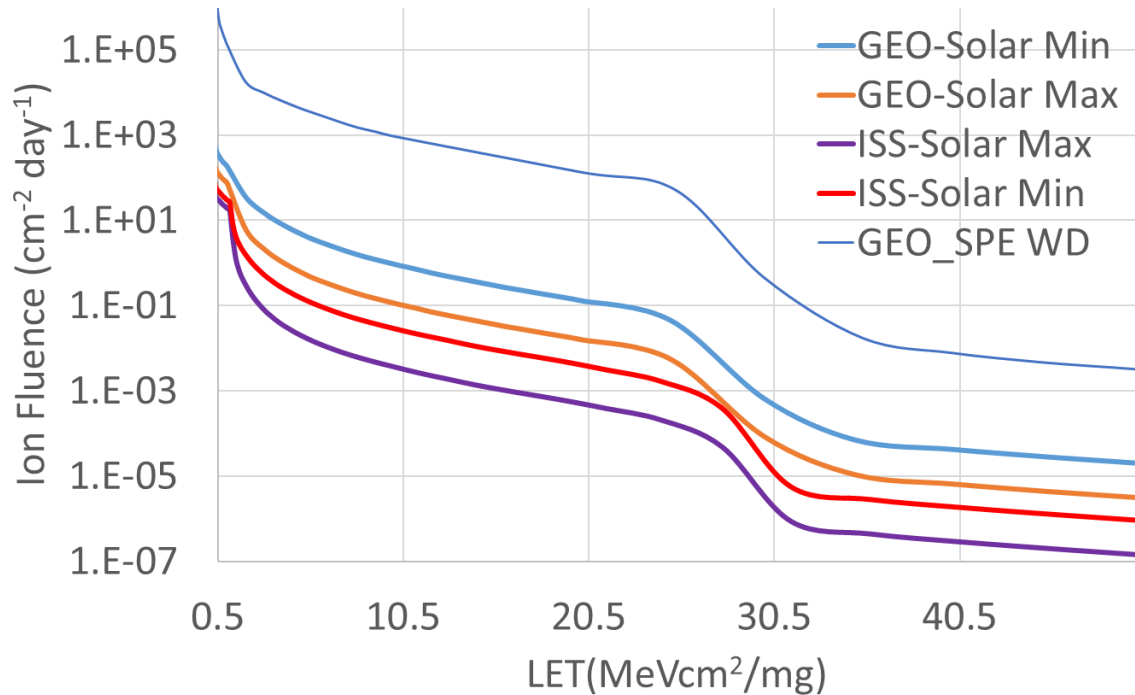
- Single-Event Effect (SEE)—a change in state, data, output or function due to charge from a single ionizing particle through a sensitive volume (SV) in the device. Can happen any time (Poisson process).
 - Particle may be primary (red arrow) from space environment or secondary (solid blue arrow)—that is generated by scattering of primary particle
 - SEE occurs when charge reaches critical charge Q_c and probability increases with increasing charge



- Charge scales \sim w/ ion LET if LET \sim constant along paths in SV
- Bin ions by LET to separate environment and device response
 - Significantly simplifies SEE rate estimation



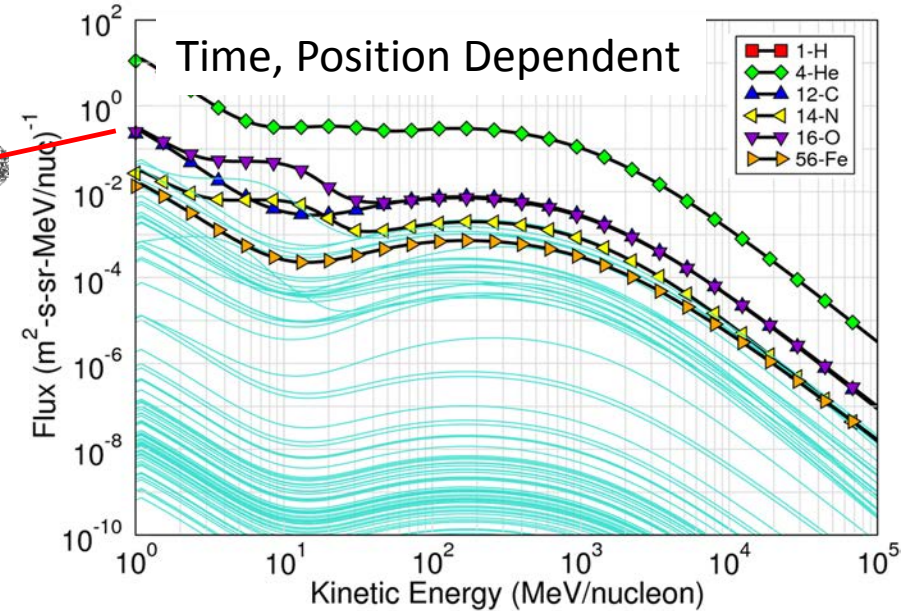
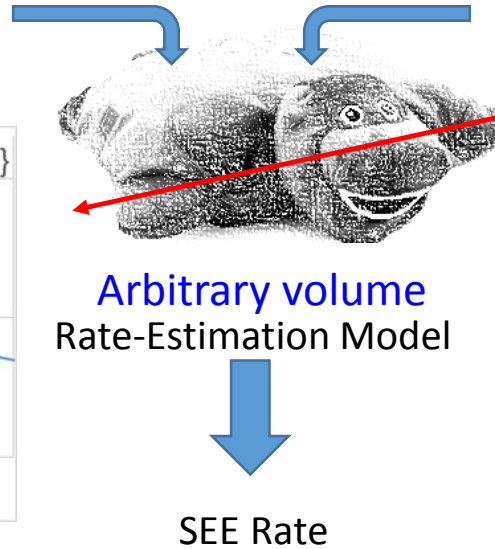
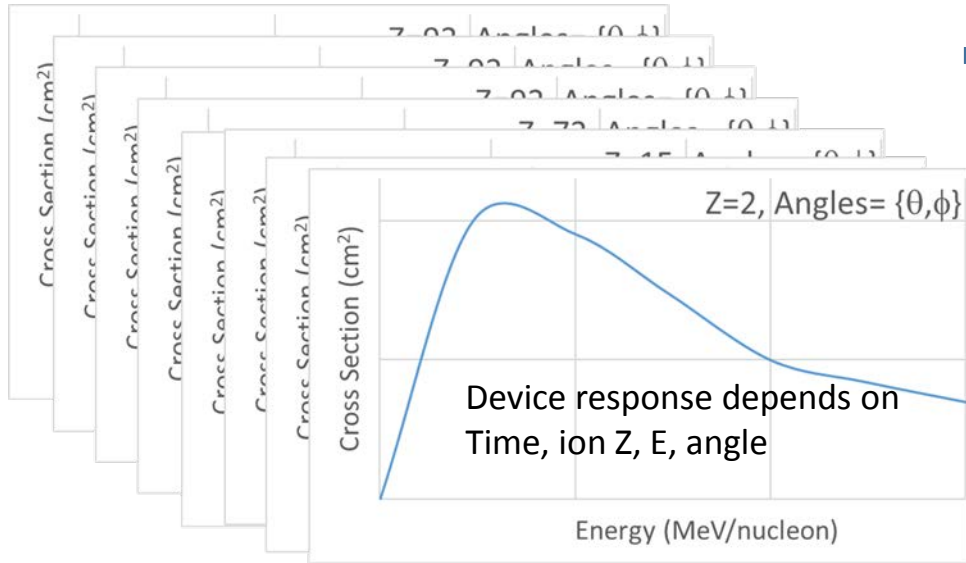
Parameterization in LET Simplifies Space Heavy Ion Models



- Binning ions by LET condenses 92 curves down to 1
 - Each environment represented by single curve
- LET ∝ to charge density of track, so if device sensitive volume (SV) sufficiently small Q ∝ LET × path length in SV
- Ion fluxes vary dramatically depending on Heliomagnetic, geomagnetic and solar weather conditions

- Device response also reduced to single curve
 - Independent of mission radiation environment
 - Assumes all charge due to ion LET (no nuclear reactions, multiple scattering, etc.)
- Cross section low at low LET, rises rapidly with LET and saturates at high LET; fit used for rate estimation.

