Application of Computational Physics Tools like GEANT4 for Studying Radiation Effects in Microelectronics

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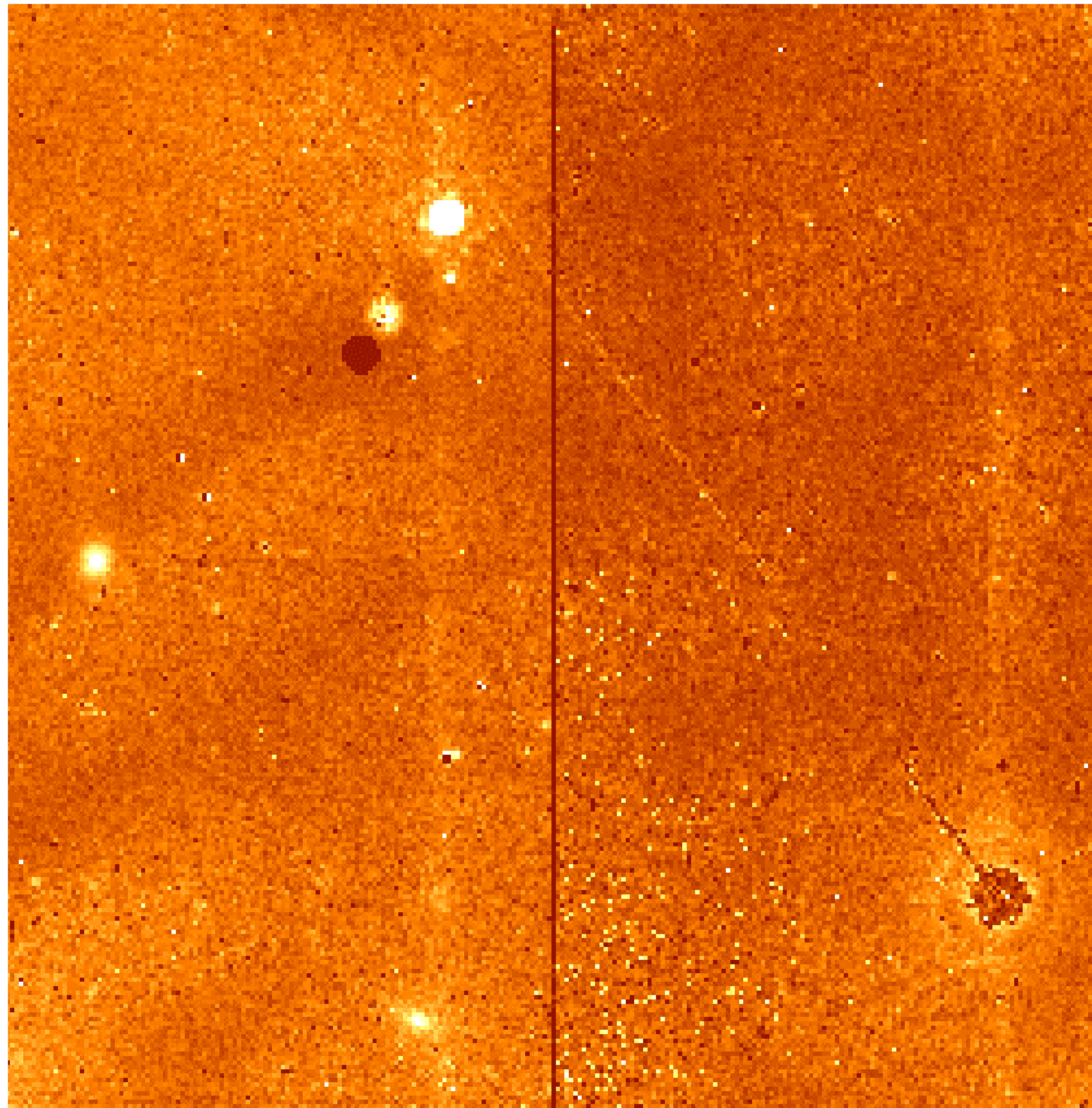
Supported in Part by:
- NASA Electronics Parts and Packaging (NEPP) Program
- Defense Threat Reduction Agency (DTRA)
- NASA Space Environment and Effects (SEE) Program
- NASA's James Webb Space Telescope (JWST)

Outline

- Introduction to space radiation effects in microelectronics
- Modeling on-orbit space radiation single event effects
  - Summary of current analytical methods and the short falls of those methods
  - Applications of computation physics tools (GEANT4 and other tools)
- Future directions in applied computation physics for SEE

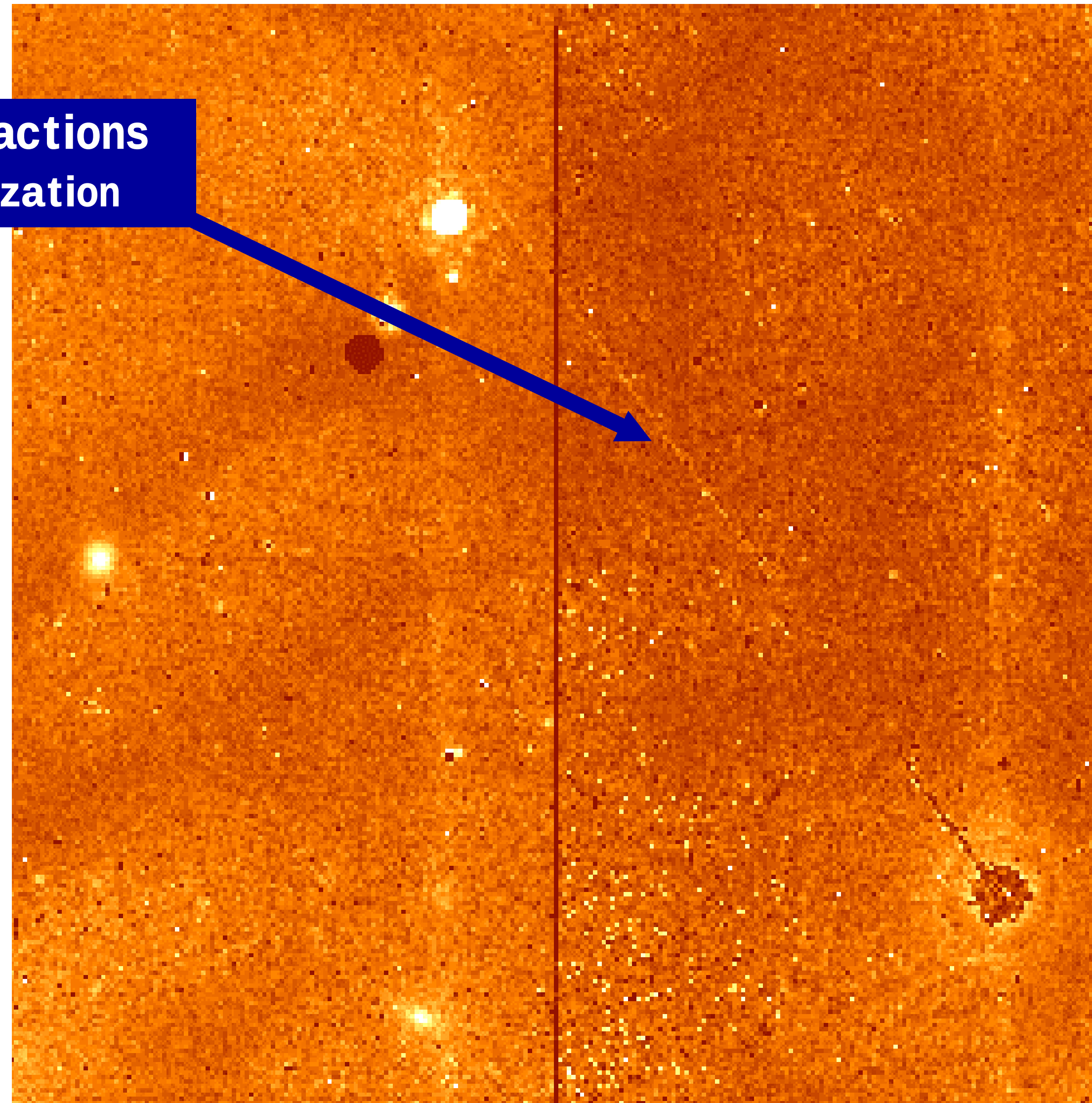
Space Radiation Interactions as Observed by NICMOS



http://www.stsci.edu/hst/nicmos/performance/anomalies/bigcr.html

Space Radiation Interactions as Observed by NICMOS

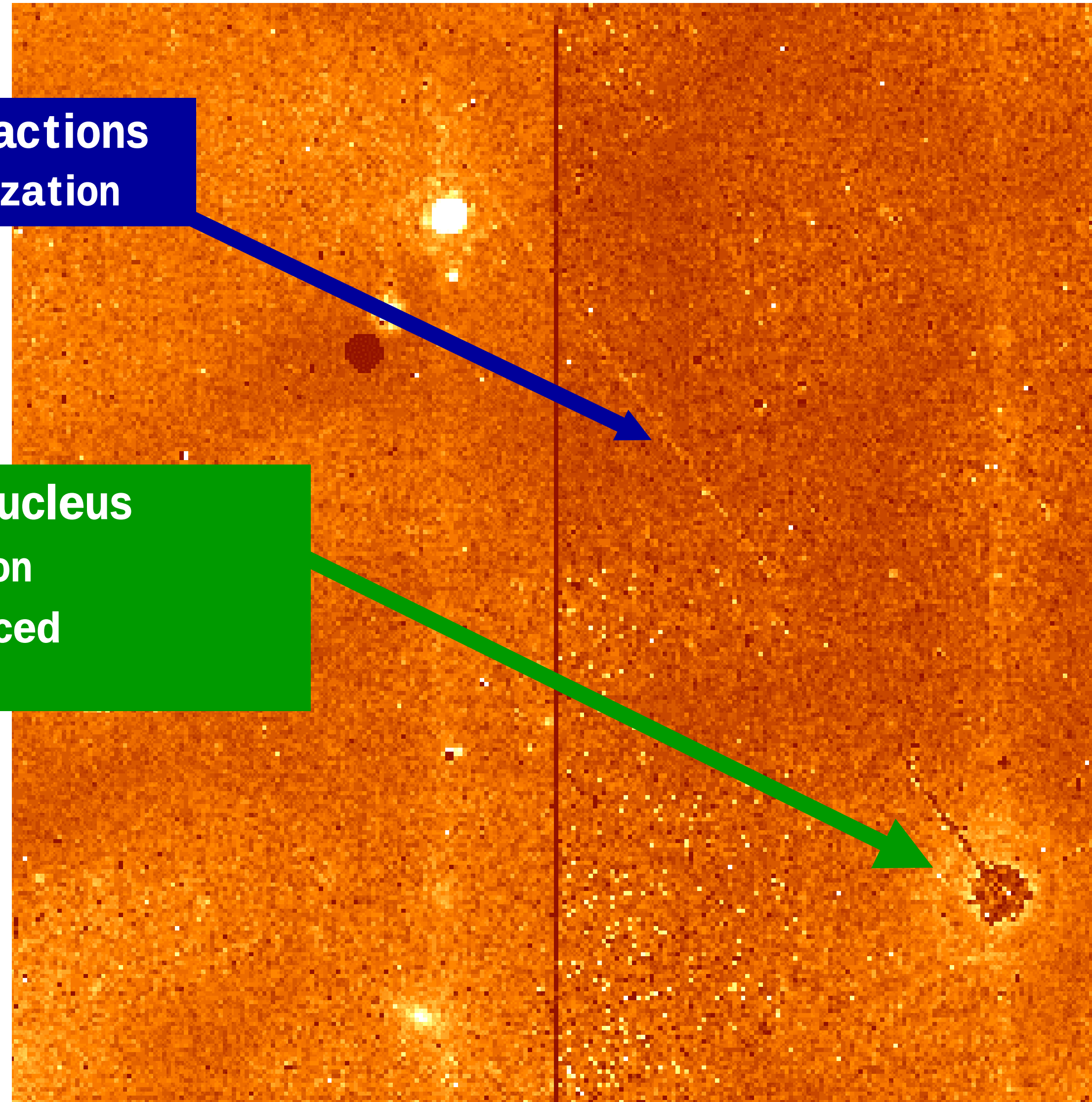
- **Atomic Interactions**
  - **Direct Ionization**



http://www.stsci.edu/hst/nicmos/performance/anomalies/bigcr.html

Space Radiation Interactions as Observed by NICMOS

- **Atomic Interactions**
  - **Direct Ionization**
- **Interaction with Nucleus**
  - **Indirect Ionization**
  - **Nucleus is Displaced**

