The case for an evaluated database of statistical nuclear quantities

Lee Bernstein

Department of Nuclear Engineering
UC-Berkeley
Nuclear Science Division
Lawrence Berkeley National Laboratory

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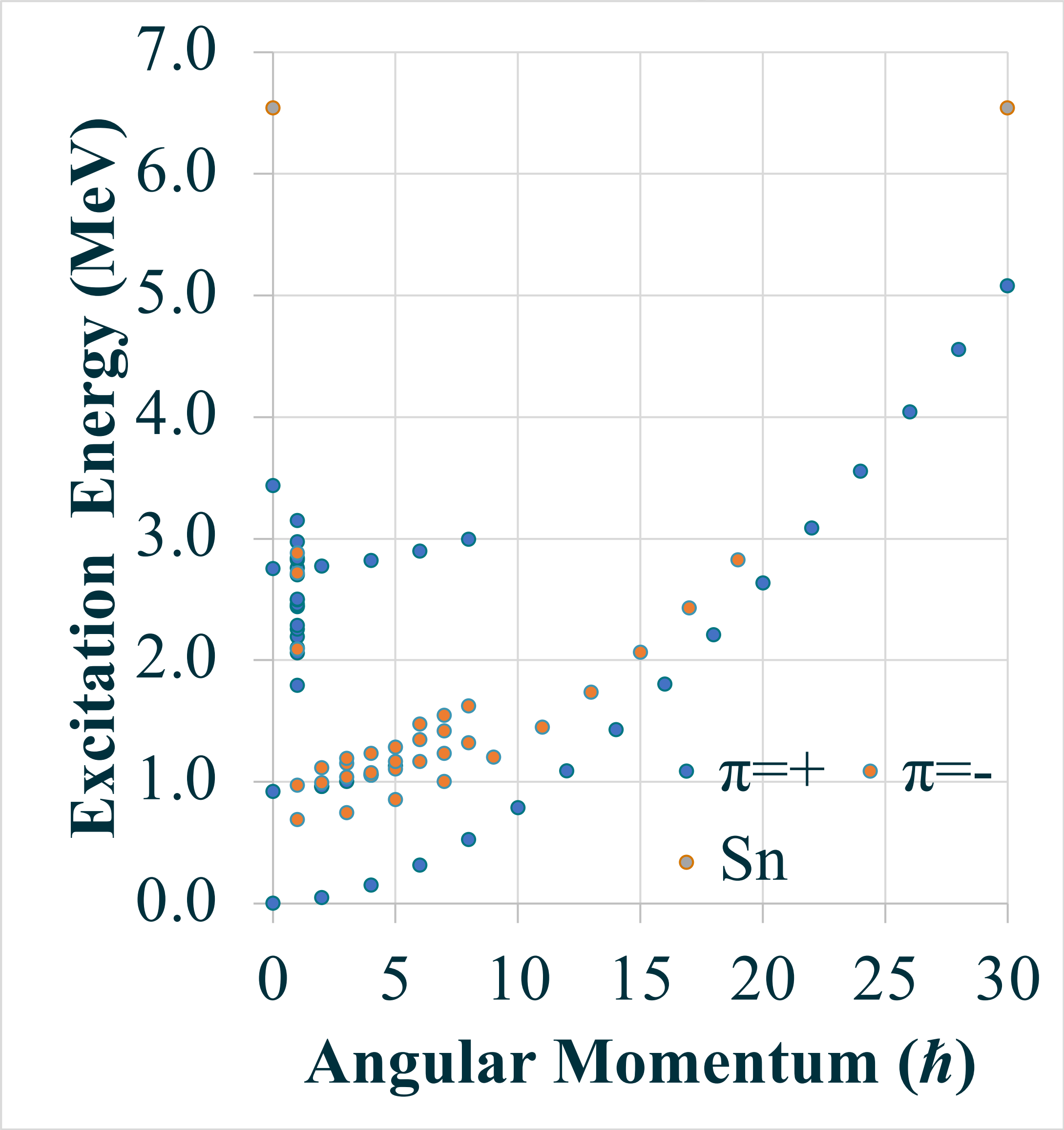
What are statistical (Quasicontinuum) nuclear data

- The Evaluated Nuclear Structure Data File (ENSDF) has information about discrete, particle-bound nuclear states and the decays connecting them.



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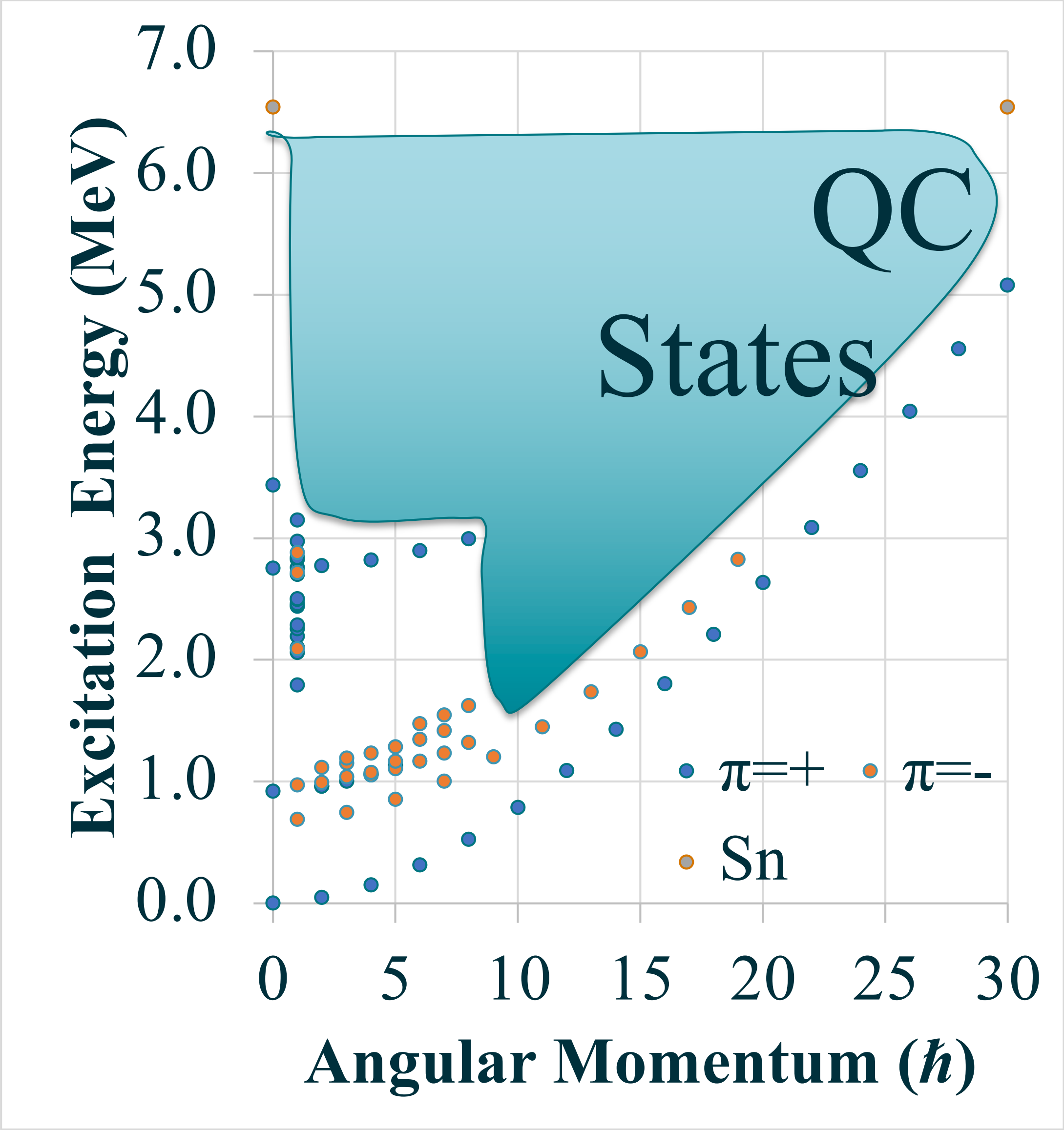
- States with E_x > a few MeV, particularly those with high-values of E_x/J, are unknown and both their E_x-J distribution and the probability that they will decay via emission of a γ-ray of a given energy are ***statistically distributed*** using continuous functions:

