Uncertainties & Correlations in Nuclear Fission Data

The role of models and experiments

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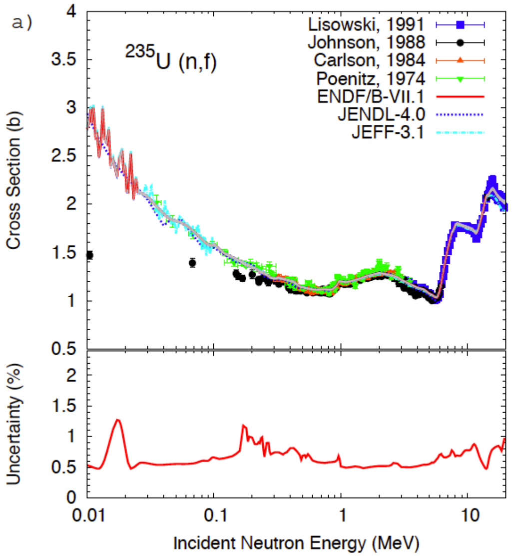
Nuclear Fission Data

Selected examples

Fission Cross Sections
(n,f), (p,f), (γ,f), (t,pf), etc



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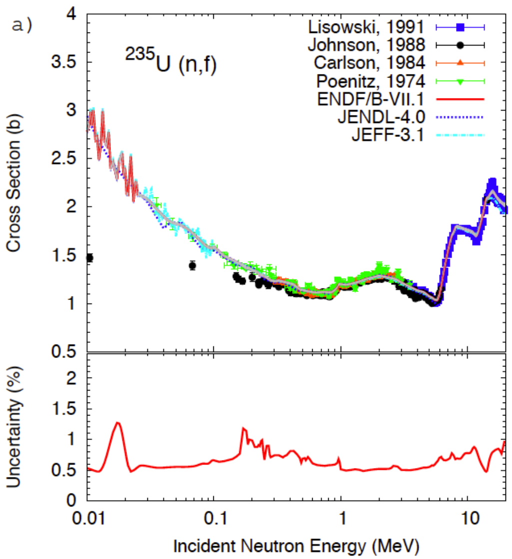
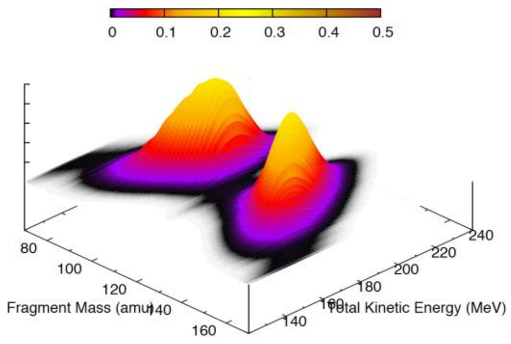


Fission Fragment Yields
Y(A,Z,KE)



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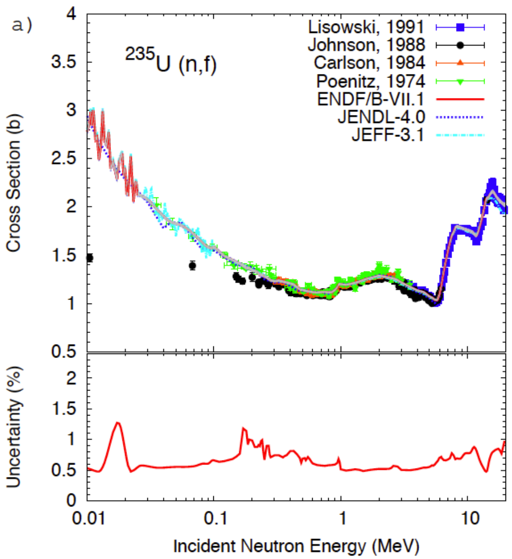

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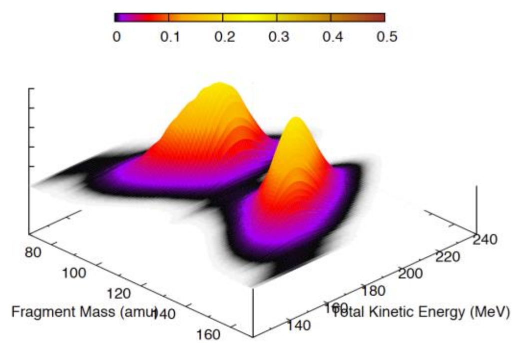
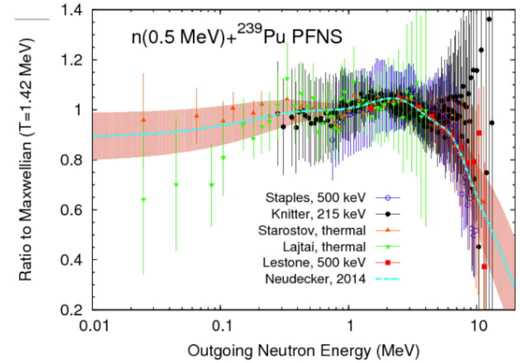
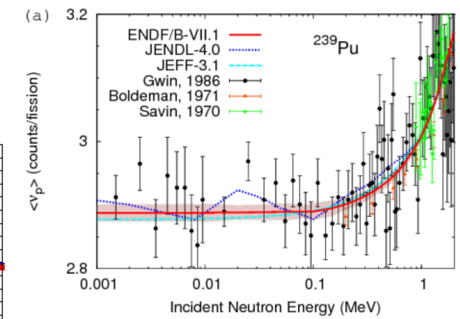
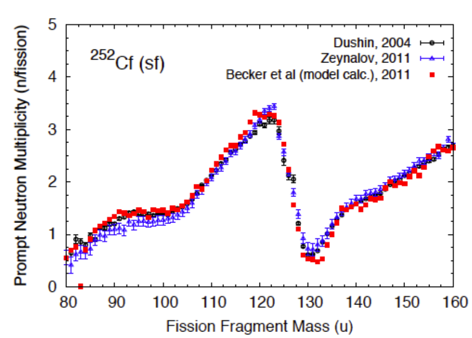


Prompt Fission Neutrons and Gamma Rays
(multiplicity, spectrum, correlations)







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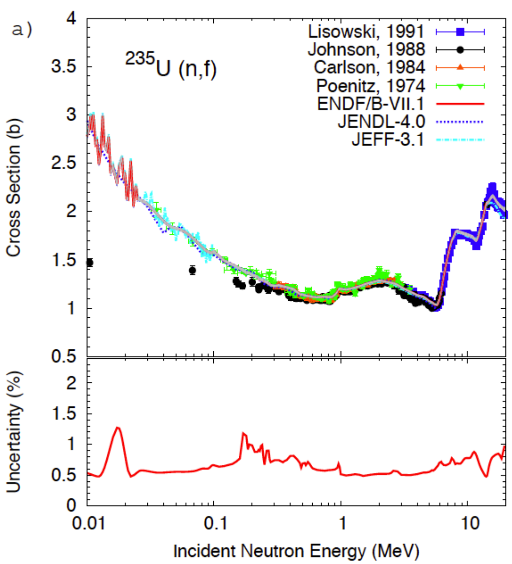

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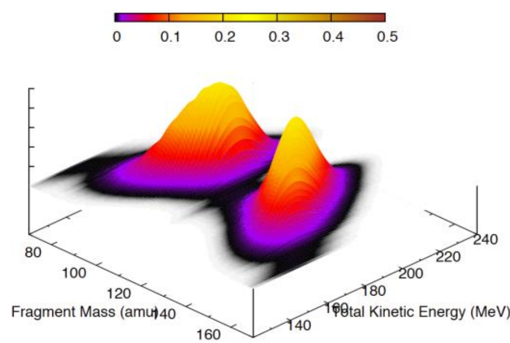

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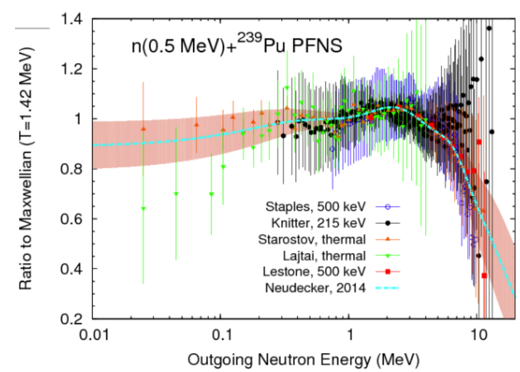

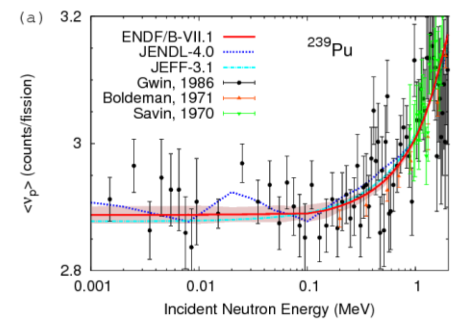

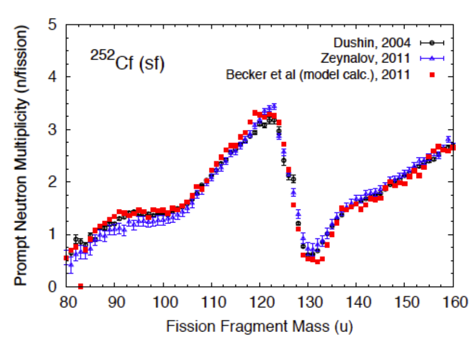

- Others?

