SCHOOL OF ENGINEERING

VANDERBILT UNIVERSITY

MRED Update

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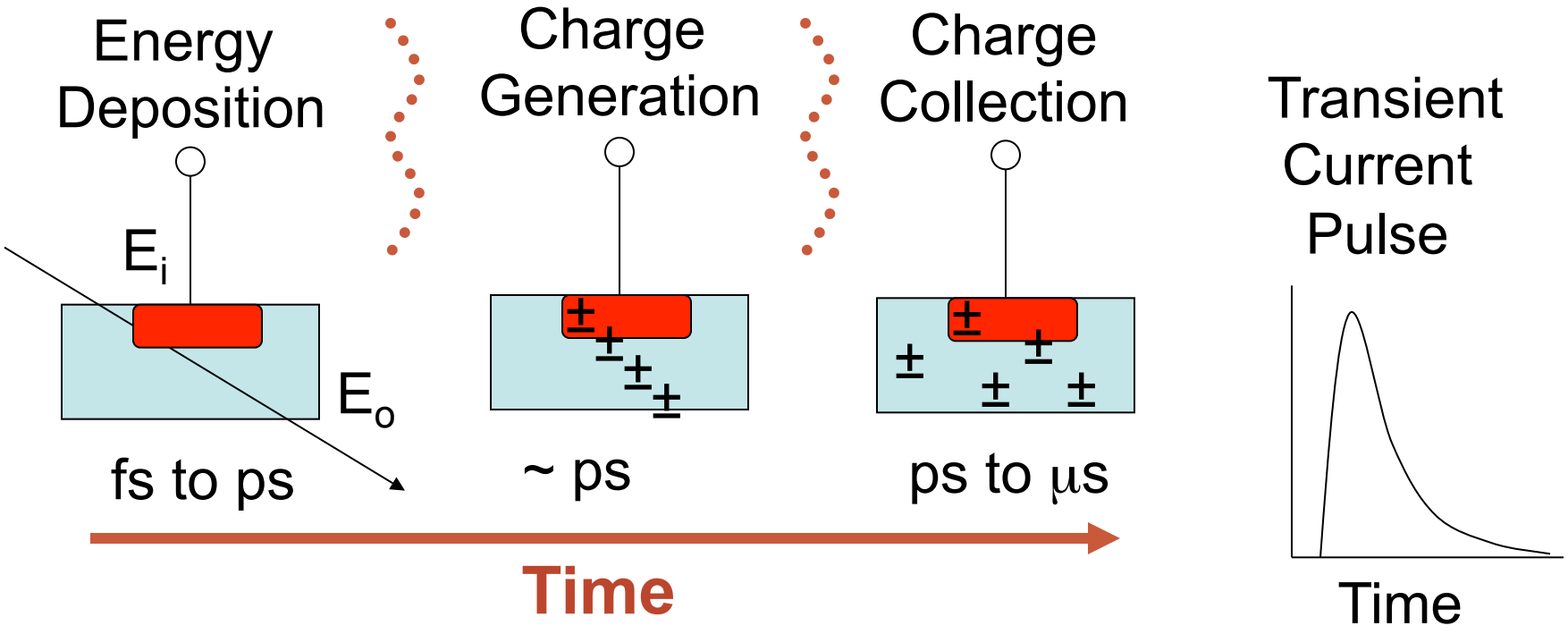
Outline

- Radiation-Induced Single Event Effects
- MRED: Monte Carlo Radiative Energy Deposition
- Review of some of the applications
  - Contribution of Ion-Ion nuclear reactions to SEU rates
  - SEU from low energy proton
  - Muon-induced SEUs
  - Single-electron SEUs
- Conclusions

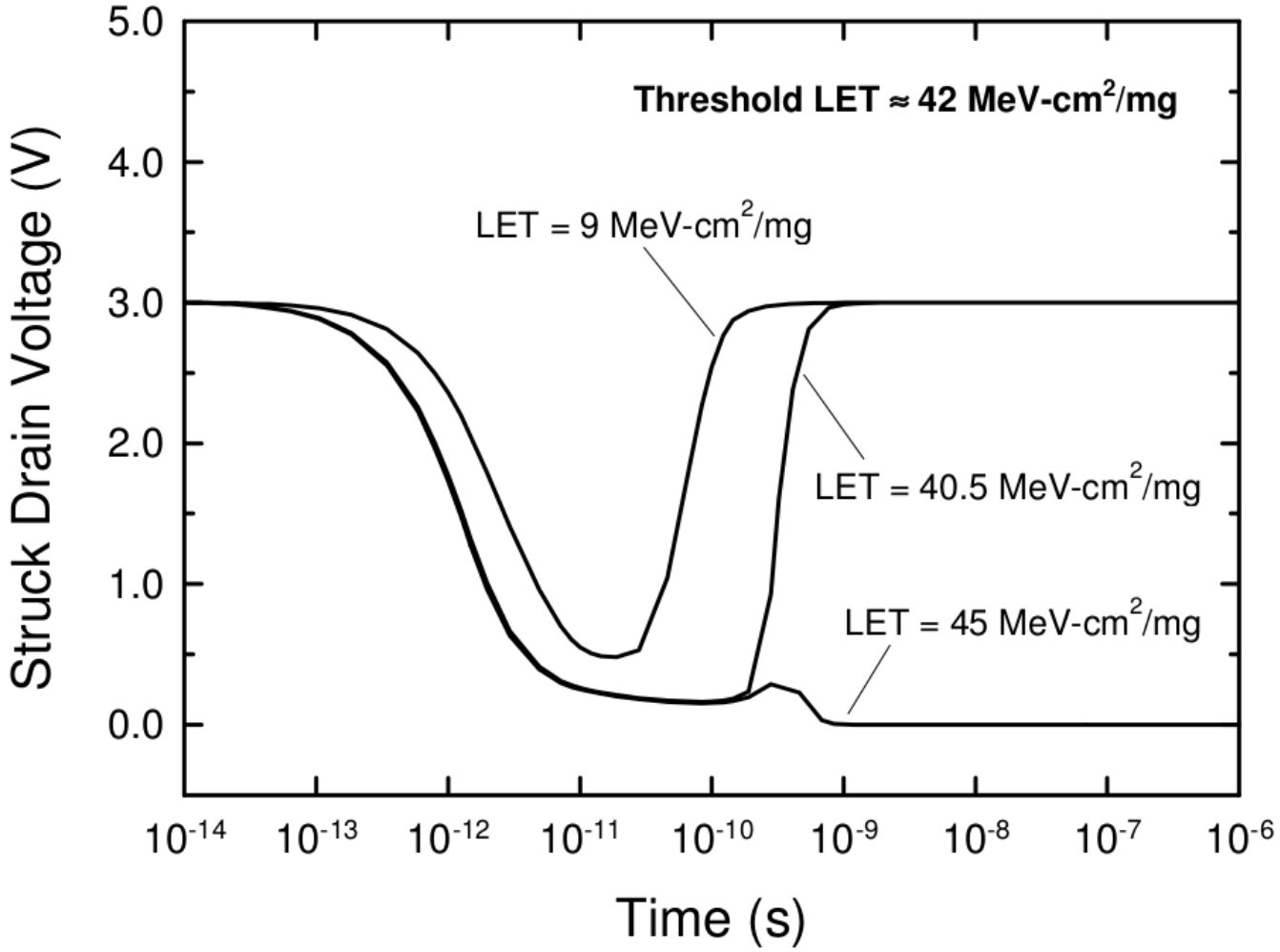
Transients from Single Particle Event



Soft Error Examples:

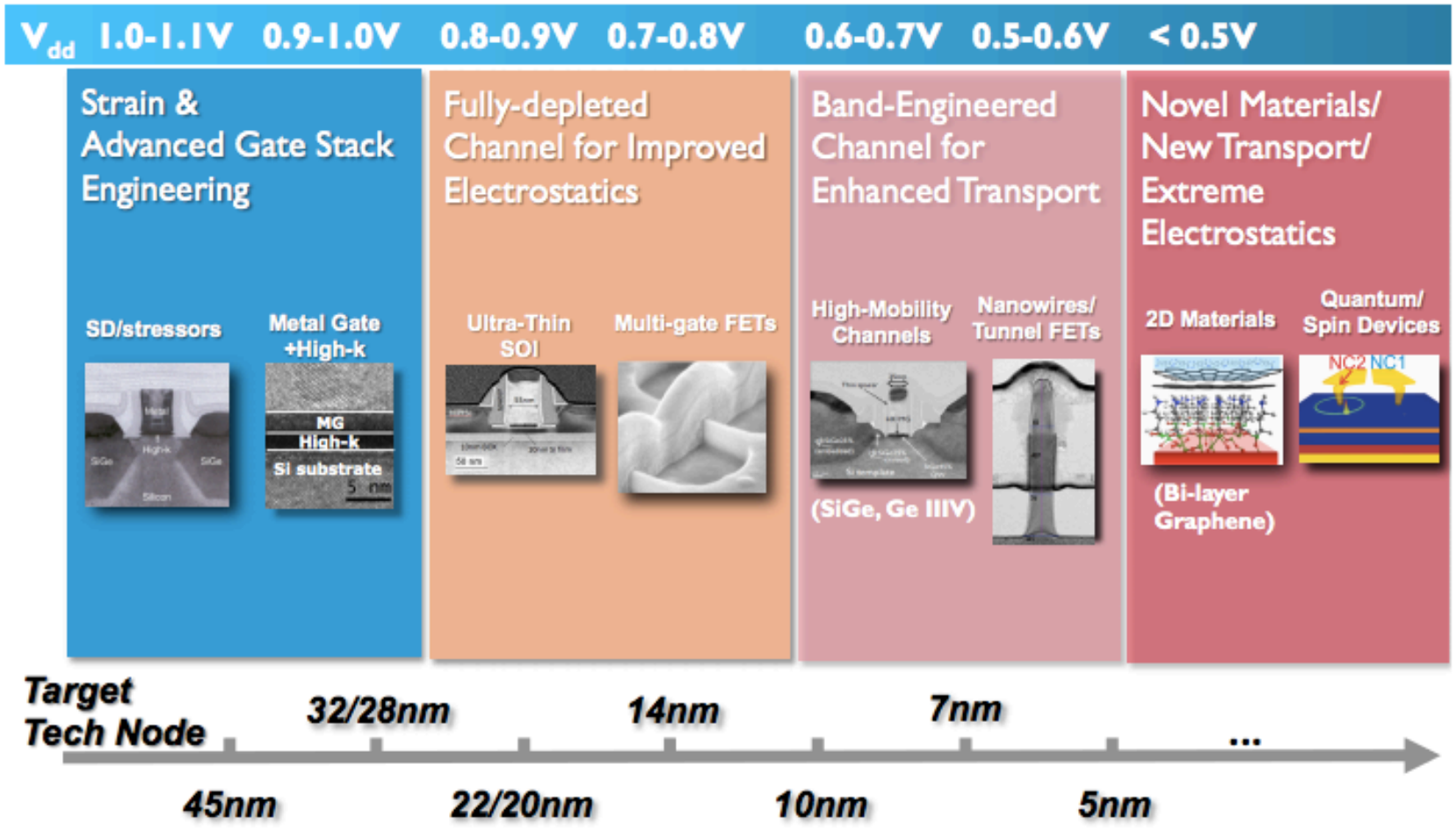
- Single Event Transient: A current pulse occurring at a circuit node due to single energetic particle event
- Single Event Upset: A change in a circuit's logic state induced by a single energetic particle event

Impact of Ion LET on SEU Response



Dodd NSREC SC 2001

Electronic Technology Roadmap



MRED

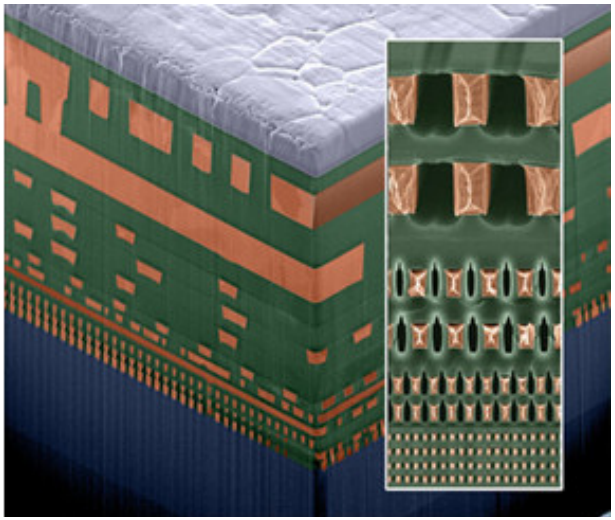
- MRED is a Python-language scriptable computer application that simulates radiation transport
- The MRED code integrates selected physics processes associated with the Geant4 toolkit with Fortran codes PENELOPE 2008, an electron transport code, and CEM03 and LAQGSM [7-9], both nuclear physics codes
- Papers that describe MRED:
  - Weller, R., Mendenhall, M. H., Reed, R., et al. (2010). “Monte Carlo simulation of single event effects.” *Nuclear Science, IEEE Transactions on*, *57*(4), 1726-1746.
  - Reed, R., Weller, R., et al. (2015). “Physical processes and applications of the Monte Carlo radiative energy deposition (MRED) code.” Accepted for publication in TNS.
  - Reed, R. A., Weller, R., et al. (2013). “Anthology of the development of radiation transport tools as applied to single event effects.” *Nuclear Science, IEEE Transactions on*, *60*(3), 1876-1911.

CREME

- CRÈME is a tool suite for predicting radiation environments and it's effects on electronics
  - Selected environment models for trapped, solar, and GRC
  - Contains analytical and Monte Carlo models for SEU rates
  - https://creme.isde.vanderbilt.edu
- MRED is the computational engine for the on-line Monte Carlo tool CRÈME-MC
  - Monte Carlo simulation of energy deposition in selected volumes
  - Ground tests
  - Event rates

MRED Applications
(2005 - 2015)