Nuclear Level Density = $\rho(E_x,J^{\pi})$

Photon Strength Function = $F(E_\gamma)$



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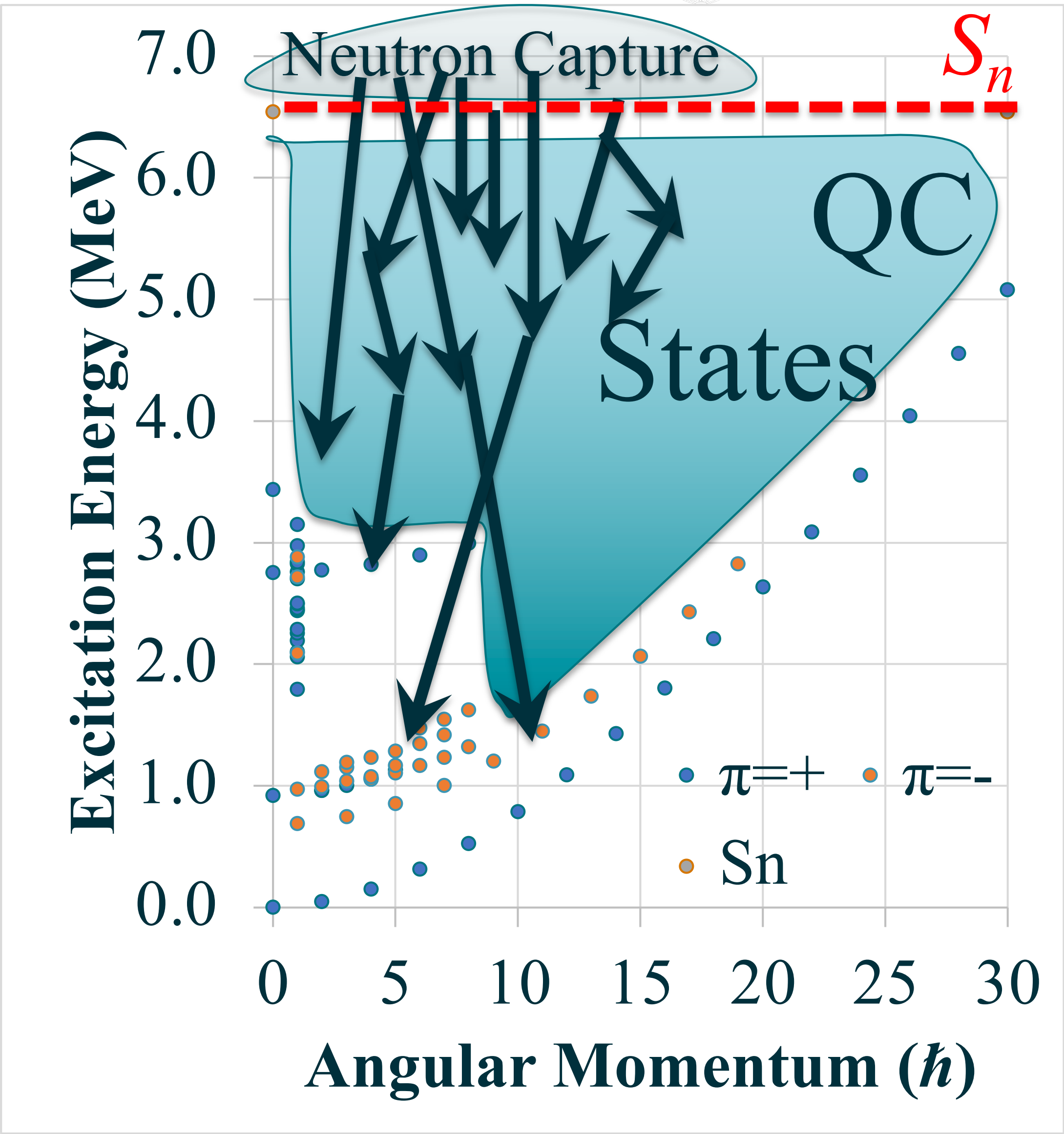
- These *Quasicontinuum* (QC) states are the ones most likely to connect to states populated in neutron capture, making $\rho(E_x, J^\pi)$ and $F(E_\gamma)$ critical to accurate nuclear reaction modeling



