# A Review of Recent R&D Efforts in Sub-Critical Multiplication Measurements and Simulations

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# Why pay attention to sub-critical, multiplying systems, Aren't critical systems more valuable and interesting?

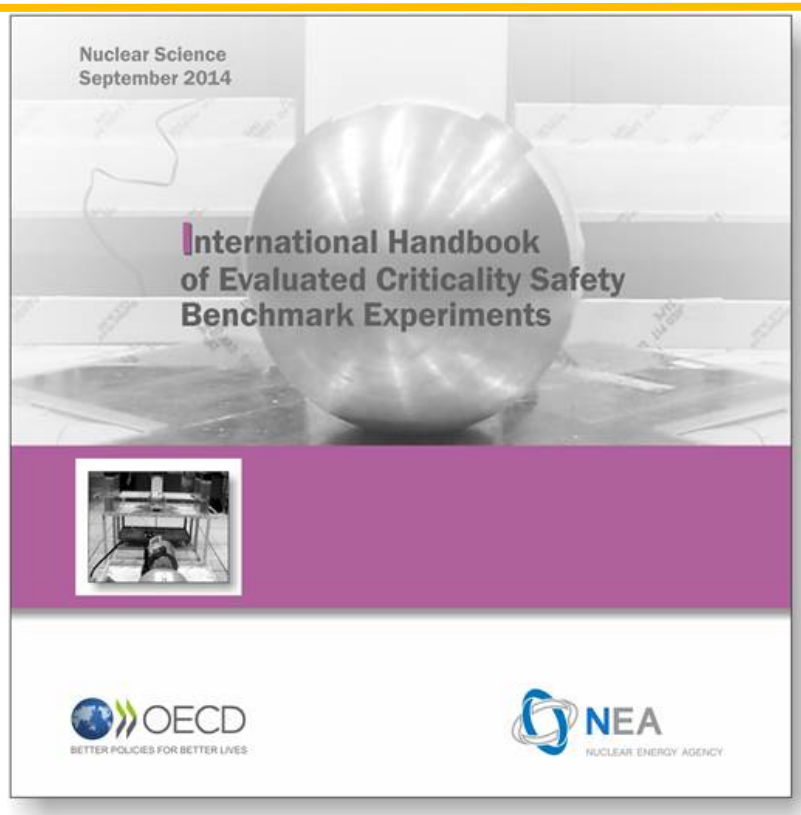
- **Critical experiments have been used to benchmark codes, measure nuclear data, well known, easy to measure, …**
- **Sub-critical, multiplying systems are providing invaluable information select few have examined:**
  - Standard comparison of simulated and measurements (fixed source, eigenvalue)
    - Design of future measurements, approach to critical, POI, …
    - Validation of MCNP, nuclear data, in other regimes.
  - New methods for interpreting measured data (keff, M)
  - Quantification of uncertainties in inferred values
  - Impact on nuclear data ($\nu$, $\sigma_t$, …)
  - Nuclear safeguards
  - Threats from unknown systems…
  - New radiation detector technologies
- **NCSP funding for sub-critical measurements/simulations has benefited many programs and vice versa!**
  - Revived a decaying capability critical to missions of DP, NP, ER, NCT

# NNSS: Access to variety of SNM
# Possible measurements are endless!

- Critical Assemblies:
  - Godiva, Flat top, Comet, Planet
- WGPu, HE, Np
- Others
- Moderators/Reflectors

# Key Objectives for our Measurements…

- **Benchmark Quality**
  - Material characterization, Assembly details, Experimental environment
- **Recent Focus on Uncertainties**
  - While planning, performing, and documenting the experiment
  - <u>Uncertainties are as important as the mean!</u>
  - MCNP Sensitivity/Uncertainty Accomplishments for the Nuclear Criticality Safety Program, B. C. Kiedrowski, F. B. Brown,J. S. Bull, A.C. Kahler, D. K. Parsons *(LANL)*, M A. Gonzales, A K. Prinja *(Univ of New Mexico)*
- **Multiple Critical Configurations**
  - To determine reproducibility
  - Various reflectors to modify neutron spectrum
- **Examine More than Critical Configuration**
  - Sub-critical and super-critical
  - External neutron and gamma spectra
  - Internal foils/detectors to measure reaction rates and reaction products




"Nickel-Reflected Plutonium Metal Sphere Subcritical Measurements," Benoit Richard, Jesson Hutchinson, Theresa Cutler, Avneet Sood,Mark Smith-Nelson *(LANL)*

**<u>Data, Analysis, and Operations for Nuclear Criticality Safety III 1415 – Wednesday, Grand Ballroom South A</u>**

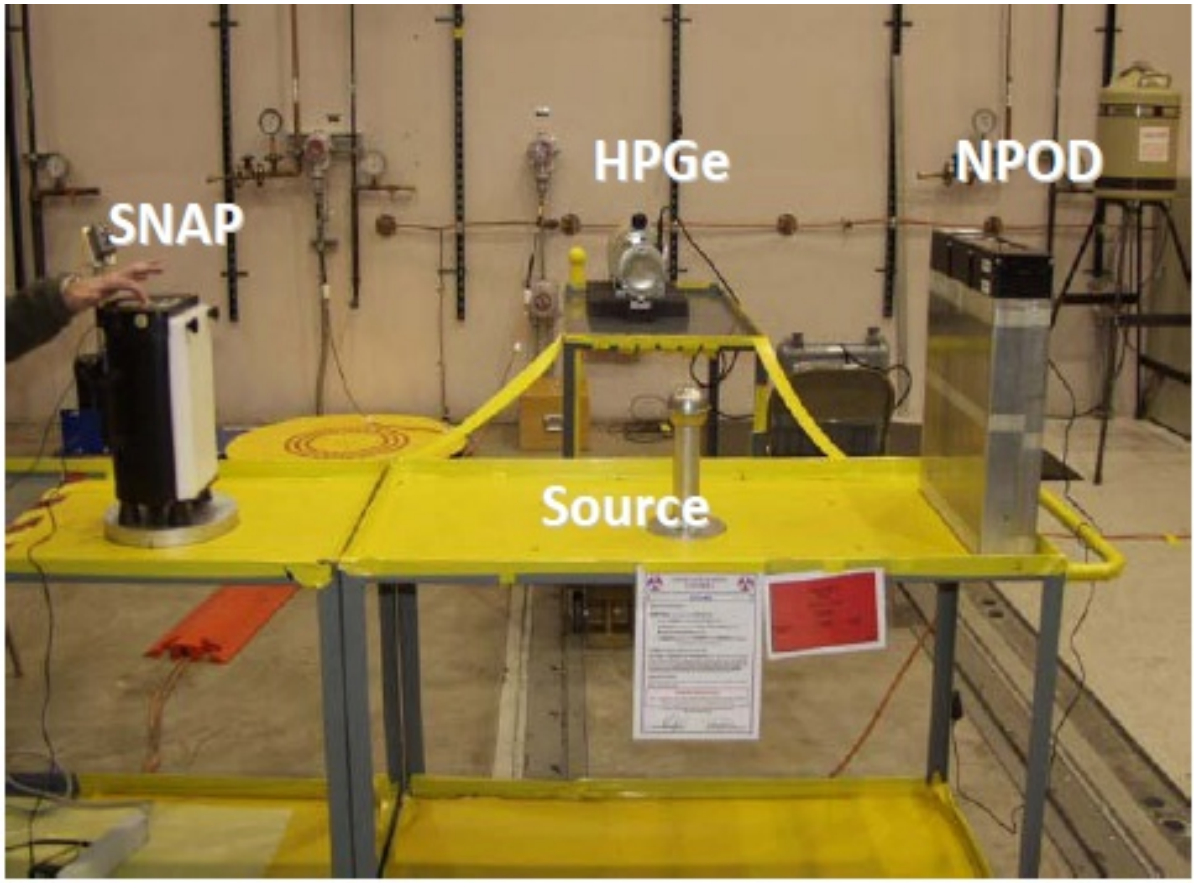
# The goal of our simulations is to be predictive!

- **MCNP – well suited for simulating sub-critical measurements**
  - Calculates relevant quantities for fixed-source, eigenvalue problems
    - Correct for averaged values but **not microscopically correct**. Energy is not conserved per collision
- **Other MCNP-like capabilities exist: MCNP-PoliMi, MCNP-DSP**
- **MCNP6 will replace these existing capabilities**
  - Key new capabilities: correlated neutron emission and list-mode data
    - "Characterization of the NPOD3 Detectors in MCNP5 and MCNP6," Kimberly Clark, Jesson Hutchinson, C. J. Solomon, Theresa Cutler, Avneet Sood *(LANL)*
    - **Data, Analysis, and Operations for Nuclear Criticality Safety II 1145 – Wednesday, Grand Ballroom South A**
  - NCSP has helped us revive, distribute this capability and validate our simulations
  - NA-22: CGMF (LANL) / Freya(LLNL) + other multiplicity packages are currently being integrated into MCNP6
    - "Correlated Neutron and Gamma-Ray Emission in MCNP6," Michael E. Rising, Avneet Sood, Patrick Talou, Ionel Stetcu,Toshihiko Kawano *(LANL)*
    - **Nuclear Nonproliferation Technical Group: General—II, 1415 Wednesday Mississippi**