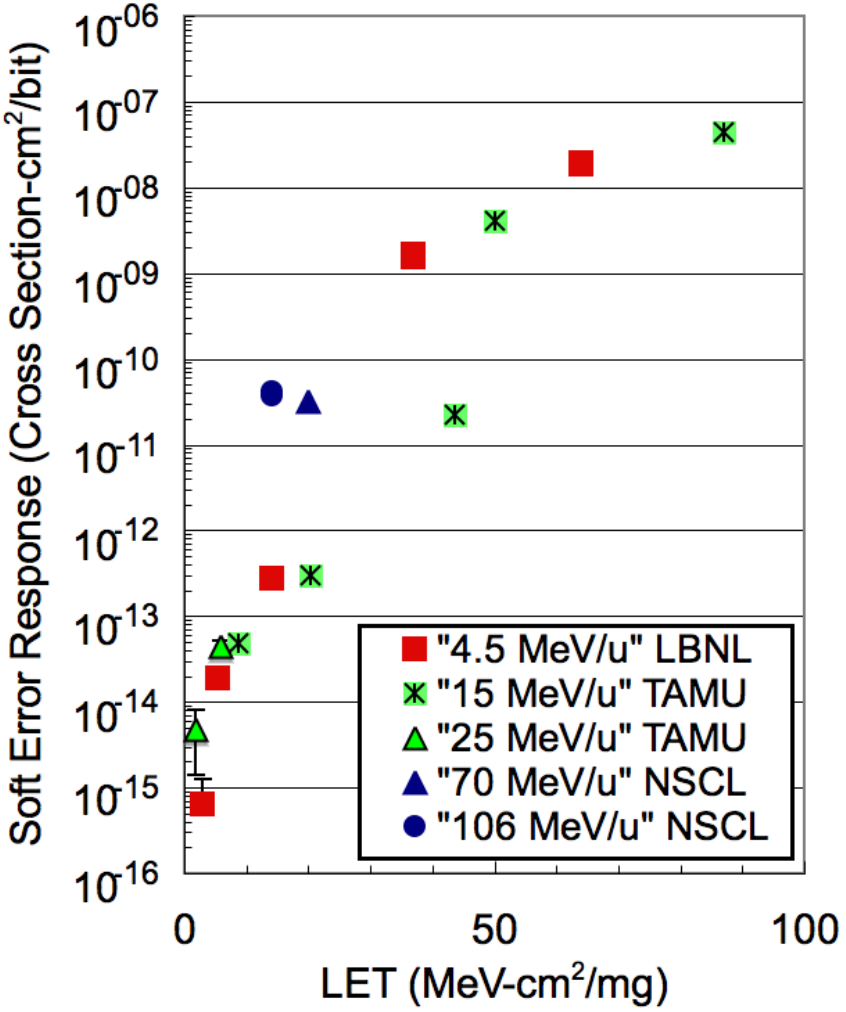
Ion-Ion Reactions



http://images.dailytech.com/nimage/4621_21476.jpg

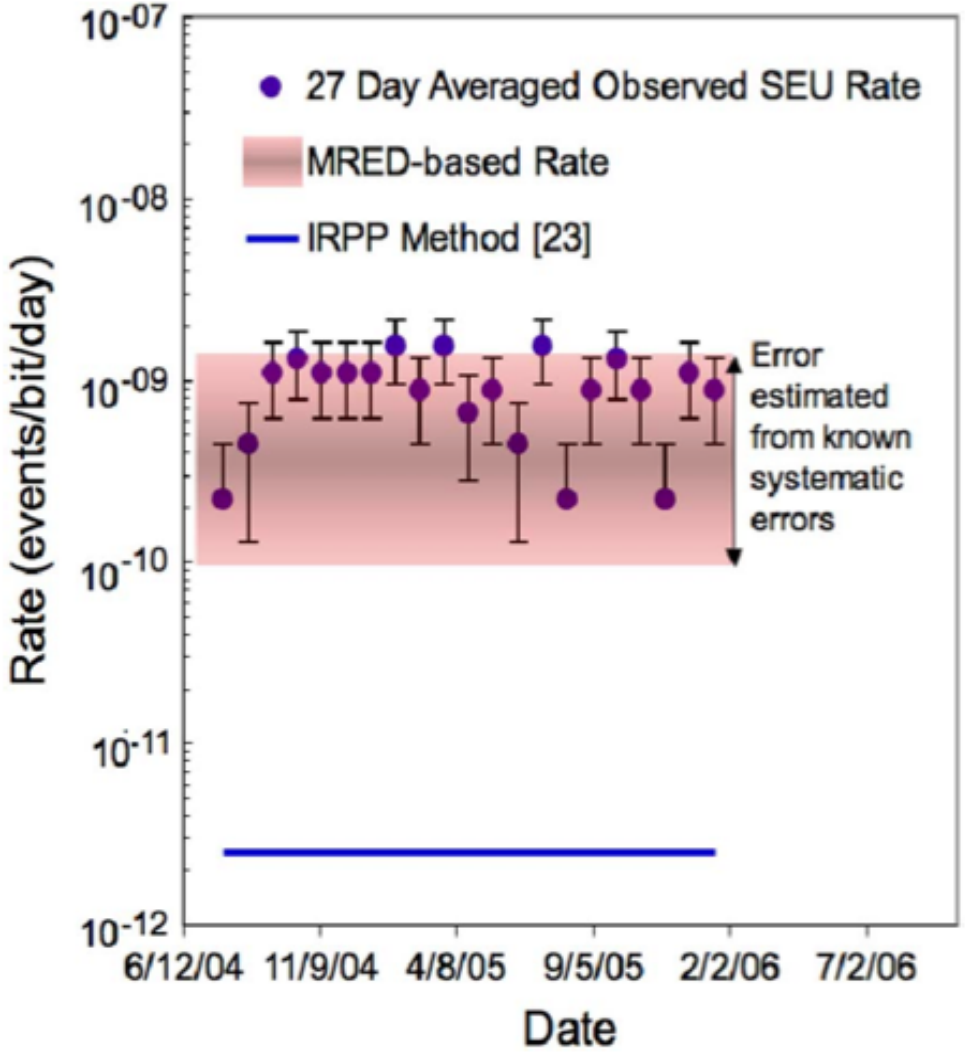
- Multi-valued cross section at same LET
  - CS = upset / fluence
- Ion-Ion nuclear reactions in non-silicon material near the sensitive volume contribute to the soft error response

Experimental evidence for this effect on a CMOS SRAM



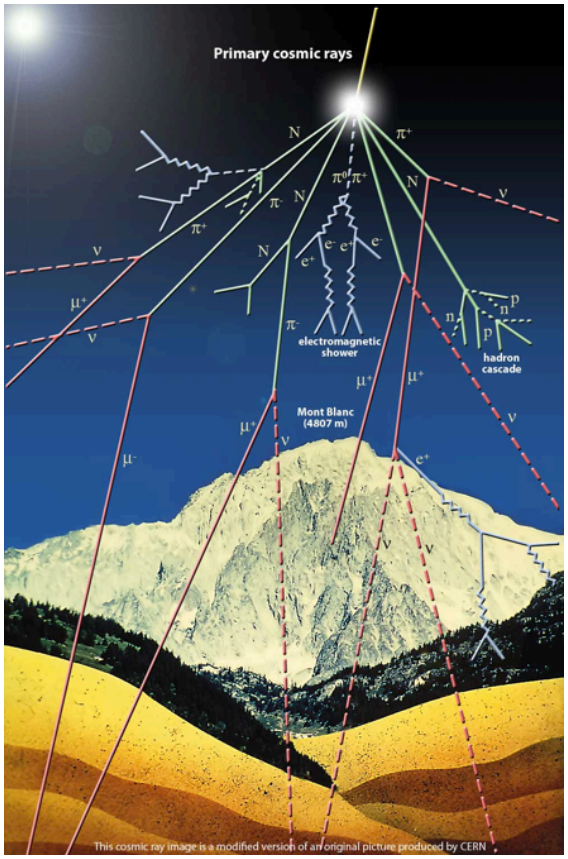
Warren et al. 2005, Dodd et al., TNS 2007, Reed et al. TNS 2007

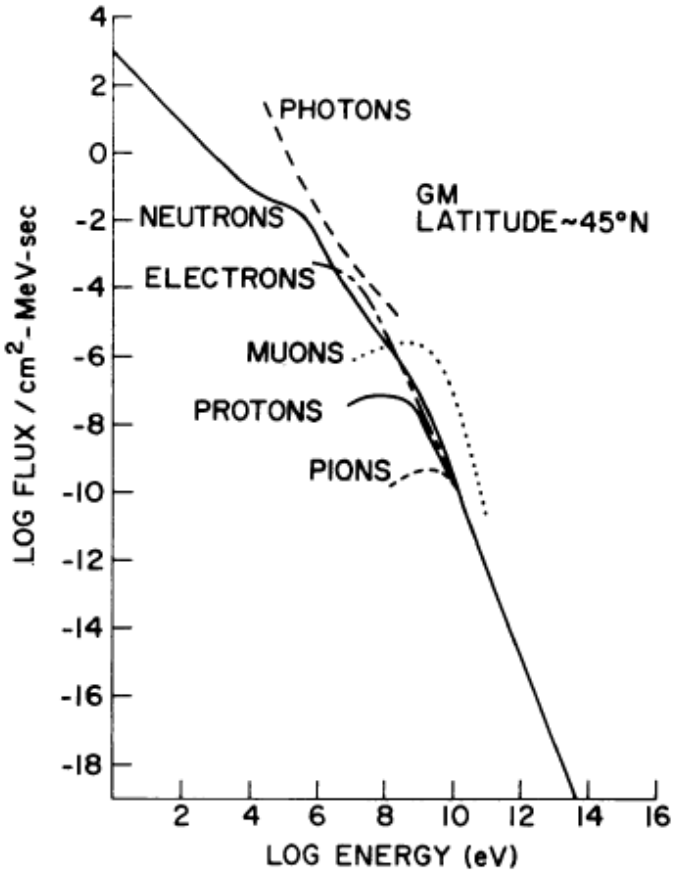
Event Rate and Ion-Ion Nuclear Reactions



