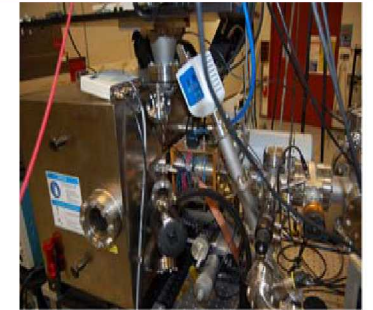
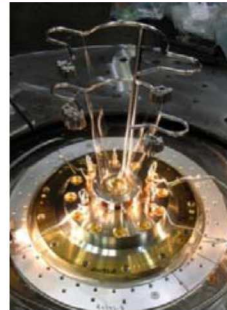
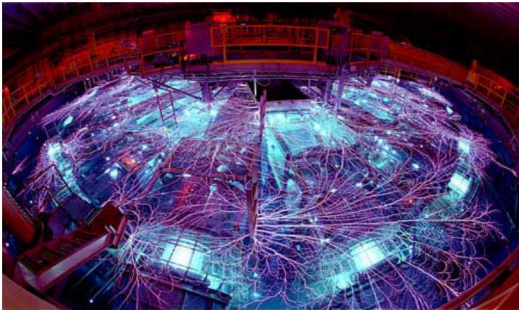


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Sandia  
National  
Laboratories



## Discussion on Collaboration Topics with NRG

November 13<sup>th</sup>/14<sup>th</sup> 2013

Patrick J. Griffin  
Senior Scientist  
Org. 1300, Radiation Effects Sciences and  
Applications Department



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## Security Guidelines

- **Information exchange on this visit is limited to unclassified unlimited release data**
  - **No U.S. export controlled discussions. No ITAR or EAR99 controlled information to be exchanged.**
  - **India is still listed as a sensitive country due to nuclear nonproliferation issues**
- **Visit request limitations:**
  - **One of the named escorts (Griffin/Vehar/Parma) required to be with visitors whenever they are on the Kirkland Air Force base**
  - **Only visit buildings/room explicitly on approved visit request paperwork**

## Topic Areas of Discussion (1/3)

- Experience in the determination of covariances (SNL/NRG)
- Discussion over various approach to determining covariances
  - Iterative, e.g. SAND-II
  - Least squares, e.g. LSL-M2
  - Maximum entropy, e.g. MAXED
  - Genetic algorithm
  - Total Monte Carlo (TMC)
- Discussion over approach to determining *a priori* covariances
  - Discussion over the NRG results to date
  - NRG plans for ongoing work
- SNL feedback/comments/opinion on the NRG work and the way forward
- LSL-M2 related questions
- TENDL-related discussions

## Topic Areas of Discussion (2/3)

- **IAEA CRP on primary radiation damage**
  - **Silicon**
    - isotope random TENDL files ( $^{28}\text{Si}$ ,  $^{29}\text{Si}$ ,  $^{30}\text{Si}$ )
    - SNL preliminary results on displacement kerma covariance
    - Uncertainty in damage vs displacement kerma, ASTM E722
  - **GaAs**
    - Ga and As isotope random TENDL files
- **IAEA CRP on IRDFF dosimetry cross section validation**
  - **Standard neutron benchmark fields**
    - $^{252}\text{Cf}$  spontaneous fission
  - **Reference neutron benchmark fields**
    - $^{235}\text{U}$  thermal fission
    - SNL reactor benchmark fields
    - NTS/DAF criticality benchmark fields



## Topic Areas of Discussion (3/3)

- **What does TENDL do for covariance in dosimetry cross sections?**
  - Need for covariance to match baseline values
  - ASTM E1018 guidance to reject ENDF/B-VII.1 covariance data
  - TENDL historical process and current process
    - over-ride when and how?
  - How to capture model defect?
- **When to over-ride low (<1%) model-based uncertainties for dosimetry applications**
- **Uncertainty in fission yield data (cumulative and independent)**
  - Recommendation for standard, JEFF vs. ENDF/B-VII vs JENDL
- **NJOY-2012 processing of cross sections**
  - File 3/6 discontinuity
- **EASY-II European Activation System**
  - EASY-2010
  - FISPACT-II

# Technical Tours of SNL Radiation Facilities

- **Facilities on tour list:**
  - **Annular Core Research Reactor (ACRR)**
  - **Sandia Pulsed Reactor (SPR-III)**
  - **Gamma Irradiation Facility (GIF)**
  - **Z Facility**
  
- **Other facilities not on tour list:**
  - **Radiation Metrology Laboratory (RML)**
  - **HERMES-III; 19-MeV 28-ns electron bremsstrahlung**
  - **Saturn; 1.8-MeV 40-ns bremsstrahlung**
  - **Ion Beam Laboratory (IBL)**

## Other Documents Discussed/Presented

- **Some other UUR Sandia documents will also be addressed in the discussions and may be transferred to the visitors. These include:**
  - **SNL Radiation Facilities Brochure, SAND 2005-5685P**
  - **SNL Poster on Genetic Algorithm, SAND2014-16004 PE**

# Computer Presentations on Software Supporting Neutron Spectrum Characterization for Research Reactors



- **Some computer presentation will also be made. Screenshots from these presentations are included in these viewgraphs. Computer presentations will include:**
  - **LSL-M2 with the Sandia Perl interface**
    - **LSL is a least squares spectrum adjustment code. The original version is from ORNL and is available from RSICC to U.S. citizens and through the NEA Databank for Europeans.**
  - **LSL-M2 with the Sandia Python interface**
  - **SNL Genetic algorithm code for spectrum unfold**
    - **This is an basic algorithm detailed in openly available peer-reviewed publications, e.g. IEEE TNS. The computer presentation will show how the algorithm has been applied to the determination of the neutron spectrum at the Sandia ACRR research reactor.**



# TOPIC:

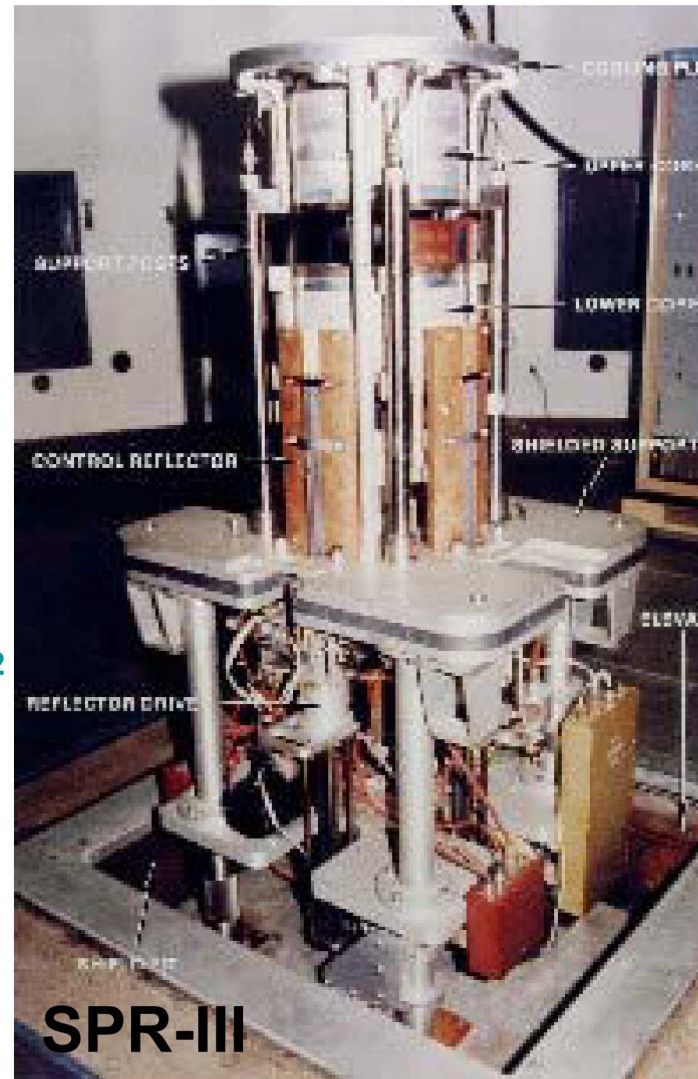
## SPR-III FAST BURST REACTOR

SPR-III is a reference benchmark neutron field.

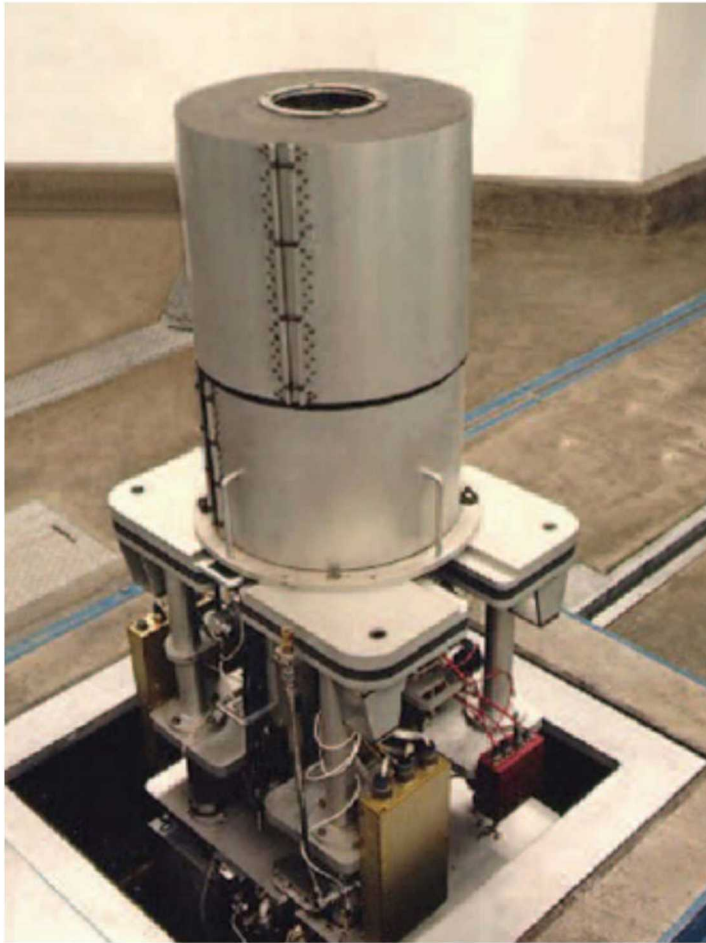
Whereas the SPR-III reactor has been decommissioned, activation data gathered here is used to support the IAEA CRP on the validation of the IRDFF dosimetry cross sections library.

## SPR-III Characteristics

- **Characteristics:**
  - Neutron lifetime  $\Lambda$ , 15 ns
  - Fuel Mass, 260 kg
  - **Pulse Width, 76  $\mu$ s**
  - Pulse Fission Yield, 10 MJ
- **Central cavity:**
  - **17-cm diameter, >30-cm high**
  - Uniformity over volume,  $\pm 25\%$
  - 1-MeV(Si) fluence,  $5.4 \times 10^{14}$  n/cm<sup>2</sup>-1MeV
  - **Max Pulsed Fluence,  $6.1 \times 10^{14}$  n/cm<sup>2</sup>**
  - Neutron Flux,  $8.0 \times 10^{18}$  n/cm<sup>2</sup>-s
  - Gamma dose rate,  $1.5 \times 10^9$  rad(Si)/s
- **Experiment access:**
  - 30-minute room access
  - remote experiment retrieval



## Sandia's Research Reactors



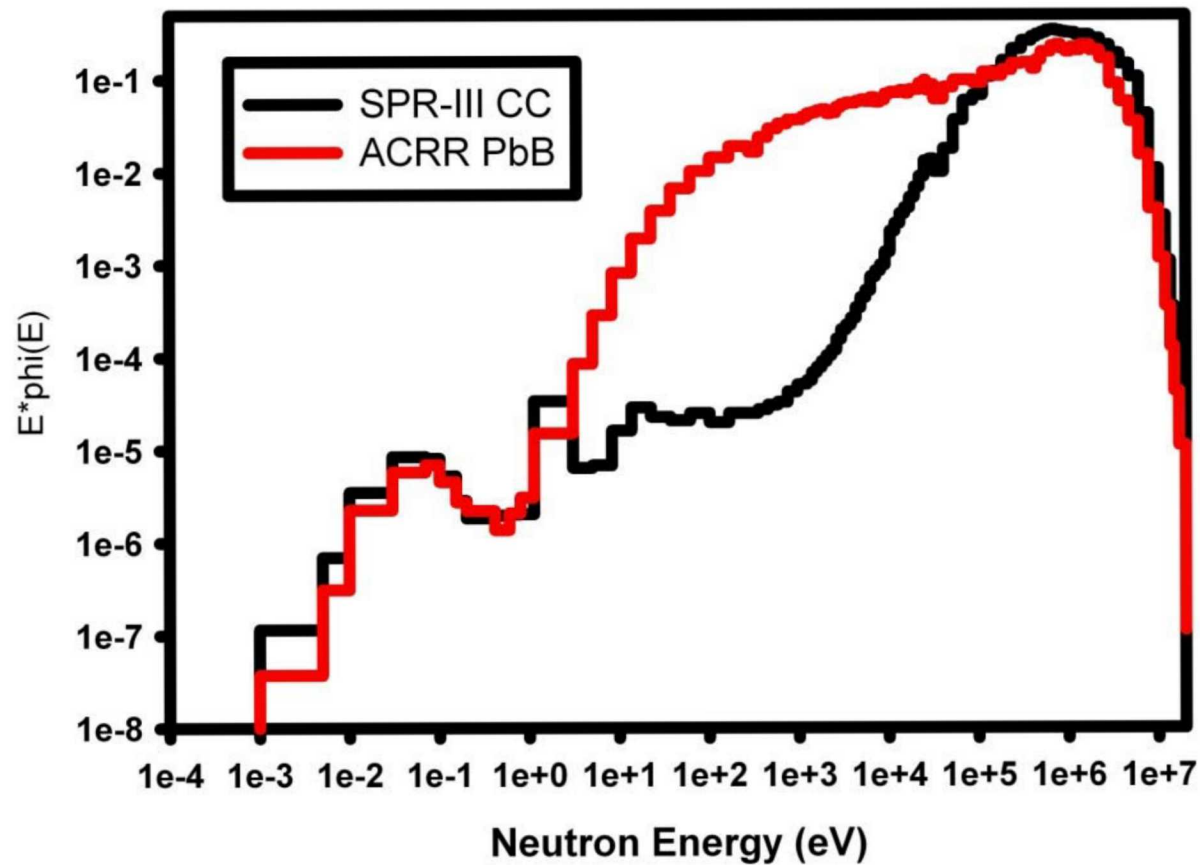
Sandia Pulsed Reactor-III  
SPR-III (decommissioned)



Sandia Annular Core Research Reactor  
ACRR

# Neutron Spectra

SPR-III, ACRR PbB





# **TOPIC:**

## **ACRR WATER MODERATED RESEARCH REACTOR**

The Annular Core Research Reactor is a reference benchmark neutron field.

ACRR is a water-moderated reactor. It uses different “buckets” to tailor the radiation field seen on experiments.

Several sets of activation data have been gathered at this facility and used to support the IAEA CRP on the validation of the IRDFF dosimetry cross sections library.



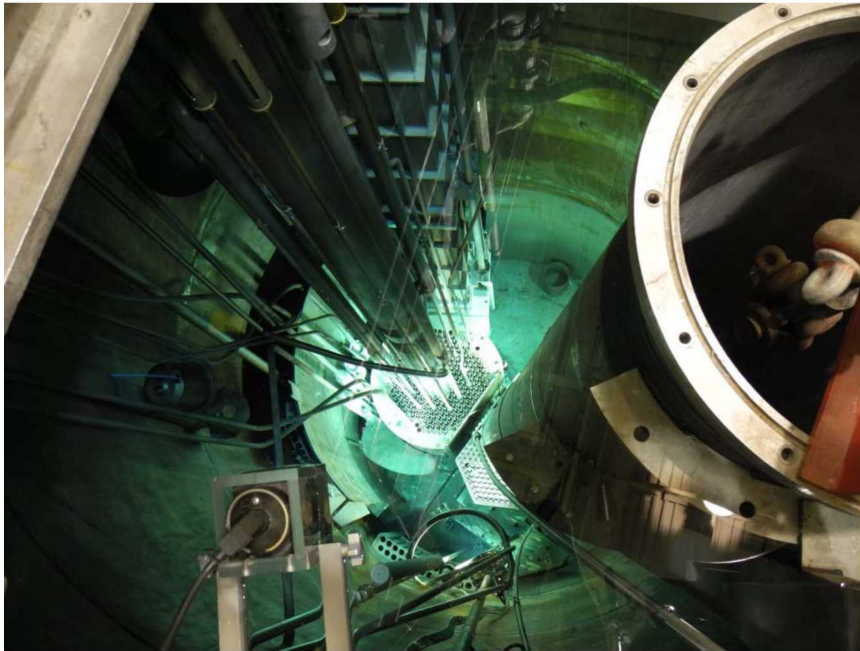
# ACRR Description



- 236  $\text{UO}_2$ -BeO fueled elements (1.5 in dia. x 20 in) (3.8 cm dia. x 51 cm) – 100 g U-235 per element – 35% enr.
- Operating Power level
  - 4 MW<sub>th</sub> Steady State Mode
  - 250 MJ Pulse Mode (6 ms FWHM)
  - 300 MJ Transient Mode (Programmable)
- Dry cavity 9 in (23 cm) diameter
  - Extends full length of pool through core
  - Neutron Flux  $4\text{E}13$  n/cm<sup>2</sup>-s at 2 MW
  - 56% > 10 keV, 45% > 100 keV
- Epithermal Spectrum
  - Flux in cavity can be tailored for desired energy spectrum
  - Poly, B4C
- Open-pool type reactor
  - Fuel elements cooled by natural convection
  - Pool cooled by HX and cooling tower
- FREC-II uses previous ACPR fuel
  - TRIGA type (UZrH) – 20 in (51 cm) dia. dry cavity
- Fuel burnup is minimal
  - Reactor used for short duration power runs, pulses, and transients

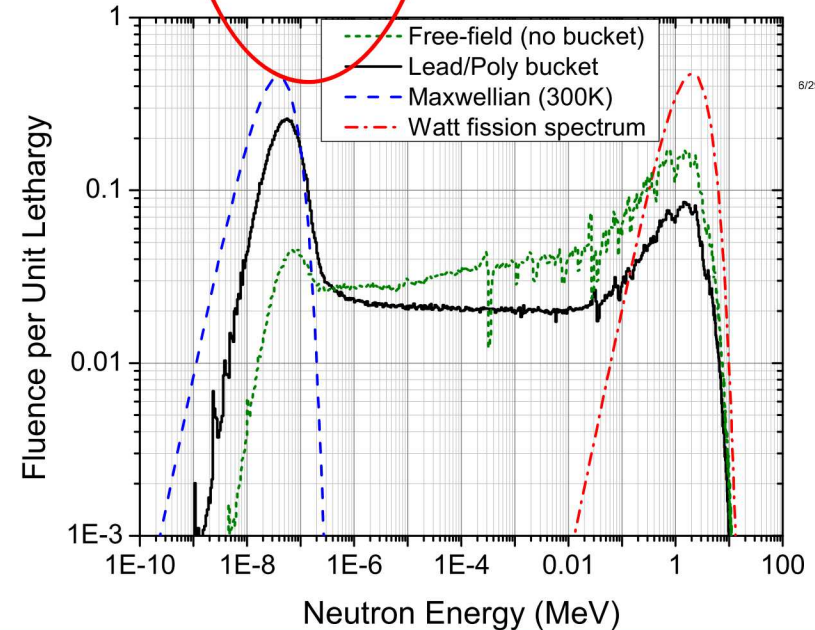
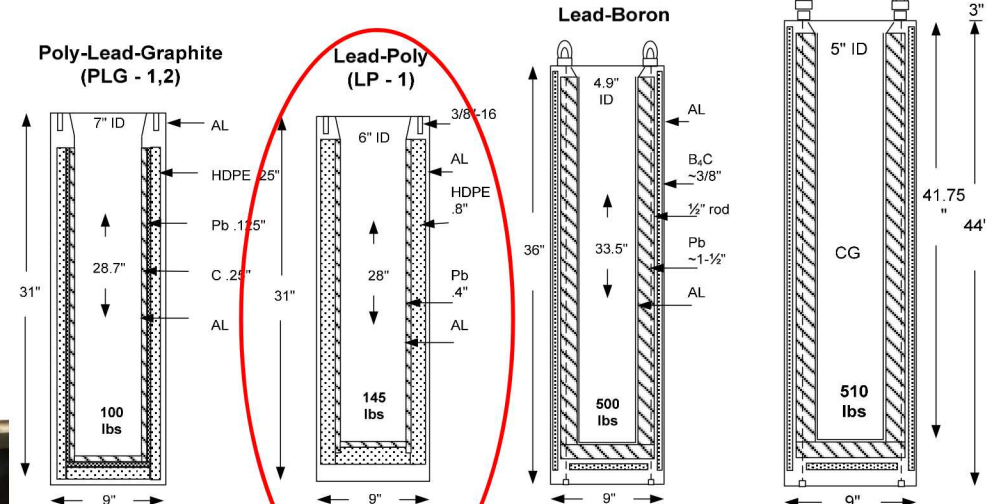
# ACRR environment

Four spectrum-modifying buckets are in common use at ACRR. Experimenters typically use: 1) lead-poly bucket (highly moderating); 2) the free-field cavity; 3) poly-lead-graphite bucket that is intermediate between the previous two.



## Experiment Buckets (ACRR)

(Dimensions are approximate)





# Experimental Setup



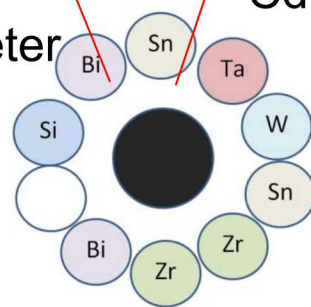
Aluminum  
stand



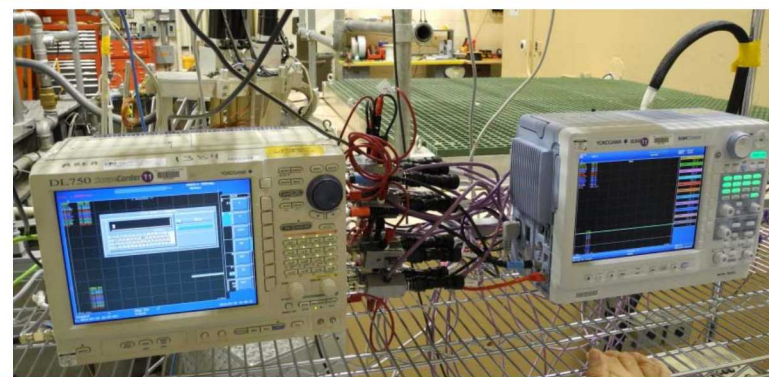
Bare  
calorimeter  
array



Cd-covered  
array

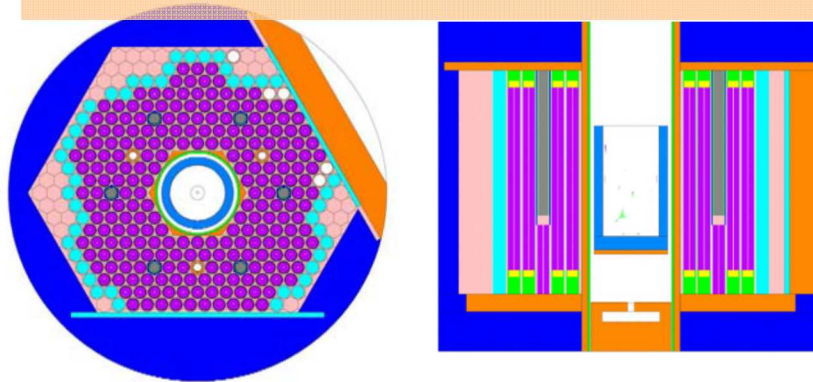


## Bucket loading & data



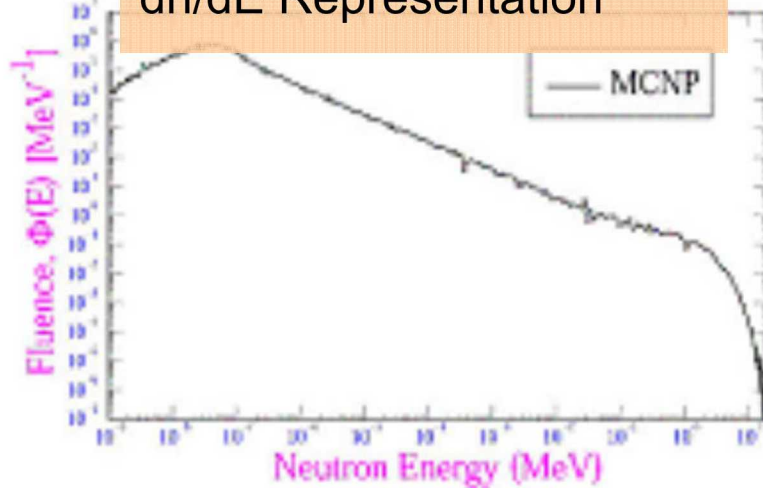
## Dosimetry Approach: ACRR Spectrum

### Radiation Transport Model

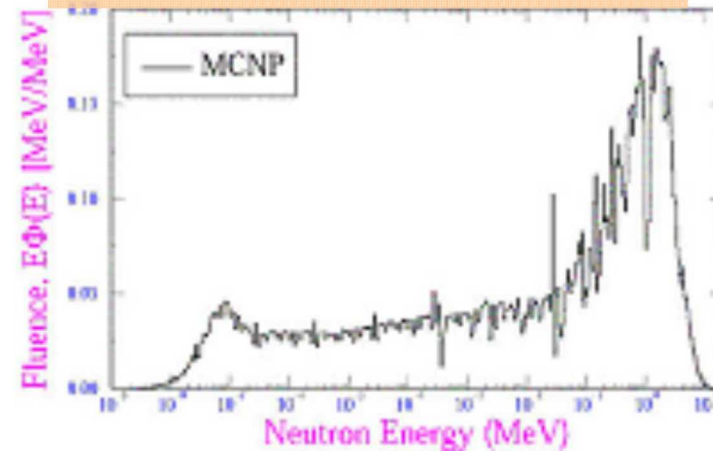


- Calculate *a priori* values
  - <1% statistical unc.
- Least squares spectrum adjustment
- Analysis of  $\chi^2$

### dn/dE Representation



### Edn/dE Representation

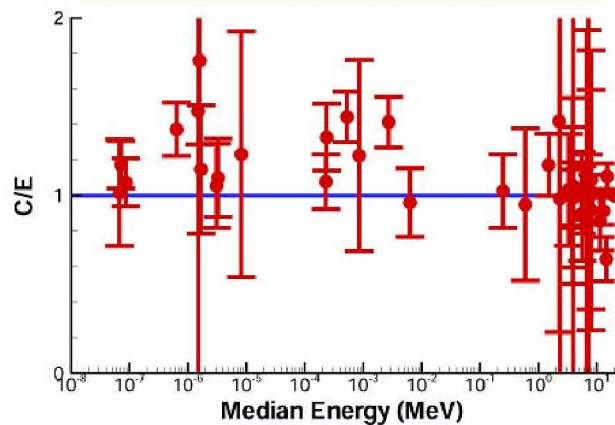


OFFICIAL USE ONLY

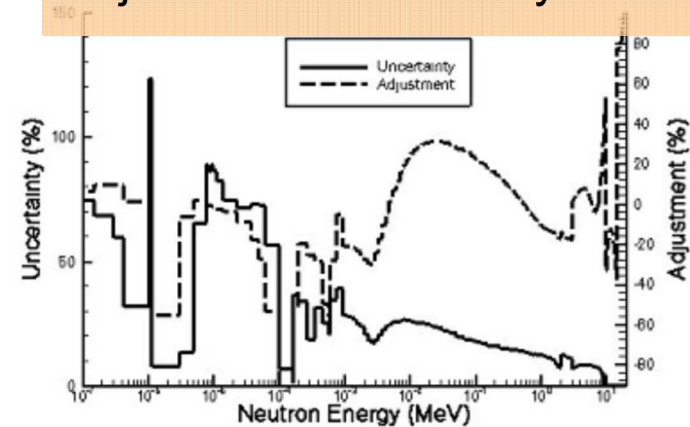


# Uncertainty/Dosimetry Approach: ACRR Spectrum Characterization

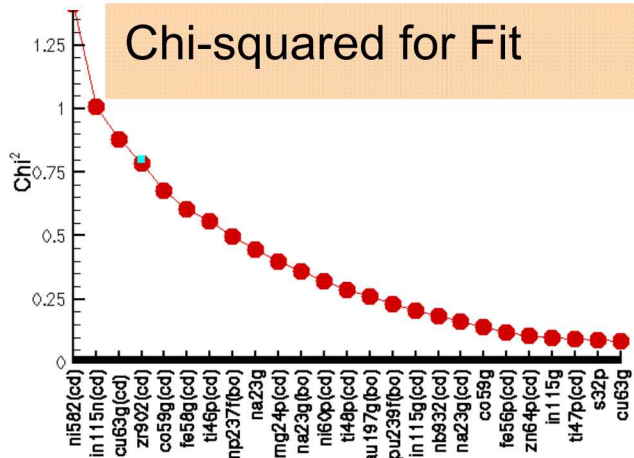
## C/E for Activities



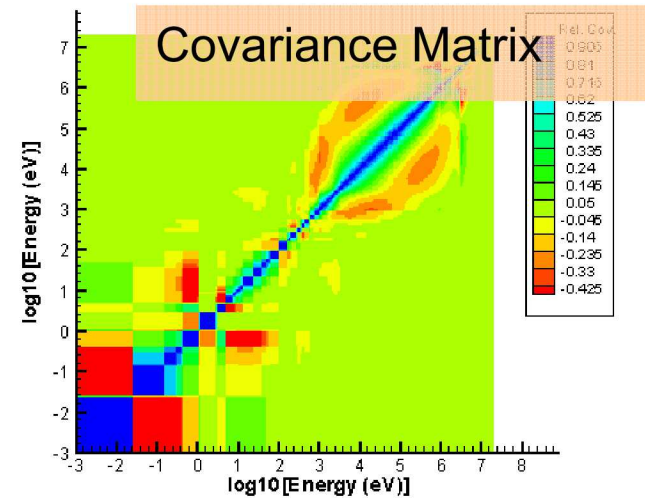
## Adjustment/Uncertainty



## Chi-squared for Fit



## Covariance Matrix





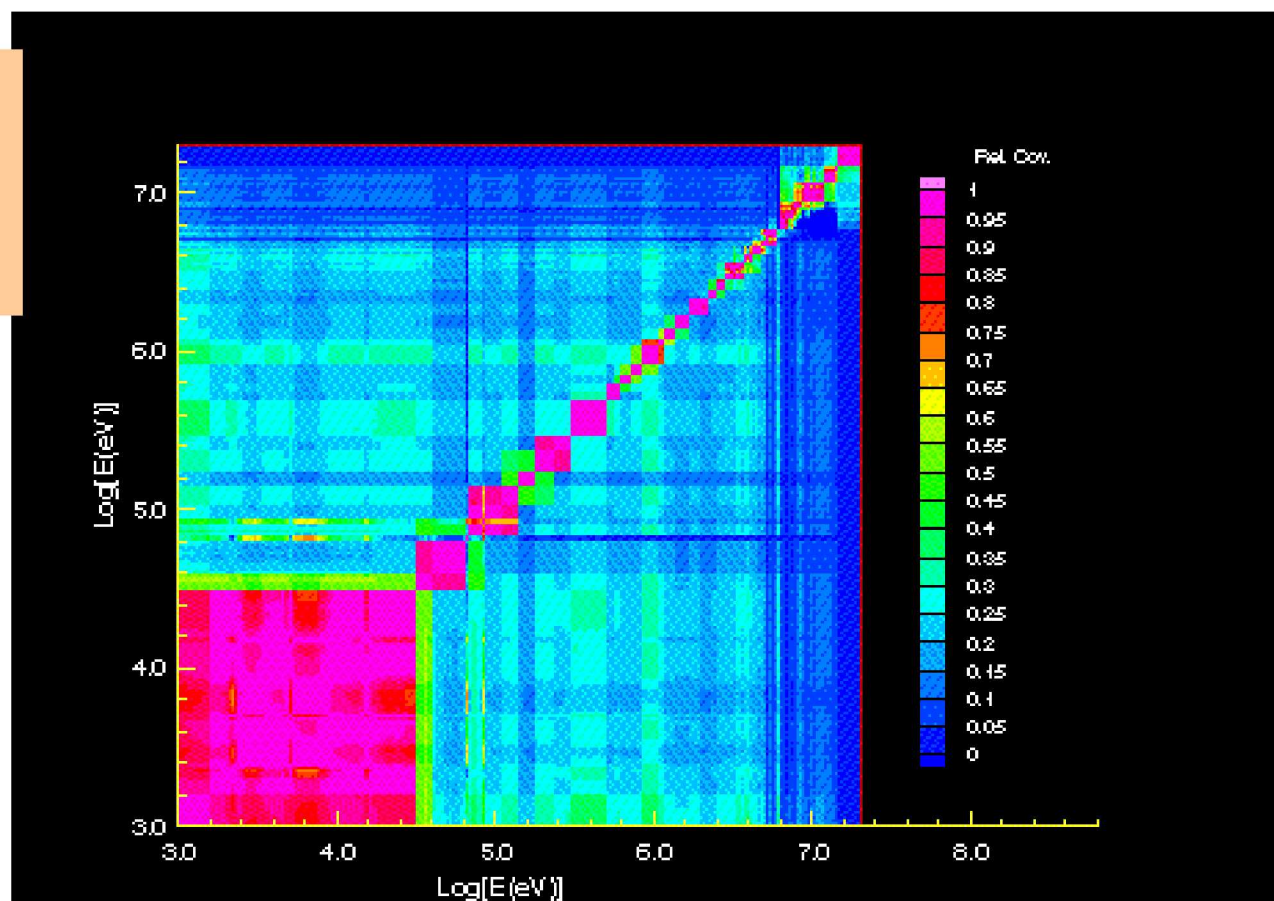
# **TOPIC: UNCERTAINTY IN SILICON DISPLACEMENT KERMA – PREVIOUS WORK**

Original work on silicon displacement kerma uncertainty used subject matter expertise and relied on the comparison of different evaluations. Older TENDL-2010 limited random library samples were investigated – but the 10 sample size was inadequate for analysis purposes.

# Si Displacement Kerma Correlation Matrix from Literature Survey



Uncertainty:  
~5% at low energy,  
~15% at high energy



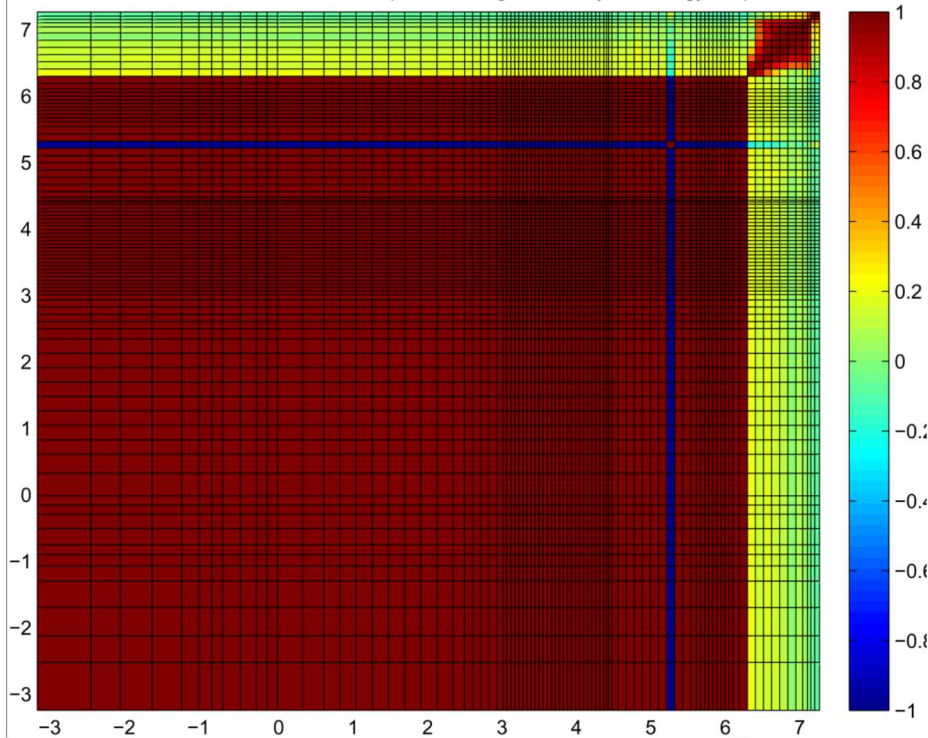
Danjaji et al., Reactor Dosimetry, Proceedings of the  
9<sup>th</sup> ISRD, World Scientific, 1996, pp. 611-618

# $^{28}\text{Si}$ Total Cross Section Covariance

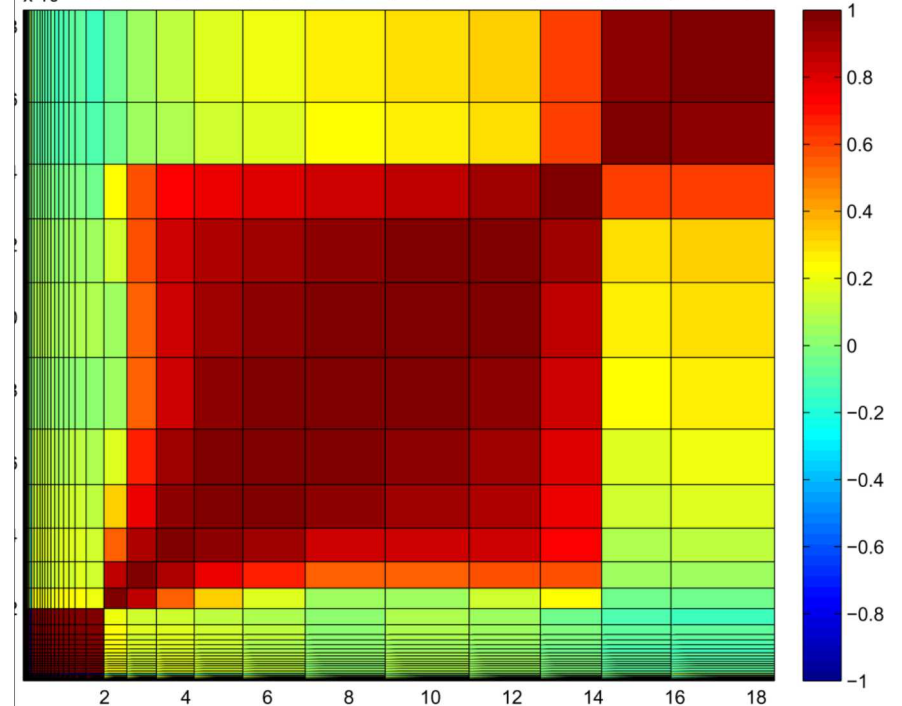
## Logarithmic Plot

## Linear Energy

Si28 Total Correlation Coefficient Color Map Plotted Logarithmically vs. Energy Midpoint of Cell



Si28 Total Correlation Coefficient Color Map Plotted Linearly vs. Energy Midpoint of Cell



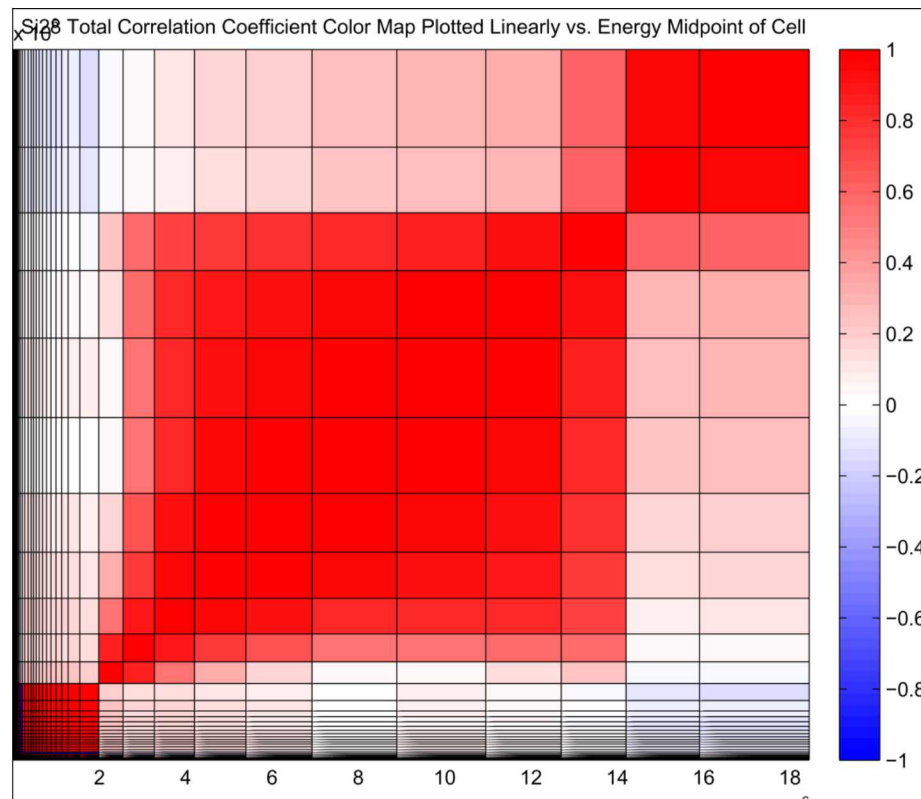
TENDL 2010

Figures by Robert Middleton, SNL

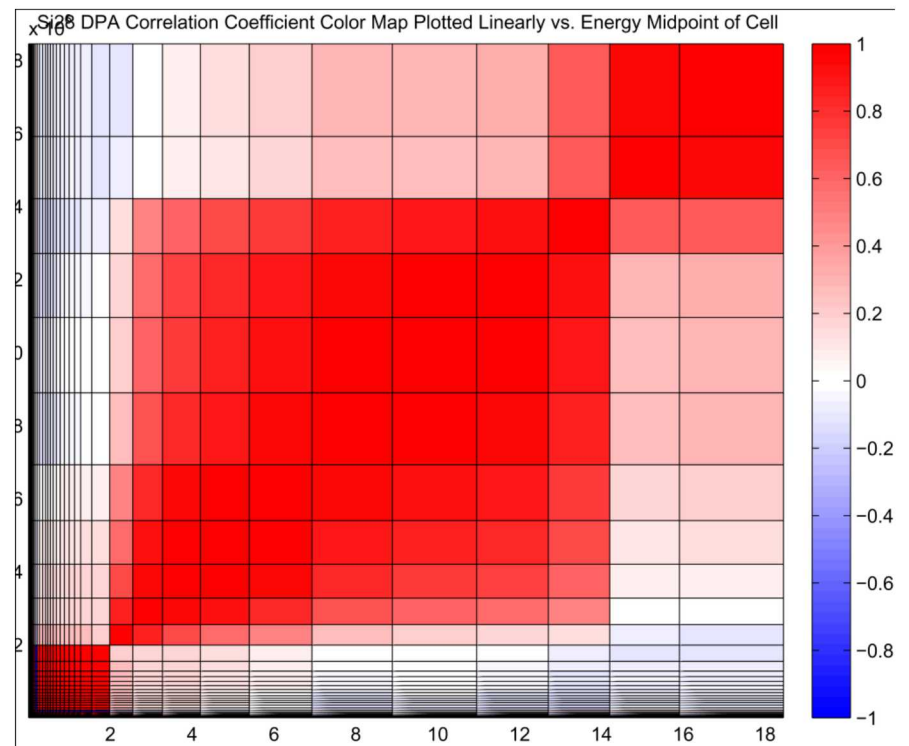
Note Potential Model Defect

# $^{28}\text{Si}$ Total and DPA correlation matrices are nearly identical

Total Cross Section



dpa Cross Section



TENDL 2010

Figures by Robert Middleton, SNL



# **TOPIC: UNCERTAINTY IN SILICON DISPLACEMENT KERMA: LATEST WORK**

Work conducted in support of the IAEA CRP on Primary Damage and using information (100 sample size random TENDL-2013 libraries for silicon isotopes) provided by NRG.

# Factors that Affect Uncertainty in Silicon Displacement Kerma

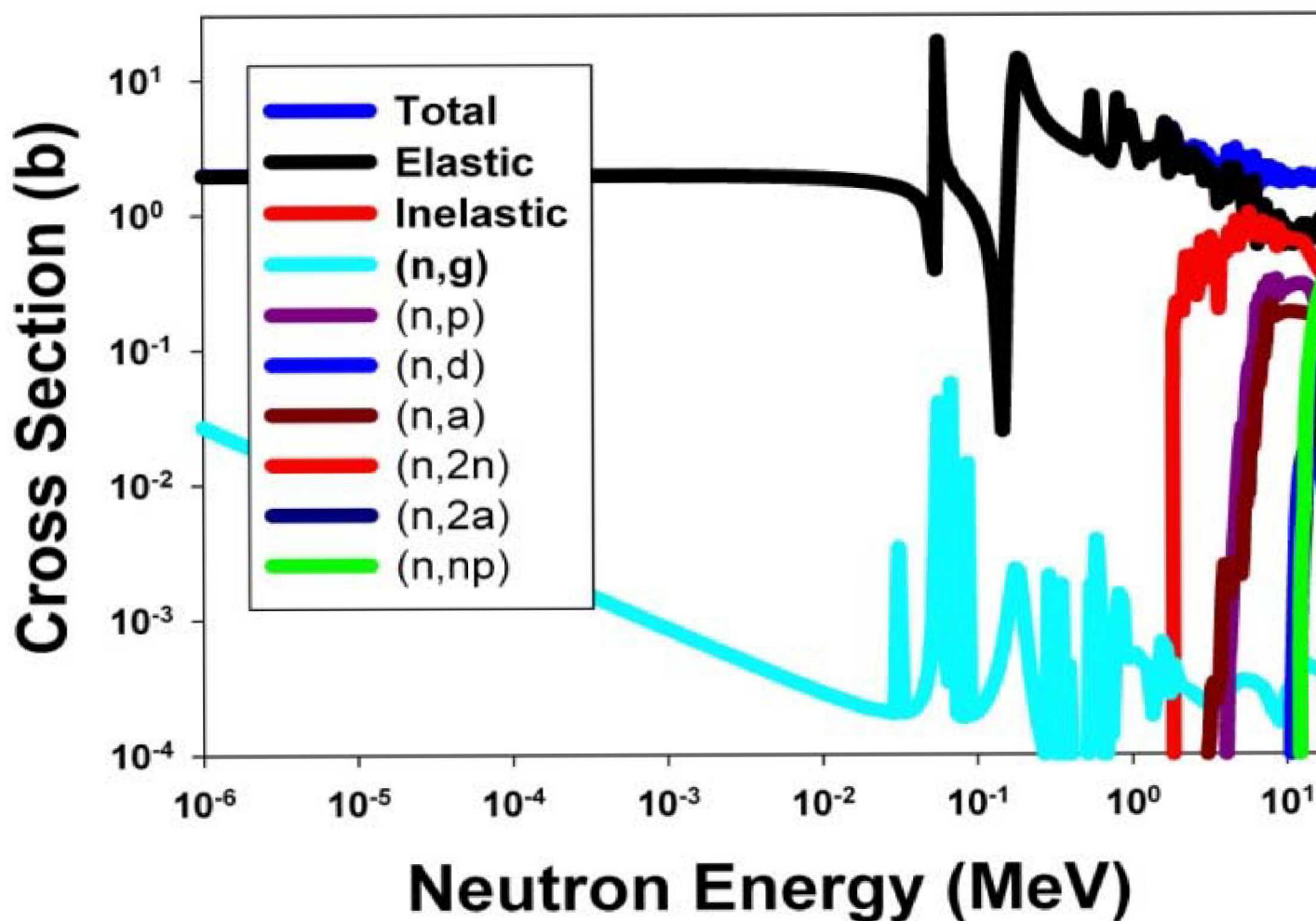


- **Cross Sections**
- **Recoil Spectra**
- **Damage Partition Function**
  - **Interatomic Potential**
  - **Displacement Threshold Energy**
  - **Polyatomic/isotope Lattice in Damage Partition**
- **Nuclear Data**
  - **Natural Abundance for Silicon Isotopes**
  - **Atomic Masses for Silicon Isotopes**
- **Model Defect**

## Additional Factors to Consider

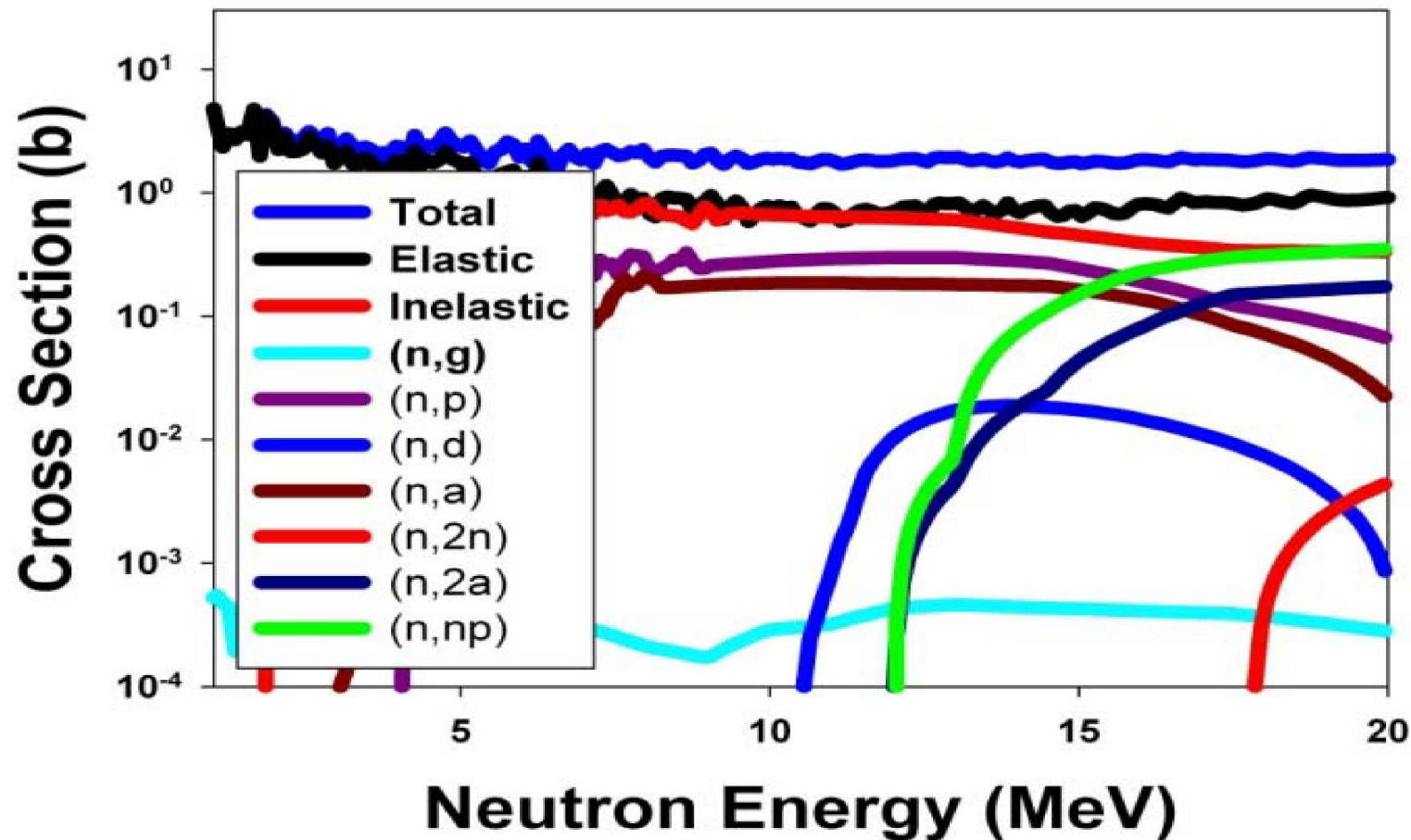
- **Displaced atom model, e.g. Kinchin-Pease, NRT, arc-dpa, rpa**
- **Displacement Kerma  $\neq$  Displacement Damage in all Cases**
  - **Low energy deviations observed in silicon**
  - **High energy deviations observed in GaAs due to damage clusters**
  - **Defect annealing with different defects having different rate constants**
  - **Role of current (electron/hole pairs) in defect interaction constants**
    - **Current injection annealing**
- **Photon-induced displacement**

## $^{28}\text{Si}$ TENDL Cross Section Components

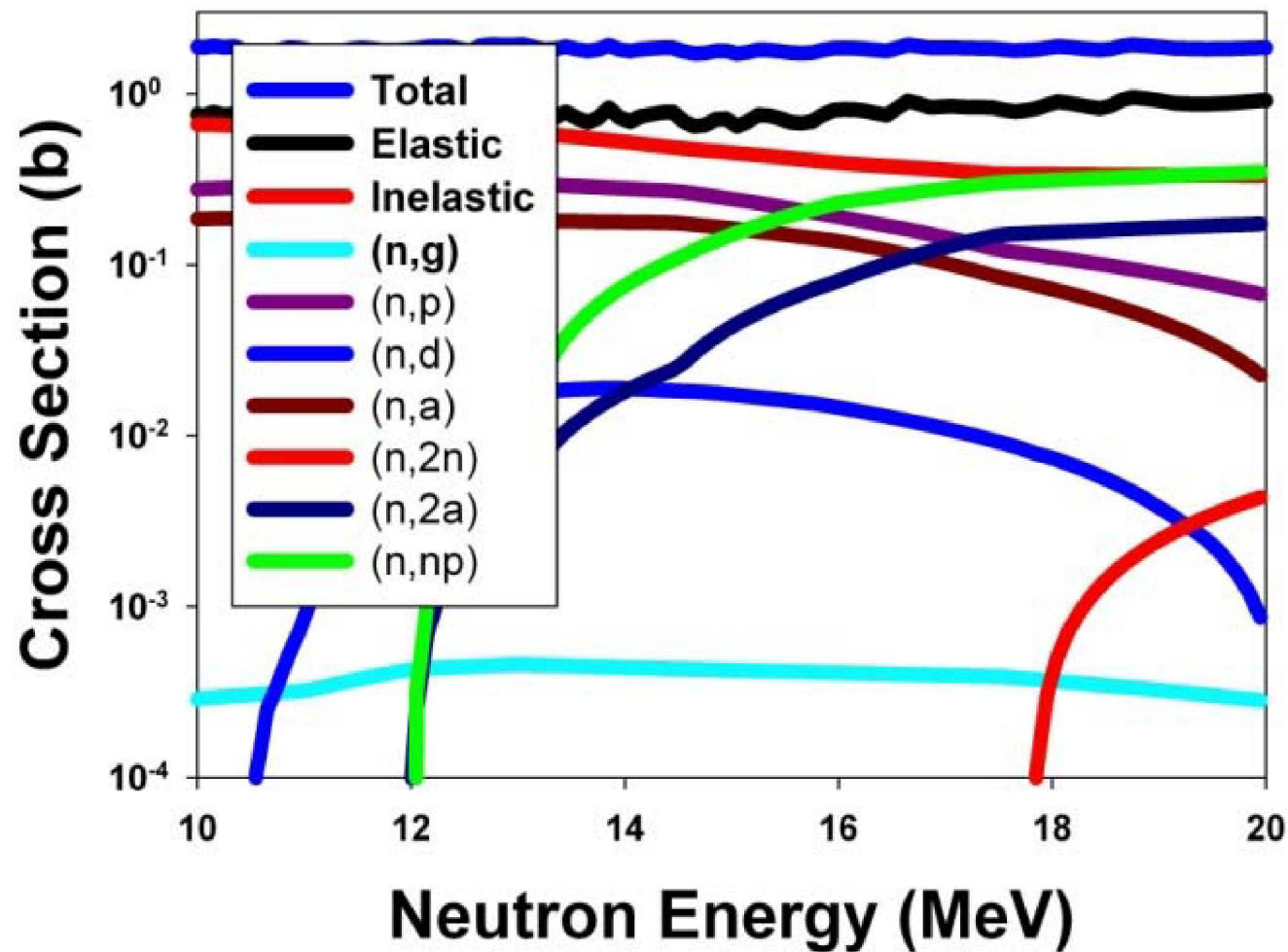




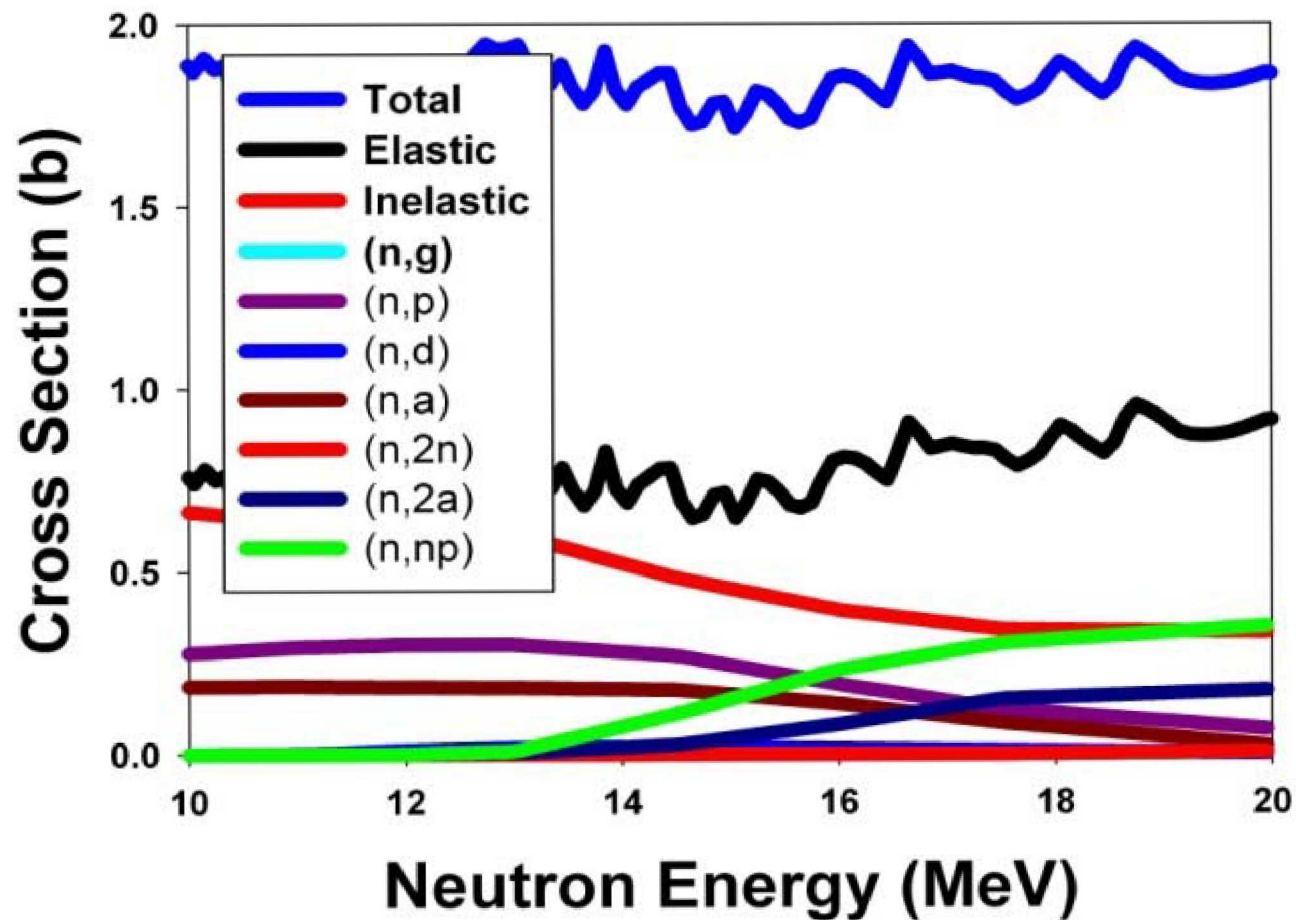
# $^{28}\text{Si}$ TENDL Cross Section Components



