Impact of Ion Energy and Species on Single Event Effect Analysis

Vanderbilt University
Institute for Space & Defense Electronics

R. A. Reed, R. A. Weller, M. H. Mendenhall K. M. Warren D. R. Ball, J. A. Pellish B. D. Sierawski C. L. Howe, L. W. Massengill, R. D. Schrimpf, M. Alles, A. L. Sternberg, A. F. Witulski, A. D. Tipton

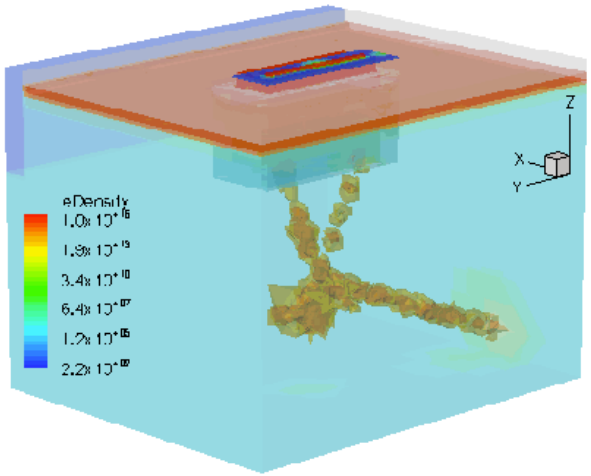
NASA/GSFC
K. A. LaBel, M. A. Xapsos, Paul Marshall (consultant)

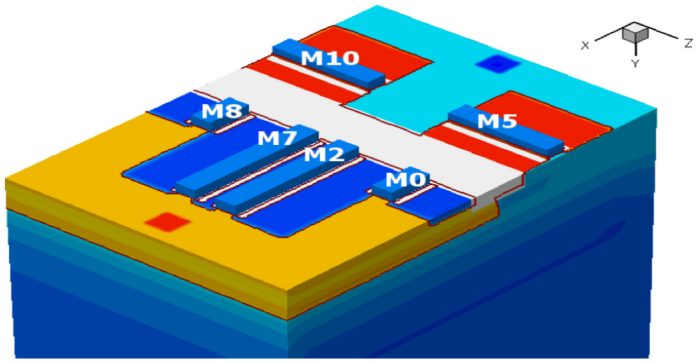
BAE Systems
N. F. Haddad, J. Bowman, R. Lawrence,

Sponsoring Agencies: NASA, DTRA, AFOSR, AEDC

OUTLINE

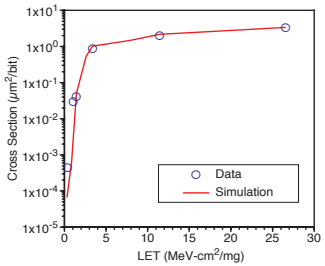
- Brief description of our applications of the RADSAFE concept
- Sample Application
  - SEU Rate Predictions
- DURIP Award

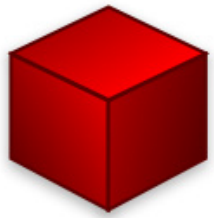




Integral Rectangular Parallelepiped Model

Model Calibration

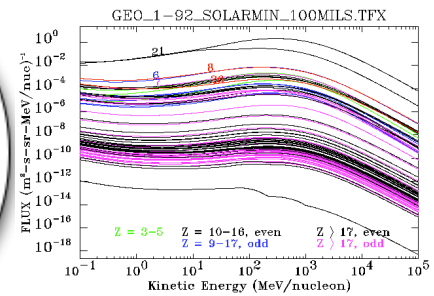


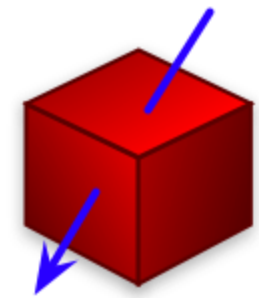


SEU Rate Prediction

Device/Circuit/System Virtualization

Radiation Event Generation

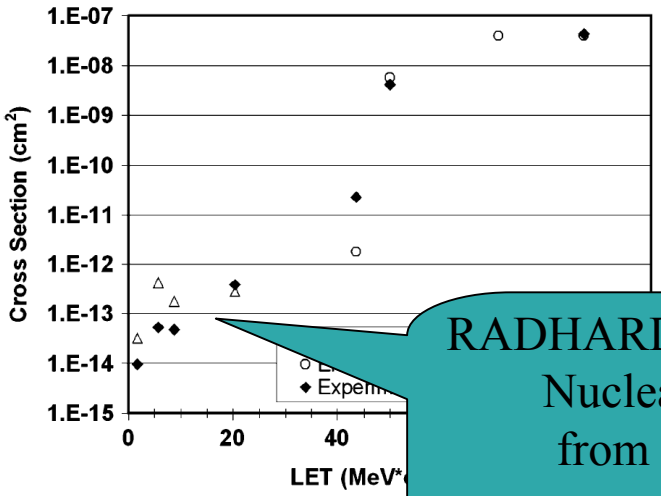




Response Prediction

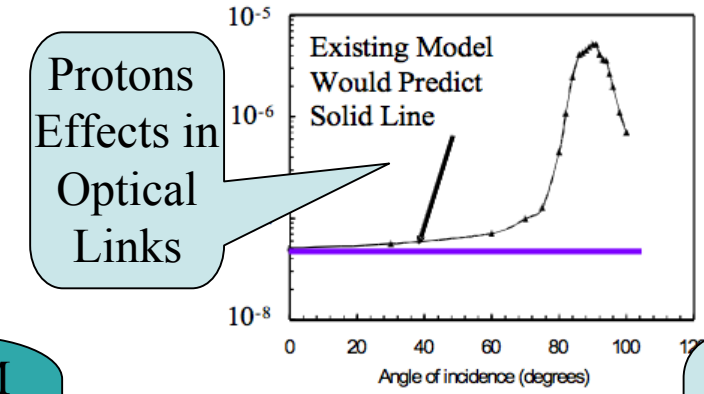
Integral over path length distribution

Examples of Breakdown of Existing SEE Models



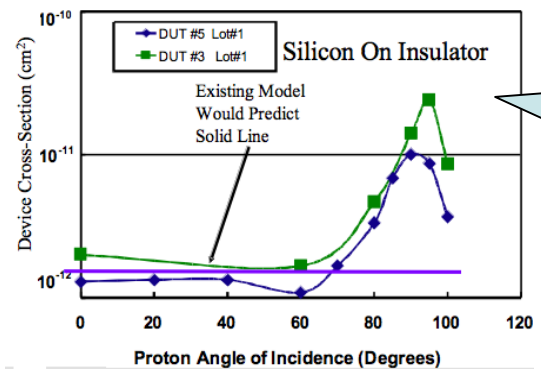
K.M. Warren, et. al IEEE Trans. Nuc. Sci., vol. 48, no. 6, Dec. 2005, pp. 2125 – 2131.

RADHARD CMOS SRAM Nuclear Reactions from Heavy Ions (Z>1)



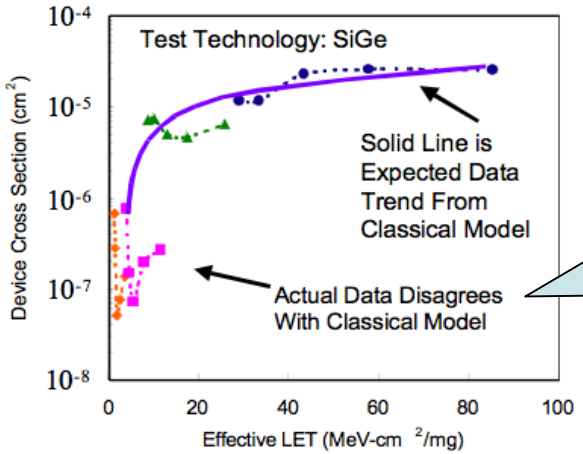
Protons Effects in Optical Links

R.A. Reed, et. al IEEE Trans. Nuc. Sci., vol. 48, no. 6, Dec. 2001, pp. 2202 – 2209.



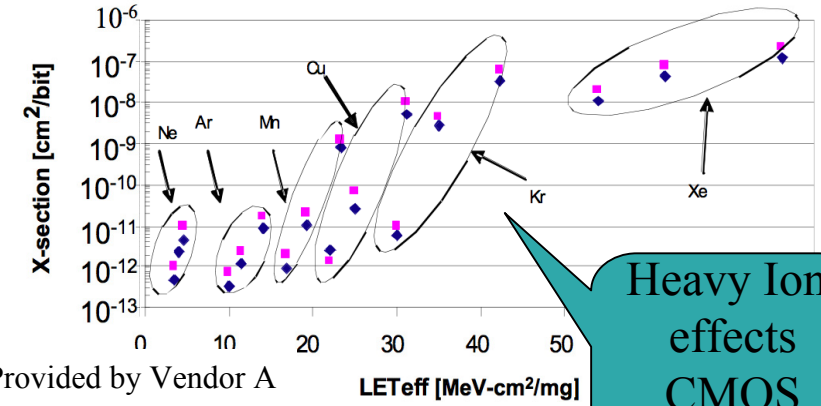
Proton effects in SOI based memories

R.A. Reed, et. al, IEEE Trans. Nuc. Sci., vol. 49, no. 6, Dec. 2002, pp. 3038 – 3044



Heavy Ion Effects in SiGe HBTs

R.A. Reed, et. al IEEE Trans. Nuc. Sci., vol. 50, no. 6, Dec. 2003, pp. 2184 – 2190



Provided by Vendor A

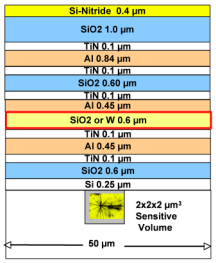
Heavy Ion effects CMOS SRAM

Scope of RADSAFE Applications

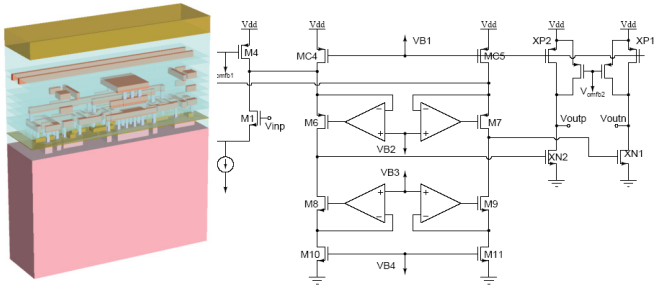
- **On-orbit predictions of SEU rate**
  - **IBM 5HP SiGe HBT Flip Flop (Georgia Tech, NASA, Auburn)**
  - **Xilinx FPGA-based SIRF DICE Latch (NASA)**
  - **IBM 9SF RHBD DICE latch (Boeing, DTRA)**
  - **Rad-Hard SRAM (NASA, APL)**
- **Space environment induced single-event upset and multiple-bit upsets in 0.5 μm, 0.25 μm, 130 nm, 90 nm, 65 nm, and 45 nm CMOS SRAMs**
  - **IBM Trusted Foundry**
  - **Xilinx**
  - **Honeywell**
  - **Texas Instrument**
  - **Sandia**
  - **others**
- **SET/SEU in SiGe HBTs (Georgia Tech/NASA/Auburn)**
- **SEGR in power MOSFETs (NASA)**
- **Transient effects in HgCdTe IR-FPAs and Silicon imagers (NASA)**
- **Dose enhancement effects**
- **Terrestrial environment (neutron and alphas) induced single-event upset and multiple-bit upsets in commercial CMOS circuits**

