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

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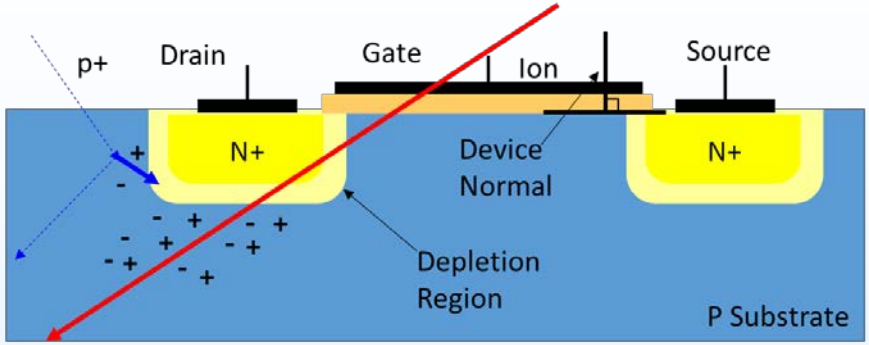
Acronyms and Symbols

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?**

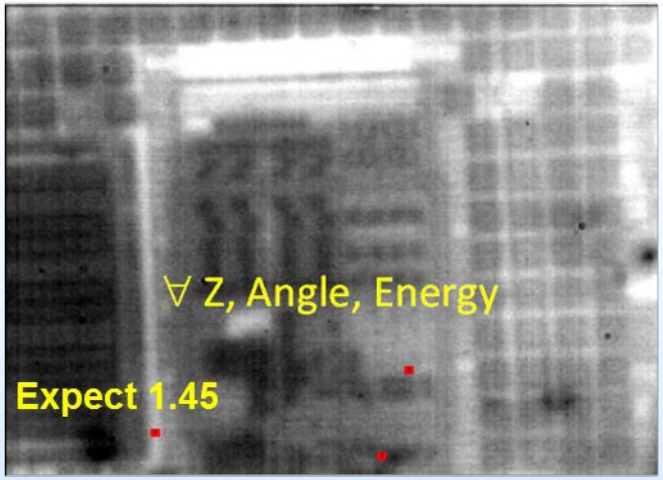


Some Challenges w/ protons

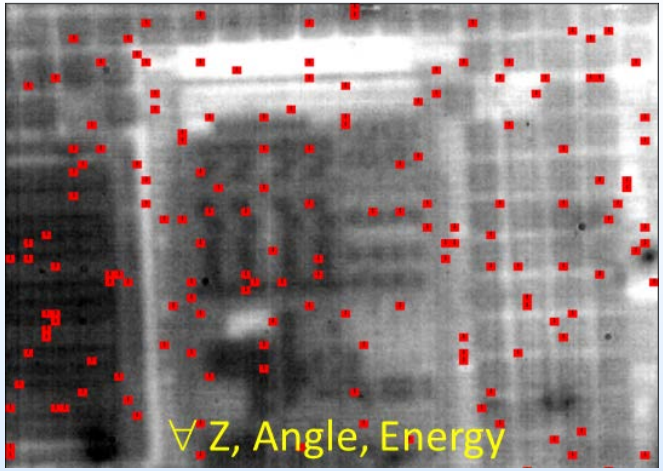
- **Protons inefficient at producing ions**
  - ~1/2.9E5 200-MeV protons produces a recoil ion; all contribute dose
- **We don't know Z, energy, angle or LET of an ion that causes a given SEE**
- **Proton recoils low energy/short range**
  - Last year, showed this was very important for assessing destructive 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

