LA-UR-14-22985

Approved for public release; distribution is unlimited.

Title:	The LANL/LLNL Prompt Fission Neutron Spectrum Program at LANSCE and approach to uncertainties
Author(s):	Haight, Robert C.; Lee, Hye Young; Taddeucci, Terry N.; O'Donnell, John M.; Fotiadis, Nikolaos; Devlin, Matthew J.; Ullmann, John L.; Bredeweg, Todd Allen; Jandel, Marian; Nelson, Ronald O.; Wender, Stephen A.; Neudecker, Denise; Rising, Michael E.; Mosby, Shea M.; Sjue, Sky K.; White, Morgan C.; Wu, Ching-Yen; Bucher, Brian; Henderson, Roger; Ethvignot, Thierry; Granier, Thierry; Chatillon, Audrey; Taieb, Julien; Laurent, Benoit
Intended for:	International Workshop on Nuclear Data Covariances, 2014-04-28/2014-05-01 (Santa Fe, New Mexico, United States)
Issued:	2014-04-29

The LANL/LLNL Prompt Fission Neutron Spectrum Program at LANSCE and approach to uncertainties

Robert C. Haight

Chi-Nu Team

International Workshop on Nuclear Data Covariances

Santa Fe, NM
April 28- May 1, 2014

LA-UR-14-xxxxx

--- more precisely

The LANL/LLNL Prompt Fission Neutron Spectrum Program at LANSCE and approach to uncertainties

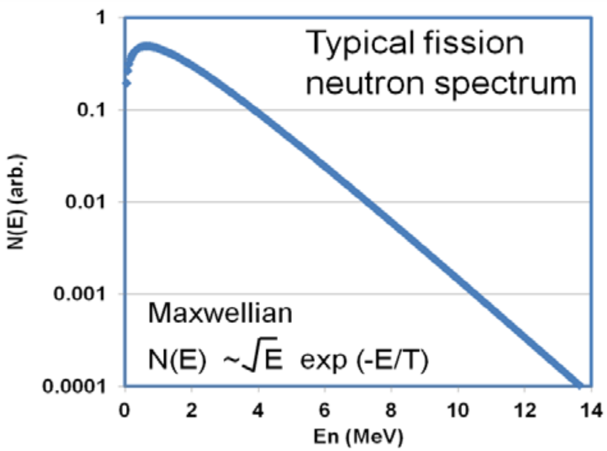
in the measurement of PFNS for $^{239}Pu(n,f)$ for incident neutron energies from 0.5 to 20 MeV and higher

Colleagues in PFNS experiments at LANSCE

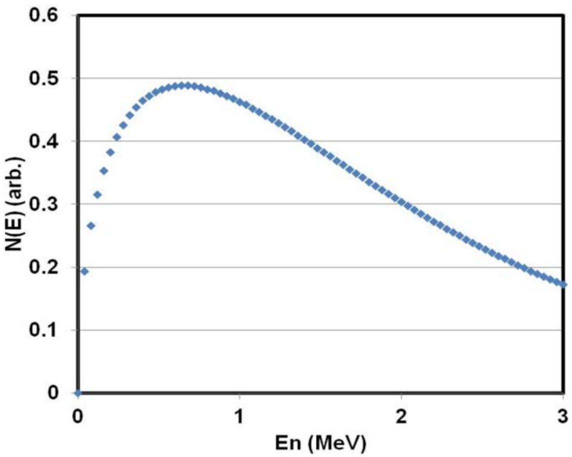
- LANL: H. Y. Lee, T. N. Taddeucci, J. M. O'Donnell, N. Fotiades, M. Devlin, J. L. Ullmann, T. Bredeweg, M. Jandel, R. O. Nelson, S. A. Wender, D. Neudecker, M. Rising, S. Mosby, S. Sjue, M. White; R. C. Haight
- LLNL: C.-Y. Wu, B. Bucher, R. Henderson
- CEA: T. Ethvignot, T. Granier, A. Chatillon, J. Taieb, B. Laurent

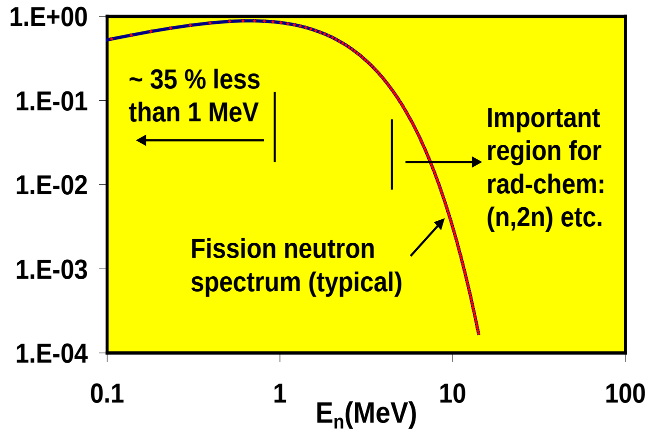
Reminder – Shape of PFNS is approximately Maxwellian

Semi-log

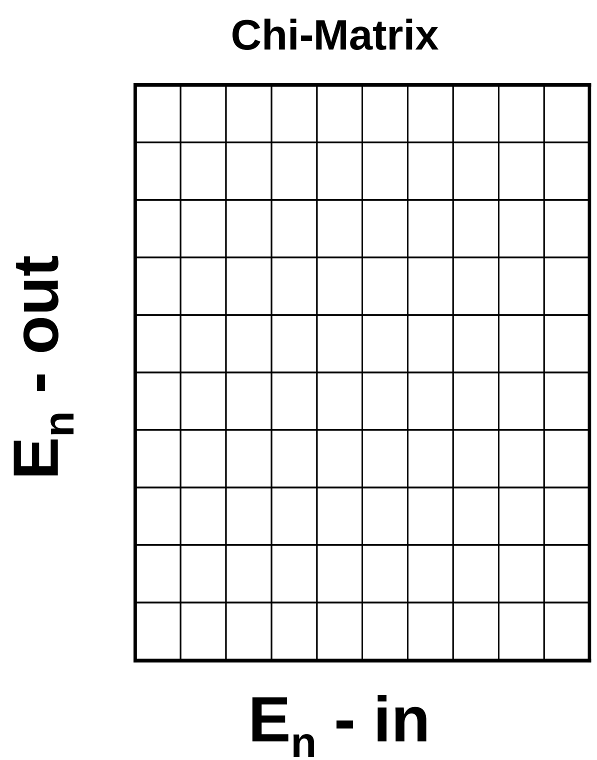


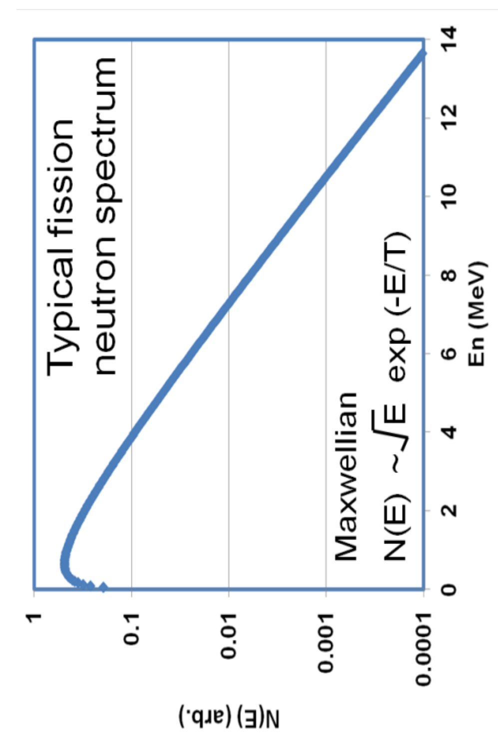
Linear





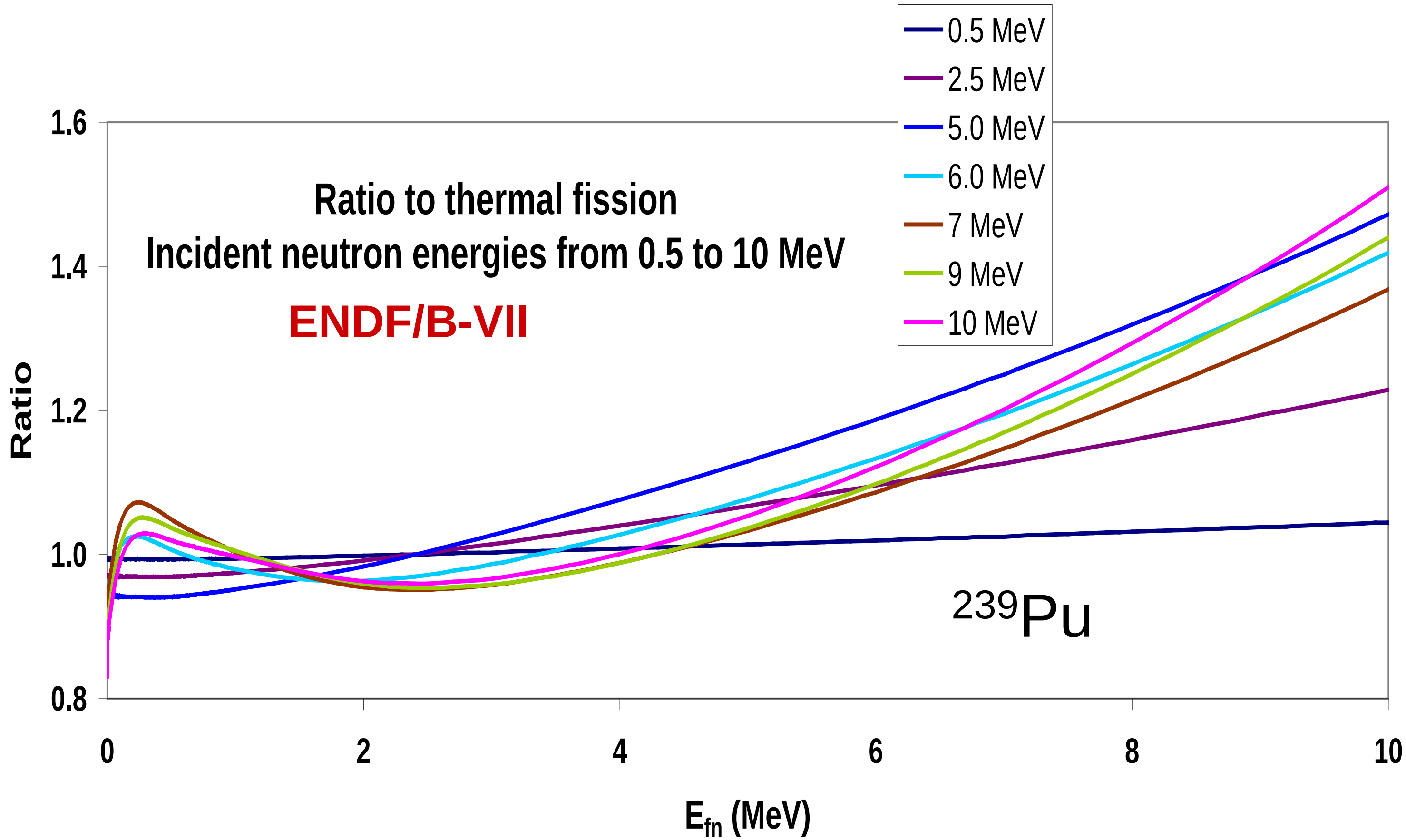
Chi-Matrix relates incident neutron energy to fission neutron output