SEE Rate Estimation (General Case)

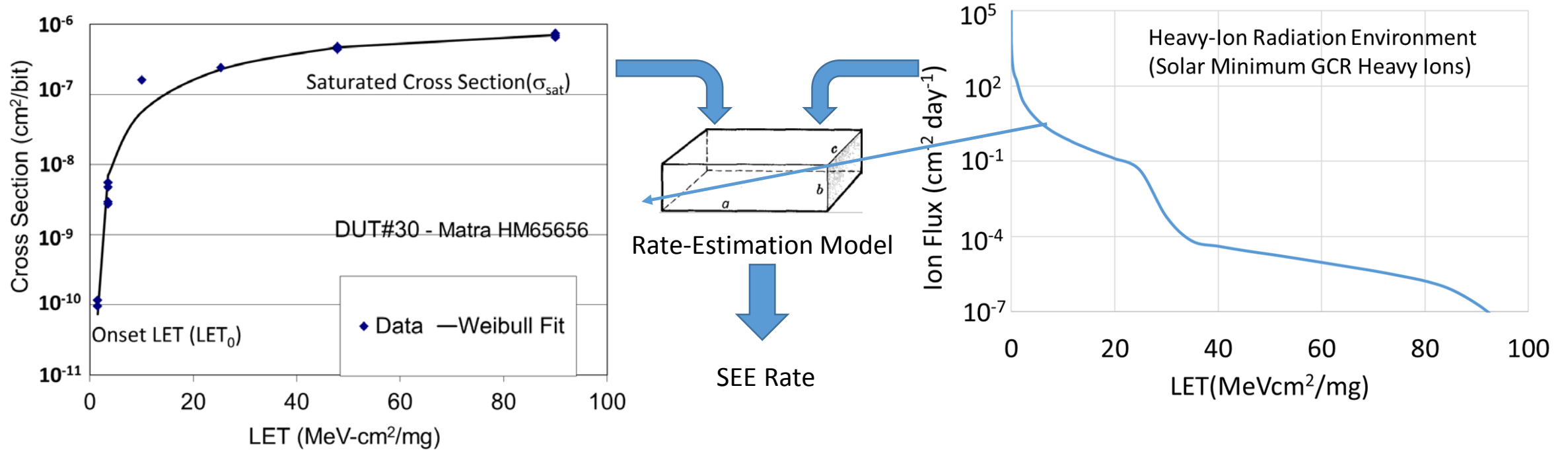


- Most general case: Device response varies with time, ion species (Z), Energy (E) and Angle (θ, ϕ) to device normal
- SEE test must measure how device SV varies over all of these parameters—time consuming and costly

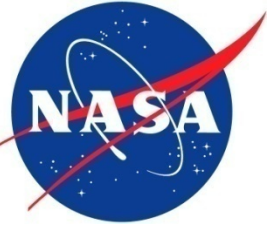
- Heavy-ion environment varies with time and position (e.g. orbit); modulated by Helio magnetic (solar cycle) and planetary magnetic fields
- General rate estimation done by Monte Carlo routines
 - CRÈME-MC (<https://creme.isde.vanderbilt.edu/>)

General SEE rate involves sum over Z, integrals over time, position and ion energy and angle

State of The Art for SEE Rate Estimation



- SEE rate estimation substantially simplified if SV is an RPP and cross section scales w/ LET
 - De facto standard routine is CRÈME96 (<https://creme.isde.vanderbilt.edu/>); provides environment models (GCR for Solar Max and Min, SPE Worst Week, Worst Day, Worst 5 minutes), particle transport and rate calculation
 - Current test guidelines (e.g. ASTM F1192, JEDEC JESD57) geared to provide data to constrain CRÈME96 calculation
 - SEE testing is expensive and time consuming (test preparation can take months and cost $> \$200$ K for complex device)
 - Simplified SV model allows fairly accurate rate estimation without SEE tests driving cost and schedule

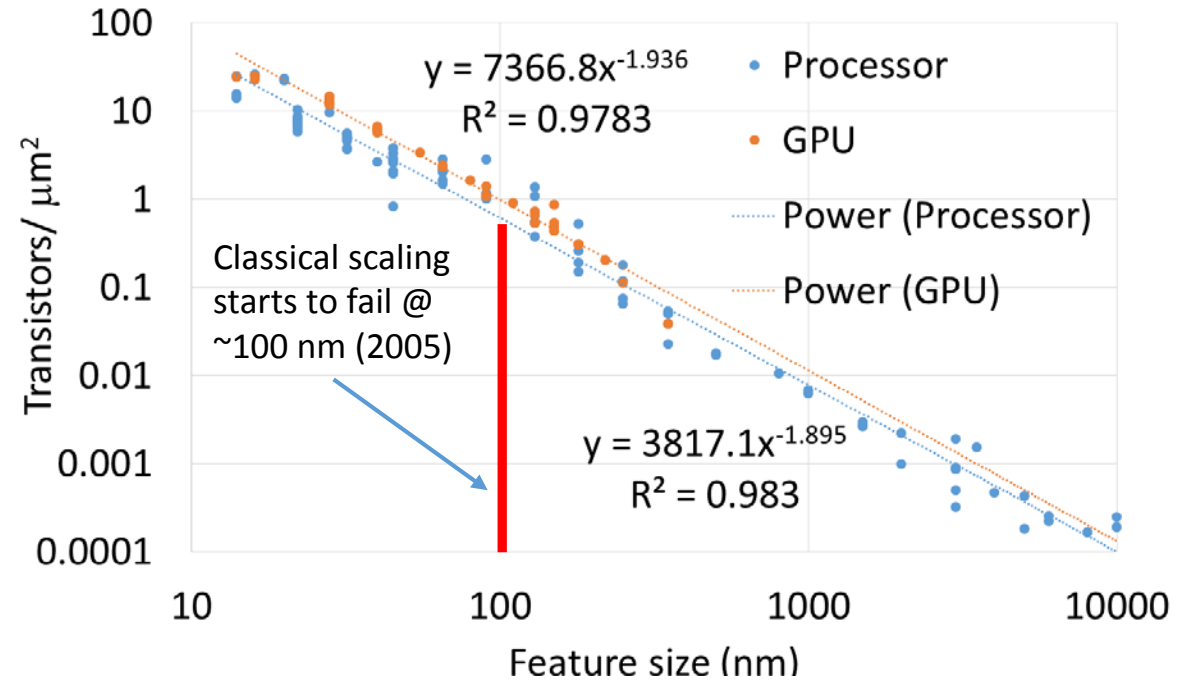


Scaling: The Recipe for Moore's Law...at First

CMOS Scaling Recipe (Denard Scaling)

Parameter	Scaling factor
Feature size, t_{ox} , L, W	1/k
Voltage	1/k
Current	1/k
Capacitance	1/k
Delay time	1/k
Doping	k
Power dissipation	1/k ²
Power density	1

- Denard CMOS scaling: The recipe for Moore's Law
 - If minimum feature size, oxide thickness (t_{ox}) scale as 1/k, other parameters scale according to above table for viable MOSFET
 - Scaling started to fail ~100 nm (2005), but Moore's law lives on!
 - Inter-generation radiation response could still change dramatically

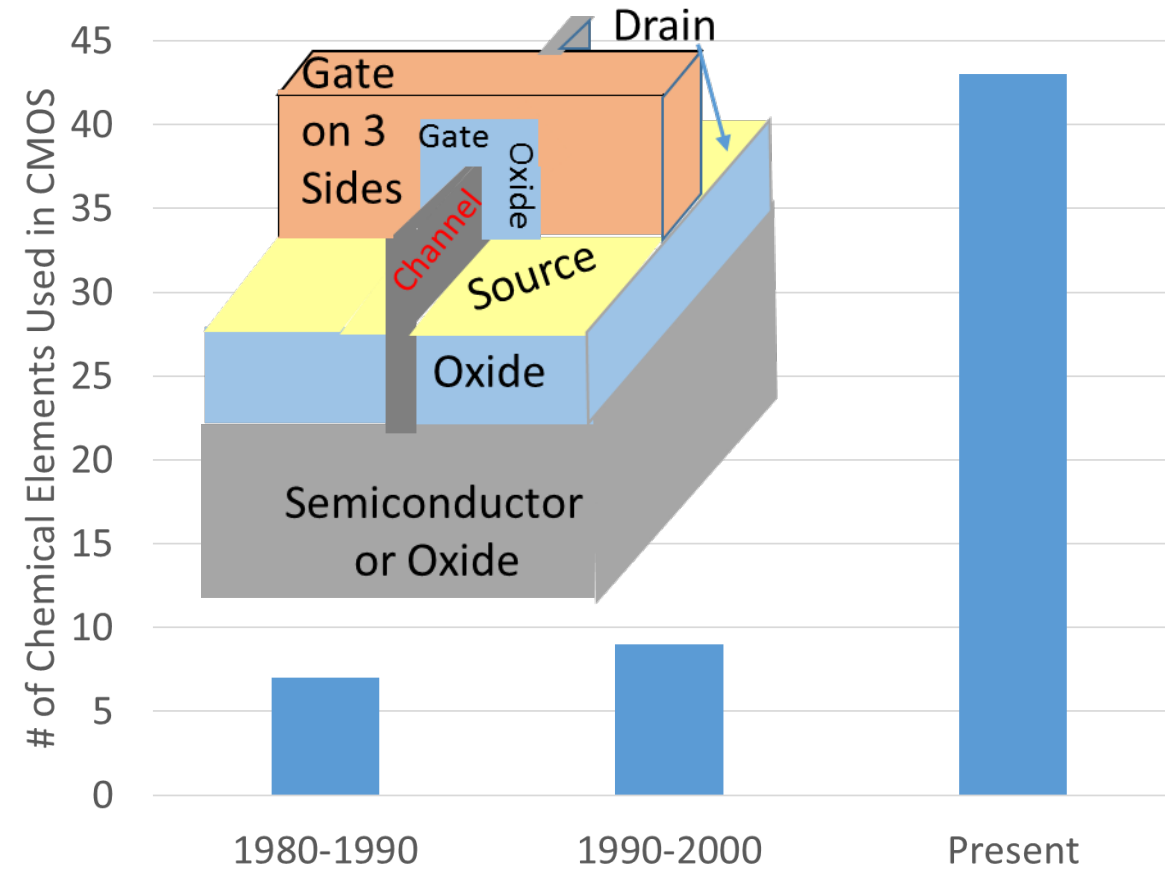


- Despite end of Denard Scaling, density increase continues
- Continued scaling (More Moore) relies more on innovation
 - New device geometries/architectures
 - New materials (dielectrics, metals, strained semiconductor)
- Also, new technologies beyond CMOS (More than Moore)



