The Role of Singly-Charged Particles in Microelectronics Reliability

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VANDERBILT

Outline

- Singly-Charged Particles
- Natural Radiation Environments
- Energy Loss Mechanisms
- Accelerated Testing
- Technology Scaling
- Predictions of Error Rates
- Recommendations
- Conclusions

Singly-Charged Particles

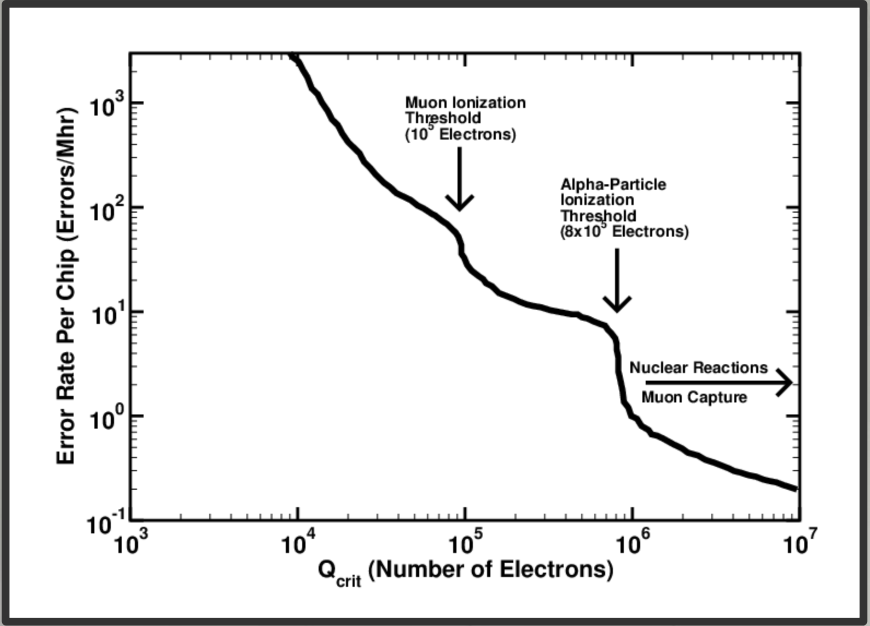
- Historically, alpha particles (Q=2e) and heavy ions (Q>2e) cause errors in microelectronics primarily through ***electronic stopping***, energetic protons and neutrons through ***nuclear stopping***
- Experimental data indicate protons are capable of causing errors due to ionization
- Stopping protons and muons are predicted to be significant contributors to error rates in sub 65 nm processes

COMMON SINGLY-CHARGED (Q=±e) PARTICLES

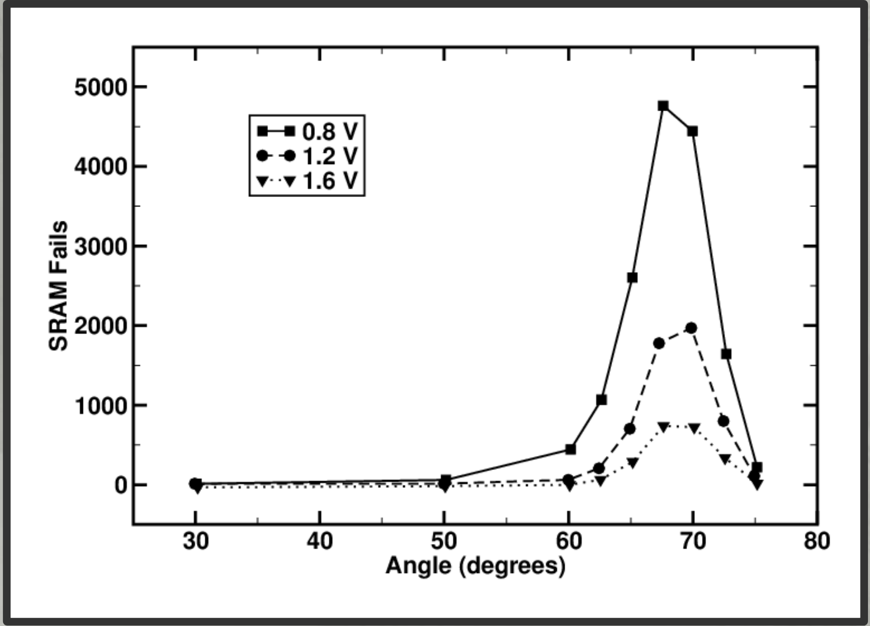
Particle	Symbol	Mass (MeV/c^2)	Mean Lifetime (s)
proton	p^+ / p^-	938	--
pion	π^+ / π^-	140	26×10^{-9}
muon	μ^- / μ^+	106	2.2×10^{-6}
electron	e^- / e^+	0.511	--

Background

- **Wallmark and Marcus (IRE '62) predicted limits to scaling**
- **Ziegler predicted muon ionization would eventually dominate chip error rates**
- **Bendel (TNS '83) asserted "a *part sensitive to the ionization in a proton track would be grossly unfit for spacecraft use*"**

