National Aeronautics
and Space Administration

Evaluating Constraints on Heavy-Ion SEE Susceptibility Imposed by Proton SEE Testing and Other Mixed Environments

R. L. Ladbury and J.-M. Lauenstein
Radiation Effects and Analysis Group
NASA Goddard Space Flight Center
Greenbelt, MD 20771 USA

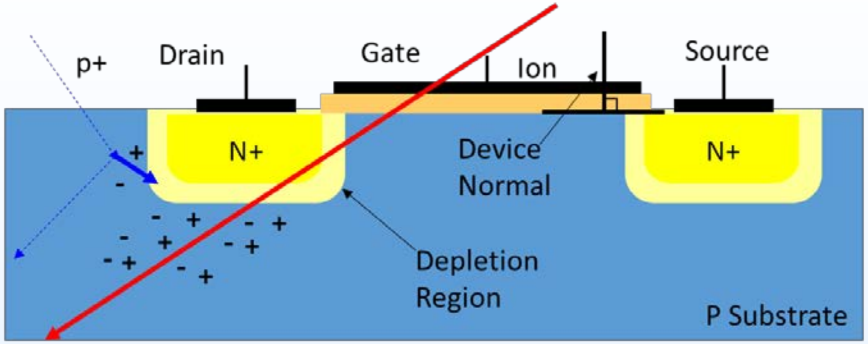
To be presented by Raymond L. Ladbury at the Institute of Electrical and Electronics Engineers (IEEE) Nuclear and Space Radiation Effects Conference (NSREC), Portland, Oregon, July 11-15, 2016.

Acronyms and Symbols

CL=Confidence Level
DSEE=Destructive Single-Event Effects
GCR=Galactic Cosmic Ray
HI=Heavy Ion
LET=Linear Energy Transfer
LET_0=Onset LET
LET_{EQ}=Equivalent Linear Energy Transfer=energy deposited in SV, divided by product of SV depth and SV density.
pdf=probability density function
ρ="rho"=density of Si (2.33 g/cm^3)
s, W=Shape and width parameters for the Weibull distribution/form
SEB-Single-Event Burnout
SEE=Single-Event Effect
SEGR=Single-Event Gate Rupture
SEL=Single-Event Latchup
SOTA=State Of The Art
SDRAM=Synchronous Dynamic Random Access Memory
SRAM=Static Random Access Memory
SPE=Solar Particle Event
SV=Sensitive Volume
σ="sigma"=Cross section
σ_{sat}=Saturated Cross Section
TID=Total Ionizing Dose
Xstr=transistor
Z=Atomic number of a nucleus or atom=# of protons in nucleus

Can Heavy-Ion Rates Be Bounded with Protons?

- **Heavy Ion (HI) Testing:**
  - Is Expensive
  - Is Time-Consuming
  - Requires extensive modification of test parts
  - Increasingly difficult to schedule
  - Some parts may be nearly impossible to test w/ normal accelerator ions.
  - Very hard to test boards/boxes.
- **Proton testing**
  - Causes SEE via recoil ions
    - $3 \leq Z \leq 15$
  - Produces ions reaching sensitive volumes even in difficult parts
  - Allows board/box-level testing
    - Promises significant savings in cost and schedule
- **Can Heavy-Ion SEE rates be bounded with proton data?**

