Low-Energy Proton Single Event Effects

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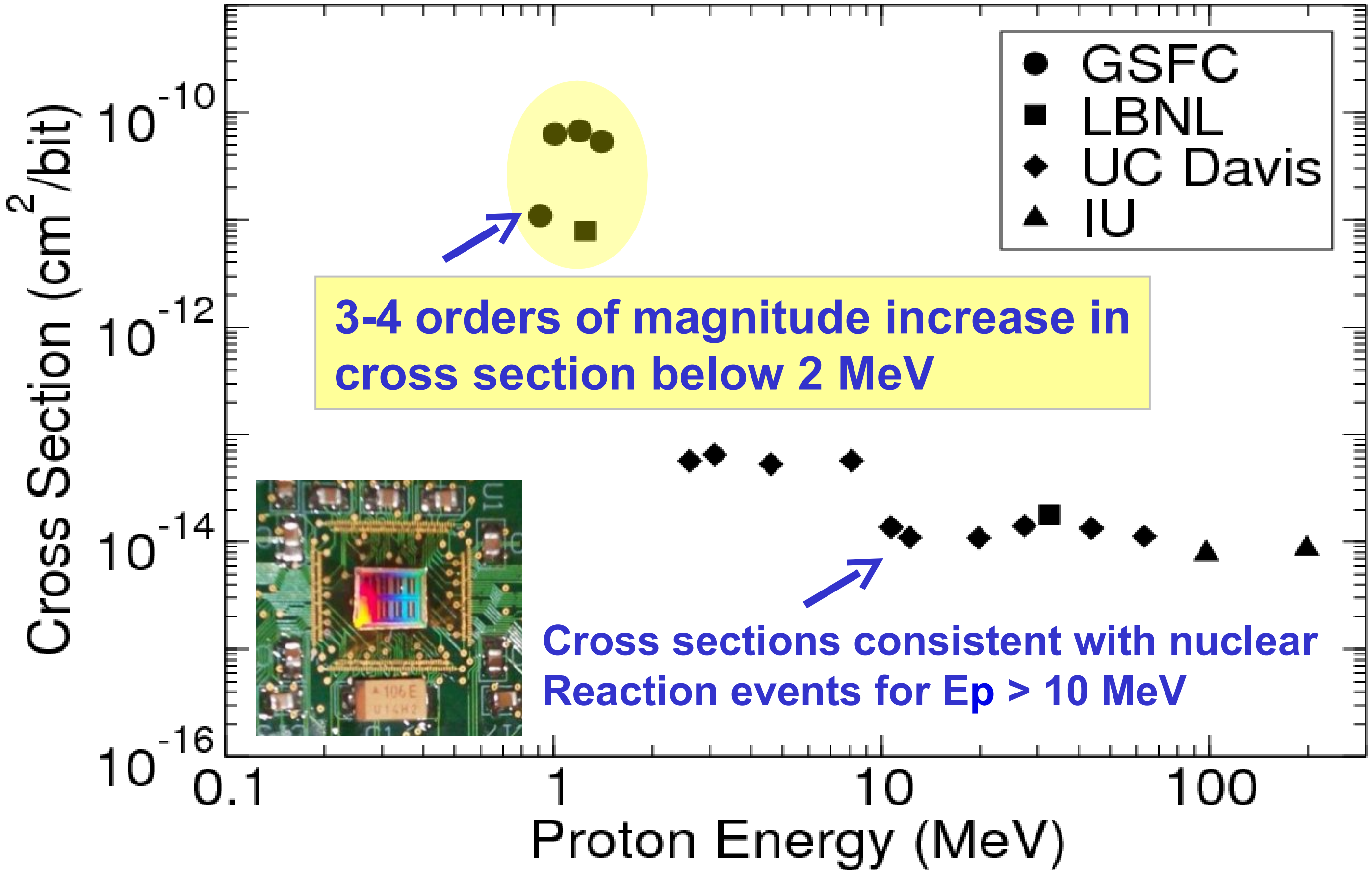
Low-Energy Proton Upset Cross Sections

Data collected by Vanderbilt and NASA Goddard on TI 65 nm bulk CMOS process



3-4 orders of magnitude increase in cross section below 2 MeV

Cross sections consistent with nuclear Reaction events for Ep > 10 MeV

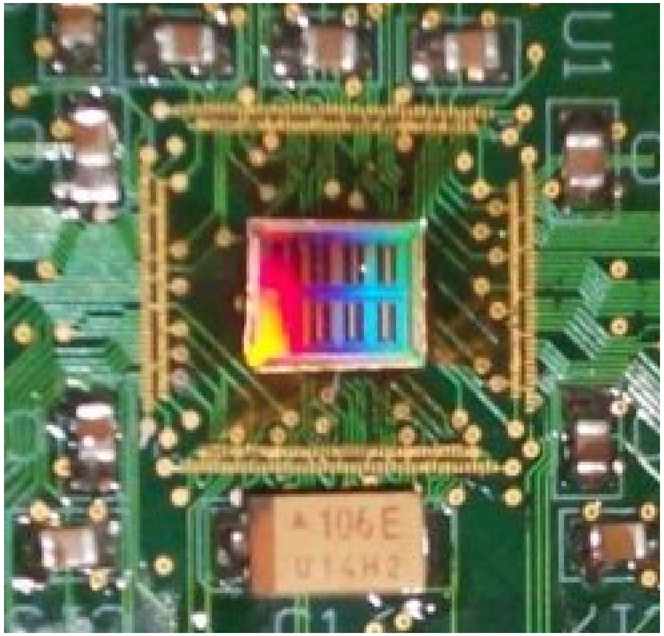
Consistent with evidence of proton direct ionization contributing to single event upsets reported for IBM 65 nm SOI process [Rodbell, TNS 2007][Heidel, TNS 2008]