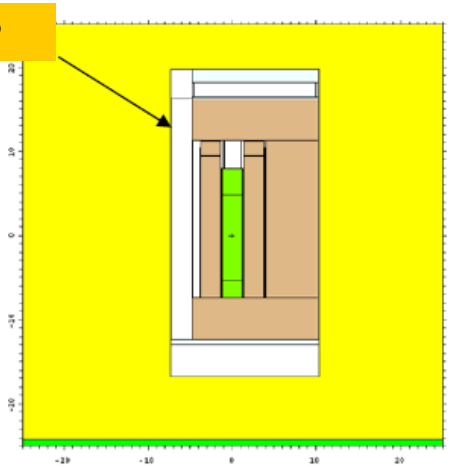
# Our Recent Work…

1. Impact on nuclear data ($\nu$, $\sigma_\iota$, …)
2. Quantification of uncertainties/sensitivities in inferred values (M)

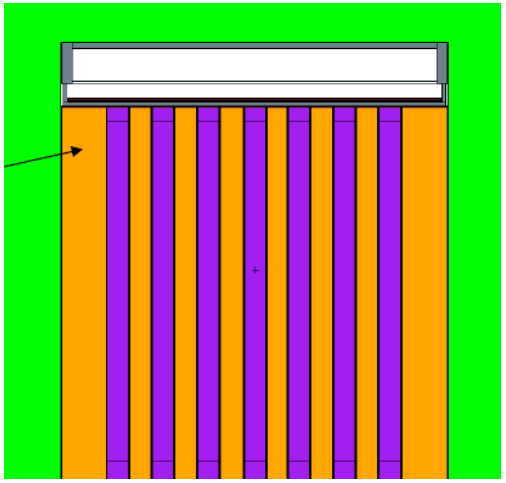
# 1st "Benchmark" Comparison: SNL - SINBAD




SNAP



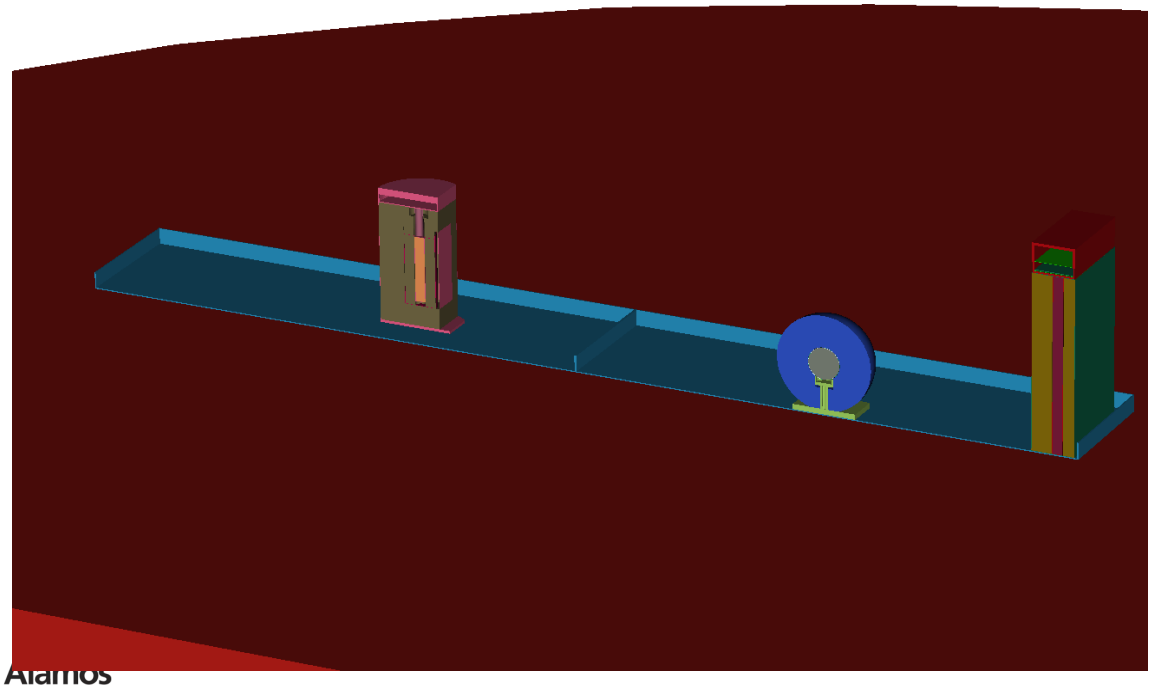
NPOD-3

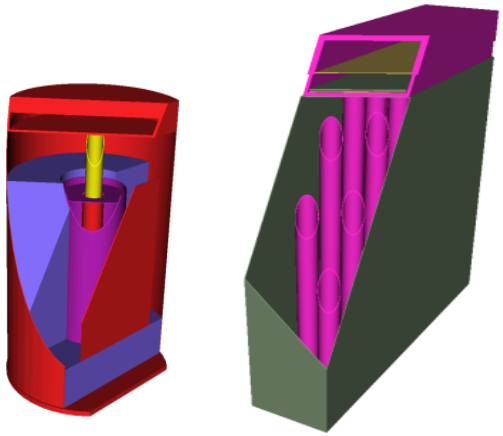


- J. Mattingly, "Polyethylene-Reflected Pu metal Sphere," SAND2009-5804

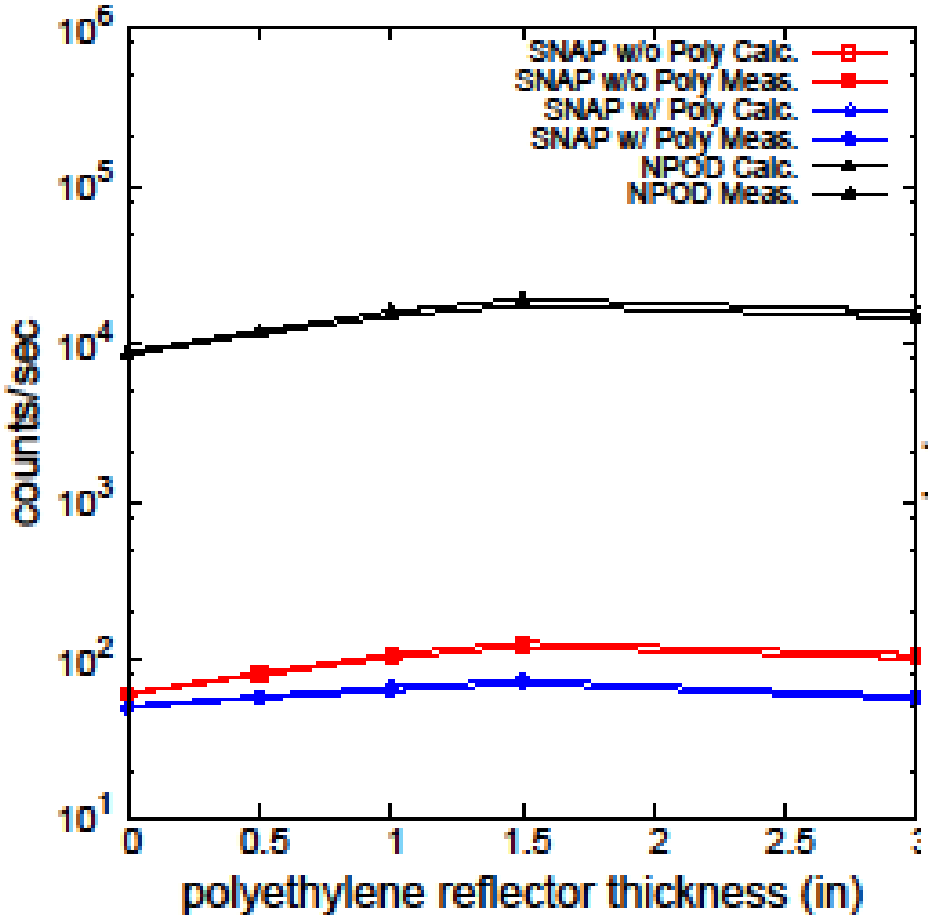
# Measurement Configurations

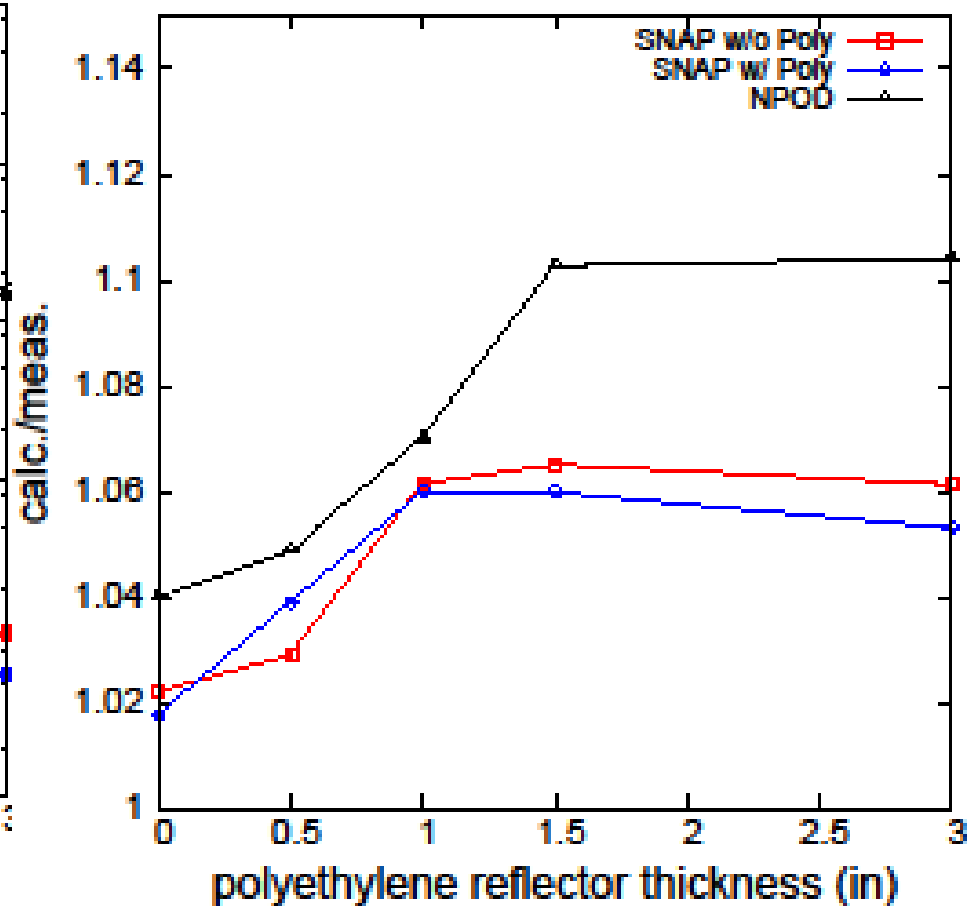
- Solid Sphere of Plutonium (BeRP Ball)
- Different thicknesses of polyethylene shells are placed around the BeRP ball (0-6” of radial reflection)
- Neutron measurements are made with SNAP and NPOD detectors



