



# Proton Testing: Opportunities, Pitfalls and Puzzles

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# Key to Abbreviations and Symbols

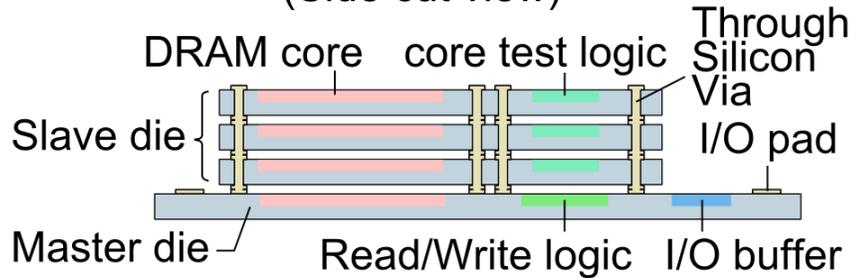
$\forall$	Logical symbol meaning "For all"	LET	Linear energy transfer
$\delta$	Delta	p	Proton
$\rho$	Density	Q	Charge
$\sigma$	Cross section	SDRAM	Synchronous DRAM
3DS	Three-dimensional stacked	SEB	Single-event burnout
C	Capacitance	SEE	Single-event effect
DRAM	Dynamic random-access memory	SEGR	Single-event gate rupture
DSEE	Destructive single-event effect	SEL	Single-event latchup
E	Energy	SV	Sensitive volume
GCR	Galactic cosmic ray	VDS	Drain-source voltage
GPU	Graphics processing unit	WC	Worst case
IC	Integrated circuit	xstr	Transistor
I/O	Input/output	Z	Ion atomic number

# Can Protons Bound Heavy-Ion SEE Risk and Why Would We Want Them To?



## 3DS die stacking concept model

(Side cut view)

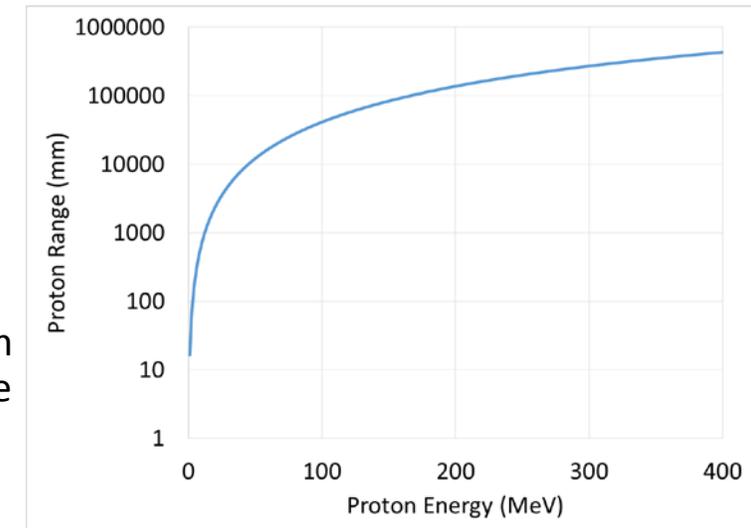
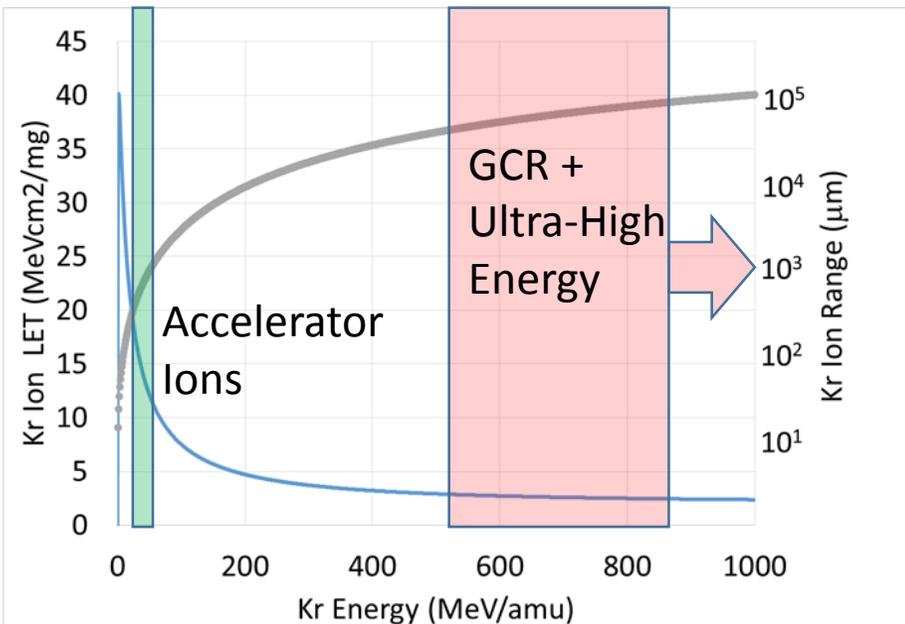


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- State-of-the-art ICs and packages often highly integrated
- Significant overburden blocks ions from device SV
- Extensive and risky modification often needed to ensure charge generated in SV



- Accelerator ion ranges 10s-100s of  $\mu\text{m}$  of Al
- GCR ions penetrate 10s of cm Al
- High-energy protons attractive
  - Penetrate >10 cm of overburden
  - Generate light ions in SV
  - Fluxes persist over most of proton range-so box-level testing feasible



To be presented by Raymond L. Ladbury at the Single Event Effects (SEE) Symposium - Military and Aerospace Programmable Logic Devices (MAPLD) Workshop, La Jolla, CA, May 22-25, 2017.

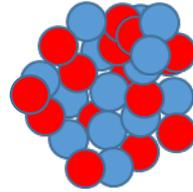


# Outline

- Generation of Recoil and Cascade Ions by Protons
- Recoil, Accelerator and GCR Heavy-Ion Environments
  - Ion Energies and Destructive SEE
  - Test Coverage
  - When are These Differences Important?
- Timely Issues
  - What About Proton-Induced Fission
  - Does Scaling Help or Hurt?
- Conclusions: Challenges, Caveats and Recommendations



# Recoil Ion Characteristics for 200-MeV Protons



## Ion Species

- $\ll 1\%$  have  $Z < 6$
- $< 18\%$  have  $5 < Z < 10$
- $\sim 78\%$  have  $10 \leq Z \leq 13$ 
  - $\sim 63\%$  Na, Mg and Al
- 4.5% Si,  $< 0.05\%$  P
- Most common ion is Mg ( $\sim 30\%$ )
- **Only one proton out of 289100 produces a recoil ion**
- Evaporation
  - Including He  $\sim$ doubles total ion count (LET up to  $1.5 \text{ MeVcm}^2/\text{mg}$  and range  $\sim 10 \mu\text{m}$ )