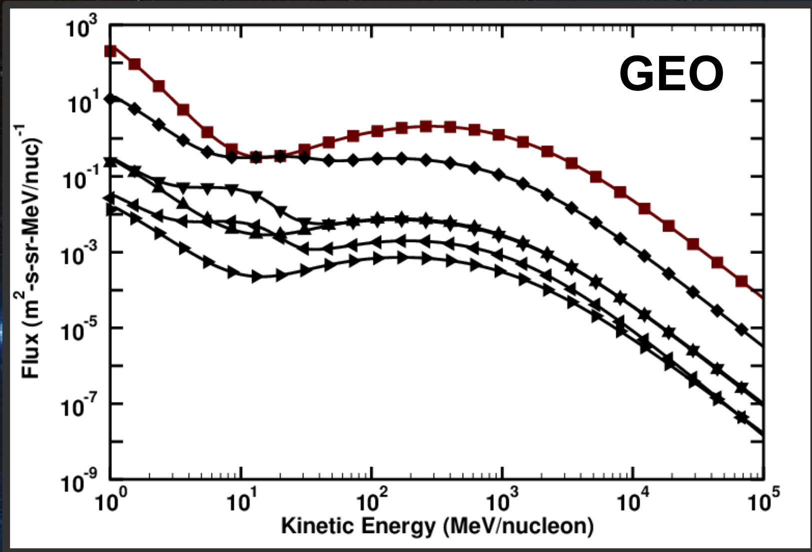


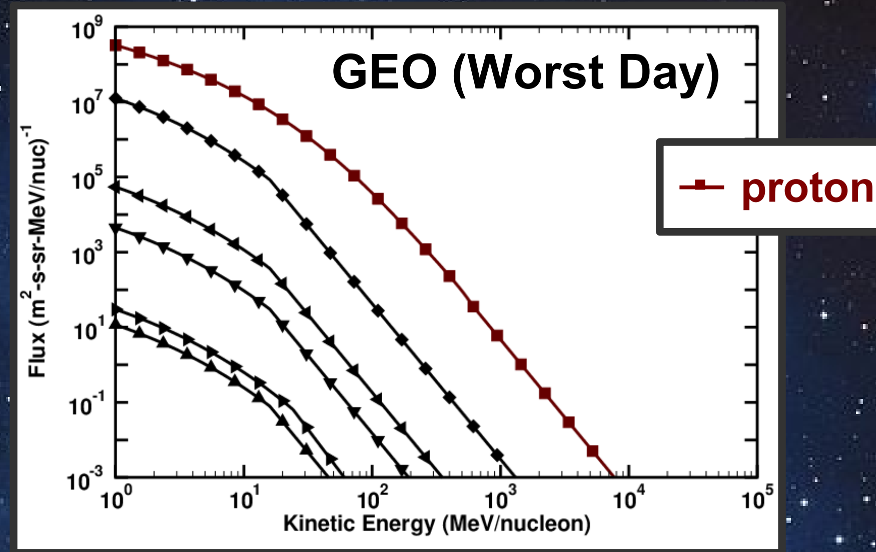
Ziegler, Sci. 1979

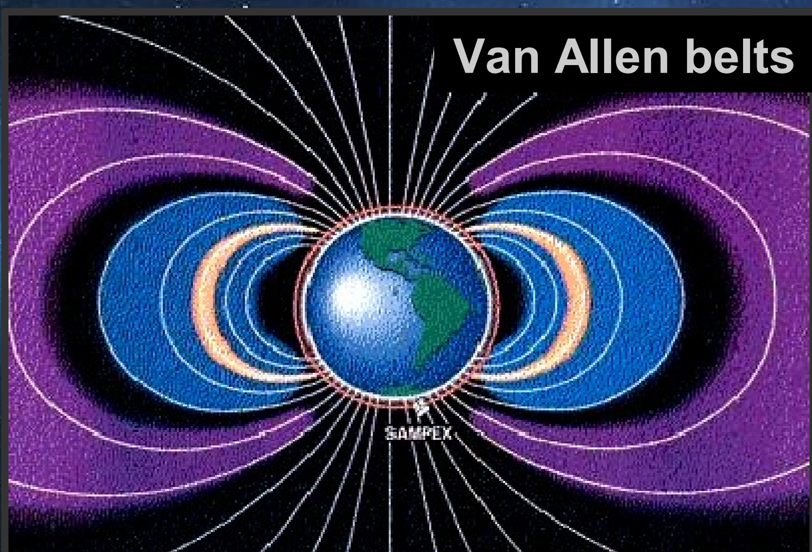


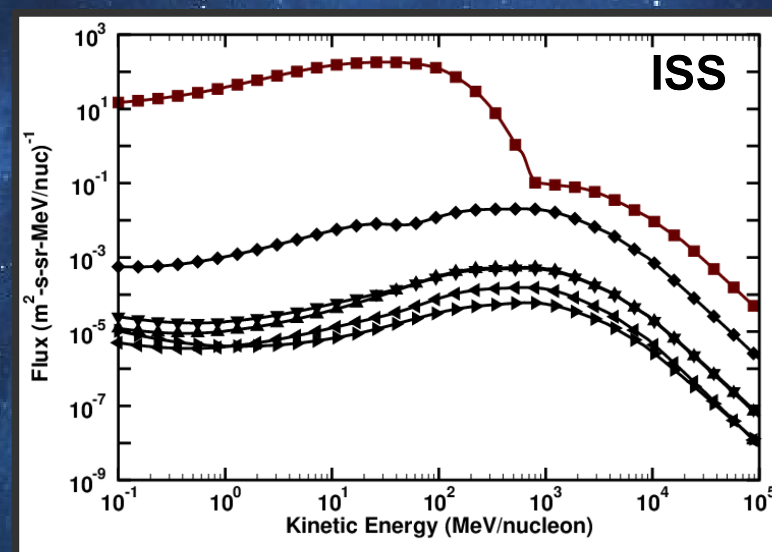
Rodbell, TNS. 2007

Space Environments

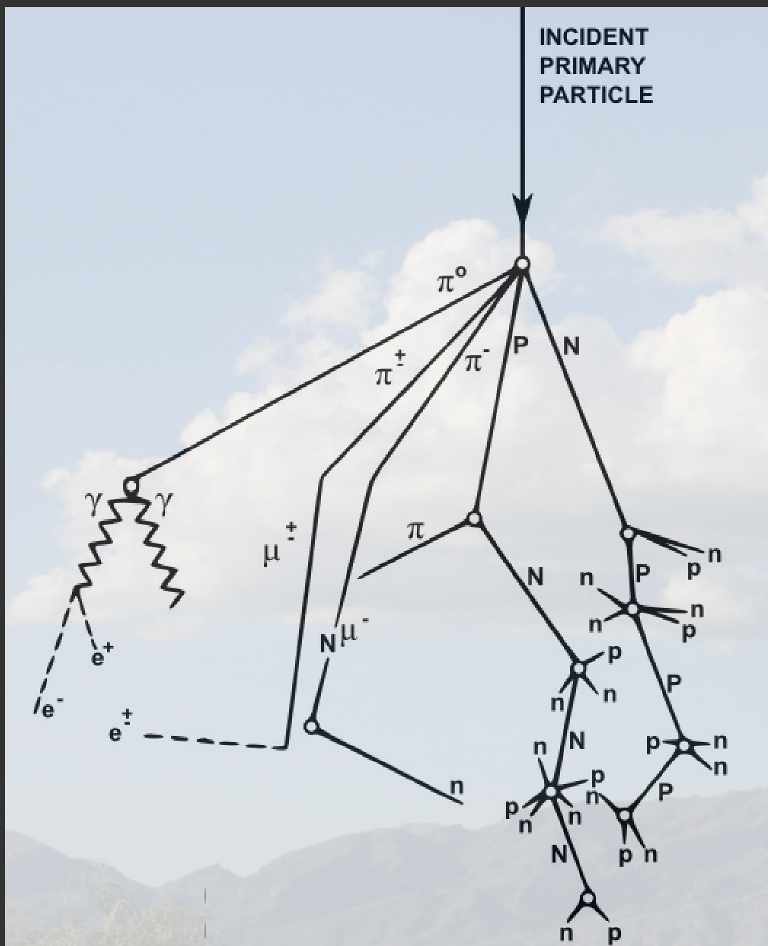


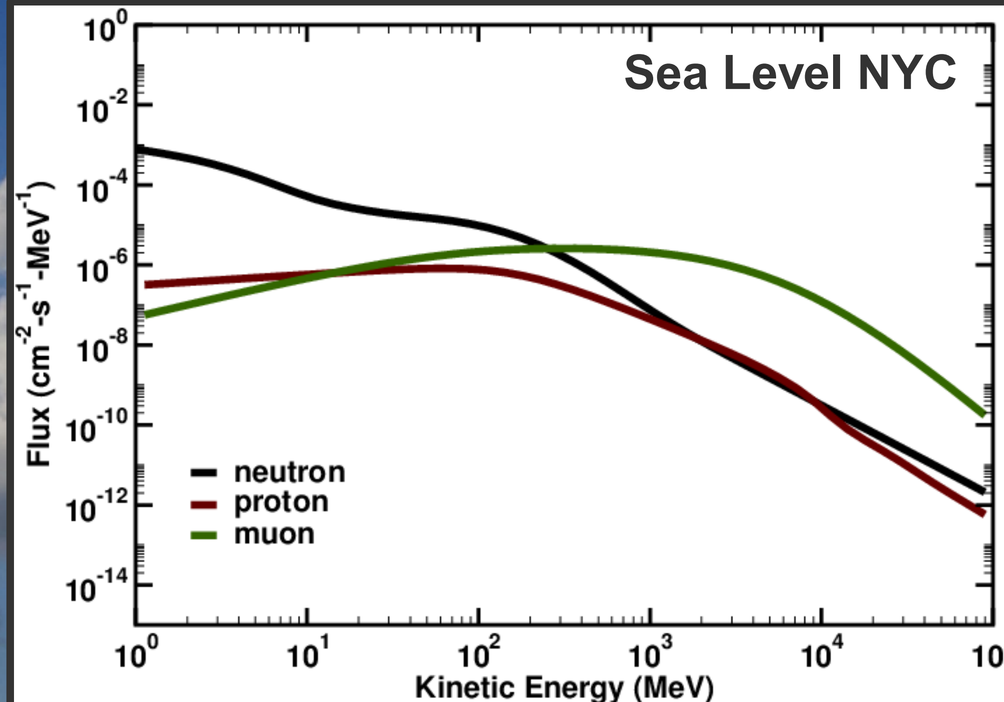






Terrestrial Environments

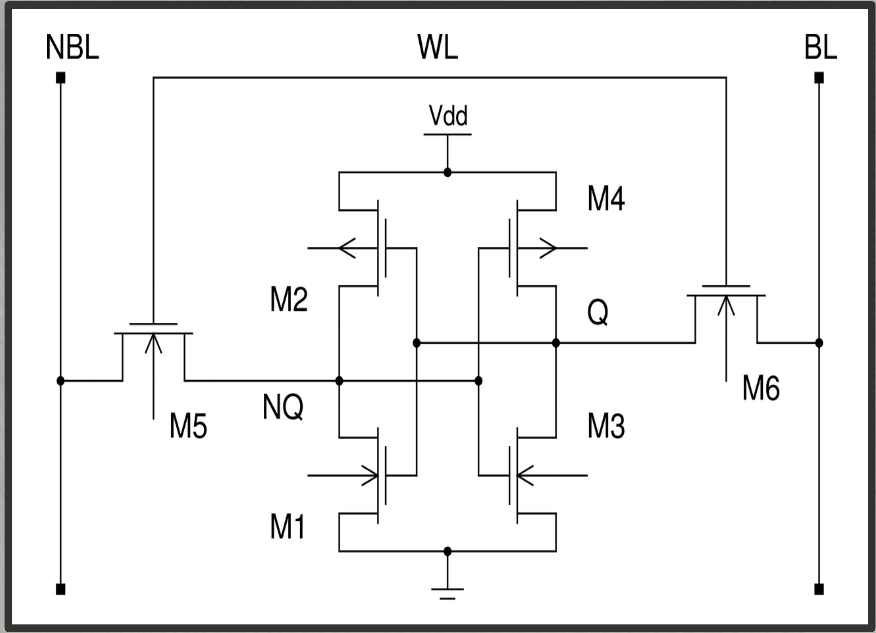


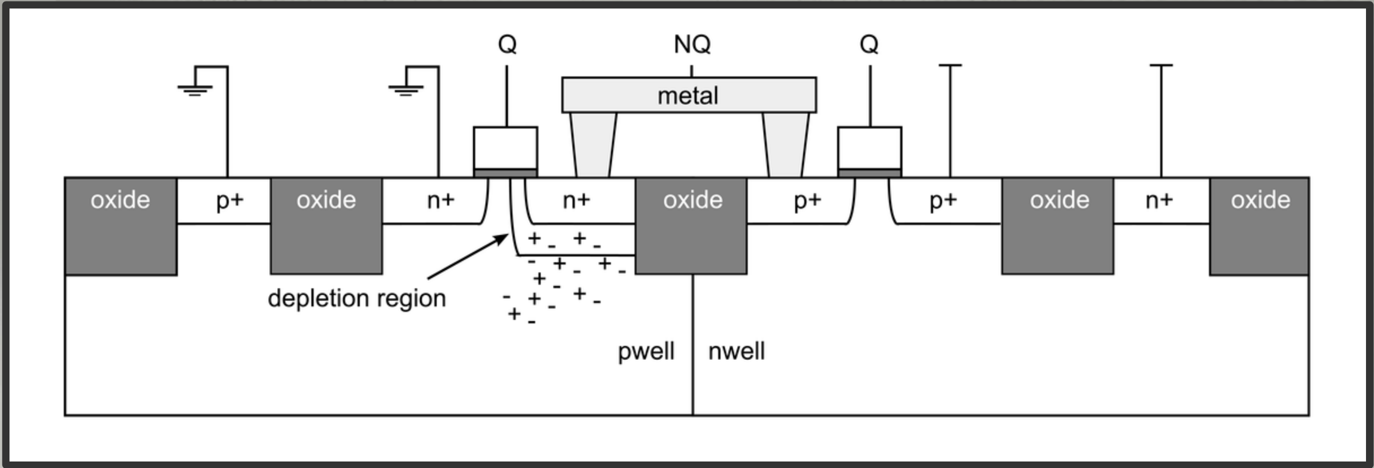


- GCR particles responsible for cosmic ray showers
  - Neutrons, protons, pions, muons, ...
- Flux spectra best modeled by Monte Carlo applications (EXPACS)

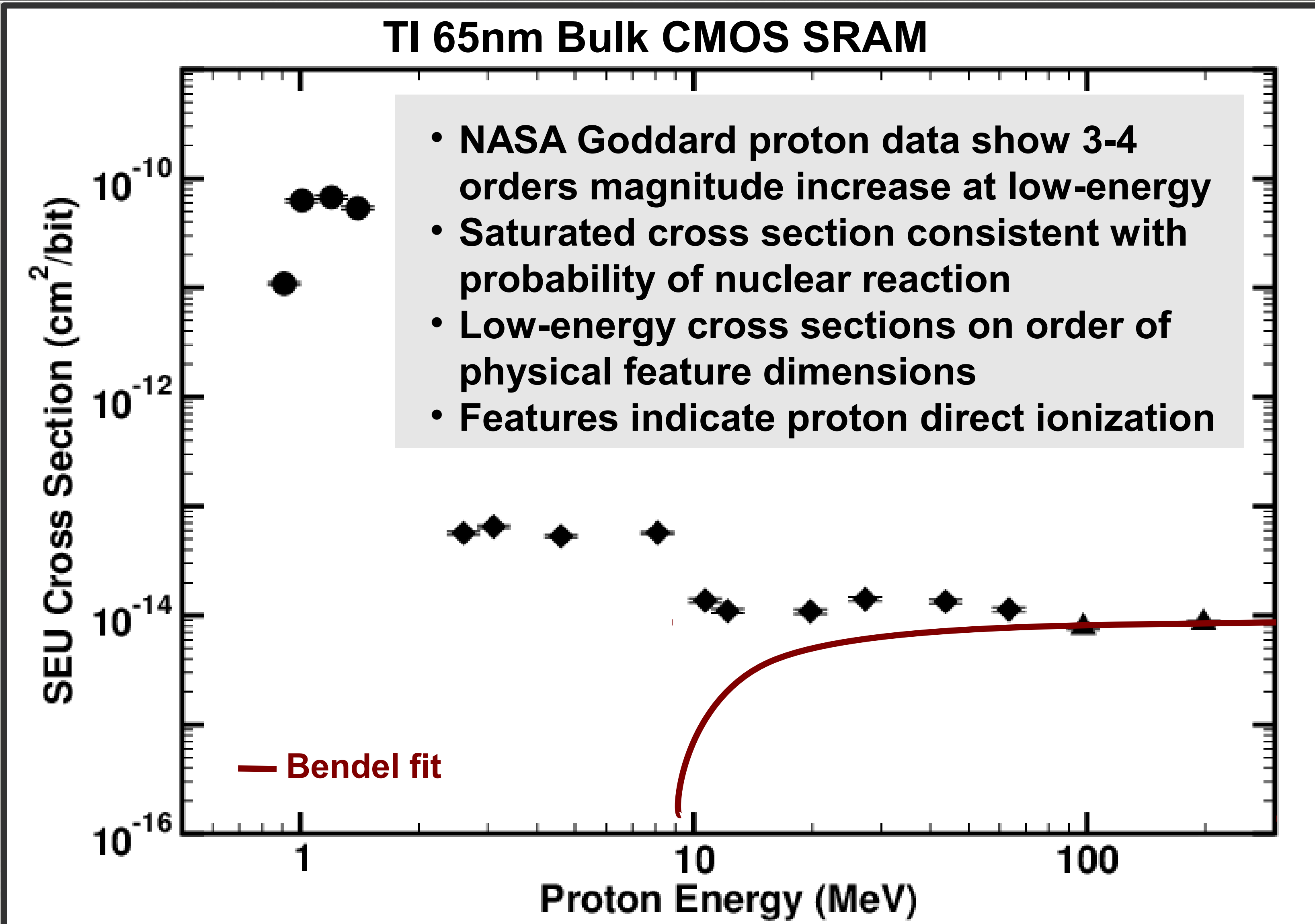
Single Event Upsets

- **SEU occur as the result of ionizing particles**
- **In older technologies, protons only able to cause upsets through nuclear interactions**
- **Reliability decreasing as gate capacitance, restoring currents decrease**