What are statistical nuclear data

Nuclear Level Density = $\rho(E_x,J^\pi)$

Fermi Gas Model

$$\rho(U) = \frac{\sqrt{\pi}}{12a^{1/4}U^{5/4}}\exp(2\sqrt{aU}),$$

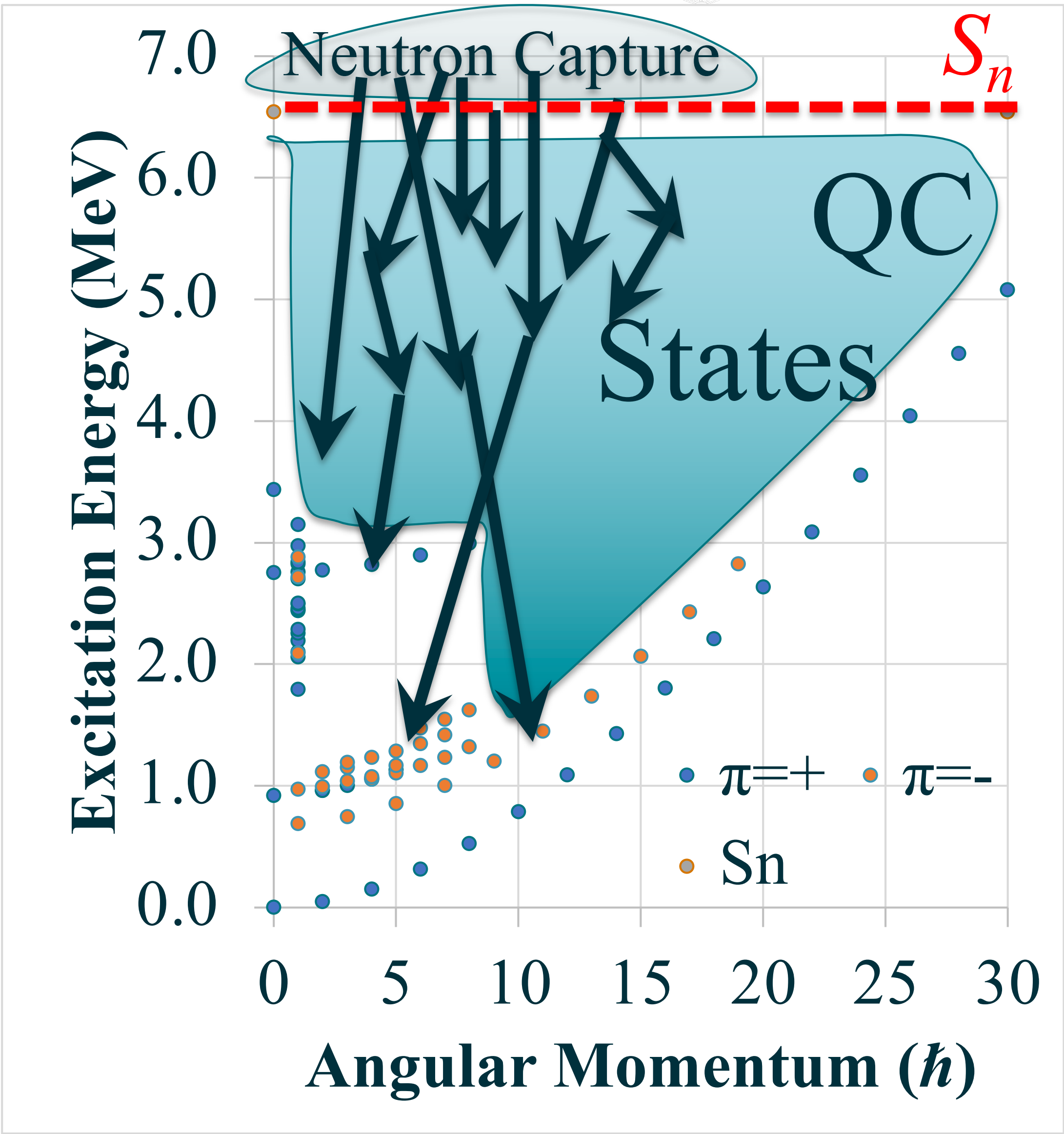
$$\rho(U,J) = \frac{2J+1}{2\sqrt{2\pi}\sigma^3}\rho(U)\exp\left[-\frac{(J+1/2)^2}{2\sigma^2}\right]$$

$$a = 2\left(\frac{\pi}{3}\right)^{4/3}\frac{m_0 r_0^2}{\hbar^2}A(1+\beta_s A^{-1/3}),$$

Constant Temperature Model

$$\rho_{lev}(U) = \frac{dN}{dU} = \frac{1}{T}\exp\left[(U-U_0)/T\right]$$

Plus many, many more…



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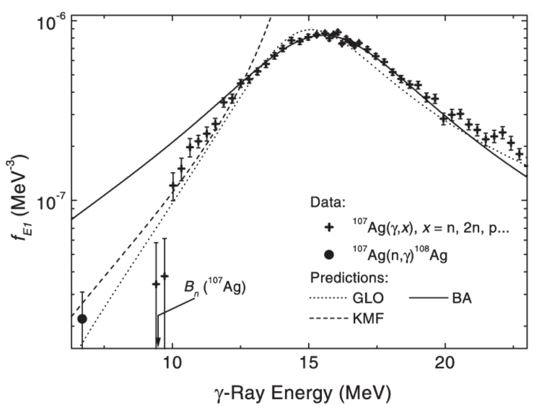