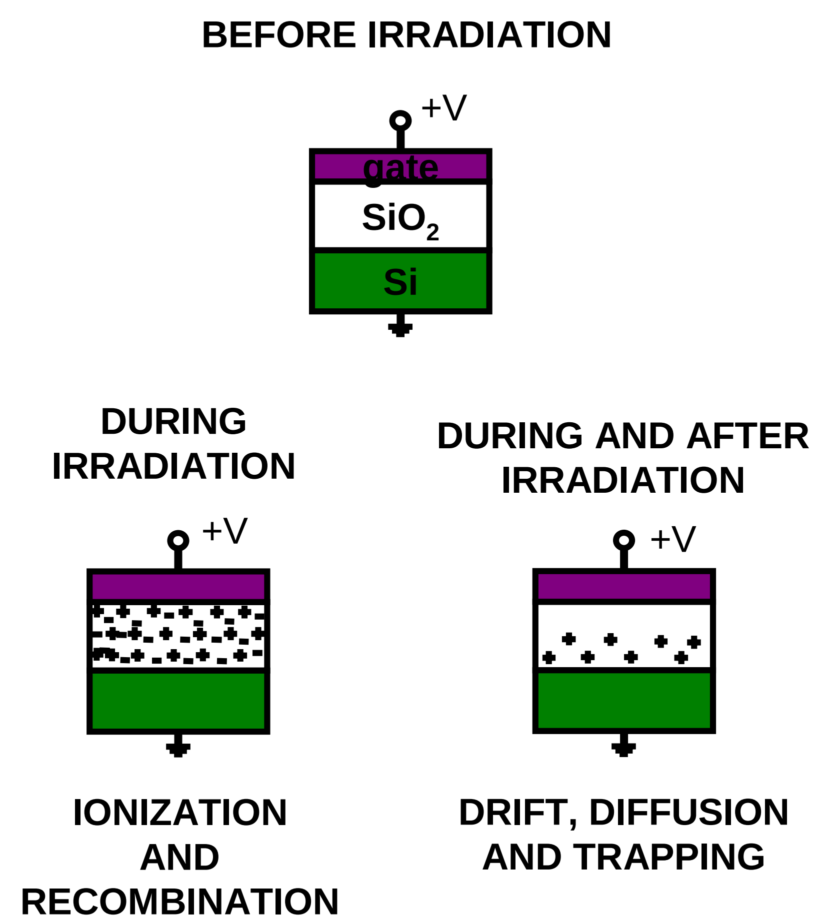


http://www.stsci.edu/hst/nicmos/performance/anomalies/bigcr.html

Cumulative Degradation for Multiple Ionizing Events

Total Ionizing Dose (TID)

- Permanent damage, some annealing occurs for certain devices
- Can lead to Functional failure

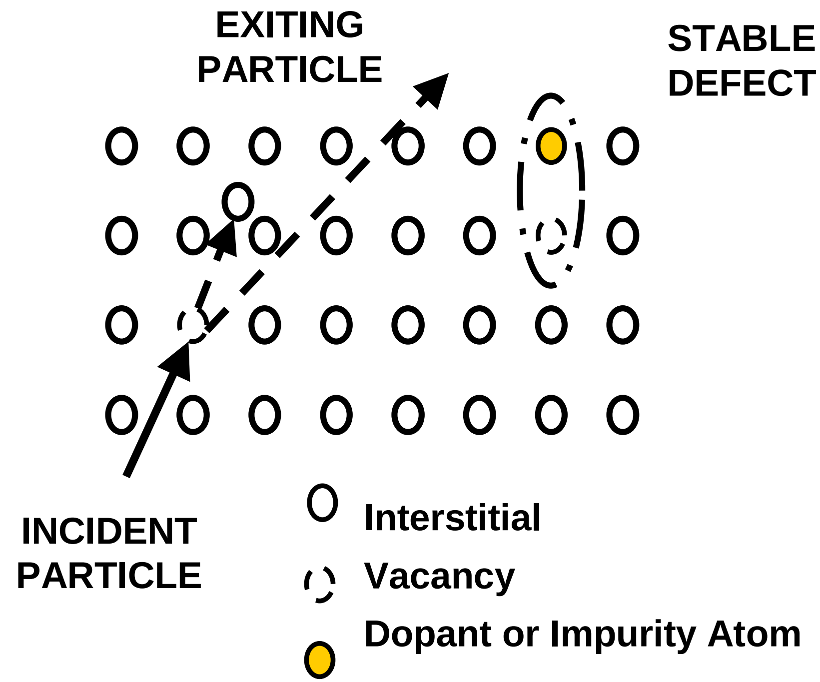


J.L. Leray, Notes from 1999 IEEE Nuclear and Space Radiation Effects Conference Short Course

Cumulative Degradation and Prompt Response for Non-Ionizing Events

Displacement Damage

- Cumulative effects that cause device performance degradation
  - Displacement Damage Dose
- Prompt effects causing device performance degradation
- Permanent damage, some annealing occurs for certain devices

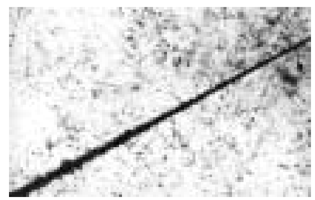


P.W. Marshall and C.J. Marshall, Notes from 1999 IEEE Nuclear and Space Radiation Effects Conference Short Course

Prompt Ionizing Events

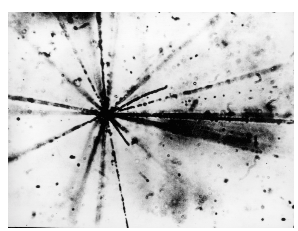
Single Event Effects (SEE)

- Direct Ionization
  - Typically Heavier Ions (Z>1)
  - Linear Energy Transfer (LET)
    - Energy per length



Direct

- Indirect Ionization
  - LET of fragments from nuclear reaction
  - Proton Energy



Indirect

P.J McNulty, Notes from 1990 IEEE Nuclear and Space Radiation Effects Conference Short Course

Prompt Ionizing Events

Single Event Effects (SEE)

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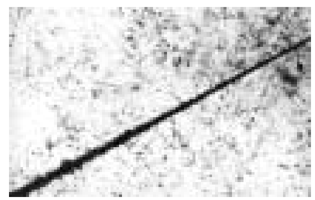

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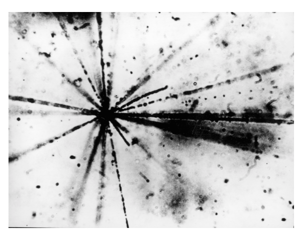

Indirect

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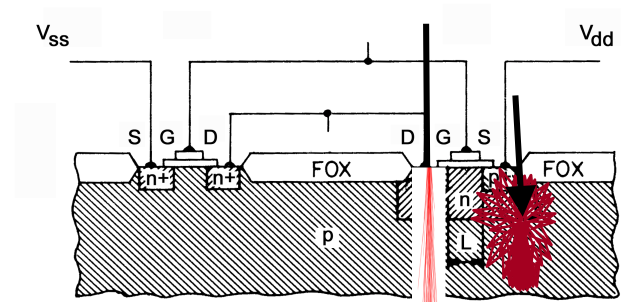
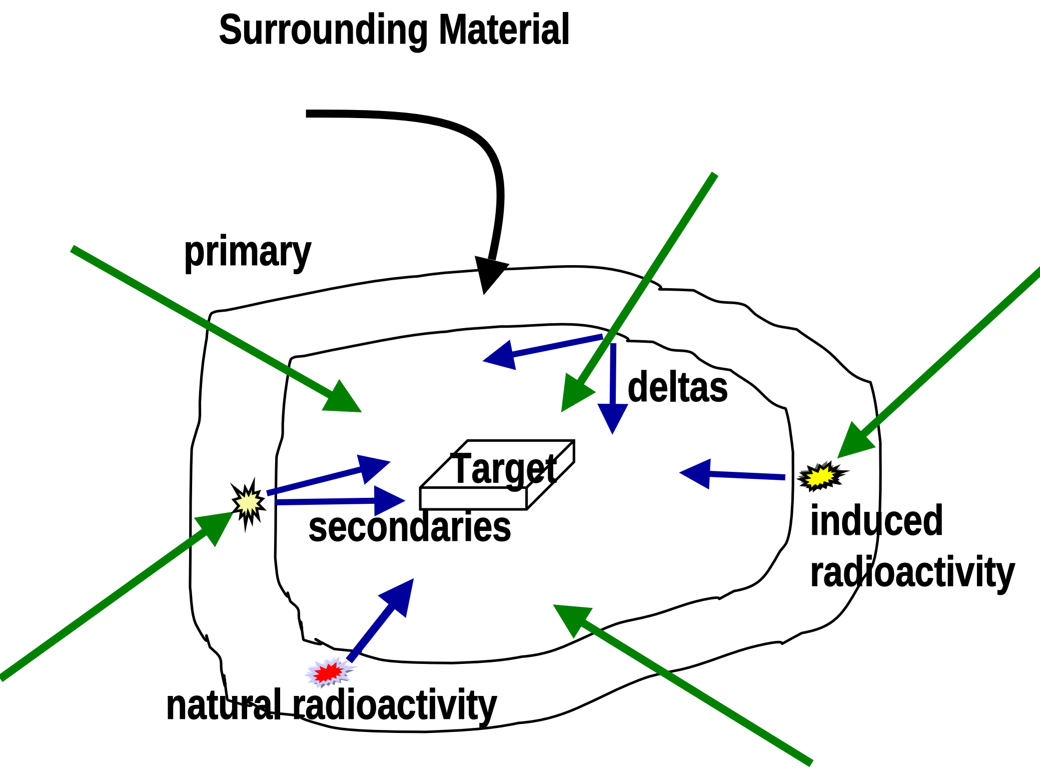


Charge collected on a sensitive node in an electrical circuit causing an unwanted change in information stored on the component

- Single Event Upset
- Single Event Latchup
- Single Event Transient
- Single Event Gate Rupture
- Single Event Functional Interupt
- Single Event …

Modeling the Interaction of the Space Radiation Environment with the Spacecraft and Targets



Predictive models needed to estimate on-orbit performance:

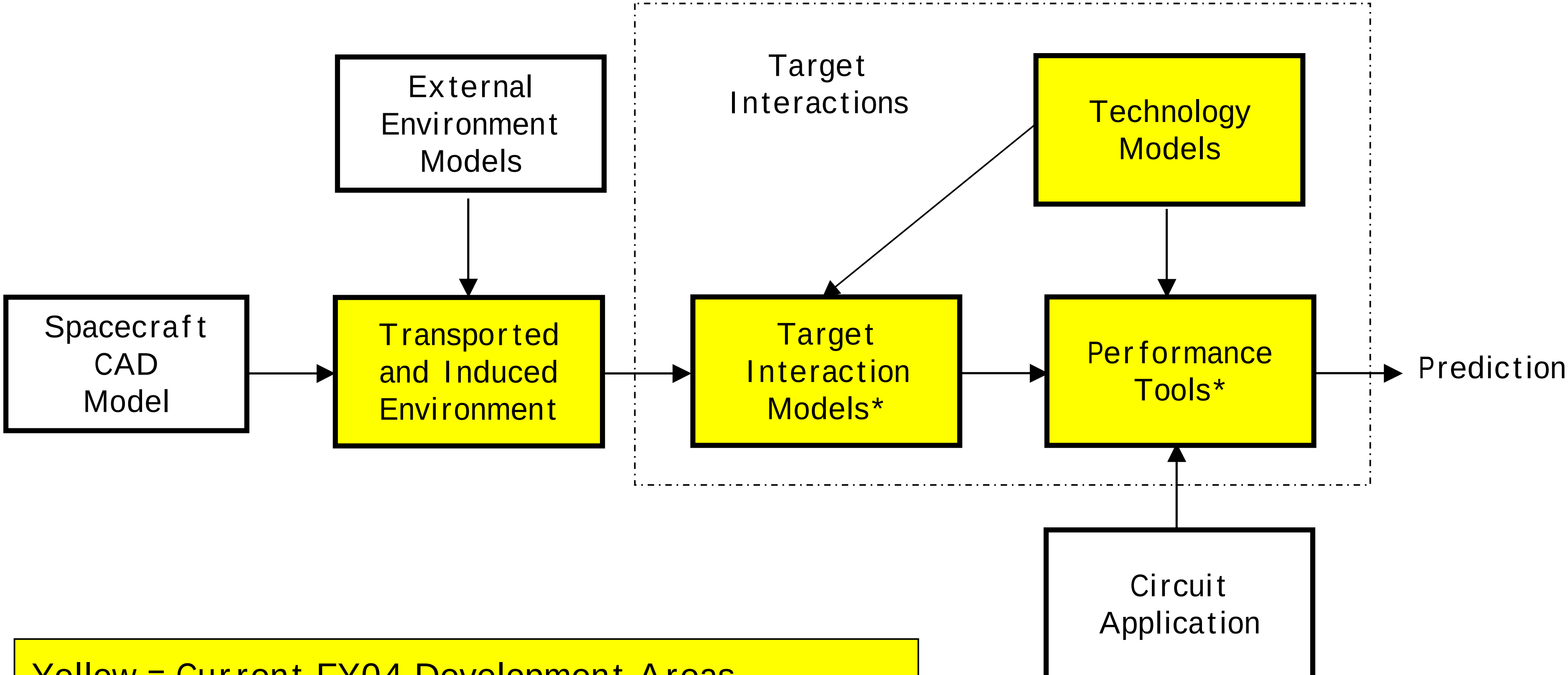
- External space radiation environment
- Transported environment through the spacecraft materials
  - Material surrounding the target
  - And, for certain cases, the target itself
- Effects on semiconductor devices (Target)

Monte Carlo Based Computation Physics Tools Currently Used at NASA/GSFC

- GEANT4
  - A multi-national team of physicists and engineers are developing Geant4 for the express purpose to Monte Carlo simulation of the passage of particles through matter.
  - Its application areas include high-energy physics and nuclear experiments, medical, accelerator and space physics studies.
- EMPC Inc.'s (a private company) NOVICE code suite
  - Developed to be a user-friendly, engineering tool for use, in part, by the space radiation effects community.
  - Its developer is highly regarded as an expert in radiation transport by the space radiation effects community.
- The Los Alamos National Laboratory's Monte Carlo N-Particle eXtended (MCNPX)
  - A general-purpose computer code that can be used for particle transport through materials.
  - Its application areas are similar to Geant4.