Key Contributions

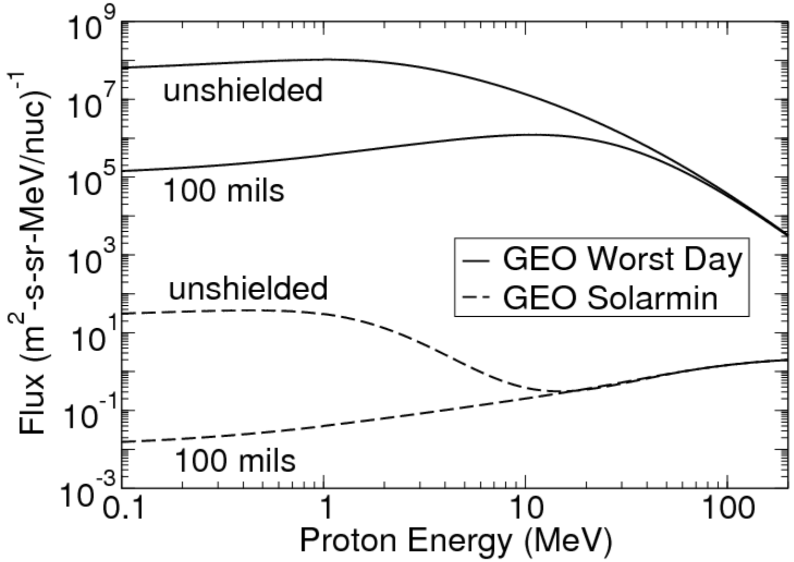
- Creation of an upset model based on first principles and calibrated to well-controlled radiation sources to predict the low-energy proton response
- Application of the model to predict the response in the space environment
- First unified rate prediction of full space environment including direct ionization from protons

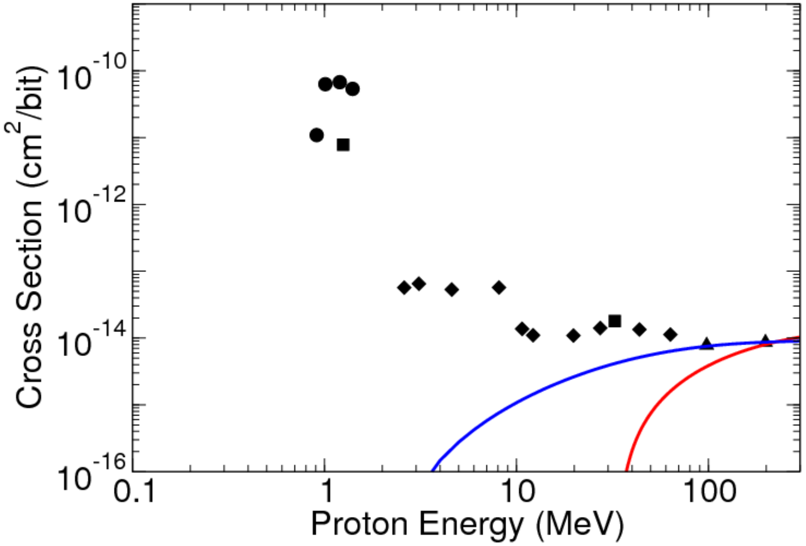
Device Under Test

- **High density 6-transistor SRAM from Texas Instruments 65 nm bulk CMOS process**
  - 4 Megabit
  - Chip-on-board
  - Operated at 1.2 Volts
- **FPGA-based tester and test board designed by NASA Goddard**