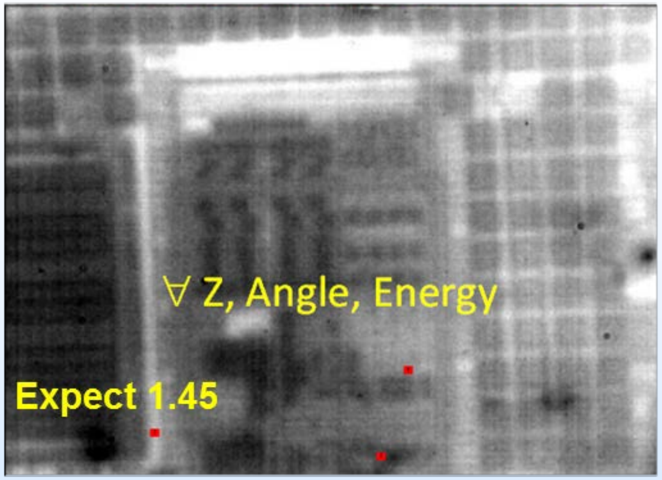


Some Challenges w/ protons

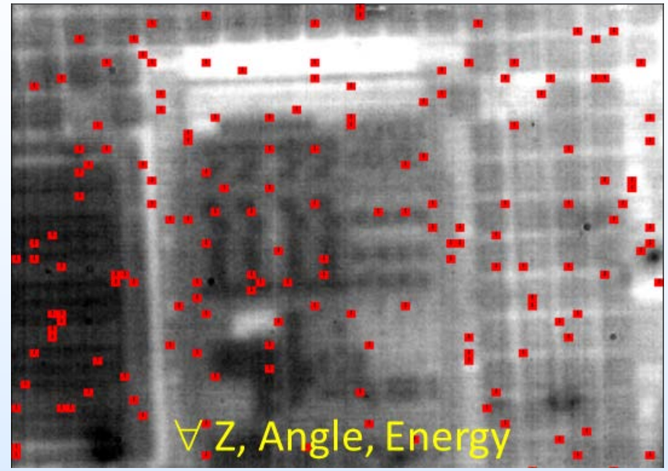
- **Protons inefficient at producing ions**
  - ~1/2.9E5 200-MeV protons produces a recoil ion; all contribute dose
- **We don't know Z, energy, angle or LET of an ion that causes a given SEE**
- **Proton recoils low energy/short range**
  - Last year, showed this was very important for assessing destructive SEE susceptibilities
  - Cannot compare recoil to GCR or SPE ions
  - Introduce $LET_{EQ} = E_{Dep}/(\rho \times d)$, ρ=Si density, d=depth of SEE SV
  - If LET ~ constant in SV, LET_{EQ} ~ Effective LET