Warren et al. 2005, Dodd et al., TNS 2007, Reed et al. TNS 2007

Terrestrial Environment



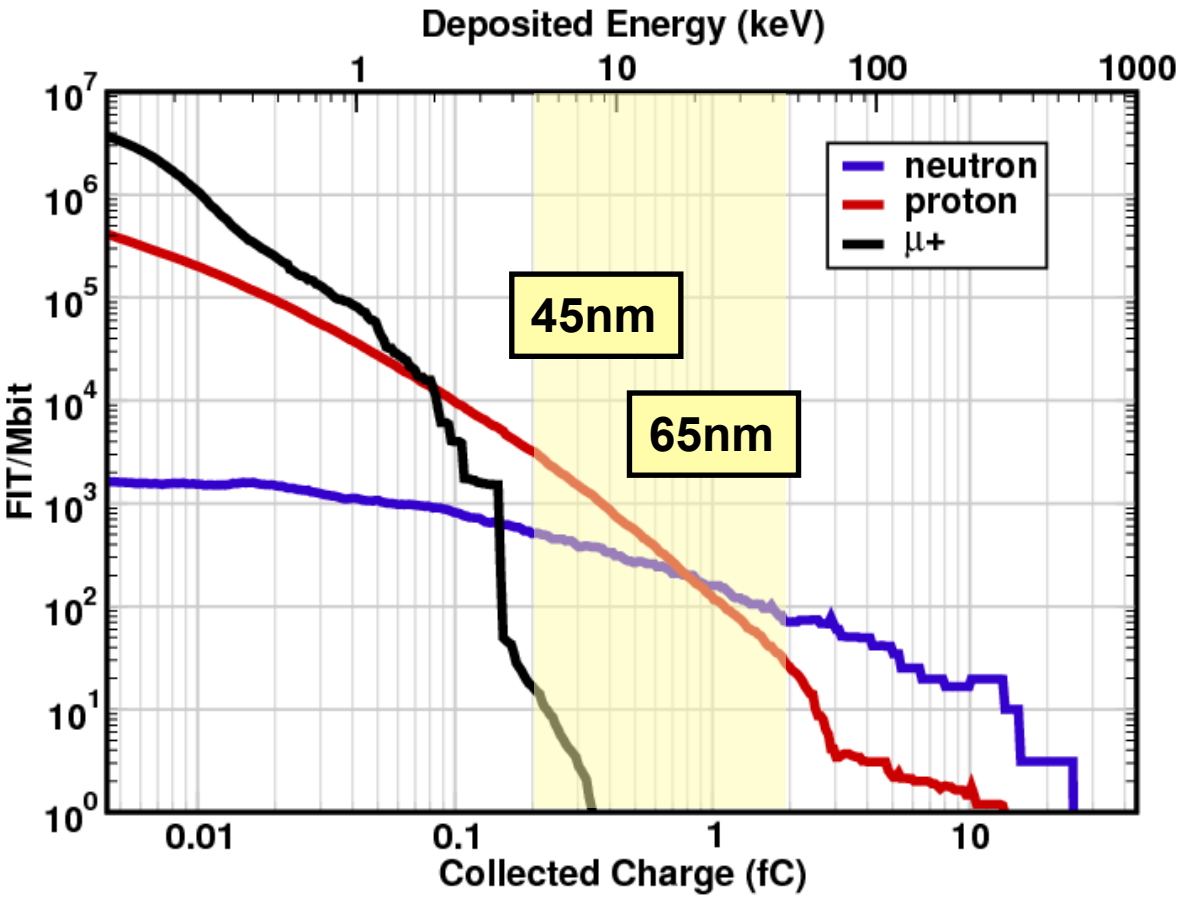


- Cosmic rays create showers (“zoo”) of secondary particles in the atmosphere
- Neutrons, while numerous, rarely interact with material leading to single event upsets
- Muons are the most abundance particle at sea level
  - –Stopping power similar to protons

Sierawski, TNS 2010

Preliminary Simulations (circa 2009)

- MRED Monte Carlo simulations indicated potential for upset from muon direct ionization
- Technology scaling (assuming same sensitive volume dimensions) will increase susceptibility to terrestrial protons, muons
- Spectra will be moderated by concrete, buildings, etc.

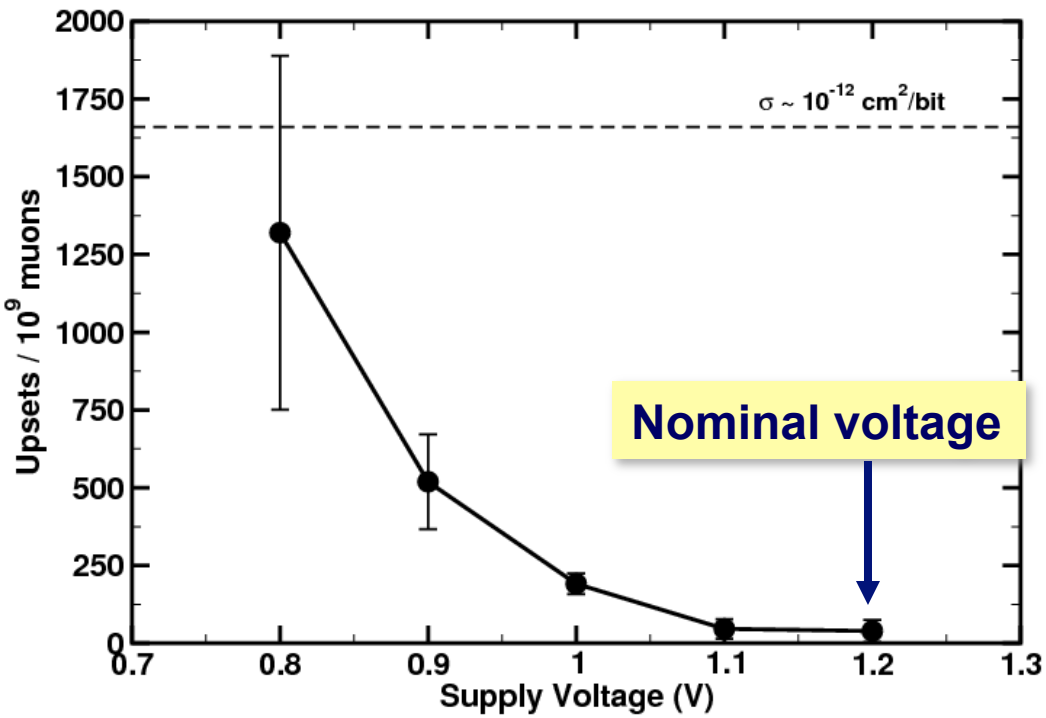


Single Event Upsets 65 nm SRAM

- Reduced bias experiments explored dependence on critical charge

$$Q = CV$$

- Few errors observed at nominal operating point, large increase for minimum functional voltage

