



# Space Solar Cell Radiation Damage Modelling

**Scott R. Messenger, Ph.D.**

**US Naval Research Laboratory, Washington, DC**

[Scott.Messenger@nrl.navy.mil](mailto:Scott.Messenger@nrl.navy.mil)

202-767-7360

**“Prediction is very difficult, especially if  
it’s about the future.”**

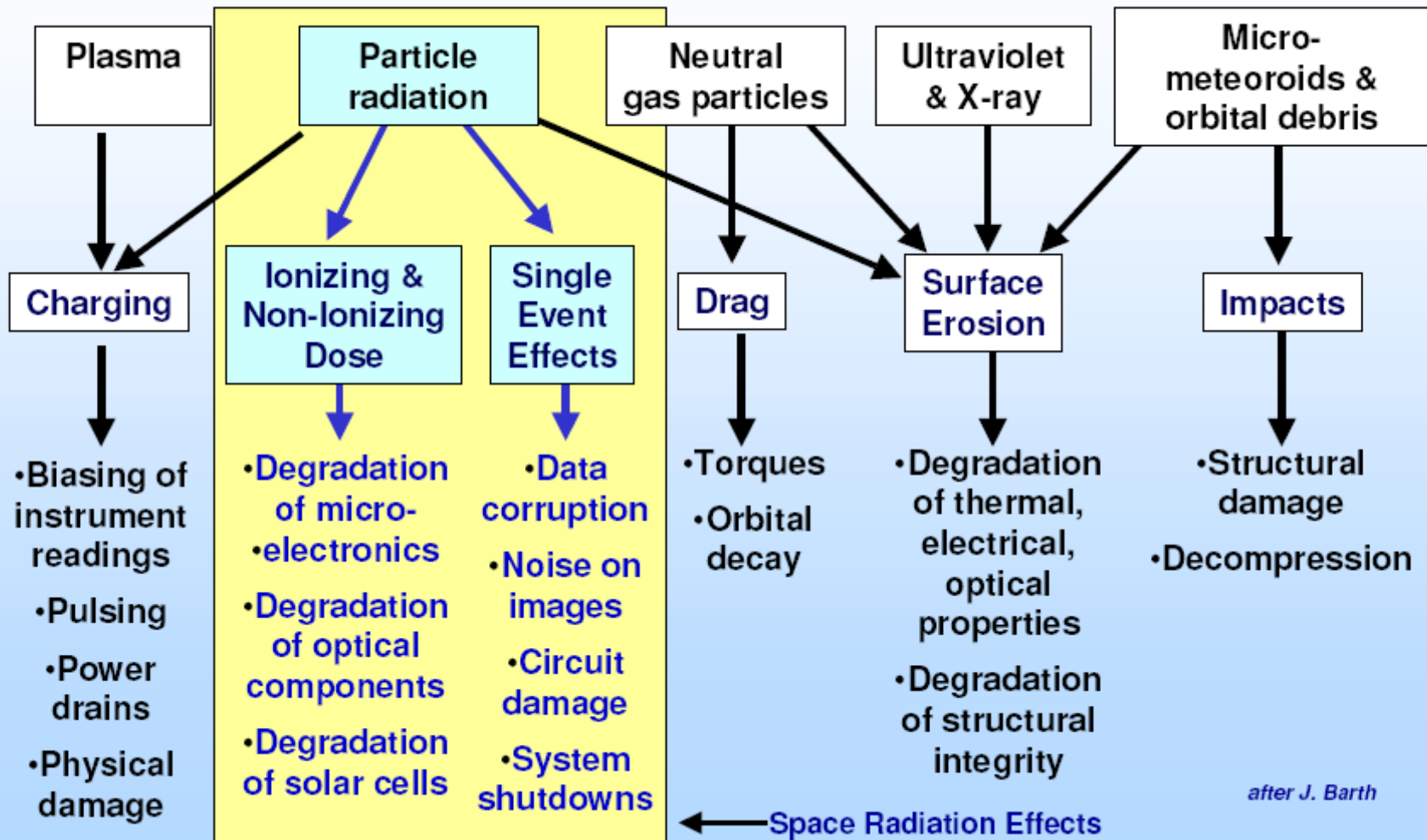
**-Niels Bohr**

**Danish physicist (1885 - 1962)**



**\*Taken from M. Xapsos, NSREC 2008**

# Space Radiation and Effects



# Outline

## 1. Motivation

## 2. The Space Radiation Environment

## 3. Solar Cell Space Radiation Degradation Modeling

- JPL Equivalent Fluence (EQFLUX)

- NRL Displacement Damage Dose (SCREAM)

## 4. Radiation Damage in Multijunction Solar Cells

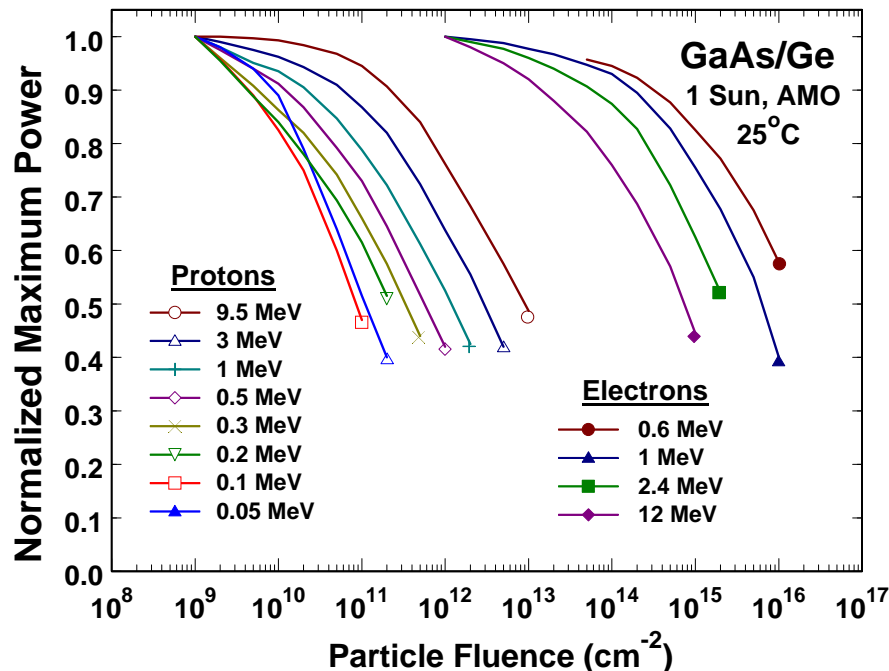
# Motivation

- Provide space solar cell community an alternate method for cell level degradation analyses
- Heritage method (JPL EQFLUX) requires several ground test energies
  - Electrons (0.6, 1, 12 MeV)
  - Protons (0.02, 0.05, 0.1, 0.3, 1, 3, 10 MeV)
- Alternate Method (NRL Displacement Damage Dose, DDD) needs significantly less ground data
  - Electrons (1, >2 MeV)
  - Protons (>1 MeV)
- AIAA S-111-2005 Space Solar Cell Qualification (Sects. 8.1 & 8.2) have been modified to include NRL DDD model as primary which can save about **\$150K** in future space cell qualifications

# Problem

- To generate ground irradiation data necessary to predict the effect of a particle spectrum (as that found in space) on a solar cell in orbit
- This is accomplished by reducing all of the ground data to a characteristic data set

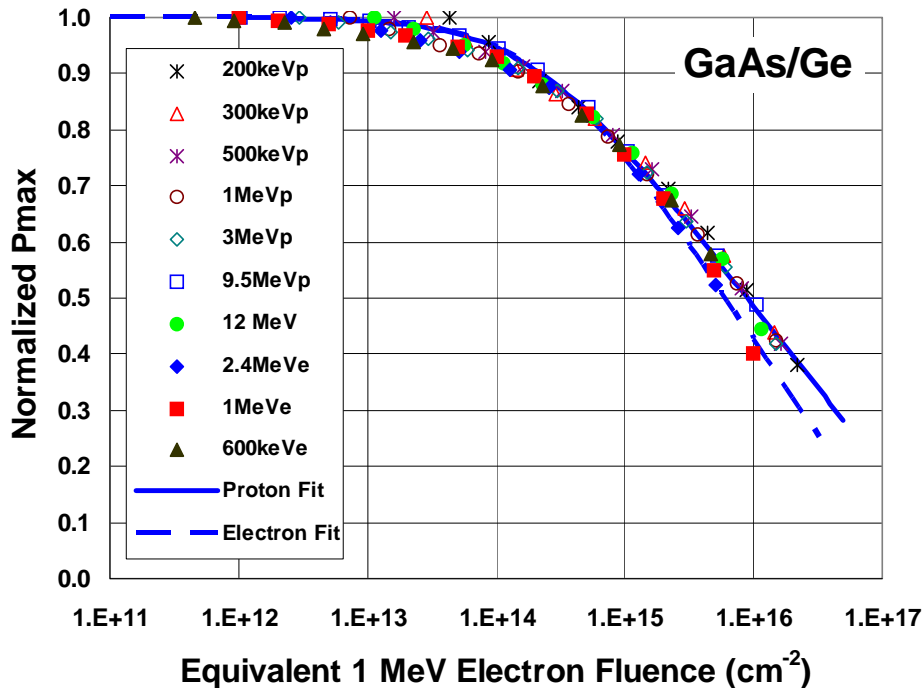
## Electron and Proton Fluence Data (GaAs/Ge, 1991)



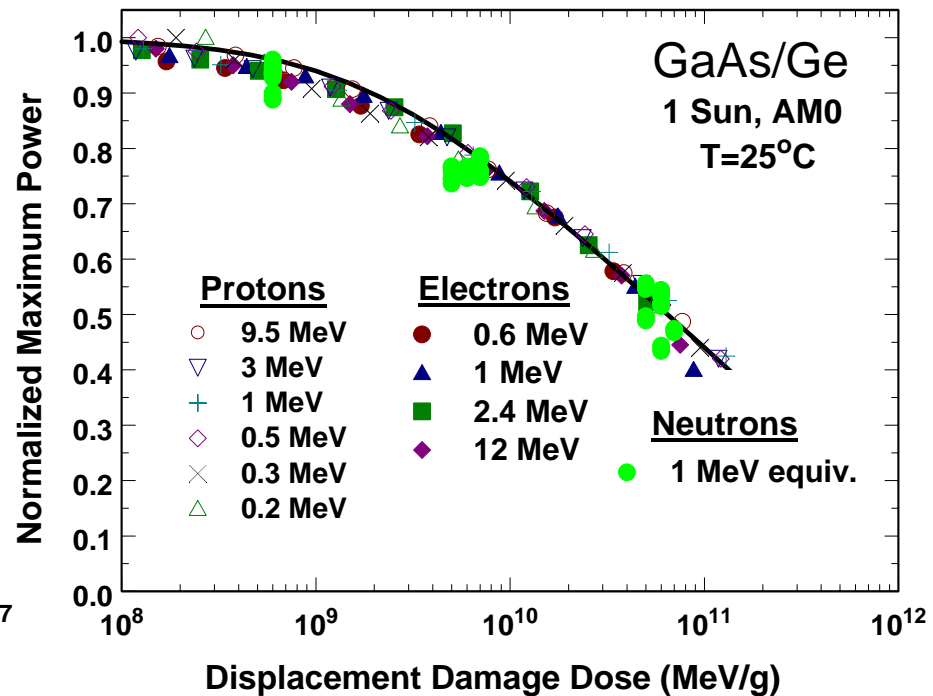
# Solution

- We want all data to collapse to a common basis
- The JPL method uses an equivalent 1 MeV electron fluence
- The NRL Method uses the displacement damage dose

## JPL Data Collapse



## NRL Data Collapse



# Outline

**1. Motivation**

**2. The Space Radiation Environment**

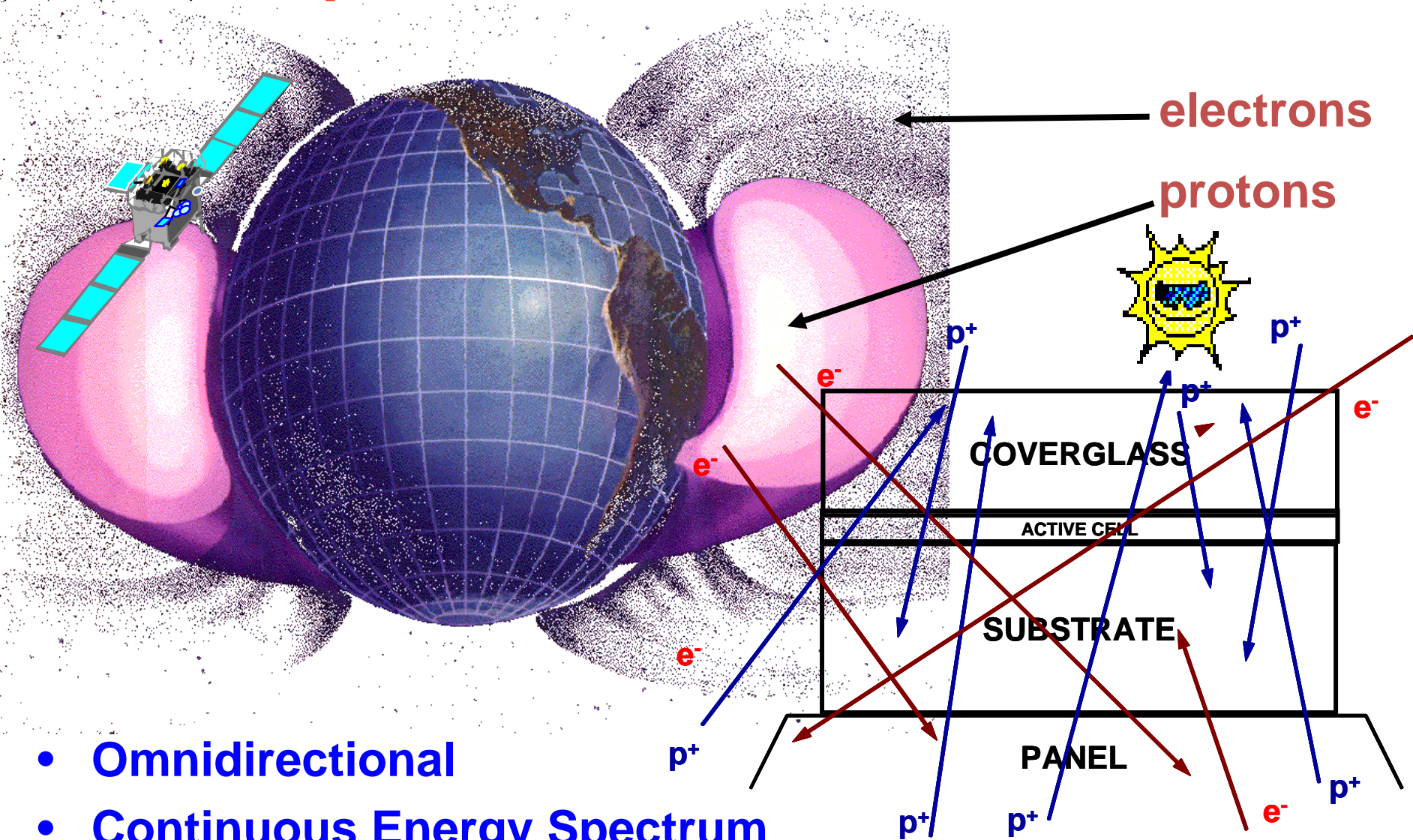
**3. Solar Cell Space Radiation  
Degradation Modeling**

-JPL Equivalent Fluence (EQFLUX)

-NRL Displacement Damage Dose (SCREAM)

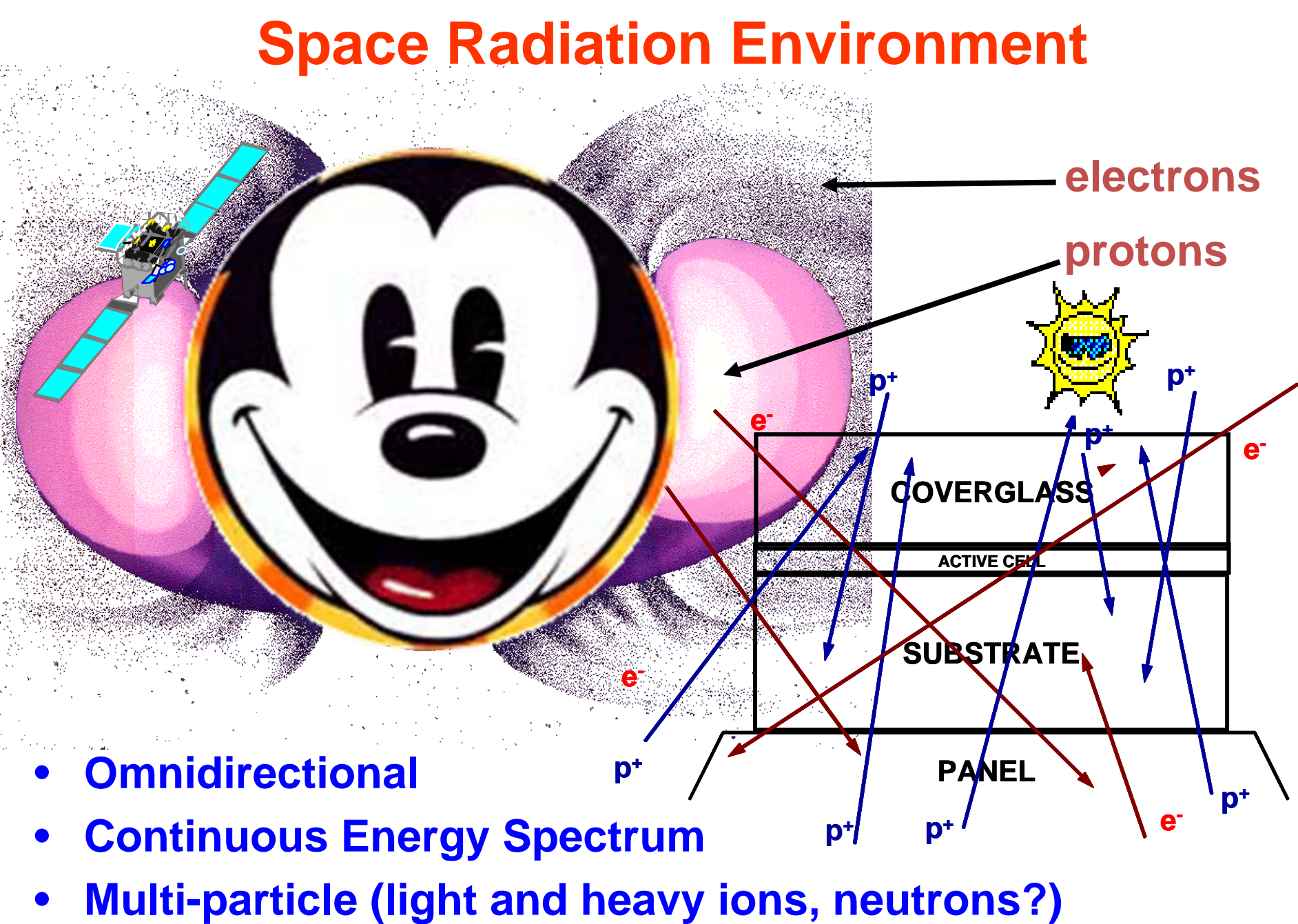
**4. Radiation Damage in Multijunction  
Solar Cells**

# Space Radiation Environment

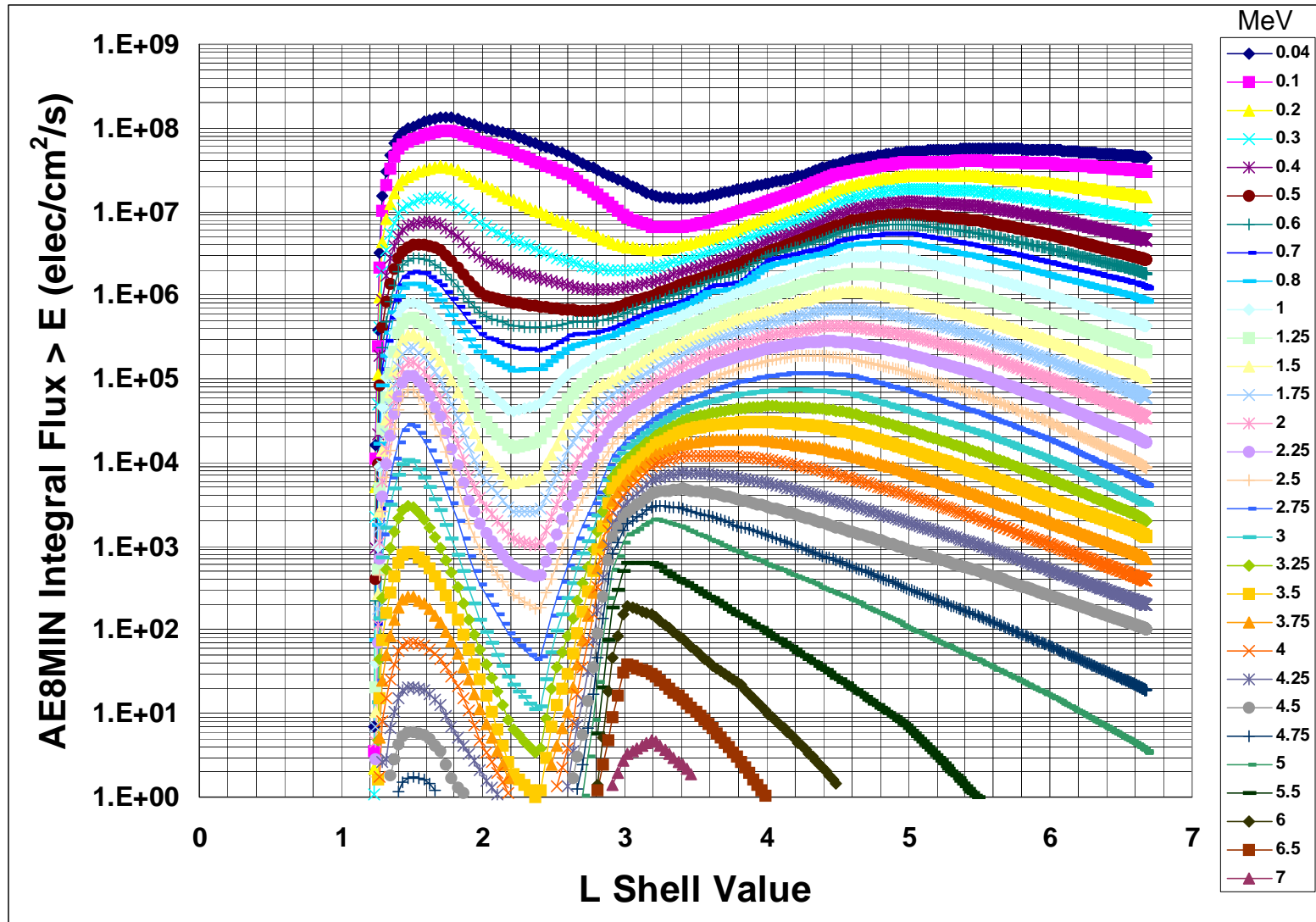


- Omnidirectional
- Continuous Energy Spectrum
- Multi-particle (light and heavy ions, neutrons?)