## Energies and Ranges

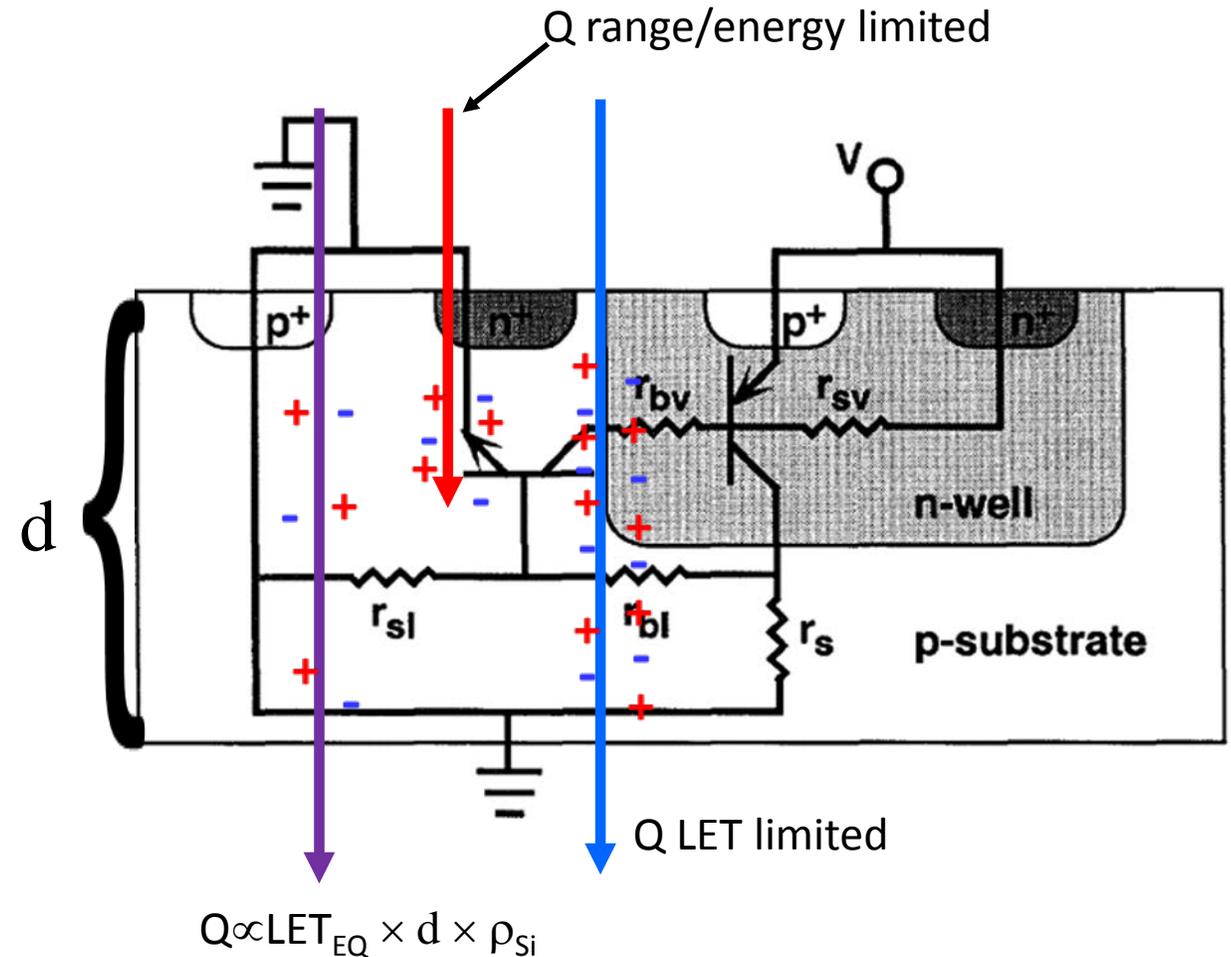
- $Z < 6$ —energies largely above Bragg Peak, but fluxes negligible
- $5 < Z < 10$ — $> 80\%$  have energy  $>$  Bragg Peak
  - Flux down 10x for  $E > 11 \text{ MeV}$
- $10 \leq Z \leq 13$ — $< 1\%$  have energy  $>$  Bragg Peak
  - Flux down  $> 10\text{x}$  for  $E > 6 \text{ MeV}$
  - Ranges  $< 4 \mu\text{m}$  for  $> 90\%$  in this range
- Si and P fluxes negligible for practical purposes

## Other Characteristics

- Angular distribution fairly flat out to  $90^\circ$  to incoming proton
- Standard wisdom: p generate LETs up to  $\sim 15 \text{ MeVcm}^2/\text{mg}$  in Si, but
  - Almost no P ions generated
  - For Si, max LET is  $14.5 \text{ MeVcm}^2/\text{mg}$ , but  $< 5\%$  of recoil ions are Si, and they are all below Bragg Peak
  - For Ne-Al, energy below Bragg Peak
  - For hardness assurance purposes, risky to assume  $\text{LET} > 10\text{-}12 \text{ MeVcm}^2/\text{mg}$  even for shallow SV
- For ion that causes SEE, Z, energy, angle are all unknown

# Proton Challenge I: Recoil Ranges and DSEE

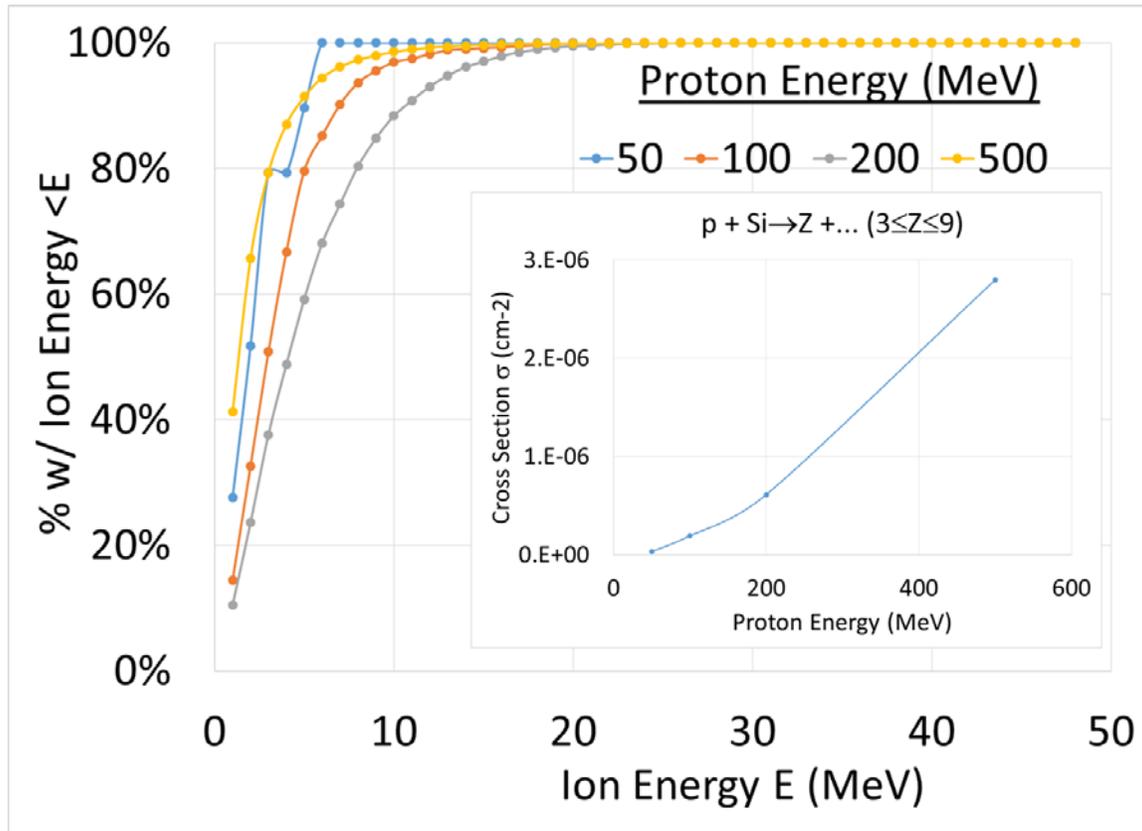
- SEE susceptibility increases not with LET, but with charge,  $Q = C \times \rho \times \int_0^d LET(x) dx$ 
  - Q generated by proton recoil ions may be limited by their energy/range rather than LET, especially for SEE with deep SV
- For DSEE, SV depths often  $\gg$  range of recoil ions
  - For SEL, charge collected well into substrate,  $\sim 10$ s of  $\mu m$
  - For SEB, cross section diminished if ion range  $< \sim 30 \mu m$
  - For SEGR, charge collected down to bottom of epi layer, 10-100  $\mu m$  depending on rated VDS
- Define  $LET_{EQ}$  in terms of energy deposited in SV  $E_{Dep}$ , SV depth  $d$  and Si density  $\rho_{Si}$ .
  - $LET_{EQ} = \frac{E_{Dep}}{(\rho_{Si} \times d)}$
  - $LET_{EQ}$  facilitates translating proton results to mission performance
  - If SV depth unknown, assume representative WC for the SEE mode of interest