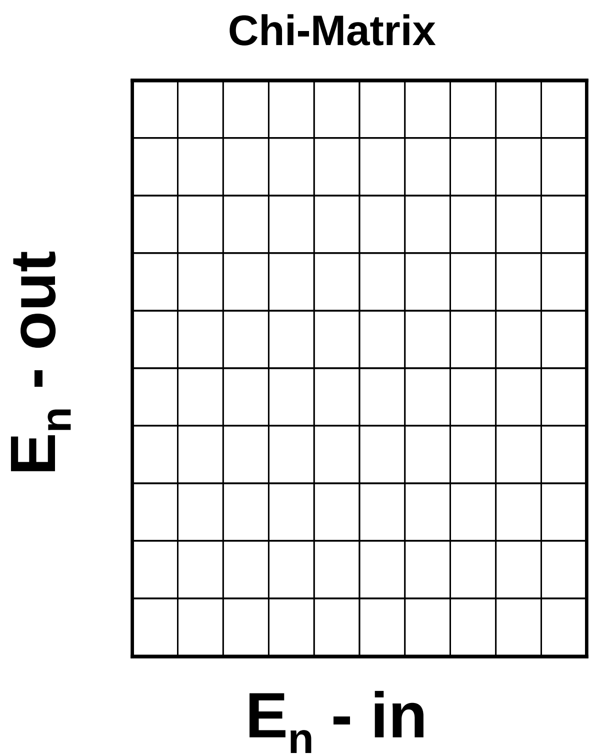


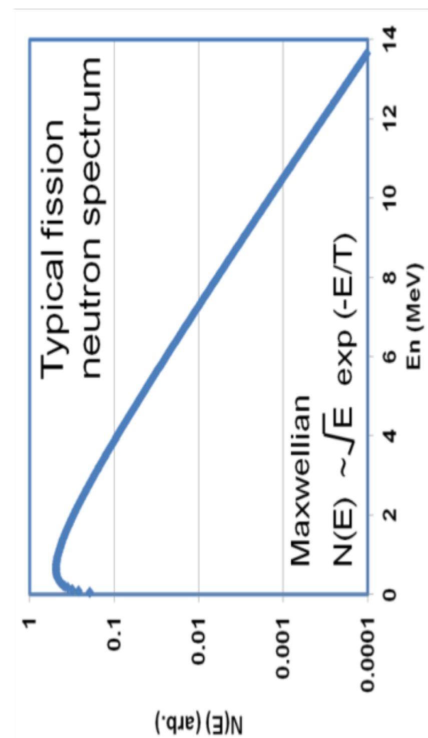
“Chi-Nu” program → ^{239}Pu(n,f) PFNS

Fission neutron spectra are predicted by models to vary with incident neutron energy

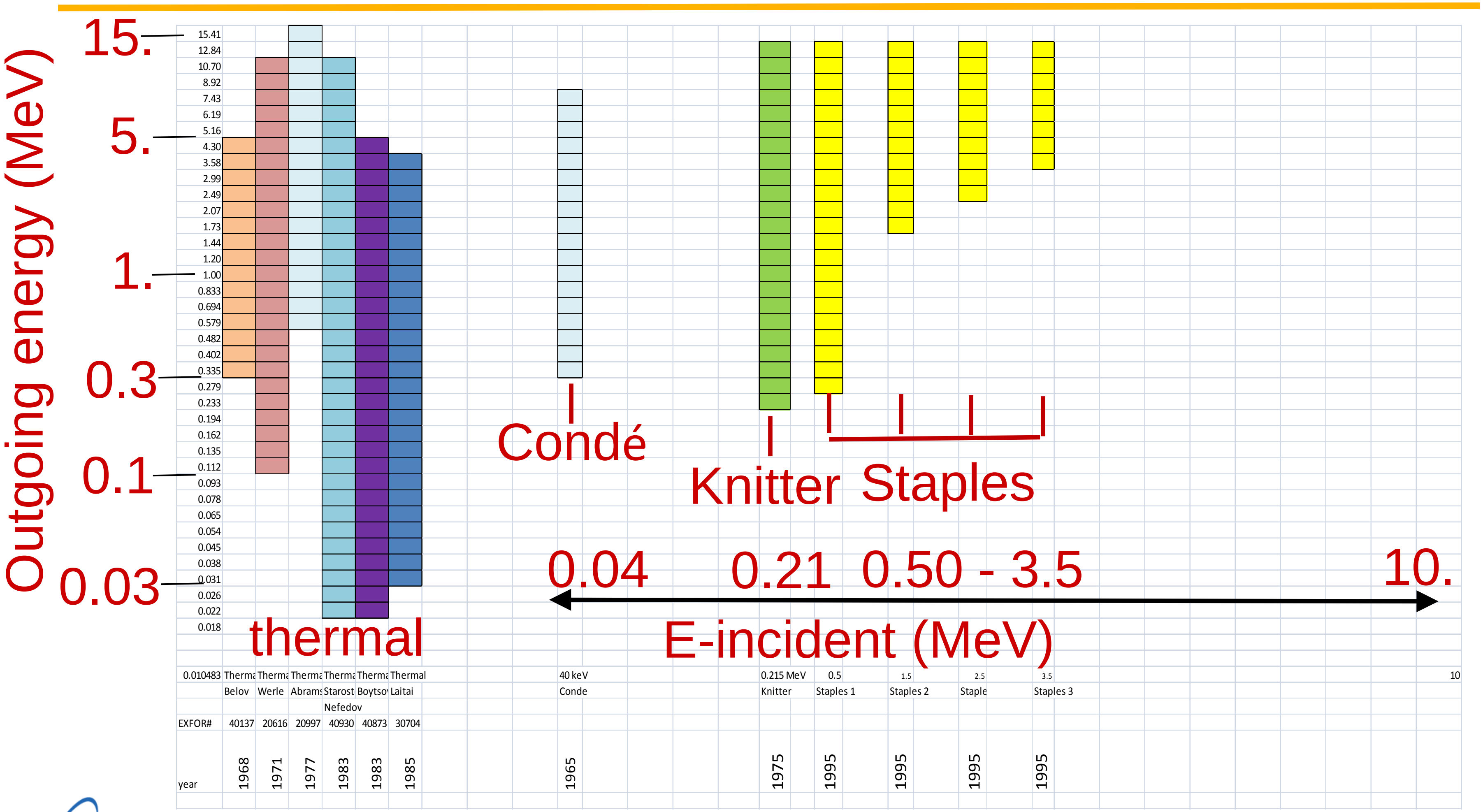


All elements of Chi-Matrix are correlated, at least to some degree, both experimentally and theoretically

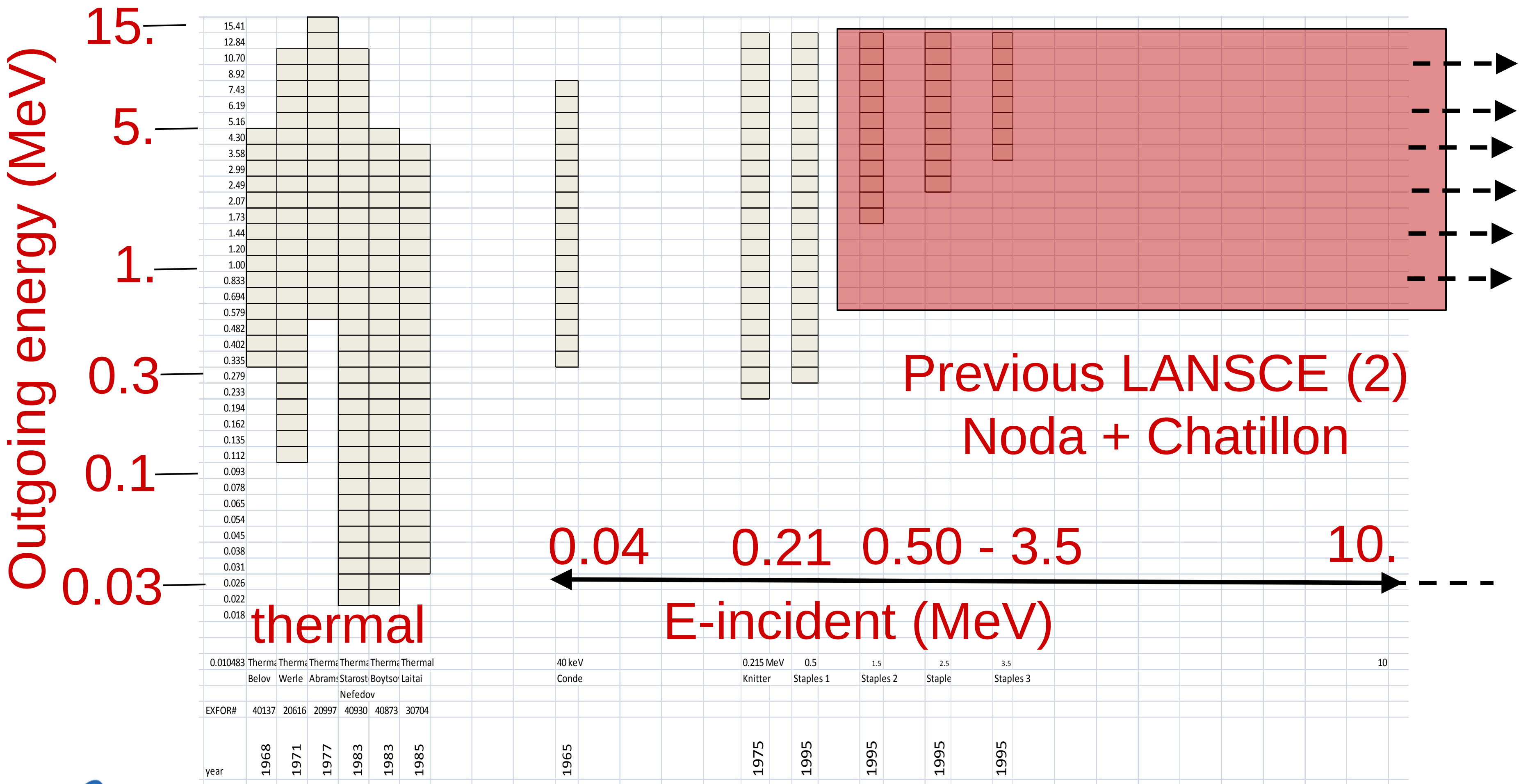




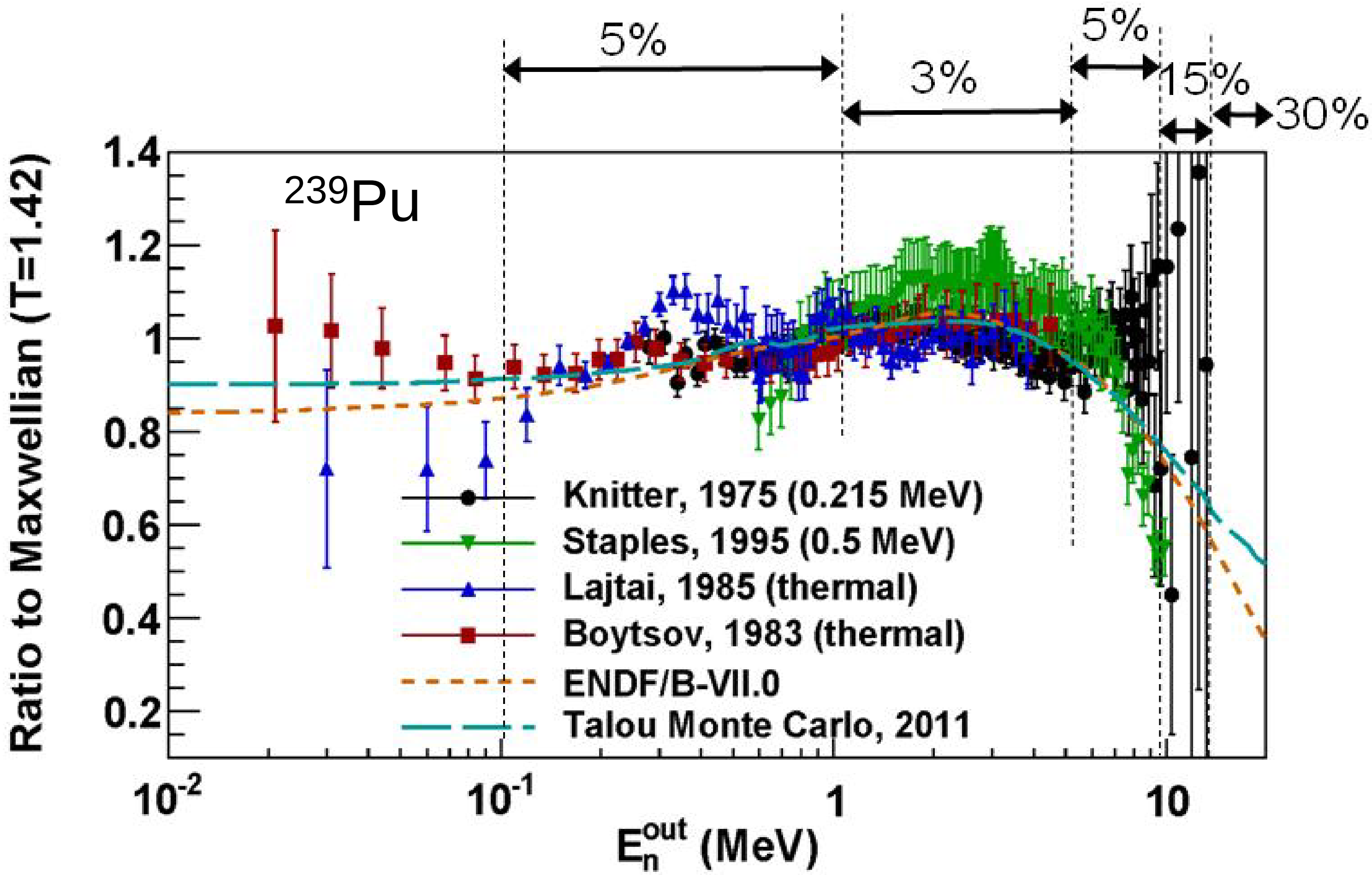
Data in the literature: PFNS for ^{239}Pu(n,f) – incident monoenergetic sources