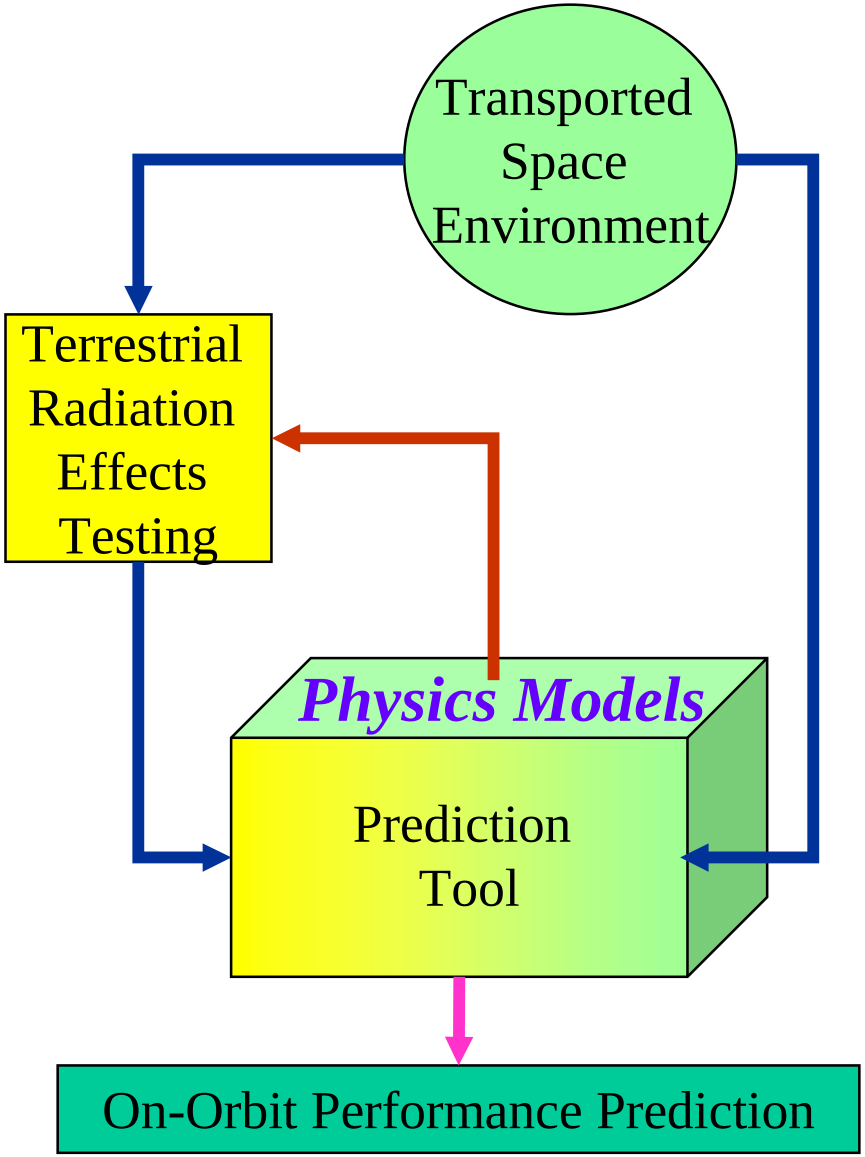
- NASA's Radiation Effects Array Charge Transport (REACT)
  - Simulation of charge transport through a semiconductor
  - Quasi-device physics (QDeP) code
- Clemson University Proton Interaction in Devices (CUPID)
  - Simulation of proton spallation reactions in Silicon
  - Tracks energy deposited in a right Rectangular Parallelepiped (RPP) volume

Space Computational Radiation Interaction Performance Tools (SCRIPT) – Simplified View



Yellow = Current FY04 Development Areas
*NEPP/DTRA/SEE : Evaluation of different MC codes for space flight applications
JWST : Develop computational methods for IR FPA

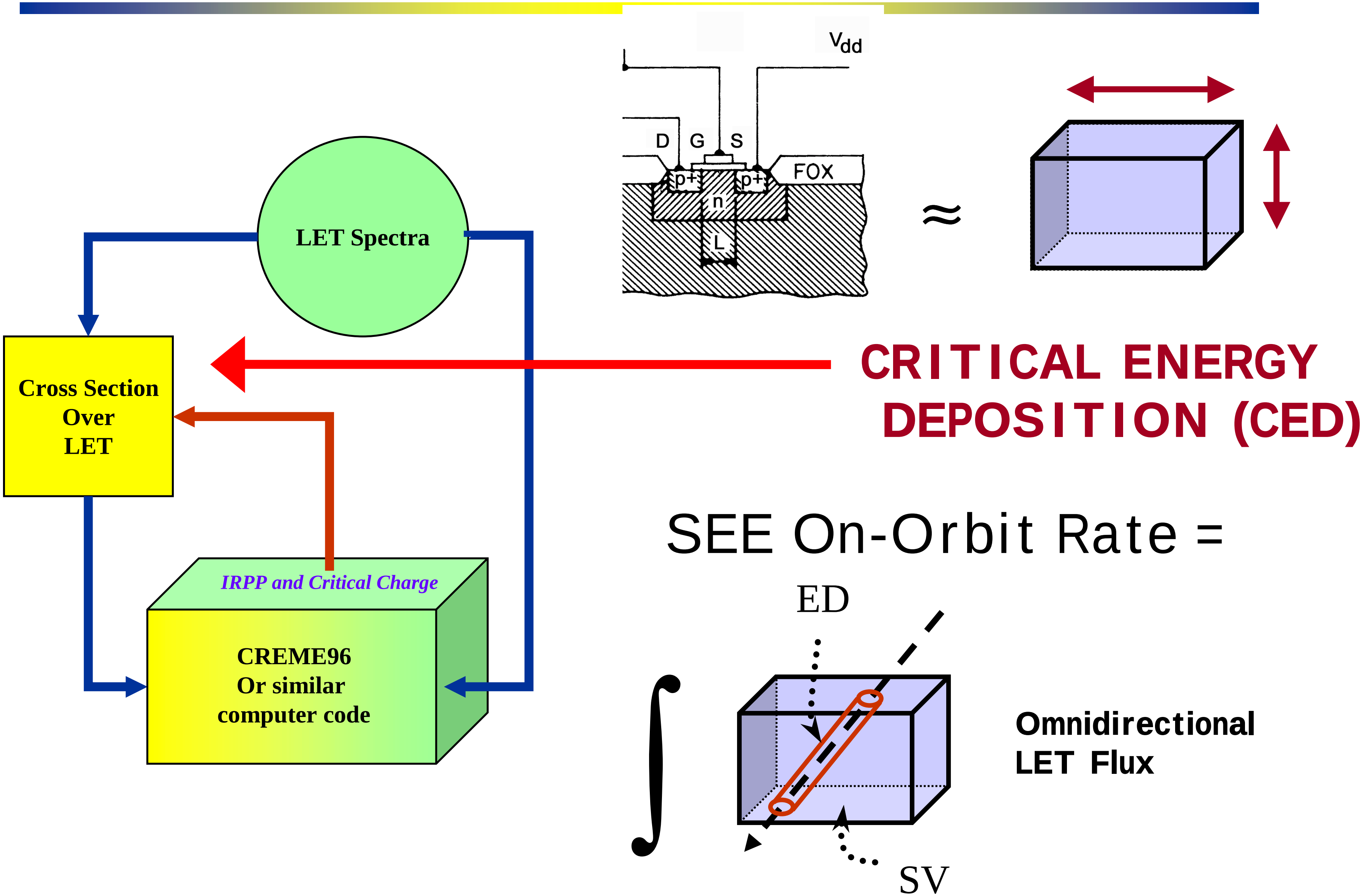
General On-Orbit Performance Prediction



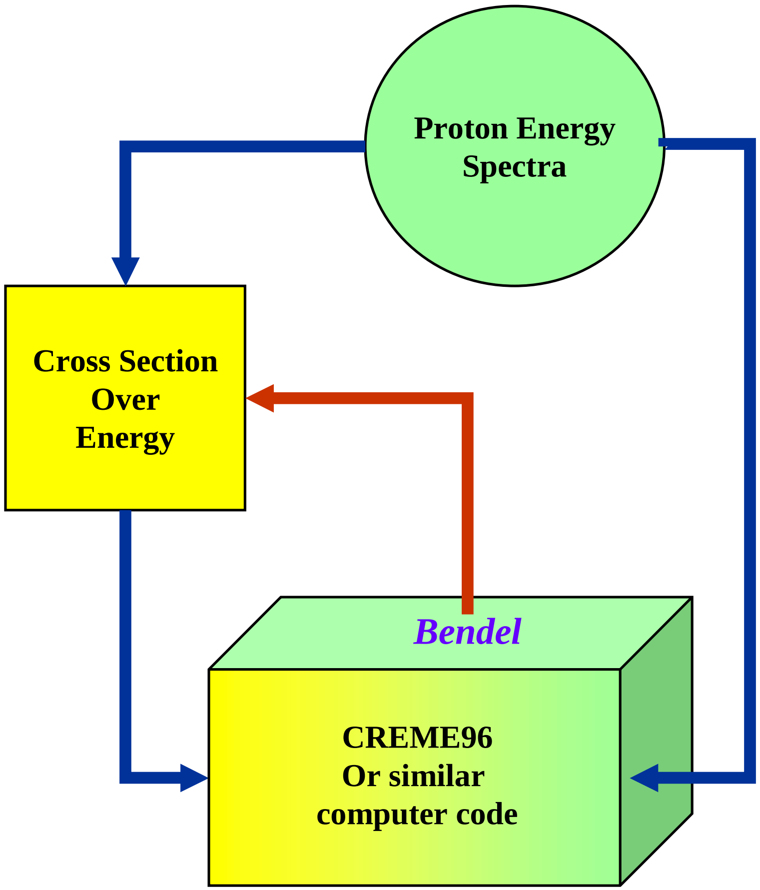
- The details of each step in this process depend on the type effect that is being analyzed
  - e.g. prompt response (SEE) will be different than cumulative degradation (TID)

This talk is focused on SEE

Classical Heavy Ion SEE Rate Prediction Technique



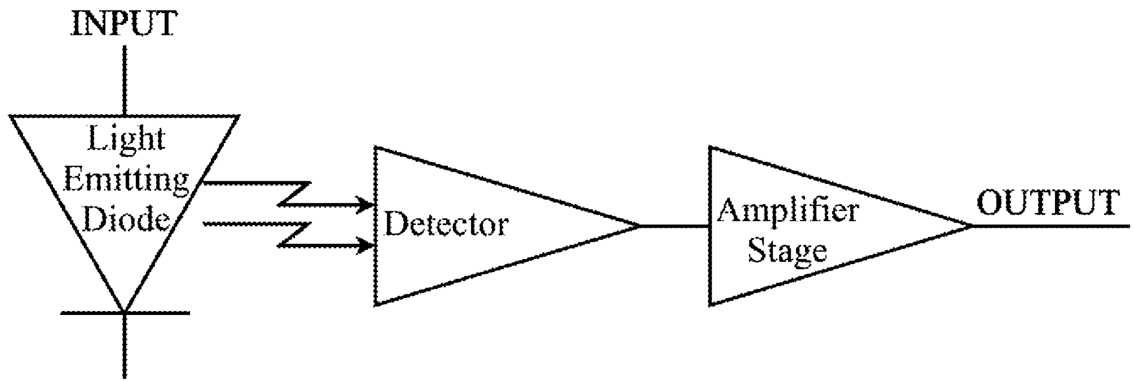
Classical Proton SEE Rate Prediction Technique

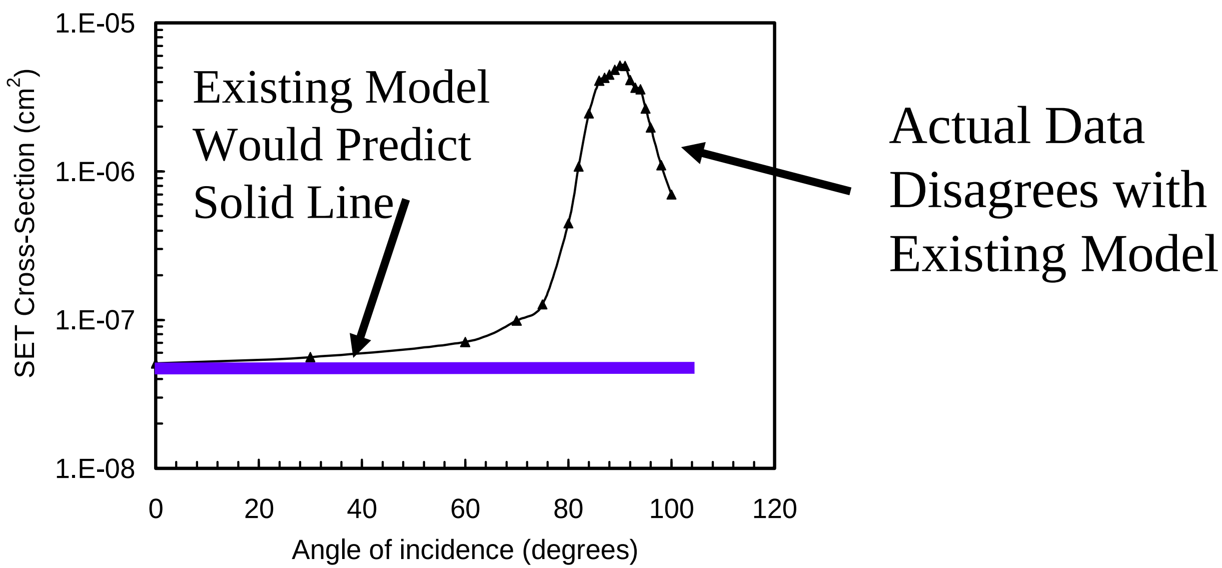


SEE On-Orbit Rate =

$$\int \text{Measured Cross Section At a certain energy} * \text{Space proton Flux at the energy} \, dE$$

Examples of the Breakdown of These Assumptions: SETs in Optocouplers and Optical Data Links