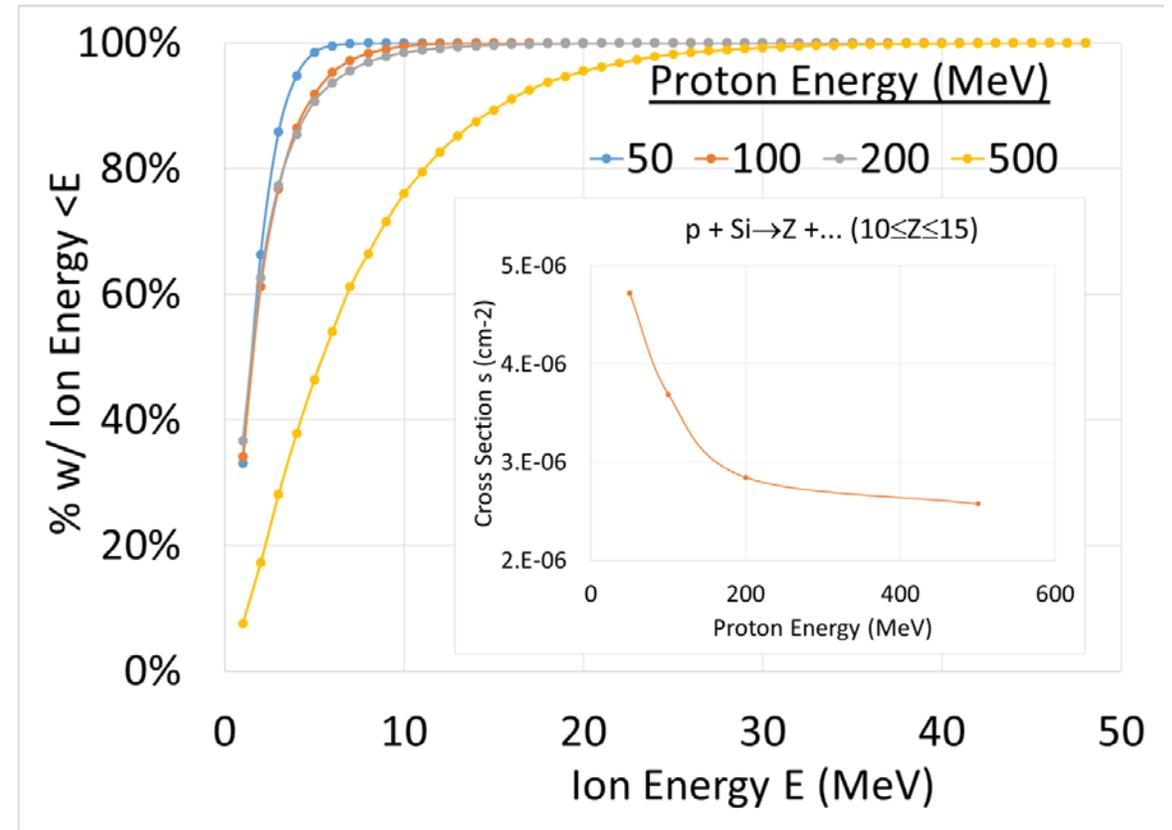


# Role of Proton Energy

For Recoil Ions w/  $3 \leq Z \leq 9$



For Recoil Ions w/  $10 \leq Z \leq 15$



- For high proton energies (>200 MeV), increase in inelastic  $\sigma$  results in large increase in ions w/  $Z < 10$ , but with lower average energy

- For high proton energies (>200 MeV),  $\sigma$  for  $Z \geq 10$  drops slightly but ion energy increases; however, detection probability improved only if SV depth  $< \sim 10 \mu\text{m}$ .

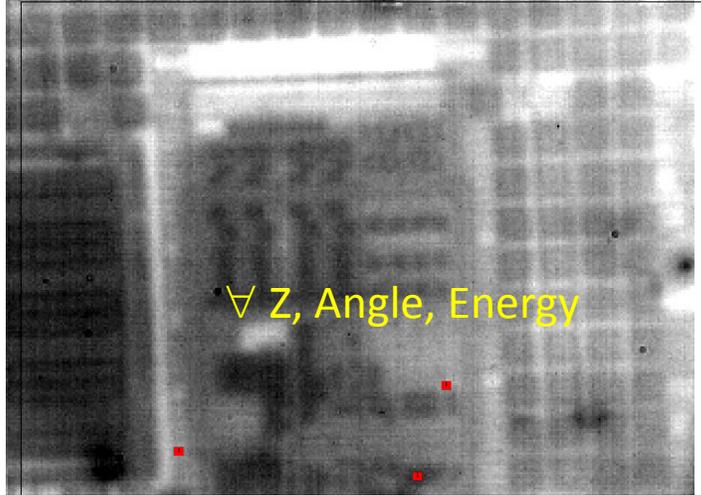
# Relative Coverage of Proton and Heavy-Ion SEE Tests

Infrared micrograph of a portion of a 512 Mb SDRAM  $\sim 60 \times 70 \mu\text{m}^2$

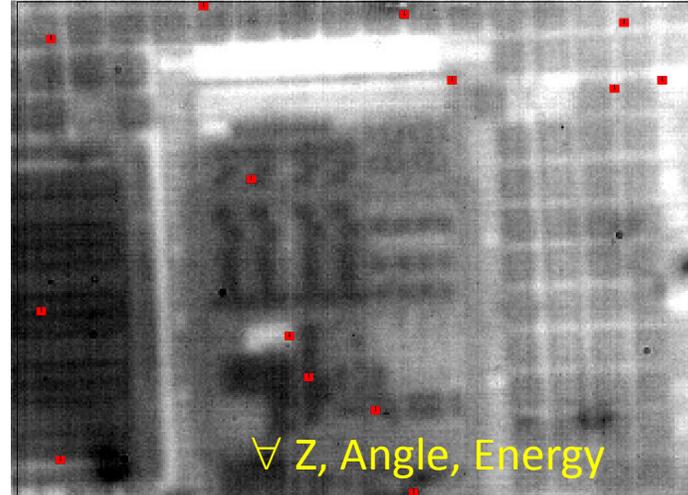


- Shows both memory cells and control logic ( $\sim 2005$ ); **Red** spots simulated random recoil ion hits w/  $1 \mu\text{m}^2$  area

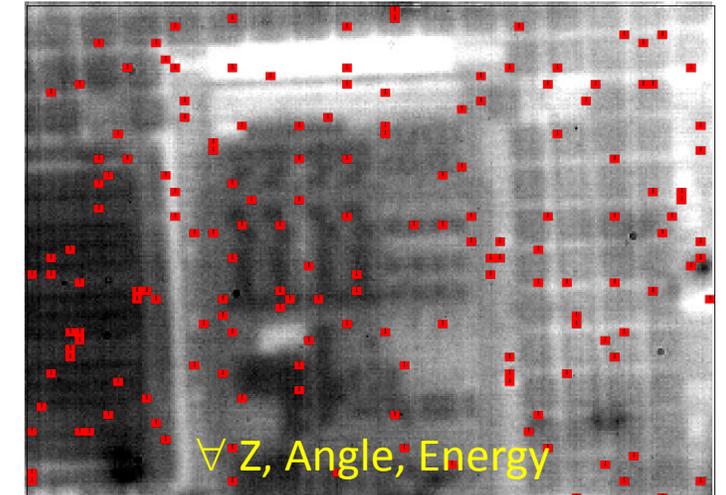
**1E10 200 MeV protons/cm<sup>2</sup>**



**1E11 200 MeV protons/cm<sup>2</sup>**

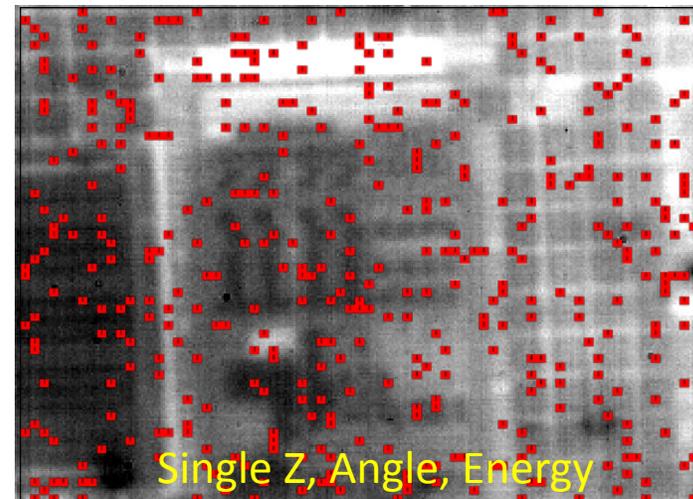


**1E12 200 MeV protons/cm<sup>2</sup>**



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

- Coverage: You can't discover an SEE mode unless you hit the feature responsible for it
- Simplest measures: ions/cm<sup>2</sup>; transistors/ion...
- 200-MeV protons,  $\sim 1/289100$  protons generates recoil ion, but every one adds to dose
  - $10^{12}$  protons/cm<sup>2</sup>:  $3.46\text{E}6$  recoil ions/cm<sup>2</sup>, 58.6 krad(Si)
  - $10^7$  15 MeV/u Ar ions: 1.2 krad(Si)

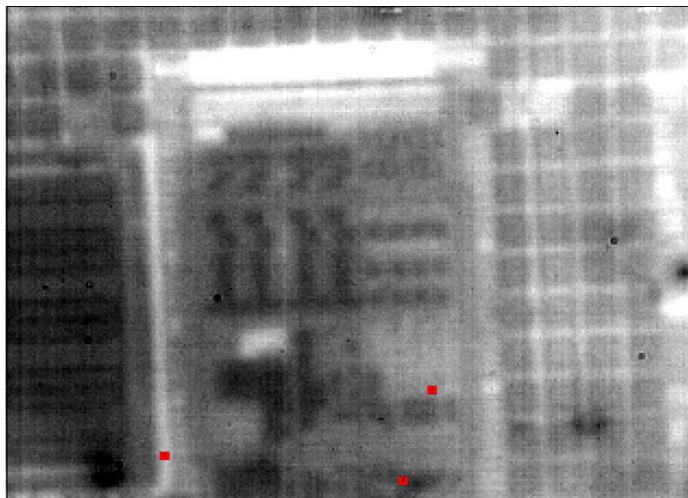


**Coverage from  
1E7 ions/cm<sup>2</sup>**

# Coverage II: Scaling Increases the Stakes

## Does this fairly represent proton-recoil coverage?

Elpida 512 Mbit  
SDRAM (EDS5108)  
w/ 130 nm CMOS  
has  $\sim 0.31$  xstr  
per  $\mu\text{m}^2$  (2005)