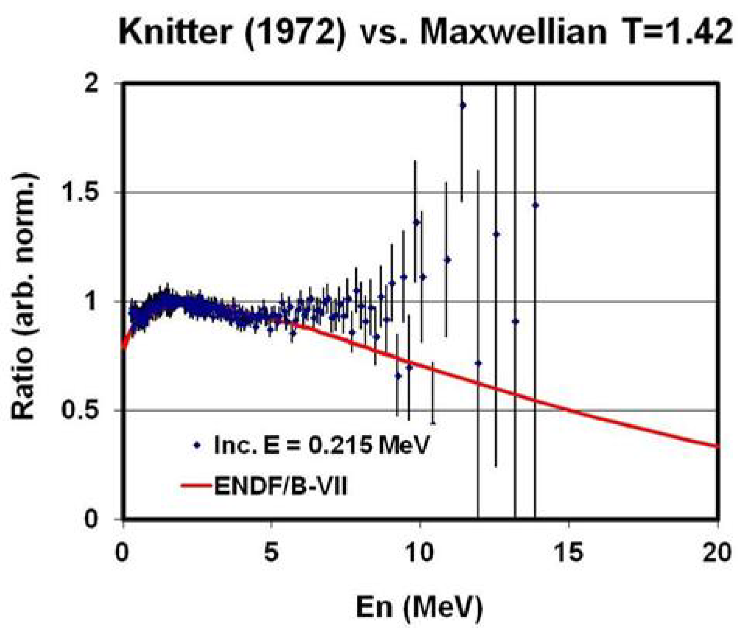
Data in the literature: PFNS for ^{239}Pu(n,f) – incident continuous sources

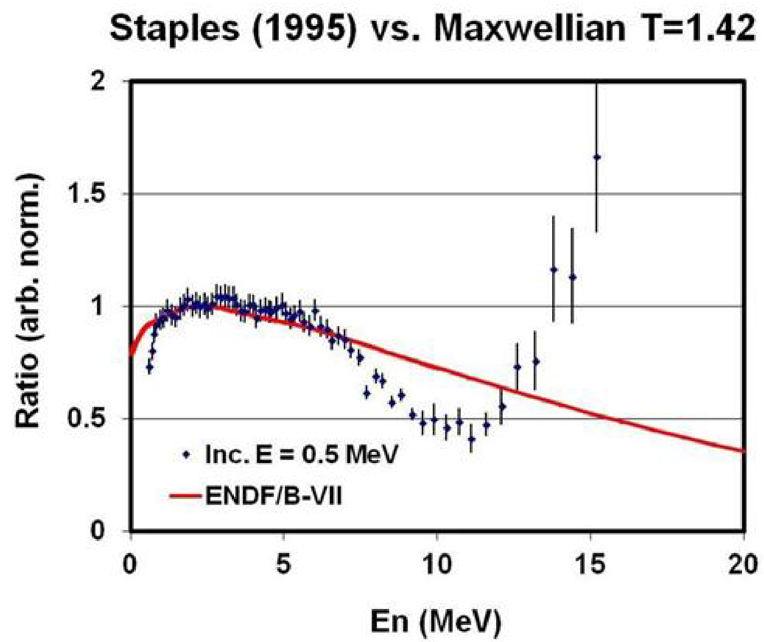


Literature data, discrepancies and target accuracies



Discrepancy in monoenergetic data for high-energy end of PFNS





Data > ENDF for Eout > 7 MeV

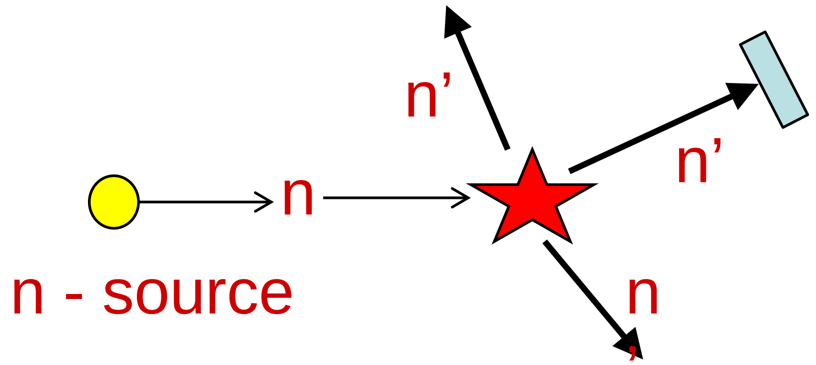
Data < ENDF for Eout 7 to 12 MeV

Note: Staples also for Einc = 1.5, 2.5, 3.5 MeV

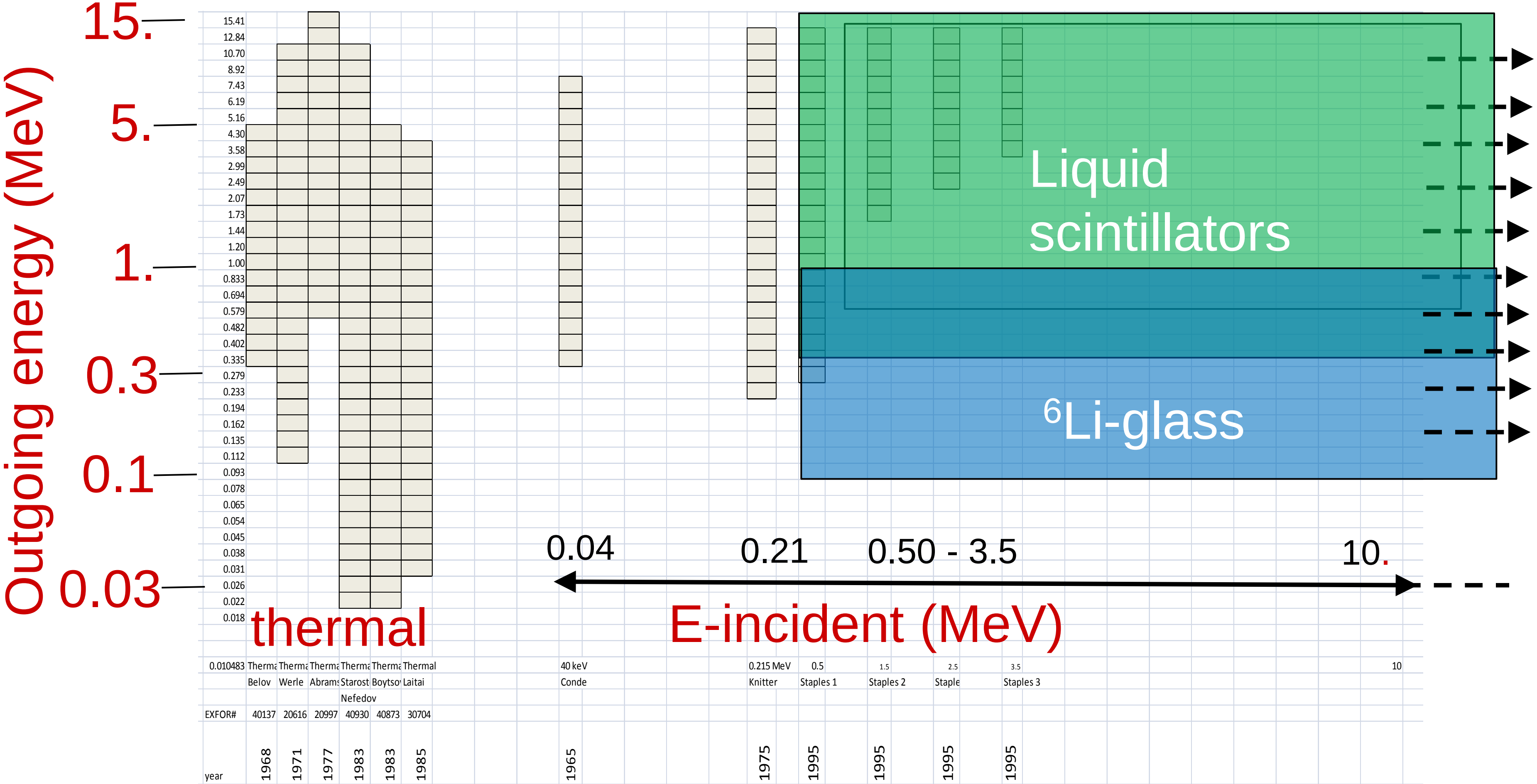
Measuring fission neutron spectra is easy in principle

- Components
  - Neutron source
  - Fissionable sample
  - Neutron detector
- Outgoing neutron energy determined by time of flight from the fission to a neutron detector

- Three approaches:
  1. Pulsed mononergetic neutron source and fissionable sample (thick or thin -- not necessary to detect fission)
  2. Pulsed spallation neutron source and fission detector (thin sample)
  3. (Thermal) – fission detector (thin sample)

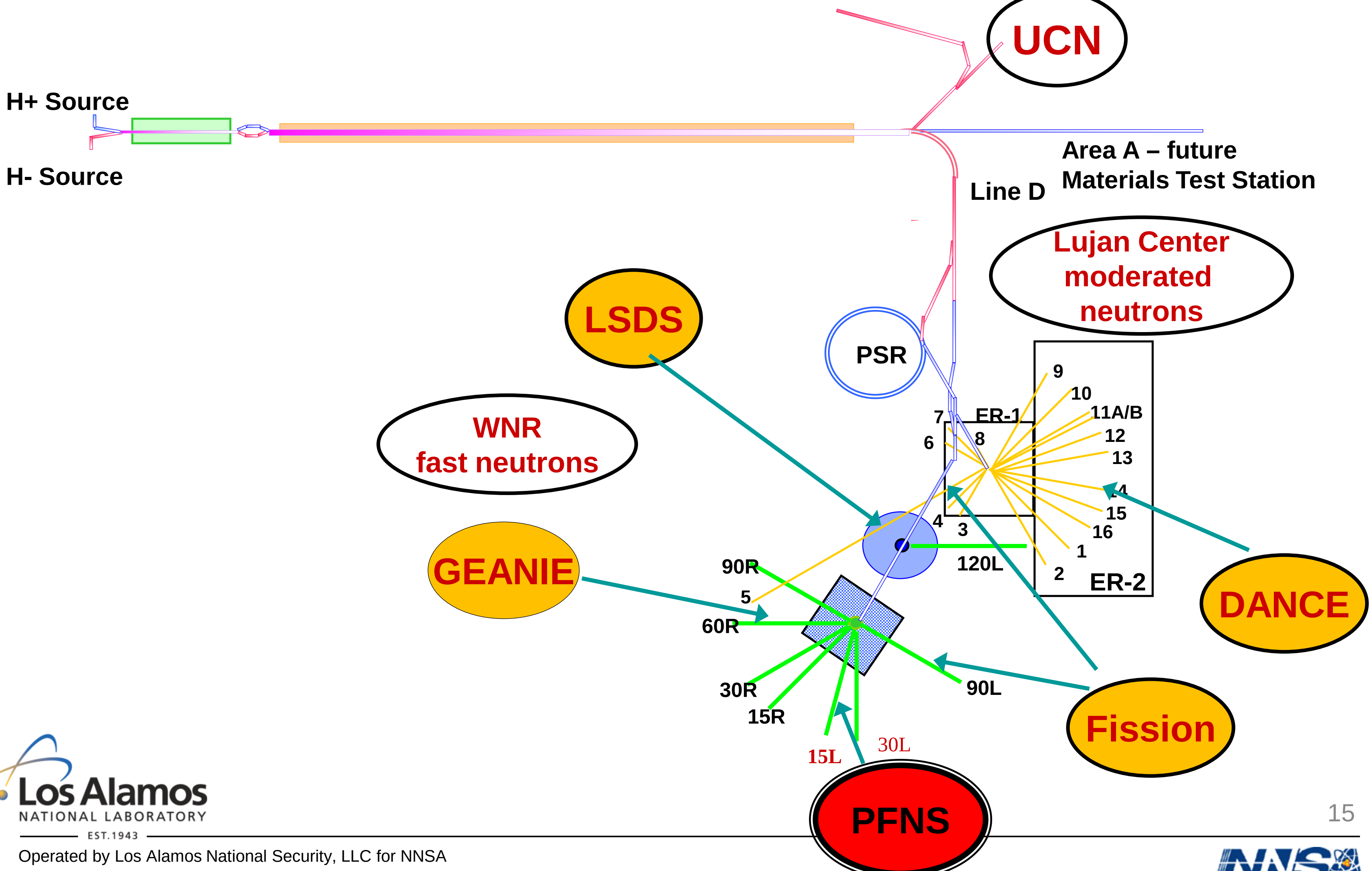


Chi-Nu measurements will be for incident neutrons 0.5 to > 20 MeV and PFN's from 0.1 to > 12 MeV