β-delayed neutrons and gammas, fission fragment angular distributions, pre-scission neutrons and photons, prompt X-rays, etc.

Uncertainties & Correlations

Uncertainties & Correlations

- Stemming from both experiments and models

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- Some examples:
  - Experiments:
    - Fission fragment yields
    - Prompt fission neutrons
  - Theory:
    - Uncertainties in modeling fission cross sections and "empirical fission barriers"
    - Modeling the prompt fission neutron spectrum

Uncertainties in Fission Experiments

Two examples

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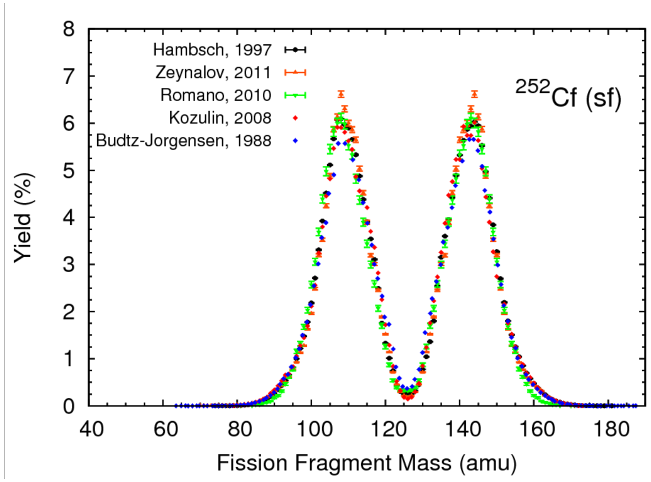
- Fission Fragment Yields
  - Typical resolutions:
    - 3-5 amu for Y(A)
    - 1-2% in Kinetic Energy
    - ΔZ~1
  - Neutron emission from fragments
    - Products, not fragments, are measured!
  - Very little data on E* dependence



Uncertainties in Fission Experiments

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- Fission Fragment Yields
  - Typical resolutions:
    - 3-5 amu for Y(A)
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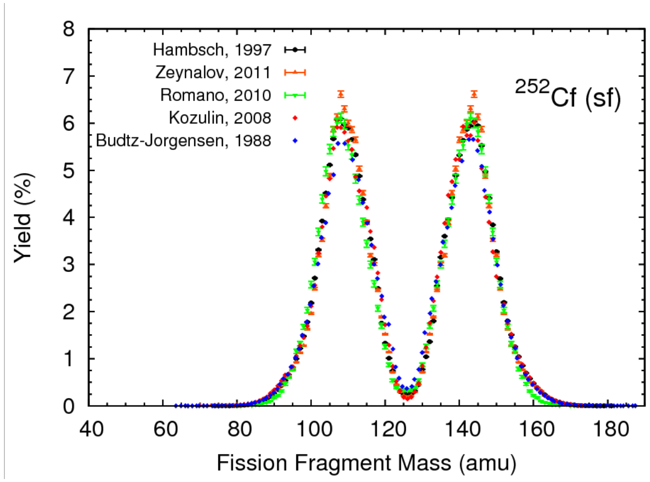
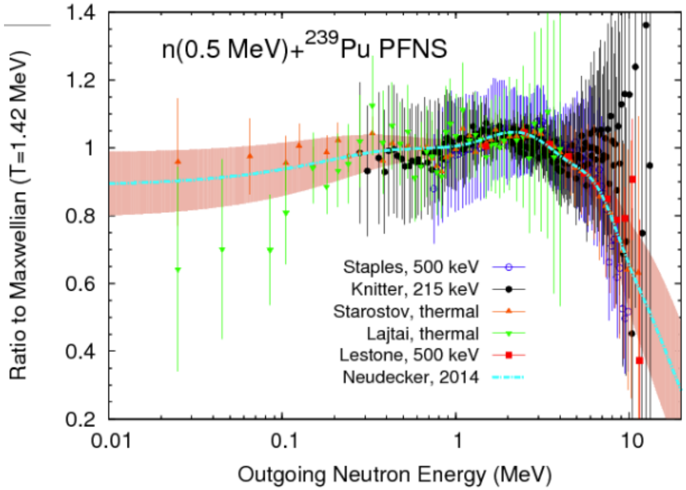


- Prompt Fission Neutrons
  - Multiplicity measurements (ν)
    - Large Gd-loaded tanks
    - No energy resolution
  - Spectrum (χ)
    - Low-energy (<500 keV) very sensitive to multiple scattering
    - High-energy (>5 MeV) poor statistics



Uncertainties in Fission Theories & Modeling

Two examples

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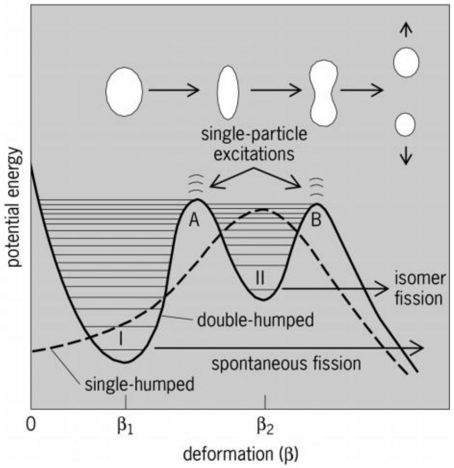
- Fission Cross Sections
  - Fission barrier
  - Double- or triple-humped
  - Deviations from simplified parabolas
  - Inertia tensor
  - Transition states, level densities at saddle points
  - Class-I,II states coupling



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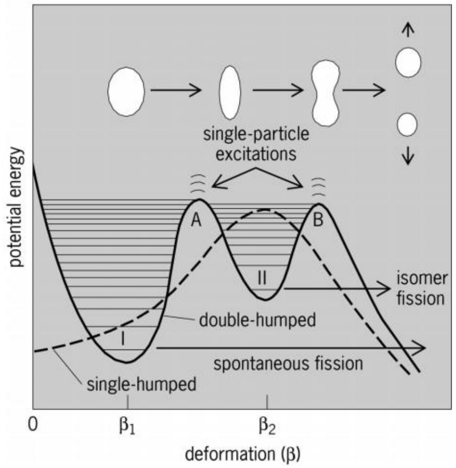
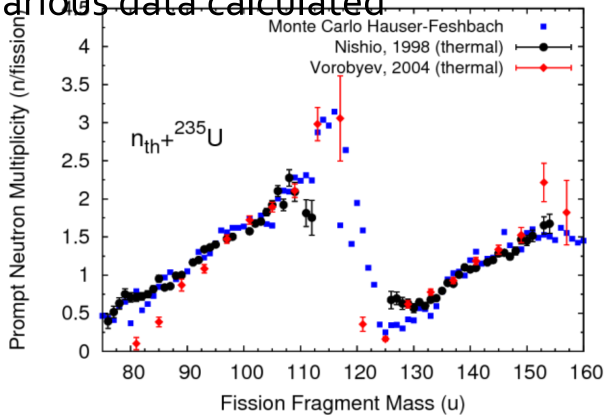


- **Prompt Fission Neutrons**
  - Simple models
    - Madland-Nix, Watt, Maxwellian
    - Few model parameters, easy to adjust but strong correlations
  - More sophisticated
    - Monte Carlo Weisskopf & Hauser-Feshbach
    - Many parameters, more difficult to adjust but (possibly) more faithful
    - Various data calculated



The Nuclear Data Evaluation Process
(in a nutshell)

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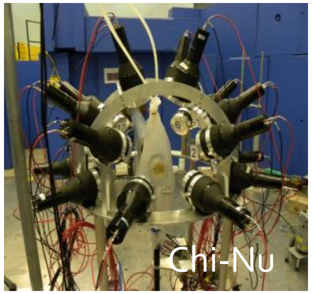

(differential)
Experimental Data

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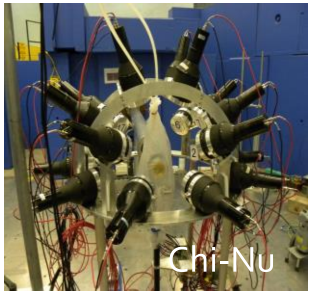

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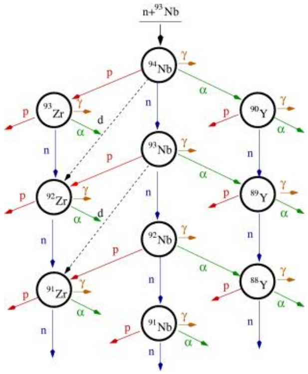

Theory/Modeling

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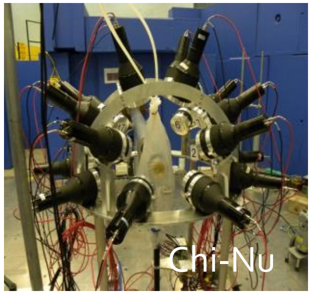

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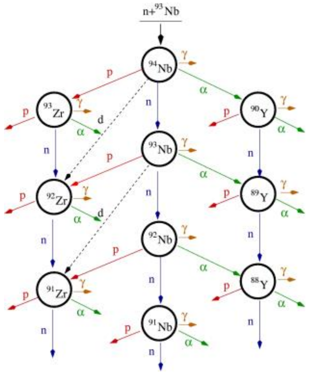

Theory/Modeling

Model Input Parameters

ENSDF
RIPL-3
...