- What about repeated similar structures?
  - They help, but you'd need  $>289$  repetitions to come close to heavy-ion coverage
- Are the red squares fair ion track representations?
  - Ion track size difficult to define, but probably  $\ll 1 \mu\text{m}^2$
  - But transistor size  $\sim 3.2 \mu\text{m}^2$ , so probably OK for this case

## Does CMOS scaling affect this conclusion?

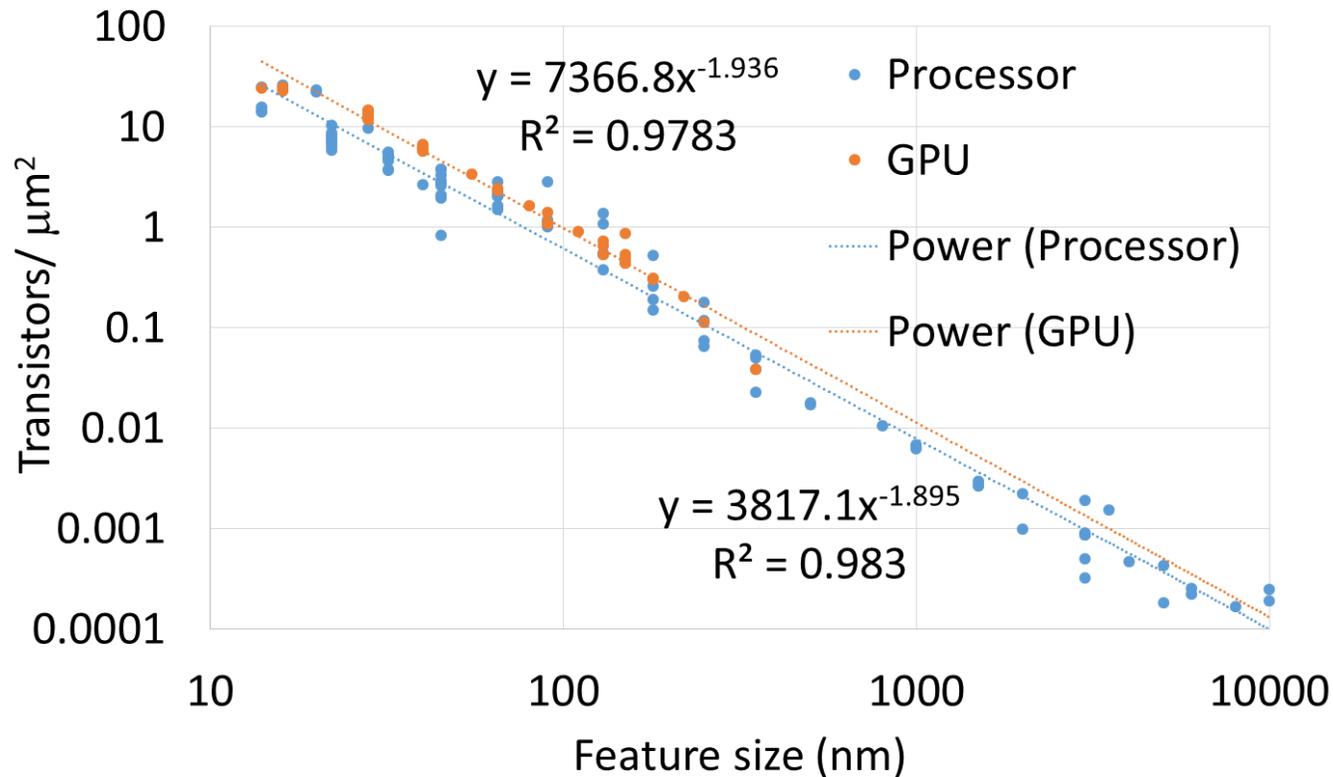


Samsung K4B2G0846  
DDR3 SDRAM w/ 35  
nm CMOS has  $\sim 4.6$   
xstr per  $\mu\text{m}^2$  (2012).  
Only gross feature  
sizes visible @  $\sim 1 \mu\text{m}$   
resolution

- Below  $\sim 65$  nm feature size,  $>1$  transistor per  $\mu\text{m}^2$
- Track structure important, but what defines a track?
- Depends on radial charge distribution (depends on Z, E)
- Also depends on device sensitivity—how much charge needed to cause SEE.

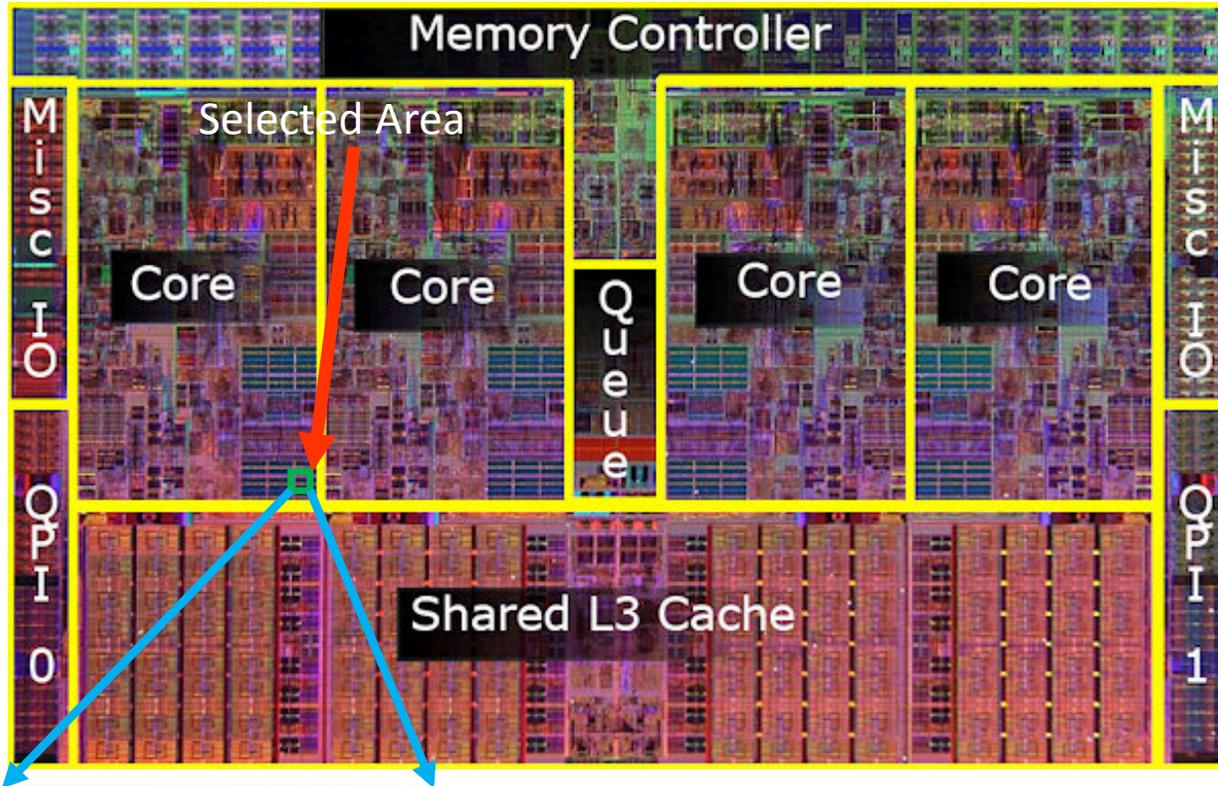


# Feature Size and Complexity: Just Geometry?

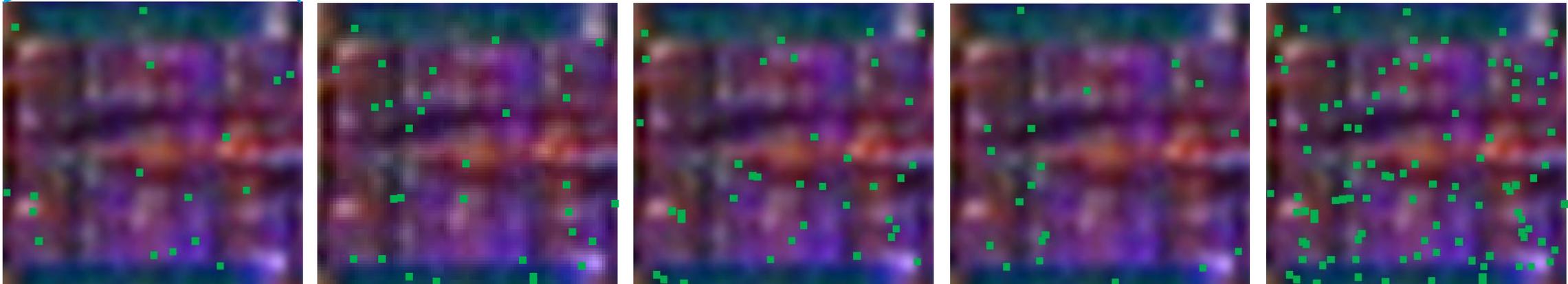


- Naïve expectation gives transistor density increasing  $\sim(\text{Feature Size})^{-2}$ .
  - Roughly true for microprocessors and GPU since 1971 (10  $\mu\text{m}$  feature size)
  - Similar trends hold for DRAMs and Flash
- Area on chip equates to xstr count
  - 2891  $\mu\text{m}^2$  per ion corresponds to
  - 130 nm:  $\sim 900$  transistors
  - 65 nm: 3300 xstr—  $\sim$  Intel 8008
  - 45 nm: 7800 xstr--  $\sim 1.2\times$  Intel 8085
  - 22 nm: 23000 xstr—  $\sim 0.8$  Intel 8088
- Imagine testing any of these w/ single ion
  - Average value—37% of such areas get no ion hits at all
- Complexities of areas left untested scale inversely w/ proton/ion flux