Los Alamos Neutron Science Center

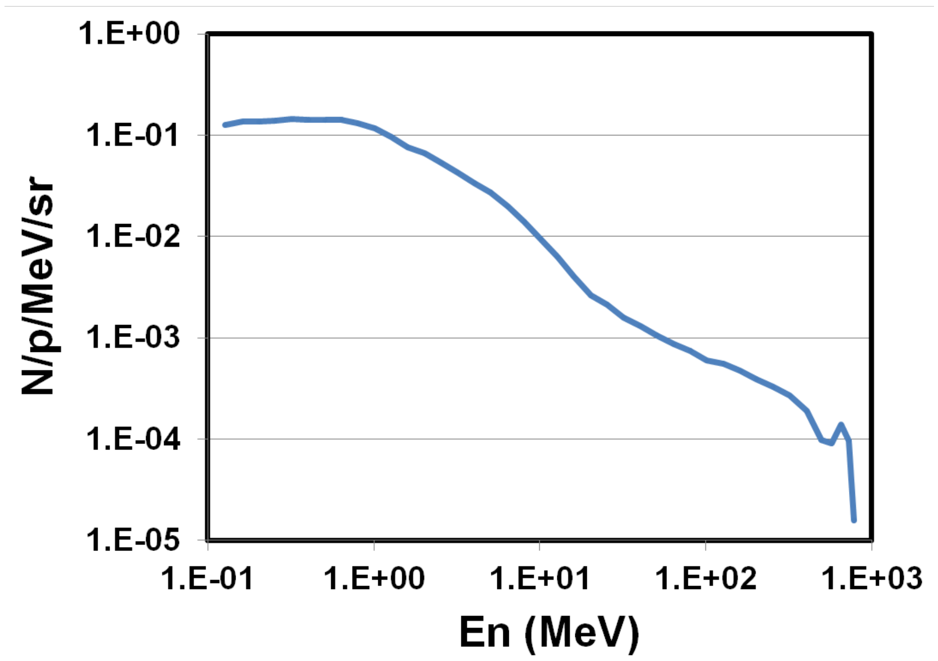
Instruments used for nuclear data measurements at the Los Alamos Neutron Science Center



Our range of incident neutron energies is from ~ 0.5 MeV to over 100 MeV

- **Energy range can be studied in one experiment**

For example, neutron spectrum at WNR/LANSCE



Website: wnr.lanl.gov

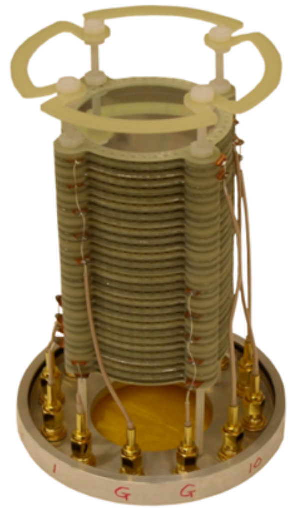
Fission sample and fission counter (LLNL) to contain ~ 100 mg of ^{239}Pu

- **Parallel-Plate Avalanche Counter (PPAC)**

In Beam

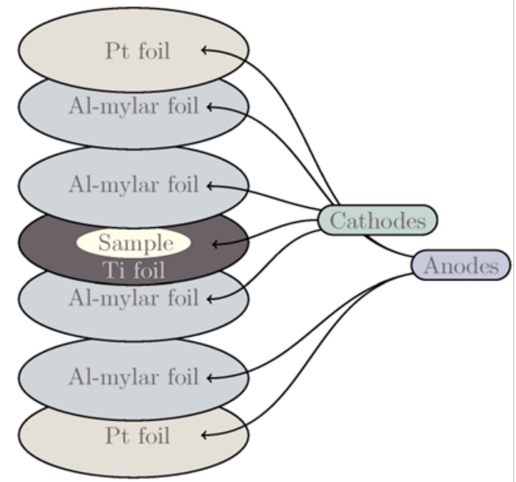
10 cm diam. × 17 cm

Cover Off



Foil: 5 cm diam.
Sample: 4 cm diam.

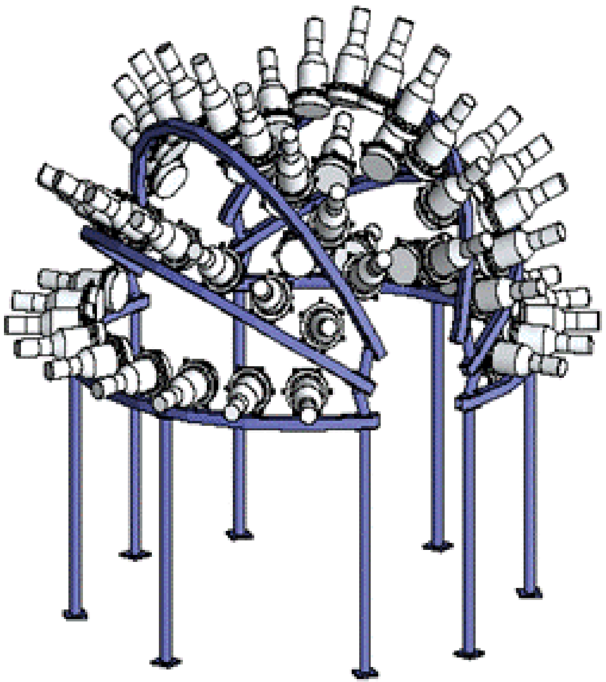
One Foil Stack (of 10)

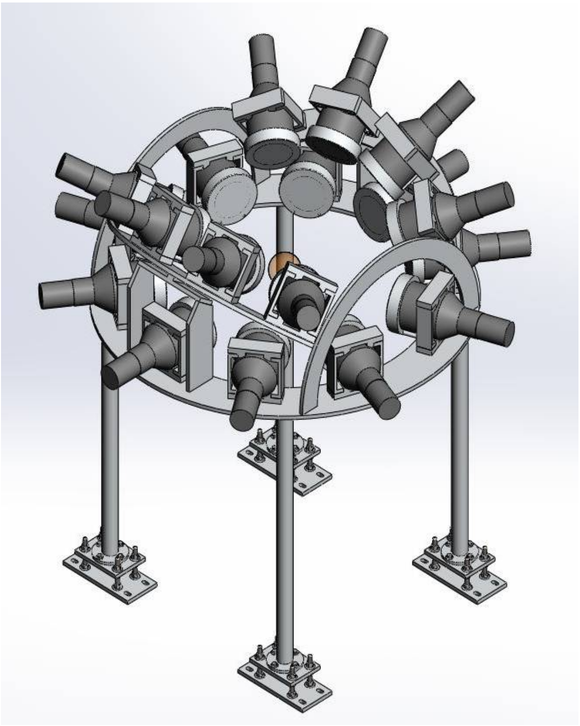


t = 400 μg/cm^2

Timing res.: 1–1.5 ns

Neutron detectors – two types





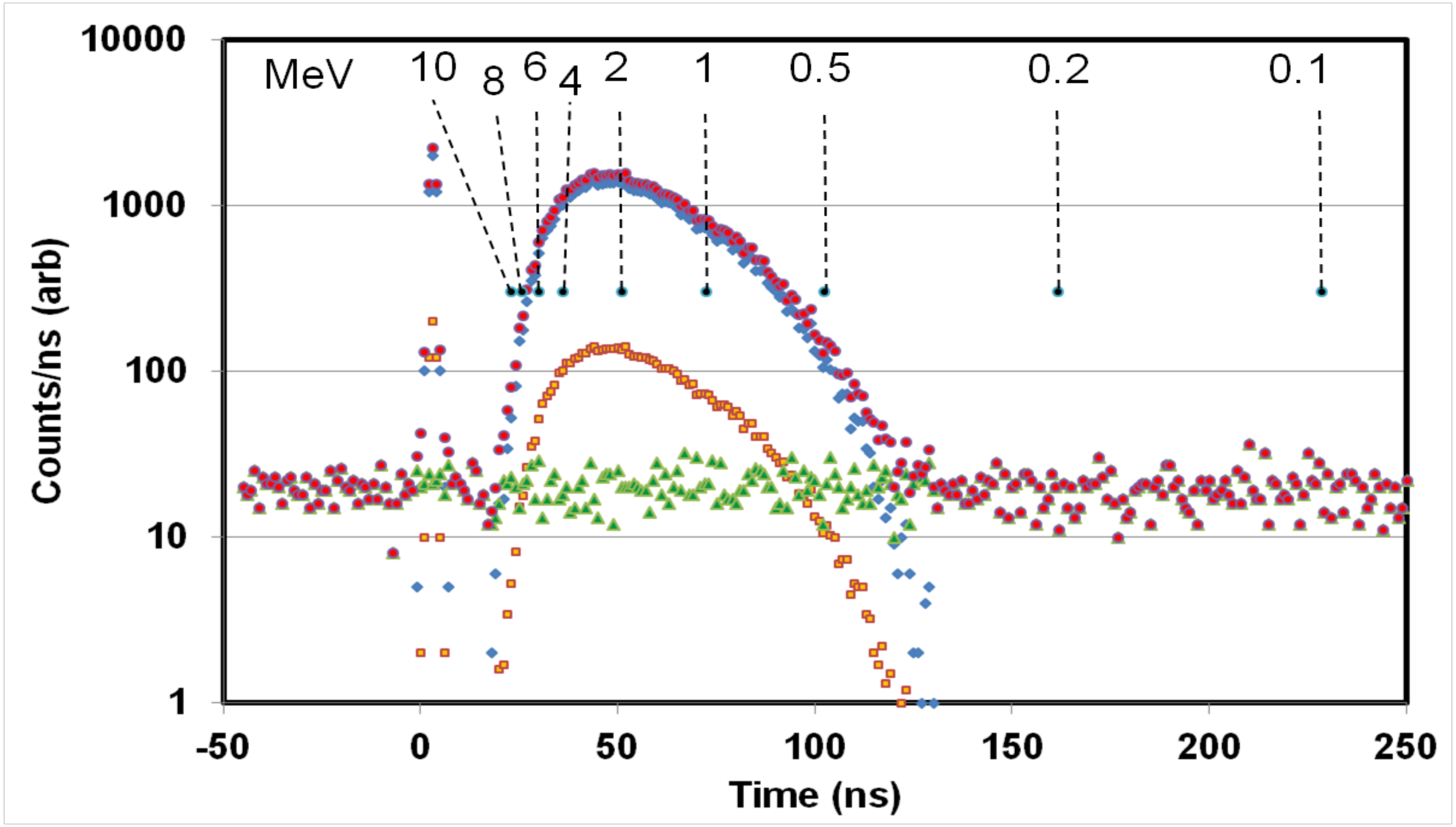
54 Liquid scintillators – 1.0 m flight path

22 ^{6}Li-glass scintillators – 0.4 m flight path

Uncertainties

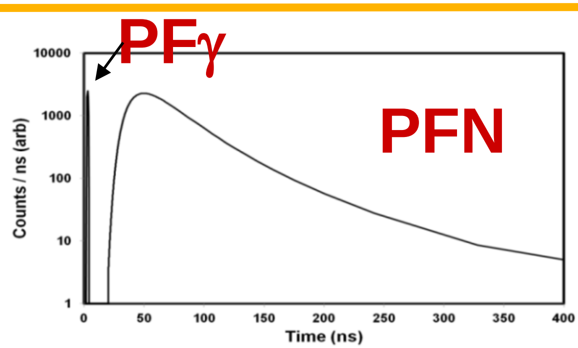
- Components
  - Conventional approach - here
  - Modern approach (next talk -- Terry Taddeucci)

