What Can We Learn From Proton Recoils about Heavy-Ion SEE Sensitivity?

Ray Ladbury

NASA Goddard Space Flight Center

Radiation Effects and Analysis Group

To be presented by Raymond L. Ladbury at the JEDEC JC-13 Meeting, Jacksonville, FL, January 11-14, 2016.

Abbreviations

CMOS—Complementary Metal Oxide Semiconductor

COTS—Commercial Off The Shelf

DUT—Device Under Test

E—Energy

E_{dep}—Energy Deposited

FPGA—Field Programmable Gate Array

GCR—Galactic Cosmic Rays

GEDI—Global Ecosystem Dynamics Investigation (a Lidar instrument set to fly on the ISS)

ISS—International Space Station

LEO—Low-Earth Orbit

LET—Linear Energy Transfer

LET_{EQ}—Equivalent Linear Energy Transfer

LET_0—Onset LET

MOSFET—Metal-Oxide Semiconductor Field Effect Transistor

SEB—Single-Event Burnout

SEE—Single-Event Effects

SEGR—Single-Event Gate Rupture

SEL—Single-Event Latchup

SEU—Single Event Upset

Si—silicon

SOTA—State-Of-The-Art

SV—Sensitive Volume

TID—Total Ionizing Dose

TNS—Transactions on Nuclear Science

WC—Worst Case

Z—Atomic number of an element

$\forall$—”For all”

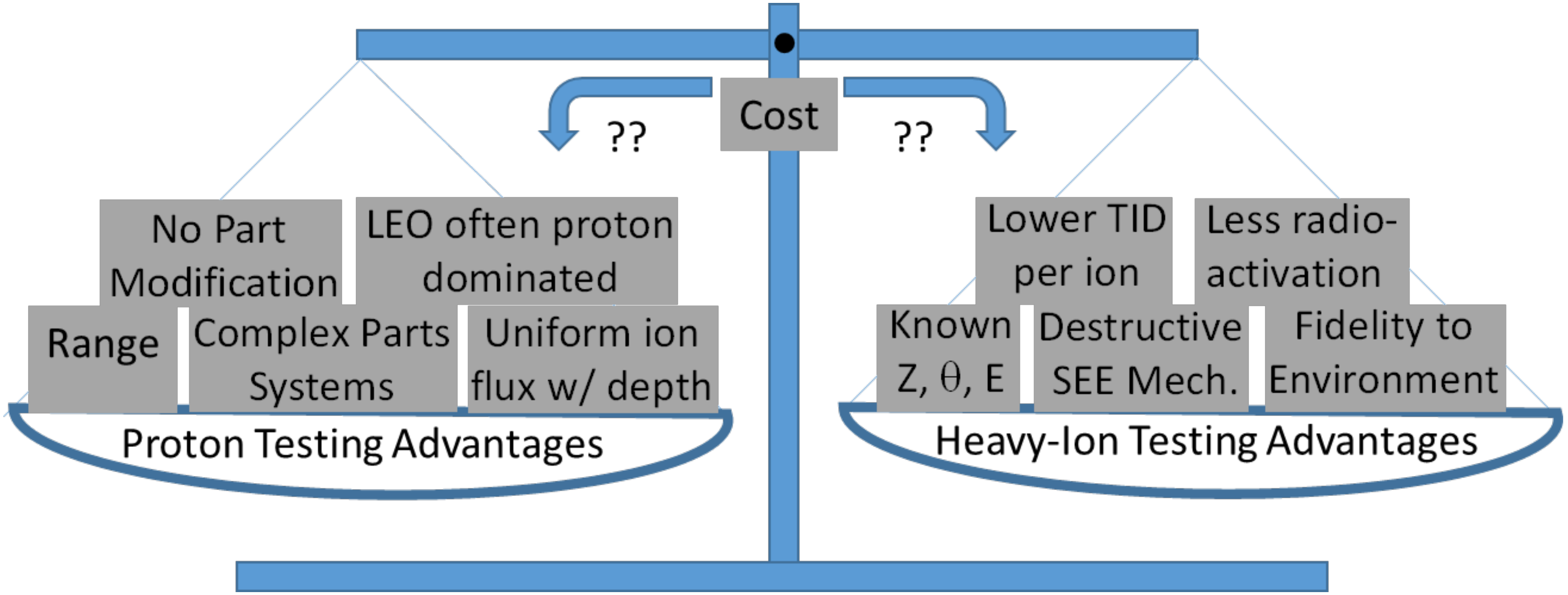
α particle—two protons and two neutrons bound together into a particle identical to a helium nucleus

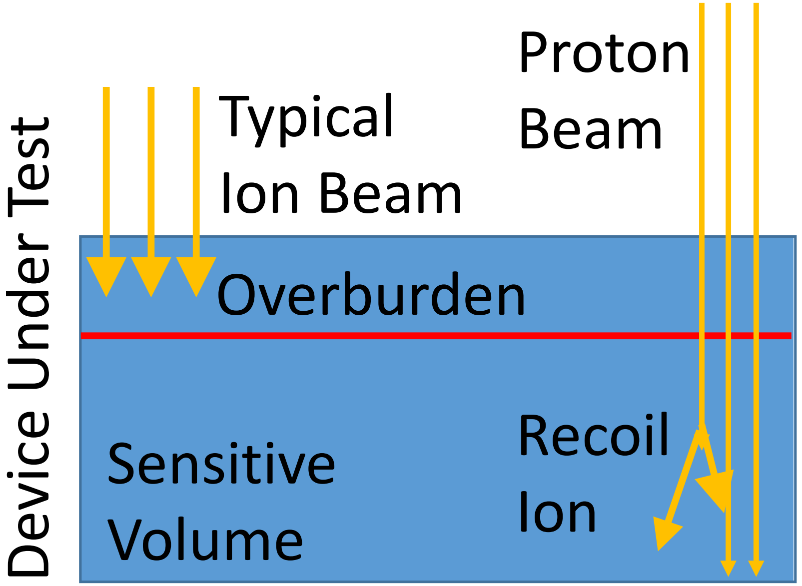
σ—Cross Section

σ_{sat}—Saturated Cross Section

θ—Angle

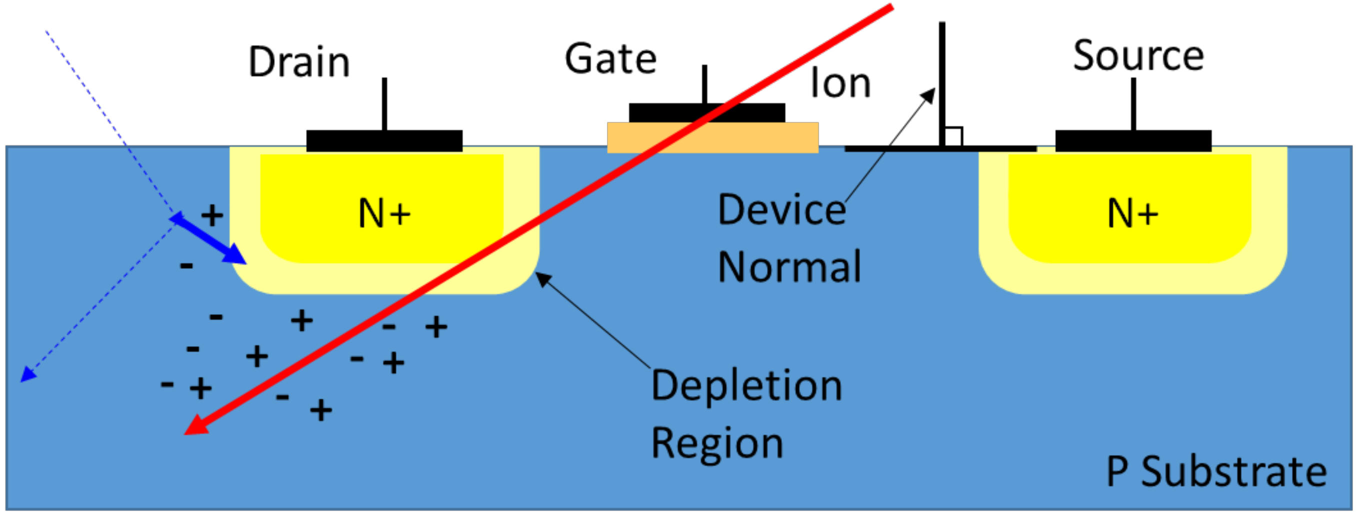
SEE Testing: Protons or Heavy Ions?