# Combining Data for Similar Features: Intel I7 Quad Core (45 nm-2008)



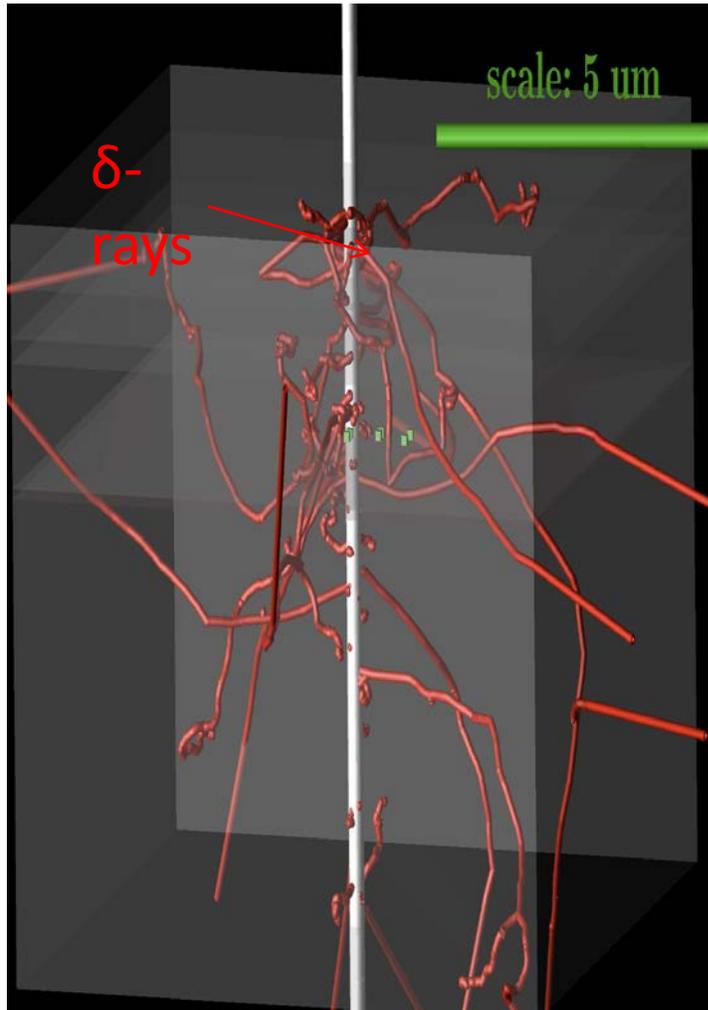
- Green square in left-most core represents  $315 \mu\text{m}$  square ( $\sim 275000$  transistors) or one Intel 80386
- Expand region  $\sim 23\times$  to show individual ion hits (green dots) from  $10^{10}$  200-MeV protons/cm<sup>2</sup>
- Each green dot  $\sim 6 \mu\text{m}$  on a side—and ion hit is somewhere in there.
- Left 4 squares on bottom could be repeated trials or same area in 4 different quads
- Right-most square combines hits for all 4 quads



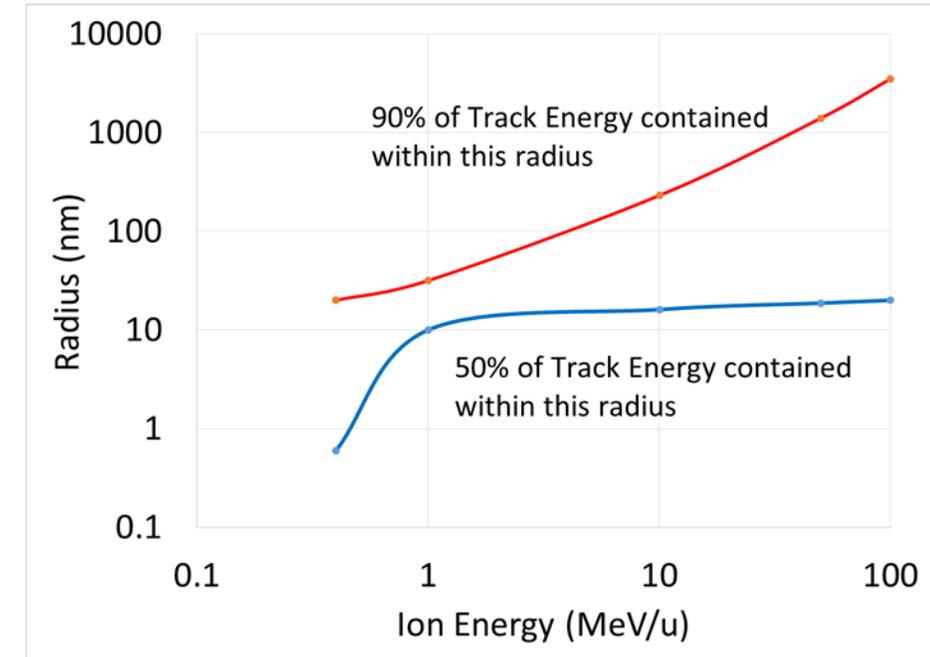
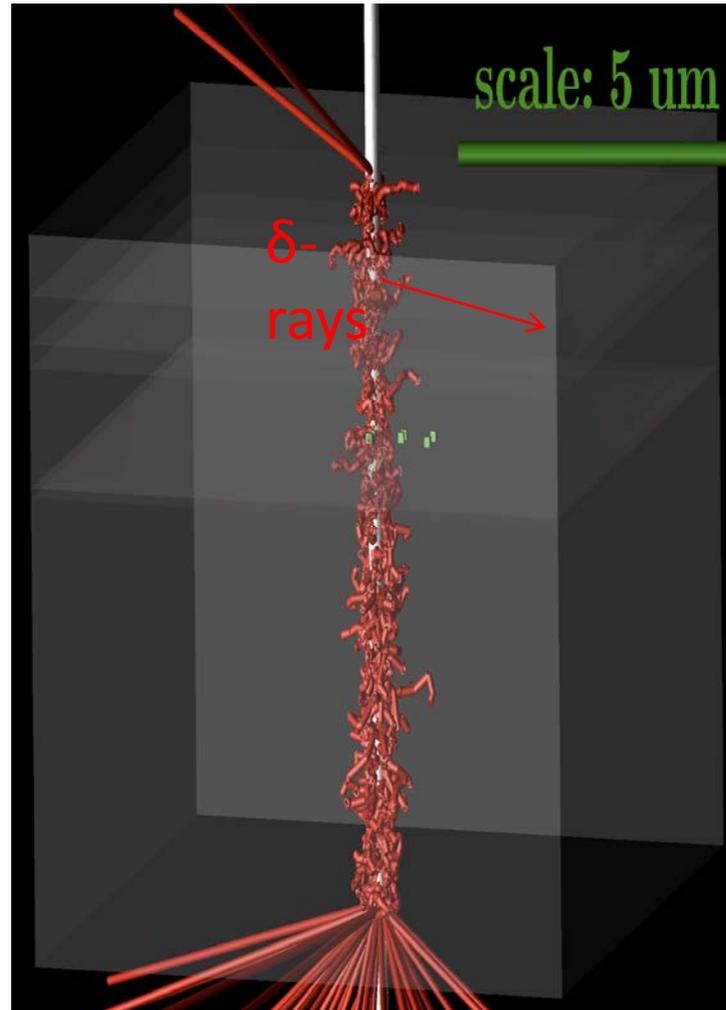
# Ion Track Structure: It's All About The Deltas



28 GeV Fe ion (500 MeV/u)



280 MeV Fe ion (5 MeV/u)



Track radius depends on how much we care if some energy escapes. High-energy ions generate energetic, long-range  $\delta$  electrons. See Murat et al., TNS 2008, p. 3046.

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# Does Scaling Help or Hurt Efforts to Constrain Heavy-Ion SEE w/ Protons?