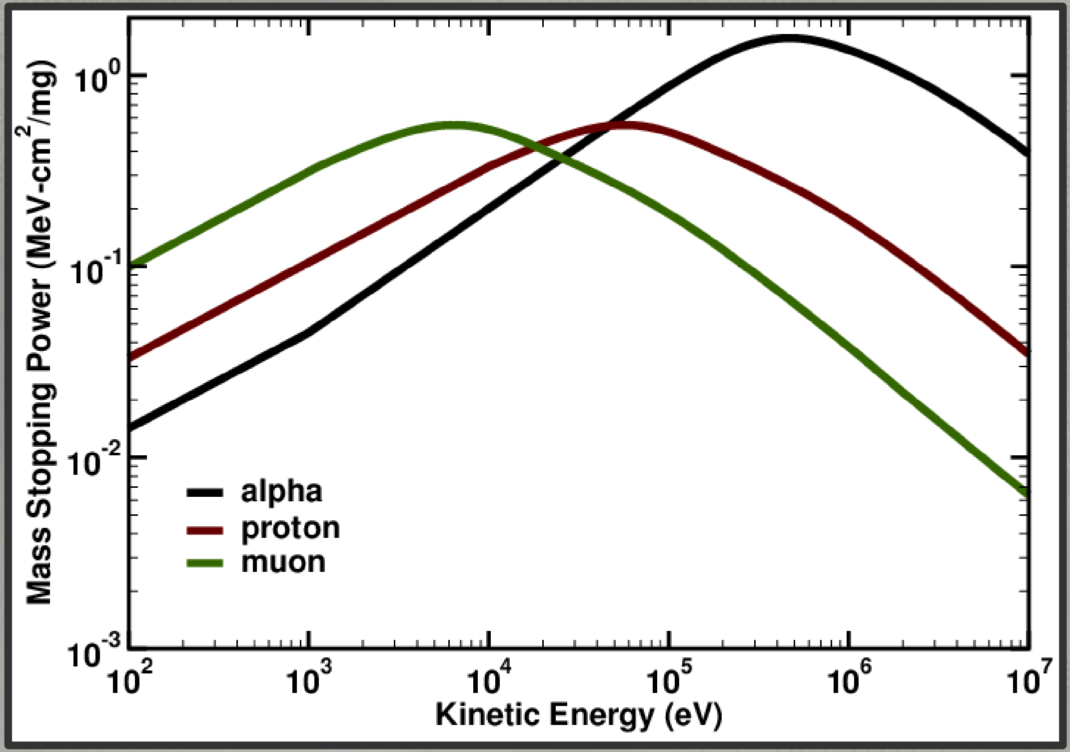


Motivation



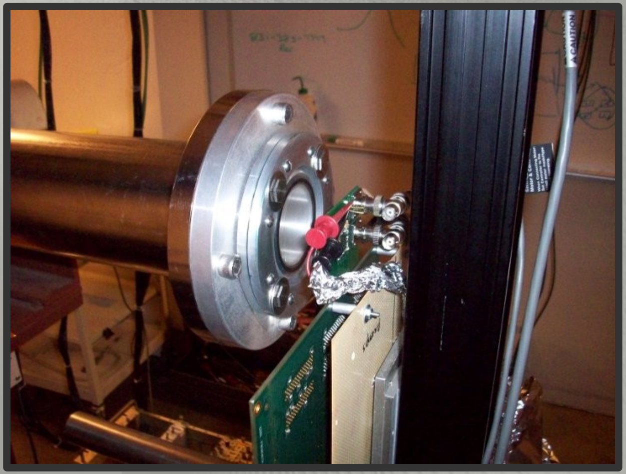
- NASA Goddard proton data show 3-4 orders magnitude increase at low-energy
- Saturated cross section consistent with probability of nuclear reaction
- Low-energy cross sections on order of physical feature dimensions
- Features indicate proton direct ionization

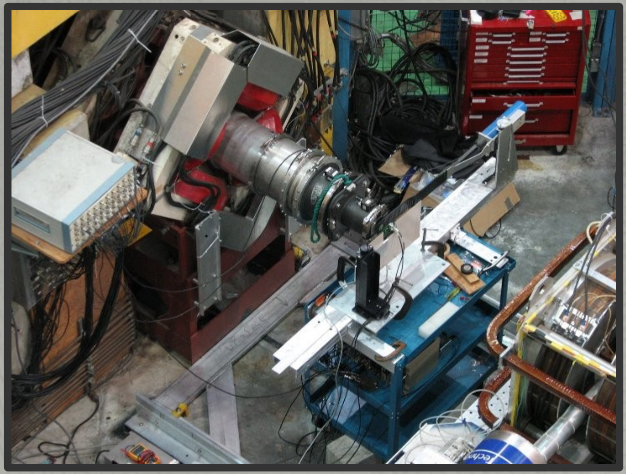
Energy Loss Mechanisms



- **Stopping power strongly dependent on particle charge and velocity**
- **Bragg peak identical for singly-charged particles ~0.5 MeV-cm^2/mg**
- **Circuits sensitive to proton direct ionization likely sensitive to other singly-charged particles**
- **Threshold LETs decreasing in modern circuits**
  - **Further decreases will include greater range of particles and energy**

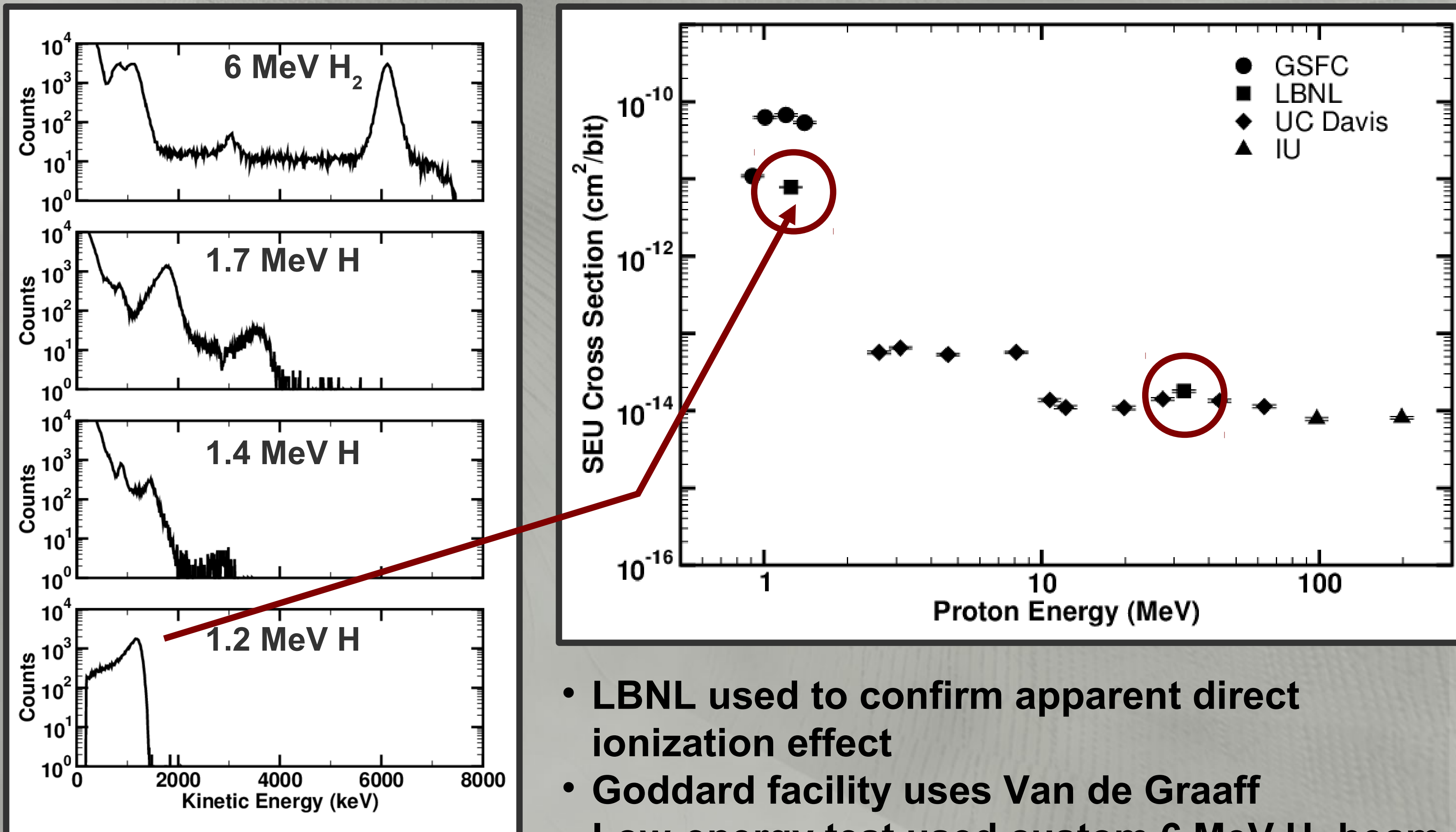
Devices Under Test





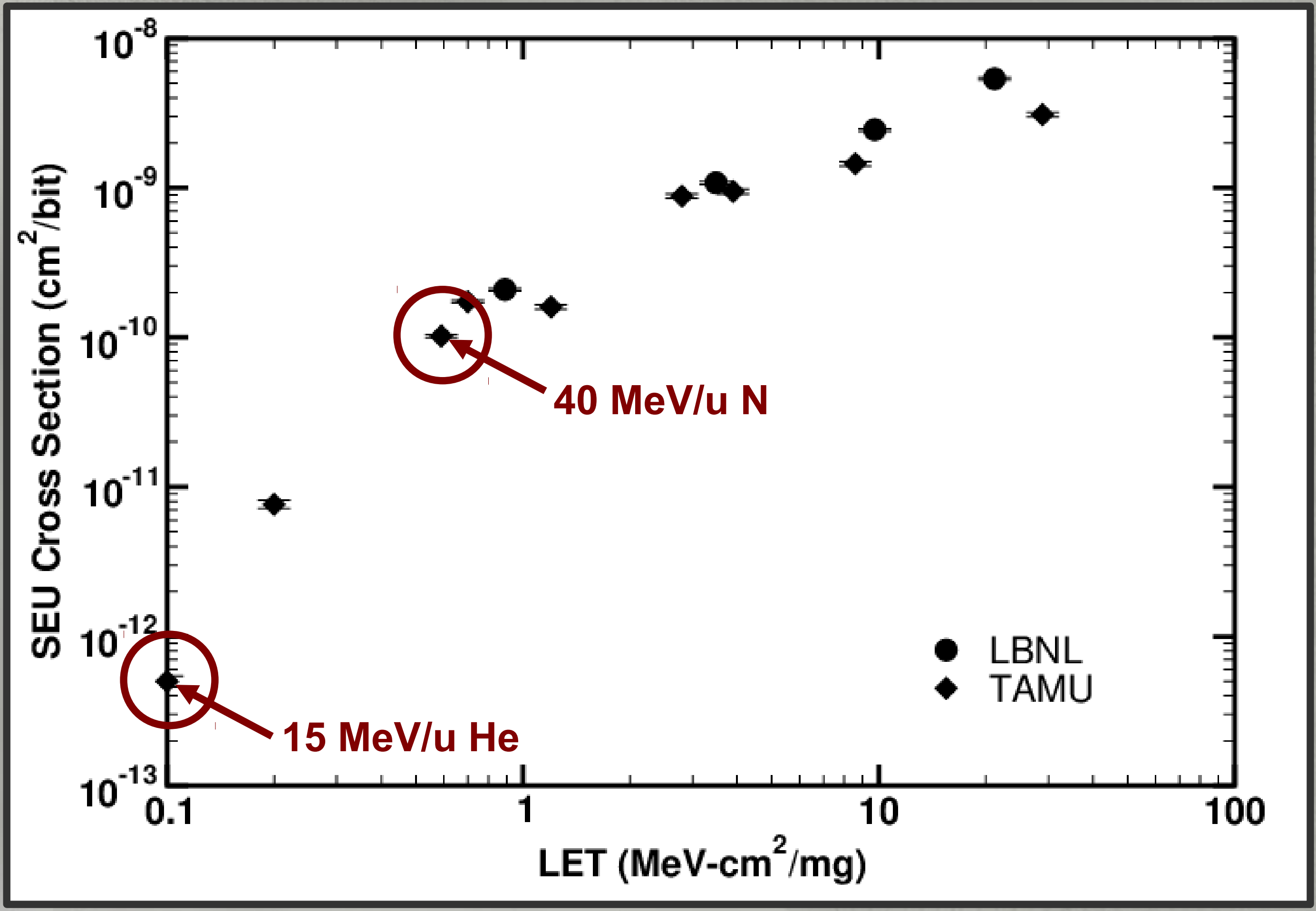
- Bulk CMOS 6-transistor SRAMs
  - Texas Instruments 65 and 45 nm
  - Marvell Semiconductor 55 and 40 nn
- Tests conducted at Berkeley, Texas A&M, and TRIUMF
- Experiments performed in air, close to beam window
- Parts bonded as chip-on-board or were de-lidded