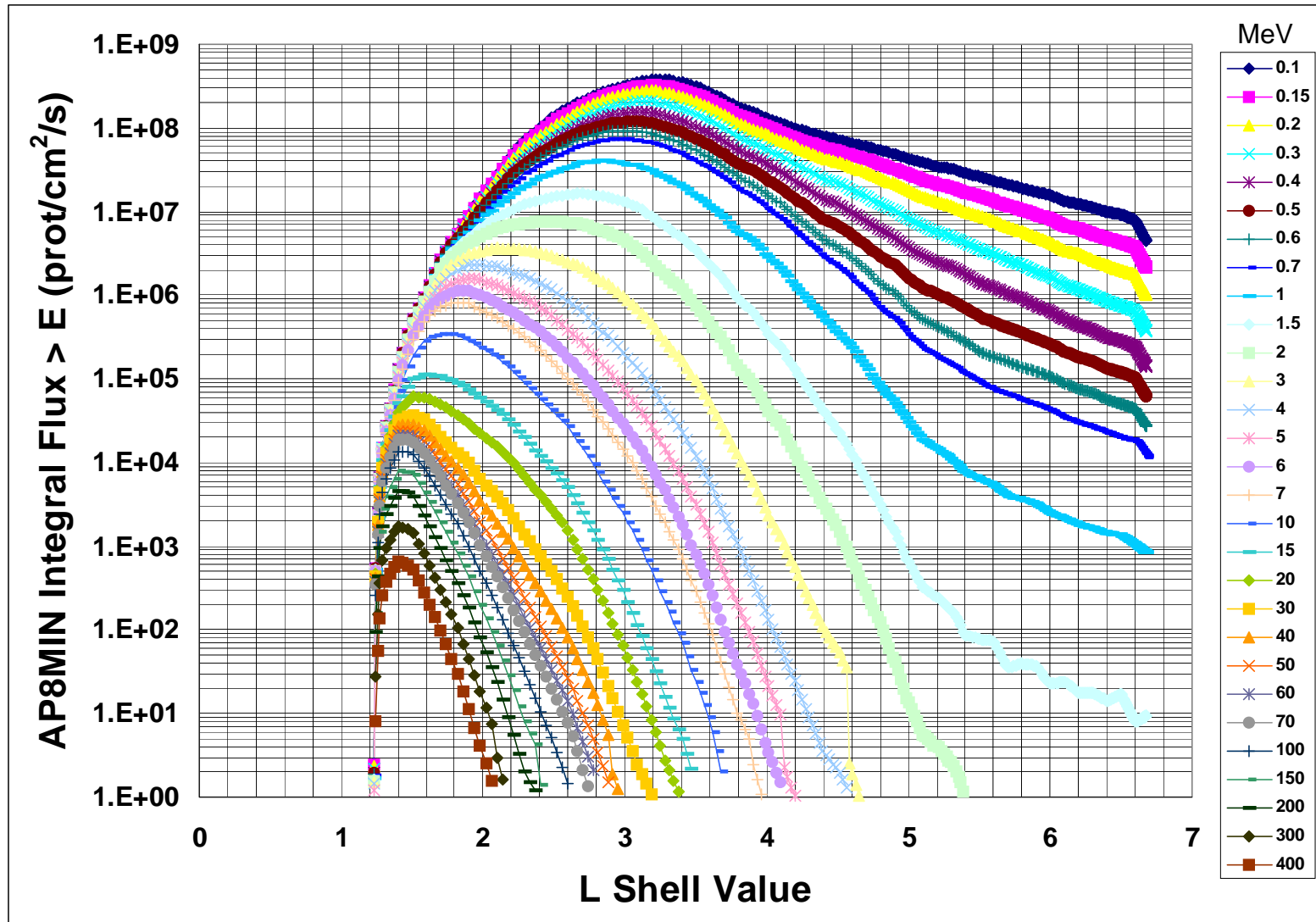
# Space Radiation Environment



# AE8MIN Electron Spectra (Static)



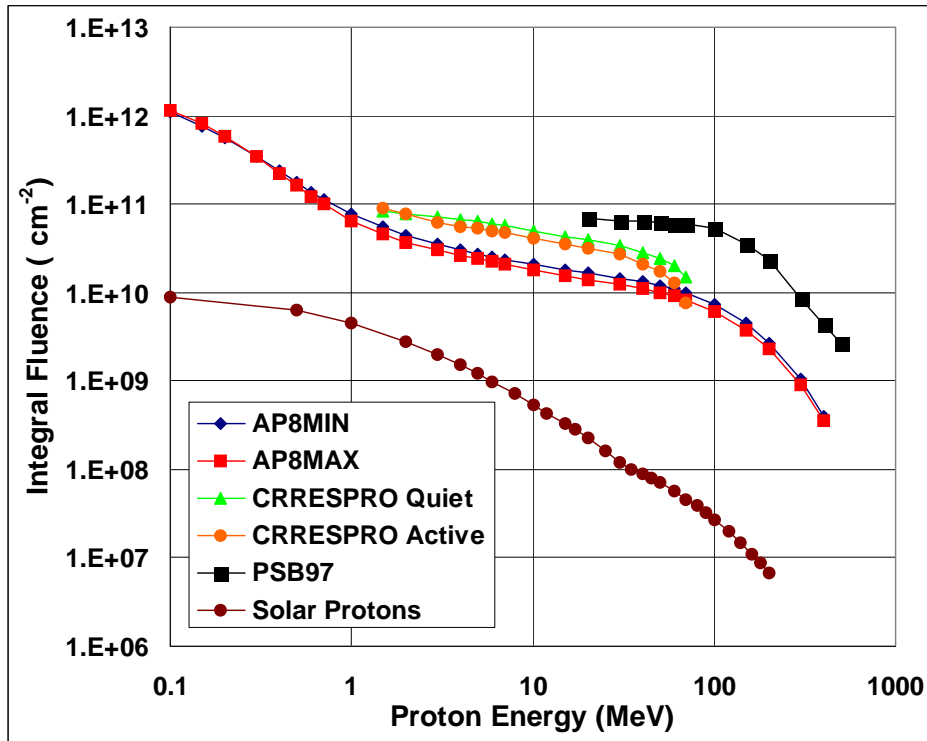
# AP8MIN Proton Spectra (Static)



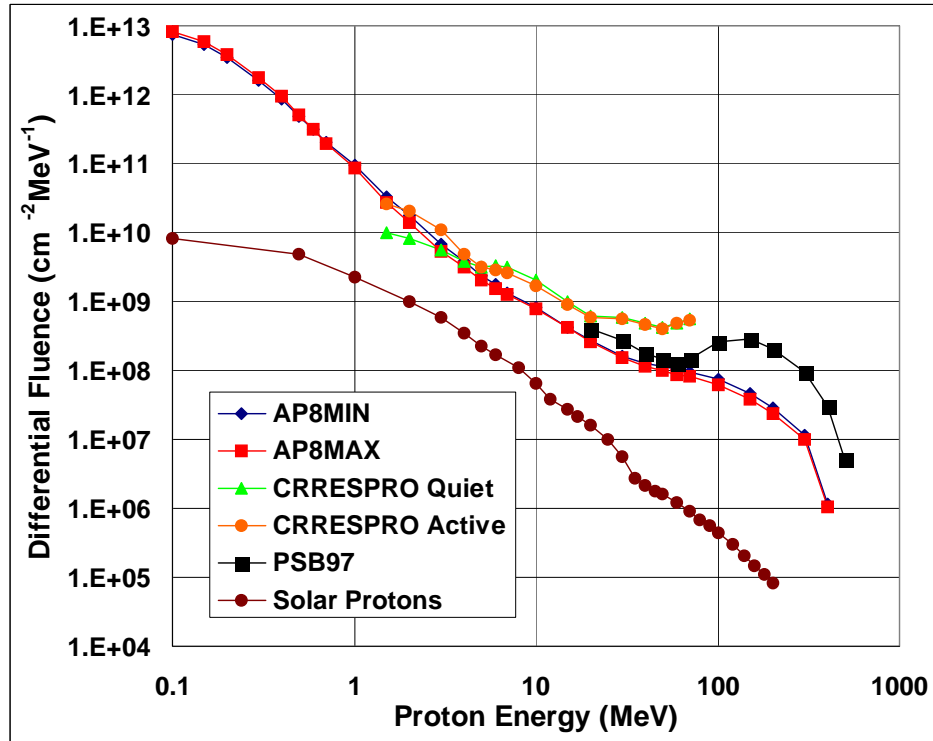
# Space Radiation Spectra

1100 km, circular, 63°, 1 year duration

## Integral Spectra

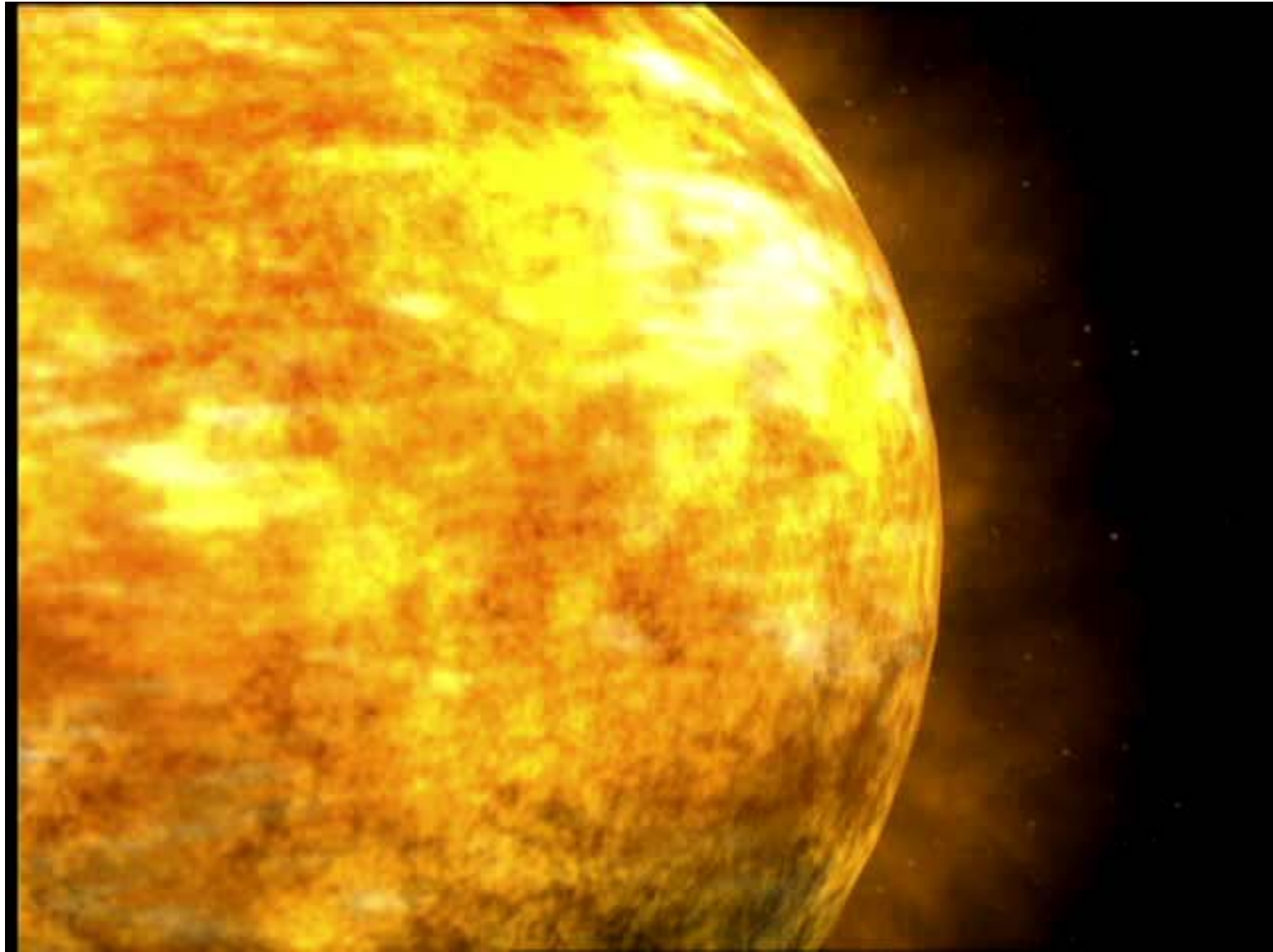


## Differential Spectra



\*The space radiation spectra is generally considered accurate to ~2X. This is the dominant error source for any degradation analysis leading to ..... MARGIN!!!!

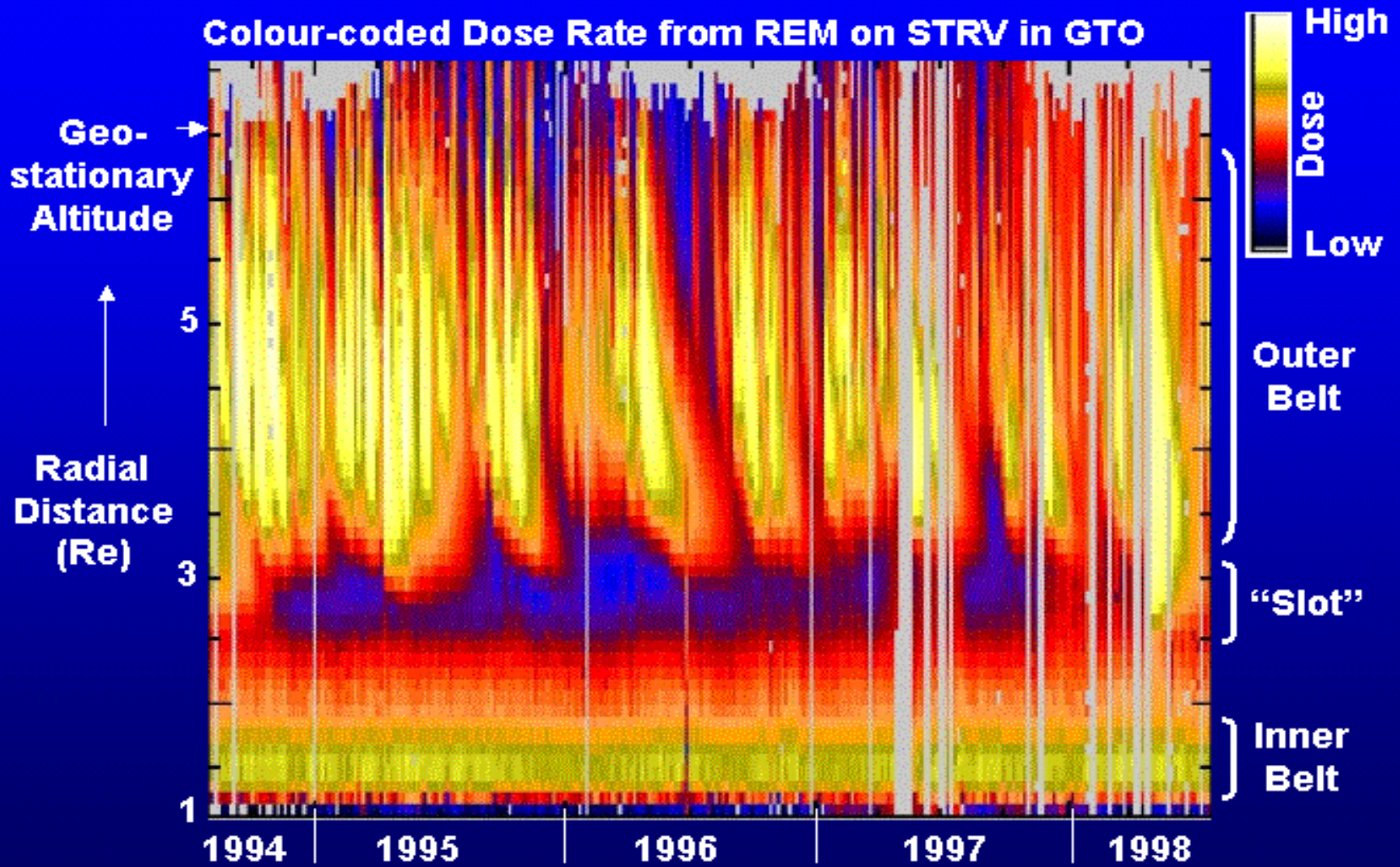
# What is a Coronal Mass Ejection?



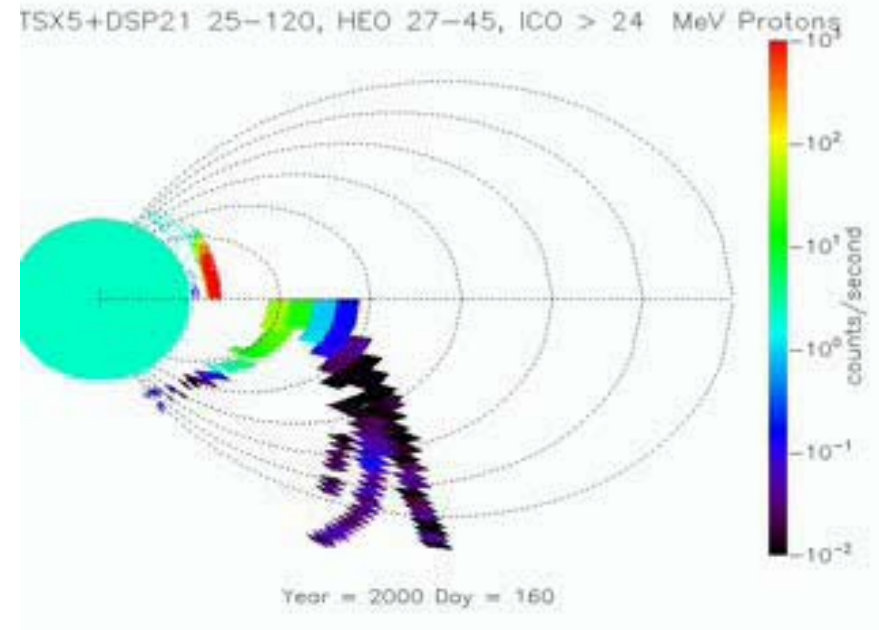
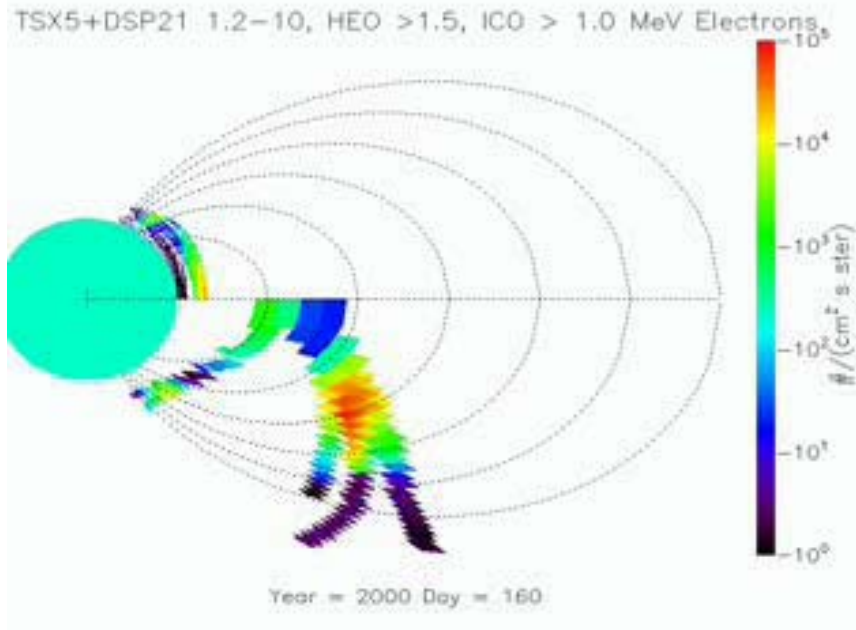




### Colour-coded Dose Rate from REM on STRV in GTO



# Electron and Proton Radiation Environment (CEASE data onboard TSX5, DSP21, HEO and ICO Satellites)



\*The present radiation environment models are known to have an accuracy of at least a **factor of 2**. AP(E)9 will greatly update the environment data. A beta version has been created in May, 2010. The NASA Radiation Belt Storm Probe (RBSP) experiment (launch in 2012) is expected to greatly enhance the understanding.

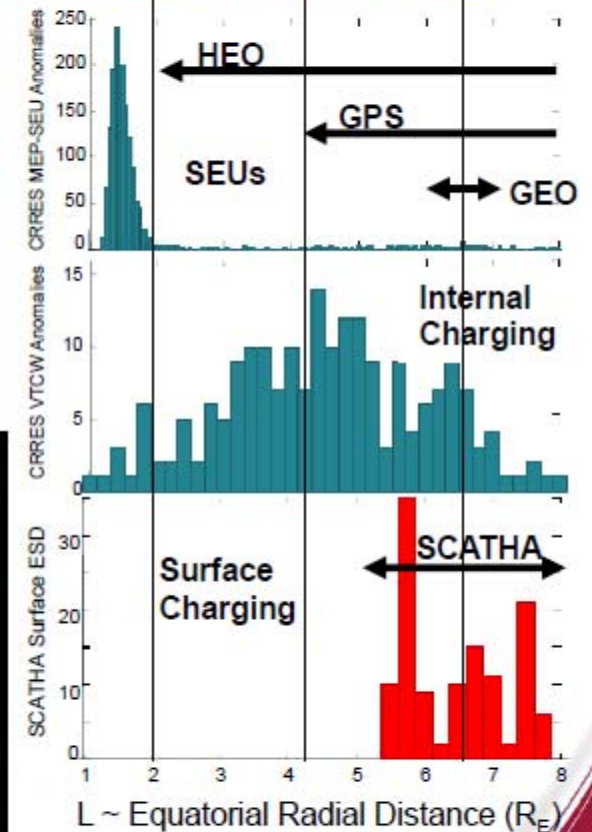
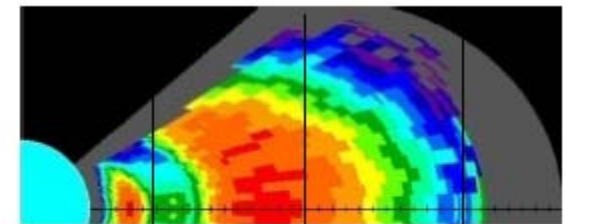
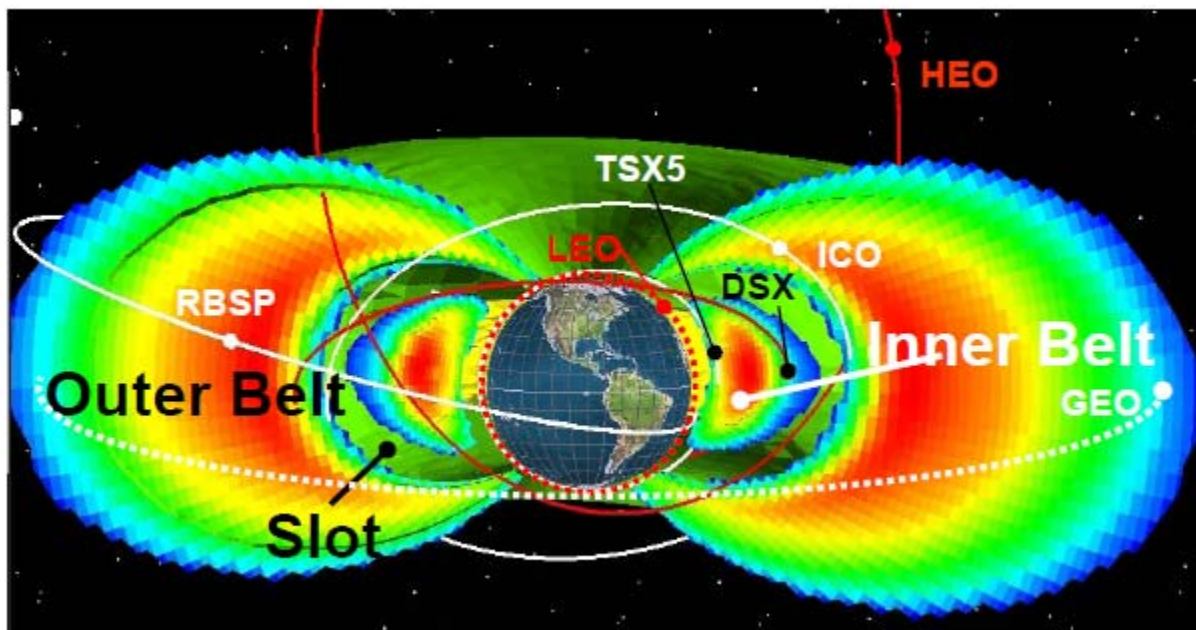
**Any model is only good to the data that is given!**

# AE9/AP9 Overview

OBJECTIVE: Provide satellite designers with a definitive model of the trapped energetic particle and plasma environment to include:

- Quantitative accuracy
- Indications of uncertainty
- Flux probability of occurrence and worst cases for different exposure periods
- Broad energy ranges including hot plasma & very energetic protons
- Complete spatial coverage

To achieve this objective, AE9/AP9 will have to be fundamentally different from and far more complex than AE8/AP8



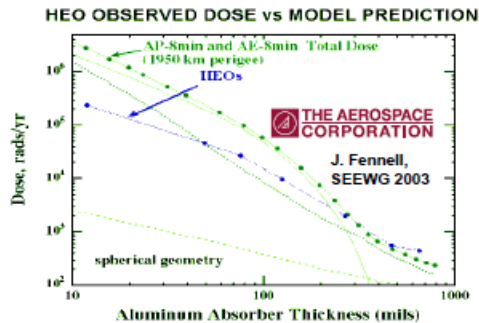


# AP-9/AE-9

## AP-8/AE-8 Deficiencies

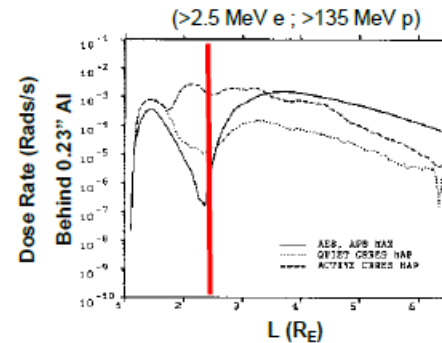


### Example: Highly Elliptic Orbit (HEO)



HEO dose measurements show that current radiation models (AE8 & AP8) **over estimate the dose** for thinner shielding

### Example: Medium-Earth Orbit (MEO)

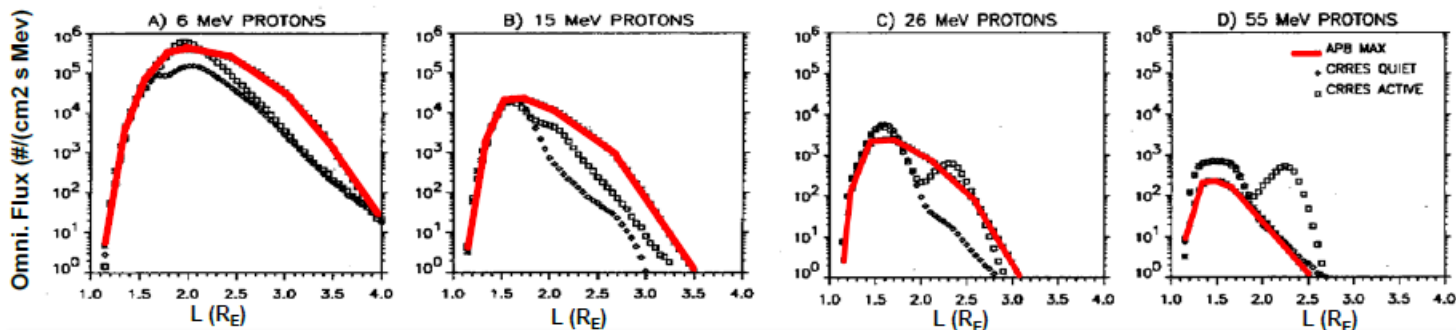


For MEO orbit ( $L=2.2$ ), #years to reach 100 kRad:

- Quiet conditions (NASA AP8, AE8) : 88 yrs
- Active conditions (CRRES active) : 1.1 yrs

