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Title: Perspectives on Measurements of Prompt Fission Neutron Spectra for Fission Induced by Fast Neutrons

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Perspectives on Measurements of Prompt Fission Neutron Spectra for Fission Induced by Fast Neutrons

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Los Alamos National Laboratory

Second International Workshop on
Perspectives on Nuclear Data for the Next Decade

CEA Bruyères-le-Châtel, France

October 14-17, 2014

LA-UR-14-xxxxx

Perspectives on measurements of prompt fission neutron spectra

- Spontaneous fission (^{252}Cf)
- Neutron-induced fission
  - Thermal neutron-induced fission
  - **Fast neutron-induced fission**

Predictions for PFNS measurements

- $^{239}Pu(n,f)$ – for incident neutron energies > 0.5 MeV and to requested accuracy
  - Resolve discrepancies for PFNS > 0.5 MeV – probable in 2-3 years
  - Produce new data for PFNS in range 0.05 to 0.50 MeV -- maybe in 3-4 years
- $^{235}U(n,f)$ – for incident neutron energies > 0.5 MeV
  - Data for PFNS > 0.5 MeV – probable in 3-4 years
  - Produce new data for PFNS in range 0.05 to 0.50 MeV -- maybe in 4-5 years

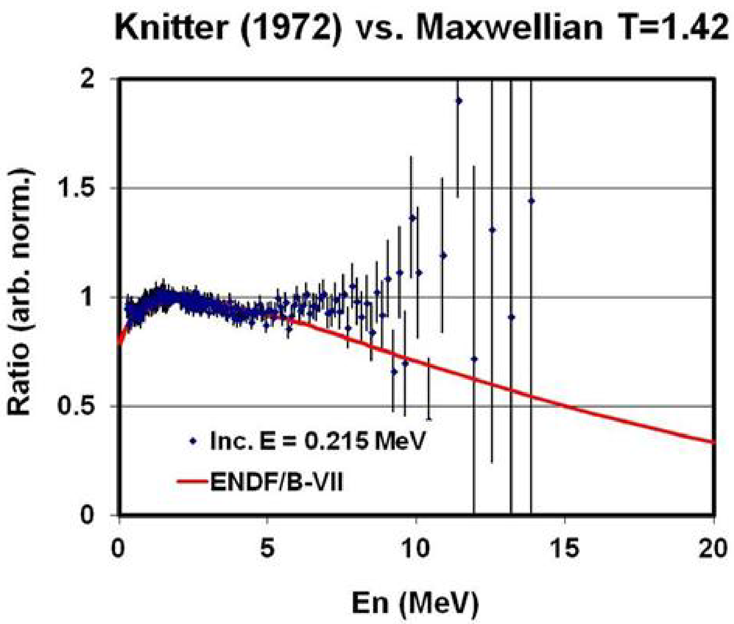
Predictions for PFNS measurement technologies

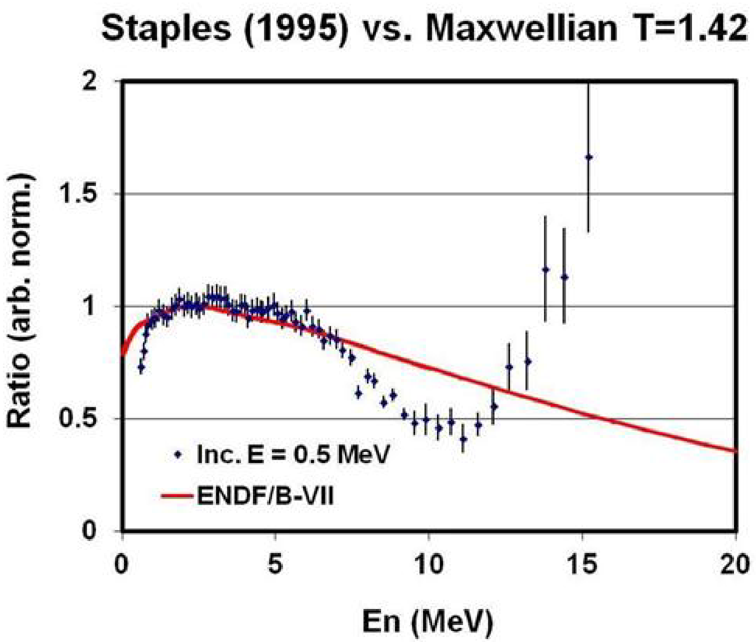
- Experiments
  - Neutron source – **intense, low background needed**
  - Detectors – **good neutron identification (psd or ?), good efficiency, “modelable” in MCNP**
  - Data acquisition – implementation of new hardware, firmware, software – **good resolution, good timing, programmable, capable of handling high counting rates**
- Modeling neutron transport as corrections to literature data, and design and analysis of new experiments

Predictions for PFNS measurement technologies

- Experiments
  - Neutron source – **intense, low background needed** -- **no new facilities for this type of measurement (?) :- (**
  - Detectors – **good neutron identification (psd or ?), good efficiency, "modelable" in MCNP** -- **nothing for greatly advanced capabilities :- (**
  - Data acquisition – implementation of new hardware, firmware, software – **good resolution, good timing, programmable, capable of handling high counting rates** **--** **In progress :-)**
- Modeling neutron transport as corrections to literature data, and design and analysis of new experiments-- **NOW and continuing ★ ★ ★ ★ :-))**

Discrepancy in monoenergetic data for high-energy end of PFNS





Data > ENDF for Eout > 7 MeV

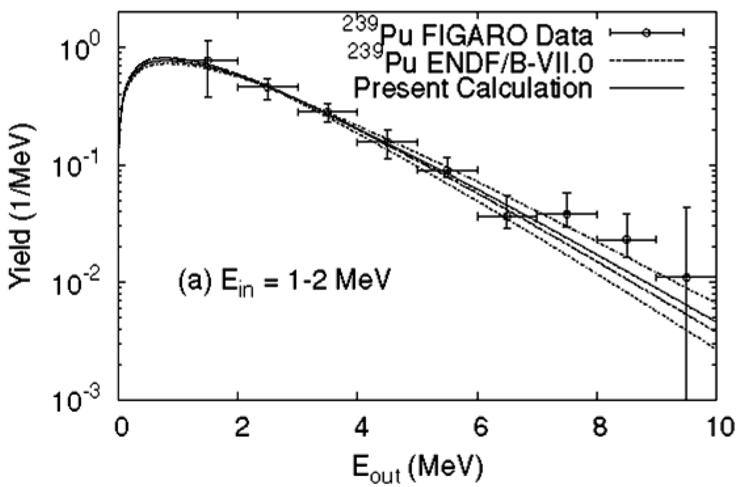
Data < ENDF for Eout 7 to 12 MeV

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

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)



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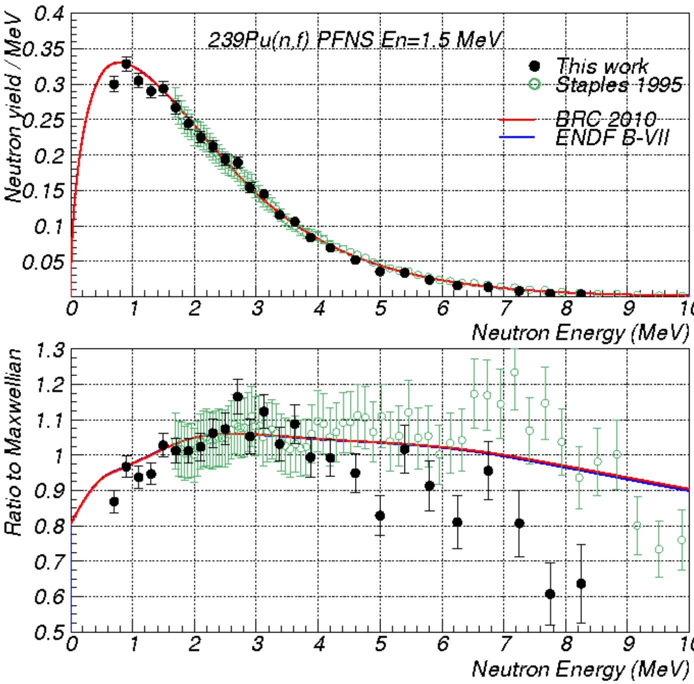


Data > ENDF for Eout > 7 MeV

Data < ENDF for Eout > 7 MeV

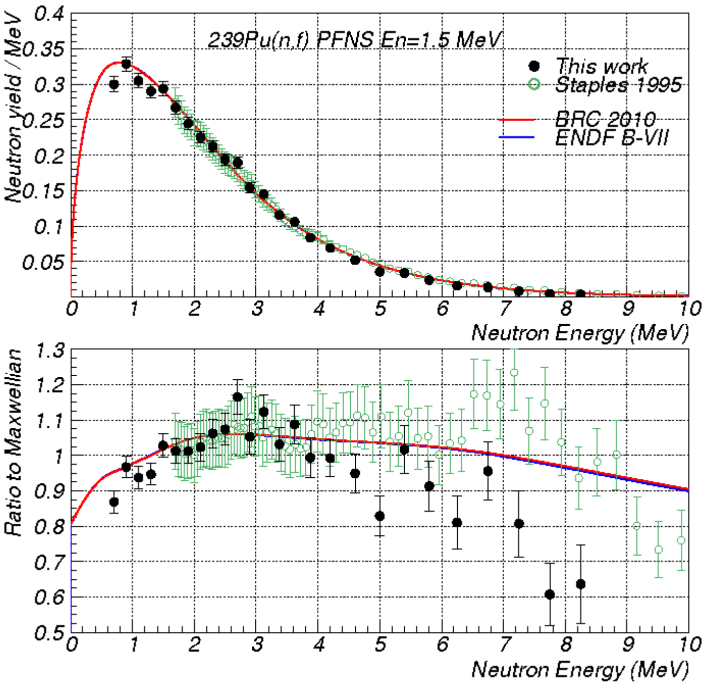
Note: Data for both also for Einc = 1.0 to > 20 MeV

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

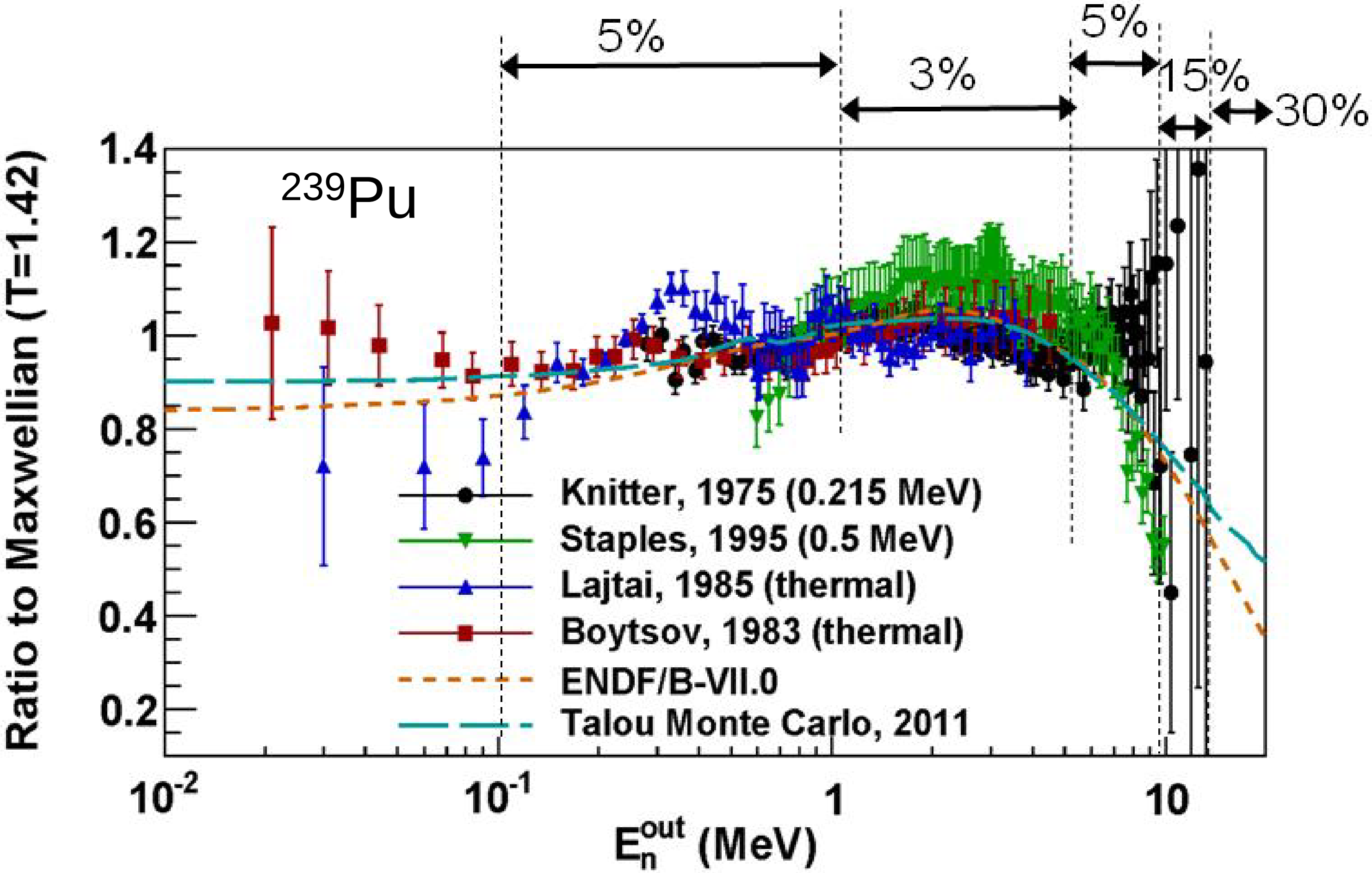
- Correction will reduce data points above 7 MeV but not so much as Noda data because of better time resolution by Bauge fission chamber