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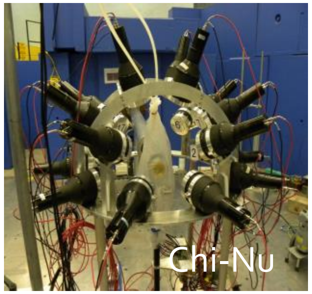

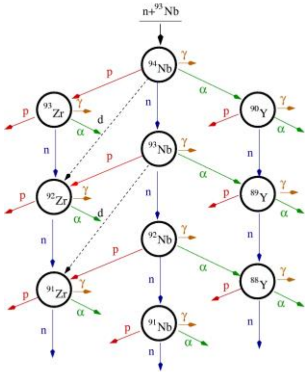

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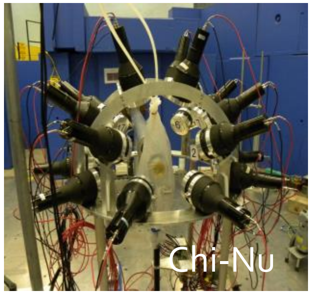

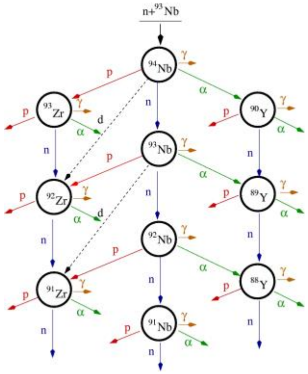

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"Least-Square Fits"

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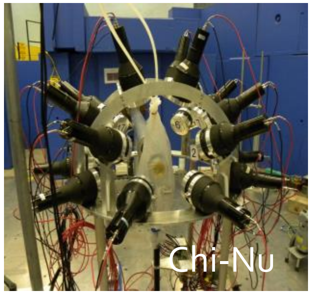

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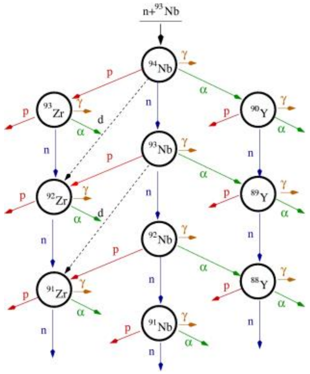

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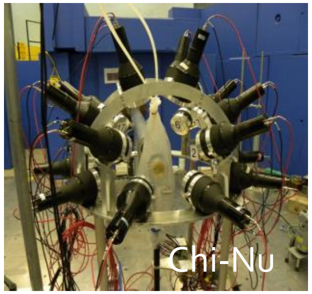

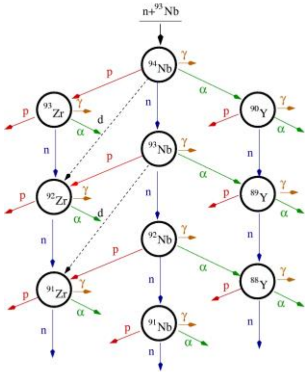

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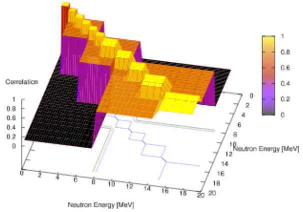

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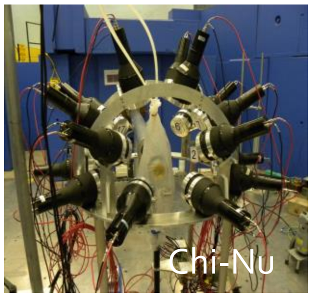

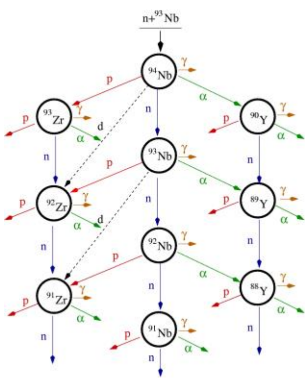

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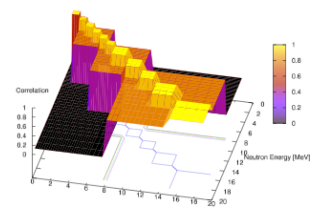
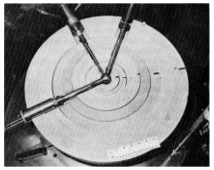


Comparisons with integral benchmarks



Feedback

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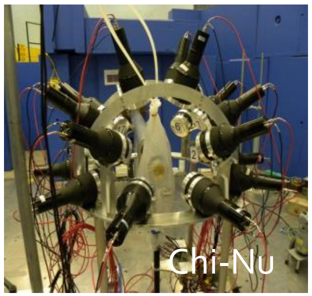

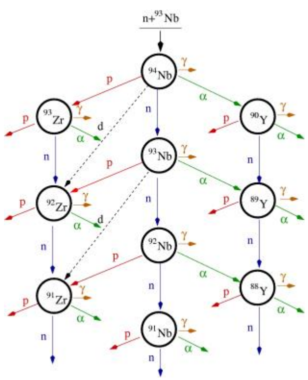

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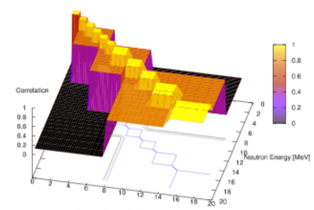

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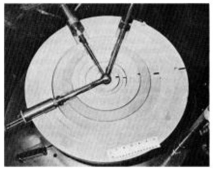
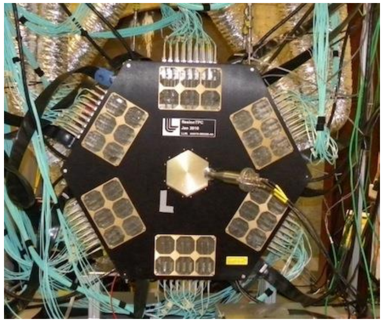


Feedback

For fission… limited use of correlated data to constrain evaluations → PFNS, $\sigma_f(E^*)$, FFAD, …

Modern Fission Experiments

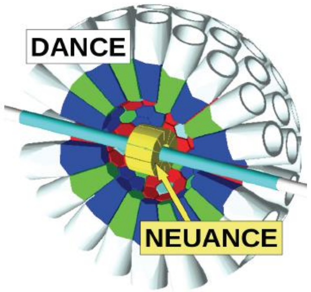
Some examples from Los Alamos



Time-Projection Chamber
for fission cross-section measurements

Chi-Nu setup
(22 6Li glass detectors) to measure prompt fission neutron spectra

SPIDER 2E-2v
for fission fragment yield measurements



DANCE w/ NEUANCE
for correlated measurements on prompt fission neutrons and γ rays with fission fragments

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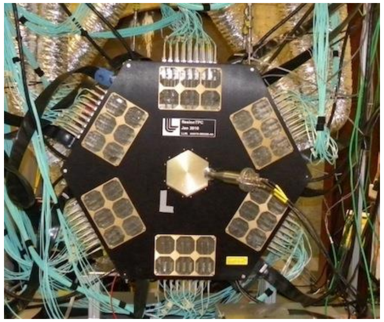

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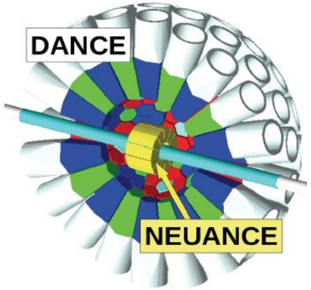

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Many other facilities and detector setups in construction worldwide:

- EAR2 at CERN
- NFS @ SPIRAL2 @ GANIL
- IGISOL-JYFLTRAP
- SOFIA: Studies On Fission with Aladin (reverse kinematics) at GSI
- STEFF
- ...