RADSAFE

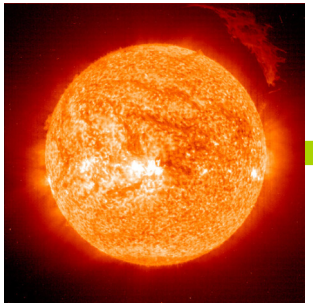
Device/Circuit/System Virtualization

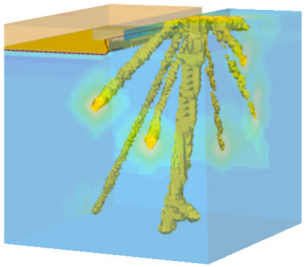


OR

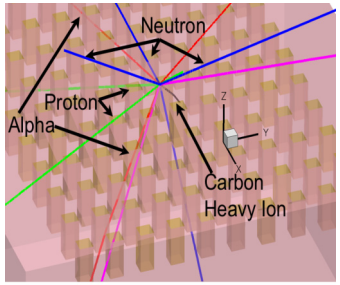


Radiation Event Generation

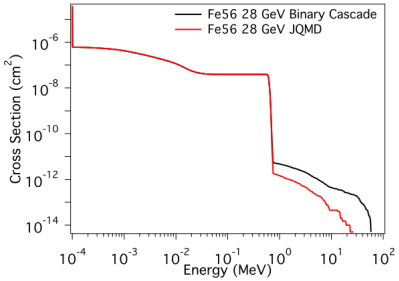




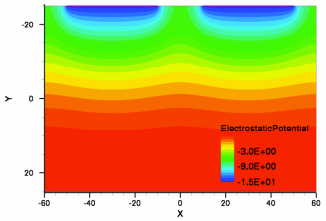
OR



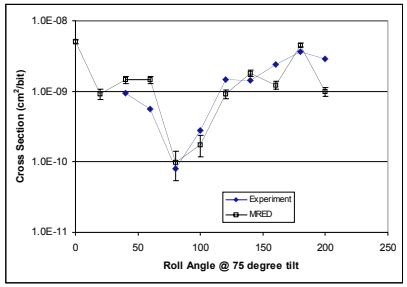
Response Prediction



Calorimetry



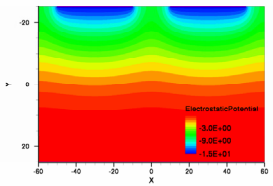
TCAD

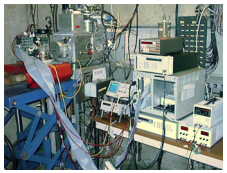


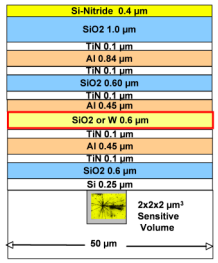
Other…

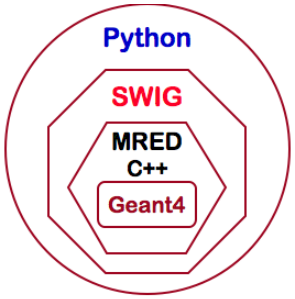
RADSAFE: Rate Prediction for a Rad-Hard SRAM

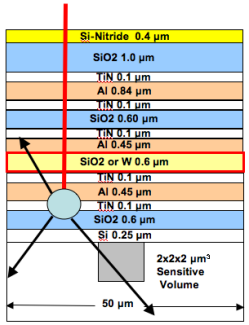
Model Calibration

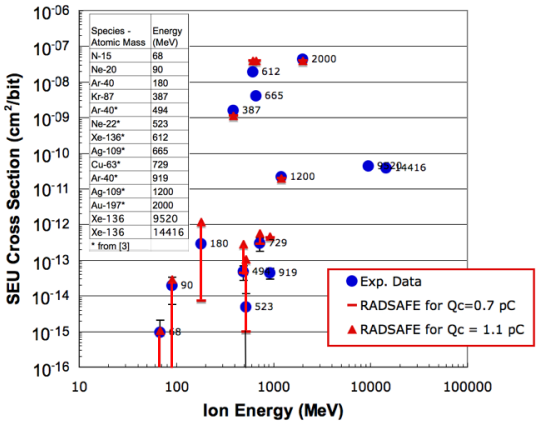








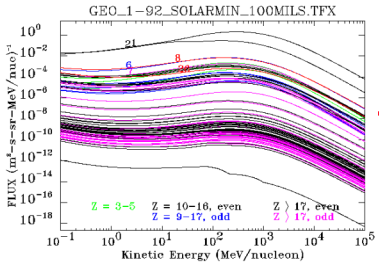


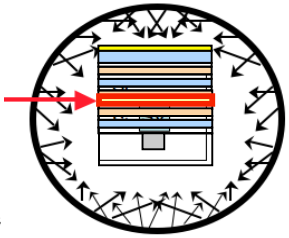


SEU Rate Prediction

Device/Circuit/System Virtualization

Radiation Event Generation





Response Prediction

Flux: Particles/m²/s/sr/MeV

MRED: Ion energy to deposited energy

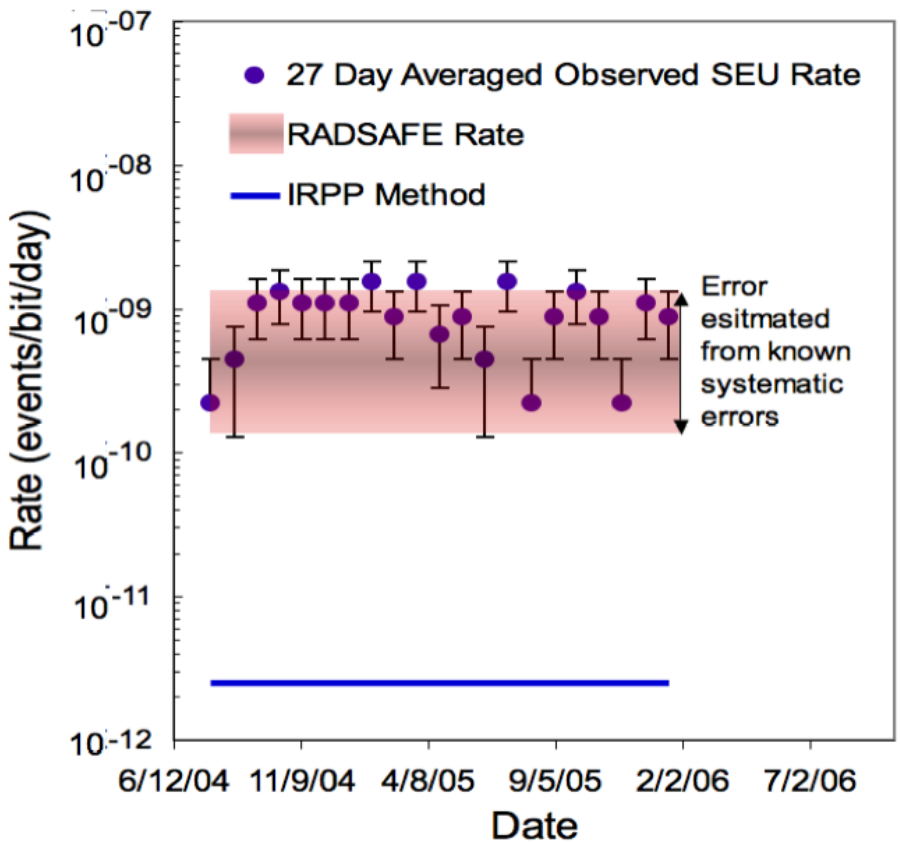
Events/s/energy | Monte Carlo

$$RATE \equiv R(E_d) = \int_{E_d}^{\infty} dE \left[\frac{dR(E)}{dE} = \sum_{z=1}^{92} (4\pi^2 \rho^2 \int_0^1 dr \left(\frac{\Phi_z(E_0(r))}{n(E_0(r))} \right) \cdot MRED_z(E_0(r), E)) \right]$$

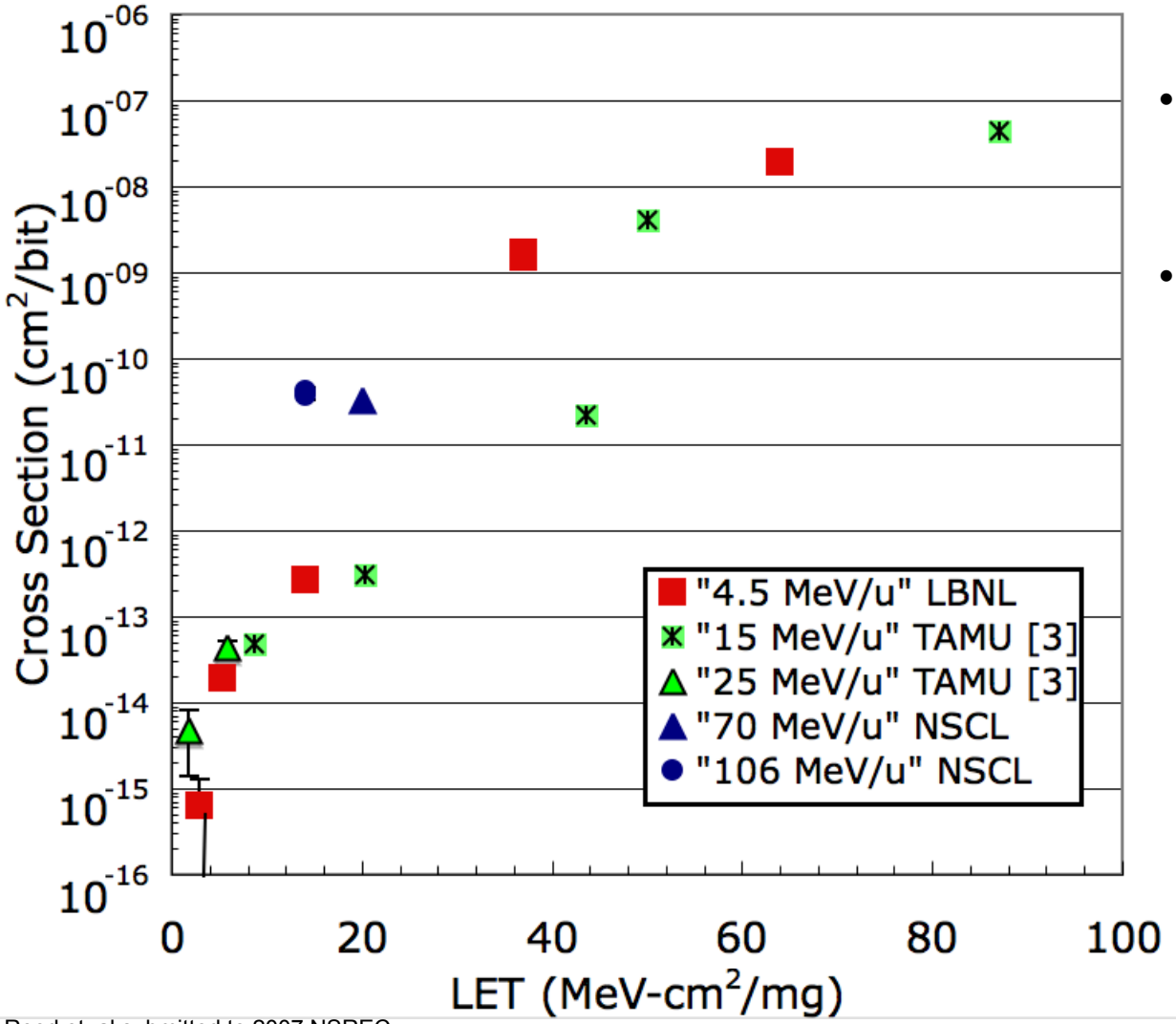
Sum all elements | Sample radius | Density of random ion energies

Observed and Predicted SEU Rate for a Modern RAD-HARD SRAM

- SRAM used on NASA spacecraft
- Observed Average SEU Rate:
  - **$1x10^{-9}$ Events/Bit/Day**
- Vendor predicted rate using CREME96:
  - $2x10^{-12}$ Events/Bit/Day
  - Classical Method nearly a factor 500 lower than observed rate