- 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)



Literature data, discrepancies and target accuracies



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

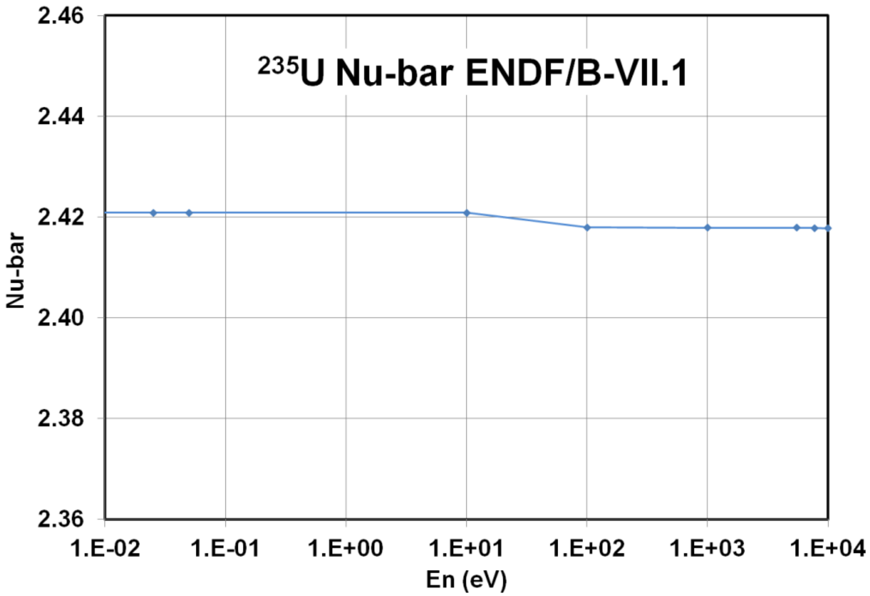
- **Prompt fission neutron spectra have been measured at thermal for ^{235}U and ^{235}Pu. Reactions at thermal can be dominated by one or only a few resonances**

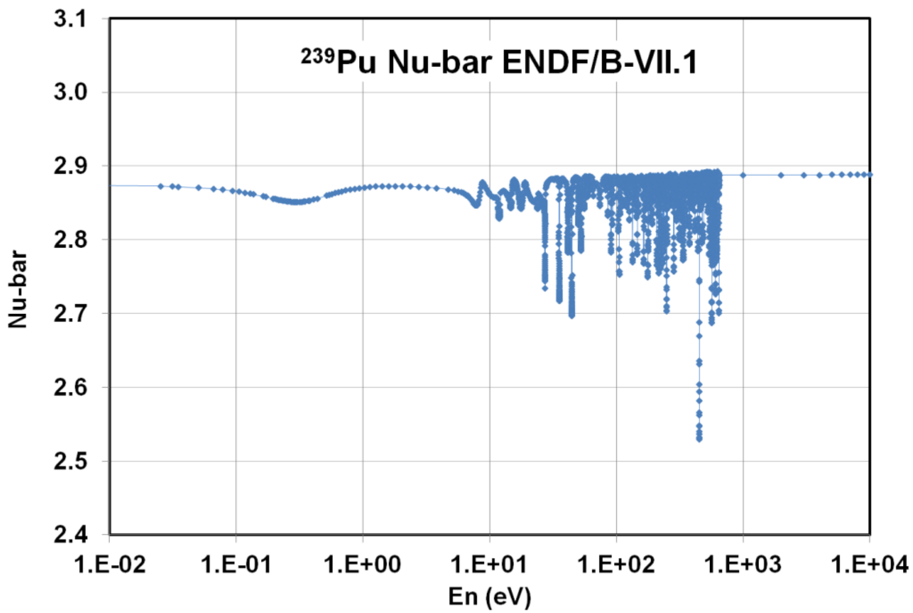
- **Do the data at thermal have any relevance to PFNS for fission induced by higher energy neutrons?**

- **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

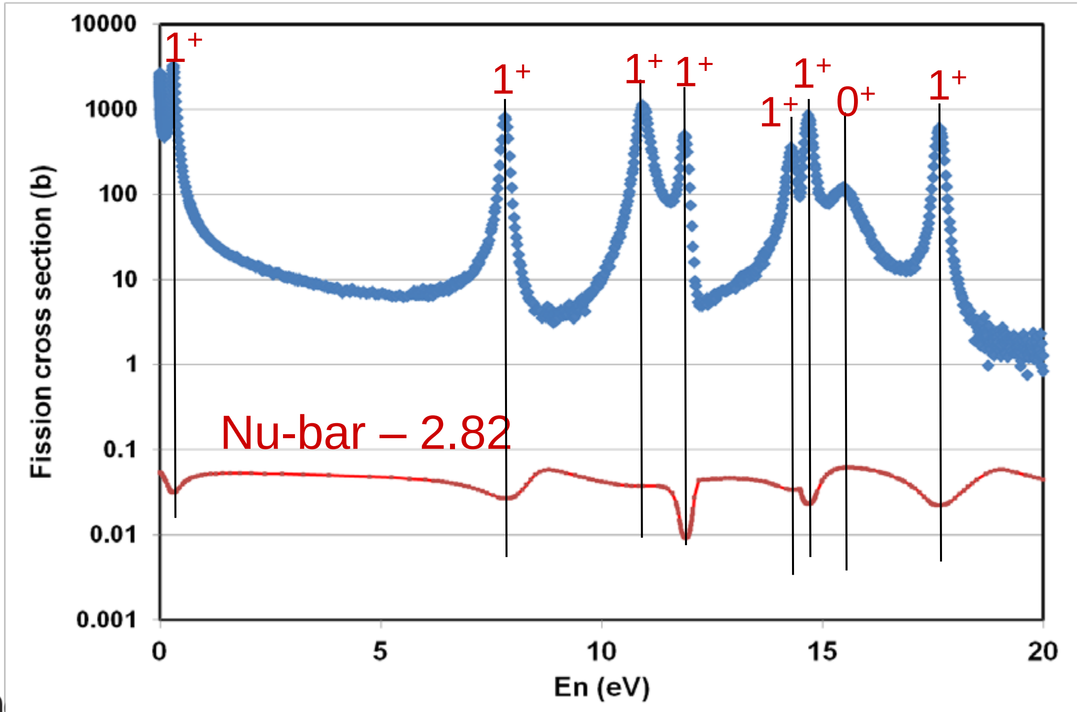




Note also the scale: <<1% for ^{235}U; up to 12 % for ^{239}Pu

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

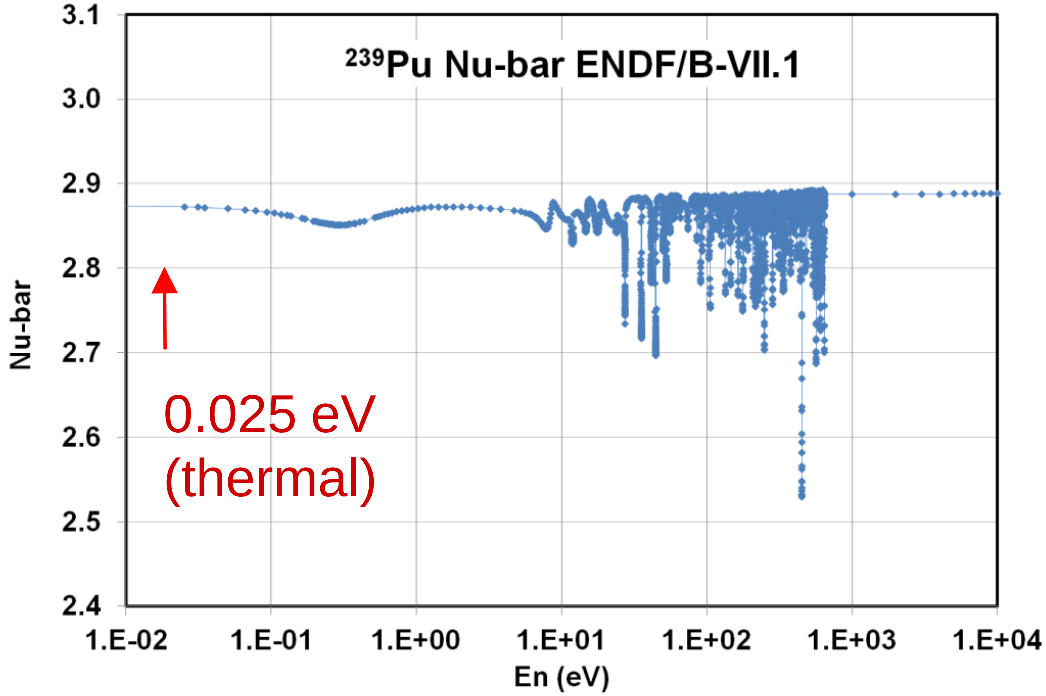
- Fission cross section from Weston [NSE 115,164 (1993)]
- Subtract a constant (2.82) from nu-bar for clarity of display
- Add spins and parities (all positive) from Mughabghab
  - 0+ resonance shows no effect in nu-bar
  - 1+ resonances show varying effects



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 ?