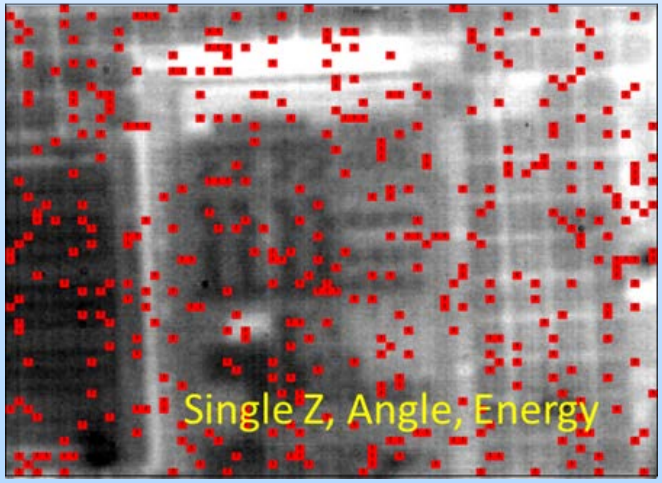
1E10 200 MeV protons/cm^2



1E12 200 MeV protons/cm^2

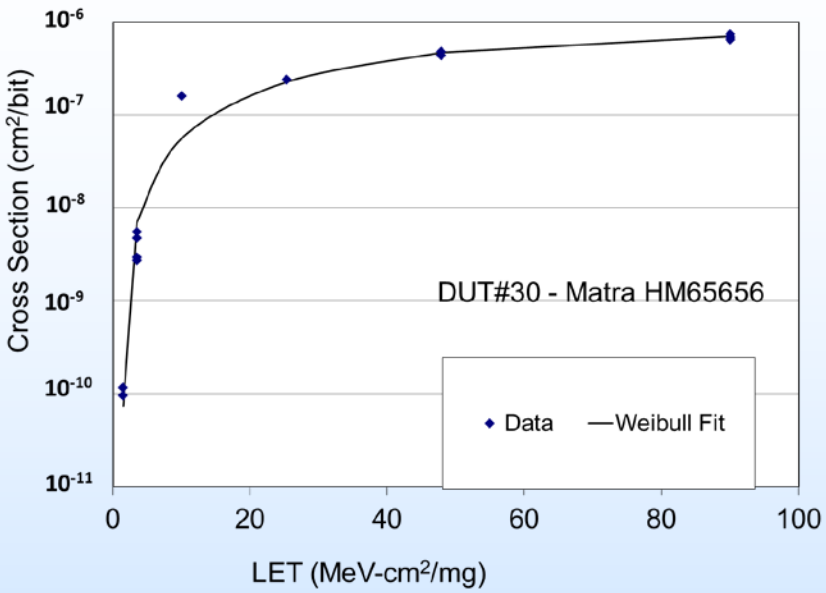


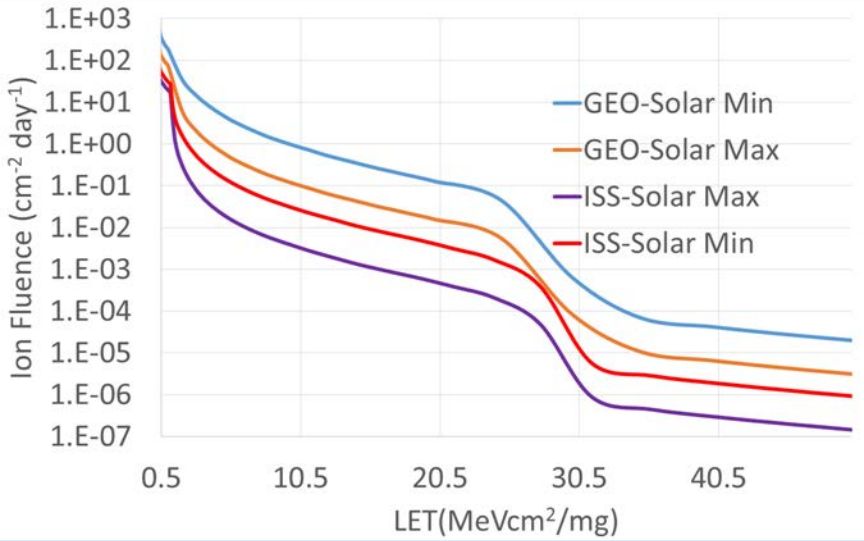
1E7 heavy ions/cm^2



- **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**

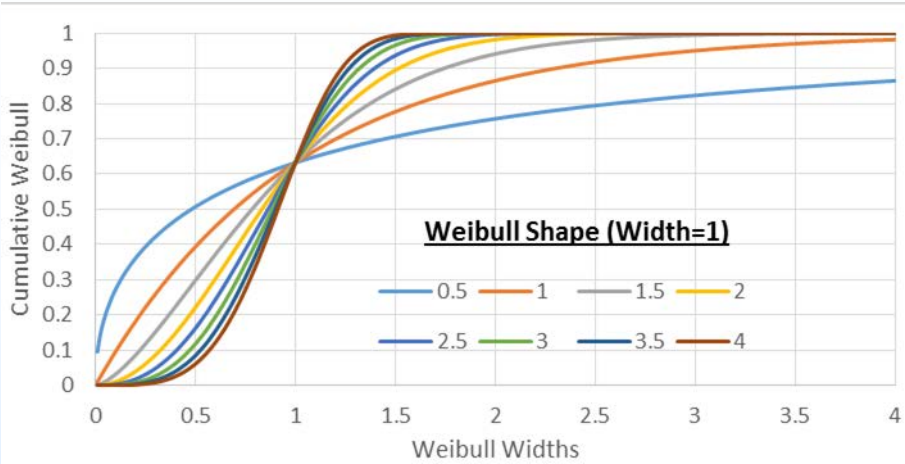
But, Not All Ions Are Created Equal

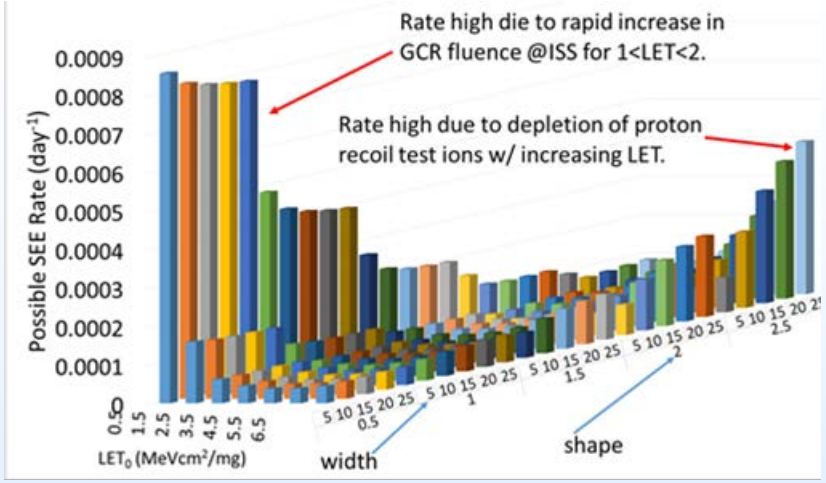




- **Low-LET ions must hit much smaller cross section to cause SEE**
- **Ion fluence drops with LET in almost any environment**
  - **Broader σ vs. LET (larger Weibull Width, W)→lower rate**