Transported Proton Spectra





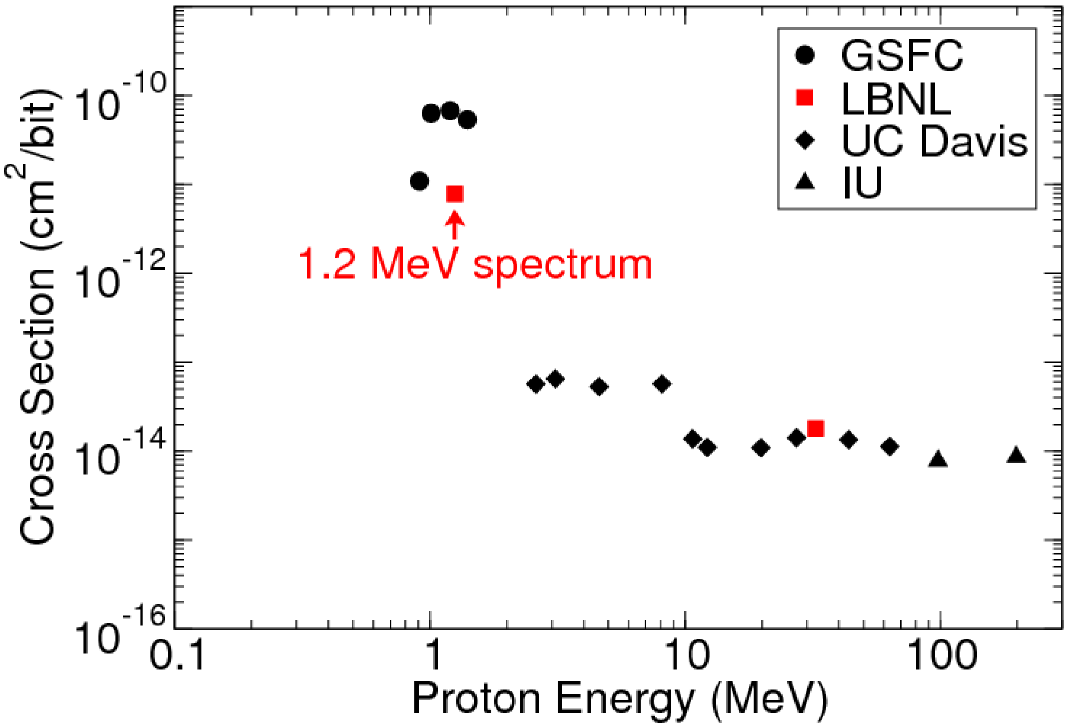
- **Proton flux that reaches device in CREME96 "Worst Day" environment is significant even with heavy shielding**
  - Low-energy protons not eliminated
- **Flux not significantly attenuated with heavier shielding in "Solar min"**

- **Bendel models provide relationship between kinetic energy and SEU cross section driven by nuclear reactions**
  - Neither adequately model the direction ionization mechanism

$$\sigma = \left(\frac{B}{A}\right)^{14}\left(1 - e^{(-0.18Y^{\frac{1}{2}})}\right)^{4}$$

$$Y = \left(\frac{18}{A}\right)^{\frac{1}{2}}(E - A)$$

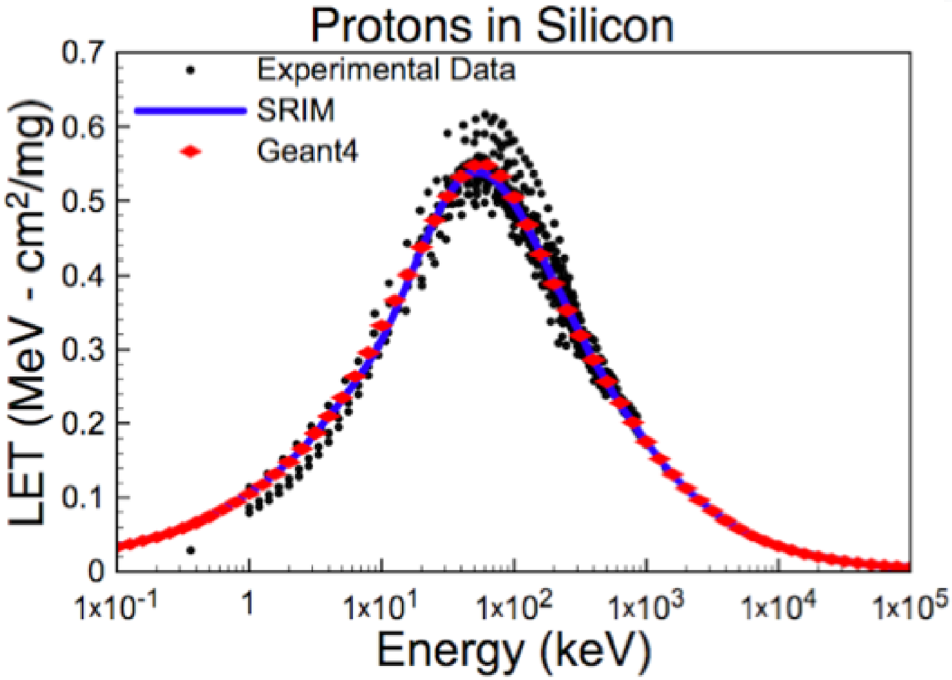
Low-Energy Mechanism



- **Data obtained at LBNL provide proof that the increase in SEU cross section is a real effect**
  - Same test setup, beamline, and dosimetry
  - Increase in cross section > 400X
- **Low-energy test has large spread in energy, can be used to determine if the device has a proton sensitivity, but difficult to quantify**