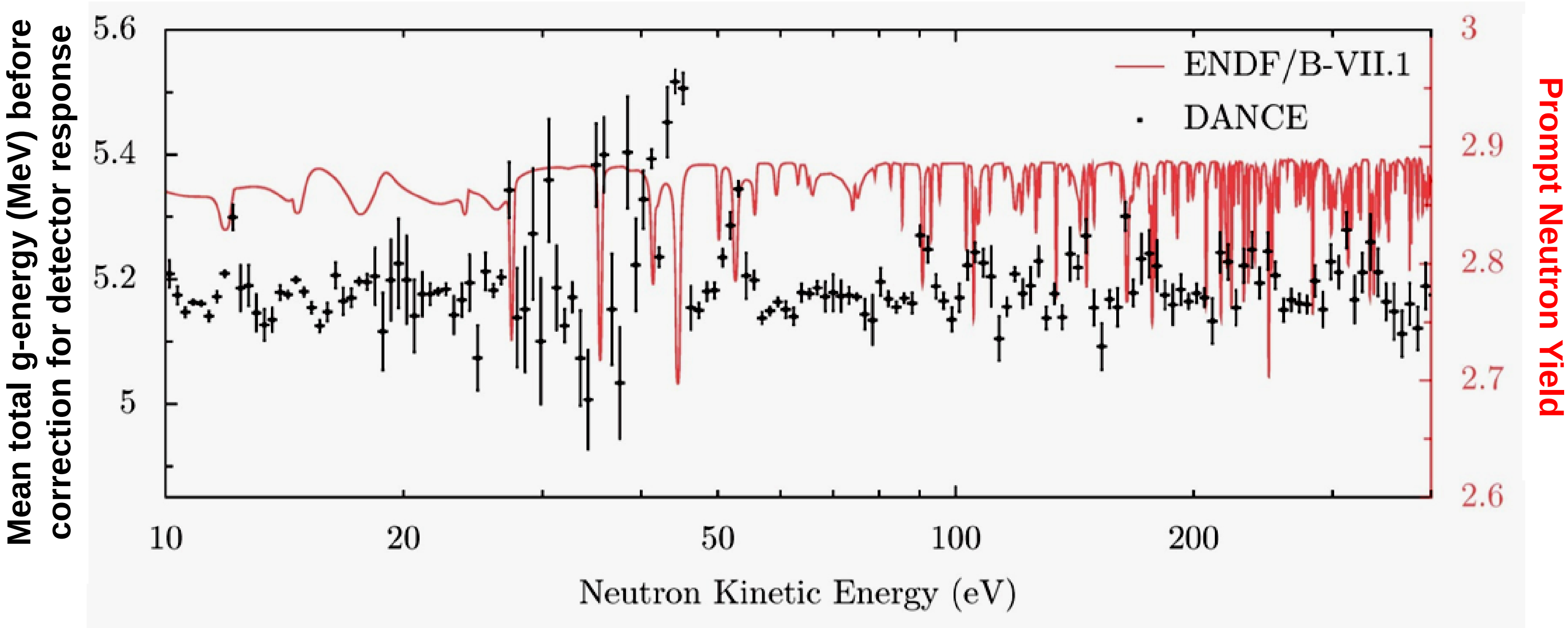


Predictions for PFNS measurements with fission induced by epithermal neutrons

- $^{239}Pu(n,f)$ – for incident neutron energies in resonance region – not planned but would be interesting physics!
  - Note: gamma production from fission in resonance region has been studied. Yes, spectra do depend on incident neutron energy and correlate with variations in nu-bar!

    Ref: S. Mosby et al., DANCE collaborations

Fission total γ-ray energy vs. incident neutron energy for $^{239}Pu(n,f)$



- Fluctuations in prompt fission gamma energy anti-correlated with neutron emission
- More detailed information on $^{239}Pu(n,\gamma f)$ process (Lynn, 1965)
- Qualitative behavior reported by Shackleton in 1972

Advanced PFNS measurements

- Correlate PFNS with fission products (Z,A) – difficult – could improve models of fission physics

Acknowledgments

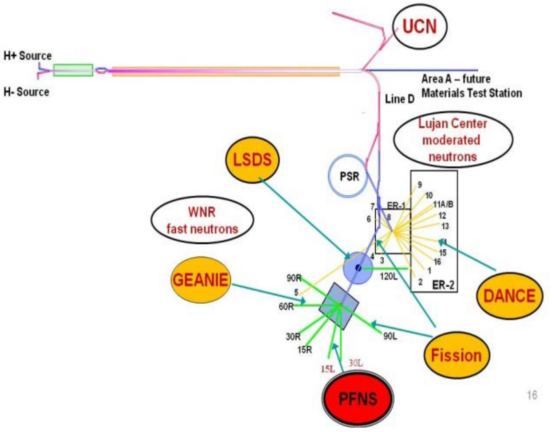
- This work is performed under the auspices of the U.S. Department of Energy by

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

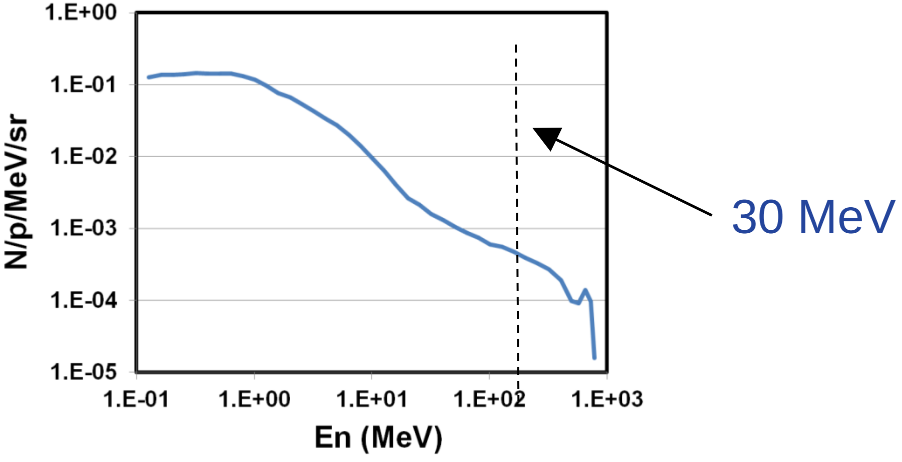
  and the Los Alamos National Laboratory under Contract DE-AC52-06NA25396.

Backup Slides

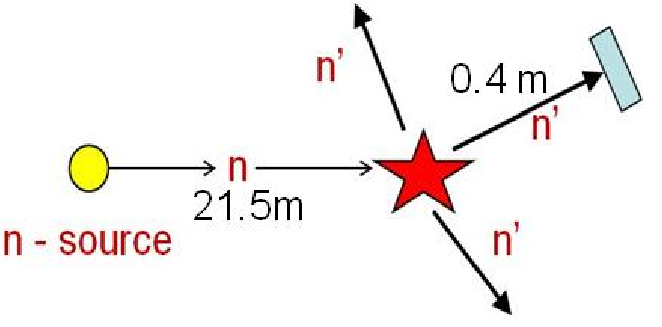
WNR/LANSCE provides neutrons from 100 keV to 200 MeV for PFNS Studies



Neutron spectrum



Double time-of-flight experiment



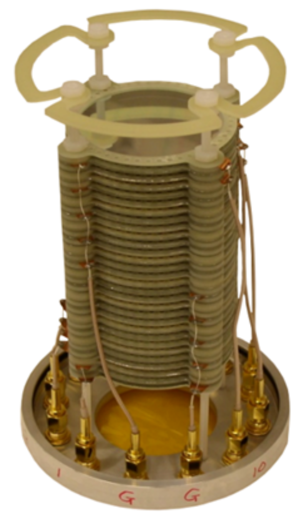
Fission sample and fission counter (LLNL) to contain ~ 100 mg of ^{239}Pu

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

In Beam

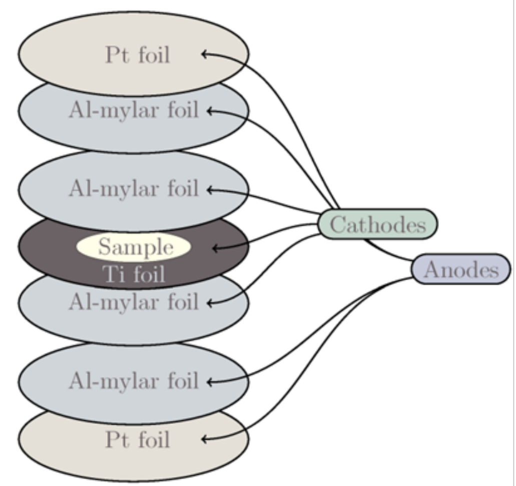
10 cm diam. × 17 cm

Cover Off



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

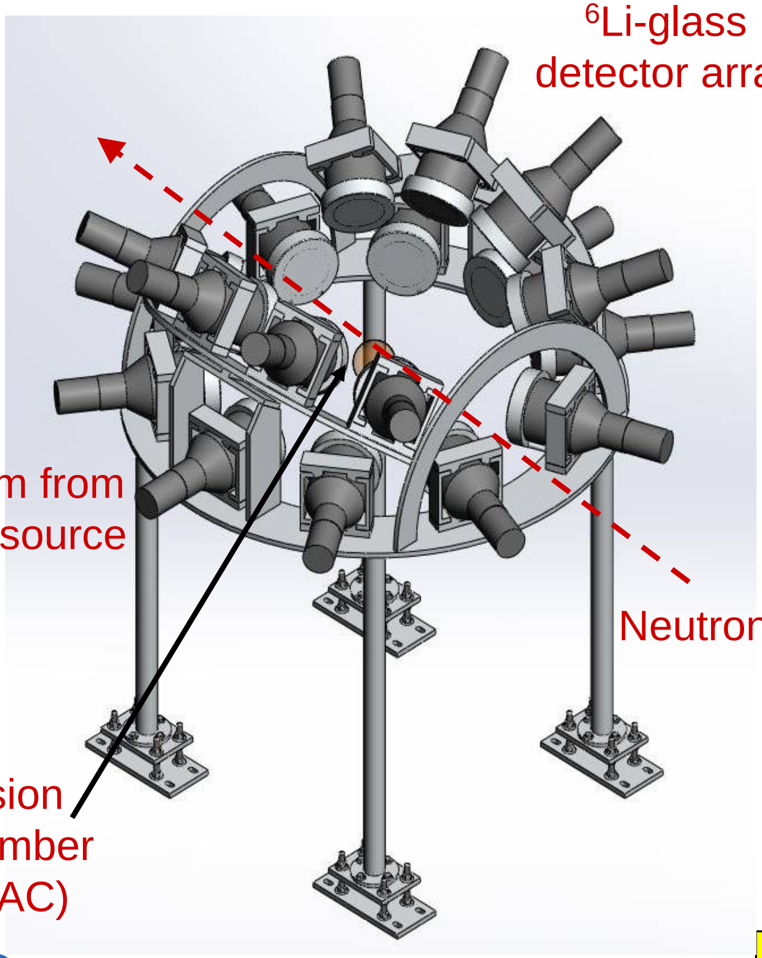
One Foil Stack (of 10)



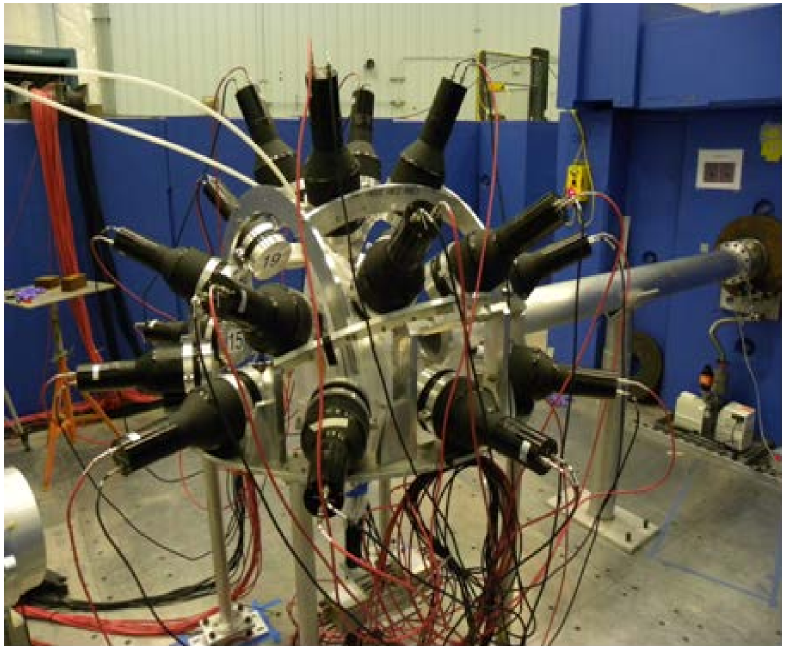
t = 400 μg/cm^2
Timing res.: 1–1.5 ns

Source – PPAC → Time of flight (1)
→ Energy of incident neutron

Chi-Nu array of fast neutron detectors measures prompt neutron spectra emitted in fission



- 22 ^{6}Li-glass scintillation detectors - - or
- 54 liquid scintillation neutron detectors