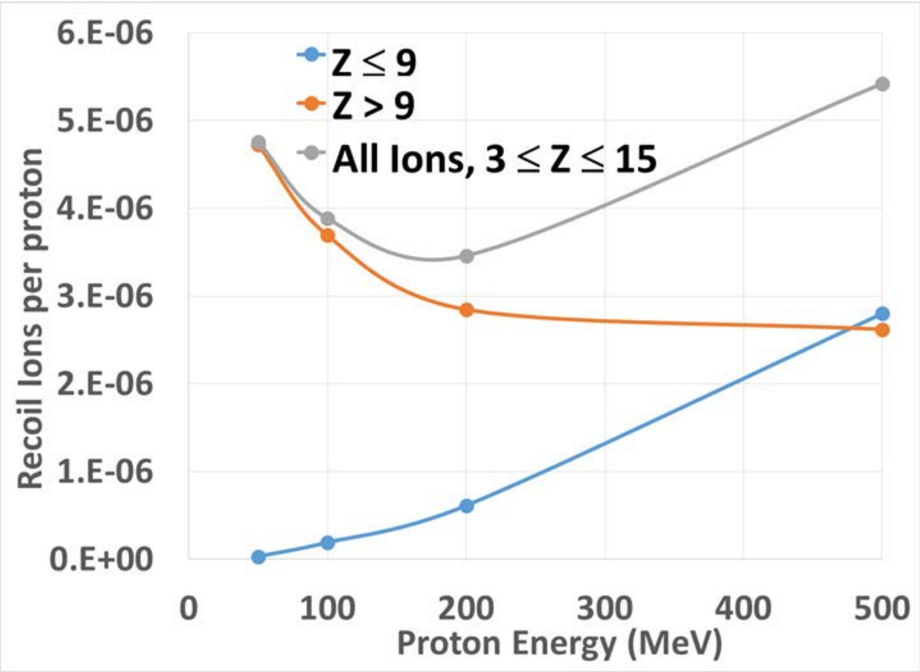




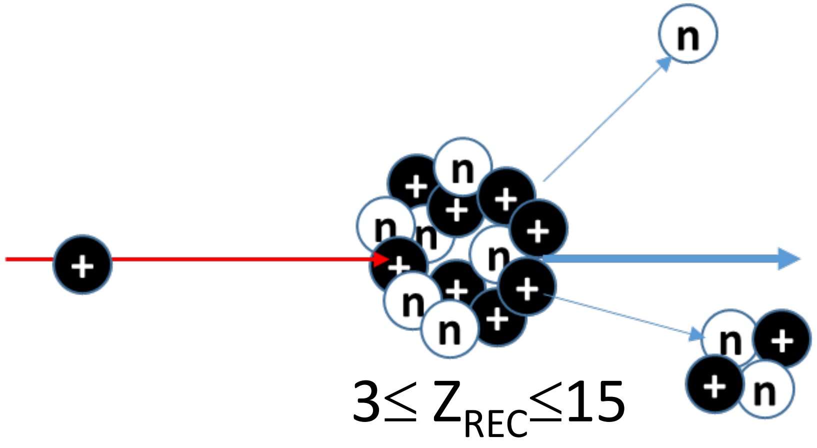
- Heavy-ion SEE testing poses well known difficulties:
  - Expensive in terms of cost and schedule
  - Often requires extensive modification of part to ensure beam reaches device sensitive volumes
  - Mainly geared to testing components rather than systems
- Protons potentially offer relief from many of these issues

Physics of Proton-Si Recoils

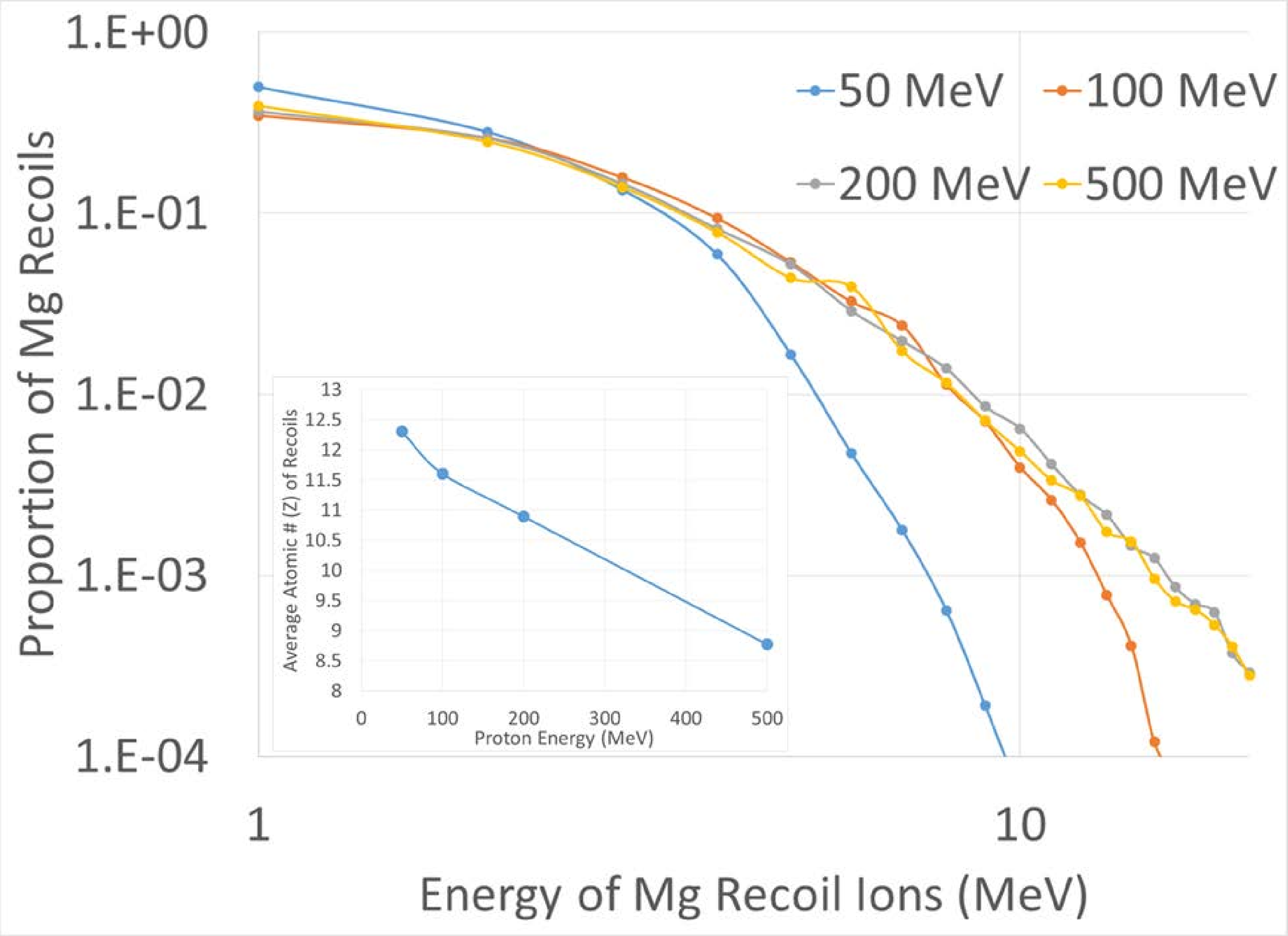




- Protons cause SEE via indirect ionization
  - Recoil ion from p-Si collision provides ionization for SEE
  - Proton accelerates and excites the ion, which then de-excites, emitting nuclear fragments n, p and α)$\rightarrow 3 \leq Z_{REC} \leq 15$
  - Recoil ions have low energy/short range, $3 \leq Z_{REC} \leq 15$ and are emitted over a range of angles
  - Evaporation particles (α particles) may be important for very sensitive devices