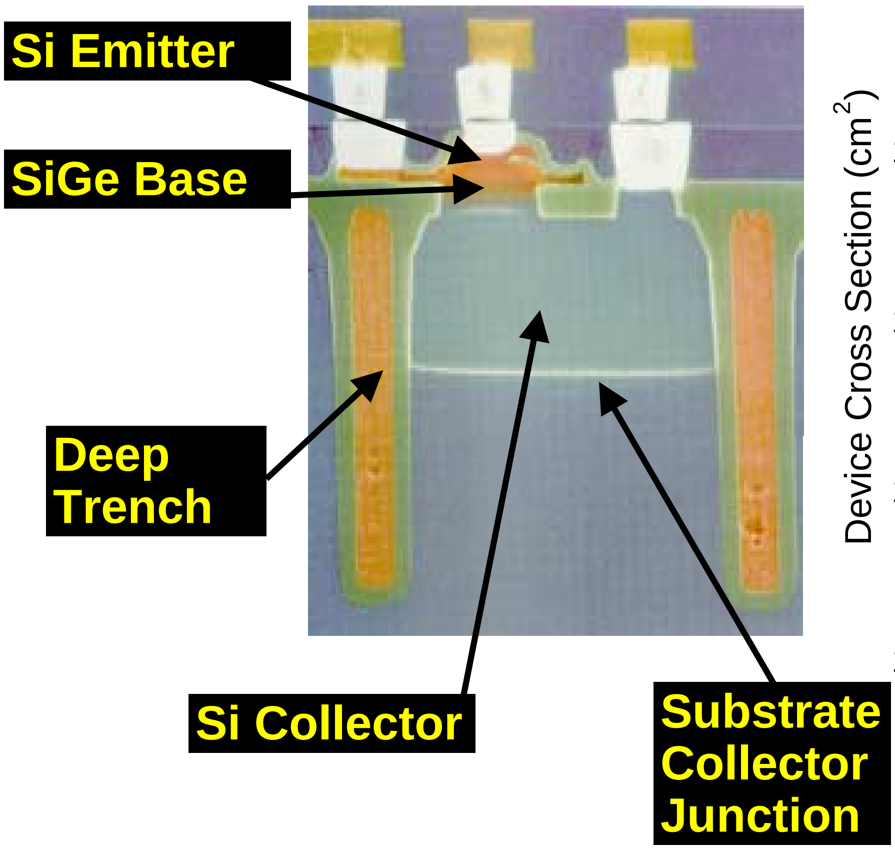




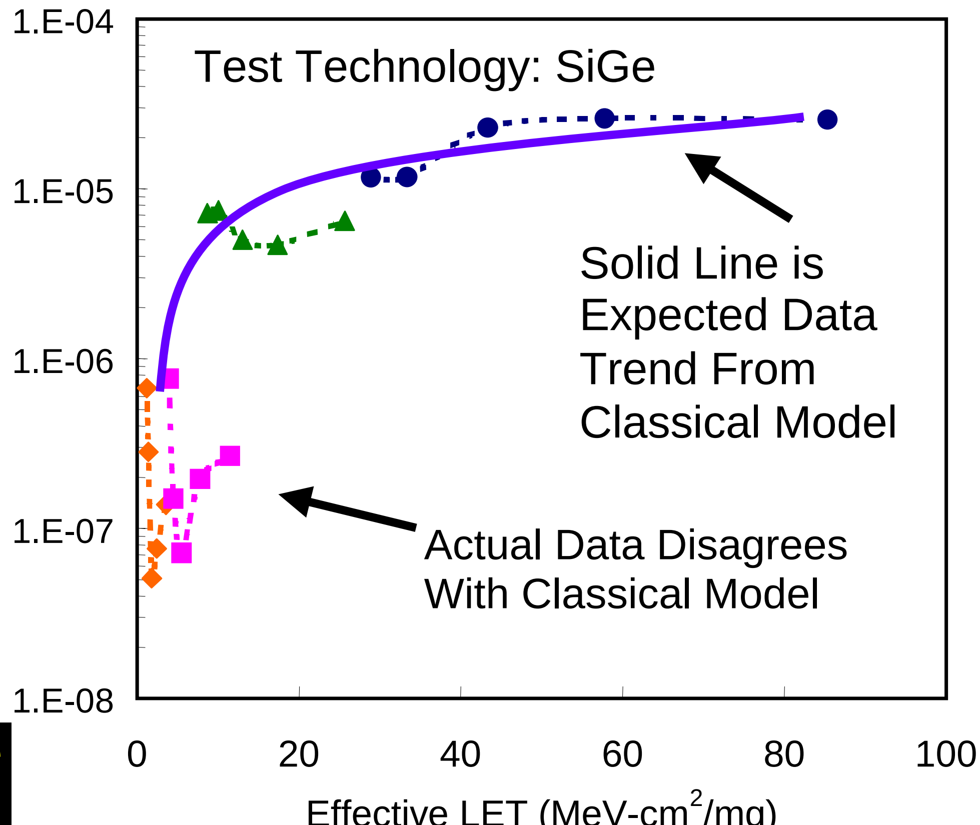
- The angular dependence was attributable to combined effects of direct and indirect ionization due to protons.

Examples of the Breakdown of These Assumptions: Application to Modern Technology

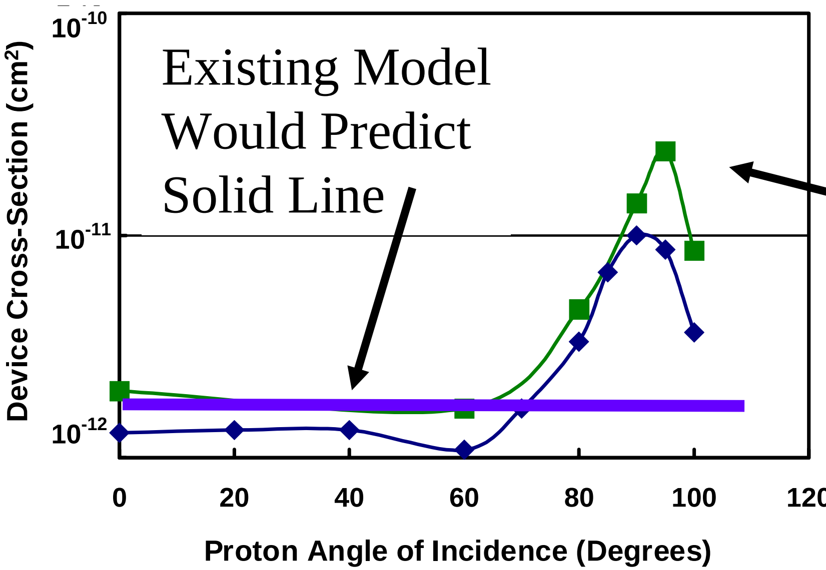
Cross Section of IBM's 0.5 Micron UHV/CVD SiGe



IBM photo from Jan. '00 IEEE Spectrum

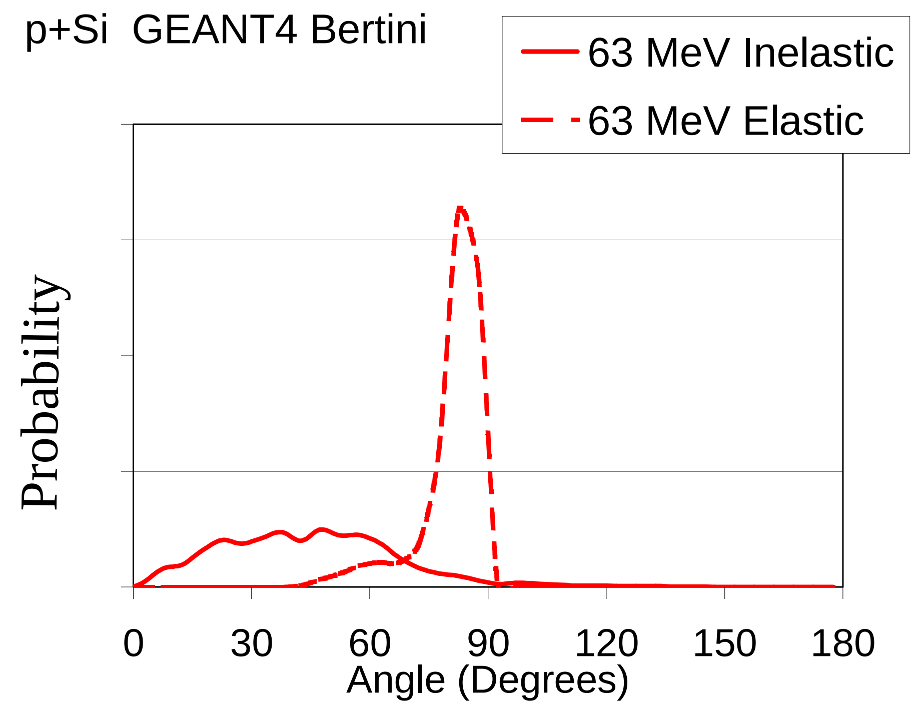


Examples of the Breakdown of These Assumptions: Proton-Induced SEUs in Sensitivity in SOI



Actual Data Disagrees with Existing Model

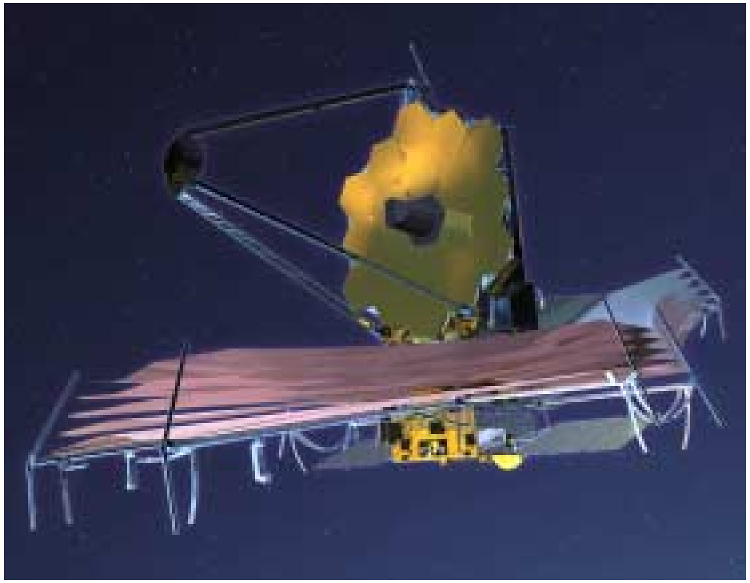
Use GEANT4 to better understand the basic mechanism for the effect

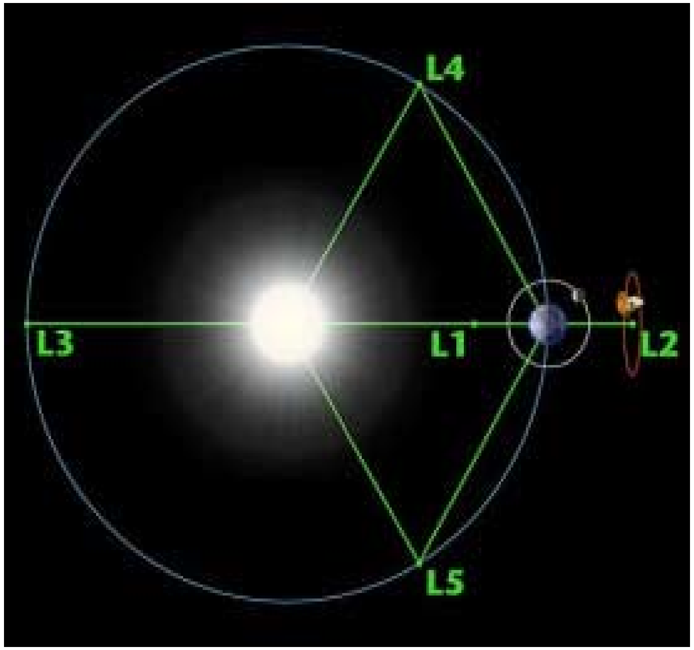


Examples of the Breakdown of These Assumptions

Monte Carlo Techniques Applied to

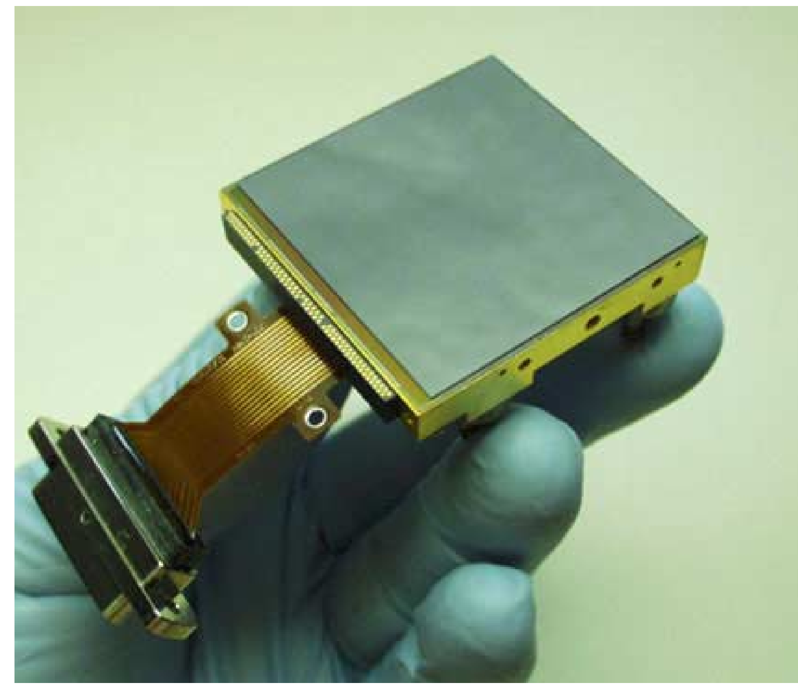
James Webb Space Telescope
NIRspec and NIRcam
IR Focal Plane Arrays