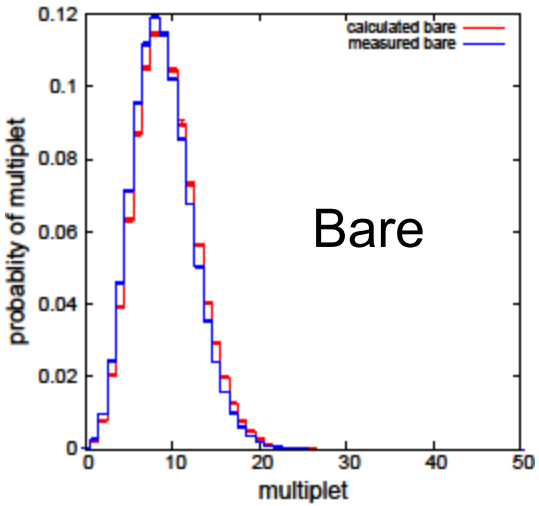


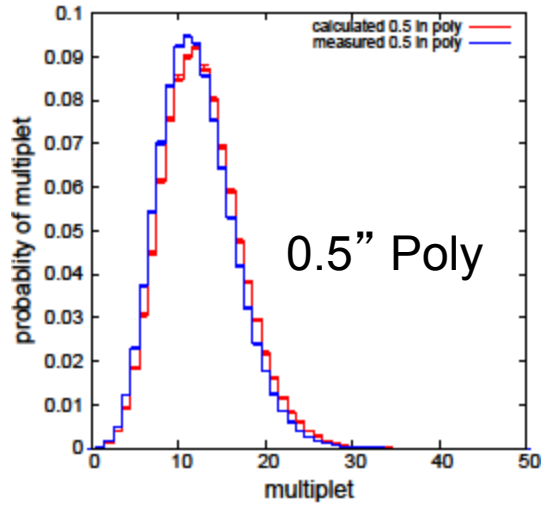
# LANL Count Rate Comparisons

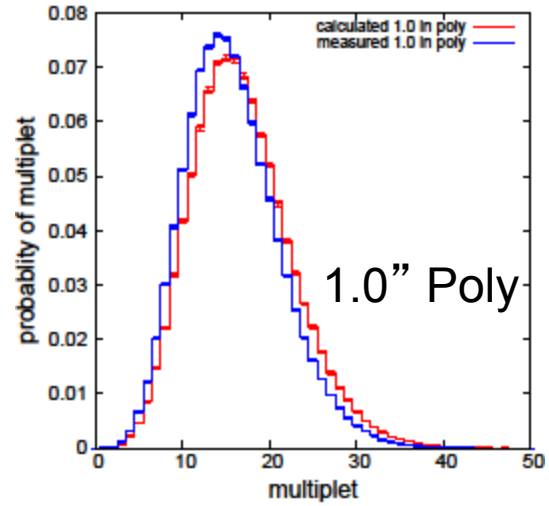


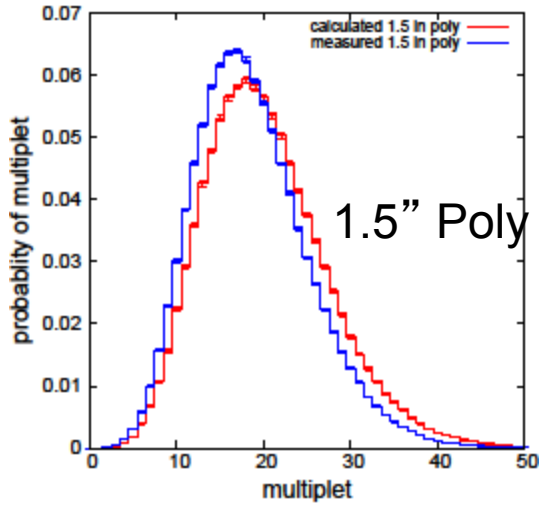



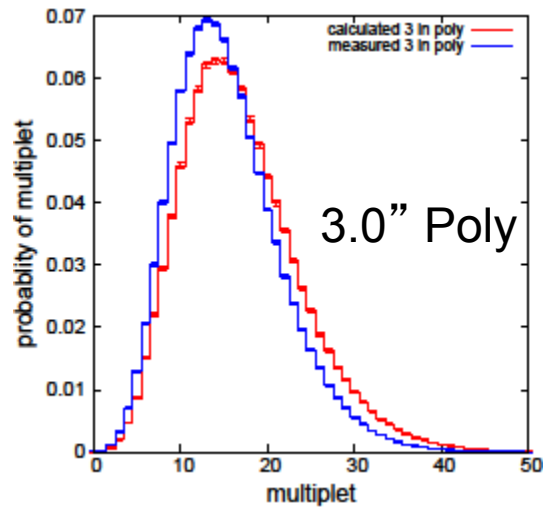
# Multiplicity Distributions (1060 μs gate)



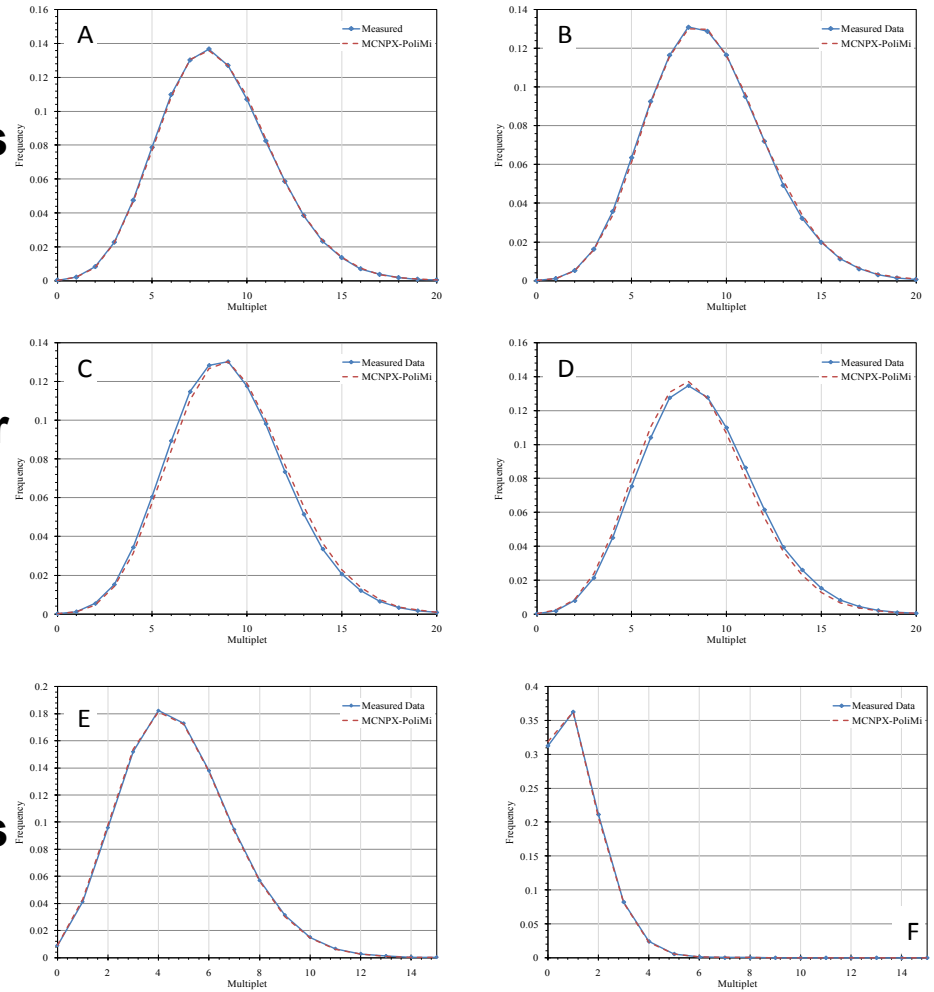



# Multiplicity Distribution Moment Comparisons

| Poly. Thick. | First Moment | | | | | Second Moment | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Calc. | Rel Err. | Meas. | Rel. Err | C/M | Calc. | Rel. Err. | Meas. | Rel. Err. | C/M |
| Bare | 9.31 | 0.0020 | 8.95 | 0.0010 | 1.04 | 99.13 | 0.0023 | 91.94 | 0.0012 | 1.08 |
| 0.5" | 12.74 | 0.0020 | 12.15 | 0.0011 | 1.05 | 182.40 | 0.0023 | 166.24 | 0.0013 | 1.10 |
| 1.0" | 16.84 | 0.0020 | 15.73 | 0.0013 | 1.07 | 317.08 | 0.0023 | 277.38 | 0.0015 | 1.14 |
| 1.5" | 20.24 | 0.0020 | 18.63 | 0.0014 | 1.09 | 461.07 | 0.0023 | 390.29 | 0.0016 | 1.18 |
| 3.0" | 16.97 | 0.0020 | 15.37 | 0.0013 | 1.10 | 335.87 | 0.0025 | 274.78 | 0.0016 | 1.22 |