Coverage of SEE Tests

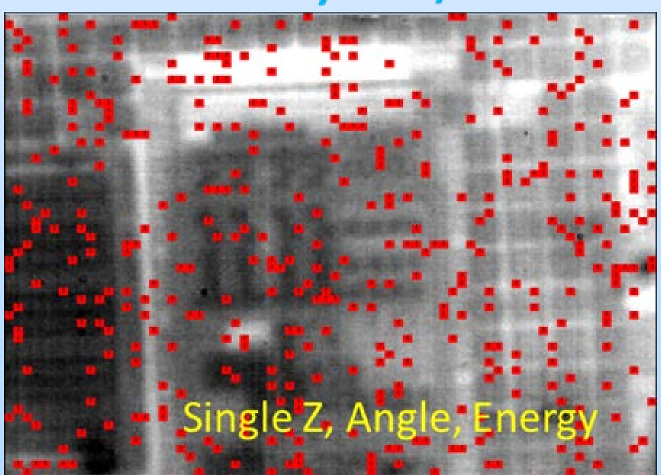
1E10 200 MeV protons/cm^2



1E12 200 MeV protons/cm^2

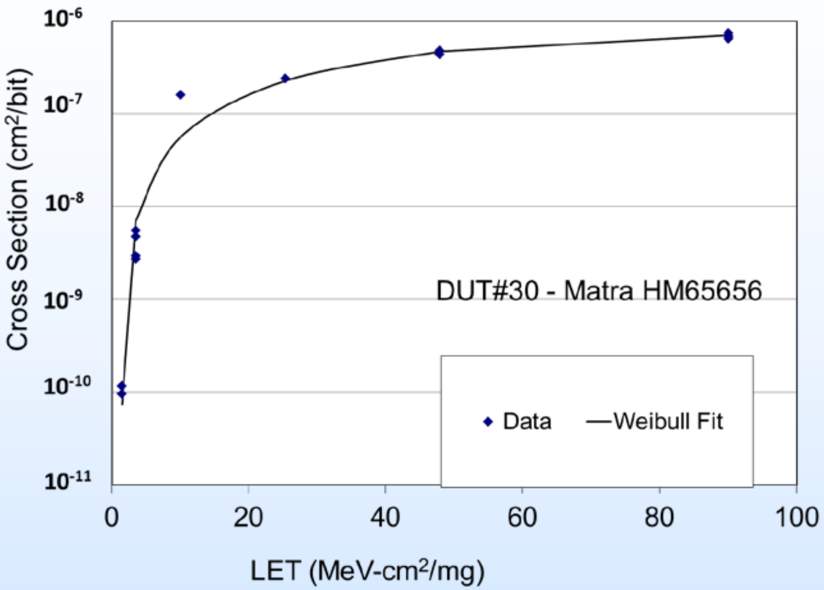


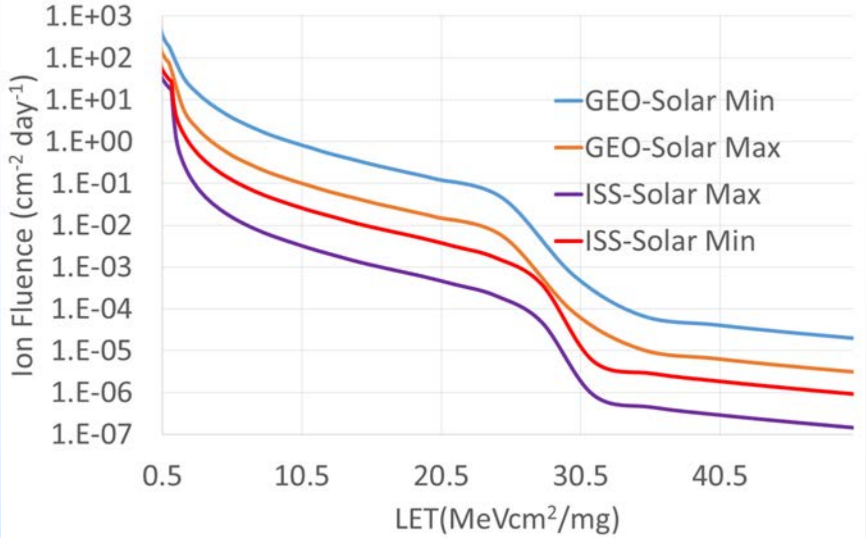
1E7 heavy ions/cm^2



- **Coverage of SEE test—how well it probes potentially vulnerable areas on test item**
  - **Units: μm^2 per ion or transistors (xstr) per ion.**
- **IR photomicrograph of 60×70 μm^2 area of ELPIDA EDS5108 512 Mbit SDRAM**
  - **Expect 1.45 recoil ions for 10^{10} 200-Mev p/cm^2**
- **Intel I7 processor ~ 1 ion per 8000 xstr**
  - **Intel 8080 8-bit processor had 6000 transistors**