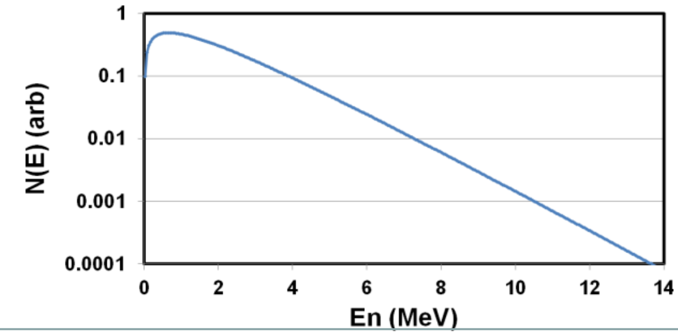
We measure time-of-flight spectra



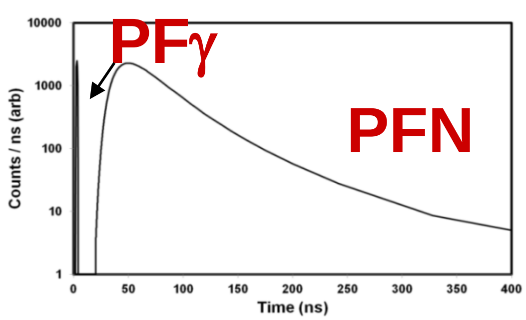
Notional time spectra – magnitudes are fictional; backgrounds are notional

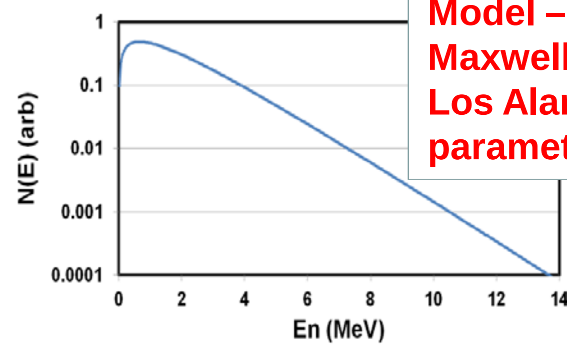
Two paths of analysis





1. Unfold: Convert TOF point by point to energy, correct for backgrounds, detector response, include uncertainties in efficiency, timing, and path length, effects of neutron scattering, rebin





Model – Maxwellian, Watt, Los Alamos.. with parameters

2. Forward analysis: Vary parameters, find best fit to TOF spectra using detector response, backgrounds and neutron scattering to get uncertainties in parameters

Uncertainties (1) – incident neutrons

- Timing – accuracy and time resolution (ΔT_{beam})
- Flight path length and spread (ΔL_{beam})
- Quality of beam
  - X-Y distribution of beam – position and uniformity
  - Beam current – stability
  - Beam energy – contaminants from down-scattered neutrons?
  - Dark current
  - Wrap around of micropulses
  - Protons in beam?
- Background from other beam lines
  - Shutter status
  - Material in beam
- Polarization of neutron beam ? Maybe, although probably small

Uncertainties (2) – fissionable sample in PPAC

- Position relative to beam
- Uniformity of distribution
  - Actual distribution in x and y
- Efficiency
  - Fission fragment angle
  - Loss due to short distance in gas (normal to foil)
  - Loss due to oblique angle (~90 degrees)
- Biases with respect to fission fragments
  - Energy Loss (function of KE, Z, A) and its distribution
- Pulse height cuts
  - at high energies, both fragments can come off foil in the forward hemisphere
- Construction materials and as-built design – needed for modeling
- Timing resolution and stability of timing (determined by photofission from gamma flash from neutron source)

Uncertainties (3) – neutron detectors

- Distance to center of fission chamber
  - Effective distance – function of neutron energy
  - Distribution of events in thickness of scintillator
- Detector response (more than just "efficiency")
  - Timing resolution and stability of timing
  - Efficiency - calculated
  - Light curve
  - N-gamma discrimination
- Gain stabilization
  - Short time -- Within macropulse
  - Long time – drifts due to temperature, line voltage, etc.
- Verification of calculated efficiency with ^{252}Cf PPAC
  - How well is the "standard" known
  - Same scattering issues as with ^{239}Pu PPAC
- Room background
  - Time independent
  - Time dependent

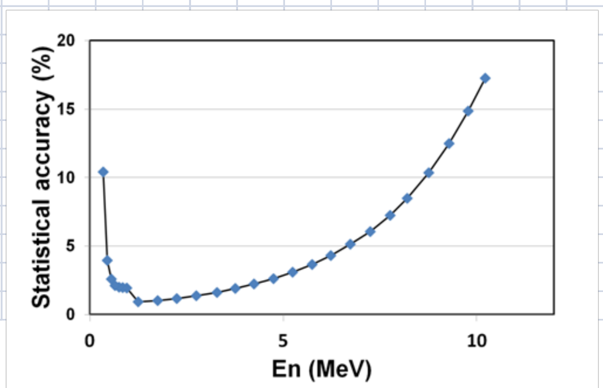
Correlations and uncertainties due to statistics in foreground spectra for 1 week of data

Correlation matrix with uncertainties for foreground statistics

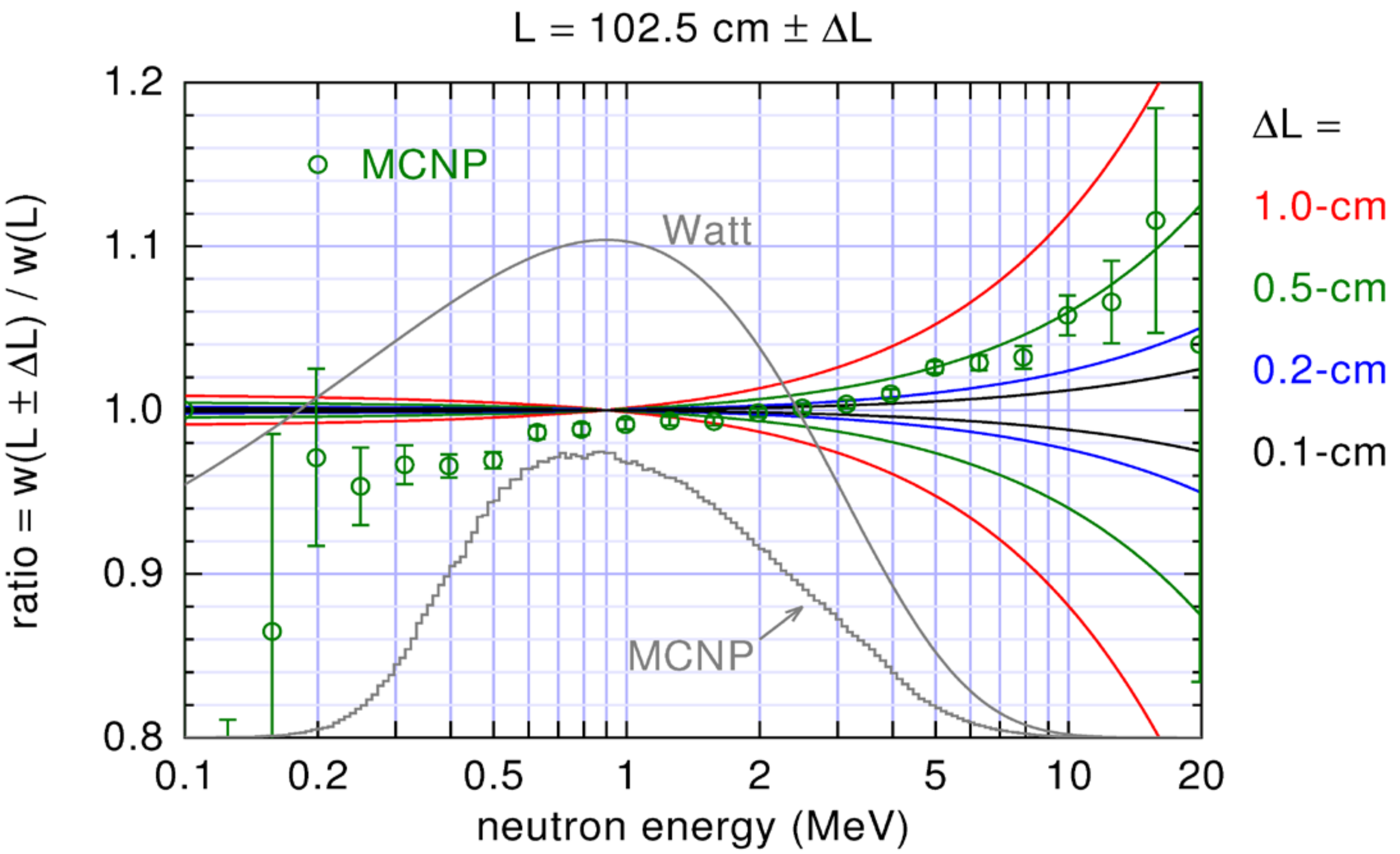
1-2 MeV incident energy bin

En (MeV) -- bin lower limit

%		0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0	6.5	7.0	7.5	8.0	8.5	9.0	9.5	10.0
NA	0.1	**NA**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
NA	0.2	0	**NA**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
10.4	0.3	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3.9	0.4	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2.6	0.5	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2.1	0.6	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2.0	0.7	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2.0	0.8	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1.9	0.9	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0.9	1.0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1.0	1.5	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1.2	2.0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1.4	2.5	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1.6	3.0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1.9	3.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
2.2	4.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
2.6	4.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
3.1	5.0	0	0	0														0	1	0	0	0	0	0	0	0	0	0	0
3.7	5.5	0	0	0														0	0	1	0	0	0	0	0	0	0	0	0
4.3	6.0	0	0	0														0	0	0	1	0	0	0	0	0	0	0	0
5.1	6.5	0	0	0														0	0	0	0	1	0	0	0	0	0	0	0
6.1	7.0	0	0	0														0	0	0	0	0	1	0	0	0	0	0	0
7.2	7.5	0	0	0														0	0	0	0	0	0	1	0	0	0	0	0
8.5	8.0	0	0	0														0	0	0	0	0	0	0	1	0	0	0	0
10.4	8.5	0	0	0														0	0	0	0	0	0	0	0	1	0	0	0
12.5	9.0	0	0	0														0	0	0	0	0	0	0	0	0	1	0	0
14.8	9.5	0	0	0														0	0	0	0	0	0	0	0	0	0	1	0
17.3	10.0	0	0	0														0	0	0	0	0	0	0	0	0	0	0	1



Systematic effect of flight path uncertainty analytic estimate versus MCNP



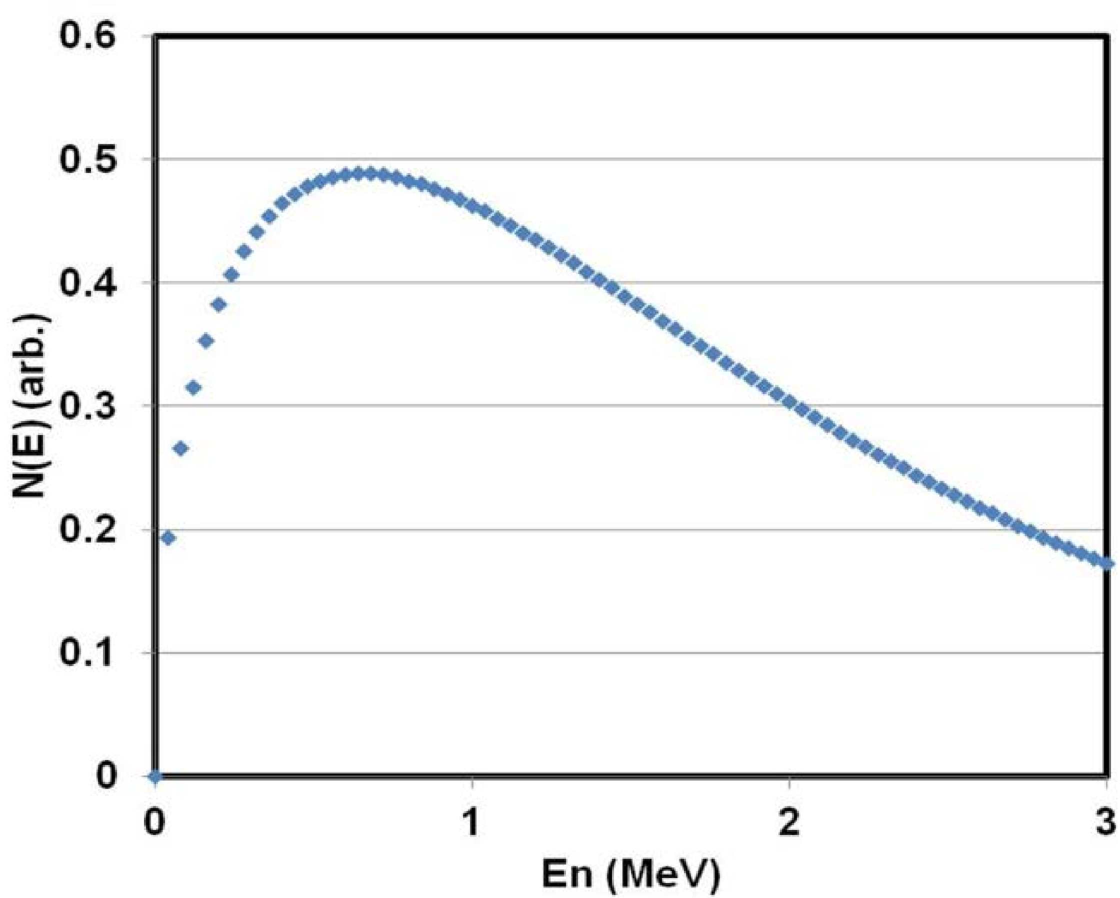
Correlations and uncertainties due to uncertainty in path length