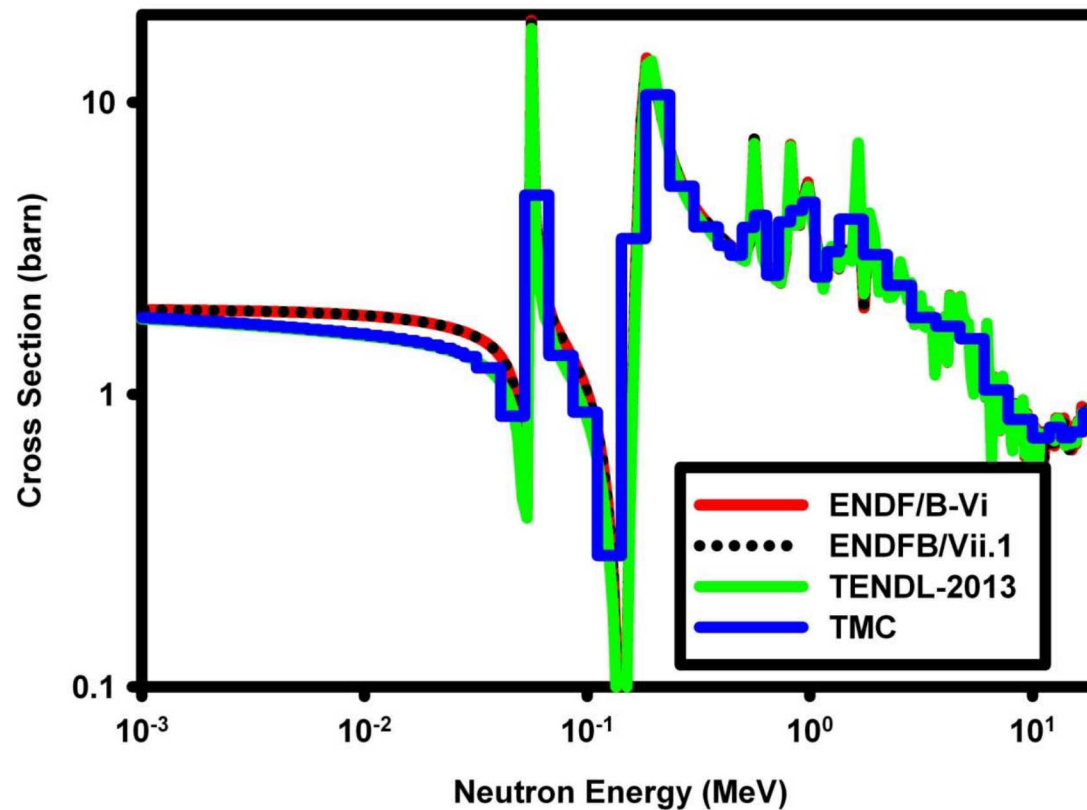
# $^{28}\text{Si}$ TENDL Cross Section Components



## $^{28}\text{Si}$ TENDL Cross Section Components

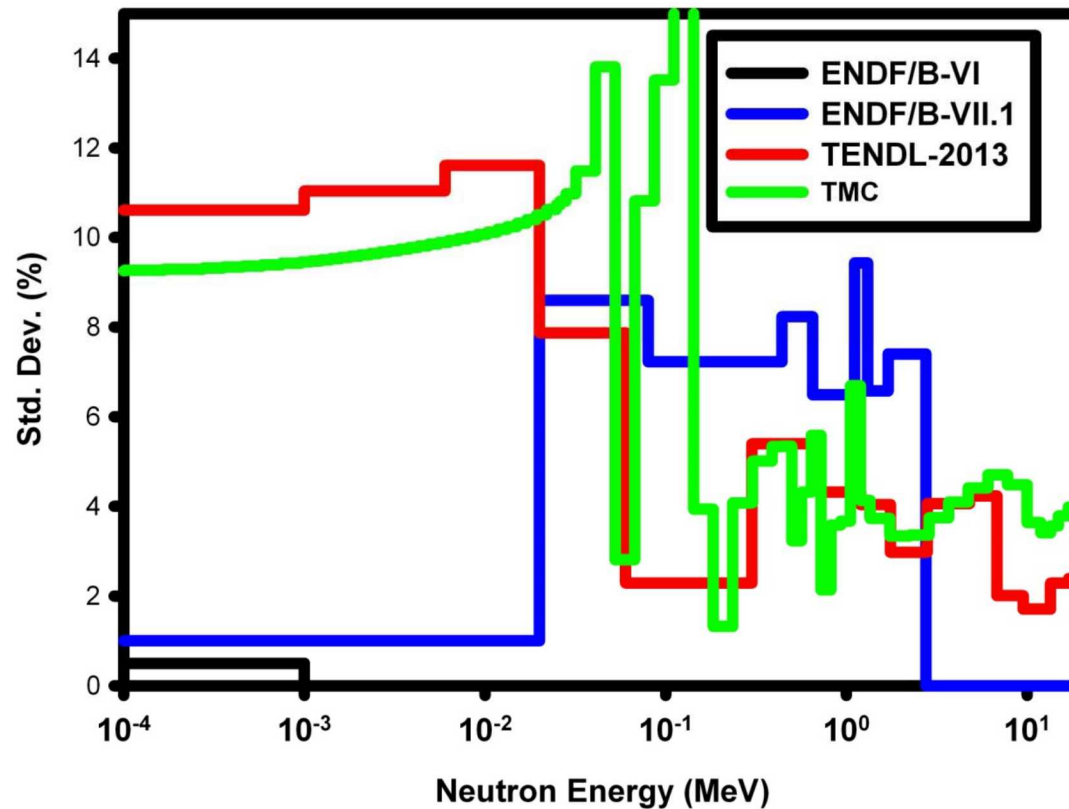


# Comparison of Various Sources of the $^{28}\text{Si}$ Elastic Cross Section

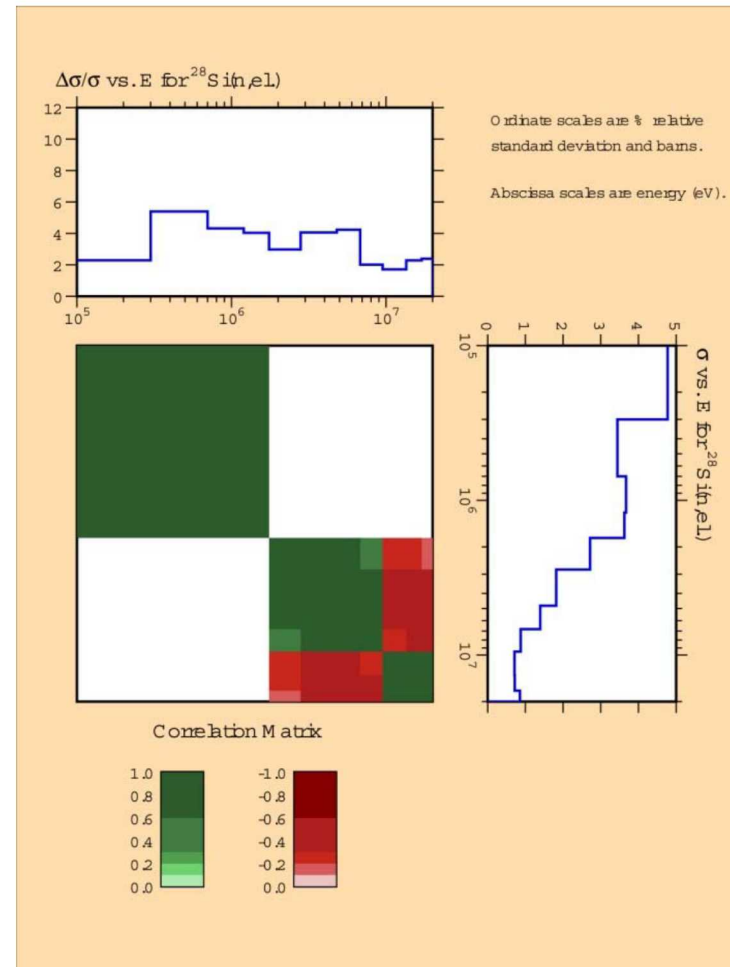
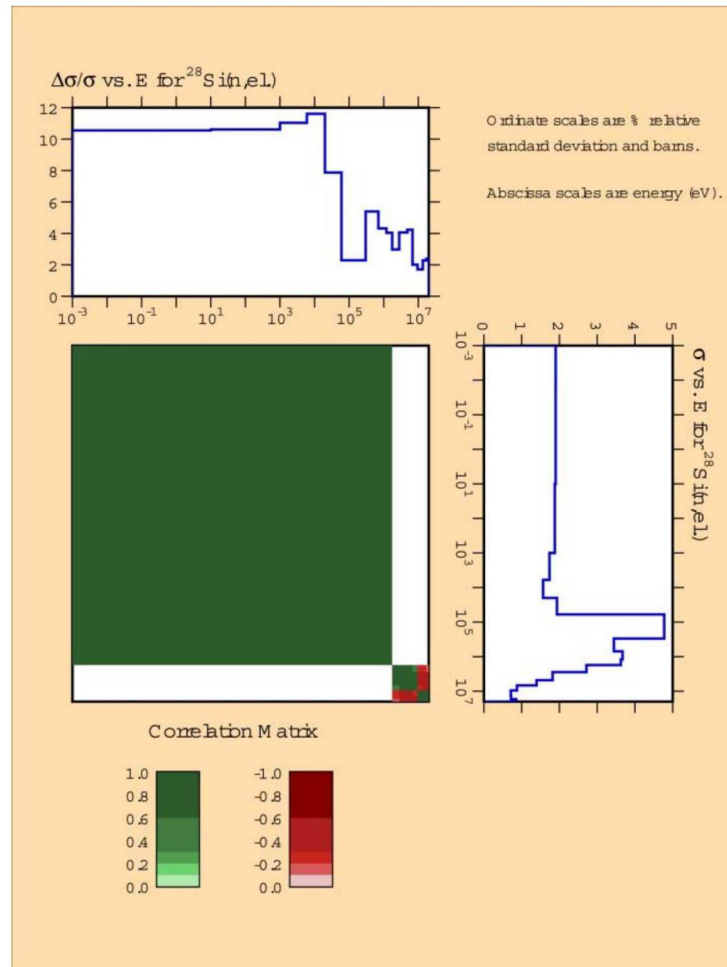




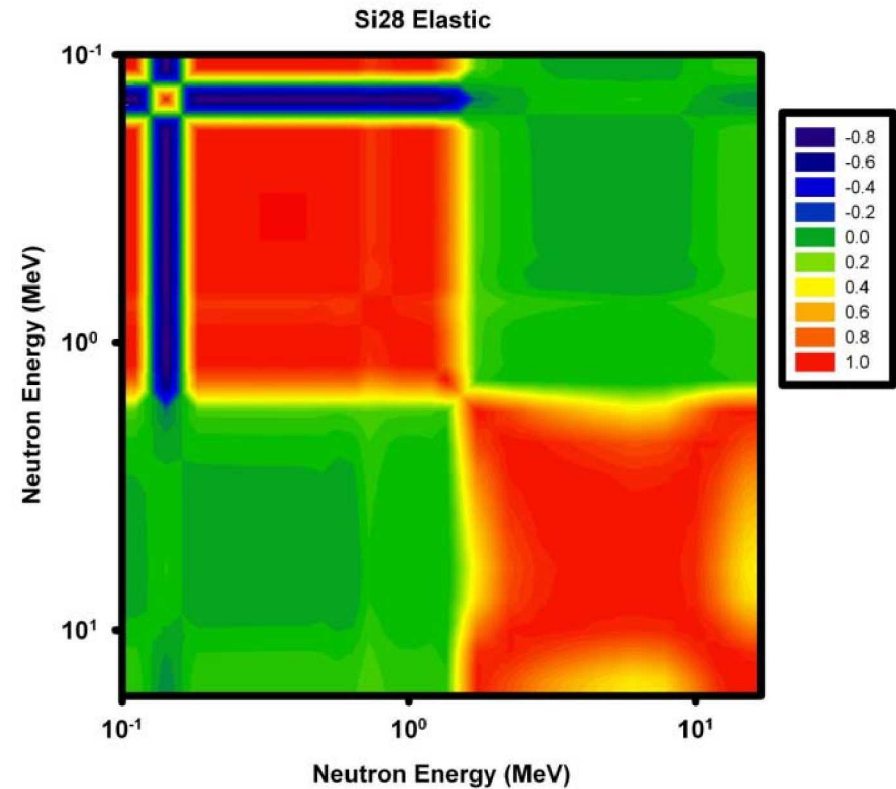
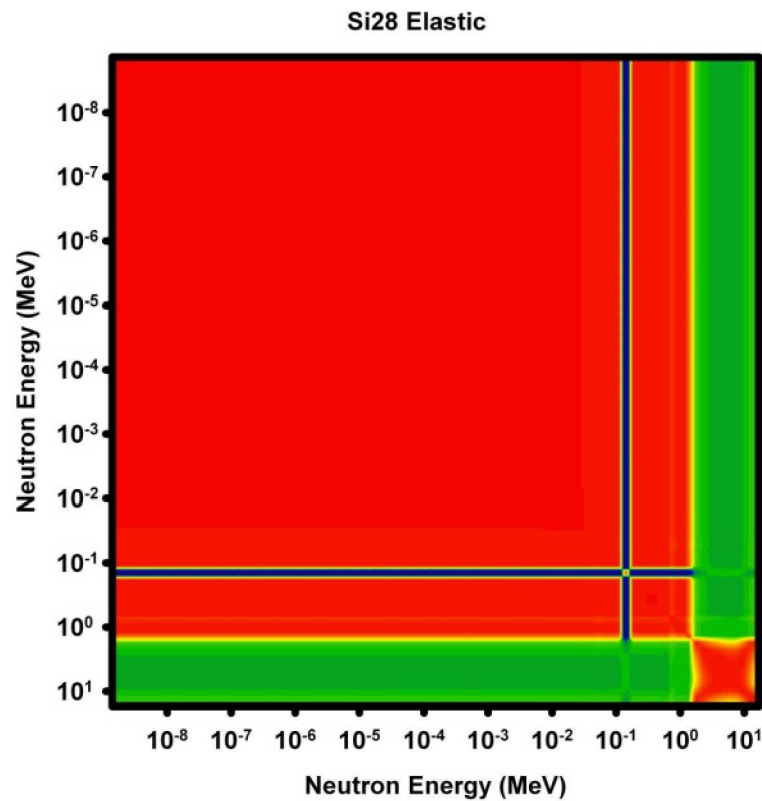
# Comparison of the Standard Deviation for the $^{28}\text{Si}$ Elastic Cross Section in Various Evaluations



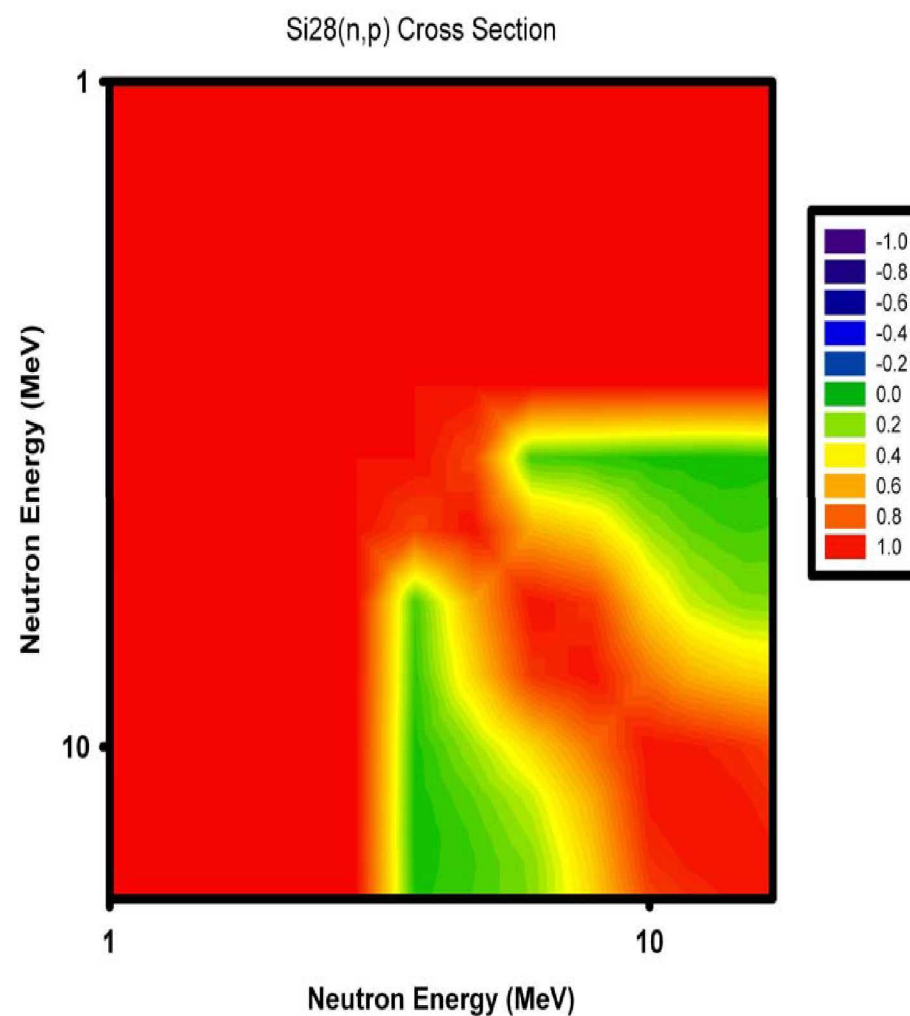
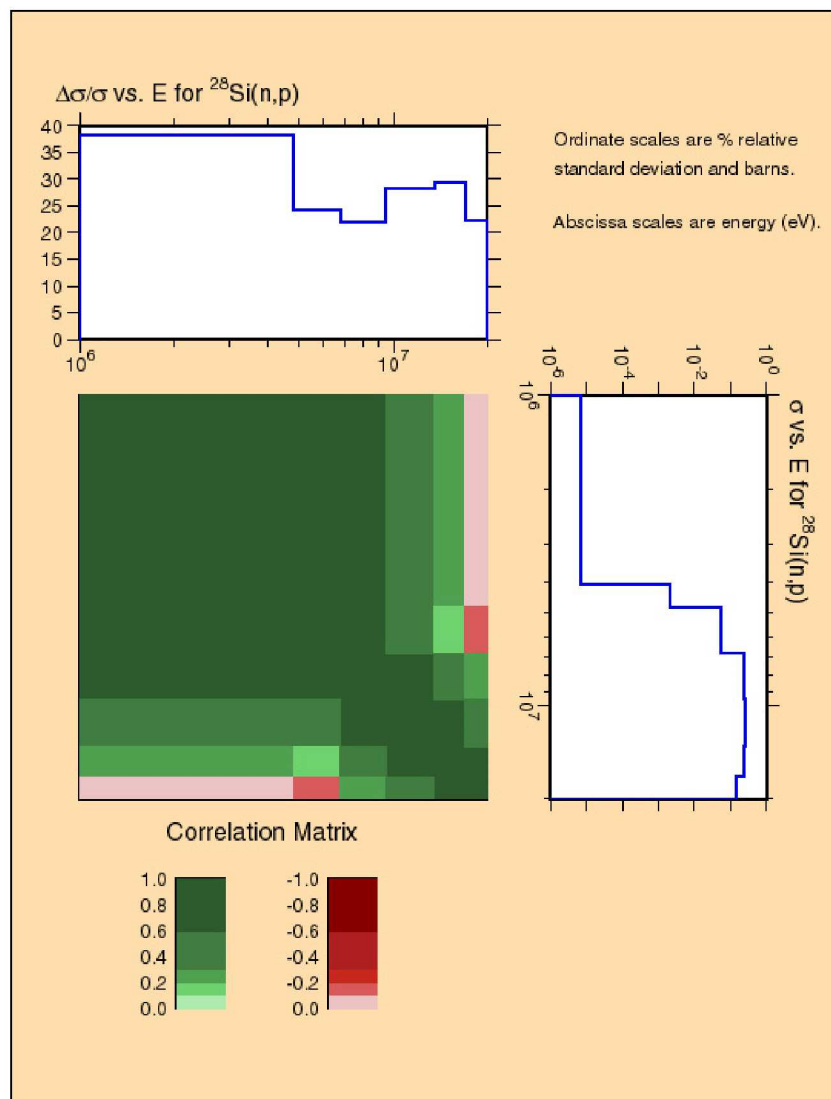
# TENDL-2013 Elastic $^{28}\text{Si}$ Covariance matrix



# TENDL Random Library (TMC) Covariance for $^{28}\text{Si}$ Elastic Cross Section

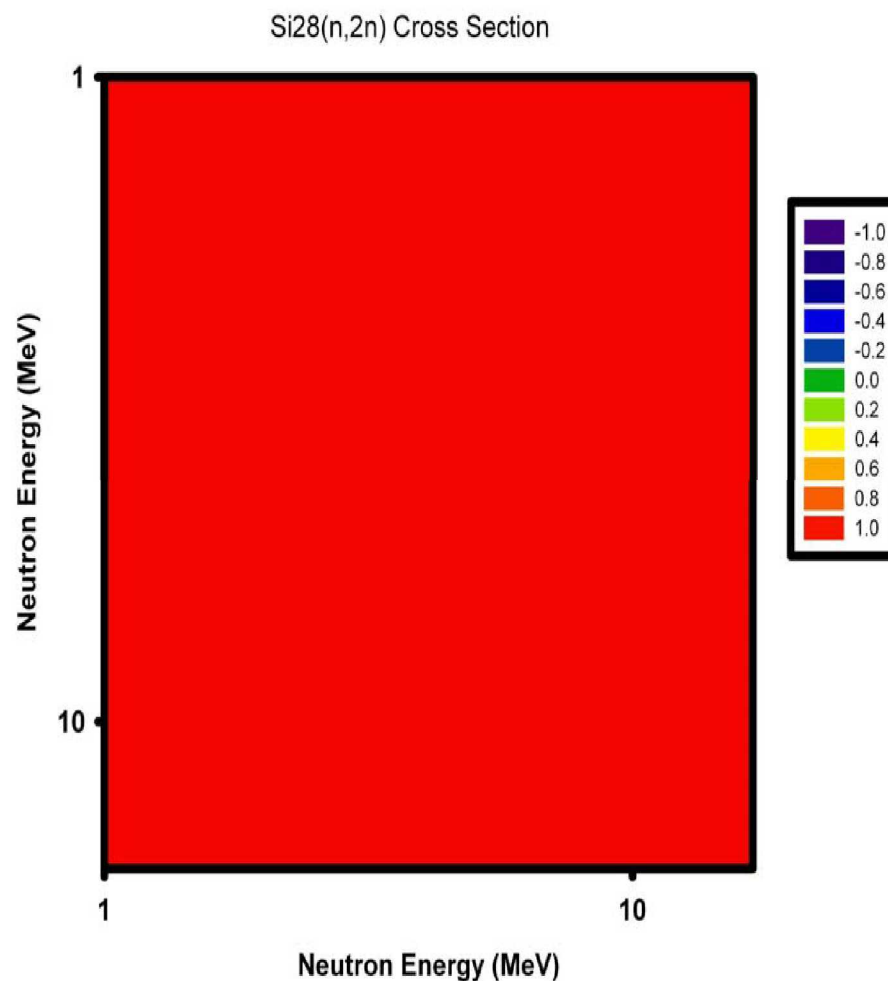
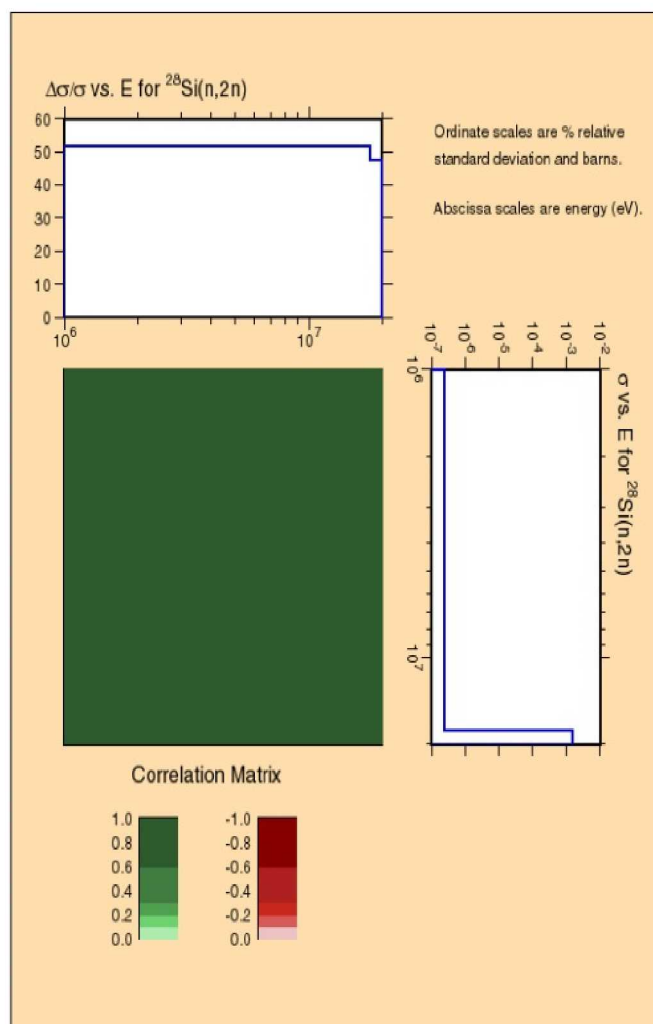


# TENDL-2013 and TMC $^{28}\text{Si}$ (n,p) Covariance Matrix

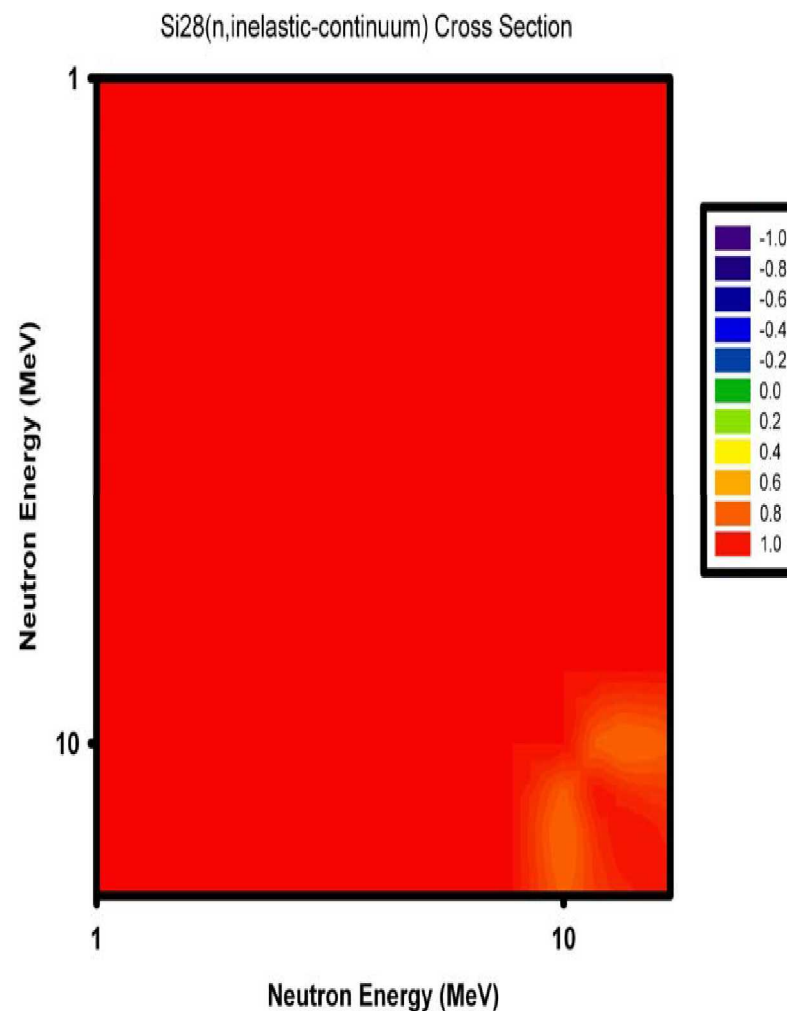
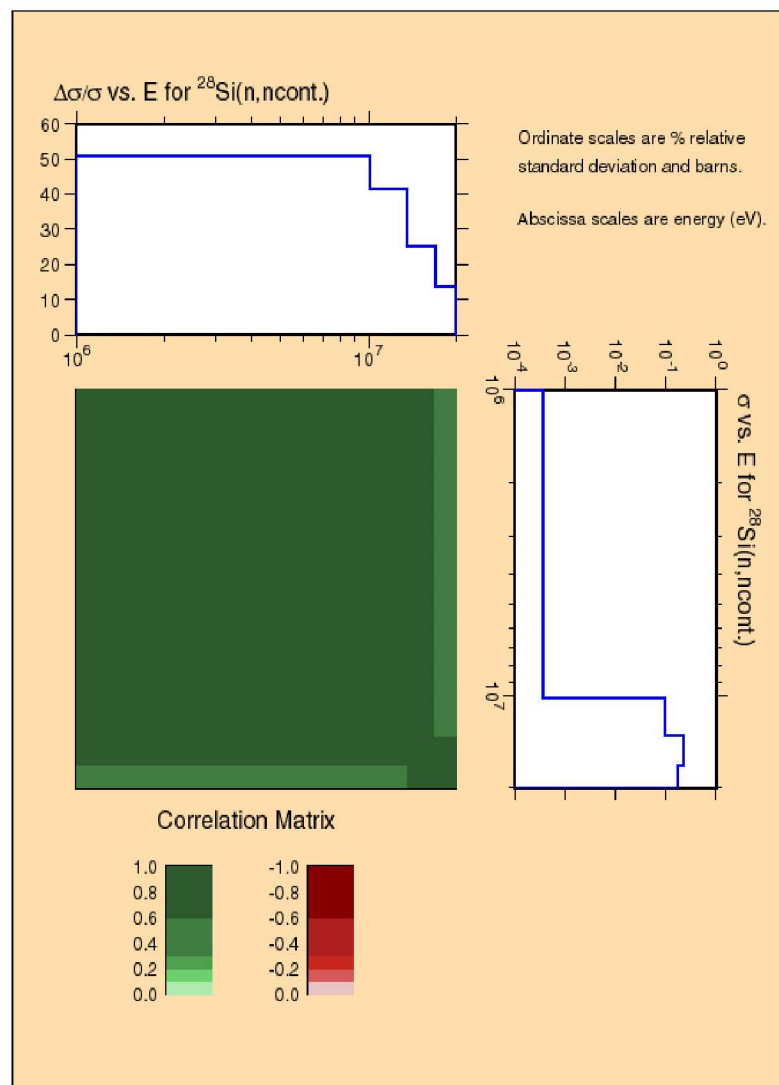




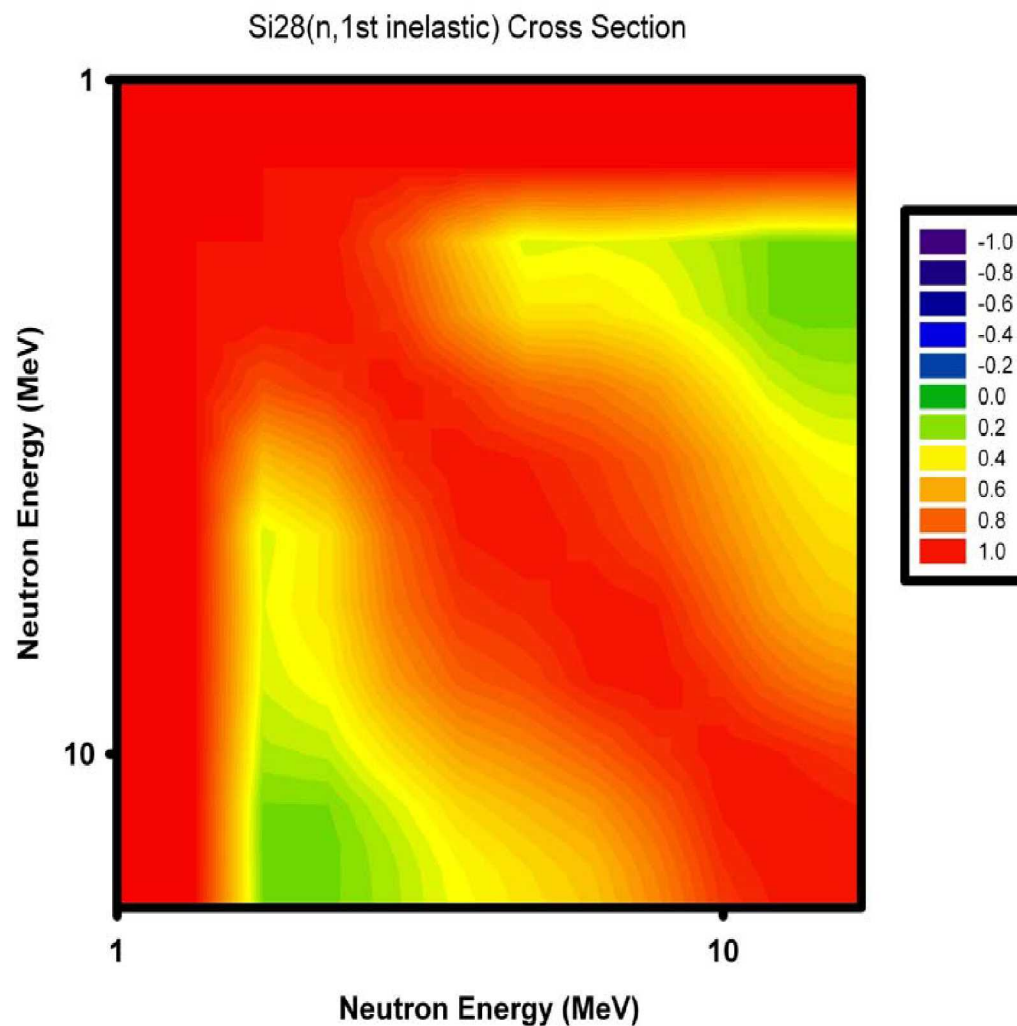
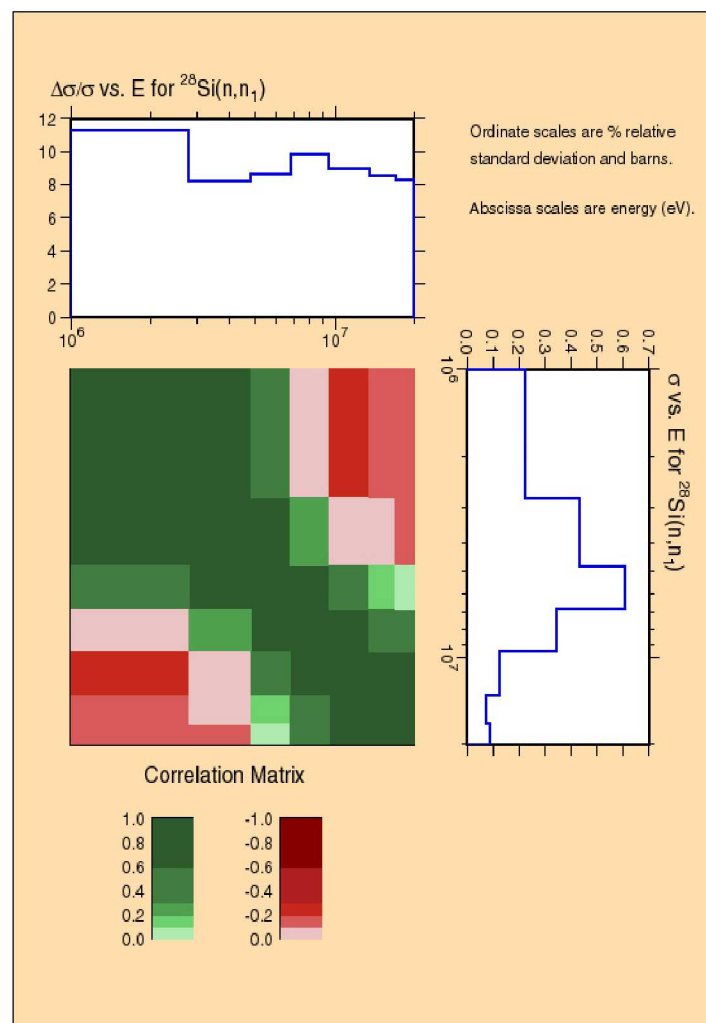
# TENDL-2013 and TMC $^{28}\text{Si}$ (n,2n) Covariance Matrix



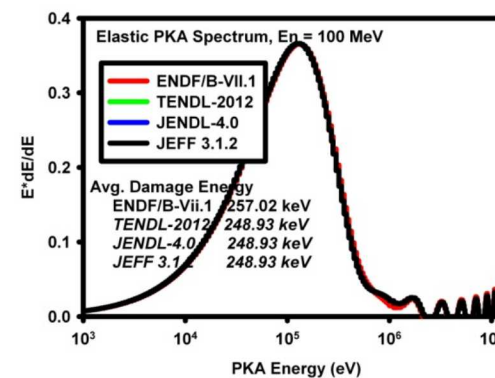
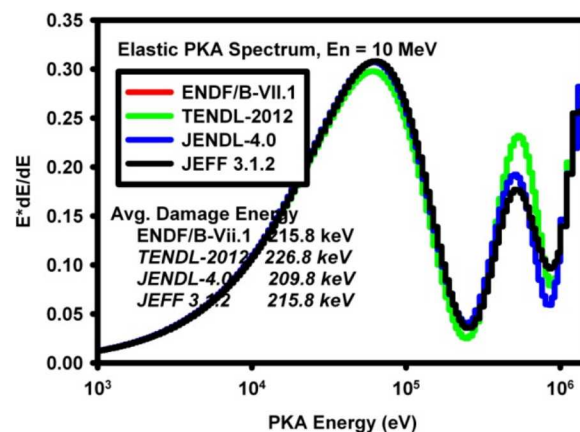
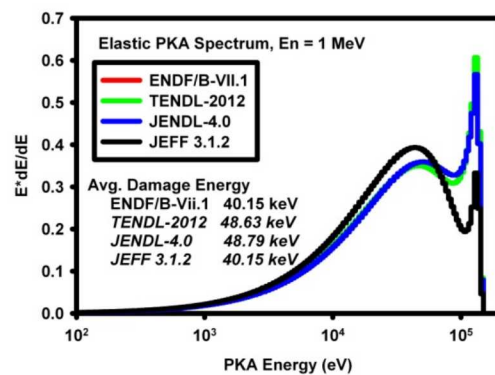
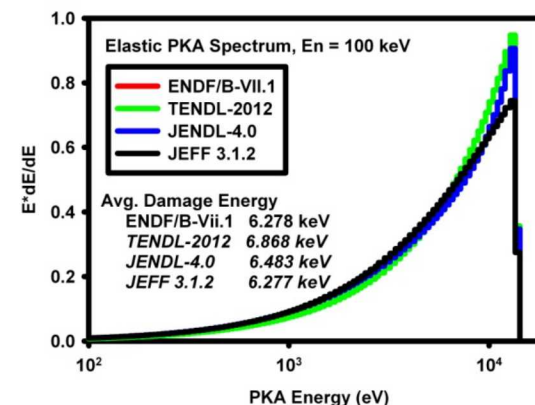
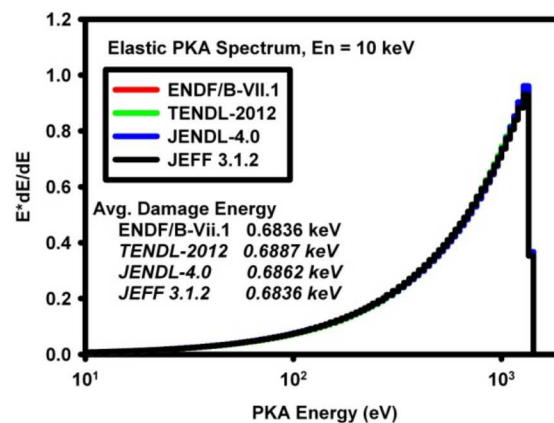
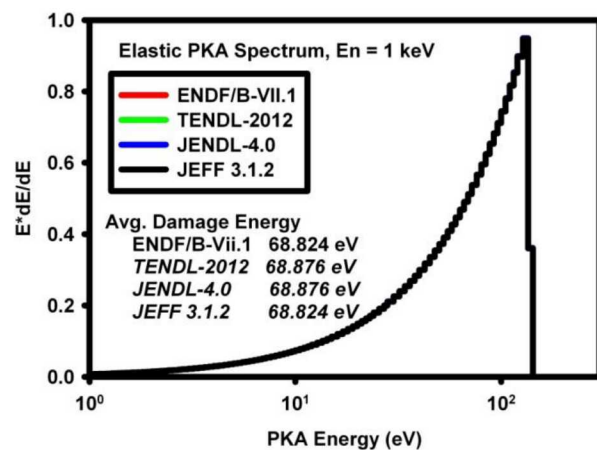
# TENDL-2013 and TMC $^{28}\text{Si}$ (n,n'-cont) Covariance Matrix



# TENDL-2013 and TMC $^{28}\text{Si}$ (n,n'-1<sup>st</sup>) Covariance Matrix

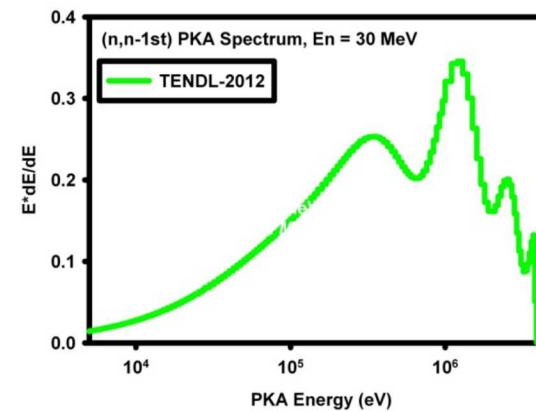
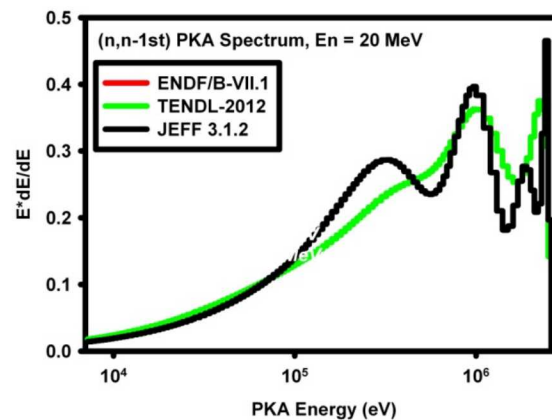
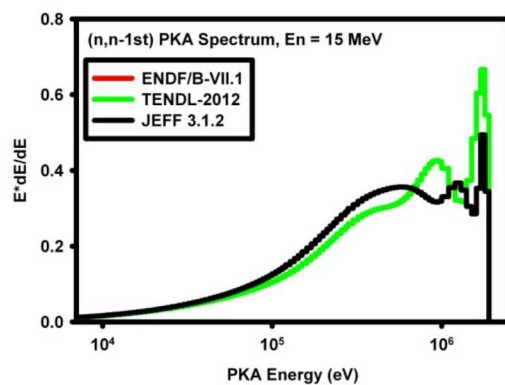
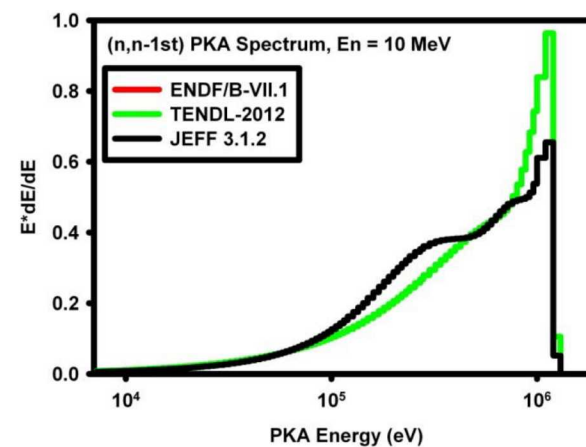
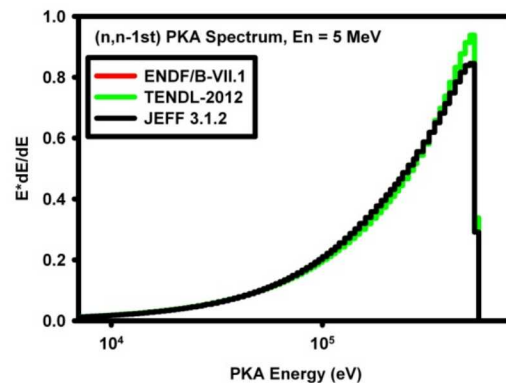
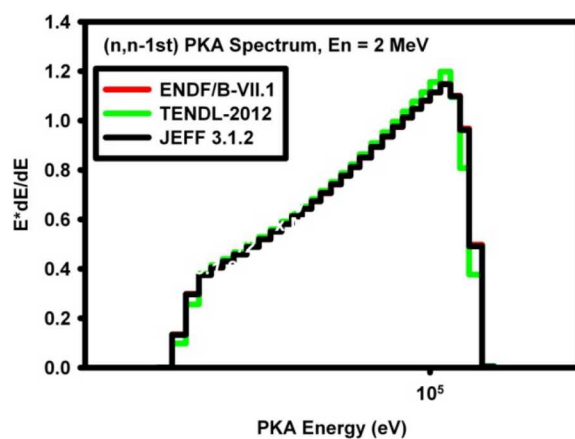


# Recoil Spectra: $^{28}\text{Si}$ Elastic

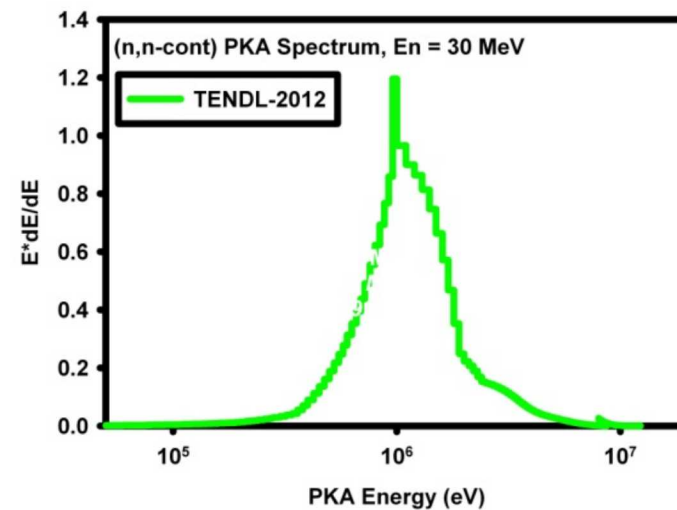
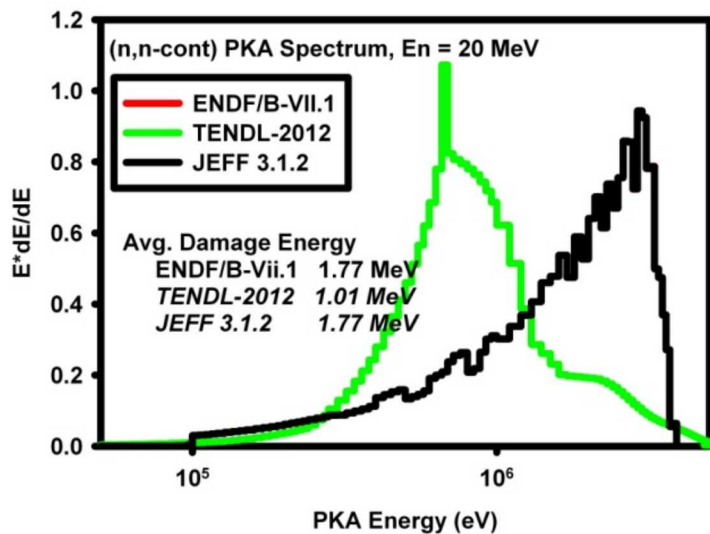
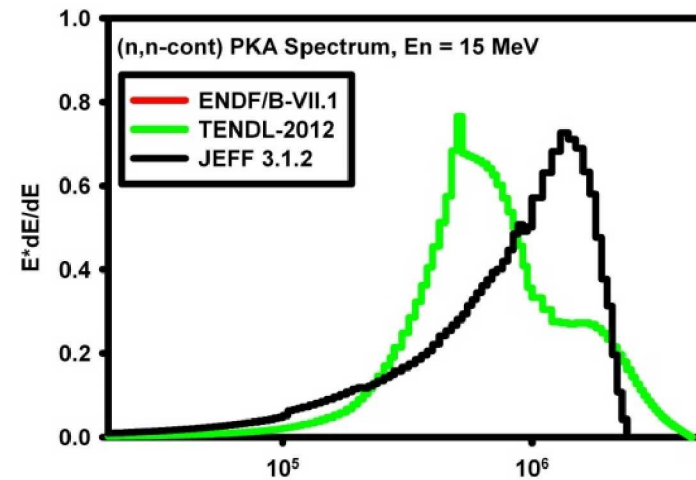
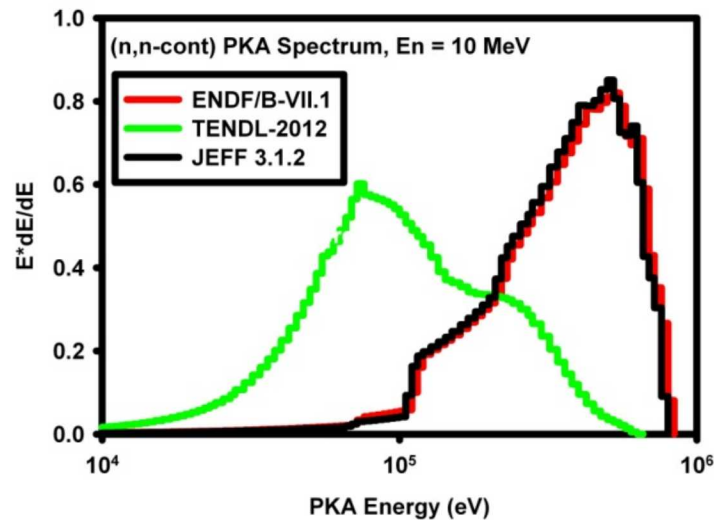




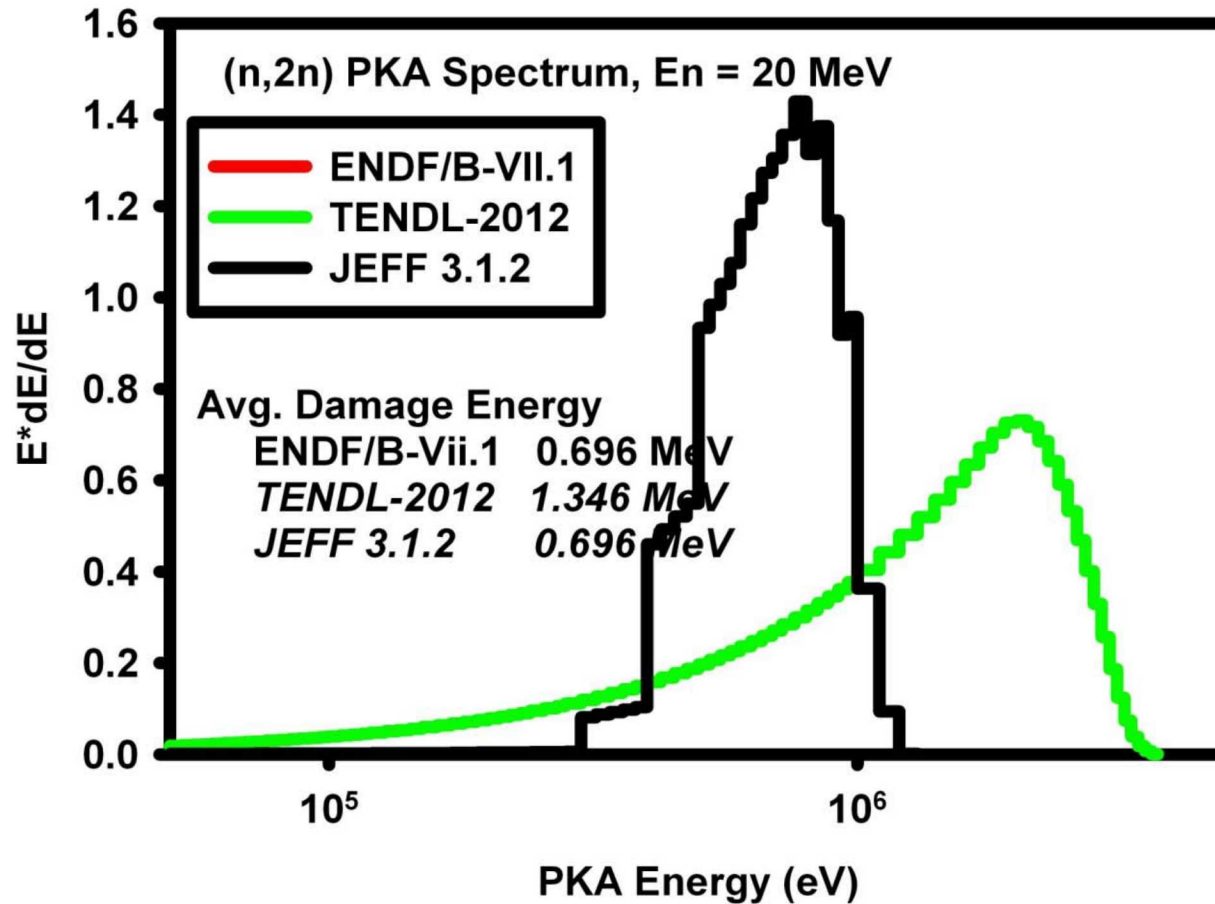
# Recoil Spectra: $^{28}\text{Si}$ 1<sup>st</sup> Inelastic



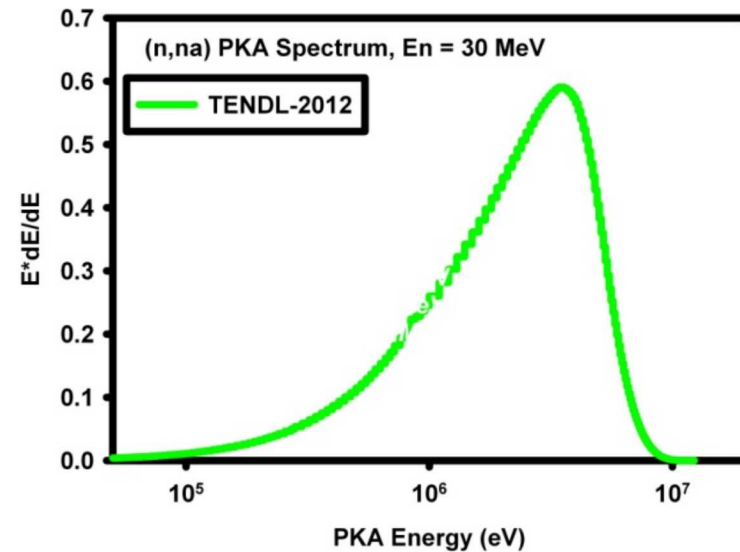
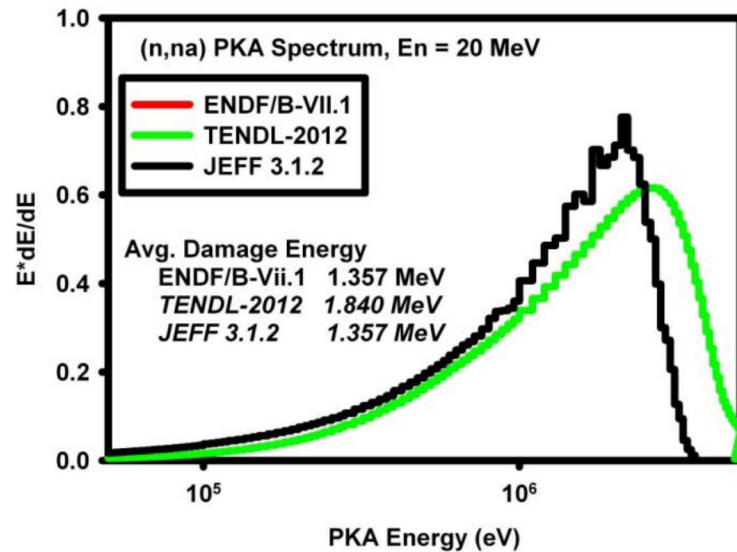
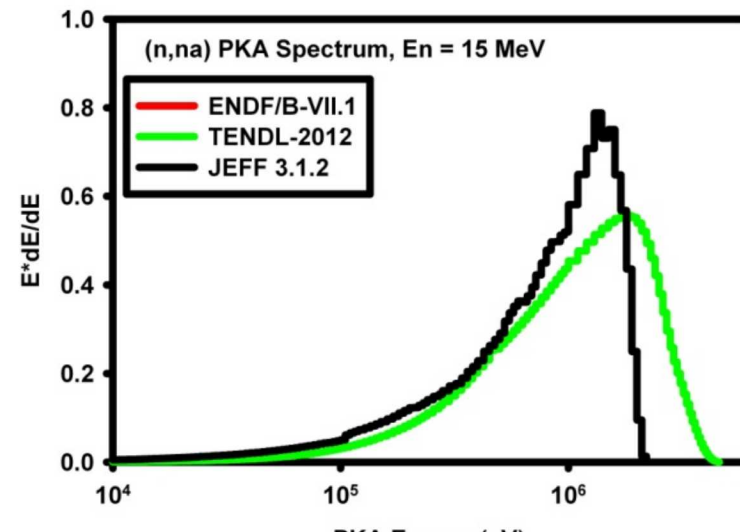
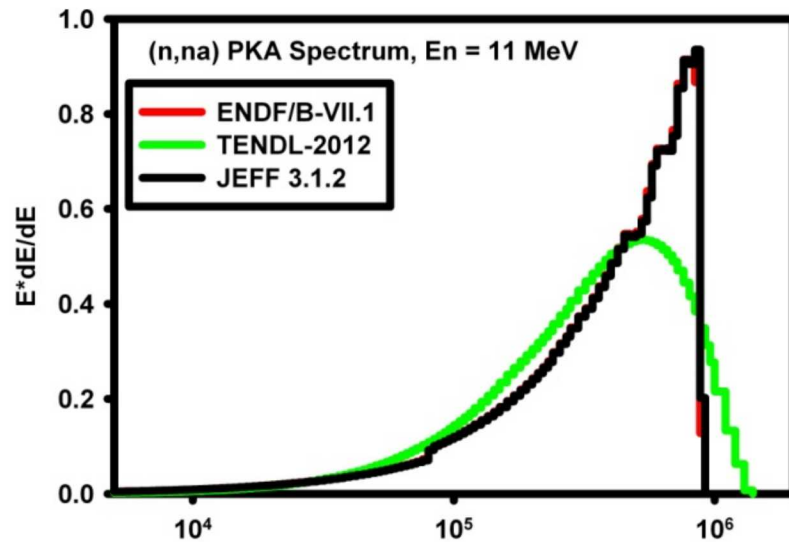
# Recoil Spectra: $^{28}\text{Si}$ Continuum Inelastic



