# Bringing Single-Event Effects Down to Earth

Ray Ladbury (Radiation Effects and Analysis Group)

NASA Goddard Space Flight Center

# Acronyms and Abbreviations

CMOS—Complementary Metal-Oxide-Semiconductor

CREME-96—De Facto Standard SEE Rate Tool

CREME-MC—Monte Carlo, Physics-Based SEE Rate Tool

DRAM—Dynamic Random Access Memory

EEE—Electrical, Electronic and Electromechanical

GCR—Galactic Cosmic Ray

HA—Hardness Assurance

I/O—Input/Output

ISS—International Space Station

LET—Linear Energy Transfer of energetic particle

MC—Monte Carlo

NA—National Academies of Science Engineering and Medicine

/Nuc.—per nucleon (in an ion)

RPP—Rectangular Parallelepiped (SV model in CRÈME-96)

SEE—Single-Event Effect

SEFI—Single-Event Functional Interrupt

SEL—Single-Event Latchup

SPE—Solar Particle Event

SV—Sensitive volume (e.g. for causing an SEE)

TID—Total Ionizing Dose (degradation Mode)

Z—Atomic Number (= # protons in nucleus)

# Outline and Background

- Talk originated from a National Academies (NA) panel assessing nation's radiation infrastructure
  - Increased concern from both radiation testing community and our customers that infrastructure coming under stress
  - Looked at test facilities, modeling and simulation capabilities and personnel
  - Report detailed 12 findings and 7 observations intended to keep nation's radiation testing infrastructure healthy through 2030
  - This talk is the backstory for the National Academy Report: *Testing at the Speed of Light – The State of U.S. Electronic Parts Radiation Testing Infrastructure*

I. Single-Event Effects (SEE)—What, How, Why and Where

II. History of the Field and the Current Infrastructure

III. Challenges facing SEE

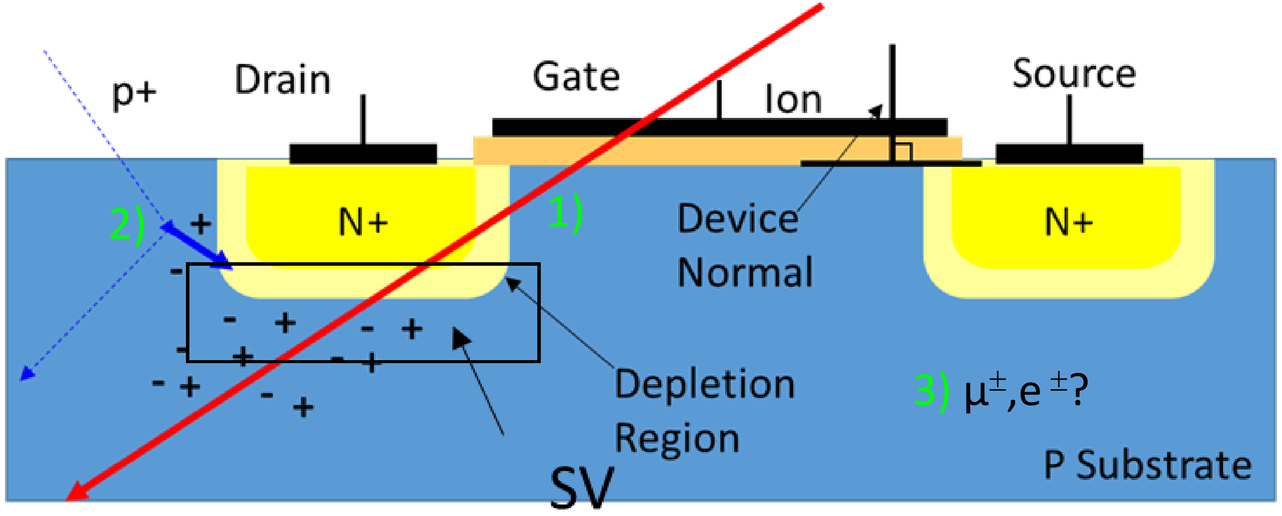
   A. New Technologies

   B. Particle Energies and the Low Frontier (Terrestrial SEE)

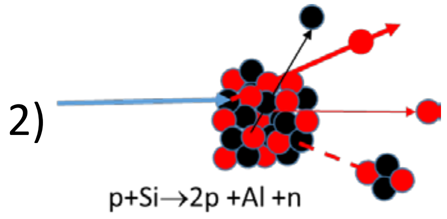
   C. Costs and New Customers

IV. NA Report Recommendations—People, Parts Particles and Prognostication (modeling)

# Single-Event Effects



- Single-Event Effect (SEE)—a change in state, stored data, output or functionality cased by passage of a single ionizing particle through a sensitive volume (SV) in the device.
  - Ionizing particle may be
    1) a primary heavy ion (red),
    2) secondary ion (blue) resulting from a scattering event
    3) primary proton (deep submicron CMOS)—or, in principle, a muon or even an electron



- SEE equally probable at any time of mission
  - Can dominate radiation risk for short missions or benign environments where TID is minimal
- SEE consequences/mode depend on device technology and can be
  - Destructive (e.g. Single-Event Latchup—SEL)
  - Nondestructive and temporary (e.g. glitch)
  - Nondestructive and recoverable (e.g. upset)
  - Nondestructive, recoverable but disruptive (e.g. Single-Event Functional Interrupt--SEFI)
- **Affect only a single part/die**

# Why Do We Care What A Single Atomic Nucleus Can Do?

## Spacecraft Anomalies

1. 25-50% of spacecraft anomalies due to SEE (exact % depends on mission environments)
2. Consequences range from trivial to catastrophic
3. SEE can occur at any time during the mission
4. Some failures remain latent and can happen any later time
5. Commercial Space departing from conventional parts selection and radiation testing approaches

## Technology Insertion

1. Commercial parts far outperform space qualified counterparts
   a) Gap keeps growing
2. Commercial part SEE threats can only be revealed by testing
3. SEE hardening of parts very time consuming
4. Past performance of parts no indicator for future parts
   a) New CMOS generation every ~18 months
   b) Data have a short shelf life

## Creeping Threats

1. Single-Event Threats starting to affect terrestrial applications
   a) Critical/medical
   b) Large Data Storage
   c) High precision (quantum?)
   d) Aviation
   e) Self-driving cars
2. General: expect highly-scaled devices to be more sensitive
   a) Deep submicron CMOS upsets to low-E protons
   b) New technologies may upset to muons
   c) New device technologies make past generations a poor guide to future

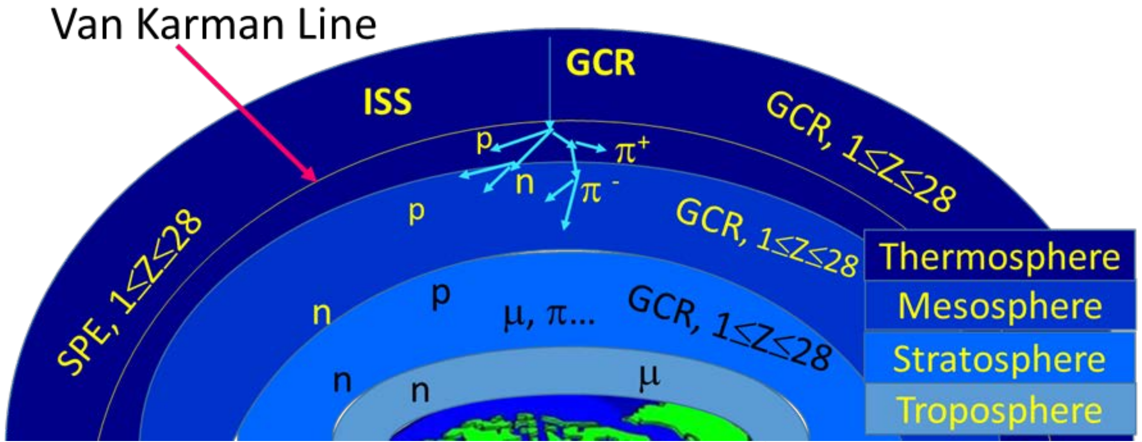
# Single-Event Effects: What, Where and When?