Correlation matrix with uncertainties for DL= 0.2 cm

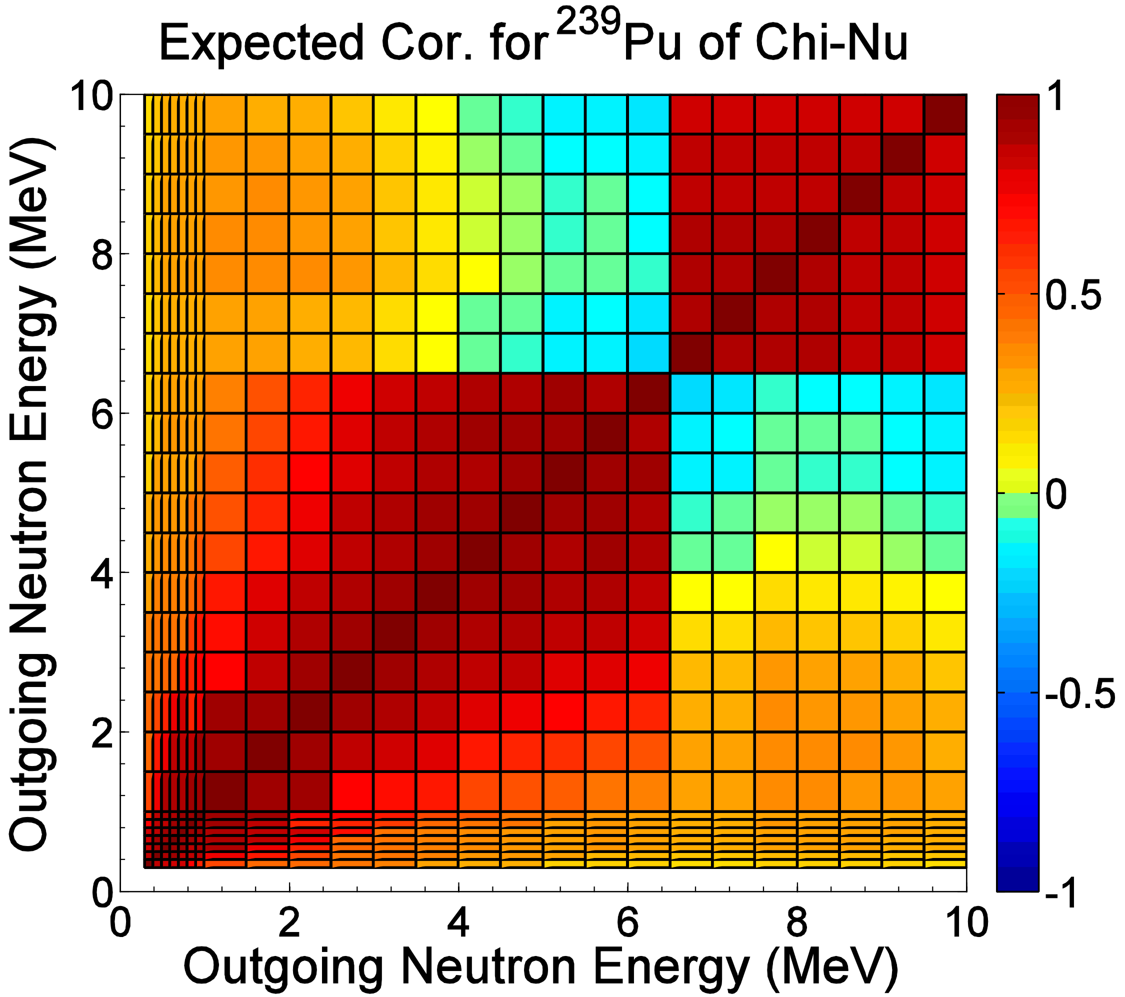
En (MeV) -- bin lower limit

%		0.1	0.2	0.3	[illegible]	[illegible]	[illegible]	7	0.8	0.9	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0	6.5	7.0	7.5	8.0	8.5	9.0	9.5	10.0
0.16	0.1	1	1	1	[illegible]	[illegible]	[illegible]	1	1	-1	-1	-1	-1	-1	-1	-1	-1	[illegible]	[illegible]	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1
0.14	0.2	1	1	1	1	1	1	1	1	-1	-1	-1	-1	-1	-1	-1	[illegible]	[illegible]	[illegible]	[illegible]	-1	-1	-1	-1	-1	-1	-1	-1	-1
0.12	0.3	1	1	1	1	1	1	1	1	-1	-1	-1	-1	-1	-1	-1	[illegible]	[illegible]	[illegible]	[illegible]	-1	-1	-1	-1	-1	-1	-1	-1	-1
0.08	0.4	1	1	1	1	1	1	1	1	-1	-1	-1	-1	-1	-1	-1	[illegible]	[illegible]	[illegible]	[illegible]	-1	-1	-1	-1	-1	-1	-1	-1	-1
0.06	0.5	1	1	1	1	1	1	1	1	-1	-1	-1	-1	-1	-1	-1	[illegible]	[illegible]	[illegible]	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1
0.04	0.6	1	1	1	1	1	1	1	1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1
0.00	0.7	1	1	1	1	1	1	1	1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1
0.02	0.8	1	1	1	1	1	1	1	1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1
0.04	0.9	-1	-1	-1	-1	-1	-1	-1	-1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
0.14	1.0	-1	-1	-1	-1	-1	-1	-1	-1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
0.28	1.5	-1	-1	-1	-1	-1	-1	-1	-1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
0.42	2.0	-1	-1	-1	-1	-1	-1	-1	-1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
0.58	2.5	-1	-1	-1	-1	-1	-1	-1	-1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
0.74	3.0	-1	-1	-1	-1	-1	-1	-1	-1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
0.90	3.5	-1	-1	-1	-1	-1	-1	-1	-1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
1.06	4.0	-1	[illegible]	[illegible]	[illegible]	-1	-1	-1	-1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
1.22	4.5	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	-1	-1	-1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
1.40	5.0	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	-1	-1	-1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
1.56	5.5	-1	[illegible]	[illegible]	[illegible]	-1	-1	-1	-1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
1.72	6.0	-1	-1	[illegible]	-1	-1	-1	-1	-1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
1.90	6.5	-1	-1	-1	-1	-1	-1	-1	-1	1	1	1	1	[illegible]	[illegible]	1	1	1	1	1	1	1	1	1	1	1	1	1	1
2.08	7.0	-1	-1	-1	-1	-1	-1	-1	-1	1	1	1	[illegible]	[illegible]	[illegible]	[illegible]	1	1	1	1	1	1	1	1	1	1	1	1	1
2.24	7.5	-1	-1	-1	-1	-1	-1	-1	-1	1	1	1	[illegible]	[illegible]	[illegible]	[illegible]	1	1	1	1	1	1	1	1	1	1	1	1	1
2.42	8.0	-1	-1	-1	-1	-1	-1	-1	-1	1	1	1	[illegible]	[illegible]	[illegible]	[illegible]	1	1	1	1	1	1	1	1	1	1	1	1	1
2.60	8.5	-1	-1	-1	-1	-1	-1	-1	-1	1	1	1	1	[illegible]	[illegible]	1	1	1	1	1	1	1	1	1	1	1	1	1	1
2.78	9.0	-1	-1	-1	-1	-1	-1	-1	-1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
2.94	9.5	-1	-1	-1	-1	-1	-1	-1	-1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
3.12	10.0	-1	-1	-1	-1	-1	-1	-1	-1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1

Correlations due to uncertainties: time-of-flight, path length and binning come from shape of PFNS



Denise Neudecker puts all these uncertainties together – correlation of uncertainties



Model-constrained data

- How much reliance should we put on the model to correlate uncertainties for fission induced by neutrons of different energies?

Example: PFNS for $^{239}Pu(n_{th},f)$ – is it a good guide for PFNS in fast-neutron-induced fission?

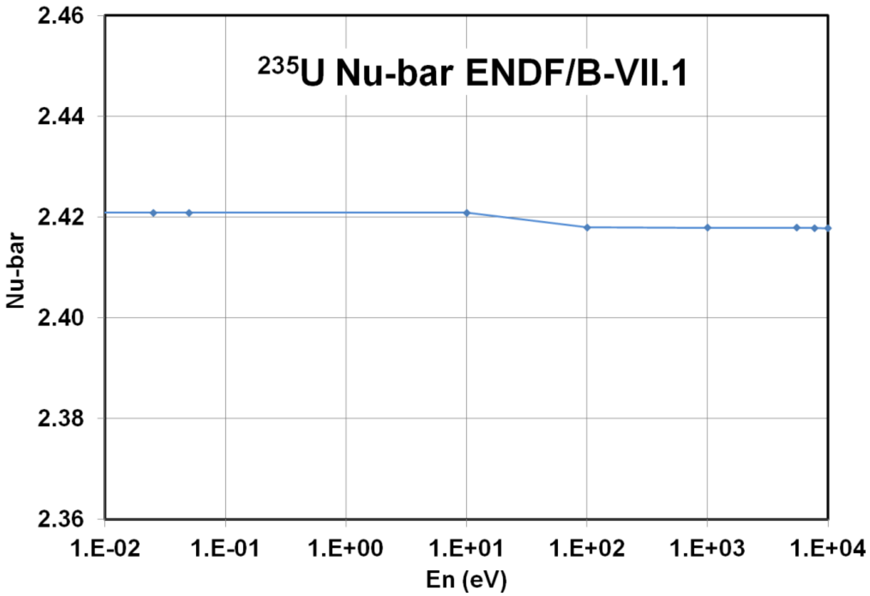
- **Prompt fission neutron spectra have been measured at thermal for ^{235}U and ^{235}Pu. Reactions at thermal can be dominated by one or only a few energies.**

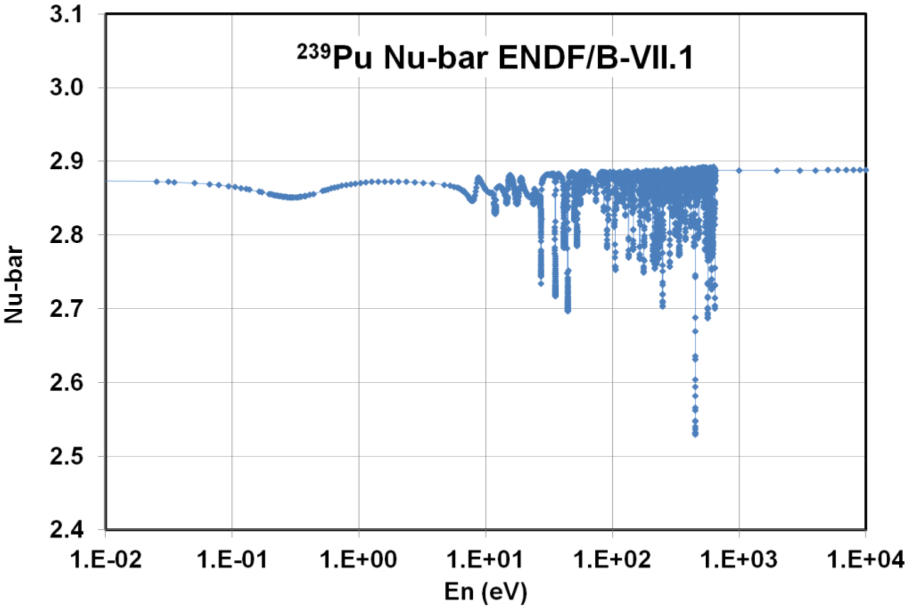
- **Do these data have any relevance to PFNS for fission induced by higher energy neutrons?**

- **Zero order analysis – look at average number of neutrons emitted in fission. If they vary with incident neutron energy, then there could well be a change in the spectra of emitted neutrons.**

Are PFNS measured at thermal relevant for higher incident neutrons?