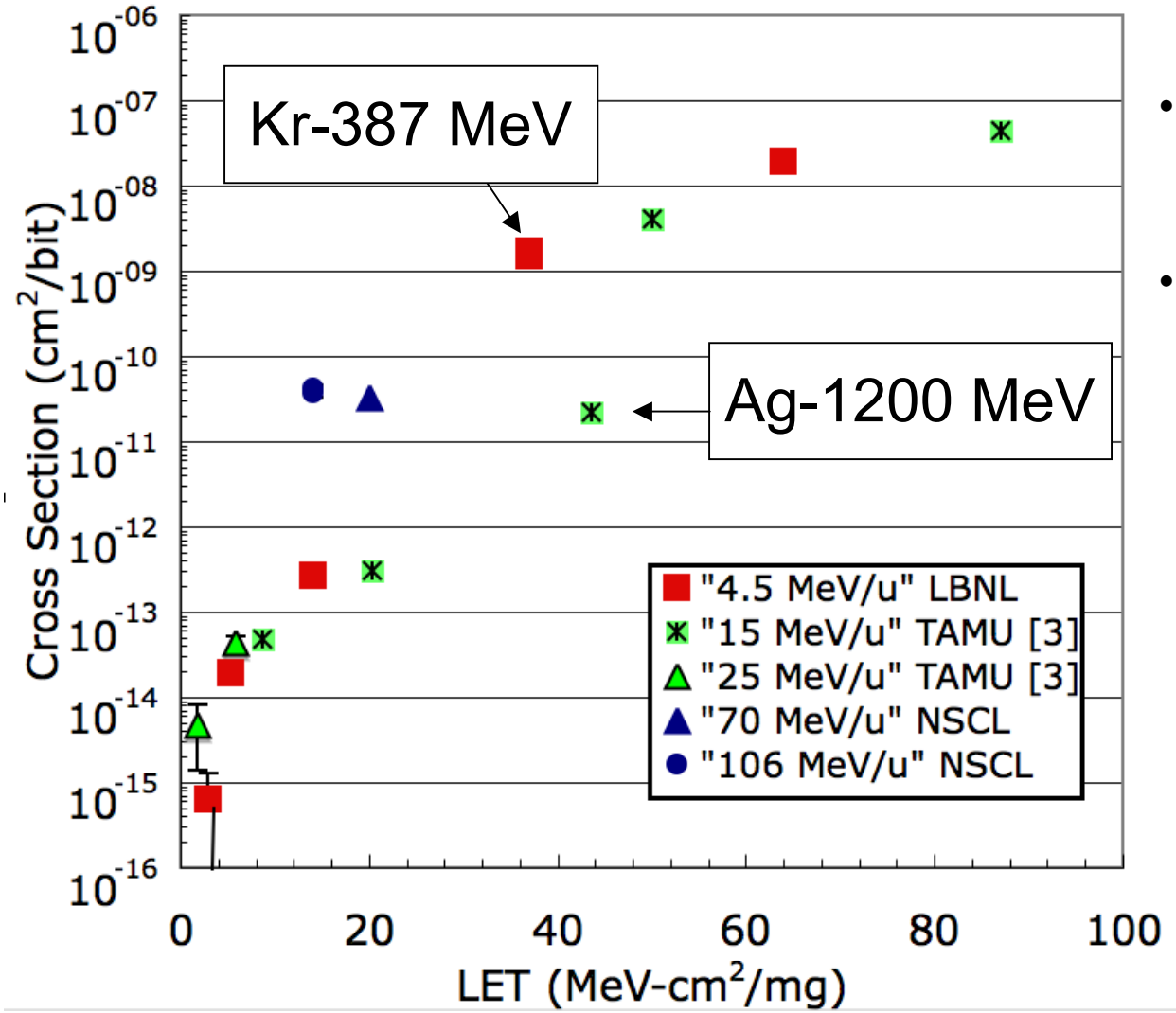
Ground Testing using Various Ion Energy and Species



- Large discontinuities in measured cross section over ion LET
- Cross section trends do not follow ion energy

1) R.A. Reed,et. al submitted to 2007 NSREC
2) Dodd, et. al submitted to 2007 NSREC
3) K.M. Warren, et. al IEEE Tr ans. Nuc. Sci., vol. 48, no. 6, Dec. 2005, pp. 2125 – 2131.
4) Dodd et. al RADECS 2006

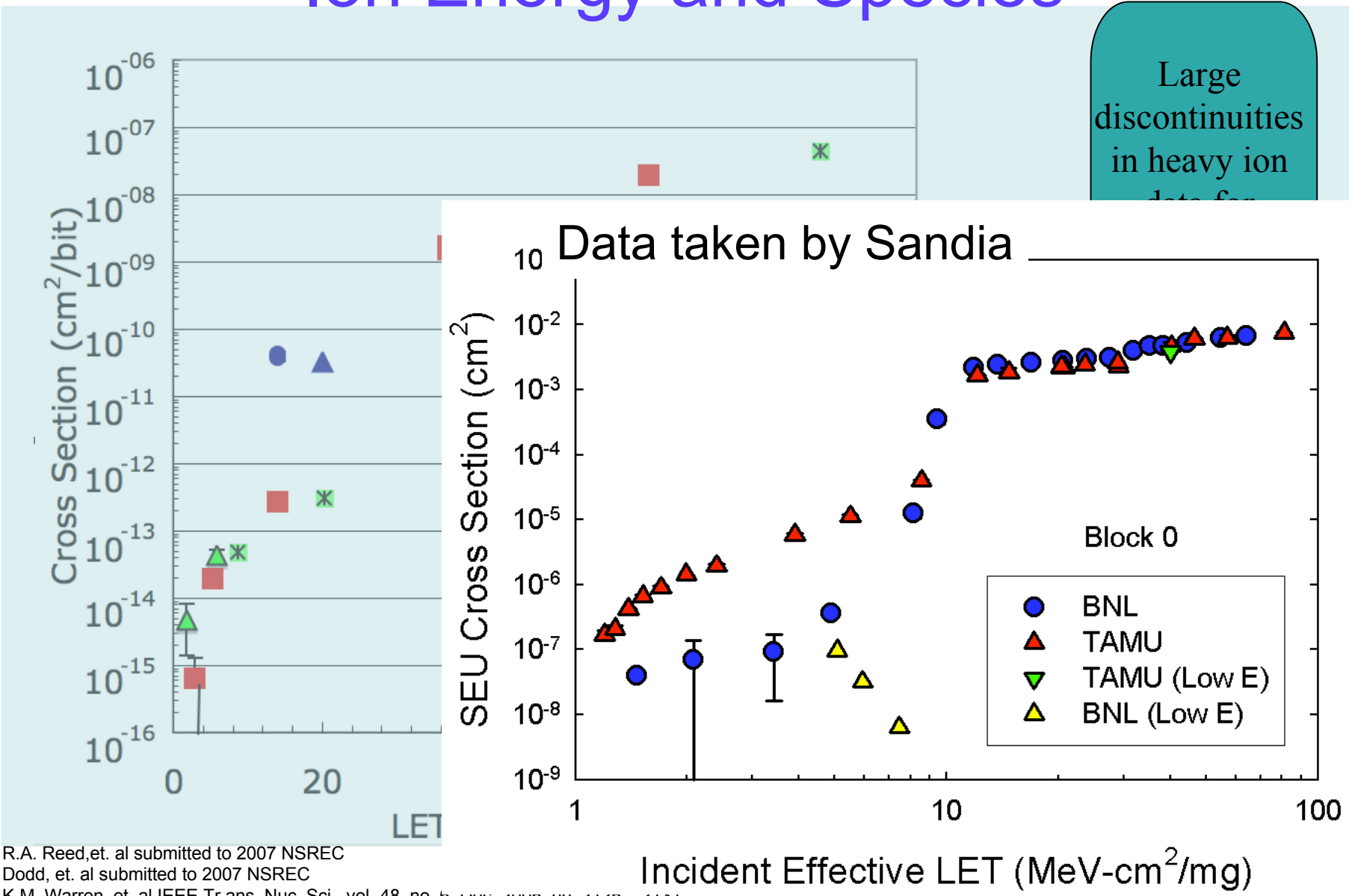
Ground Testing using Various Ion Energy and Species



- Large discontinuities in measured cross section over ion LET
- Cross section trends do not follow ion energy

1) R.A. Reed,et. al submitted to 2007 NSREC
2) Dodd, et. al submitted to 2007 NSREC
3) K.M. Warren, et. al IEEE Tr ans. Nuc. Sci., vol. 48, no. 6, Dec. 2005, pp. 2125 – 2131.
4) Dodd et. al RADECS 2006

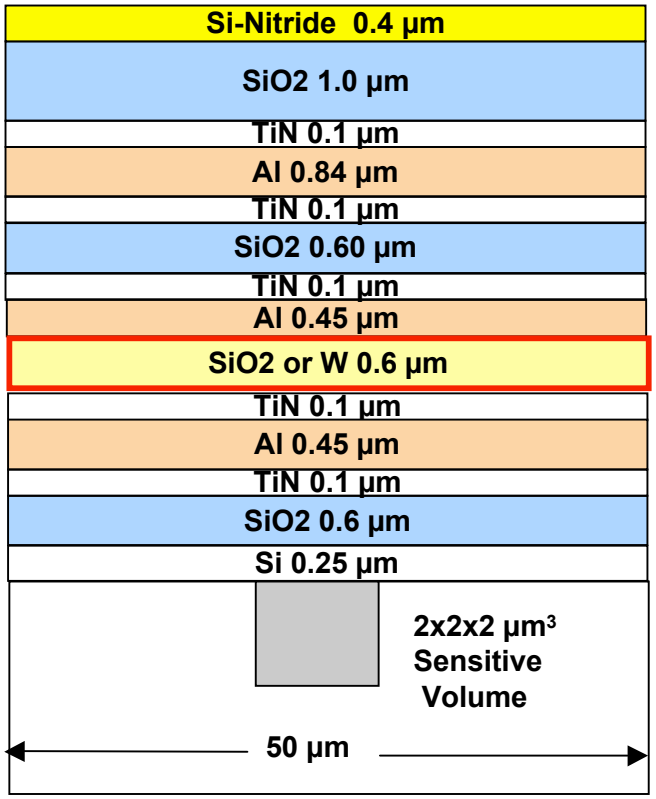
Ground Testing using Various Ion Energy and Species



Large discontinuities in heavy ion data for

1) R.A. Reed,et. al submitted to 2007 NSREC
2) Dodd, et. al submitted to 2007 NSREC
3) K.M. Warren, et. al IEEE Tr ans. Nuc. Sci., vol. 48, no. 6, Dec. 2005, pp. 2125 – 2131.
4) Dodd et. al RADECS 2006

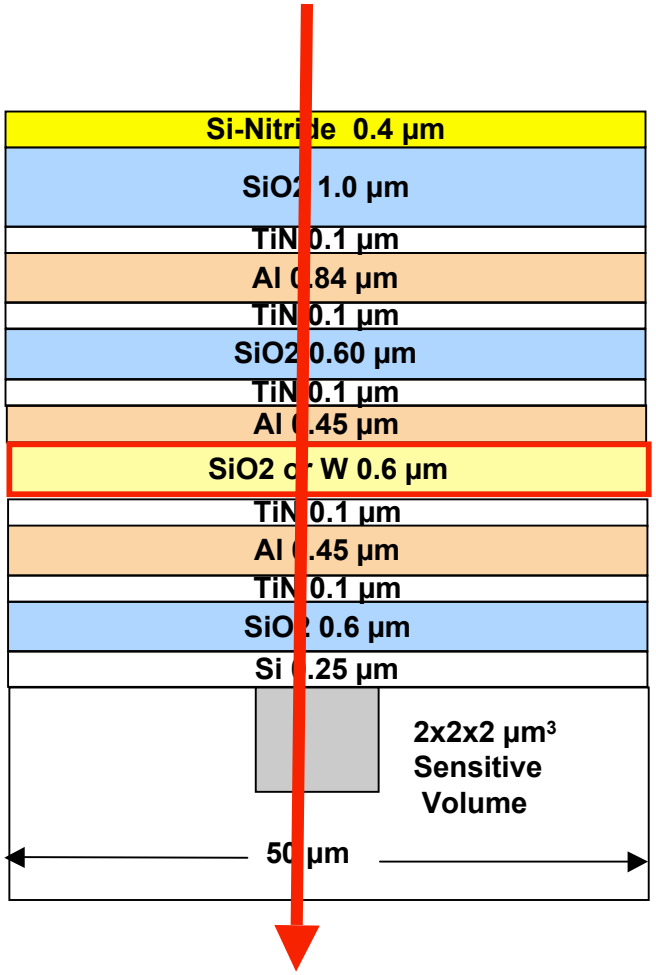
RADSAFE Prediction of Energy Deposition in Sensitive Volume