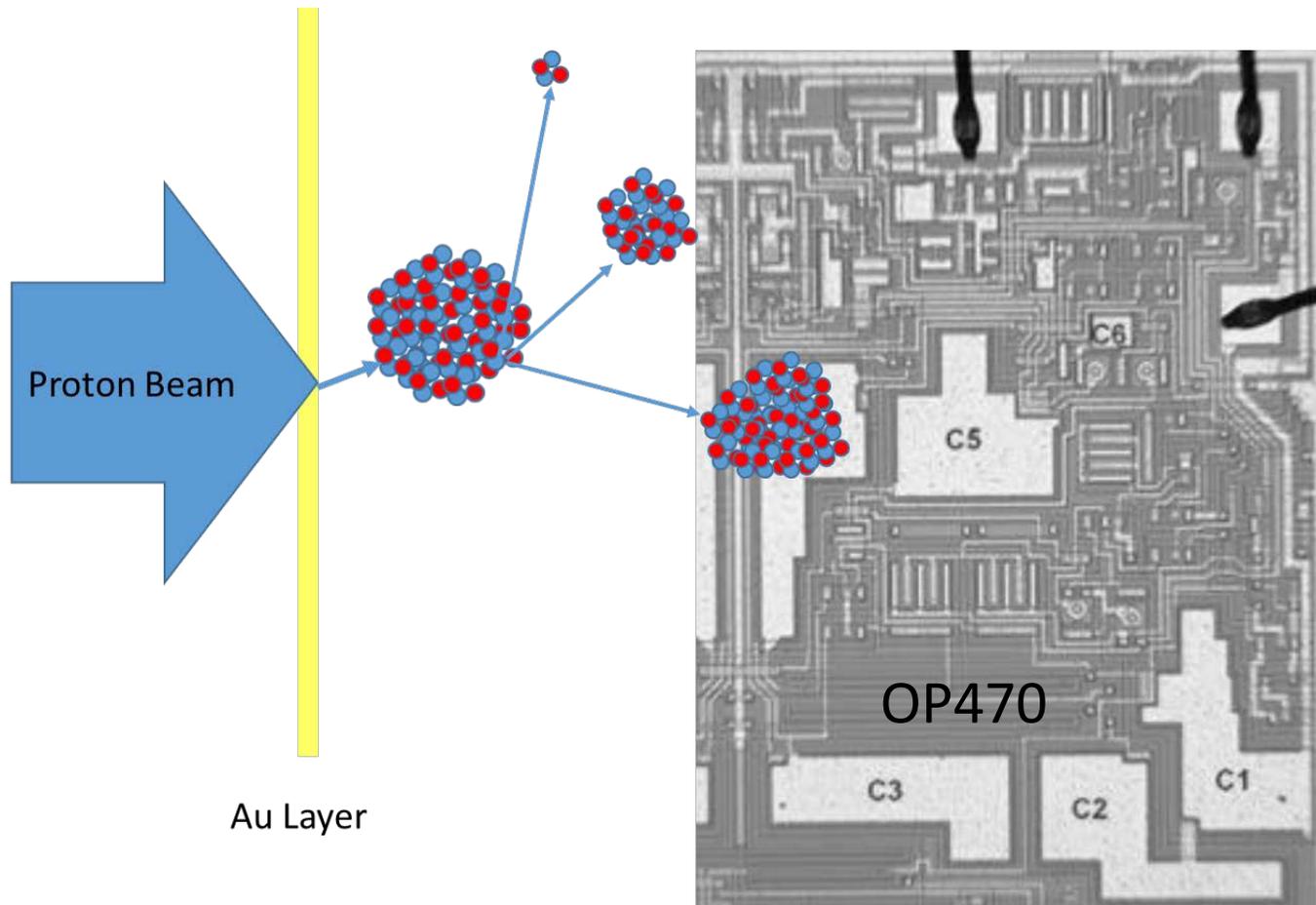
## Well, it could help...

- Onset LET decreases w/ feature size
  - More ions to detect susceptibility
- $\sigma$  vs. LET rises rapidly w/ increasing LET
  - Higher  $\sigma$  facilitates detection if present
- Supply voltages are decreasing, so maybe SEL susceptibility will decrease as well...?
  - Conflicting evidence—seems to be true for SDRAMs, but processors, FPGAs, SRAMs still prone to SEL
- TID tolerance of deep submicron CMOS increasing
  - May allow testing to higher proton fluence without risk of device failure or alteration of SEE performance via TID/SEE synergistic effects

## On the Other Hand...

- Proportion of protons generating recoil ions constant—still 1 per 289100 200-MeV protons
  - Device complexity (# transistors/ $\mu\text{m}^2$ ) continues to increase
  - State space continues to get more complex as devices add functionality.
- Lower critical charge coupled with multiple transistors per  $\mu\text{m}^2$  means track structure effects more important
  - GCR, SPE and accelerator ion tracks 50-1000x broader than proton recoil tracks
  - Hardening of commercial chips against neutrons (e.g. using DICE Latch) may not work in space
    - Proton testing might not reveal this.

# Proton-Induced Fission: Can We Use Its Powers For Good?

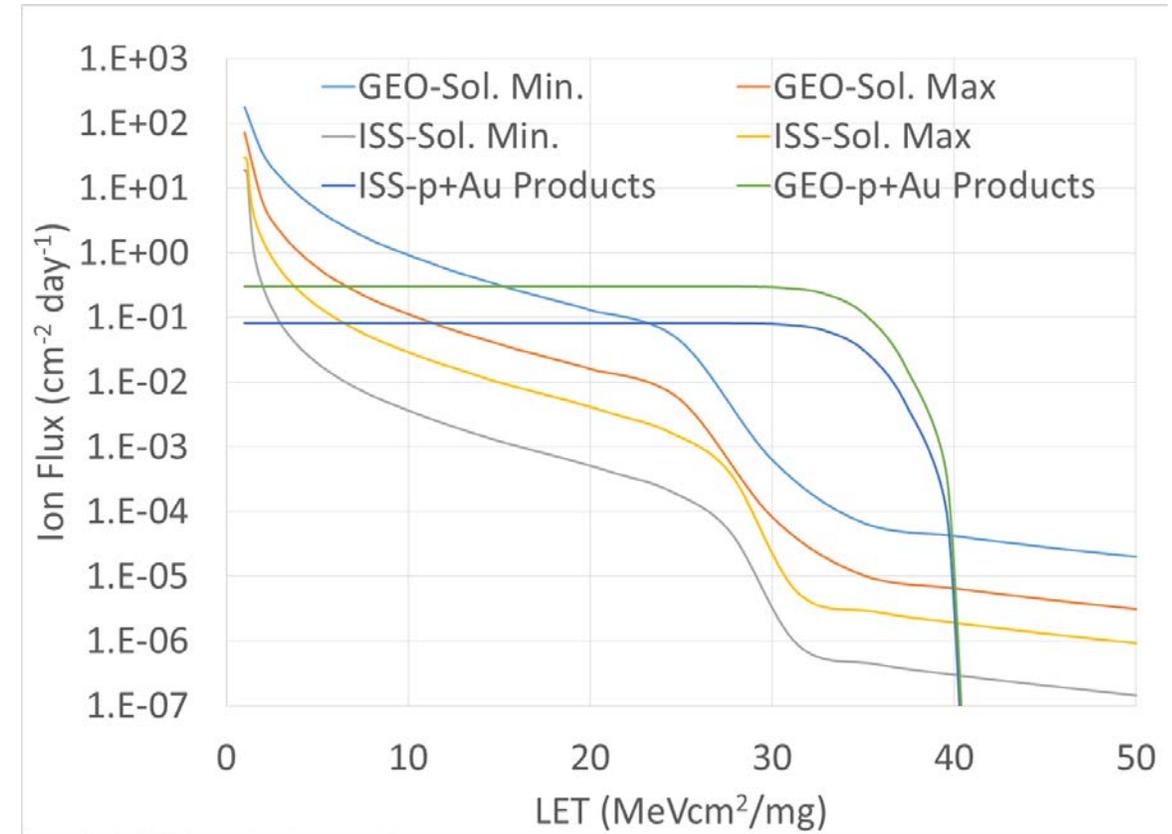
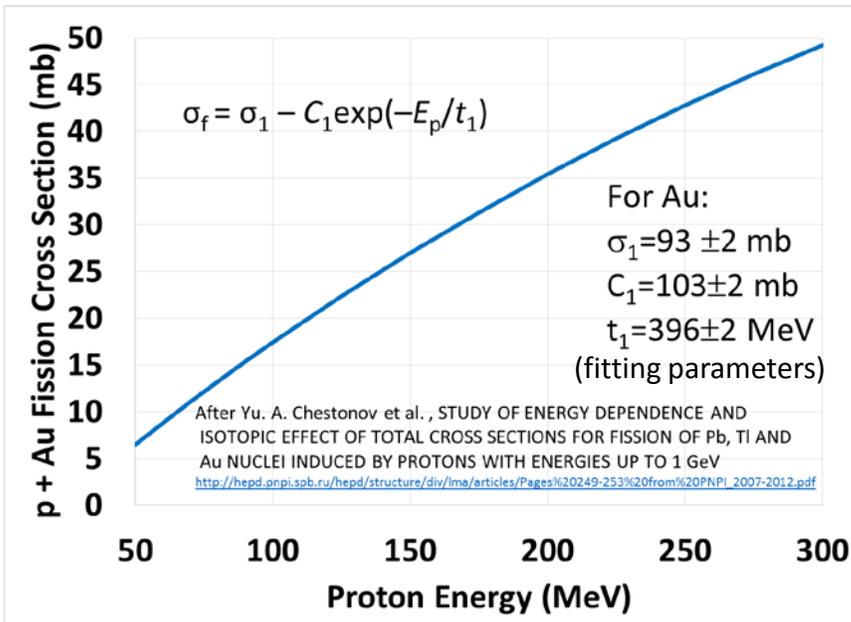