LBNL Proton Testing



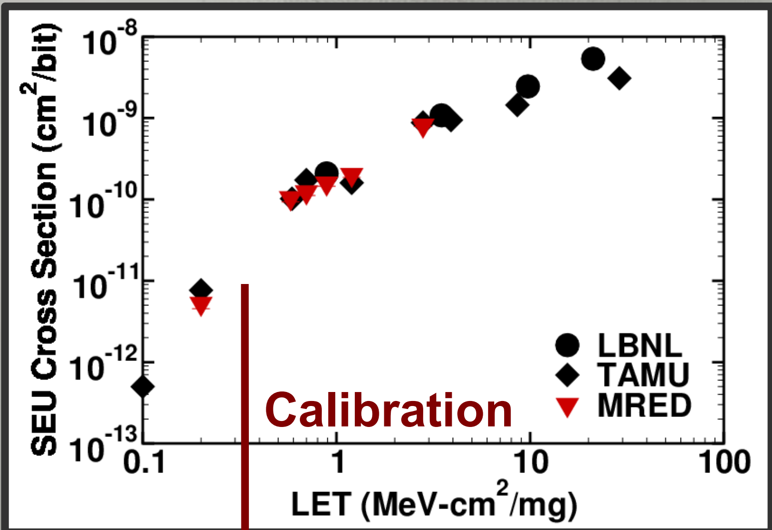
- **LBNL used to confirm apparent direct ionization effect**
- **Goddard facility uses Van de Graaff**
- **Low-energy test used custom 6 MeV H_2 beam**
- **Results rule out dosimetry issues**

Heavy Ion Test Results

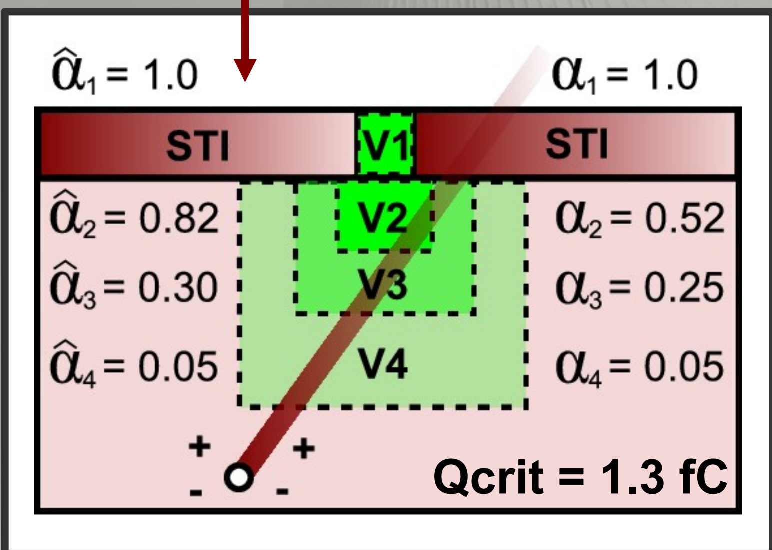


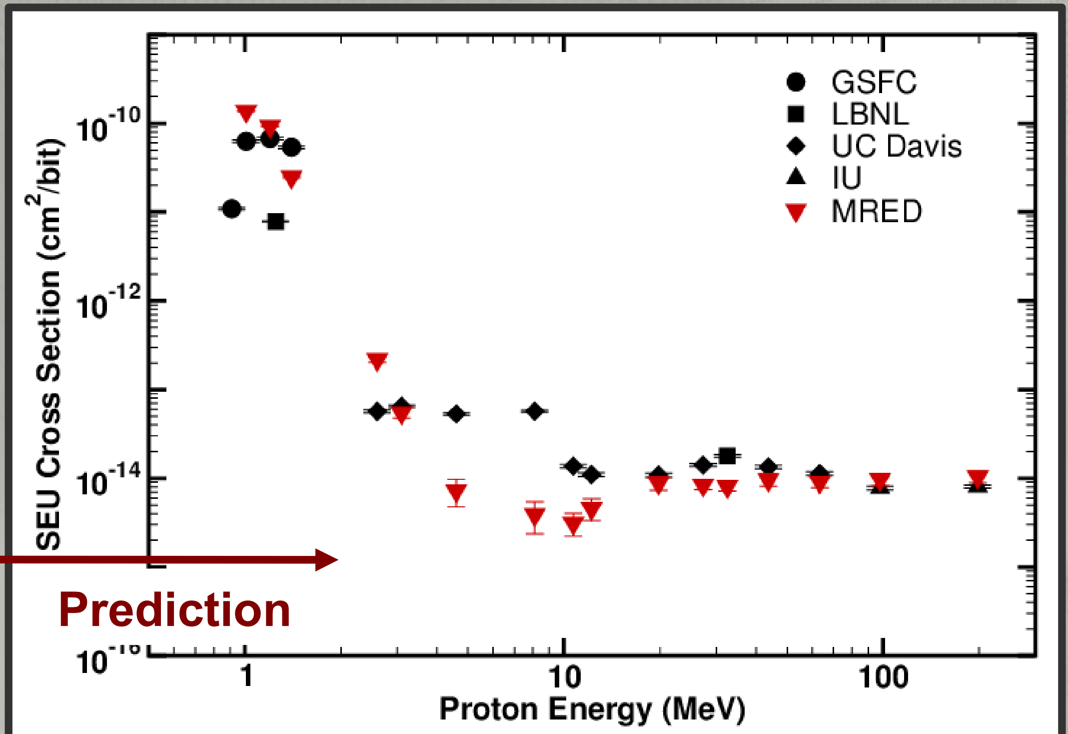
- Heavy ion data demonstrate sensitivity to small quantities of charge
- Low-LET data require high-energy tests at TAMU
- Low-energy protons comparable with 0.5 MeV-cm^2/mg heavy ions

Single Event Upset Model

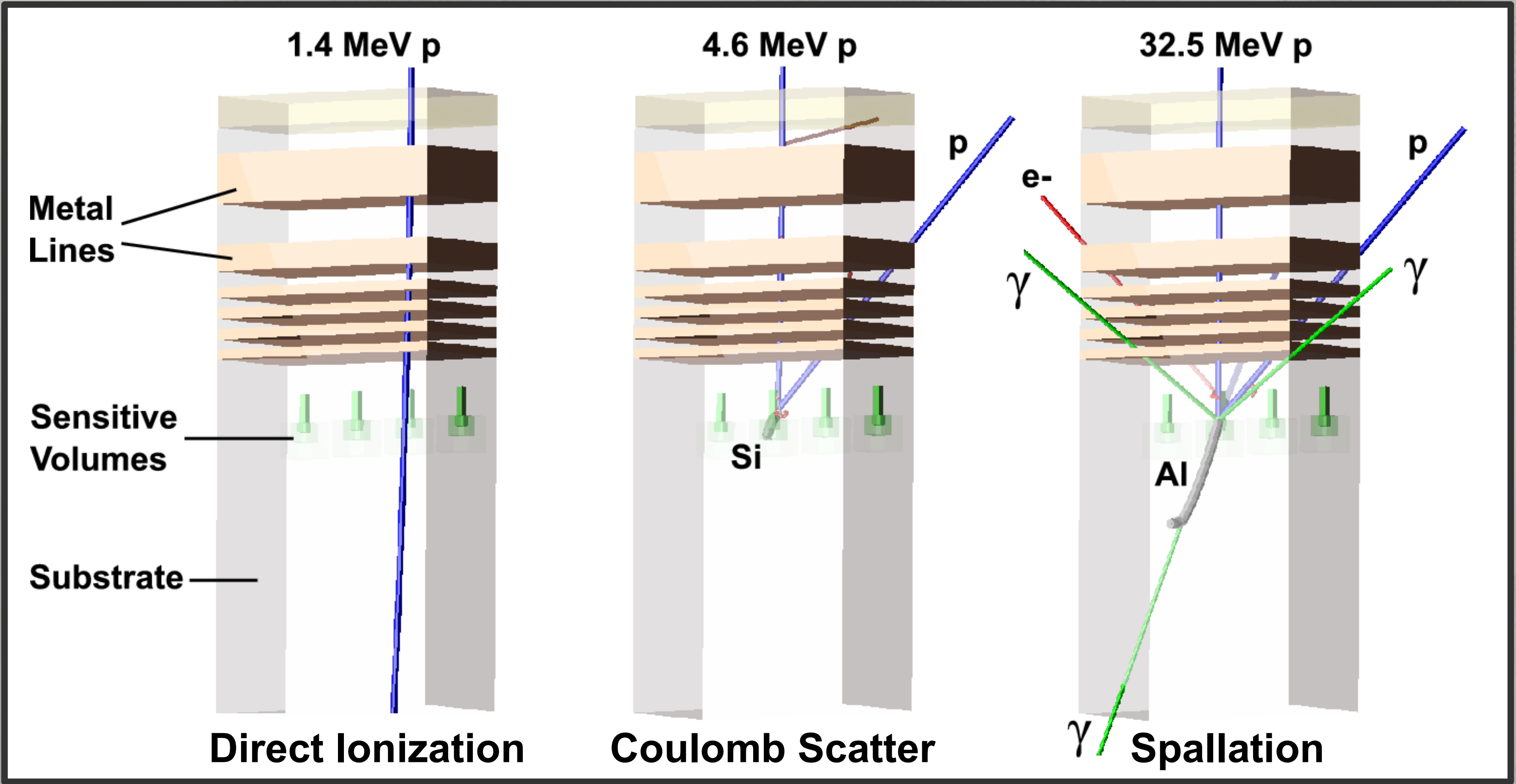


- Single bit cross sections correspond to physical device areas
- Low-LET heavy ion cross sections used to define sensitive area
  - Single, well-known stopping power
- MRED code predicts low-energy proton response