  - **Larger shape parameter s → lower rate**
- **Proton recoil fluences**
  - **Very few proton recoil ions w/ 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





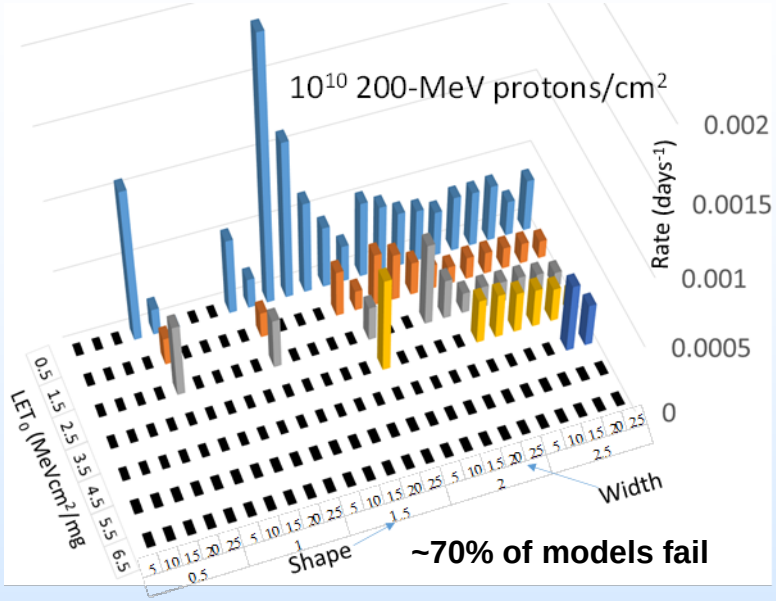
- **Constraints from proton testing too weak to determine σ vs. LET, but event count can tell us which models are inconsistent with the proton data**
- **Assume device SV made up of N_{SV} representative 1-micron cube SVs**
  - **LET varies little across this sensitive volume, so LET_{EQ} ~effective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