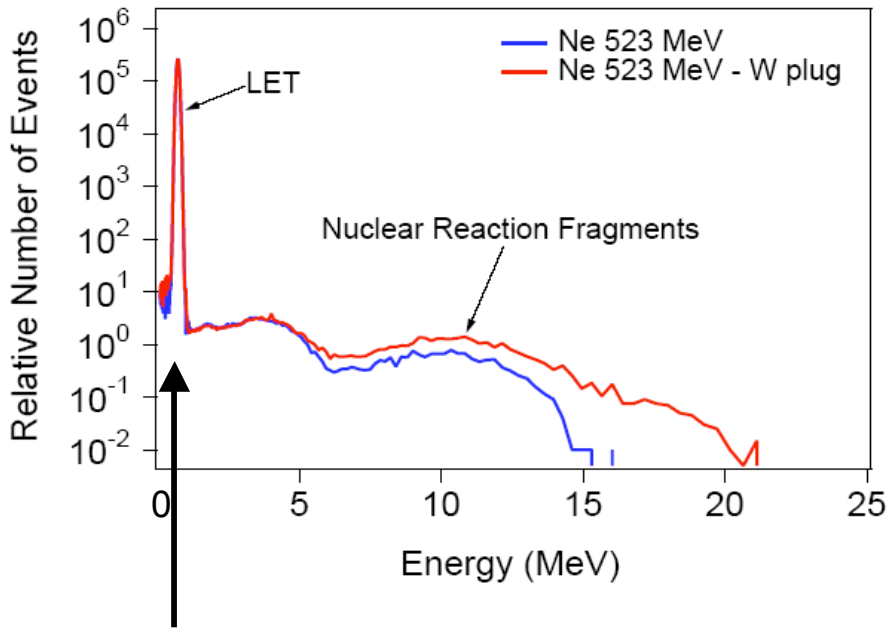


- **Approximate metalization by multi-layered stack**
- **Sensitive volume determined from broadbeam testing and technology information**

K.M. Warren, et. al IEEE Trans. Nuc. Sci., vol. 48, no. 6, Dec. 2005, pp. 2125 – 2131.

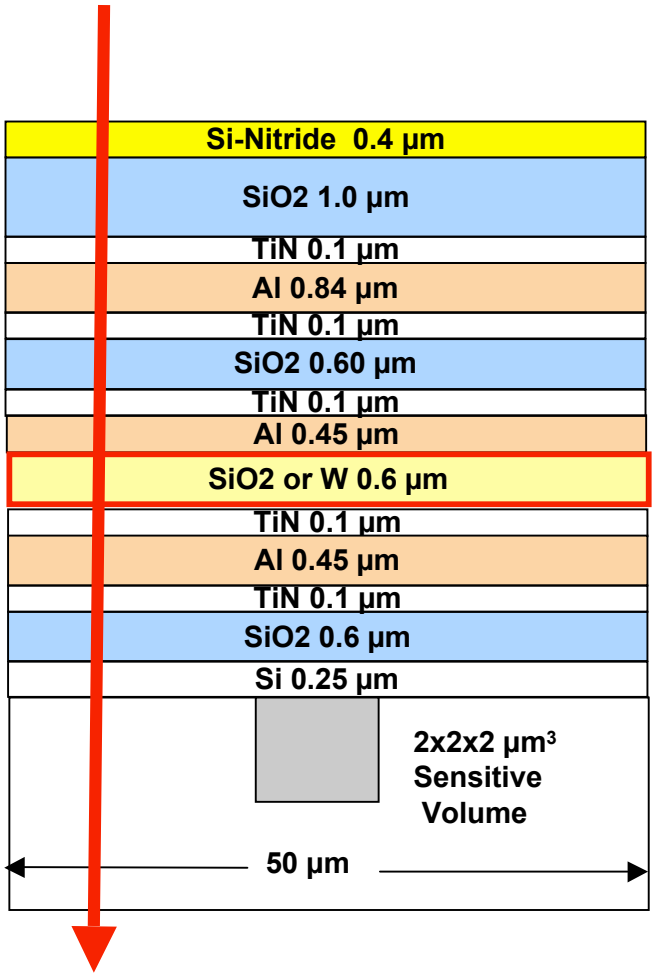
RADSAFE Prediction of Energy Deposition in Sensitive Volume

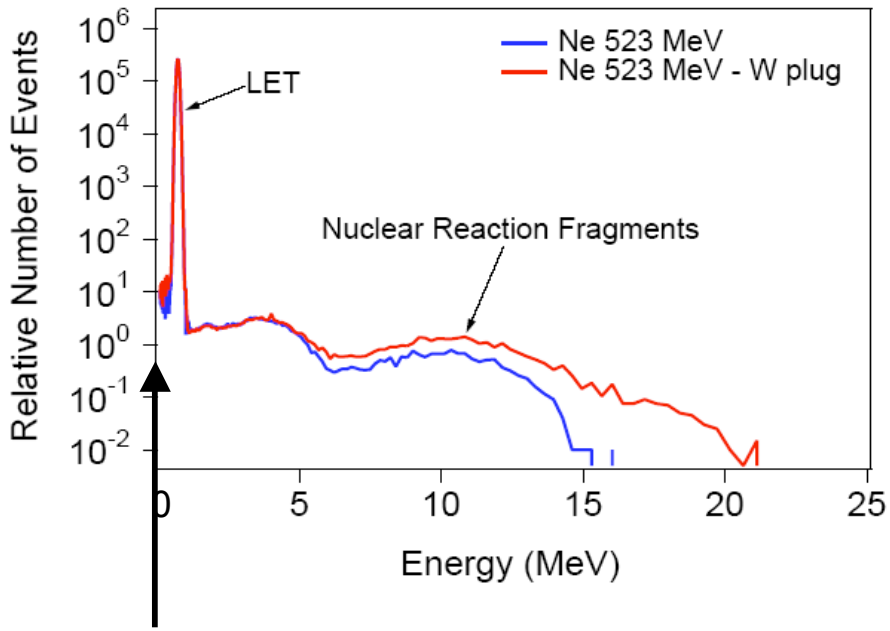




K.M. Warren, et. al IEEE Trans. Nuc. Sci., vol. 48, no. 6, Dec. 2005, pp. 2125 – 2131.

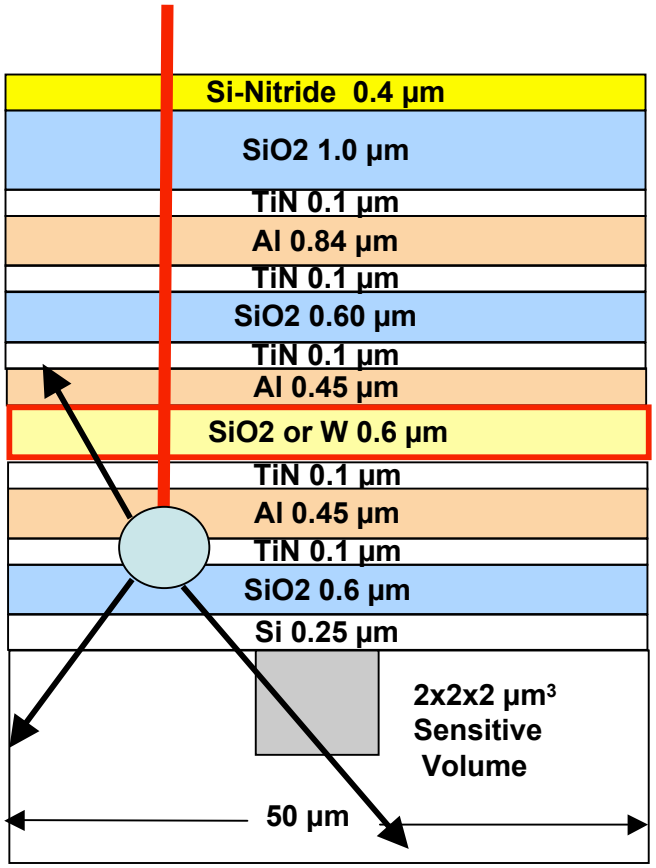
RADSAFE Prediction of Energy Deposition in Sensitive Volume

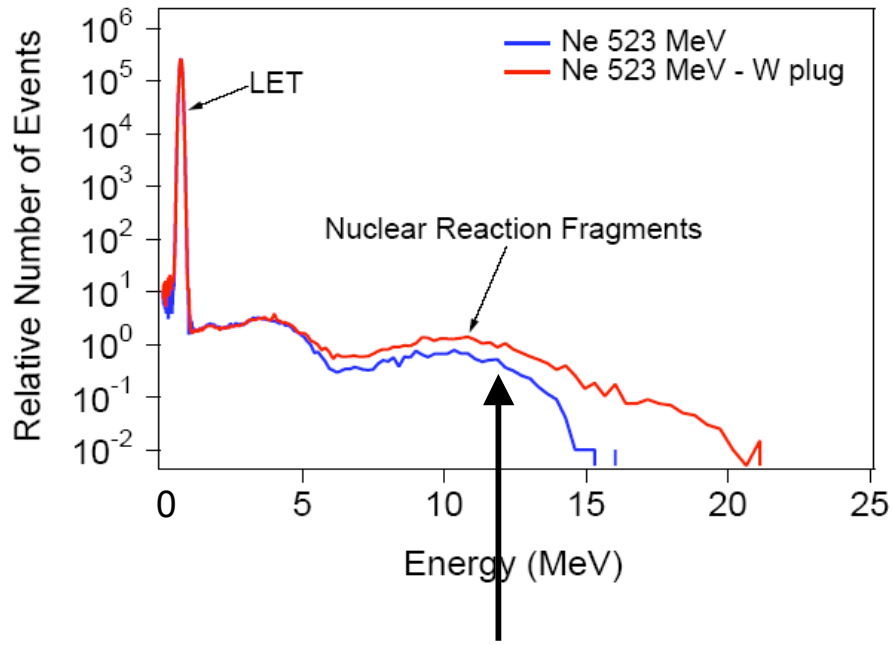




K.M. Warren, et. al IEEE Trans. Nuc. Sci., vol. 48, no. 6, Dec. 2005, pp. 2125 – 2131.