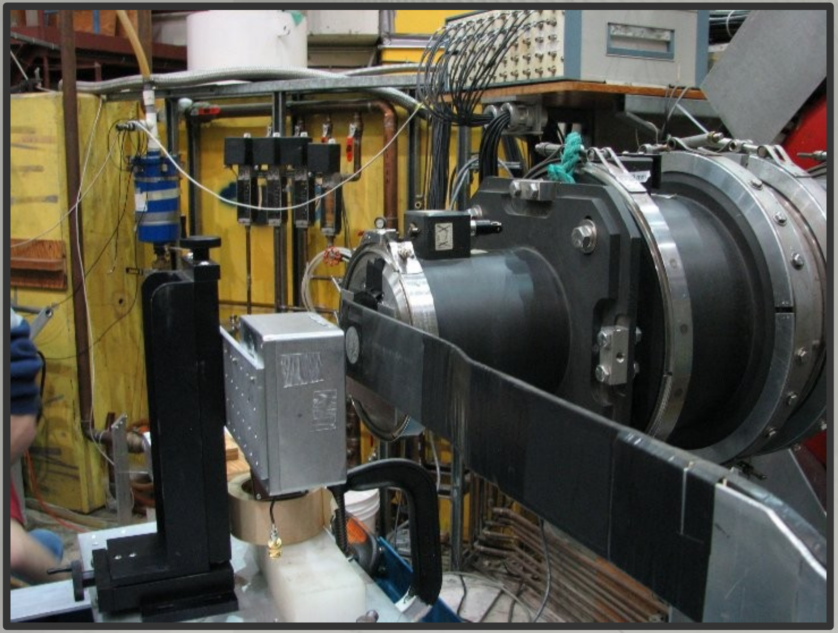


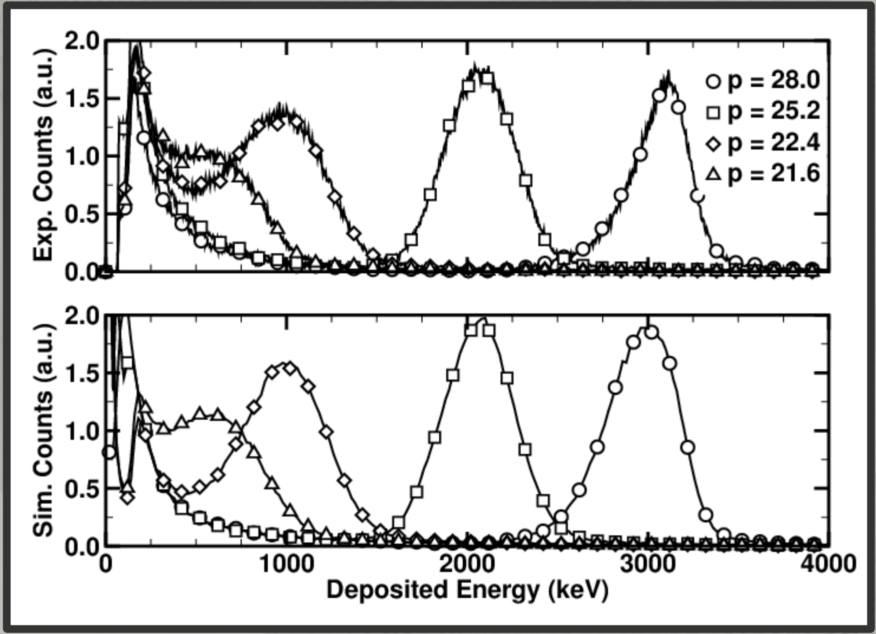
Proton Mechanisms



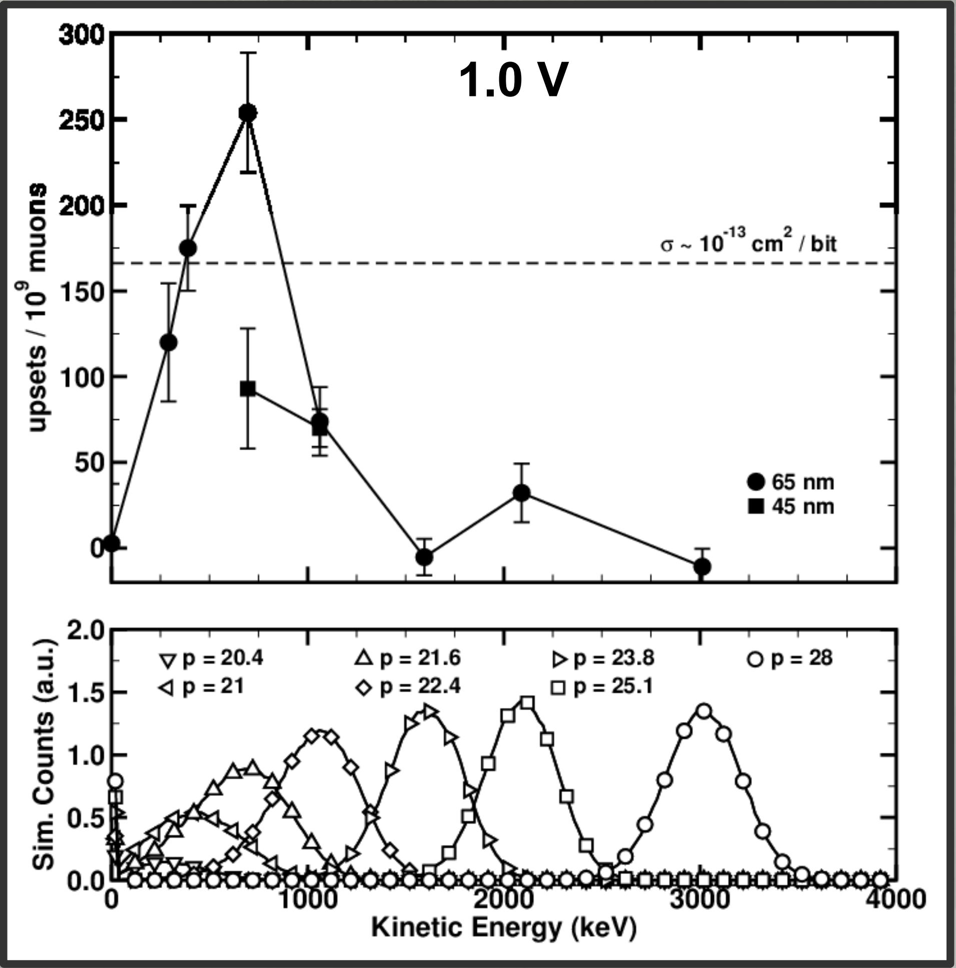
Muon Testing

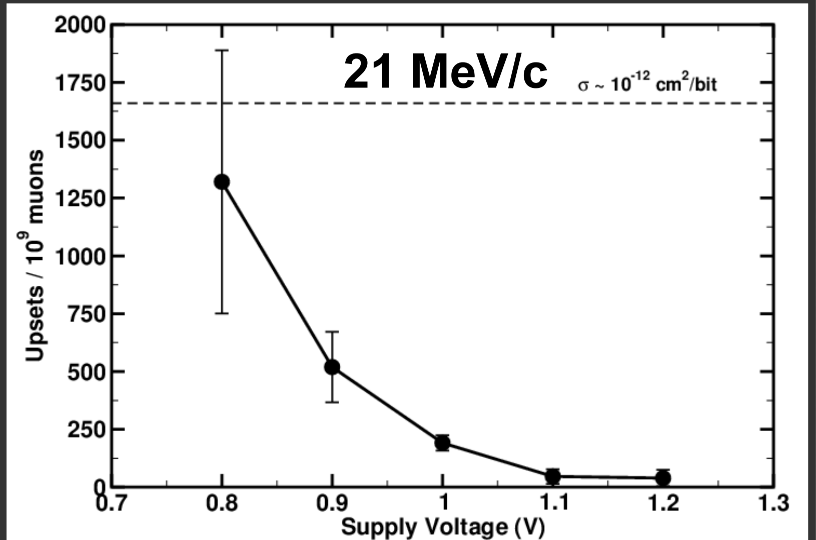
- **Proton sensitivity suggests muon sensitivity**
- **TRIUMF M20 beam produces 30 MeV/c surface muons (μ^+)**
- **Surface barrier detector characterized beam**
- **Geant4 muon transport agrees with calorimetry**

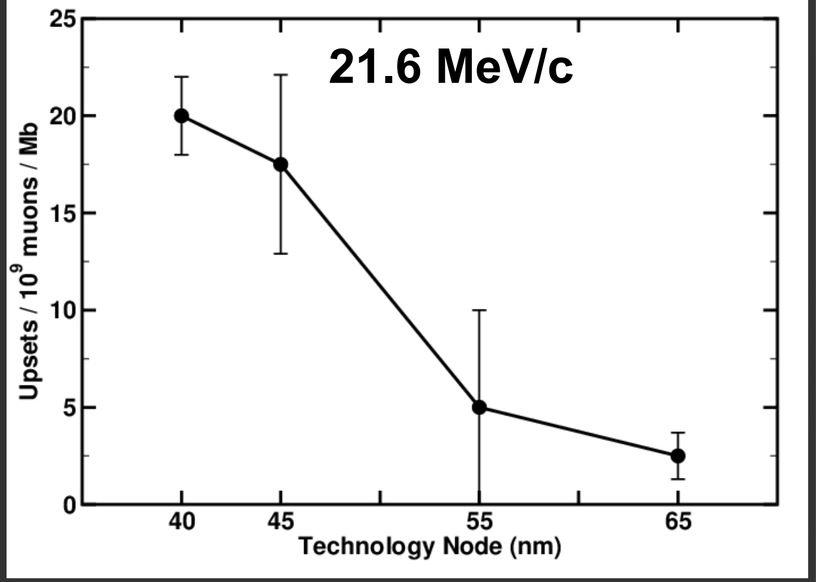




Muon Results

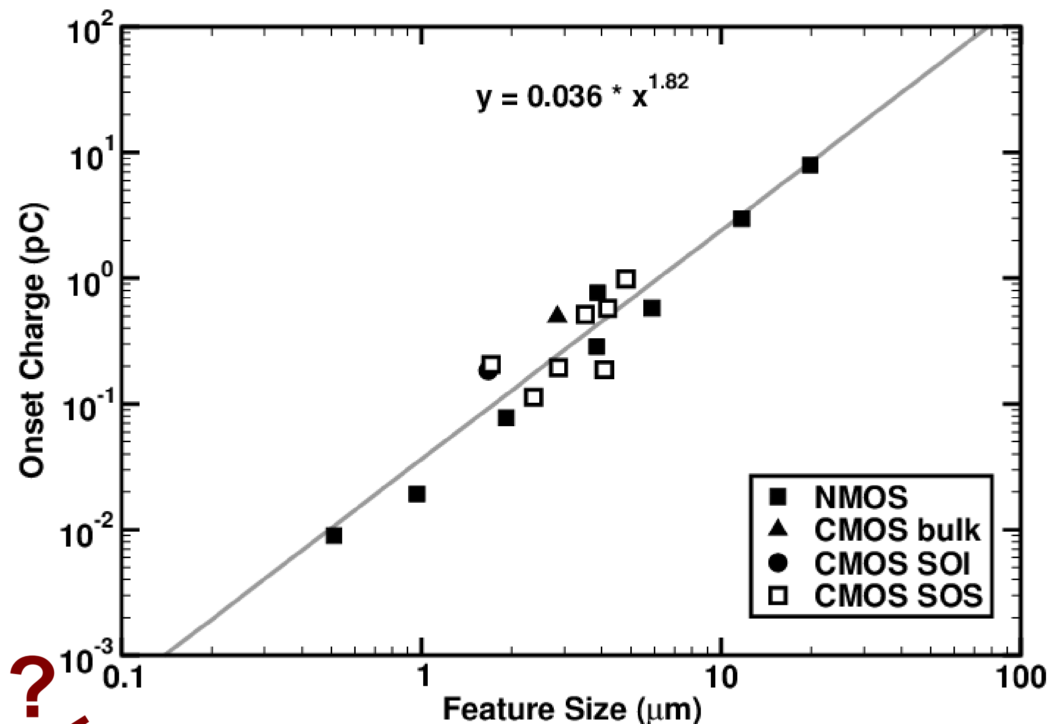






Scaling Trends

- Device sensitivity steadily decreasing
- Predictions of charge threshold based on ITRS and SPICE
- IBM published 65 nm SOI SRAM critical charge 0.21 – 0.27 fC