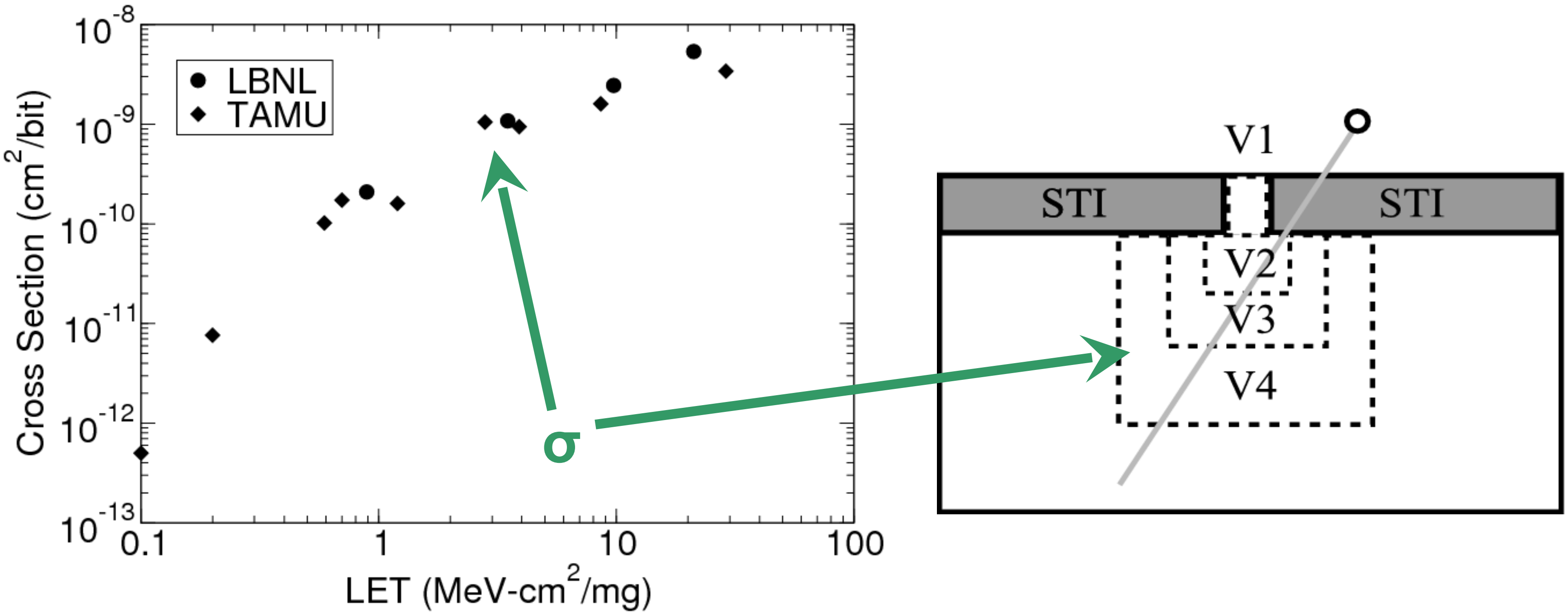
Stopping Power Uncertainty

- **Low proton energy leads to several important topics**
  - Where's the Bragg peak?
  - Tune the beam or degrade it
  - Topside testing (wire-bonded DUT) or backside (C4)
  - Straggling, which affects both range and energy
- **Hard to fit an error rate prediction model with unknowns in incident particles**
  - Real physics is important and not well characterized by dE/dx
  - Systematic complication from both an experimental and simulation perspective
- **SRIM cites variation in reported stopping power and Bragg peak**



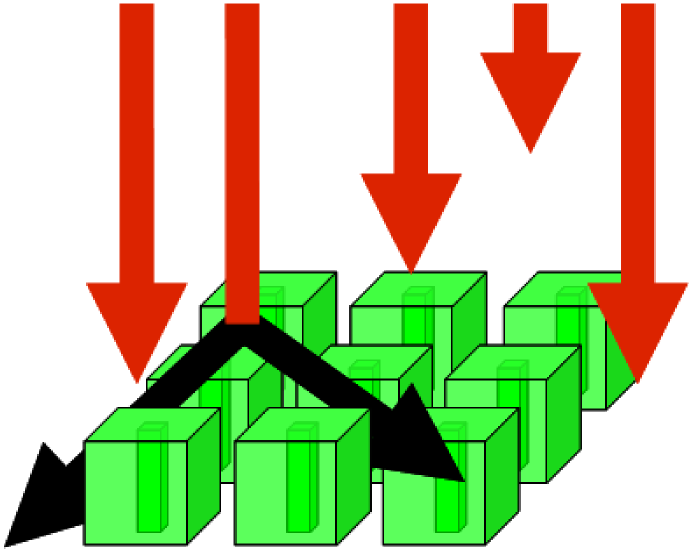
Modeling from Heavy Ion Data

- **Assume that single bit cross sections correspond to physical device area**
- **Low-LET heavy ion cross sections used to define sensitive areas**
  - Single, well-known stopping power
- **Allow nuclear transport codes and calibrated model to predict low energy proton response**