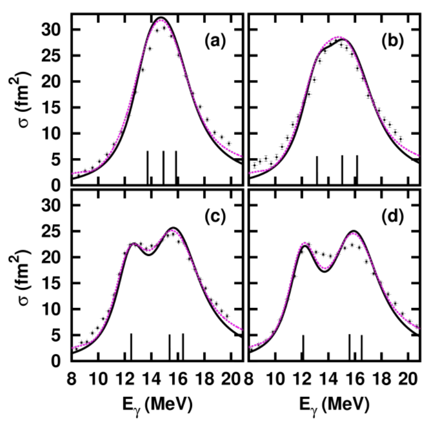

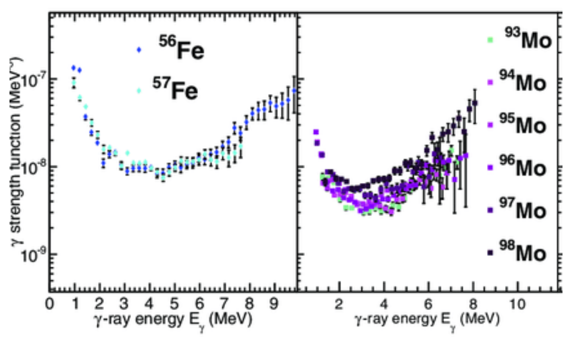

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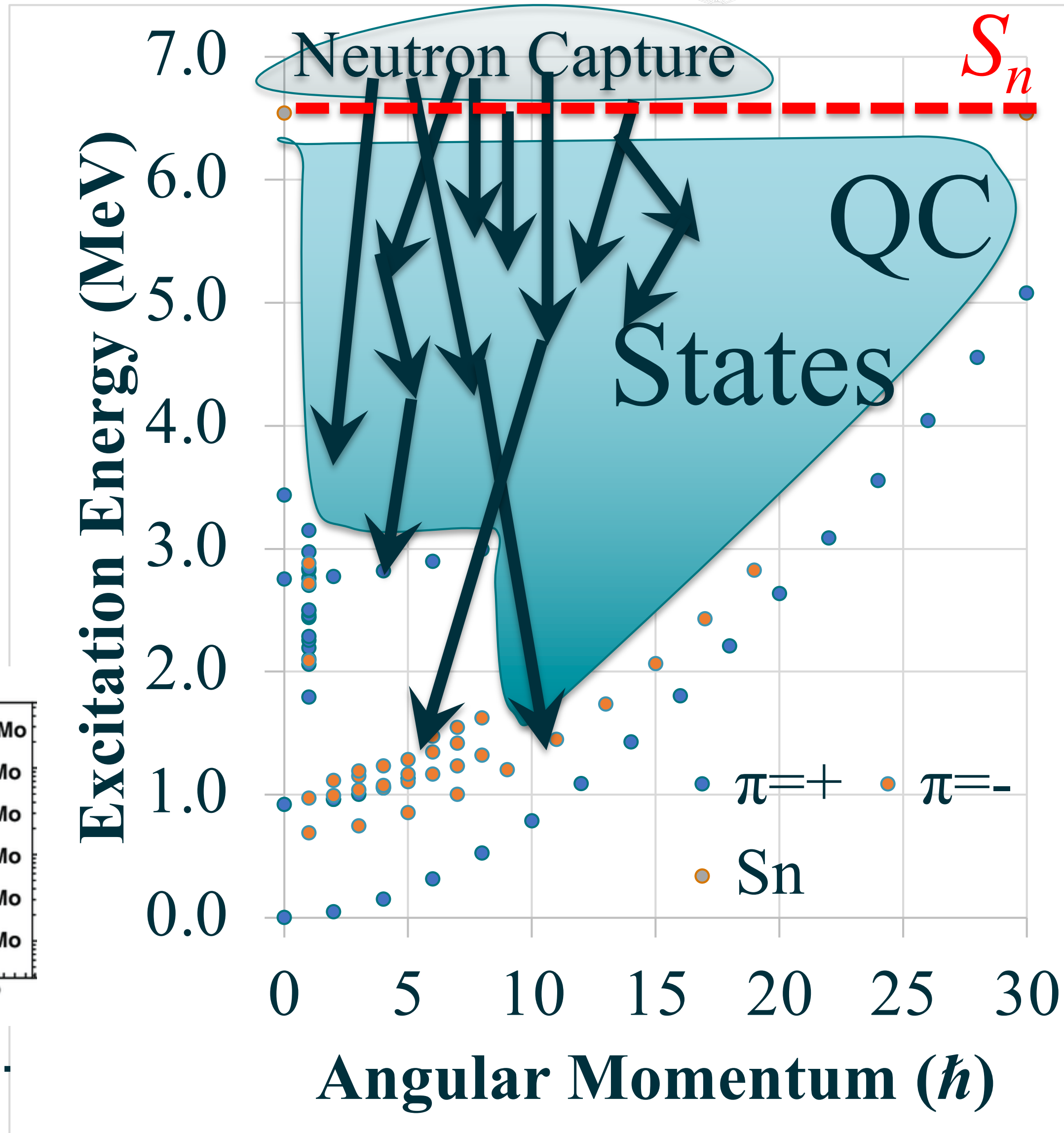

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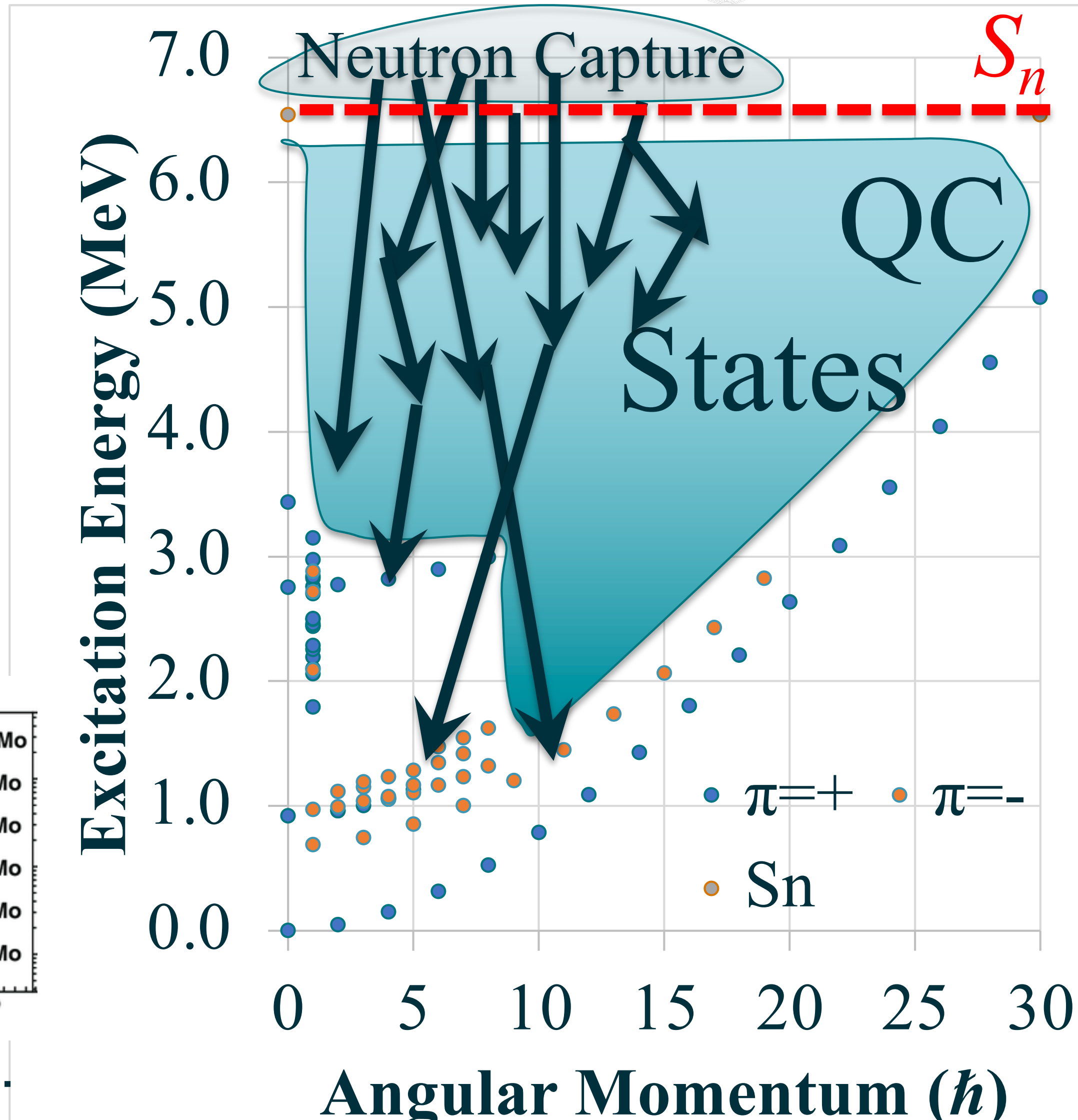