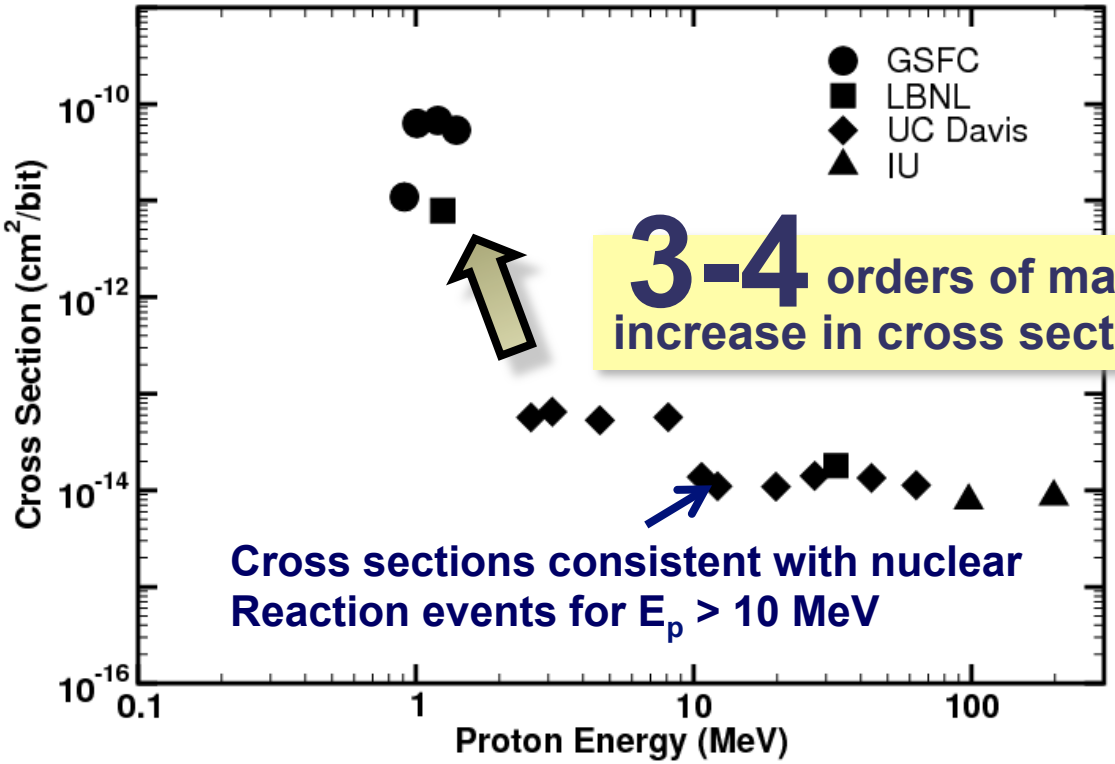


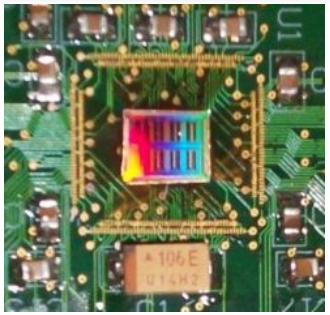
- **Bias is a possible indicator for susceptibility at the next technology node**
  - Geometric effects still need to be considered

Sierawski, TNS 2010

Low-Energy Proton Upsets

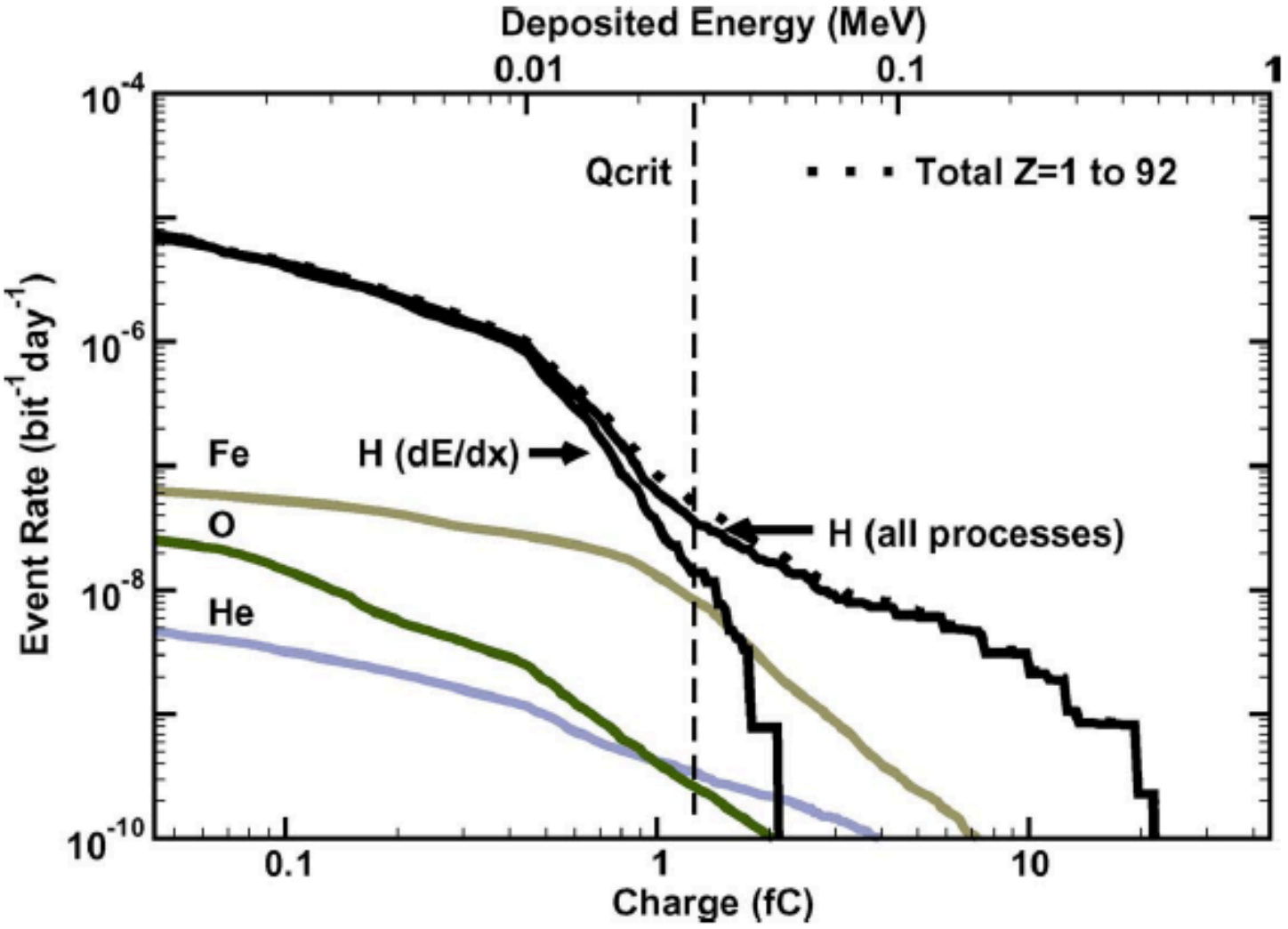
- Previous work reported data collected by Vanderbilt and NASA Goddard on TI 65 nm bulk CMOS process [Sierawski, TNS 2009]
- Consistent with evidence of proton direct ionization contributing to single event upsets (SEUs) reported for IBM 65 nm SOI process [Rodbell, TNS 2007][Heidel, TNS 2008]





Sierawski, TNS 2009

Low-Energy Proton Upsets



Sierawski, TNS 2009

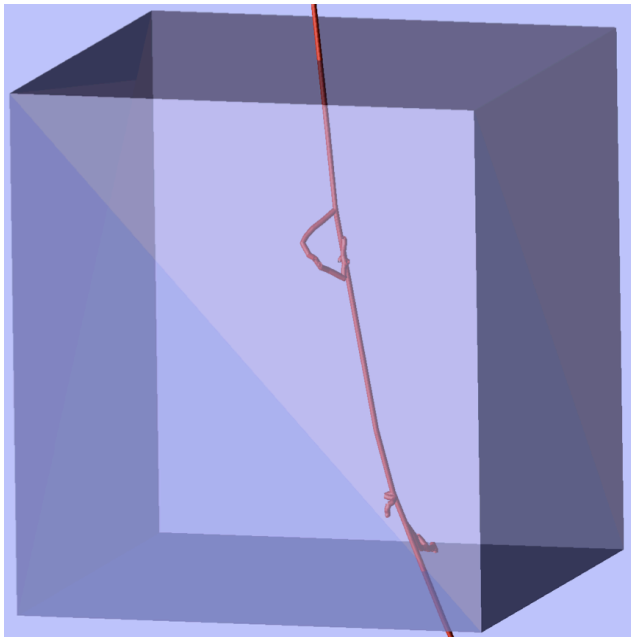
Single Electron-Induced SEU (circa 2010)

- **Critical charge estimates for 22 nm on the order of 0.1 fC – 0.35 fC at nominal supply voltage**
- **Devices are becoming increasingly sensitive to lightly ionizing particles**
  - **Low-energy Protons**
  - **Muons**

MRED simulations suggested electrons can deposit energy in excess of critical charge estimates