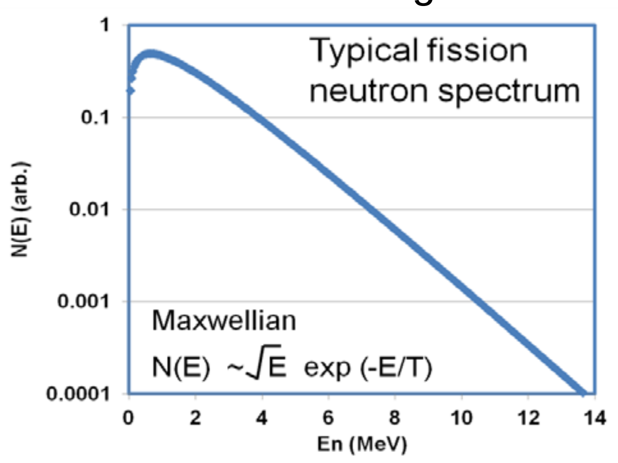
Double time-of-flight experiment

Challenges for experiments

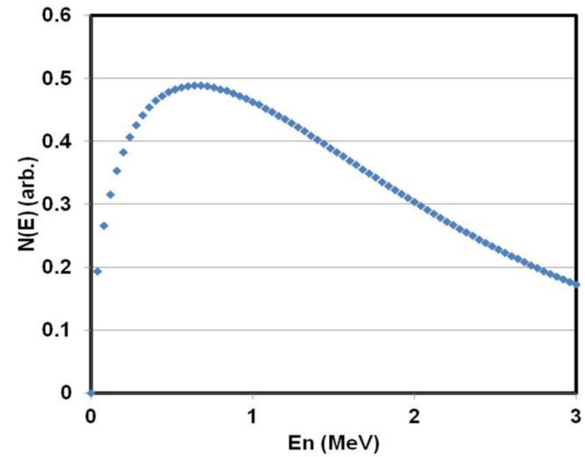
- Low energy part of the PFNS (below ~ 500 keV)
    - Small yields
    - Scattering of PFN
    - Detector efficiency -- 6Li-glass
  - Neutron scattering
  - Clean experimental beam
  - Data acquisition (DAQ) rate
- Challenges of systematic uncertainties - TBMIND*
- Dream experiment – TBMIND* - **(maybe)**

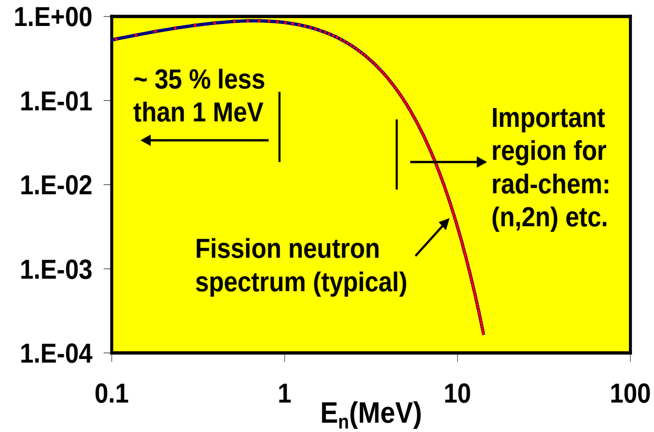
Reminder – Shape of PFNS is approximately Maxwellian

Semi-log

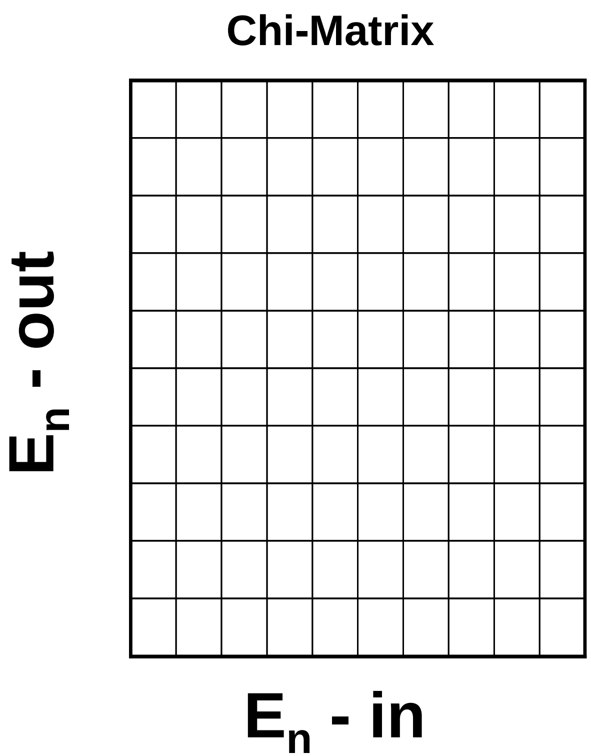


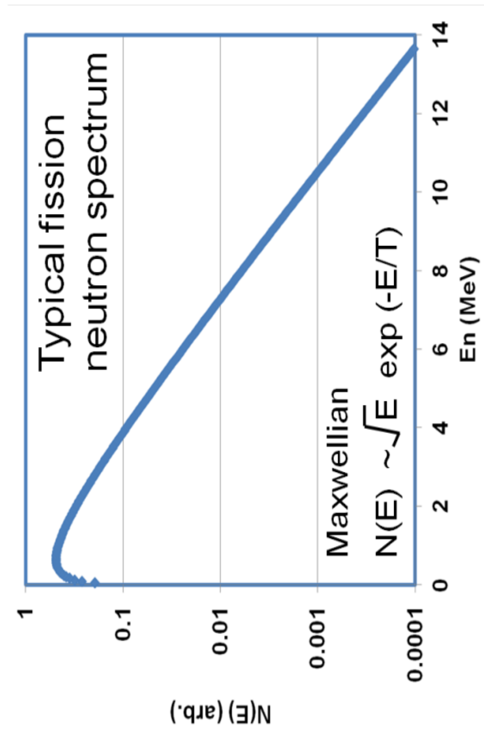
Linear





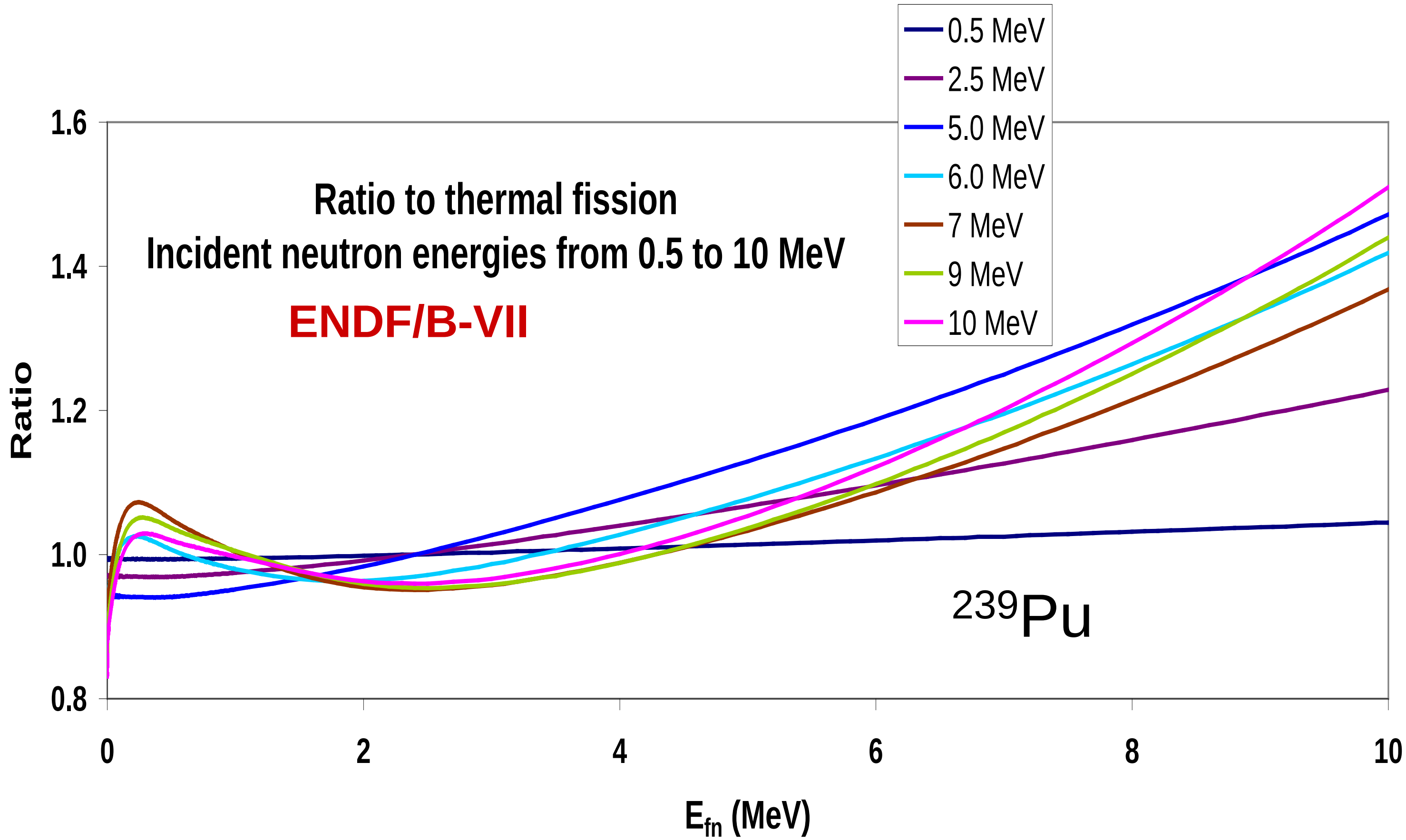
Chi-Matrix relates incident neutron energy to fission neutron output





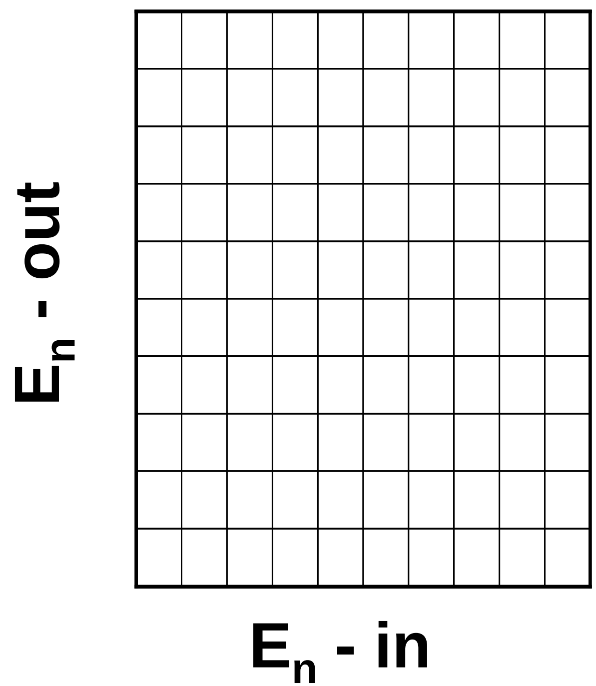
"Chi-Nu" program → ^{239}Pu(n,f) PFNS

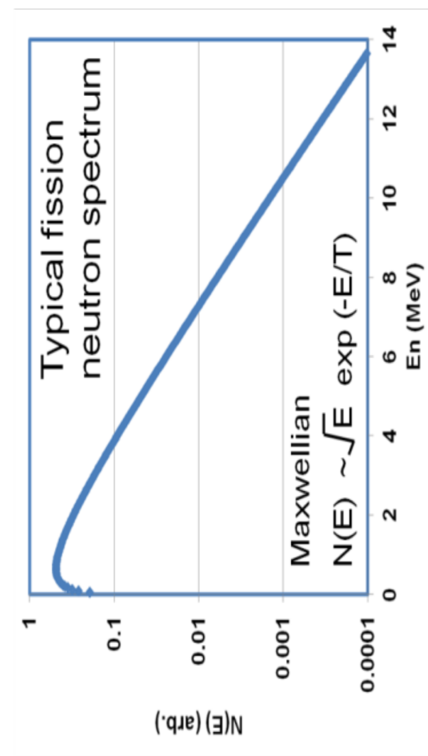
Fission neutron spectra are predicted by models to vary with incident neutron energy