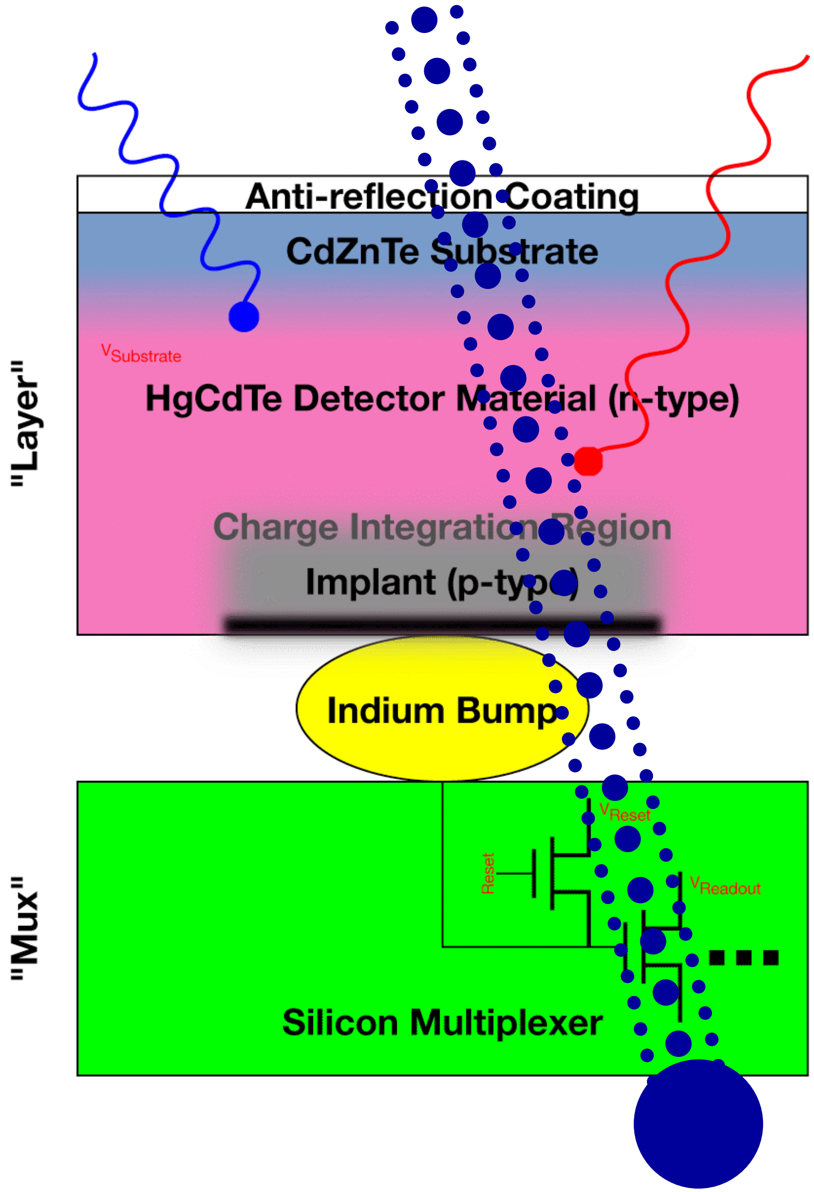


JWST IR Focal Plane Array Detectors

- Radiation induced transient (Prompt Response)
  - Low noise requirement: 3-10 electrons for 1000 sec integration time
- Permanent degradation (TID and Displacement Damage)
  - Requirement of <4% effected after 5 year mission goal
  - Topic of next talk given by Bryan Fodness

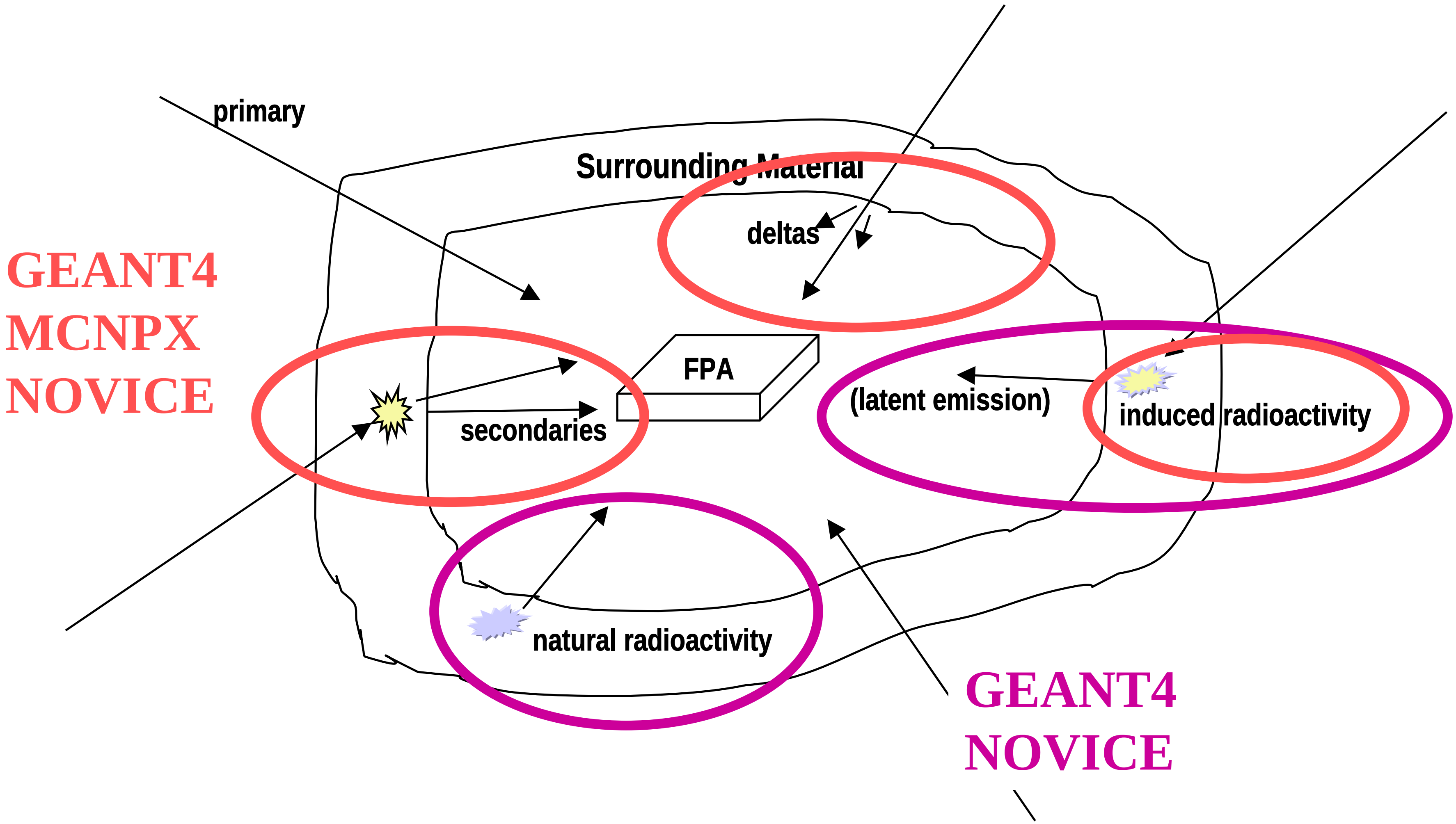


IR Detectors are Excellent Particle Detectors

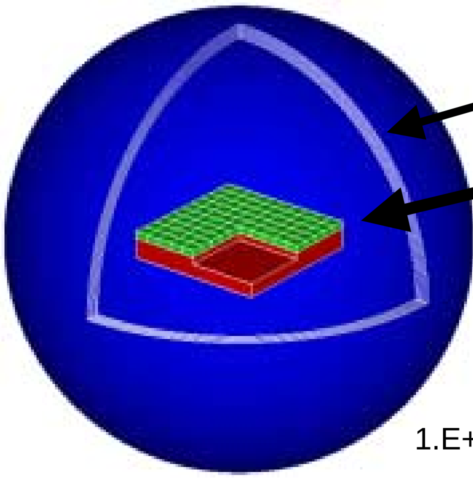


- Detector doesn't distinguish between IR photon or energetic particle
- Charge generated in depletion regions of p-n junction is collected
- Charge generated in quasi-neutral substrate regions can diffuse to junction and be collected
  - Charge that diffuses to neighboring pixels results in crosstalk
- Charge generated in ROIC ("Mux") can be collected