- Mechanism: Proton beam knocks Au nucleus out of Au layer
- Excited Au nucleus oscillates then fissions into two nuclei ( $30 < Z < 50$ )
- Fission fragment strikes capacitor, depositing enough charge to rupture capacitor oxide ( $< 100$  nm)
- Failure more likely if ion incident normally to device surface
- Almost all energy of fission ions comes from fission rather than from incident proton
- Ions have short range.

# Well, There's Good News and Bad News

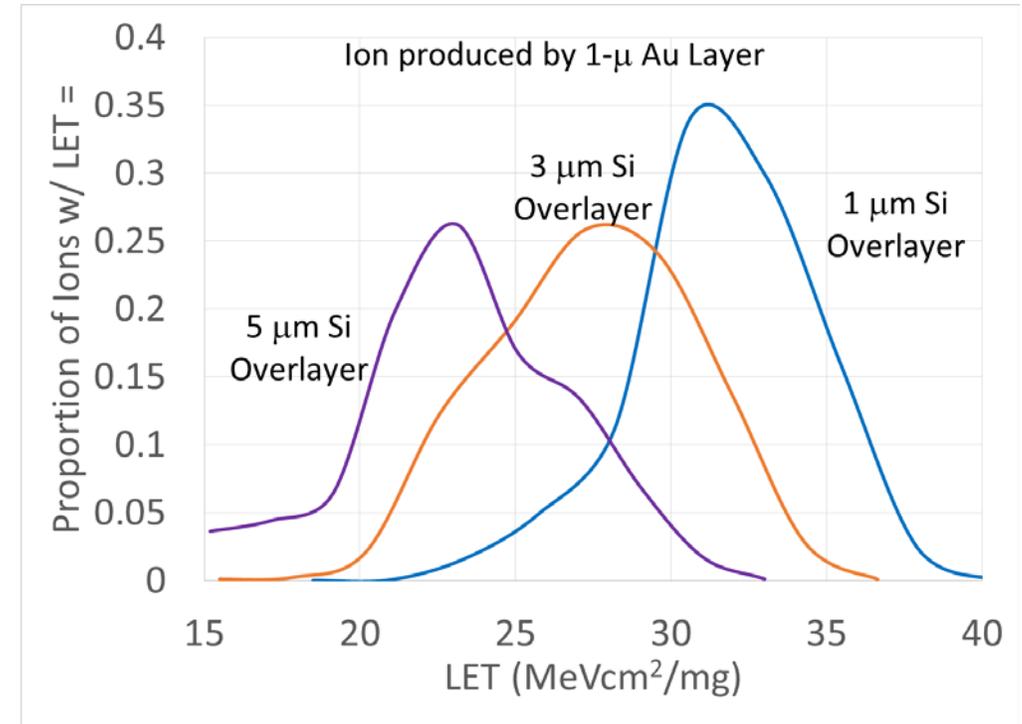
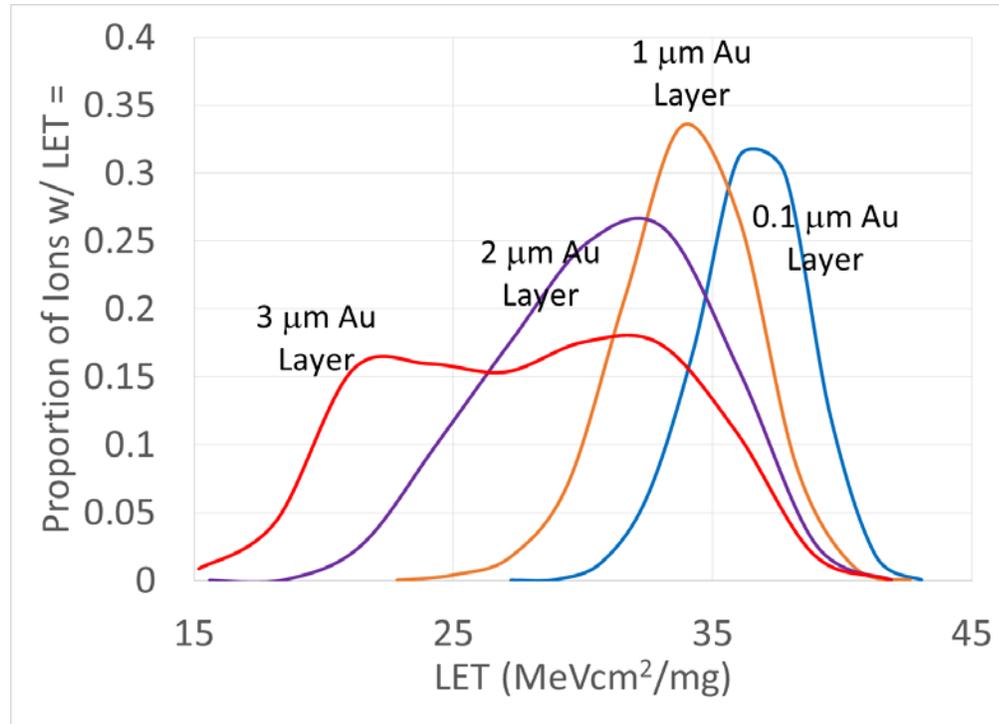


- Cross section per Au nucleon  $\sim 35$  mbarn, or  $3.5E-26$   $\text{cm}^2$  @ 200 MeV
- $1 \text{ cm}^2$  of  $1\text{-}\mu\text{m}$  thick Au foil has  $\sim 5.9E18$  Au nuclei
- Daughter products have  $30 < \text{LET} < 40 \text{ MeVcm}^2/\text{mg}$
- $10^{10}$  200-MeV p/cm<sup>2</sup>  $\rightarrow$  2100 Au fissions per  $\mu\text{m}$  Au
  - Even  $3 \mu\text{m}$  Au  $\rightarrow$  6300 fissions. Even if  $>1$  ion per fission, coverage likely  $>3x$  worse than for p + Si recoil ions



Although high LET, daughter products are short range ( $< 17 \mu\text{m}$ ), well below Bragg Peak, and produced outside of die.

# Nuclei Must Traverse Overlayers to Reach SV



- Each additional  $\mu\text{m}$  of Au produces more ions but also degrades ions already produced.
- WC fission product range in Au is  $\sim 6.5 \mu\text{m}$

- Overburden on top of SV degrades LET spectrum
- May include passivation, oxides, metal, etc.
- Range in Si  $< 17 \mu\text{m}$

**The same factors that keep this threat from killing us on orbit limit its usefulness for SEE testing w/ Protons**



# Could p on Au Fission Testing Work? If so, how?

## Challenges and Limitations

- Fission fragment flux limited
  - Even with 3  $\mu\text{m}$  Au and  $10^{12}$  200-MeV p/cm<sup>2</sup>, get  $<10^5$  ions/cm<sup>2</sup>,  $\sim 1$  ion/1000  $\mu\text{m}^2$
  - Ions produced in 3  $\mu\text{m}$  Au have  $\sim$ flat distribution from 20-35 MeVcm<sup>2</sup>/mg
- Fission products originate outside of Si
  - Must traverse Au layer and overlayer above SV
  - Degrades LET spectrum and may reduce flux if  $>\sim 10$   $\mu\text{m}$  Si equivalent overburden
- Cannot know which ion causes a given SEE
  - Z, Energy, angle all uncertain
  - Yields limited understanding of SEE mechanisms
  - Estimating bounding rate very difficult