AE8 & AP8 **under estimate the dose** for 0.23" shielding

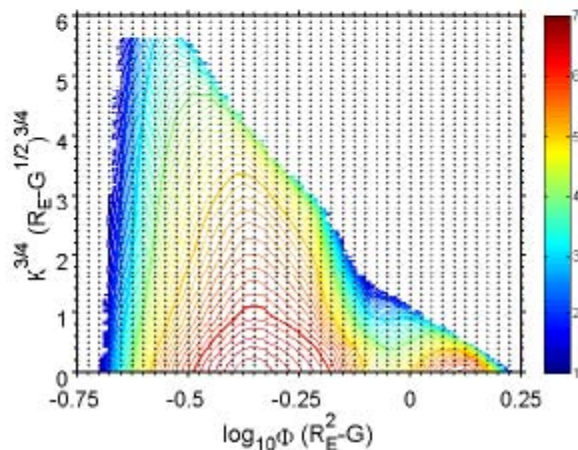
### Model differences depend on energy:



**AP-8/AE-8 inadequate for modern spacecraft design and mission planning**

# AE9/AP9 Implementation

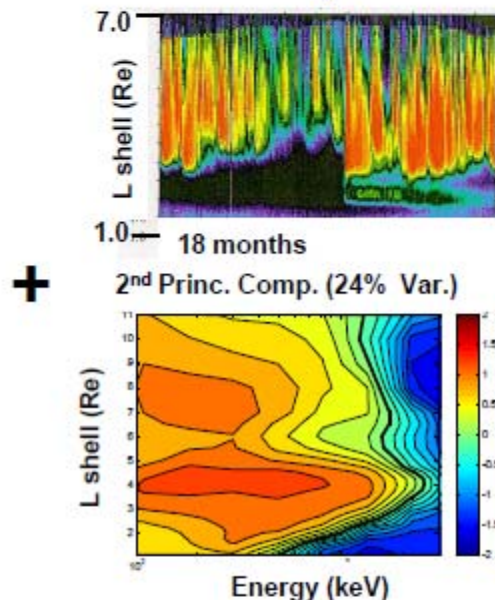
Satellite data



## Flux maps

- Median, 95<sup>th</sup> percentile of statistical distribution at each grid point
- Derived from empirical data
- Interpolation algorithms needed to fill in the gaps

Satellite data & physics-based models

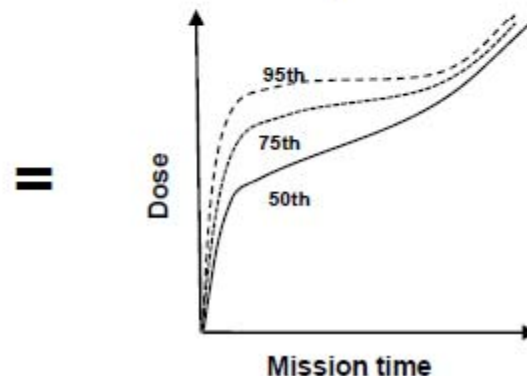


## Space/time covariance

Correlate data in space and time

- From data, if enough (electrons)
- From physics-based models when not enough (protons, plasma)
- Fixed sampling time scale (one day)

User's orbit & Monte-Carlo simulations



## User application

Flux vs time in "Standard Solar Cycle" or in Monte Carlo scenarios

Compute dose, SEE, charging etc in post-processing

Obtain median, 75<sup>th</sup>, 90<sup>th</sup> or other confidence levels





# AP-9/AE-9

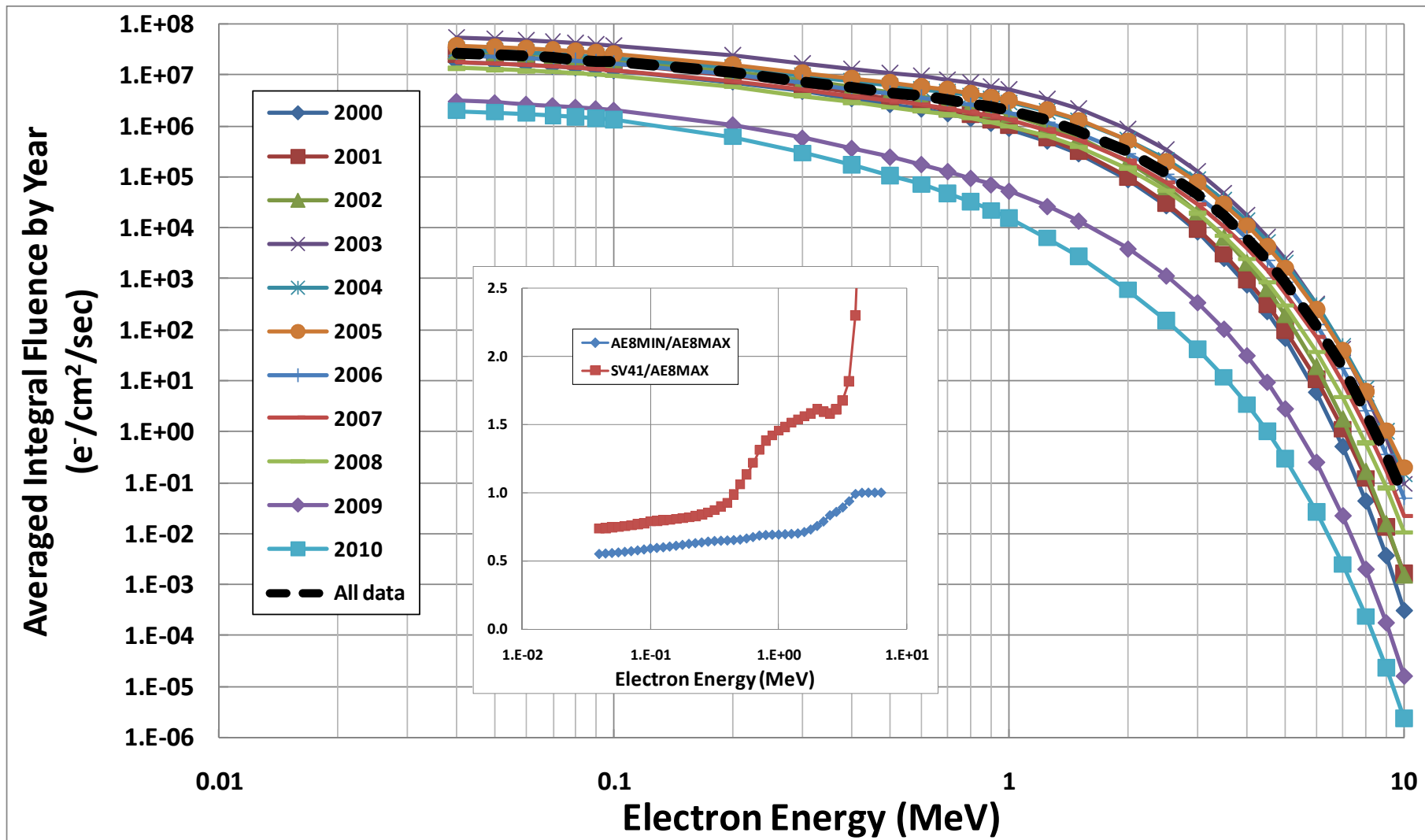
## Data Sets for Spiral 1



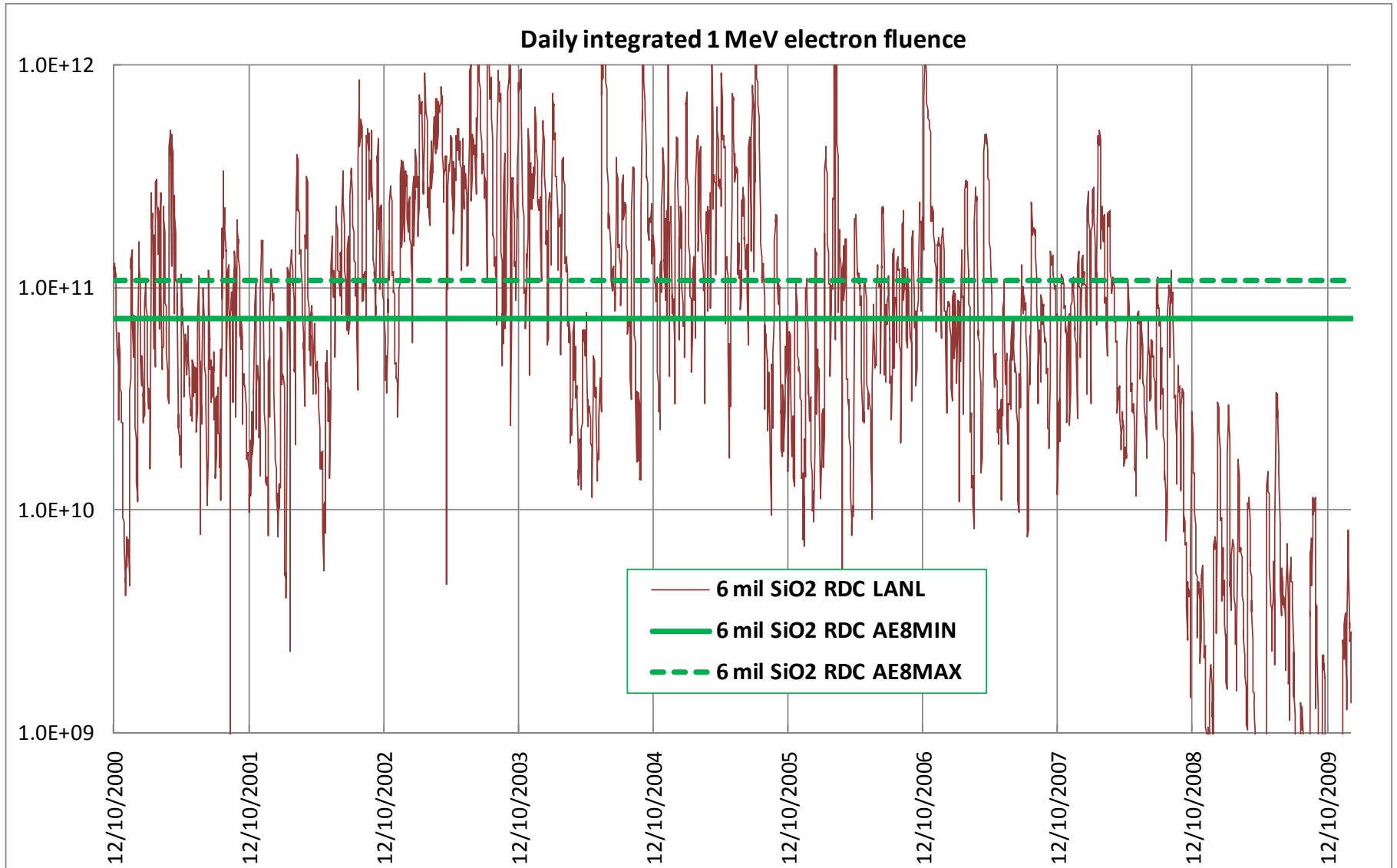
Data Set	Orbit/Duration	Measurements
HEO-1	Molniya, L>2, little coverage L<4, 1994 onward	p+: >80, >160, >320 keV, >20, >40, >55, >66 MeV e- : >130, >230 keV, >1.5, >4, >6.5, >8.5 MeV
HEO-3	Molniya, L>2, 1997 onward	p+: >80, >160, >320 keV, >5, 8.5-35, 16-40, 27-45 MeV e- : >130, >230, >450, >630 keV, >1.5, >3.0 MeV
ICO	45°, 10000 km circular, MEO L>2.5, 2001 onward	p+: >15, >24, >33, >44, >54 MeV e- : >1.2, >2.2, >4, >6, >8 MeV
TSX-5	67° LEO, 400 x 1700 km, June 2000- Jul 2006	CEASE (dosimeter & telescope) p+: 20 – 100 MeV, 4 integral channel e- : 0.06 – 4 MeV, 5 integral channels
CRRES	GTO, L>1.1, contamination issues in inner zone, Jul 1990 – Oct 1991	PROTEL(p+): 1 – 100 MeV, 22 channels HEEF(e-): 0.6 – 6 MeV, 10 channels MEA(e-): 0.1 – 1.0 MeV LEPA(p+ & e-): 100 ev – 50 KeV
S3-3	97.5° MEO, 236 x 8048 km, 1976-1979	p+: 80 keV – 15.5 MeV (5 ch), > 60 MeV (no GF) e- : 12 keV – 1.6 MeV (12 ch)
GPS	54°, 20000 km, MEO L>4.2, Jan 1990 onwards	BDD/CXD, p+: 5/9 – 60 MeV e- : 0.1/0.2 – 10 MeV
Polar	90°, 1.8 x 9.0 Re, Feb 1996 – Apr 2008	CAMMICE/MICS, p+, O+: 1-200 keV/e HYDRA, p+, e-: 2 eV – 35 keV IES/HISTe, e-: 30 keV – 10 MeV
GOES 7,8 & 11	GEO 1986 onwards	SEM, p+: 0.8 – 700 MeV, 10 differential channels >1, >5, >10, >30, >50, > 100 MeV integral channels
SAMPEX	LEO (500 km) 1992.5 onward	PET, p+: up to 400 MeV e- : >0.5, >1, 1-6, 3-16, 10-20 MeV
LANL	GEO 1985 onwards	MPA/CPA/ESP/SOPA p+: 0.1 keV – 200 MeV e- : 0.1 keV - > 10 MeV
DSP-21	GEO Aug 2001 onward	CEASE (dosimeter & telescope) p+: 20 – 100 MeV, 4 integral channel e- : 0.06 – 4 MeV, 5 integral channels

Primarily calibration in AE-9/AP-9 beta

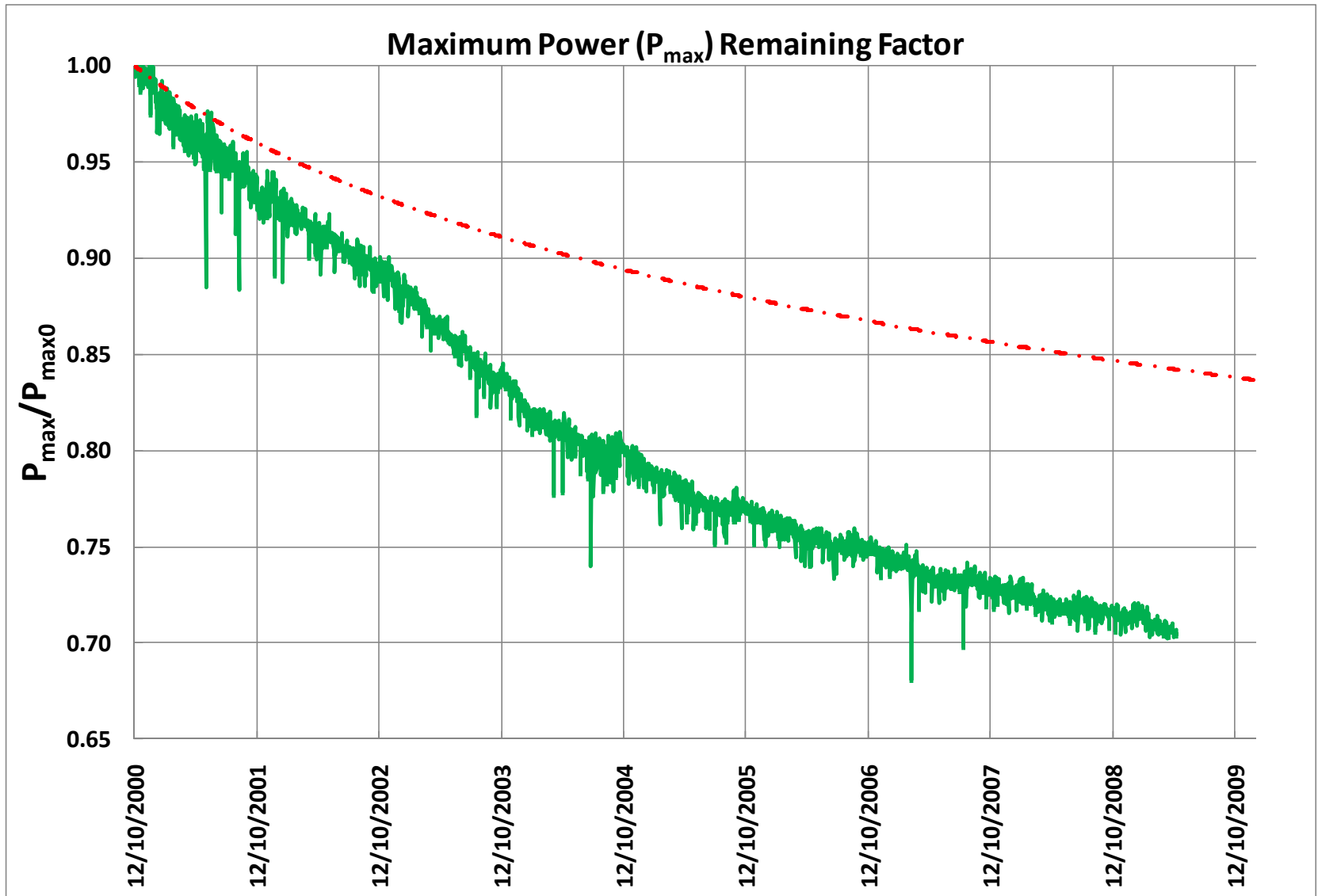
# GPS Environment Data (LANL)



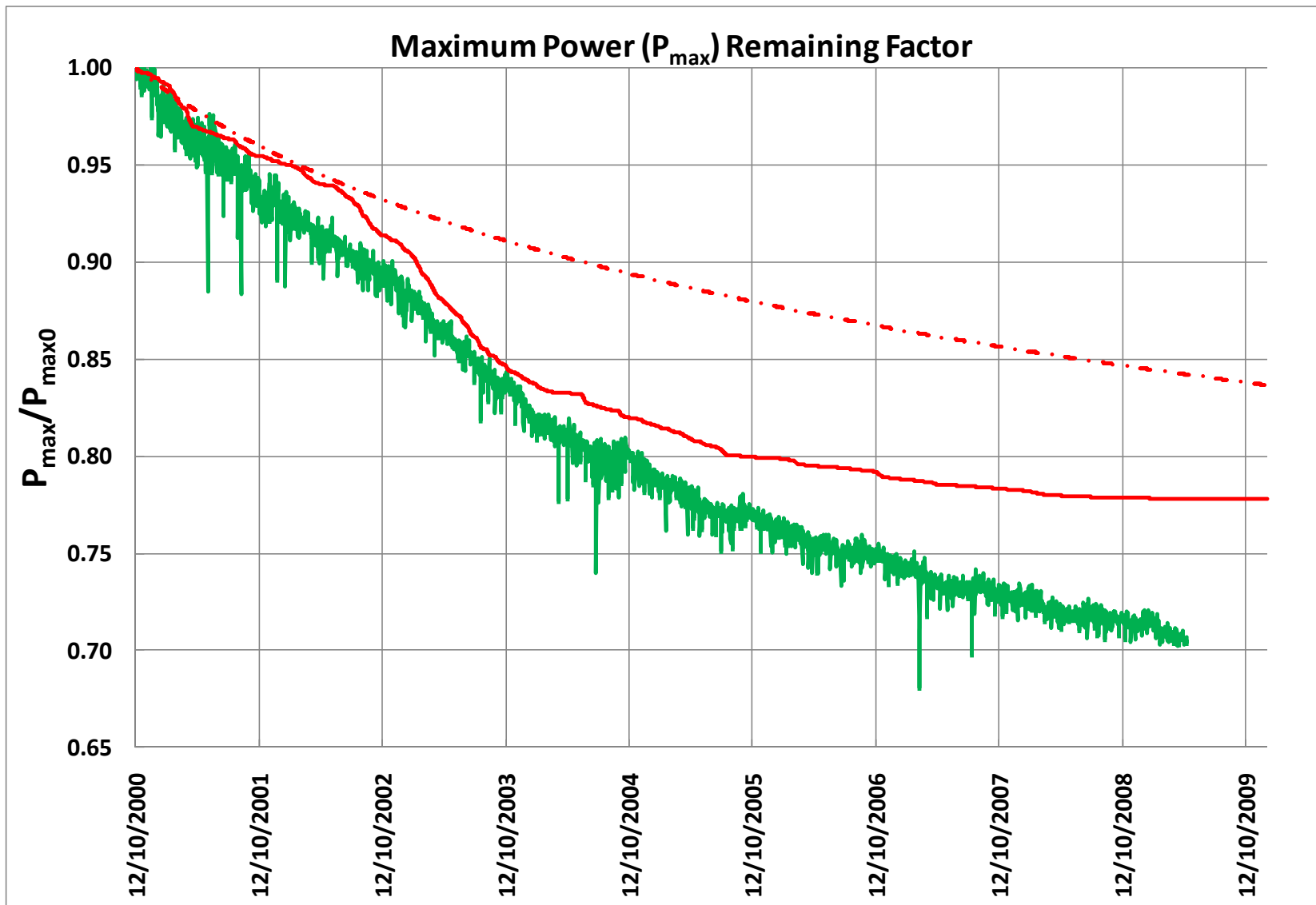
# GPS Environment Data (LANL)



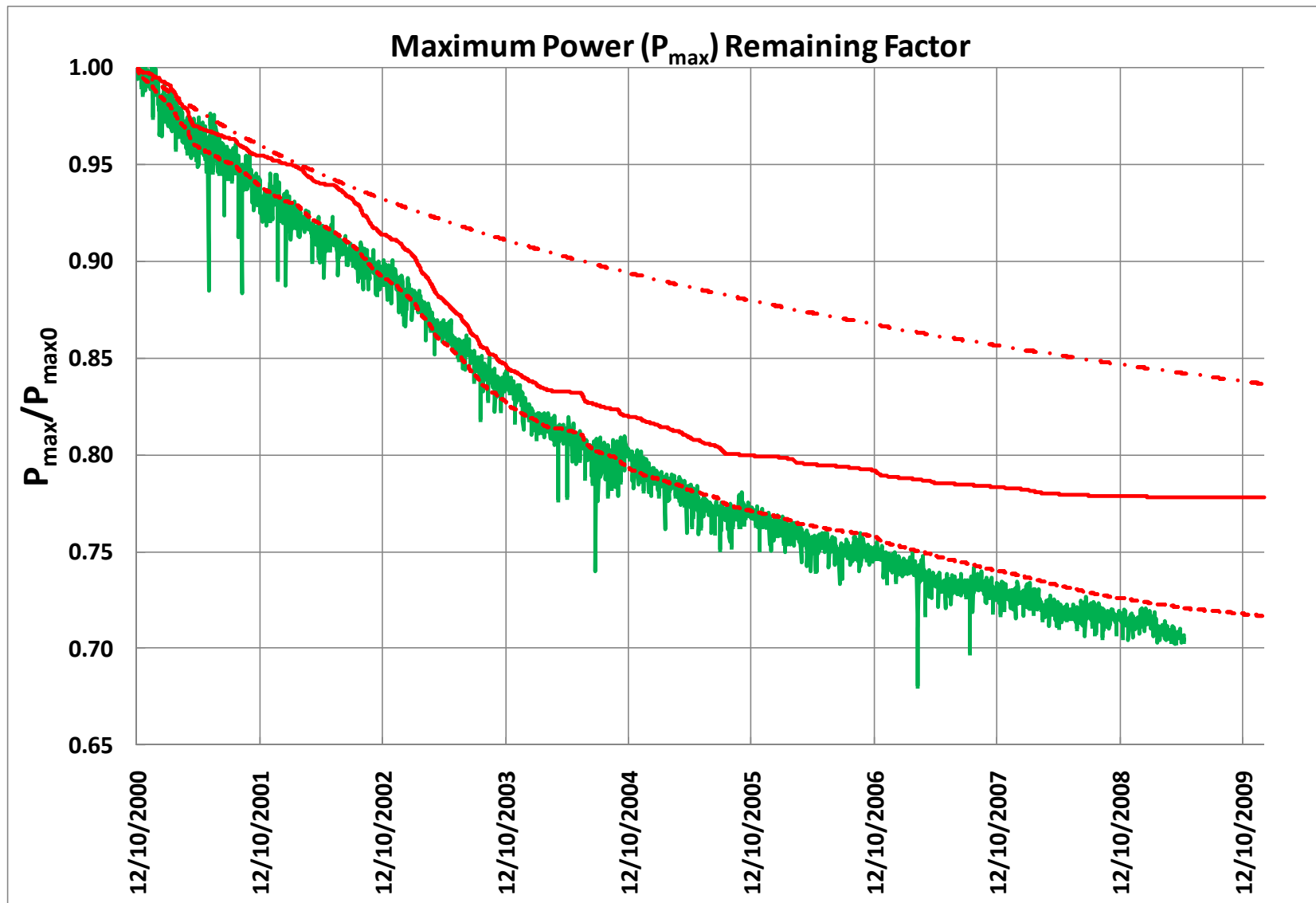
# GPS Array Data with Environment Data (LANL)



# GPS Array Data with Environment Data (LANL)



# GPS Array Data with Environment Data (LANL)



# **Bottom Line**

**The environment is a significant source of error, depending on the mission and lifetime.**

# Outline

**1. Motivation**

**2. The Space Radiation Environment**

**3. Solar Cell Space Radiation  
Degradation Modeling**

-JPL Equivalent Fluence (EQFLUX)

-NRL Displacement Damage Dose (SCREAM)