# Initial Conclusions

- Seem to be consistently over calculating the count rates and moments of the Feynman histograms
- Similar measurements and analysis made by E. Miller and J. Mattingly (collaborations with LANL)
- No dead time issues, source-detector uncertainty effects quantified
- Measurements were also performed using a Cf-252 source inside each reflector
- This test validated the geometry and material models of the poly reflectors and the NPOD



# Summary from Moderated/bare $^{252}$Cf & WGPu

- **Simulation of two different polyethylene reflected plutonium experiments exhibit similar systematic trends**
- **Two independent modifications to MCNP produce the same systematic trend**
  - most modeling errors have been investigated (Mattingly et. al.)
  - $^{239}$Pu $\nu$ , $\sigma_f$ , and possibly $\chi$ may be the source of the error
- **these subcritical differential experiments are highly sensitive**
  - (correlated counts on 100s–1000s μs) to input data
- **subcritical experiment and critical experiment data, including but not limited to keff, should be used for data regression**

# Investigation into the nuclear data

- **Nu bar is adjusted by CSWG to make simulations match**
  - In $^{239}$Pu artificially high below ~1.5 MeV to match JEZEBEL
  - Lies about 2 std. dev above covariance data
- **Let's use covariance data to generate random samples of energy dependent nubar**
- **Input the new samples of nu bar into MCNP**
- **Run simulations and compare to experimental data**
- **Repeat until a set of nu bar that matches multiplicity distribution without significantly altering $k_{eff}$ is found**

# Methodology: Use covariance data to vary nu-bar

- **Read in original nu bar from ACE:** $\nu\ (E)$
- **Read in covariance data from ENDF/B-VII.0**
- **Generate a set of correlated random numbers:** $\mathbf{R}$
  - Each element of $\mathbf{R}$ corresponds to an energy group $Eg$
  - Each element $\mathbf{R}\ Eg$ is the number of std. dev. to shift $\nu$
- **Generate a new a new set of nu bar:**
  - Need to map $\nu$ energies to groups $Eg$:
  - $E$ in $Eg$: $\nu' E = \sigma E\ \mathbf{R}\ Eg + \nu(E)$
- **Rewrite the new data** $\nu'(E)$ **to a unique ACE File**
- **Run 6 different MCNP simulations**
  - 5 different BeRP ball experiments
  - JEZEBEL fast critical experiment
- **Generate multiplicity distributions and use FOM to evaluate best data set**

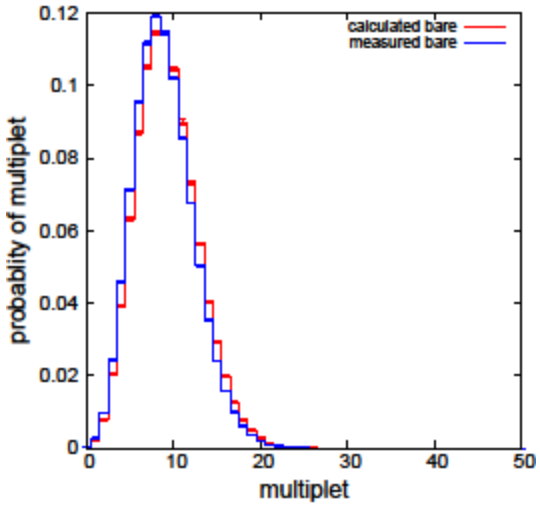
# Results: Does Nu-bar change impact critical experiments?

## $k_{eff}$ comparison between Trial with lowest FOM and original ENDF7 Data

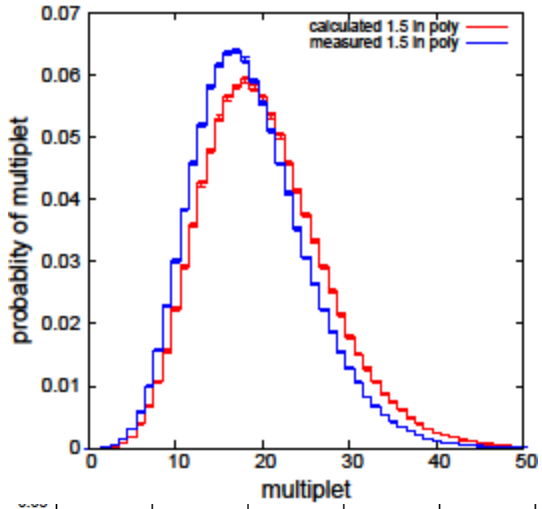
| | Benchmark | | Original ACE Data | | | Lowest FOM | | |
|---|---|---|---|---|---|---|---|---|
| Benchmark | k-eff | Rel Error | k-eff | Rel Error | # Sigma | k-eff | Rel Error | # Sigma |
| pu-met-fast-021-case-1 | 1.0000 | 0.0026 | 1.0021 | 0.0003 | | 1.0001 | 0.0031 | |
| pu-met-fast-003-case-103 | 1.0000 | 0.0030 | 0.9981 | 0.0003 | | 0.9958 | 0.0031 | ** |
| pu-comp-inter-001 | 1.0000 | 0.0110 | 1.0121 | 0.0002 | * | 1.0099 | 0.0029 | * |
| mix-comp-therm-002-case-pnl30 | 1.0024 | 0.0060 | 1.0011 | 0.0003 | | 0.9983 | 0.0043 | |
| mix-comp-therm-002-case-pnl31 | 1.0009 | 0.0047 | 1.0025 | 0.0003 | | 1.0004 | 0.0044 | * |
| mix-comp-therm-002-case-pnl33 | 1.0024 | 0.0021 | 1.0079 | 0.0003 | ** | 1.0046 | 0.0042 | * |
| mix-comp-therm-002-case-pnl34 | 1.0038 | 0.0025 | 1.0042 | 0.0003 | | 1.0017 | 0.0029 | * |
| mix-comp-therm-002-case-pnl35 | 1.0029 | 0.0027 | 1.0066 | 0.0003 | * | 1.0036 | 0.0033 | * |
| | TOTAL RMS DIFFERENCE: | | 0.49% | | | 0.51% | | |