- 2.6 keV or 0.12fC

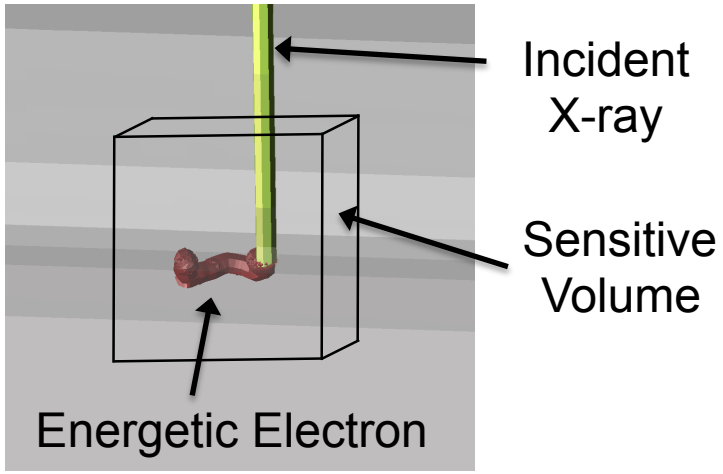
10 keV electron

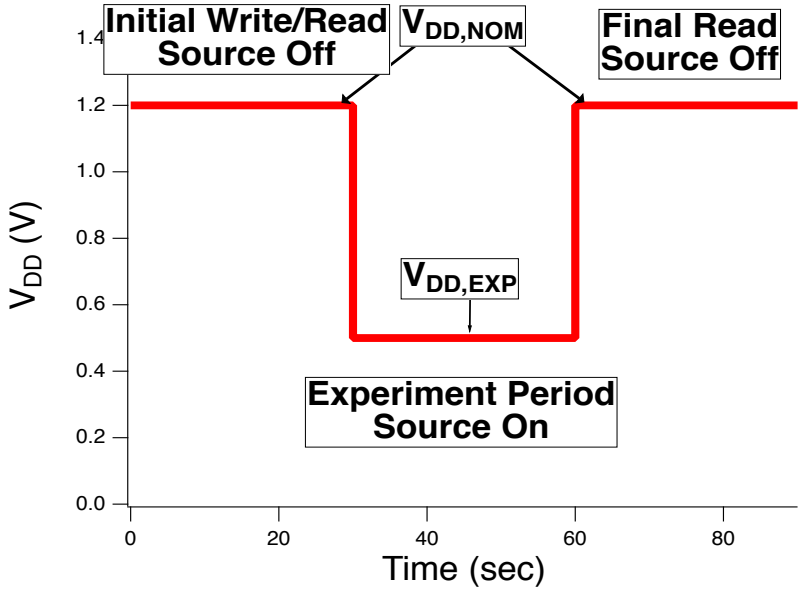


50 nm Cube

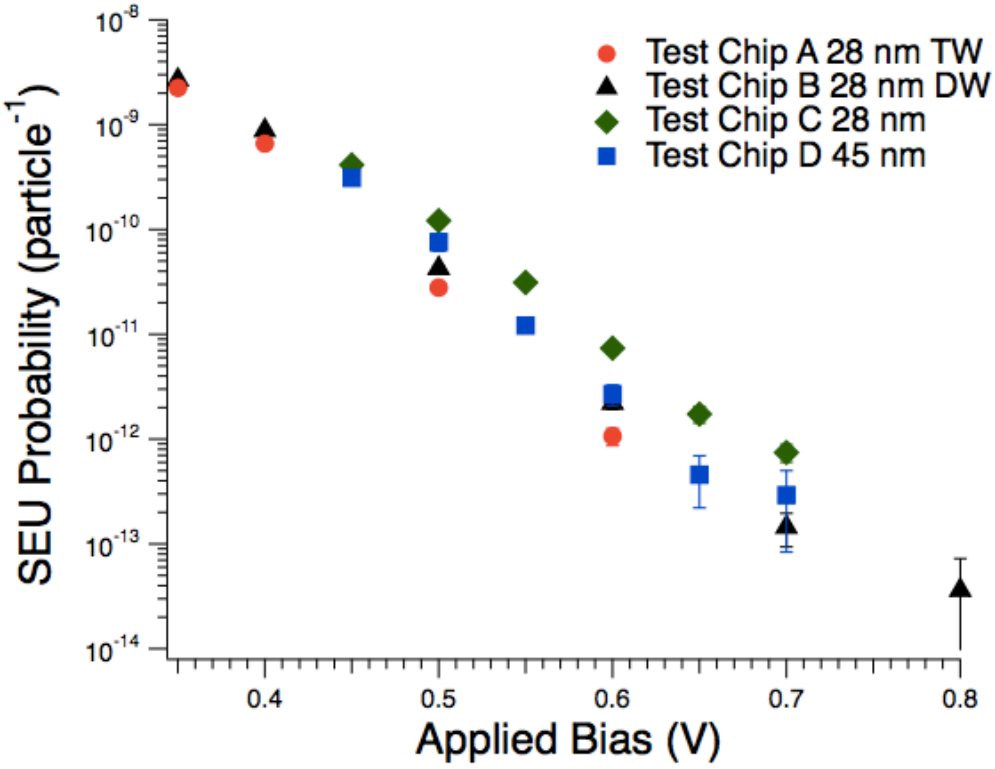
Experimental Method – X-ray Irradiation

- **28 nm and 45 nm SRAMs**
- **X-rays used to generate secondary energetic electrons**
- **Dose rate of 100 rad(SiO_2)/min**
- **Reduced bias testing**
- **Devices were designed and verified experimentally to be functional at all supply voltages used in this experiment**





Upsets in 28 & 45 nm SRAMs



King TNS 2013

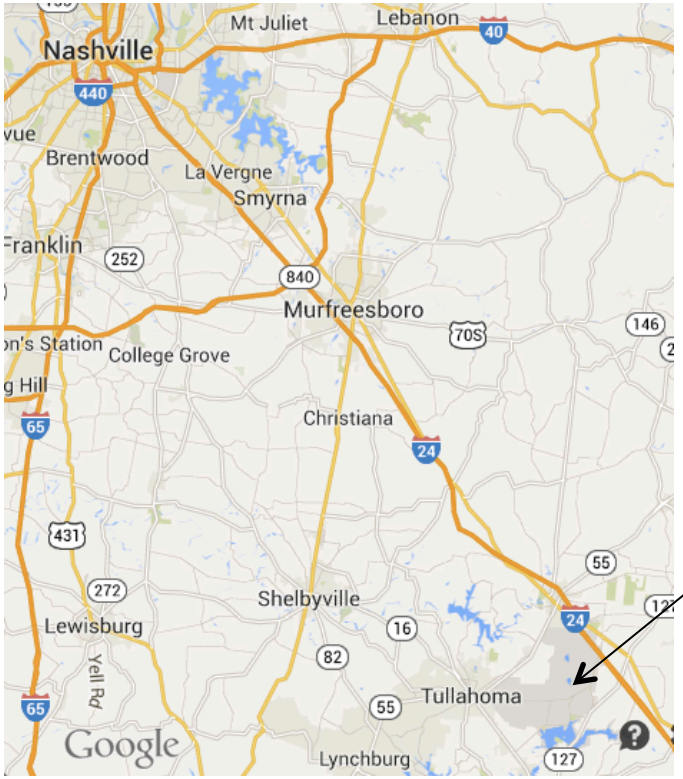
- **SEU probability**

$$Pr(V_{DD}) = \frac{N}{M}\frac{1}{A_{cell}\Phi}$$

- **Eliminated TID, photocurrents, and functionality as source of observed errors**
- **No significant parametric degradation; power supply current stable**