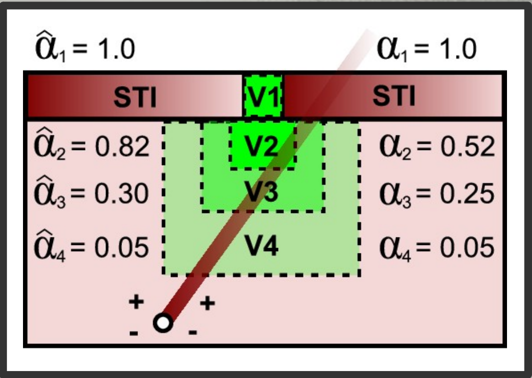


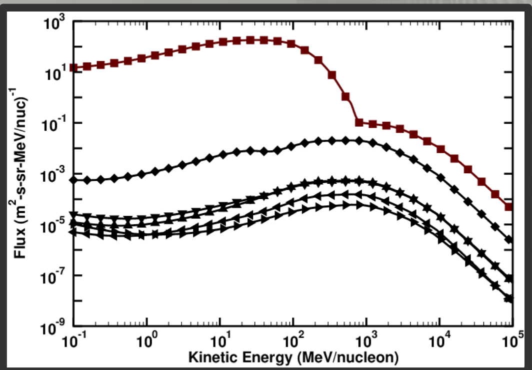
Petersen, NSREC 97

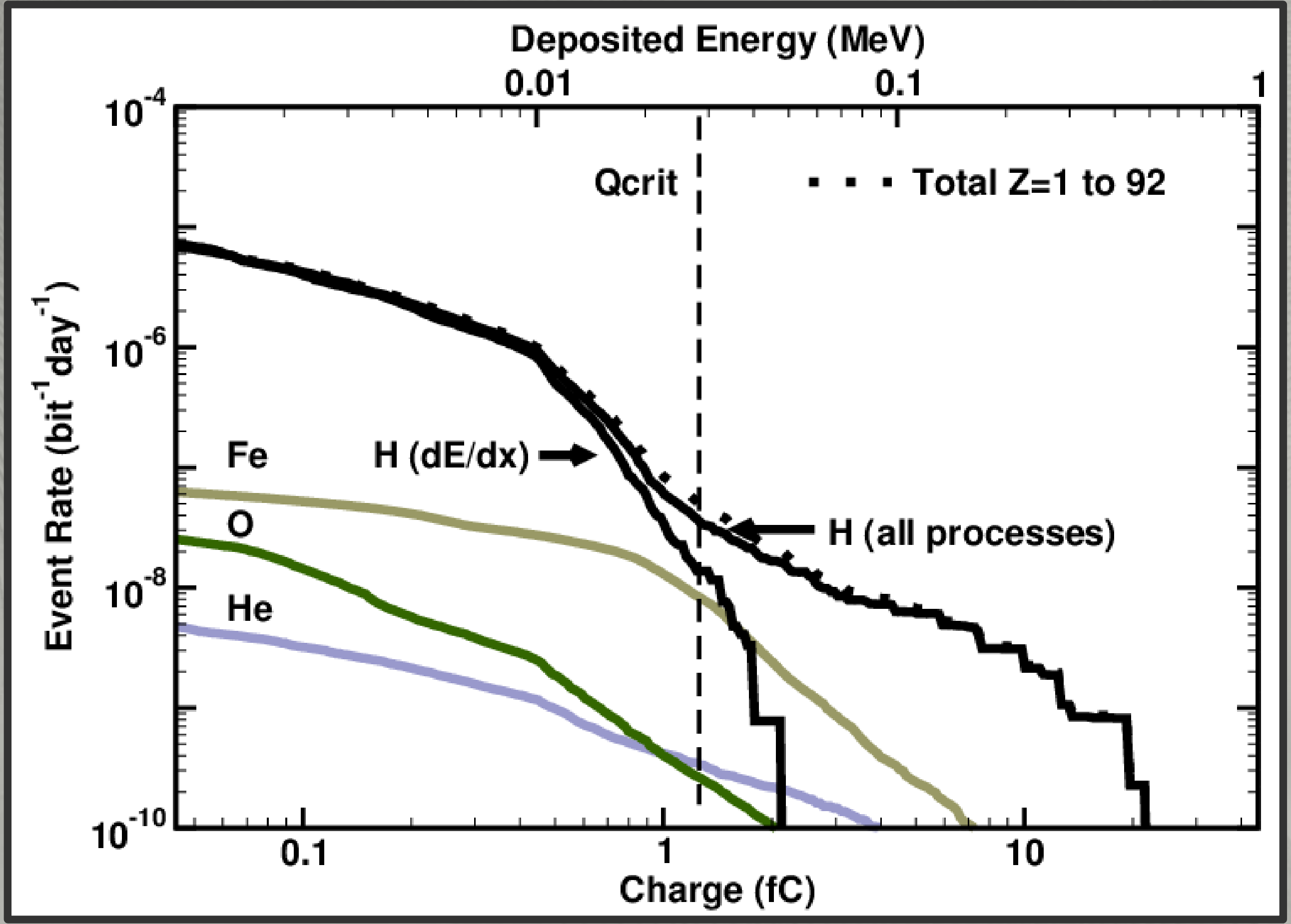
?

Technology (nm)	65	45	32	22	16
Vdd (V)	1.2	1.1	0.97	0.90	0.84
Capacitance (fC)	0.32	0.21	0.13	0.088	0.056
Spice Threshold (fC)	1.3	0.71	0.44	0.36	0.19

Contribution of Protons in ISS

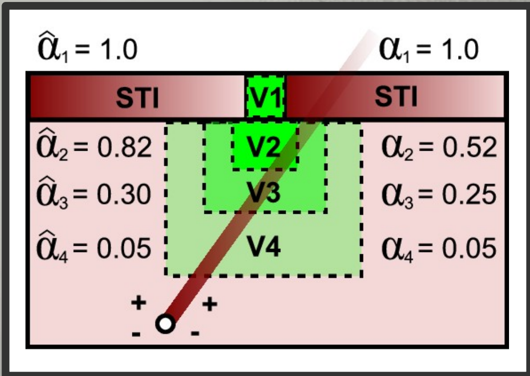


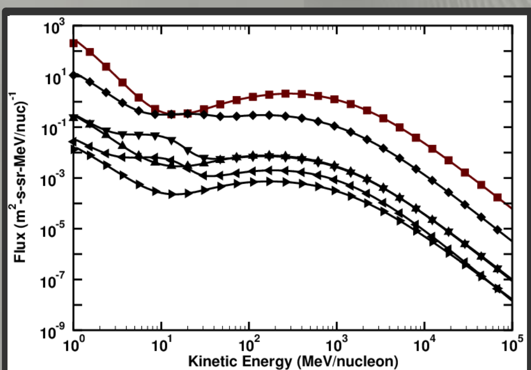


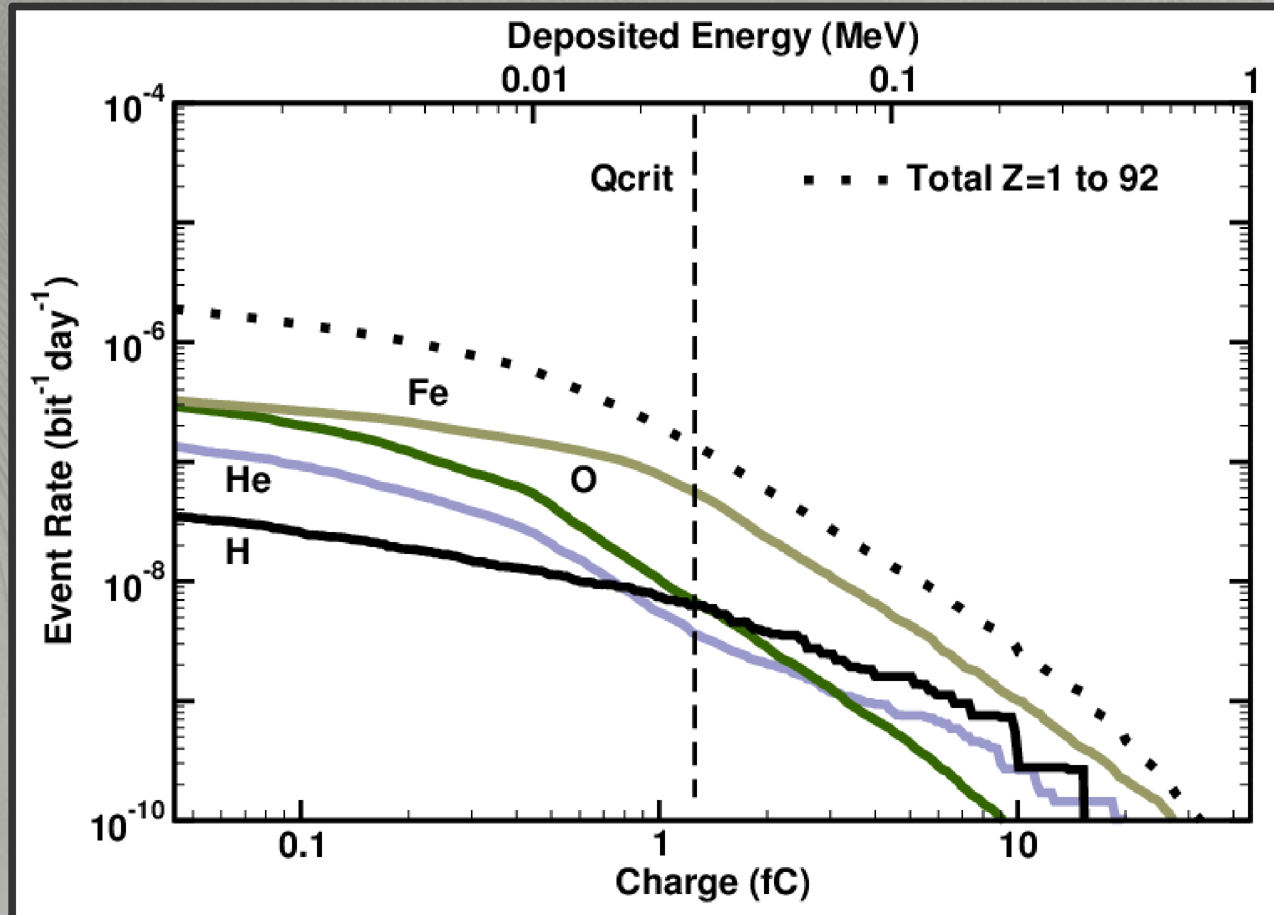


- **Applying ISS environment to sensitive volume model reveals error rate as function of species and critical charge**
- **Direct ionization is becoming the dominant upset mechanism for protons**