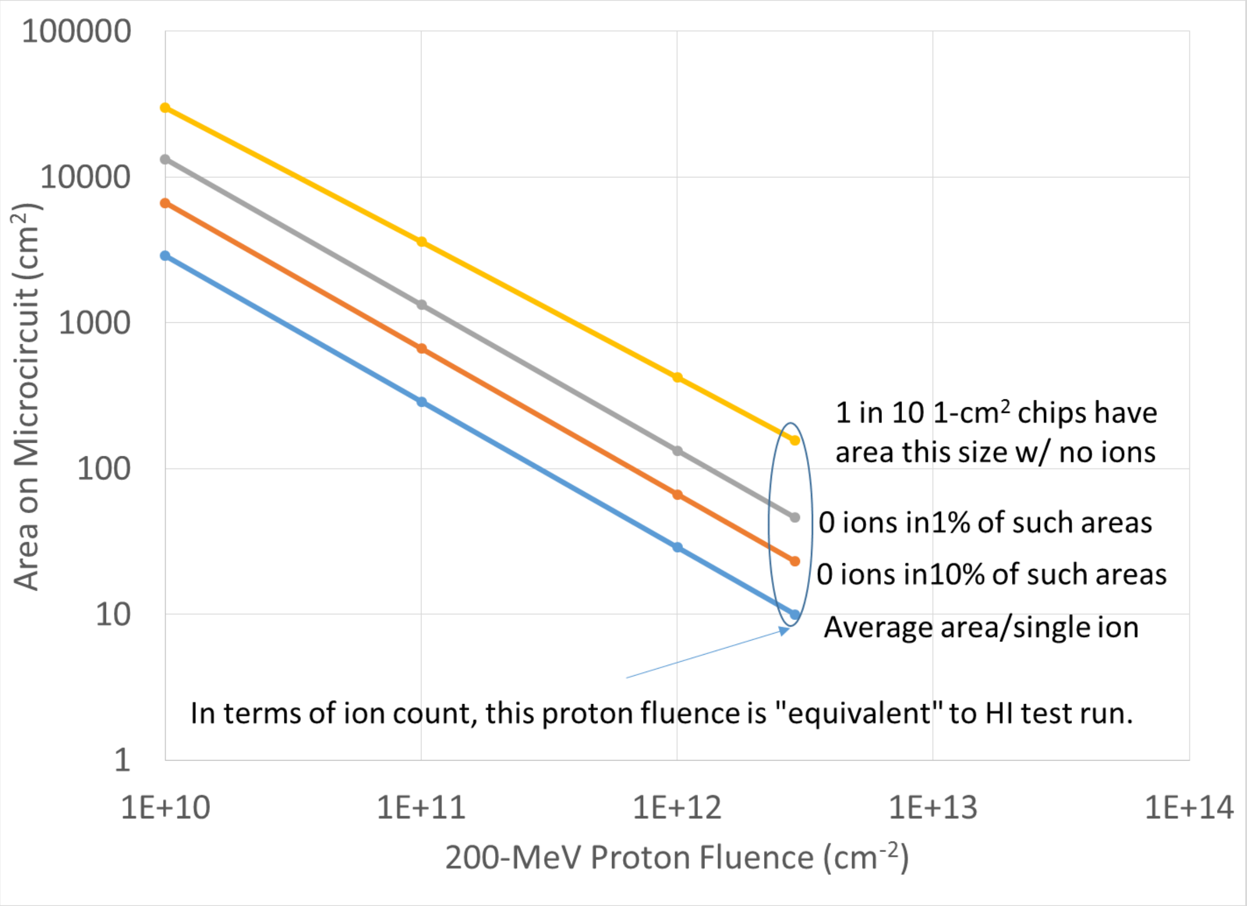


Why 200 MeV protons?



Proton Fluence: How Much is Enough?

- SEE test goal
  - Realize representative sample of error modes that might realistically occur
  - SEE are Poisson; so they can occur any time, even if they are low probability
- JESD-57 goal of establishing "…with high statistical confidence that all sensitive volume on the DUT have been irradiated…" likely not feasible for current parts
  - Finite fluence + small feature sizes mean some features will be missed
  - How repetitive is device architecture?
  - Complicated devices (e.g., FPGAs, Processors, etc.) need higher fluence than simple ones (e.g., simple memory, logic…)



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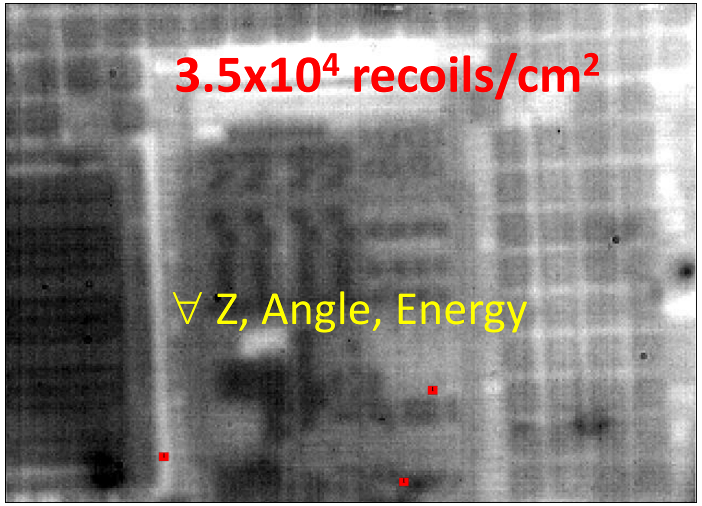
What Proton Fluence is Enough?

Infrared micrograph of a portion of a 512 Mb SDRAM ~60×70 μm²

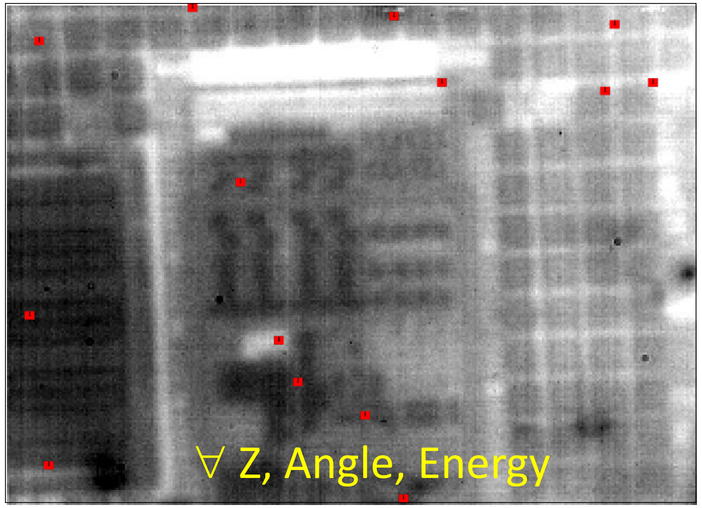
- Shows both memory cells and control logic (10 yr. old tech.) Red spots are ion hits