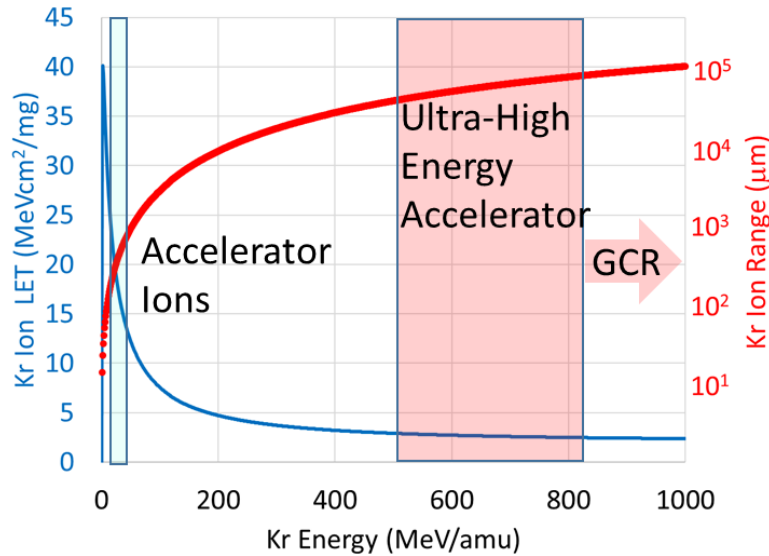
Not Your Father's CMOS Anymore: What Does It Mean For Radiation?

- During CMOS scaling era, Moore's Law was "easy"
 - Denard scaling gives a recipe for new generation
 - Technical challenges solved w/o large changes to basic device architecture or materials
 - Intergenerational radiation response could vary significantly from generation to generation, but SEE modes the same
 - Quantitative prediction based on past technology risky
- Now two types of trends to consider
 - Continued shrinking of device geometries
 - Smaller cross sections per device (lowers per-device SEE rate)
 - Smaller critical charge to cause SEE (increases SEE rate)
 - More devices per chip (increases per-chip SEE rate)
 - Introduction of new device types and materials
 - May raise or lower per-device SEE rate
 - High-Z materials can induce nuclear effects via high LET ions
 - Can introduce new modes not seen in conventional devices
 - Prediction based on past technology risky
 - Qualitative or quantitative



- CMOS processing much more complex since 2005
- New device types and ~5x more chemical elements

Packaging and Integration Also Create Challenges



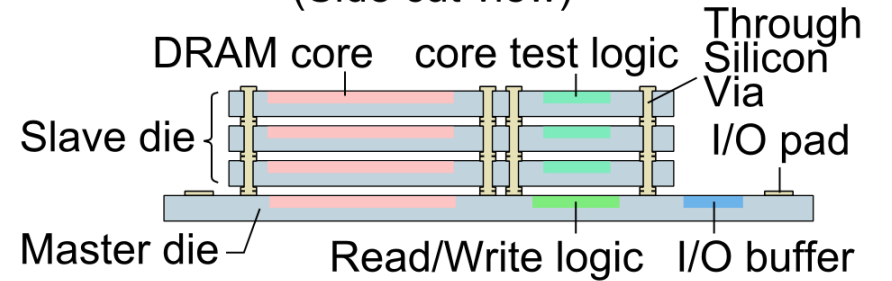
Damaged during thinning



System In a Package (SIP)

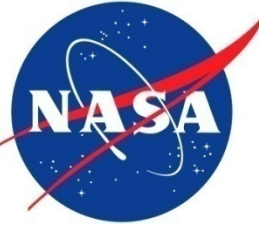
3DS die stacking concept model

(Side cut view)



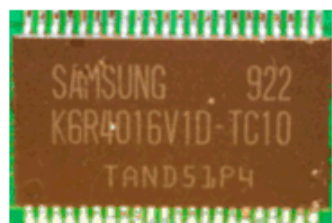
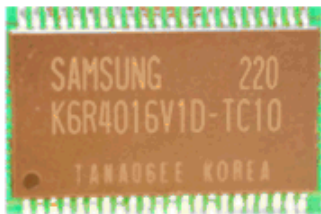
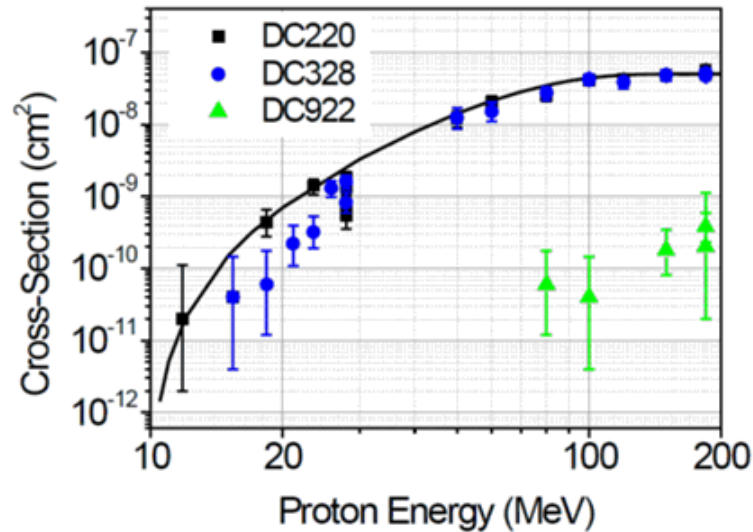
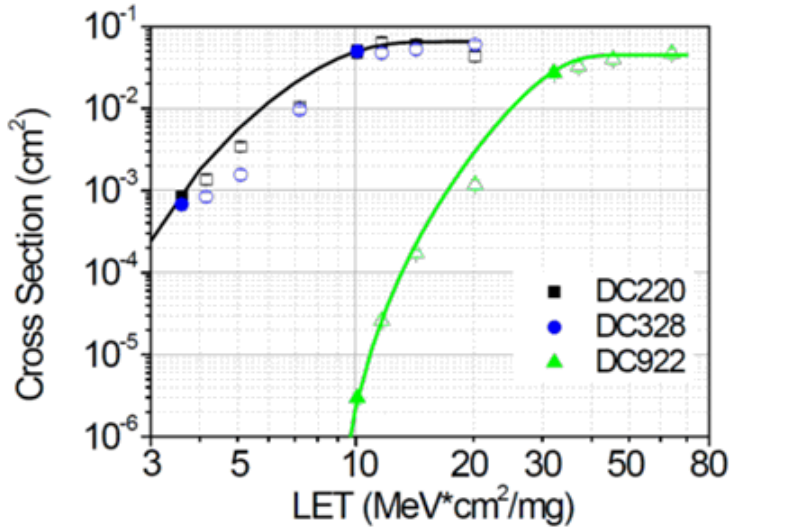
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- Ions at conventional accelerators have limited energy/range that cannot penetrate one or multiple die
 - System In a Package (SIP), die stacking and flip-chip (die face down on substrate) pose challenges
 - Disassembly, repackaging, die thinning all used to ensure ions reach sensitive volume; can compromise reliability
- Ultra-high-energy accelerators provide penetrating ions, but expensive (~\$5K/hr) and less convenient
 - Increased energy adds capability to test new devices
 - Simplifies test part preparation



Perils of Generalizing to New Technologies: A Cautionary Tale

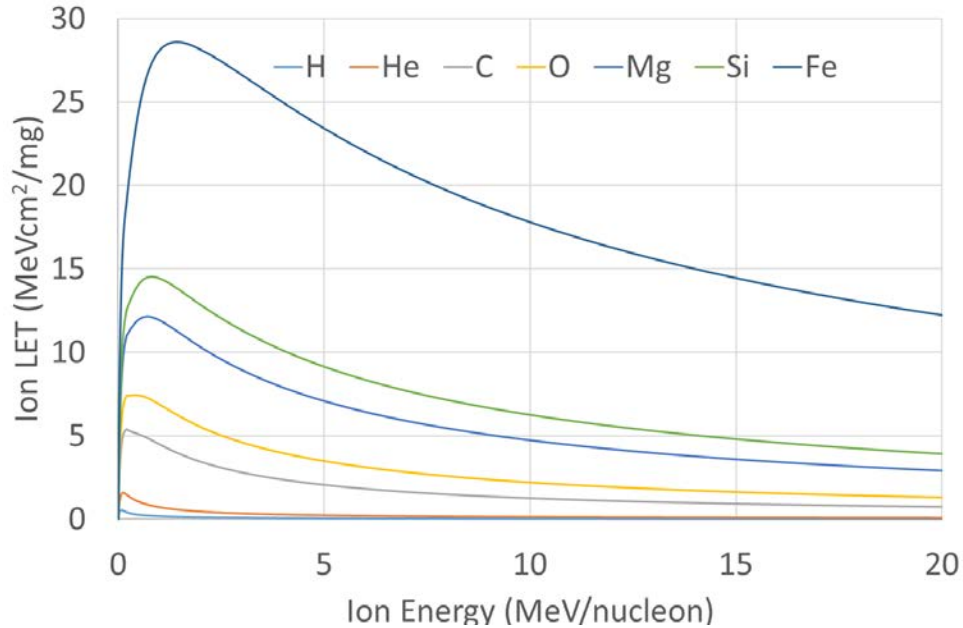
- 3 lots of SRAM obtained—one tested and had acceptably low failure (SEL) rate
 - Unbeknownst to customer, die for other lots were a different die revision
 - Failure rate $\sim 100x$ worse for new die revision as for original part