# Recoil Spectra: $^{28}\text{Si}$ (n,2n)

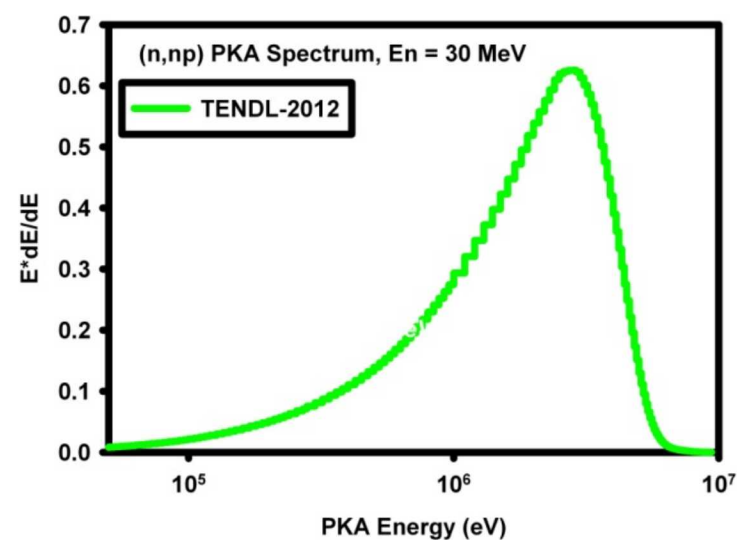
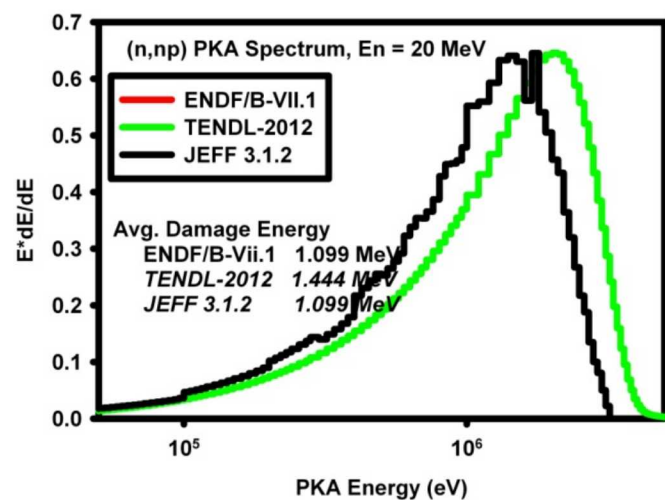
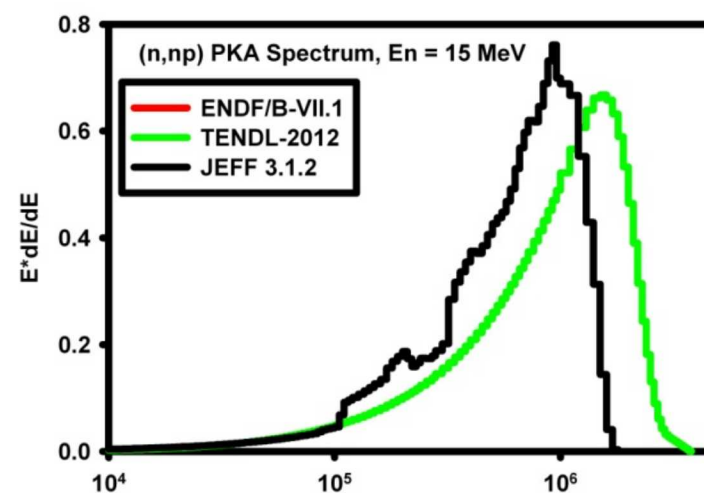
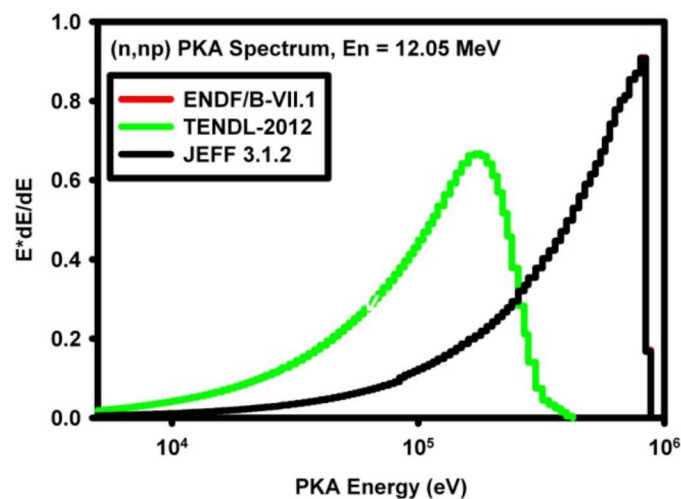


# Recoil Spectra: $^{28}\text{Si}$ (n,n $\alpha$ )

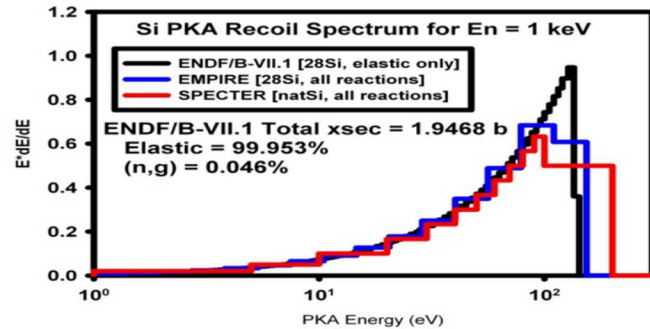




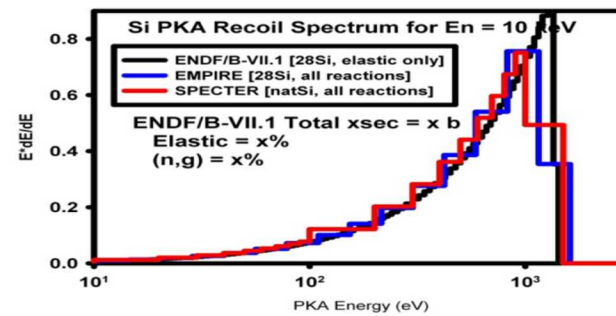
# Recoil Spectra: $^{28}\text{Si}$ (n,np)



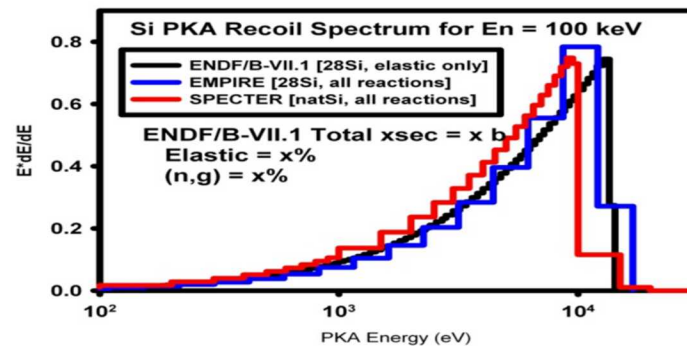
# Recoil Spectra: Empire vs. Specter vs. ENDF/B-VII.1 (elastic only) for Silicon



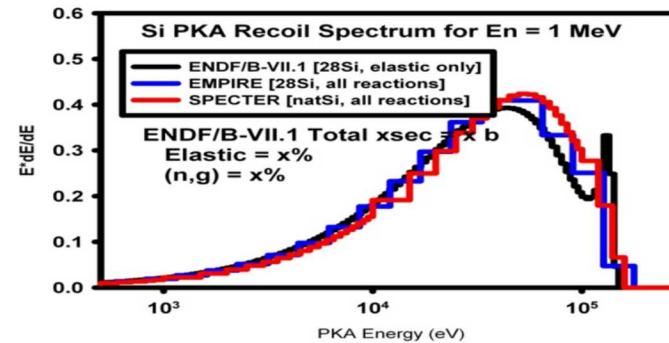
1 keV



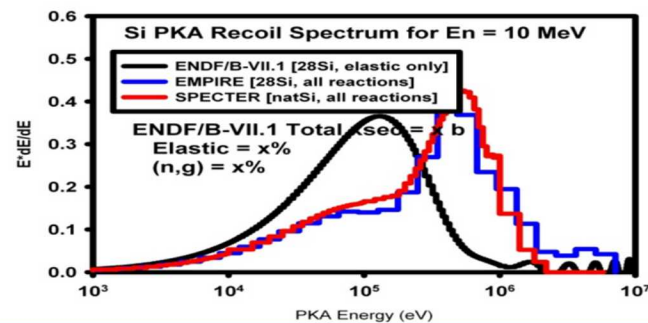
10 keV



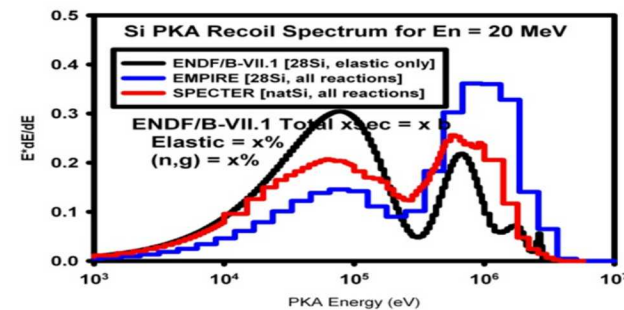
100 keV



1 MeV

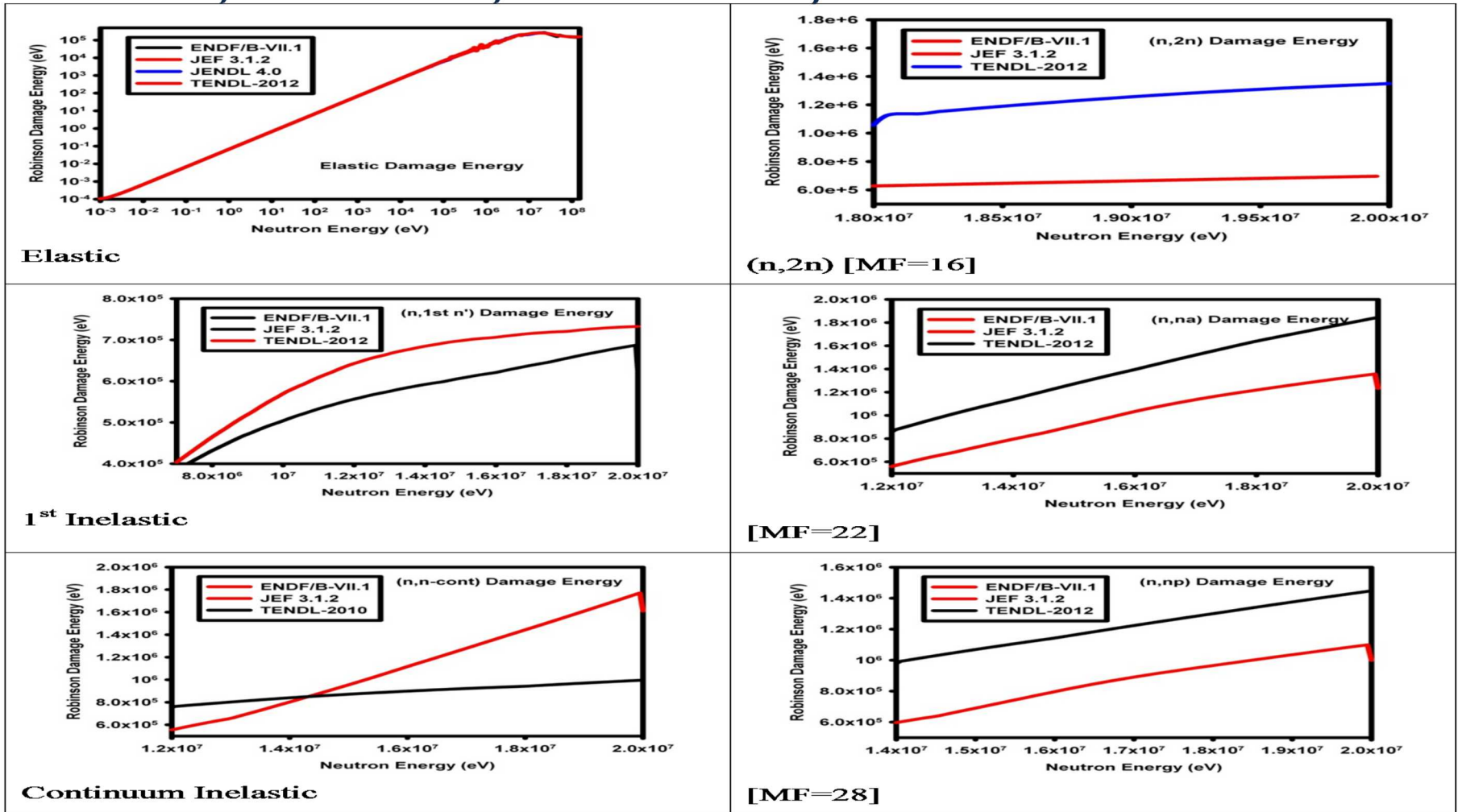


10 MeV

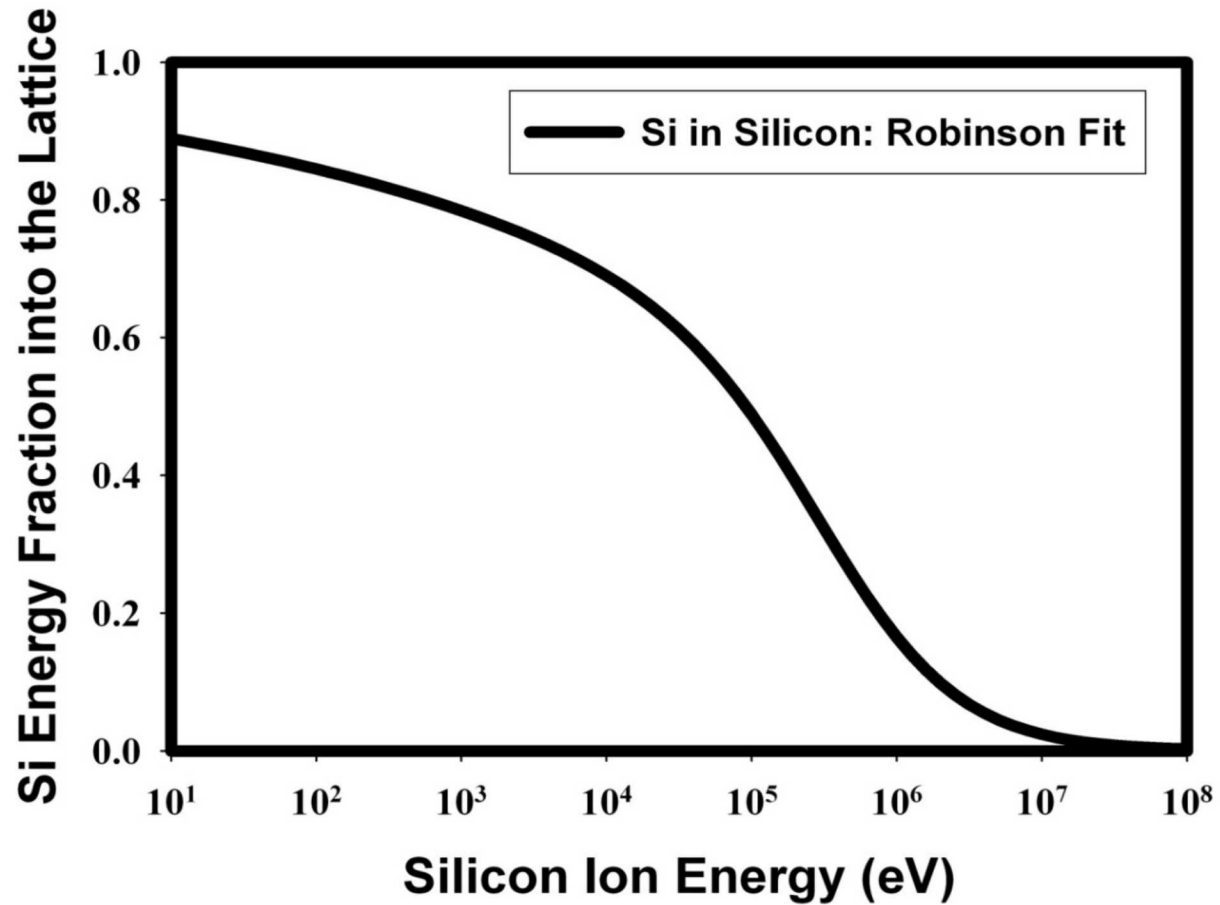


20 MeV

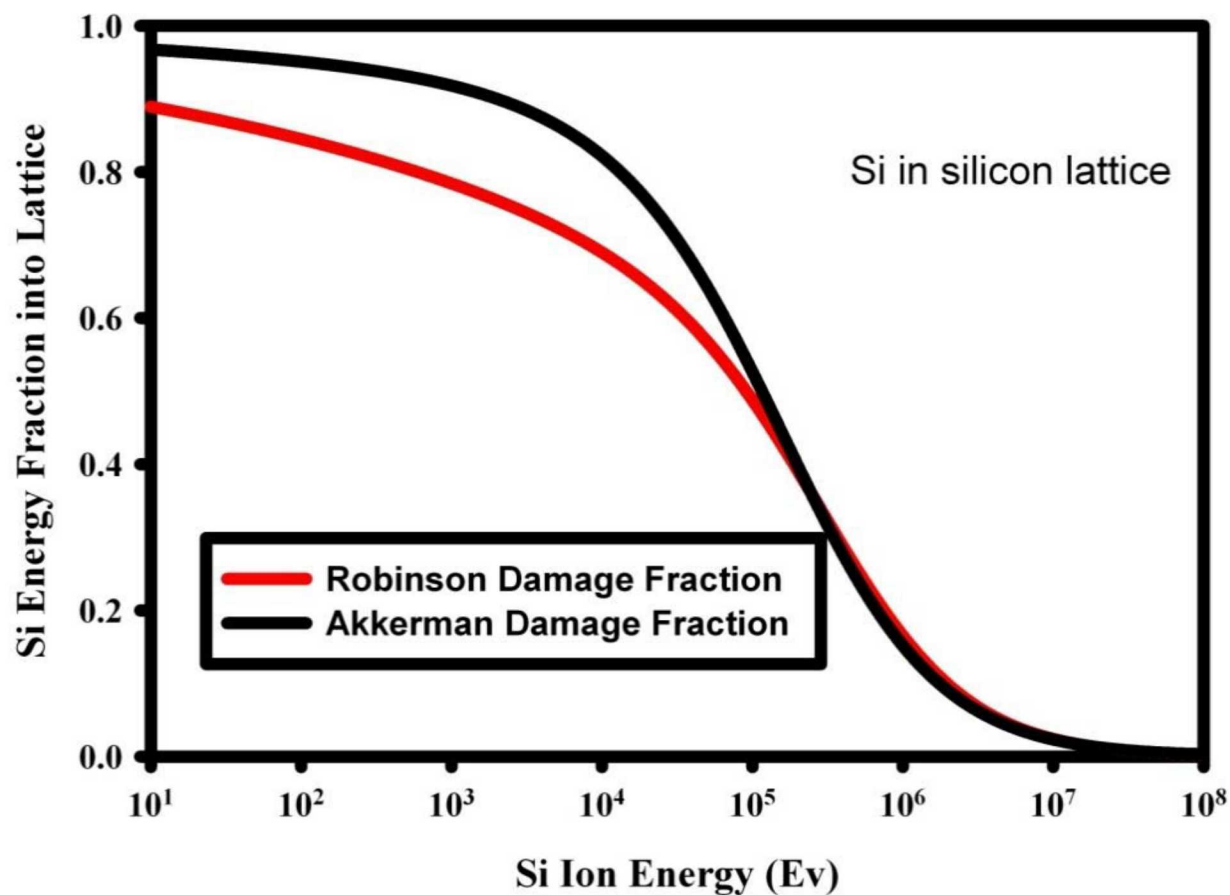
# Comparison of $^{28}\text{Si}$ Displacement Kerma Components for Various Evaluations (ENDF/B-VII.1, JEF 3.1.2, JENDL-4.0, TENDL-2012)



# Robinson Silicon Energy Partition Function

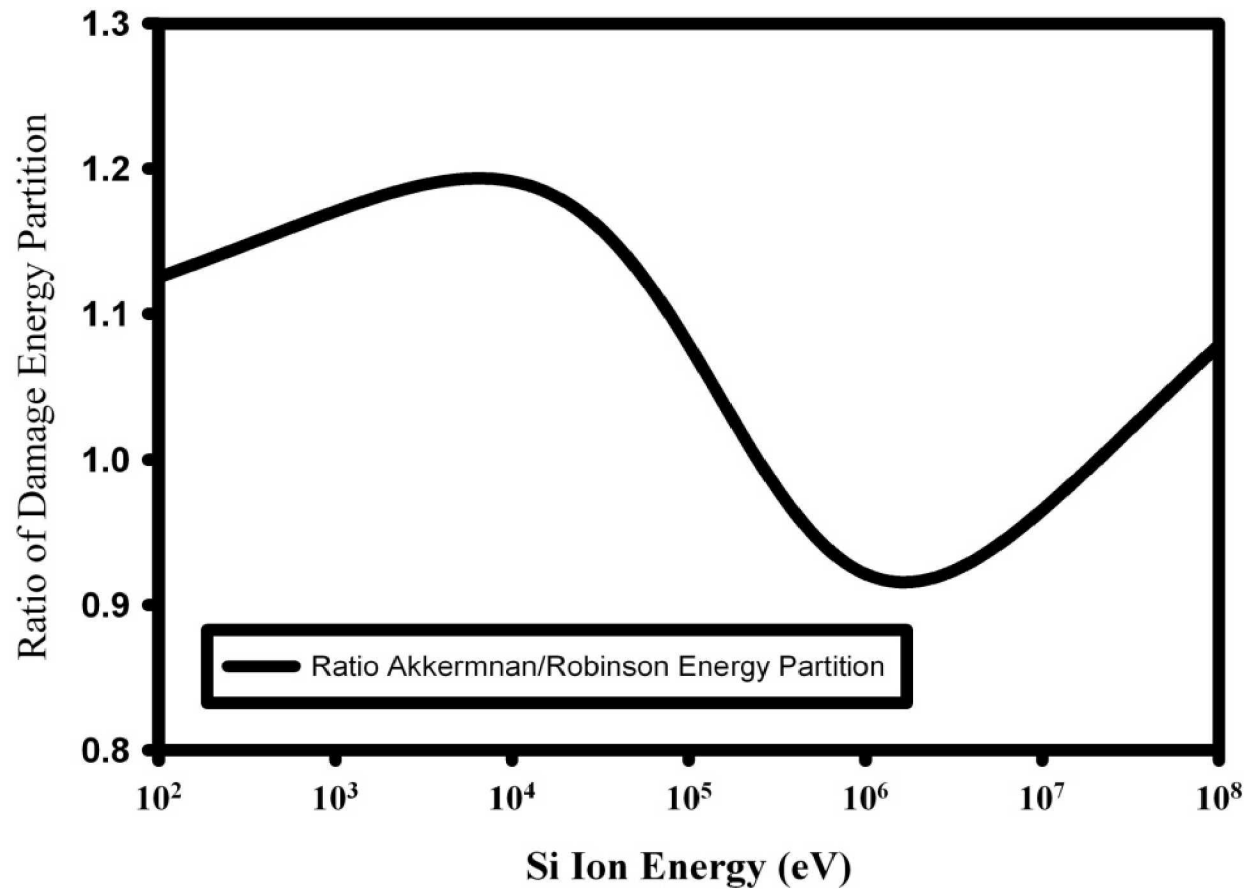


# Comparison of Akkerman and Robinson Silicon Energy Partition Function





# Ratio of Akkerman and Robinson Silicon Energy Partition Function (+20% / -10%)



# Effect of Interatomic Potential on the Damage Partition Methodologies



| <b>Si Ion<br/>Energy<br/>(keV)</b> | <b>MARLOWE BCA<br/>Code Using:</b> |                          | <b>LSS</b> |
|------------------------------------|------------------------------------|--------------------------|------------|
|                                    | <b>Moliere<br/>Potential</b>       | <b>ZBL<br/>Potential</b> |            |
| 30 keV                             | 29.1                               | 32.9                     | 38.5       |
| 50 keV                             | 35.1                               | 38.9                     | 43.3       |
| 100 keV                            | 44.0                               | 47.8                     | 52.        |
| 500 keV                            | 72.0                               | 72.9                     | 74.5       |
| 1 MeV                              | 82.7                               | 82.7                     | 83.5       |
| 10 MeV                             | 94.7                               | 95.0                     | 97.6       |

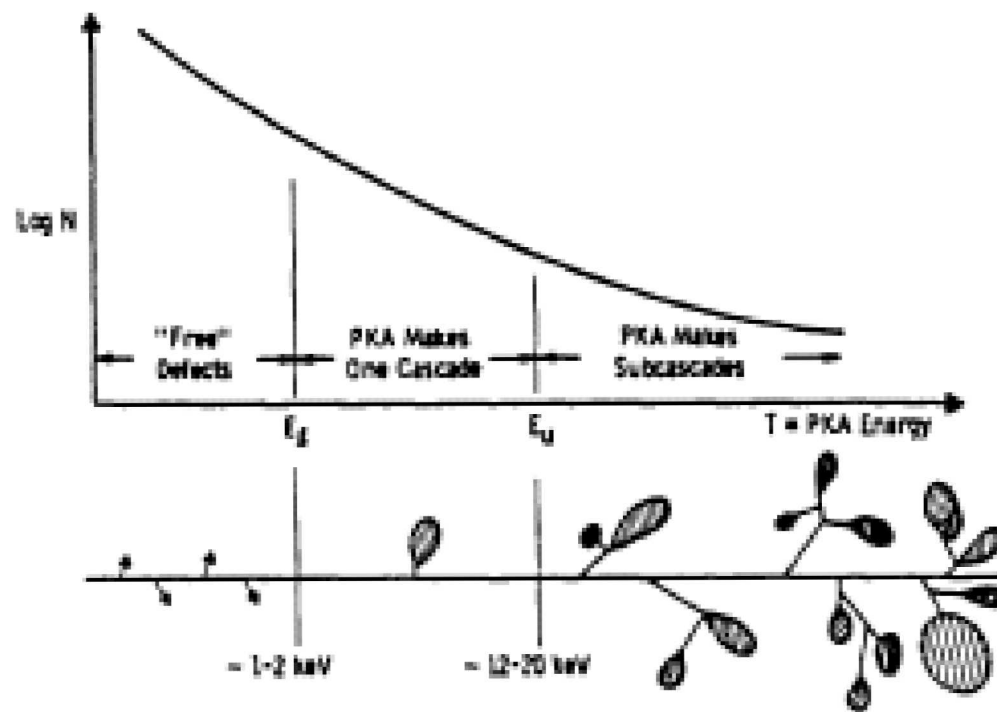
# **TOPIC:**

# **SILICON TRANSISTOR GAIN**

# **DEGRADATION**

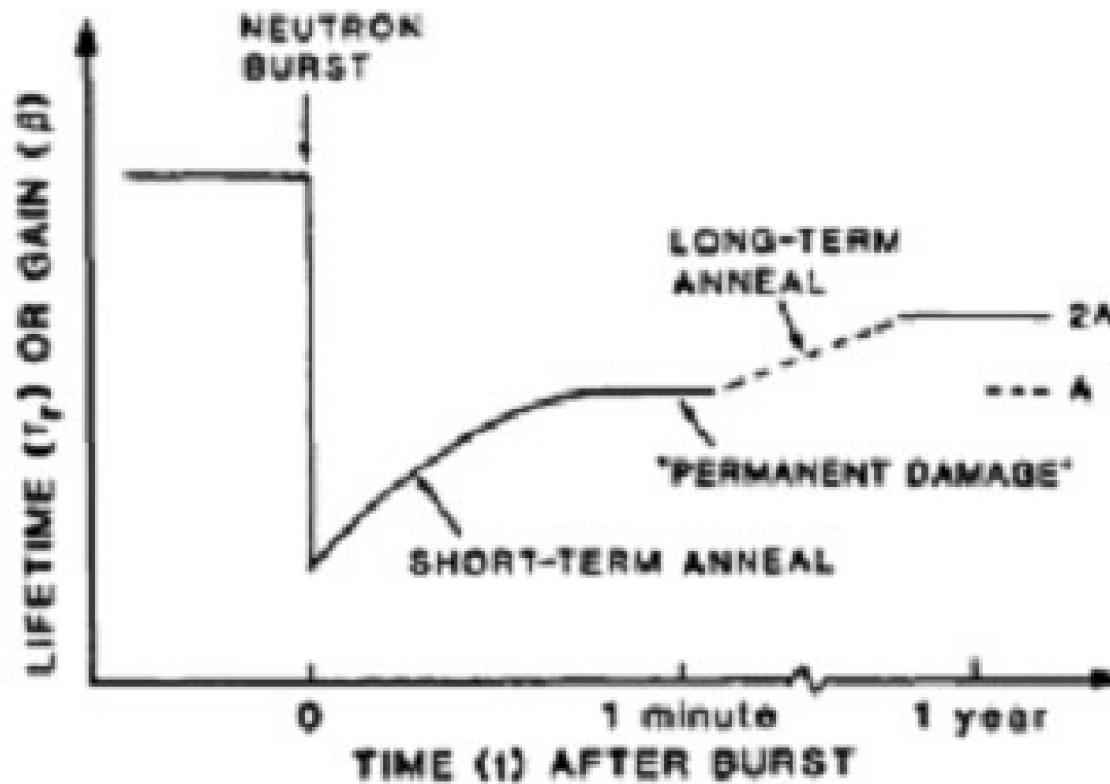
This is a measure of displacement damage in silicon. In principle, it should scale with the displacement kerma. Issues arise with the fact that different defect types anneal with different reaction time constants – hence affecting the measured damage metrics.

# Neutron Damage Clusters Depend on Recoil Particle LET



① The relationship between defect cascade structure in Cu

## Damage Anneals in Different Stages





# Annealing Function Defn.



## Messenger-Spratt Eqn.

$$\left( \frac{1}{H_{fe}(\infty)} - \frac{1}{H_{fe}(0)} \right) = k_n \varphi_n$$

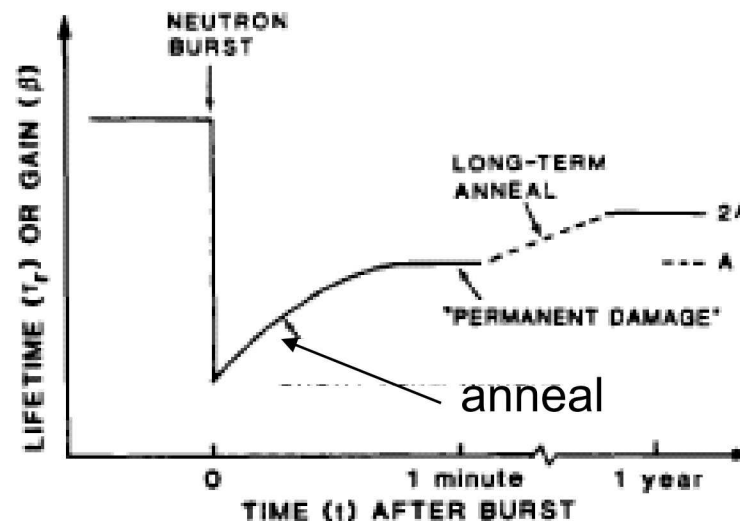
## Annealing Function

$$\left( \frac{1}{H_{fe}(t)} - \frac{1}{H_{fe}(0)} \right) = AF(t) k_n \varphi_n$$

## Normalized Metric

$$AF(t) = \frac{\frac{1}{H_{fe}(t)} - \frac{1}{H_{fe}(0)}}{\frac{1}{H_{fe}(\infty)} - \frac{1}{H_{fe}(0)}}$$

# What is Early-time Damage Annealing?

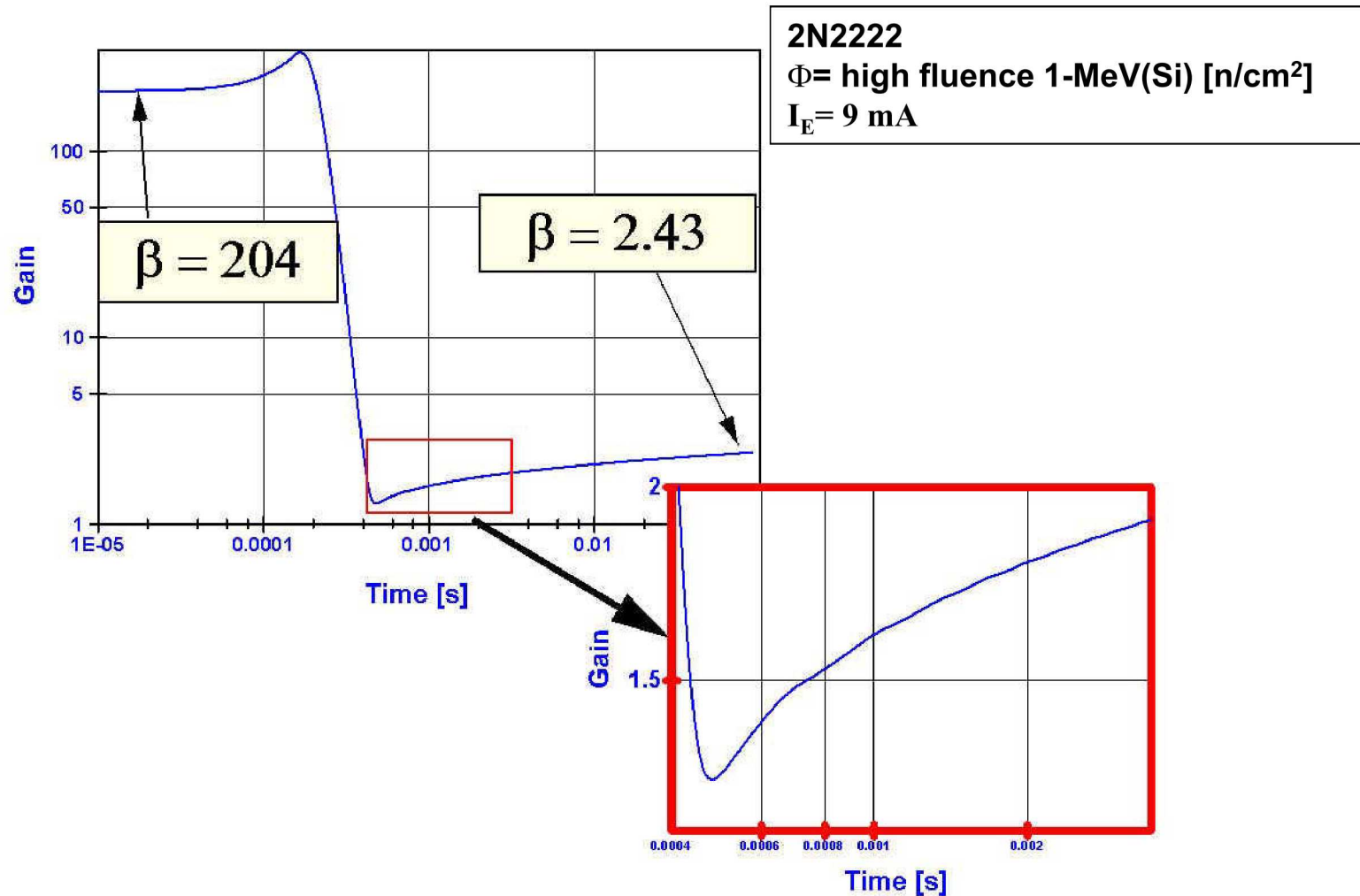


$$\text{ANNEALING FACTOR} = AF(t) = \frac{\frac{1}{\tau_r(t)} - \frac{1}{\tau_{r0}}}{\frac{1}{\tau_r(\infty)} - \frac{1}{\tau_{r0}}}$$

FOR TRANSISTORS, SUBSTITUTE  $\beta$  FOR  $\tau_r$

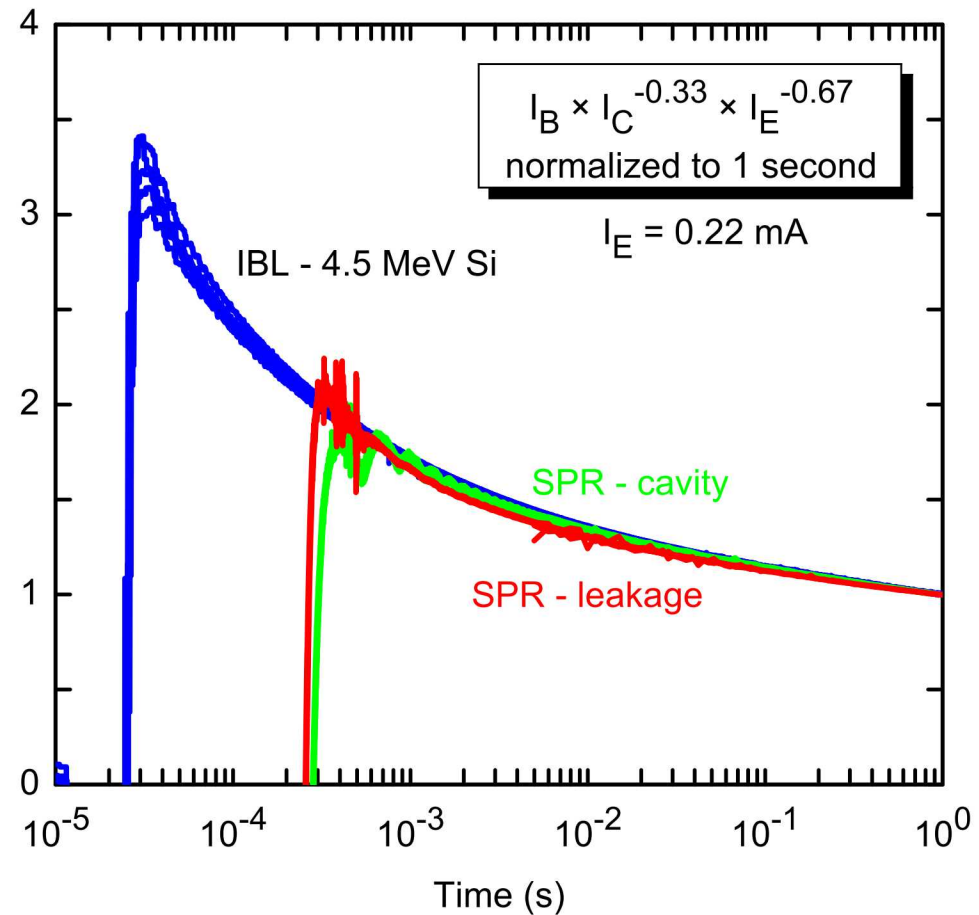
Figure 21: Illustration of the short-term and long-term recovery processes that occur in neutron-irradiated silicon.

# Example of 2N2222 9 mA Anneal



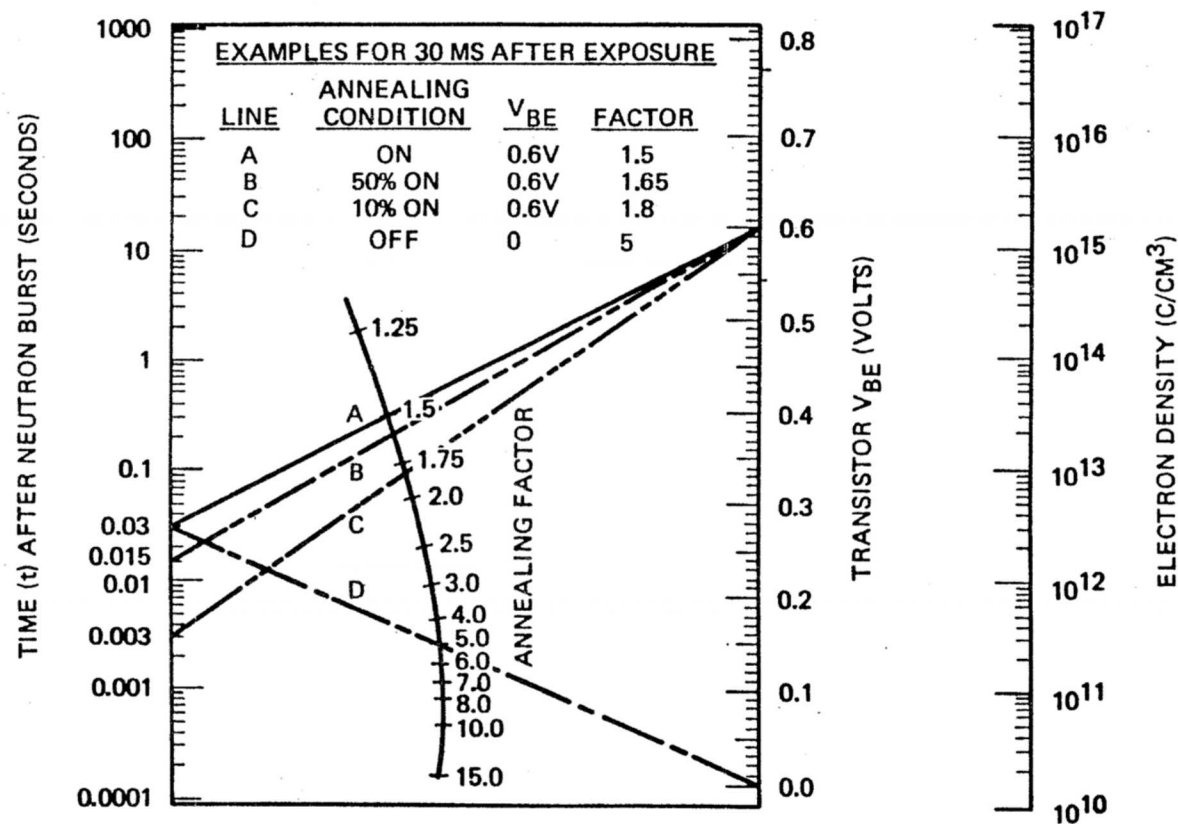
# Silicon annealing function

- SPR and IBL data for Microsemi device
- Normalized transient shape shown to be invariant



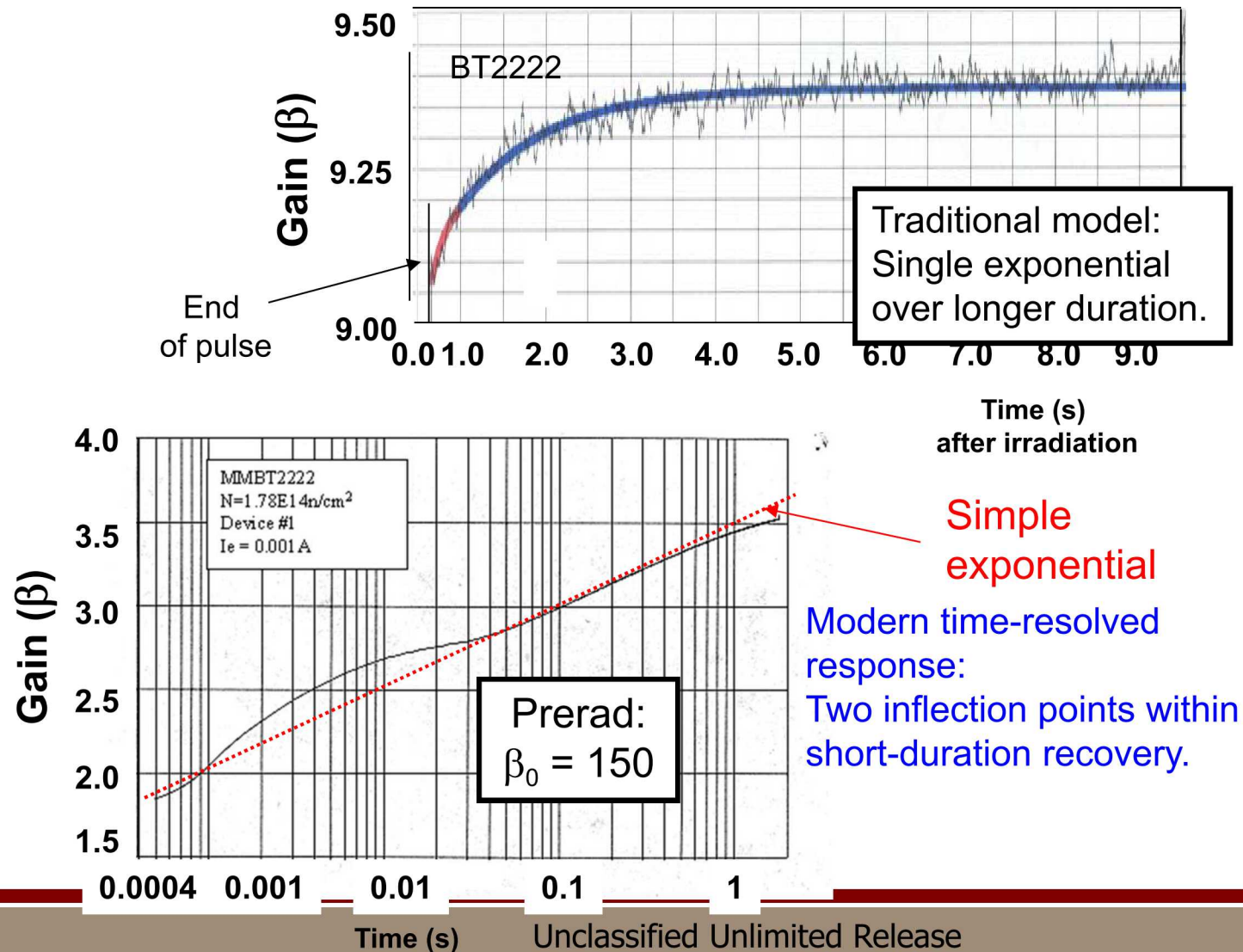
# Nomograph-Based Compact Model

Not developed to predicted early time behavior (<1 ms)



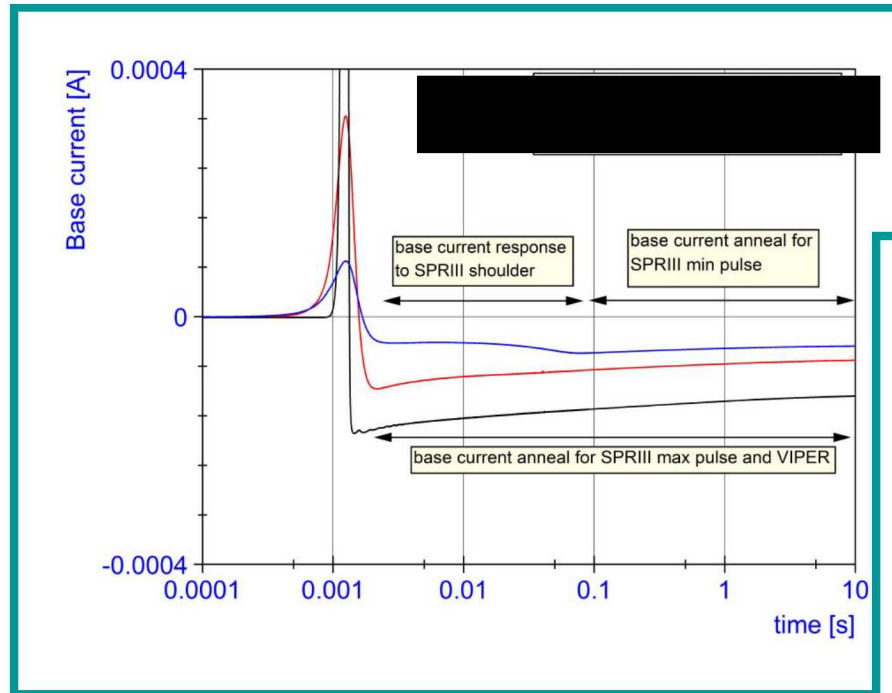


# Early-time Transistor Gain in Radiation Pulse Must be Predictable

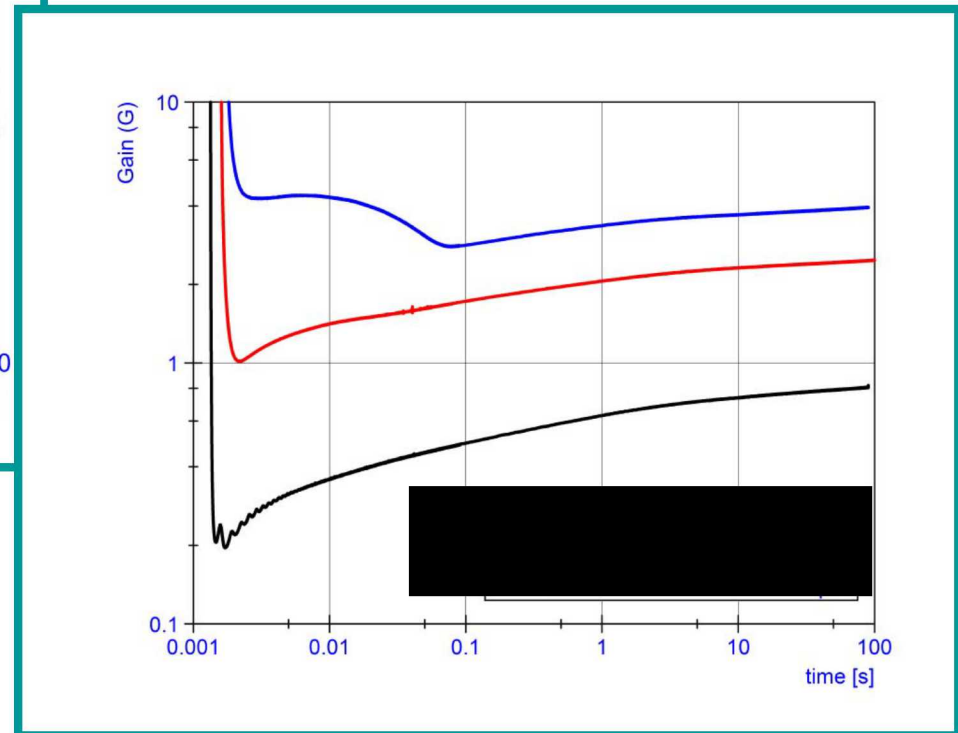


# Transistor Response in SPR-III and Viper

**Enlarged View of transistor gain**



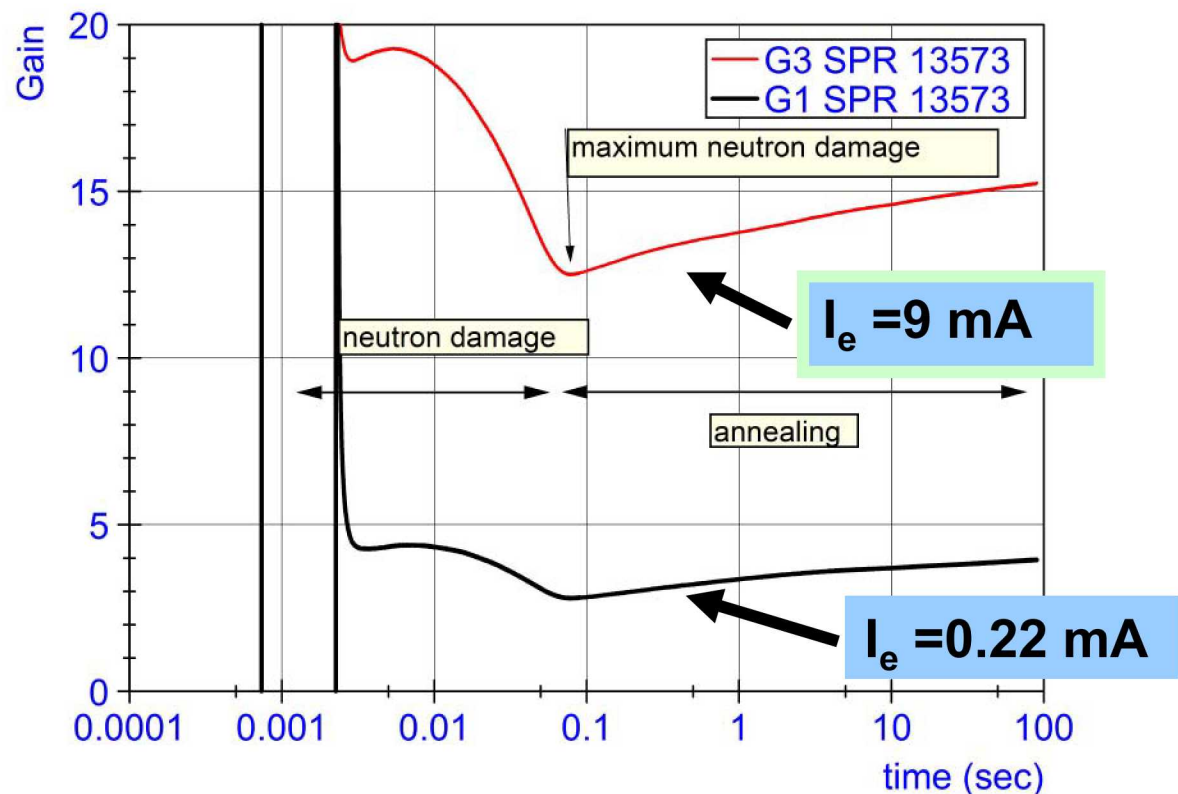
**View of transistor gain**



# Complicated interpretation of measured transistor gain

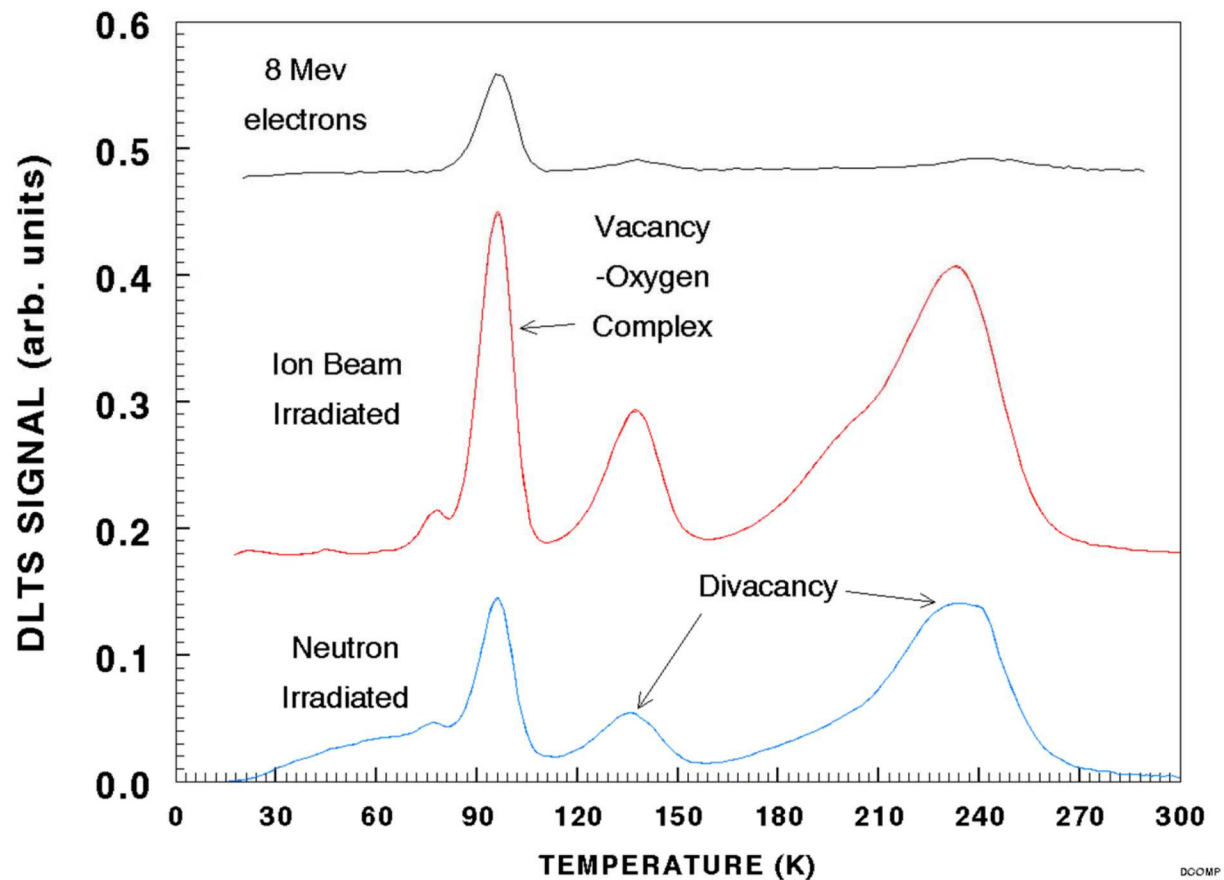
## • Factors:

- ♦ Neutron defects affect gain (▼)
- ♦ Photocurrent affects gain (▲)
- ♦ Photocurrent more pronounced for low current
- ♦ Injection annealing affects gain (▲)
- ♦ Injection annealing more pronounced for high current