- **These are average values**
  - **10% of parts could have missed areas >78800 μm^2**

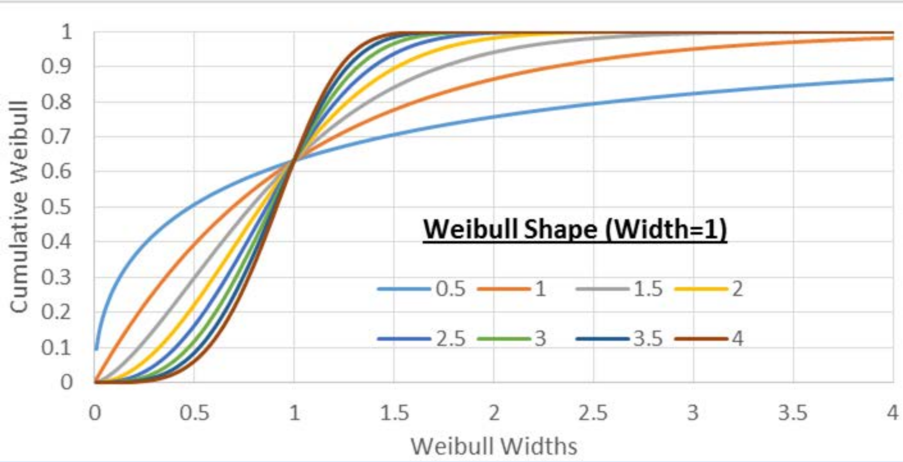
But, Not All Ions Are Created Equal

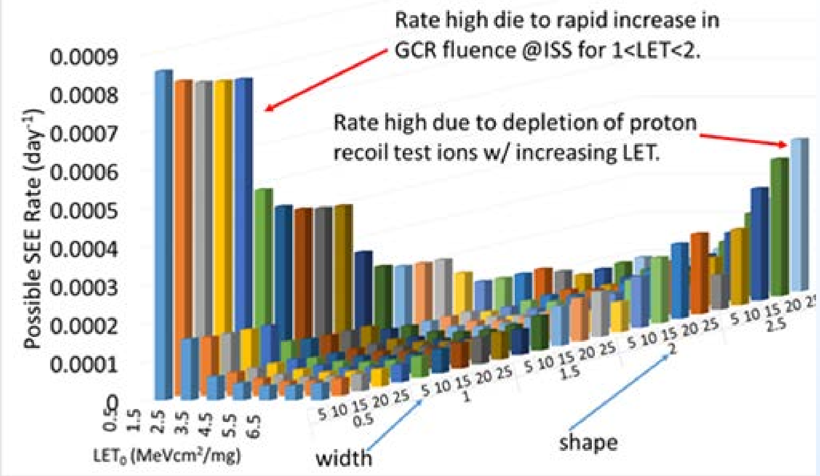




- **Low-LET ions must hit much smaller cross section to cause SEE**
- **Ion fluence drops with LET in almost any environment**
  - **Broader σ vs. LET (larger Weibull Width, W)→lower rate**
  - **Larger shape parameter s → lower rate**
- **Proton recoil fluences**
  - **Very few proton recoil ions w/ LET>10 MeVcm²/mg**
  - **Short range of proton recoils → fluence vs. LET_{EQ} drops even faster for deep SV**