RADSAFE Prediction of Energy Deposition in Sensitive Volume

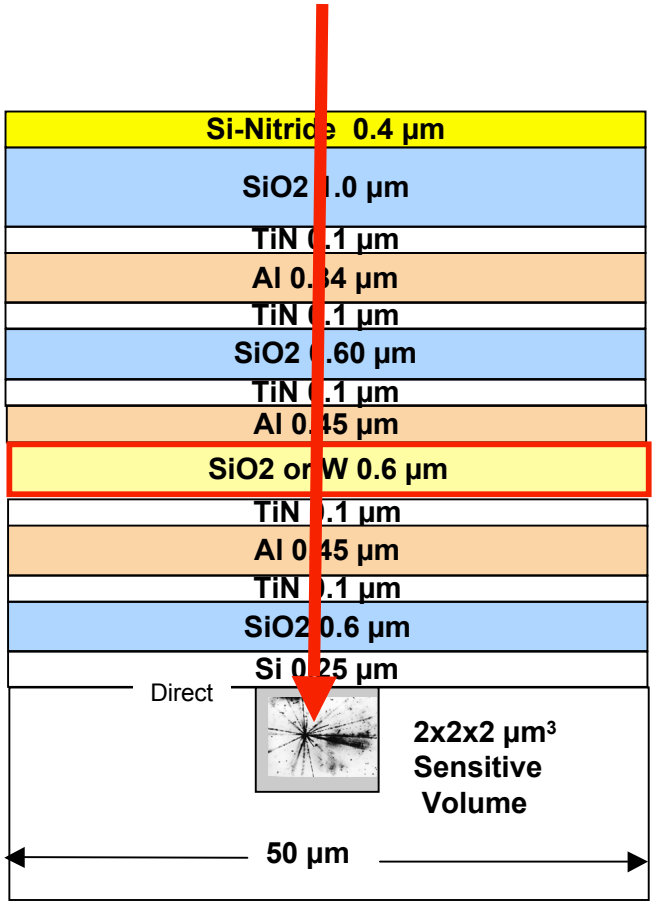




High-Z materials must be included to accurately predict energy deposition profile

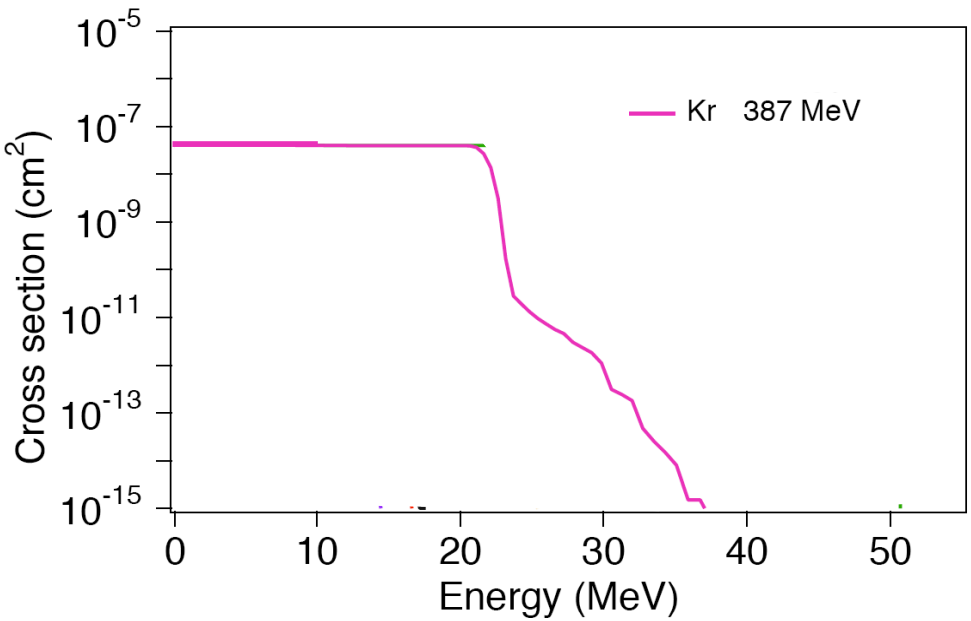
K.M. Warren, et. al IEEE Trans. Nuc. Sci., vol. 48, no. 6, Dec. 2005, pp. 2125 – 2131.

RADSAFE Prediction of SEU Cross Section

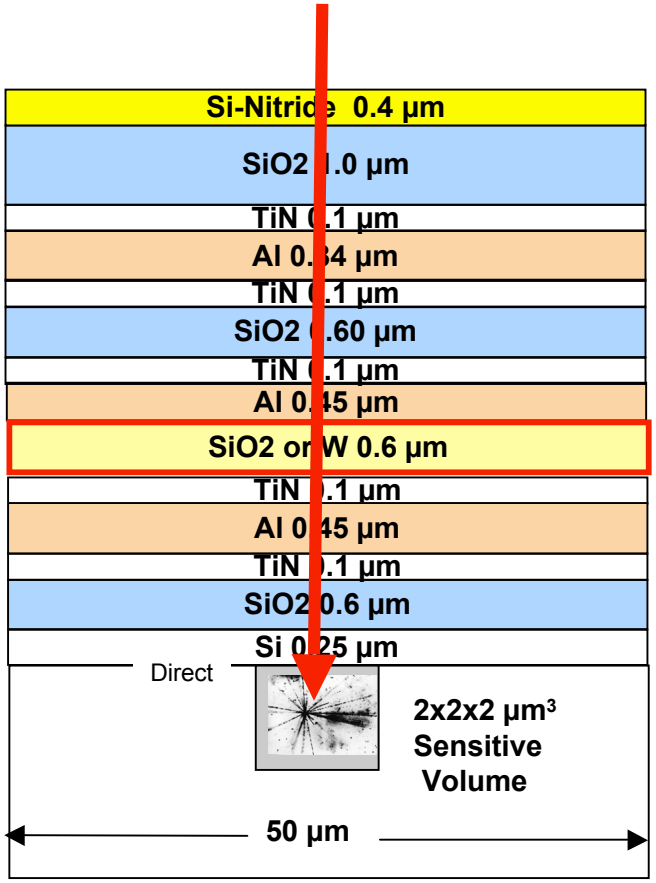


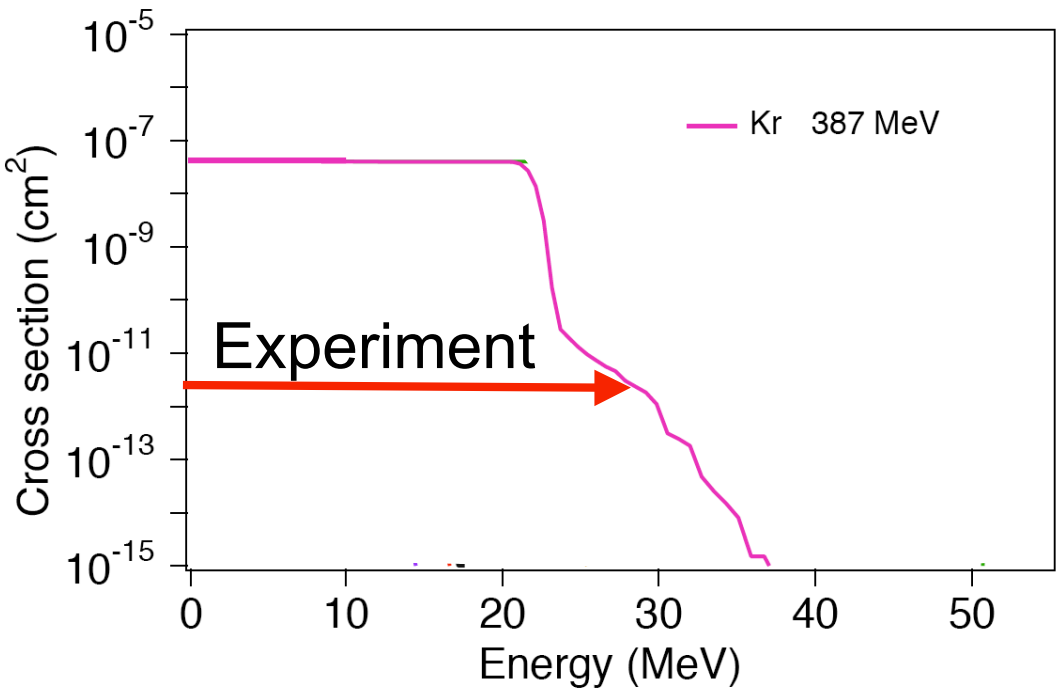
K.M. Warren, et. al IEEE Trans. Nuc. Sci., vol. 48, no. 6, Dec. 2005, pp. 2125 – 2131.

- **Run 1×10^9 particle**
  - **For each determine energy deposited in sensitive volume**
- **Histogram of energy deposition**
- **Reverse integrate histogram**
- **Divide counts by fluence**
- **For a fixed critical energy, the SEU cross section can be predicted**

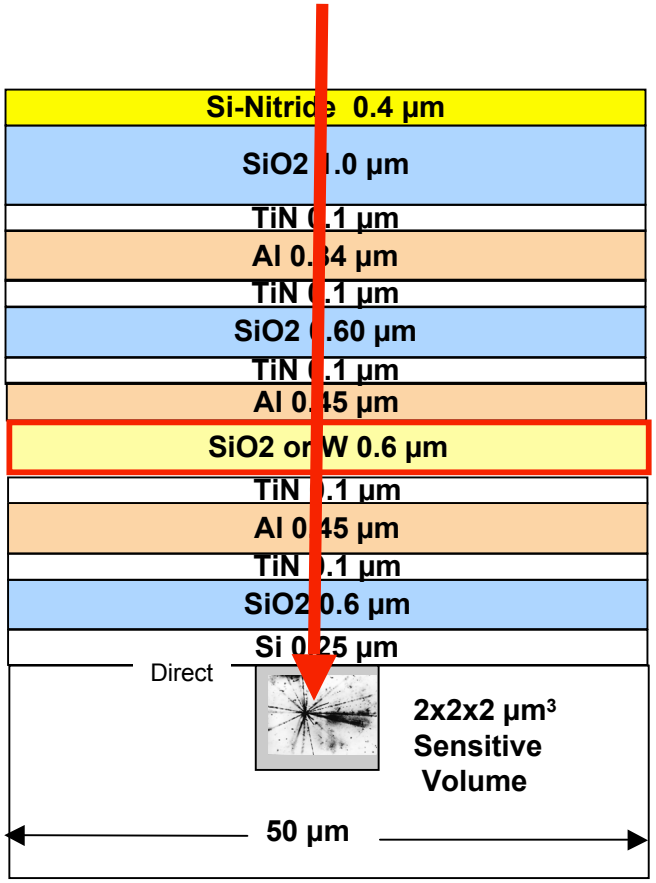


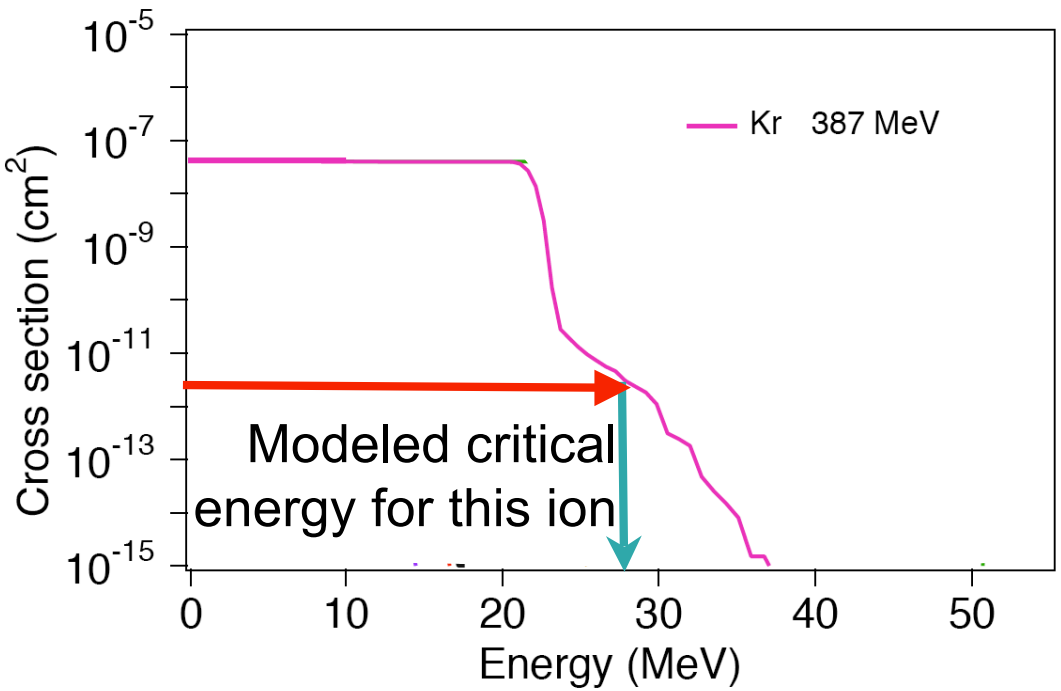
Determine Modeled Critical Energy for Kr @ 387 MeV