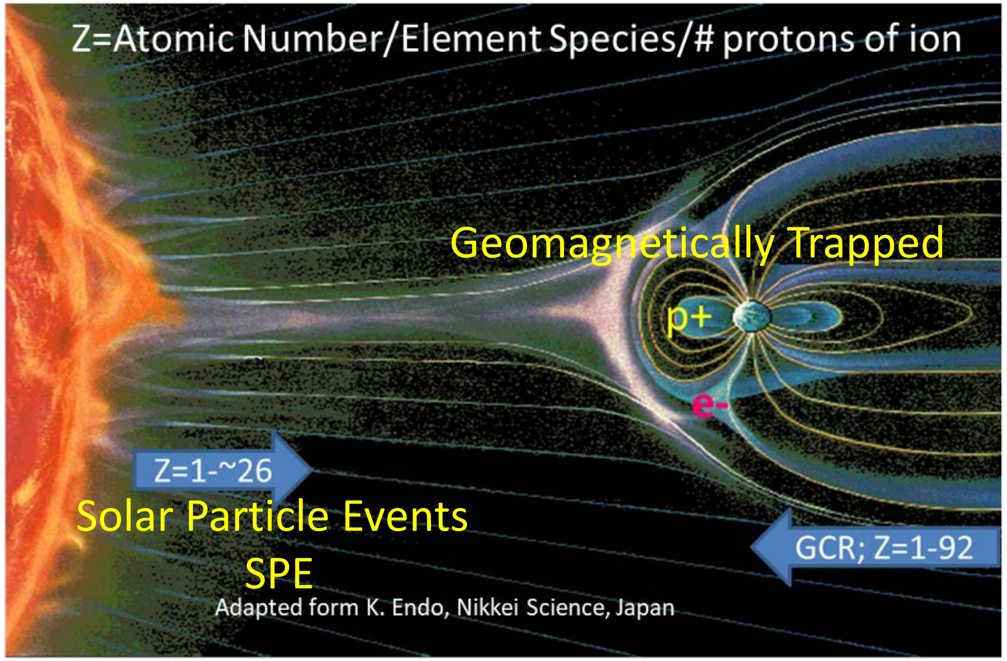
- Single-Event Effect—a malfunction in a microelectronic part caused by passage of a single energetic, *sufficiently* ionizing particle through a sensitive volume of the part
- Where they occur—wherever energetic and sufficiently ionizing particles are found
  - Can occur on Earth, but rates in space are orders of magnitude higher and particles much more dangerous
- When—can occur any time. Galactic Cosmic Rays (GCR), neutrons and trapped protons present at all times and generate continual fluxes of particles at ground level
  - Solar particle events (SPE) can drive space rates up by >100x and sometimes increase terrestrial rates as well

**Terrestrial environment**

“Soft” parts upset when neutrons collide with Si nuclei

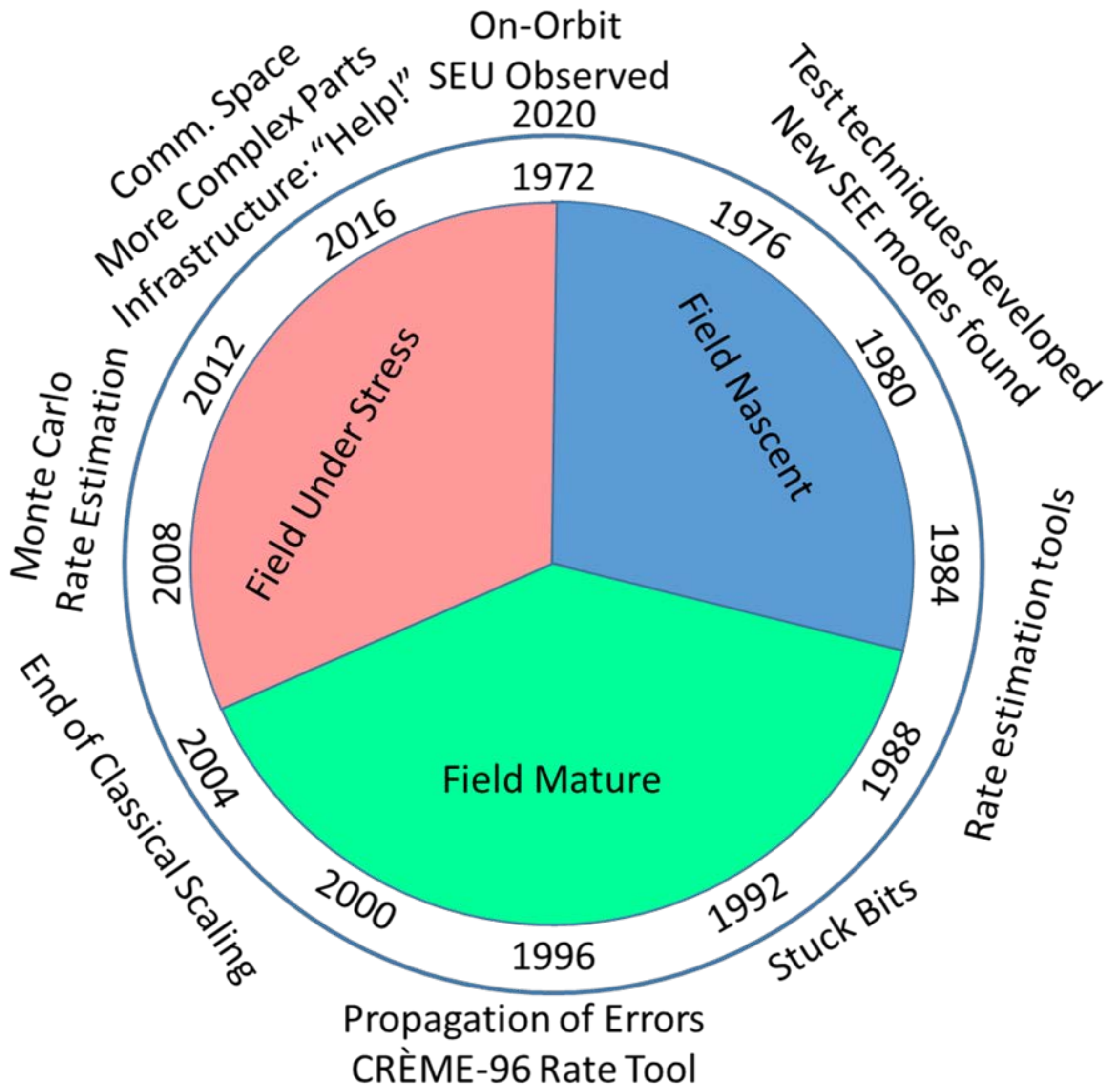
Very soft parts soon may even upset due to muons