**4. Radiation Damage in Multijunction  
Solar Cells**



# Displacement Damage

## INTERACTIONS

### PROTONS

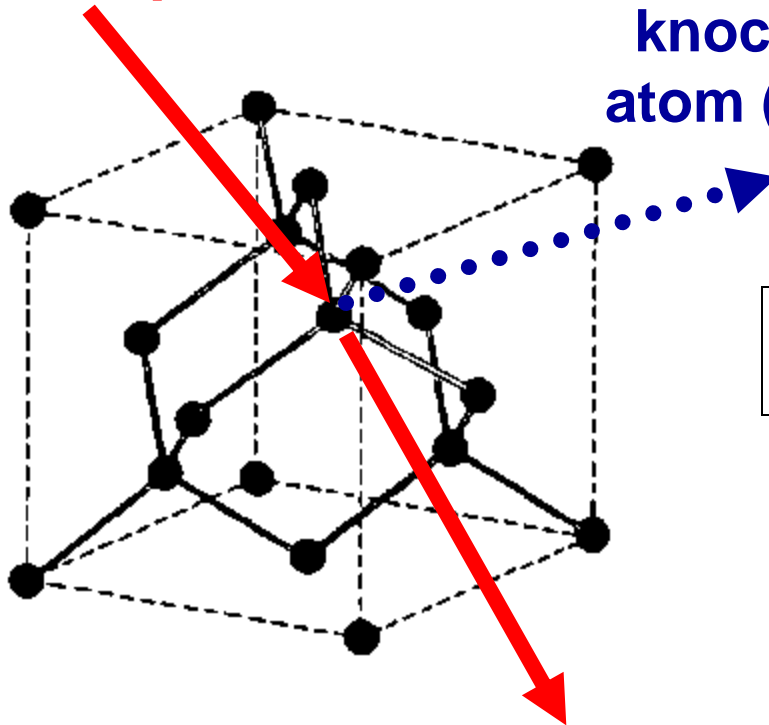
Rutherford  
Nuclear Elastic  
Nuclear Inelastic

### ELECTRONS

Rutherford

**Incident particle**

**Primary  
knock-on  
atom (PKA)**



## DAMAGE

### SIMPLE DEFECTS

Vacancies  
Interstitials

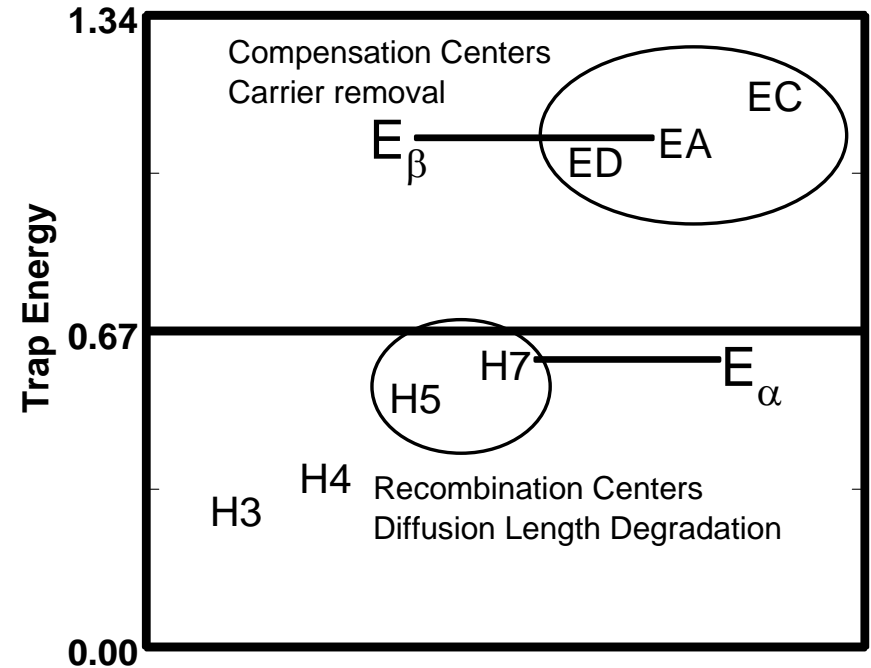
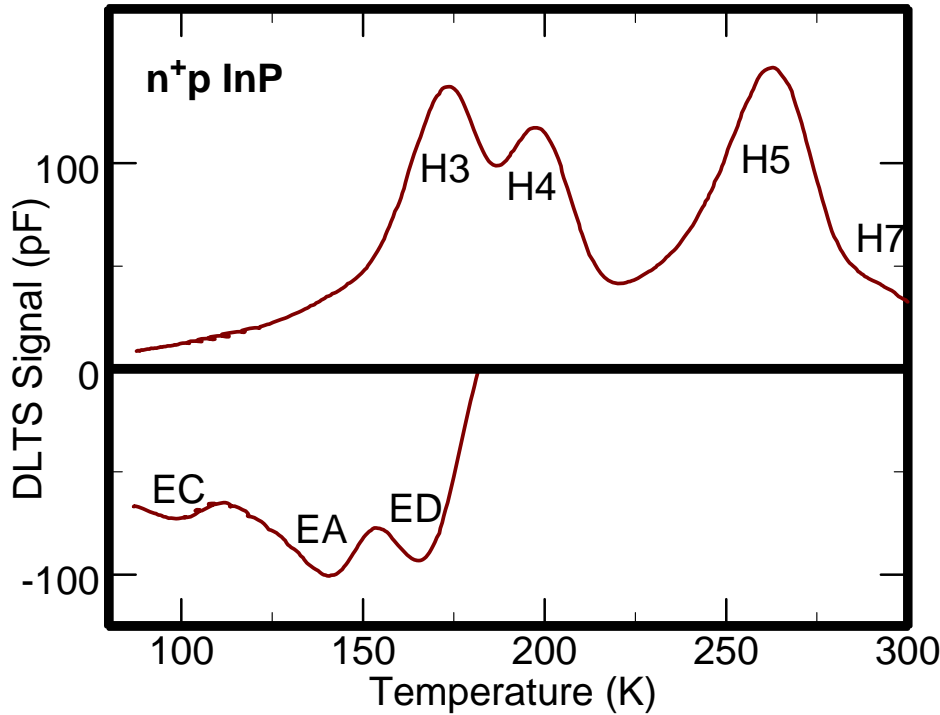
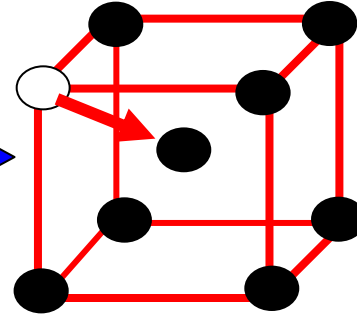
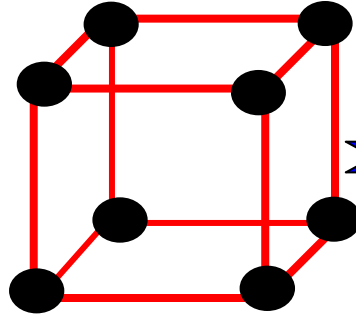
### COMPLEXES

Vacancy/impurity  
Multi-vacancy/interstitial  
Clusters

**Scattered particle**



# Effect of Particle-Induced Damage



# JPL and NRL Methods

- **NASA Jet Propulsion Laboratory (Pasadena, CA)**
  - **Calculate equivalent 1 MeV electron fluence for mission**
    - Uses empirically determined relative damage coefficients (RDCs)
  - **Read EOL power from measured 1 MeV electron curve**
- **Naval Research Laboratory (Washington, DC)**
  - **Calculate displacement damage dose ( $D_d$ ) for mission**
    - Uses calculated values of nonionizing energy loss (NIEL)
  - **Read EOL power from measured “characteristic” curve**

\*Both methods have the same general approach.

# Orbital Degradation Calculations

## JPL Method

$$\Phi_{1\text{MeV electron}} = \int \frac{d\phi_e(E_e)}{dE_e} \cdot \text{RDC}(E_e, t) dE_e + C_{pe} \int \frac{d\phi_p(E_p)}{dE_p} \cdot \text{RDC}(E_p, t) dE_p$$

**$C_{pe}$  is determined empirically (75-90% degradation level)**

## NRL Method

$$D_d = \int \frac{d\phi(E_p)}{dE_p} \cdot \text{NIEL}(E_p) dE_p + R_{ep} \int \frac{d\phi(E_e)}{dE_e} \cdot \text{NIEL}(E_e) \left[ \frac{\text{NIEL}(E_e)}{\text{NIEL}(1\text{ MeV})} \right]^{n-1} dE_e$$

**$R_{ep}$  is determined empirically (ratio  $D_{xe}/D_{xp}$ )**

**\*Both methods currently rely on *single-valued* electron-proton degradation correlation. However, these methods can be adapted to account for degradation-dependent correlation (WCPEC 2006).**

# Heritage Model

## JPL Equivalent Fluence Method

- Data needed

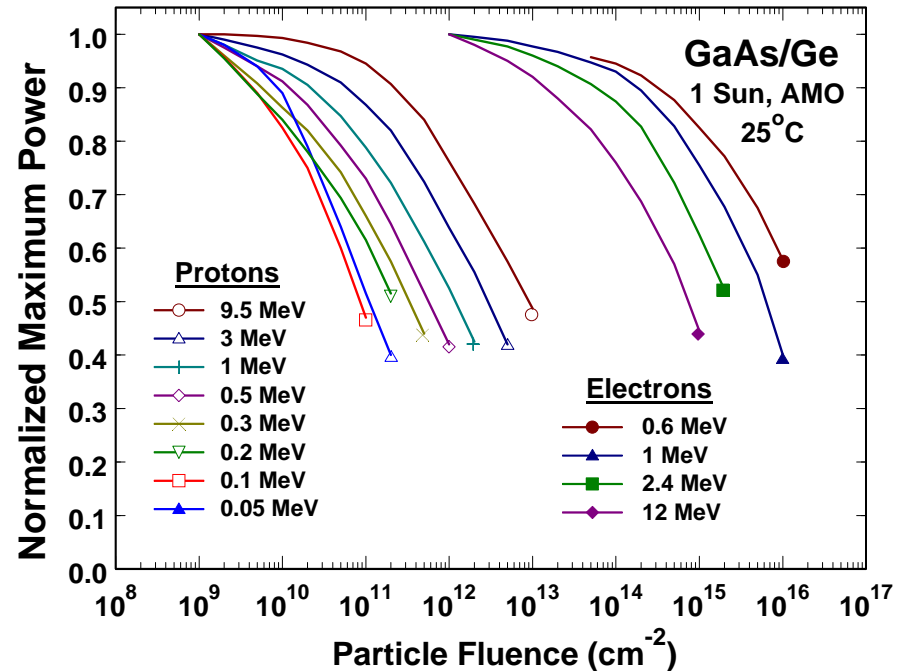
- Protons

- $E = 0.02, 0.05, 0.1, 0.3, 1, 3, 10 \text{ MeV}$
- $\phi = 3e9 \text{ to } 2e12 \text{ p}^+/\text{cm}^2$

- Electrons

- $E = 0.6, 1, 12 \text{ MeV}$
- $\phi = 2e13 \text{ to } 1e16 \text{ p}^+/\text{cm}^2$

### Electron and Proton Fluence Data (GaAs/Ge, 1991)

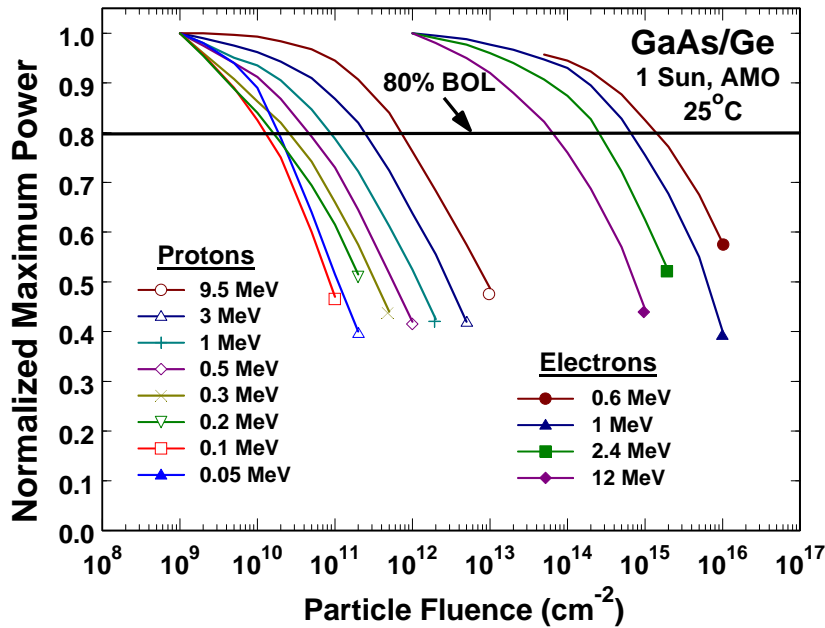


# Electron Damage Coefficients

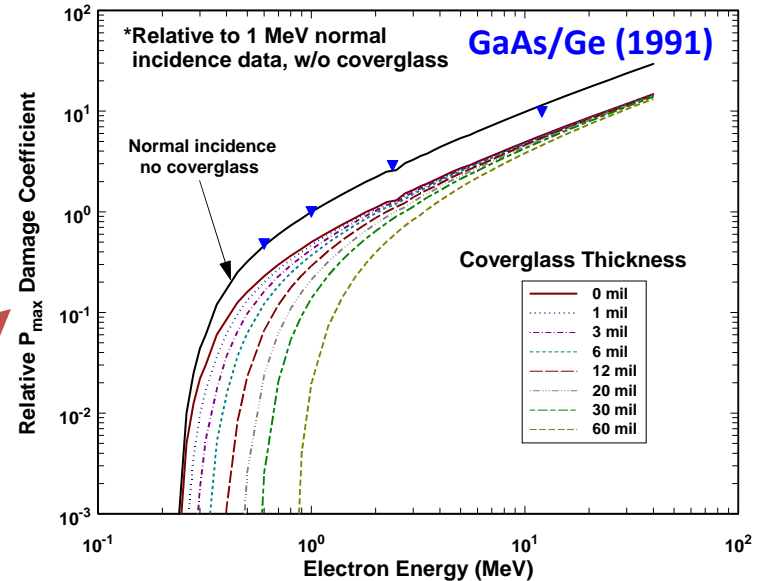
## RDC Calculation

(10 MeV Protons & 1 MeV electrons)

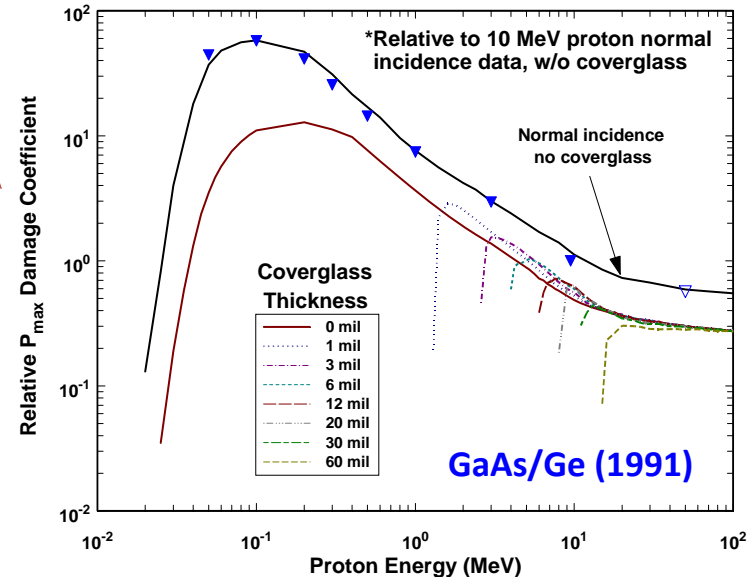
## Electron and Proton Fluence Data (GaAs/Ge, 1991)



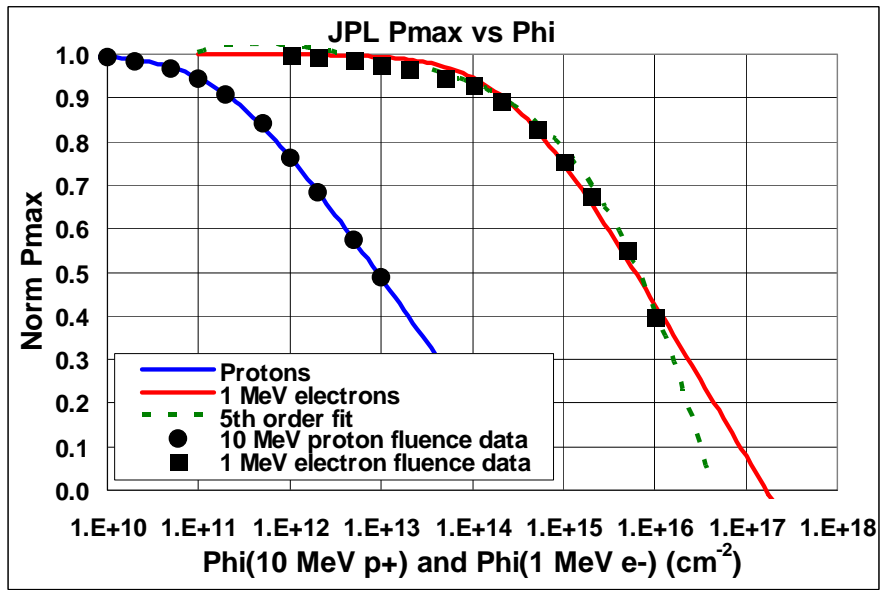
- Data exist for  $P_{max}$ ,  $I_{sc}$ , and  $V_{oc}$  for both electrons and protons
- Solar cell technologies available include Si, GaAs/Ge, MJ (2001)
- Empirical values for  $C_{ep}$  (based on 75-90% level)
- Measurement intensive (\$\$)



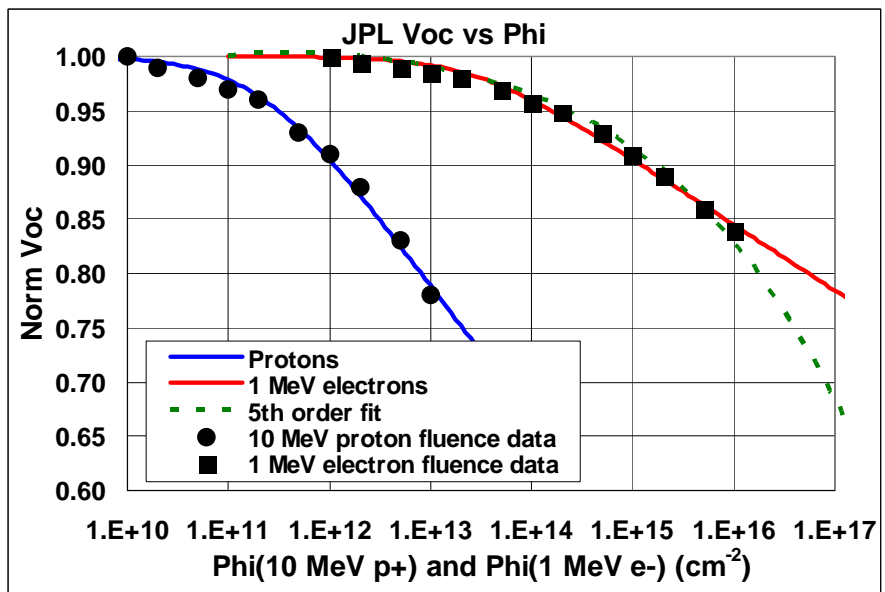
# Proton Damage Coefficients



# Equivalent Fluence Analyses of GaAs/Ge Solar Cells



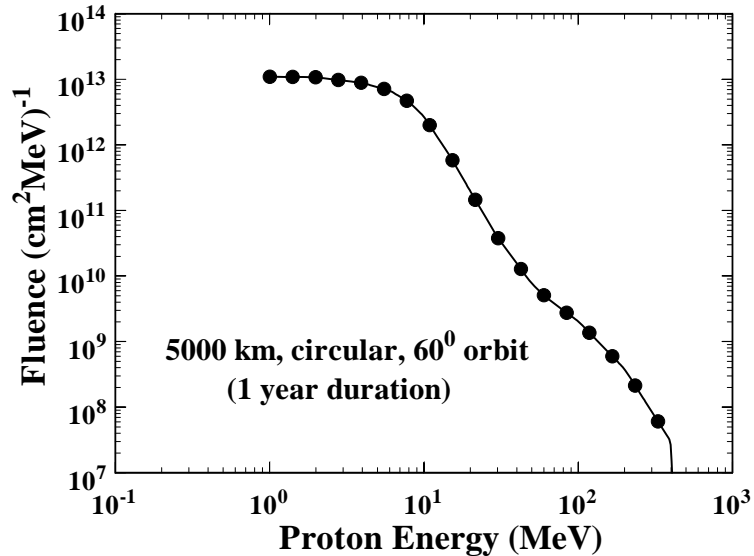
$$\frac{P(\phi)}{P_0} = 1 - C \cdot \log \left[ 1 + \frac{\phi}{\phi_x} \right]$$



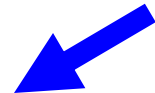
10 MeV Proton and 1 MeV electron fit results						
10 MeV Protons						
	Pmax		Voc		Isc	
	value	error	value	error	value	error
C	0.297	0.003	0.124	0.008	0.236	0.018
Phix	1.92E+11	5.44E+09	2.04E+11	3.88E+10	5.34E+11	1.00E+11
Cep	1000		1400		400	
1 MeV Electrons						
	Pmax		Voc		Isc	
	value	error	value	error	value	error
C	0.351	0.025	0.061	0.003	0.361	0.0341
Phix	2.38E+14	4.85E+13	2.79E+13	6.04E+12	4.46E+14	1.07E+14

# JPL Equivalent Fluence Method

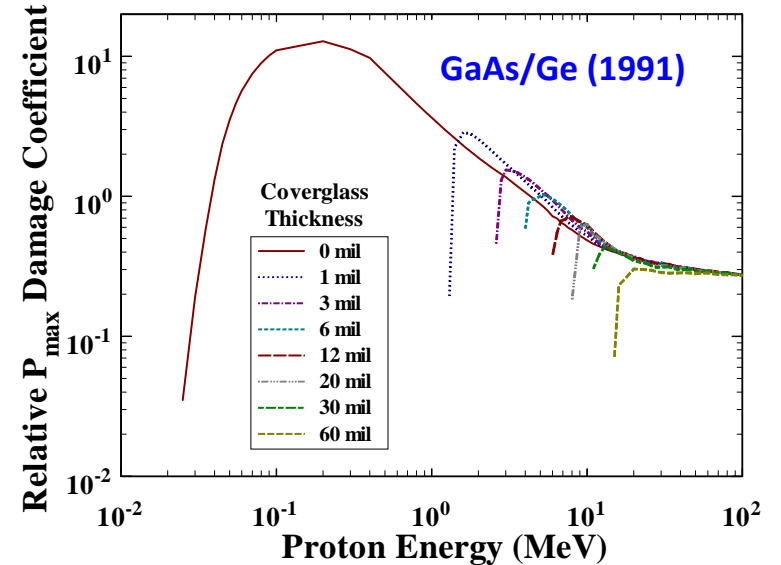
## Initial Omnidirectional Spectrum



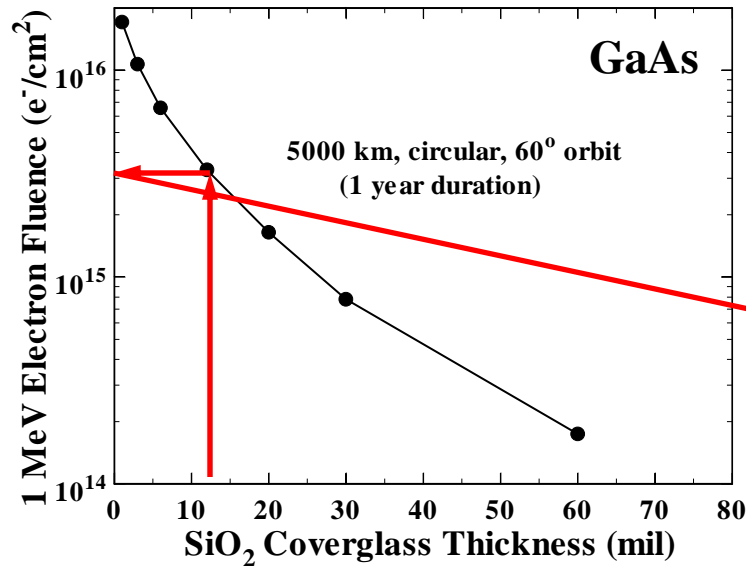
$w/C_{ep}$



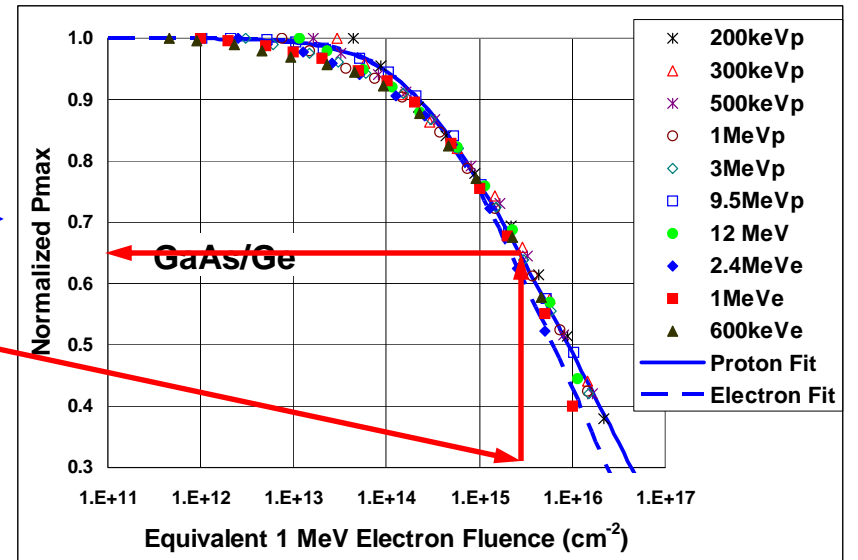
## Proton Damage Coefficients



## Equivalent 1 MeV Electron Fluence



## 1 MeV Electron $P_{\max}$ Degradation



# JPL Model Pros/Cons

- **Pros:**

- Heritage (developed in the 1980s)
- Widely available and already incorporated into many space radiation suites (SPENVIS, Space Radiation™, OMERE, etc.)