Contribution of Protons in GEO

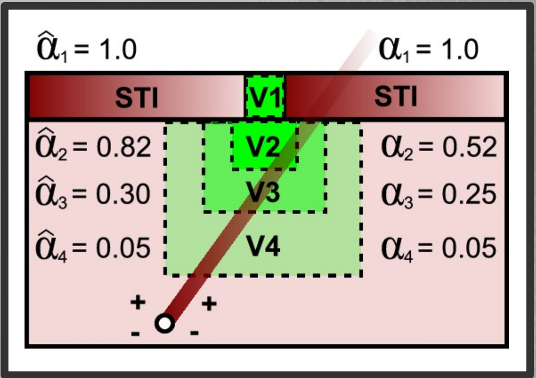


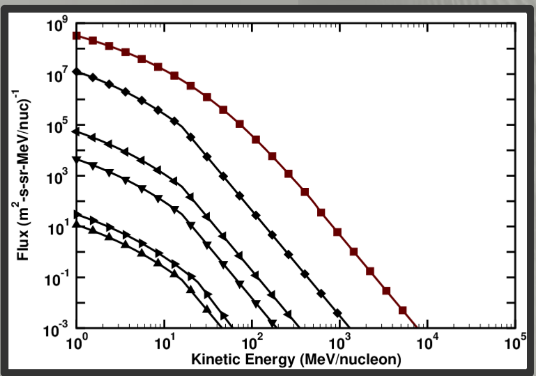


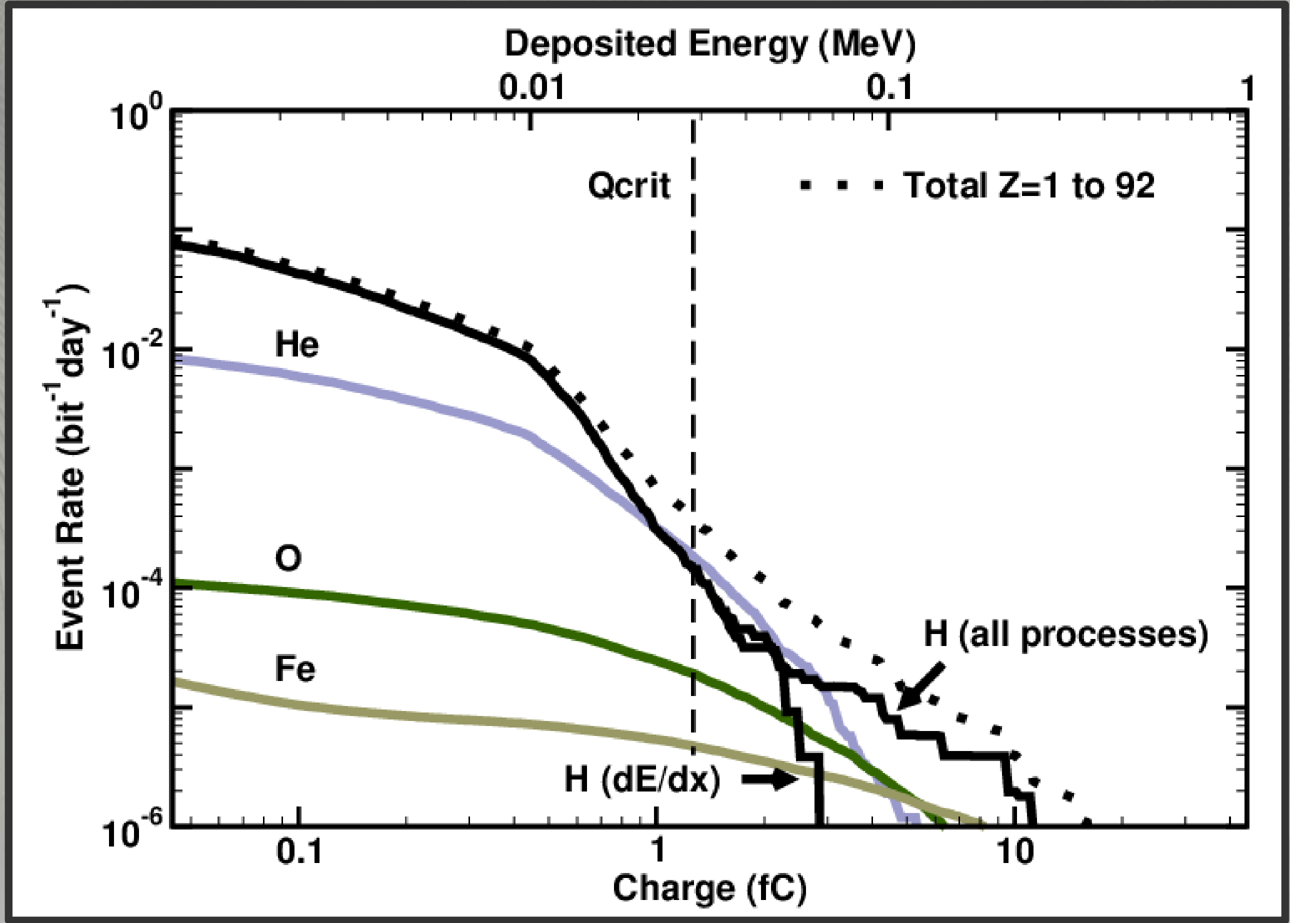


- **Applying GEO environment shows iron and other common ions drive the error rate**
- **Proton flux too low to be an issue (in quiescent conditions)**

Contribution of Worst Day Protons



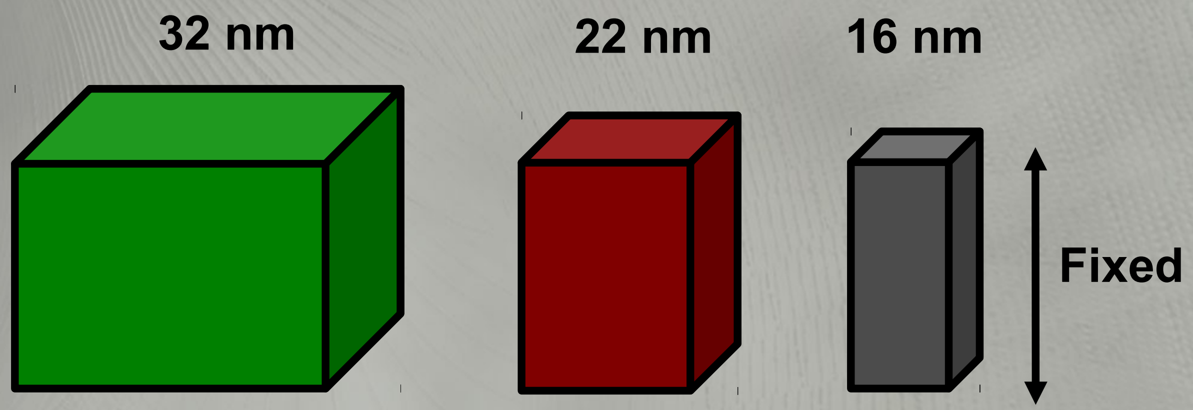




- **Worst Day shows large contributions to error rate from both protons and alpha particles**
- **Need to assess impact on reliability**

Predictive SEU Models

- Protons already relevant at 65 nm
- Muon SEU increasing below 65 nm
- What are the effects of scaling, process technologies?



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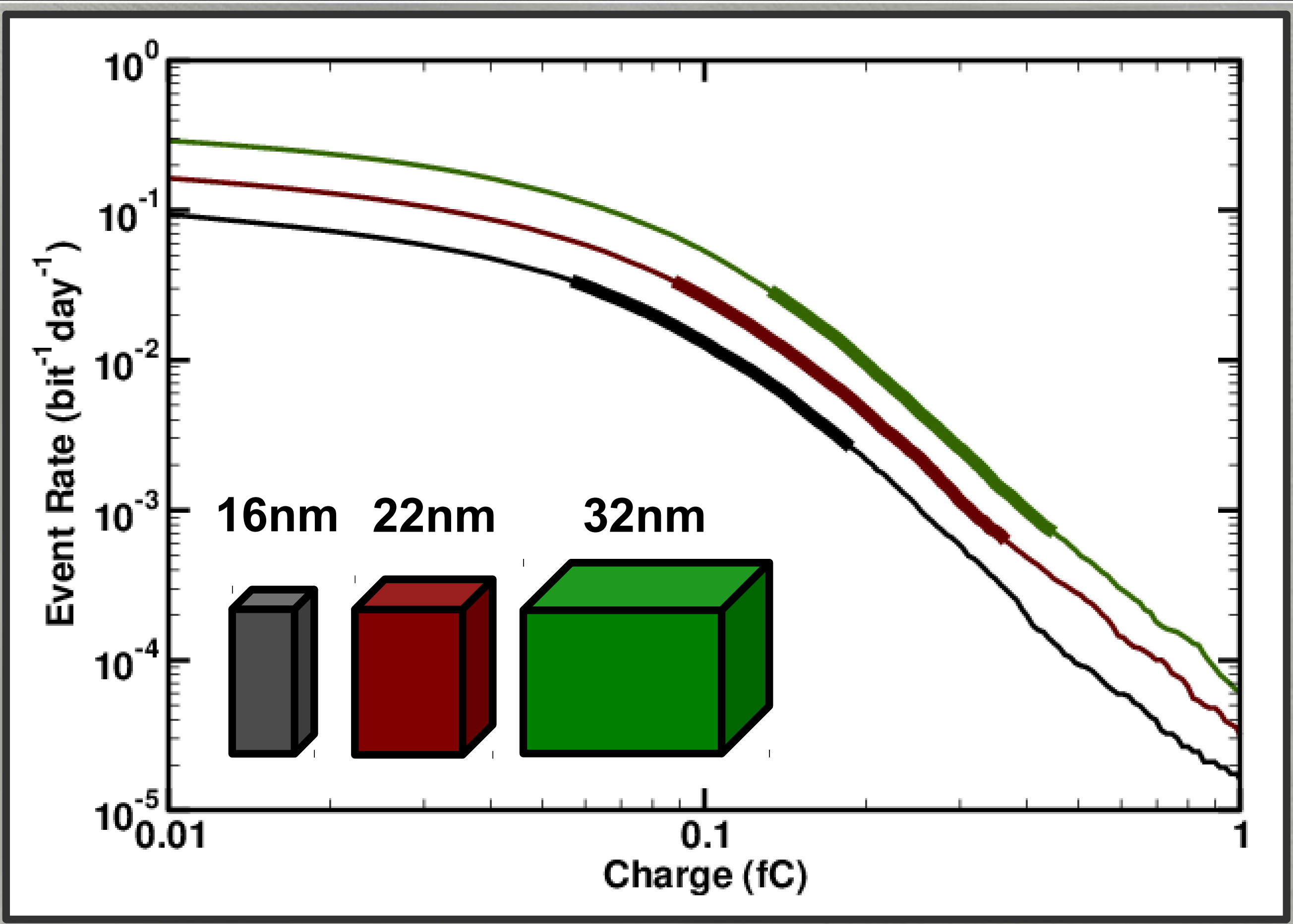
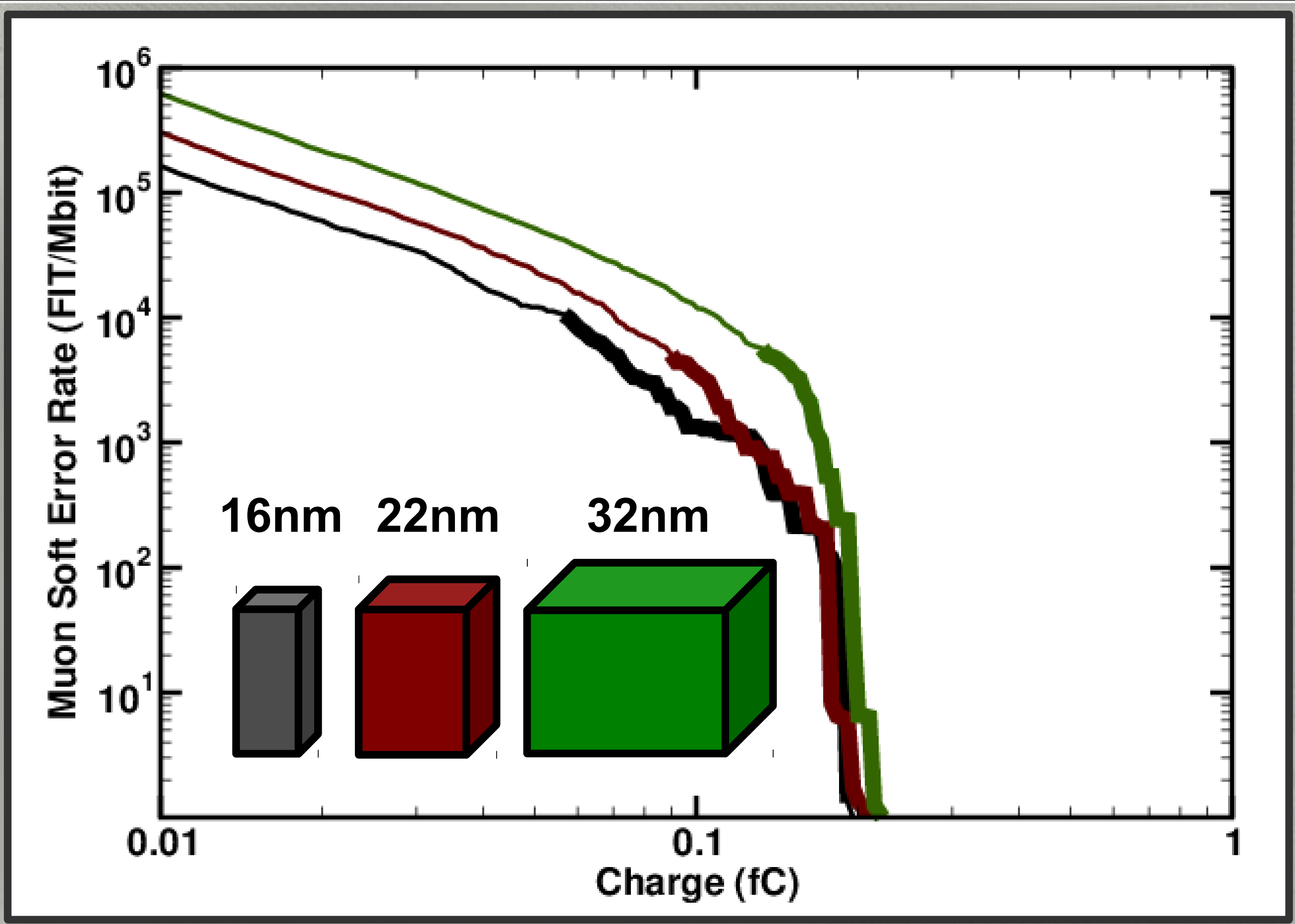
GEO Worst Day Protons