80 °C SPR-III Central Cavity

## What does damage equivalence imply?



Data by C. Seager

## True Equivalence Should Require Equal Defect Ratios!

**Hermes electron irradiated (8 MeV, 5-32 cal/cm<sup>2</sup>): ratio = 1:10**

**Divacancies -  $1.4 \times 10^{12} \text{ cm}^{-3}$**

**Vacancy – O pairs -  $1.3 \times 10^{13} \text{ cm}^{-3}$**

**White Sands neutron Irradiated (  $3.6 \times 10^{13} \text{ n/cm}^{-2}$ ): ratio 1:1**

**Divacancies -  $2 \times 10^{13} \text{ cm}^{-3}$**

**Vacancy – O pairs –  $2 \times 10^{13} \text{ cm}^{-3}$**

**Sandia ion Irradiated ( 28 MeV Si 4<sup>+</sup>ions): ratio 1:0.6**

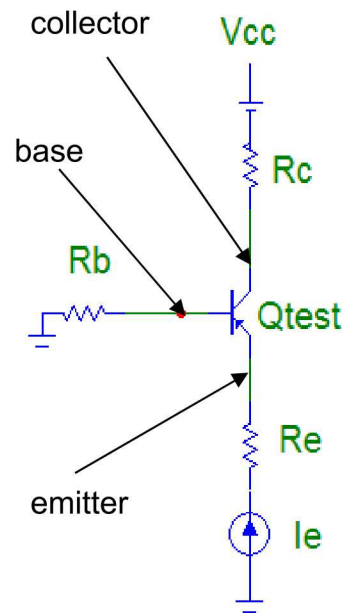
**Divacancies –  $5.1 \times 10^{13} \text{ cm}^{-3}$**

**Vacancy- O pairs –  $5.7 \times 10^{12} \text{ cm}^{-3}$**

**Data by C. Seager**

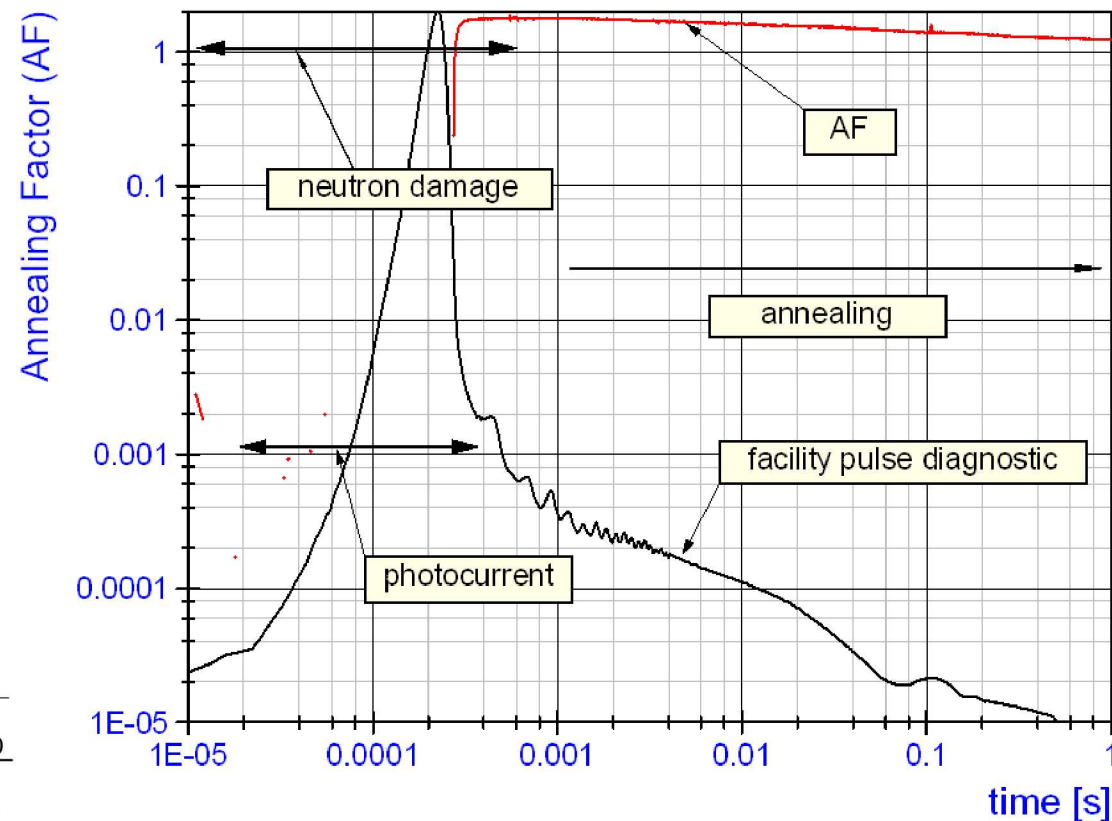


The transistor inverse gain is the metric used for this study

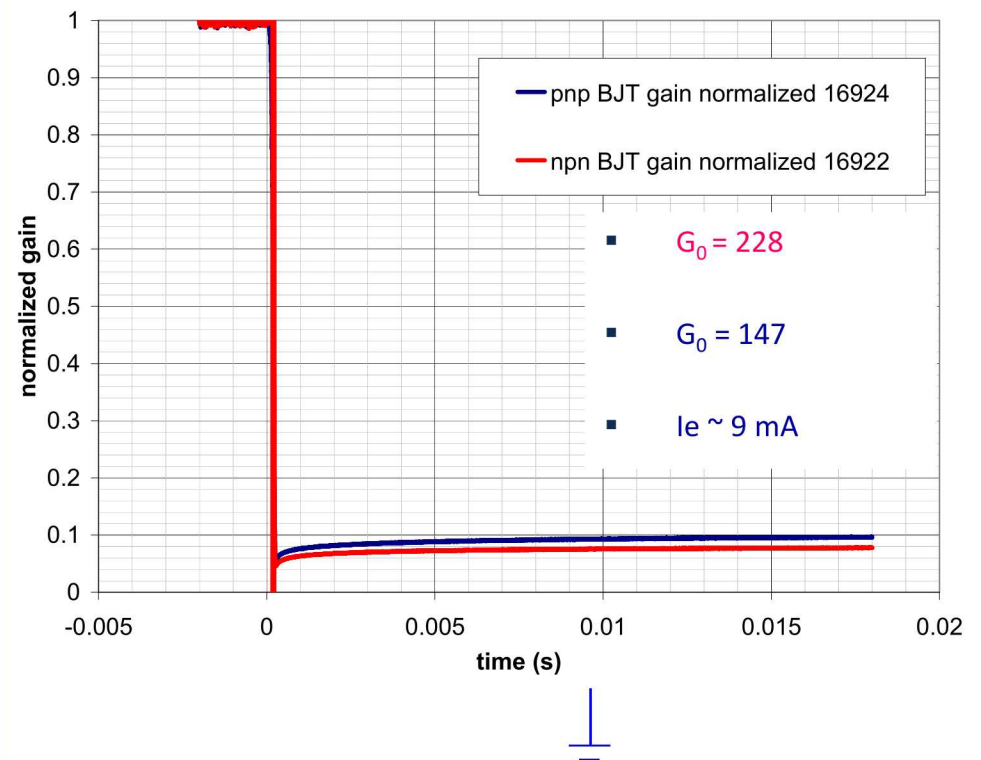
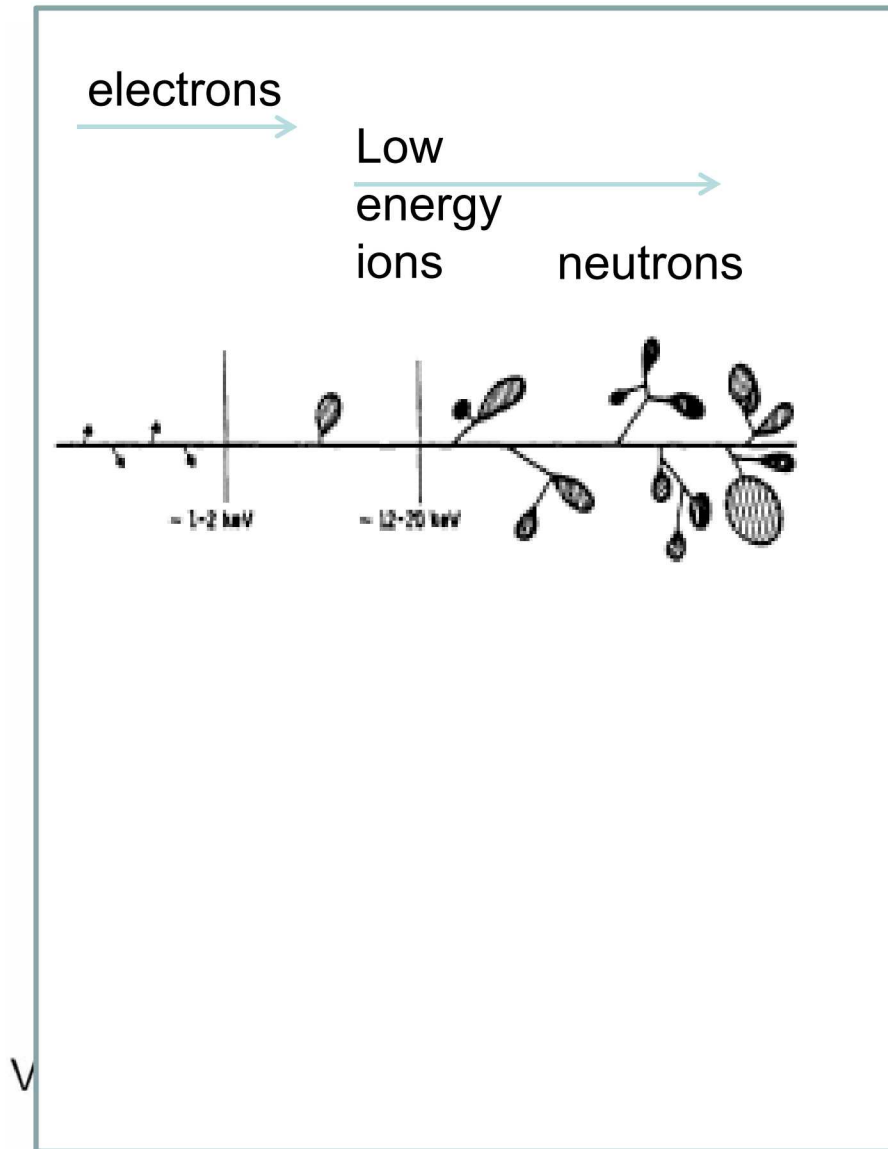


Test circuit uses ASTM  
Standard F 980M-961  
techniques

$$AF(t) = \frac{\frac{1}{G(t)} - \frac{1}{G_0}}{\frac{1}{G_\infty} - \frac{1}{G_0}}$$



# Neutrons create displacement damage in bipolar junction transistors (BJTs)



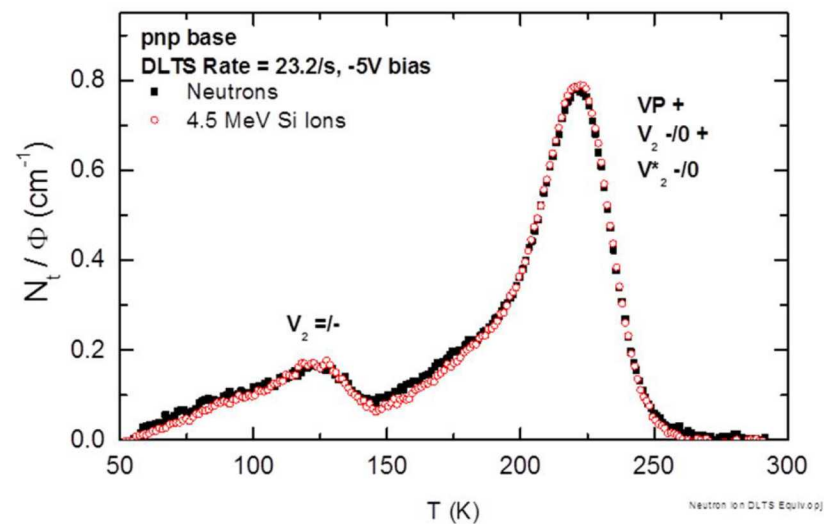
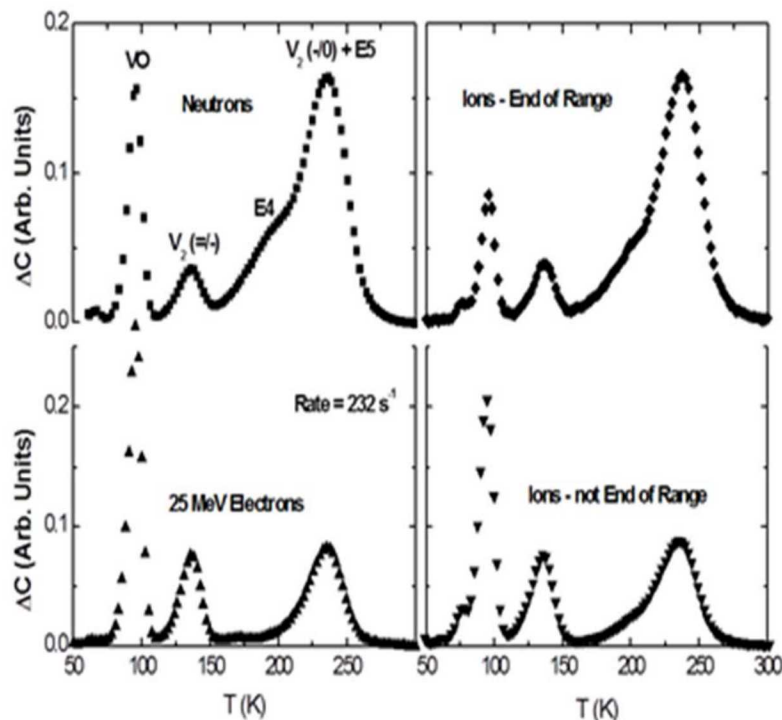
Gain:  $\beta = I_c / I_b$   $\beta$  typically 100 to 300

BJT: a small  $I_b$  controls a large  $I_c \rightarrow$  GAIN

# Displacement Damage in Silicon

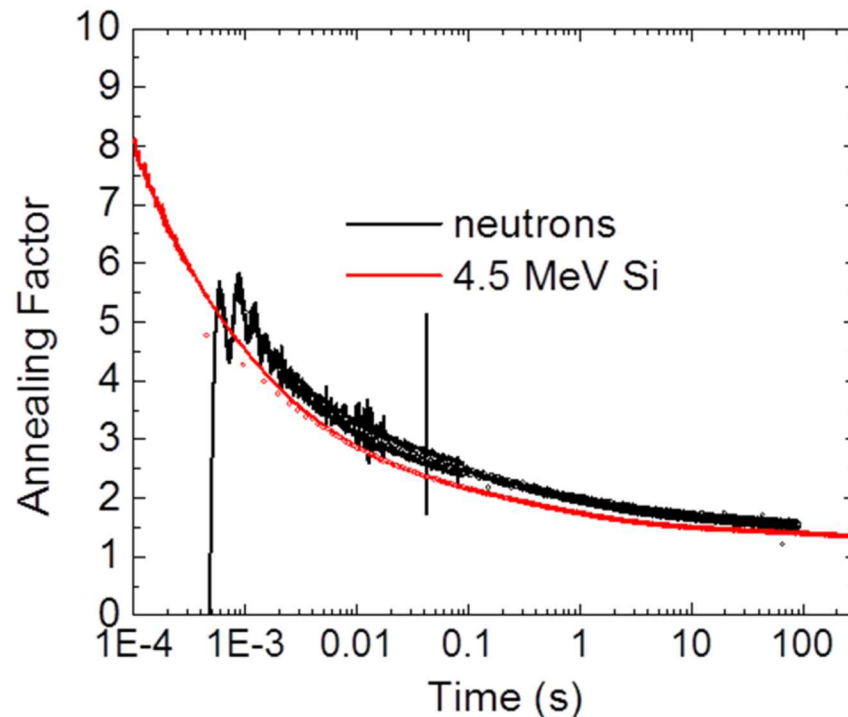
Different types of particles cause different ratios of defect types to be generated. Even different ion energies cause different ratios of defect types.

In silicon, we can select incident ions (type/energy) that duplicate the DLTS defect signature in the base/emitter junction of a device. This ion selection depends upon the packaging over-layers in the device.



## Matching late time gain and defect spectra at FBR and IBL results in agreement of AFs at all test times for Si npn BJTs

FBR  $I_e = 0.22$  mA, 2N2222



Annealing Factor

$$AF(t) = \frac{\frac{1}{G(t)} - \frac{1}{G_0}}{\frac{1}{G_\infty} - \frac{1}{G_0}}$$

$$\delta AF < 5\%$$

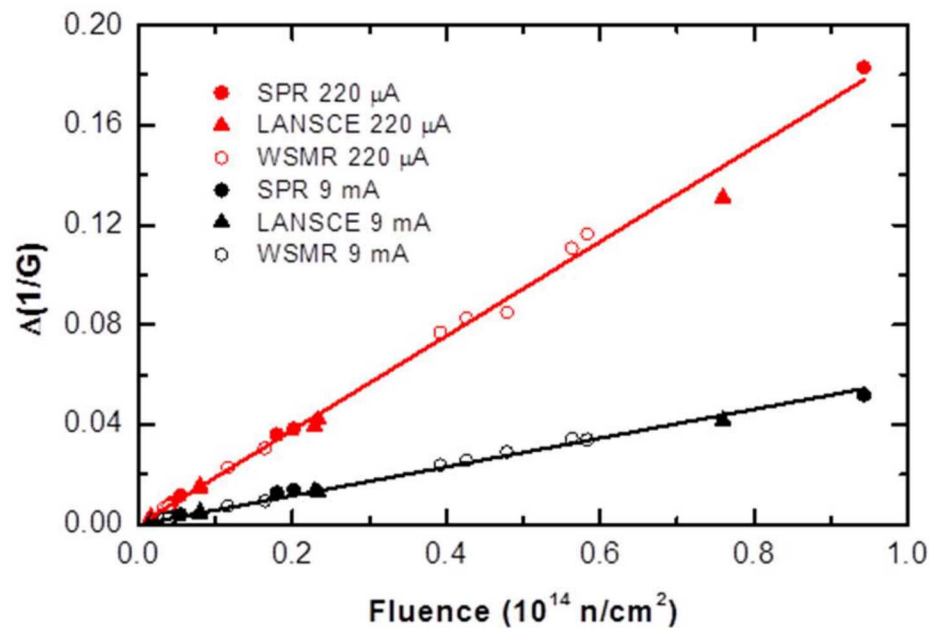
reactor gamma environment delays gain measurement compared to IBL

Agreement between the annealing factors indicates that the annealing kinetics are similar for ion and neutron irradiations – critical for early-time predictive capabilities

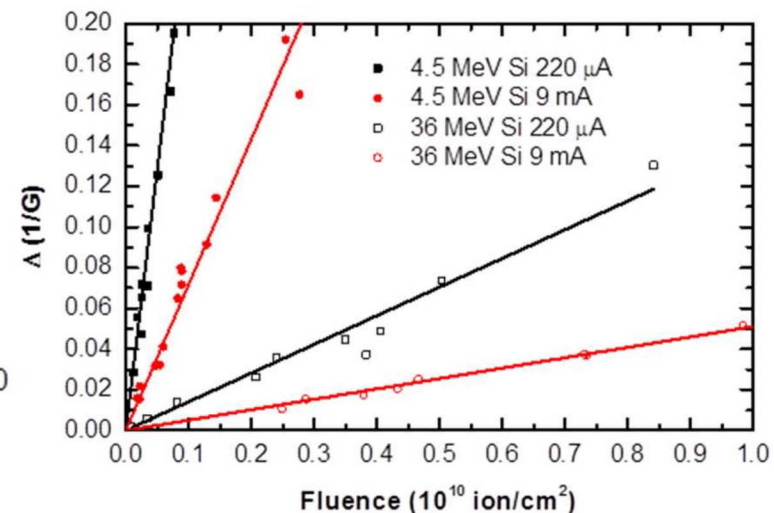
# Displacement Damage in Silicon

The Messenger-Spratt equation states that the change in inverse gain is linearly related to the incident displacement damage.

This relationship has been demonstrated to hold for neutrons and ions. The damage constant depends upon the ion/particle type and energy.

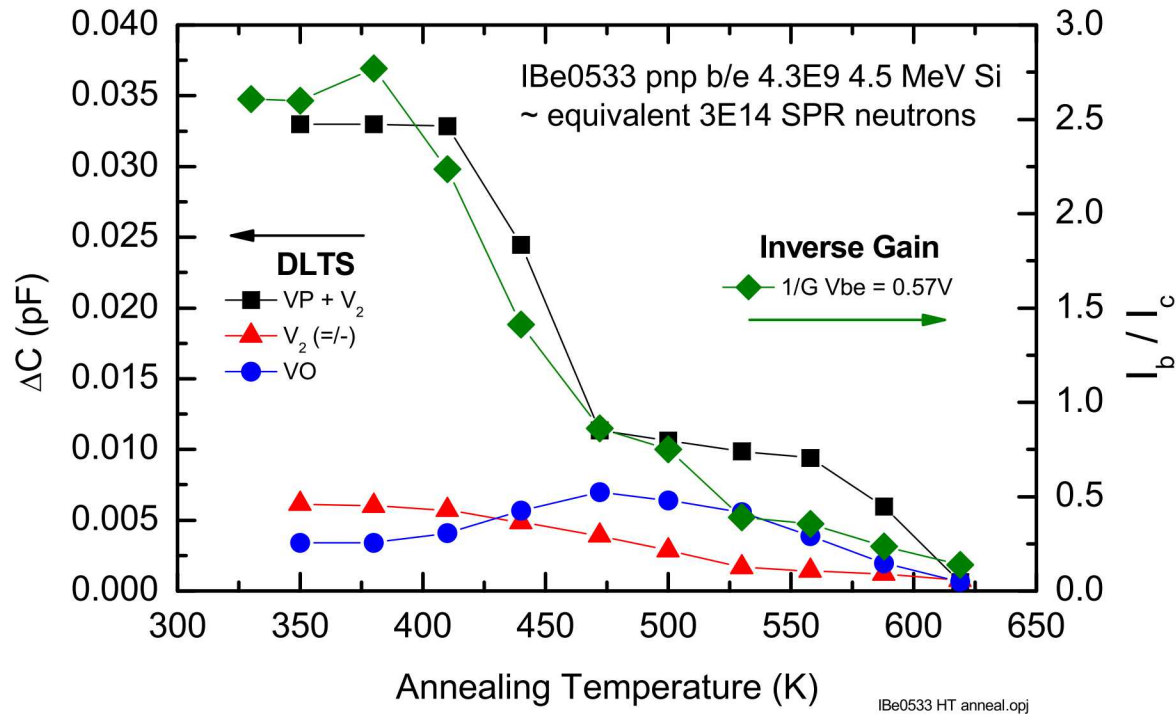


| Si Energy | $k_{\text{ion}}/k_{\text{neutron}}$ |
|-----------|-------------------------------------|
| 4.5 MeV   | 134,000                             |
| 36 MeV    | 7,300                               |

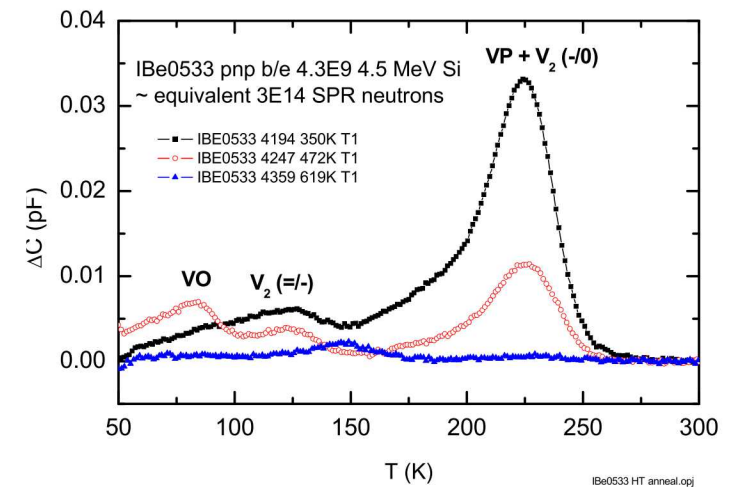




# Annealing studies show the VP+V<sub>2</sub> peak to be the main contributor to gain damage

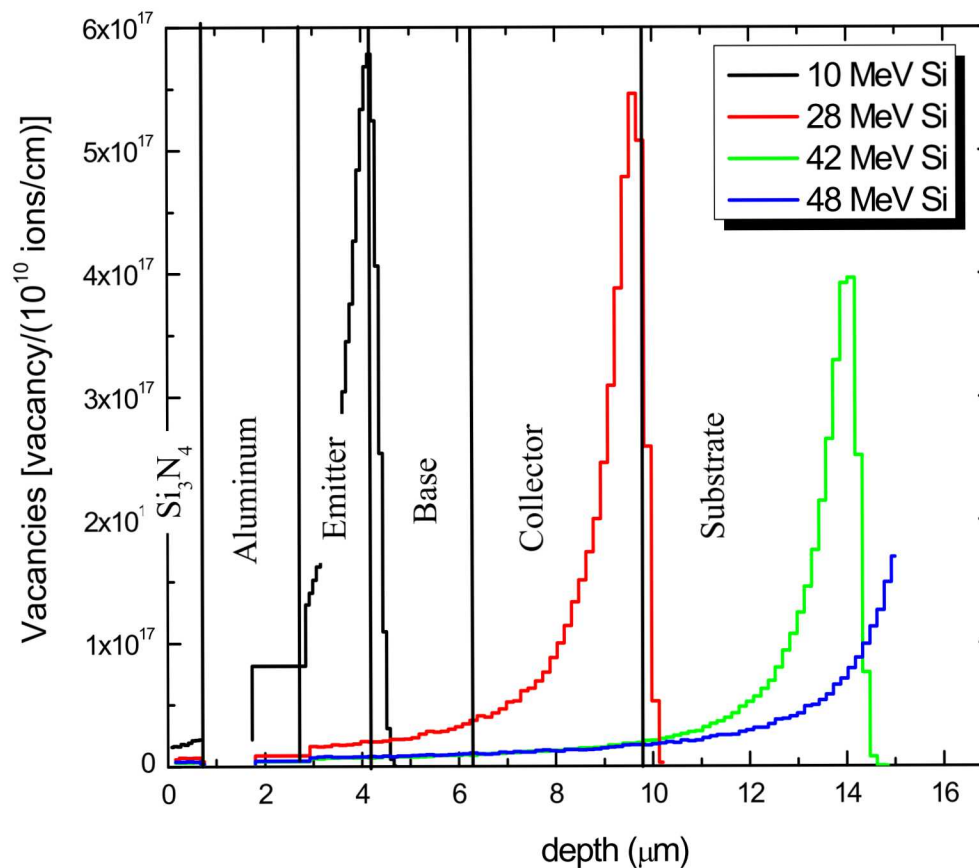


Annealing temperatures agree with literature:  
Kimmerling and Watkins



Annealing above room temperature improves gain by annealing the VP defect

The combination of thick metal and thin features homogenizes frenkel pair production – EOR does not exist in HBTs



- III-V technology has interesting implications for IBL tests
- EOR has different meaning for HBTs, DLTS diode, PL samples
- Modeling correlation gives us a consistent comparison in test devices

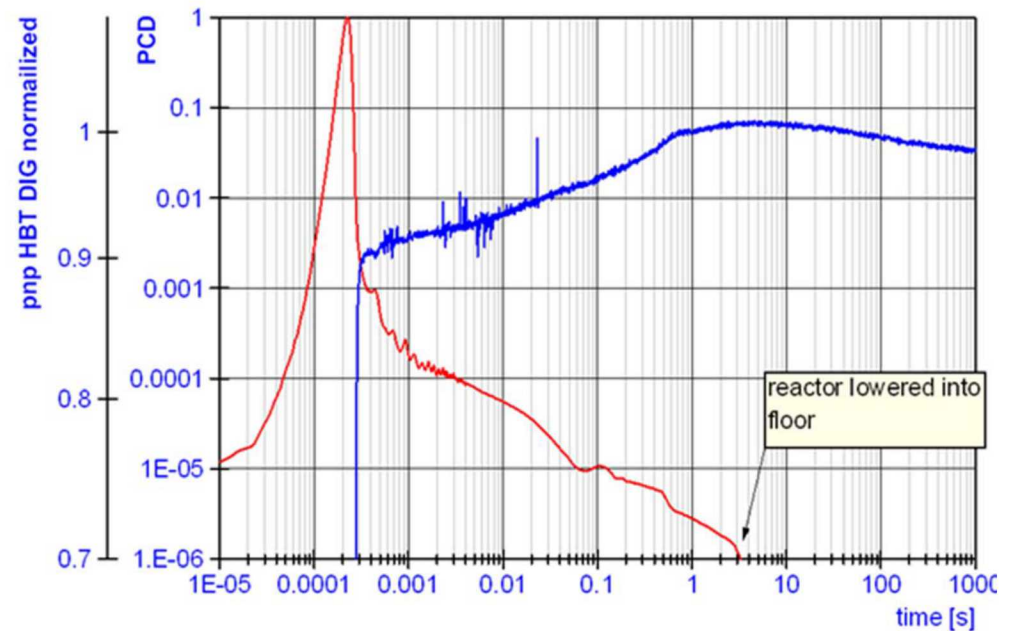
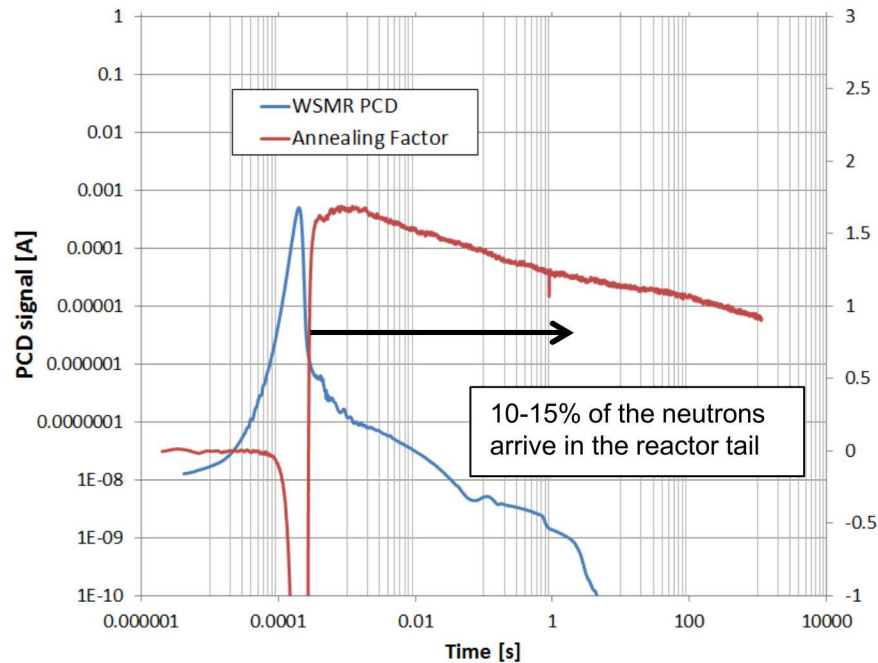
# TOPIC:

## DEFECT ANNEALING IN GAAS

We are also interested in defect annealing in III-V semiconductor materials, e.g. GaAs, InP, GaN. Here the issues can be different than what was seen for silicon.

We are interested in performing a Total Monte Carlo analysis of the uncertainty in the displacement kerma for GaAs.

# Reactor environments obscure early-time operation of HBTs



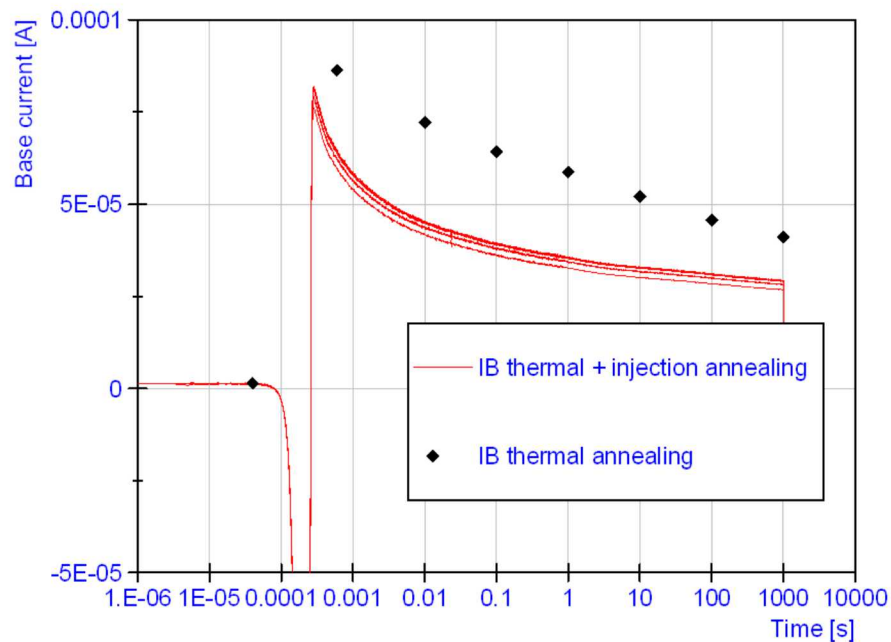
$$AF(t) = \frac{\frac{1}{G(t)} - \frac{1}{G_0}}{\frac{1}{G_\infty} - \frac{1}{G_0}}$$

- Late-time neutrons dramatically affect HBT annealing
- Annealing discovery tests with HBTs reveal test methods to compensate for late time neutrons and photocurrent effects

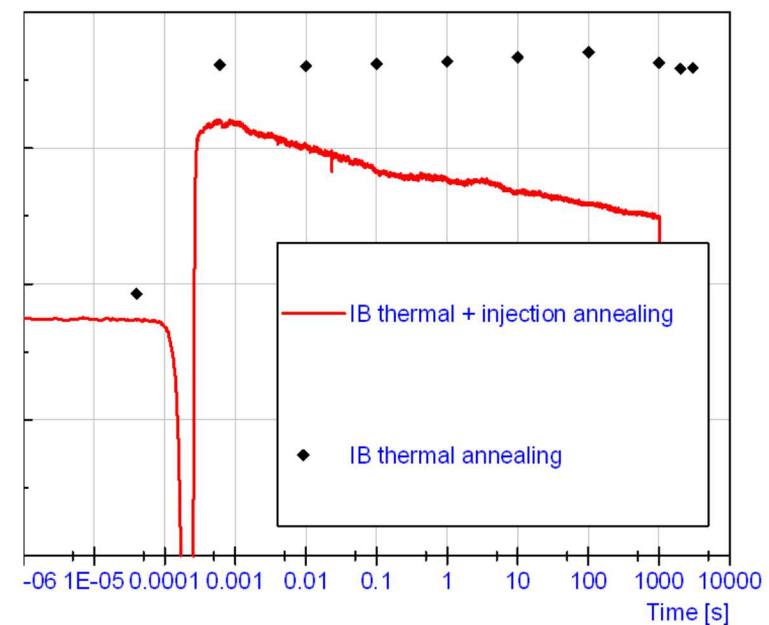
# npn HBTs exhibit only injection annealing – no thermal annealing is measured

## WSMR FBR

npn Si BJT,  $I_E = 0.22$  mA



npn HBT,  $I_E = 0.22$  mA

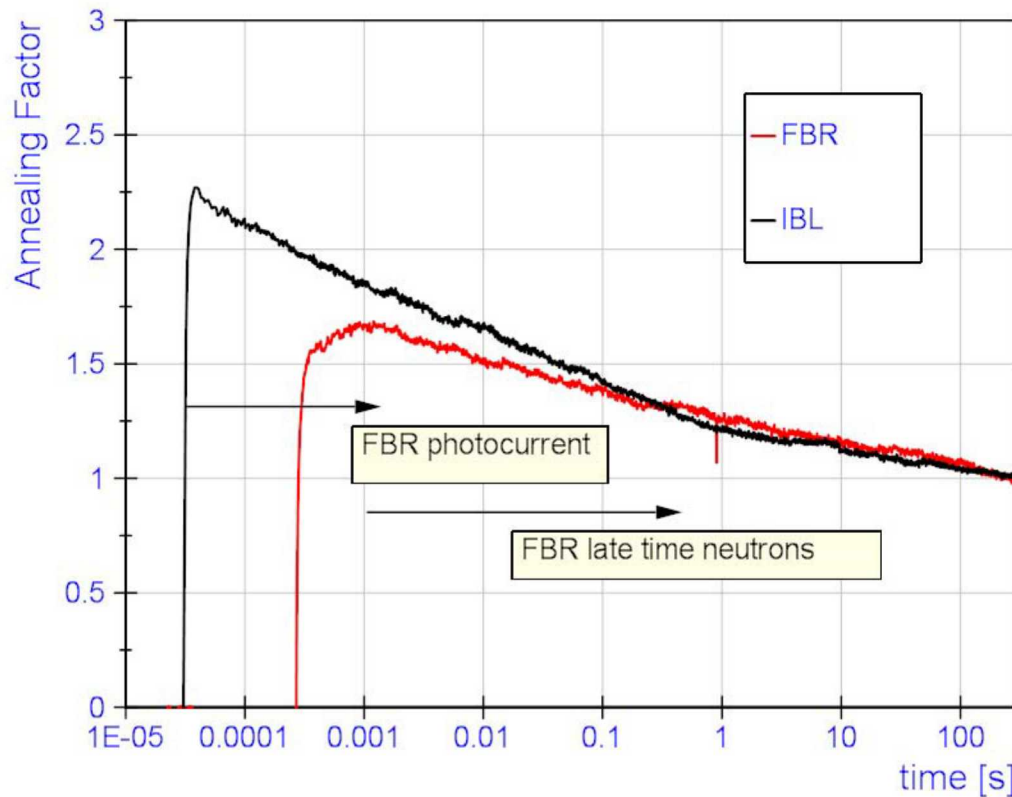


**This lack of thermal annealing allows us to compensate reactor facility shortcomings: early time gamma dose rate and late time neutrons**



# Equivalent damage is demonstrated between IBL and FBR for Npn HBTs using late-and early-time gain metrics

Npn HBT, IE = 0.22 mA



$$\left( \Delta \frac{1}{G} \right) = \frac{1}{G_{\infty}} - \frac{1}{G_0} = k\Phi$$

7.5 MeV Si:  $k_{Si} = 4.91E-11$

Neutron:  $k_n = 1.05E-16$

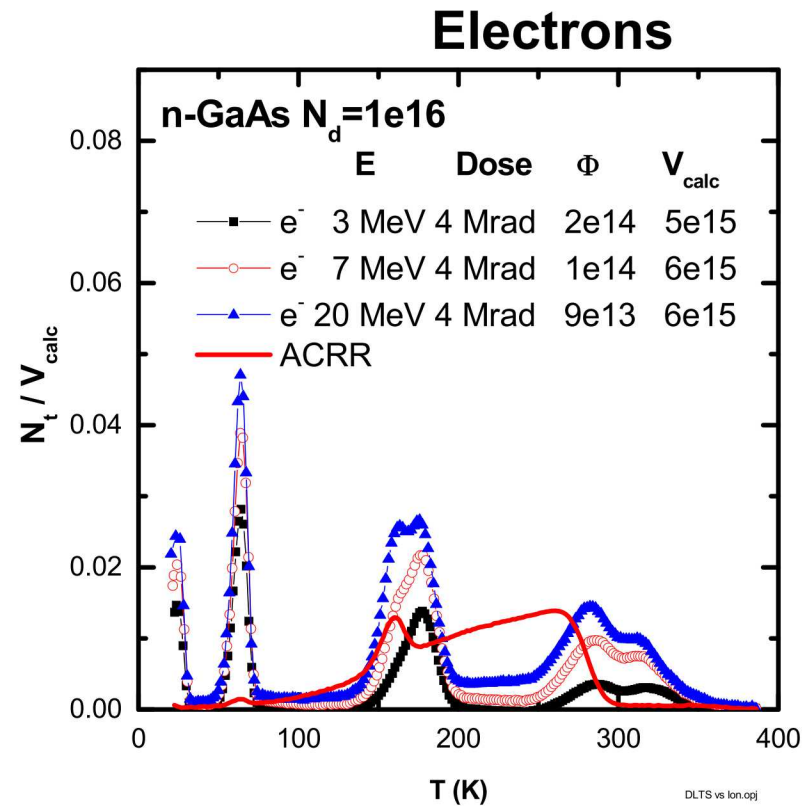
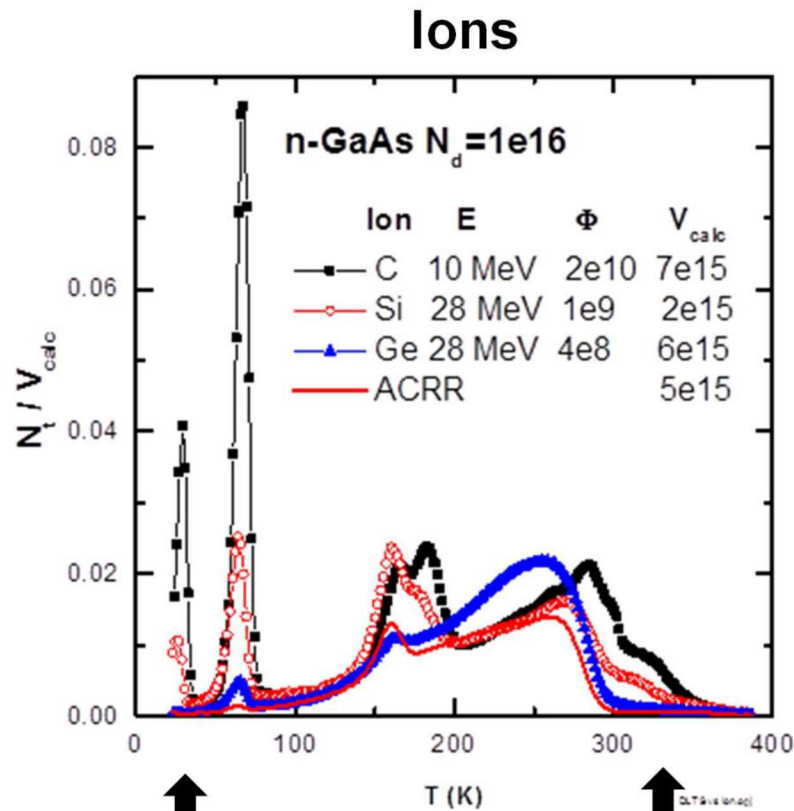
$k_{Si}/k_n = 4.7E5$

For 7.5 MeV Si,  $5E13 \text{ n/cm}^2 \sim 1.1E8 \text{ Si/cm}^2$

$$AF(t) = \frac{\frac{1}{G(t)} - \frac{1}{G_0}}{\frac{1}{G_{\infty}} - \frac{1}{G_0}}$$

- FBR gamma and late time neutron prevent match until 0.1 s
- Matching of annealing factors after 0.1 s indicates that defect annealing kinetics are similar

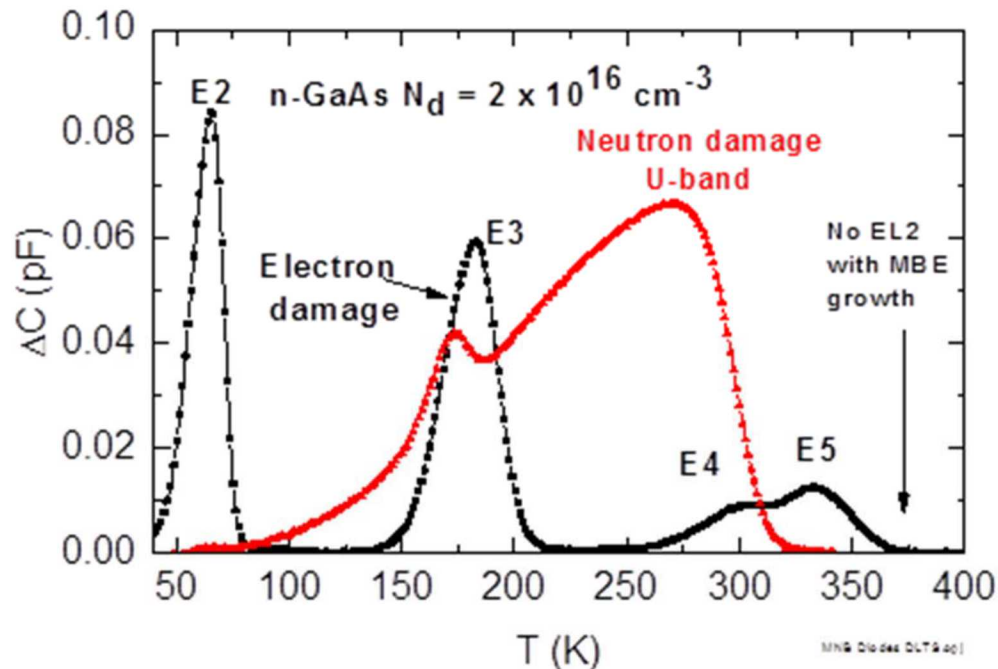
# Ions and electrons can produce spectra characteristics between point and Uband



HT roll-off decreases with clustering (BG narrowing & PAT)

Shallow peaks sensitive to the degree of clustering (charging & PAT)

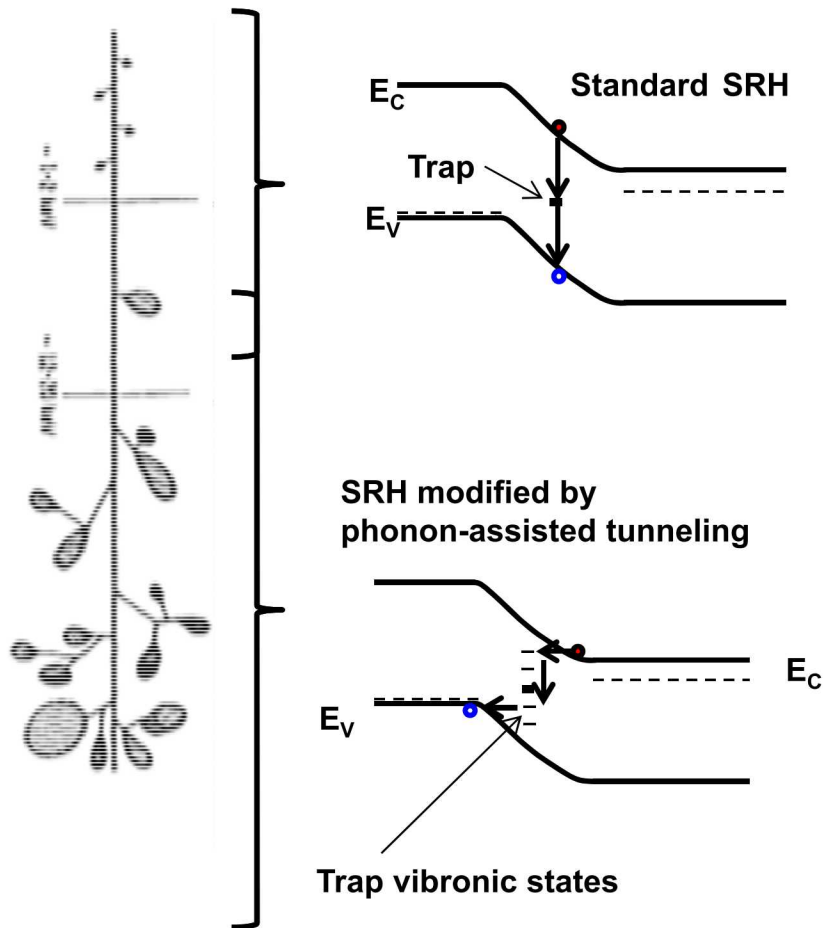
## DLTS in GaAs : Analysis is more complex



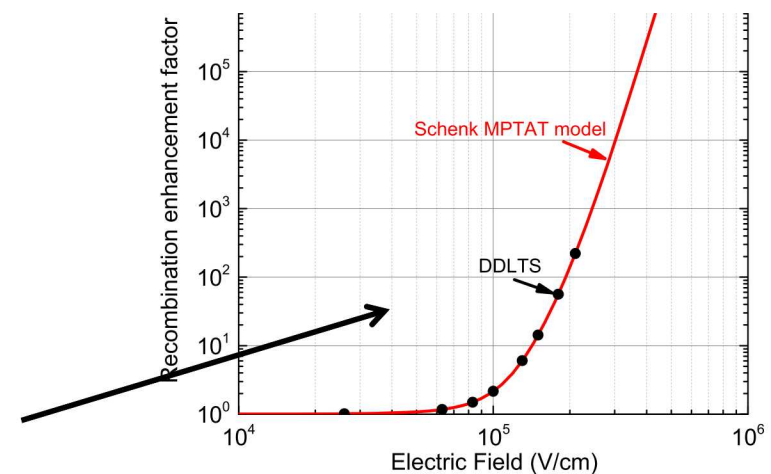
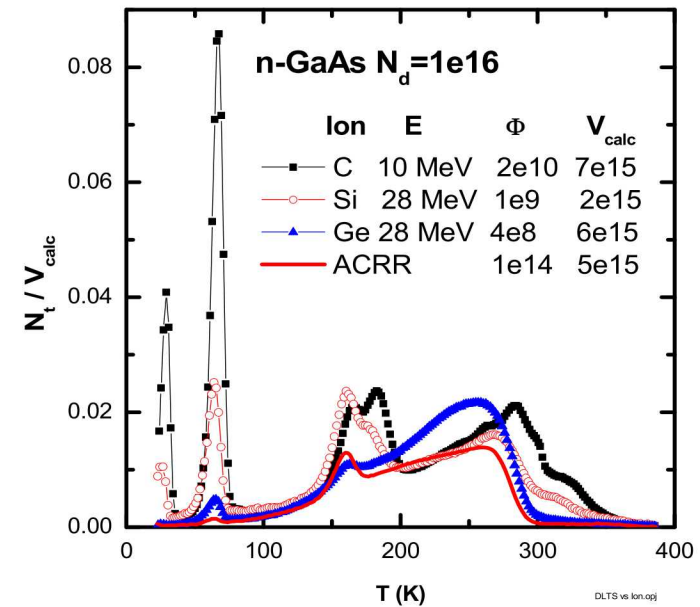
- neutron spectra is radically different from electron damage.
- The broad features after neutron/ion damage are known as the “U-band” (n-GaAs) and the “L-band” (p-GaAs)

|                                                                           | Silicon                                     | GaAs                                                                                   |
|---------------------------------------------------------------------------|---------------------------------------------|----------------------------------------------------------------------------------------|
| Defect library from prior work                                            | Extensive (from EPR/DLTS)                   | Minimal (EPR not effective)                                                            |
| Additional defect species in clusters                                     | A few, e.g. bistable $V_2$ , strained $V_2$ | Unknown at present, work in progress                                                   |
| Electric-field enhanced emission from defects (phonon assisted tunneling) | Minimal                                     | Extensive – Contributes to broad DLTS features after clustered damage (U-band, L-band) |

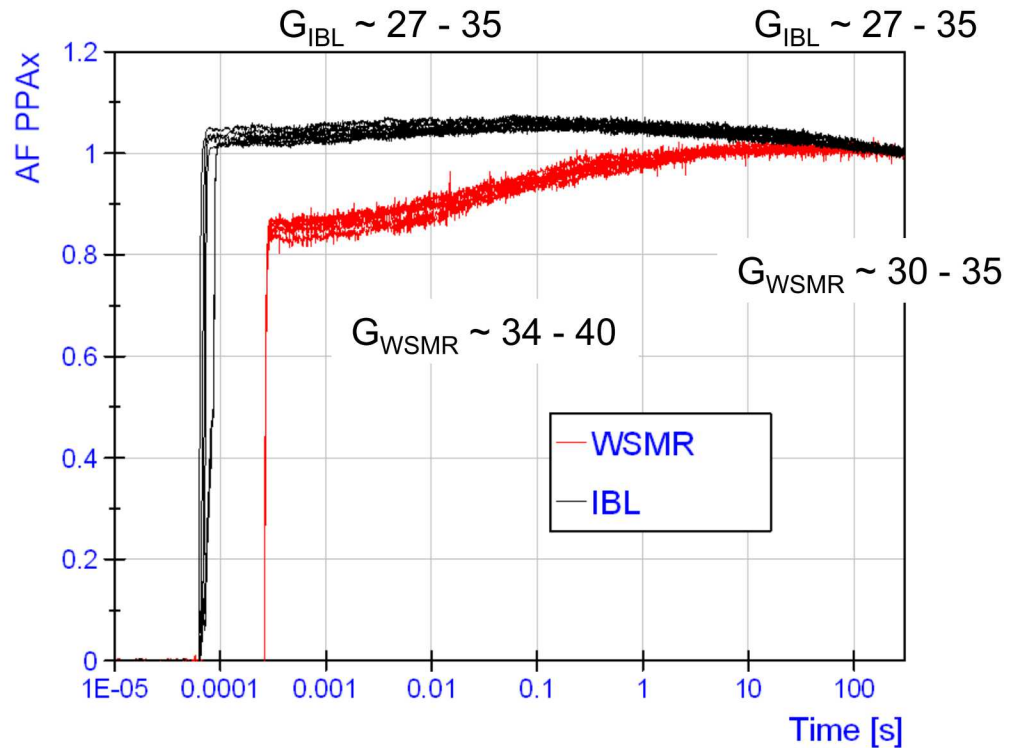
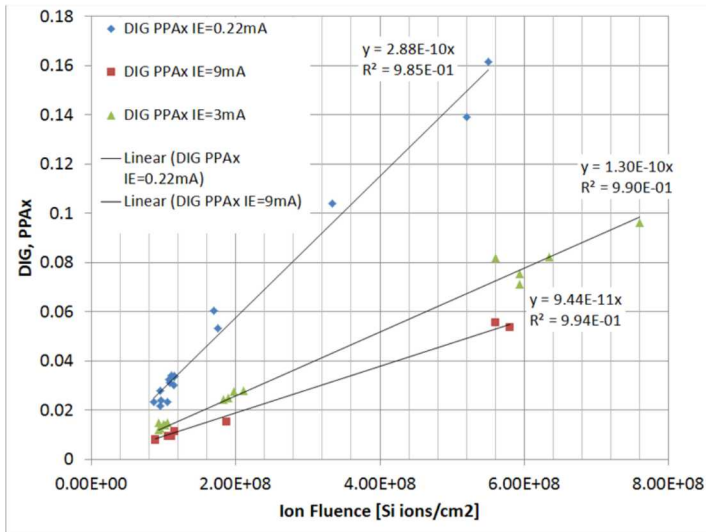
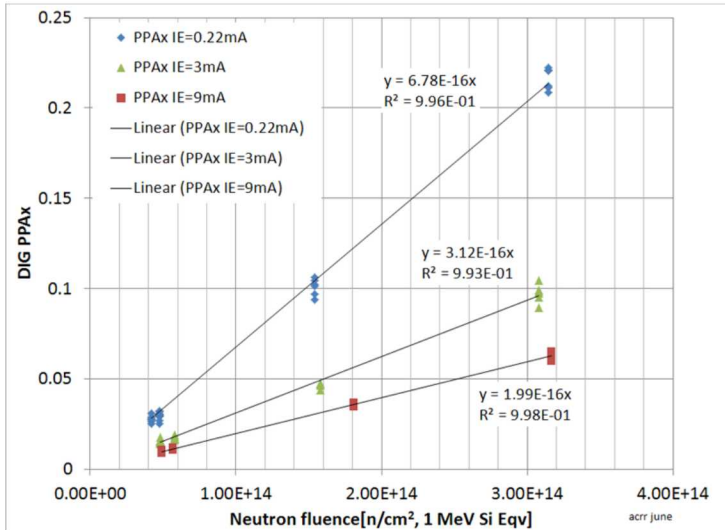
**Lack of an experimental structural tool in GaAs (minimal information with EPR) requires development of theoretical tools (e.g. DFT) to calculate defect structures.**



## DLTS assists modeling of enhanced recombination in clusters



# Equivalent late-time damage is demonstrated between IBL and WSMR For FY12 25x85 PnP HBTs

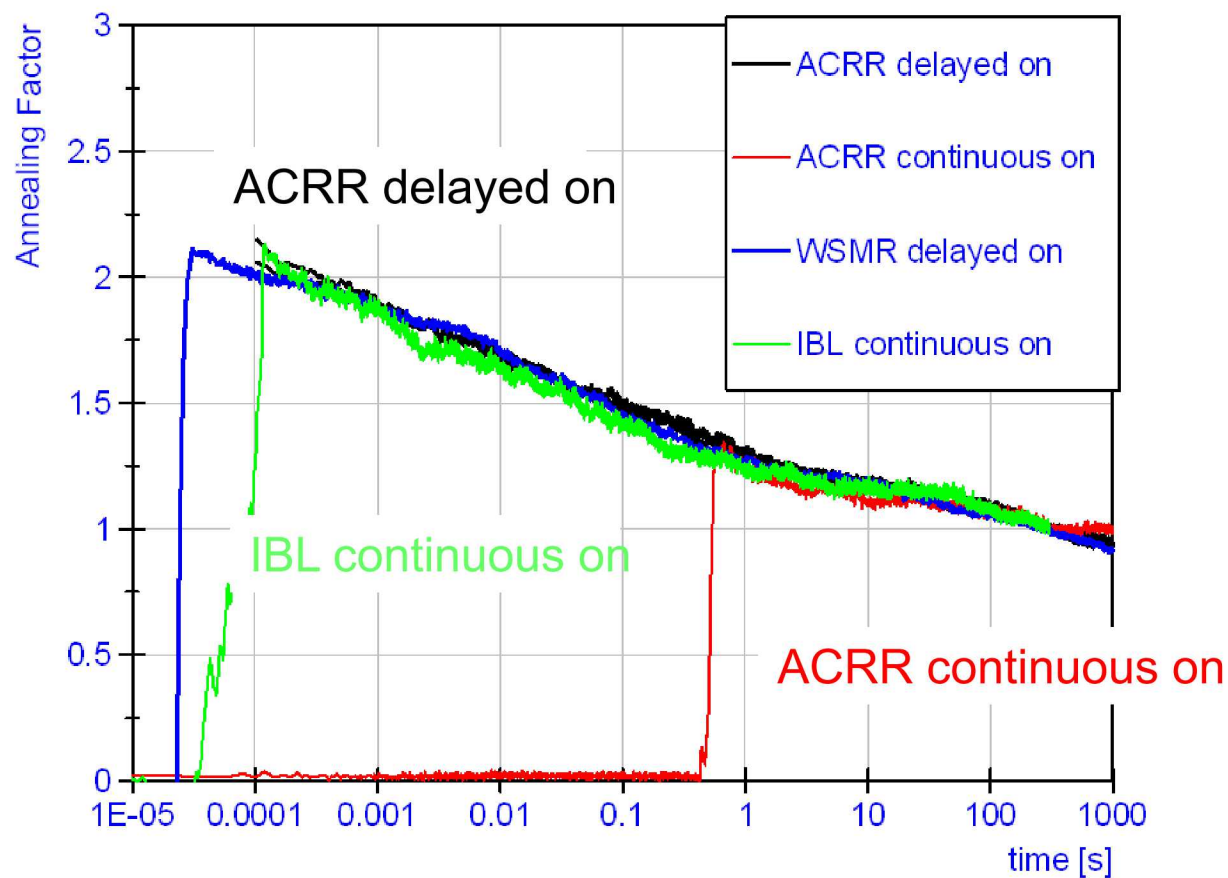


- IBL gain continues to degrade through 0.2 s
- Late time neutrons force gain to degrade
- IE = 0.22 mA
- 8.5 MeV Si ions
- WSMR: 5E13 n/cm<sup>2</sup>
- $k_{ion}/k_n = 4.2E5$
- $G_0 \sim 220 - 250$