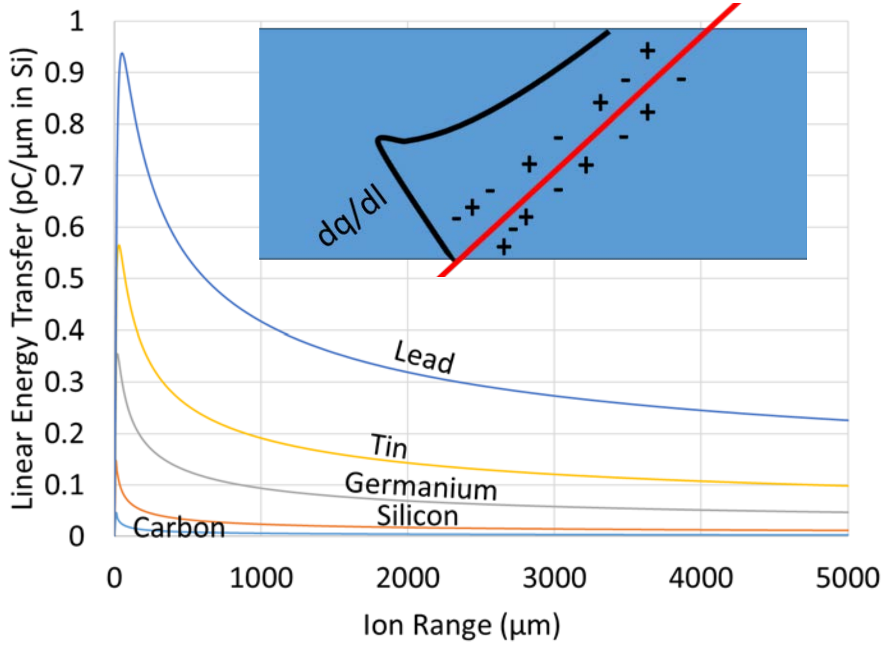
Adapted form K. Endo, Nikkei Science, Japan

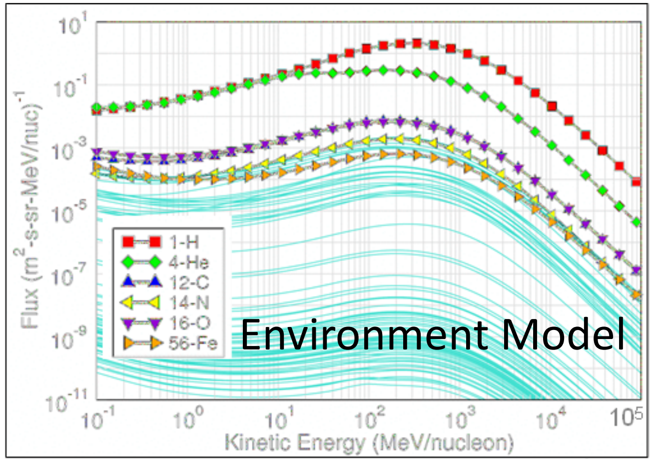
# A History of Single-Event Effects—In One Slide



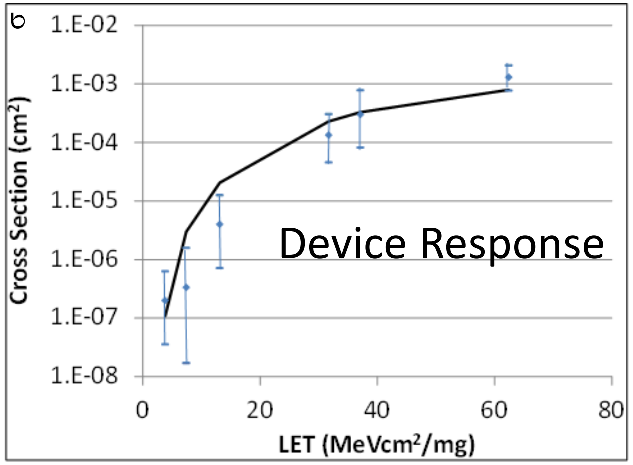
- History of SEE studies divides roughly into 3 periods
  - Discovery('72) to methodology for rate estimation (~'86)
    - New SEE modes being discovered
    - Test techniques being developed
  - Formalism complete ('86) to end of classical CMOS scaling
    - More new modes discovered
    - CREME-96 rate estimation package (still de facto standard)
    - Classical (Denard) scaling breaks down ~2005
  - 2005-present: Increasing stress…a lot going on
    - End of scaling means each new generation may be very different than prior ones—especially for radiation
    - Continuation of Moore's Law means more complex parts
      - Packaging also ever more complex, causing more difficulties in preparing parts for test
    - CREME-MC allows more physics-based Monte Carlo SEE rate estimation for new device types/technologies
    - Commercial space born and growing rapidly
    - Combination of demand, financial stress, ancient hardware place strain on test facilities

# SEE Testing, Modeling and Rate Estimation

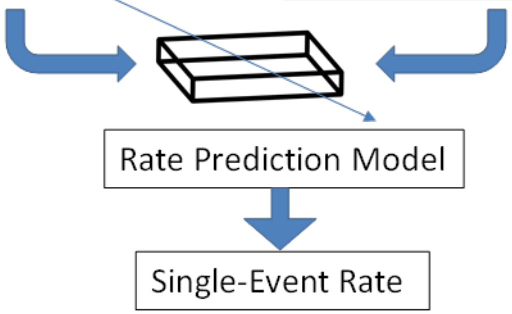




Ion flux vs. energy for Z=1-92 from CREME96



SEE σ vs. LET for heavy ions



Rate Prediction Model

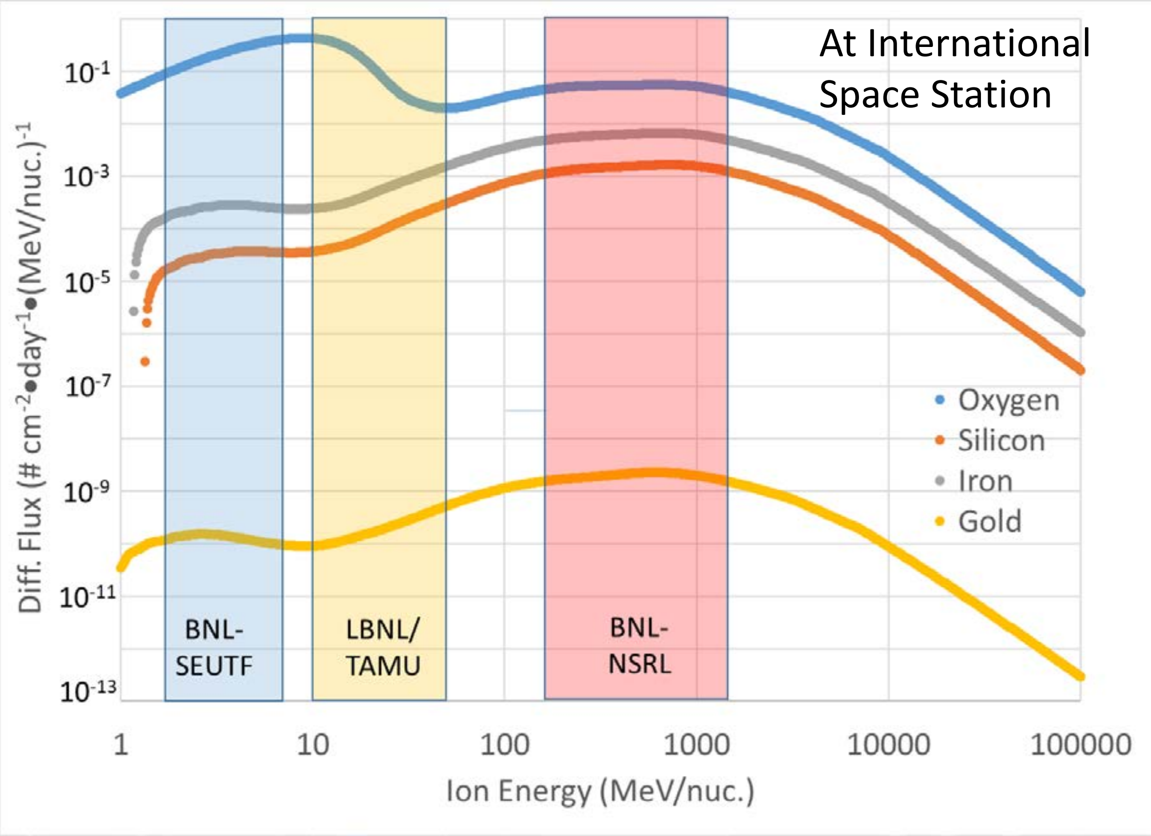
Single-Event Rate

- On-orbit environment too complicated (ion species, energy, angle…) to measure SEE rate
- Charge Track Density~Linear Energy Transfer
  - (LET)—1 pC/μm = 97 MeVcm$^2$/mg
  - Device response scales w/ deposited charge
  - Deposited charge scales ~with LET
  - LET often used as proxy for deposited charge
    - Range/energy also important
- SEE rate estimation tools drive SEE test techniques
  - Measure device response w/ heavy-ion beams (controlled charge dep.)
  - Use data to constrain rectangular parallelepiped (RPP) device model
- Advanced Monte Carlo rate models use more realistic SV model
  - Test techniques still catching up and really needed only for a few parts