10^{10} 200 MeV protons/cm²

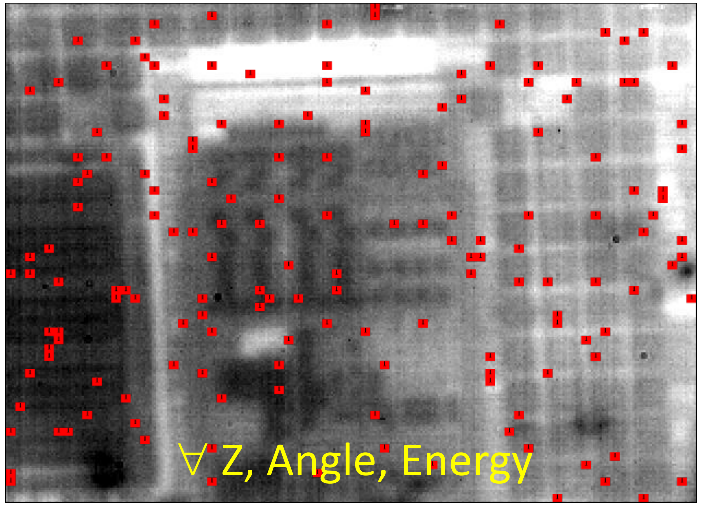


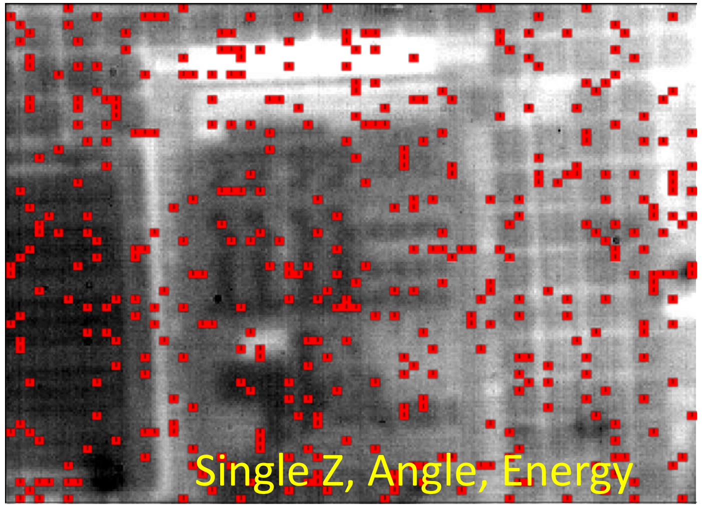
20% of areas this size get 0 hits for 10^{10} cm^{-2}

10^{11} 200 MeV protons/cm²



10^{12} 200 MeV protons/cm²



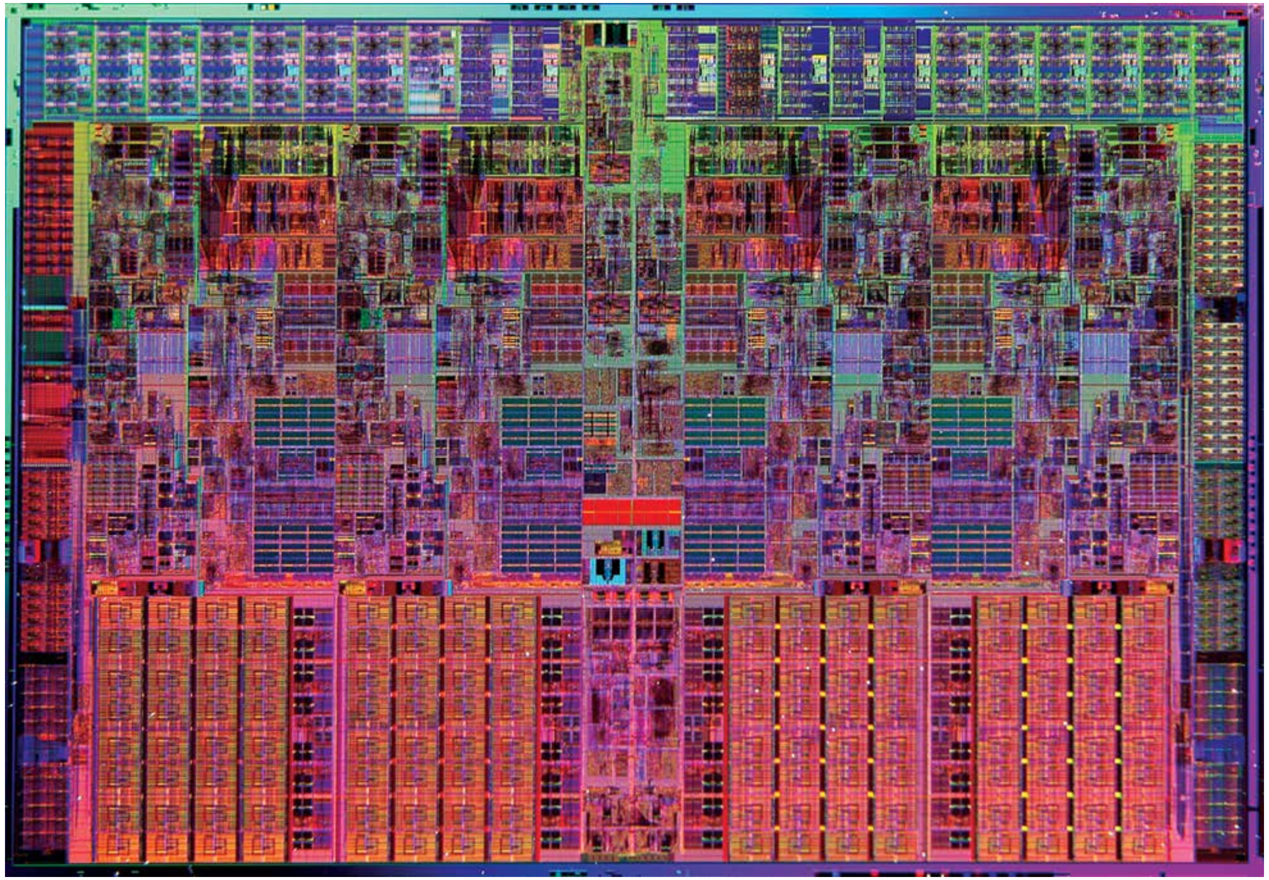


Coverage from 10^7 heavy ions/cm²

What About More Recent Technologies?

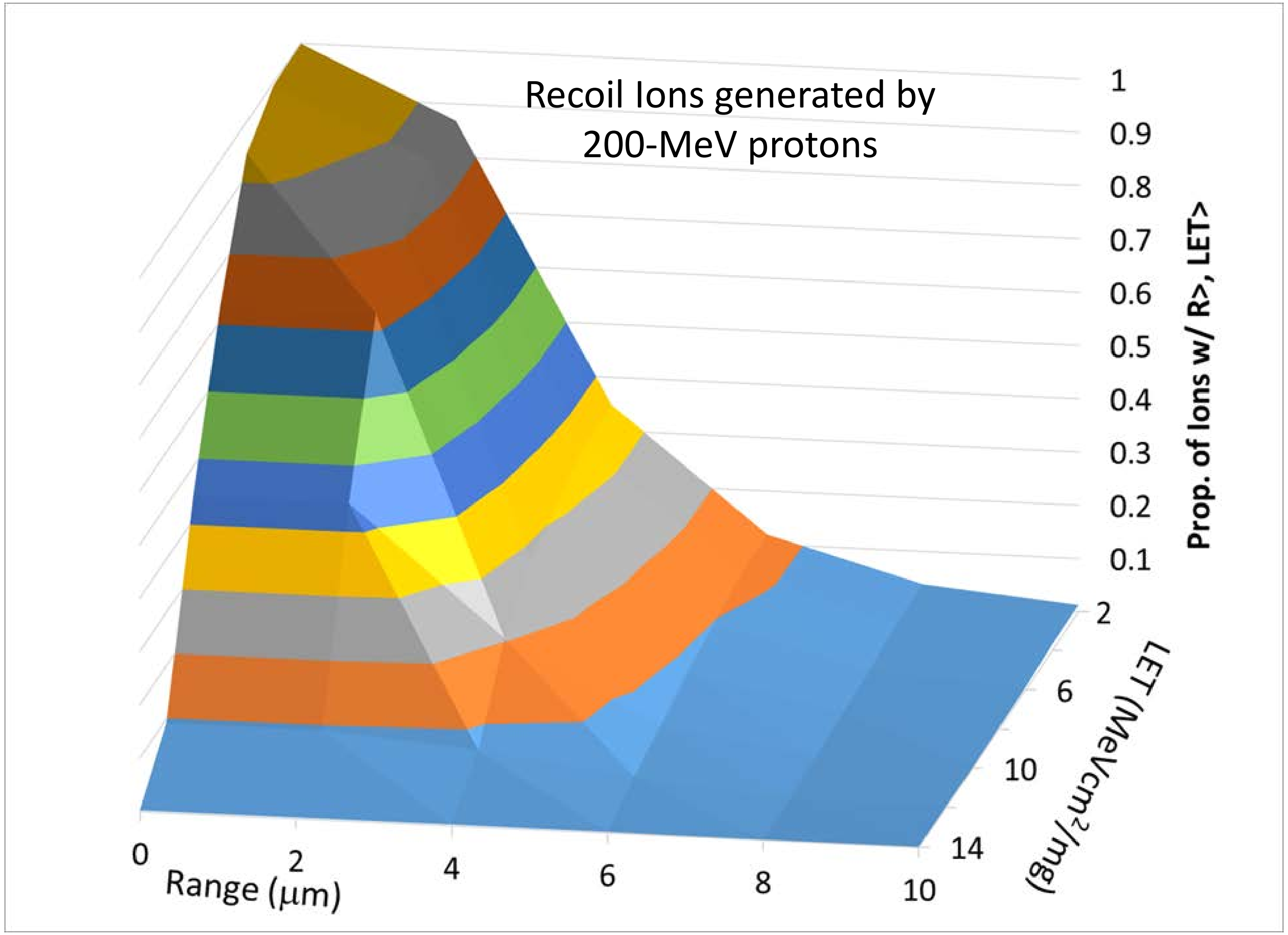
Intel I7 Processor (2008)