- Nu-bar for $^{235}U(n,f)$ has no structure
- Nu-bar for ^{239}Pu has a lot of structure

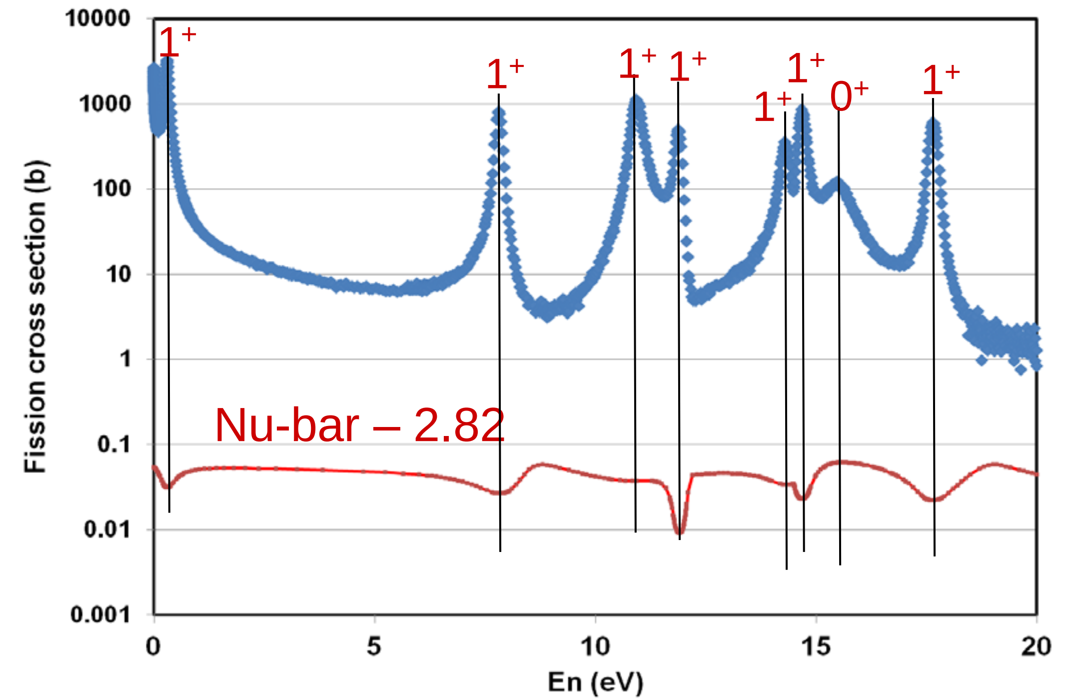




Note also the scale: <<1% for ^{235}U; up to 12 % for ^{239}Pu

Correlate structure in nu-bar for ^{239}Pu(n,f) with fission cross section

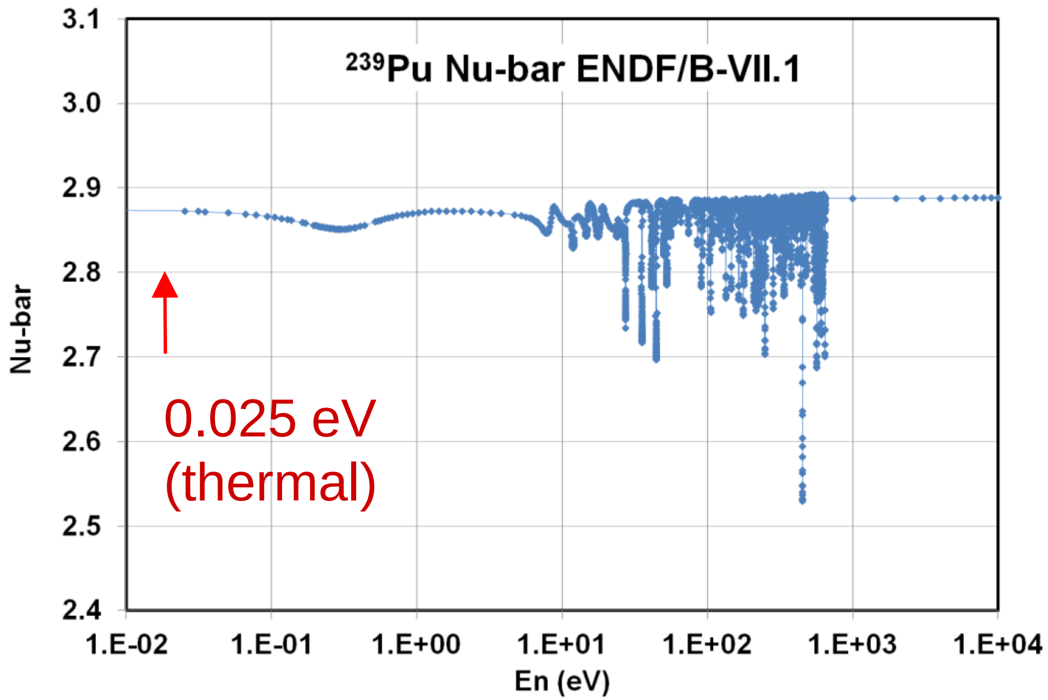
- Fission cross section from Weston [NSE 115,164 (1993)]
- Subtract a constant (2.82) from nu-bar for clarity of display
- Add spins and parities (all positive) from Mughabghab
  - 0+ resonance shows no effect in nu-bar
  - 1+ resonances show varying effects



Probably (n,γ f) process

Now the good news (maybe)

- Nu-bar at thermal for ^{239}Pu(n,f) is almost the same as for 1-10 keV. Maybe the thermal neutron PFNS is relevant to higher energies
- Q: Is nu-bar at thermal dominated by the 1^+ resonance at 0.3 eV ?



Summary

- Some data in literature for PFNS for $^{239}Pu(n,f)$
  - Discrepancies
  - Uncertainties not well documented
- New experiments are underway at LANSCE
  - Many components of uncertainties; most are correlated
  - Forward analysis
- Question – how closely should analysis and evaluation be tied to fission model?

Acknowledgments

- This work is performed under the auspices of the U.S. Department of Energy by

  Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344

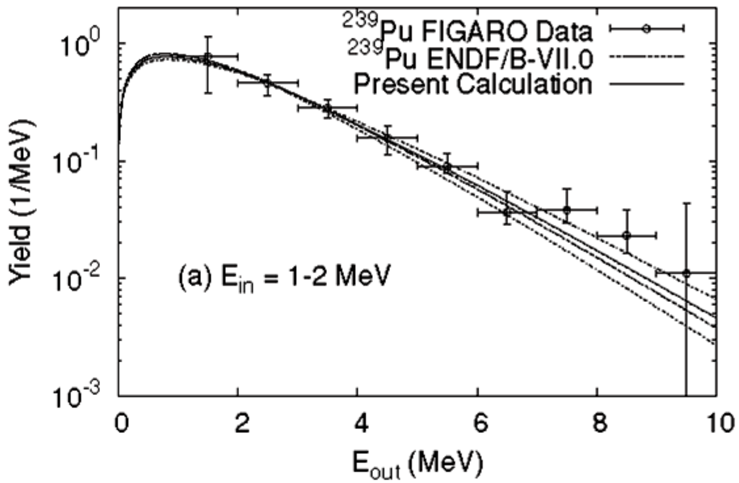
  and the Los Alamos National Laboratory under Contract DE-AC52-06NA25396.

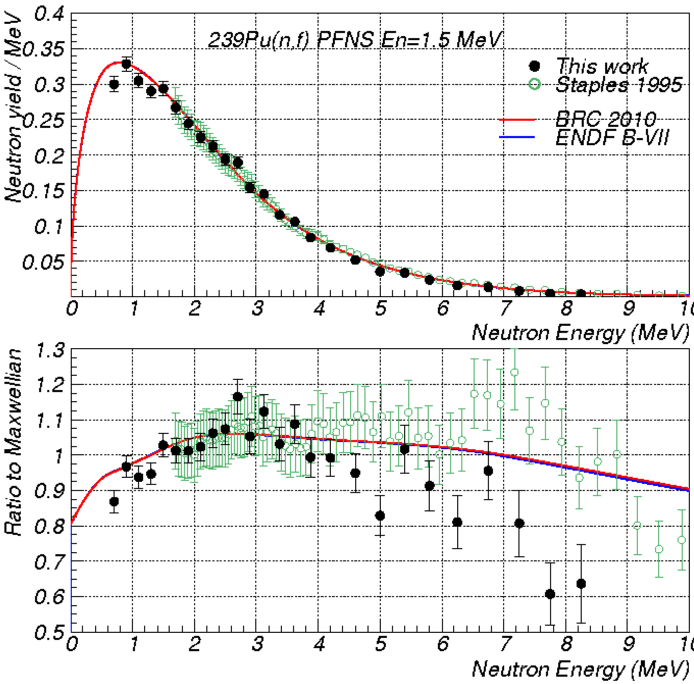
Backup slides

Measurements made with “white” neutron source at LANSCE for ^{239}Pu(n,f): CEA-LANL collaboration

S. Noda et al., Phys. Rev. C 83, 034604 (2011)

A. Chatillon et al., Phys. Rev. C 89, 014611 (2014)





Data > ENDF for Eout > 7 MeV

Data < ENDF for Eout > 7 MeV

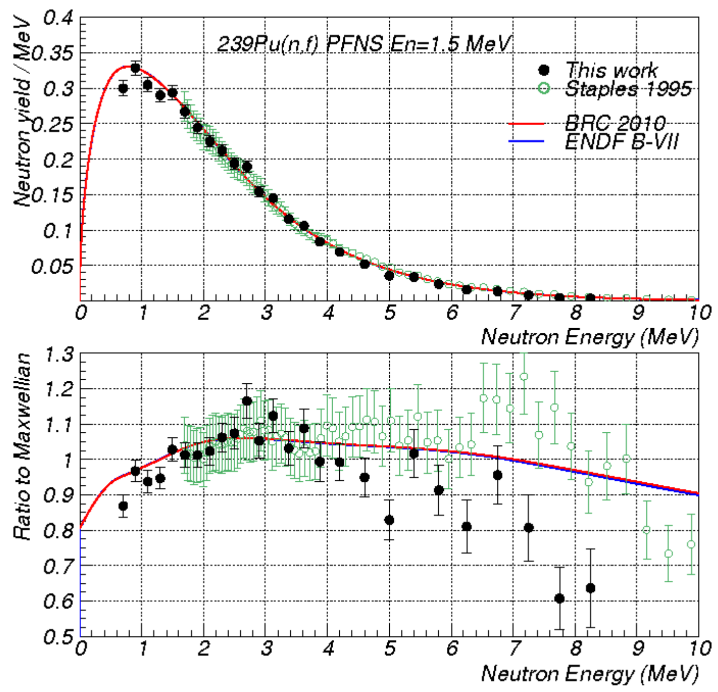
Note: Data for both also for Einc = 1.0 to > 20 MeV

Chatillon data will also be reduced due to time resolution. Detector calibration difference needs to be included also.