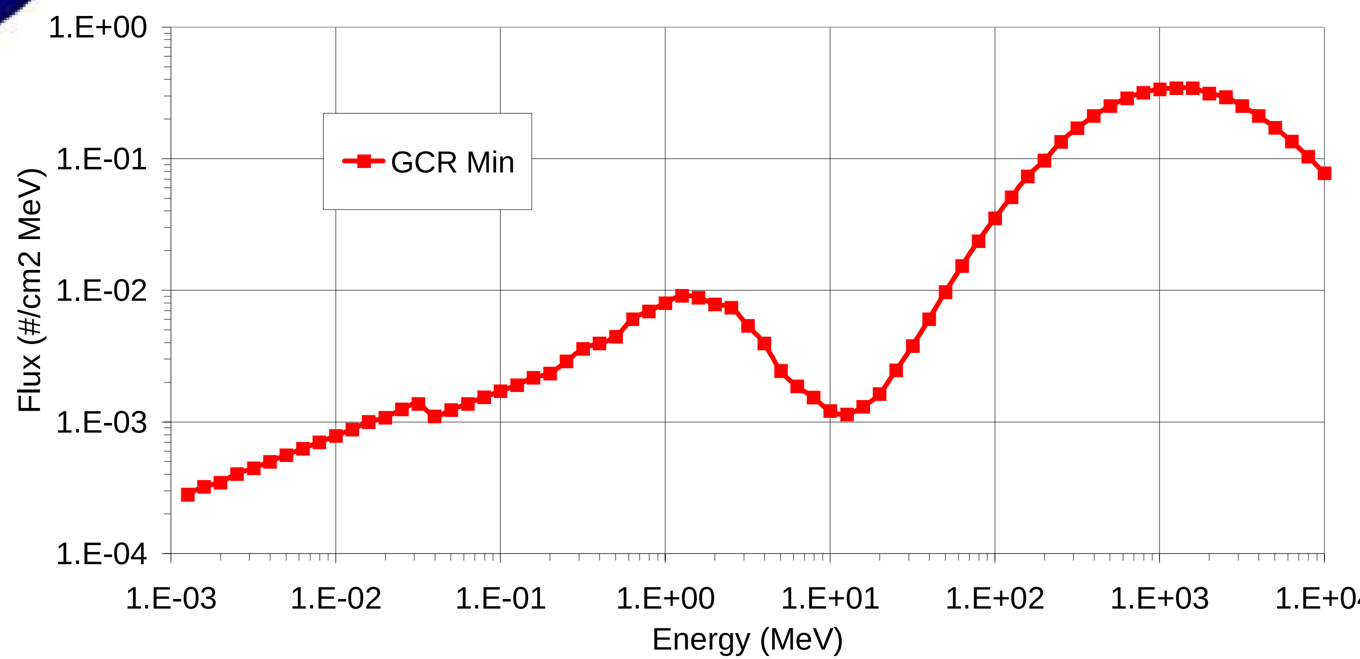
Ionizing Particle Impacts to FPA



Preliminary Simulations for Secondary Environment

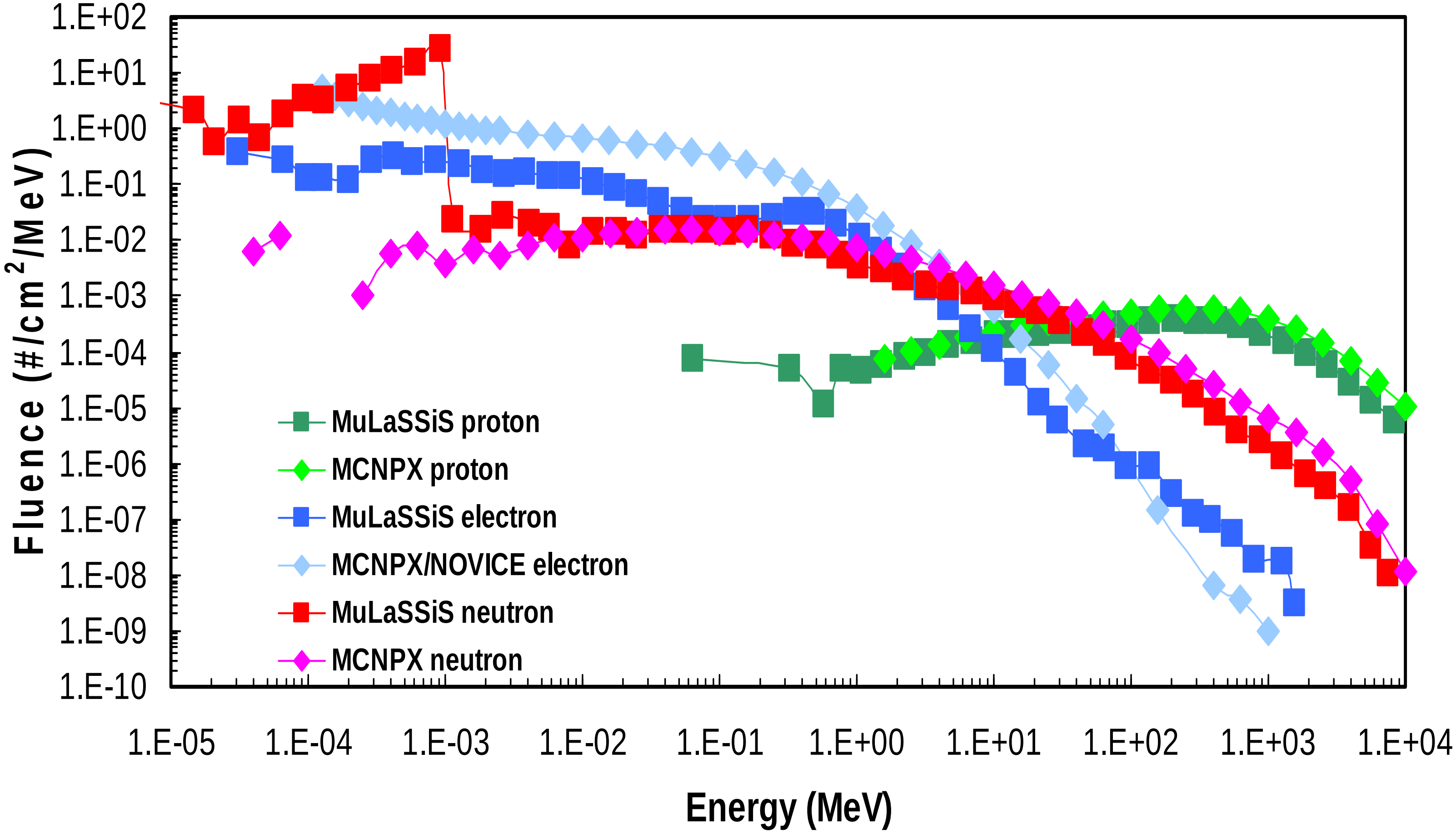


- 100 mil Al shielding
- Detector array assembly
- GCR Min Proton Spectrum

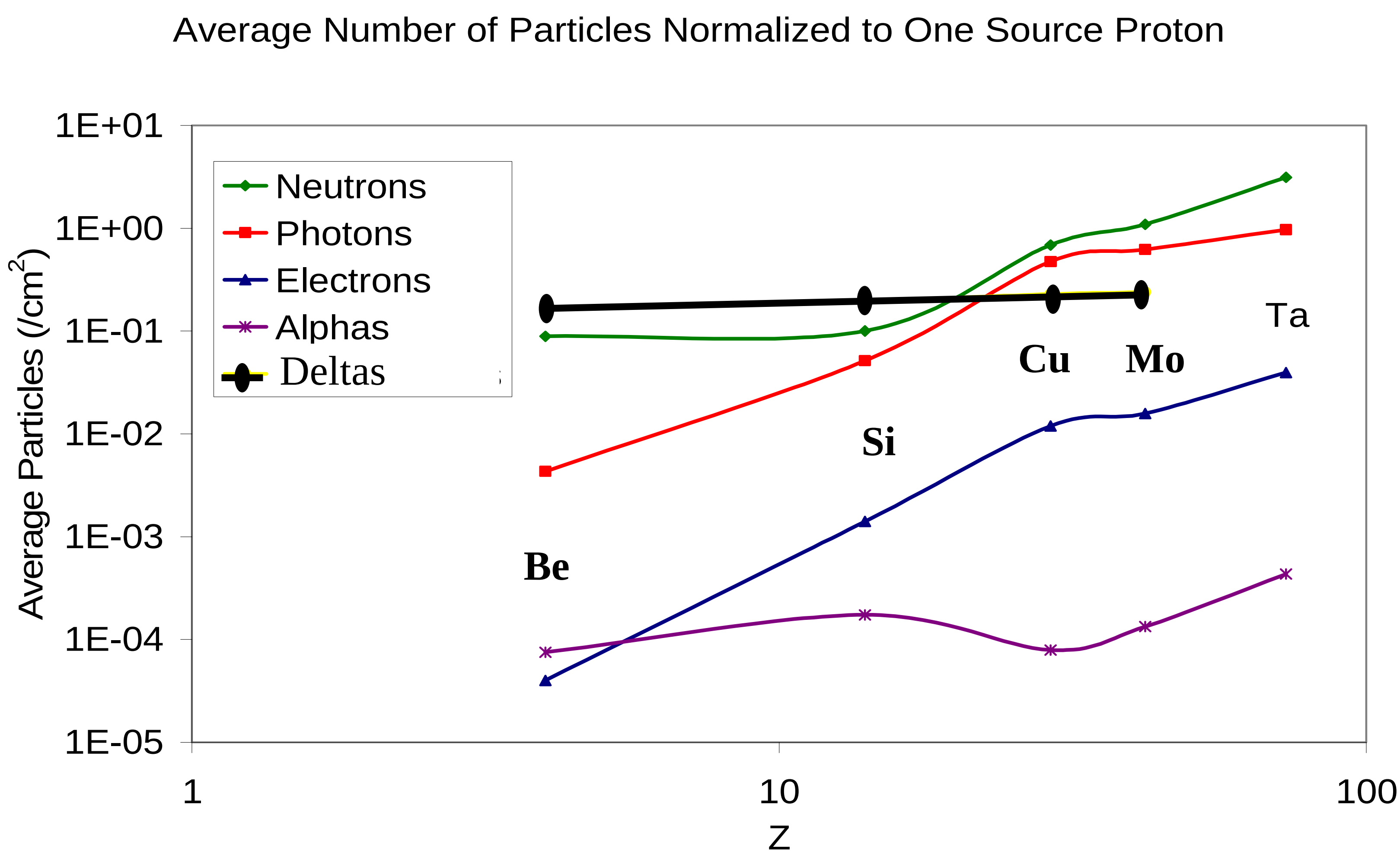


Secondary Environment at the Center of a 1 inch Aluminum Spherical Shell for GCR

Comparison of MCNPX+NOVICE to GEANT4 (ESA MuLaSSiS code)

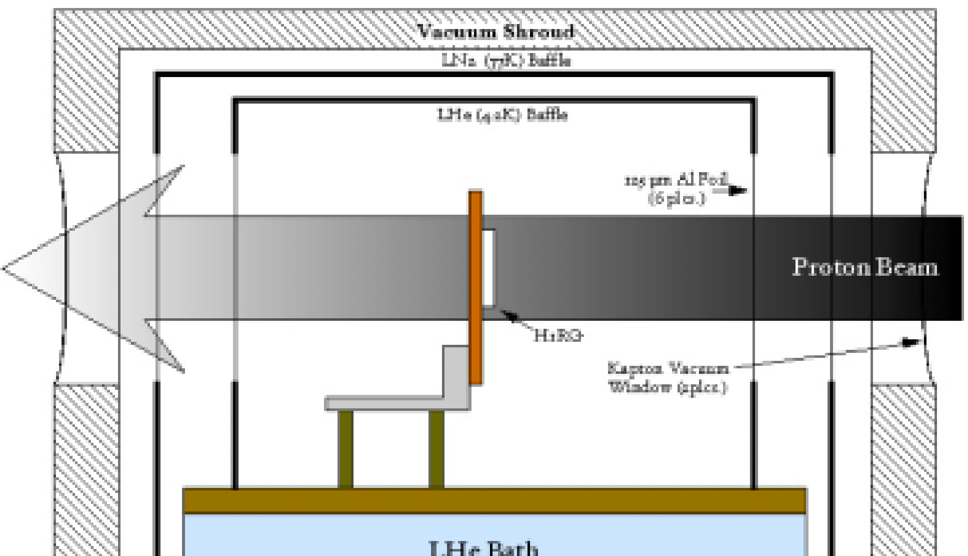


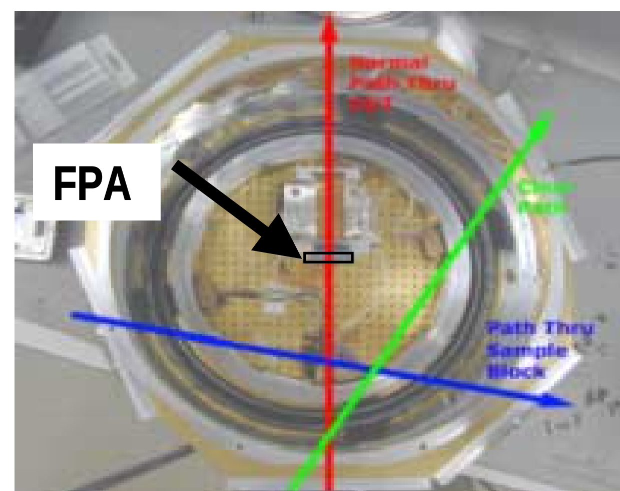
Secondary Environment at the Center of a 1 inch Spherical Shell for GCR: MCNPX and NOVICE



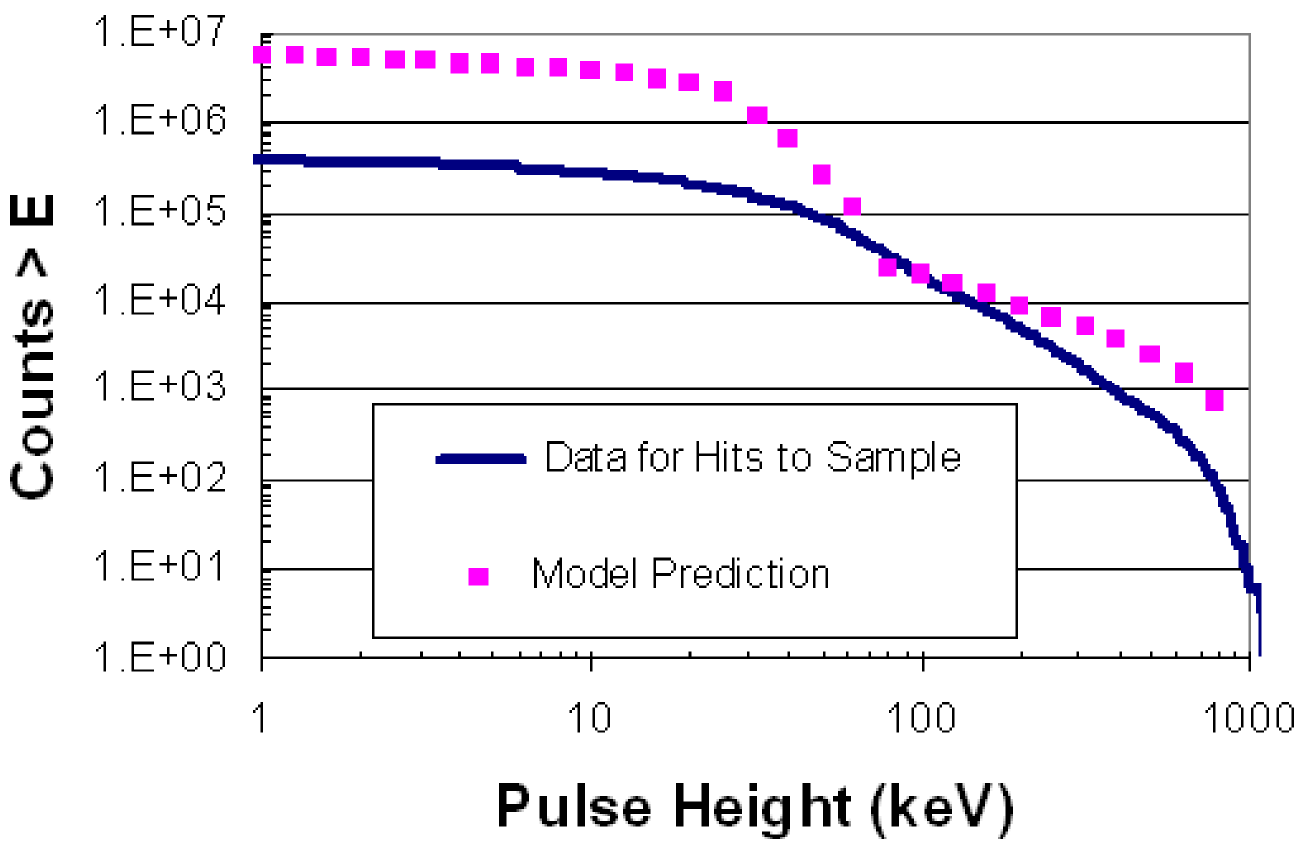
Transient Testing for HgCdTe Arrays

- Use 30 and 63 MeV protons
- Use 0, 45 and 67 degree incidence
- Very low flux so that single particle event can be identified





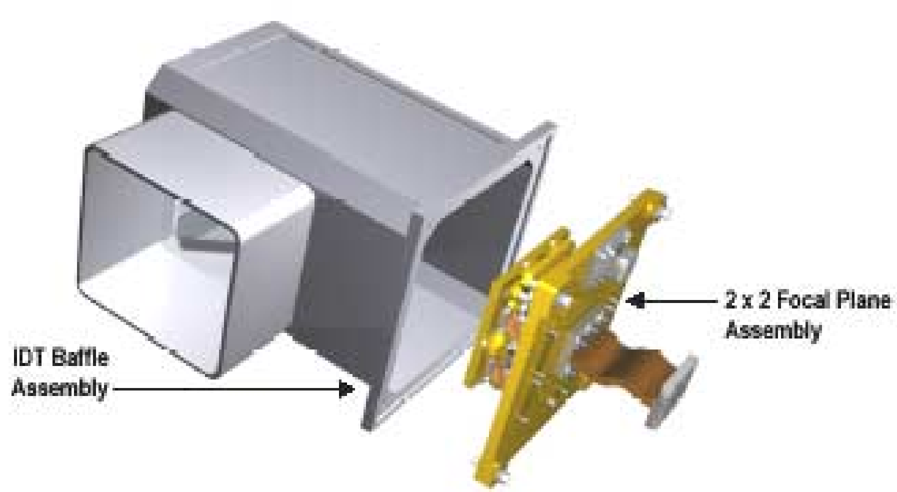
NOVICE+MCNPX Model Prediction is Higher than Data



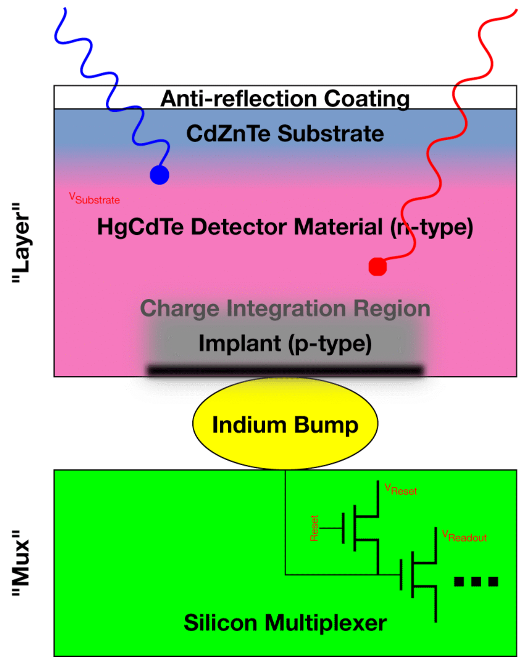
RECALL THAT, FOR CERTAIN ENERGIES, NOVICE+MCNPX ELECTRON ENVIRONMENT WAS AN ORDER OF MAGNITUDE HIGHER THAN MuLaSSiS