- **Cons:**

- Much ground test data needed (\$\$)
- Requires 1 MeV electron (to 12 MeV) AND 10 MeV proton data
- Currently available for Si (1982), GaAs/Ge (1996), MJ (1999)
- Program not particularly user friendly in FORTRAN version
- Entire calculation is technology specific (every design change needs requalification, \$\$)
- Calculation of omnidirectional RDCs for covered cells not trivial and coverglass and technology specific
- Assumes that the total damage can be characterized by 1 MeV electrons which may not be appropriate for proton-dominated orbits

# Proposed Model

## NRL Displacement Damage Dose Method

- Data needed

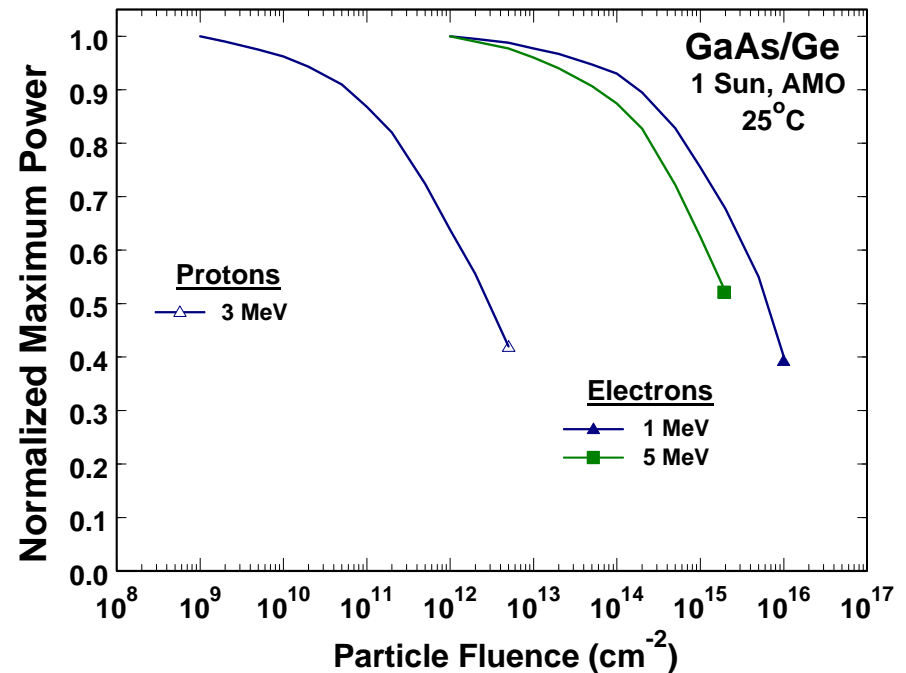
- Protons

- $E = 3 \text{ MeV}$
- $\phi = 1e10 \text{ to } 1e13 \text{ p}^+/\text{cm}^2$

- Electrons

- $E = 1 \text{ and } 5 \text{ MeV}$
- $\phi = 1e13 \text{ to } 1e16 \text{ p}^+/\text{cm}^2$

### Electron and Proton Fluence Data (GaAs/Ge, 1991)



# NonIonizing Energy Loss

**NIEL**=Rate at which energy is lost to nonionizing events;  
analogous to LET or stopping power for ionizing  
events **(UNIT=MeV/cm or MeVcm<sup>2</sup>/g)**

$$\text{NIEL}(E) = \int_{\theta_{\min}(T_d)}^{\pi} \left( \frac{d\sigma(\theta, E)}{d\Omega} \right) T(\theta, E) L[T(\theta, E)] d\Omega$$

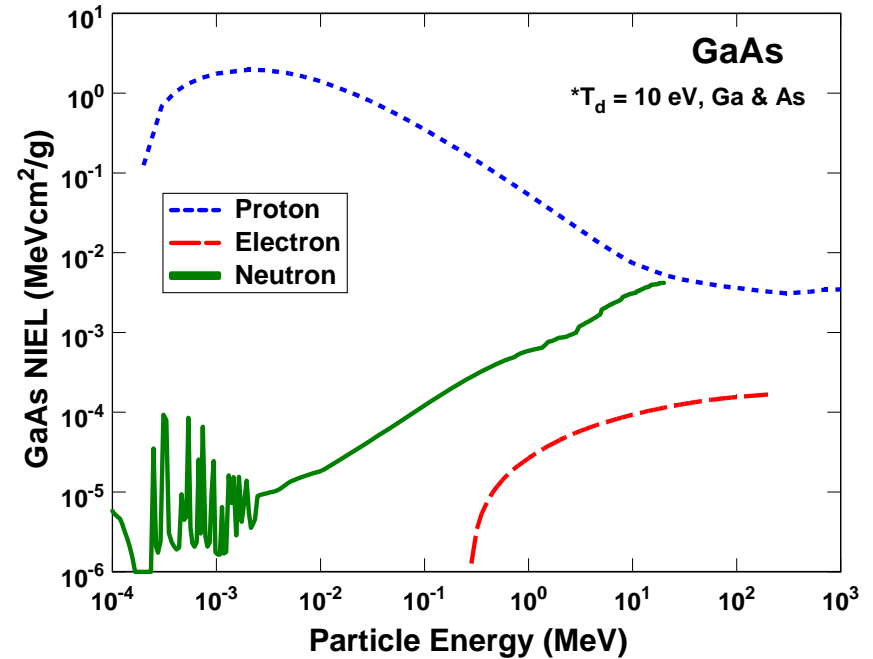
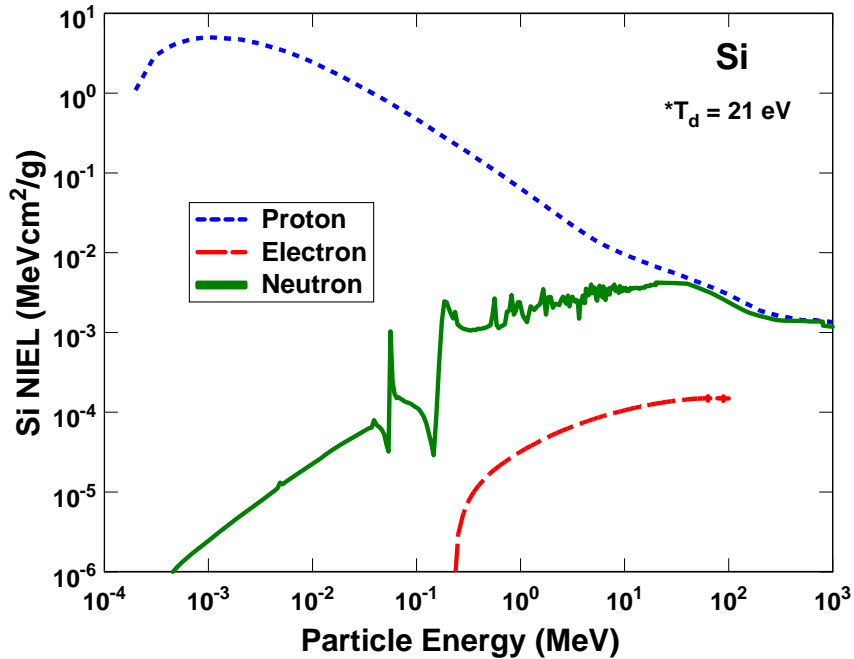
Differential scattering  
cross section for  
displacements

Recoil energy

Lindhard partition  
factor

**NOTE: Energy dependence of NIEL similar to experimental RDCs**

# NIEL in Si and GaAs



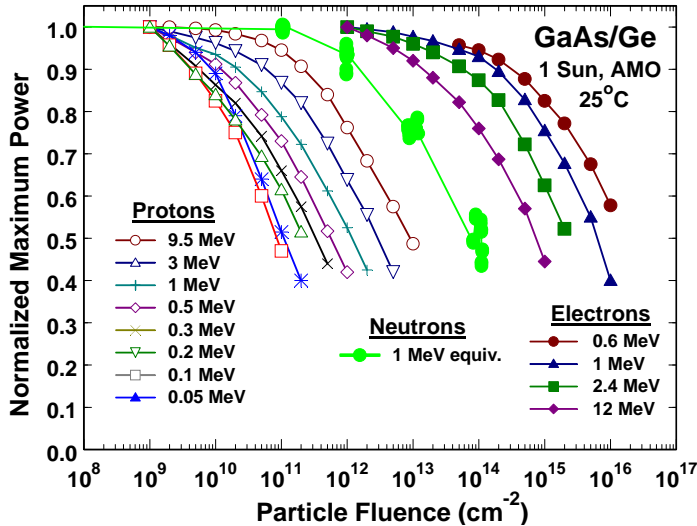
**\*NIEL calculation available for any charged particle in any material**

**\*Neutron NIEL determined from Displacement Kerma calculation**

$$\text{NIEL (MeVcm}^2\text{/g)} = \text{KERMA (MeVmb)} \times (10^{-27} N_A / A)$$

# Displacement Damage Dose Analysis of GaAs/Ge Solar Cells

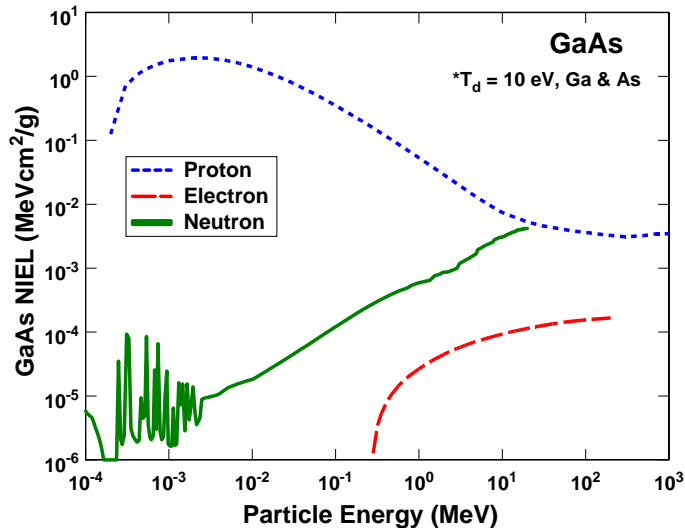
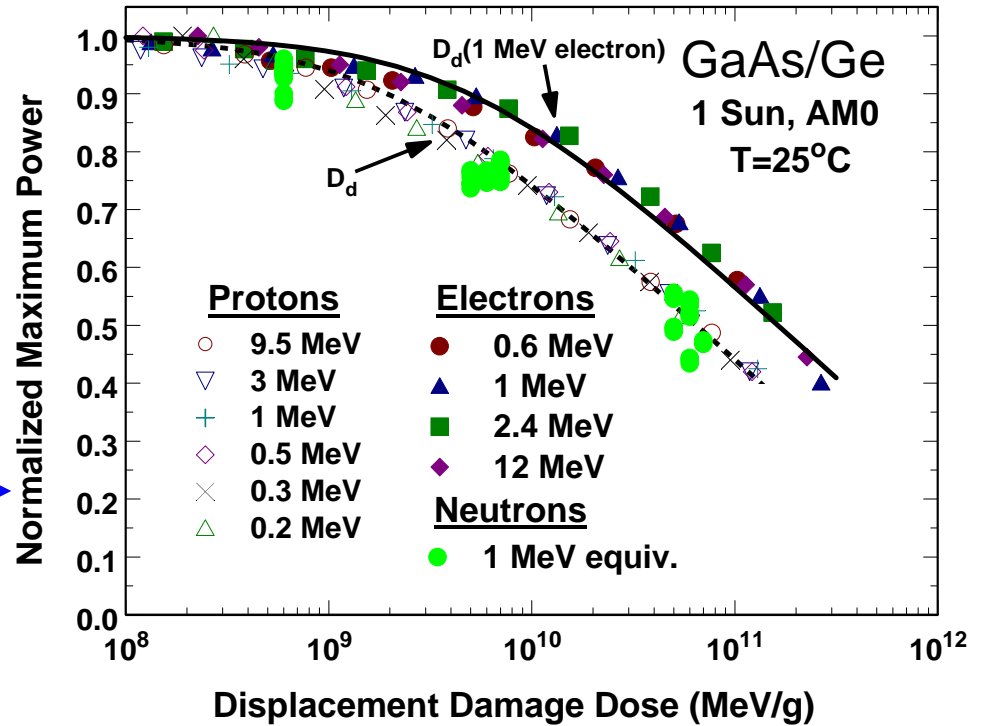
## Measured Data



w/ NIEL



## Characteristic Curves

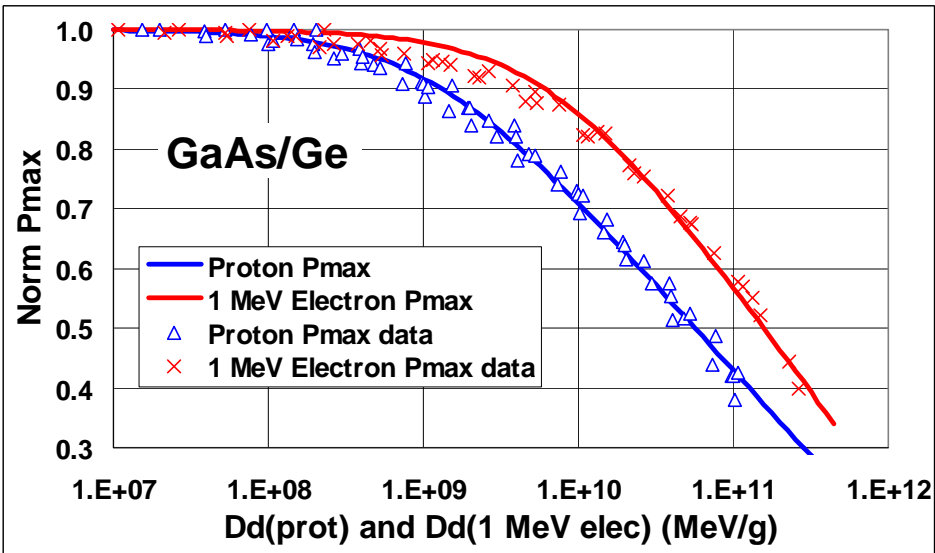


- Calculated NIEL gives energy dependence of damage coefficients (well-matched to RDCs)
- Characteristic curves can be fit to simple expressions (similar to JPL handbook method)
- Characteristic curve can be generated using minimal ground test data (only 1 proton and two electron energies)

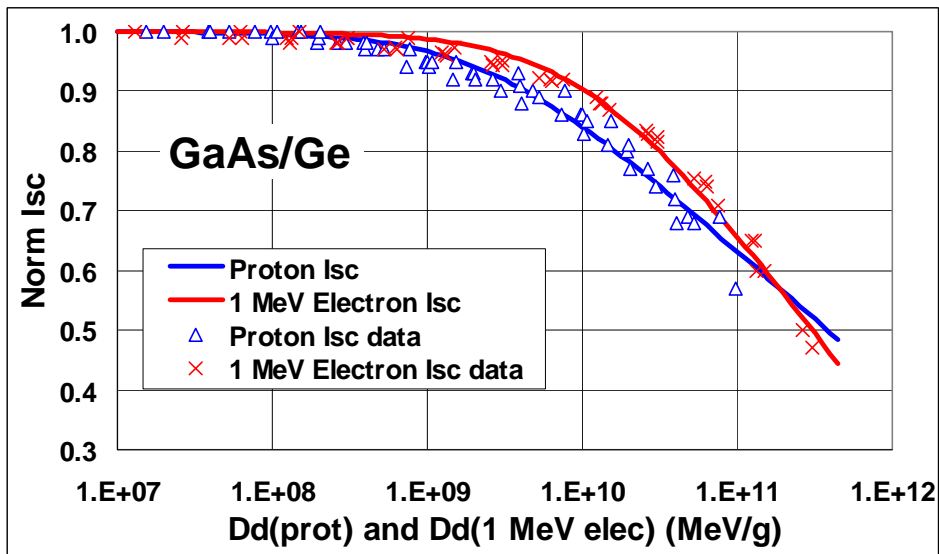
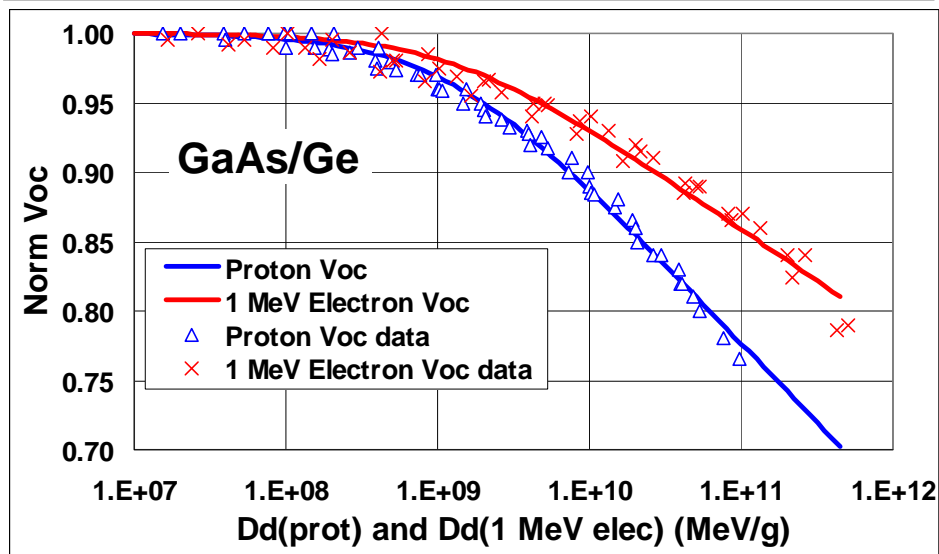
# Dd Analyses of GaAs/Ge Solar Cells

$$D_d(E) = \Phi(E) \cdot \text{NIEL}(E) \left[ \frac{\text{NIEL}(E)}{\text{NIEL}(E_{\text{ref}})} \right]^{n-1}$$

$$\frac{P(D_d)}{P_0} = 1 - C \cdot \log \left[ 1 + \frac{D_d}{D_x} \right]$$

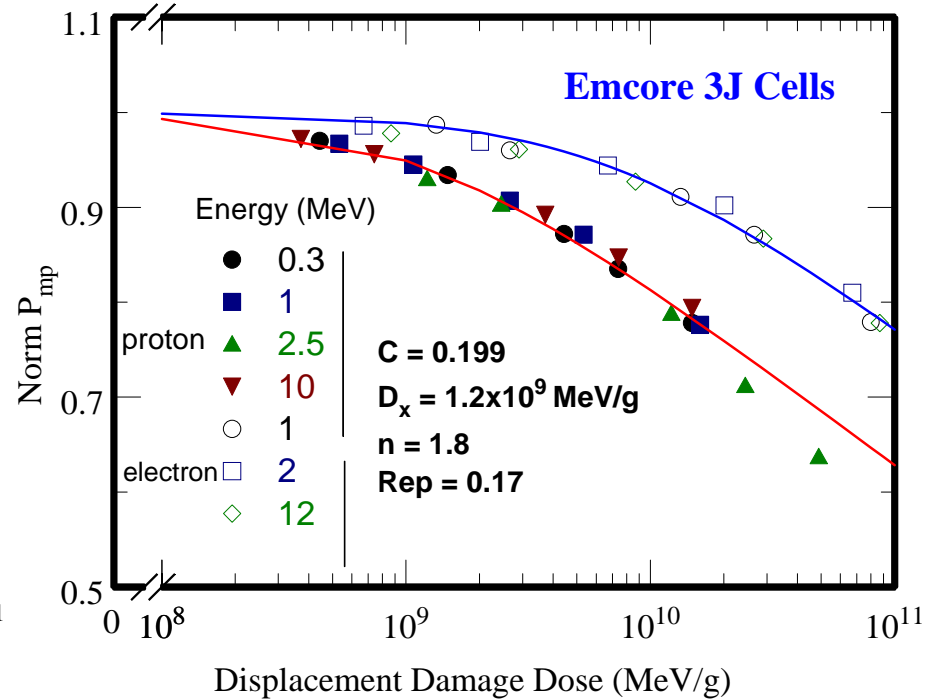
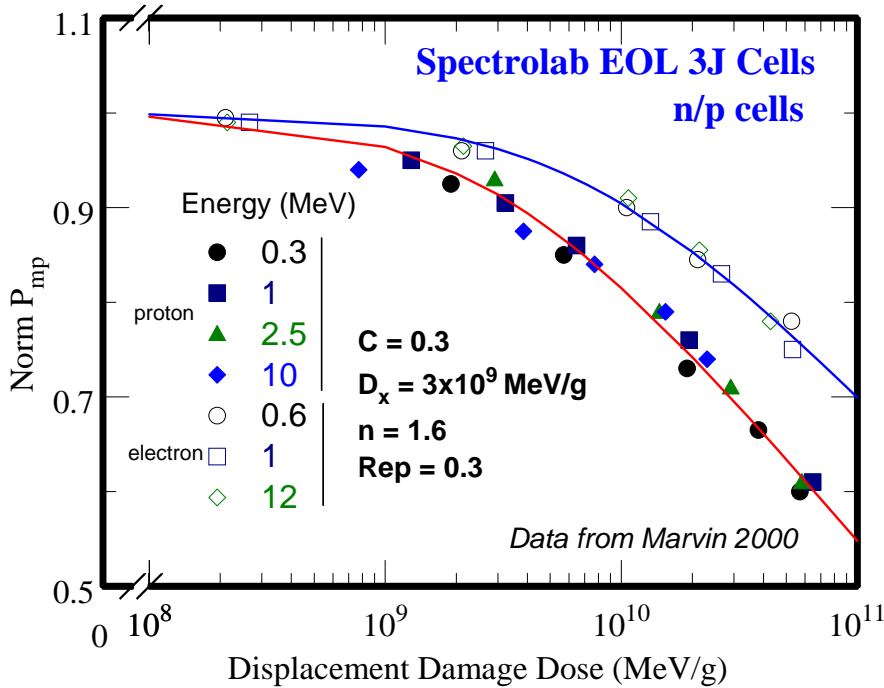


Protons						
	Pmax		Voc		Isc	
	value	error	value	error	value	error
C	0.2904	0.0071	0.115	0.00317	0.229	0.0158
Dx	1.10E+09	8.66E+07	1.15E+09	9.31E+07	2.52E+09	4.45E+08
Electrons						
	Pmax		Voc		Isc	
	value	error	value	error	value	error
C	0.363	0.025	0.0745	0.0078	0.343	0.03
Dx	6.90E+09	1.52E+09	1.28E+09	5.32E+08	1.10E+10	2.59E+09
n	1.647	0.086	2.128	0.201	1.326	0.096



# MJ Solar Cell Radiation Response in terms of $D_d$

\*GaAs NIEL used in the correlation



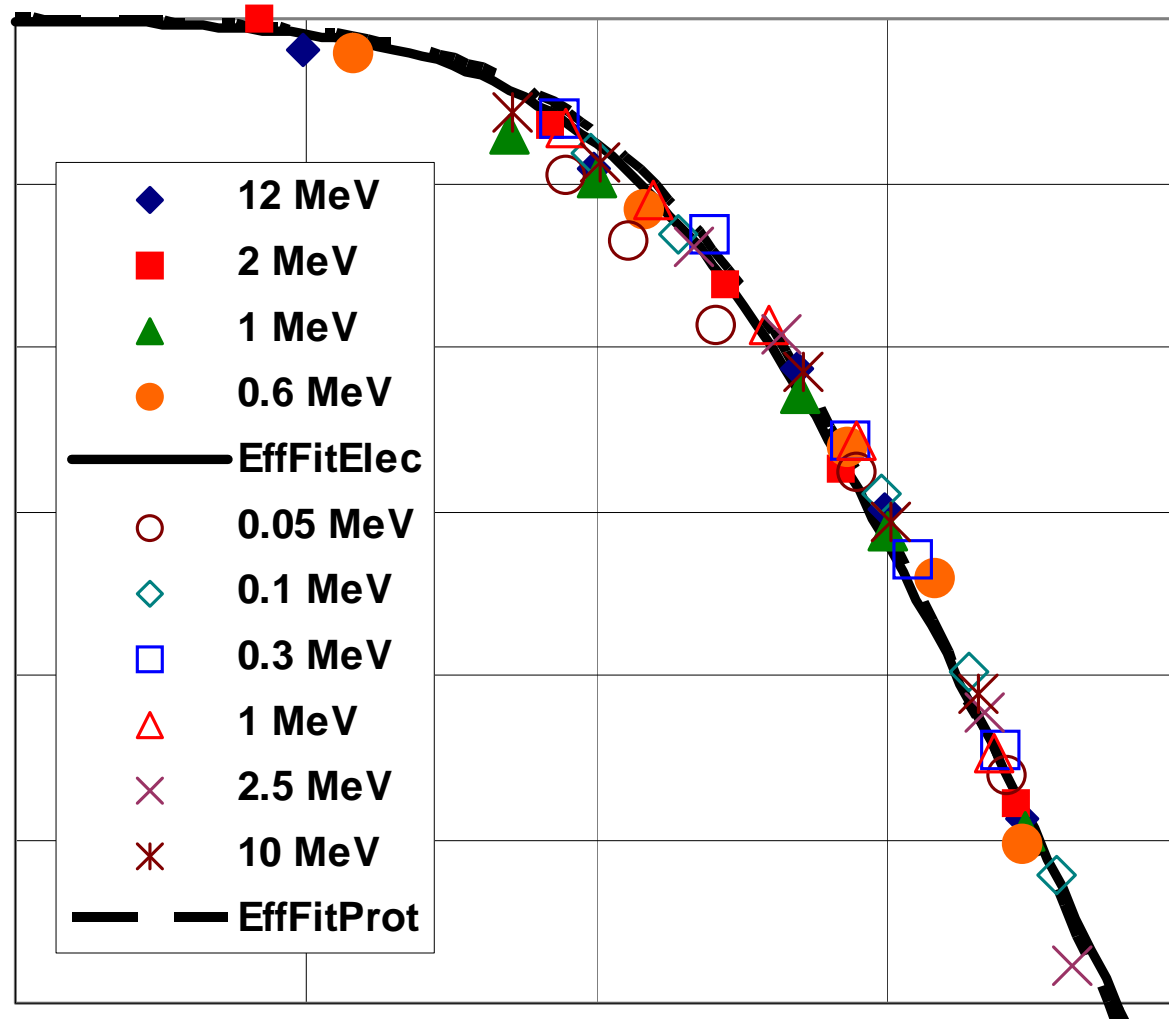
$$D_d(E) = \Phi(E) \cdot \text{NIEL}(E) \left[ \frac{\text{NIEL}(E)}{\text{NIEL}(E_{\text{ref}})} \right]^{n-1}$$

$$\frac{P(D_d)}{P_0} = 1 - C \cdot \log \left[ 1 + \frac{D_d}{D_x} \right]$$

$$R_{\text{ep}} = \frac{D_{\text{xe}}}{D_{\text{xp}}}$$

\*Experimentally determined variables ( $C$ ,  $D_{\text{xp}}$ ,  $D_{\text{xe}}$ ,  $n$ )