- cf. Talk by X.Ledoux

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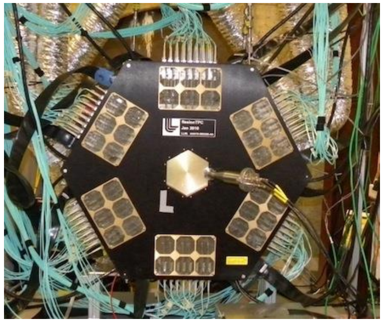

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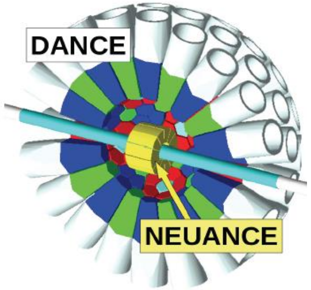

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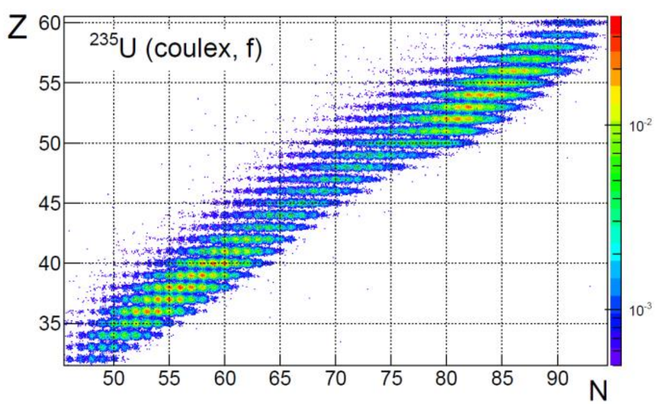
- New data to fill obvious gaps in our experimental database
- Better accuracy
- Innovative measurements
- Correlated data
- …

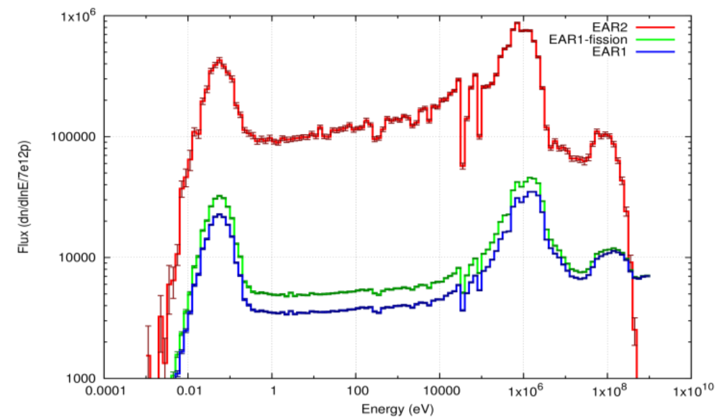
Modern Fission Experiments

Elsewhere



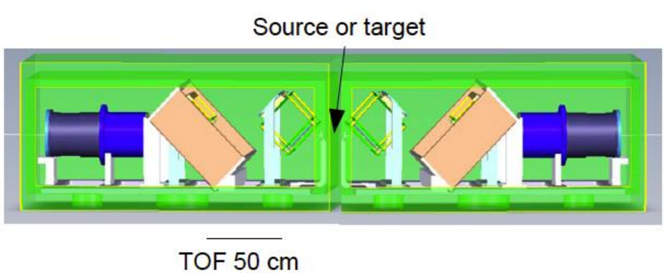
SOFIA: Studies on Fission with Aladin @ GSI

reverse kinematics, GSI: ΔA~0.6-0.8, ΔZ~0.4



EAR2 @ n_TOF @ CERN

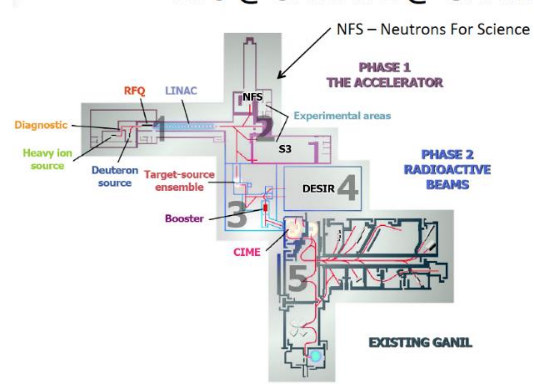
Fission x/s measurements of actinides with half-lives ~years

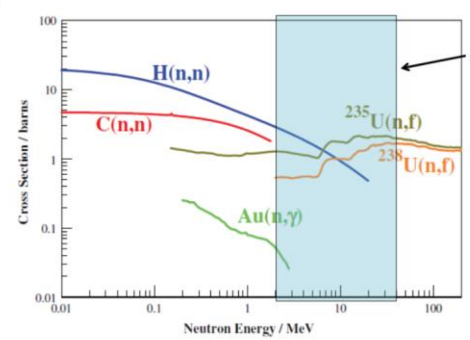


FALSTAFF @ NFS

Four Arm cLover for the STudy of Actinide Fission Fragments

NFS @ SPIRAL 2 @ GANIL





NFS @ SPIRAL2 @ GANIL

Modern Fission Theories & Models

Time-Dependent Microscopic Approaches

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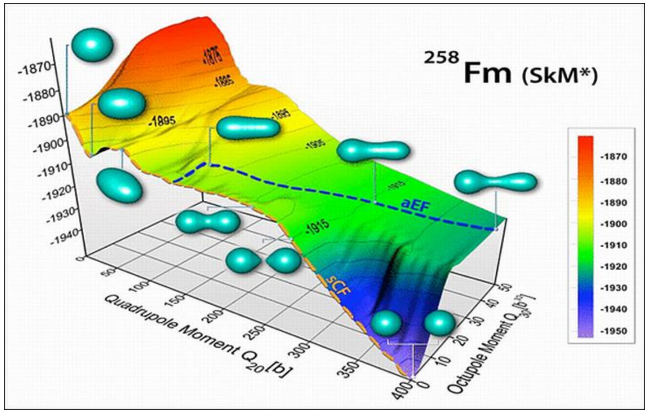
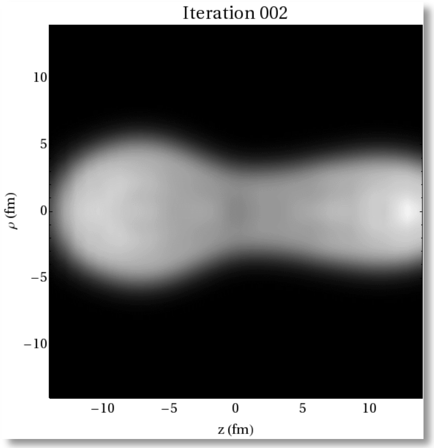
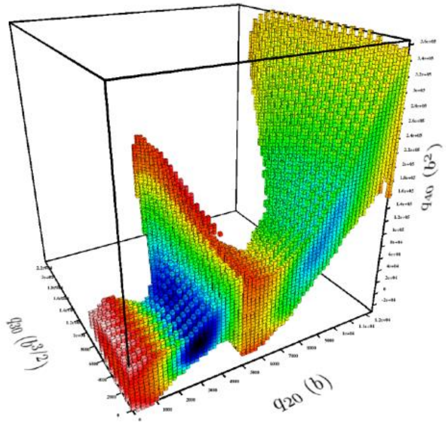


From ascr-discovery.science.doe.gov
Credit: *A. Staszczak et al., ORNL*



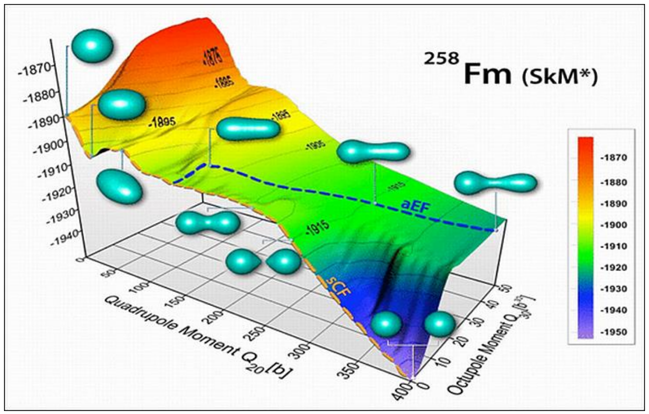
W.Younes, FIESTA school,
Sep. 8-9, 2014, Santa Fe



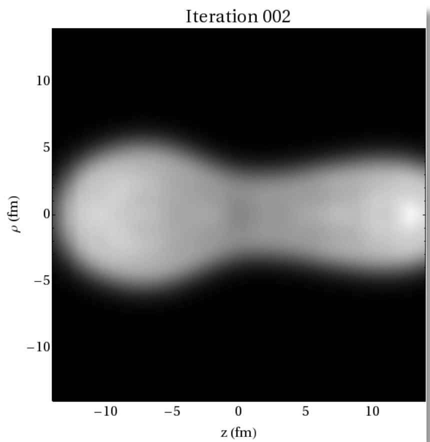
N.Dubray, FIESTA workshop,
Sep. 10-12, 2014, Santa Fe

Modern Fission Theories & Models

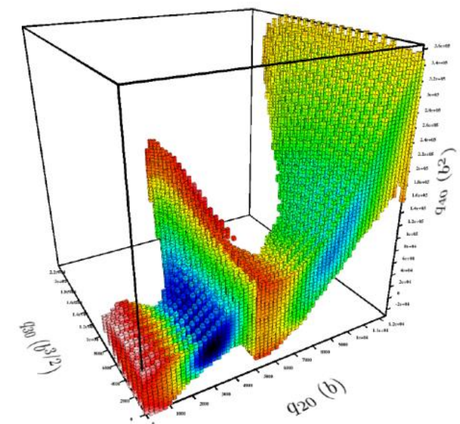
Time-Dependent Microscopic Approaches



From ascr-discovery.science.doe.gov
Credit: *A. Staszczak et al., ORNL*



W.Younes, FIESTA school, Sep. 8-9, 2014, Santa Fe



N.Dubray, FIESTA workshop, Sep. 10-12, 2014, Santa Fe

Uncertainties & Errors…

- Fundamental n-n force
- Constrained calculations; parameter space?
- Class-3 PES (N.Dubray)
- Correlations s.p. and collectivity (H.Goutte)
- Need for very large scale computations