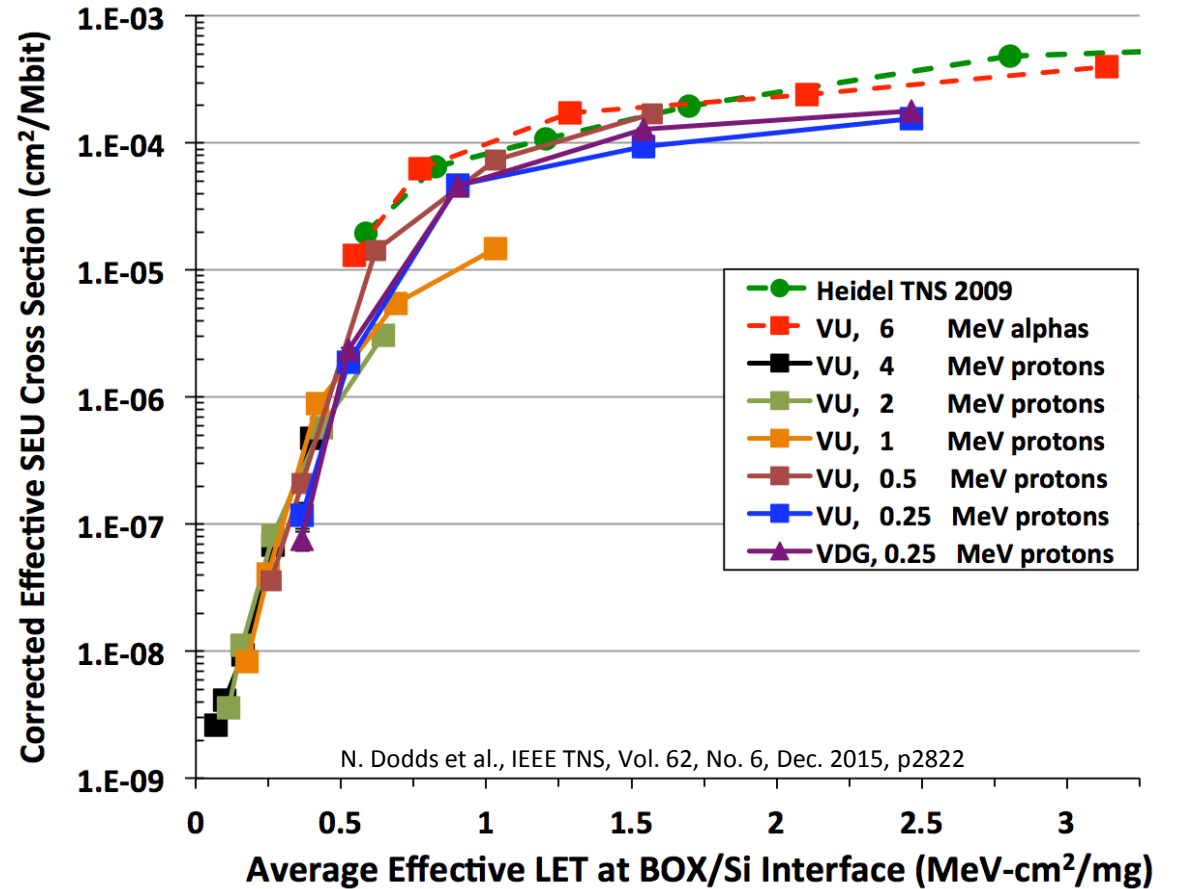
DC220 or DC328: ~ 1 SEL every 3 days on LEO polar orbit

- Generally, prior generations are a poor guide to future SEE threats
- SEE (especially destructive) can depend on circuit layout, as well as device size/sensitivity
 - Many effects are driven by parasitic elements—difficult to constrain without test data
- Sometimes, the news is good
 - Destructive SEE mode (Single-event latchup) was a significant barrier to use of SDRAMs up to 2010
 - No SDRAM has been susceptible to SEL since 2010
- Sometimes (at left), it's bad
- Heavy-ion testing is only reliable way to constrain susceptibility of new technologies

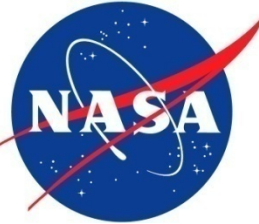
Consequences of Scaling: The Low-Energy Frontier



- Capacitance scaling w/ feature size means more ions can cause SEE as features shrink
 - @90 nm generation and smaller, upsets due to direct ionization by protons observed
 - Cross section increases ~200x as proton energy nears Bragg Peak

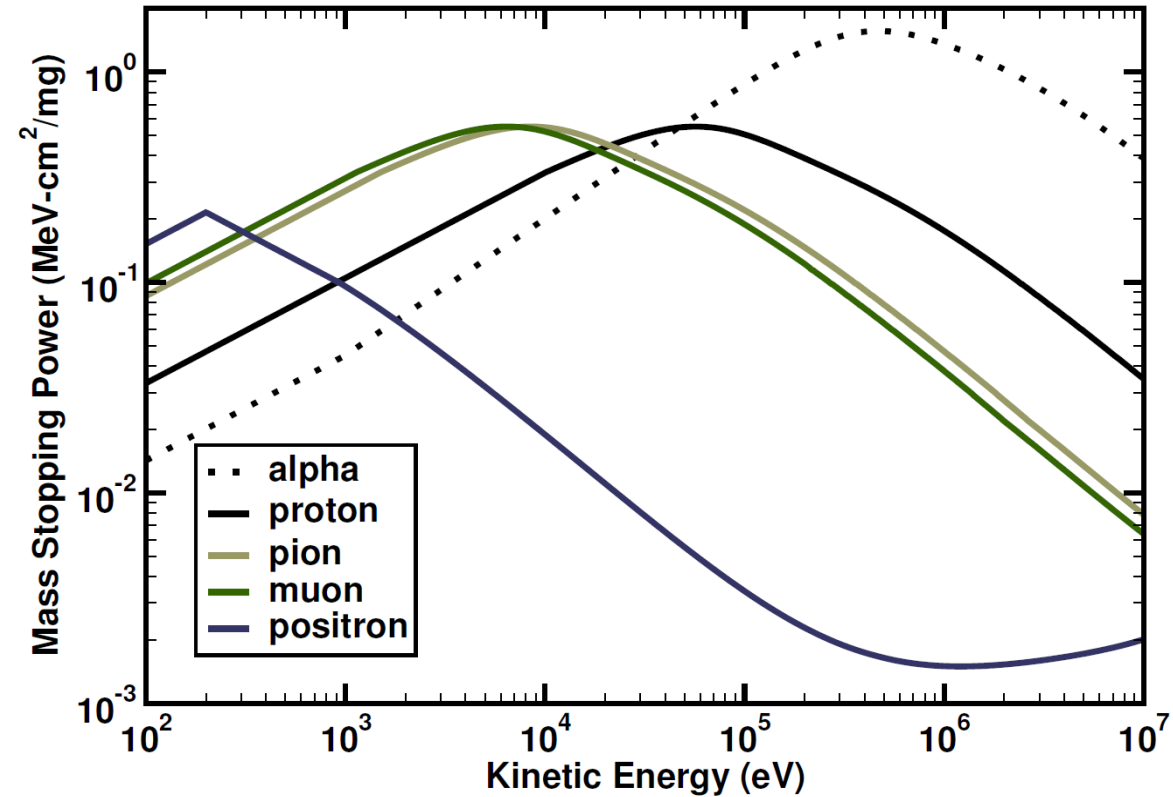
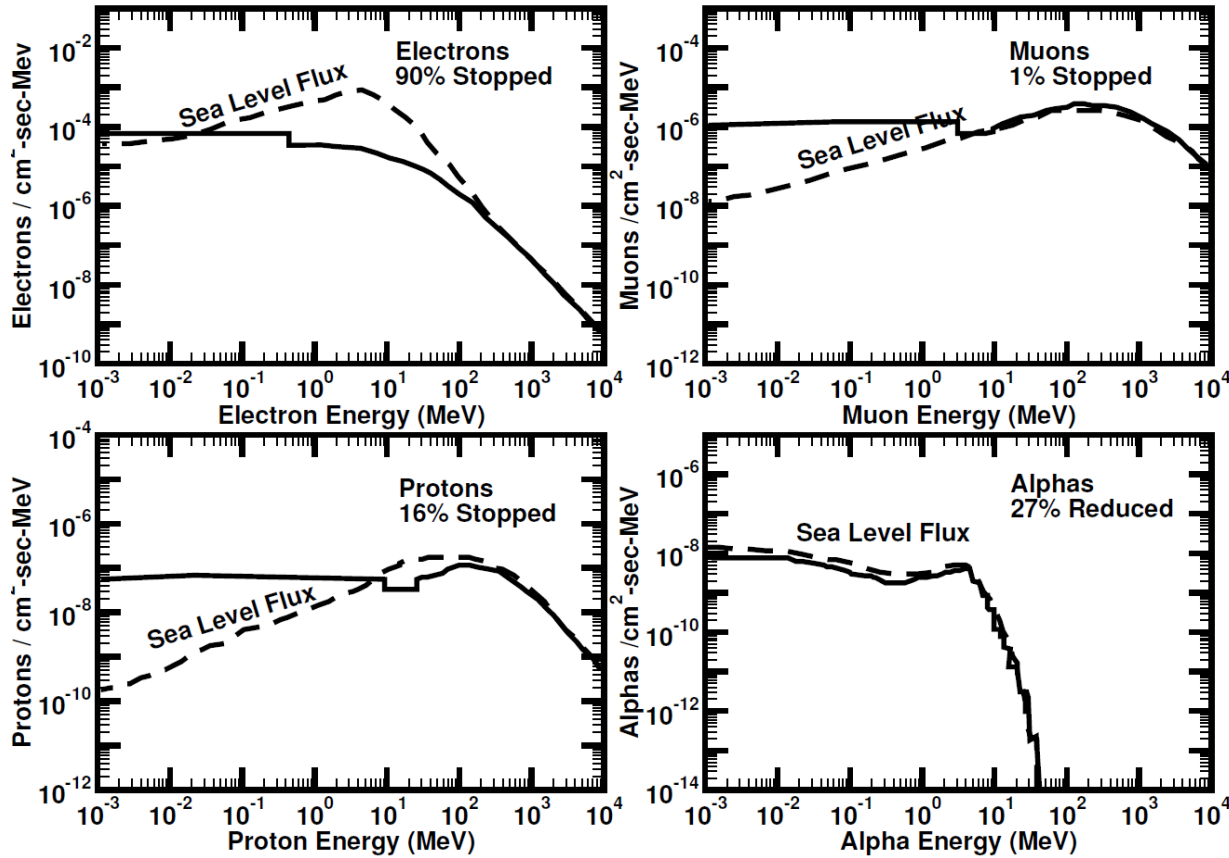