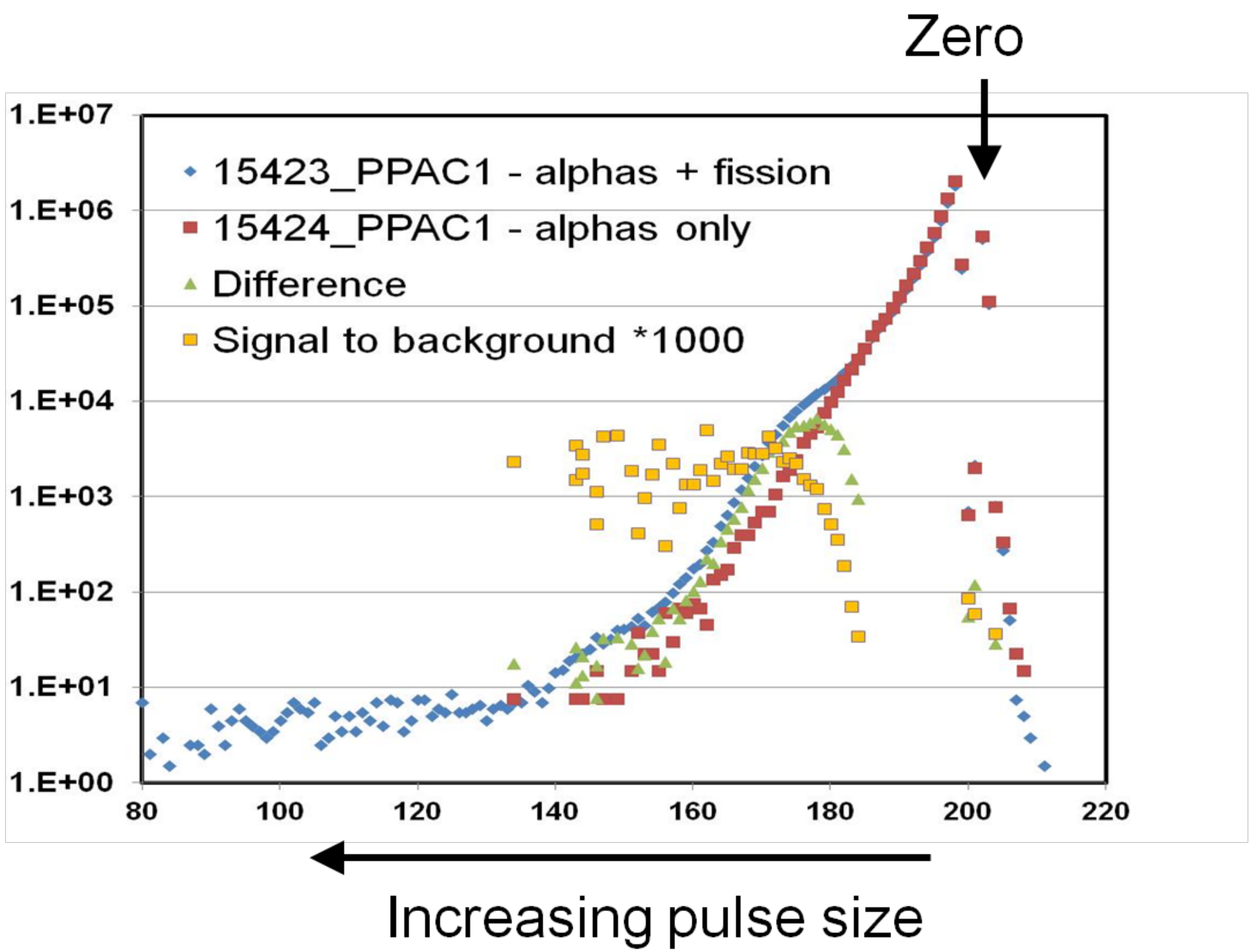
- Correction will reduce data points above 7 MeV but not so much as Noda data because of better time resolution by Bauge fission chamber

- Major difference with Noda is in calibration of neutron detector efficiency, which explains why Bauge < Noda above 7 MeV.

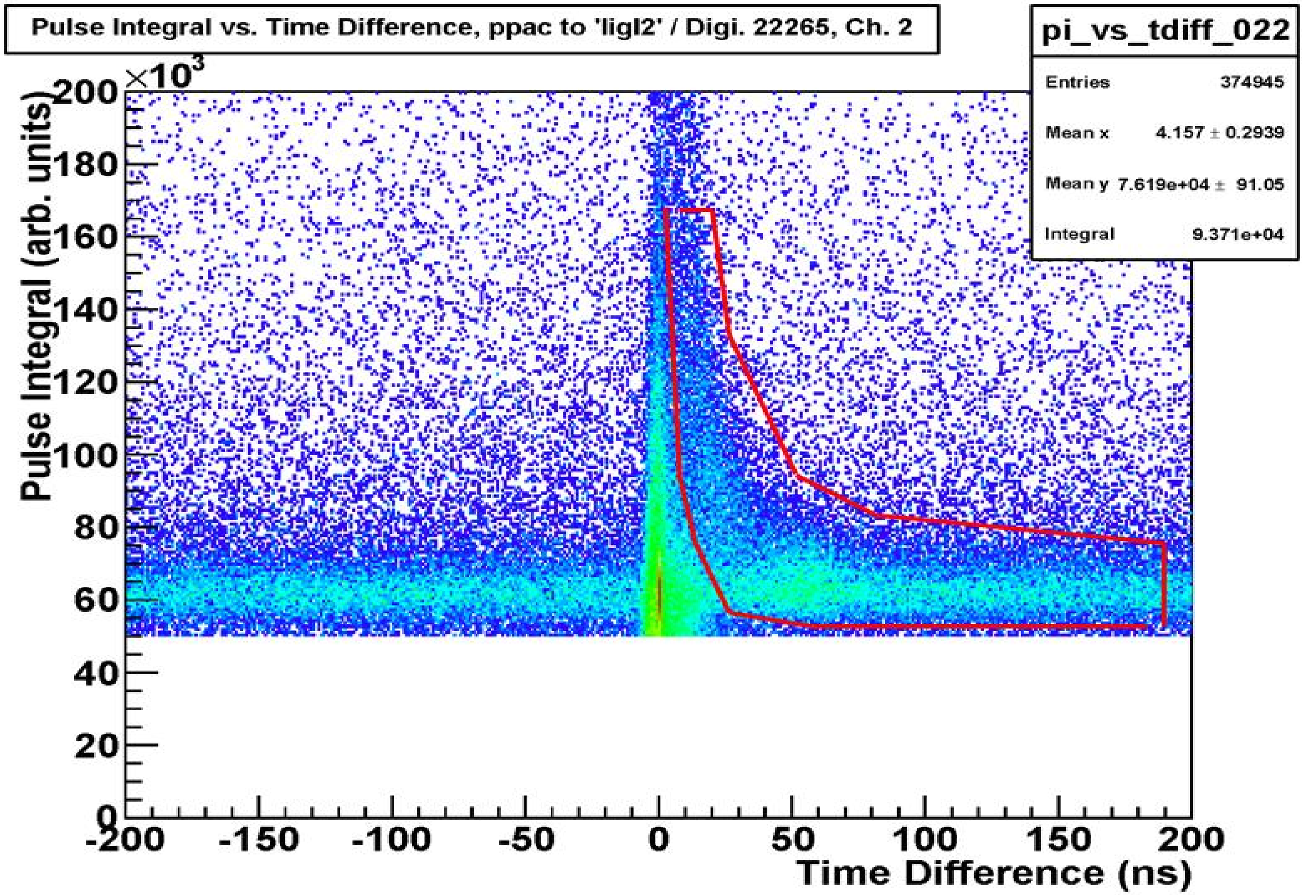
A. Chatillon et al.,Phys. Rev. C89, 014611 (2014)



PPAC alphas from ^{239}Pu decay are not cleanly separated from fissions

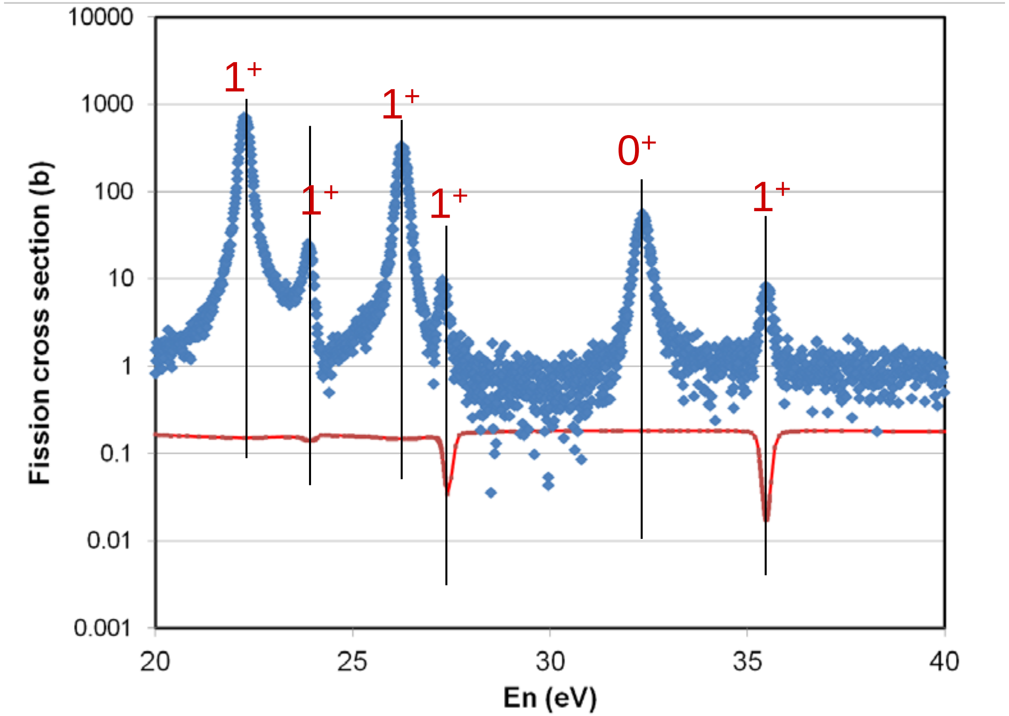


Signal is within the red polygon; background is everything else



Go to next energy range of resonances, 20-40 eV

- Fission cross section from Weston [NSE 115,164 (1993)]
- Subtract a constant (2.70) from nu-bar for clarity of display
- Add spins and parities (all positive) from Mughabghab
  - 0+ resonance shows no effect in nu-bar
  - 1+ resonances show varying effects



Uncertainties and correlations

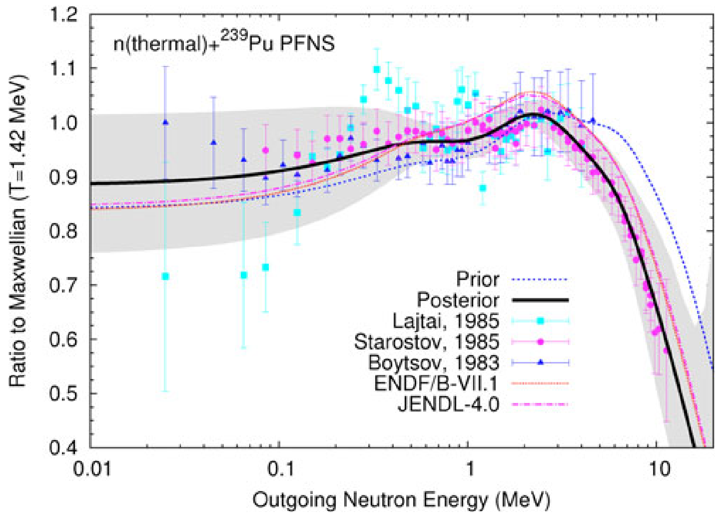
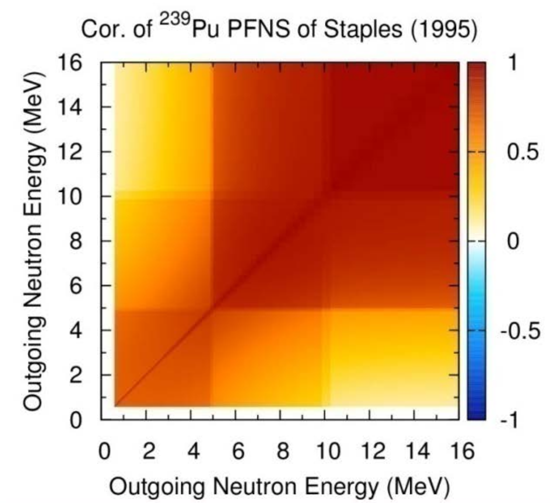


Fig. 11. The PFNS of the n(thermal) + ^{239}Pu reaction plotted with experimental data and the current ENDF/B-VII.1 evaluation. The posterior parameters in Table V were used in Eq. (27) to compute this present evaluation. Note that the experimental data have been normalized to the posterior PFNS.

M. Rising et al., Nucl. Sci. Eng 175, 81(2013).

Due to unknown sample composition, an uncertainty in the multiple scattering correction should be considered.



Timeline for ChiNu Measurements

30-Jan-14