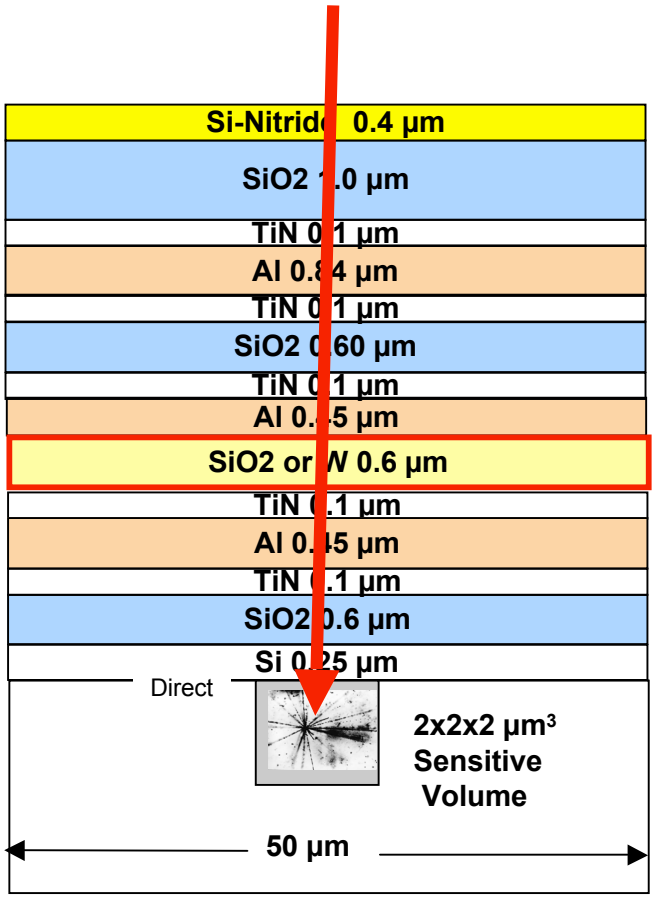


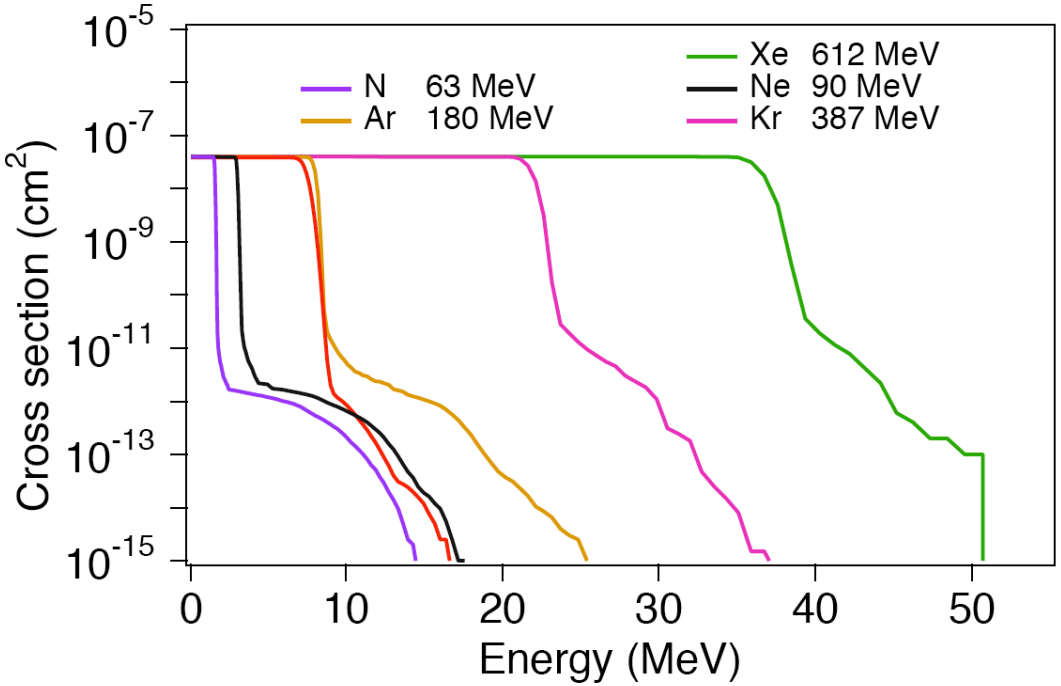
Contribution From Secondary Products in Overlaying Materials



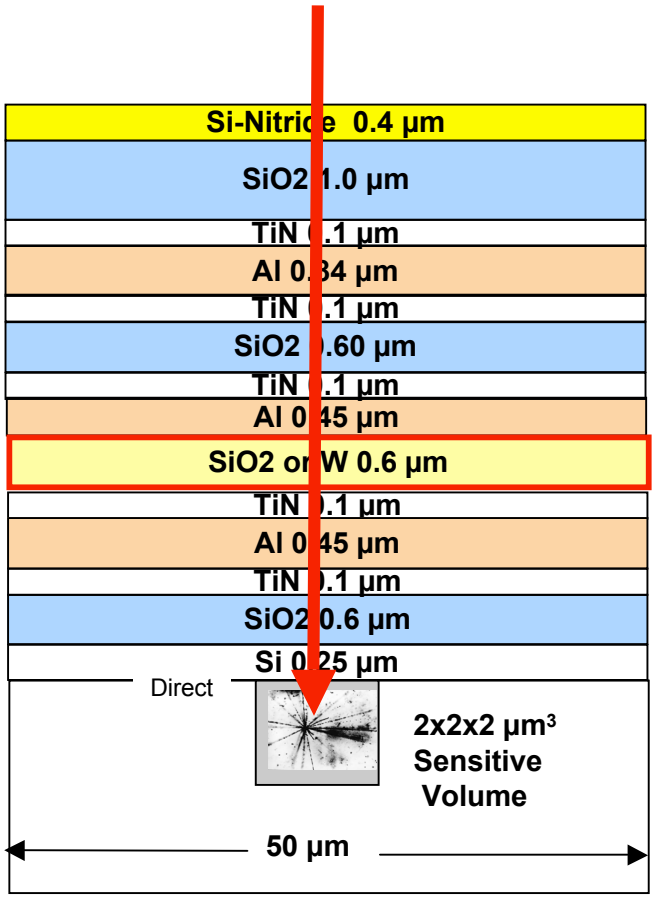


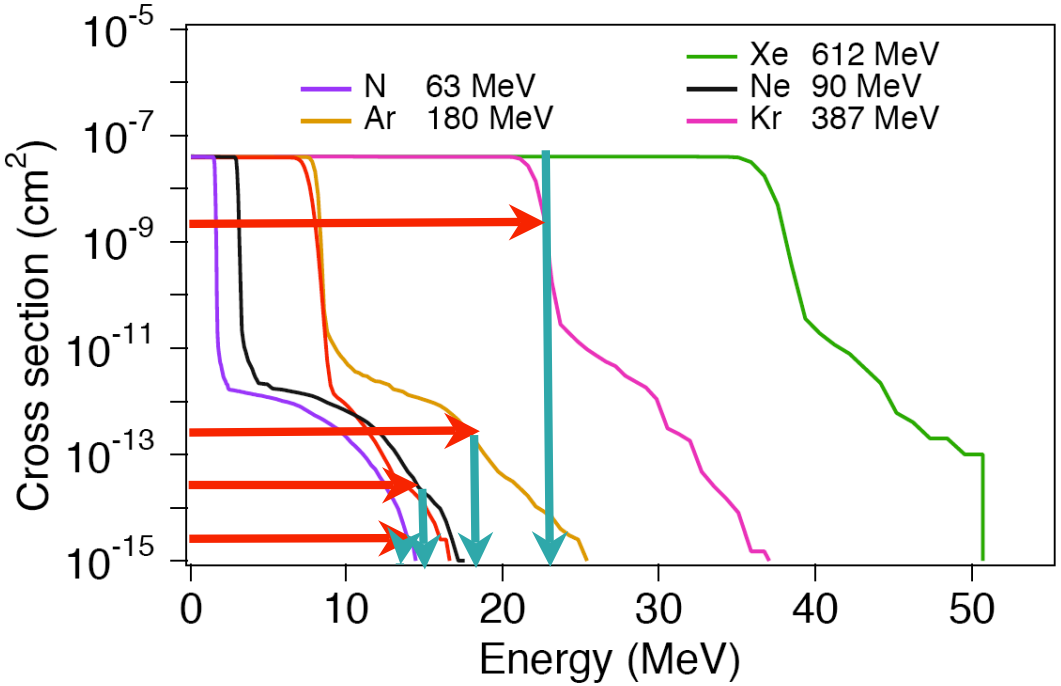
Determine Range for Modeled Critical Energies (i.e. Critical Charge)



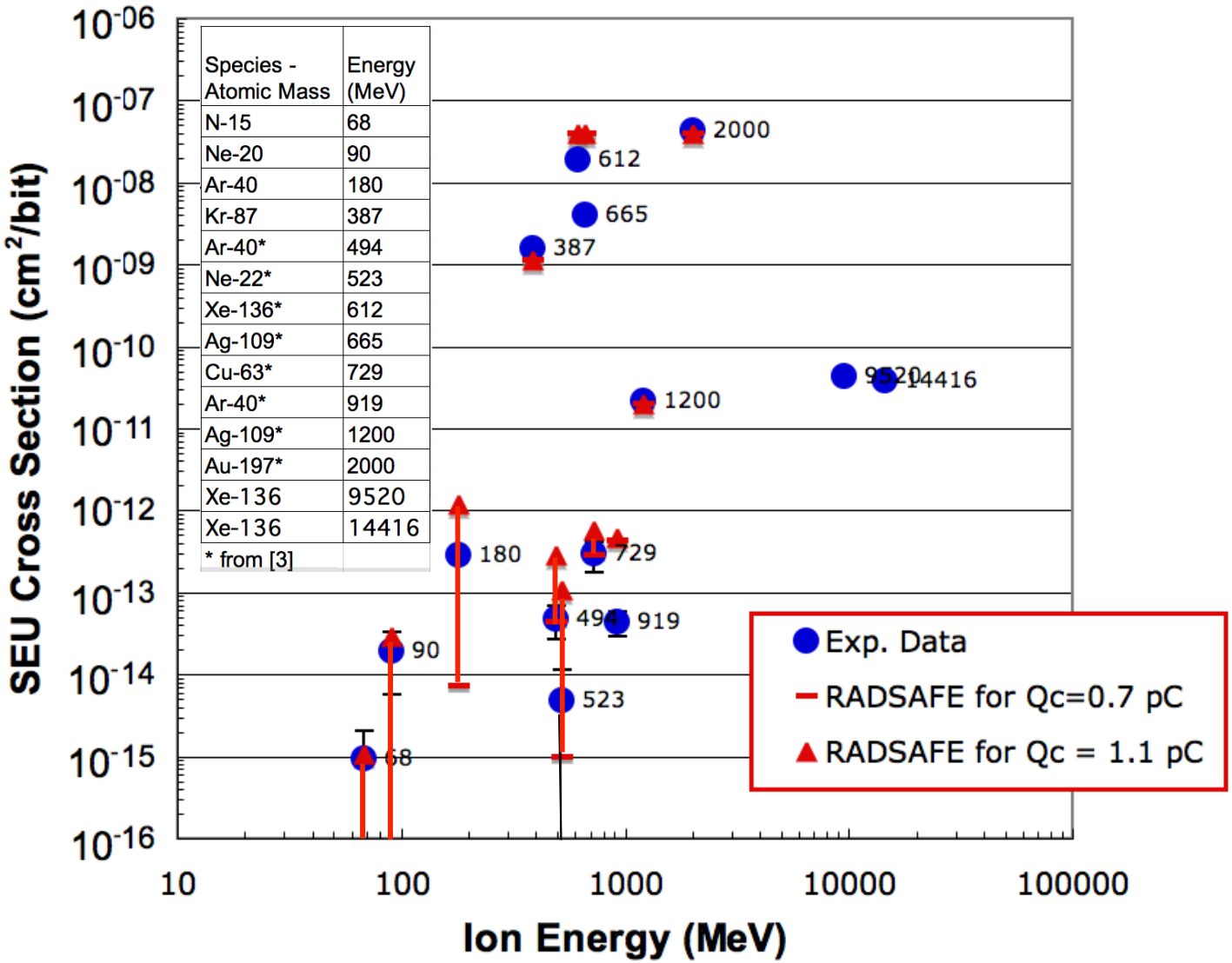


Determine Range for Modeled Critical Energies (i.e. Critical Charge)