- Angular and energy dependence shows that low-energy proton upsets due to direct ionization
 - Follow LET mostly, but multiple scattering important



For Future Technologies, Concern Extends Beyond Protons

% Stopped by 10 cm of Concrete

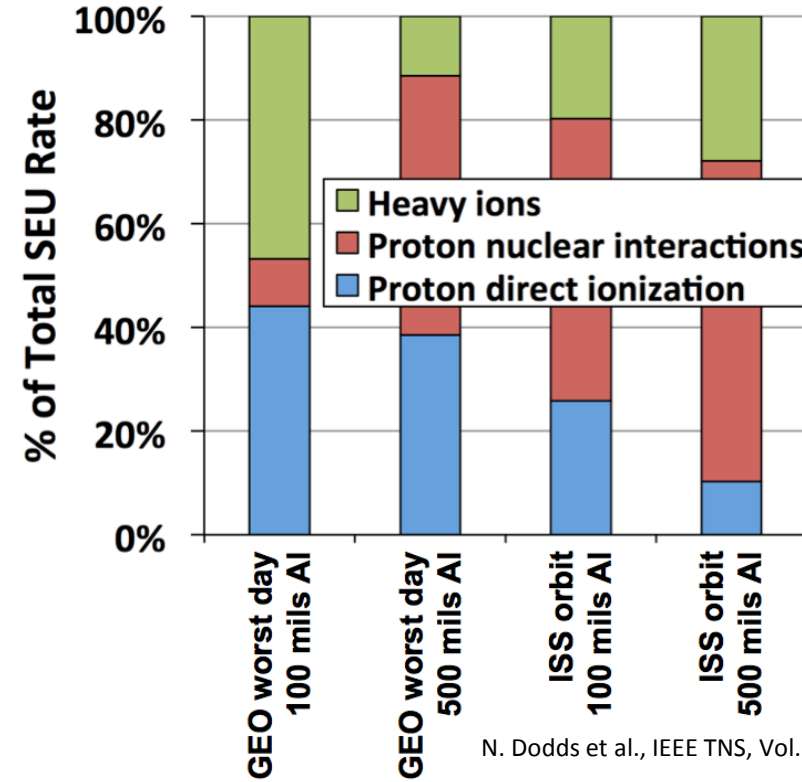
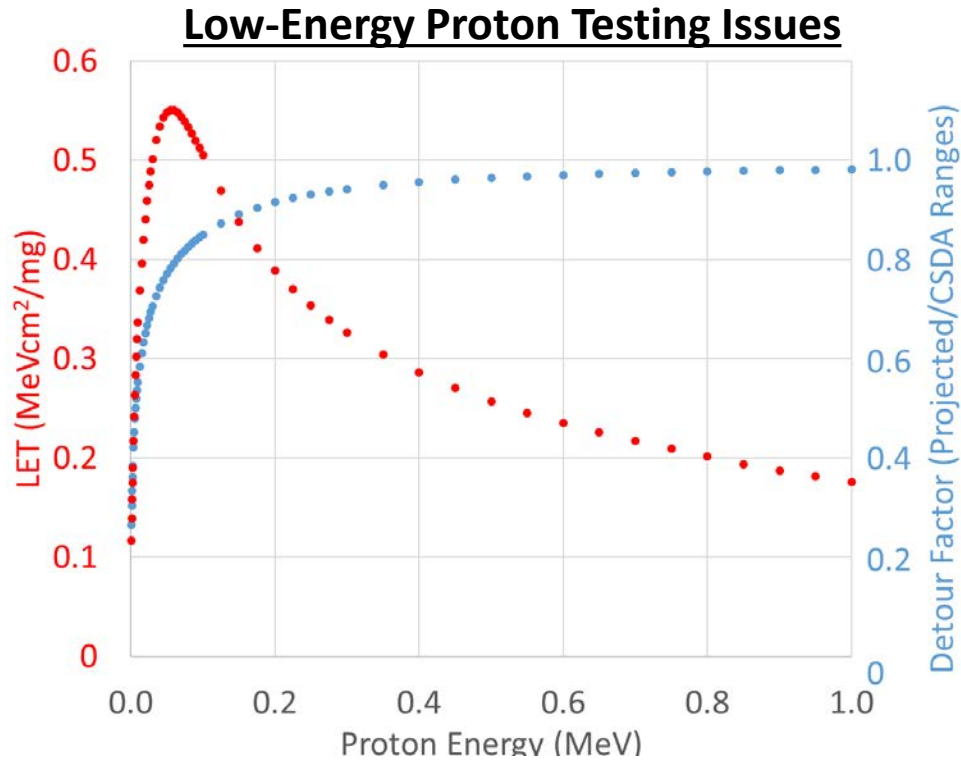


B. Sierawski, PhD Dissertation, Vanderbilt University,
<http://etd.library.vanderbilt.edu/available/etd-12012011-134348/>

- # and range of muons raise concerns for terrestrially
 - For very soft devices (upset caused by collected charge < 6 fC), muons may dominate terrestrial upset rate

- Peak LET comparable to protons, but @ 10x lower energy

Low-Energy Testing and Hardness Assurance

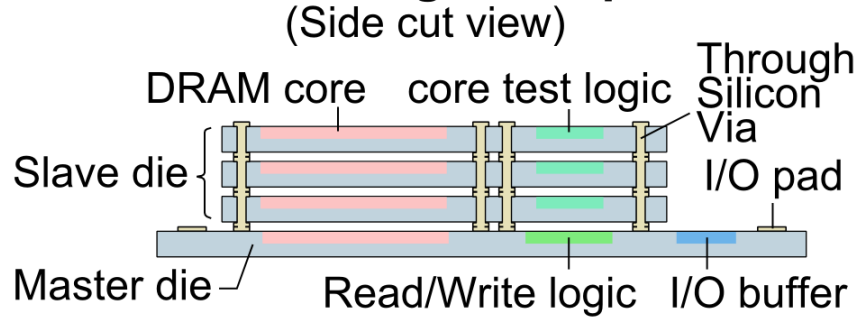


- Multiple scattering reduces projected range by ~20%
 - Leads to more multiple upsets than for other ions
- Overburden can significantly alter test results
- Difficult to obtain all relevant energies at 1 facility

- Low-E proton SEE rate depends on environment/shielding
 - Transport of low-energy protons through spacecraft shielding highly sensitive to errors; low-energy proton environment highly variable