# Effects of nu-bar change on moderated WGPu

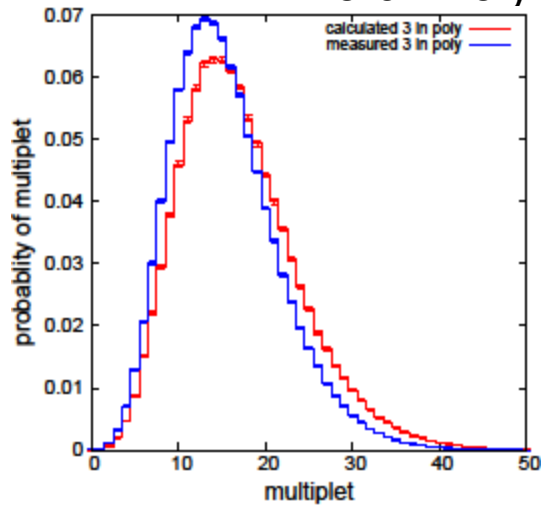
Bare

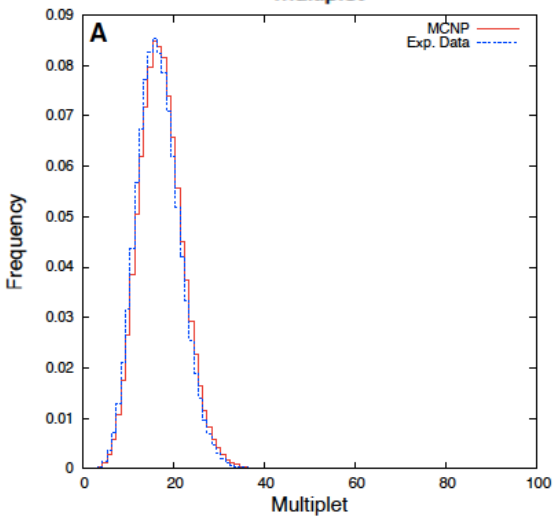


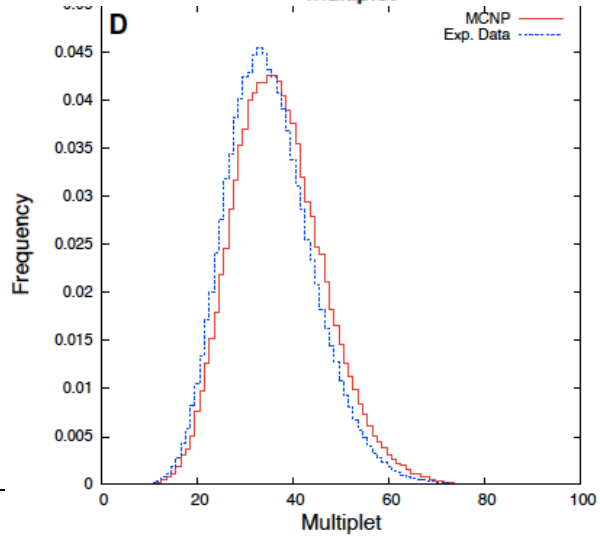

1.5” Poly

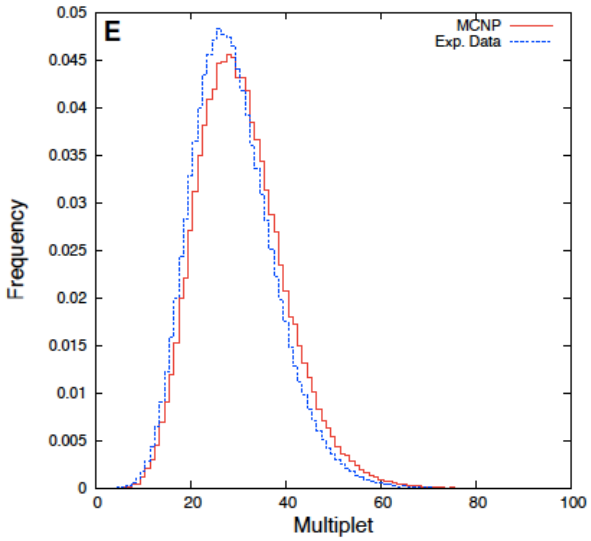



3.0” Poly

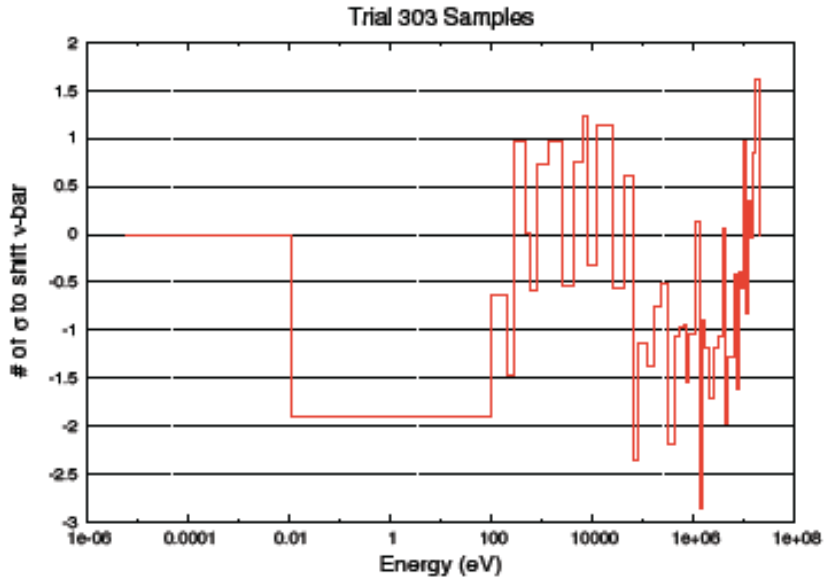


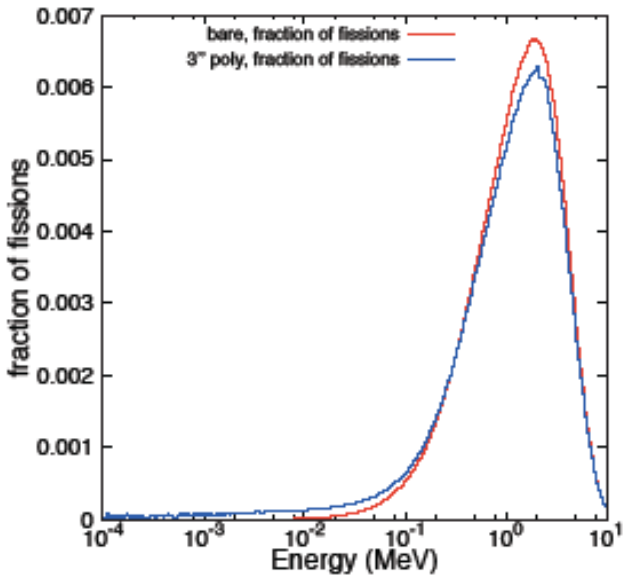



# Observations from our optimized $^{239}$Pu nu-bar



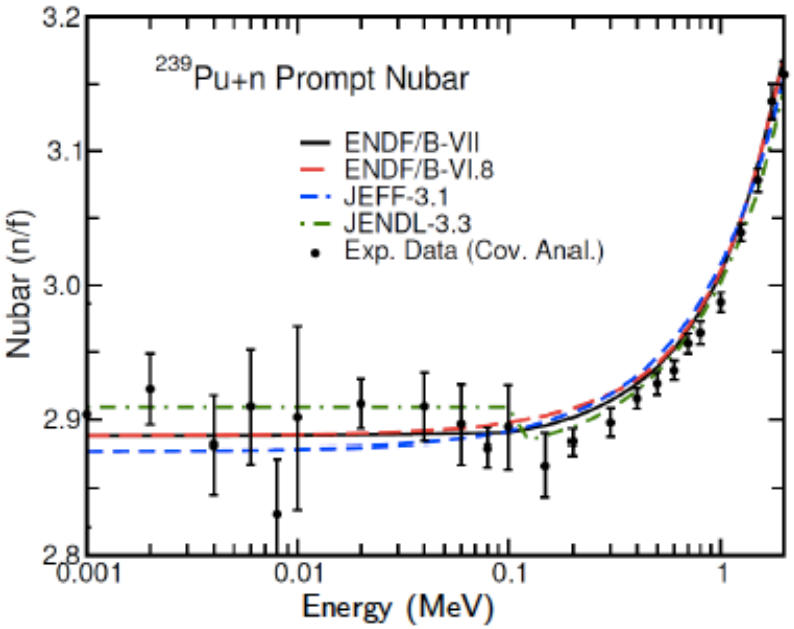

Modified $\overline{\nu}$ data (top-left) suggests:

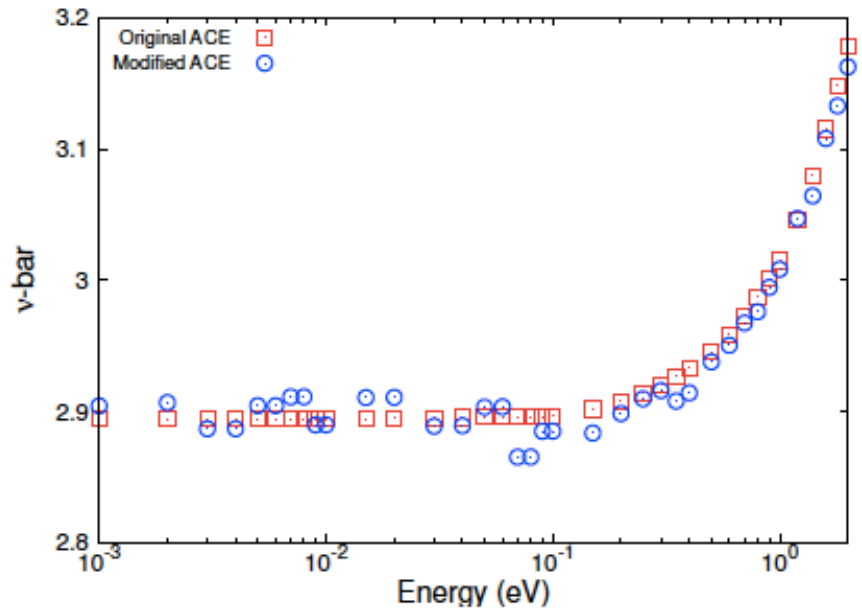
1. a decrease to Pu-239 $\overline{\nu}$ above ≈100 keV
2. an increase to Pu-239 $\overline{\nu}$ below ≈100 keV

The spectrum of neutrons causing fissions (top-right) in this system

1. is highly peaked around fission energies with only 2-5% of the fissions induced by neutrons less than 100 keV
2. indicates that the modifications to $\overline{\nu}$ below ≈10 keV and above ≈10 MeV are not meaningful

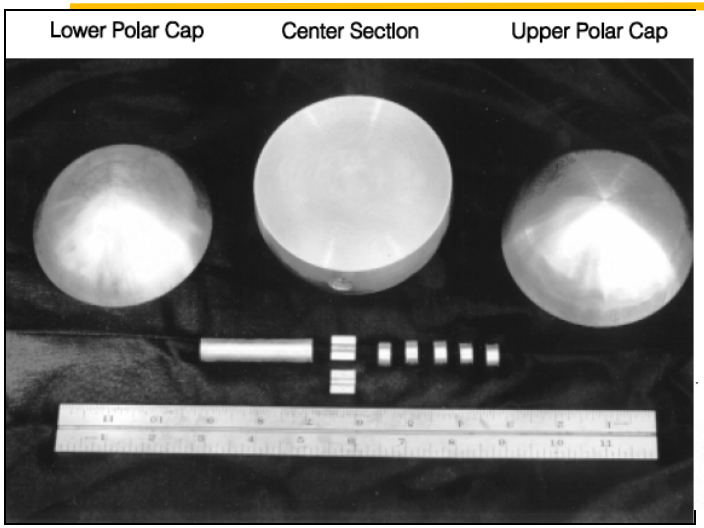
# Comparison of Modified Data with Young et al.