SEE Rate Bounds for Shallow SV





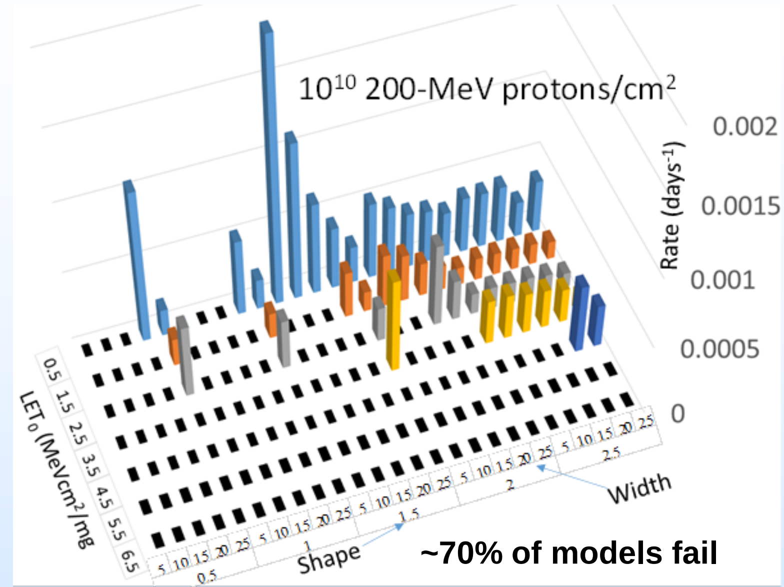
- Constraints from proton testing too weak to determine σ vs. LET, but event count can tell us which models are inconsistent with the proton data
- Assume device SV made up of N_{SV} representative 1-micron cube SVs
  - LET varies little across this sensitive volume, so LET_{EQ} ~effective LET

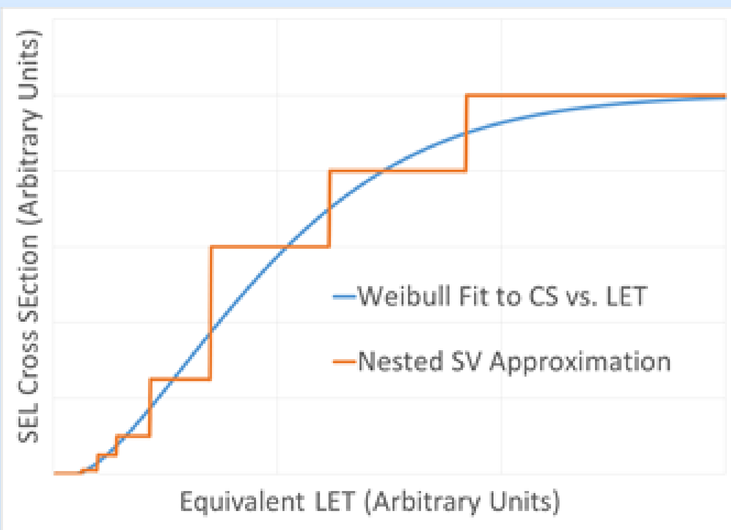
$$N_E = \int_{LET_0}^{LET_{Max}} N_{SV} \times F(LET_{EQ}) \times \sigma(LET_{EQ}, LET_0, w, s)\, dLET_{EQ}$$