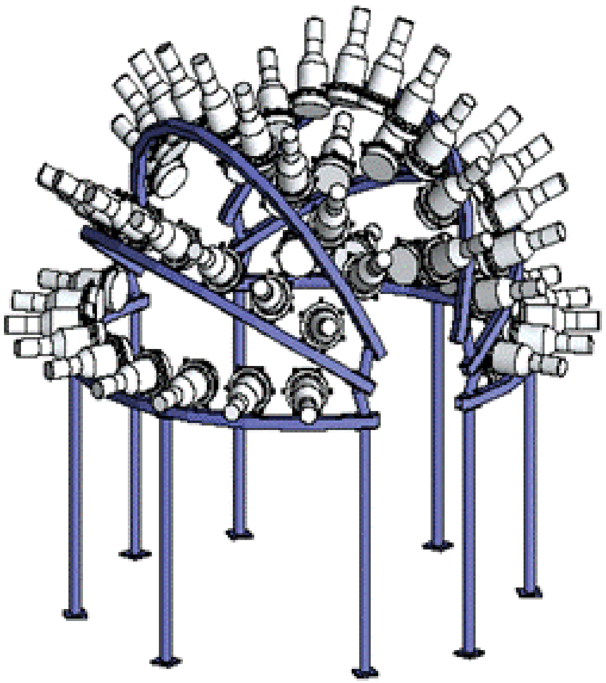
All elements of Chi-Matrix are correlated, at least to some degree, both experimentally and theoretically

Chi-Matrix

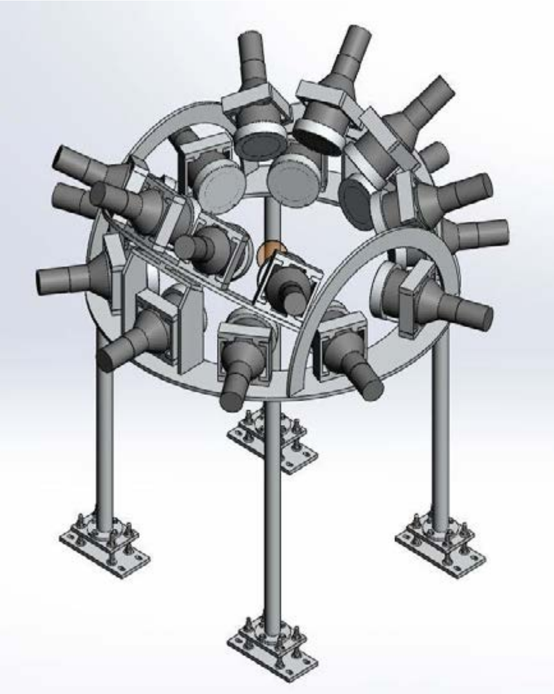




Neutron detectors – two types



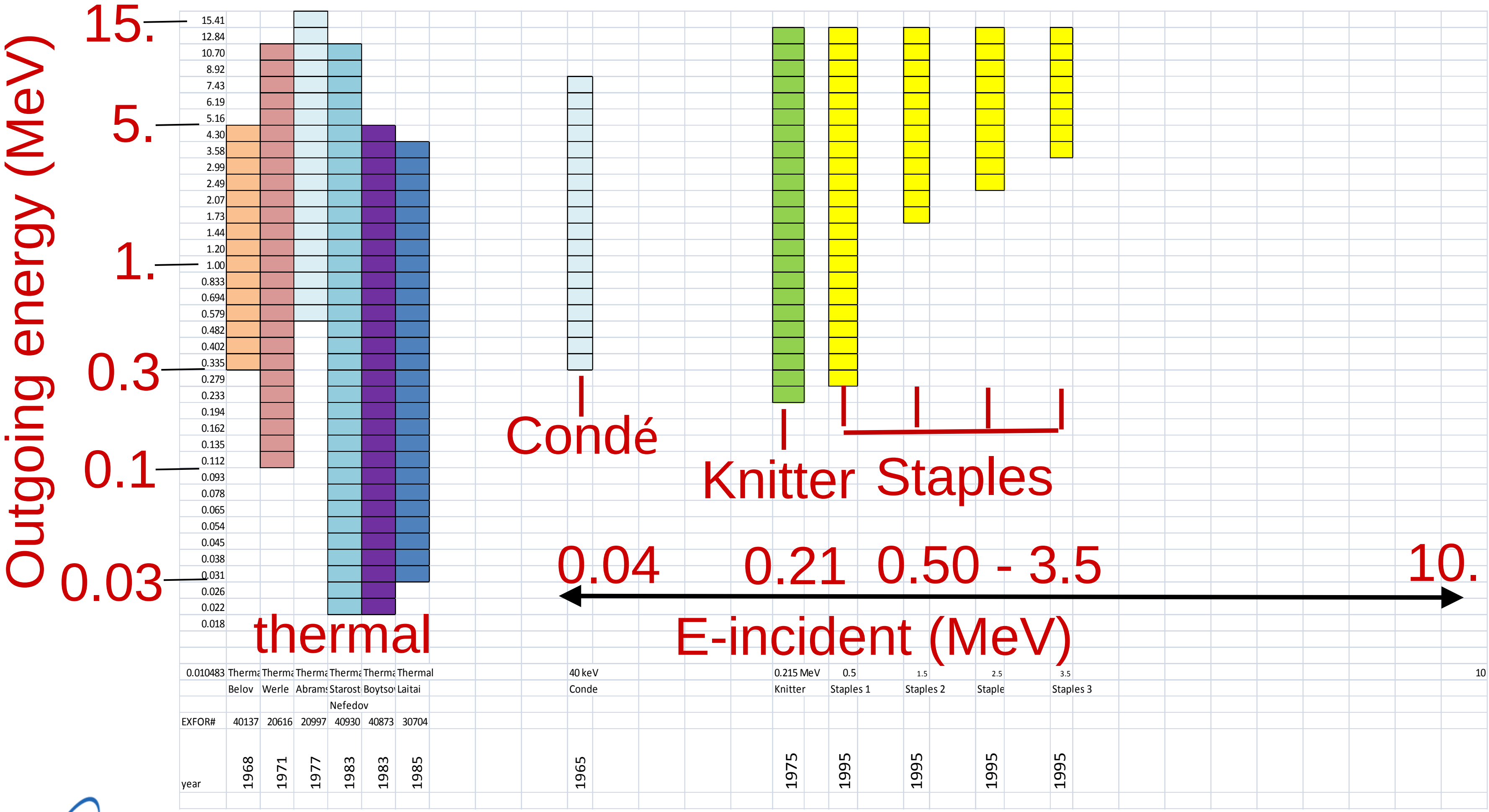
54 Liquid scintillators – 1.0 m flight path



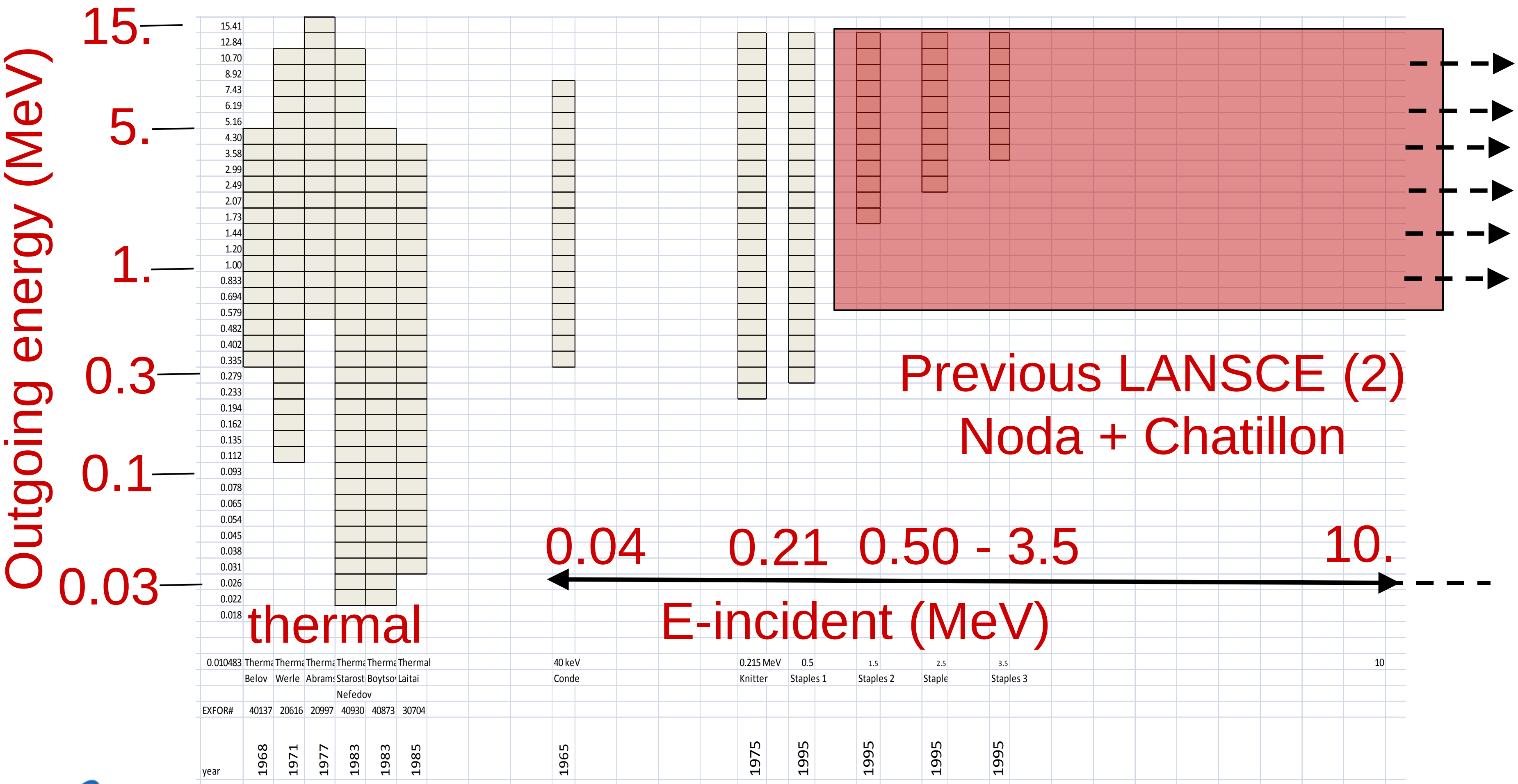
22 ^{6}Li-glass scintillators – 0.4 m flight path