Process Size:	45 nm
Transistors:	731 million
Die Size:	263 mm²

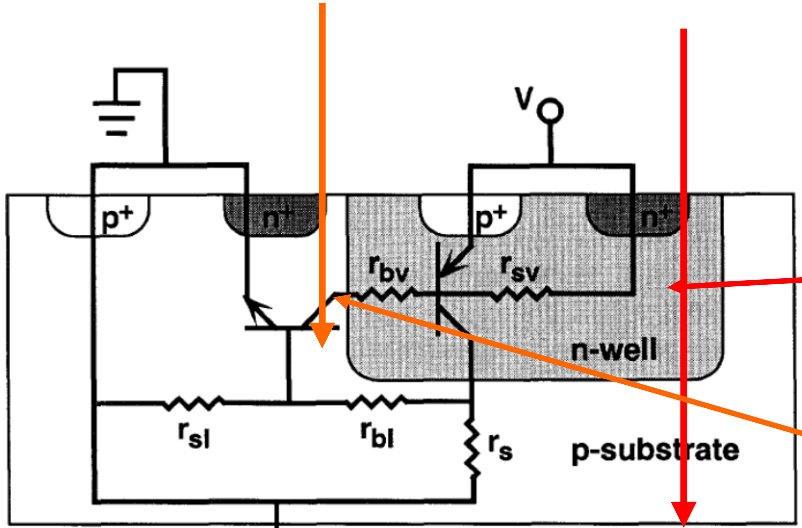


- For 10^{10} 200-MeV protons/cm^2
  - Average area per ion (~2890 μm^2) contains about 7800 transistors
  - For comparison, an Intel 8080 8-bit processor had ~6000 transistors.
  - 10% chance no ions strike an area >70000 μm^2) containing >90000 transistors (half way between an Intel 80186 and 80286 (16-bit))
- For 10^{12} 200-MeV protons/cm^2
  - Average area per ion contains 80 transistors
  - 10% chance of missing area w/ 1250 transistors
- Heavy-ion test run (10^7 ions/cm^2)
  - Transistor counts in 10 μm^2 are 28.9 and 460
- But!
  - Recoil Ions not all created equal
  - Produced w/ range of Z, energy, LET and angle

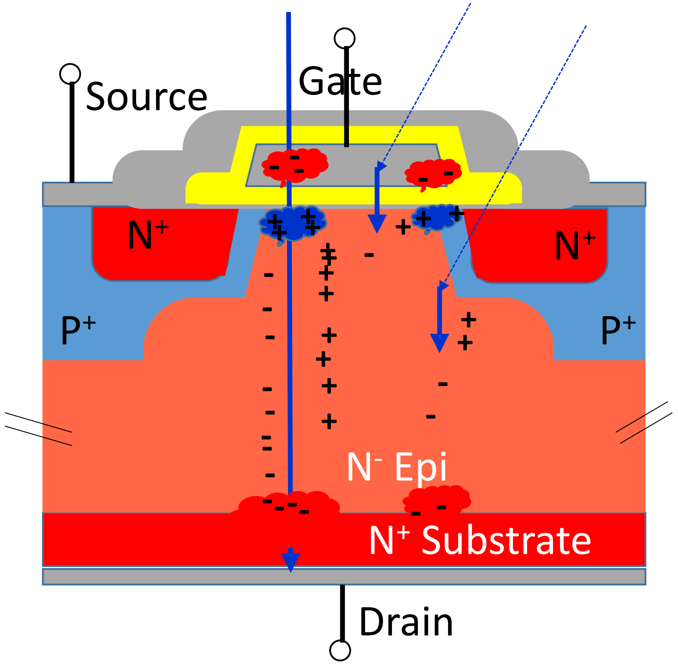
Recoil Ion Fluence Falls Rapidly If We Require Greater Range

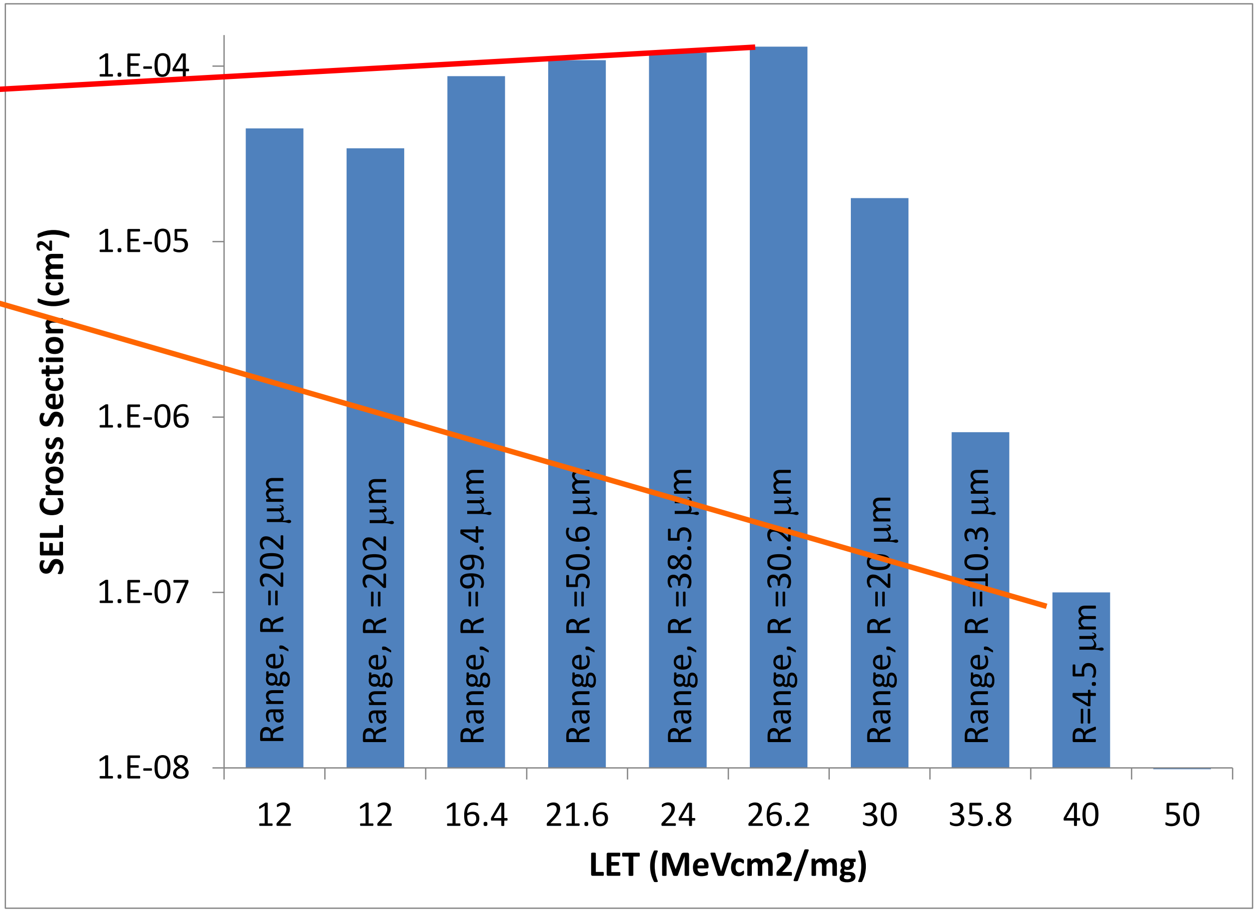


Destructive SEE and Ion Range



After A. Johnston, TNS (1996)