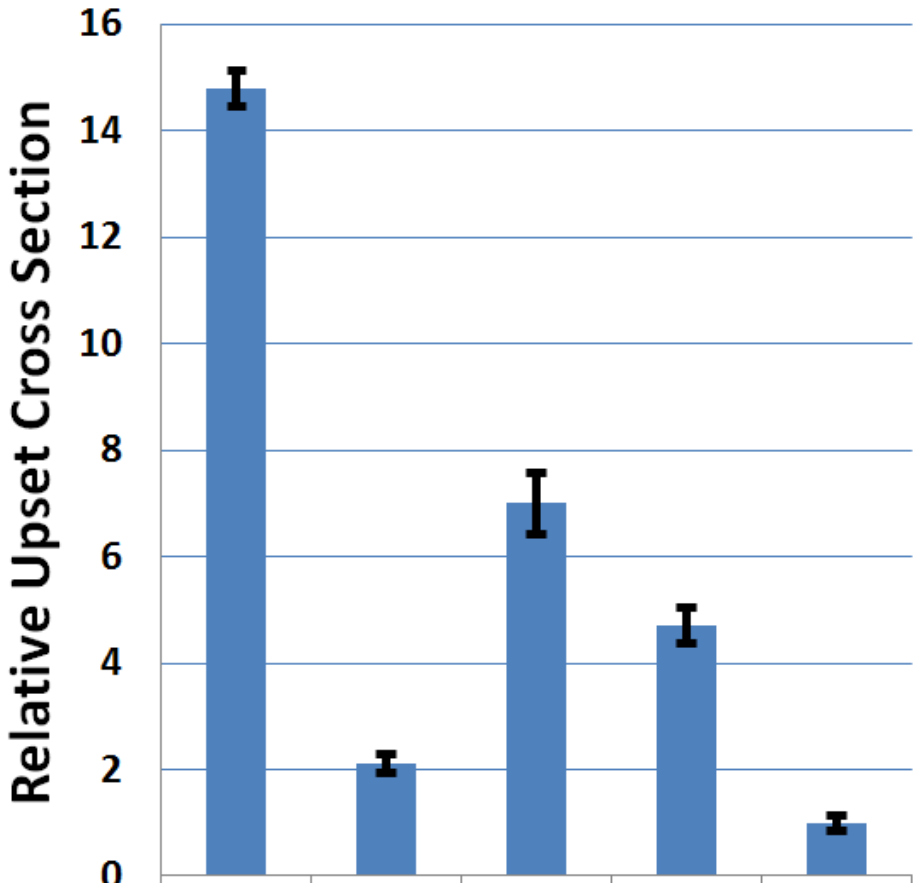
Electron Irradiation

- **Arnold Engineering Development Center**
- **Space Threat Assessment Testbed (STAT)**
- **Electrons, protons, photons, and others**



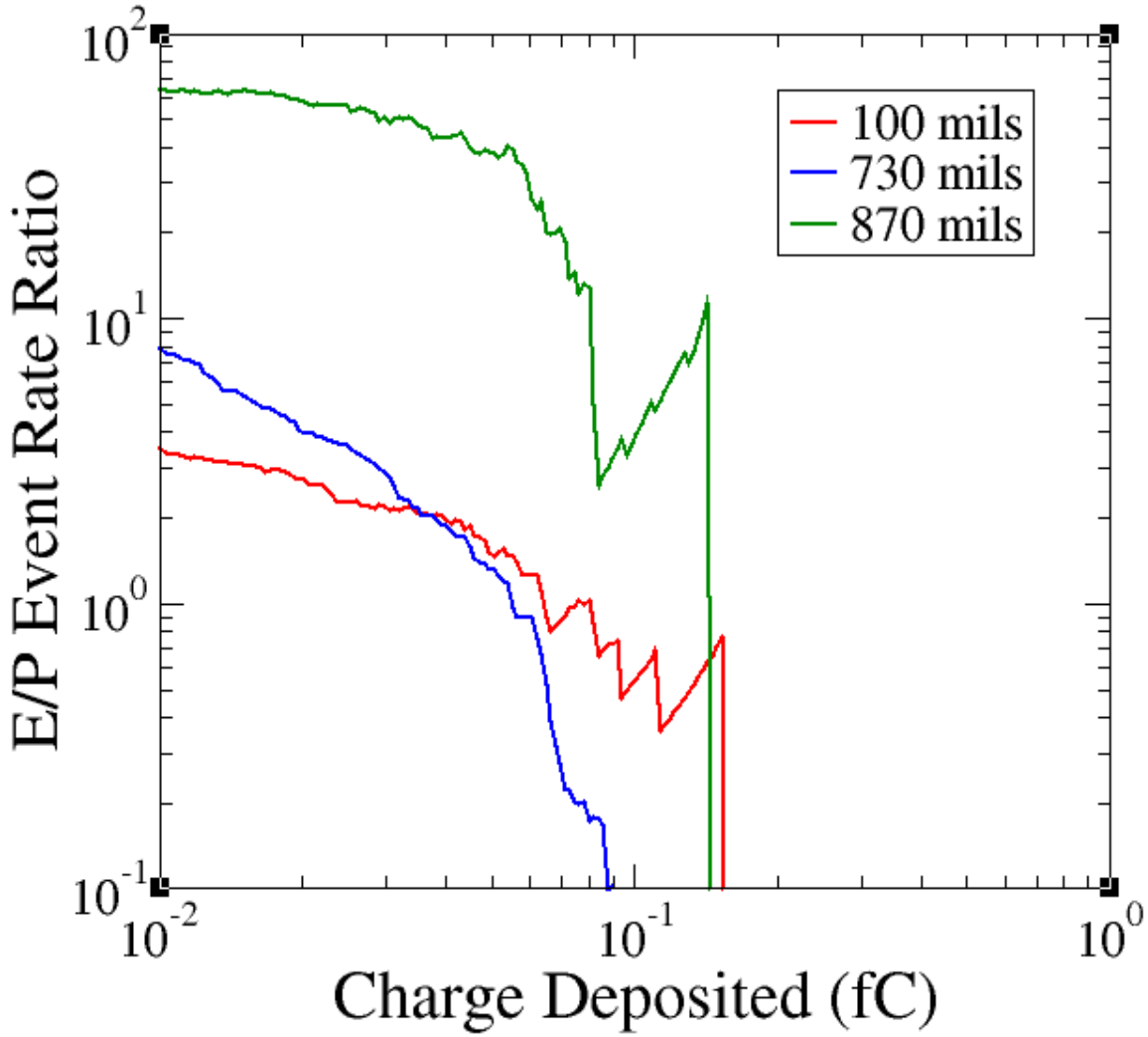
Electron Irradiation Results

- All data normalized to Data ID #5
- Relative cross section increases with reduced bias and smaller technology node
- This provides significant evidence that these upsets were caused by single electron effects
- These trends are consistent with previous experiments with low energy protons and muons