## Delayed turn on techniques allow early-time displacement damage annealing tests to be completed at ACRR and WSMR

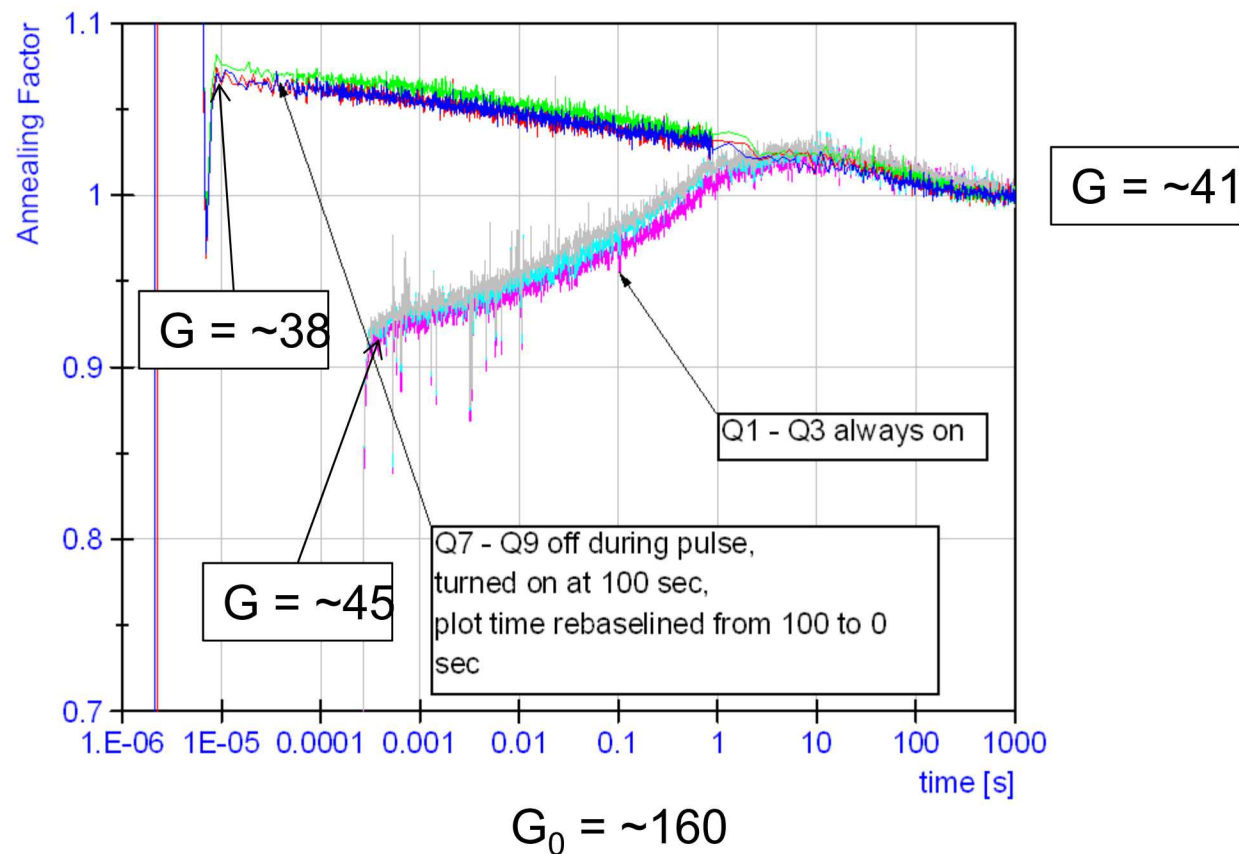
Npn HBT, IE = 0.22 mA, all shots 5E13 n/cm<sup>2</sup> 1 MeV Si Eqv



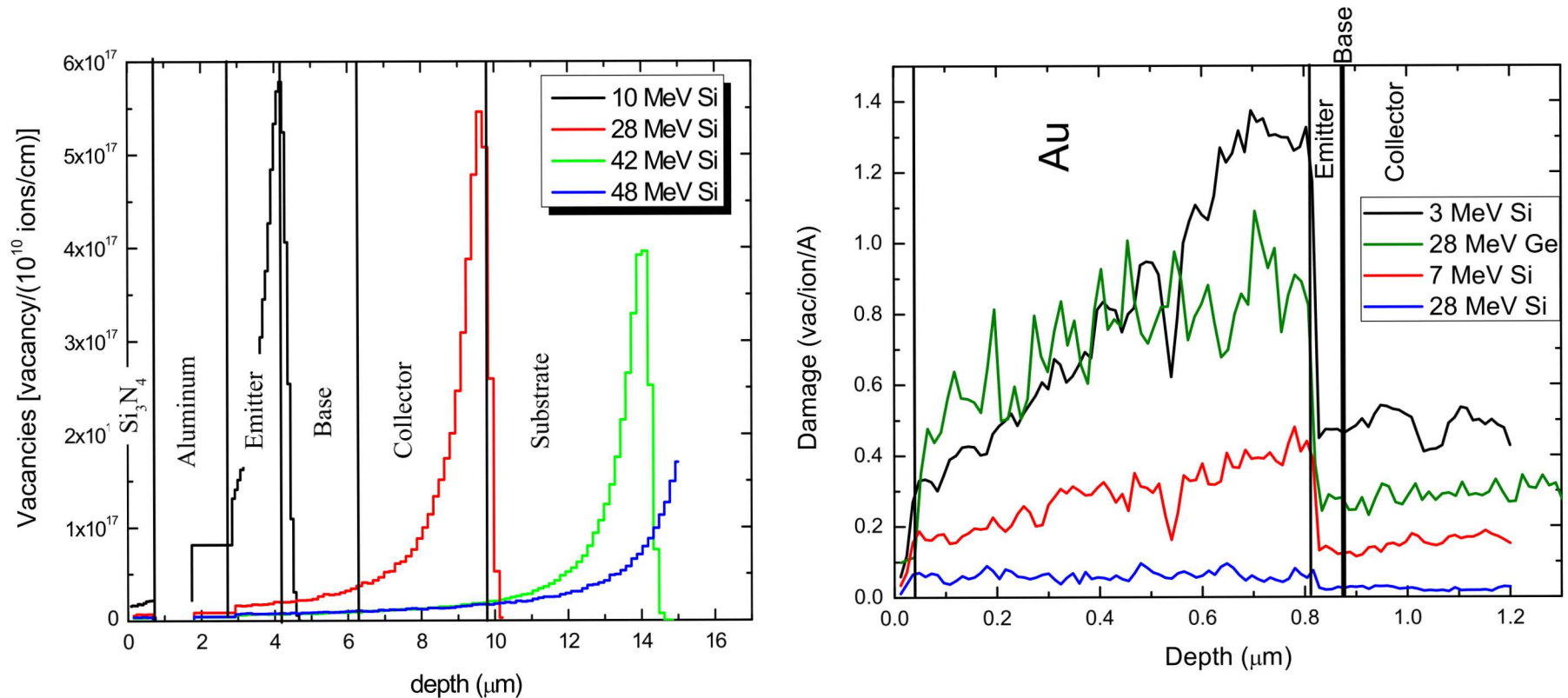
# pn<sub>p</sub> HBT delayed turn on allows observation of early time anneal

## at facilities with late neutrons

pn<sub>p</sub> HBT, IE = 1mA, WSMR shot, 5E13 n/cm<sup>2</sup>



# The combination of thick metal and thin features homogenizes Frenkel pair production – EOR does not exist in HBTs

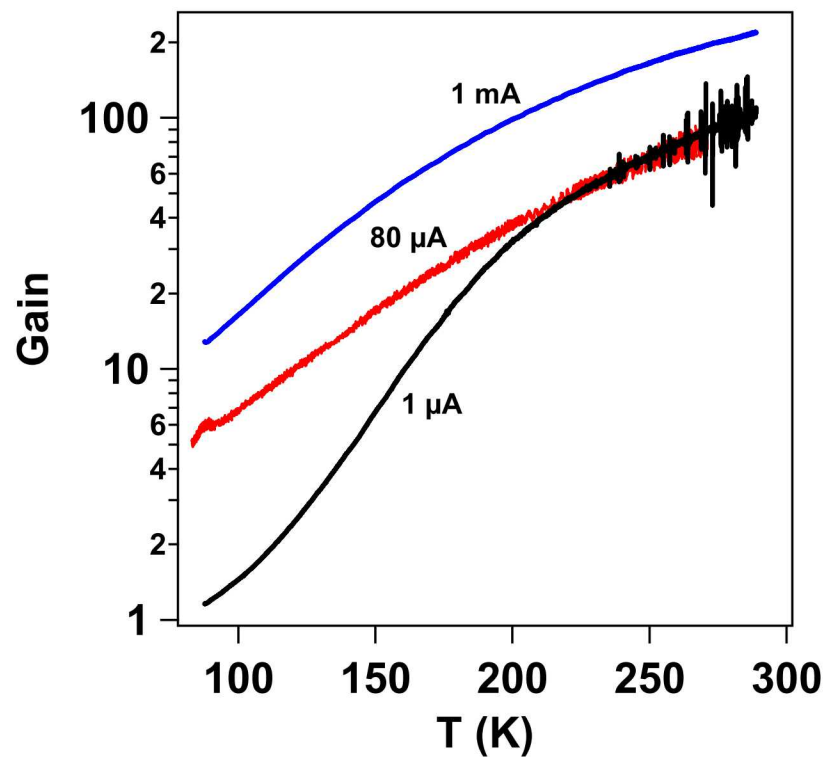


- III-V technology has interesting implications for IBL tests
- EOR has different meaning for HBTs, DLTS diode, PL samples
- Modeling correlation gives us a consistent comparison in test devices

# **TOPIC: TEMPERATURE-DEPENDENT ANNEAL OF DAMAGE IN SILICON**

The investigation of device gain under different temperatures during irradiation and annealing stages offers a unique opportunity to validate our calculated models.

## Effect of Temperature on Gain

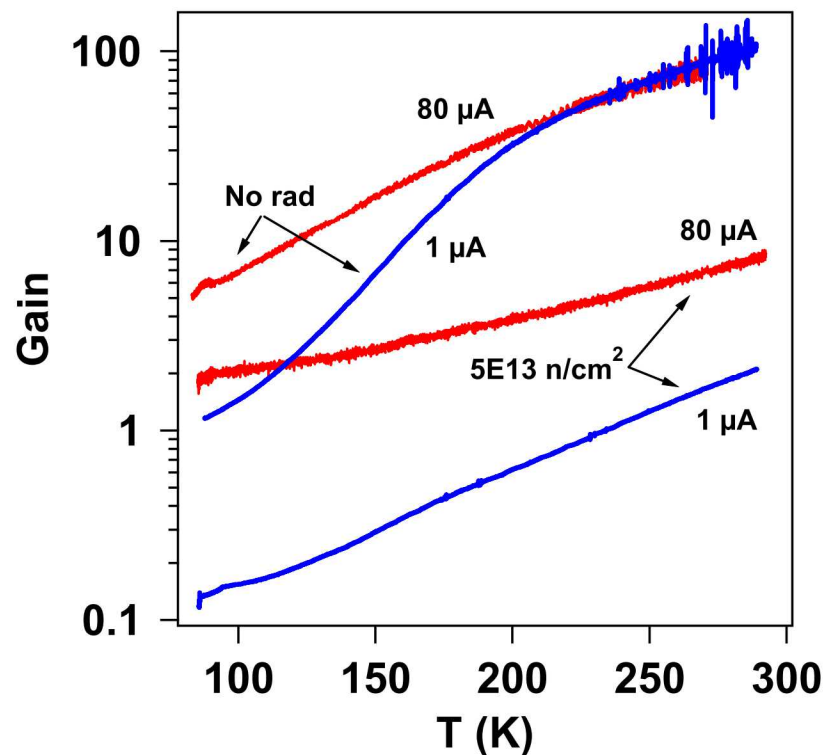


- 2N2222
- $I_E = 1 \mu\text{A}$ ,  $80 \mu\text{A}$ , and  $1 \text{ mA}$
- Cooled to 85 K
- Heated to RT (shown)
- NO radiation

► Temperature significantly affects gain



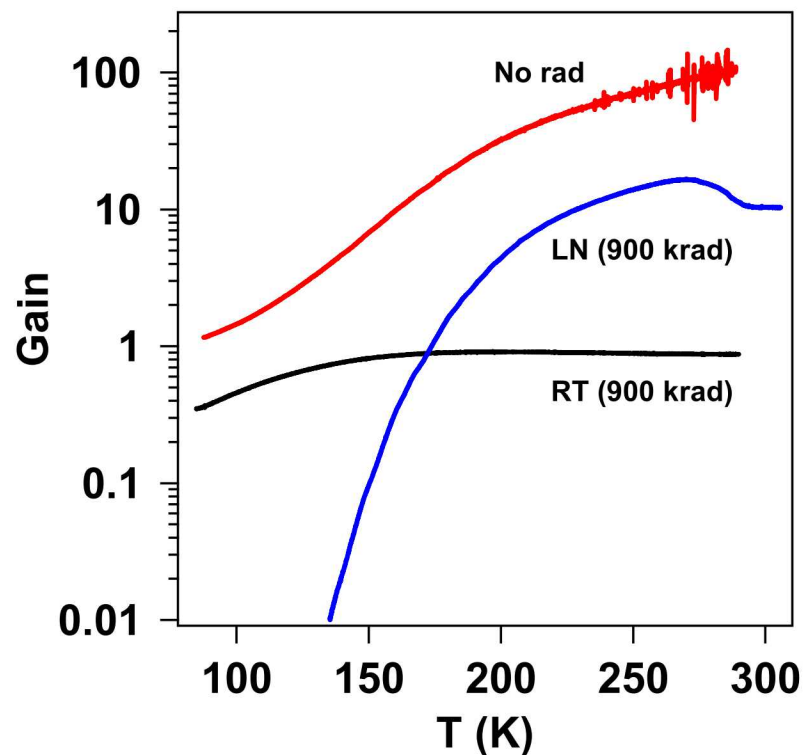
## Effect of Irradiation at 85 K (Neutrons)



- 2N2222
- $I_E = 1 \mu\text{A}$  and  $80 \mu\text{A}$
- Cooled to 85 K
- Irradiated
  - $5\text{E}13 \text{ n/cm}^2$
- Heated to RT (shown)

► Gain degradation observed at all temperatures

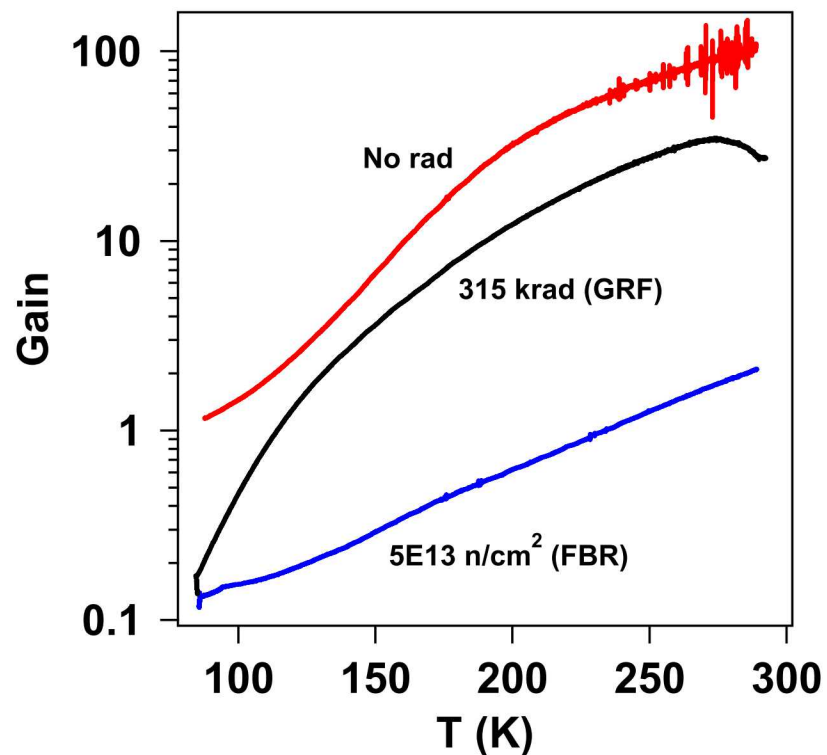
## Effect of Temperature on Radiation Response (Gammas)



- 2N2222
- $I_E = 1 \mu\text{A}$
- Irradiated at RT
  - 900 krad
- Cooled to 85 K
- Heated to RT (shown)

► Large differences observed between RT and LN irradiation

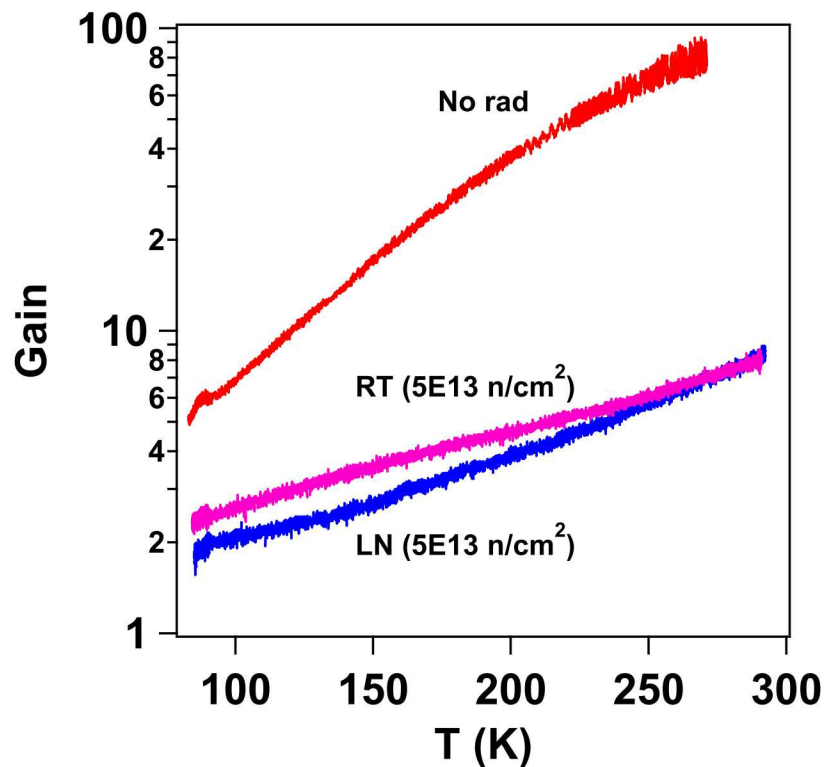
## Comparison of Neutron and Gamma Effects at 85 K



- 2N2222
- $I_E = 1 \mu A$
- Cooled to 85 K
- Irradiated
  - 5E13 n/cm<sup>2</sup> (FBR)
  - 315 krad (GRF)
- Heated to RT (shown)

► Differences observed between neutrons and gammas

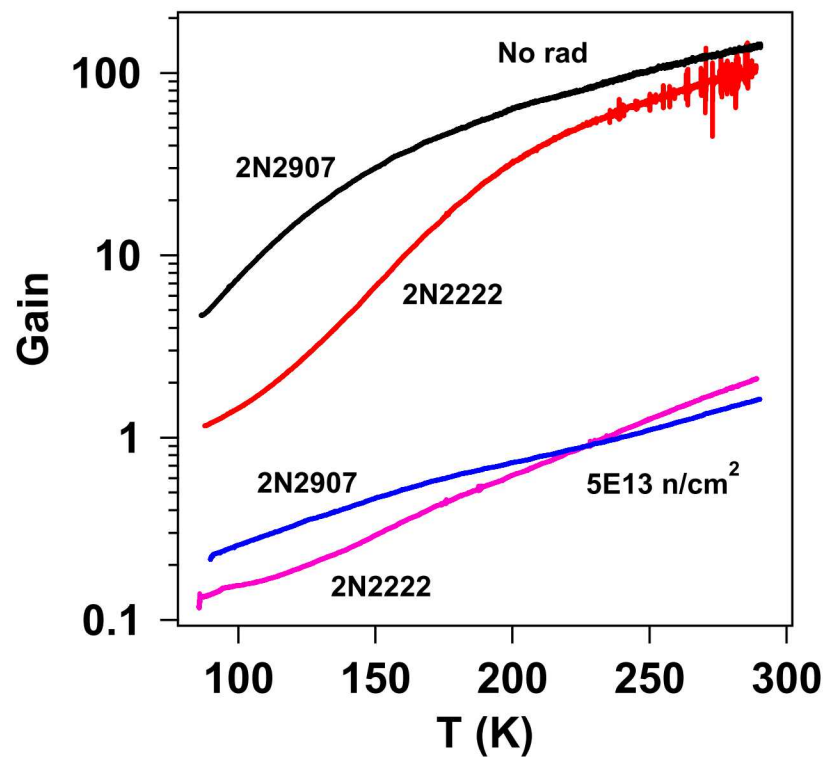
## Effect of Temperature on Radiation Response (Neutrons)



- 2N2222
- $I_E = 80 \mu\text{A}$
- Irradiated at RT
  - 5E13 n/cm<sup>2</sup>
- Cooled to 85 K
- Heated to RT (shown)

► Small differences observed between RT and LN irradiation

## 2N2222 vs 2N2907 (Neutrons)

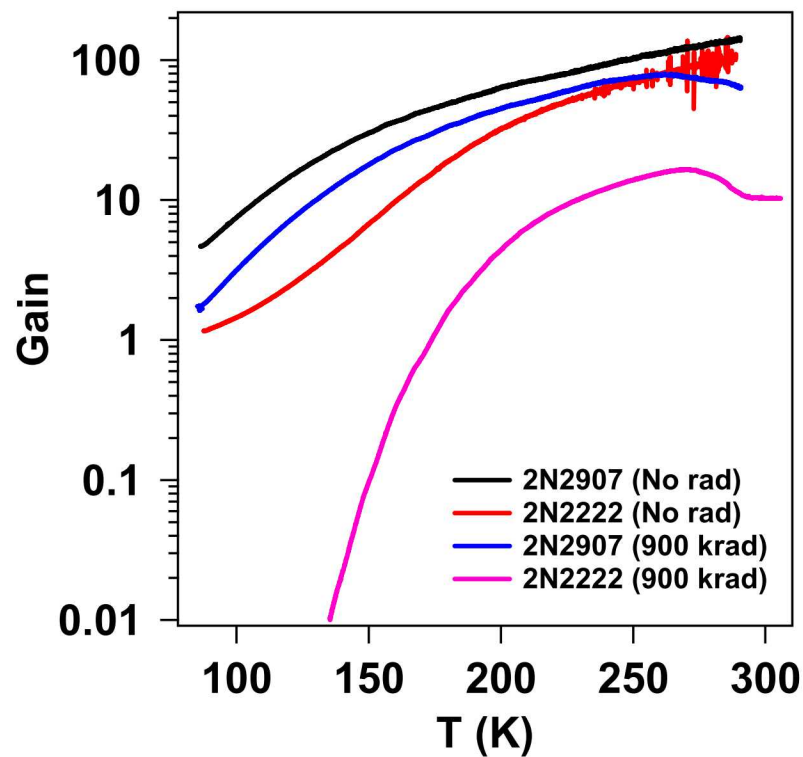


- $I_E = 1 \mu\text{A}$
- Cooled to 85 K
- Irradiated
  - $5\text{E}13 \text{ n/cm}^2$
- Heated to RT (shown)

► Small differences observed between device types



## 2N2222 vs 2N2907 (Gammas)

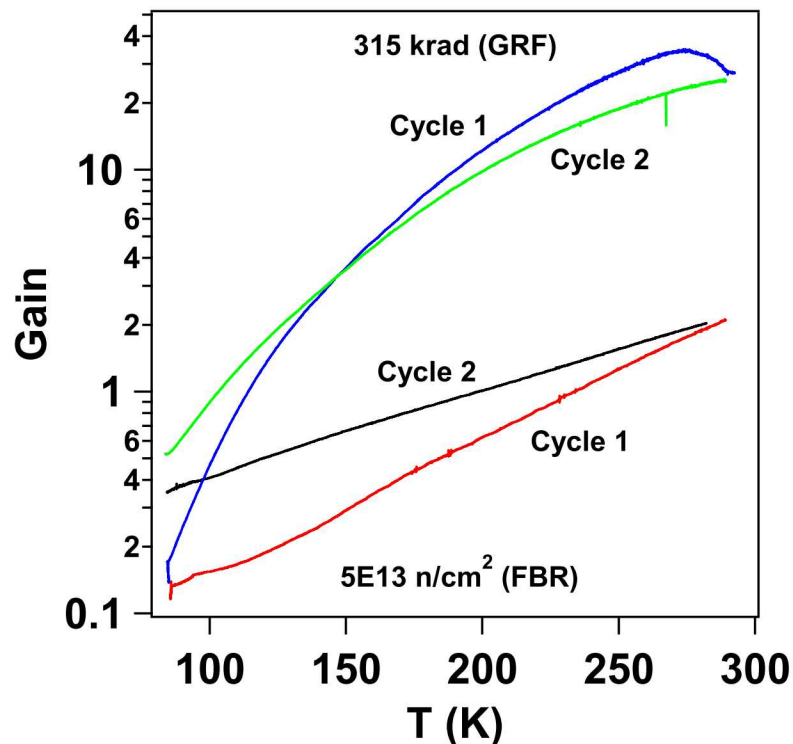


- $I_E = 1 \mu\text{A}$
- Cooled to 85 K
- Irradiated
  - 900 krad
- Heated to RT (shown)

► Large differences observed between device types

# Effect of Temperature Cycling

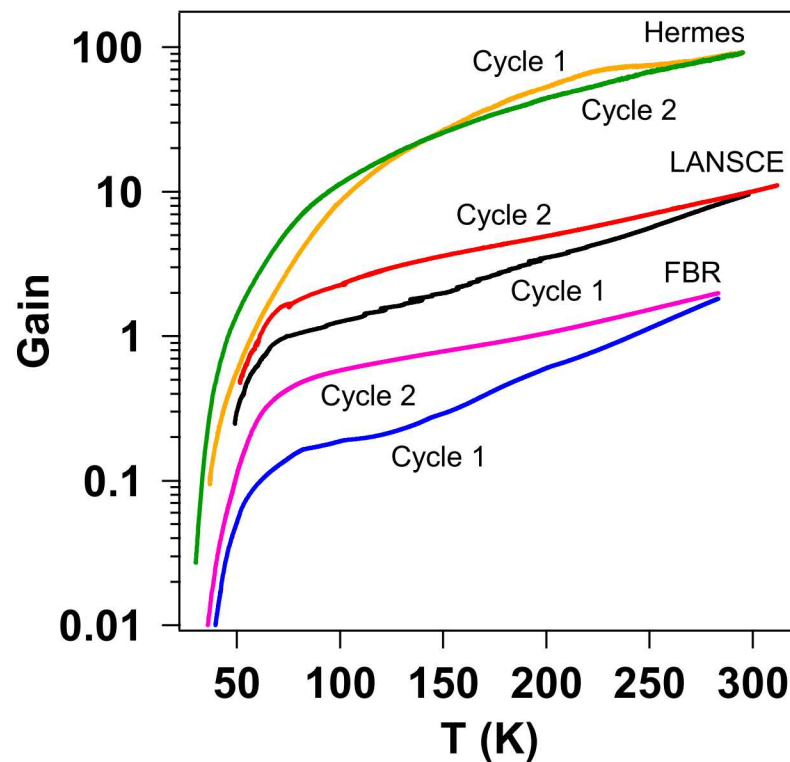
Neutrons annealing effects seen as sample warmed and then cycles back to RT conditions. Gamma effects much more complex



- **Cycle 1**
  - Cooled to 85 K
  - Irradiated
    - 5E13 n/cm<sup>2</sup> (FBR)
    - 315 krad(Si) (<sup>60</sup>Co)
  - Heated to RT
- **Cycle 2**
  - Cooled to 85 K
  - Heated to RT

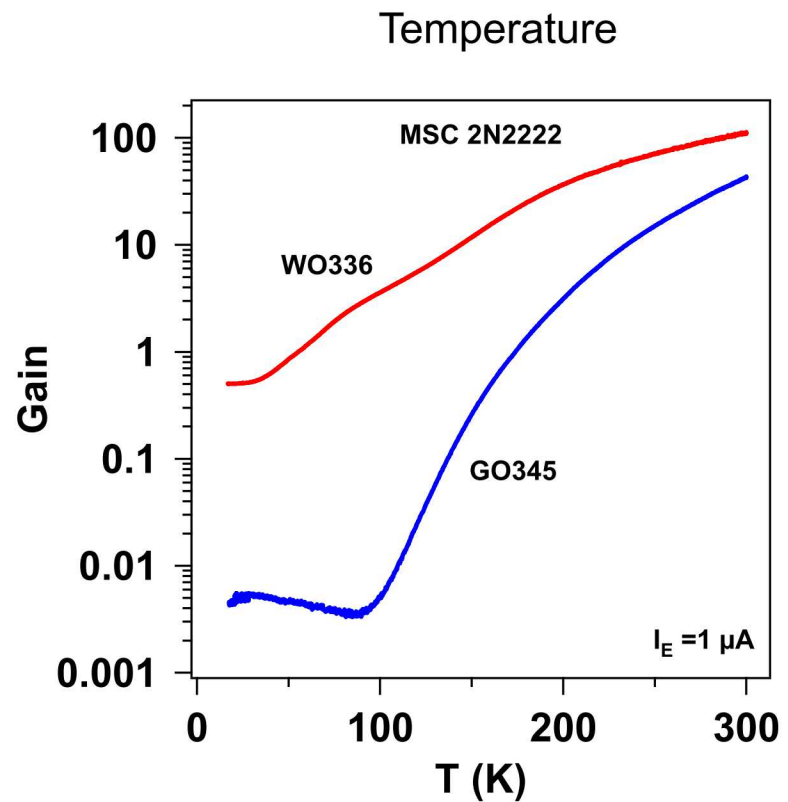
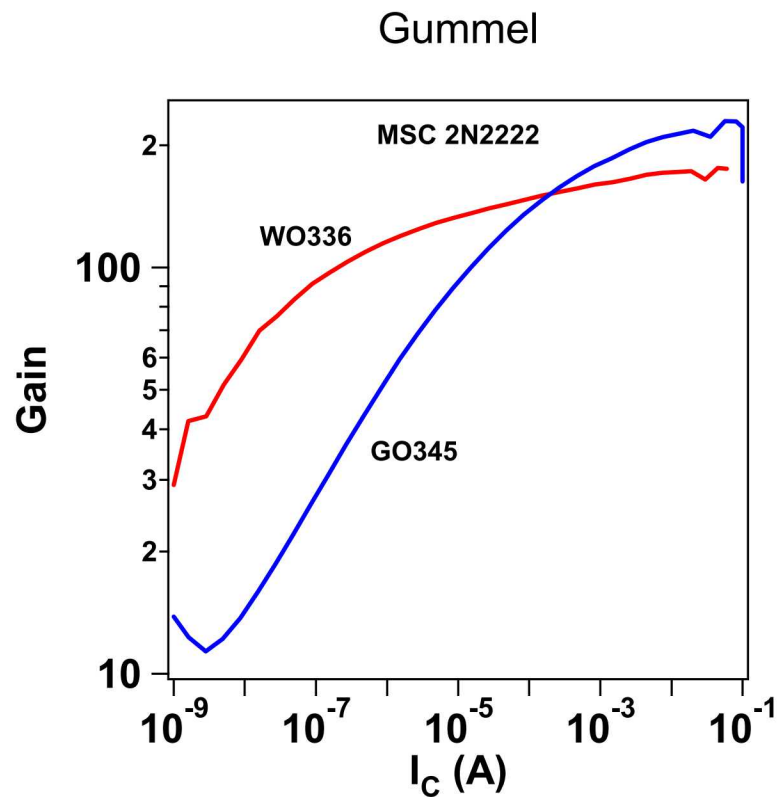
Data by K. McDonald

## Temperature Cycling



- $I_E = 1 \mu A$
- **Cycle 1**
  - Cooled to ~25 K
  - Irradiated
    - 90 krad (Hermes)
    - $1E13 \text{ n/cm}^2$  (LANSCE, 8 shots)
    - $3E13 \text{ n/cm}^2$  (FBR, pulsed)
  - Heated to RT (shown)
- **Cycle 2**
  - Cooled to ~25 K
  - Heated to RT (shown)

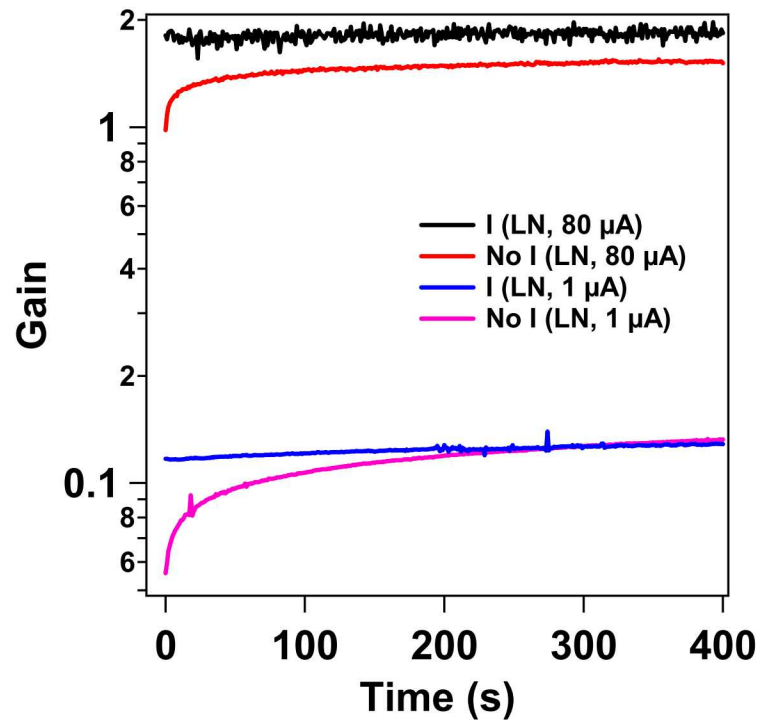
# Comparison of 2N2222 Gain Characteristics



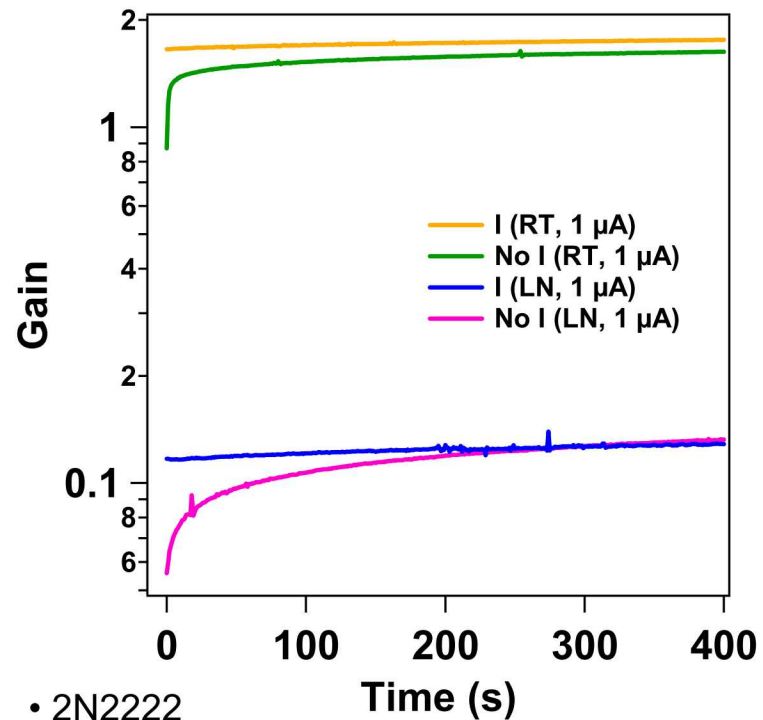
► 2N2222 variations can be significant

# Effect of Current During Irradiation (Neutrons)

Same temperature, different current



Different temperature, same current



- 2N2222
- Current turned off
- Irradiated ( $5E13$  n/cm<sup>2</sup>)
- Current turned on
- Temperature held constant

►Current affects annealing



# TOPIC: DOSIMETRY AT SNL

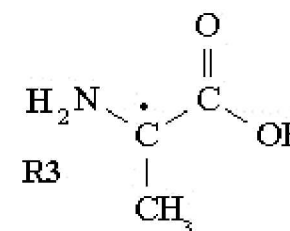
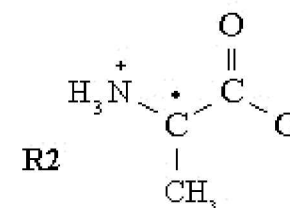
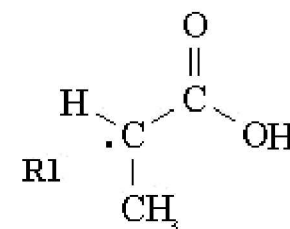
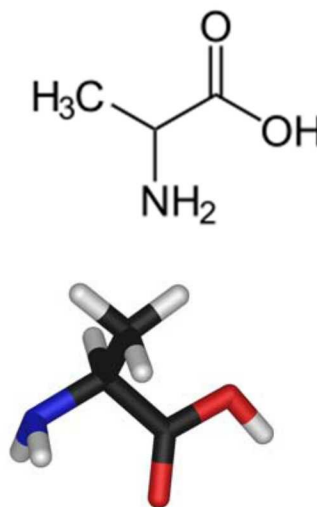
The Radiation Metrology Laboratory (RML) is the center of experiment-oriented dosimetry at SNL.

## A photograph of various forensic evidence items. At the top is a yellow ruler with black markings in inches (0 to 6) and centimeters (0 to 150). Below the ruler is a color calibration strip with several color patches. To the left of the ruler is a clear plastic syringe. To the right of the ruler is a clear plastic bag with a white label that reads "H14 60" and "6301-05". Below the ruler are several small objects: a group of white and yellow pills, a group of blue and white capsules, and a group of small white and yellow pills. To the right of the ruler is a group of small white and yellow pills, a group of blue and white capsules, and a group of small white and yellow pills.

# High accuracy ionization dosimetry requires refined modeling of $n/\gamma$ response

Alanine ESR dosimetry has a 1-2% accuracy and is a non-destructive read-out, but can not be used in  $n/\gamma$  fields due to poor modeling of neutron effective-response

Interactions between and density of 3 types of radicals causes a complex interaction chemistry and recombination process.



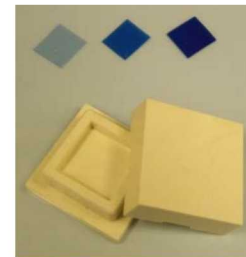
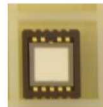
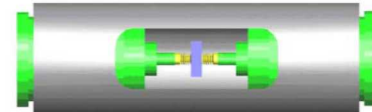
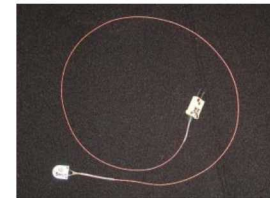
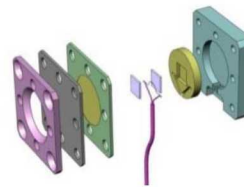


# Sandia uses a range of state-of-the-art dosimetry at pulsed gamma facilities



**For each application, we choose the best dosimeter**

- **TLDs**
  - $\text{CaF}_2\text{:Mn}$ , LiF, others
- **Calorimeters**
  - Ta, Cu, Si, GaAs, others
- **Photoconducting Detectors (PCD)**
  - diamond, GaAs
- **PIN Diodes (Si)**
- **Compton Diodes**
- **Alanine**
- **Radiochromic Film**



**There are different pros/cons for dosimeters at SATURN/HERMES-III. Guidance found in ASTM E1894 standard: Standard Guide for Selecting Dosimetry Systems for Application in Pulsed X-Ray Sources**

# TOPIC:

## PROCESS USED IN TENDL CALCULATED LIBRARIES

The TENDL libraries are evolving and different processes are now used to address how “model defect” is addressed and the previous lack of consideration for experimental data. Older TENDL versions had cases where the deviation of the calculated cross section from the experimental data was over 2 standard deviations. Current processes have addressed this, apparently, by normalizing the baseline value to the experimentally-informed value for well known standard and dosimetry reactions. How does this affect the overall cross section, i.e. does total cross section still equal the sum to the individual reactions?

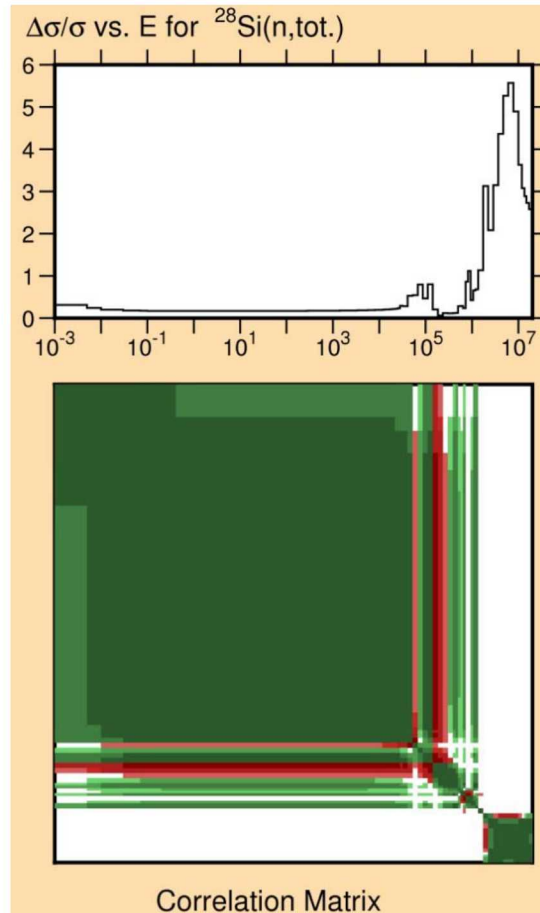


# Are the Cross Section Covariance Matrices Similar?

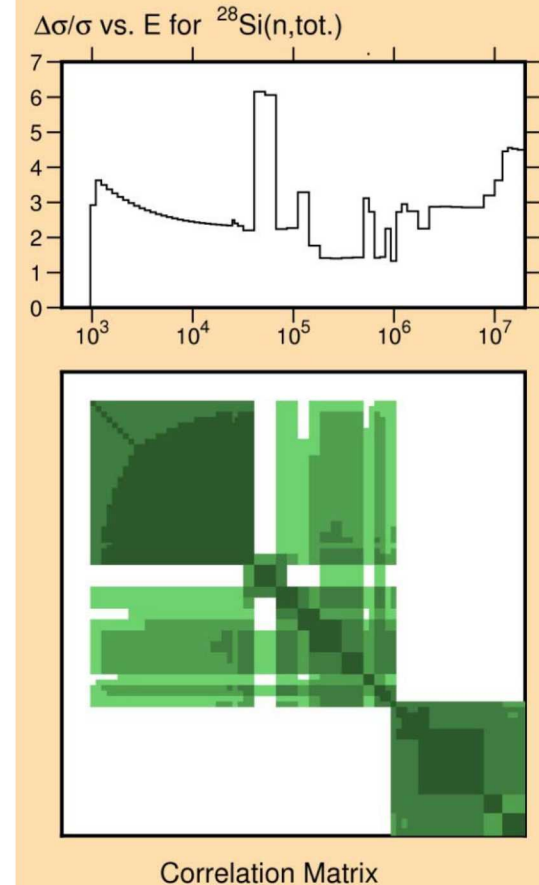
Isotope:  $^{28}\text{Si}$   
Code: NJOY99.259  
Reaction: MT=1

The correlation matrices are different – but both can be correct based on the evaluation techniques. Note one MUST only use a correlation matrix matched to the cross section.

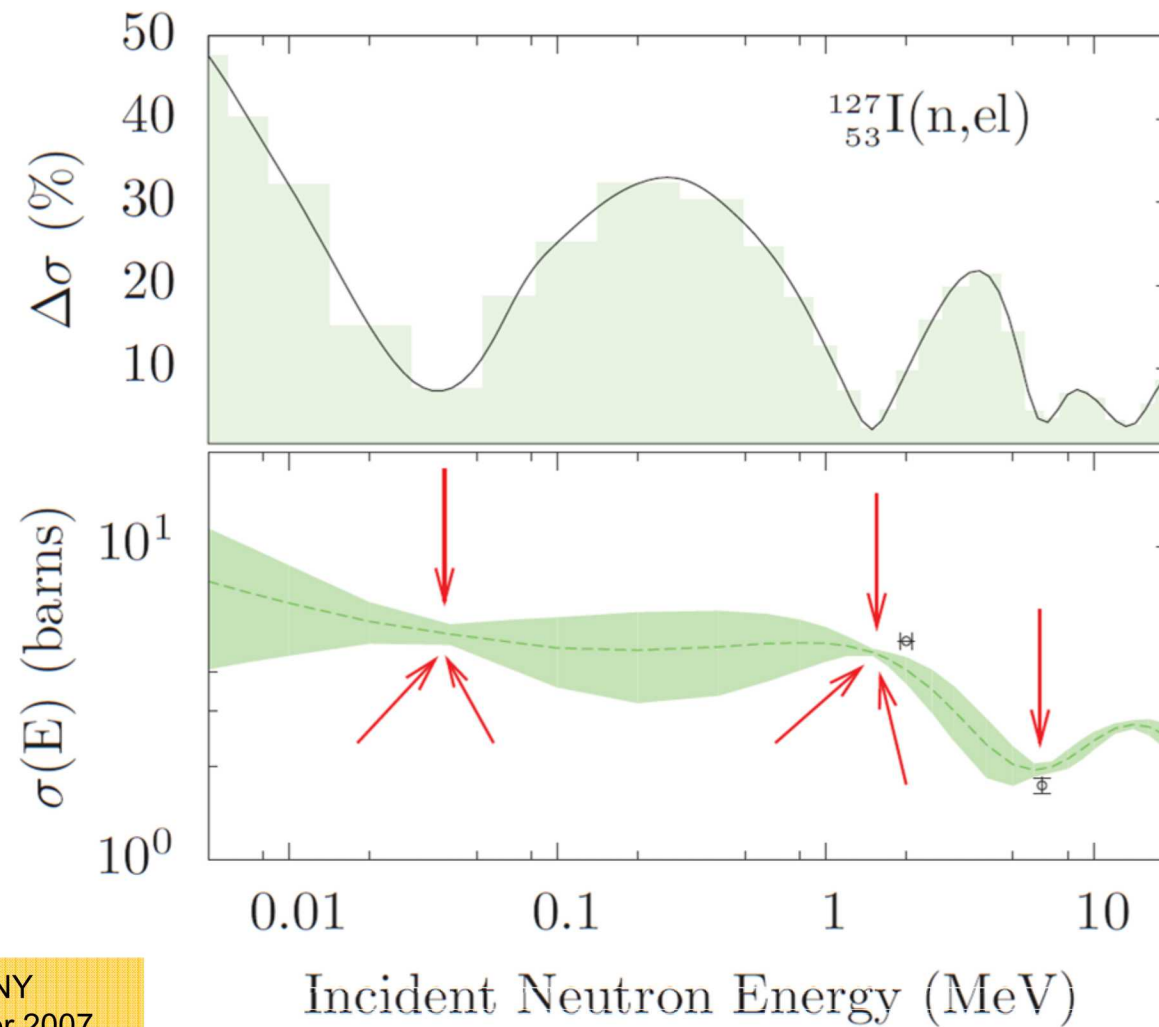
TENDL-2008



ENDF/B-VI.r8, (ORNL)

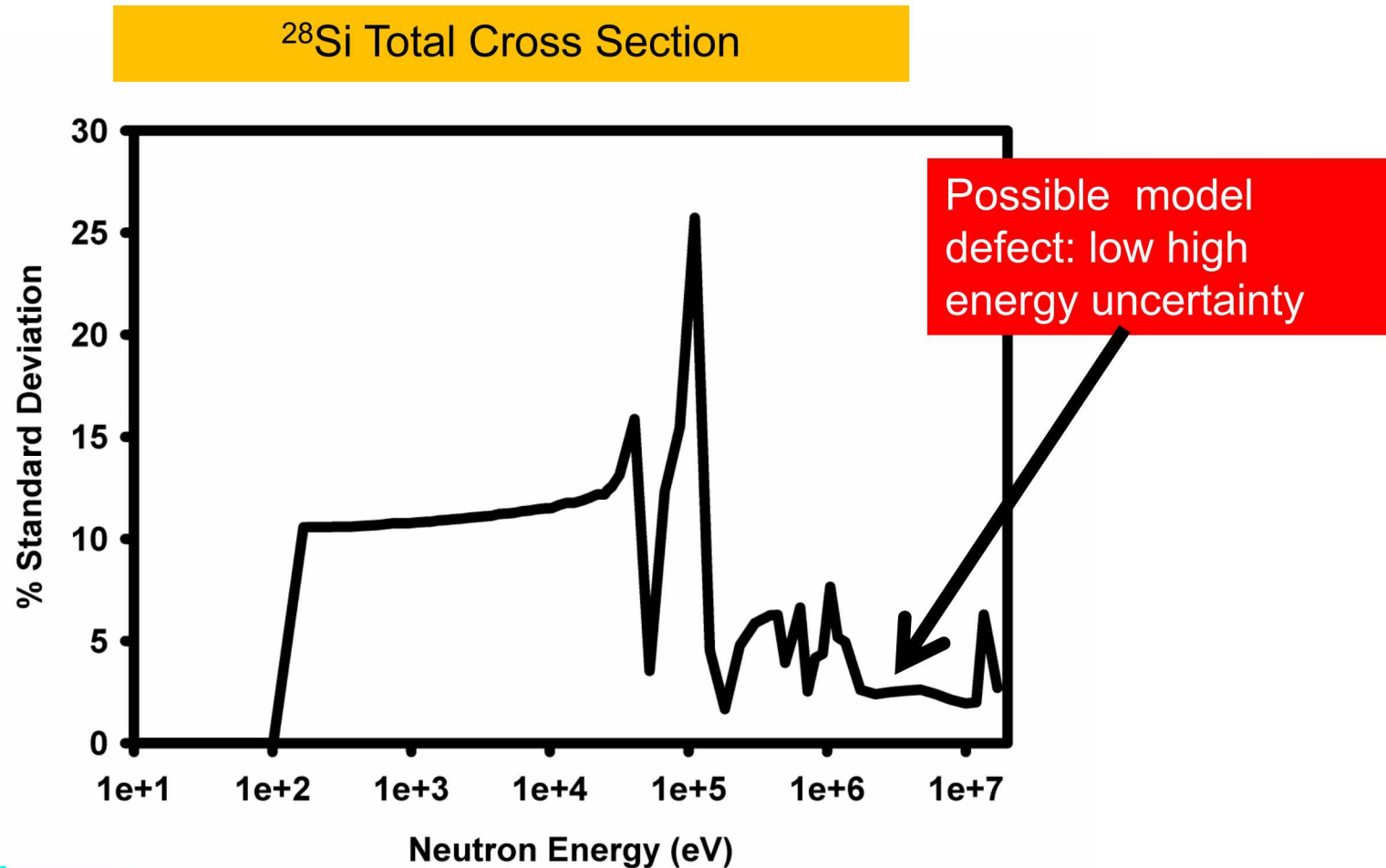


## Example of Model Defect in UQ



Pigni et al., Port Jefferson, NY  
CSEWG meeting, November 2007

# Probable Model Defect in High Energy Standard Deviation

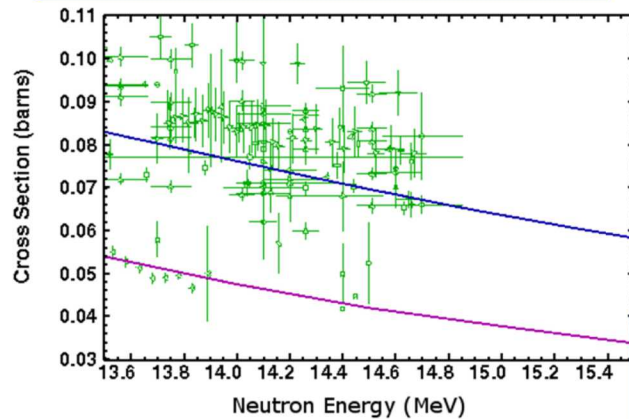


TENDL 2010

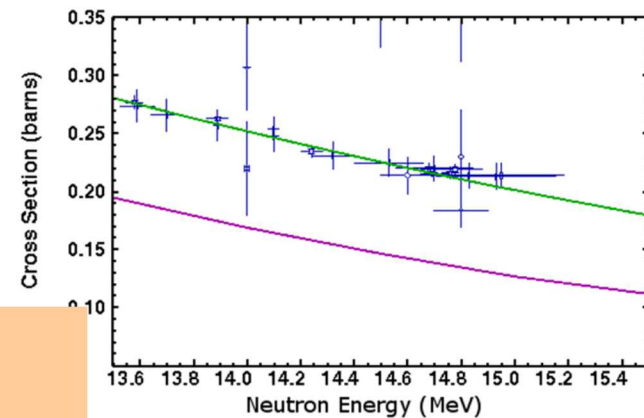
Analysis by Robert Middleton, SNL

# Historical TENDL evaluations can have a large deviation from measurement (1/2).

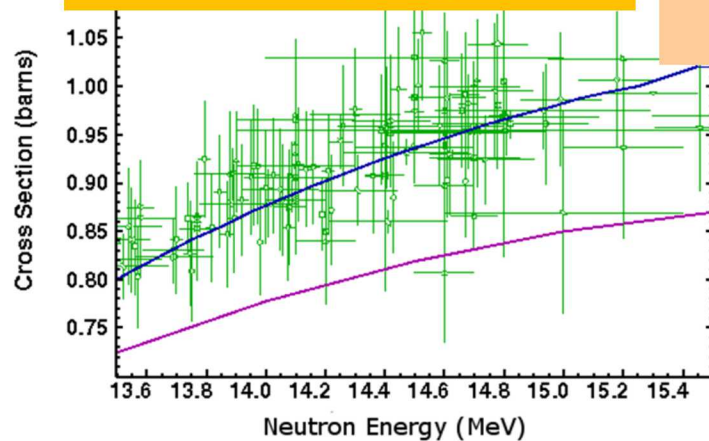
$^{27}\text{Al}(n,p)$



$^{32}\text{S}(n,p)$

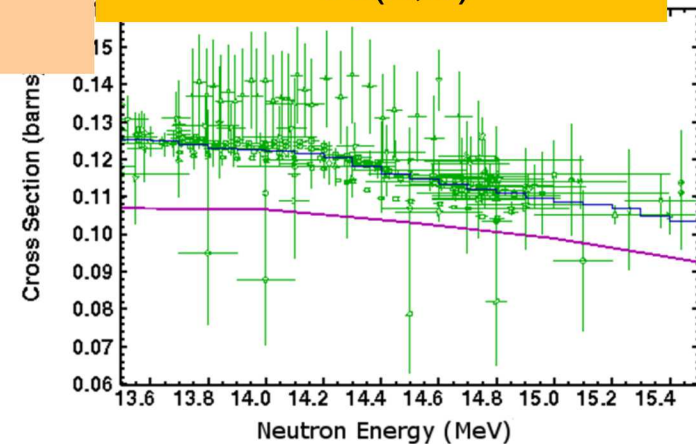


$^{65}\text{Cu}(n,2n)$



IRDF-2002: blue  
TENDL-2008: red  
EXFOR: green

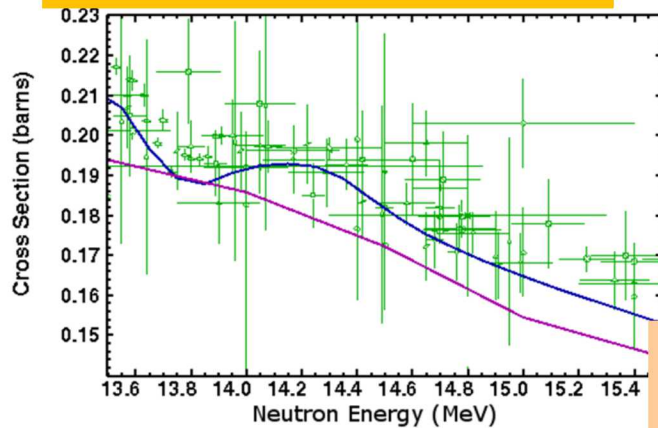
$^{27}\text{Al}(n,\alpha)$



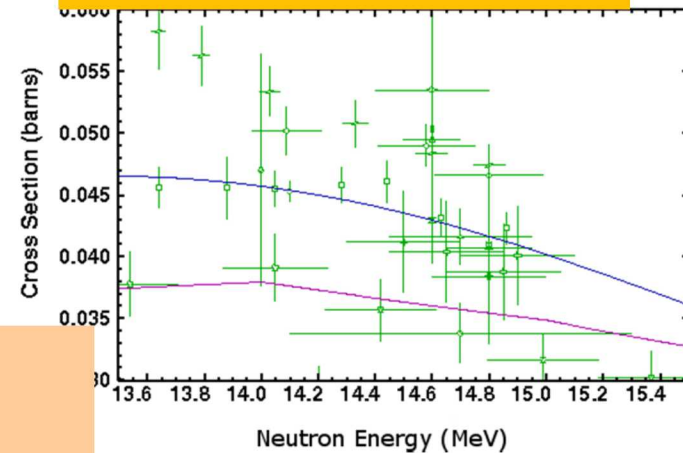


# Historical TENDL evaluations can have a different energy-dependent correlation (2/2).

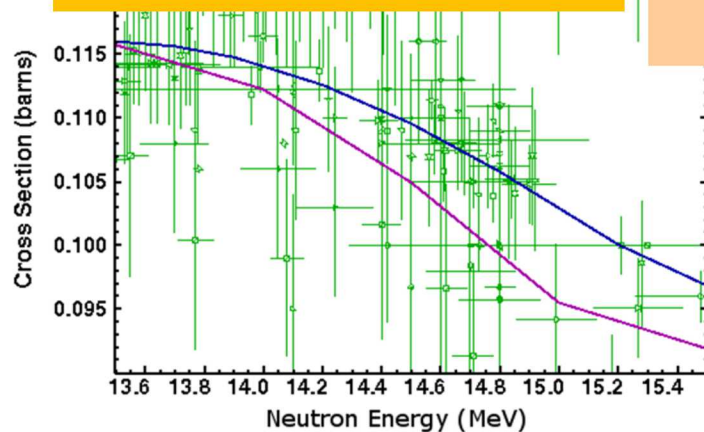
$^{24}\text{Mg}(n,p)$



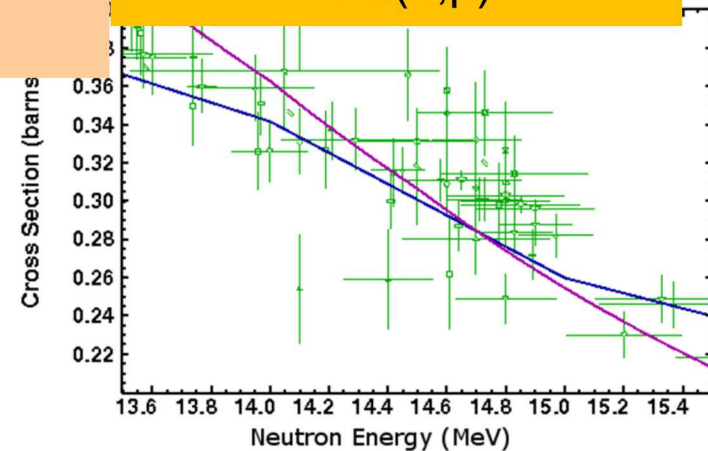
$^{63}\text{Cu}(n,\alpha)$



$^{56}\text{Fe}(n,p)$



$^{54}\text{Fe}(n,p)$



IRDF-2002: blue  
TENDL-2008: red  
EXFOR: green

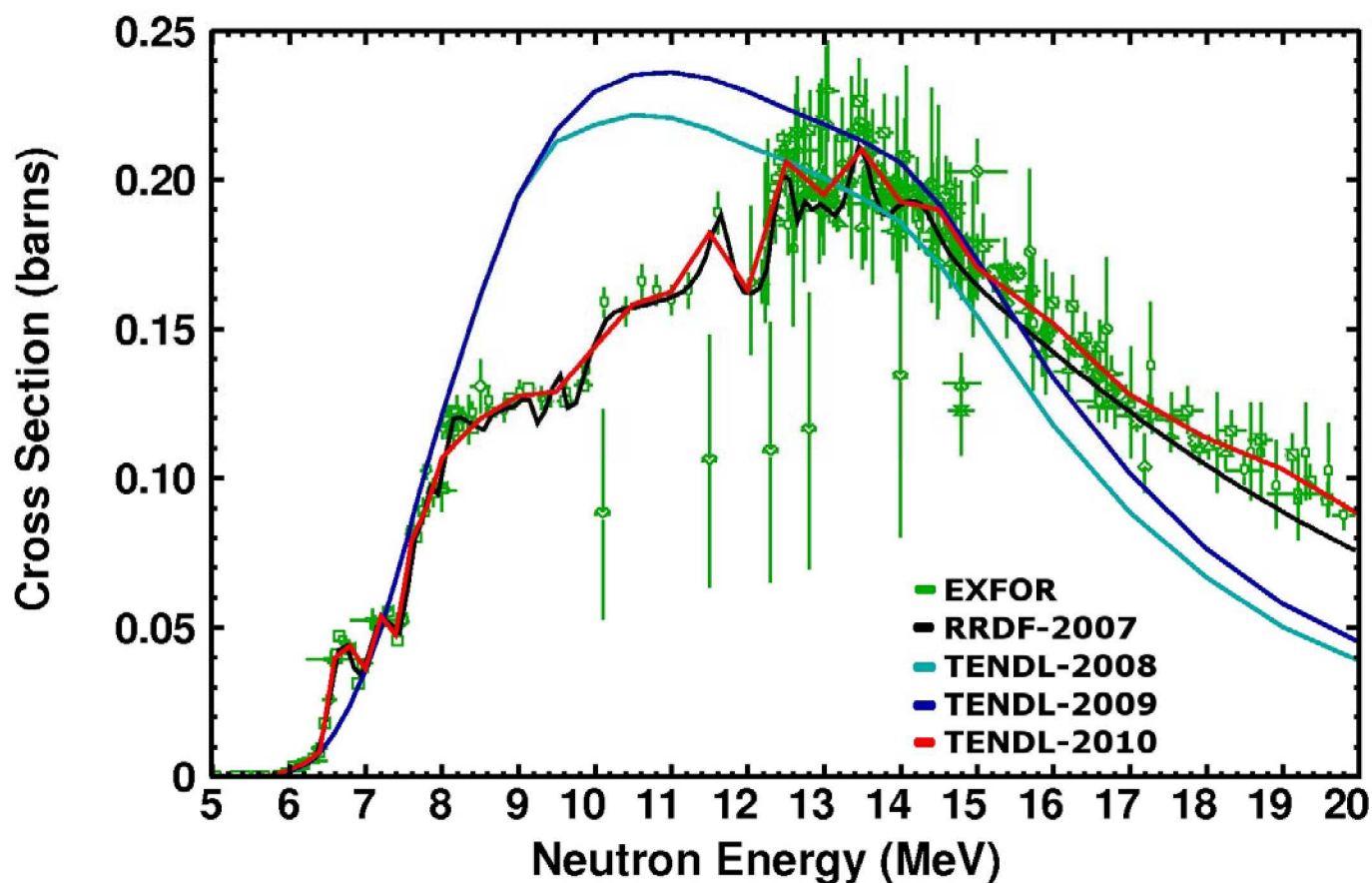


# Impact of Using Calculation-based Evaluations (TENDL-2010)

| Reaction                   | Xsec Ratio | TENDL Unc. | IRDF Unc. | # Std. Dev. | Unc. Ratio |
|----------------------------|------------|------------|-----------|-------------|------------|
| $^{27}\text{Al}(n,\alpha)$ | 0.87       | 15.0 %     | 3.74 %    | 0.84        | 4.0        |
| $^{27}\text{Al}(n,p)$      | 0.62       | 14.9 %     | 7.31 %    | 2.28        | 2.0        |
| $^{63}\text{Cu}(n,\alpha)$ | 0.83       | 23.4 %     | 1.61 %    | 0.73        | 14.5       |
| $^{63}\text{Cu}(n,2n)$     | 0.99       | 10.8 %     | 1.20 %    | 0.13        | 9.0        |
| $^{65}\text{Cu}(n,2n)$     | 0.89       | 6.93 %     | 1.51 %    | 1.62        | 4.6        |
| $^{54}\text{Fe}(n,p)$      | 1.06       | 4.46 %     | 3.37 %    | 1.03        | 1.3        |
| $^{56}\text{Fe}(n,p)$      | 0.98       | 18.5 %     | 1.07 %    | 0.10        | 17.3       |
| $^{24}\text{Mg}(n,p)$      | 0.96       | 10.1 %     | 0.70 %    | 0.41        | 14.4       |
| $^{58}\text{Ni}(n,2n)$     | 1.40       | 17.0 %     | 2.38 %    | 2.31        | 7.1        |
| $^{58}\text{Ni}(n,p)$      | 0.98       | 5.26 %     | 2.04 %    | 0.39        | 2.6        |
| $^{32}\text{S}(n,p)$       | 0.67       | 12.8 %     | 1.33 %    | 2.58        | 9.6        |
| $^{64}\text{Zn}(n,p)$      | 0.90       | 16.6 %     | 1.81 %    | 0.60        | 9.2        |
| $^{90}\text{Zr}(n,2n)$     | 1.08       | 10.6 %     | 0.59 %    | 0.77        | 18.        |