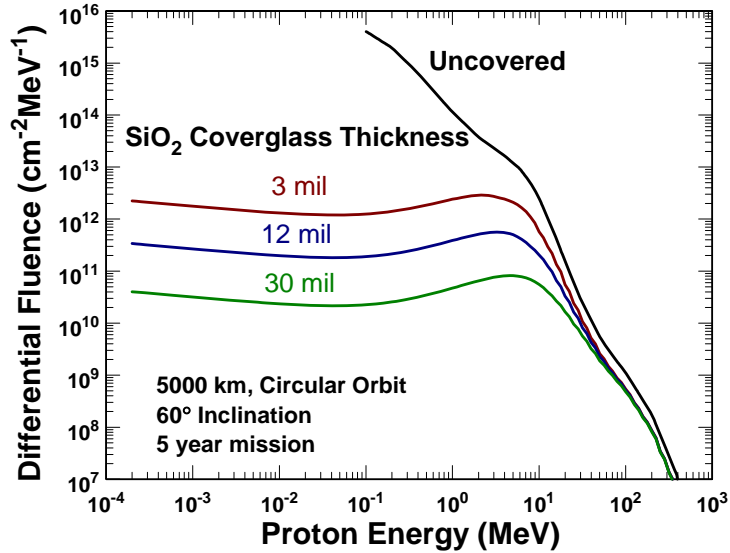
# Emcore ATJ Solar Cell Radiation Response



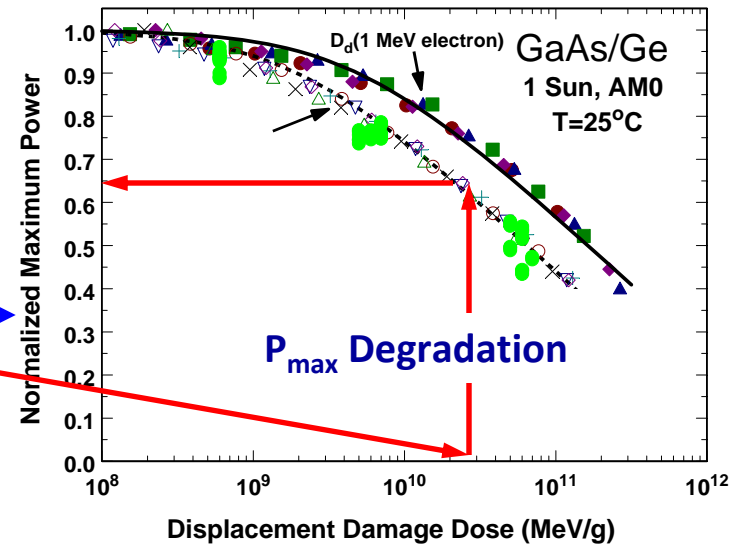
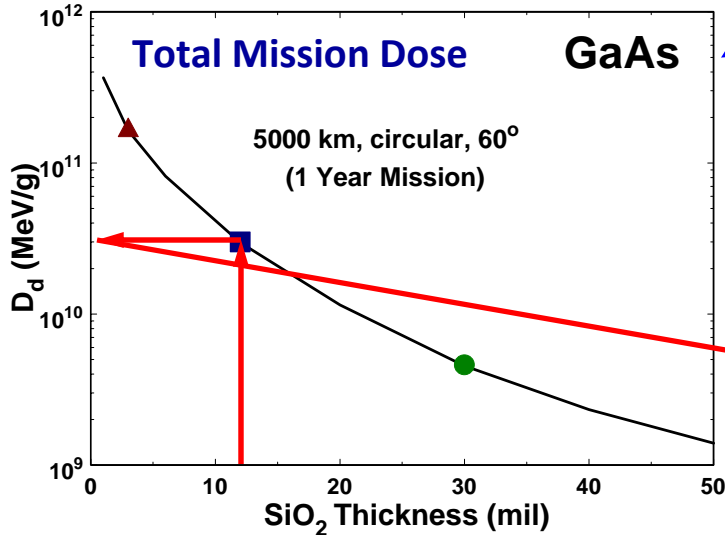
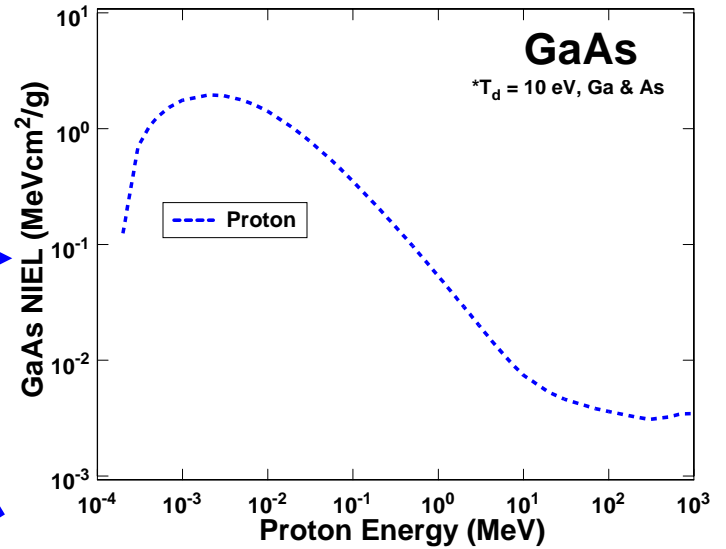
**\*This shows that the Emcore ATJ multijunction (3J) solar cell is well-behaved in that indeed a single characteristic curve is generated from the ground data. This data set is included in SCREAM development.**

# NRL Displacement Damage Dose Method

## Incident and SDS (Isotropic)



## Nonionizing Energy Loss (2003)



# NRL Model Pros/Cons

- **Pros:**

- Few ground test measurements needed (3)
- Ground test particle energies can be conveniently chosen
- Shielding algorithm is independent
- Allows for rapid analysis of emerging cell technologies
- Allows for easy trade studies
- Can combine data from different experiments
- Allows for alternate radiation particles (neutrons, alphas, etc.)

- **Cons:**

- Lack of heritage (developed in the mid-1990s)
- More suited for sufficiently thin devices (~few mm)
  - Uniform damage deposition required over active region
- Program currently not available to general public
- No interlaboratory cross calibration of method

# Analytical Model Comparison

- Proton Dd to 1 MeV electron equivalent fluence

$$\phi_{1\text{MeV electron}} = \left[ \left( 1 + \frac{D_{dp}}{D_{xp}} \right)^{\frac{C_p}{C_e}} - 1 \right] * \frac{D_{xe}}{\text{NIEL}(1)}$$

- 1 MeV electron fluence to equivalent proton Dd

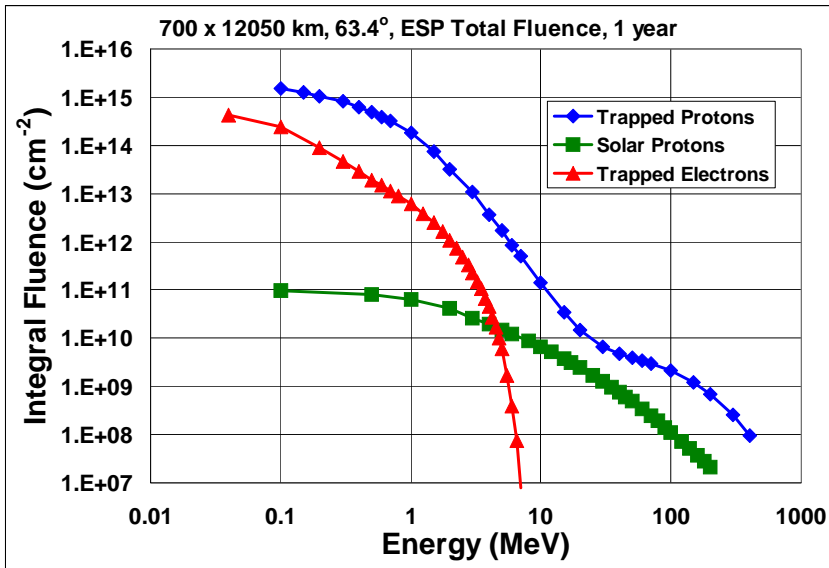
$$D_{dp} = D_{xp} \left[ \left( 1 + \frac{\phi_{1\text{MeV electron}} * \text{NIEL}(1)}{D_{xe}} \right)^{\frac{C_e}{C_p}} - 1 \right]$$

**\*General rule of thumb:  $10^{15}$  1 MeV e-/cm<sup>2</sup> ~  $10^{10}$  MeV/g**

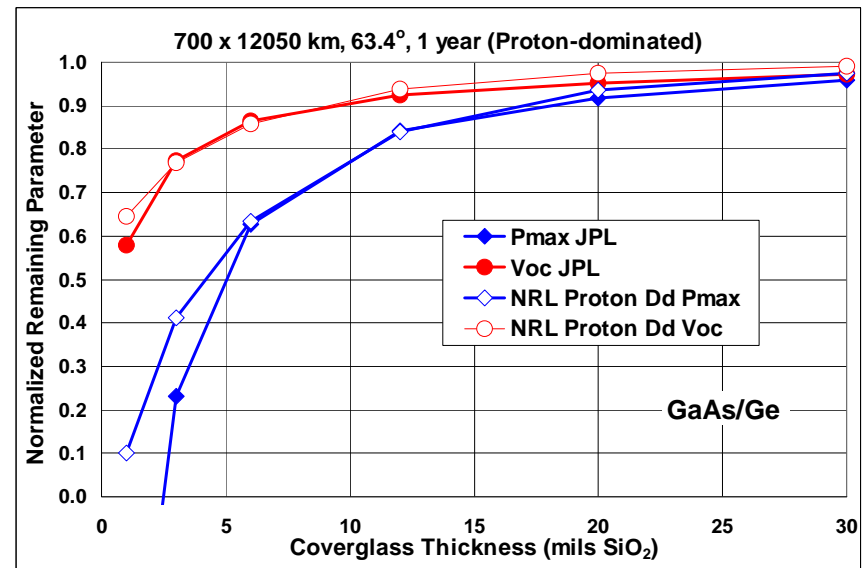
# Orbit Examples (SPENVIS)

1 year, 700 x 12050 km, 63.4°, w/ solar event protons

## Fluence Spectra



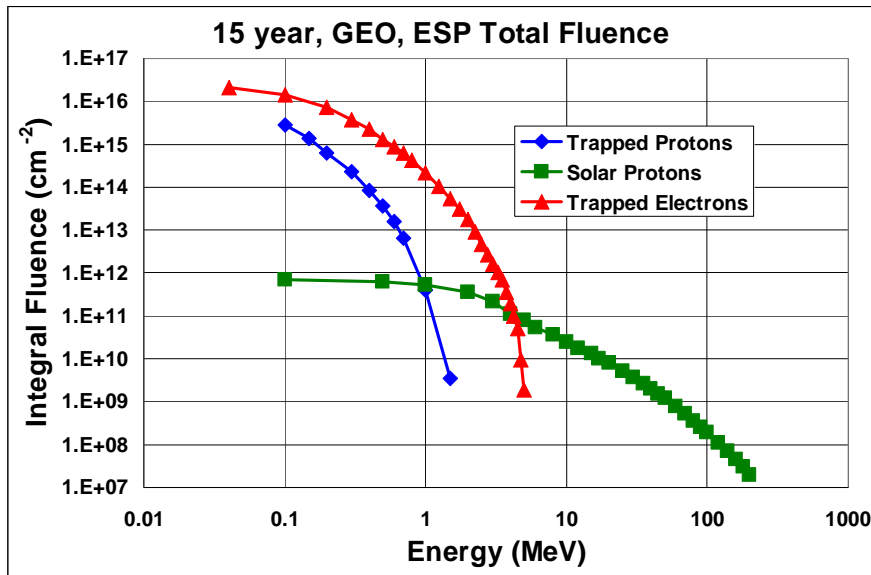
## GaAs/Ge Cell degradation vs. Coverglass Thickness



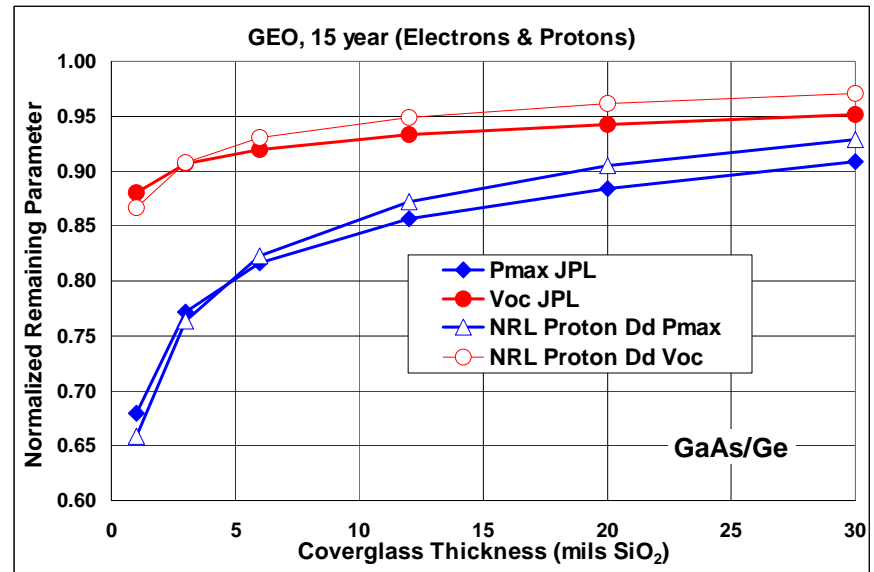
# Orbit Examples (SPENVIS)

## 15 year GEO w/ solar event protons

### Fluence Spectra

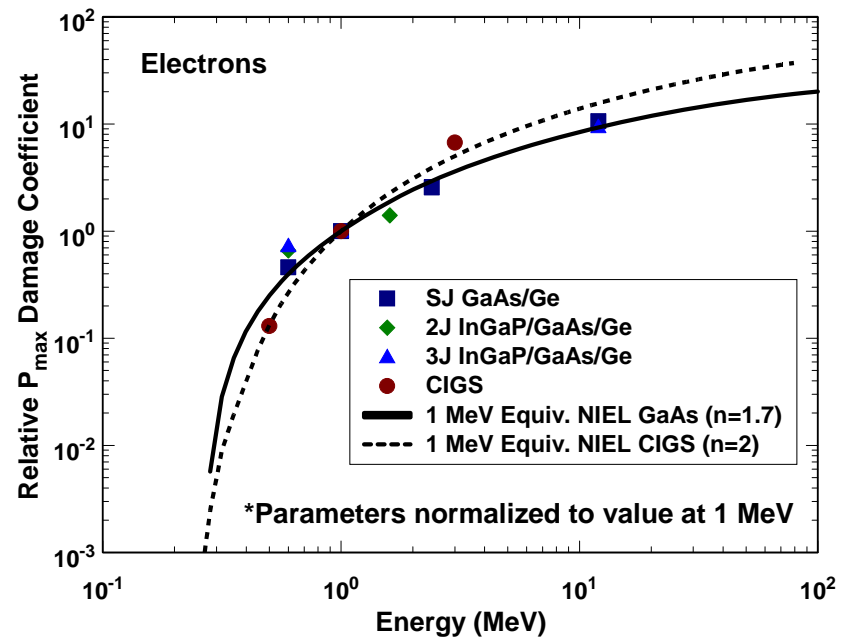
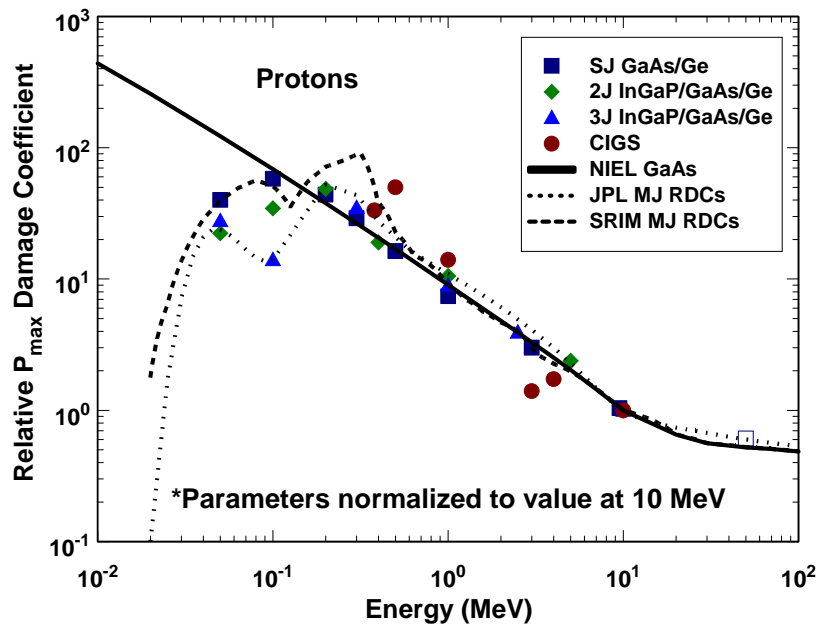


### GaAs/Ge Cell degradation vs. Coverglass Thickness



# Why Do The Models Agree?

The energy dependence of the experimentally determined RDCs closely match that of the calculated NIEL.



# DDD Implementation History

- **Quickbasic code (user proton spectrum input)**
  - Developed by NRL with Ed Burke (mid 1990's)
  - Transformed into Mathcad (mid 1990's to present)
    - Enabled both proton and electron conditions in 2005
- **NASA GRC support to Maxwell Labs (AP8/AE8)**
  - 1<sup>st</sup> version of SAVANT (late 1990's)
  - Developed for inclusion into NASA Environmental Work Bench
- **1<sup>st</sup> NASA Living With a Star (LWS-SET) Data Mining NRA**
  - NRL and NASA GRC created a FORTRAN-based, stand-alone, Windows<sup>TM</sup>-based, version of SAVANT (2003) distributed by NASA MSFC (SEE Program, now defunct)
  - Only beta version produced (large laundry list created)
- **SCREAM (Solar Cell Radiation Environment Analysis Models)**
  - Transformed MATHCAD version into MATLAB-based executable
  - Available by request
- **Spennis/Mulassis (MC-SCREAM)**
  - All of the components are there except solar cell damage info
  - The enabling component is MULASSIS to calculate the SDS
  - User interface created by Daniel Heynderickx (DHC, Consultancy)

# SAVANT DDD Analysis Code

The screenshot shows the SAVANT software interface with the following parameters:

**Inputs:**

- Orbit: Apogee: 1902.1
- Semimajor Axis: 7452.3
- Perigee: 246.30
- Eccentricity: 0.11109
- Inclination: 30.02
- Advanced Orbit:
- Solar Activity: Min
- Coverglass: CMG Glass, Thickness: 4
- Cell material: GaAs ARFC cells
- Mission Duration: 21,  Daily Orbit calculation

**Outputs:**

	Displacement Dose	Pmax/P0
Protons	4.417770e+07	0.9907
Electrons	5.748284e+06	0.9996
Total	4.644984e+07	0.9966

Buttons: Calculate, Reset, Exit

**SAVANT: Solar Array Verification and ANalysis Tool  
(NASA, NRL, OAI)**

# SCREAM

- **Integral Radiation Spectrum Input (user input)**
  - Converts the log-log spectral data into a 10<sup>th</sup> order polynomial fit
  - Differentiates the polynomial fit to get the differential spectrum
- **Shielding Range data**
  - Protons and ions: SRIM 2006
  - Electrons: ESTAR
- **Slowed-Down Spectrum (SDS) Calculation**
  - Slab model adjoint calculation based on Haffner model (1967)
  - Benchmarked with Space Radiation<sup>TM</sup>, Mulassis
- **Calculation of DDD (integral of NIEL\*SDS over energy)**
  - NIEL data from WINNIEL2 (ions) and MATHCAD (electrons)
- **Calculation of Parametric Degradation**
  - Uses 5 empirically-determined parameters for each metric

# Start-Up Page

Cell\_Degradation\_Calc

File Help

## SCREEN

### Shielding Parameters

Material

Thickness   mil  um

### Cell Technology Parameters

Cell Type

Degradation Parameter

### Load Integral Spectra

Primary Spectrum  Slowed Spectrum

### Calculated Quantities

The plot area is a log-log grid. The x-axis is labeled with  $10^{-1}$  at the left and  $10^0$  at the right. The y-axis is labeled with  $10^{-1}$  at the bottom and  $10^0$  at the top. The grid consists of 10 major divisions on both axes, with dashed lines for minor divisions.

# Materials Menu Options

The screenshot displays the 'Cell\_Degradation\_Calc' application window. At the top, the title bar reads 'Cell\_Degradation\_Calc' and the menu bar includes 'File' and 'Help'. A prominent cyan box with the text 'SCREAM' is centered at the top of the main interface area.

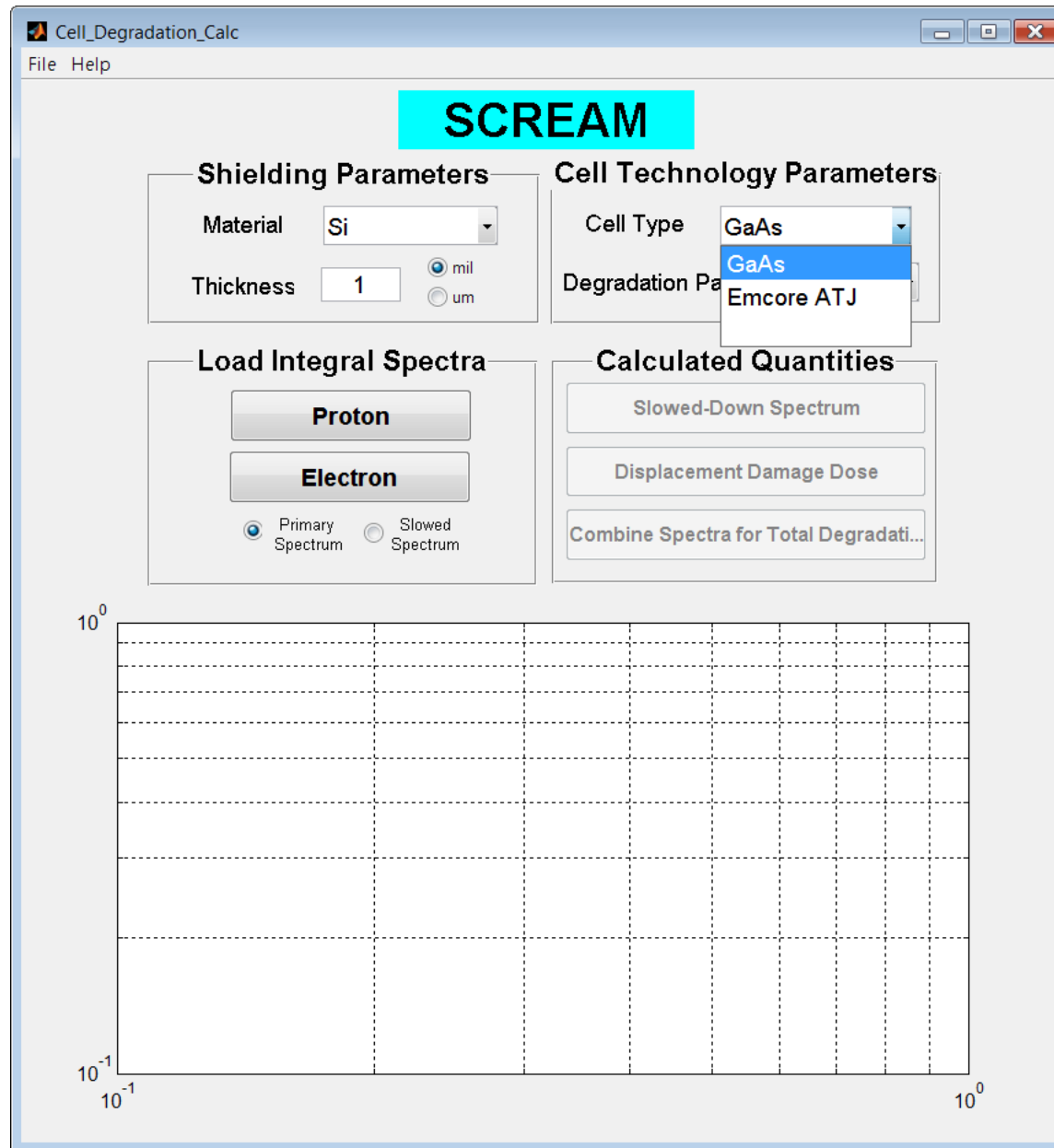
The interface is divided into several sections:

- Shielding Parameters:** Includes a 'Material' dropdown menu currently set to 'Si' and a 'Thickness' input field.
- Cell Technology Parameters:** Includes a 'Cell Type' dropdown menu set to 'GaAs' and a 'Degradation Parameter' dropdown menu set to 'Pmax'.
- Load Intensity:** Features two input fields labeled 'F' and 'E', and a radio button labeled 'Primary Spectrum' which is currently selected.
- Calculated Quantities:** Contains three buttons: 'Slowed-Down Spectrum', 'Displacement Damage Dose', and 'Combine Spectra for Total Degradati...'.