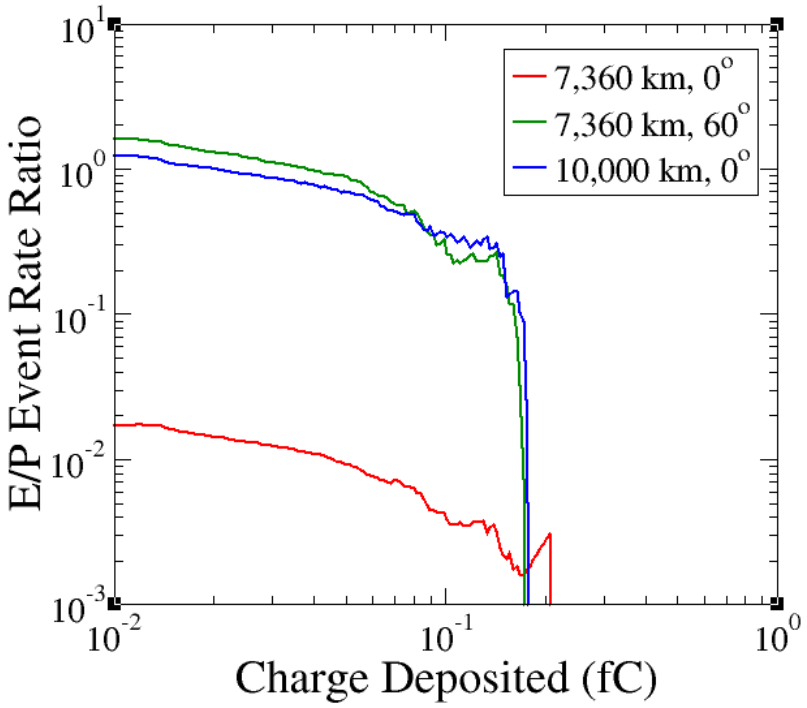


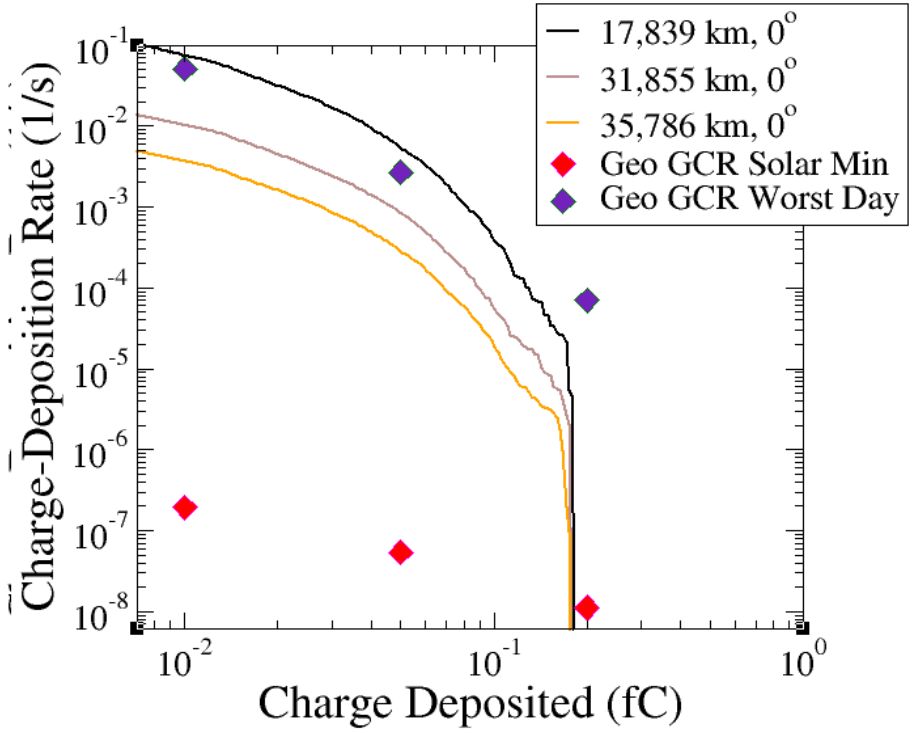
Technology Node	28 nm	28 nm	45 nm	45 nm	45 nm
Beam Energy	40 keV	40 keV	40 keV	100 keV	100 keV
Bias Voltage	0.45 V	0.55 V	0.45 V	0.45 V	0.5 V
Data ID	1	2	3	4	5

Rate Predictions – Europa orbit

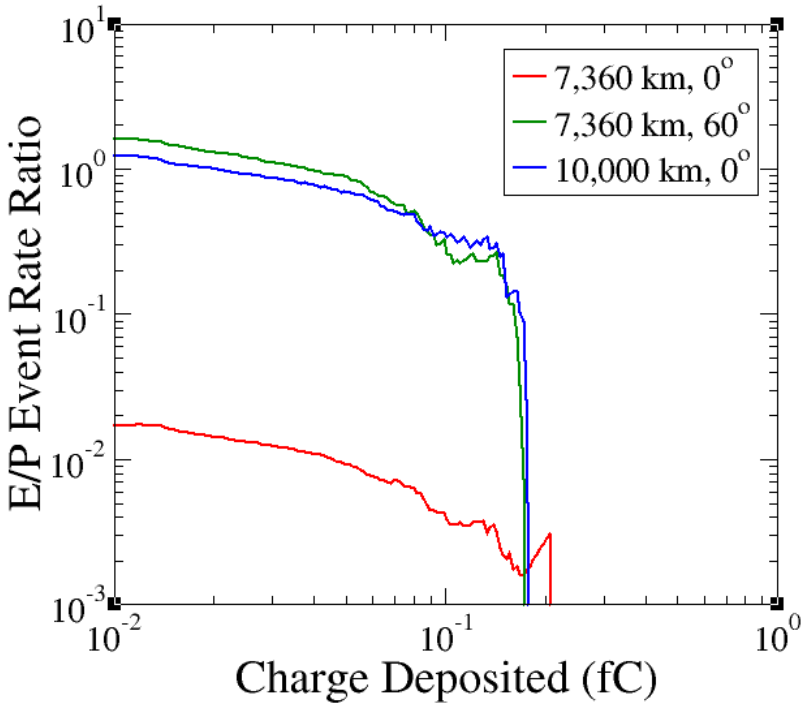


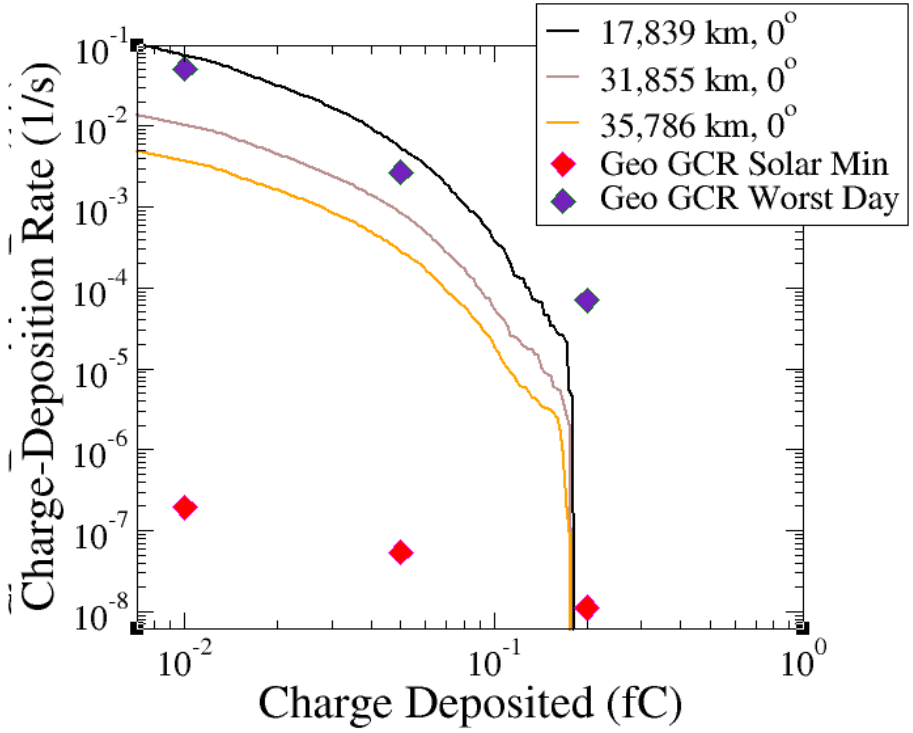
Rate Predictions – EARTH orbit





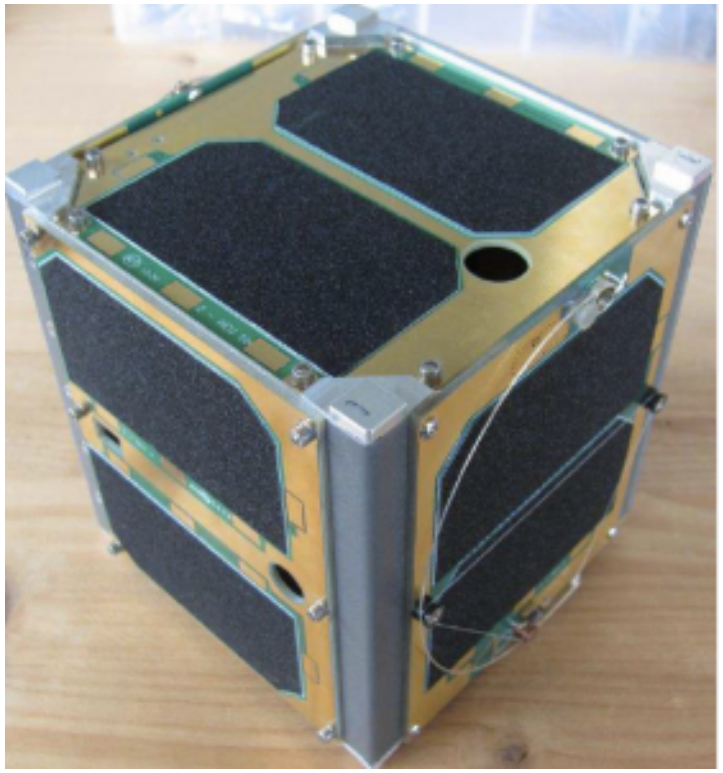
Rate Predictions – EARTH orbit





CubeSat

- Radiation effects experiments
- Vulcan
  - SRAM SEU (65nm)
  - Launch Oct 2015
- Independence
  - SRAM SEU (65 nm)
  - Latchup test
  - Launch Oct 2015
- RadFxSat
  - SRAM SEU test (28 nm)
  - Launch Nov 2016



Conclusions

- MRED development is frozen at the current version with no future updates planned
- Application of MRED continues
  - Research new effects
  - Solving engineering problems
- CRÈME website maintenance and user support is funded by NASA Electronic Parts and Packaging Program