# SEE Test Accelerators vs. Space Environment

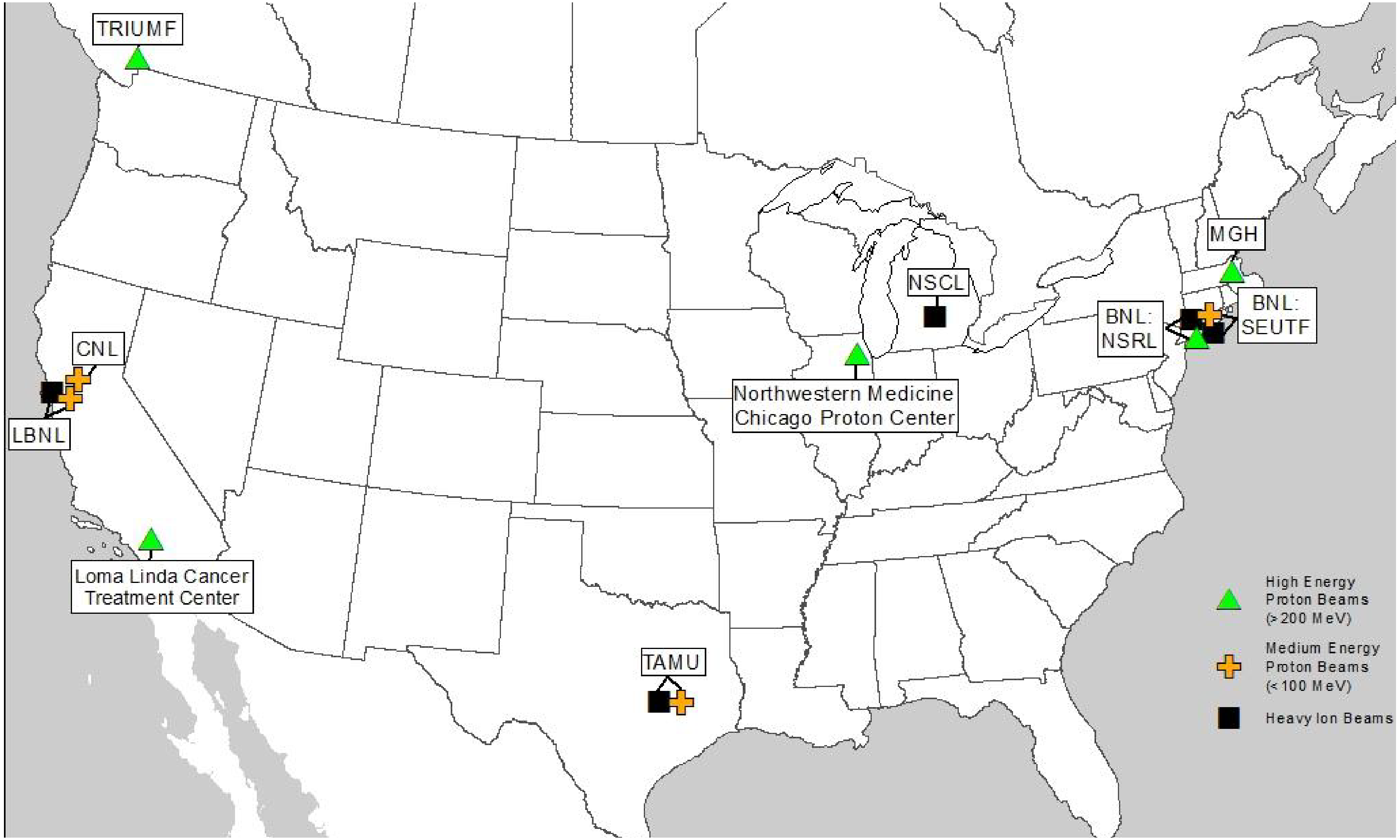
- Heavy-ion accelerators
  - Texas A&M University Cyclotron (TAMU)
    - ~3100 hours/year (main workhorse for community)
    - 15-40 MeV/nucleon energies (good penetration)
  - Lawrence Berkeley Laboratory 88-inch cyclotron
    - ~2000-2500/year
    - 10, 16 and 20 MeV/nucleon w fast beam changes
  - Brookhaven National Lab. has two facilities
    - SEU Test Facility (4 MeV/nucleon, <100 hours/year)
    - NASA Space Radiation Laboratory (<200 hr/year)
      - Energies>1000 MeV/nucleon (~median GCR energies)
      - Highly penetrating and can of study effects of track structure vs. energy for deep submicron CMOS
- Proton Accelerators—We're just parasitic users
  - Main workhorse high-energy proton accelerator (U. of Indiana) shut down in 2014
  - Community has made do by using extra time at cancer treatment facilities
  - Facilities, time available etc. vary depending on management attitude, medical demand, finances…

**Differential GCR Flux (selected ions) vs Accelerator Energies**



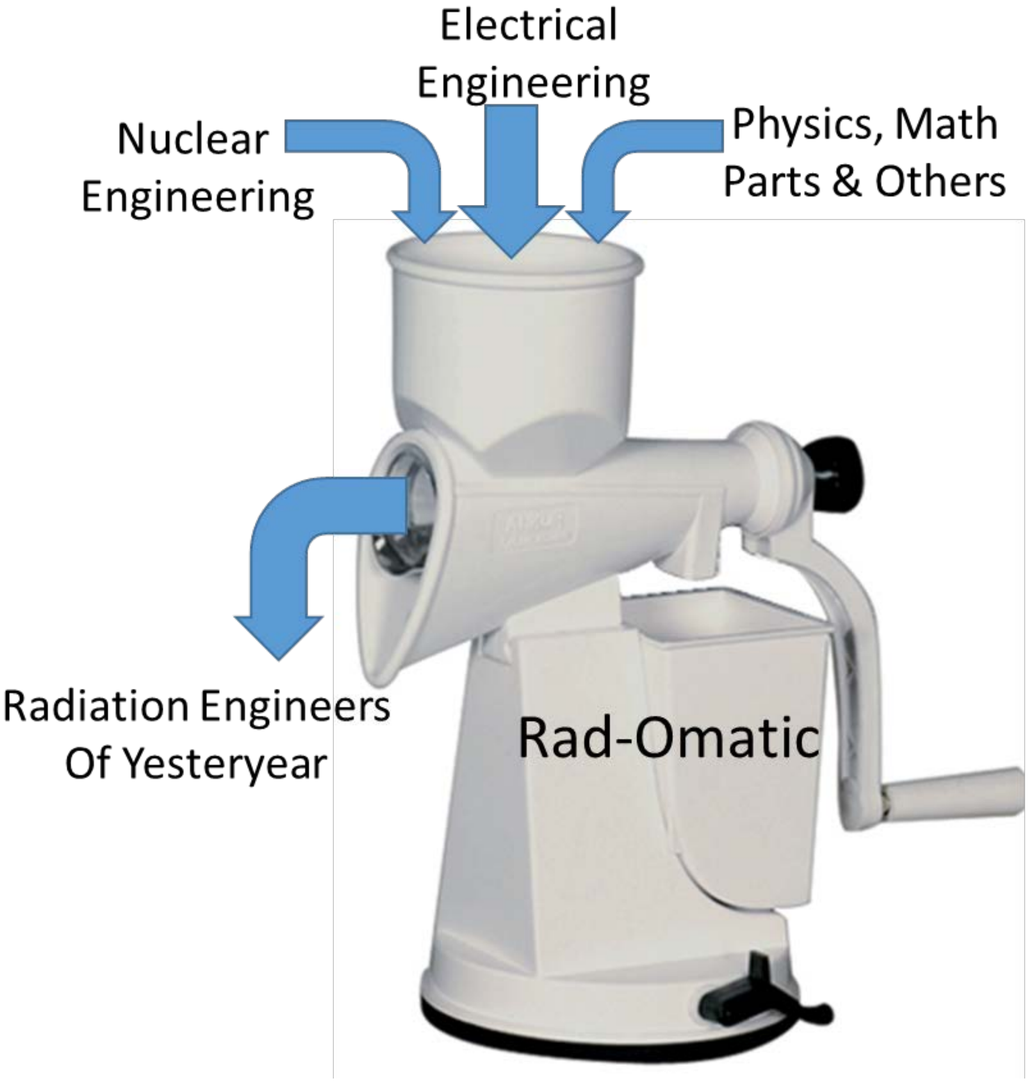
- GCR ions have energies out to 10s of GeV/nucleon
  - Low-energy accelerator (SEUTF)—OK for nondestructive SEE testing
  - Med. Energy (LBNL/TAMU)—OK for general purpose testing
  - High-energy (NSRL)—mainly special purpose (expensive) testing