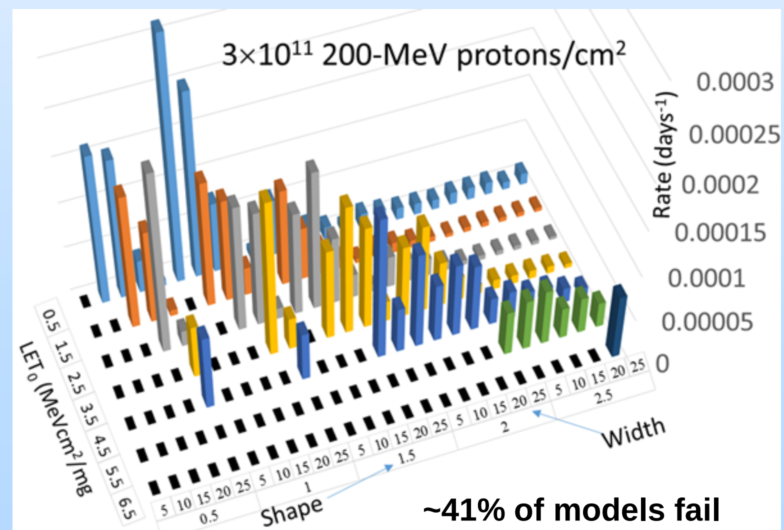
  - Estimate # errors expected for a single 1-micron-cube SV for 175 representative models
    - W={5, 10, 15, 20, 25}, s={0.5, 1, 1.5, 2, 2.5}, LET0= {0.5, 1.5, 2.5, 3.5, 4.5, 5.5, 6.5 MeVcm2/mg)}
  - Solve for N_{SV} using upper bound on Poisson Mean for N_E (e.g. 2.31 for 90% CL if 0 events seen)
  - Result: *Model performs worst at both high LET_0 (where ions are scarce) and low LET_0, where increase in GCR fluence is more rapid than increase in fluence of recoil + cascade ions.*
  - Note: CRÈME-MC emulator—uses stored CRÈME-MC results for proton recoils and CRÈME-96 rates for each candidate σ vs. LET model—can be generalized for any SV

Deep SV Are More Challenging

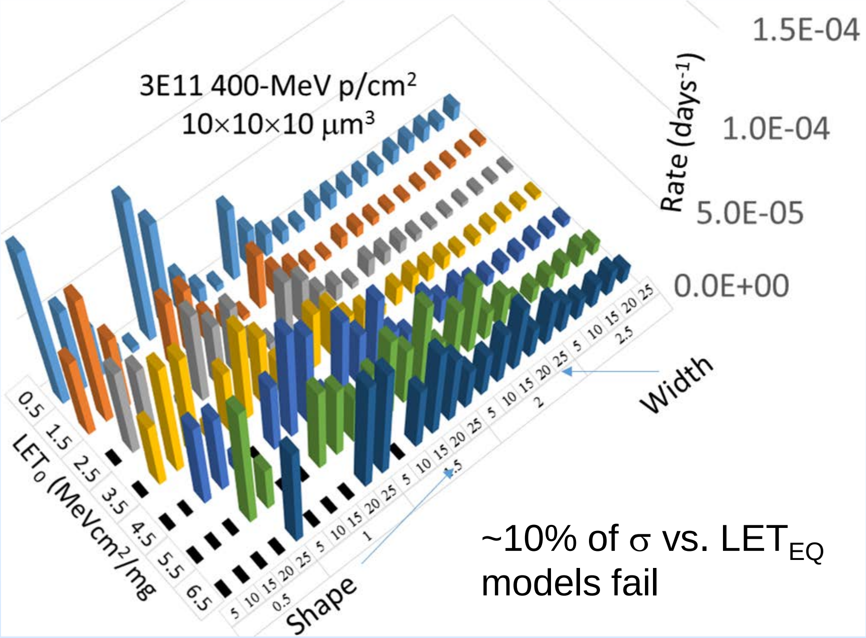
- **Chord-length pdf changes as σ rises**
  - **Use Nested SV to approximate σ vs. LET model**
  - **Use Fluence(LET_{EQ}) for SV depth**
  - **Estimate N_E and solve for N_{SV}**
- **For 10-μm cube SV**
  - **If device σ bound >10^{-2} cm^2, method fails**
  - **For 10^{10} 200-MeV p/cm^2 122 failures/175 models**
  - **For 3E11 200-MeV p/cm^2, 40.6% of models fail**
  - **Protons can bound rate if fluence high, LET_0 is low and σ vs. LET_{EQ} rises rapidly enough**
  - **Requires added information or assumptions**