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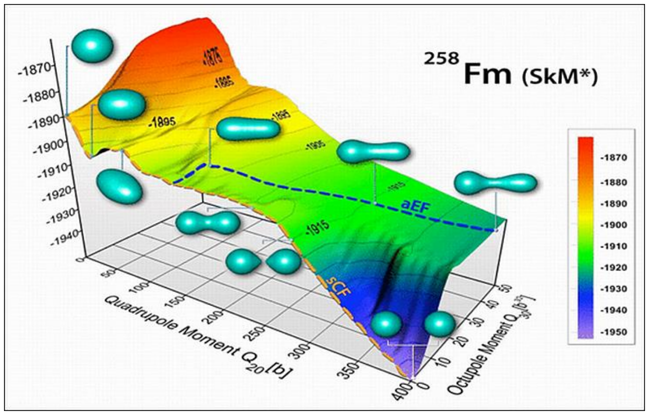

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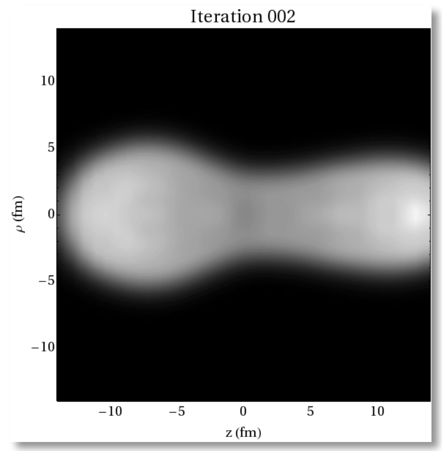

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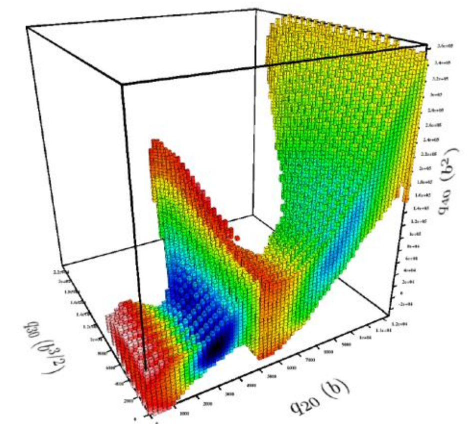

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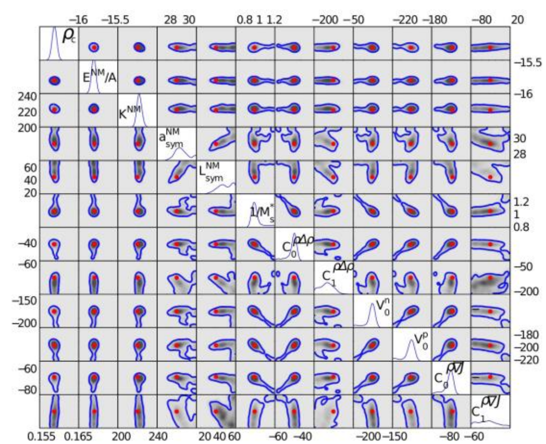

N.Schunck,
CW2014 workshop, April 28-May 1, 2014, Santa Fe

Modern Fission Theories & Models

Dynamics in the macro-micro theory

Modern Fission Theories & Models

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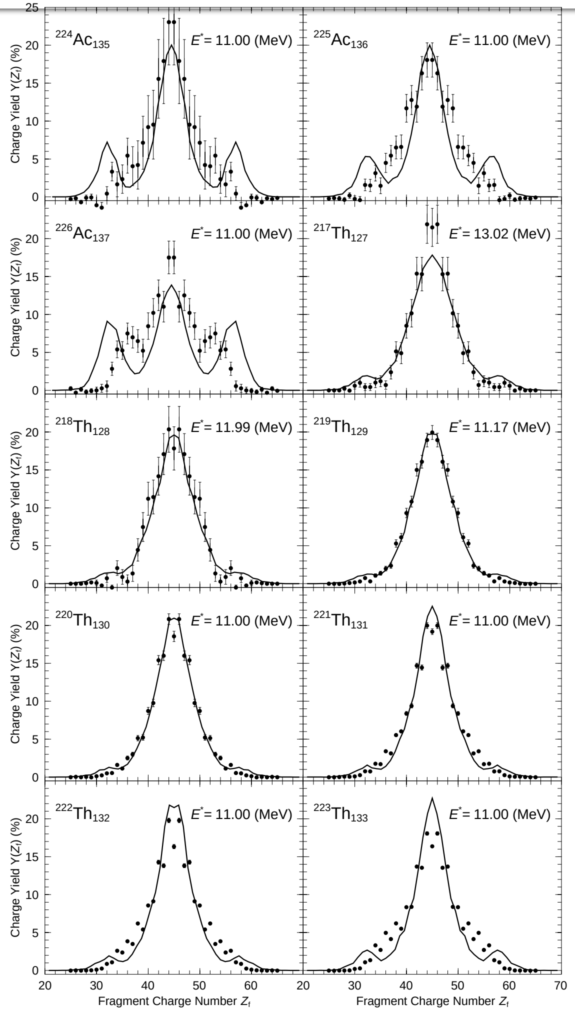

J. Randrup & P. Möller, Phys. Rev. C **88**, 064606 (2013)
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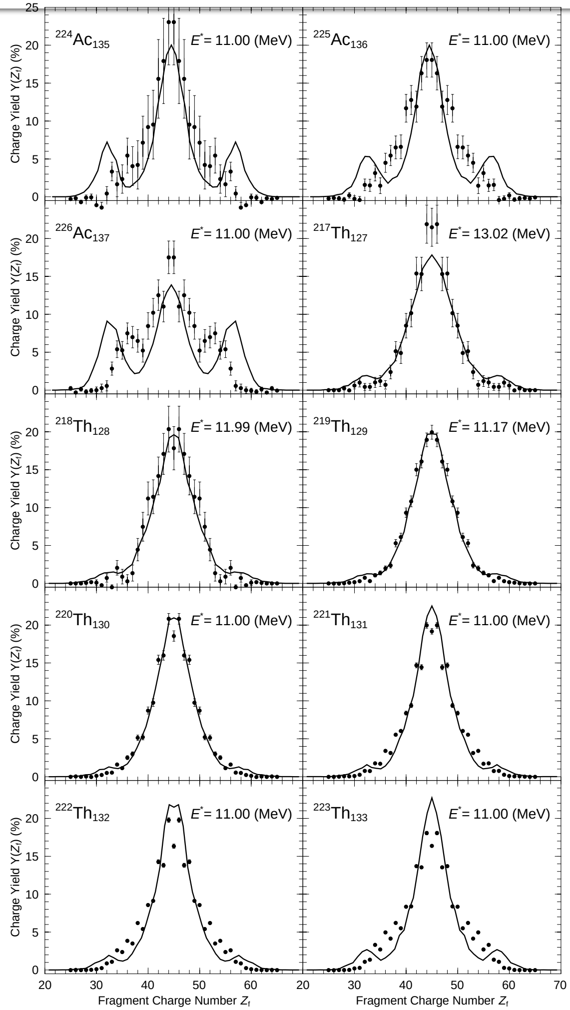