# Test Accelerators: Few and Far Between--Literally



- Radiation test demands are increasing
  - More commercial parts
  - Commercial space
  - Terrestrial applications
  - Aging facilities require more maintenance
- ~ Dozen facilities account for nearly all SEE testing
- Losing single facility would place excessive demands on those remaining
- Facilities are responding
  - More hours

# Radiation Engineer Training: More Apprenticeship than Formal Education



Electrical Engineering

Nuclear Engineering

Physics, Math Parts & Others

Rad-Omatic

Radiation Engineers Of Yesteryear

- Radiation engineers require a special set of skills
  - Nuclear Physics and transport of particles in materials
  - Physics of conductors, insulators and semiconductors
  - Materials science
  - Semiconductor manufacturing and packaging
  - Electrical, Electronic and Electromechanical EEE parts engineering
  - Space environment, electrical engineering, spacecraft design…
- Reaching full productivity takes ~a decade
  - Few formal university programs in radiation engineering
  - Even grads of such programs require mentoring
    - Some gaps are hard to fill in a classroom or a lab setting
    - Mentorship, conference attendance and experience are critical
- Problem: Transferring cumulative knowledge to next generation
  - Inconsistent funding → bimodal age distribution for rad. engineers
    - Many radiation engineers near retirement or early career
    - Few midcareer professionals
  - Also fewer large satellite projects → fewer learning opportunities

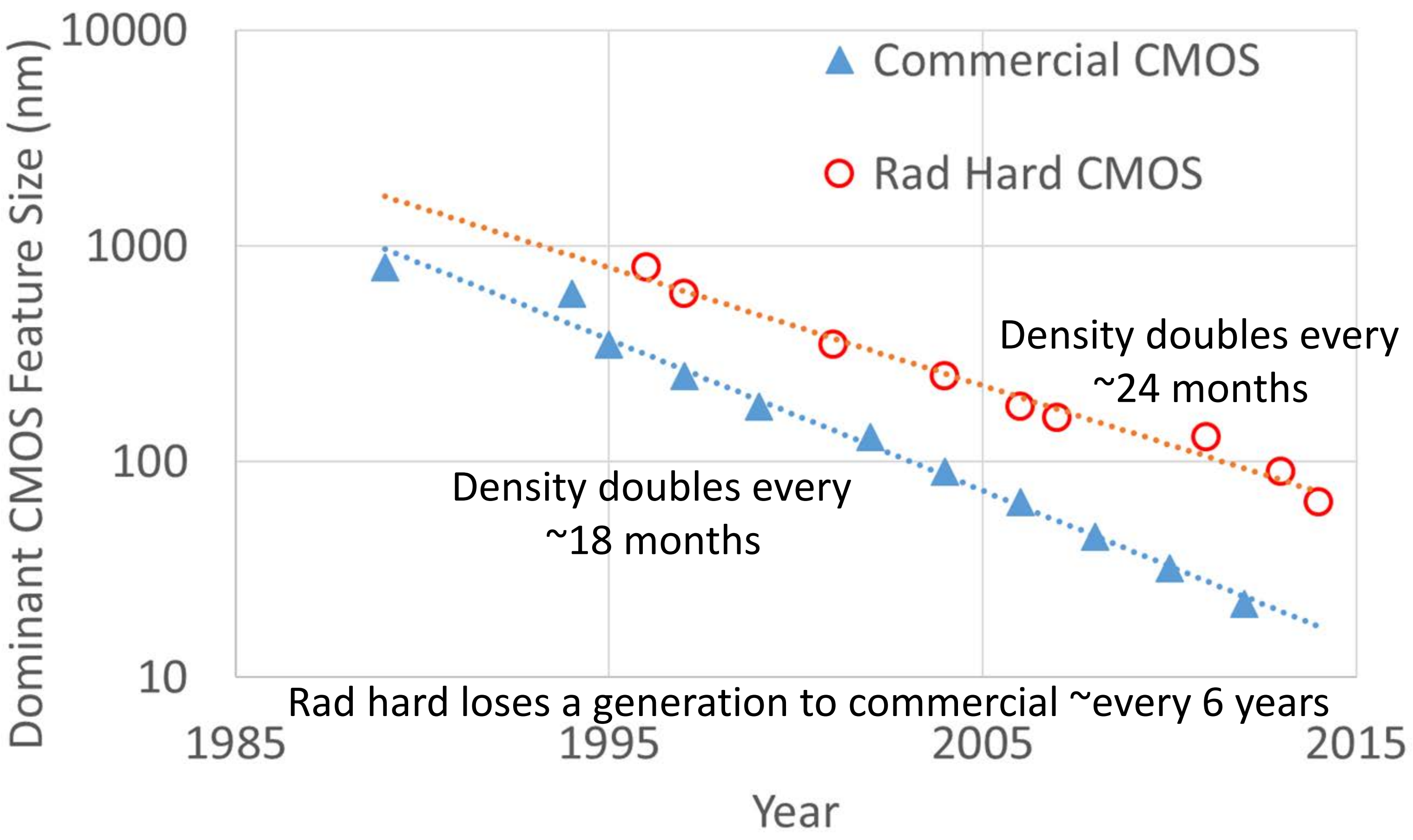
# SEE Hardness Assurance: Success and Challenges

- SEE hardness assurance is a field that emerged out of huge challenges less than 50 years ago
  - First SEE observed were caused by GCR—with energies up 1000x those of accelerator ions
  - No model for the process existed
  - No test methodology
  - New effects emerging every ~3 years
  - New technology every ~18-24 months
- Yet by 1986 SEE hardness assurance ~mature
  - Rate estimation based on simplified model of device charge collection volume (RPP)
  - Test methodology informed to:
    - Detect as many SEE modes as possible
    - Constrain device models for rate estimation
  - Results:
    - Rate estimation (done properly) good to ~2x
    - Yields reliable design guidance economically
    - Guides radiation hardening of parts