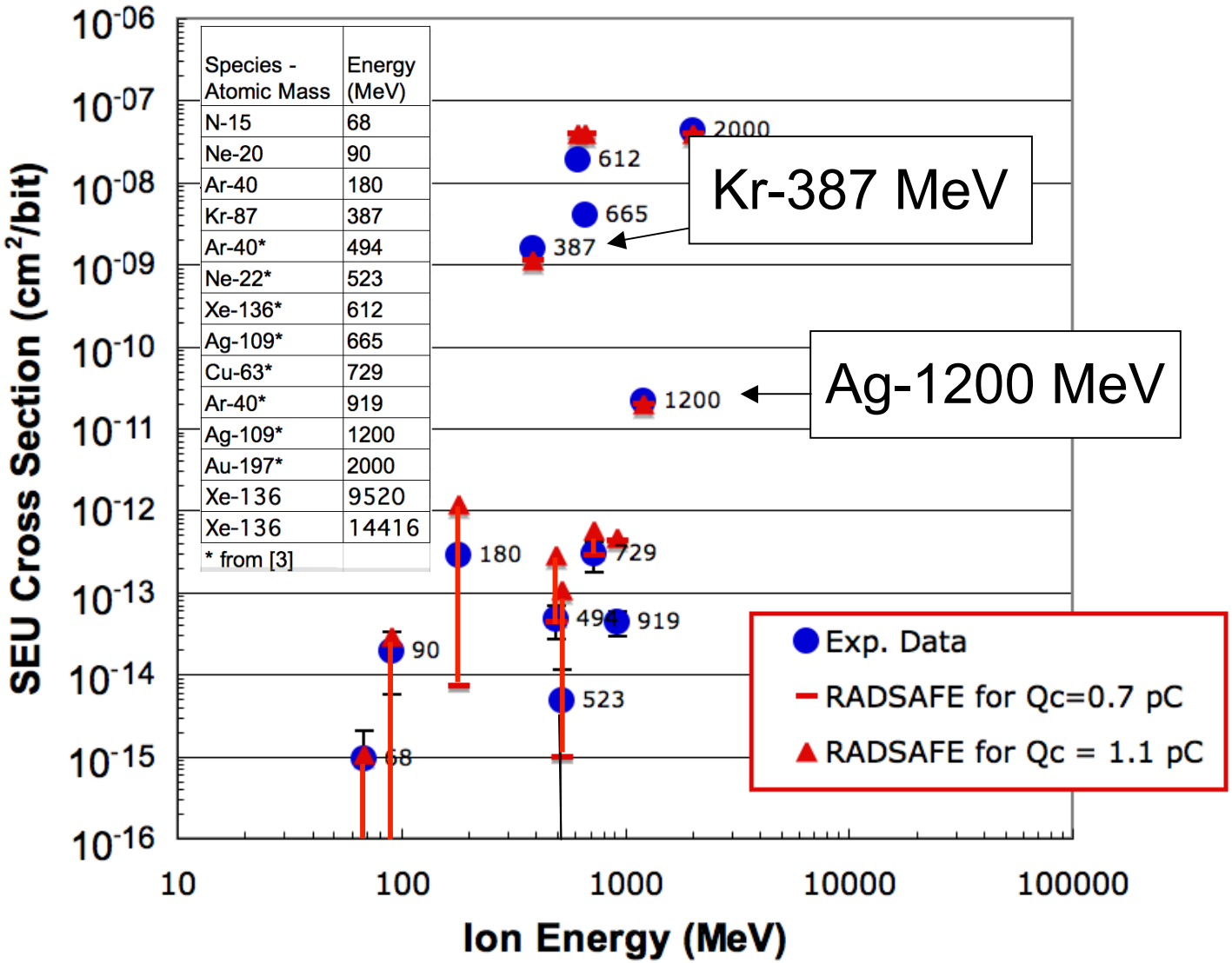




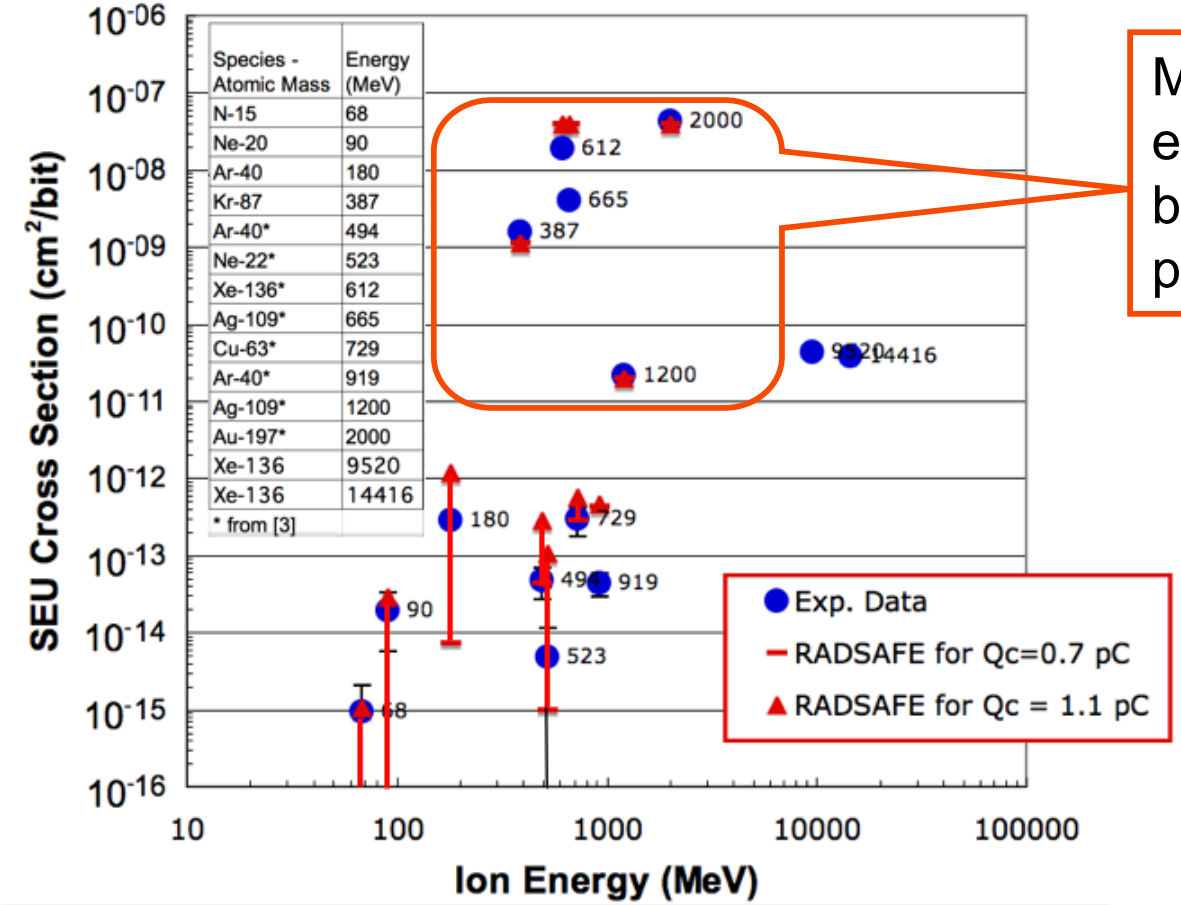
Using Ground Data to Calibrate Model



Using Ground Data to Calibrate Model



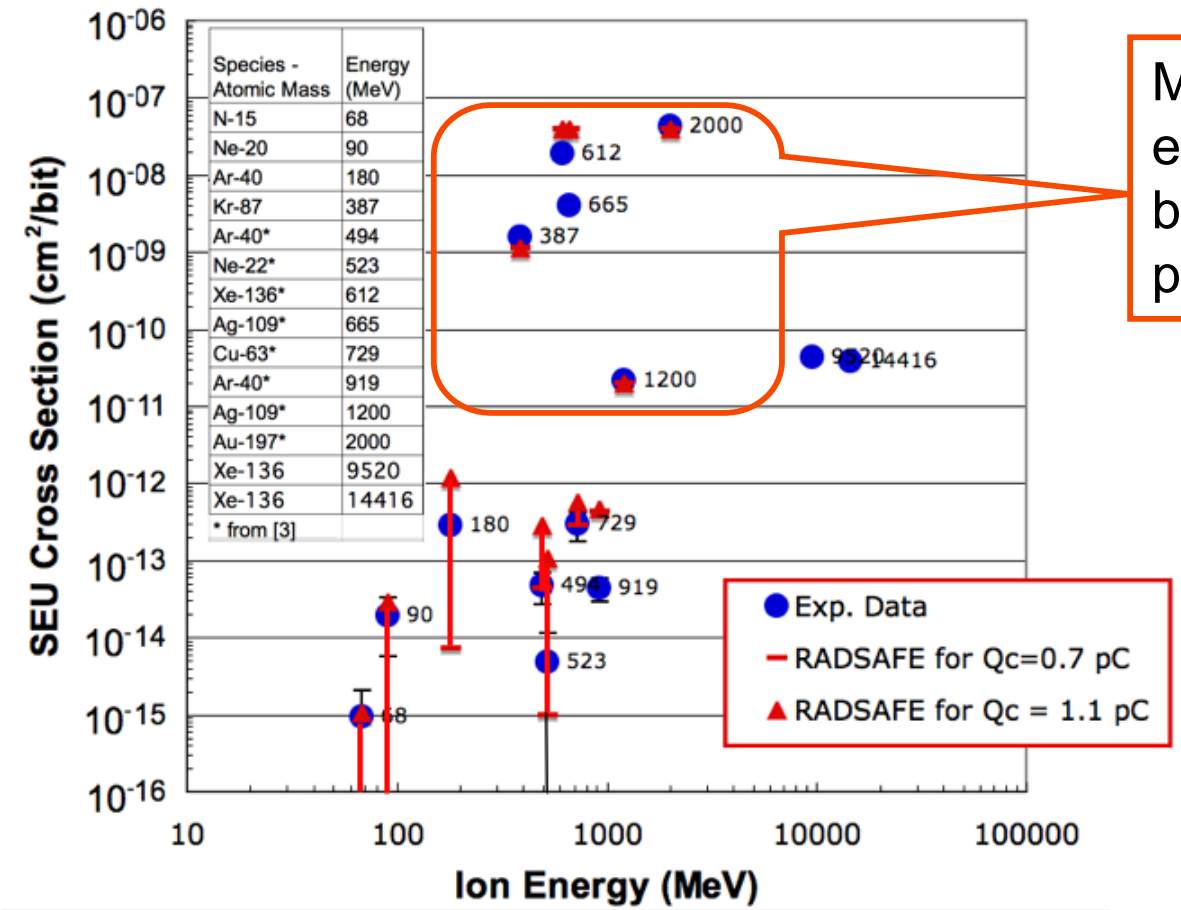
Using Ground Data to Calibrate Model



Model predicts that these events are **not** dominated by nuclear reaction products

Others are predicted to be dominated by nuclear reactions.