PPAC – neutron detector → Time of flight (2) → Energy of outgoing neutron

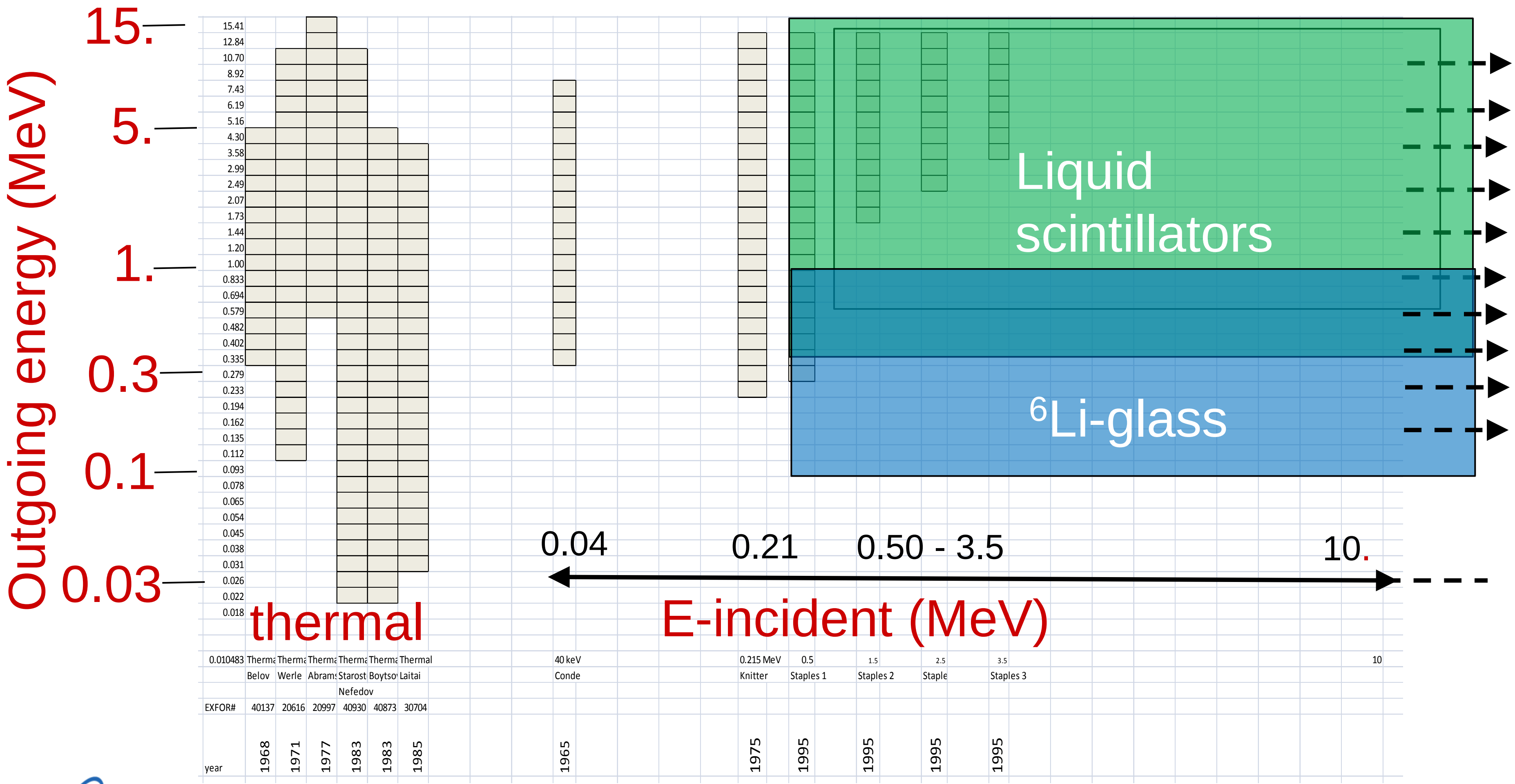
Data in the literature: PFNS for $^{239}Pu(n,f)$ – incident monoenergetic sources



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

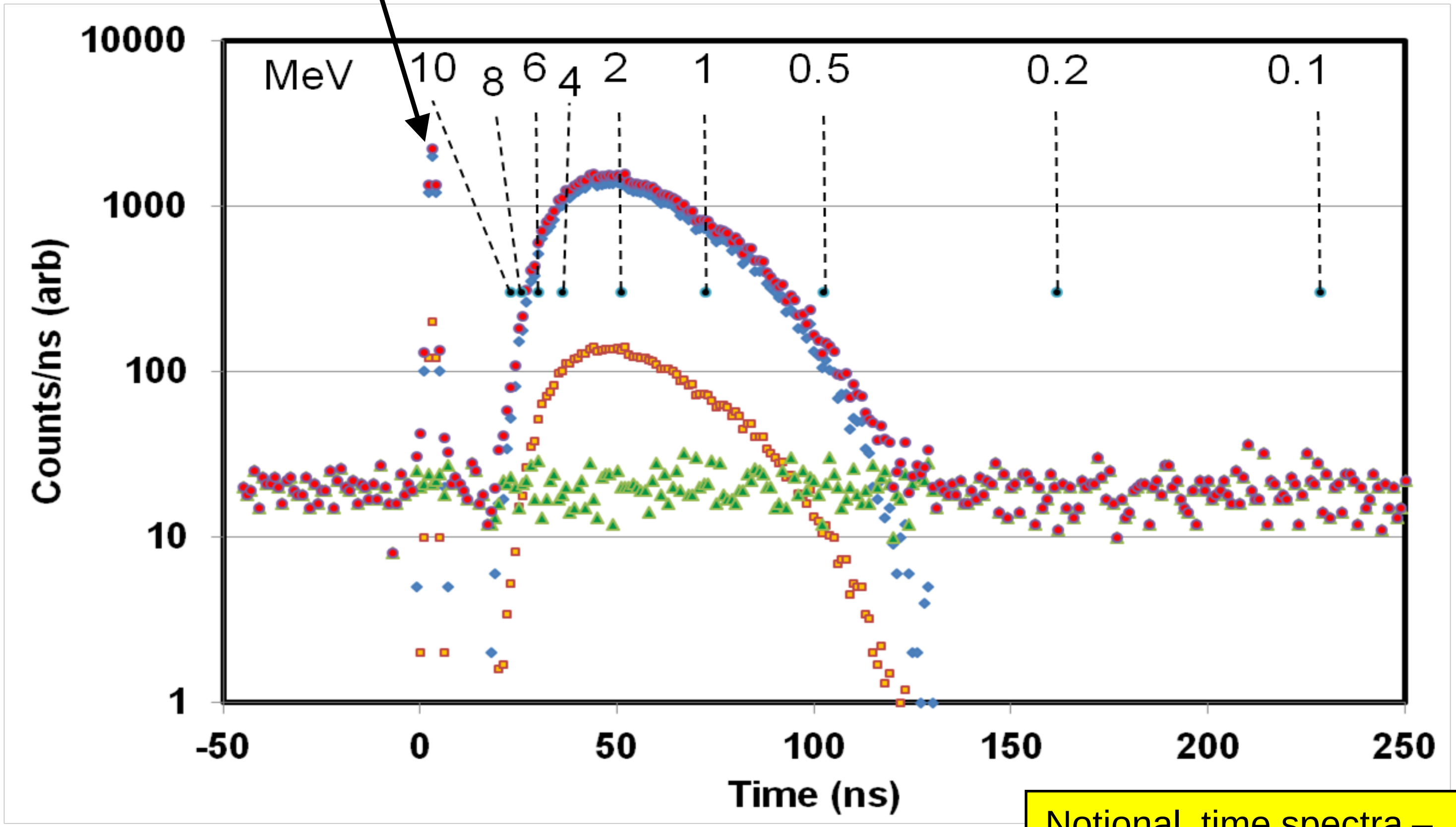


Chi-Nu measurements will be for incident neutrons 0.5 to > 20 MeV and PFN's from 0.1 to > 12 MeV



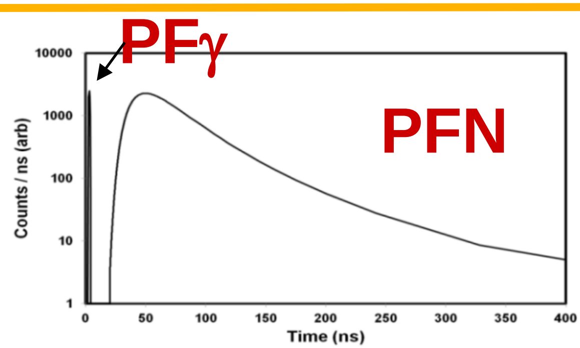
Time-of-flight spectra from PPAC to neutron detector

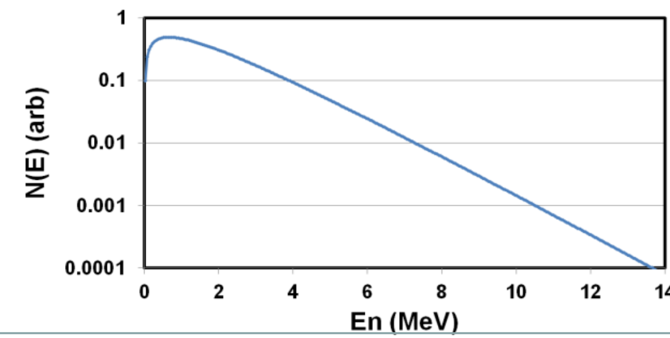
Prompt fission gammas



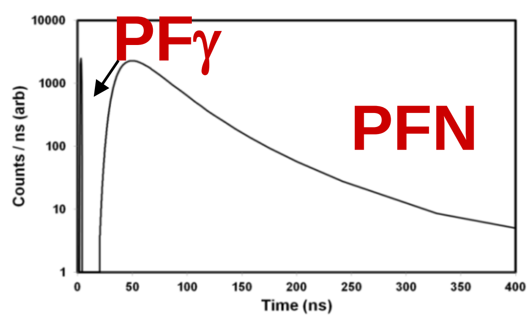
Notional time spectra – magnitudes are fictional; backgrounds are notional

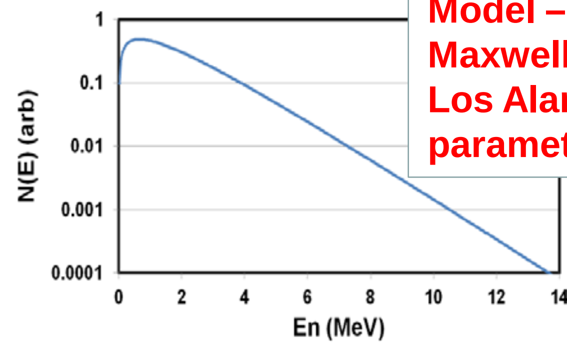
Two paths of analysis





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

Model-constrained data

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

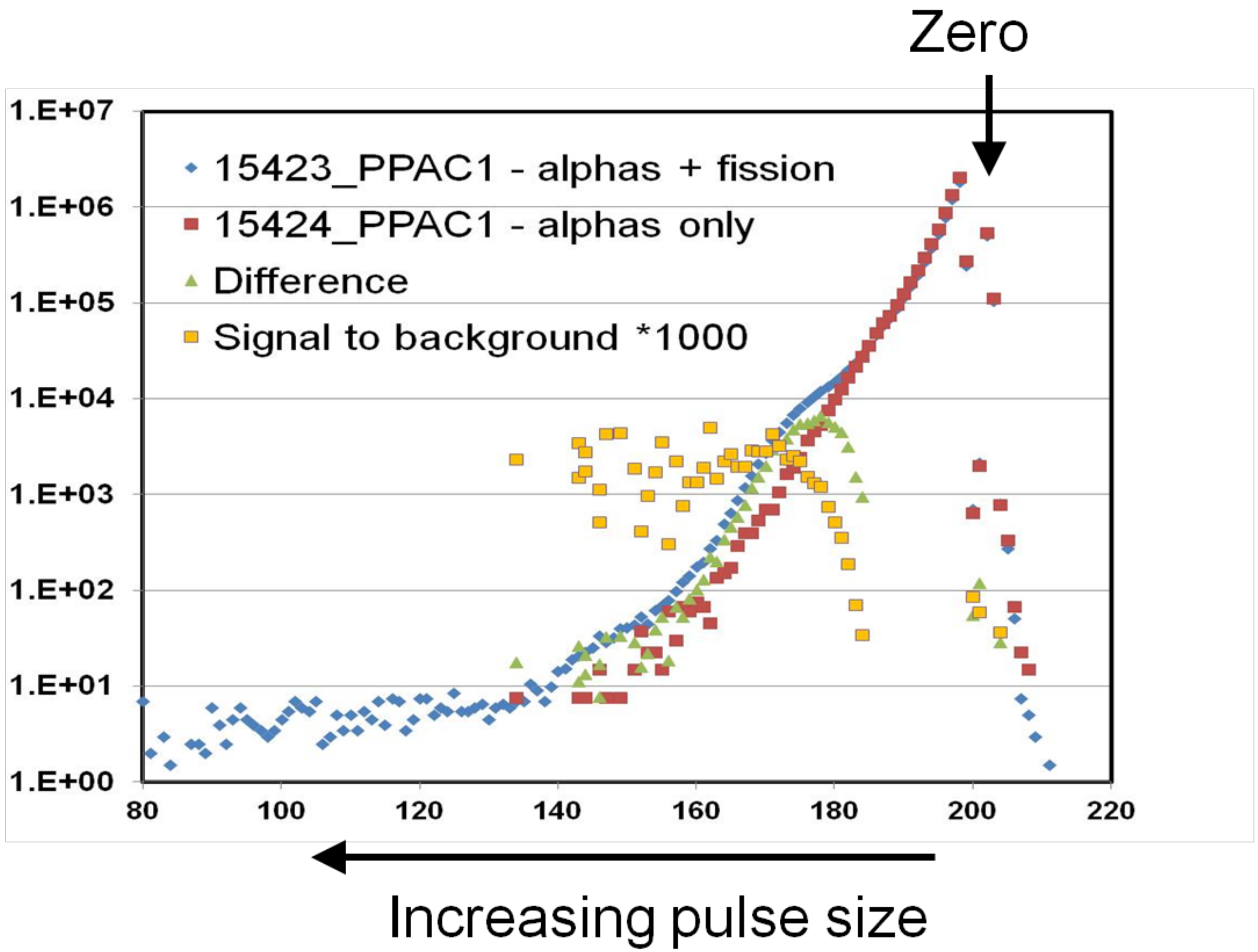
Summary

- 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?