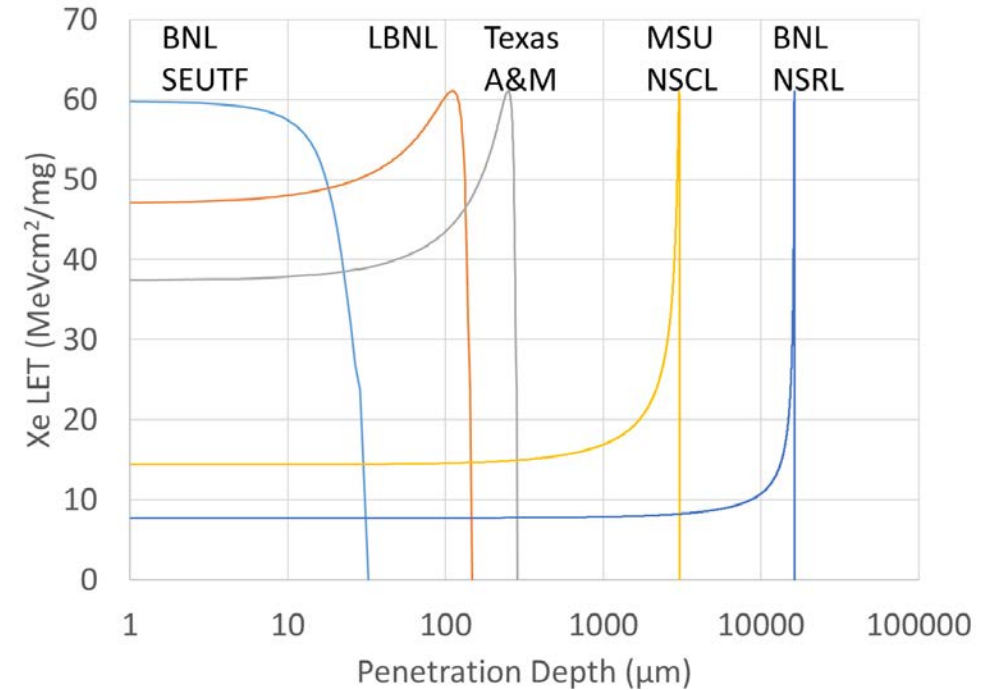
High-Energy Frontier: Testing New Parts

3DS die stacking concept model



- Increasing integration poses problems for SEE testing
 - Multiple die stacked together in packages
 - Behavior may differ if dis-assembled, tested separately
 - Packages now intrinsic to part performance
 - Dis-assembly may compromise timing, thermal and structural characteristics—especially if thinning required
- Parts may contain metal as well as light Si, plastics, etc.
 - Lead frames, radiators are integral to part functionality
 - High-Z materials pose issues at even high-energy facilities
 - Can also contribute to ion environment (discussed later)

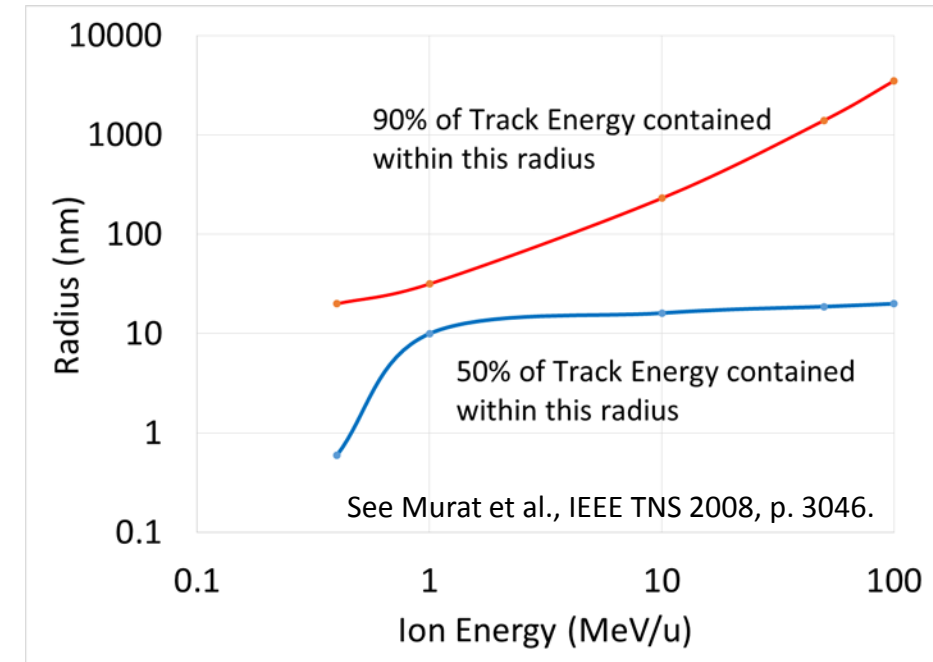
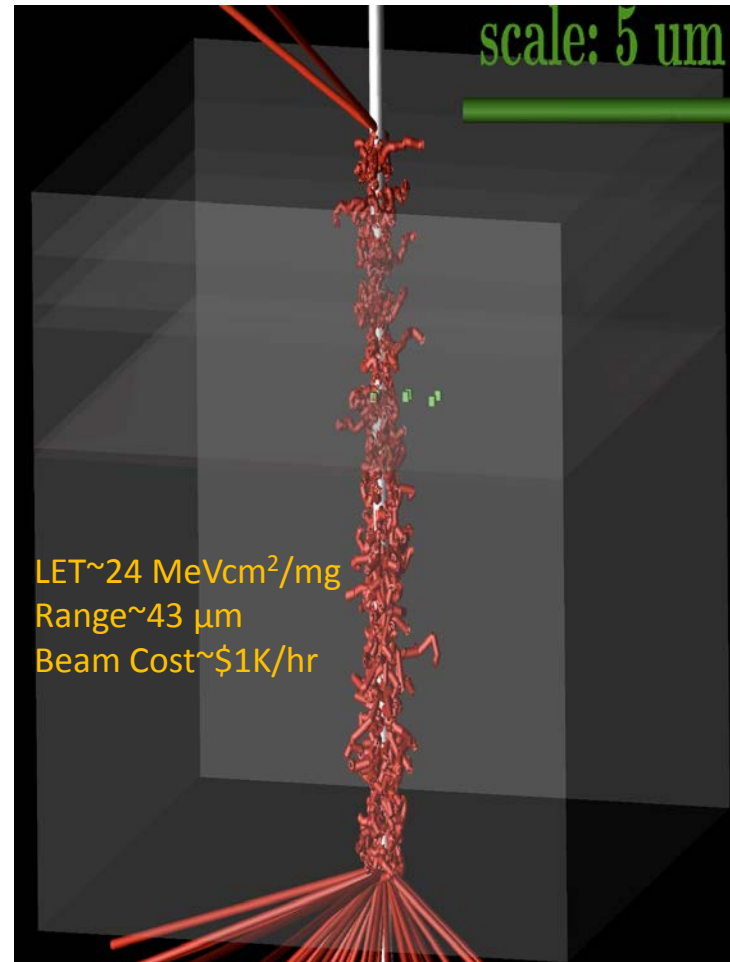
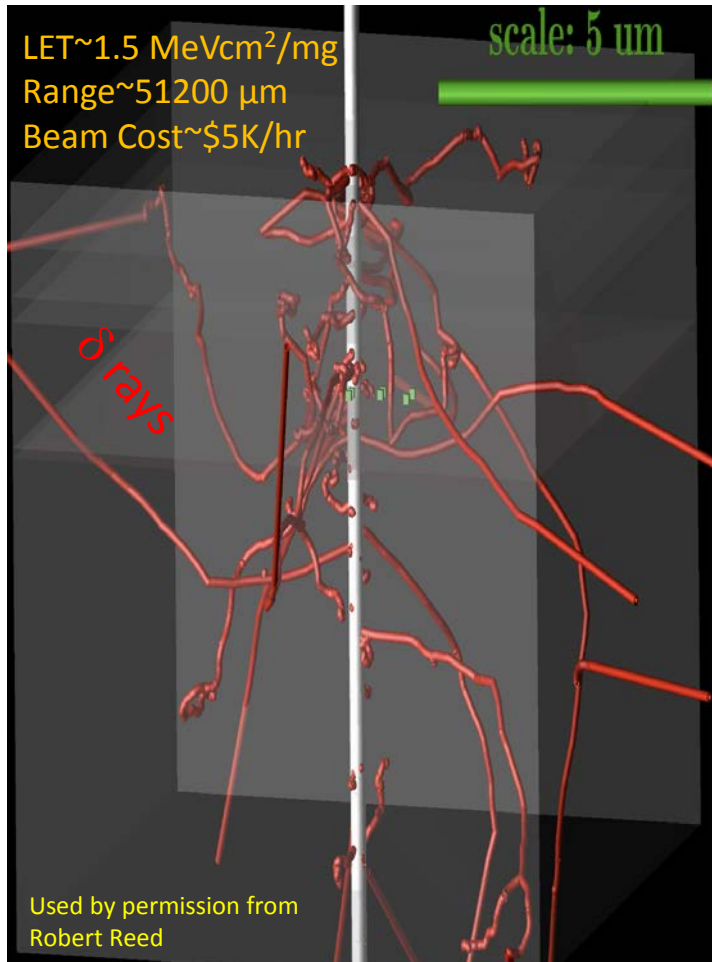
LET vs. depth for Highest Energy Xe Ion



- Different accelerators enable different capabilities
 - BNL SEUTF—some parts for nondestructive SEE threats
 - TAMU, LBNL—most tests, but may require risky part modification
 - NSCL, NSRL—able to test almost any part, but expensive