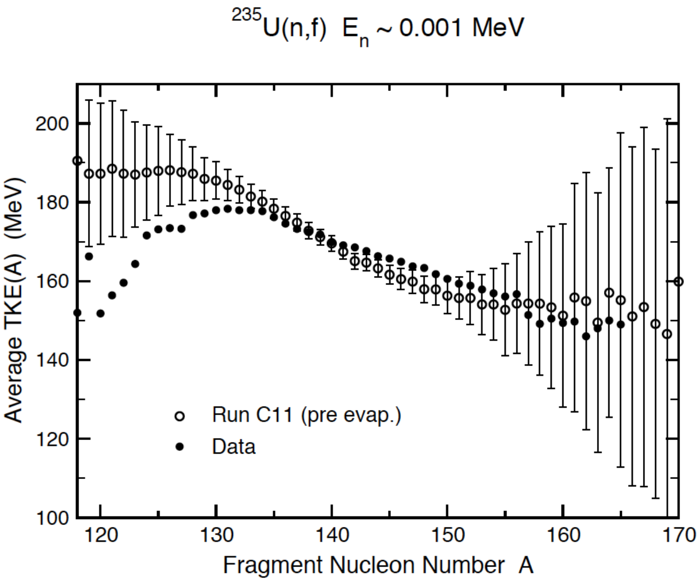

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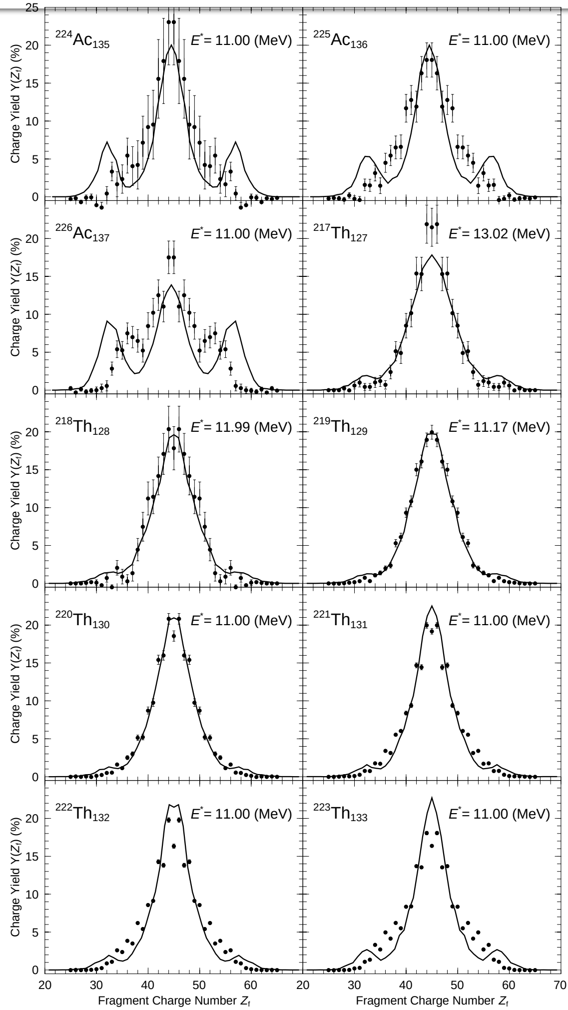

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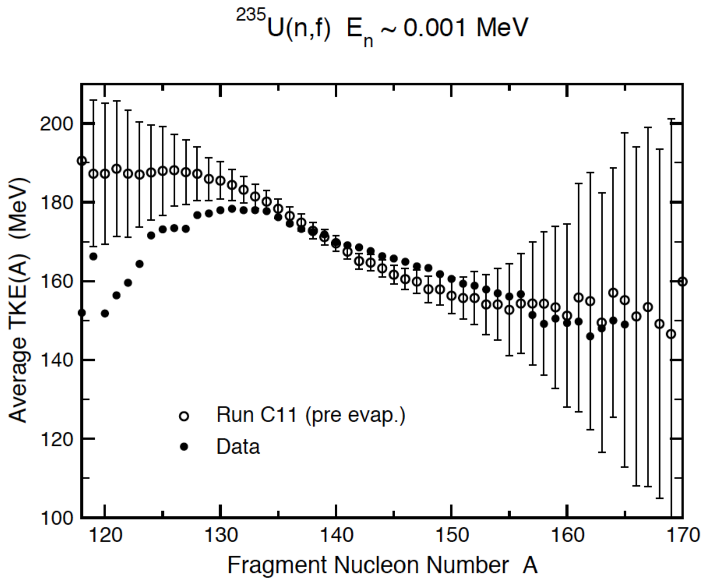


A.J.Sierk, FIESTA workshop,
Sep. 10-12, 2014, Santa Fe

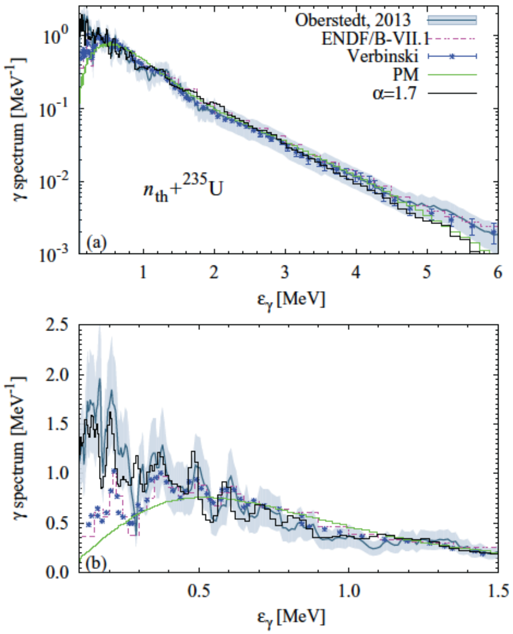
Uncertainties & Errors…

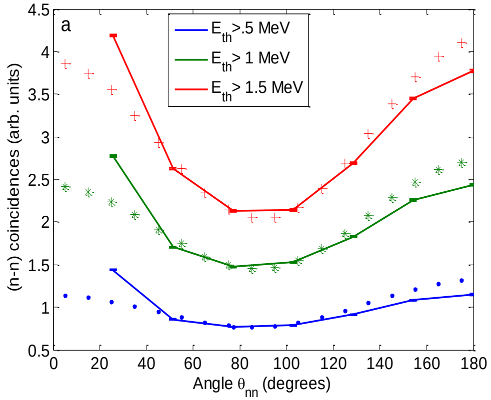
- Macro-micro fundamental assumptions
- Inertia tensor
- Temperature
- Sub-barrier fission
- …

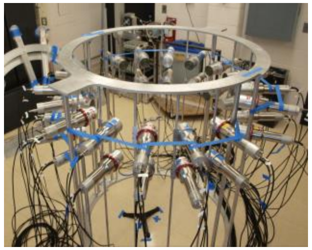
Modern Fission Theories & Models

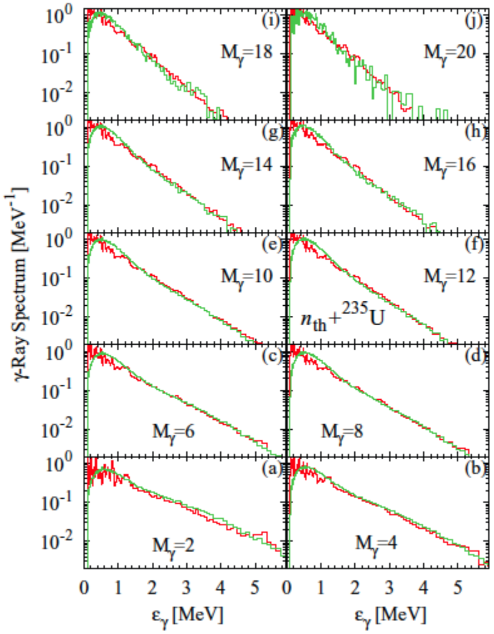
Prompt neutrons and photons

Monte Carlo codes to follow the de-excitation of fission fragments:
CGM/F, FREYA, FIFRELIN, GEF, …









Uncertainties & Errors…

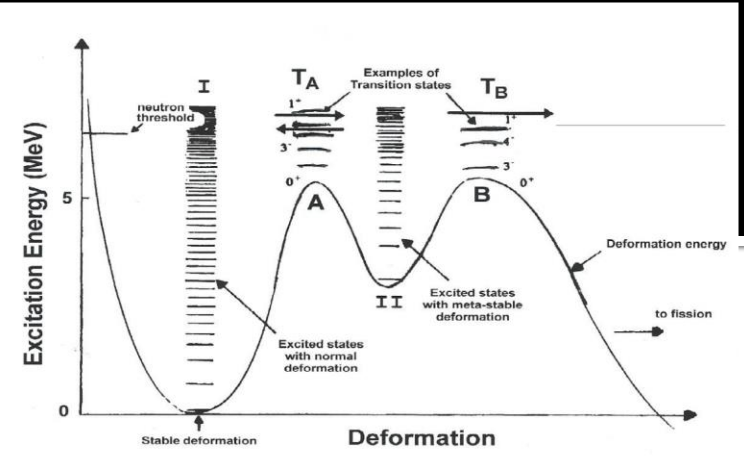
- Nuclear structure data
- OMP for neutron-rich nuclei
- Excitation sorting mechanisms at scission
- …

Modern Fission Theories & Models

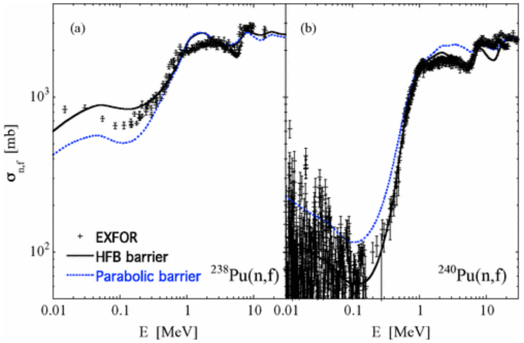
Fission Cross Sections

Modern Fission Theories

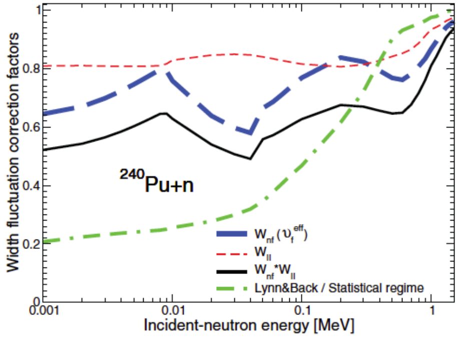
Fission Cross Sections



- Modern Theory of Fission Cross Section
  - Numerical integration of V(fission path)
  - Inertia tensor along the path
  - Coupling between Class-I and Class-II states
  - Class-III states
  - Fission transition states
  - Level densities
  - Different fission paths/modes?
  - Microscopic input?