- SEE HA also faces significant challenges
  - The Technology Challenge
    - New CMOS generation every ~18 months
    - Now no CMOS scaling—each generation even more different
  - The High-Energy Frontier
    - High energy needed for complex parts and packages
    - High-energy different from low-energy ions for small dimension CMOS
  - The Low-Energy Frontier
    - Low-energy protons may have high enough energy to upset deep-submicron CMOS directly (no recoil interaction needed)
    - Low-altitude/low-energy frontier—terrestrial upsets could occur due to atmospheric muons as well as neutrons
  - The $$$ frontier
    - Satellites using more state-of-the-art parts w/o radiation pedigree
    - Parts are more complicated and take longer to test
  - The Rad Hard Viability frontier
    - Radiation hardening expensive and sales volumes small
    - If rad-hard sector collapses, almost every part would need testing
  - New customers with different needs
    - Commercial space demands are increasing
      - Often use commercial parts due to schedule, cost, performance

# Technology Frontier

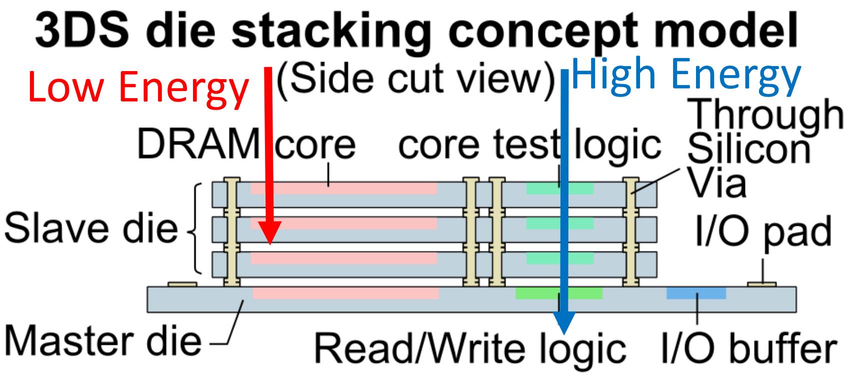
Lag between rad hard and commercial CMOS increases exponentially



Rad hard loses a generation to commercial ~every 6 years

- During CMOS scaling epoch (<2005)
  - New generation every 18 months
  - New generation= changed radiation risk
  - Past generations are poor predictors
- Post CMOS scaling (>2005)
  - Moore’s law involves changes to device design, materials, etc., as well as scaling
  - Some technologies are entirely new
    - Phase-change and spin-torque memories
    - Nanotube technologies
  - Some new failure modes, but most are analogous to those seen previously
- Some technologies will require more advanced rate estimation tools
  - Physics-based Monte Carlo
- Heavy-ion irradiation still the most controlled tool for measuring device response to radiation

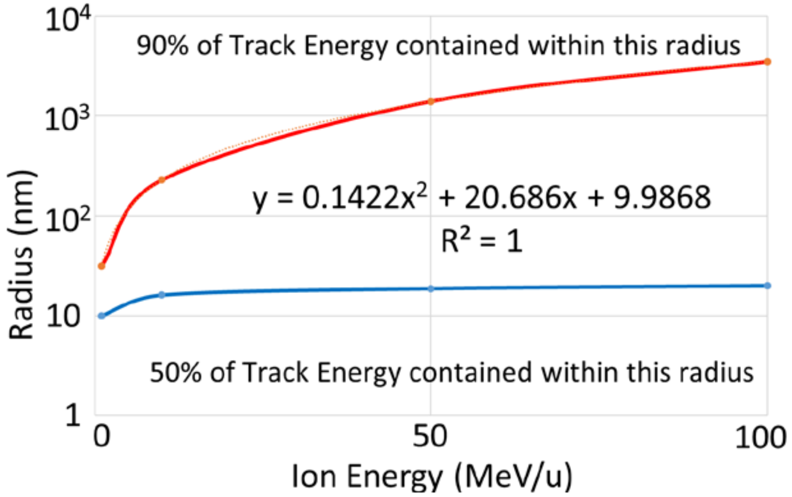
# The High-Energy Frontier



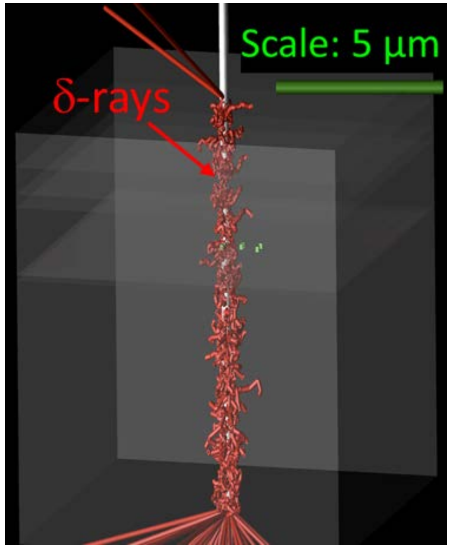
Re-use granted under Creative Commons Attribution-Share Alike 3.0 Unported license

- Increasingly complicated parts and packages
  - Too much overburden for beam to penetrate to reach device sensitive volumes
  - Multiple die in the same package
    - Thicker overburden
    - Different technologies may require different beams
  - Lower-energy ions may require part modification
    - Expensive and risky
    - Can affect results of SEE testing

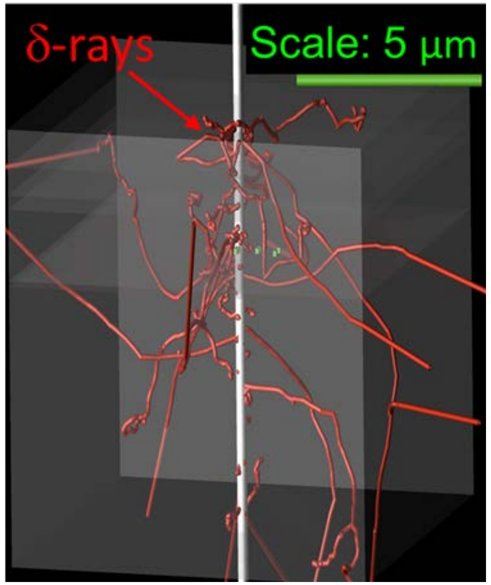
- SEE mechanisms may also depend on ion energy
  - High-energy ions deposit energy differently
  - High-energy ion may be more likely to upset multiple bits or upset a hardened cell based on redundant nodes