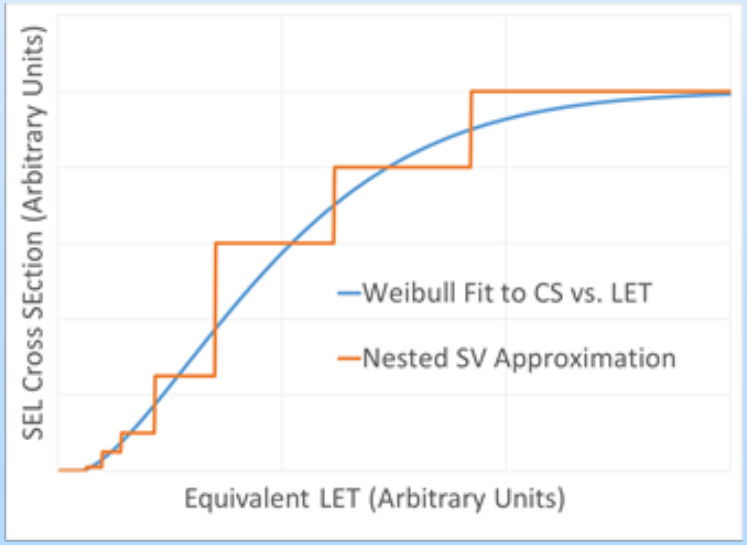
$$N_E = \int_{LET_0}^{LET_{Max}} N_{SV} \times F(LET_{EQ}) \times \sigma(LET_{EQ}, LET_0, w, s)\, dLET_{EQ}$$

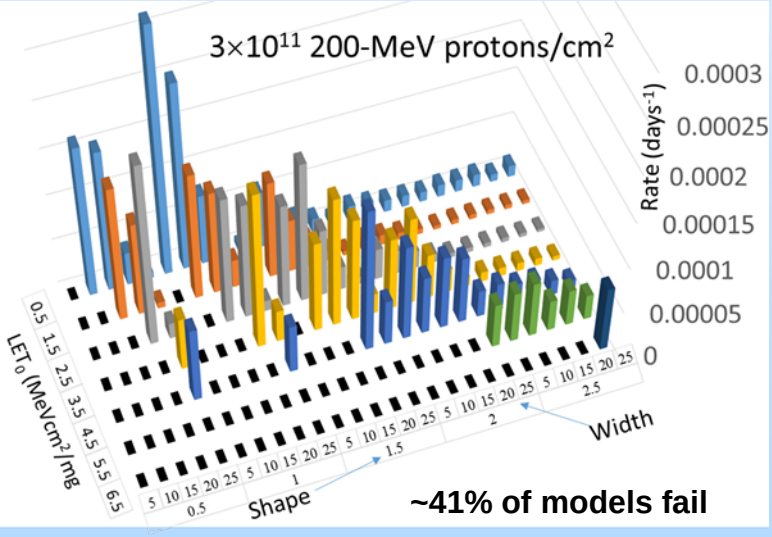
  - **Estimate # errors expected for a single 1-micron-cube SV for 175 representative models**
    - **W={5, 10, 15, 20, 25}, s={0.5, 1, 1.5, 2, 2.5}, LET0= {0.5, 1.5, 2.5, 3.5, 4.5, 5.5, 6.5 MeVcm2/mg)}**
  - **Solve for N_{SV} using upper bound on Poisson Mean for N_E (e.g. 2.31 for 90% CL if 0 events 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