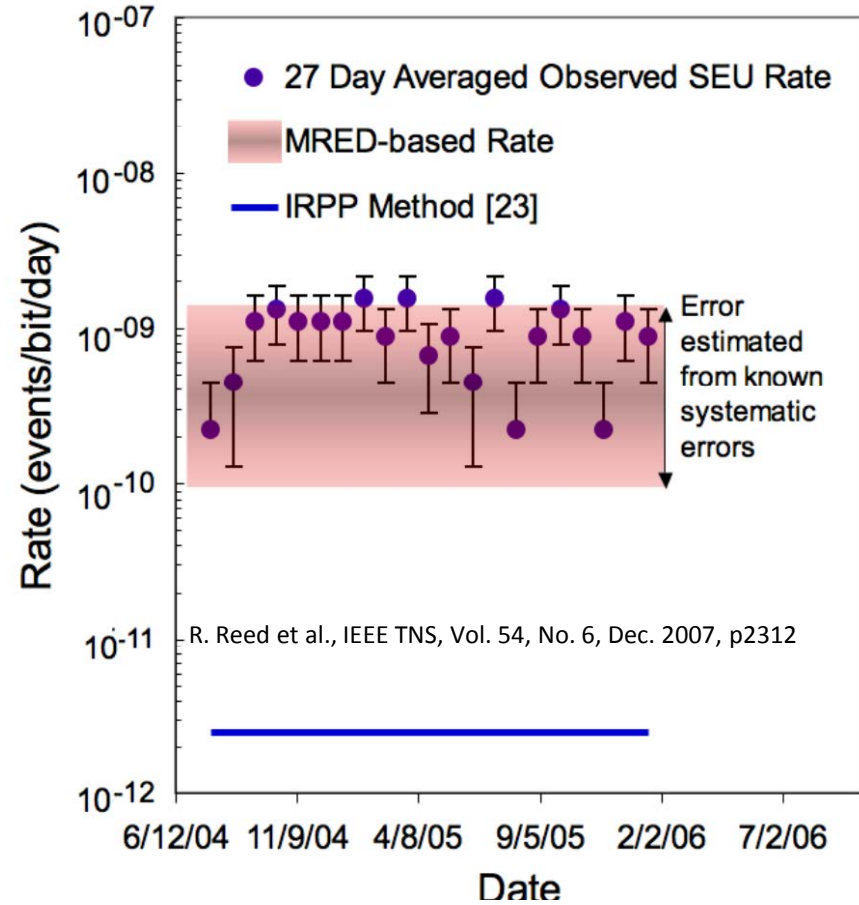
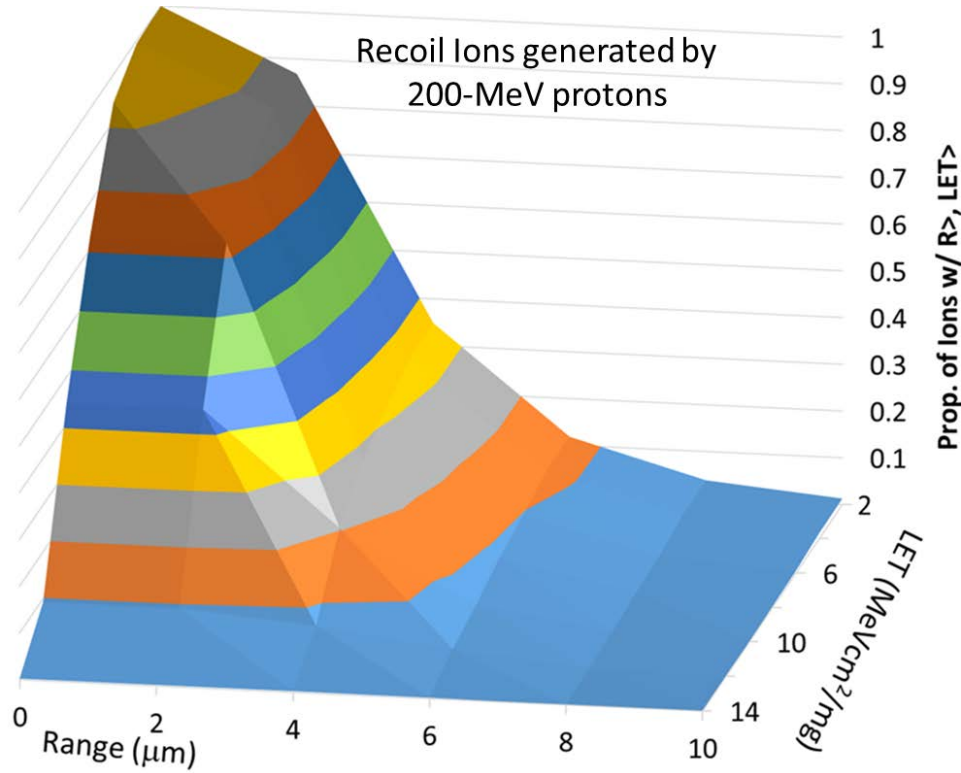
High-Energy Frontier: It's Not Just LET Anymore

28 GeV Fe ion (500 MeV/u) 280 MeV Fe ion (5 MeV/u)



- High/low energy ions deposit energy very differently
- Central charge track of low-energy ion denser
- Deltas for high-energy tracks deposit energy far away
 - Important for multi-bit upsets, hardened cell upsets
 - Likely more important as critical charge decreases

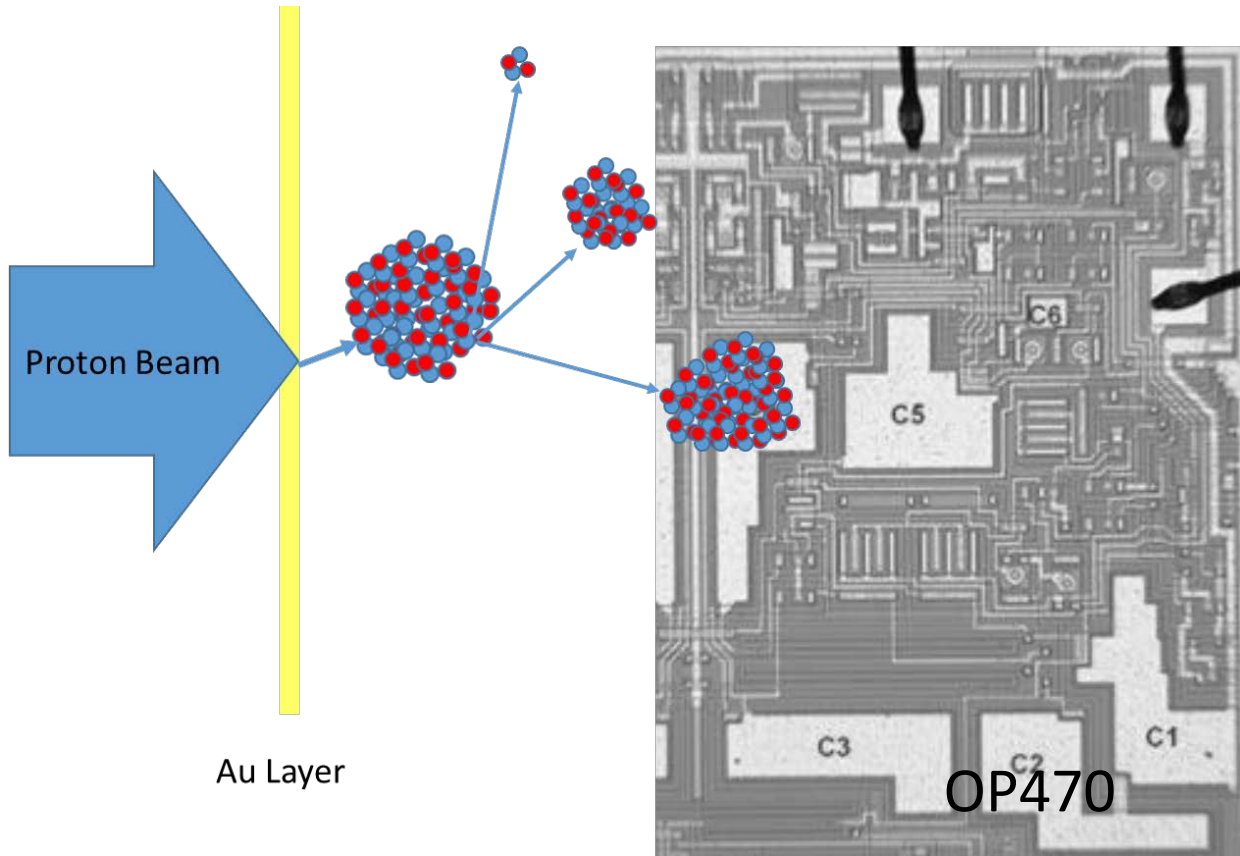
Nuclear Interactions: Important and Getting More So