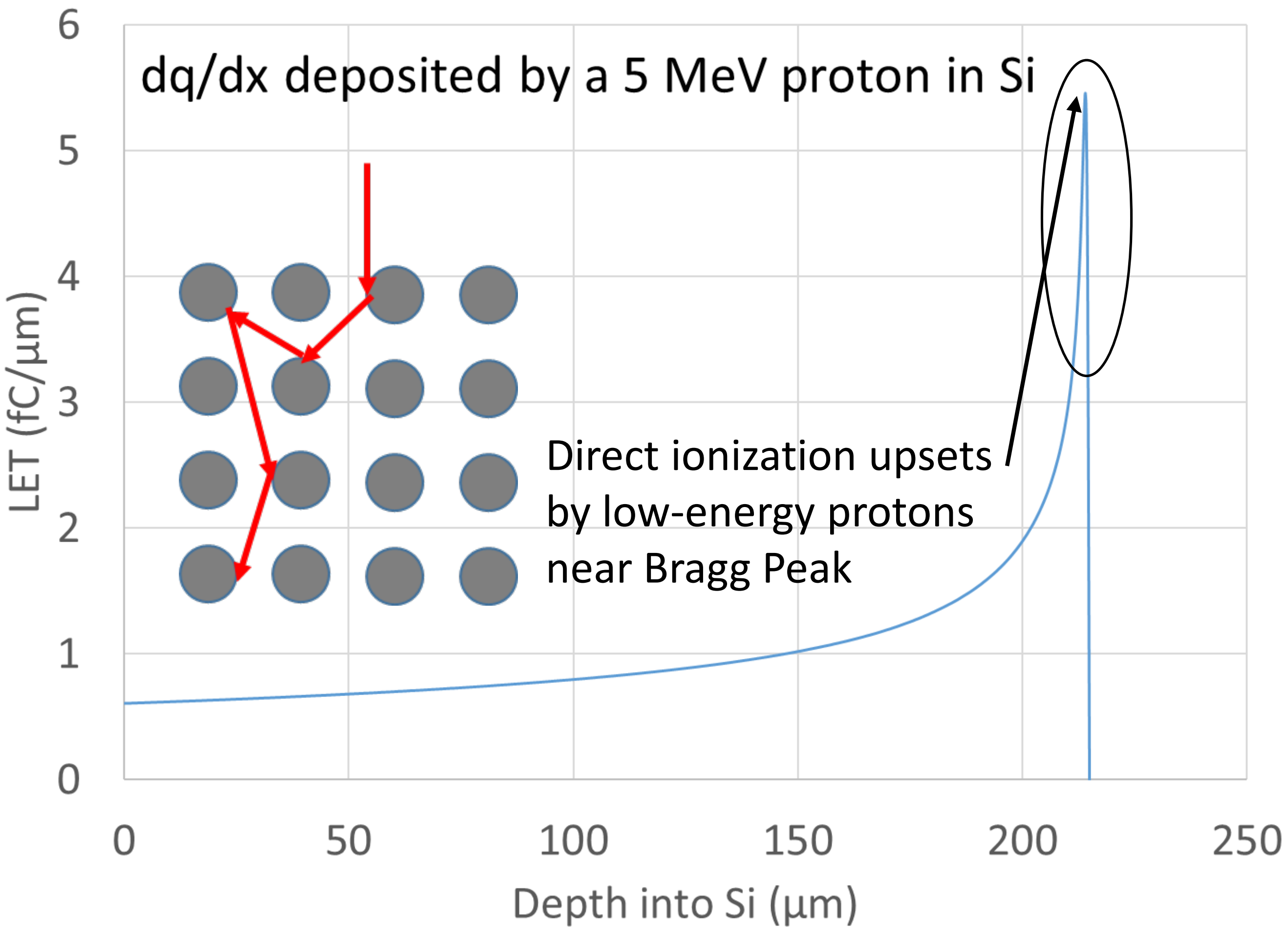
280 MeV Fe ion



28 GeV Fe ion

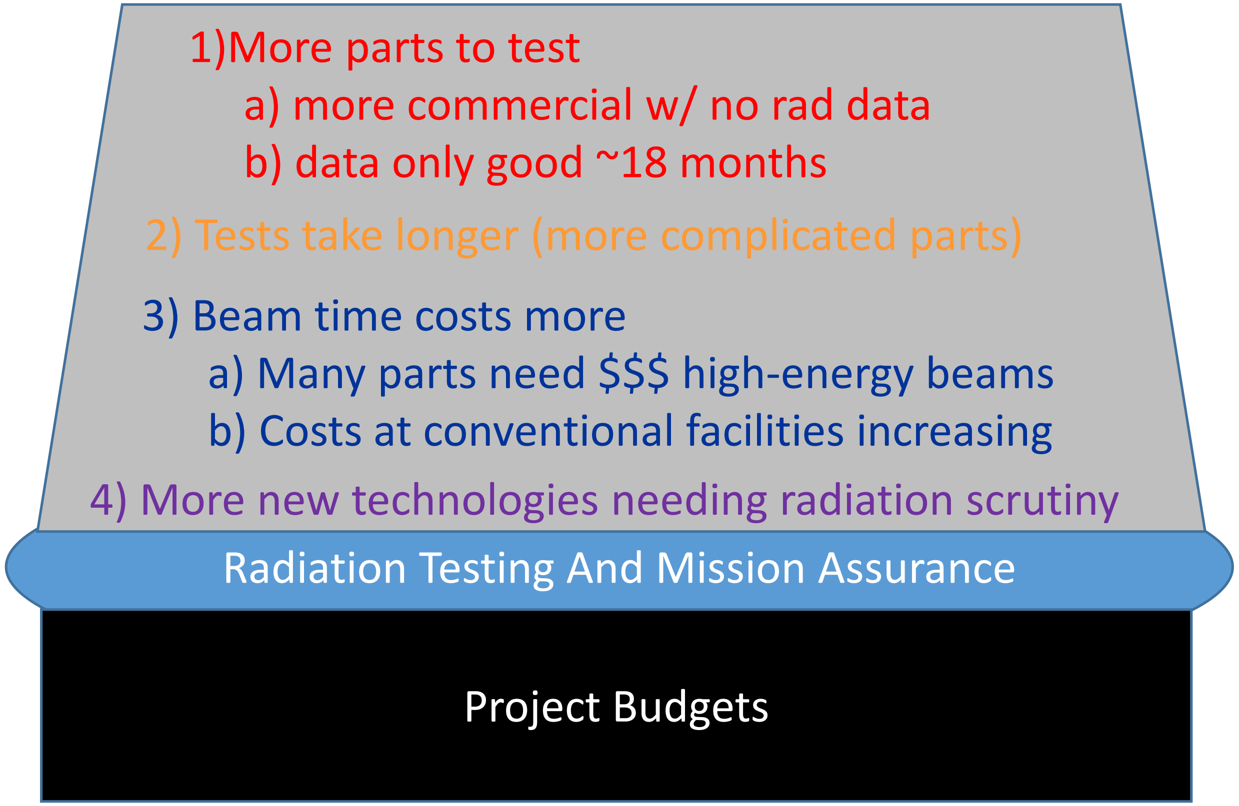


# The Low-Energy (and Low Altitude) Frontier



- CMOS technologies w/ minimum feature size <100 nm can have SEE due to direct ionization by protons (no nuclear recoil needed)
- Mechanism for low-energy protons
  - At ~0.08 MeV, proton deposits~5.5 pC/µm
  - scattering increases path/energy, which increases energy deposited in sensitive volume
- Narrow Bragg Peak means flux that can cause SEE will be low
  - Limited concern for satellites; none terrestrially
- But, what works for protons also works for muons
  - Comparable energy deposition + more scattering
- Threats on the “Low Frontier”: Terrestrial SEE
  - Neutrons dominate terrestrial SEE despite low flux
    - Ultra-high precision/reliability applications
    - Very large data storage or computing

# Cost Challenges



1)More parts to test
    a) more commercial w/ no rad data
    b) data only good ~18 months

2) Tests take longer (more complicated parts)

3) Beam time costs more
    a) Many parts need $$$ high-energy beams
    b) Costs at conventional facilities increasing