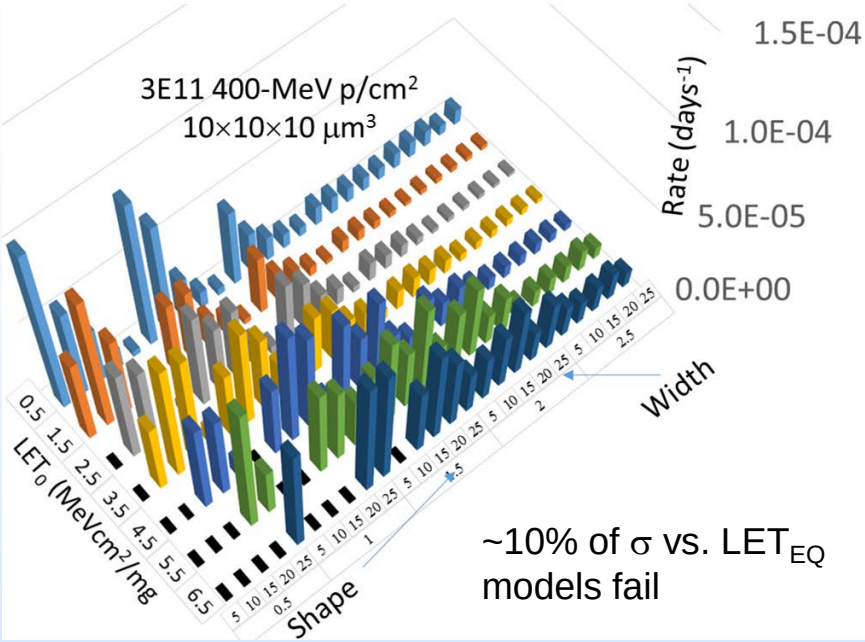
- **Chord-length pdf changes as σ rises**
  - Use Nested SV to approximate σ vs. LET model
  - Use Fluence(LET_{EQ}) for SV depth
  - Estimate N_E and solve for N_{SV}
- **For 10-μm cube SV**
  - If device σ bound >10^{-2} cm^2, method fails
  - For 10^{10} 200-MeV p/cm^2 122 failures/175 models
  - 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