Energy and Fluence Dependence



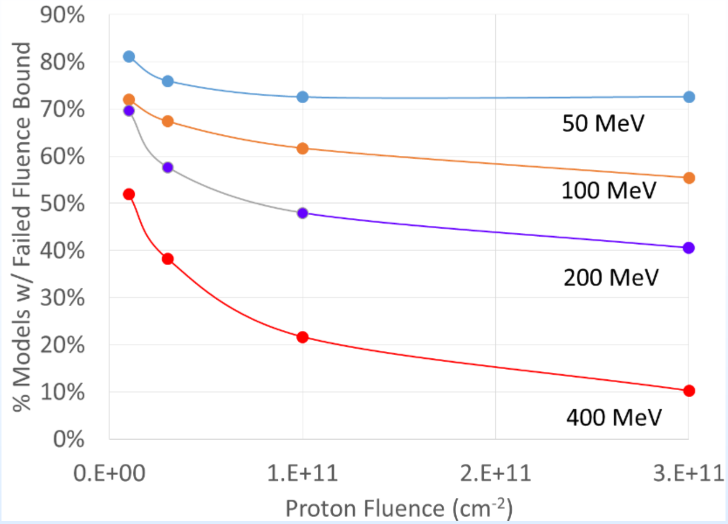
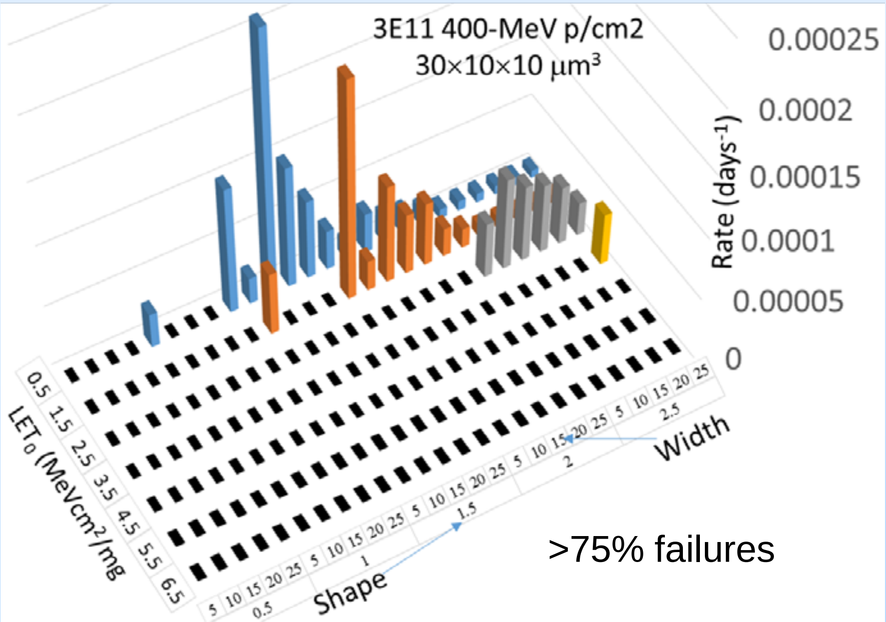
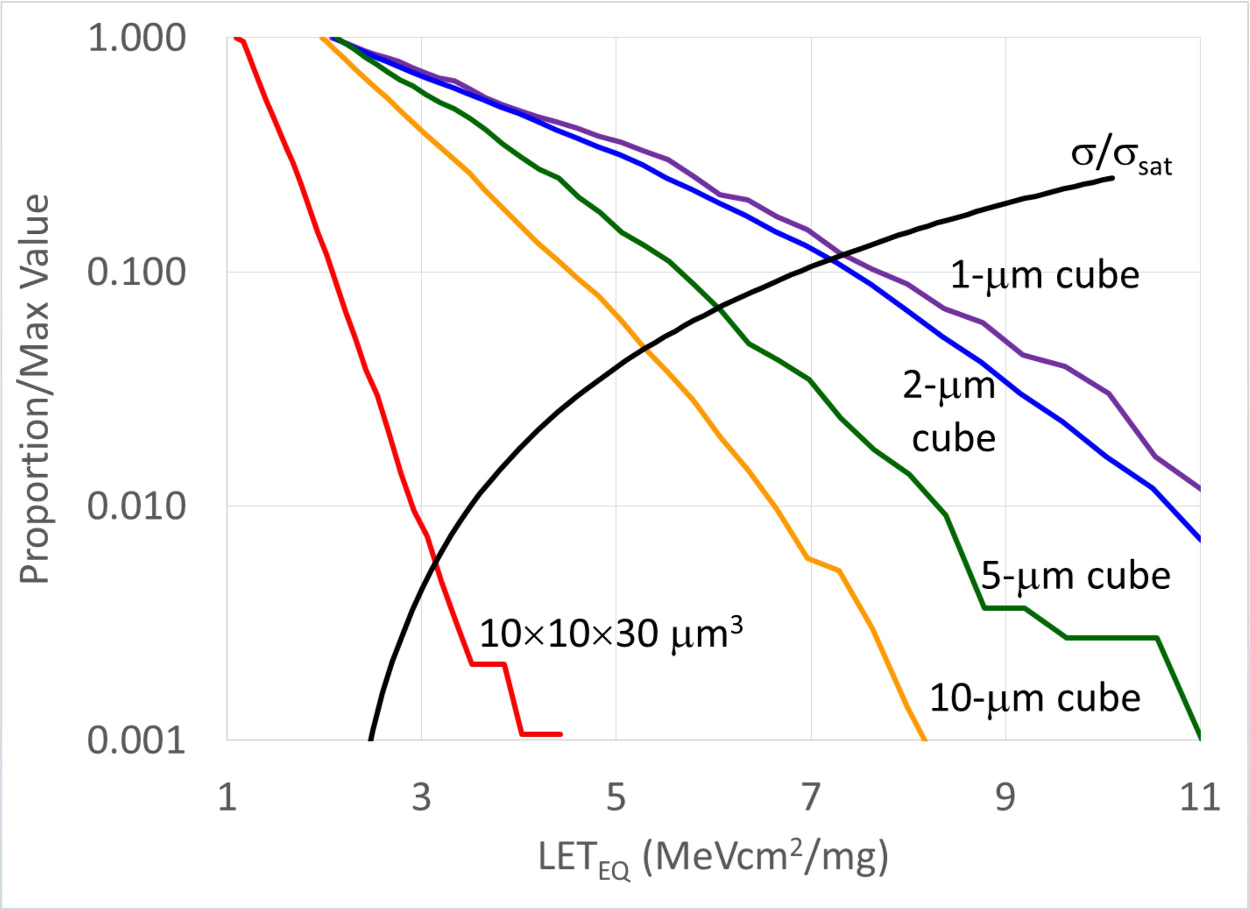