4) More new technologies needing radiation scrutiny

Radiation Testing And Mission Assurance

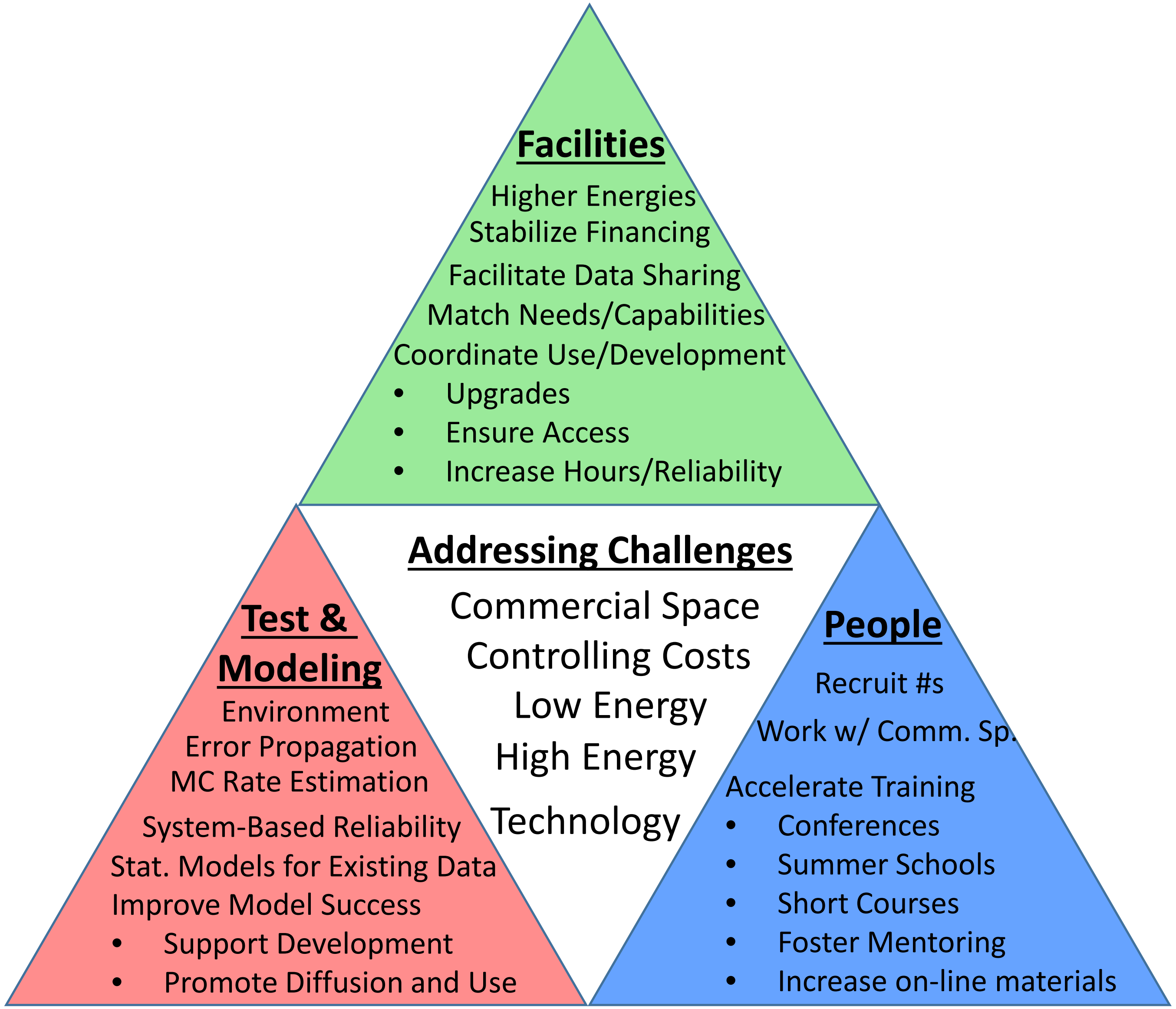
Project Budgets

- SEE hardness assurance efforts face increasing cost pressure
  - Commercial parts are designed w/o thought of radiation
    - Rapid life cycle means data has shelf life of a dairy product.
  - Increased circuitry density →greater part complexity →greater challenges and time to test the part
  - More complicated part packaging and more highly integrated parts more likely to require long-range, high-energy ion beams to reach device sensitive volumes
  - End of CMOS scaling means more innovation required to meet Moore's Law for increasing density
    - Response of novel technologies needs to be thoroughly characterized—may exhibit novel susceptibilities or enhanced susceptibility to known failure modes.
- Radiation hardened parts critical to managing test load
  - Despite higher per-part cost, saves testing costs and allows testing to focus on where it provides most benefit
  - Rad hard parts market a tiny fraction of commercial
  - Hardening efforts costly
  - But…rad hard lifecycles much longer than commercial

# Strictly Commercial: These Aren’t Your Fathers’ Spacecraft

- Wikipedia lists ~100 commercial space companies
  - Includes established space companies (Lockheed, Boeing, Northrup Grumman…) and brand new companies
    - Many short-lived, single-purpose companies (e.g. founded to compete for X-prize)
    - Dozens of products: Launch vehicles, Asteroid mining, rovers, space habitats, smallsats…
- Promise of commercial space is greater variety of services in space, quicker and at lower cost
  - Rad hard electronics not only more costly, lower performance, but also have a long lead time
  - Testing of commercial electronics is costly, technically demanding and time consuming
- Many commercial space companies are trying “alternative” approaches to radiation hardness assurance
  - Buy-it-and-fly-it? Protons only? Worst case based on “similarity”?—all problematic from reliability perspective
  - System-oriented SEE hardness assurance uses modeling to concentrate test/analysis where it is most effective
  - Still too early to judge efficacy, but depends critically on fidelity and flexibility of system model(s)
- Many doing radiation analysis for commercial space isolated from radiation effects community
  - Commercial space and Radiation conferences often do not overlap
    - Commercial space misses experience of conventional space builders
    - Conventional builders miss out on possibly innovative approaches that could benefit them

# National Academies to the Rescue



**Facilities**

Higher Energies
Stabilize Financing
Facilitate Data Sharing
Match Needs/Capabilities
Coordinate Use/Development

- Upgrades
- Ensure Access
- Increase Hours/Reliability

**Addressing Challenges**

Commercial Space
Controlling Costs
Low Energy
High Energy
Technology

**Test & Modeling**

Environment
Error Propagation
MC Rate Estimation
System-Based Reliability
Stat. Models for Existing Data
Improve Model Success

- Support Development
- Promote Diffusion and Use

**People**

Recruit #s
Work w/ Comm. Sp.
Accelerate Training

- Conferences
- Summer Schools
- Short Courses
- Foster Mentoring
- Increase on-line materials

- 2016—National Academy evaluated state of nation's electronics testing infrastructure for space missions
- Panel Concentrated on SEE Infrastructure
  - Heavy-Ion and Proton Accelerators (some neutrons)
    - Emphasis on ensuring adequate access/capabilities
  - Modeling & Simulation capabilities
    - Emphasis on coordination and promoting use
  - People
    - Ensuring training of next generation
    - Coordinating with commercial space rad. engineers
- 2017 National Academies report released
  - Available as free download:
  - https://www.nap.edu/catalog/24993/testing-at-the-speed-of-light-the-state-of-us
  - 7 Recommendations—summarized in figure at left
    - Deal with facilities, organization, funding, work force, modeling and simulation and data curation and management

# Acknowledgments

- **We thank NASA's Office of Safety and Mission Assurance for support of this work.**
- **The National Academies gave us their customary excellent support and encouragement.**

**National Academy Staff**

DWAYNE A. DAY, Senior Program Officer, *Study Director*

ERIK B. SVEDBERG, Senior Program Officer

NEERAJ P. GORKHALY, Associate Program Officer

HEATHER LOZOWSKI, Financial Associate

JOSEPH PALMER, Senior Project Assistant

HENRY KO, Research Associate

**Committee**

BHAVYA LAL, IDA Science and Technology Policy Institute, *Co-Chair*

PAUL D. NIELSEN, Software Engineering Institute, *Co-Chair*

ARDEN BEMENT, Global Policy Research Institute

JAMES BURCH, Southwest Research Institute

HENRY B. GARRETT, (Retired)California Institute of Technology-JPL

JAMES HARRIS, Stanford University

SANDRA L. HYLAND, Northrop Grumman Corporation

LINDA KATEHI, University of California at Davis

RAY LADBURY, NASA Goddard Space Flight Center

JOE MAZUR, The Aerospace Corporation

LEONARD ROCKETT, Technology Metrics, LLC

RON TURNER, Analytic Services