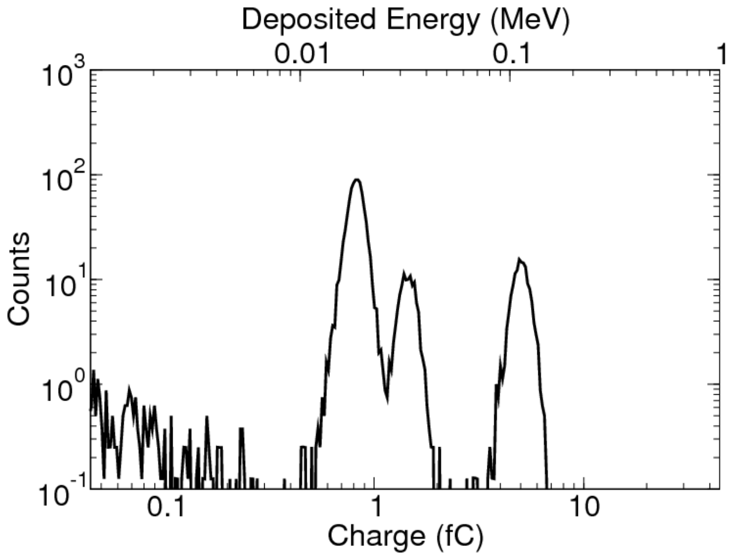


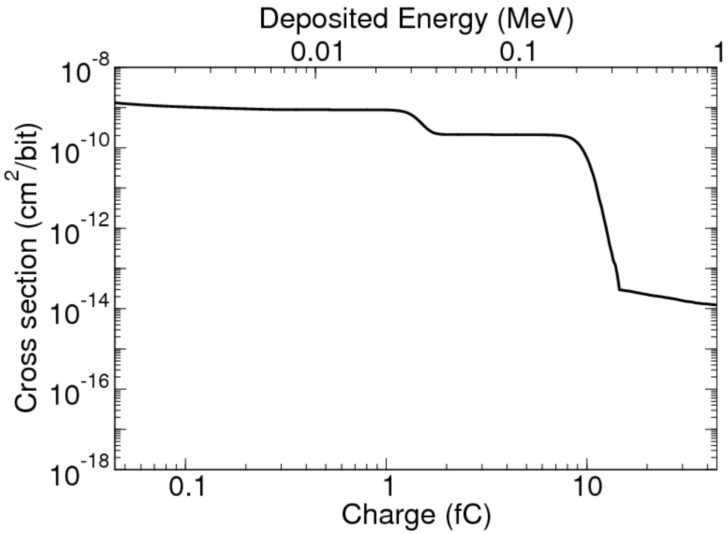
Monte Carlo Simulation

- **Vanderbilt's MRED code randomizes protons over array of devices**
- **Captures energy deposition from direct ionization, recoils, and nuclear reactions and weights to collected charge**

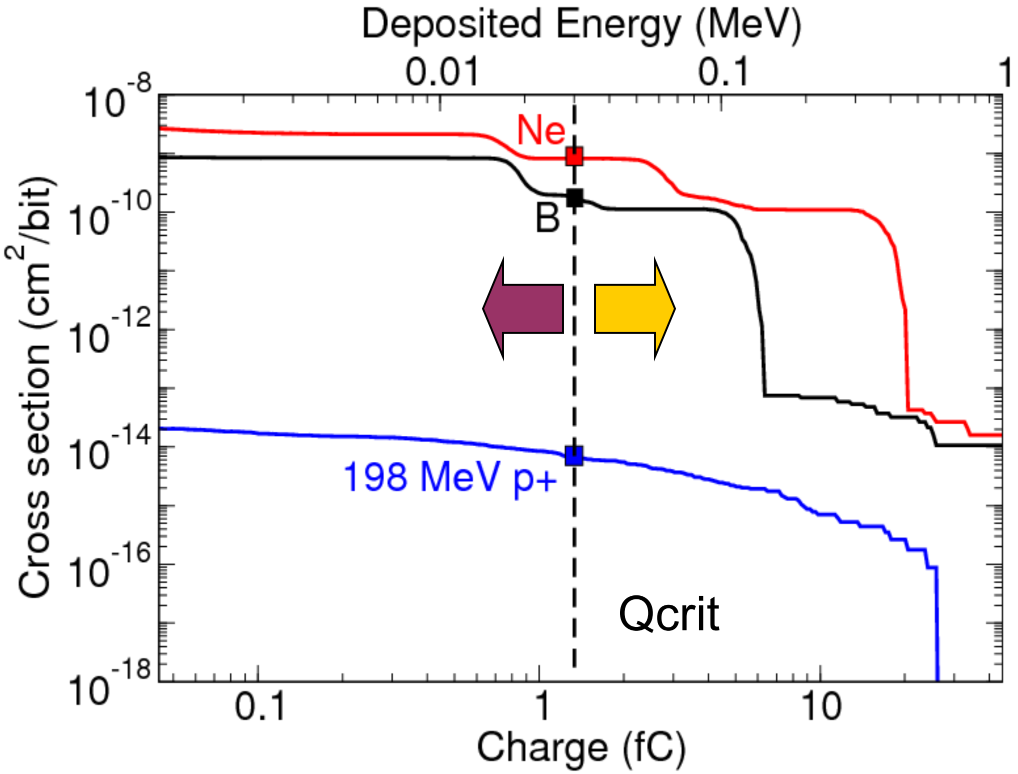


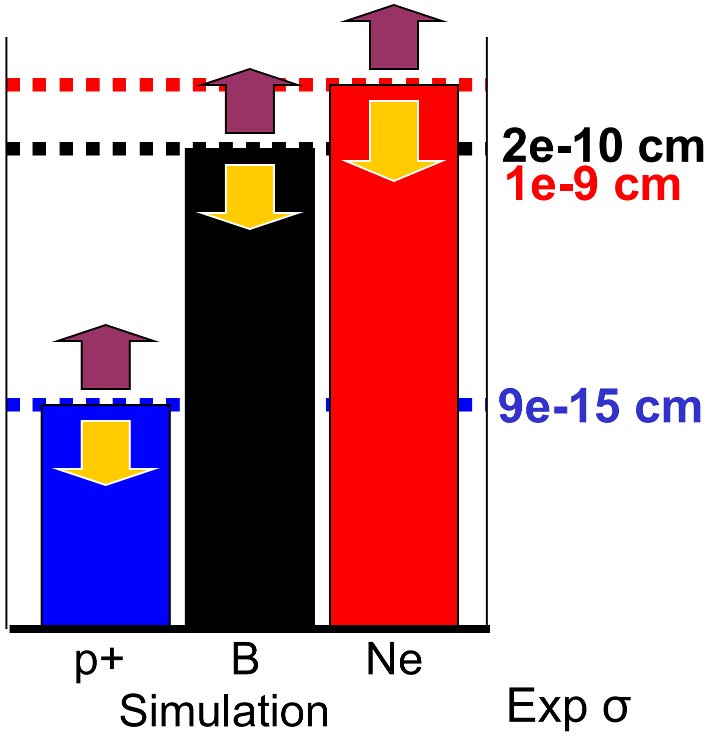
$$Q_{coll,j} = \frac{pC}{22.5MeV}\sum_{k=1}^{N_j} a_{k,j}E_{dep,j,k}$$