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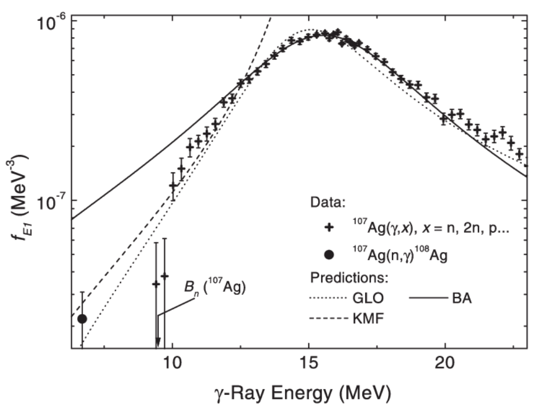
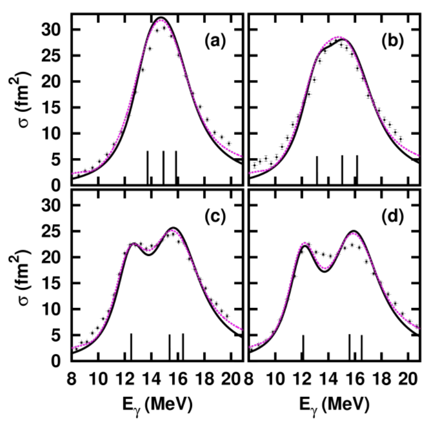
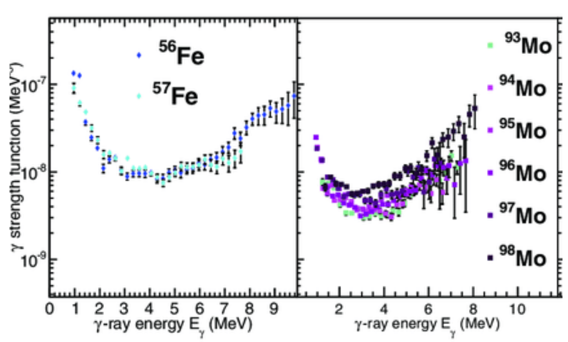




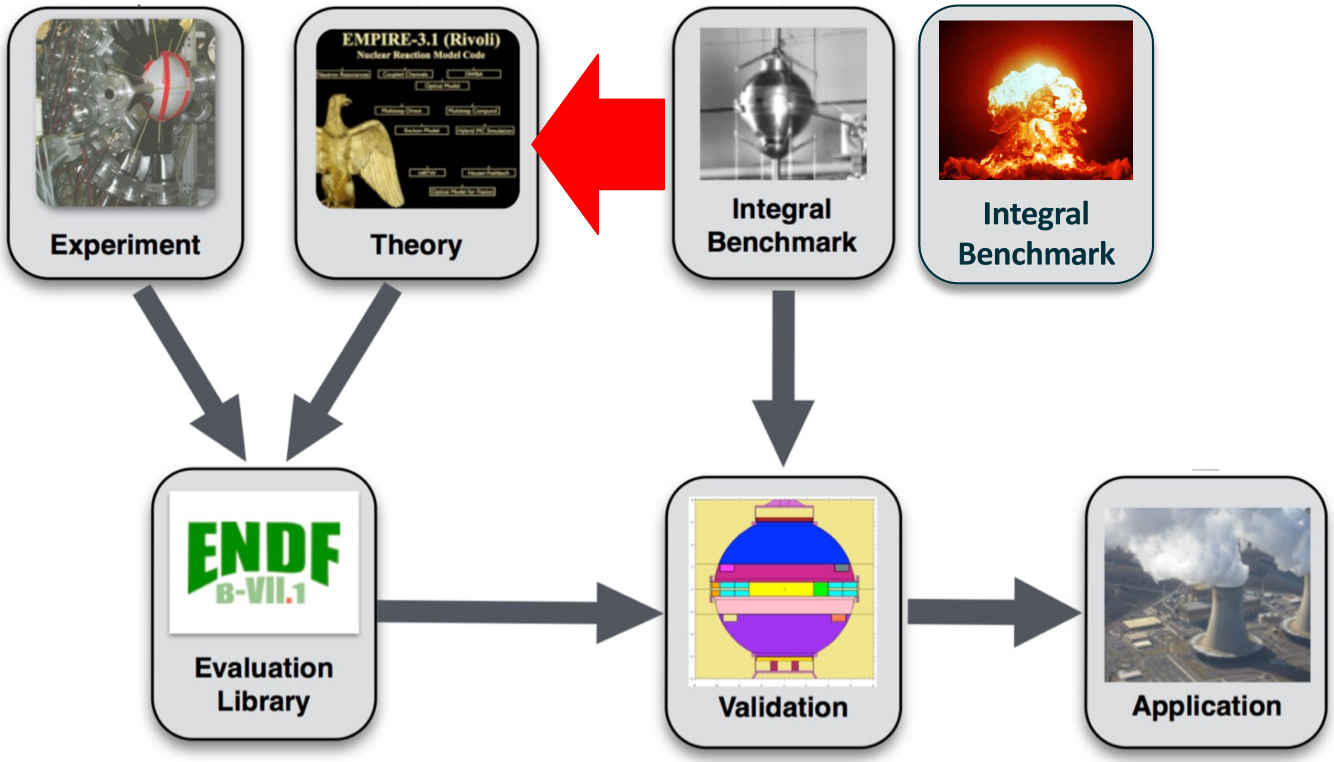


Plus many, many more…

How do these data effect the reaction rates needed for applications?