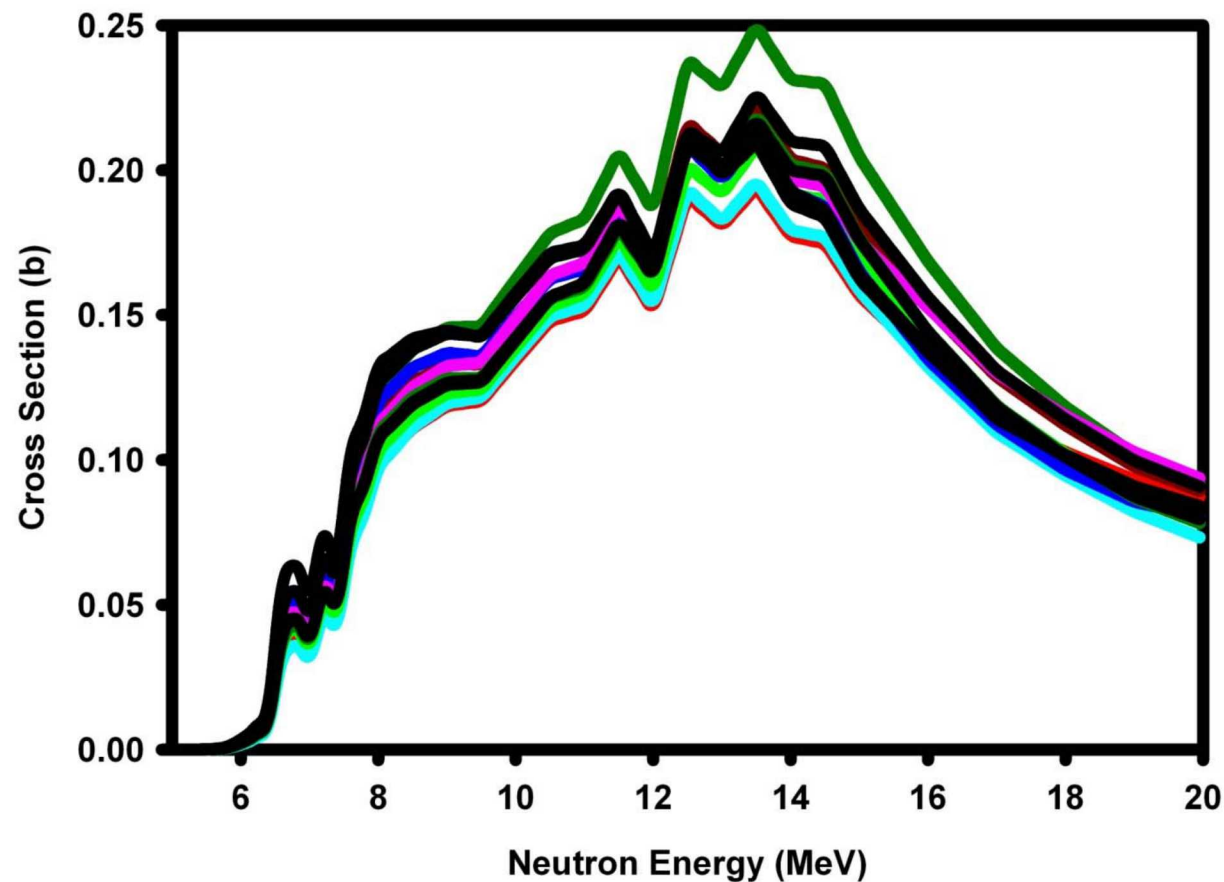
TENDL-2010 applied a normalization for many dosimetry reactions.

$^{24}\text{Mg}(n,p)^{24}\text{Na}$  reaction



The parameter variation reflects this new shape

$^{24}\text{Mg}(n,p)^{24}\text{Na}$  reaction



# **TOPIC:**

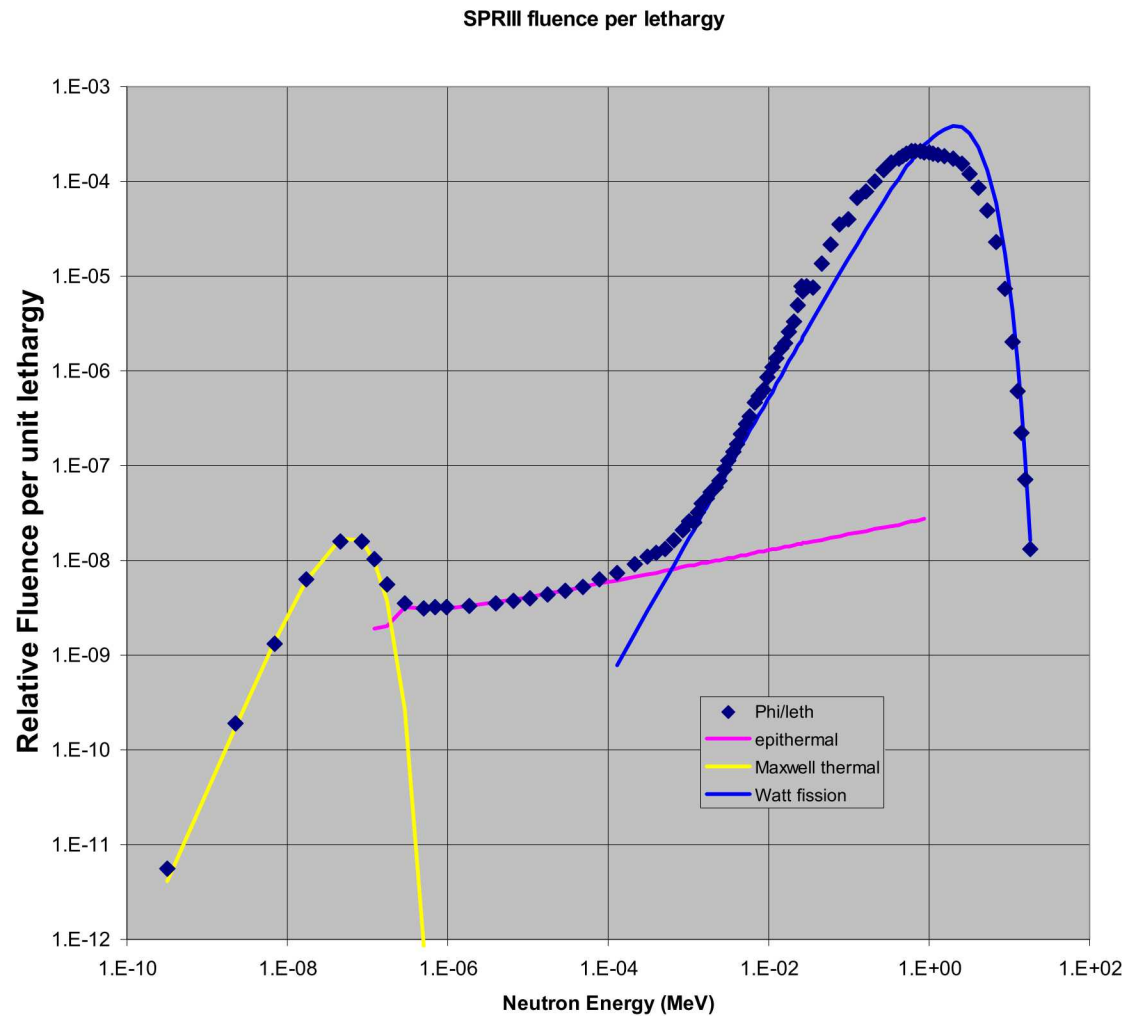
## **A PRIORI COVARIANCE FOR CALCULATED SPECTRA**

A prior calculated spectrum is used as input in a least squares analysis. The uncertainty in this prior information should be included in a complete least squares analysis of the uncertainty in the resulting adjusted spectrum.

## SPR-III Central Cavity Neutron Spectrum



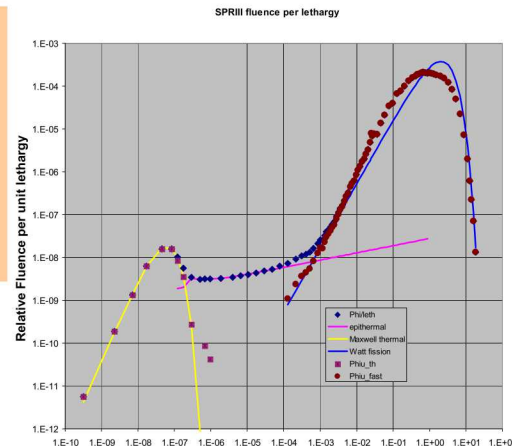
MCNP Calculation in 89 energy groups



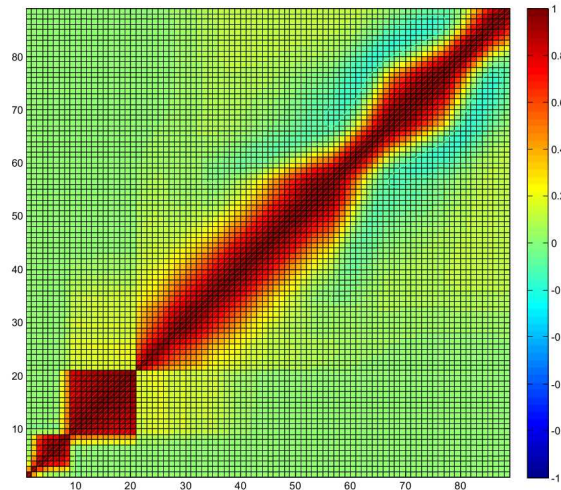


# SPR-III Input Uncertainty Information

**MCNP *a priori* spectrum with decomposed terms**



**prior covariance matrix**

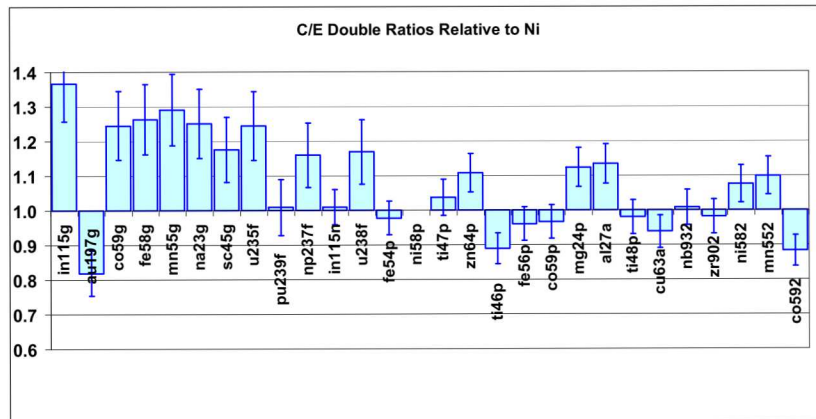


## COMPONENTS OF ACTIVITY UNCERTAINTY

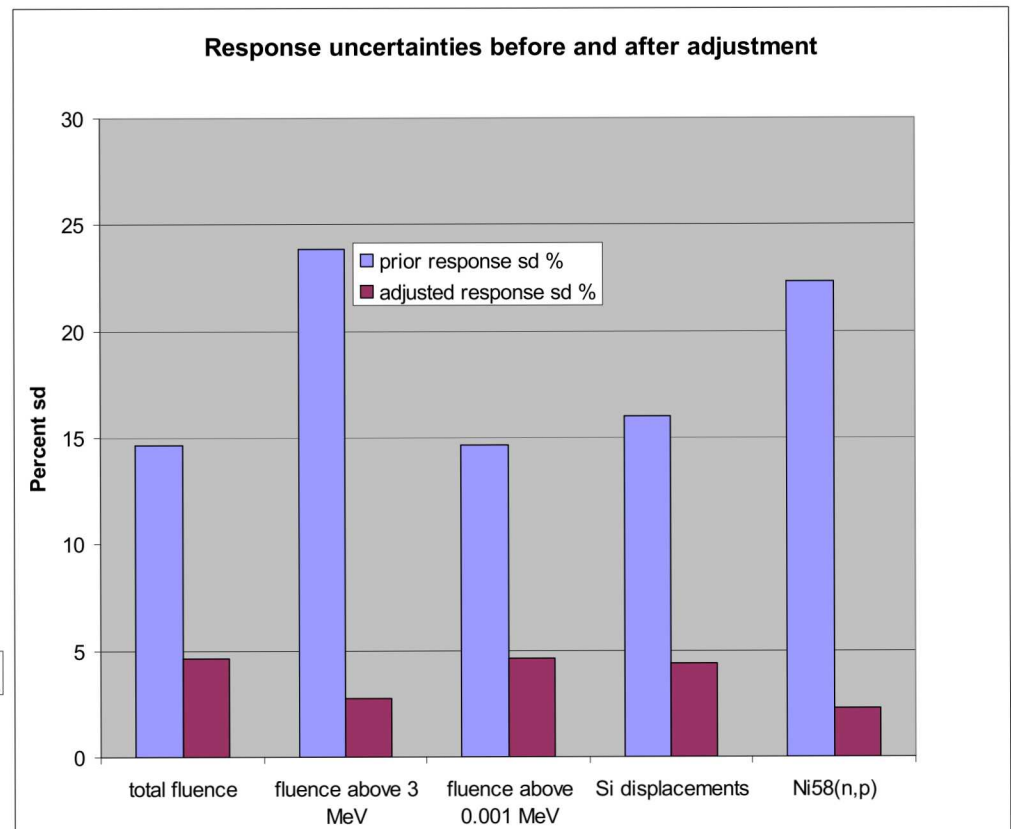
|                           | %          |            |
|---------------------------|------------|------------|
| Counting statistics       | 0.2        | 2          |
| Detector efficiency       | 2          | 4          |
| Isotope mass              | 0.1        | 3          |
| Counting reproducibility  | 1          | 2          |
| Nickel normalization      | 2          | 3          |
| Flux gradients            | 1          | 2          |
| Nuclear data              | 0.1        | 2          |
| Thermal flux variations   | 0          | 5          |
| Boron sphere transmission | 0          | 4          |
| <b>Total</b>              | <b>3.1</b> | <b>9.5</b> |
|                           | <b>7</b>   | <b>4</b>   |

# SPR-III Spectrum Output Uncertainties

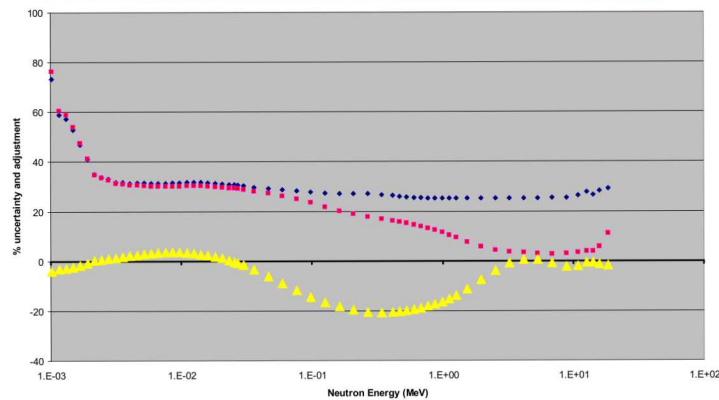
## C/E for Activities



## Spectral Metrics (before and after)



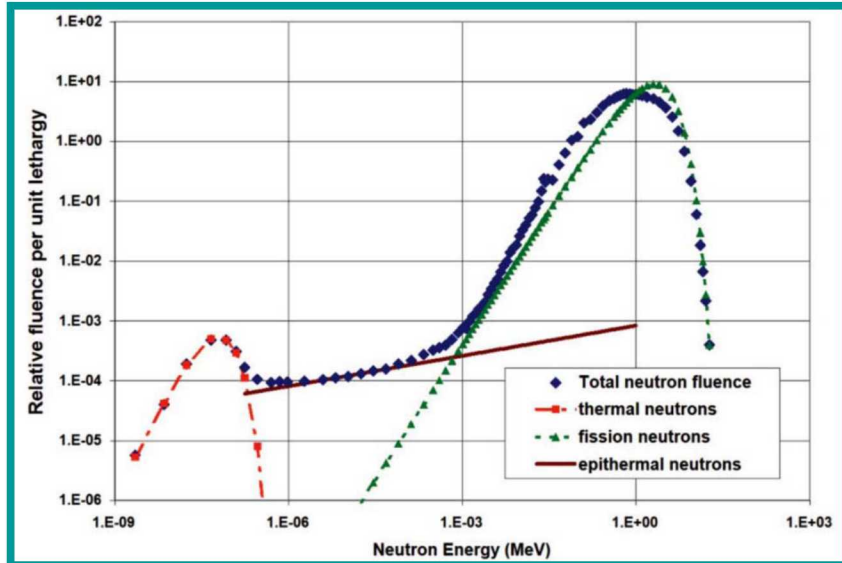
## Spectrum adjustment and uncertainties



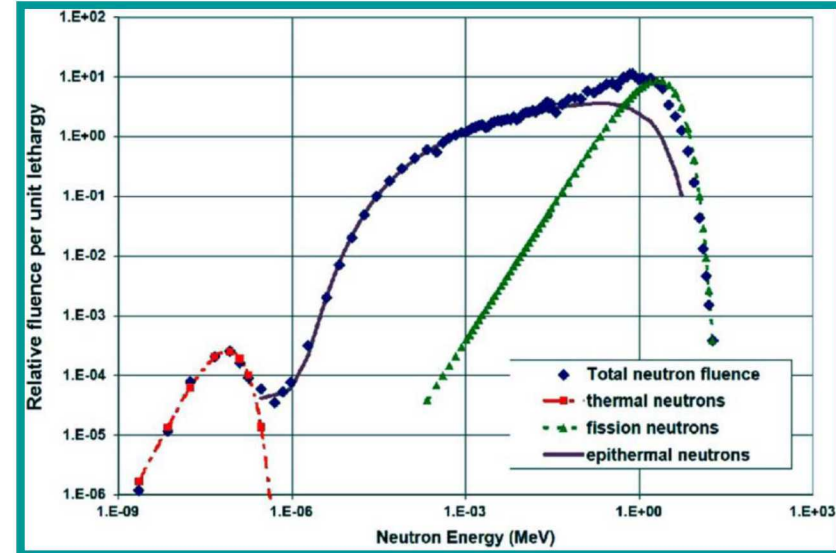
## Covariance in *a priori* Spectrum

Use fission,  $1/E^\alpha$ , and Maxwellian components coupled with transitional regions as determined by fit to *a priori* spectrum

### Fast Burst Reactor



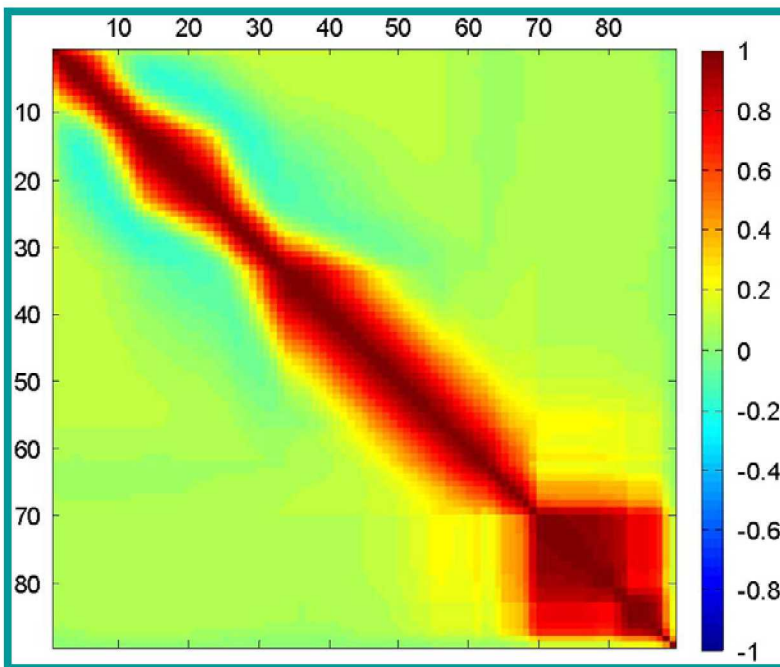
### ACRR PbB Bucket



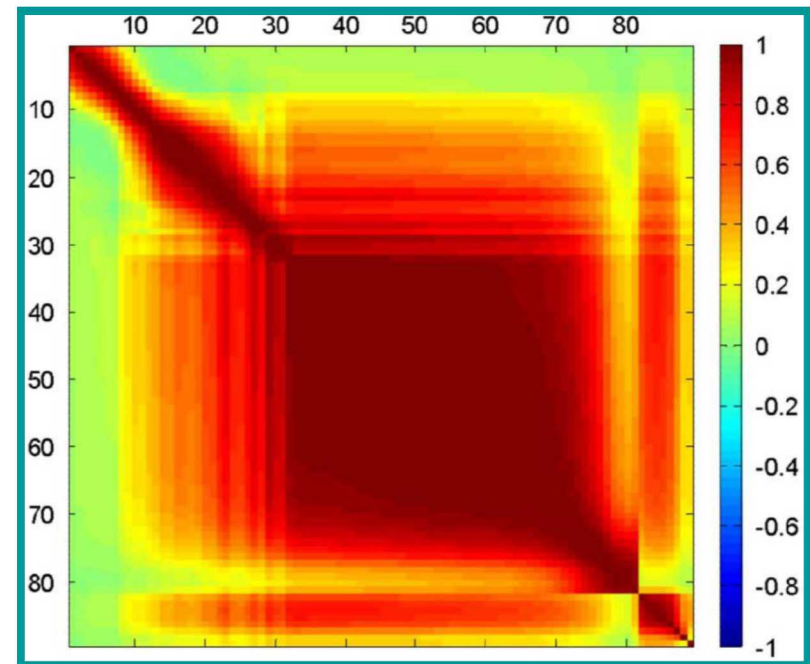
# Covariance in *a priori* Spectrum

Example of constructed *a priori* spectrum covariance matrices

Fast Burst Reactor



ACRR PbB Bucket

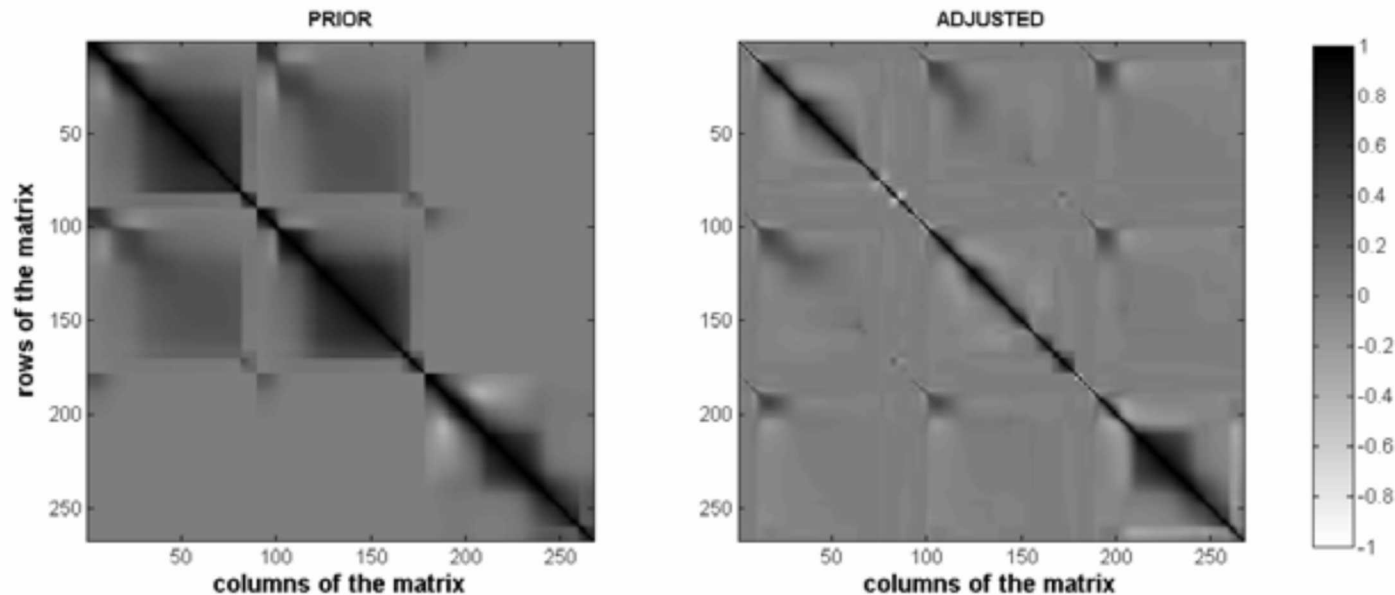




# Simultaneous Spectrum Adjustment: Neutron Spectrum

## Simultaneous spectrum adjustment:

- fast burst reactor cavity
- pool-type reactor cavity
- pool-type reactor in PbB bucket

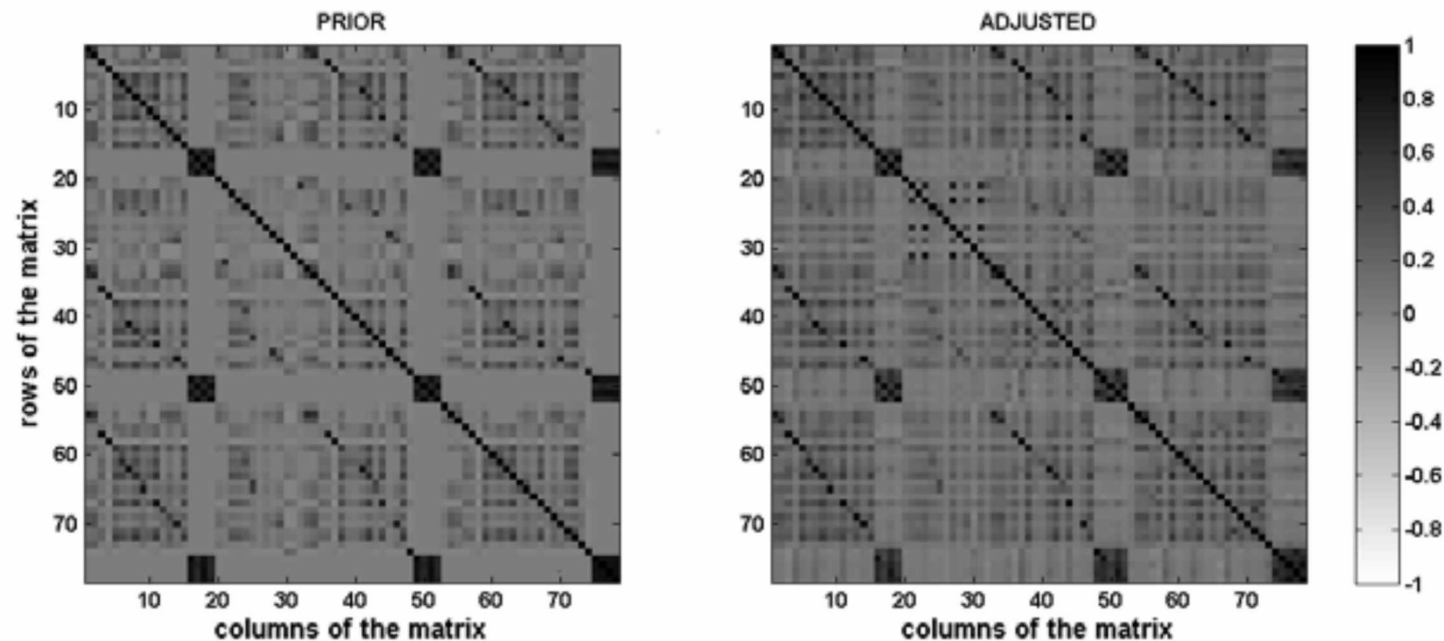




# Simultaneous Spectrum Adjustment: Activities

## Simultaneous spectrum adjustment:

- fast burst reactor cavity
- pool-type reactor cavity
- pool-type reactor in PbB bucket



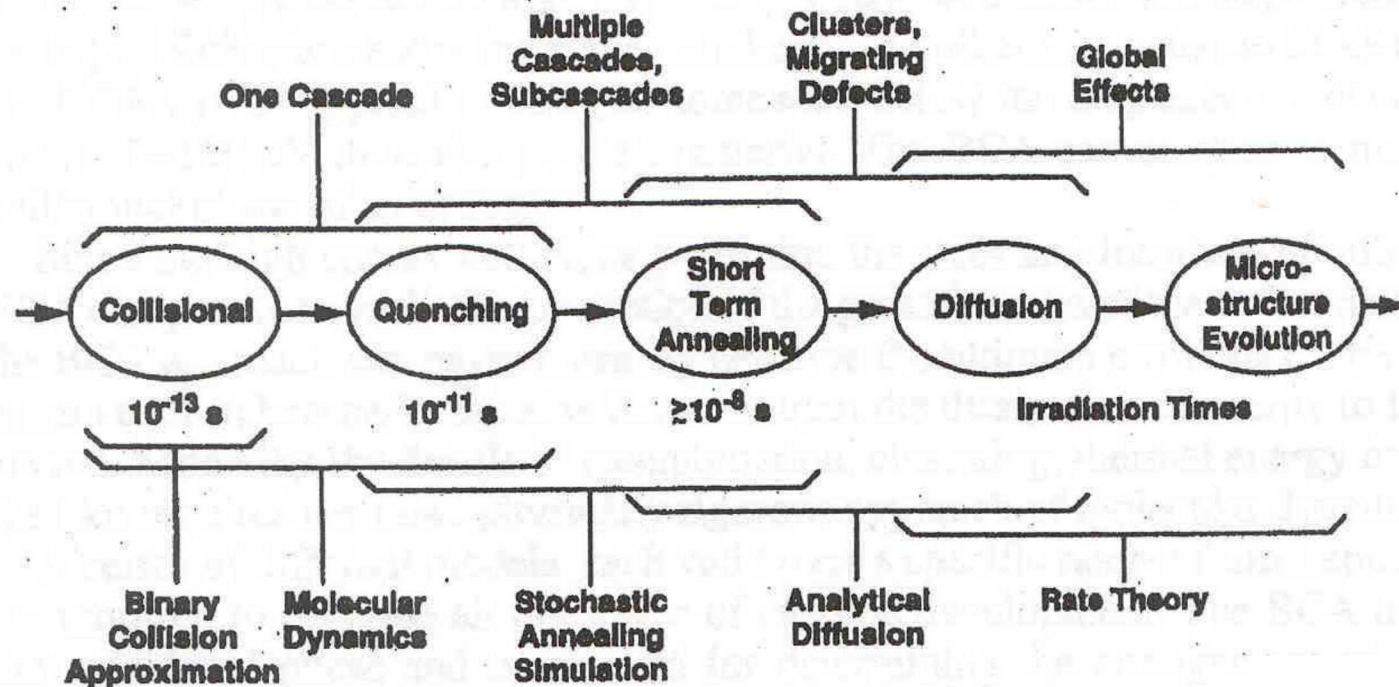
# TOPIC:

## DEFECT CREATION AND DAMAGE CASCADES

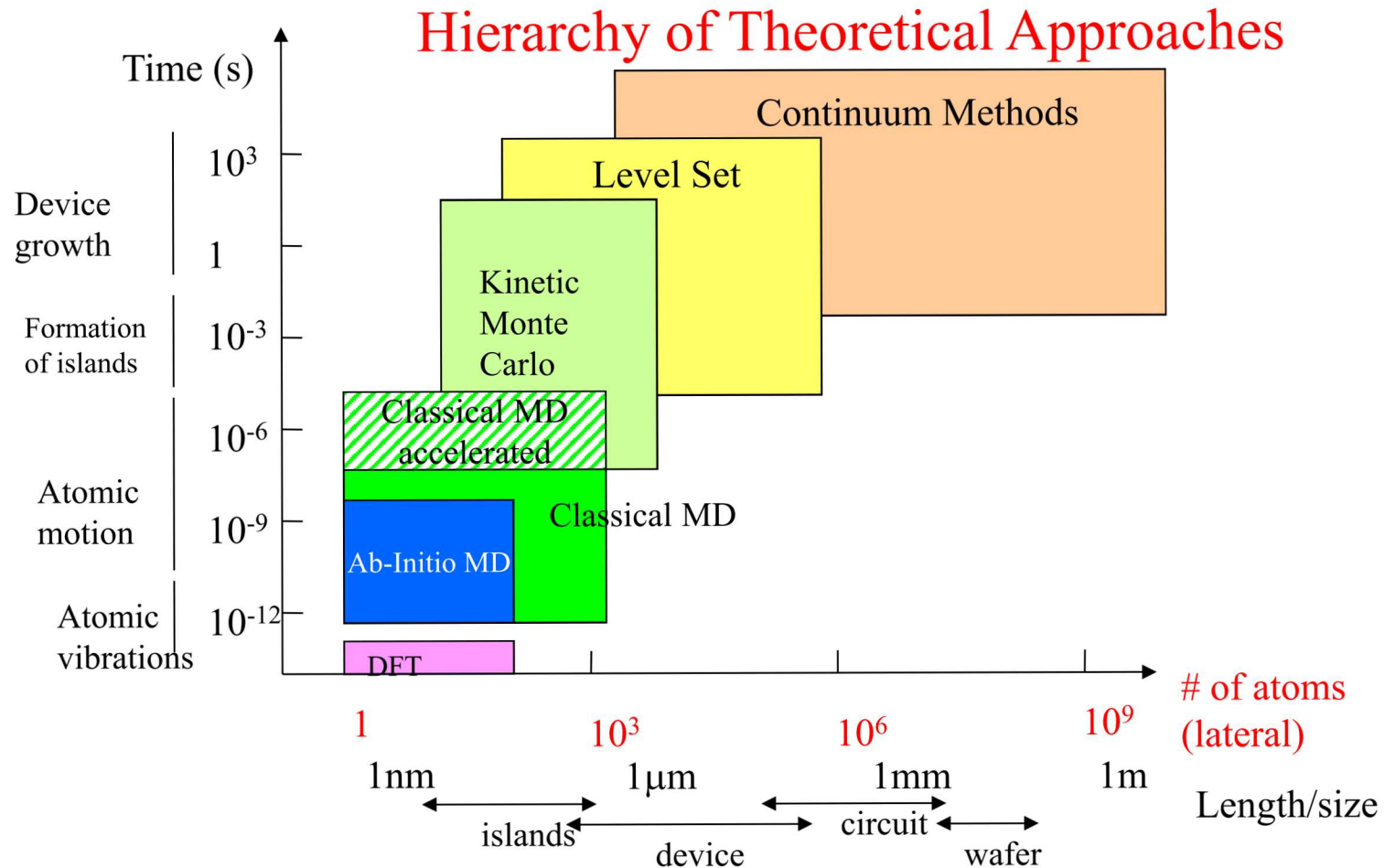
Binary collision approximation (BCA) and molecular dynamics (MD) methods can be used to examine defect creation. Polyatomic matrices can generate many different defect types, e.g. anti-site defects. MARLOWE is a classic BCA code.

Defect evolution makes correlation of experimentally measured damage metrics with initial calculated primary damage metrics extremely difficult.

# Multi-scale modeling is now required for radiation damage

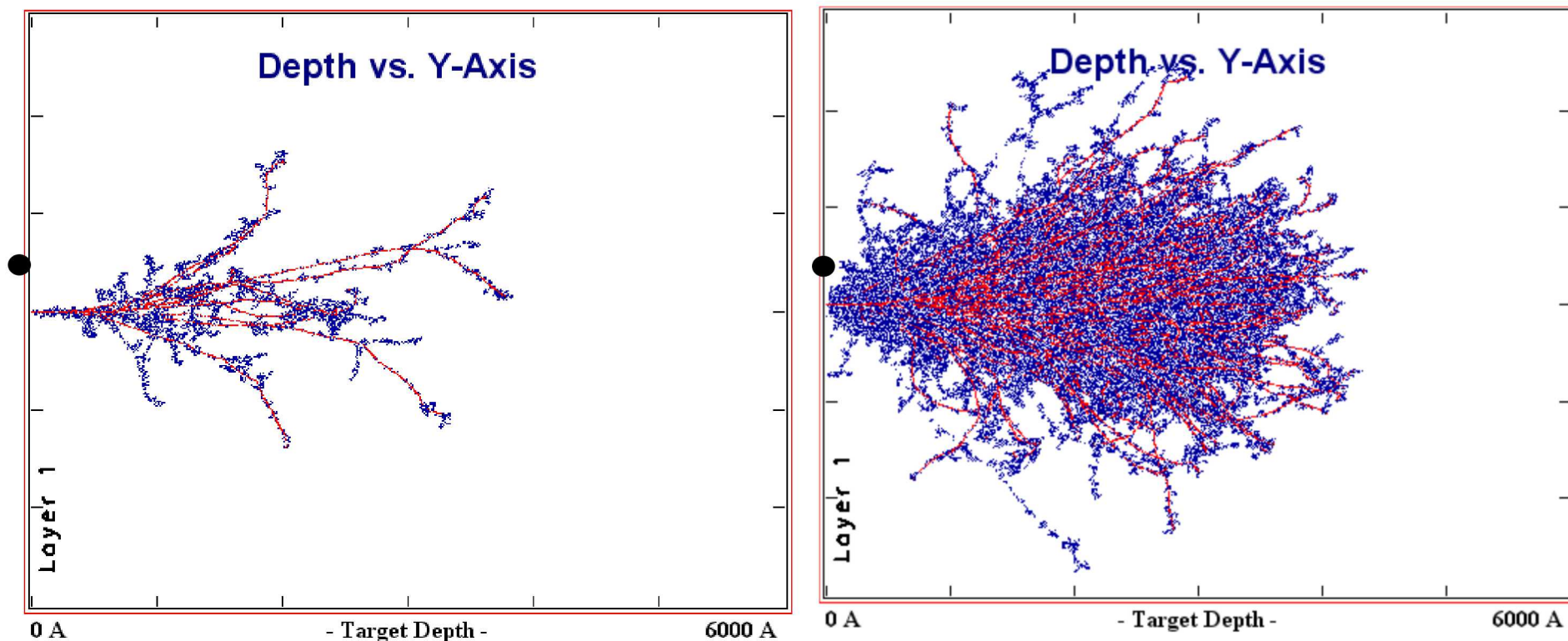


# The modeling tools change with the scale of “time for” and “range of” interactions



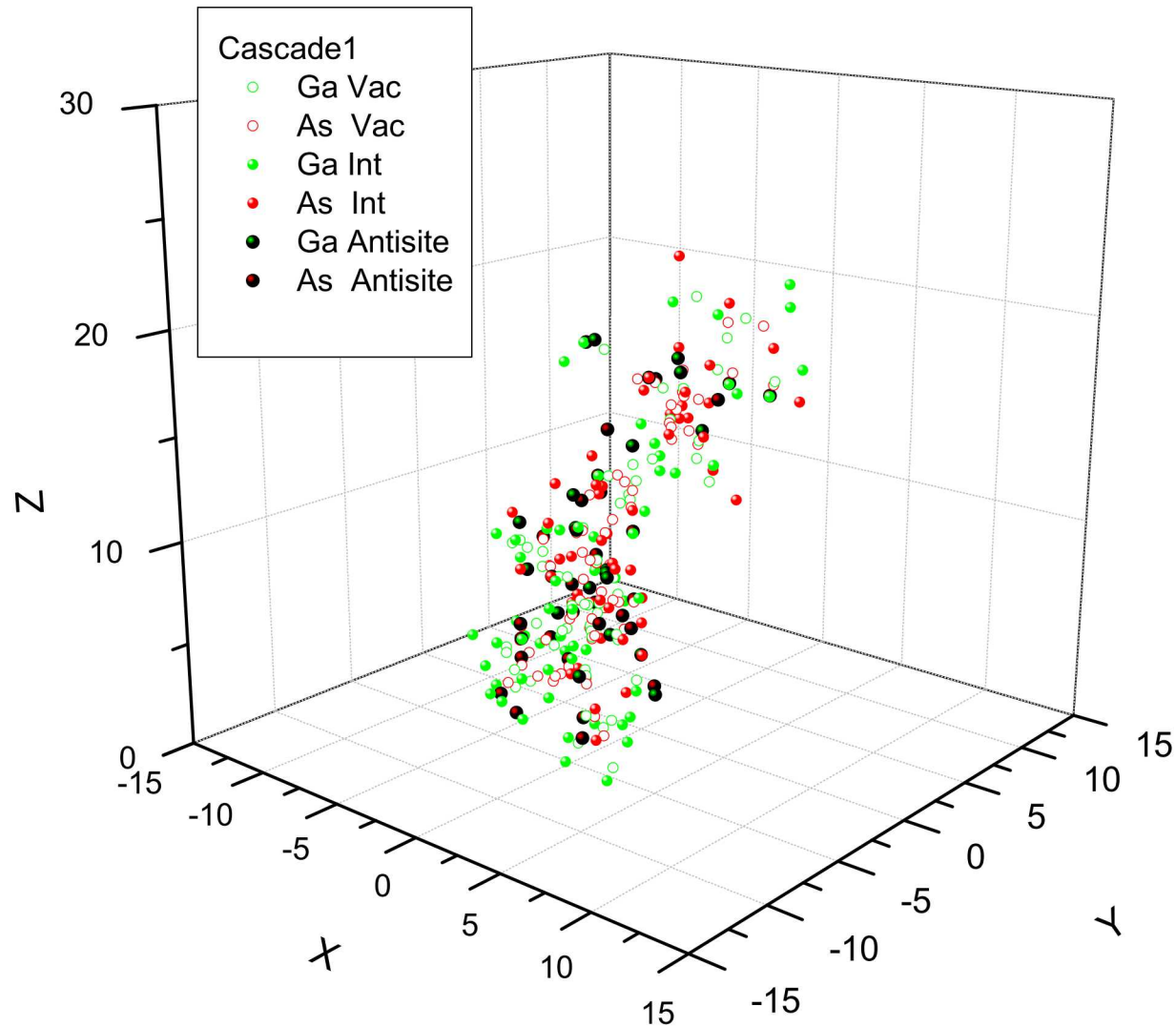
# SRIM Vacancy Cascade

200 keV Si on amorphous Si  
15 eV displacement energy  
2350 avg. vacancies/ion, 0.27  $\mu\text{m}$  range

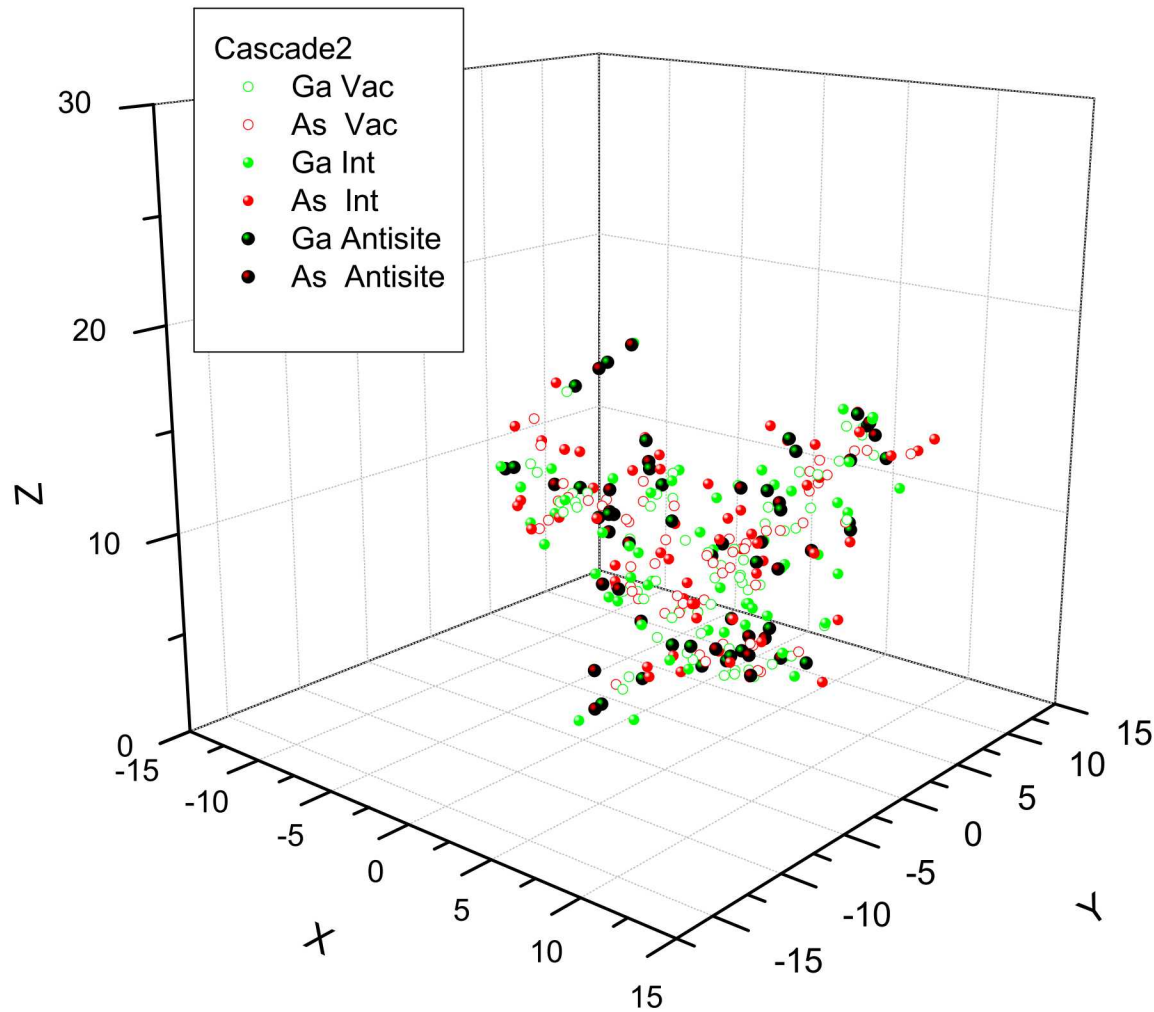




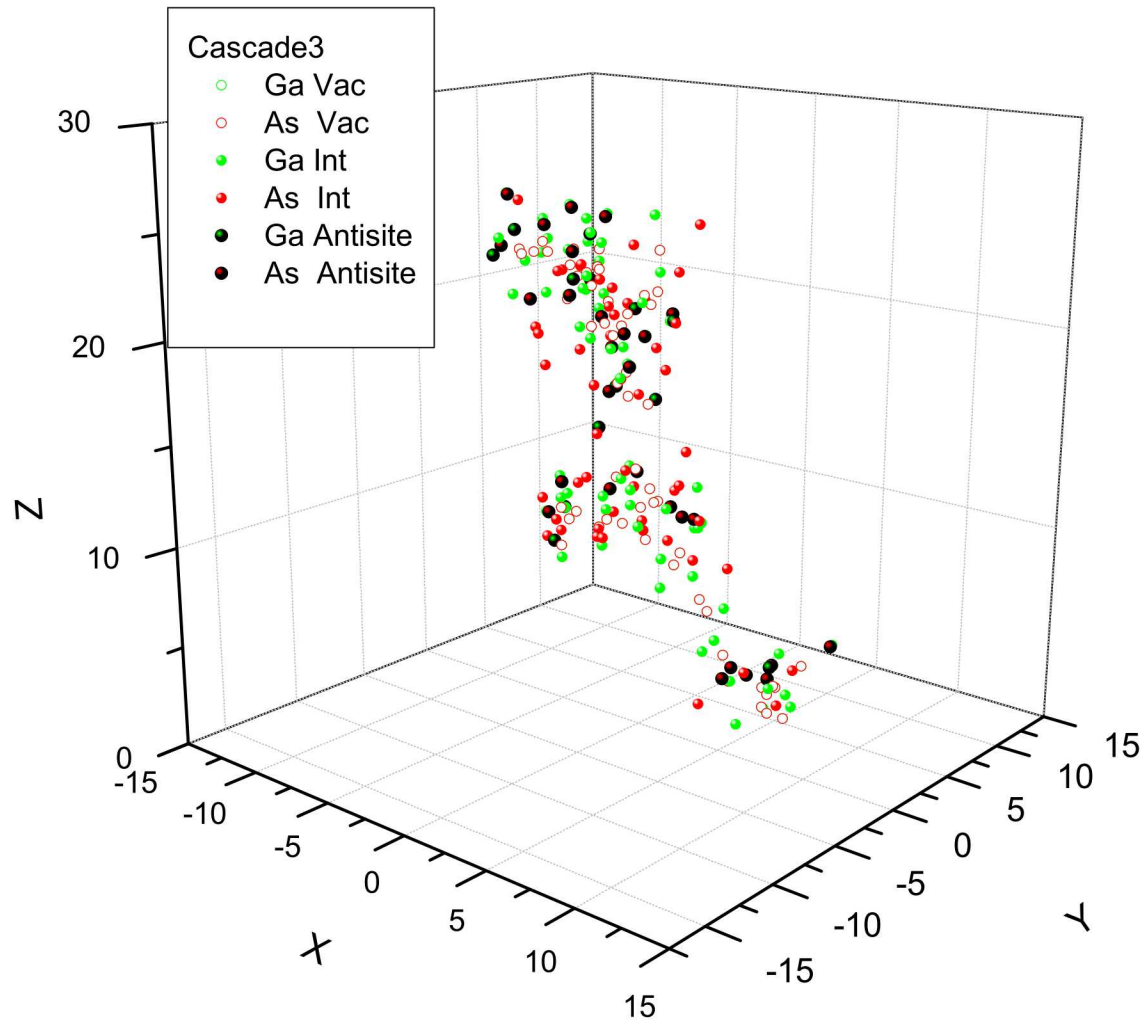
# 10 keV As into GaAs Cascade – Cascade #1



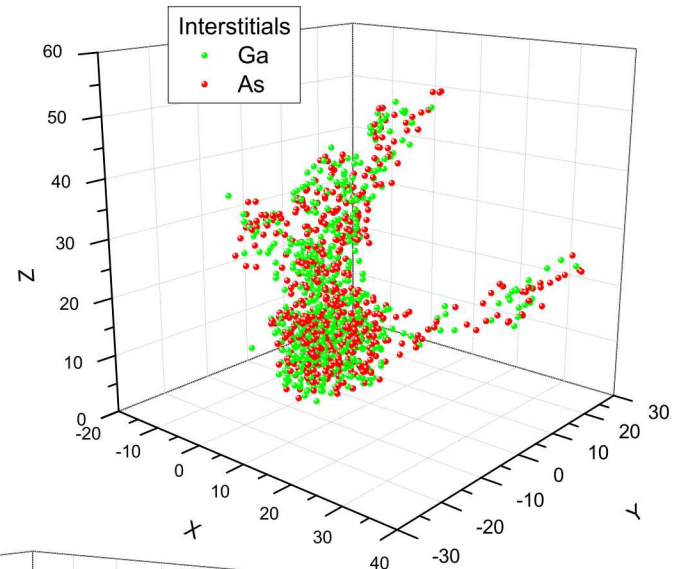
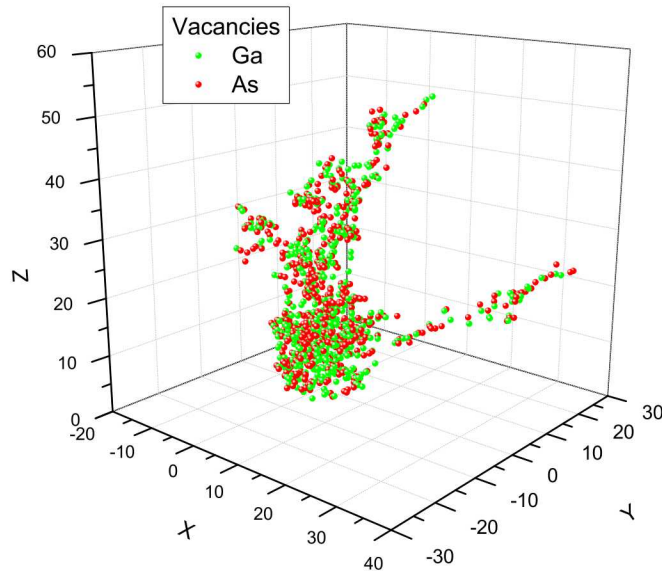
# 10 keV As into GaAs Cascade – Cascade #2



# 10 keV As into GaAs Cascade – Cascade #3

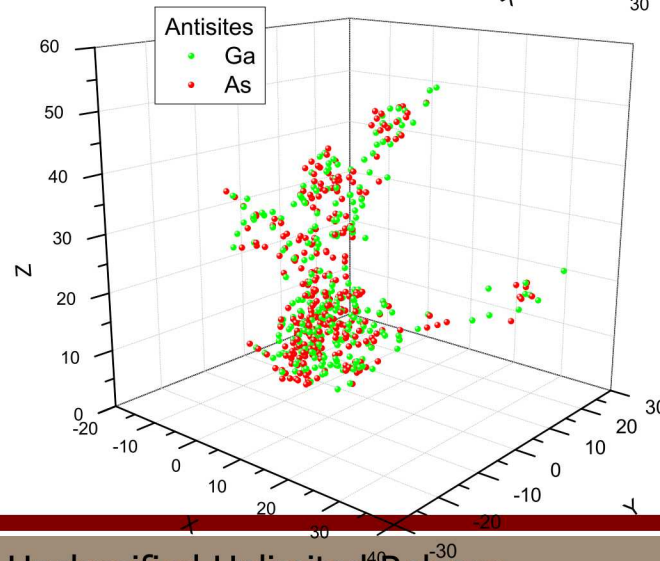


# MARLOWE 10 keV As recoil in GaAs



| # of defects in 10 cascades |     |     |
|-----------------------------|-----|-----|
|                             | Ga  | As  |
| Vacancy                     | 605 | 641 |
| Interstitial                | 624 | 622 |
| Antisite                    | 277 | 303 |

Spatial coordinates are in units of GaAs lattice constant=0.5653 nm  
Cluster diameter ~ 20 to 30 nm.