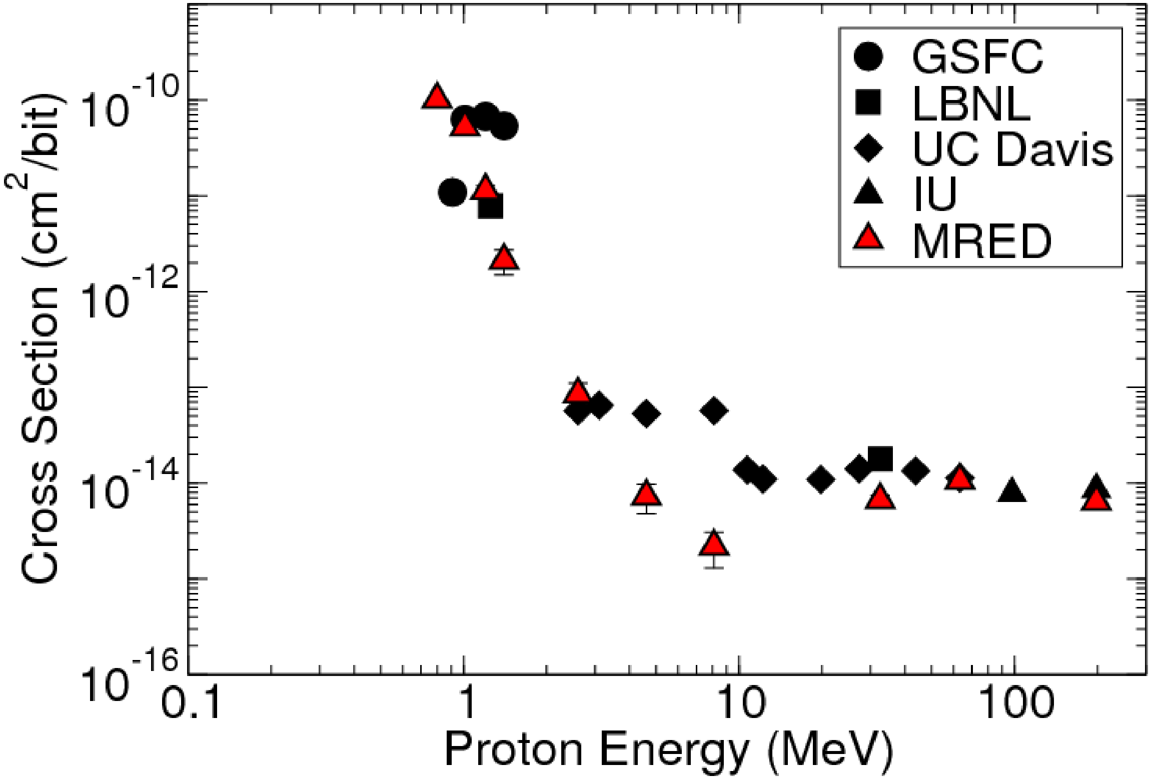
Qcrit Parameter Estimation





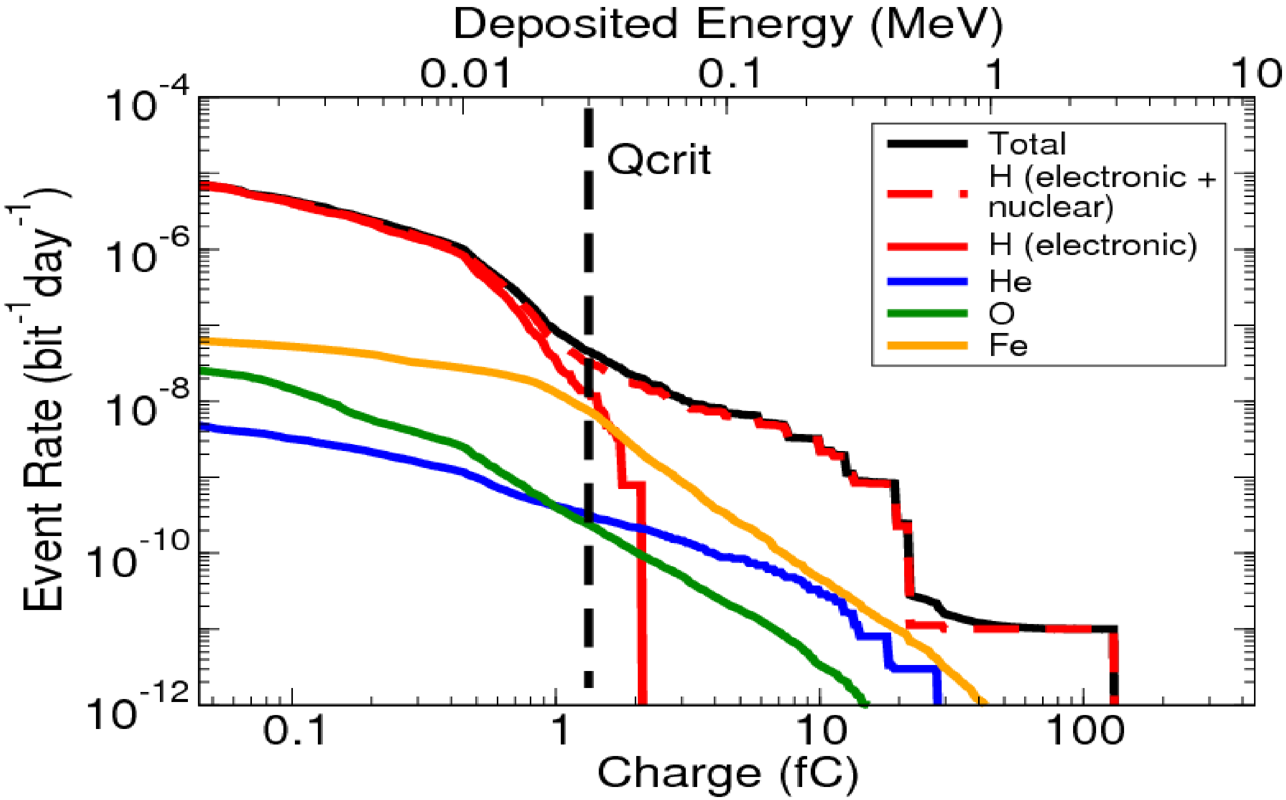
- **MRED produces SEU cross section as a function of collected charge**
- **Least-squares fit to heavy ion and high energy proton SEU cross sections is used to determine the circuit critical charge (Qcrit)**