Where Statistical Data Enters Reaction Evaluation

1. Reaction models are ***"tuned"*** by varying underlying physics knobs, such as QC properties and OM parameters, by evaluators to reproduce measured angle- and energy-differential ***cross section*** data (since we can't measure everything needed).
2. Models of "integral benchmarks" (e.g., systems that depend on multiple nuclear data inputs) are compared to the "real deal" to validate the underlying nuclear data

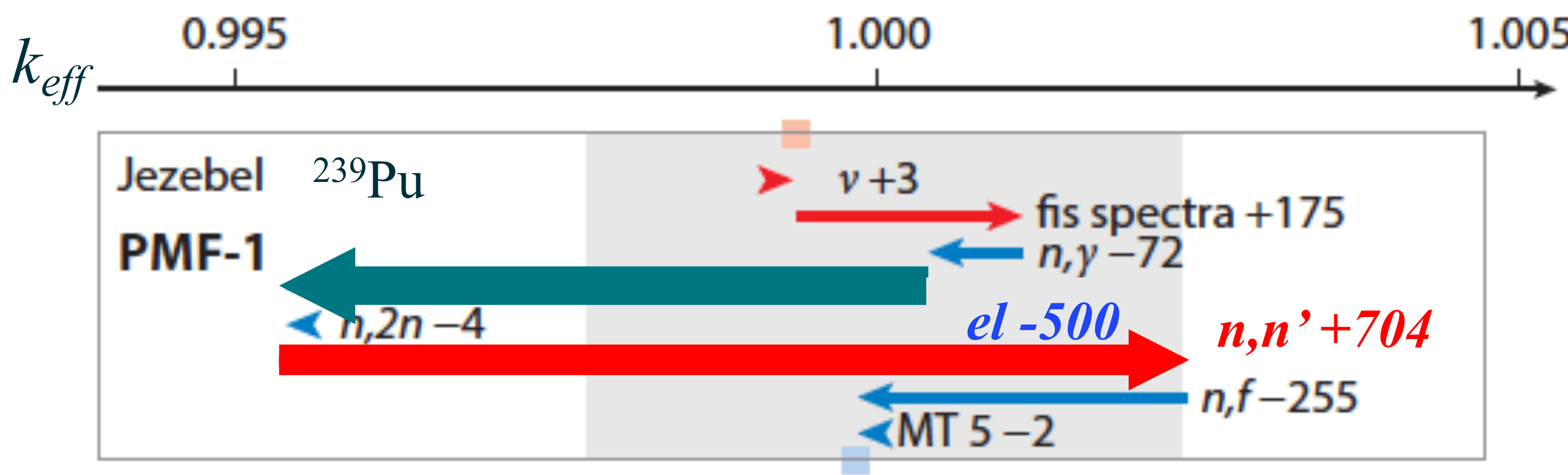


BUT QC properties such as Nuclear Level Density ($\rho(E_x,J,\pi)$) and Gamma Strength Functions ($\Gamma(E_\gamma)$) are now being measured regularly and their values should not be adjusted "at will" by evaluators

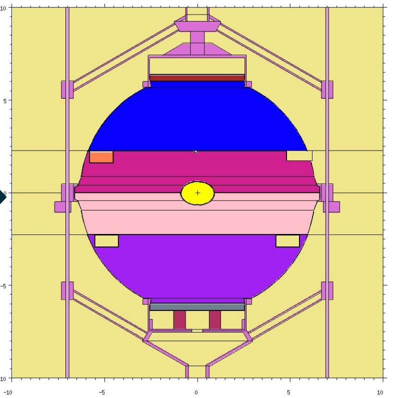
e.g., QC properties are another "trash can" (to quote Dave)

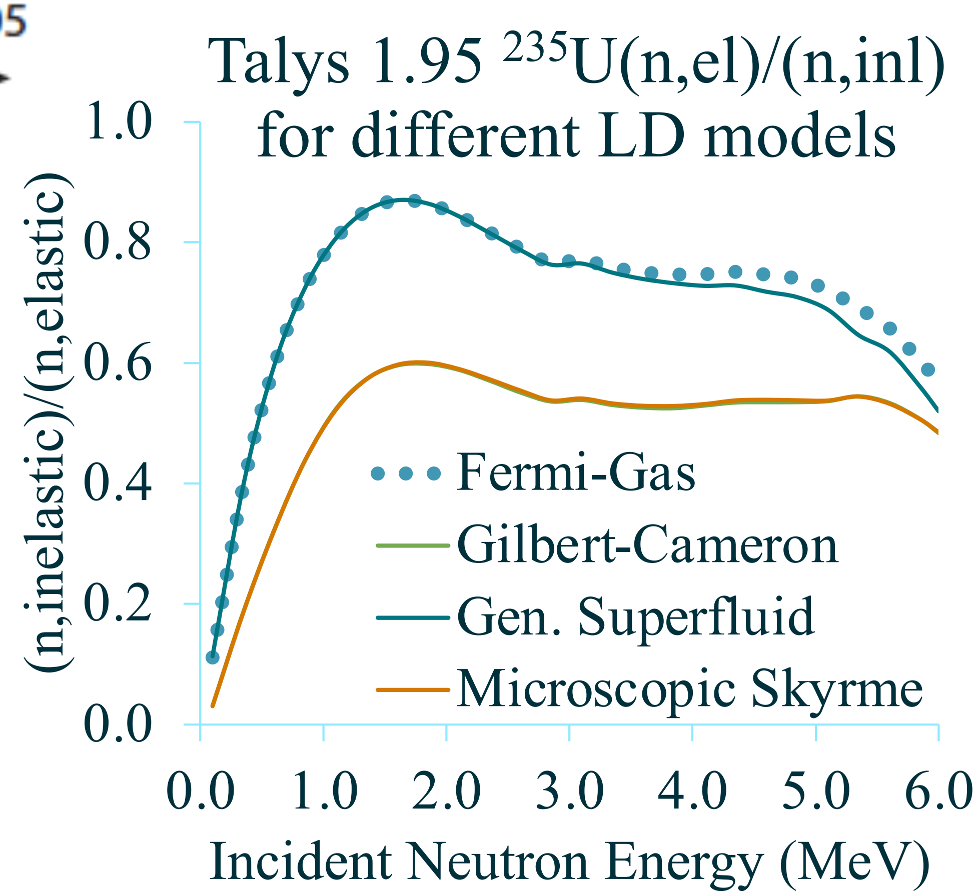
Thanks to Dave Brown (BNL/NNDC)