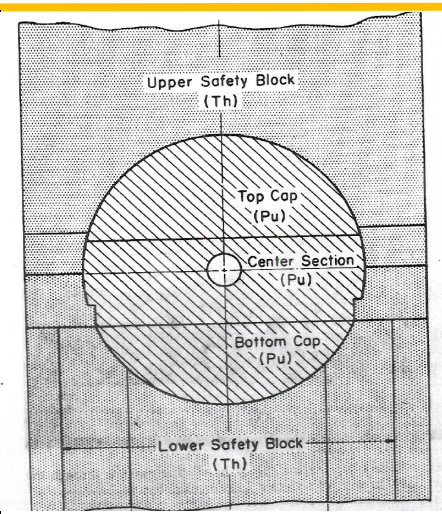


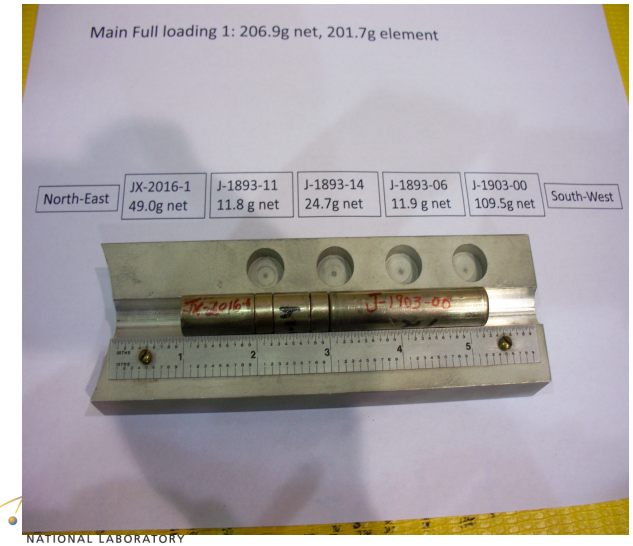

- The Young et al. “raw" data was shifted upward to match the integral Jezebel $k_{eff}$.
- However, “raw" data is seemingly more consistent with the “best" match to the NPOD simulations

# Quantifying Uncertainties in Sub-critical Multiplying Systems: Mass and Position Perturbations




| Configuration Number | Thor Core | | | Glore hole mass (g) |
|---|---|---|---|---|
| | Lower | Center | Upper | |
| 1 | + | | | 0 |
| 2 | | + | | 0 |
| 3 | | + | | 206.9 |
| 4 | | | + | 0 |
| 5 | + | + | | 0 |
| 6 | + | + | | 206.9 |
| 7 | + | | + | 0 |
| 8 | | + | + | 0 |
| 9 | | + | + | 206.9 |
| 10 | + | + | + | 0 |
| 11 | + | + | + | 206.9 |
| 12 | + | + | + | 109.5 |
| 13 | + | + | + | 49.0 |
| 14 | | | | 206.9 |



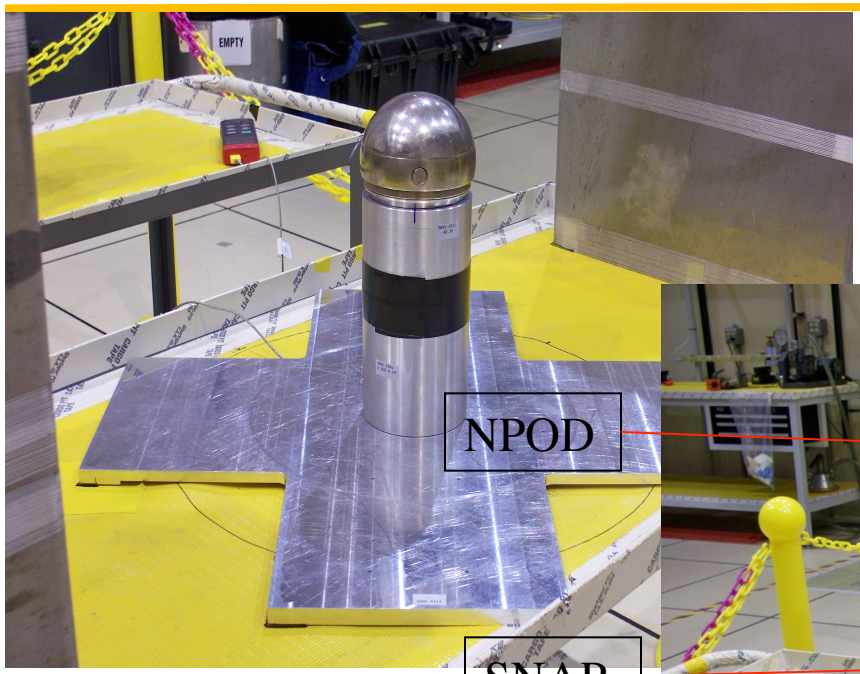

"List-Mode Simulations of the Subcritical Thor Core Benchmark Sensitivity Experiments," Rian Bahran, Jesson Hutchinson, Benoit Richard, Avneet Sood *(LANL)*

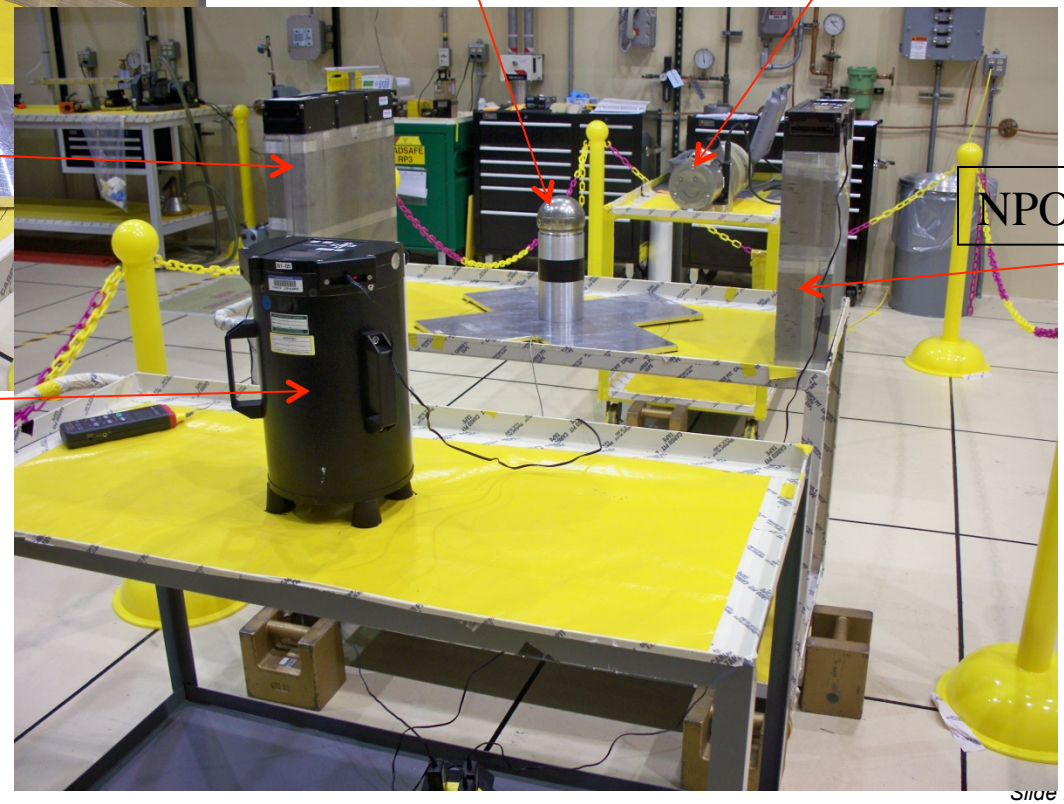
**Data, Analysis, and Operations for Nuclear Criticality Safety I 0830– Tuesday, Grand Ballroom South A**

The upper, center, and lower sections have net masses of 3273.9 g, 4158.2 g, and 2216.9 g respectively.

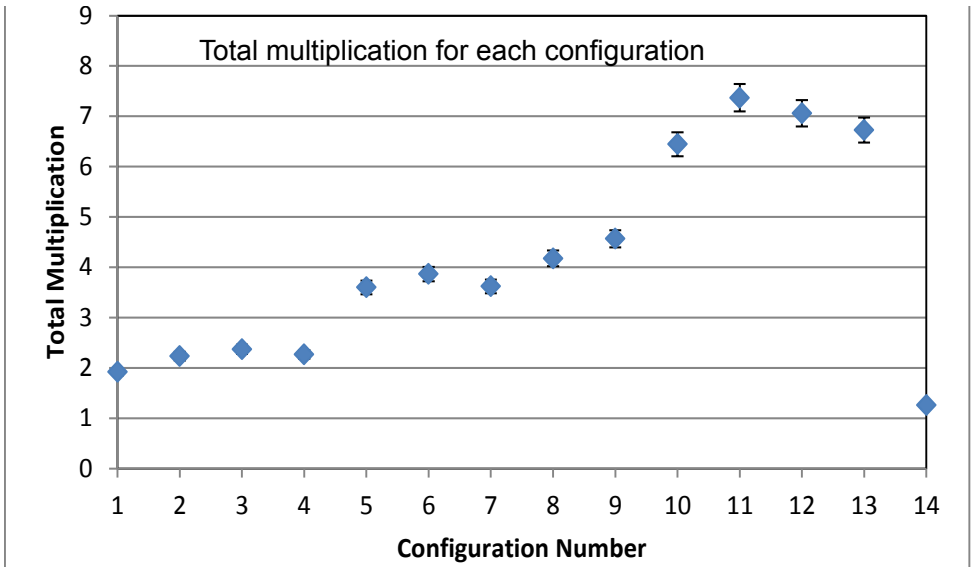
When put together, the three pieces form an approximate sphere with a total net mass of 9649.0 g.