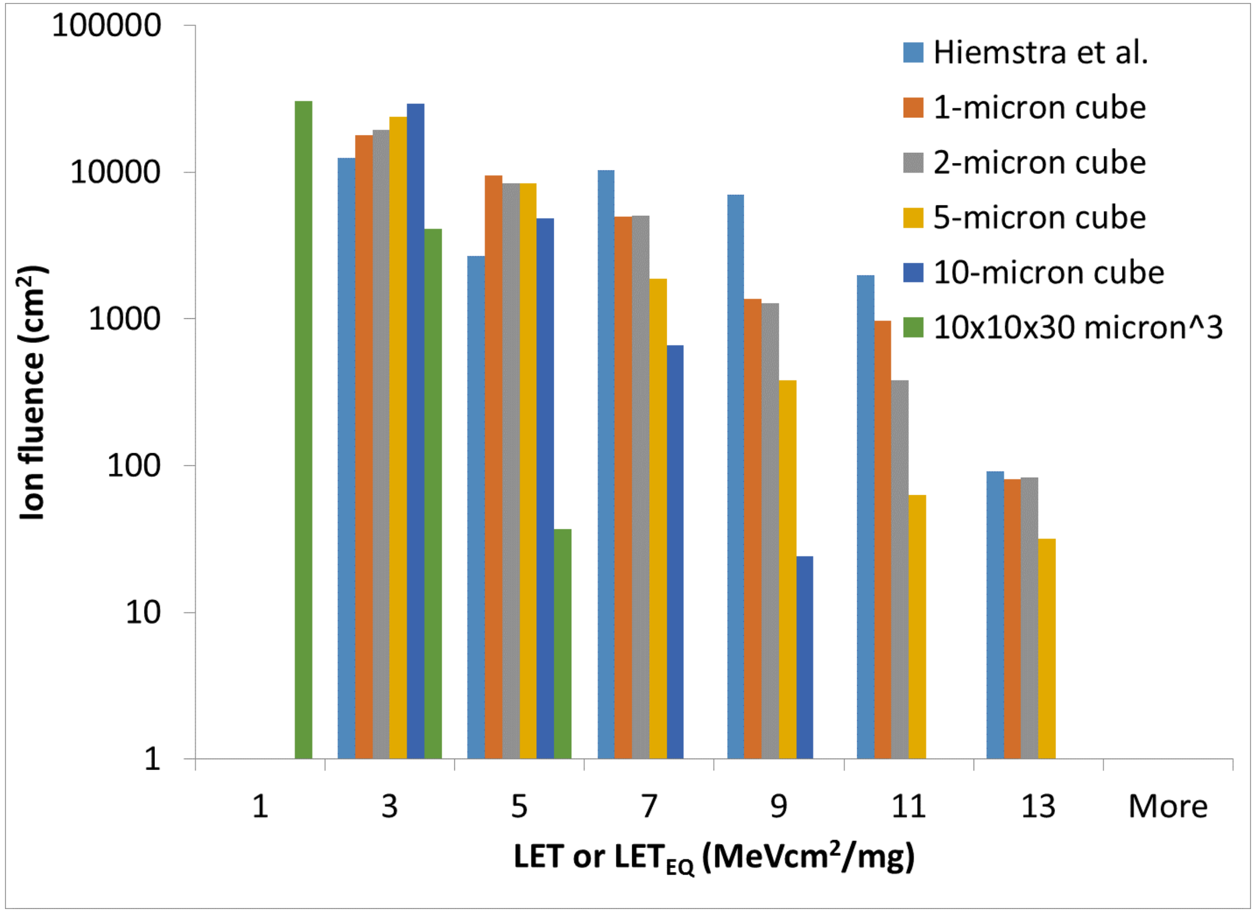
Data from C. Marshall et al., IEEE TNS Vol. 57, No. 6, pp. 3078-3086 (2010)

Dealing with Range Limitation

- LET dependence is an approximation
  - SEE susceptibility depends on charge collected in the sensitive volume
  - For recoil ions in deep SV, charge deposited limited by range, not LET
- Introduce equivalent LET, LET_{EQ}

$$LET_{EQ} = E_{dep} / (\rho \times z)$$

  - E_{dep} is energy deposited in SV by ion
  - ρ is density of Si, z is SV depth
  - LET_{EQ} is the ion's average LET if it reaches the bottom of the SV
  - LET_{EQ} is the constant LET an ion would need to deposit E_{dep} in SV assuming normal incidence



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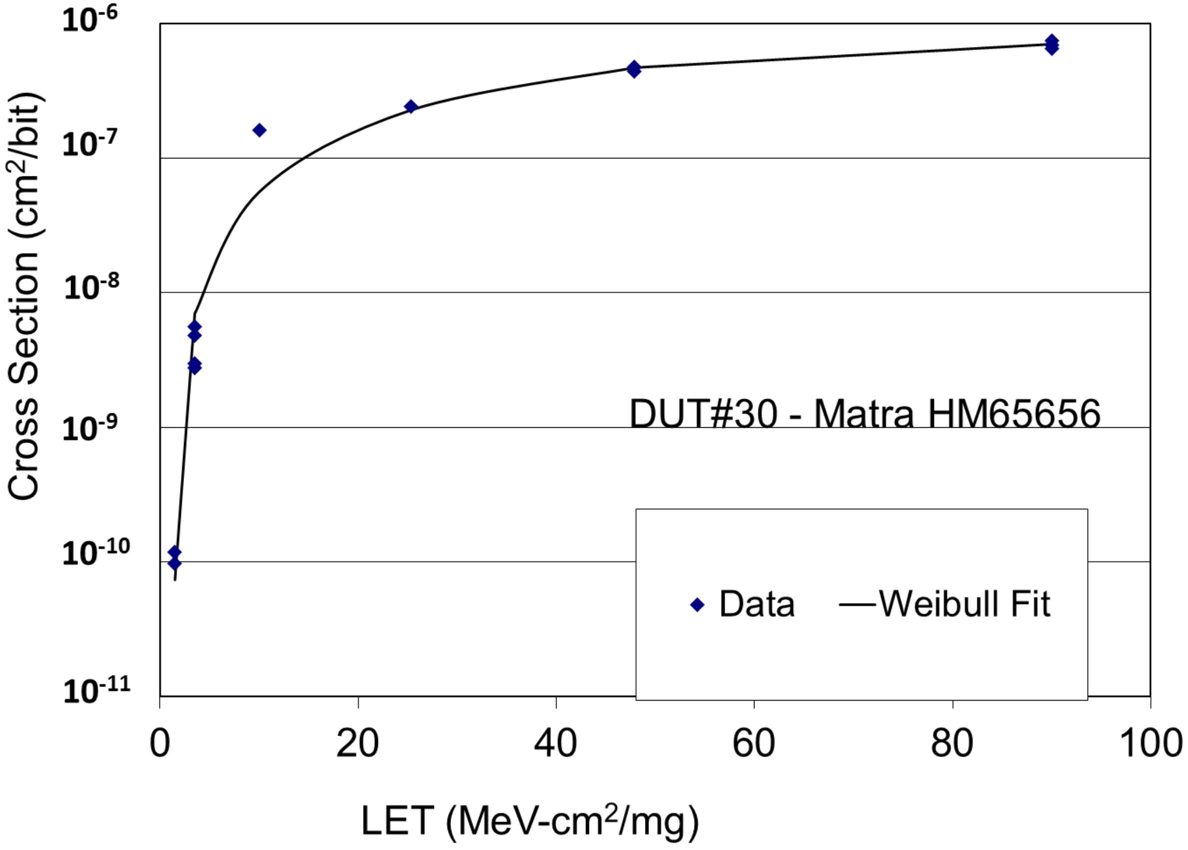
But: Not Every Ion Is Equally Likely to Cause an SEE