Example: ^{239}Pu(n,x) in Jezebel modeled using cross sections from two different nuclear data libraries



ENDF/B-VIII.0 vs. JEFF-3.3



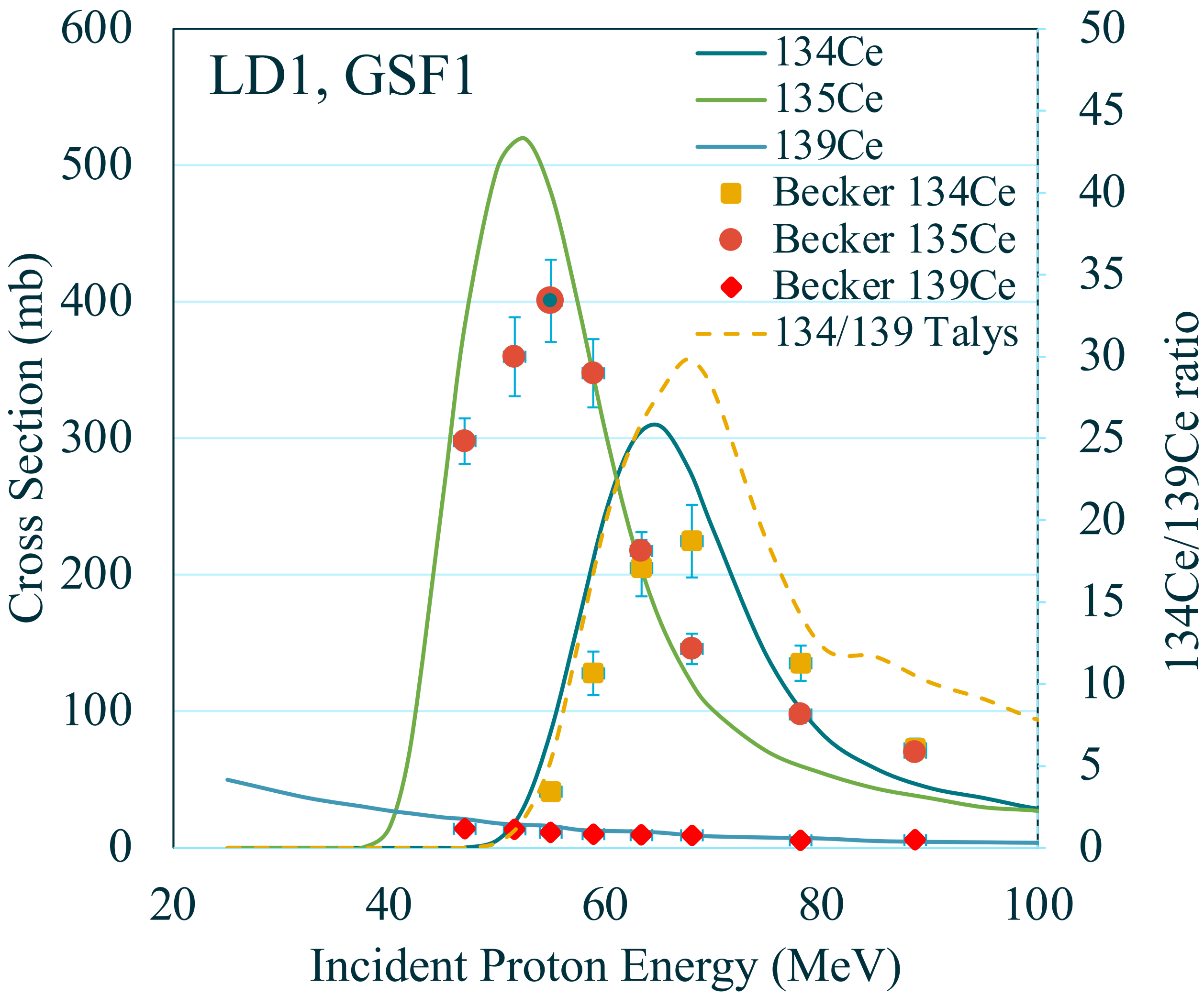


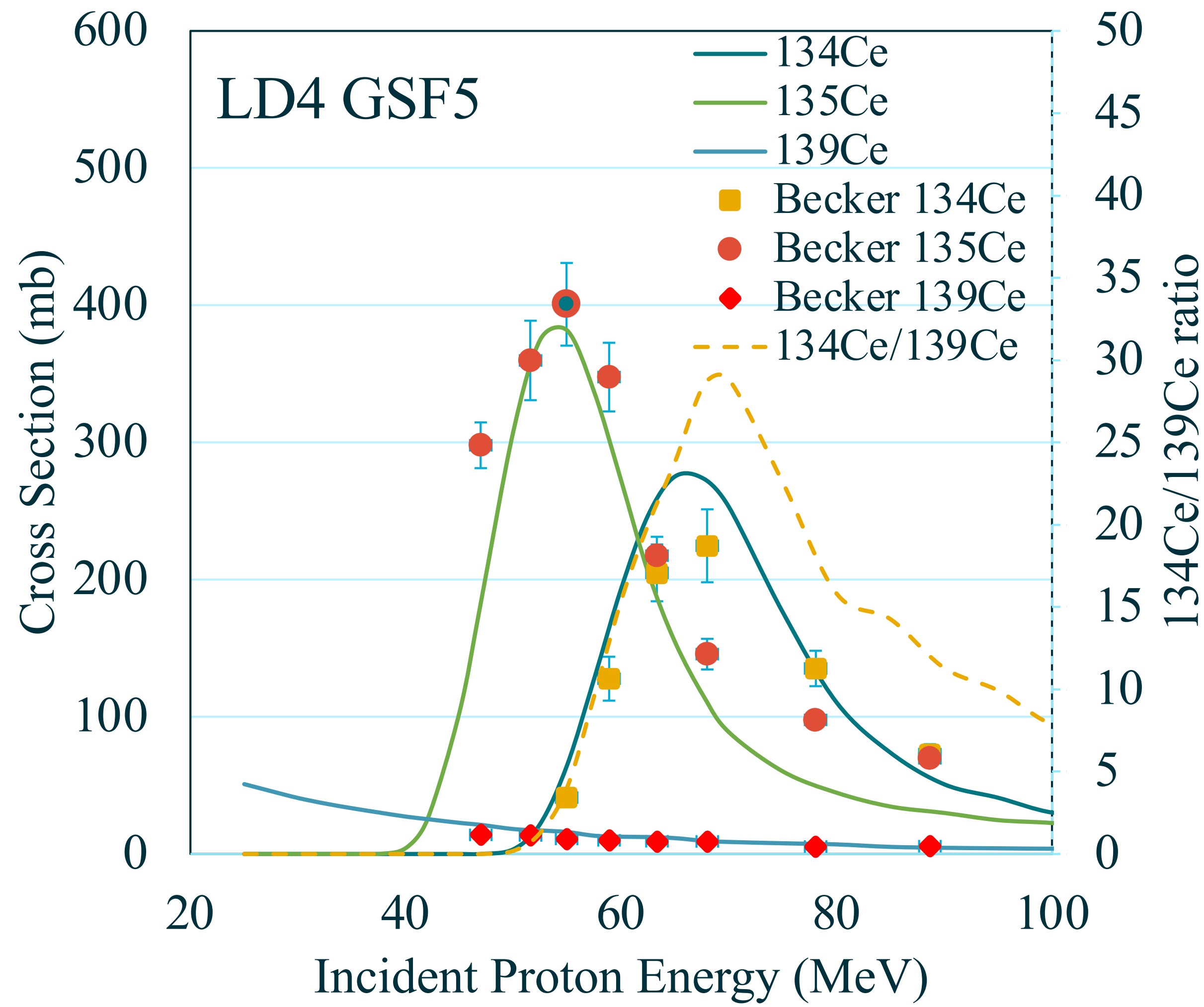
QC measurements of could help address compensating uncertainties