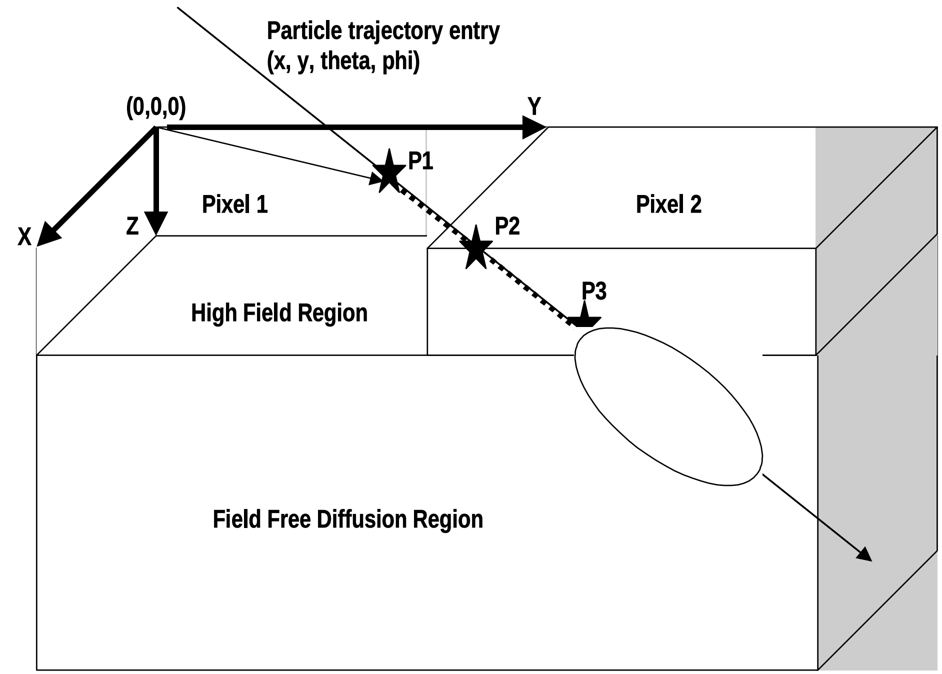
JWST/NIRcam Shield Design

- Requirement is to predict transient event rate
  - Must account for every ionizing event: Electrons > 10eV, Protons etc...
  - Details of shielding can have a significant effect : CAD model is required
  - Computing power not sufficient to use detail 3D device physics model: must use an approximation model
- Have selected NOVICE to model delta electrons
  - Adjoint mode (reverse MC)
  - Able to import detailed CAD model
  - Able to model >10eV electrons



Array Charge Collection Model (REACT)





- Breakdown of current modeling is due to lack of predicting diffusion charge
- Must have time efficient and conservative method for modeling this charge diffusion

Charge spread by diffusion from a single event effect from 30 MeV proton

Experimentally Measured Ground Testing

63 MeV, 0 Degrees, 1976 Hits

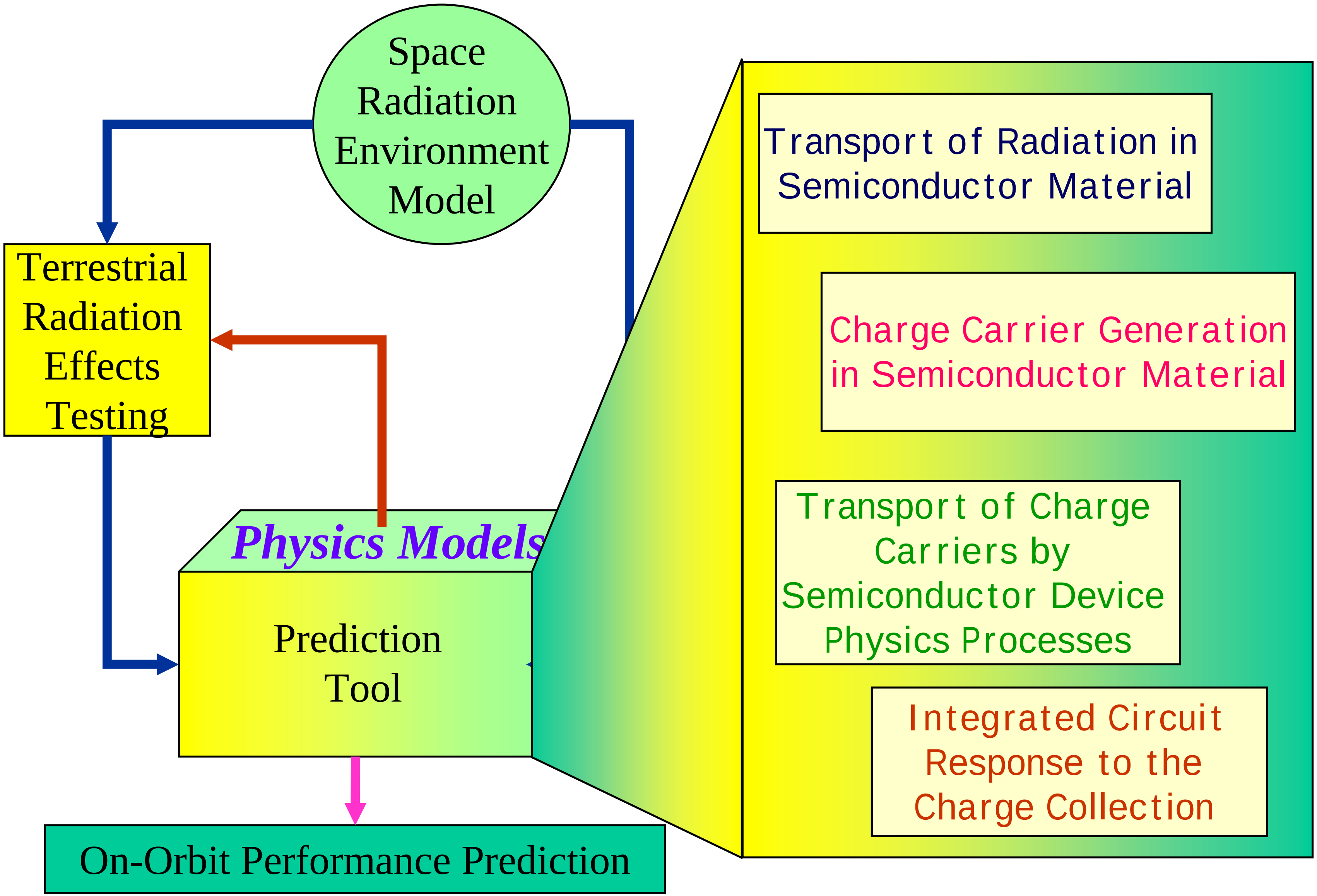
-0.01%	-0.04%	-0.01%	0.01%	0.00%	-0.01%	-0.02%
-0.03%	-0.05%	-0.02%	0.07%	0.01%	-0.05%	-0.03%
-0.03%	0.01%	1.50%	7.57%	1.15%	0.03%	-0.02%
-0.02%	0.09%	8.75%	100.00%	8.35%	0.19%	-0.01%
-0.02%	0.00%	1.52%	8.47%	1.27%	0.01%	-0.01%
-0.02%	-0.03%	0.01%	0.07%	0.01%	-0.03%	0.00%
0.01%	0.00%	0.00%	0.01%	0.01%	-0.01%	0.00%

Modeled with REACT

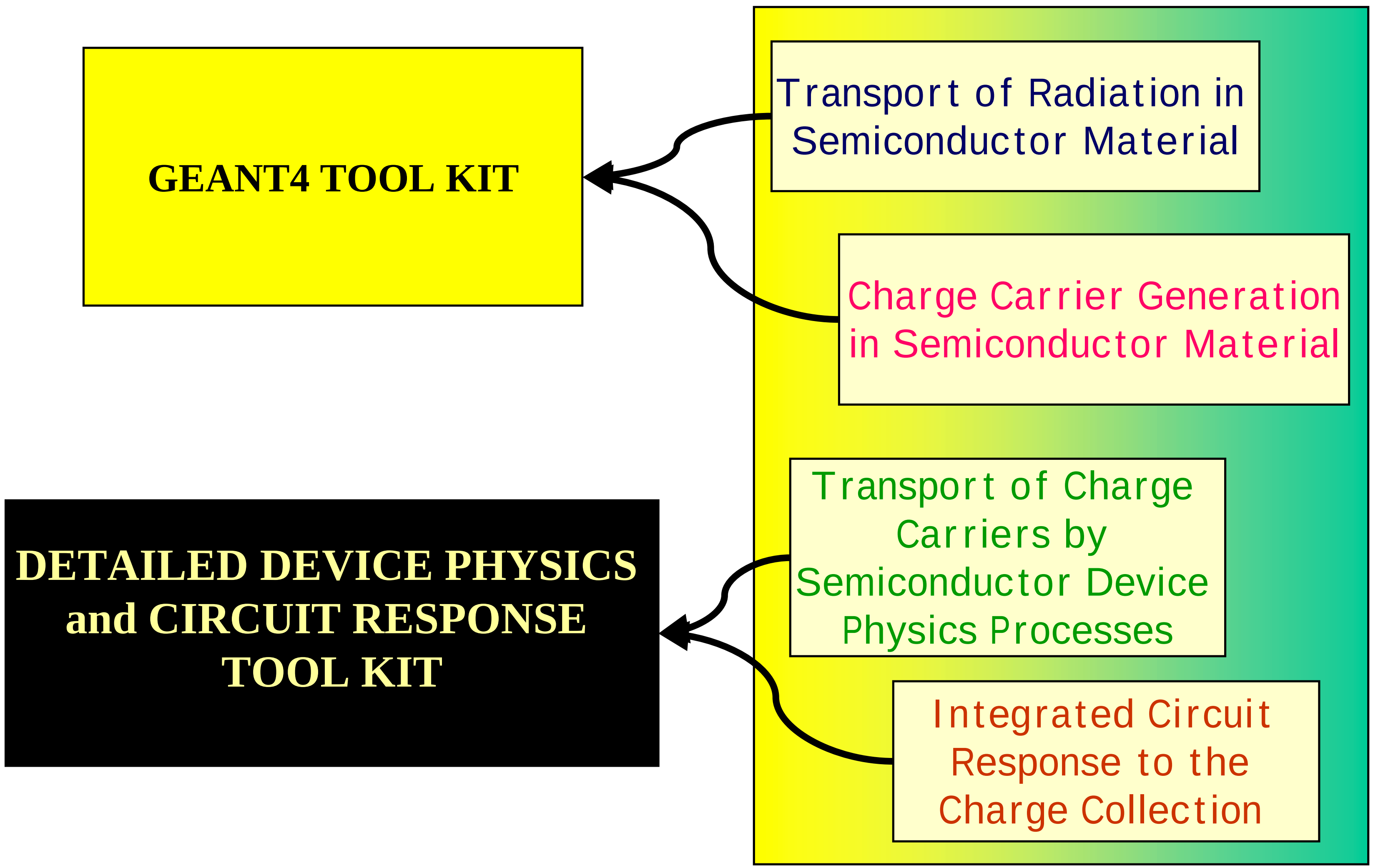
0.1%	0.1%	0.1%	0.2%	0.1%	0.1%	0.1%
0.1%	0.2%	0.4%	0.6%	0.4%	0.2%	0.1%
0.1%	0.4%	2.1%	8.9%	2.8%	0.4%	0.1%
0.1%	0.5%	6.9%	100.0%	11.4%	0.6%	0.2%
0.1%	0.4%	2.0%	7.8%	2.2%	0.4%	0.1%
0.1%	0.2%	0.4%	0.5%	0.4%	0.2%	0.1%
0.0%	0.1%	0.1%	0.1%	0.1%	0.1%	0.1%