Table I: Parameters w/ >50% Successful Bound

Parameter	LET$_0$		
Fluence (cm^{-2})	(MeVcm2/mg)	s	W
200 MeV, 10^{10}	< 2	< 1	< 10
200 MeV, 3×10^{11}	< 5	< 1.7	< 22
400 MeV, 10^{10}	< 3.5	< 1.2	<12
400 MeV, 10^{11}	< 6.5	< 2.2	< 25

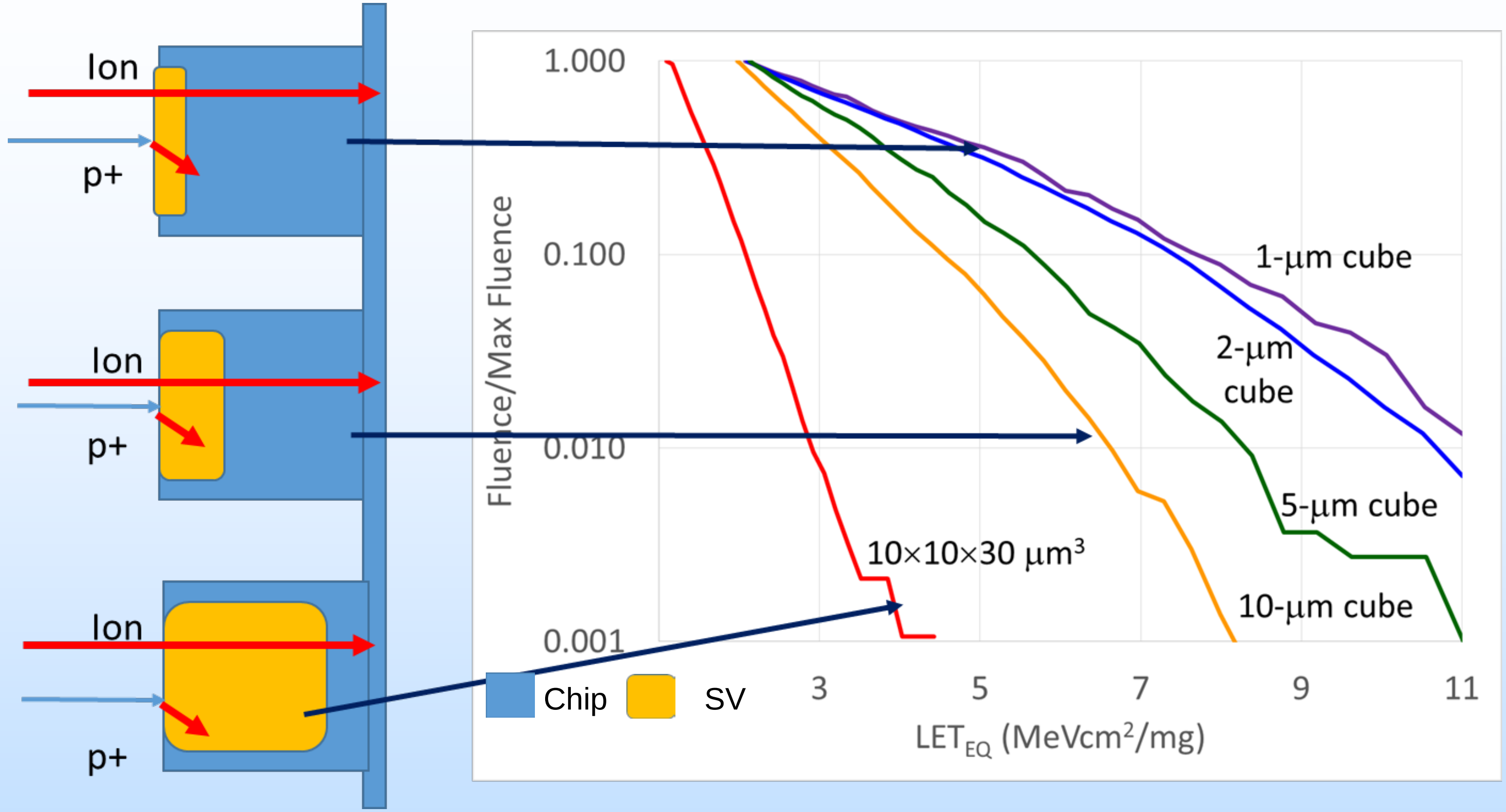


Why Bounding Fails



- **Method fails to bound heavy-ion susceptibility if ion fluence falls faster then cross section rises vs. LET_{EQ}. (high LET0, W or s).**
  - **Deep SV push fluence distribution left—increasing likelihood of method failure**

Board/Box-Level Testing



- **Board/box-level testing irradiates many parts w/ diverse technologies**
  - **Saves money, but different SV depths mean parts see different Fluence vs. LET_{EQ} dist.**
  - **Proton test may vary in effectiveness for every device on board**
  - **Need to know as much as possible about technology of each device to make sense of proton data**

Summary and Conclusions

- **Proton SEE data does constrain heavy-ion SEE performance**
  - Constraints may be weak due to important differences between recoils and GCR
- **Coverage key to whether test reveals SEE susceptibilities**
  - Ions per unit area or per transistor is a first approximation, but not all ions equally capable of causing SEEs
  - Rate bounds that consider potential σ vs. LET form are more informative
- **Shallow SV: LET~ constant through SV—bounding straightforward**
  - Consider σ vs. LET models for which proton recoils may be effective
    - $LET_0 \leq 6.5$ Mevcm^2/mg, width≤25, shape≤2.5—other models will perform worse.
  - Estimate rate for single SV—How many SVs possible for test to yield null result?
  - Bounding rate likely ≤0.001/day—worst bounds at both low and high LET_0
- **For deep SV, ions range limited—use nested SV approach**
  - Many plausible models fail to yield meaningful bound
  - Increased fluence and energy help, but only for SV depth ≤ 10 μm
- **The problem is inherent to proton testing**
  - Charge deposited by proton recoils in deep SV limited by range, not LET
  - Fluence vs. LET_{EQ} compressed toward lower LET_{EQ}, where σ
- **Applies to SEL—even worse for SEB/SEGR (coverage worse)**

Possible Future Directions

- **Proton SEE data only weakly constrain HI SEE susceptibility**
  - **Must supplement data with other information to increase effectiveness**
    - **E. g. constrain LET0, w, s, σ_{sat} w/ process and/or similarity data**
    - **Well suited to Bayesian treatment—as this makes subjective assumptions explicit**
- **Current analysis predicated on DSEE physics of failure**
  - **Need to understand SV geometry for DSEE better**
  - **Are there mitigating factors that would lead to tighter WC bounds on HI rates?**
    - **Cannot be ruled out, but no indication at present**
- **Develop methods to make sense of board/box-level tests**
  - **Fluctuations lead to worse coverage for some chips than others**
    - **Improves less than linearly with increased fluence**
  - **Different SV depths lead to exposure to different equivalent environments**
    - **Significantly complicates extrapolation of board-level proton tests to HI environment**
  - **For these reasons, board/box-level bounding rates must increase at least linearly with board/box complexity (e.g. # of parts)**
- **Despite problems, proton testing may be the only option for many complicated highly integrated components**
- **One certainty: interpreting results will not be simple**