A large dropdown menu is open, listing various materials. The 'Si' option is highlighted in blue. The list includes: Si, SiO2, GaAs, Al, Air, Kapton, Stainless, Ta, Pb, ZnO, Ag, Au, CMO, CMG, CMX, Corning 0214, and Adhesive.

At the bottom of the window is a large empty plot area with a dashed grid. The y-axis is labeled with  $10^0$  at the top and  $10^{-1}$  at the bottom. The x-axis is labeled with  $10^{-1}$  on the left and  $10^0$  on the right, indicating a logarithmic scale.

# Cell Technology Options



# Degradation Parameter Options

Cell\_Degradation\_Calc

File Help

## SCREEN

### Shielding Parameters

Material:

Thickness:   mil  um

### Cell Technology Parameters

Cell Type:

Degradation Parameter:

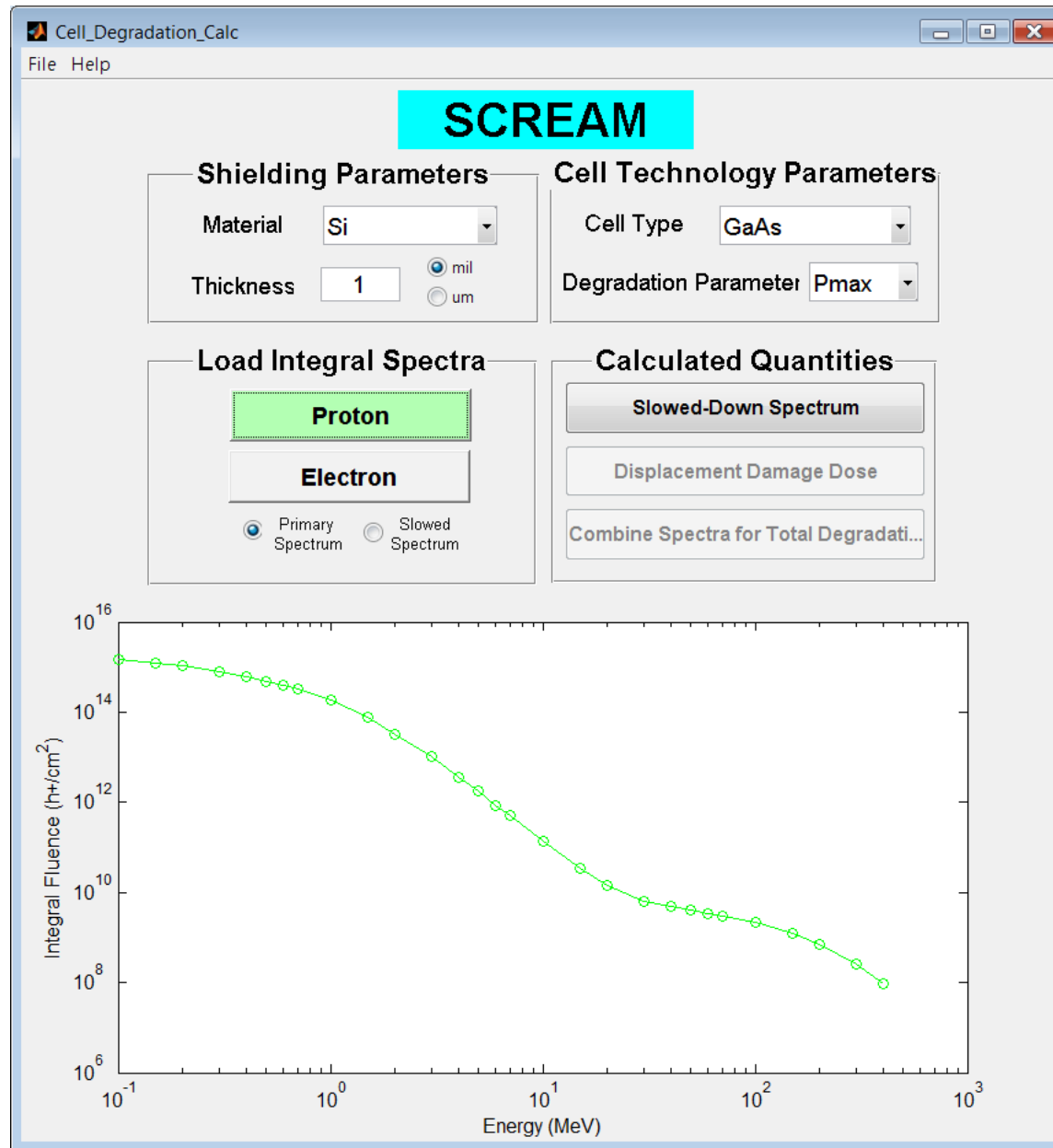
### Load Integral Spectra

Primary Spectrum  Slowed Spectrum

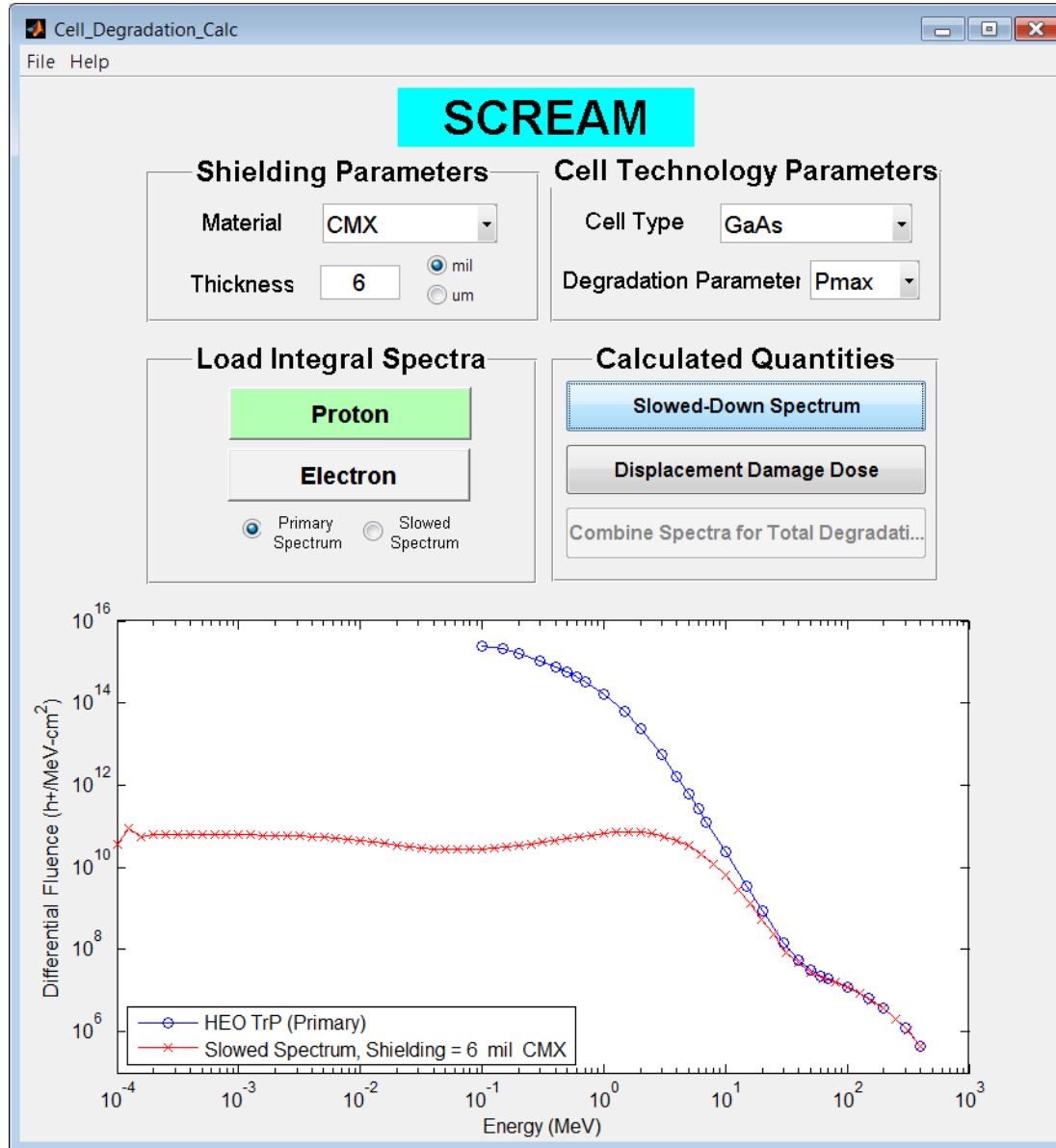
### Calculated Quantities

The plot area is a log-log grid. The vertical axis (y-axis) has major ticks at  $10^{-1}$  and  $10^0$ . The horizontal axis (x-axis) has major ticks at  $10^{-1}$  and  $10^0$ . The grid consists of 10 major divisions on both axes, with dashed lines for intermediate ticks.

After selecting HEO\_TrP.txt and entering, the data are plotted

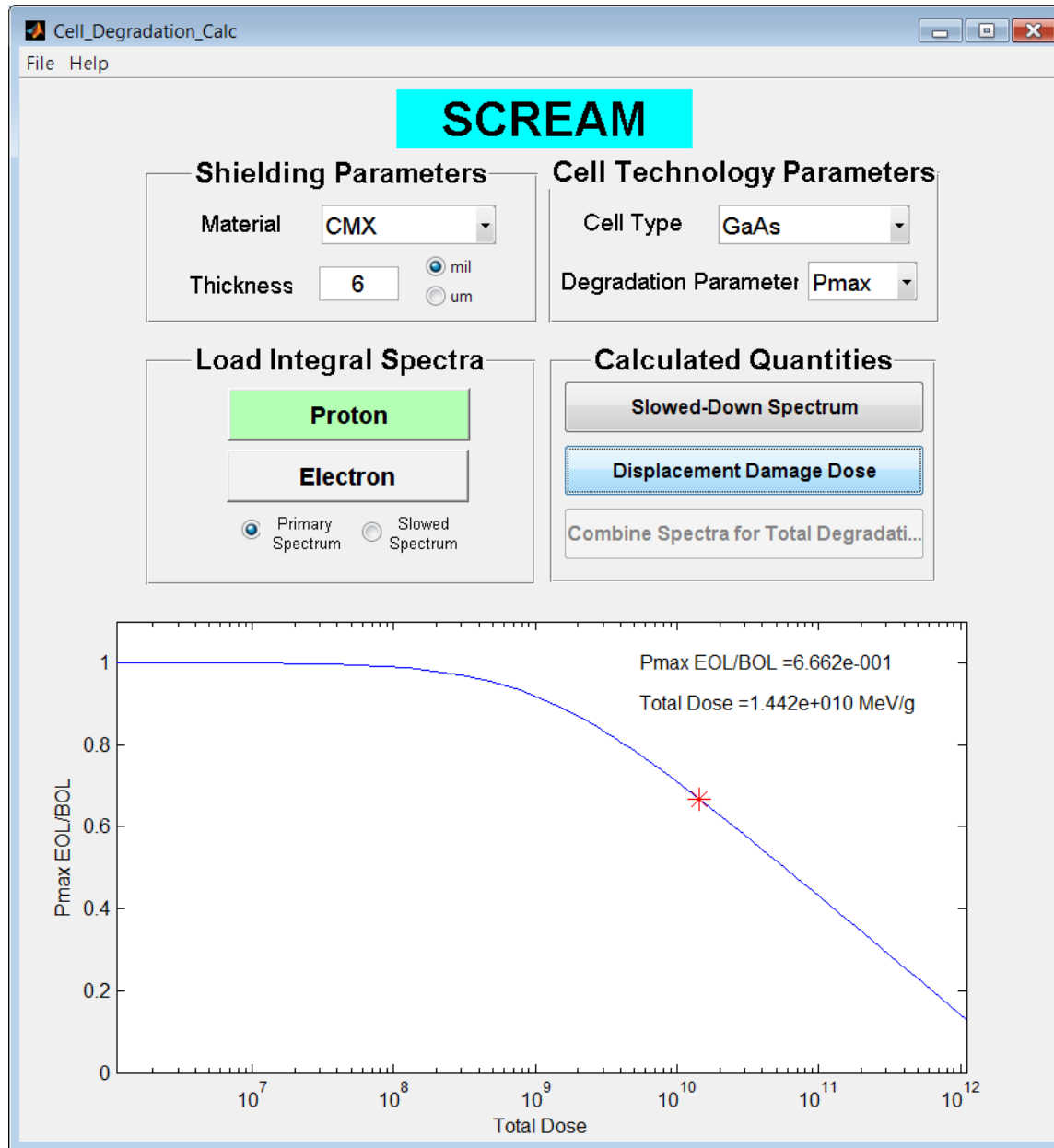


After choosing CMX and 6 mils, and pressing Slowed-Down Spectrum (“Primary Spectrum” button selected)



At this time, you can save the SDS using the FILE - Save SDS menu option

# After pressing Displacement Damage Dose



# MC-SCREAM

- Incident differential radiation spectra (SPENVIS)
  - Can choose several proton, electron, and solar proton models
- Calculation of the “slowed-down” spectra after having passed through shielding (analytical, MULASSIS)
  - Monte Carlo model
  - Several material layers can be used to describe cell
- Calculation of total DDD for the mission (SPENVIS)
  - NIEL data from WINNIEL2 (ions) and MCAD (electrons)
  - Already implemented in Mulassis
- Determination of the expected cell degradation
  - Uses 5 empirically-determined parameters for each metric
  - Will have several cell technologies included
  - User entry option for proprietary/developmental cells

**Solar cell radiation damage**  
Damage equivalent fluences for solar cells  
NIEL based damage equivalent fluences for solar cells (MC-SCREAM)

Cell definition	Radiation environment
<b>Cell type:</b> GaAs <b>Cover glass thickness [<math>\mu\text{m}</math>]:</b> 254	<b>Particle selection</b> <input checked="" type="checkbox"/> Trapped protons <input checked="" type="checkbox"/> Trapped electrons <input checked="" type="checkbox"/> Solar protons <b>Energy biasing:</b> no <b>Interpolation type:</b> linear <b>Nr. of primary particles:</b> 1,000,000
<input type="button" value="Reset"/> <input type="button" value="Run"/>	

Cell type dropdown menu:

- GaAs
- GaAs
- Azur 3G28
- Azur Gagat 2
- Emcore ATJ
- Manual input

Tool developed by



**NIEL parameters**

	<input checked="" type="checkbox"/> $P_{max}$	<input checked="" type="checkbox"/> $V_{OC}$	<input checked="" type="checkbox"/> $I_{SC}$	<input checked="" type="checkbox"/> $V_{pmax}$	<input checked="" type="checkbox"/> $I_{pmax}$
<b>Proton parameters</b>					
<b>C</b>	0.2904	0.115	0.229	0.115	0.229
<b><math>D_x</math> [<math>10^9</math> MeV/g]</b>	1.10	1.15	2.52	1.15	2.52
<b>Electron parameters</b>					
<b>C</b>	0.363	0.0745	0.343	0.0745	0.343
<b><math>D_x</math> [<math>10^9</math> MeV/g]</b>	6.90	1.28	11.0	1.28	11.0
<b>n</b>	1.647	2.128	1.326	2.128	1.326

**Output:**

1. Slowed down spectra for each incident behind shielding
2. DDD for each particle

# Outline

**1. Motivation**

**2. The Space Radiation Environment**

**3. Solar Cell Space Radiation  
Degradation Modeling**

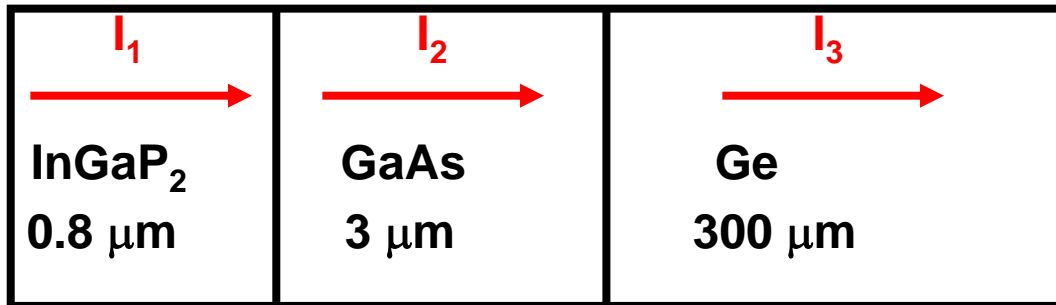
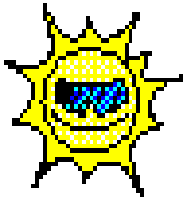
-JPL Equivalent Fluence (EQFLUX)

-NRL Displacement Damage Dose (SCREAM)

**4. Radiation Damage in Multijunction  
Solar Cells**

# Multijunction Solar Cell Radiation Response

Monolithic 3J InGaP<sub>2</sub>/GaAs/Ge (AM0, 1 sun  $\eta \sim 28\%$ )

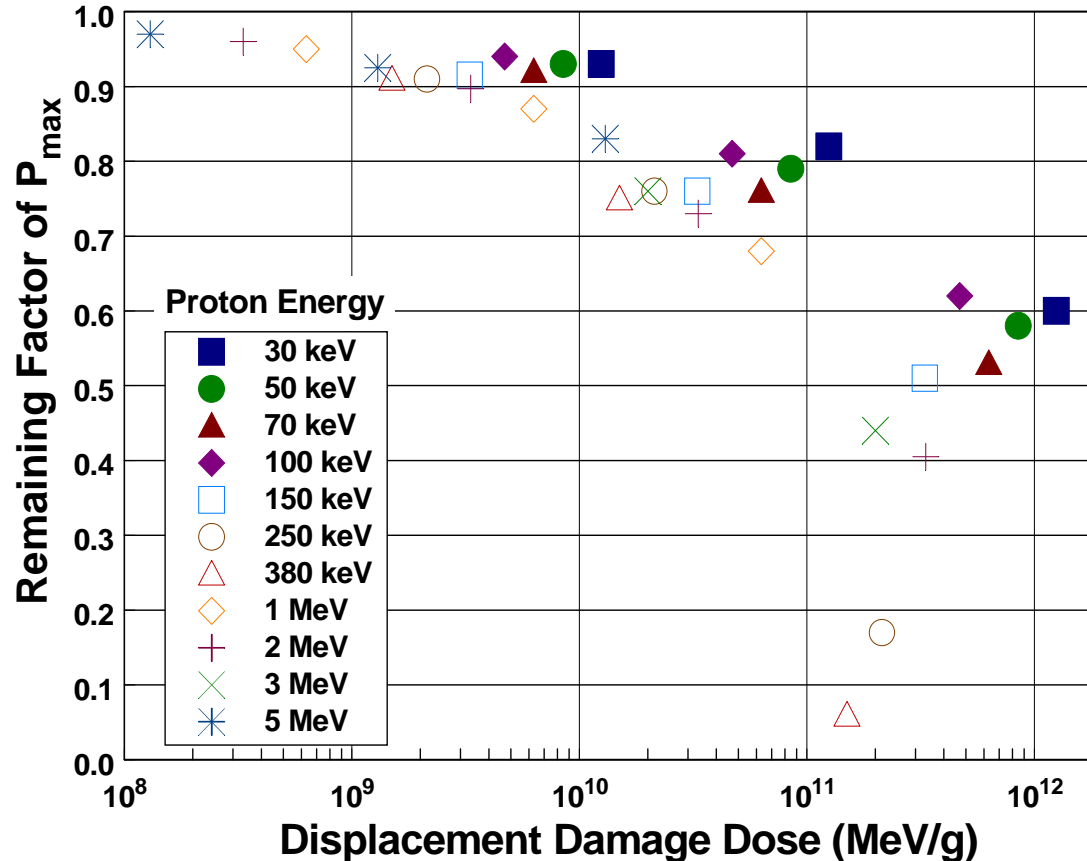


Monolithic: Current-limiting,  $I_{\text{cell}} = \text{minimum}(I_1, I_2, I_3)$

- Whichever cell is the softest will control the overall cell performance.
- MJ cell design can alleviate this to some extent by forcing the cell to degrade by the most radiation hard subcell.
- The (beginning-of-life) BOL properties are slightly sacrificed in such a design for better (end-of-life) EOL behavior.

# Ground Test MJ Solar Cell Data

$P_{\max}$  Proton Degradation vs. Displacement Damage Dose ( $D_d$ )



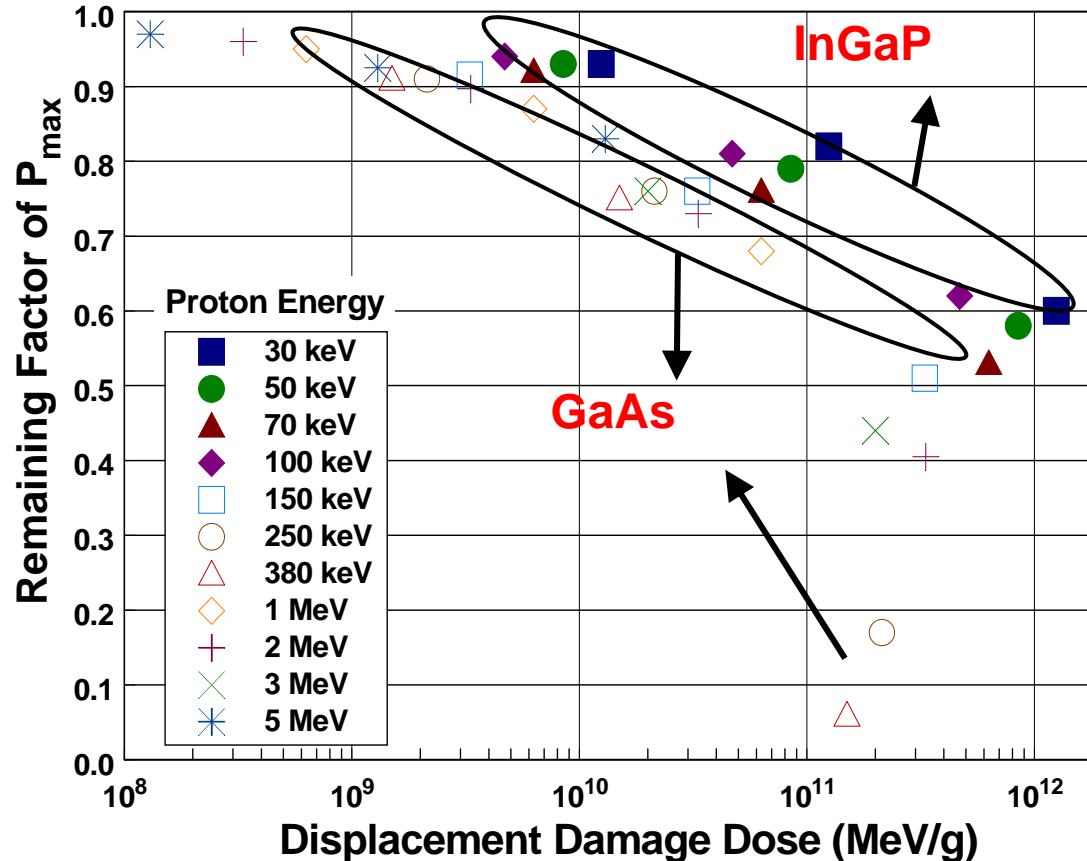
$$D_d = \text{NIEL} \times \phi$$

Another good example of NIEL correlation!

\*T. Sumita, M. Imaizumi, S. Matsuda, T. Ohshima, A. Ohi, and T. Kamiya, Proc. 19<sup>th</sup> EPVSEC, Paris, 2004.