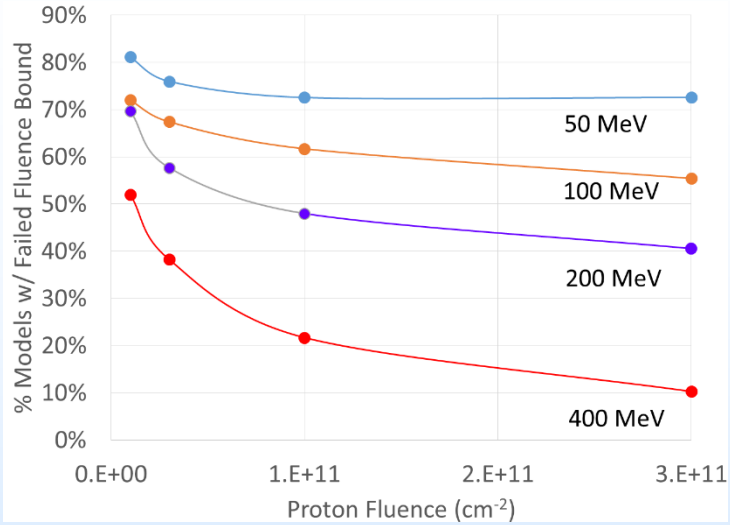
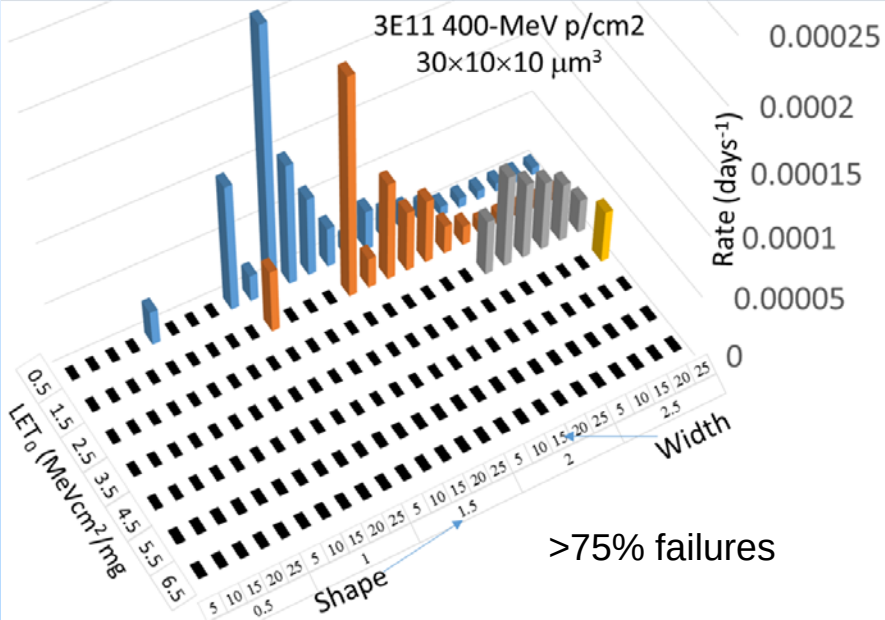
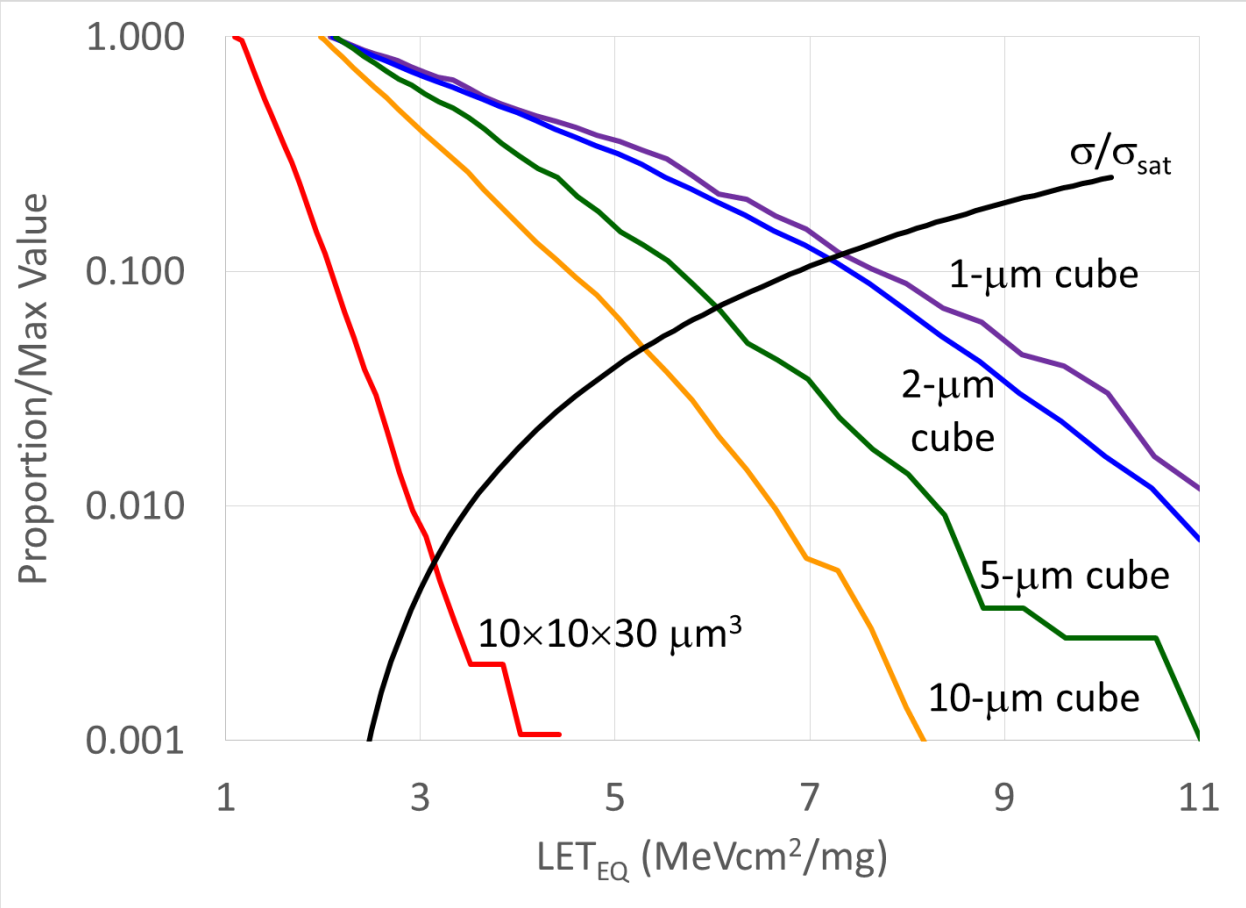