“Future” Directions for SEE

SCRIPT for SEE in Microelectronic and Photonic Devices



SCRIPT for SEE Using Detailed Device Physics and Circuit Response Simulation



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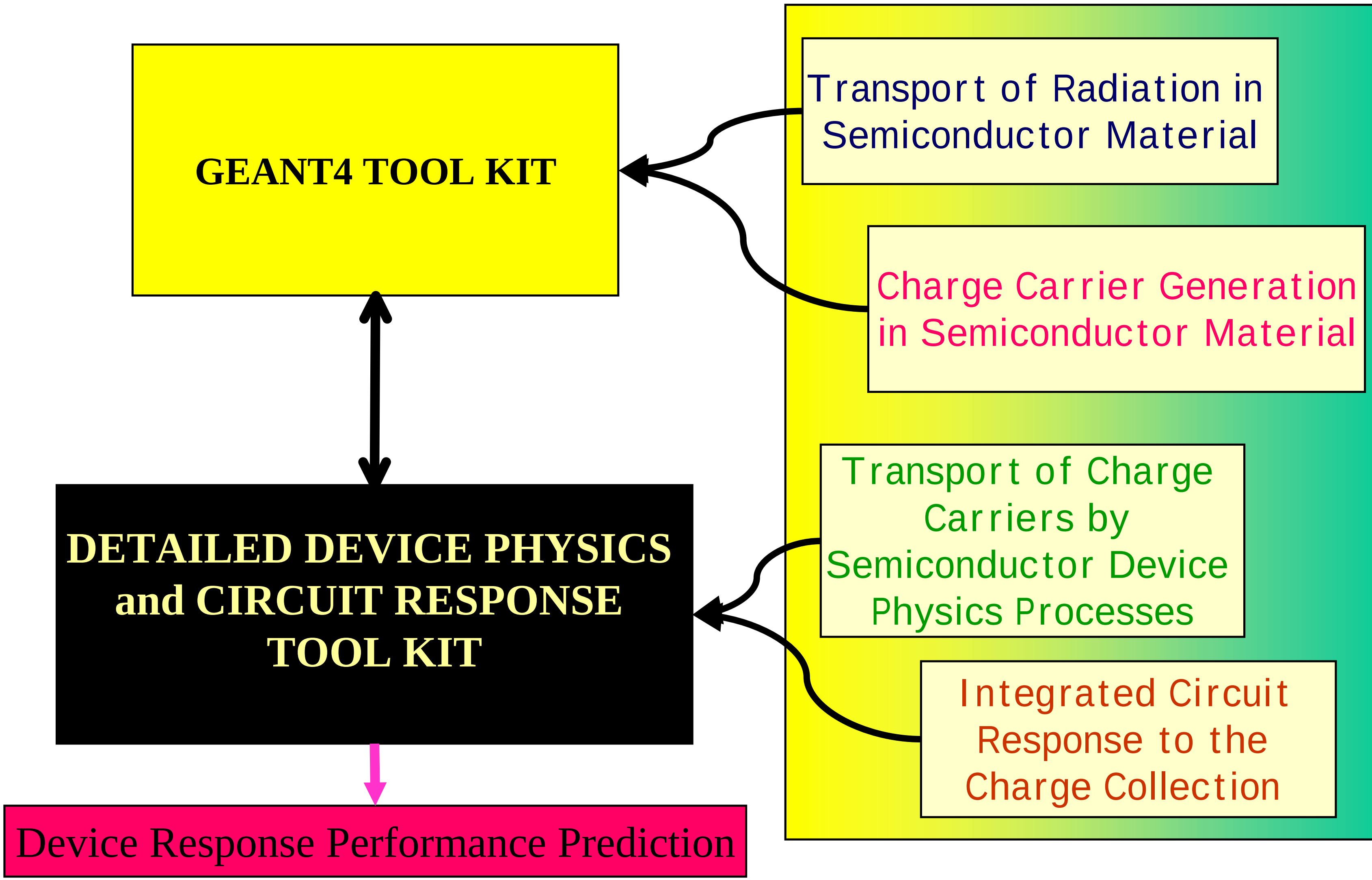
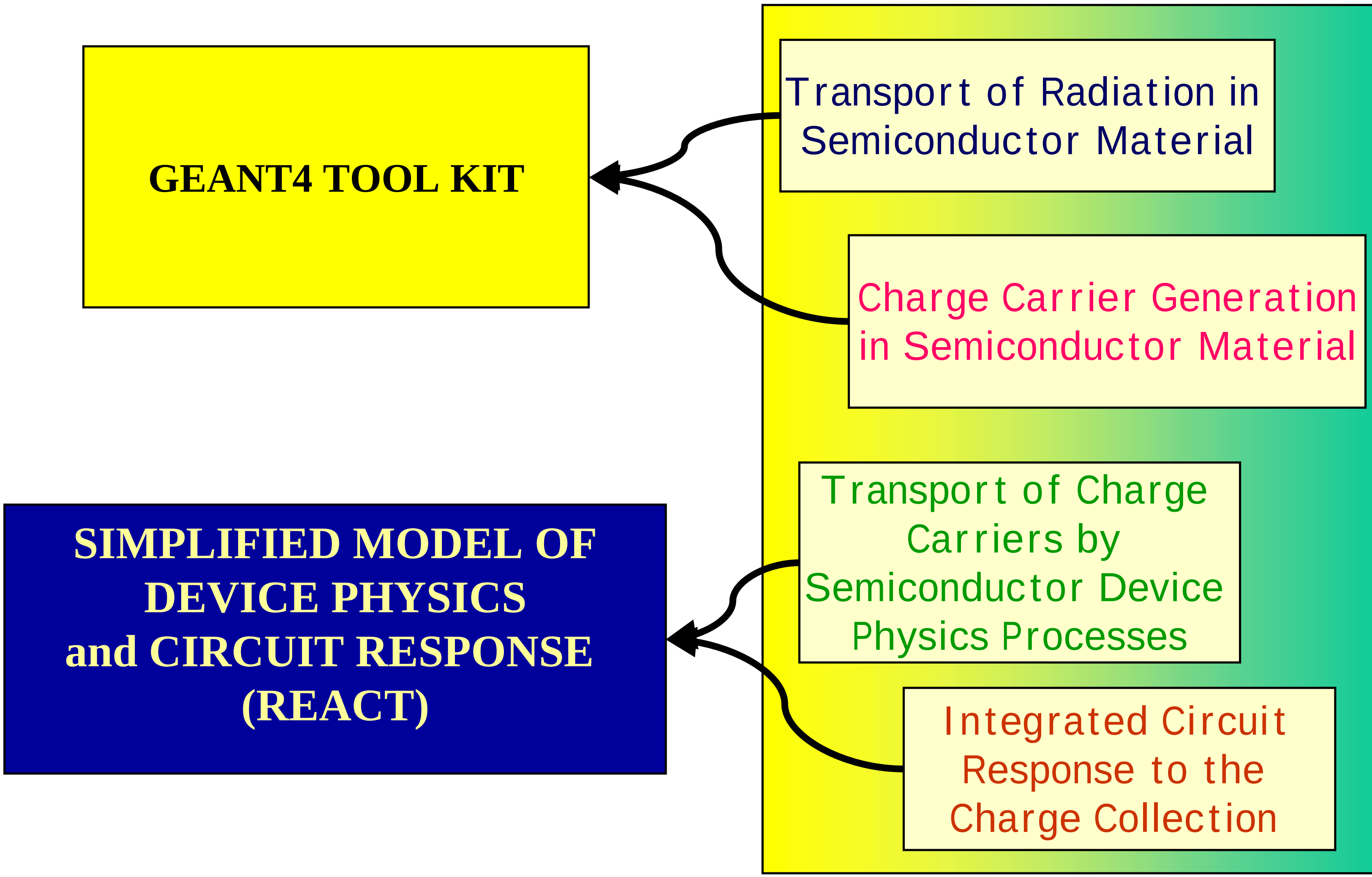
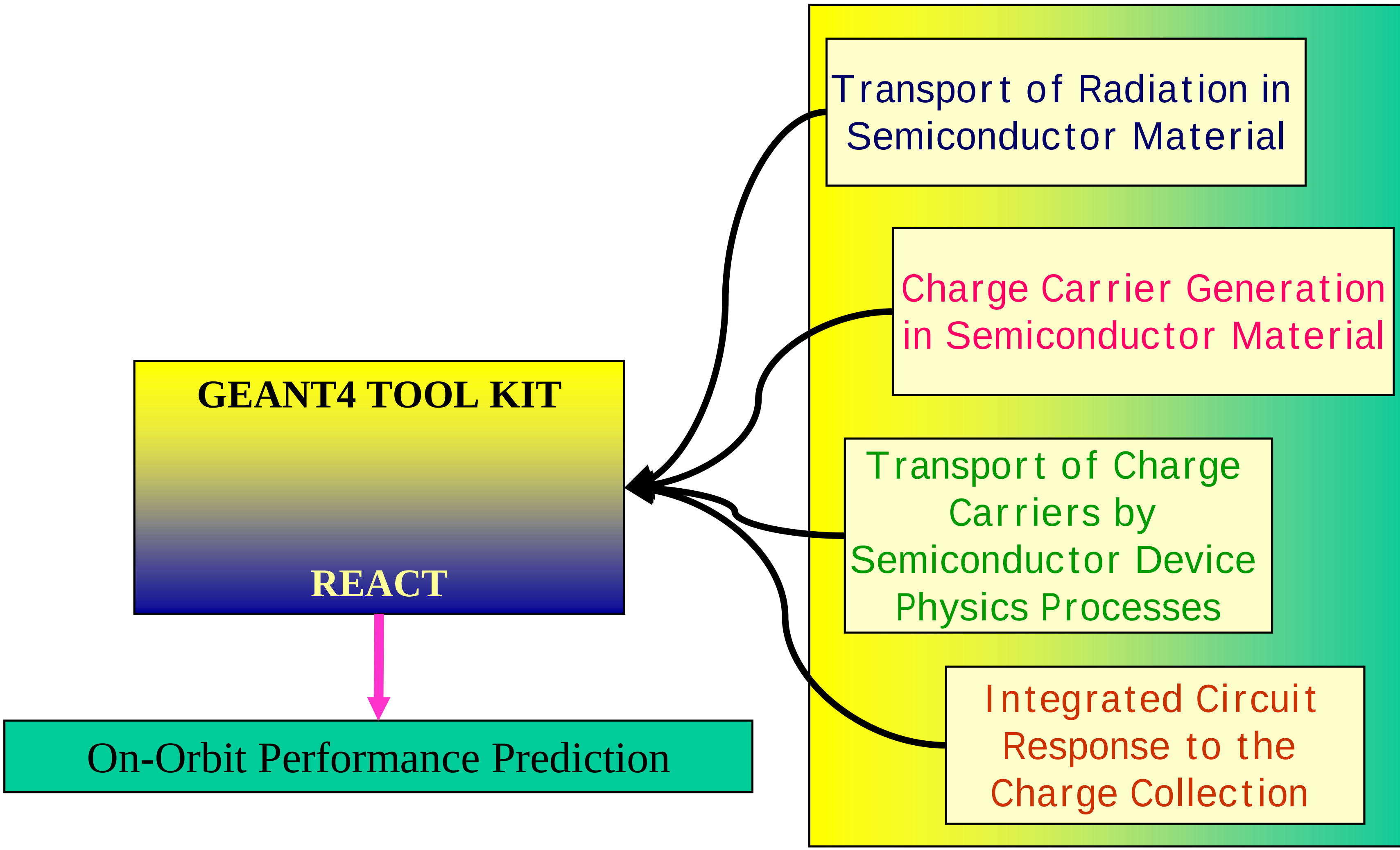


SCRIPT for SEE Using REACT



SCRIPT for SEE Using GEANT4 + REACT for Rate Predictions



Monte Carlo Approach for proton SEE

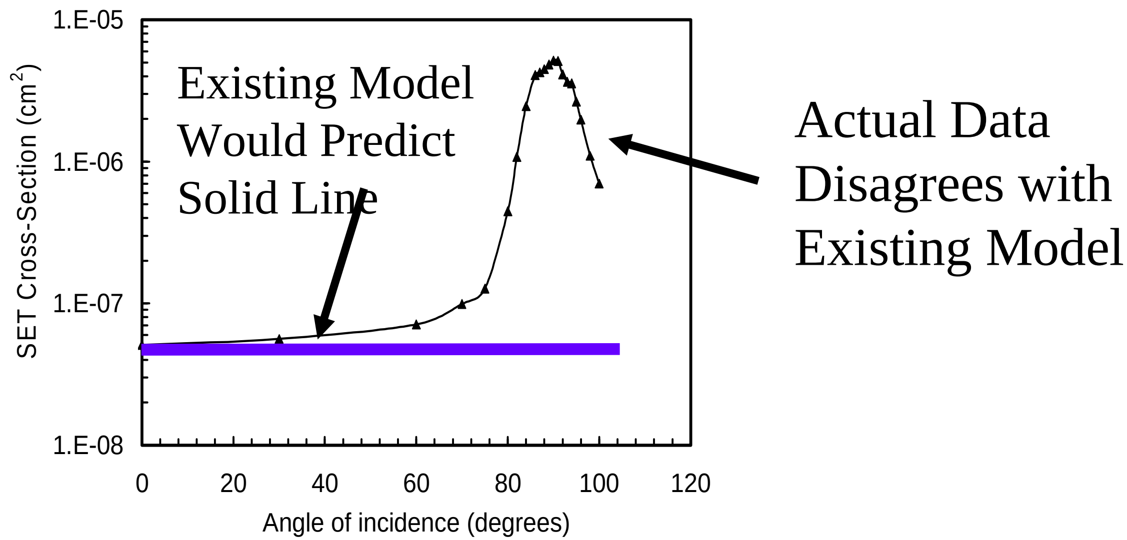
- Using GEANT4, MCNPX or other codes determine set of lookup tables for cross section (σ) estimates on:
  - Nuclear charge (Z), Atomic mass (A), Energy (E) and emission angle (θ) of reaction products
- Using GEANT4 or other codes determine typical track structure
  - LET(E)
  - Amount of charge liberated in semiconductor as a function of radial distance away from center of track
- Monte Carlo:
  1. Space environment to select incident proton energy
  2. $\sigma(Z) \rightarrow \sigma(A) \rightarrow \sigma(E) \rightarrow \sigma(\theta)$: selects a unique (Z_i, A_i, E_i, θ_i)
  3. Event location within semiconductor
  4. Use typical track structure for (Z_i, A_i, E_i, θ_i) along with device geometry and REACT code to determine component response for that particle
  5. Repeat 1-4 until sufficient statistics are achieved for on-orbit SEE rate

Roadmap for Single Event Effects portion of SCRIPT

- Major concern over breakdown of SEE rate prediction model for modern technology
- Collaborators:
  - NASA/GSFC
  - Vanderbilt University
- Near Term Goals
  - Develop physics based infrastructure for a tool development
    - Ion track structure in Silicon
    - Proton+Silicon reaction product cross sections
  - Develop techniques to be capable of predicting heavy ion and proton SEE rates using existing models
  - Convert NASA's drift and diffusion modeling routines (REACT) to be compatible with OO
  - Develop capability of using Geant4 with Detailed Device Physics simulation for predicting device/circuit response

Roadmap: Intermediate and Long Term Goals for SEE

- Intermediate Goals
  - Develop Geant4 routine capable of predicting SEEs using REACT
  - Develop user define modules for using Geant4/REACT for SEEs in fiber link / optocoupler and benchmark against available radiation test data



- Long Range Goals
  - Develop user define Geant4/REACT modules for other technologies: SOI/SOS, SiGe and others