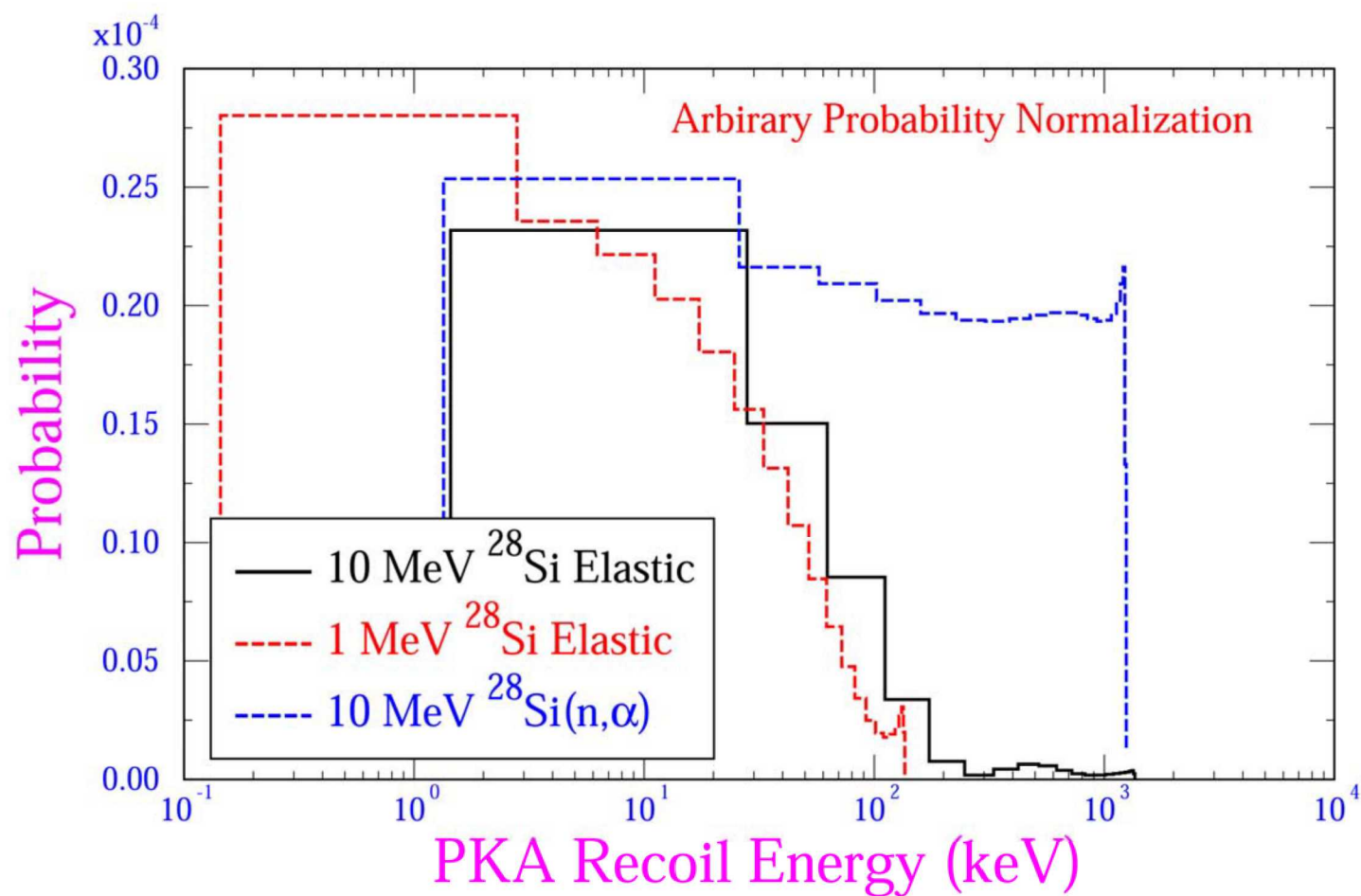
These plots show defects from 10 recoils summed together

# TOPIC: RECOIL SPECTRA

Recoil spectra are the foundation to the calculation of displacement kerma and damage partition between ionization and displacement.



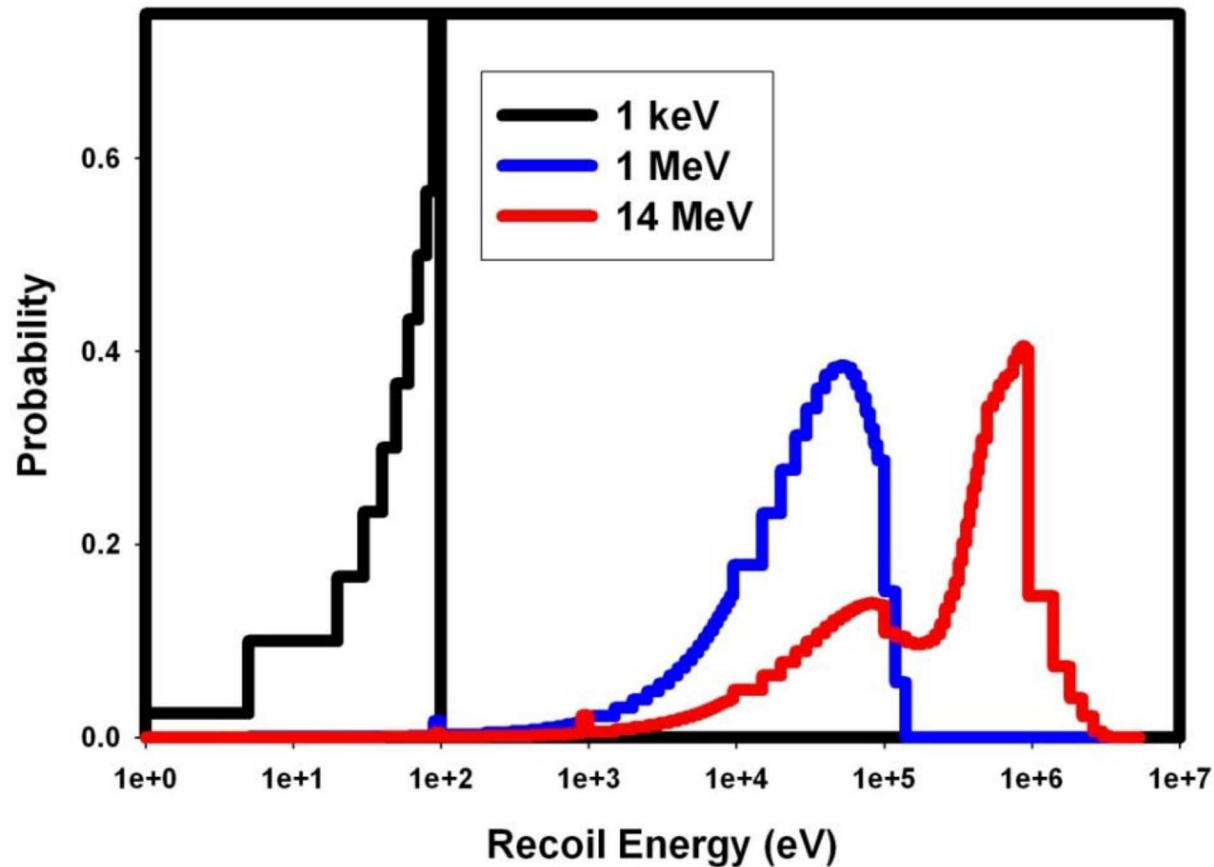
# Silicon Recoil Spectra



# Neutron Spectra → Recoil Spectra

## Mono-energetic Neutron

Max. recoil ion  
energy for elastic  
reactions

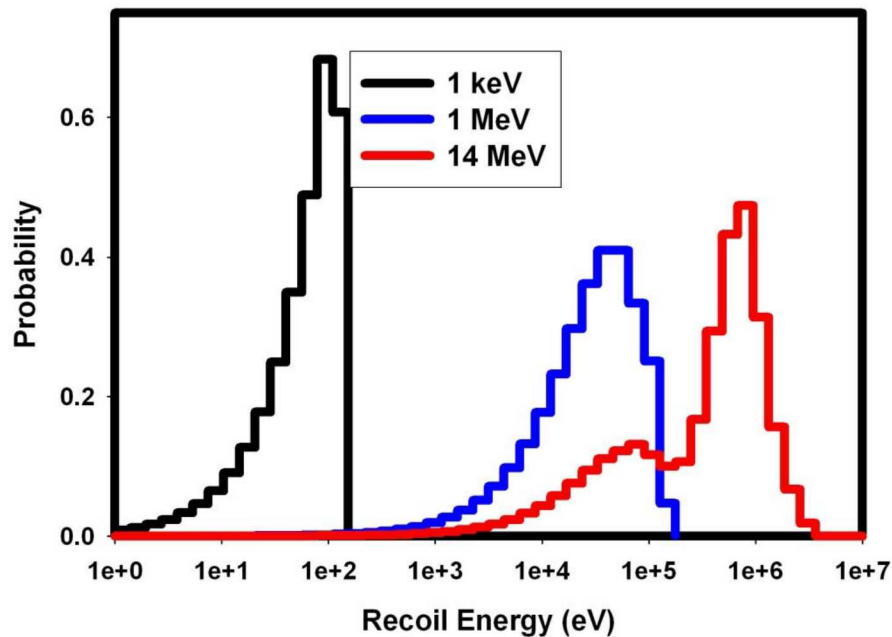


Silicon recoil with EMPIRE module

# Alternate Silicon Recoil Spectra Models



## EMPIRE module

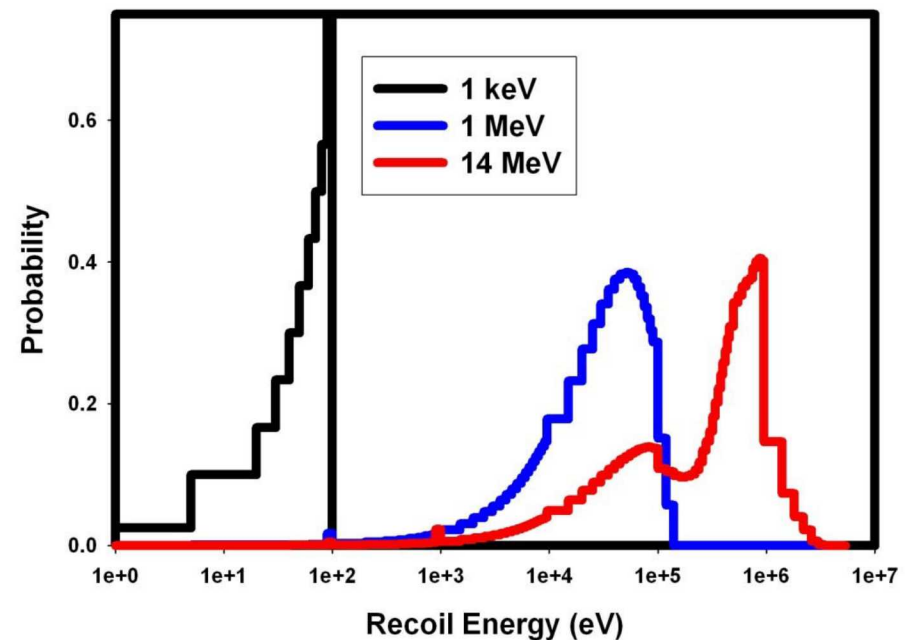


$$\langle E \rangle_{1\text{-kev}} = 70 \text{ eV}$$

$$\langle E \rangle_{1\text{-Mev}} = 41 \text{ keV}$$

$$\langle E \rangle_{14\text{-Mev}} = 569 \text{ keV} + 5.58 \text{ MeV } \alpha$$

## SPECTER module



$$\langle E \rangle_{1\text{-kev}} = 59 \text{ eV}$$

$$\langle E \rangle_{1\text{-Mev}} = 39 \text{ keV}$$

$$\langle E \rangle_{14\text{-Mev}} = 490 \text{ keV}$$

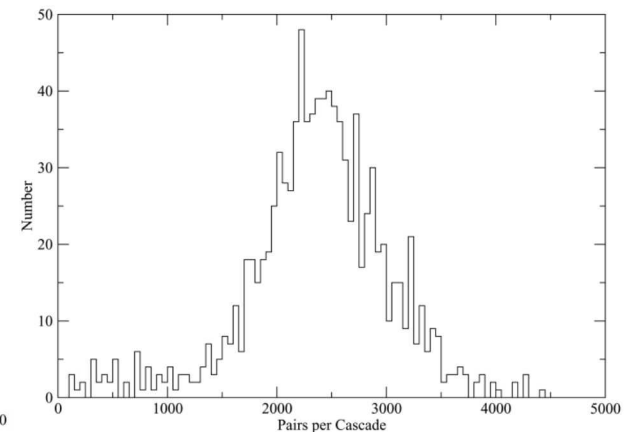
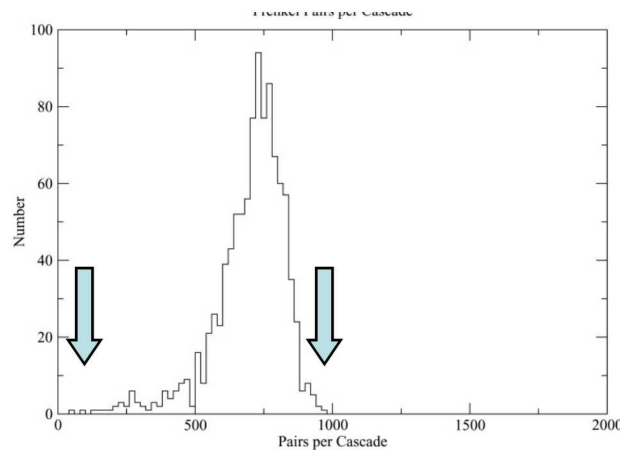
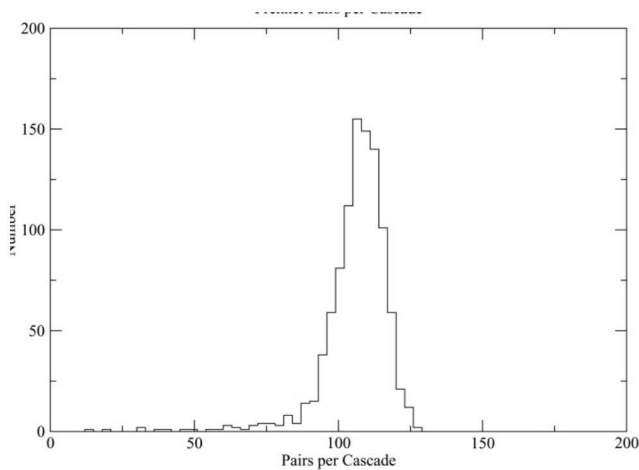
# Probability distribution for FP production for a given ion energy

pdf for number of FPs from three different silicon ion energies in silicon lattice.

10 keV  
 $\langle \text{FP} \rangle = 103$   
FWHM = 11.5

100 keV  
 $\langle \text{FP} \rangle = 680$   
FWHM = 129

1 MeV  
 $\langle \text{FP} \rangle = 2320$   
FWHM = 656

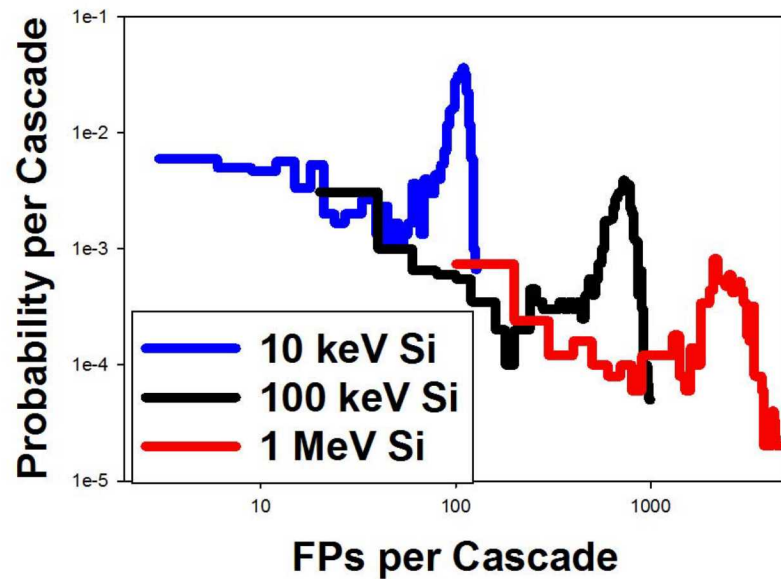


From P. J. Cooper

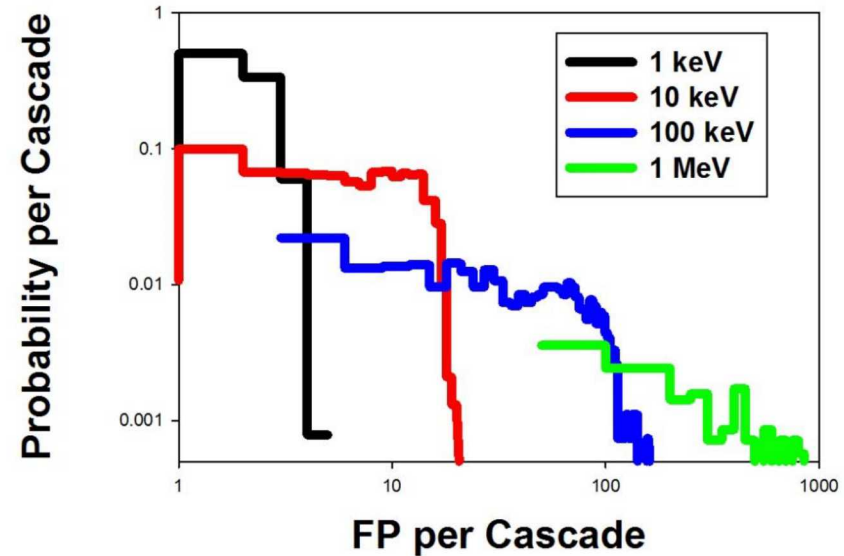
Selected cascades: ↓

# Ion & neutron Energies → FP Distribution in Si

**Mono-energetic Si Ions**  
10, 100, 1000 keV



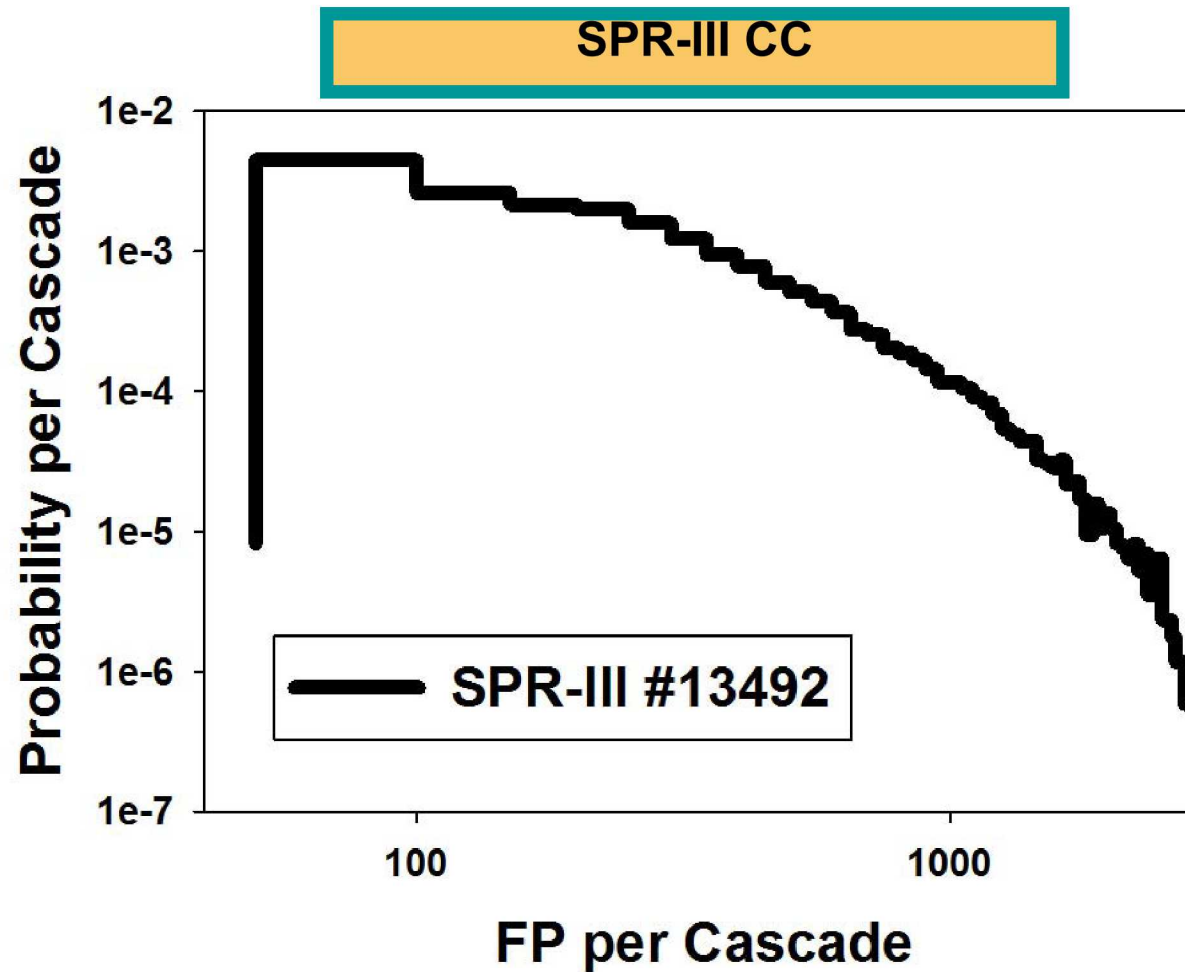
**Mono-energetic Neutrons:**  
1 keV, 10 keV, 100 keV, 1 MeV



**Silicon recoil with SPECTER module**



## Neutron Spectra → FP Distribution



Silicon recoil with SPECTER module

# TOPIC:

# ENERGY DEPOSITION IN MATERIALS

Energy from neutron interactions can go into ionization or displacement. There is a big difference between total dose and ionizing dose in mixed neutron/gamma radiation fields.

# n/γ Environment in ACRR Central Cavity Irradiation



| Matl.                    | Neutron Kerma | Gamma Kerma | % Dose from neutrons |
|--------------------------|---------------|-------------|----------------------|
| Alanine                  | 469.2         | 208.2       | 69%                  |
| Diamond                  | 74.3          | 192.9       | 28%                  |
| Silicon                  | 16.0          | 203.2       | 7%                   |
| CaF <sub>2</sub> :Mn TLD | 31.45         | 202.4       | 13%                  |

## n/γ dose components?

- photon component varies with Z
- neutron component varies with hydrogen content

Only some of the energy is deposited as ionization!

| Energy Loss Mechanism,<br>(50 keV Si ion in Si lattice, range = 736 A, straggle = 290 A) | % Energy Loss |              |
|------------------------------------------------------------------------------------------|---------------|--------------|
|                                                                                          | Primary Ion   | Recoil Atoms |
| Ionization                                                                               | 30.50         | 25.67        |
| Vacancies                                                                                | 0.23          | 3.38         |
| Phonons                                                                                  | 0.77          | 39.44        |

# Silicon energy partition for reactor spectrum

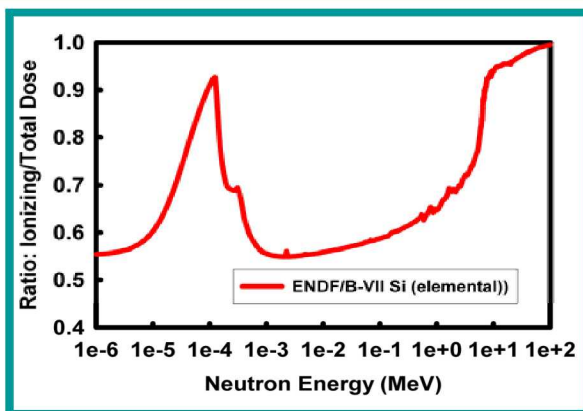


- Total Dose  $\neq$  Ionizing Dose
- Correction factor used for Si PIN

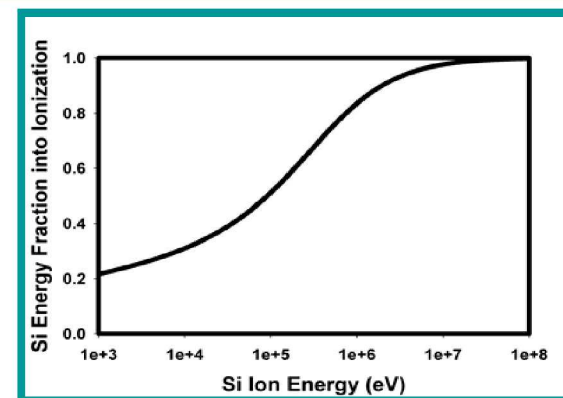
## Si Neutron Response

| Spectrum    | % n-dose | % n- dose Ionizing | % Effect on Rsp. |
|-------------|----------|--------------------|------------------|
| SPR-III CC  | 24.7     | 56.74              | 14.0             |
| WSMR FBR 6" | 32.9     | 57.4               | 18.9             |
| ACRR CC     | 7.32     | 55.66              | 4.07             |
| ACRR Pb-B   | 26.8     | 52.95              | 14.2             |

## Si Neutron Ionization/Total Dose



## Si Ion Ionization/Total Dose



# Carbon energy partition for reactor spectrum

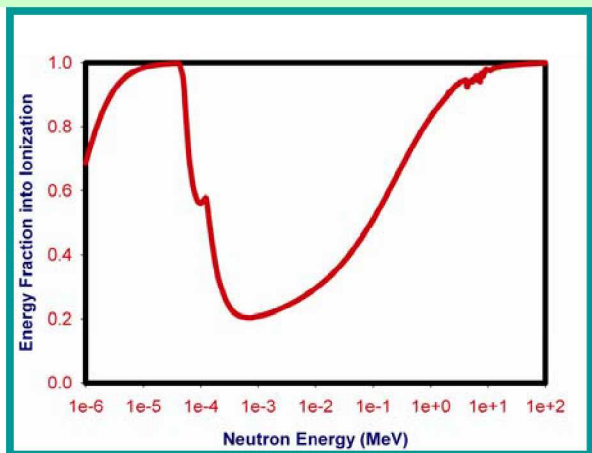


- Total Dose  $\neq$  Ionizing Dose
- Correction factor for Si PIN

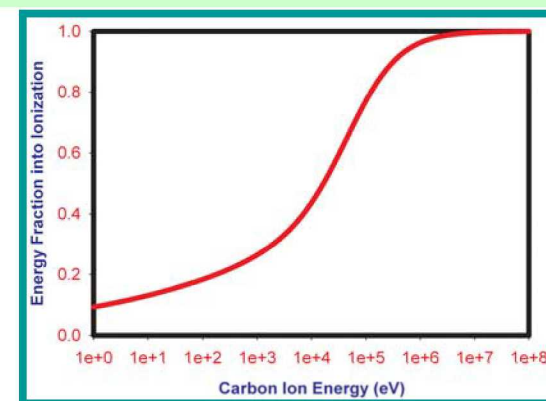
## Carbon PCD Neutron Response

| Spectrum    | % n-dose | % n- dose ionizing | % Effect on Rsp. |
|-------------|----------|--------------------|------------------|
| SPR-III CC  | 59       | 77                 | 14               |
| SPR-III 17" | 69       | 77                 | 16               |
| ACRR CC     | 27       | 61                 | 11               |
| ACRR Pb-B   | 68       | 63                 | 25               |

## C Neutron Ionization/Total Dose



## C Ion Ionization/Total Dose





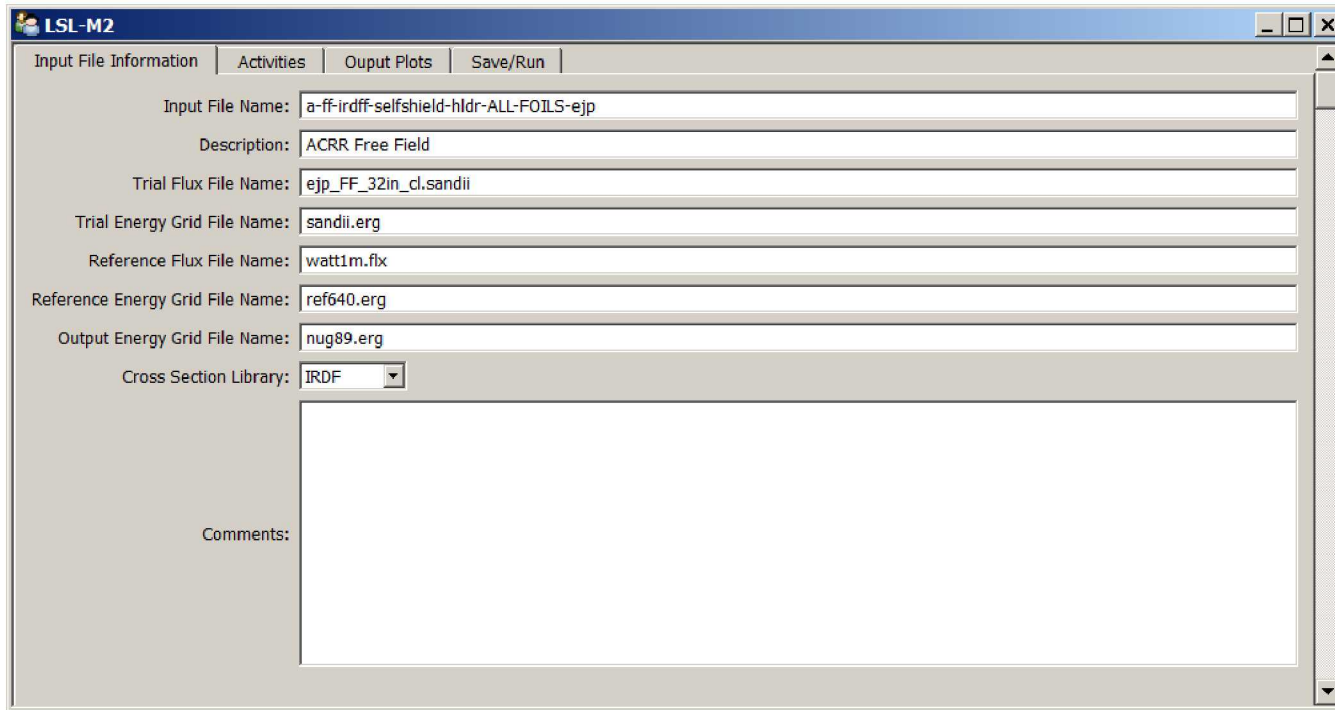
# **TOPIC:**

## **SCREENSHOTS FROM COMPUTER DEMONSTRATION OF SNL SOFTWARE USED FOR SPECTRUM CHARACTERIZATION/UNFOLD**

Sandia has modified some openly available software to support the neutron spectrum characterization at our research reactors. One example is the Perl and Python interfaces to the least squares adjustment code, LSL-M2.

We have also applied modern genetic algorithm to the neutron spectrum characterization/unfold problem.

# LSL-M2 with Perl/Python Wrapper



The screenshot shows the LSL-M2 software interface with the following fields and values:

| Field                            | Value                                    |
|----------------------------------|------------------------------------------|
| Input File Name:                 | a-ff-irdff-selfshield-hldr-ALL-FOILS-ejp |
| Description:                     | ACRR Free Field                          |
| Trial Flux File Name:            | ejp_FF_32in_cl.sandii                    |
| Trial Energy Grid File Name:     | sandii.erg                               |
| Reference Flux File Name:        | watt1m.flx                               |
| Reference Energy Grid File Name: | ref640.erg                               |
| Output Energy Grid File Name:    | nug89.erg                                |
| Cross Section Library:           | IRDF                                     |
| Comments:                        |                                          |

LSL-M2

Input File Information   Activities   Output Plots   Save/Run

Ag109g  
Number of Foils: 0

Al27a  
Number of Foils: 1   Self-shielding/Cover 1: ml3x-bahl   Activity 1: 6.1585e-18   % STD 1: 0.023   Normalize to Al27a: ☐

Al27p  
Number of Foils: 0

Au197g  
Number of Foils: 2   Self-shielding/Cover 1: dil3-cdhl   Activity 1: 4.7342e-13   % STD 1: 0.032   Normalize to Au197g: ☐  
Self-shielding/Cover 2: dil3-bahl   Activity 2: 5.6538e-13   % STD 2: 0.032

Co59g  
Number of Foils: 0

Co59p  
Number of Foils: 1   Self-shielding/Cover 1: ml2-cdhl   Activity 1: 1.7965e-19   % STD 1: 0.058   Normalize to Co59p: ☐

Co592  
Number of Foils: 0

Cr522  
Number of Foils: 0

Cu63a  
Number of Foils: 0

Cu63g  
Number of Foils: 0

Cu652  
Number of Foils: 0

Fe54p  
Number of Foils: 1   Self-shielding/Cover 1: ml5-bahl   Activity 1: 1.6954e-18   % STD 1: 0.022   Normalize to Fe54p: ☐

Fe56p  
Number of Foils: 1   Self-shielding/Cover 1: ml5-bahl   Activity 1: 5.8136e-17   % STD 1: 0.018   Normalize to Fe56p: ☐

Fe58g  
Number of Foils: 2   Self-shielding/Cover 1: ml5-bahl   Activity 1: 8.327e-17   % STD 1: 0.022   Normalize to Fe58g: ☐

LSL-M2

Input File Information   Activities   Output Plots   Save/Run

Adjusted and Original Spectrum: ☒

Percent Standard Deviation Before and After: ☒

Percent Adjusted: ☒

Relative Contributions to Reaction Probabilities: ☒

Correlation Coefficient Matrix Comparison: ☒

LSL-M2

Input File Information   Activities   Output Plots   Save/Run

Save file

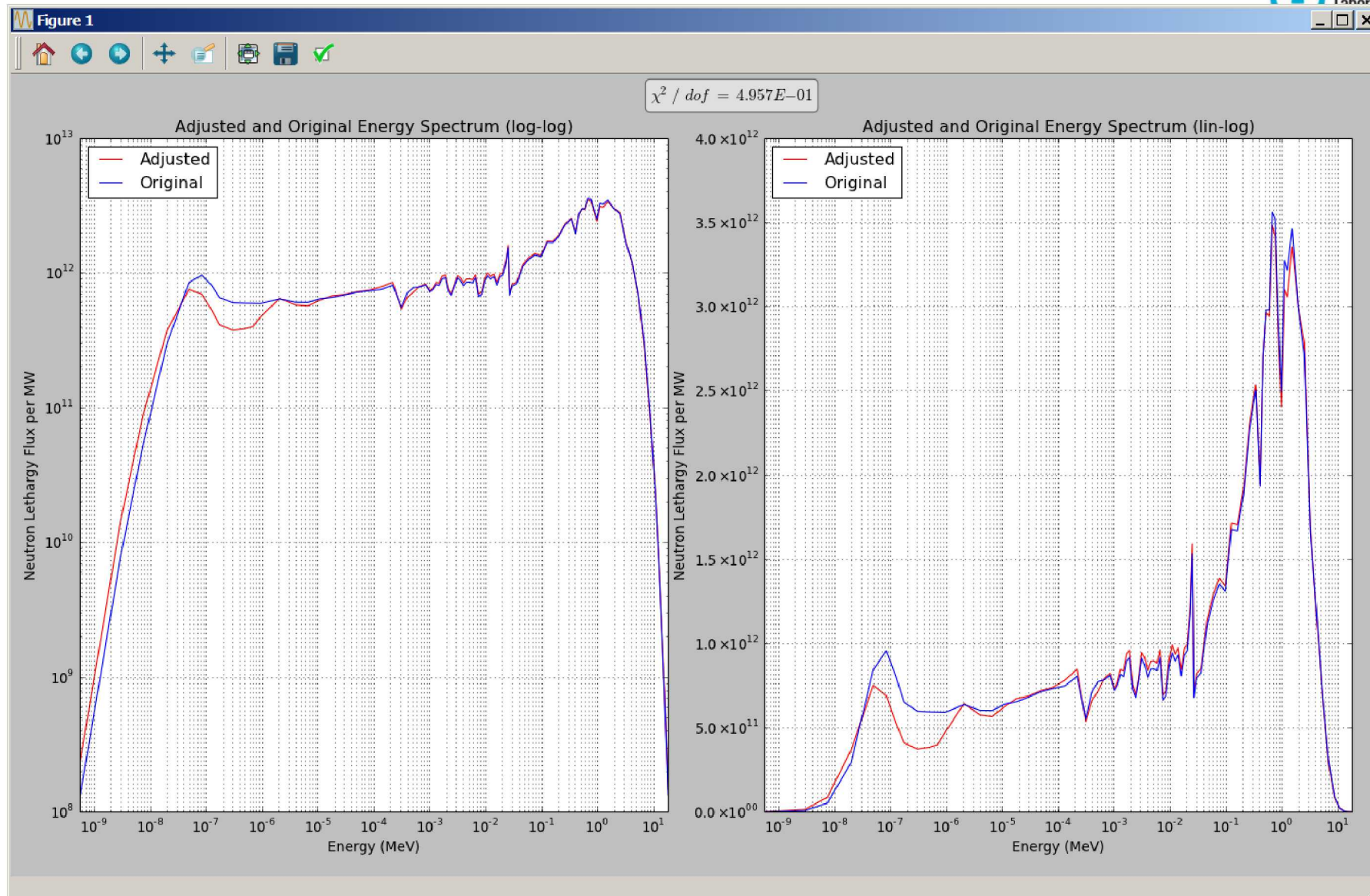
Run wo plots: ☐

Run plots: ☒

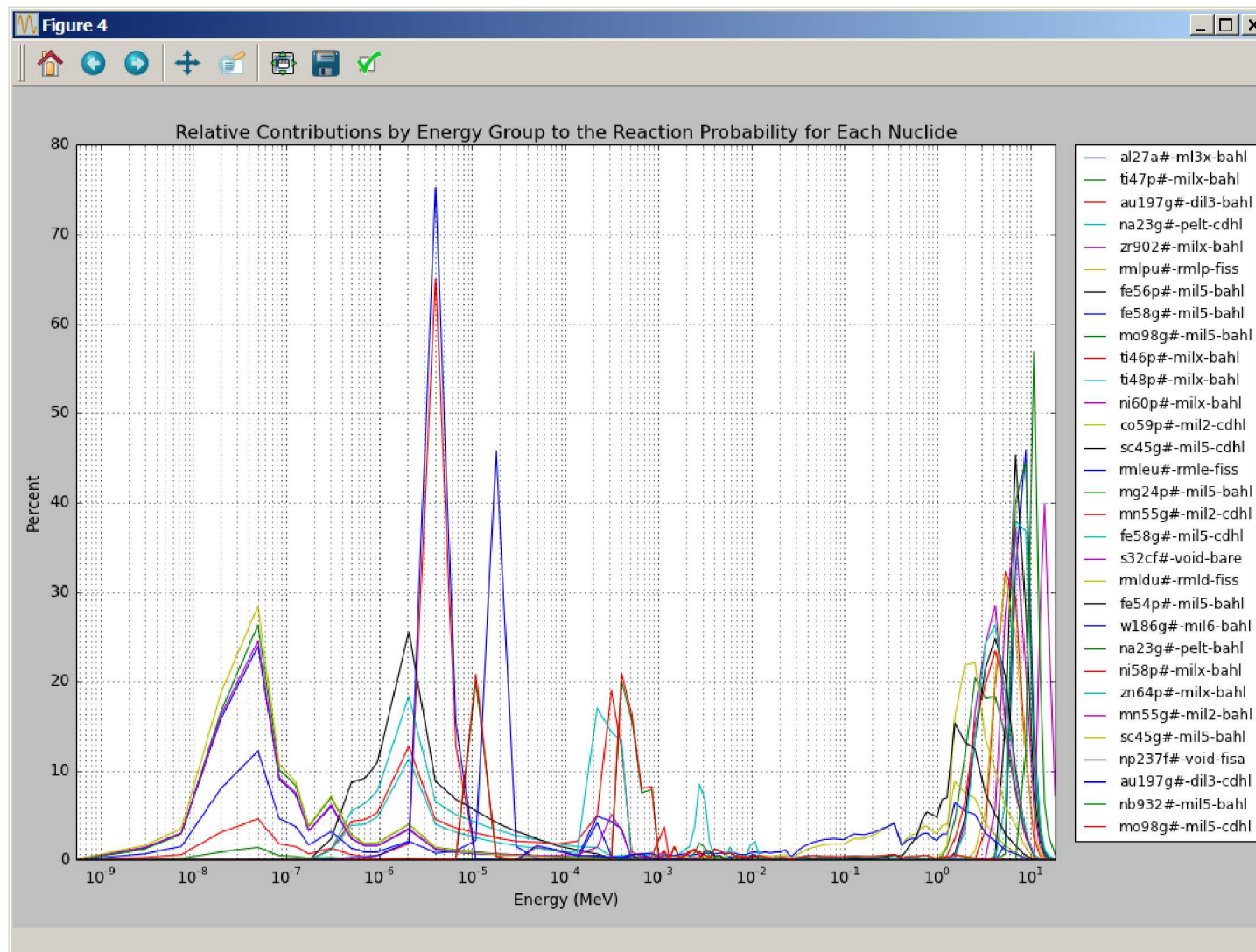
Run

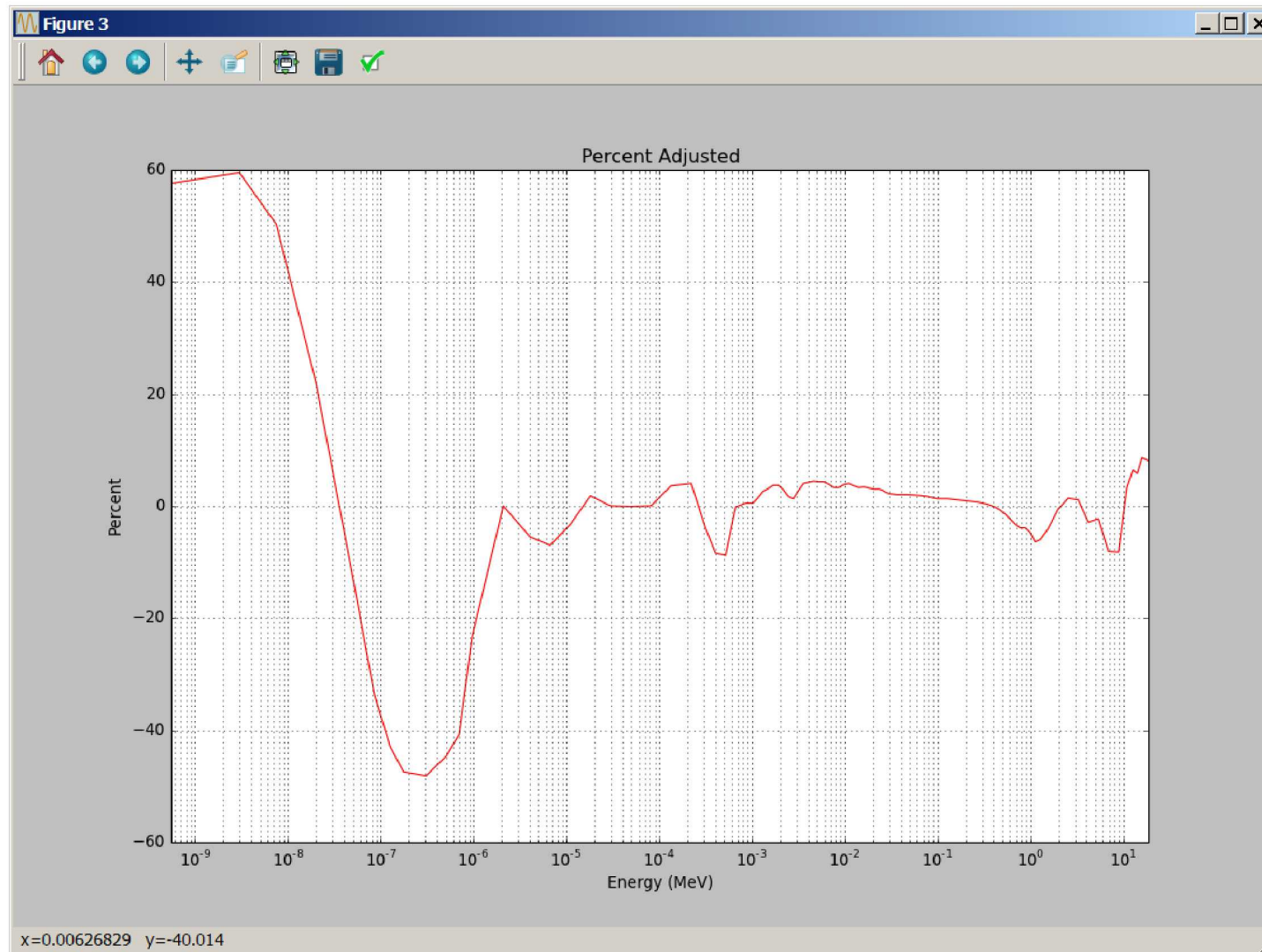
OR

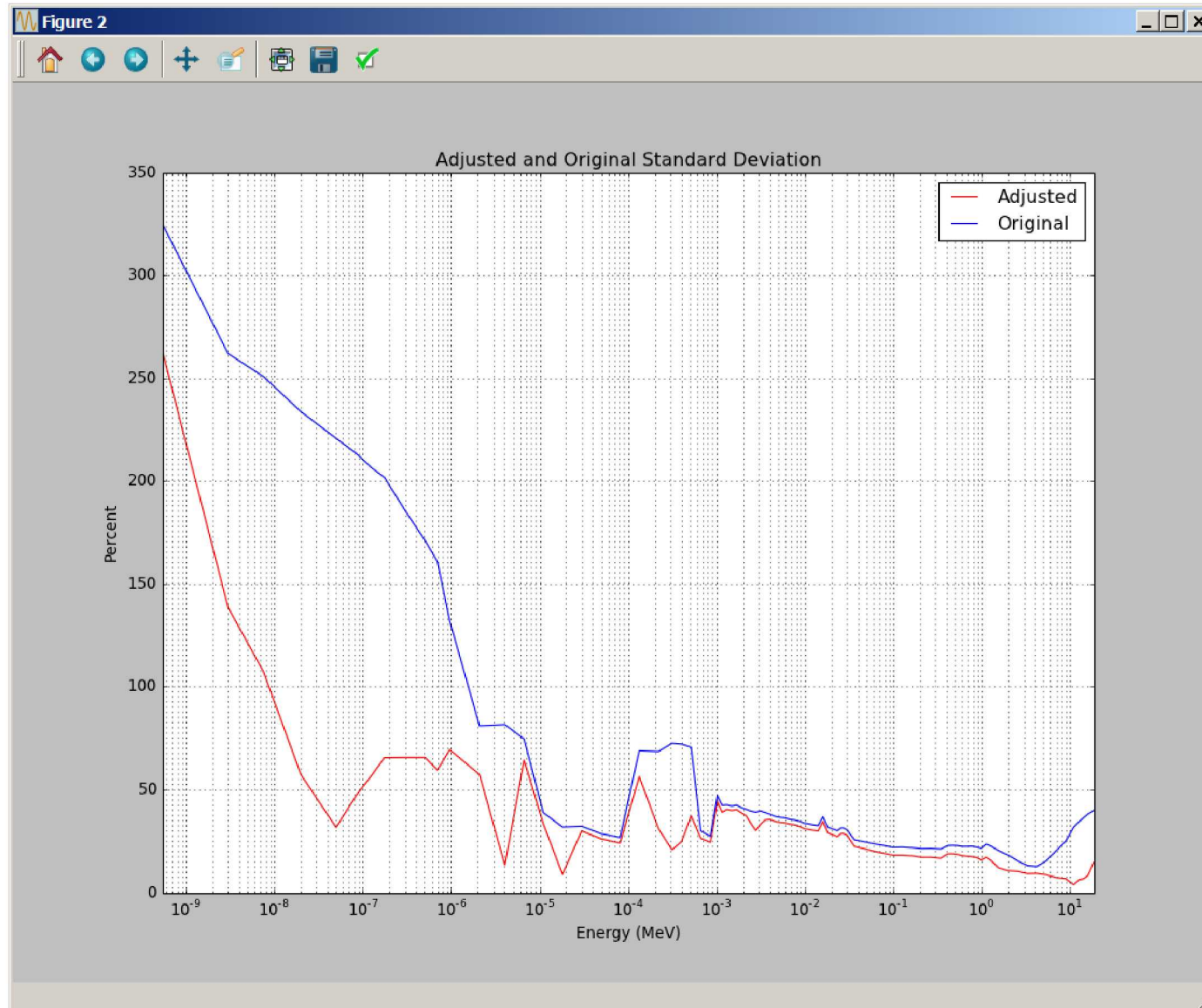
Run from text file   Text file:

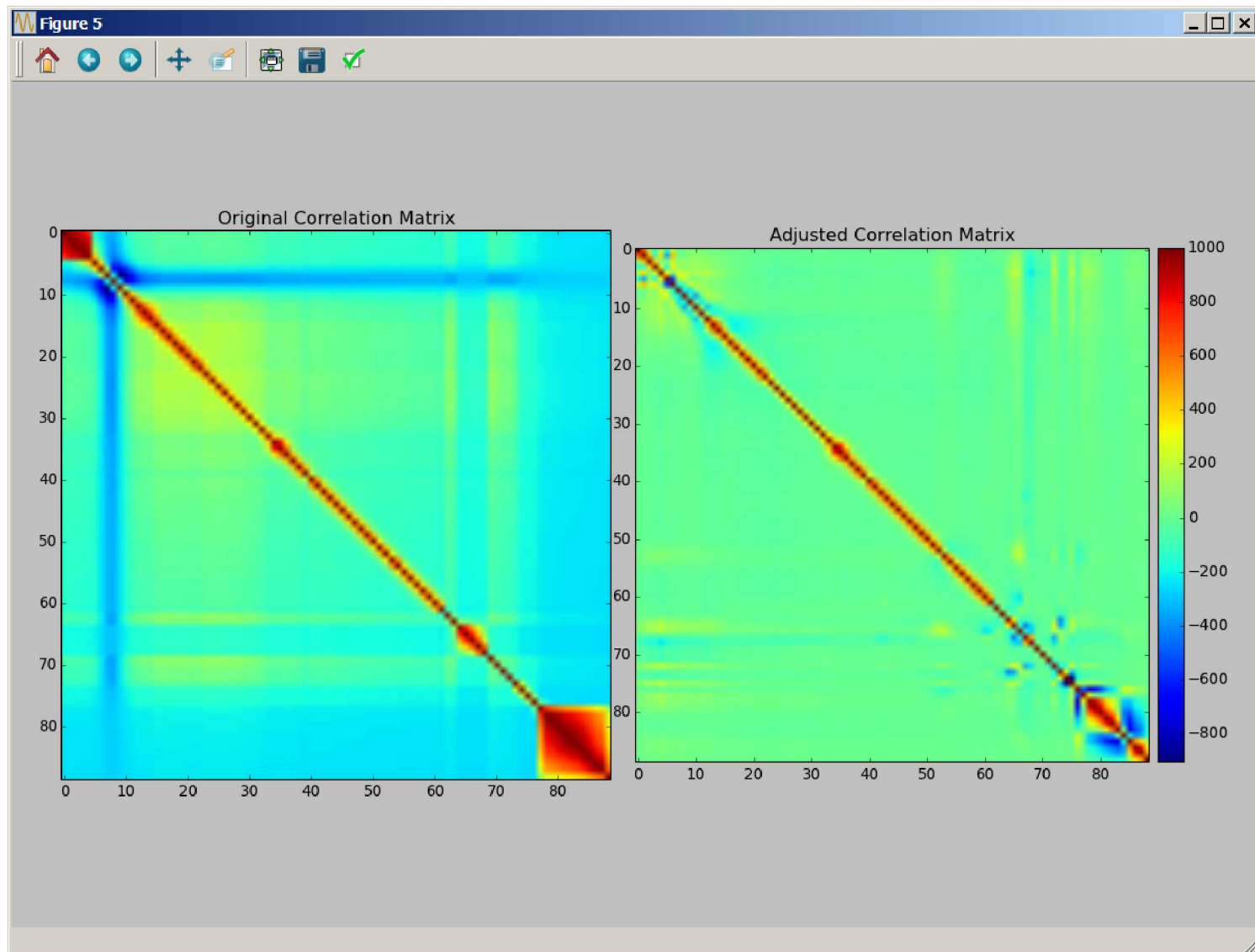






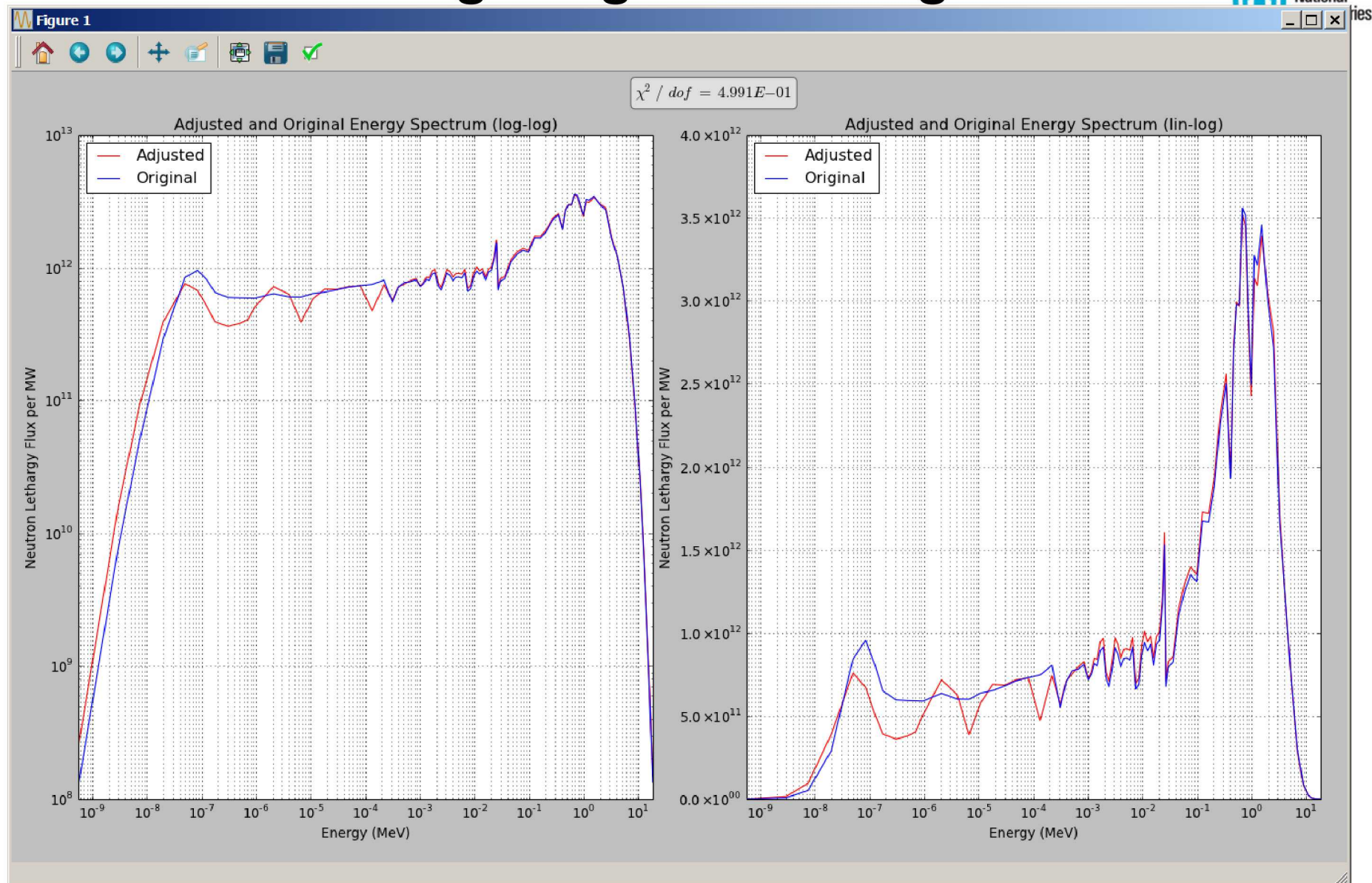




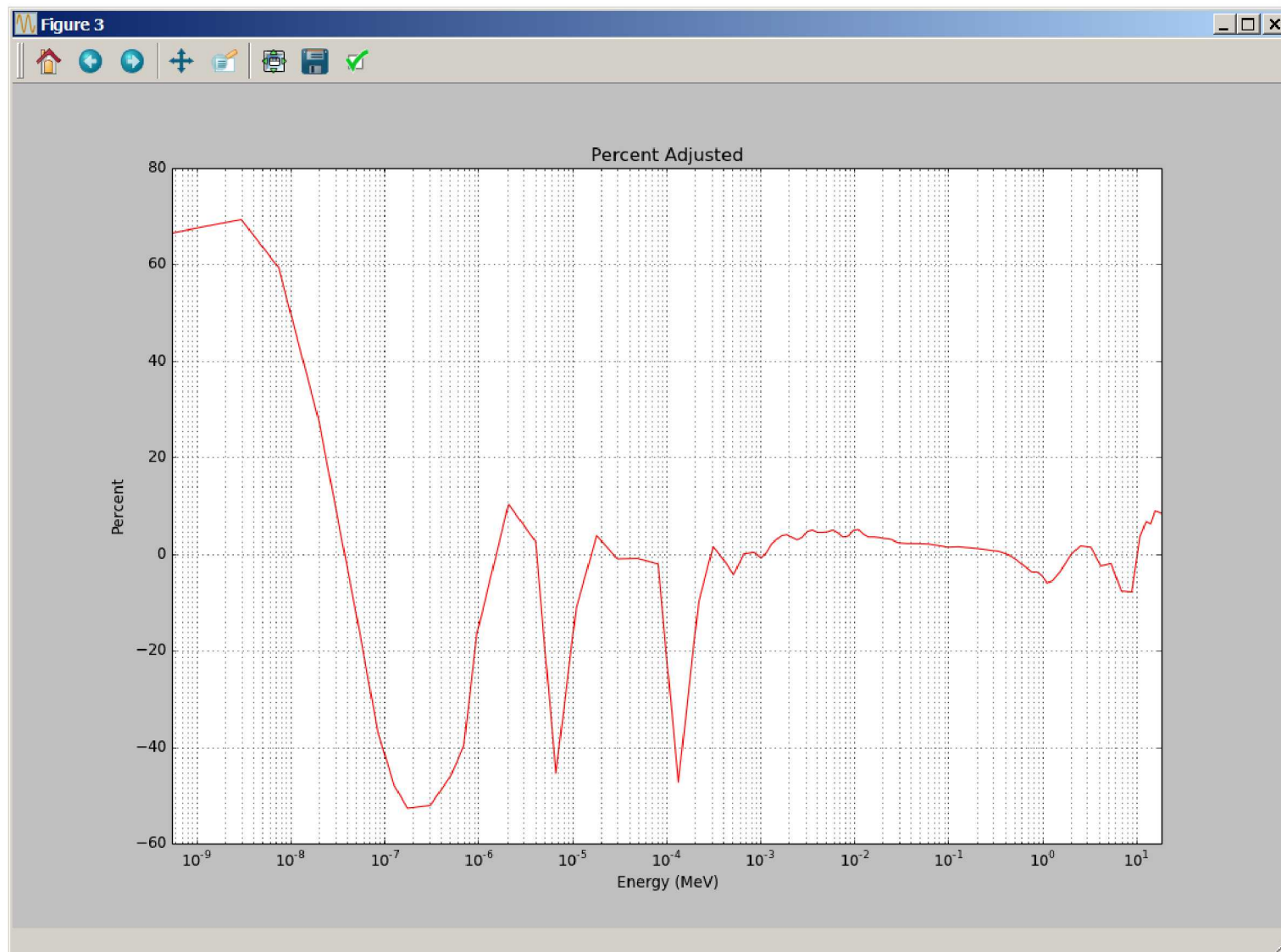




# With Ag-109g and Co-59g

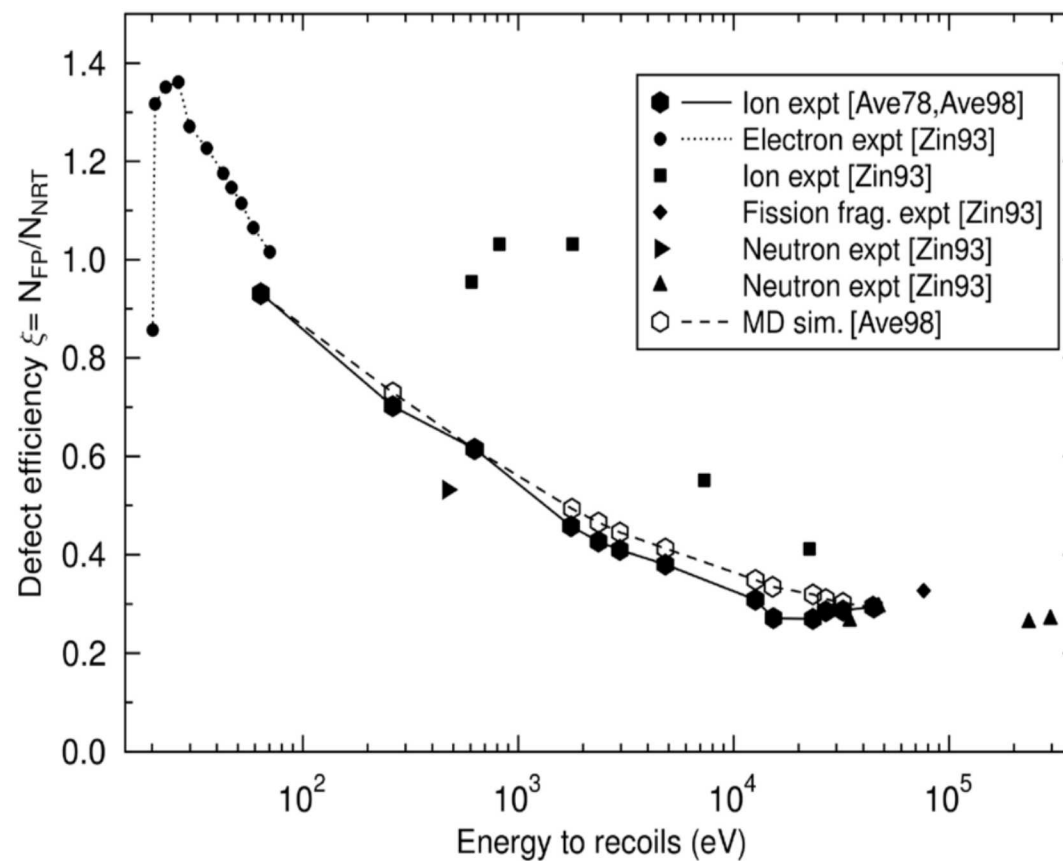




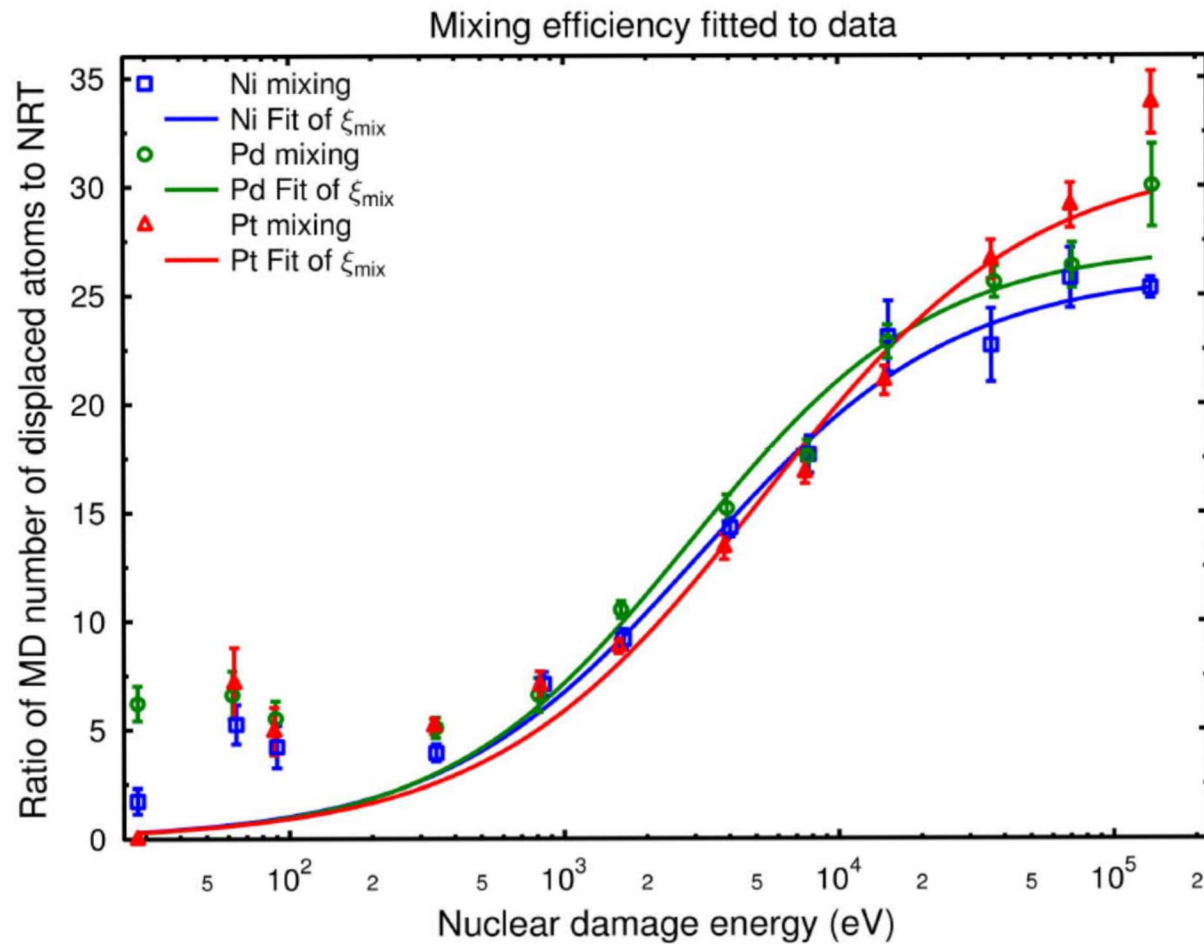


# MISCELLANEOUS MATERIAL

# Energy Dependence of the Defect Efficiency for Ions in Cu

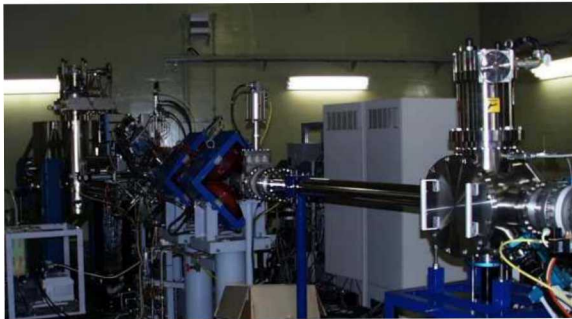


# Calculated rpa Efficiency Factors and Fits in Ion Beam Mixing for Metals



# Types of SEU Simulation Facilities

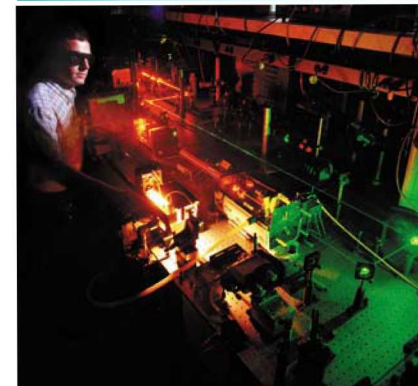
## Heavy Ions



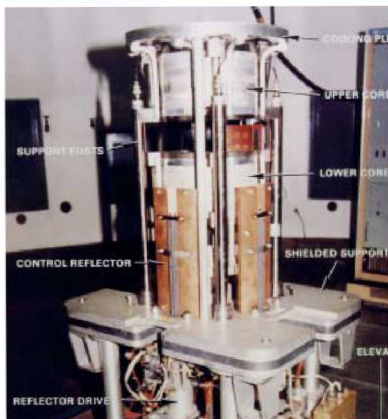
## $^{252}\text{Cf}$ Fission



## Laser

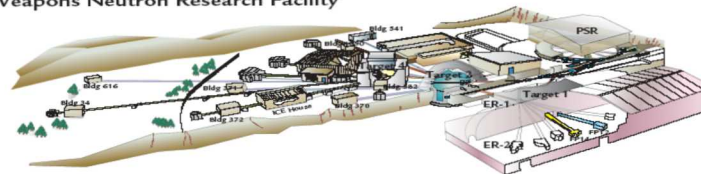


## Reactor Neutron



## Spallation Neutron

Weapons Neutron Research Facility



## 14-MeV Neutron





# Number of Calculated Cascades in Active Volume

| Device<br>[Active Area(E) x<br>Thickness(B)]                        | Scenario<br>#Cascades and Cascades/( $\mu\text{m}^3$ ) |                                    |                                    |
|---------------------------------------------------------------------|--------------------------------------------------------|------------------------------------|------------------------------------|
|                                                                     | SPR-III<br>Shot 13492                                  | WSMR FBR<br>Shot 17769             | ACRR PbB<br>Shot 9374              |
| <b>Si: 2C2222A</b><br>(34100 $\mu\text{m}^2$ x 3.25 $\mu\text{m}$ ) | 7.75E6<br>70.0/( $\mu\text{m}^3$ )                     | 1.40E6<br>12.6/( $\mu\text{m}^3$ ) | 1.10E7<br>99.2/( $\mu\text{m}^3$ ) |
| <b>Si: BFR90A</b><br>(394 $\mu\text{m}^2$ x 0.56 $\mu\text{m}$ )    | 1.54E4<br>70.0/( $\mu\text{m}^3$ )                     | 2780.<br>12.6/( $\mu\text{m}^3$ )  | 2.19E4<br>99.2/( $\mu\text{m}^3$ ) |
| <b>GaAs: npn</b>                                                    | 132.<br>83.7/( $\mu\text{m}^3$ )                       | 23.4<br>14.88/( $\mu\text{m}^3$ )  | 408.<br>259/( $\mu\text{m}^3$ )    |
| <b>GaAs: pnp</b>                                                    | 1569.<br>83.7/( $\mu\text{m}^3$ )                      | 279.<br>14.88/( $\mu\text{m}^3$ )  | 4856.<br>259/( $\mu\text{m}^3$ )   |

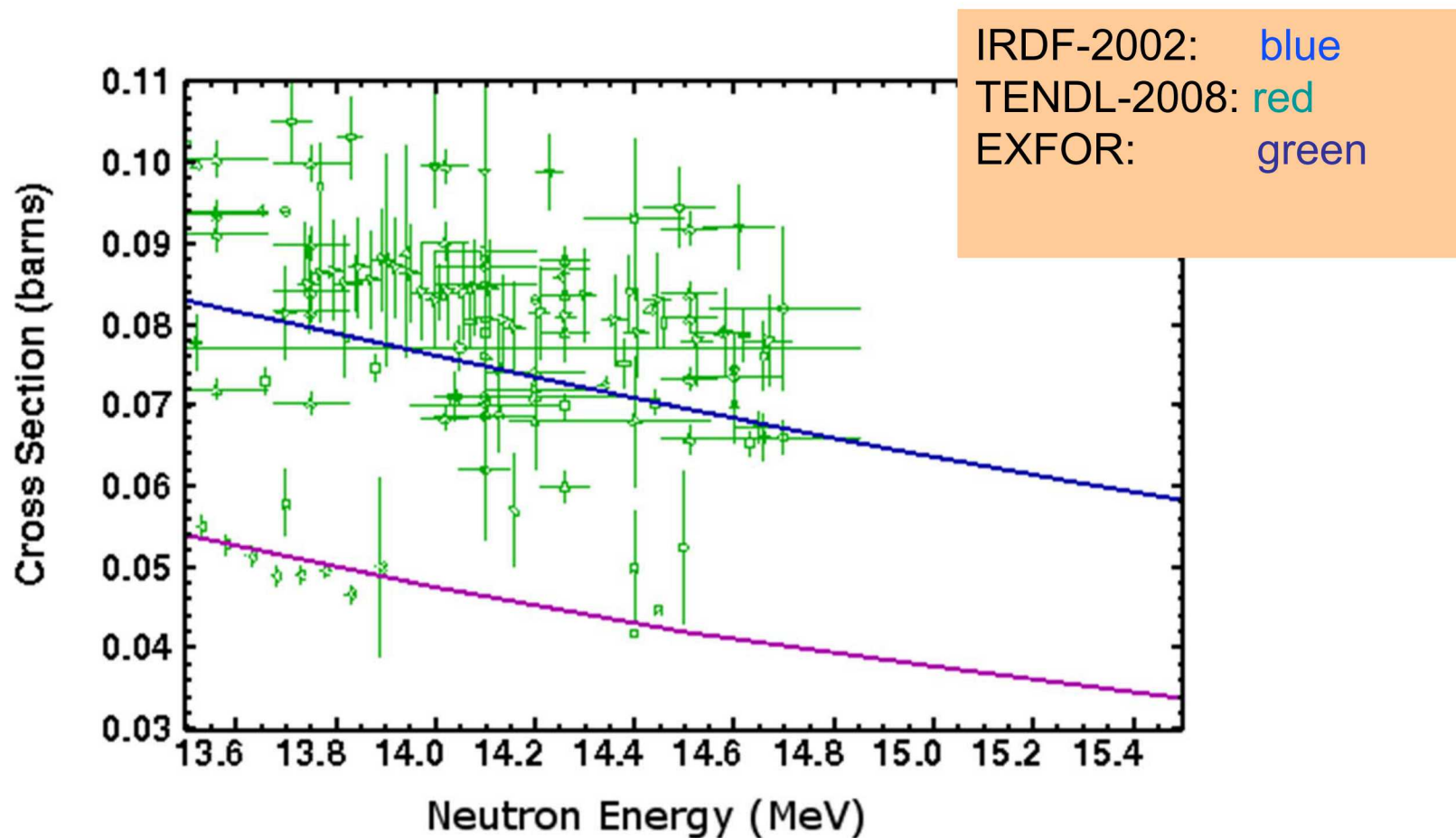
Note: ACRR PbB is a softer spectrum and requires more cascades to produce the same FP density.

# Questions

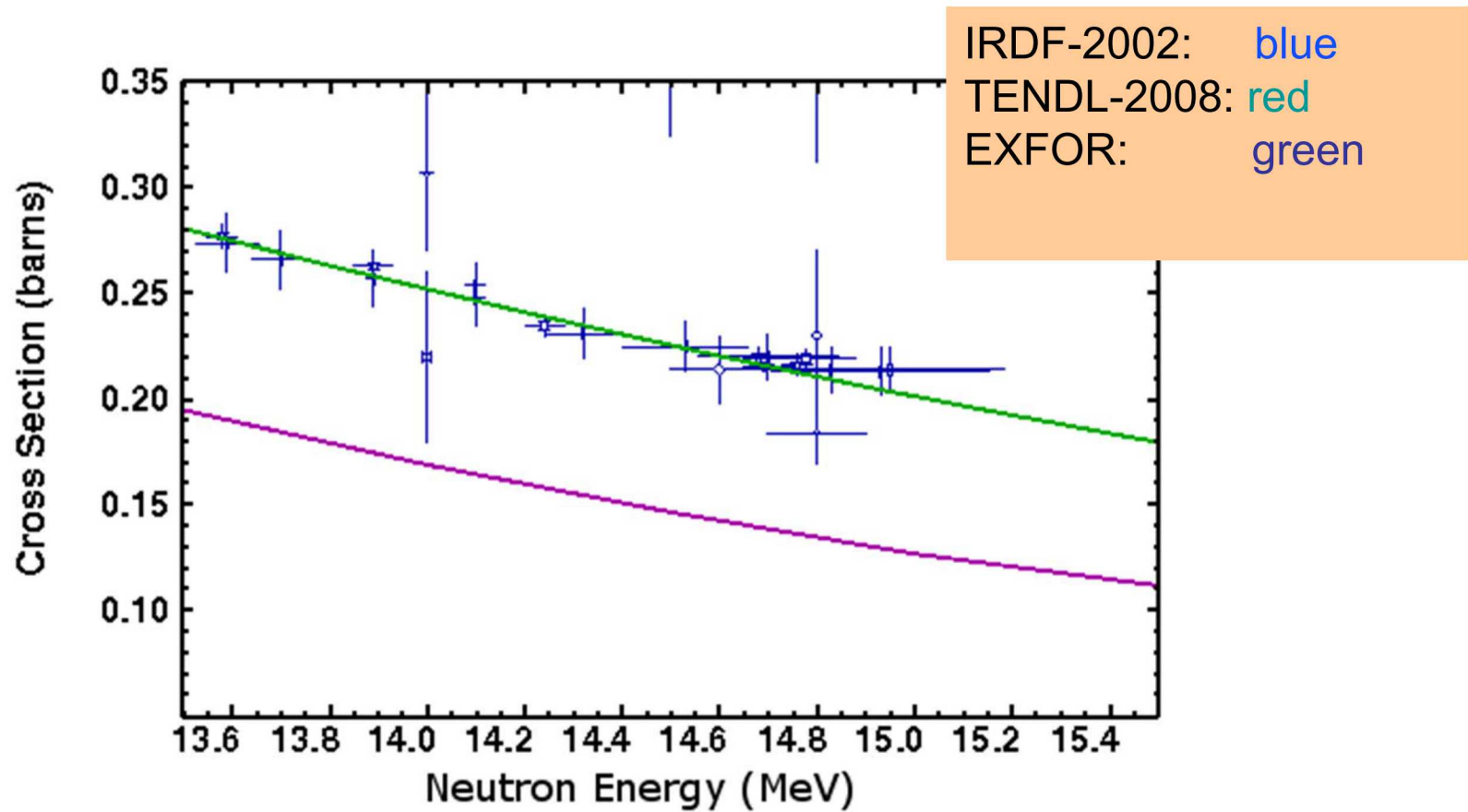


# Back-up Material

## $^{27}\text{Al}(n,p)$ Cross Section

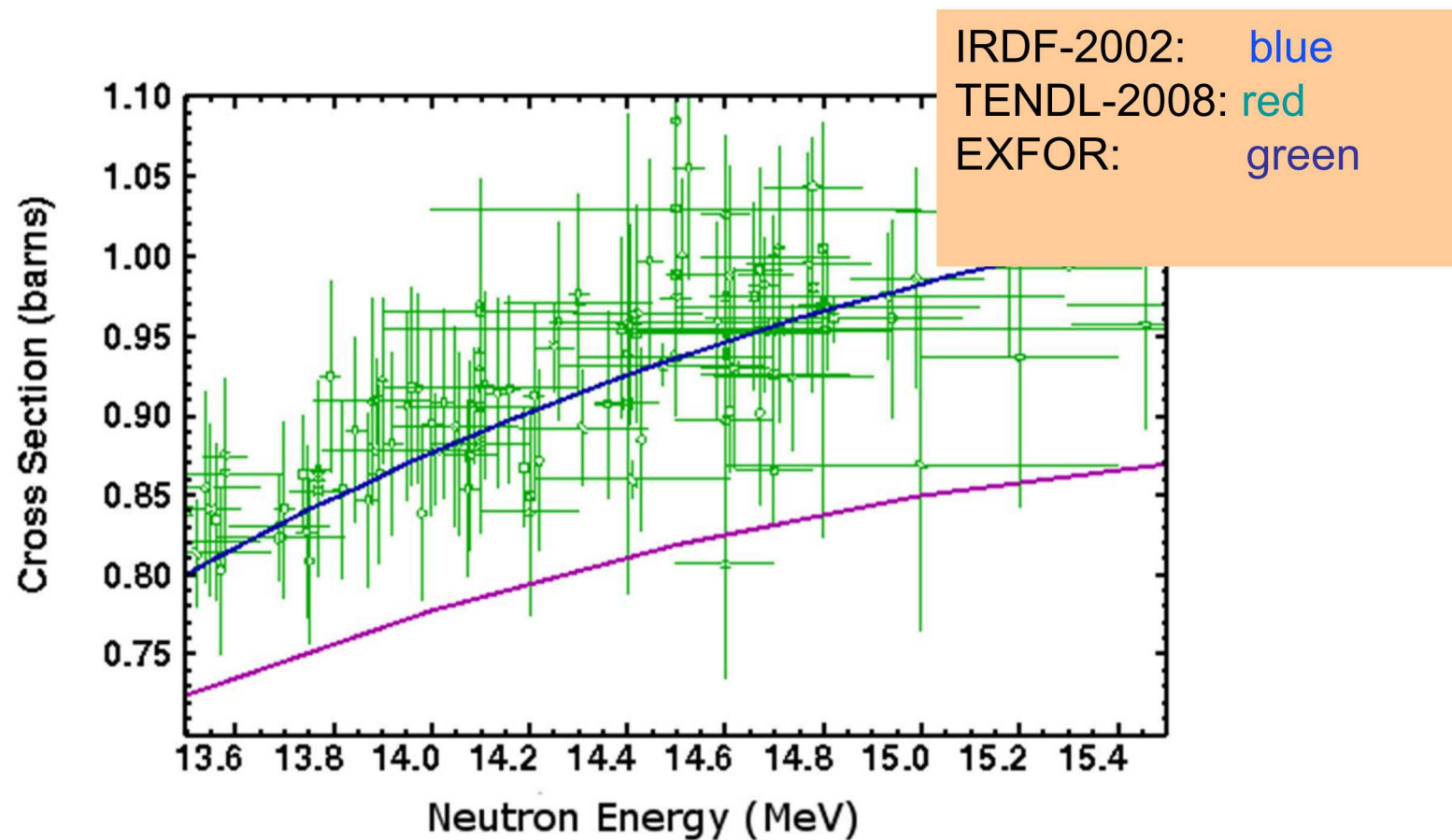


# $^{32}\text{S}(n,p)$ Cross Section

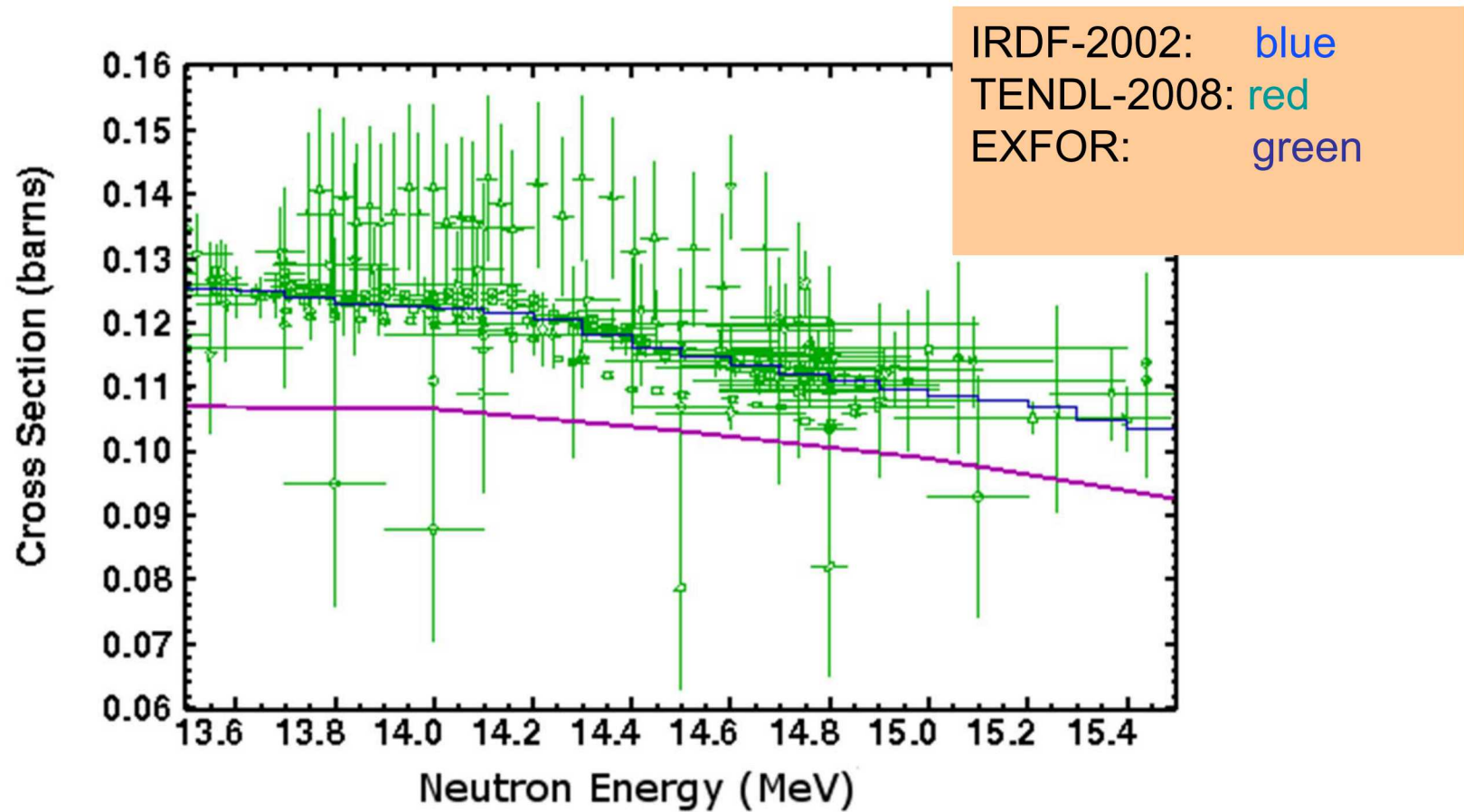




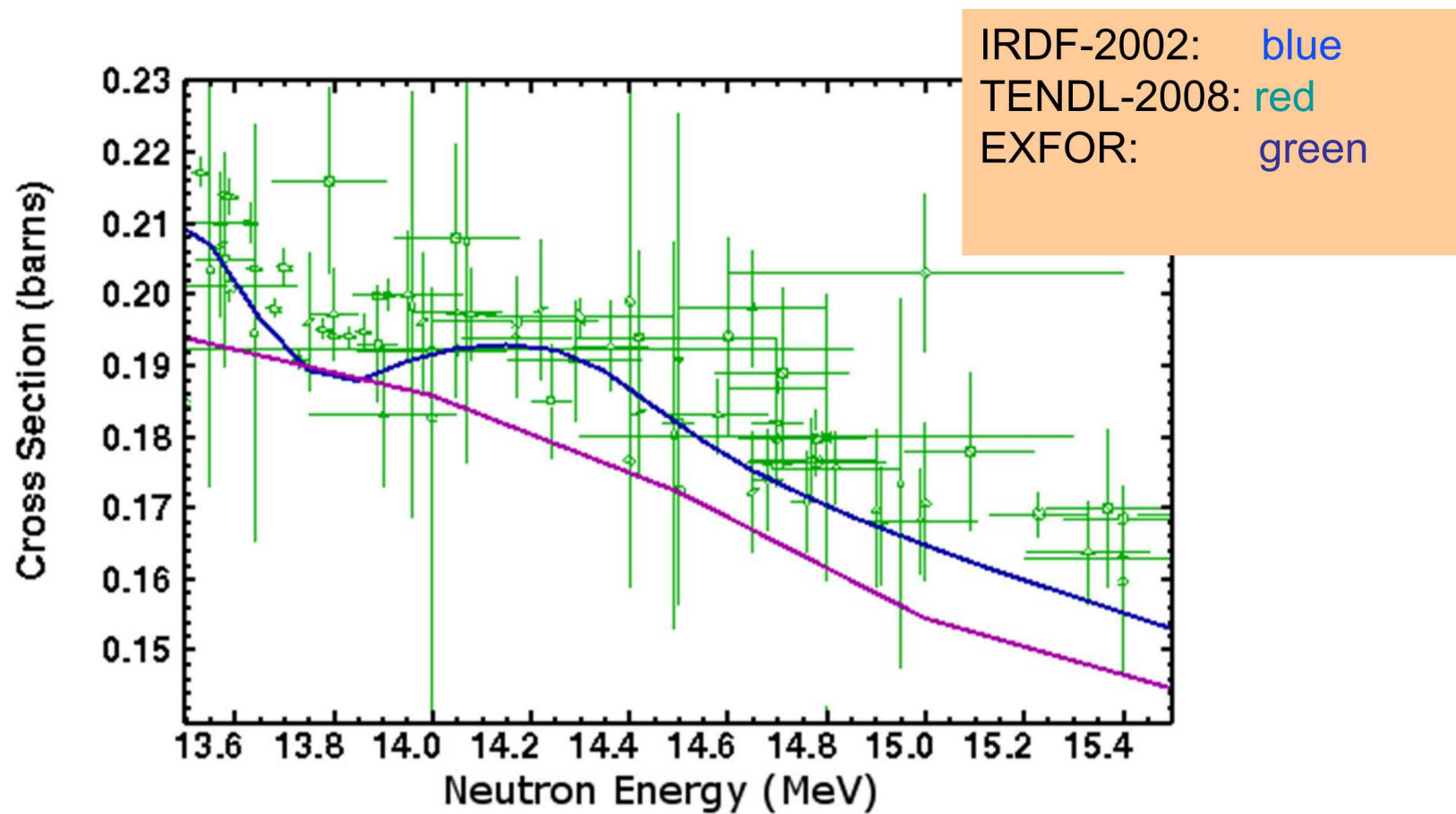
## $^{65}\text{Cu}(n,2n)$ Cross Section



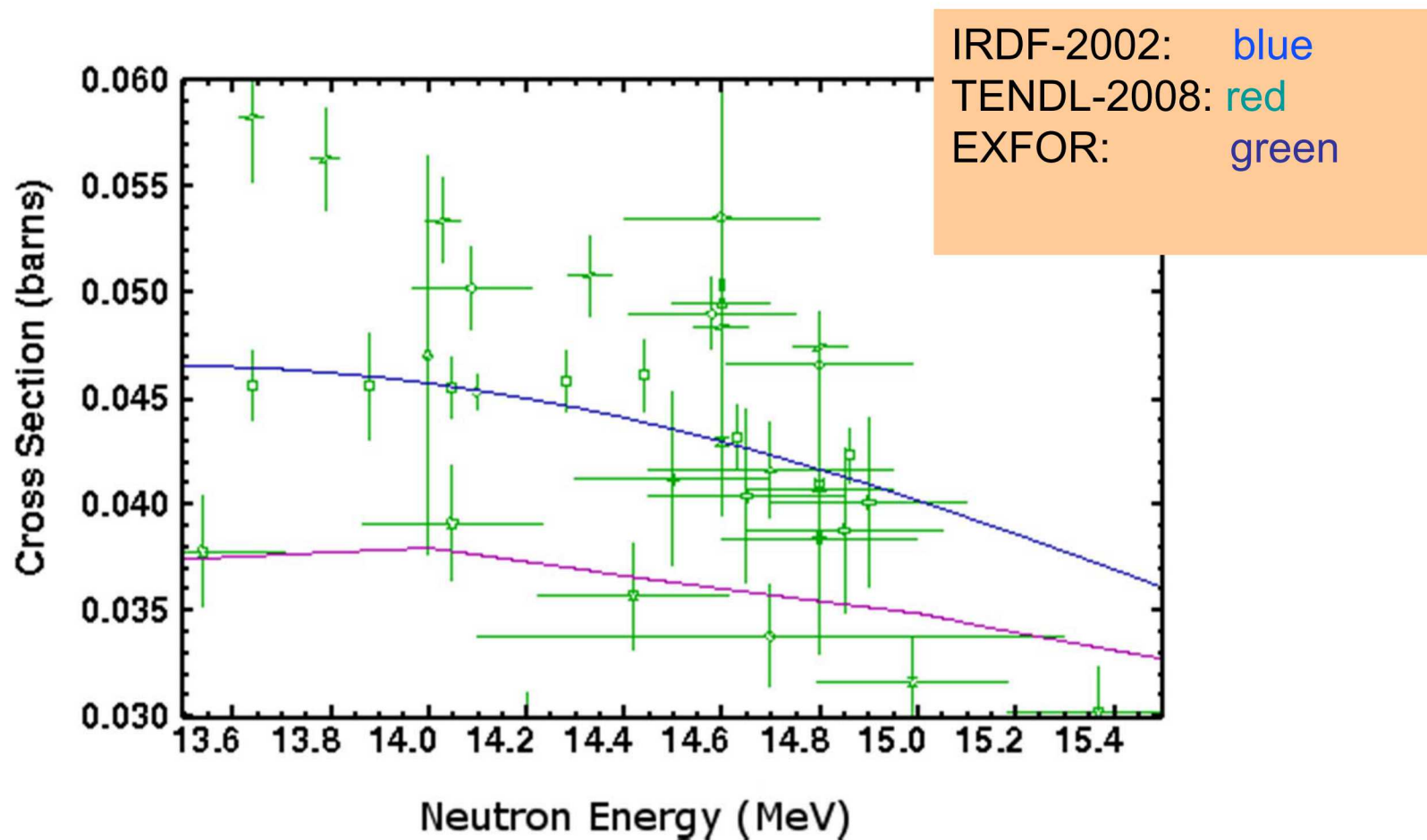
# $^{27}\text{Al}(n,\alpha)$ Cross Section



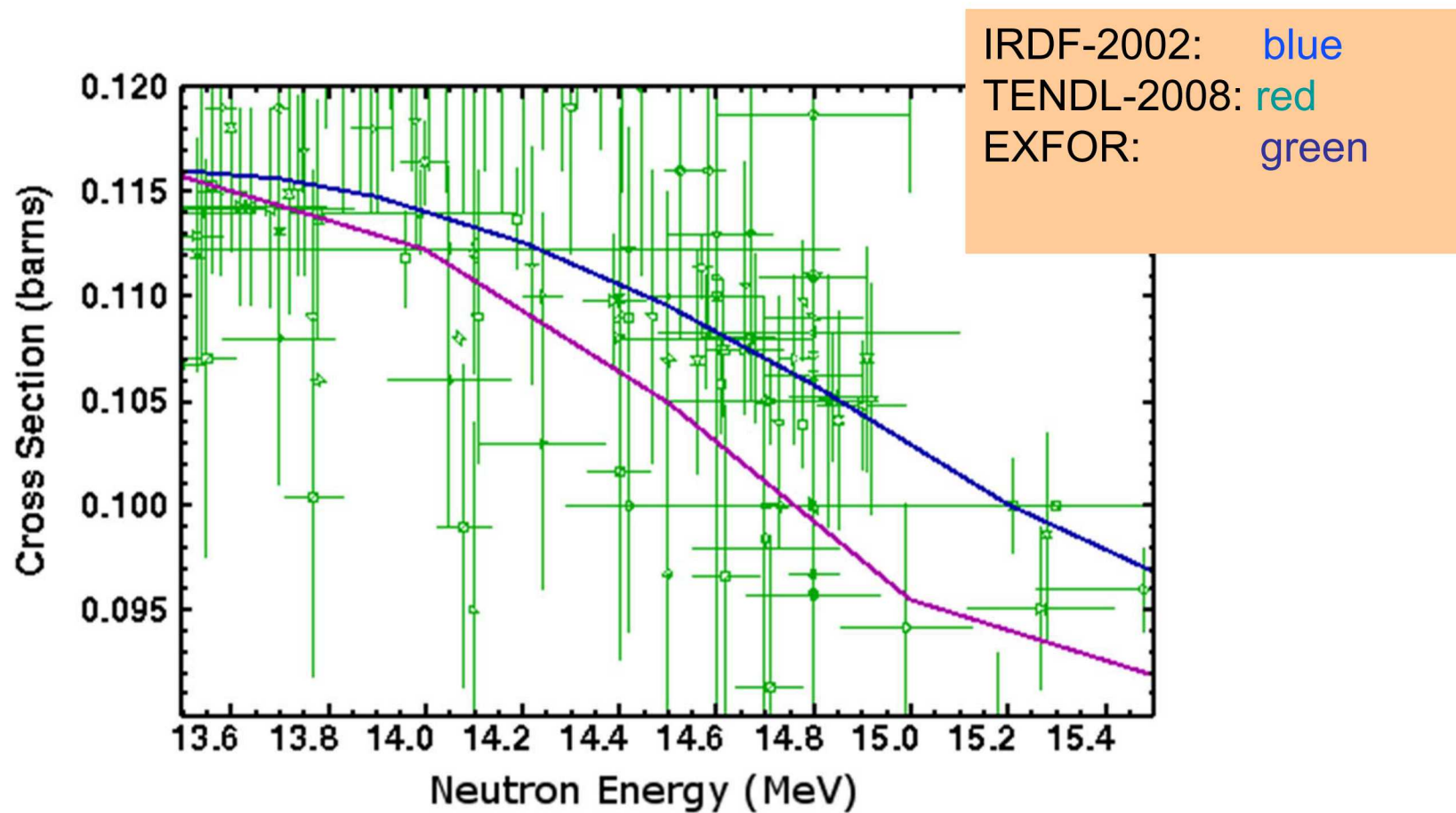
## $^{24}\text{Mg}(n,p)$ Cross Section



# $^{63}\text{Cu}(n,\alpha)$ Cross Section

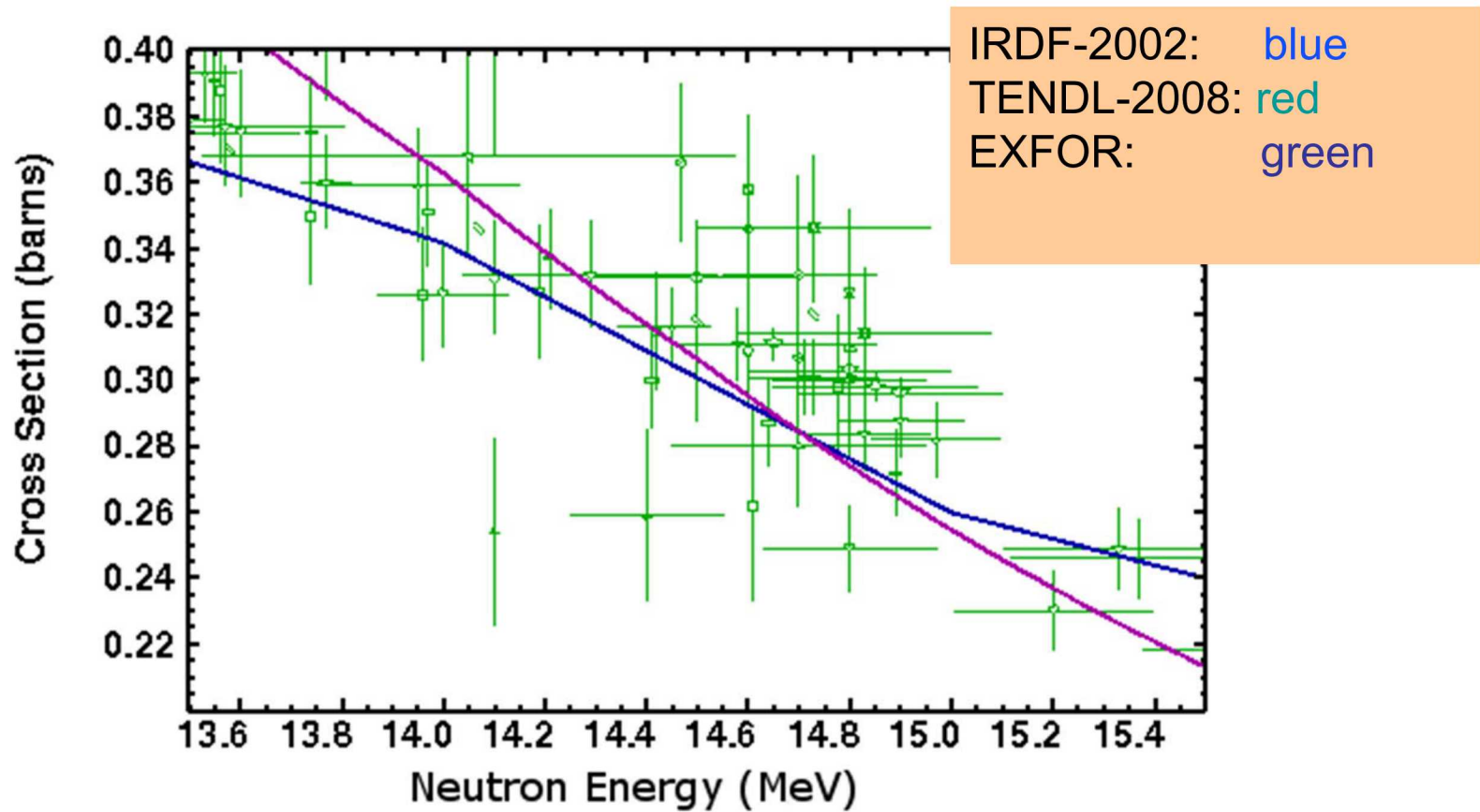


# $^{56}\text{Fe}(n,p)$ Cross Section

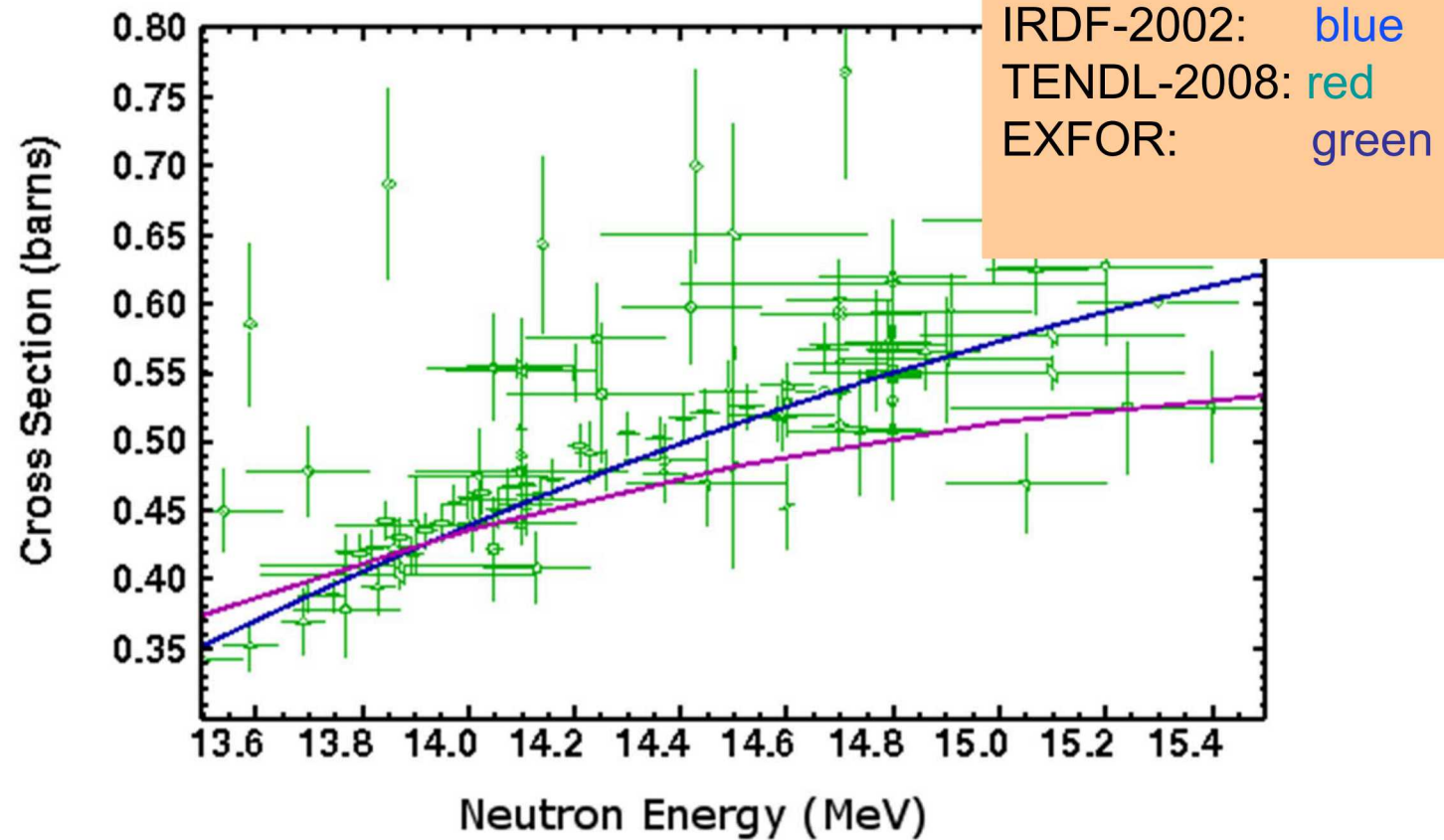




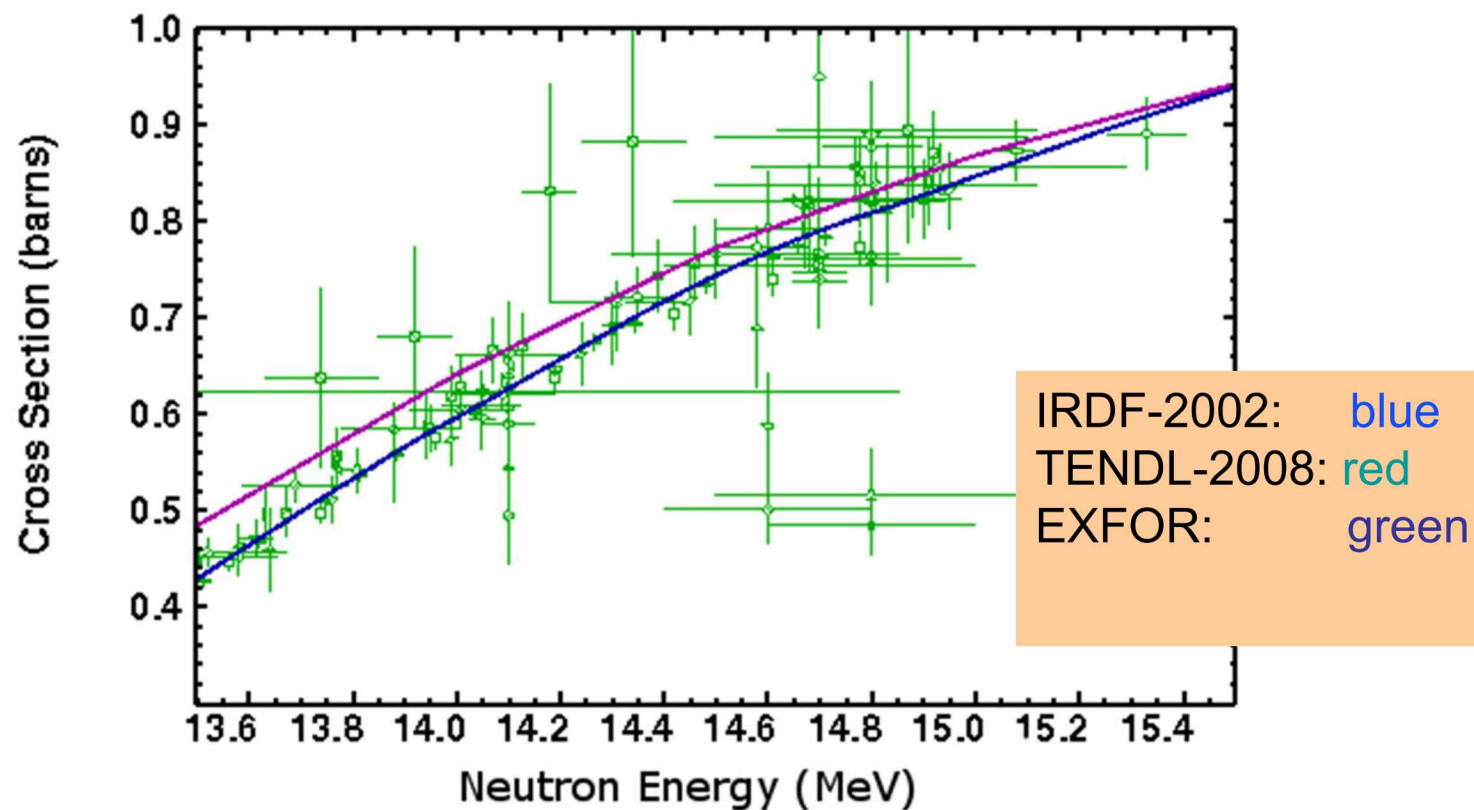
# $^{54}\text{Fe}(n,p)$ Cross Section



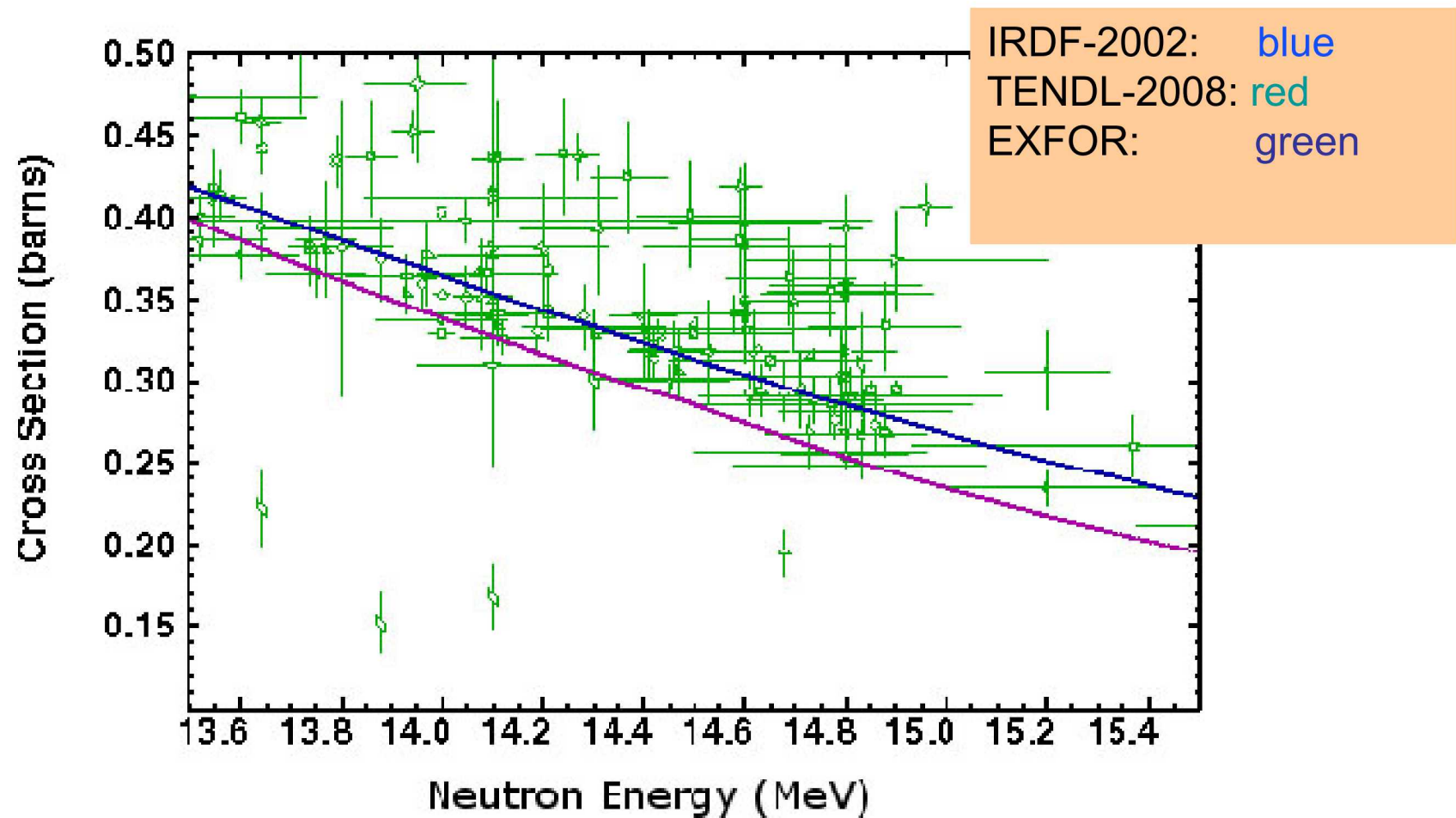
## $^{63}\text{Cu}(n,2n)$ Cross Section



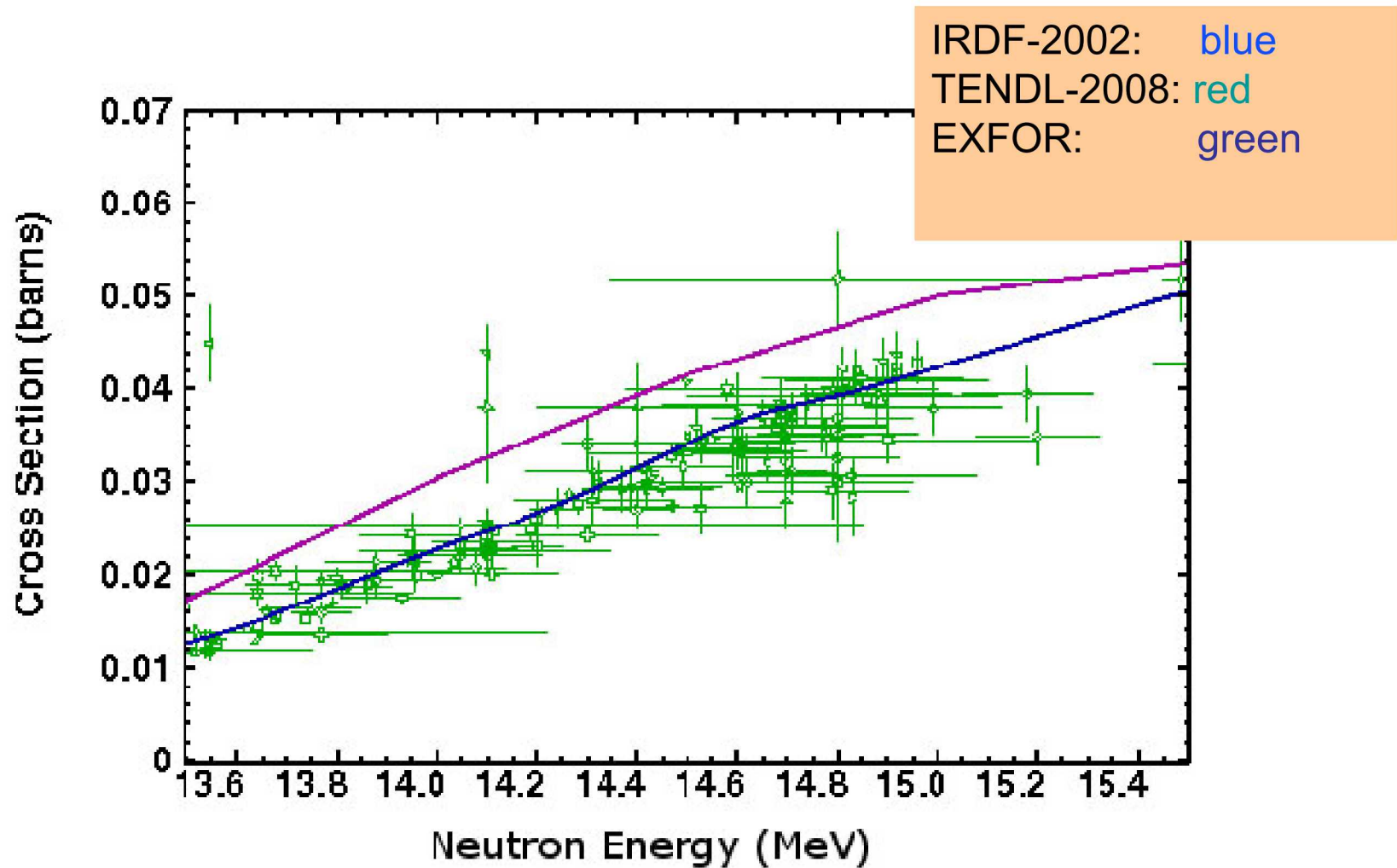
# $^{90}\text{Zr}(n,2n)$ Cross Section



## $^{58}\text{Ni}(n,p)^{58}\text{Co}$ Cross Section



## $^{58}\text{Ni}(n,2n)^{57}\text{Ni}$ Cross Section





# $^{64}\text{Zn}(n,p)$ Cross Section