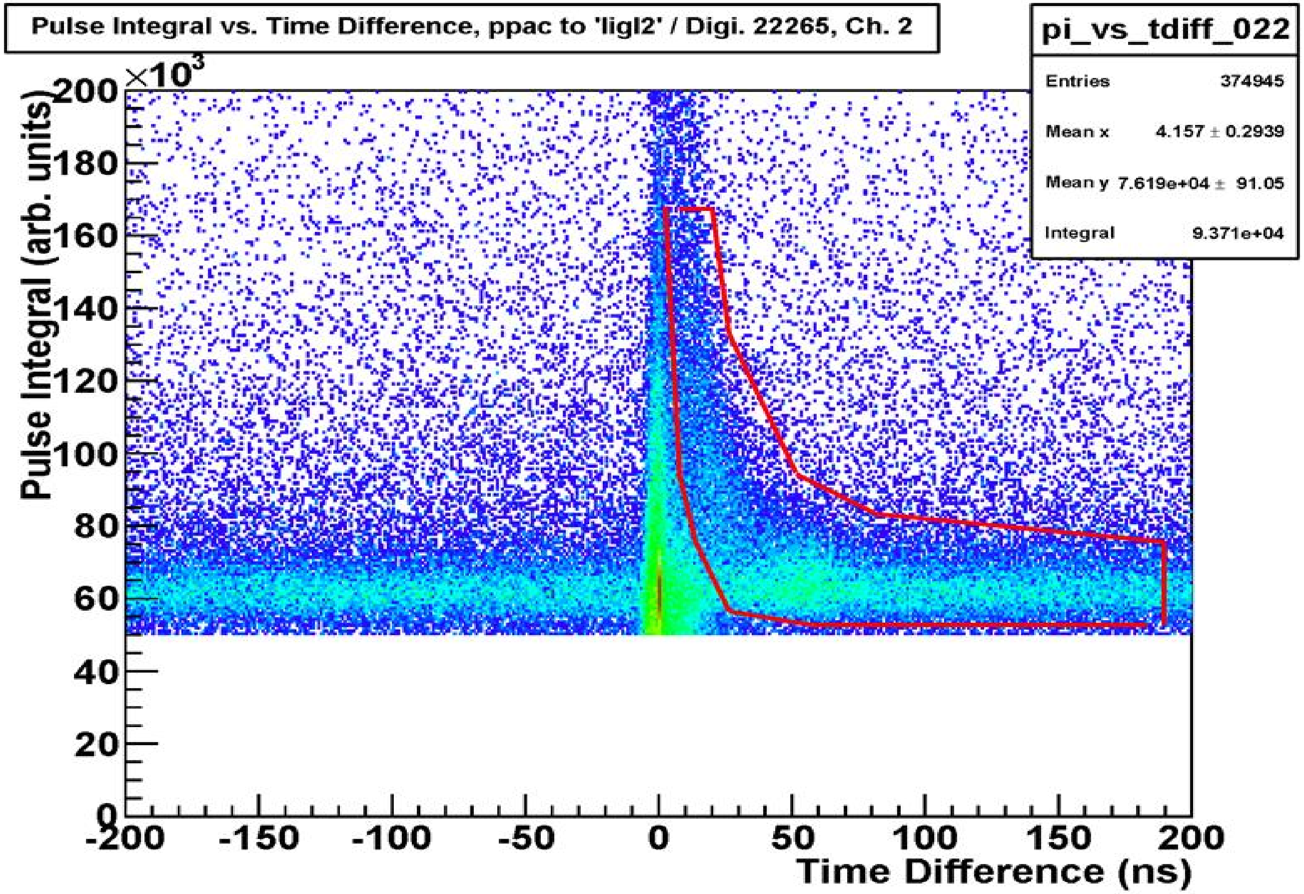
Some perspectives on NDND for PFNS

- Mining of past data with new analyses (not just PFNS)
  - MODELING!!
  - Covariances
- Need new experimental approaches
  - Low background facilities
  - Neutron detectors for fission neutrons below 0.5 MeV
    - Good n-gamma discrimination
    - Good efficiency
    - Good timing
  - Measure direction of fission product in coincidence (reduce systematic error)
  - Identify fission product Z,A after neutron emission (reduce possible systematic errors, improve understanding of fission
- Any experiment to search for pre-acceleration neutron emission
  - Induced by neutron or proton or photon or …

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

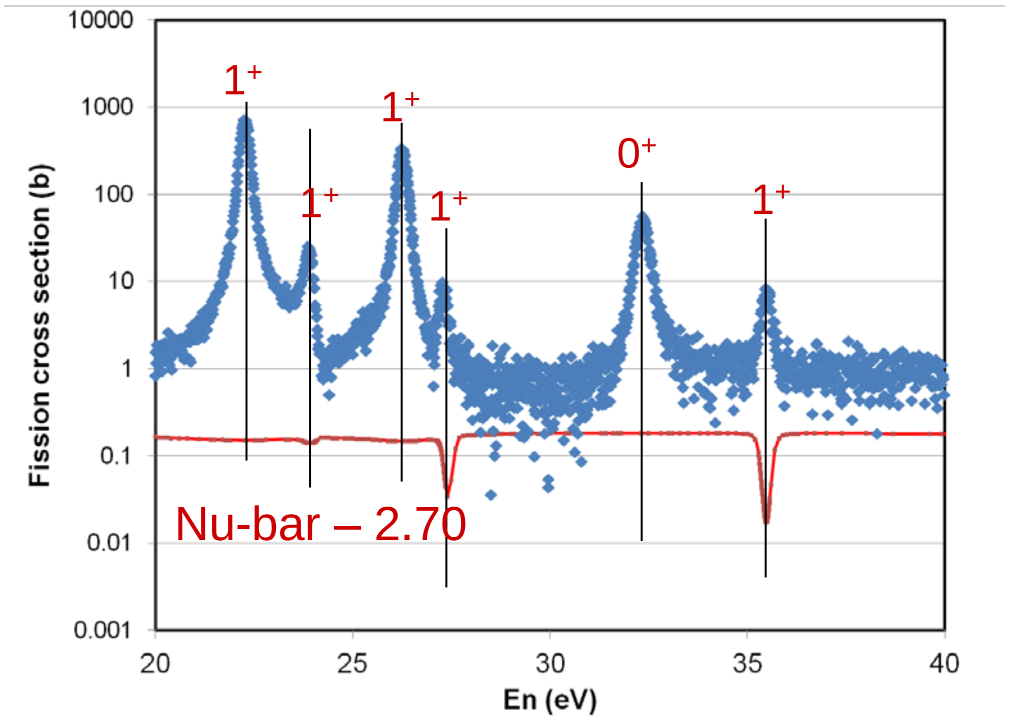


Signal is within the red polygon; background is everything else



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

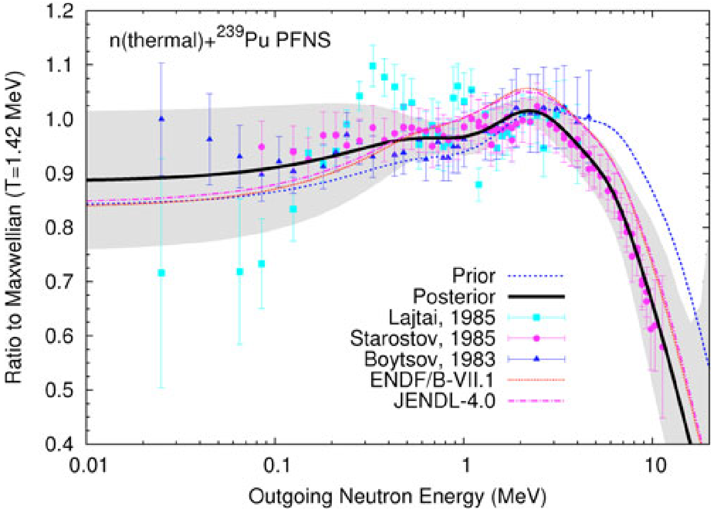
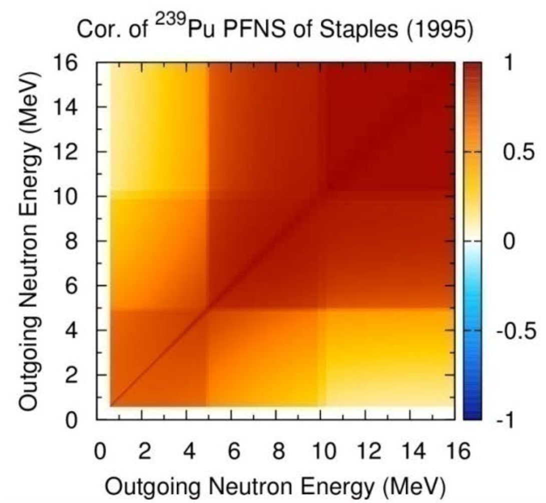


Fig. 11. The PFNS of the n(thermal) + ^{239}Pu reaction plotted with experimental data and the current ENDF/B-VII.1 evaluation. The posterior parameters in Table V were used in Eq. (27) to compute this present evaluation. Note that the experimental data have been normalized to the posterior PFNS.