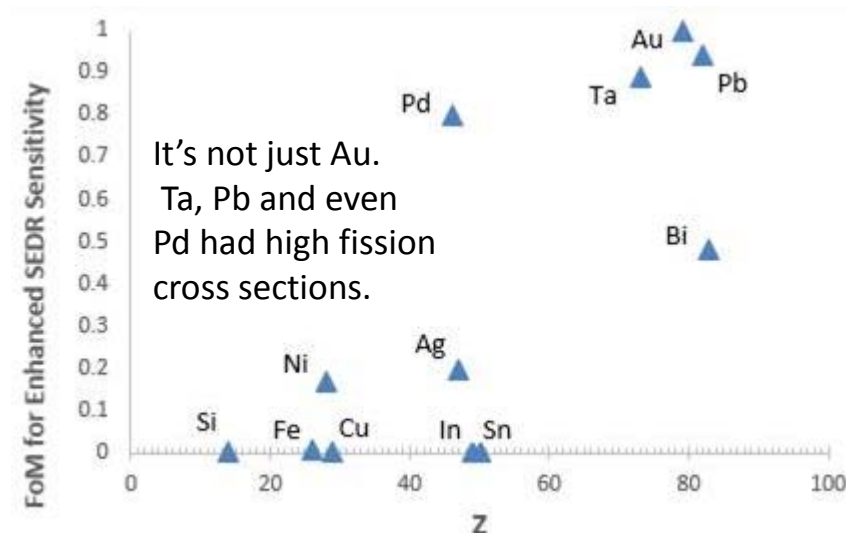
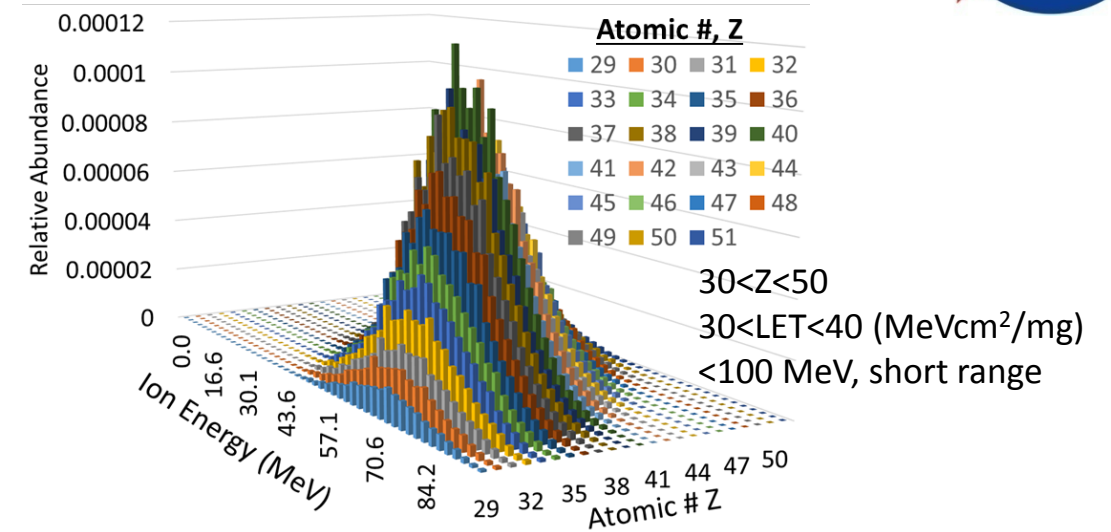
- Nuclear effects always important for some environments
- Recoils for proton-Si collisions cause SEE in soft devices
 - Can dominate SEE rates in some environments even though only 1 in ~290K protons generates a recoil ion

- Nuclear interactions between low-LET, high-energy ions and high-Z materials in SRAM cause 100x increase in error rate.

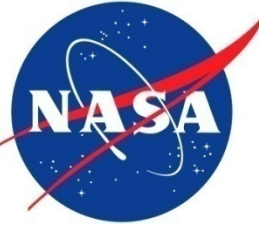
New Materials Mean Enhanced Importance for Nuclear Physics



- Protons on Au foil cause Au nuclei to fission in rare events
 - Fission products have high LET and can result in destructive events
 - Cross section 10s of mbarns, but $\sim 10^{18}$ Au ions/cm² in 1- μ m Au foil
 - 10^{10} 200-MeV protons \rightarrow 2100 Au fissions/ μ m of Au (≥ 1000 x GCR fluxes)



T. Turflinger et al., IEEE TNS, Vol. 64, No. 1, Jan. 2017, p309

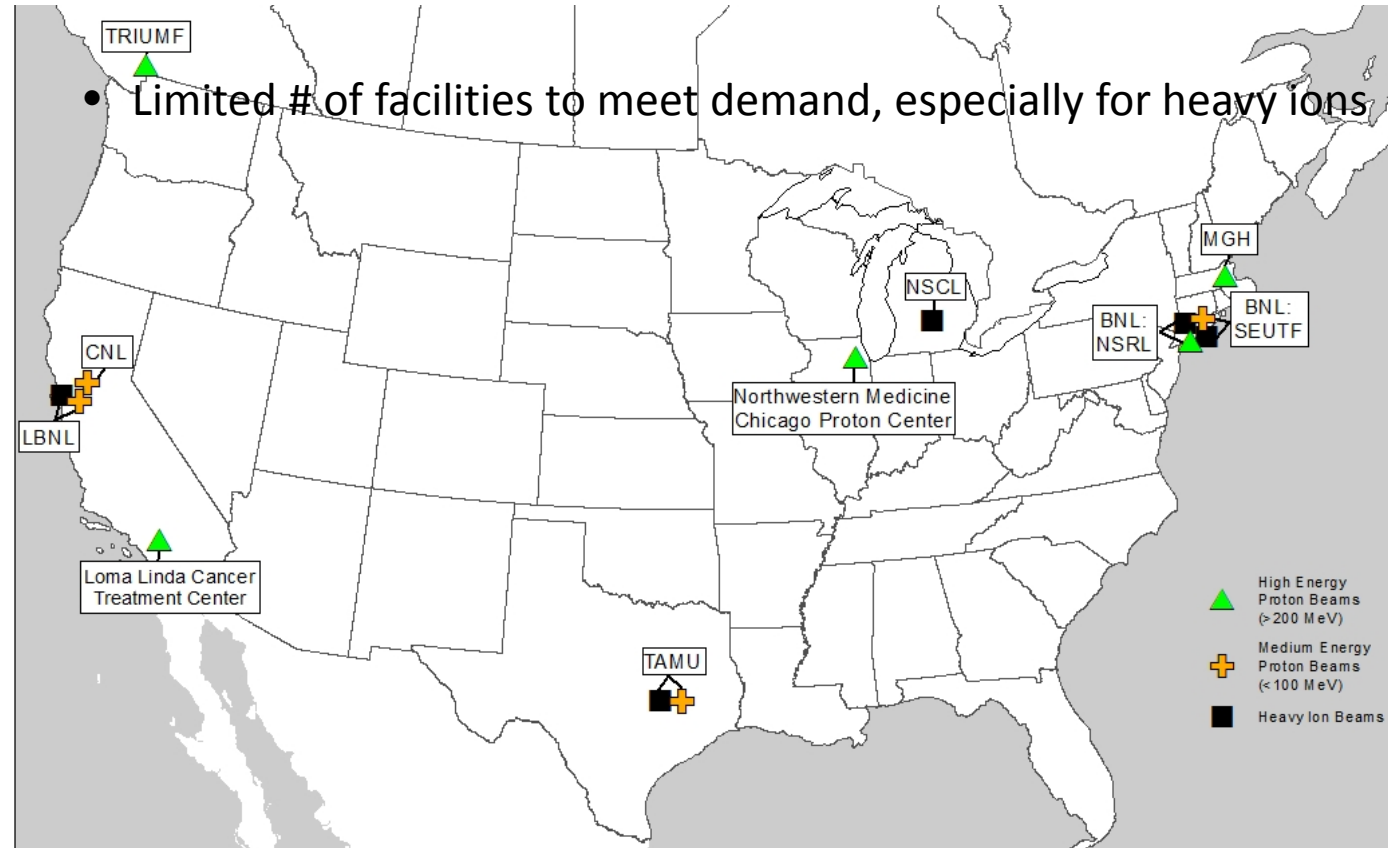


Increasing Demands for Radiation Testing and Assurance

Commercial Space Sector (USA)

Commodity	# companies
Space Habitat	3
Launch Vehicle	12
Space Tourism	4
Probes	10
Sounding Rocket	4
Space Mining & Mfg.	2
Engines	10

- Growing commercial space sector will increase testing demands as it matures
- Testing complex commercial parts more time consuming



National Academies of Sciences, Engineering, and Medicine. 2018. *Testing at the Speed of Light: The State of U.S. Electronic Parts Radiation Testing Infrastructure*. Washington, DC: The National Academies Press. <https://doi.org/10.17226/24993>.



Conclusions

- SEE are among the most formidable obstacles to reliable use of parts in space
 - Occur in all space environments (much more severe than on Earth)
 - Radiation not typically a terrestrial concern—commercial designers don't think about SEE hardening
 - Can occur at any time, resulting in consequences from trivial to catastrophic
 - Current test methods are optimized to limit risk economically, but cost and schedule pressures persist
- Heavy-ion and proton testing remain the only reliable way to bound SEE risk
 - Device response too difficult to model (especially for commercial devices with limited information)
 - Device technology changes literally exponentially
 - Scaling changes device susceptibilities to known SEE and can introduce new ones
 - Track structure effects due to delta rays likely to complicate future testing and analysis
 - Increased circuit density also making it more difficult to fully test any device
 - In post-scaling era, Moore's law driven by innovation—all bets are off with each new generation
 - New packaging, system in a package all placing new demands on testing methods and facilities
- Demand for the limited number of facilities is increasing
 - Complex parts take more time to test
 - Commercial space and other new players also likely to increase demand for beam time
- Throughout a 46-year history, the story of SEE hardness assurance has always been at its beginning