- Even for shallow SV, low-LET ions are less likely to cause an SEU
  - Can derate fluence at each LET/LET_{EQ} by Weibull factor

$$Weibull(LET_{EQ} - LET_0, W, s)$$

  - Results in an equivalent fluence
  - Can be used to find worst-case rate for a null result at a given confidence level.
- Matra 256 K SRAM has limiting cross section of 0.2 cm^2
- Predict ~131 upsets with 10^{10} 200-MeV protons
  - Limiting cross section measured by B. Doucin ('95 RADECS) ~2x10^{-8} cm^2/dev (within a factor of 2)



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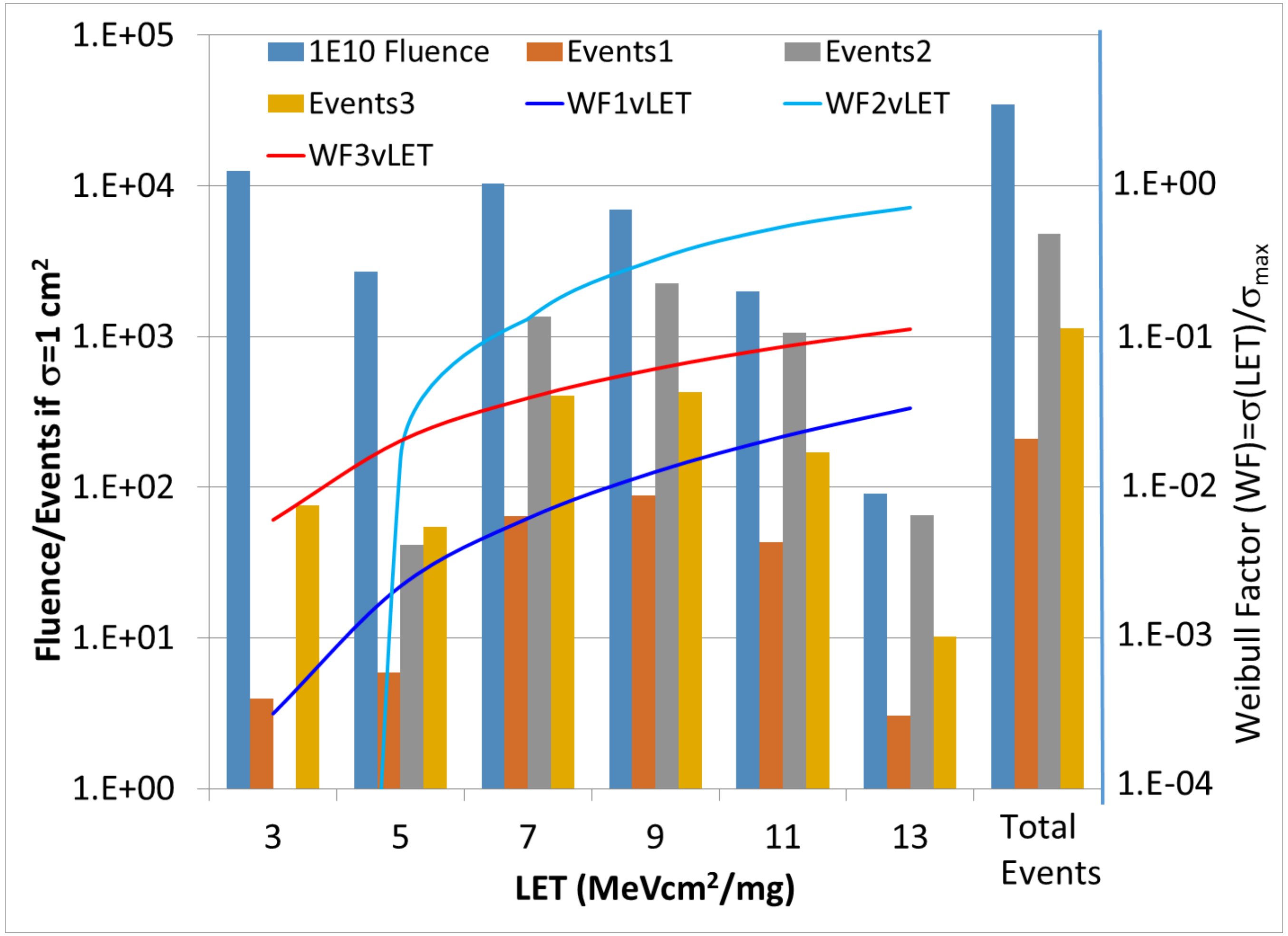
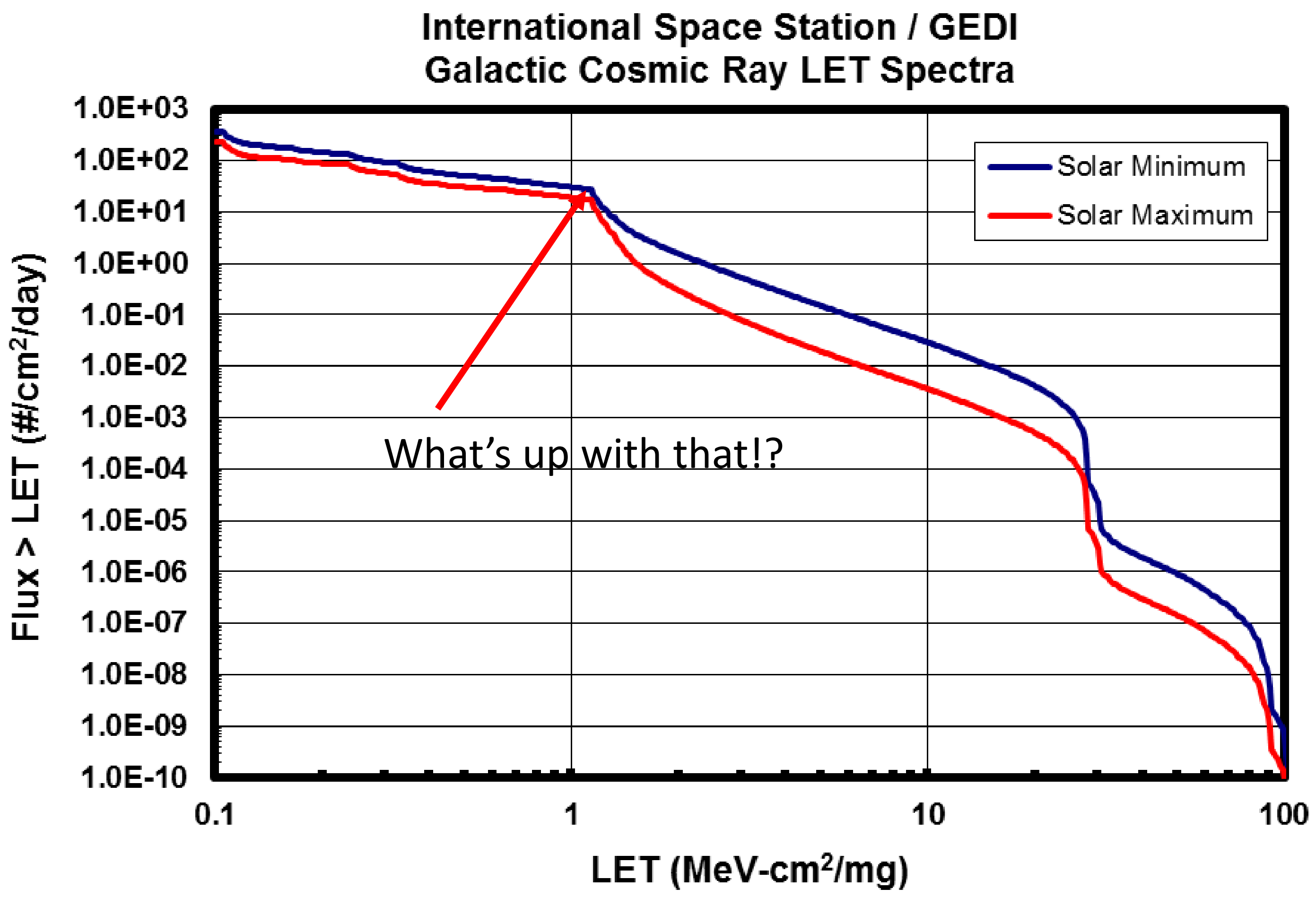
Effect of Cross Section vs. LET Shape