Goriely, Hilaire, Koning, Sin, Capote
PRC 79, 024612 (2009)



Bouland, Lynn, Talou
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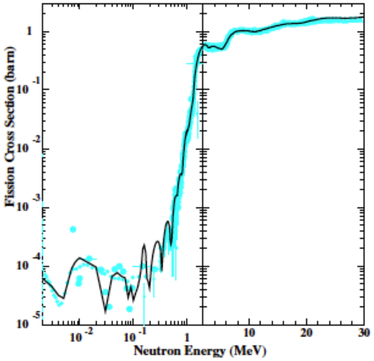
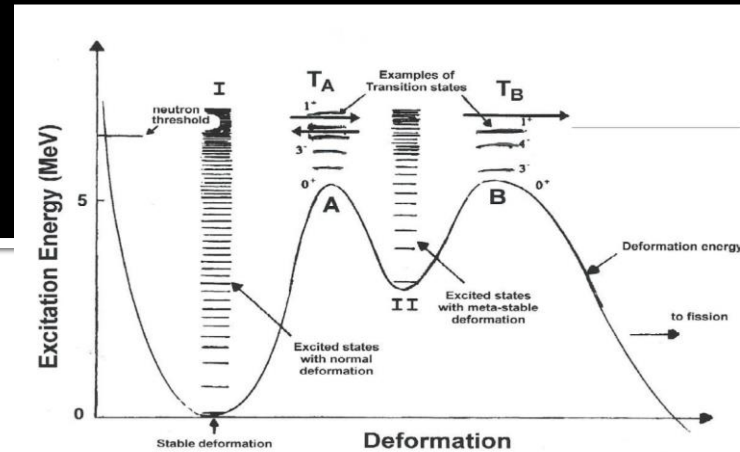


Romain, Morillon

Modern Fission Theories

Fission Cross Sections



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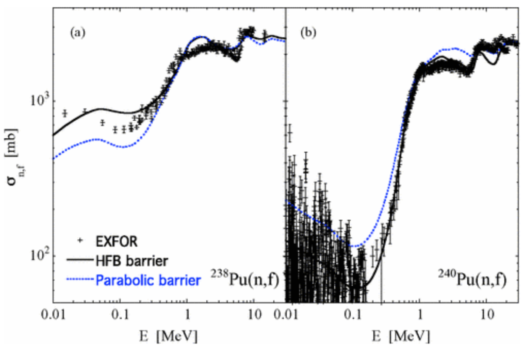

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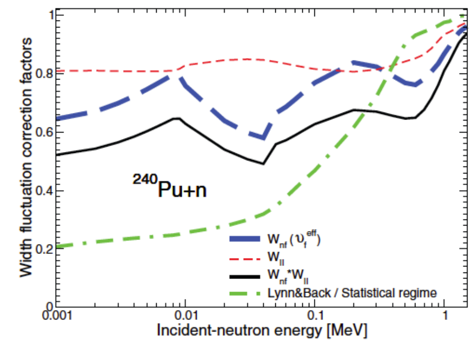

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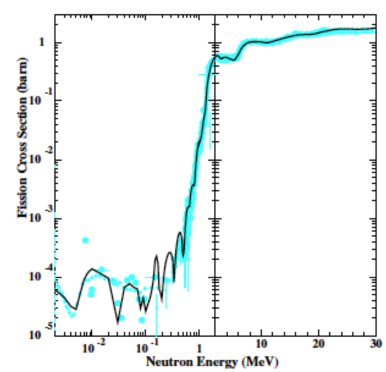
Uncertainties & Errors…

- Many adjustable parameters
- Can be reduced but not eliminated
- Need for correlated data



Romain, Morillon

Correlated Fission Data

Two examples (among many)

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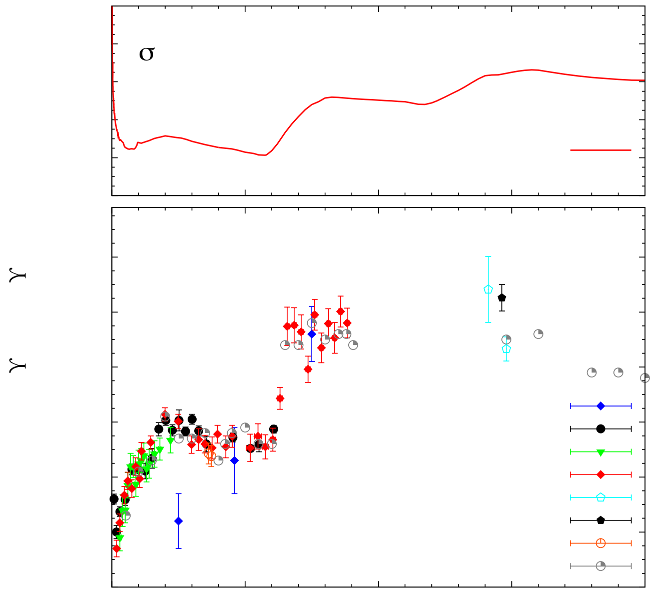

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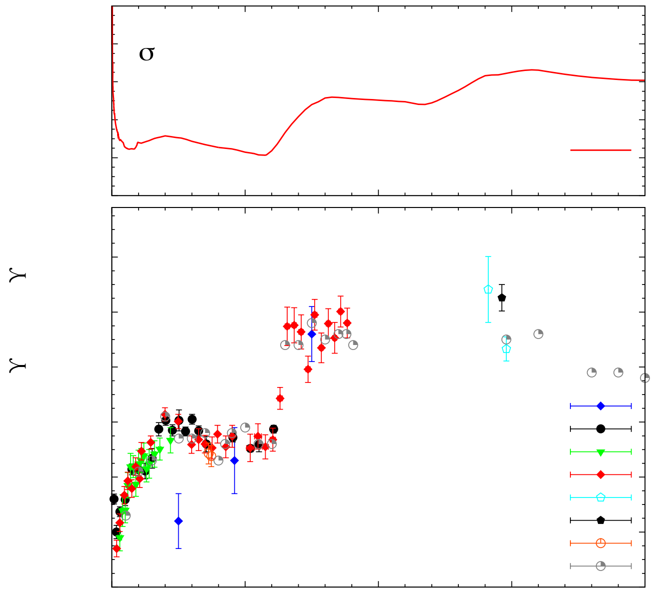
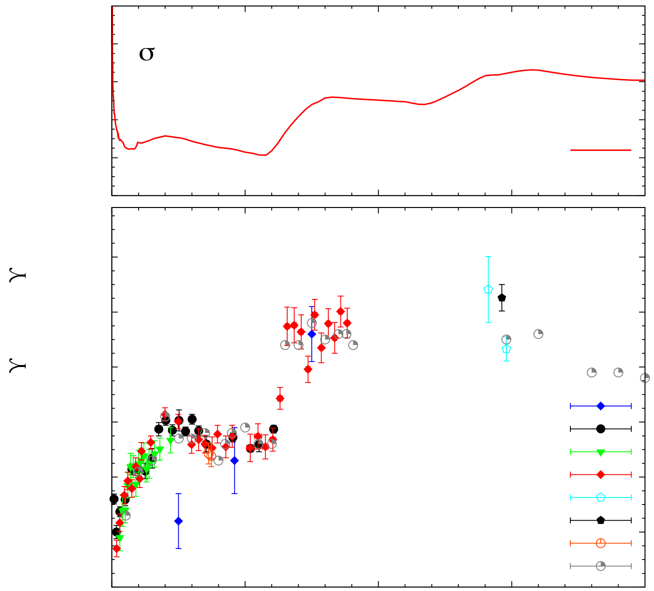


- Simultaneous measurements of $\sigma_f(E_n)$ and $dY_{FF}/d\Omega$
- Work at LANSCE w/ TPC and CERN n_TOF

Correlated Fission Data

Two examples (among many)

- Fission cross sections & Fission fragment angular distributions
- $<\nu_p>$ and $<E_\gamma^{tot}>$ fluctuations in resonance region



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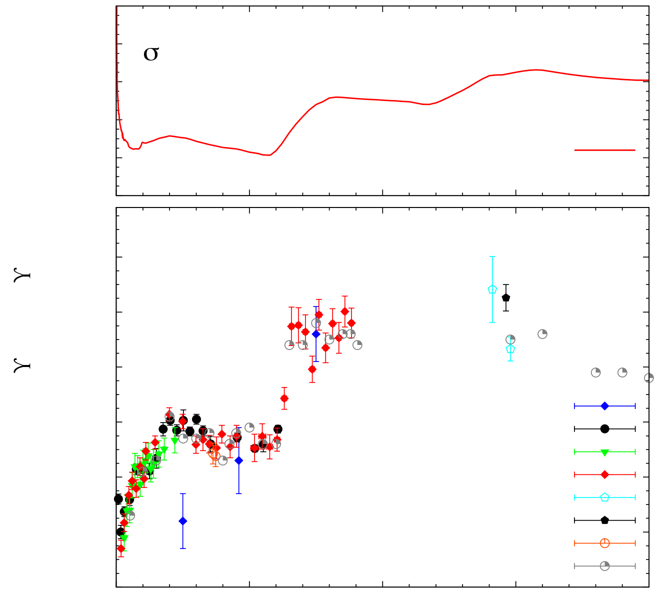