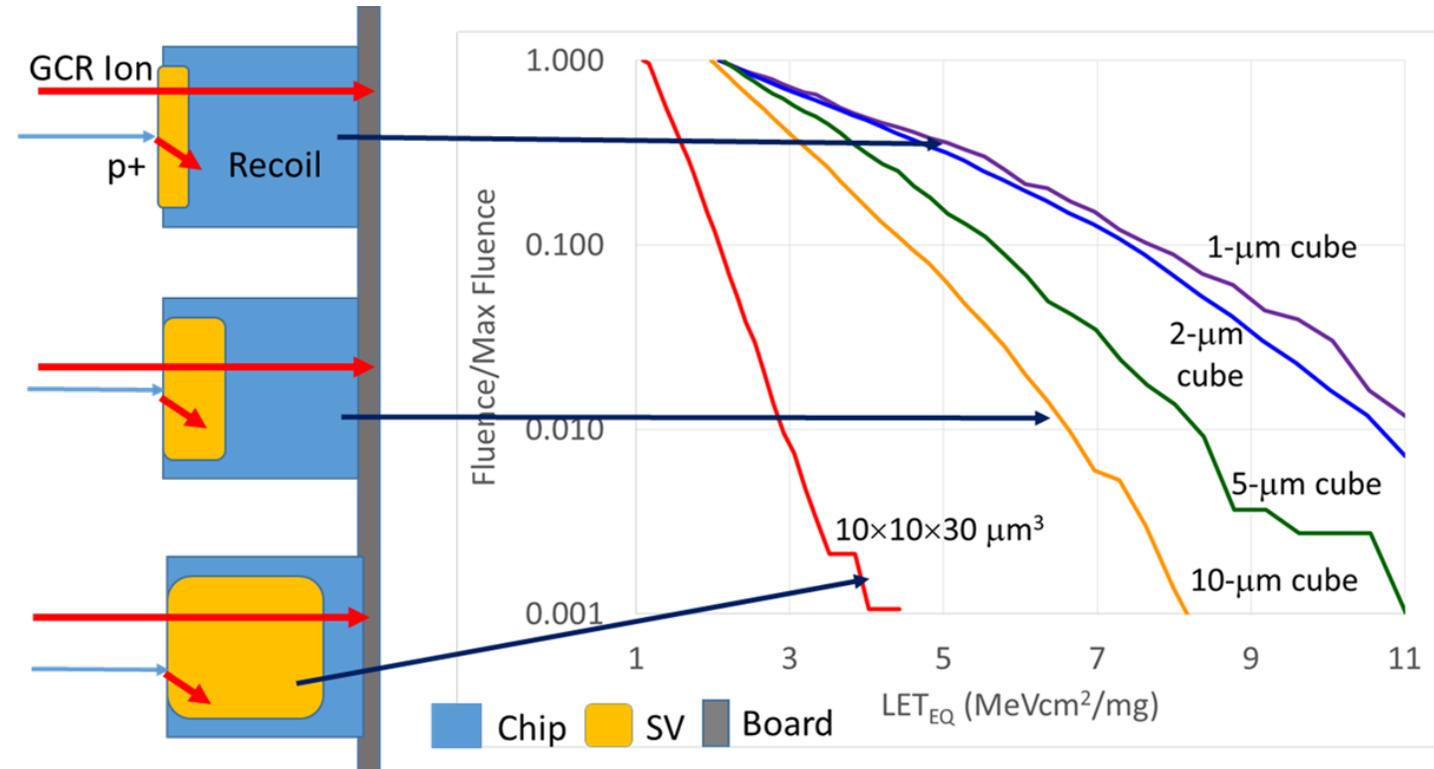
## Making It Work...Sort Of

1. Measure thickness of overburden (passivation, metallization, etc.)
2. Perform Test in Vacuum if possible and/or place foil on top of die
3. Obtain Au or Pb foils 2-3  $\mu\text{m}$  thick
4. Perform TID testing in advance to determine limiting proton fluence
  - a) Higher-energy proton beam lowers dose/fission
5. Perform test to high fluence w/o foil, then with
6. If SEE mode seen with, but not without foil:
  - a)  $10 \text{ MeVcm}^2/\text{mg} < \text{LET}_0 < 20\text{-}35 \text{ MeVcm}^2/\text{mg}$  -or-
  - b) You got lucky in the run with the foil
7. At least, you now know about the new SEE mode
8. Multiple runs increase confidence in results

# Board-Level Testing Just Makes Things More Complicated



- Ability to test at board level one of the biggest draws for protons
- Board-level testing means giving up even more information
  - Test detects far fewer SEE modes
    - Some not detected due to accelerated nature of test
    - Some masked temporally or logically –may be different during different operation stages
- Part-to-part variability difficult to evaluate w/o testing many boards
  - Don't even think about differences in synergistic interactions
- It's not just protons—board-level testing w/ heavy ions poses similar issues (e.g. overburden affects ion LET)



- LET<sub>EQ</sub> means same proton fluence will mean different things for different SEE modes—even in same device
- Proton test cannot be optimized to detect each SEE mode
  - Test is the same whether for SET or SEGR

# Relative Advantages of Heavy-Ion and Proton Testing



Heavy-Ion Testing	
Advantages	Limitations
More likely to reveal Destructive SEE (DSEE) modes	Limited ion range may preclude testing some parts/require others be repackaged/modified
Lower TID per ion allows higher fluence/better coverage for test	Testing at board level difficult; at box level, impossible
Known ion Z, energy, LET and angle better elucidate SEE mode mechanism/physics of failure	Heavy-ion testing costly; high-energy facilities even more so
Greater fidelity to Space Ion Environment	Heavy-ion facilities overbooked, difficult to schedule beam time
Can select ion characteristics to tailor test to physics of failure of SEE mode of interest	

Proton Testing	
Advantages	Limitations
Long proton range ensures ions reach depth of SEE sensitive volume	Likely to underestimate DSEE risk if it reveals susceptibility at all.
Can test highly integrated, complex parts/boards/systems without modification	High TID* limits recoil ion fluence. At board/system level, weakest part limits test fluence
Can save money if testing done at system level	Test result interpretation can be complicated, especially for system-level tests
	Inability to control characteristics of recoil ions means less understanding of SEE mechanisms
	Cannot tailor test to specific SEE modes of concern

Important Advantage

Important Limitation

\*TID=Total Ionizing Dose—cumulative energy lost by all ionizing particles that goes into generating charge in material



# Conclusions

- Testing with proton recoils means giving up information
  - Inability to control recoil ion Z, E, angle limits understanding of SEE mechanisms and dependencies
  - Limited reliability for revealing destructive SEE modes and other modes with deep SV
  - Coverage limited by TID susceptibility of part(s). Adequate coverage depends on:
    - Density and complexity of parts and degree of repetition in circuitry within part (e.g. multiple cores, lots of memory, etc.)
    - Whether variability of SEE response across the part is of interest
    - Onset LET for SEE and rapidity with which  $\sigma$  vs. LET rises (affects # of particles that can cause an effect)
- May be useful to look at complexity of device as # transistors/ion or rough equivalent IC

Proton Fluence (200 MeV)	Ion Fluence	Ion Density ( $\mu\text{m}^2/\text{ion}$ )	90 nm CMOS (xstr per ion)	45 nm CMOS (xstr per ion)	22 nm CMOS (xstr per ion)
$10^{10} \text{ cm}^{-2}$	$34590 \text{ cm}^{-2}$	2891	2009 (~Intel 4004)	8035 (>Intel 8086)	32142 (>Intel 8088)
$10^{11} \text{ cm}^{-2}$	$345900 \text{ cm}^{-2}$	289.1	201	804	8035
$10^{12} \text{ cm}^{-2}$	$345900 \text{ cm}^{-2}$	28.91	29	80	320
$2.89 \times 10^{12} \text{ cm}^{-2}$	$1 \times 10^7 \text{ cm}^{-2}$	10	7	28	112

# Conclusions II



- Effect of scaling is complicated, with conflicting trends
  - Positive: Scaling *generally* improves TID hardness, allowing testing to higher fluence
  - Positive: Lower voltages suggest lower SEL susceptibility, lowering importance of ion range
  - Positive: Generally lower onset LET and more rapid rise of  $\sigma$  vs. LET  $\rightarrow$  more fluence to detect SEE modes
  - Negative: Concept of LET breaks down; energy deposition for  $<45$  nm qualitatively different between high-energy and low-energy ions
    - Protons may not detect susceptibilities to MBU and DSEE, underestimate susceptibility of hardened technology
  - Negative: Increased density means coverage worsens  $\sim$ inverse square of feature size
- Same factors limiting proton-induced fission impact on orbit limits its hardness assurance impact
  - Fission products short range ( $<17$   $\mu\text{m}$  in Si,  $<6.5$   $\mu\text{m}$  in Au) and on low-energy side of Bragg Peak
  - Fission occurs outside of die, necessitating transport across Au layer and device overburden
  - Coverage for fission products even poorer than for recoil ions
  - **BUT**, may reveal some susceptibilities missed by conventional proton testing
- Board-level testing
- Protons not a panacea for hard/expensive-to-test parts. Sometimes, it's the best last resort we have