# Ground Test MJ Solar Cell Data

$P_{\max}$  Proton Degradation vs. Displacement Damage Dose ( $D_d$ )

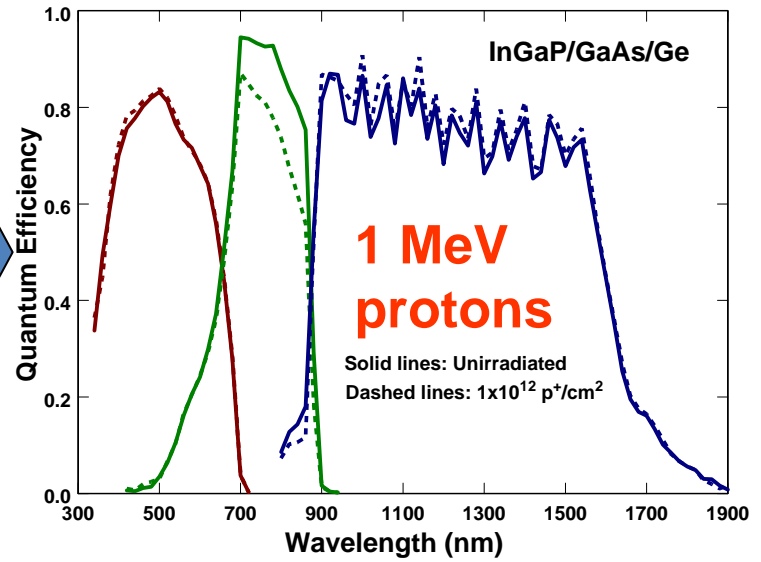
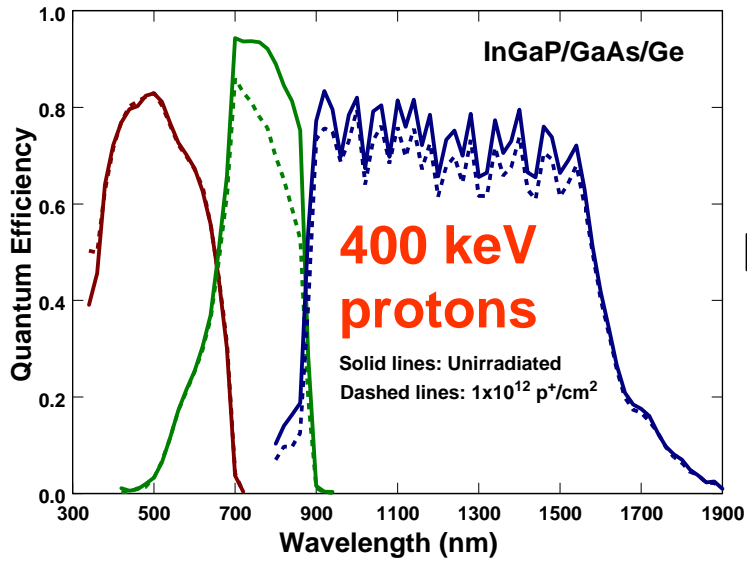
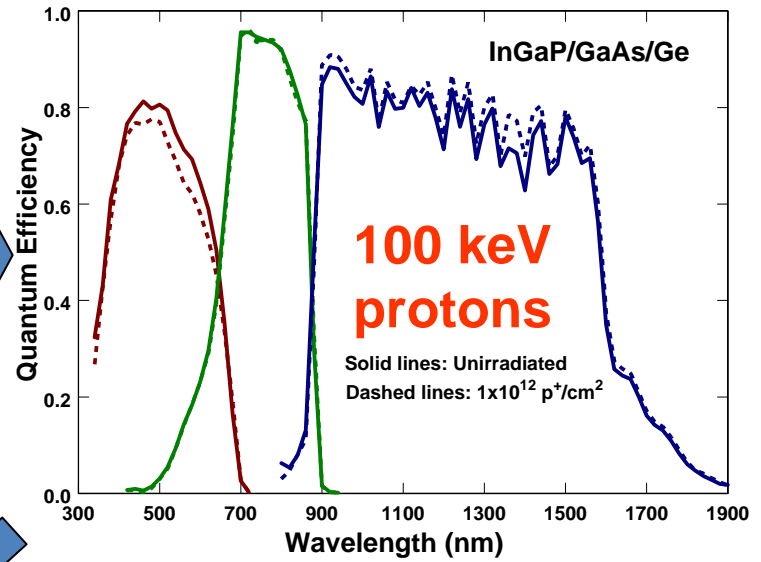
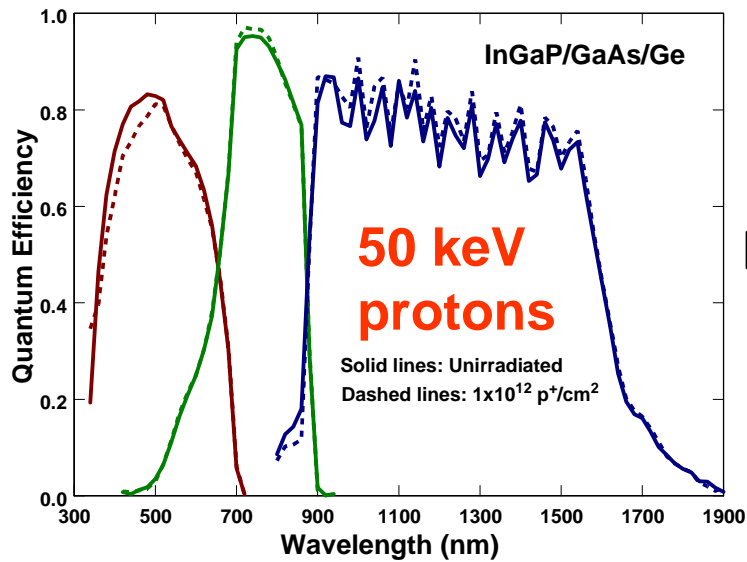


Two separate damage curves are apparent!

Which damage curve will apply in space?

\*T. Sumita, M. Imaizumi, S. Matsuda, T. Ohshima, A. Ohi, and T. Kamiya, Proc. 19<sup>th</sup> EPVSEC, Paris, 2004.

# Proton-Induced QE Degradation in MJ Cells



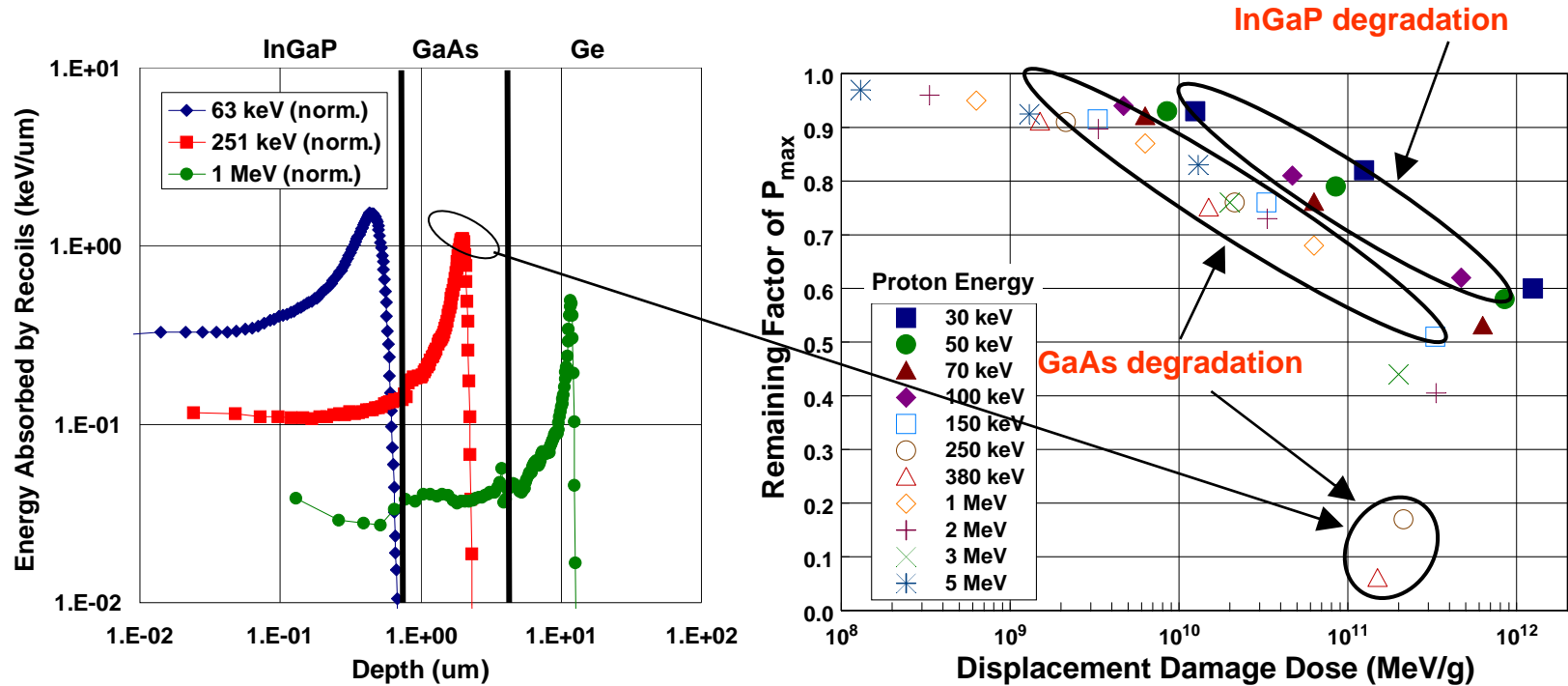
# SRIM 2003.26 Simulation

- 3J InGaP<sub>2</sub>/GaAs/Ge structure
- 3 Proton Energies
  - 63.1 keV (0.6 μm range)
  - 251 keV (2 μm range)
  - 1 MeV (11 μm range)

InGaP <sub>2</sub> 0.8 μm	GaAs 3 μm	Ge 300 μm
------------------------------	--------------	--------------

- Monoenergetic, normal incidence (“normal” SRIM run)
  - Monoenergetic, omnidirectional
  - Spectrum, omnidirectional
  - Spectrum, non-omnidirectional
- ‘TRIM.DAT’  
SRIM input file

# Monoenergetic, Unidirectional Irradiations

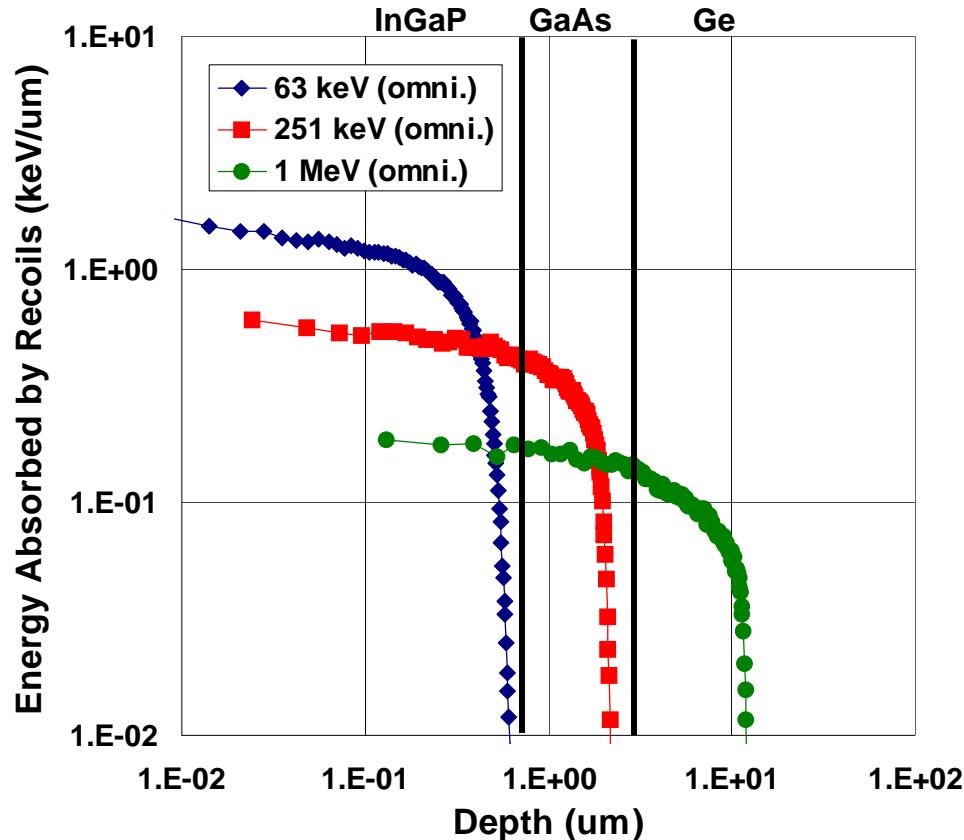


\*Results from SRIM 2003 v.26  
(www.srim.org)

\*T. Sumita, M. Imaizumi, S. Matsuda, T. Ohshima, A. Ohi, and T. Kamiya, Proc. 19th EPVSEC, Paris, 2004.

- Typical ground test conditions (not space conditions)
- Nonuniform vacancy distribution – Bragg Peak at end of track
- Different energies can preferentially degrade one sub-junction
- This effect is not seen in 1 MeV electron irradiation (longer ranges)

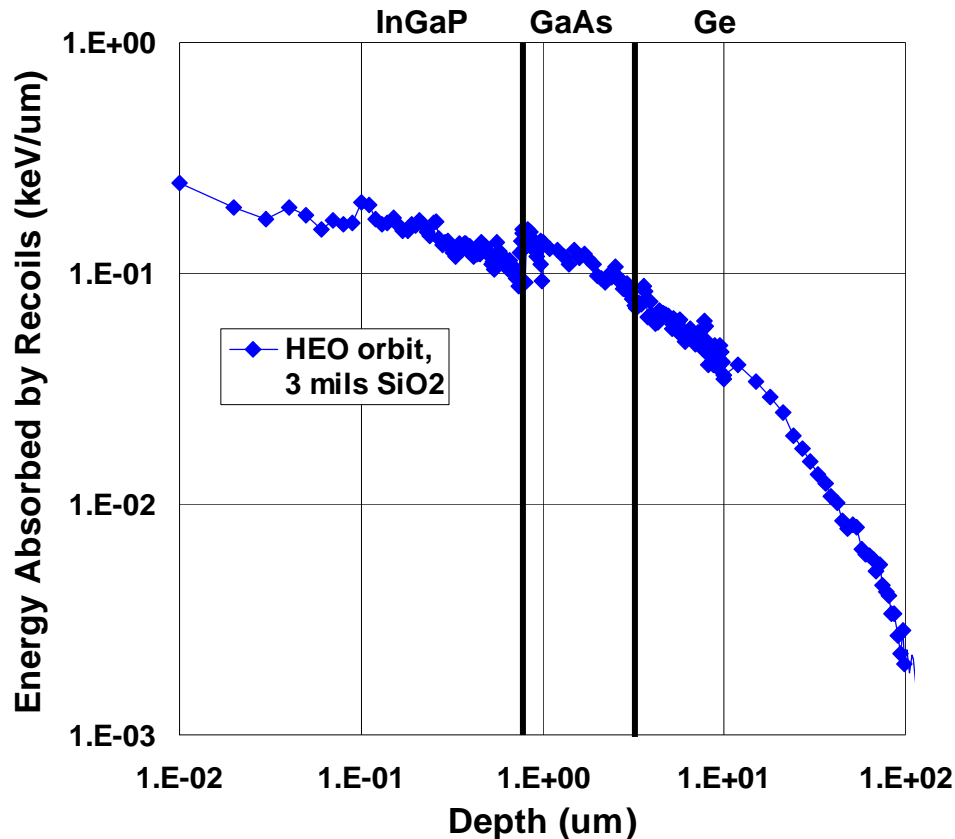
# Monoenergetic, Omnidirectional Irradiation



\*Results from SRIM 2003 v.26 using special input file (TRIM.DAT) which specifies random incident **angles** (via direction cosines) over  $2\pi$  geometry

- More uniform vacancy distribution than a unidirectional beam
- Bragg peak not seen

# Energy Spectrum, Omnidirectional Irradiation



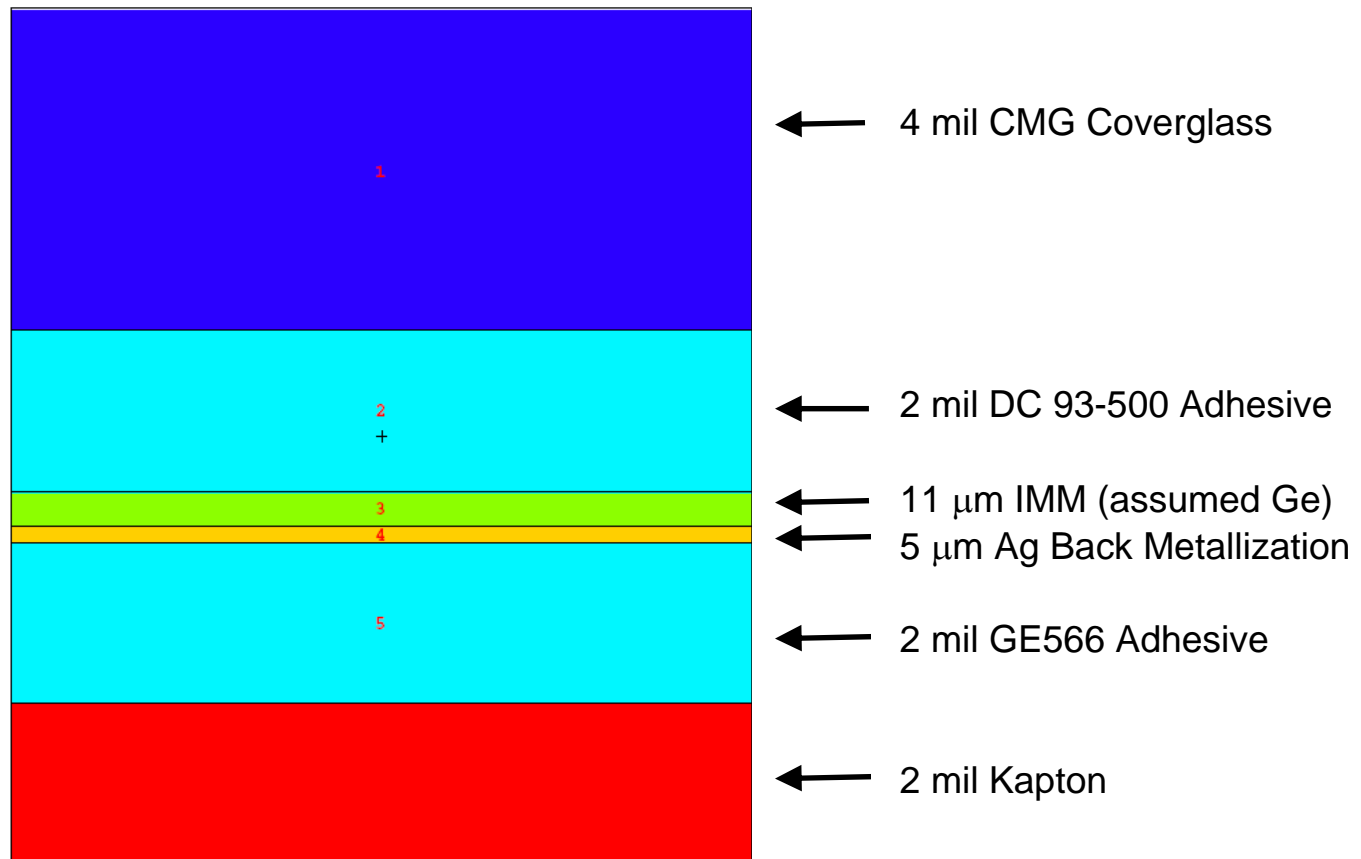
\*Results from SRIM 2003 v.26 using special input file (TRIM.DAT) which specifies random incident **angle** and **energy** to simulate HEO spectrum (**3 mil SiO<sub>2</sub>**)

- Representative of exposure in the space radiation environment
- The vacancy distribution profile is nearly uniform over active region

**No special effects due to low energy protons apparent!**

# Blanket Structure for Monte Carlo Simulation

Assumed Structure for Monte Carlo N-Particle eXtended (MCNPX) Simulation



# *Ionizing Energy Deposition In Blanket*

Monte Carlo (MCNPX) simulation of Tacsat4 Radiation Environment on IMM  
blanket structure

## TACSAT4 Omnidirectional Proton Irradiation (Entire Structure)

Bottom-Side Radiation

Top-Side Radiation

4 mil CMG

1

1

2 mil DC93-500

2

2

11  $\mu\text{m}$  IMM

3

3

5  $\mu\text{m}$  Ag

4

4

2 mil GE566

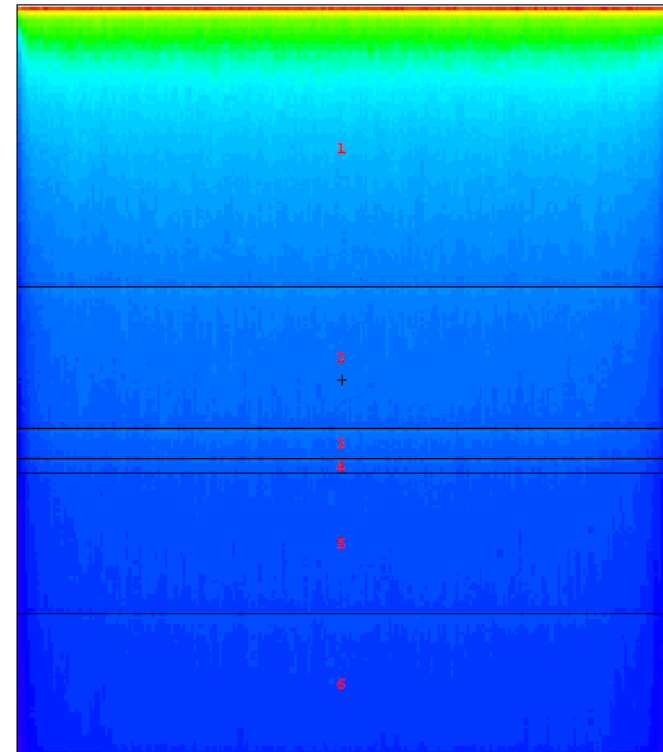
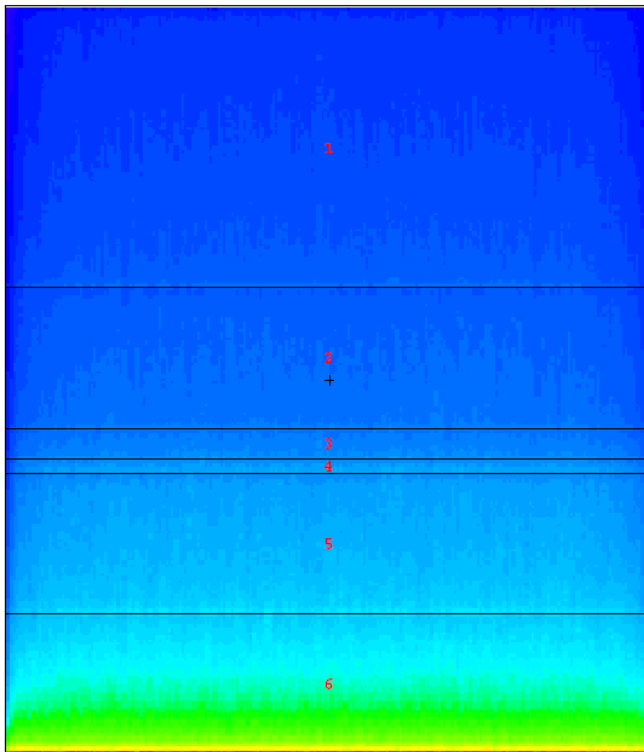
5

5

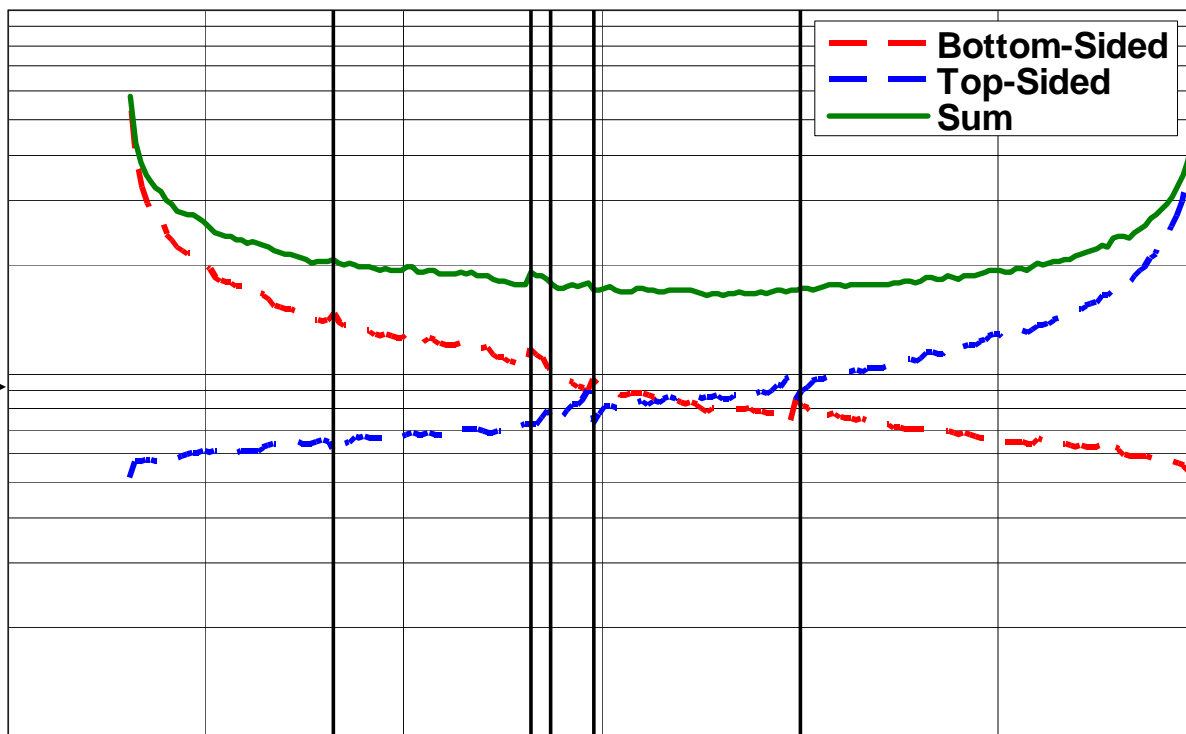
2 mil Kapton

6

6



# Energy Deposition vs. Depth in Blanket



Irradiation from  
bottom

Irradiation  
from top

↑  
cell

# Effect of Thin Shielding on Spectrum Irradiation

## Omnidirectional Irradiation