- **Fit estimates a Qcrit of 1.3 fC, Spice simulations estimated 1.4fC**

Proton Predictions



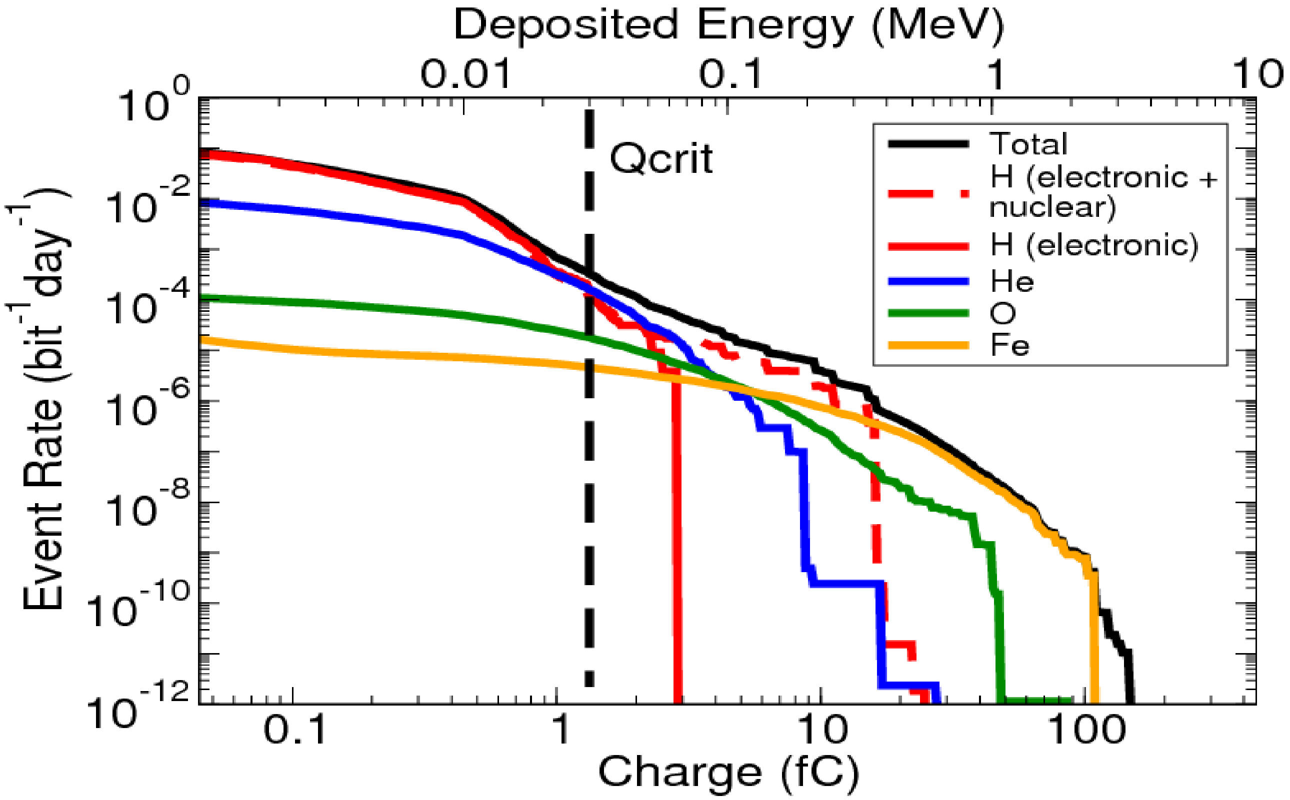
- **Estimation of critical charge from previous slide yields the SEU cross section over all proton energies**
- **Underprediction in 3 – 10 MeV range possibly due to spread in beam energy**