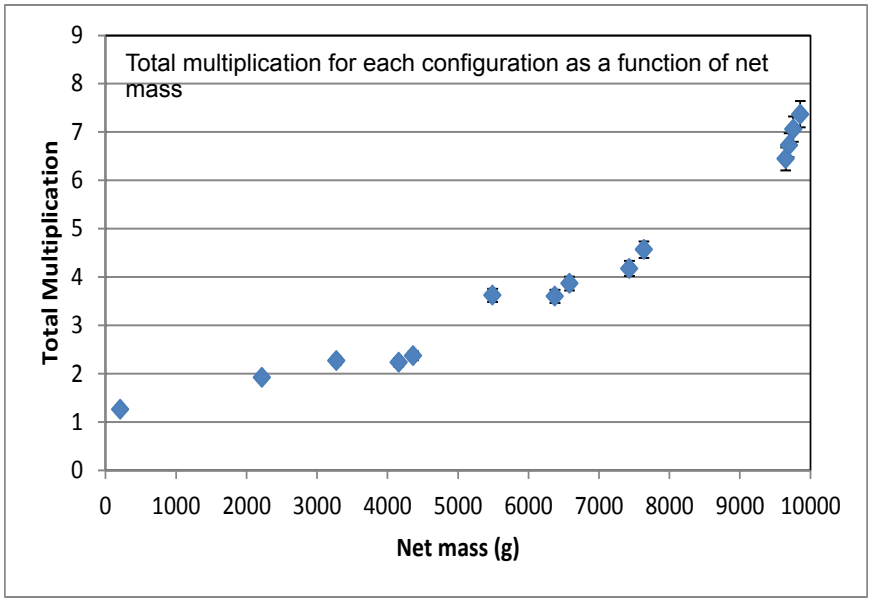
# Experimental Setup for Sensitivity Measurements



# Are these configurations distinguishable?

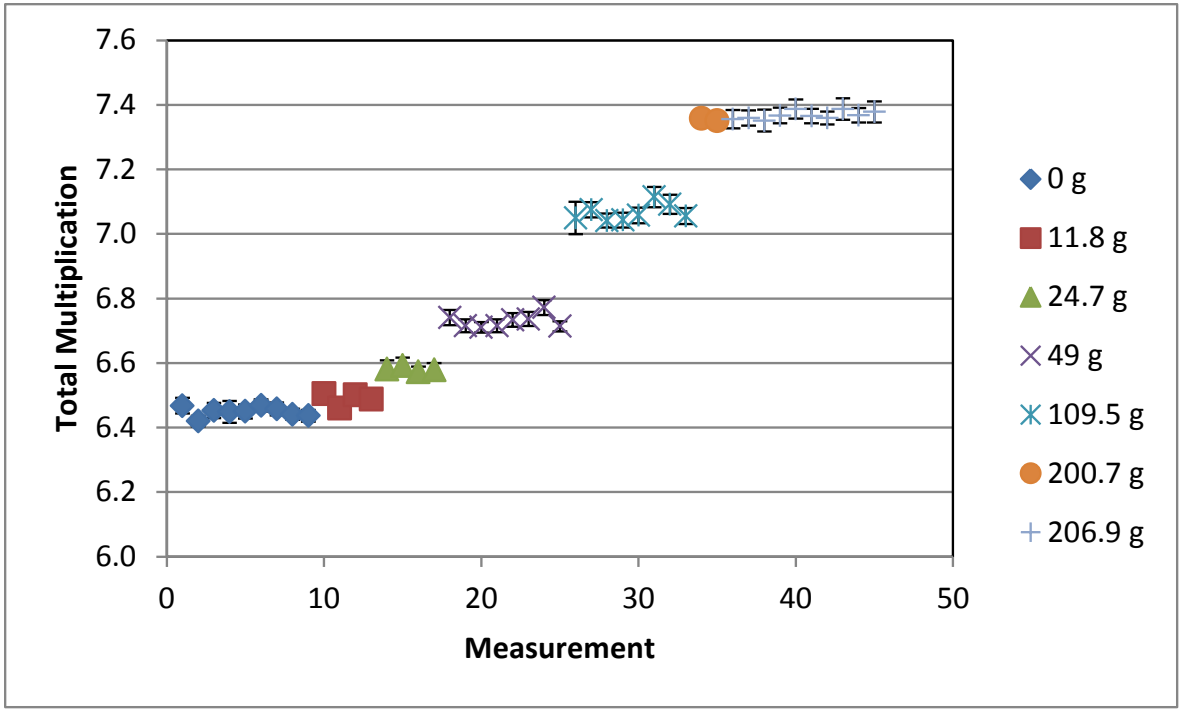



- Error bars are total uncertainty in the measurement (due to measured data, detector efficiency, and nuclear data)

# Mass Perturbations

- **Measured total multiplication for the full Thor core.**
- **Error bars are uncertainty due to the measured data only (detector efficiency and nuclear data not included).**

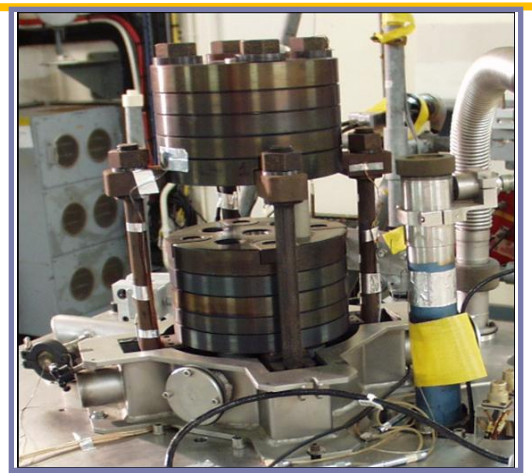



- **Full Thor Core**
  - 6.2 g difference is not distinguishable (200.7 g same as 206.9 g)
  - 11.8 g has a standard deviation between 1 and 3.
  - 12.9 g or greater is easily distinguishable.
- **Thor Core Center:**
  - 24.7 g is equivalent but 151.7 g clearly different.

As mass (and consequently multiplication) increases, the mass threshold decreases.

# Sub-critical measurements on critical assemblies: Caliban and Godiva

CEA – Valduc, France 2012



Caliban

- **Metallic cylindrical core**
  - $^{235}U$ and Mo alloy
  - Diameter = 19.5 cm
  - Height = 25 cm
  - 113 kg of HEU
- **2 blocks**
  - A mobile one (below)
  - A fixed one (above)
- **4 control rods**
  - Same composition as the blocks
- **Cylindrical central irradiation channel**

NNSS – Nevada, USA 2013


Godiva IV

- Cylindrical uranium metal fast burst assembly
- 65 kg, 93% enriched
- 7-inch diameter (17.8 cm), 6-inch tall (15.2 cm)
- Operates at delayed critical or prompt critical
- Maximum burst is approximately 90,000 $MW_{th}$ with a full width half max (FWHM) pulse of 25 μs

# Results: Sub-critical assemblies

- **Joint CEA/LANL measurements performed on four critical assembly machines (this work only focused on Caliban and Godiva-IV results).**
- **Over 50 configurations were measured. Configurations were at various subcritical multiplications as well as at and above delayed critical.**
- **Results were favorable:**
  - The largest $\Delta k_{eff}$ between the measured data and the control rod worth curves was 0.008.
  - The largest $\Delta k_{eff}$ between the measured and simulated data was 0.009.
- **CEA**
  - Chapelle to defend thesis in May 2014.
- **US**
  - Apply recent subcritical uncertainty analysis to all measured data.
  - Document list-mode simulations for all configurations.
  - Analyze Planet and Flat-Top results (“best” nubar for Flat-Top?).
  - Investigate SCRAM and other measurements.

# Future plans

- **Historical measurements have included:**
  - Point sources (bare, moderated) (SF, (a,n))
  - Spherical sources (WGPu, HEU), point sources (SF, (a,n))
  - Critical Assemblies (Caliban, Godiva)
- **NCSP sponsored simulations/measurements of sub-critical systems have:**
  - Helped to eliminate multiple MCNP codes versions; maintain one modern version
  - Driven us to examine both correlated neutrons and gamma emissions (simulation)
  - Re-examine fundamental nuclear data
  - Quantify and document our uncertainty methodology
  - Examine sensitivity/uncertainty in our measurements to determine M
- **What's next?**
  - University research reactors?
  - Refine our analysis capabilities for unknown, sub-critical, multiplying systems
- **Lots of data has been accumulated**
  - Analysis of this data is needed

# Extra

# Review: Relevant Physics for Sub-Critical Multiplication

- **(Source) Passive neutrons from fissionable material emitted from:**
  - Spontaneous fission neutron sources:
    - Correlated in time and location of fission
    - Examples: Cf-252, Pu-240
  - ($\alpha$ ,n) reactions:
    - Produced when $\alpha$ particle is absorbed and neutron is emitted
    - Not correlated in time and location
    - Examples: Am-Be
- **(Induced) Neutron multiplication dominated by two physical processes:**
  - (n,2n)
    - Occurs mostly above 7 MeV
    - Does not contribute significantly to most scenarios
  - Neutron-induced Fission

Simulations need to be "microscopically" correct for comparisons with measured data.