- Inferring proton susceptibility from heavy-ion data is straightforward
  - Use σ vs. LET and recoil ion spectrum to estimate expected events <N>
- Constrain rate w/ proton data
  - Recoil fluences + LET$_0$, s and W set relative contributions
  - Choose σ_{sat} so probability of seeing no events>10%$\rightarrow$ <N>=2.3
  - Highest rate bounds null result in proton test at the 90% confidence level

WC Rate	<N>@1cm2	Per bit cs	s	W	LET0
0.000856	32226.38947	1.19E-07	0.5	5	0.5
0.000159	18577.27893	1.28E-08	0.5	5	1.5
6.17E-05	12970.74197	3.47E-09	0.5	5	2.5
4.5E-05	8703.467731	1.7E-09	0.5	5	3.5
3.75E-05	6097.639989	9.91E-10	0.5	5	4.5
0.000818	24892.46517	8.82E-08	0.5	10	0.5
0.000153	14486.82459	9.57E-09	0.5	10	1.5
6.09E-05	10092.54183	2.66E-09	0.5	10	2.5
4.47E-05	6765.500655	1.31E-09	0.5	10	3.5
3.75E-05	4714.079379	7.64E-10	0.5	10	4.5



ISS SEE Rates Increase Rapidly as LET_0 Decreases from 2 to 0.5 ($MeV\text{-}cm^2/mg$)



What's up with that!?

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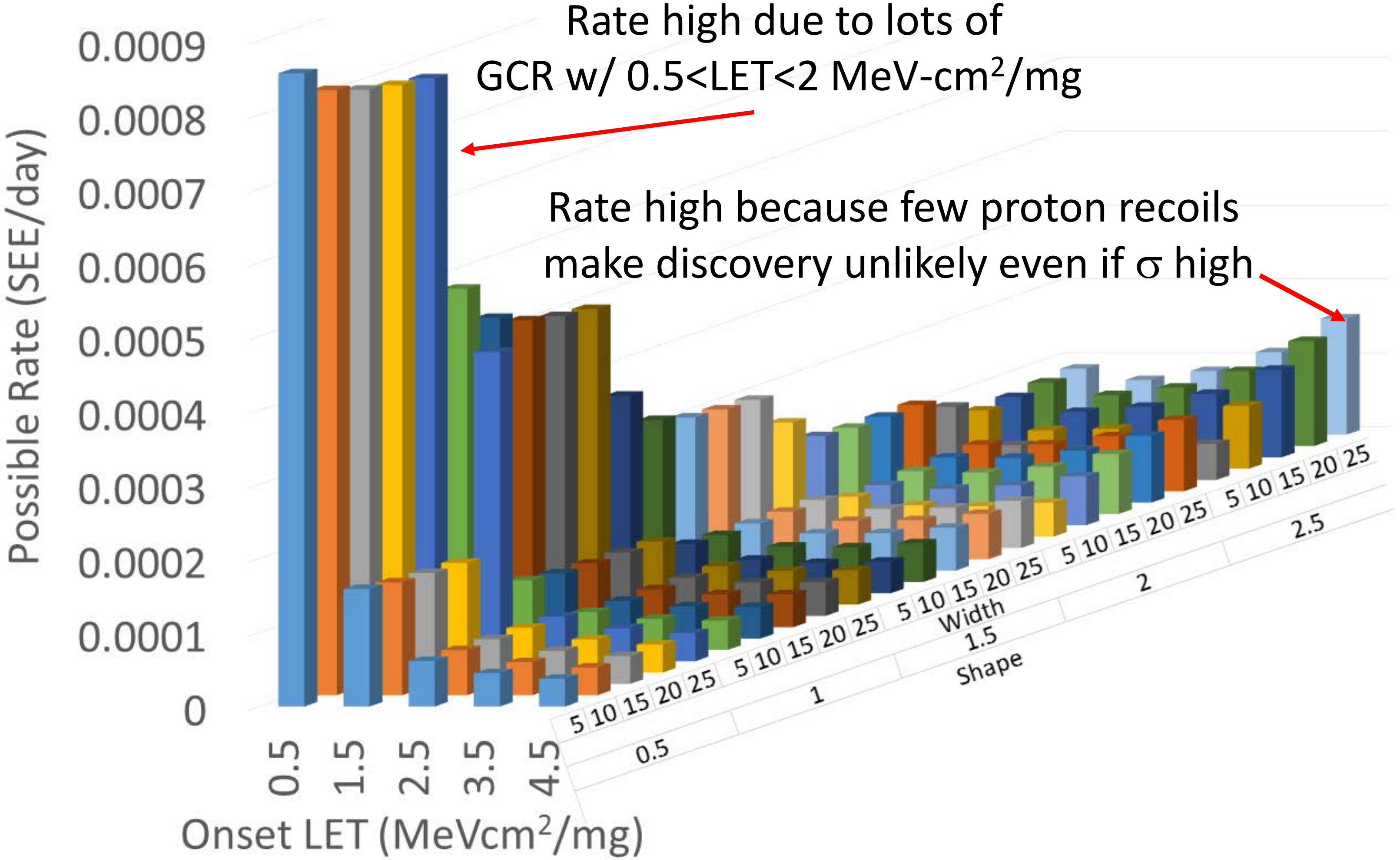
How High Can the SEE Rate Be if We Didn't See It in the Test?

- Recoil fluence vs. LET due to nuclear physics
  - $3<Z<15$—produce LET from 2-12 MeV-cm^2/mg
  - $Z=2$ due to evaporation process→mainly $0.5<LET<2$
  - Ions w/ $0.5<LET<2$ ~1.6x more than w/ $2<LET<12$
- For GCR @ ISS ~30x more ions w/ $0.5<LET<2$ than from $2<LET<12$
- More SOTA COTS have onset LET<2 MeV-cm^2/mg
  - Proton test method may be less effective for latest generation parts

Select σ so >10% chance of seeing 0 events w/ 10^{10} 200-MeV p/cm^2 test.



Rate high due to lots of GCR w/ $0.5<LET<2$ MeV-cm^2/mg

Rate high because few proton recoils make discovery unlikely even if σ high

How Do We Better Bound Heavy-Ion SEE w/ Proton Testing?

- First, don’t try to make protons do what they cannot do well
  - If SEGR/SEB are probable concerns, recommend a go/no-go heavy-ion test
    - WC voltages, single ion w/ predetermined LET, Z and range
  - For SEL in bulk CMOS where depth of SV likely >5-10 μm, recommend go/no-go heavy-ion test
    - Especially if many copies of same part used in design
    - WC temperature, bias, single-ion w/ predetermined LET, range.
  - May also be inappropriate for studying multi-bit upsets and upsets in technologies with deep SV (e.g. SiGe)
- Increase proton fluence
  - Ensures errors/failures observed during test more likely to resemble those seen on orbit
  - Reduces bounds on rates for “unknown SEE modes”
    - True for both high LET_0 and low LET_0
  - If dose is too high, can test multiple copies of device/board/box
    - High-energy neutron testing may also be an option
- Proton SEE data must be analyzed conservatively
  - Using LET_{EQ} of recoils reduces chances of underestimating SEE sensitivity
    - LET_{EQ} better reflects physics of SEE modes and reduces to LET if SV for SEE mode is thin
  - Understanding device technologies can improve bounds on SEE rates achievable by proton testing