Table I: Parameters w/ >50% Successful Bound

Parameter Fluence (cm^{-2})	LET_0 (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

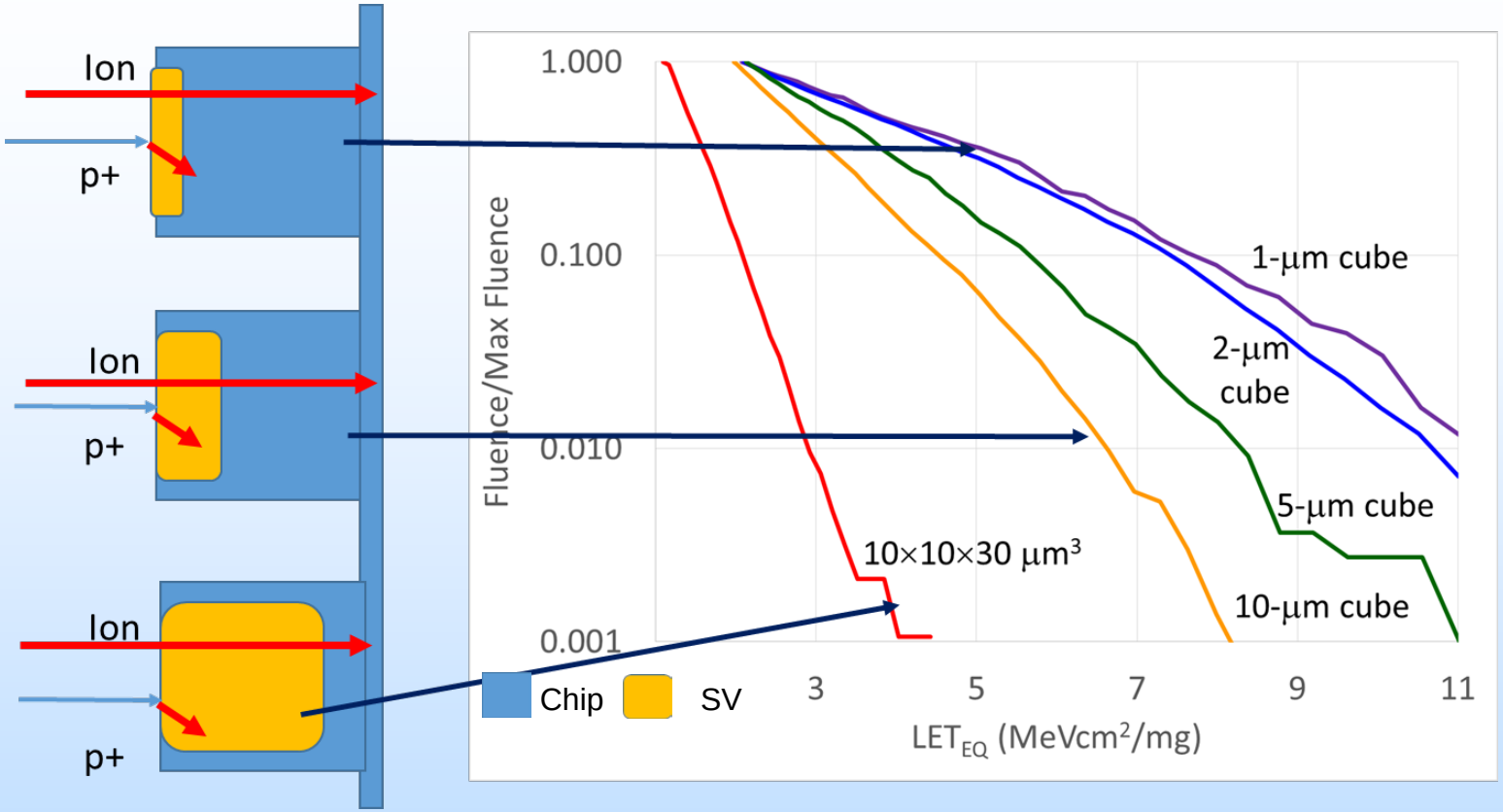


Why Bounding Fails



- **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$\leq$25, shape$\leq$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 $\leq$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 $\leq$ 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**