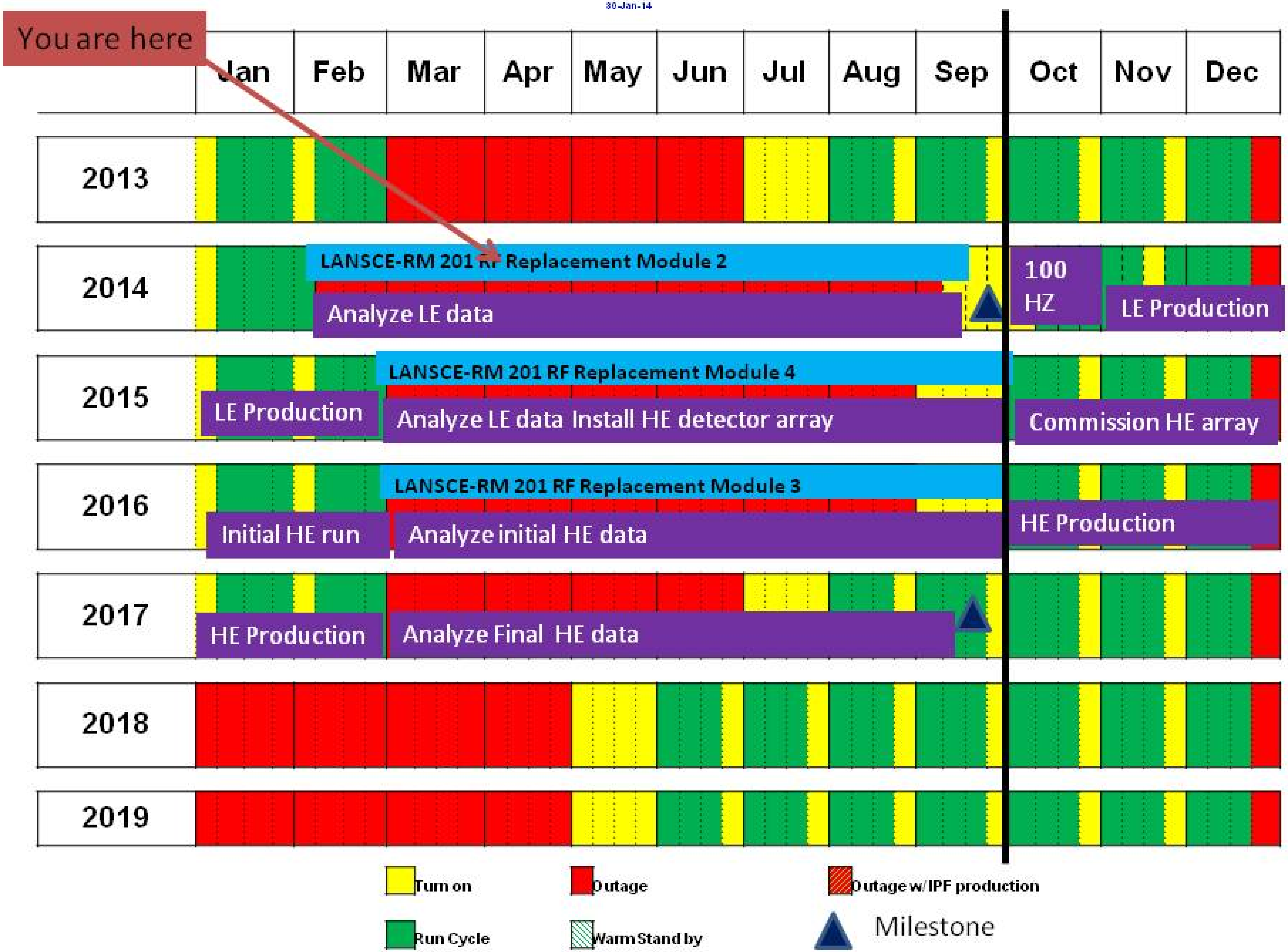
M. Rising et al., Nucl. Sci. Eng 175, 81(2013).

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



Timeline for ChiNu Measurements

30-Jan-14

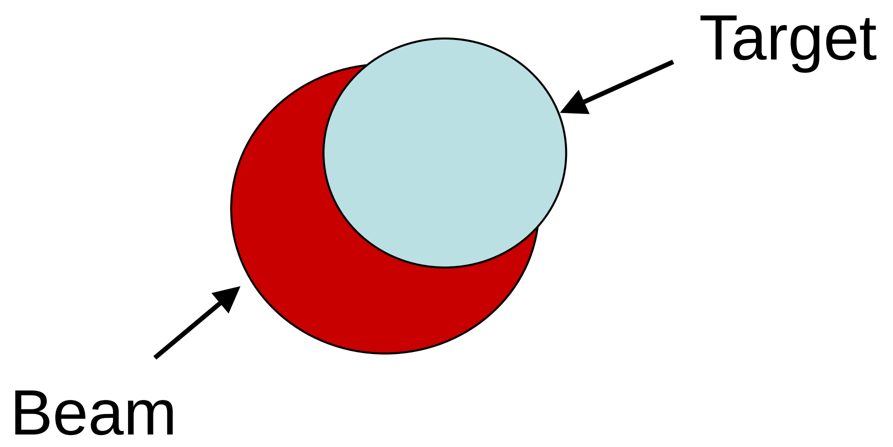


Uncertainties (1) – incident neutrons

- 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

Determining the centroid of the fission events requires care

- Alignment of beam and ^{239}Pu sample
- Uniformity of beam and sample



Fissions = product of beam x target

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

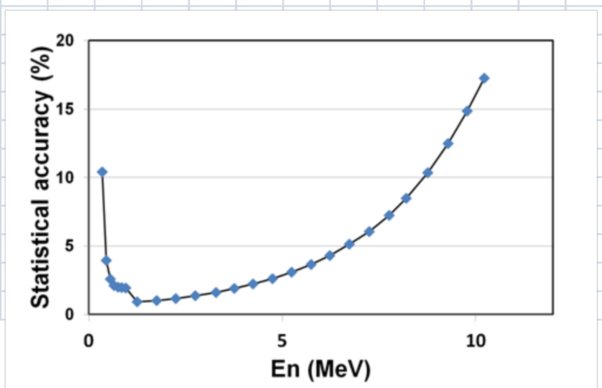
Correlations and uncertainties due to statistics in foreground spectra for 1 week of data

1-2 MeV incident energy bin

Correlation matrix with uncertainties for foreground statistics

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



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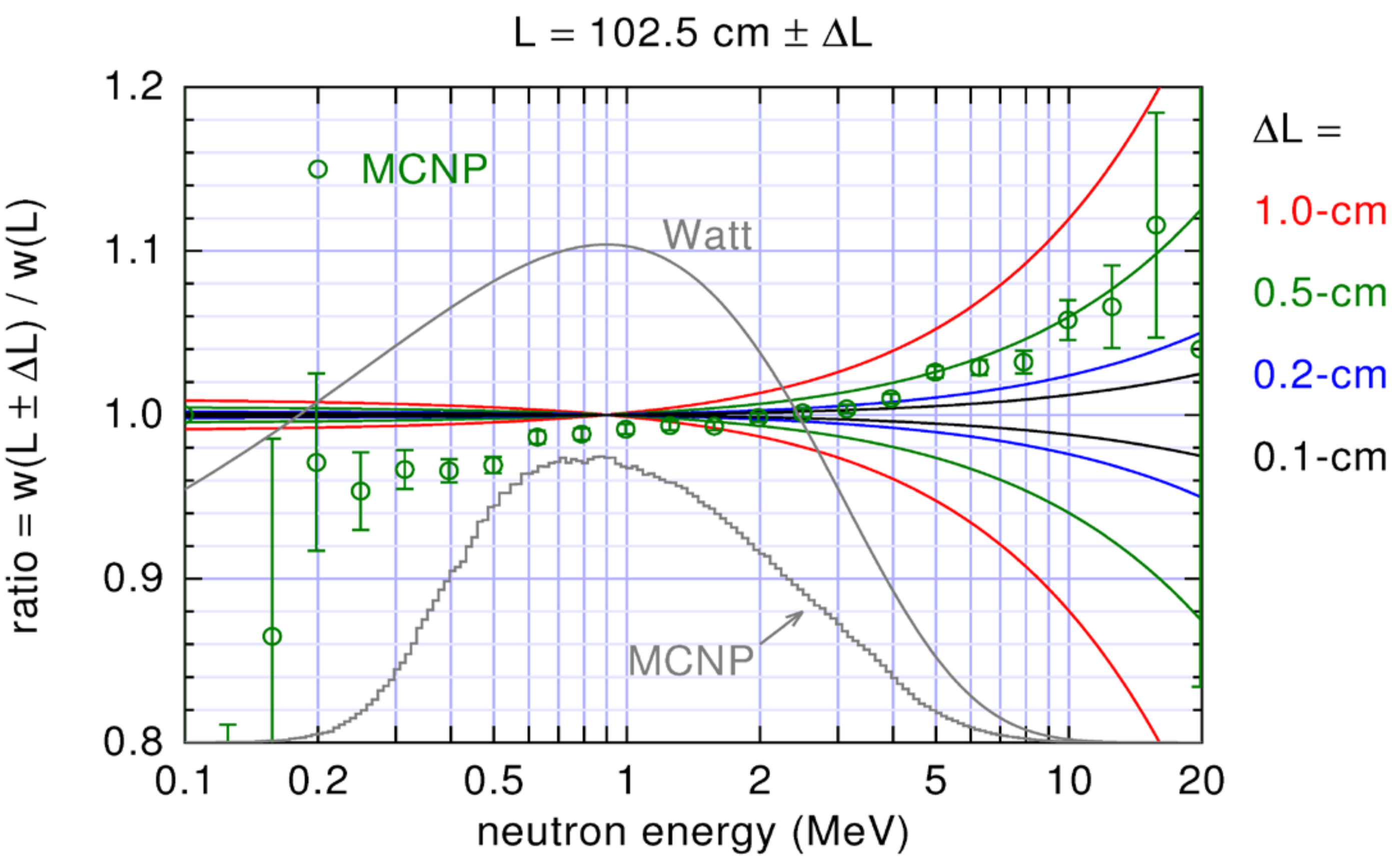
Systematic effect of flight path uncertainty analytic estimate versus MCNP



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]	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
0.16	0.1	1	1	1	1	[illegible]	1	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]	-1	-1	-1	-1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
1.40	5.0	[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
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	1	1	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	1	1	1	1	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	1	1	1	1	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	1	1	1	1	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	1	1	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	[illegible]	[illegible]	[illegible]	1	1	1	1	1	1	1	1

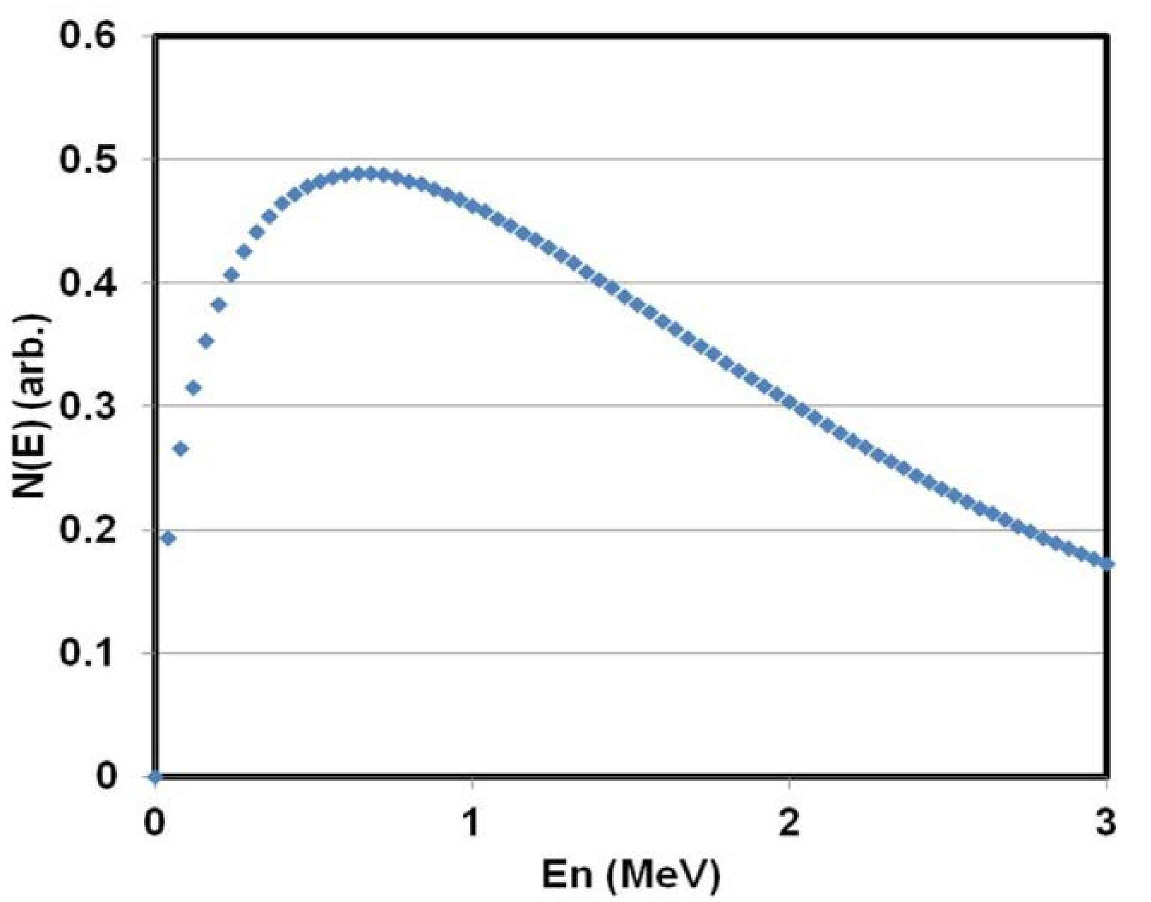
+1

-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