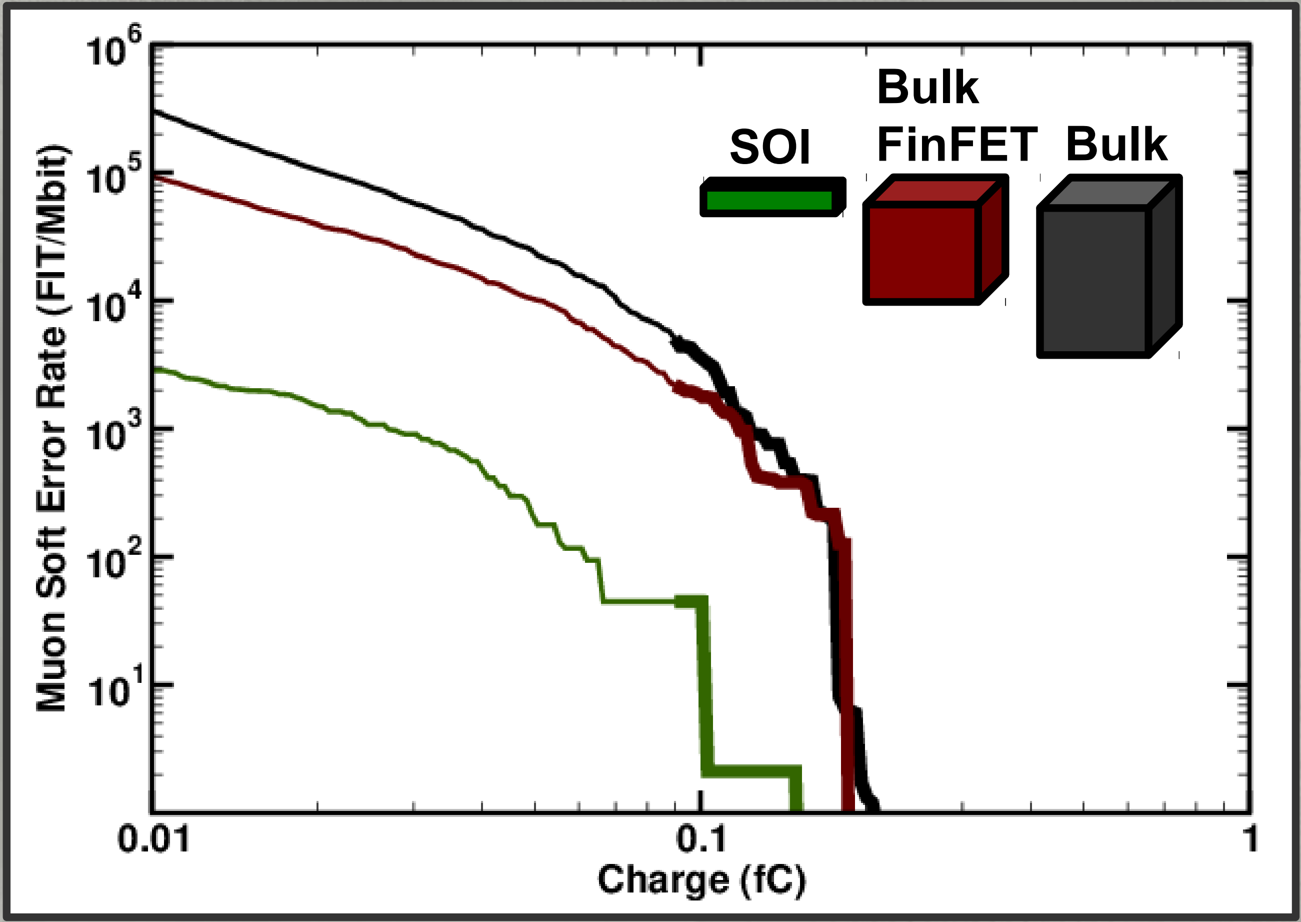
- Critical charge bounds define valid range in error rates
- Proton ionization contribution substantial, but relatively constant with scaling

NYC Sea Level Muons



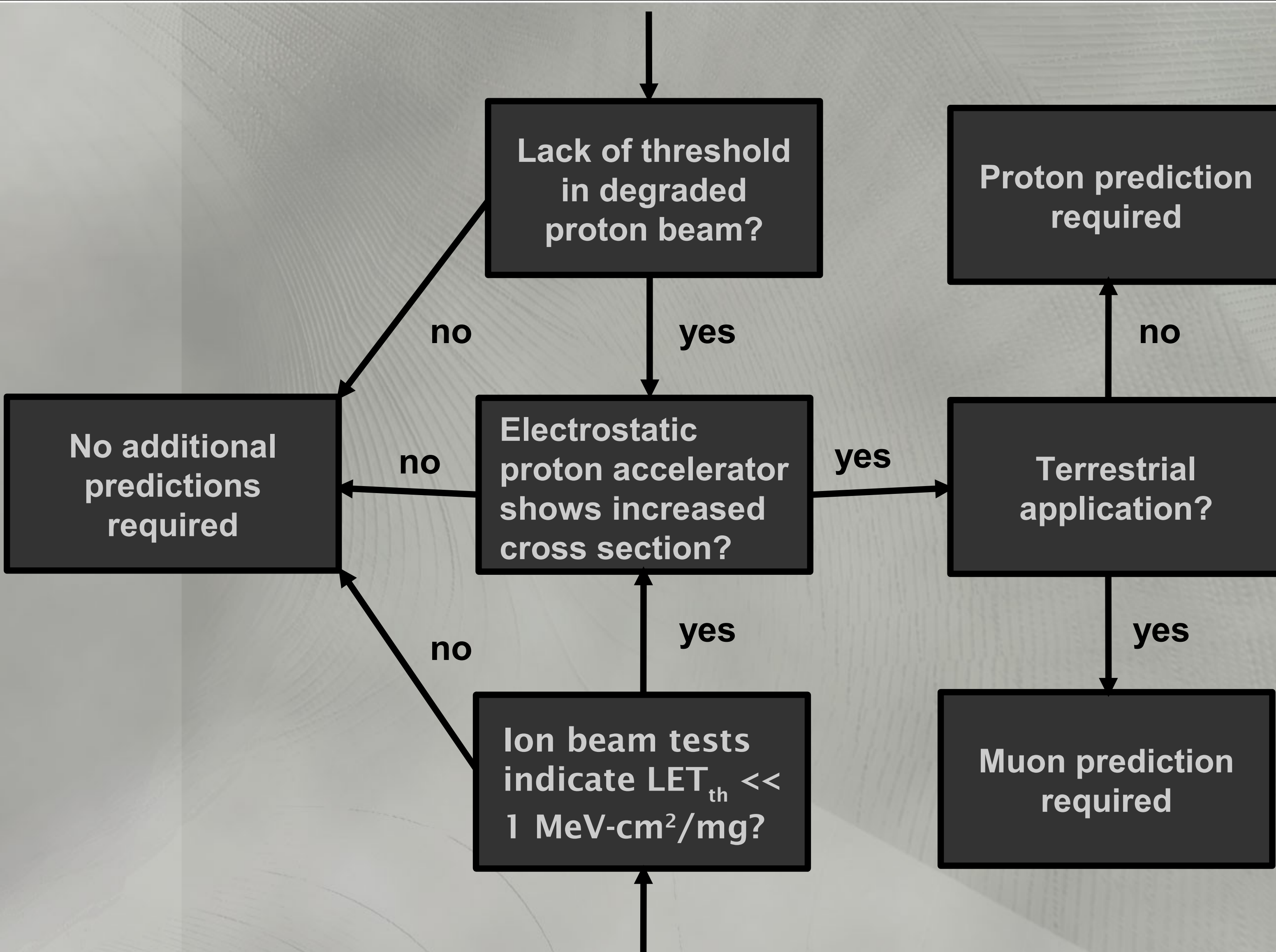
- Range of error rates relatively unchanging with scaling
- Prediction ranges from insignificant to > 10,000 FIT
- Steep rise indicates small differences between cells may make substantial differences in reliability

Effect of Process Technology



- 22nm process SEU models assumed to differ by charge collection depth
  - Bulk 500nm, bulk FinFET 240nm, SOI 10nm
- SOI may have lower threshold thereby increasing maximum error rate

Recommendations



Conclusions

- Neutrons and high-energy protons only rarely interact with nuclei, low-energy protons and muons are able to cause upsets through ionization
- Accelerated tests can demonstrate sensitivity
  - Few high-energy facilities in the world produce muon beams
  - If a part has been shown to be insensitive to proton direct ionization, there is a high confidence that it is also immune to muon direct ionization
- Simulations show that singly-charged particle direct ionization is a concern for reliability
  - Small changes in design (eg. Collection depth, cell area, low power) may cause large changes in error rates