Contribution of Protons to Error Rate in ISS Orbit



- **Applying isotropic space environment (AP8MIN, magquiet, solar min, 100 mils Al) to sensitive volume model reveals error rate as function of species and critical energy**
  - Direct ionization is becoming the dominant upset mechanism for protons

Contribution of Protons to Error Rate in GEO (Worst Day)



- **Worst Day environment shows large contributions to error rate from both protons and alpha particles**
    - Need to assess impact on reliability

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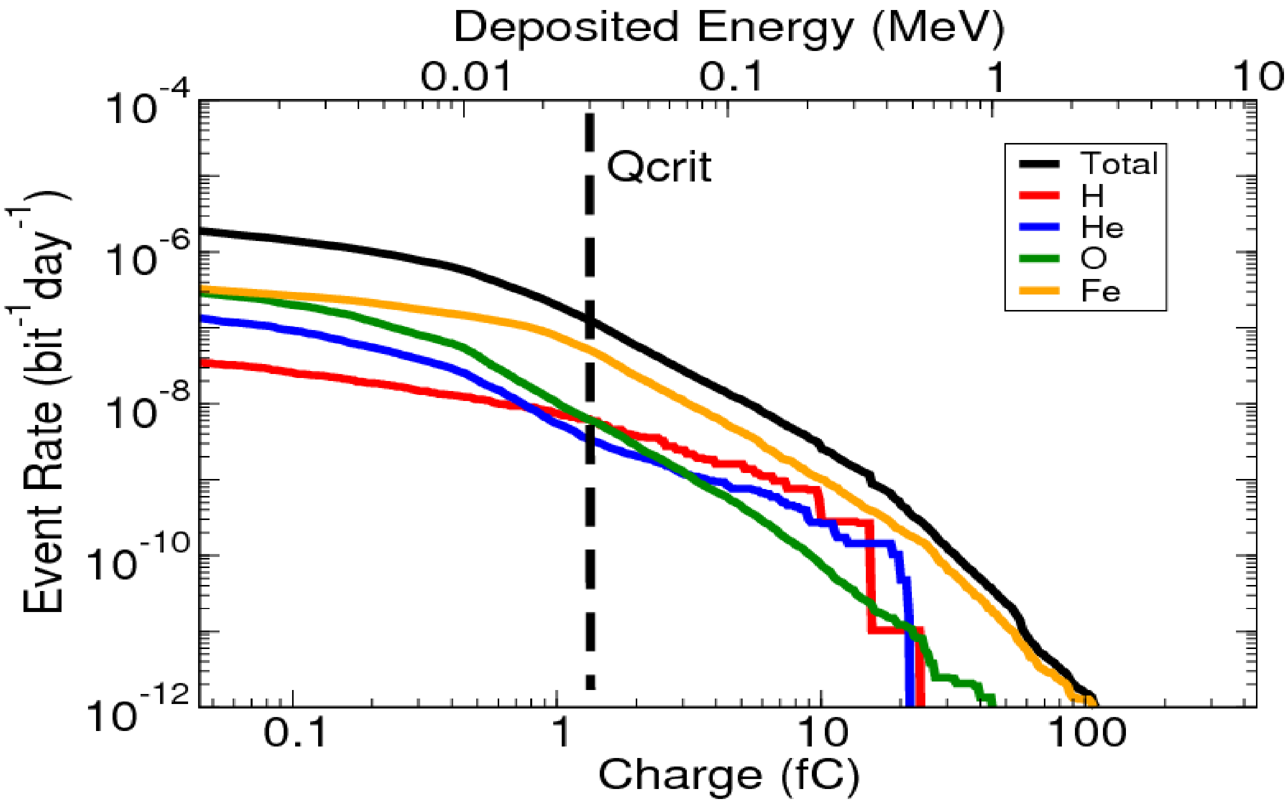
Contributions of Species to Error Rate in GEO (Solar Min)



- **Iron dominates rate in the GEO solar min with 100 mils Al shielding environment**
  - Proton flux too low to be an issue
- **Low-LET particles will drive the rate as technology scaling continues**

Low Energy Proton Testing Implications

- **Details regarding materials upstream from the sensitive DUT regions are important**
  - Kapton/aramica windows, degrader foils, air gap, substrate or BEOL thickness, PCBs, package lids, etc
- **Tune the primary beam energy as much as is feasible to achieve lower particle energy**
  - Don’t forget straggle (range AND energy)
- **Nearly unavoidable systematic error in proton energy at DUT plane**
- **Best used to show device sensitivity**

Summary

- **< 2 femtoCoulombs of collected charge can induce errors in modern circuits**
  - direct ionization from protons, alpha particles, and low-LET heavy ions
- **The high abundance of these particles makes a detailed understanding of the SEU response critical**
- **Tests with low-energy protons are difficult to interpret**
  - Use of data can be difficult due to uncertainty and variability in dE/dx, limited range of particles, transport through back-end-of-line
  - High-energy, low-LET ions may be better suited for characterization in this regime
- **MRED models fit experimental data and can be used with higher confidence for predicting SEU rates in arbitrary space environments**