# Sub-critical Measurements

- **Neutron multiplication measurements (passive and active) designed to separate the correlated emission events, e.g., SF, from the uncorrelated events, e.g. , ($\alpha$,n),**
  - Record time of neutron capture in a neutron detector over a large collection time (e.g. 300 sec)
  - Group these capture times in a large number (e.g. 1 M) smaller time sub-intervals (e.g. 250 $\mu$sec)
    - These time sub-intervals are larger than typical neutron detection and lifetimes (~50 $\mu$sec)
  - Multiplicity histogram is constructed
    - Obeys Poisson statistics if system is non-multiplying (i.e. neutrons are emitted randomly in time)
    - Data analysis begins…Feynman Variance-to-Mean, CSDNA, etc

Data recorded is neutron detector location and time: list-mode data

Simulations need to produce list-mode data for comparisons

# MCNP Simulations of Sub-Critical Measurement

- **MCNP simulation of neutron sources and detection**
  - User can define location, direction, energy, time, and intensity of SF, ($\alpha$,n) neutron sources
  - User **cannot** define fission events
    - e.g. sample number of neutrons emitted from $\nu_{bar}$
  - User **cannot** define correlated (time, location) neutron sources
    - MCNP samples these values from user's input
  - User cannot (easily) record location and time of detection.
    - Possible using MCNP's PTRAC capability and a user-created external script to extract this information

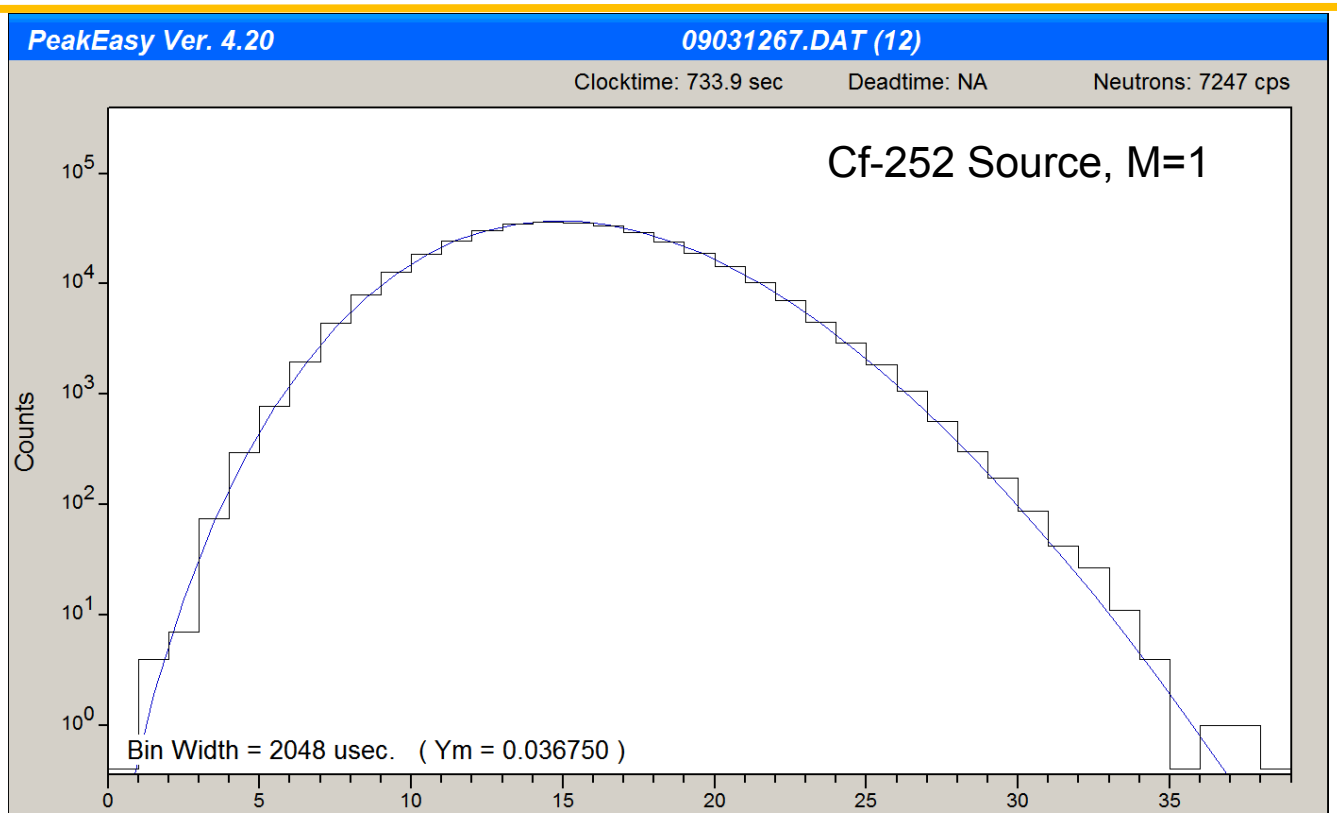
Standard MCNP is not microscopically correct enough to compare with current sub-critical measurements:

# MCNP Modifications

- **SOURCE/TALLYX subroutines written**
  - Subroutines intended for user-defined source and tally
  - Independent of MCNP – no modification of MCNP is required
  - Works with MCNP5.1.60 (current release)
- **SOURCE—modifies definition of starting particle to be a starting reaction, e.g., spontaneous fission, samples starting particles from that reaction**
- **TALLYX—modifies a type 4 tally to produce a file of absorption times in tally cell, a.k.a. list-mode data**
- **Tally output can be processed to analyze inferred multiplication**

Adaptation into MCNP6 with documentation, validation benchmarks, etc in progress

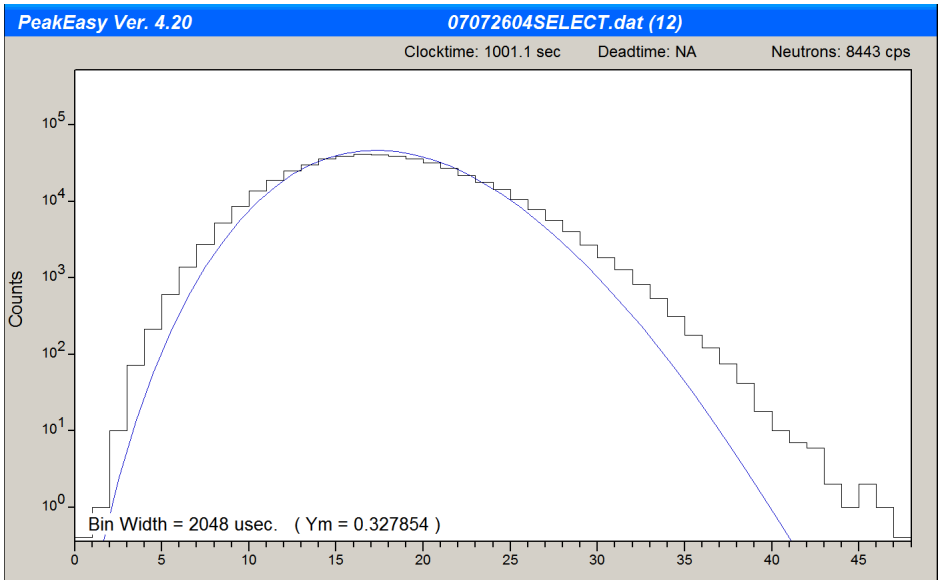
# Sub-critical Data Analysis: Feynman Histogram Randomly fissioning source follows Poisson Distribution



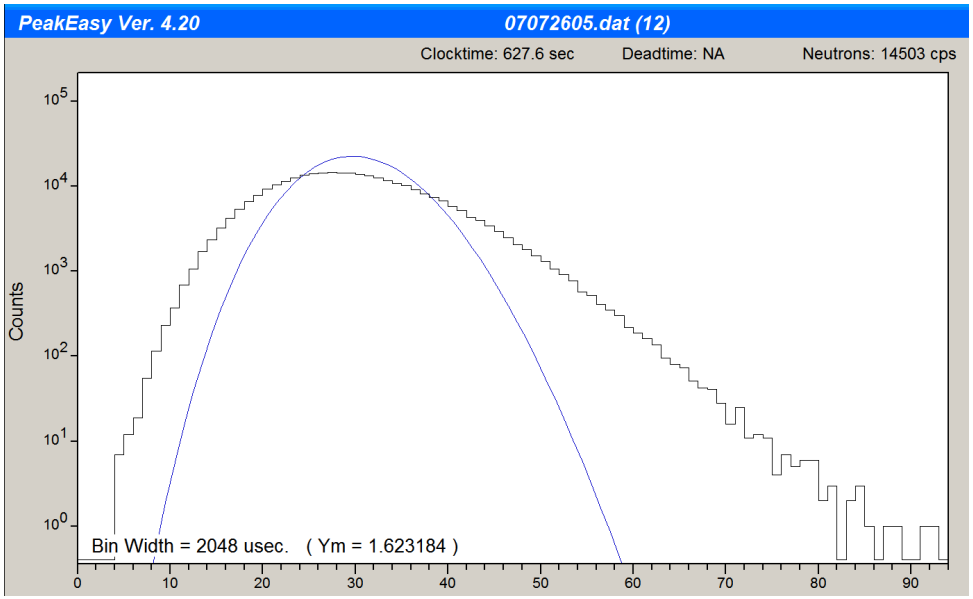

Feynman distributions are constructed and the deviation of the distribution from a Poisson gives us information about the multiplication of the system.

# Sub-critical Data Analysis: Feynman Variance-to-Mean Multiplying source Deviates from Poisson Distribution

- **As the multiplication of a system increases, the deviation from a Poisson distribution will increase.**




BeRP Ball (4.5 kg Pu sphere), M=4.4




BeRP Ball reflected by 3” polyethylene, M=13.5