Using Ground Data to Calibrate Model

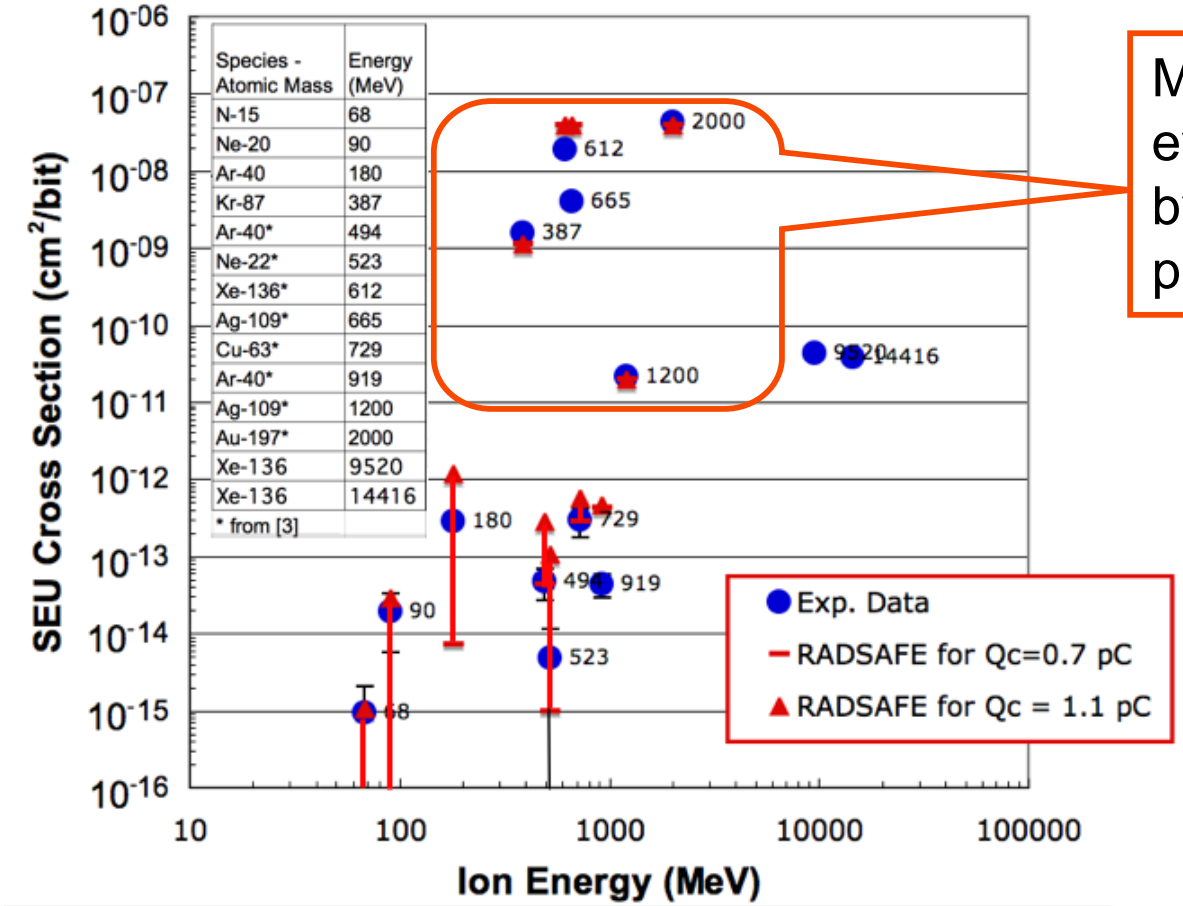


Model predicts that these events are **not** dominated by nuclear reaction products

Others are predicted to be dominated by nuclear reactions.

Limitations in Geant4 nuclear physics prevent computing nuclear reactions for Z>36

Using Ground Data to Calibrate Model



Model predicts that these events are **not** dominated by nuclear reaction products

Others are predicted to be dominated by nuclear reactions.

Limitations in Geant4 nuclear physics prevent computing nuclear reactions for Z>36

Uncertainty in Q_{crit} is due to:
- Systematic errors in Geant4 physics when predicting recoil production from nuclear reactions.
- Use of simple model for SEU sensitive volume.

RADSAFE Prediction of SEU Rate

Flux: Particles/m²/s/sr/MeV

MRED: Ion energy to deposited energy

Events/s/energy

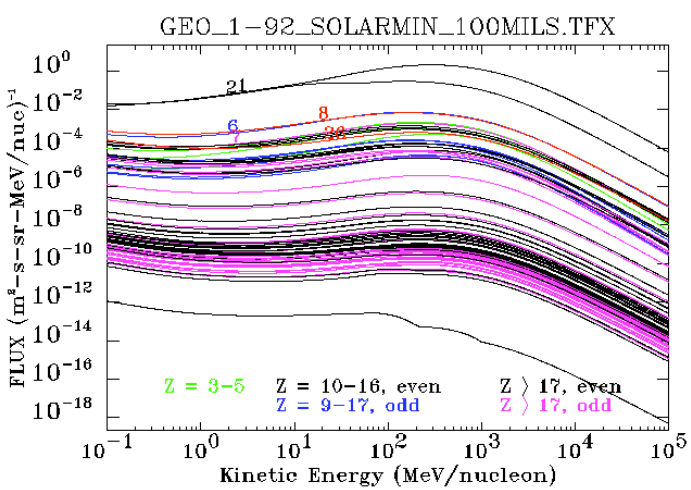
Monte Carlo

$$RATE \equiv R(E_d) = \int_{E_d}^{\infty} dE \left[\frac{dR(E)}{dE} = \sum_{z=1}^{92} \left(4\pi^2 \rho^2 \int_0^1 dr \left(\frac{\Phi_z(E_0(r))}{n(E_0(r))} \right) \cdot MRED_z(E_0(r), E) \right) \right]$$

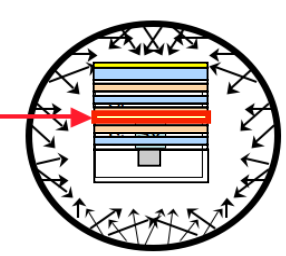
Sum all elements

Sample radius

Density of random ion energies

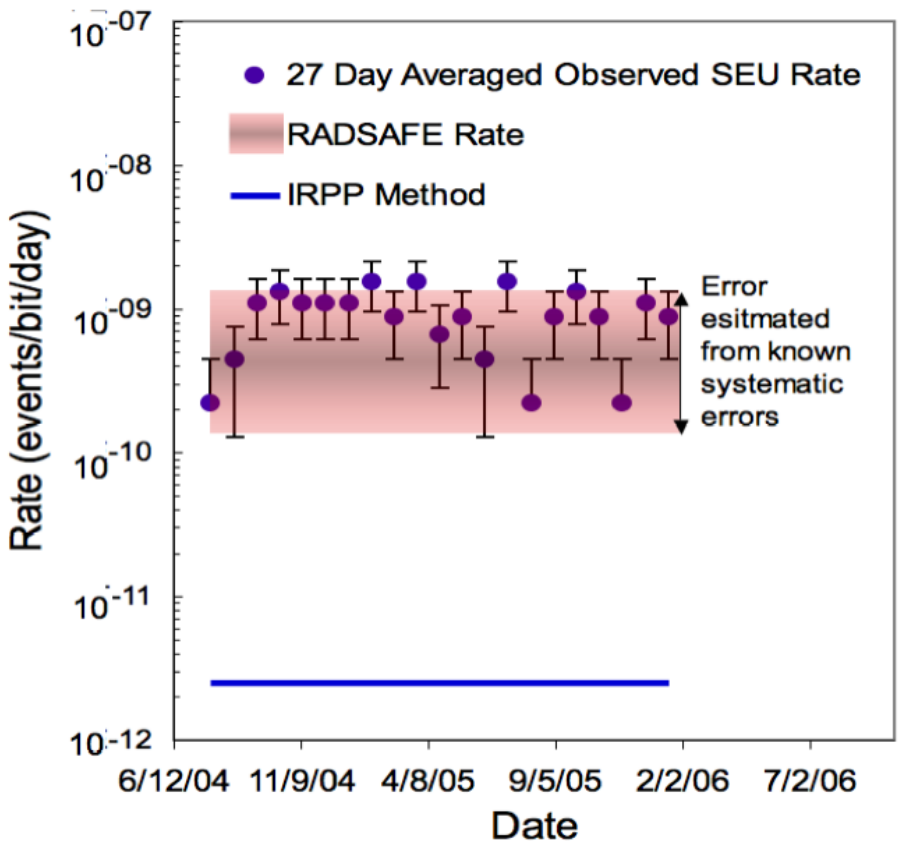


Multi-layered Stack



Observed and RADSAFE Predicted SEU Rate for a Modern RAD-HARD SRAM

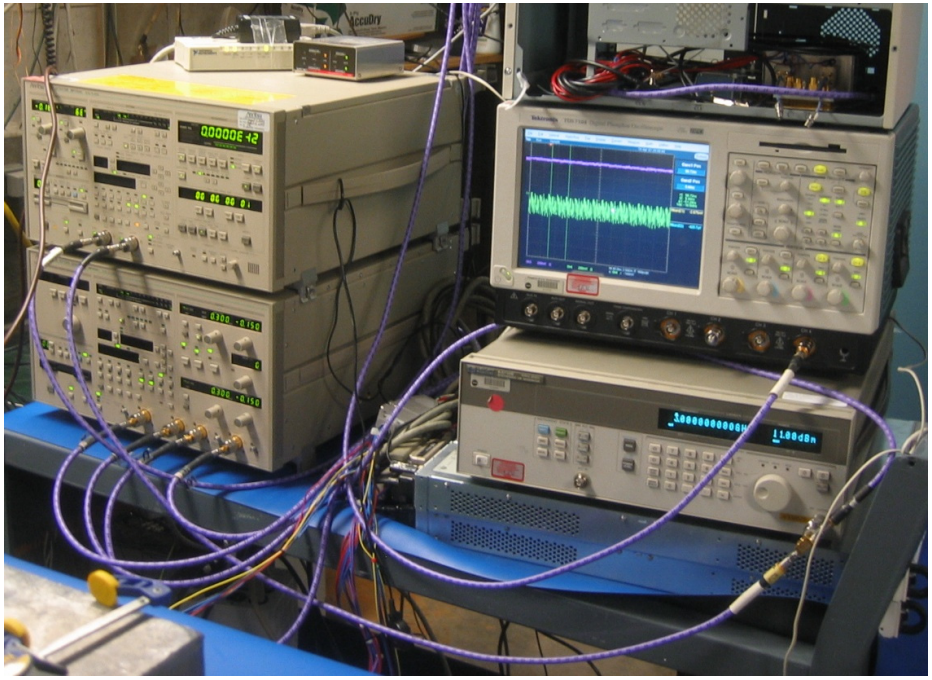
- SRAM used on NASA spacecraft
- Observed Average SEU Rate:
  - **$1x10^{-9}$ Events/Bit/Day**
- RADSAFE rate (includes reaction products):
  - **Between $1.3x10^{-10}$ and $1.3x10^{-9}$ Errors/Bit/Day**



Conclusions

- Clearly, heavy ion energy and species impact SEU response
  - Most obvious in circuits that are not sensitive to direct ionization effects from “low” LET particles and contain higher Z materials
- There is no reason to expect an increase SEU cross-section with increasing ion energy
  - Different mechanism dominate at different ion energies
  - LET and Effective LET concepts will not be valid for certain cases
- RADSAFE concept can be used to predicting error rates
  - Systematic errors can be large
  - Improvements in Geant4 nuclear physics models are needed
- Clear impact on heavy ion test methods
  - More research is needed to clearly define the recommendations
  - e.g., Fluences > 10^7 particles/cm^2, ion energy, species, and angle
- Ion energy and species will impact other SEEs
  - Single-event latchup for example

DURIP-funded High-Speed SEE Test Equipment



- 12.5 Gbit/s bit error rate tester
- 31.5 GHz analog signal generator
- 12 GHz real-time digital storage oscilloscope
- DC-40 GHz RF coax assemblies

- **Requires high-speed packaging**

- DC-40 GHz probe station
- 100 nm-step resolution stage
- Configure horizontally or ***vertically***
  - NIR laser irradiation
  - Broadbeam heavy ion

- **Eliminates need for high-speed packaging**