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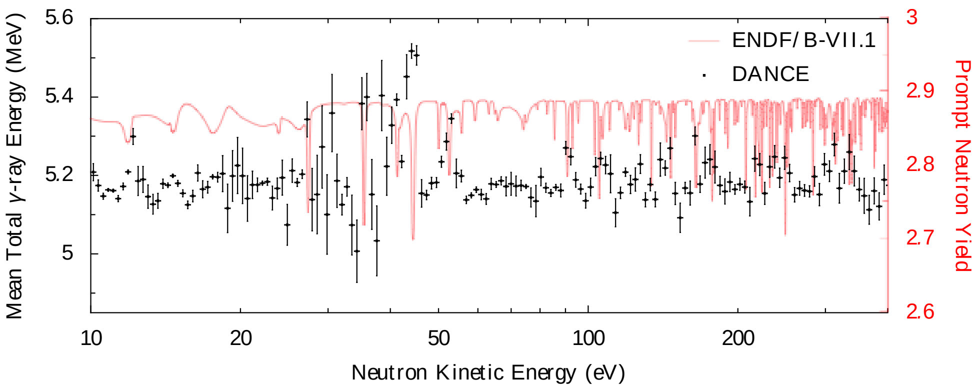

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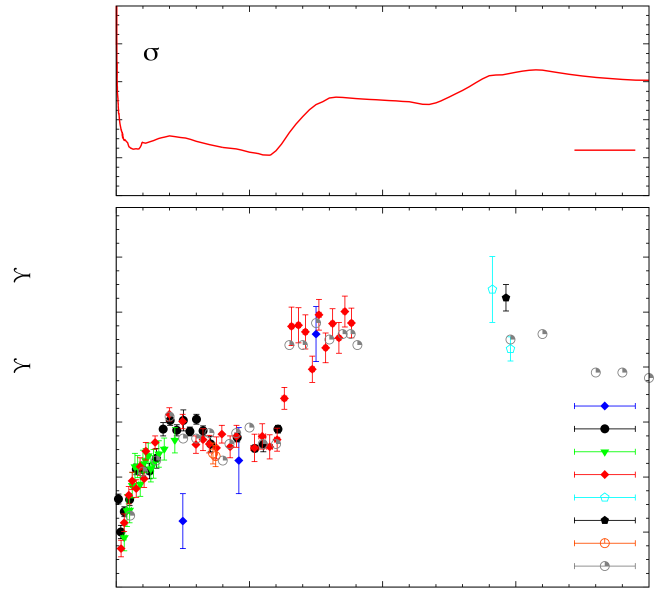

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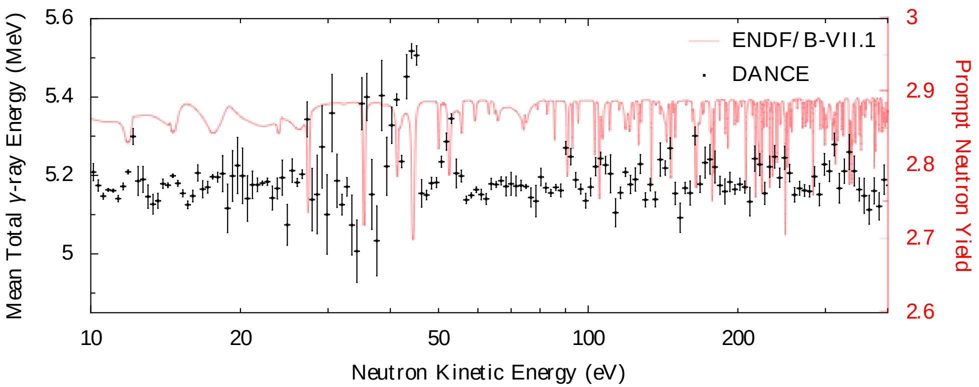

- New DANCE measurement of $\langle E_\gamma^{tot} \rangle(E_n)$
- Theoretical interpretation based on the (n,γf) process
- New $\langle \nu_p \rangle(E_n)$ measurements would be welcome!

- Simultaneous measurements of $\sigma_f(E_n)$ and $dY_{FF}/d\Omega$
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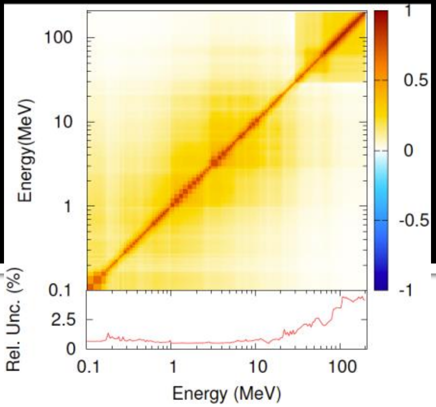
Reducing Uncertainties

in our Predictions of Fission Observables



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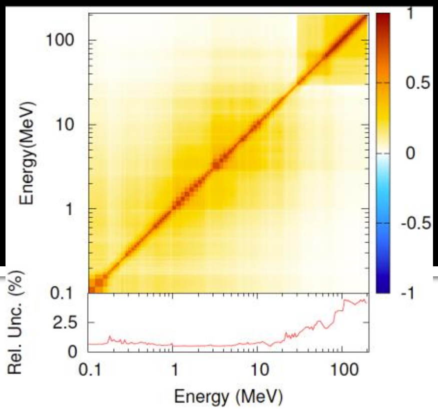

- Predictions for related data:
  - Fission cross sections across isotopes and incident channels, fission fragment angular distributions, fission modes, etc.
  - Prompt fission neutrons: multiplicity, spectrum, n-n correlations in energy and angle, etc., as a function of fragment (A,Z,KE)
  - Same for prompt fission gamma rays (cf. Oberstedt, Jandel)
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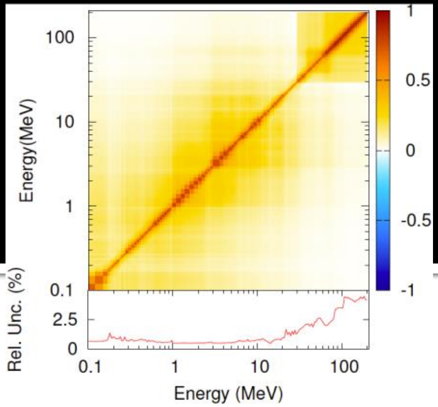

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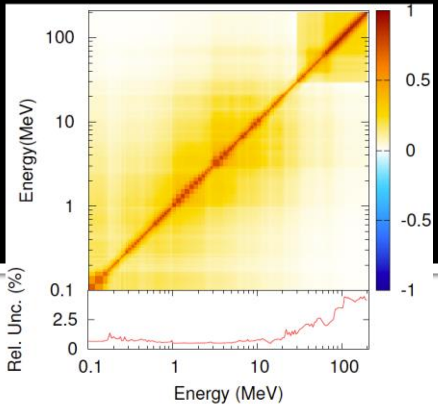

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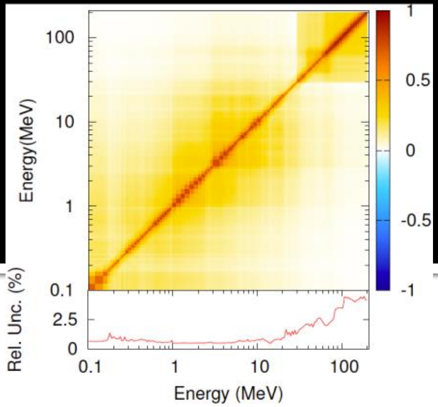

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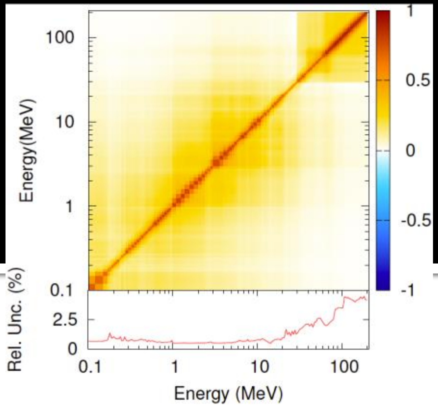

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- Evaluated uncertainties can be kept small when *nearby* data are available – adjusted libraries – **beware of extrapolations!**

The next decade

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"Uncertainties in Nuclear Fission Data,"
P.Talou, T.Kawano, M.B.Chadwick, D.Neudecker, and M.E.Rising

to appear in a Special Issue of J. Phys. G: Nuclear and Particle Physics on

"Enhancing the interaction between nuclear experiment and theory through information and statistics"