*L.A.B. *et al.*, Annu. Rev. Nucl. Part. Sci. 2019.69:109-136.

Let's consider an example from Medical Applications

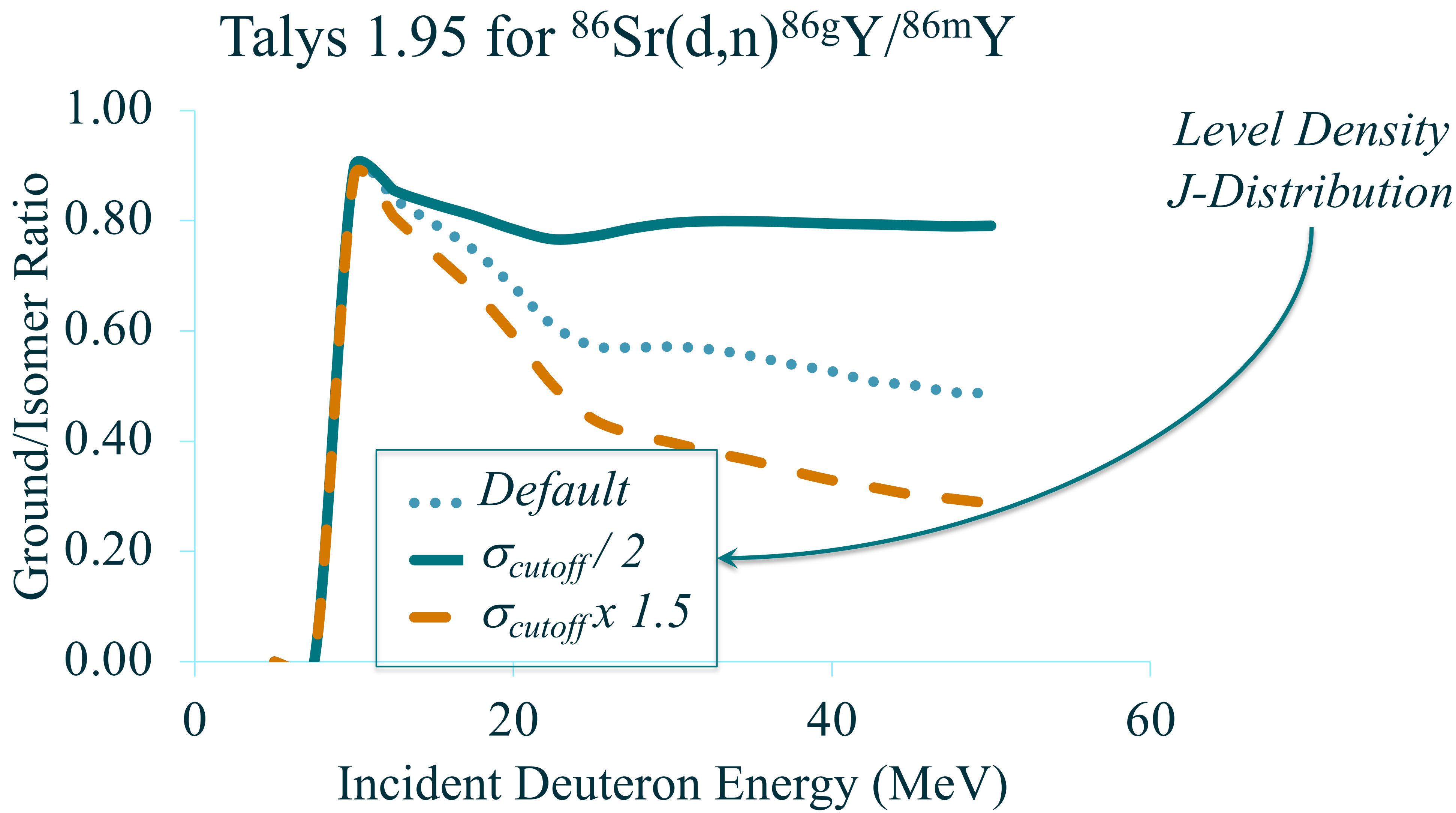
Production of ^{134,139}Ce for medical imaging using high energy protons





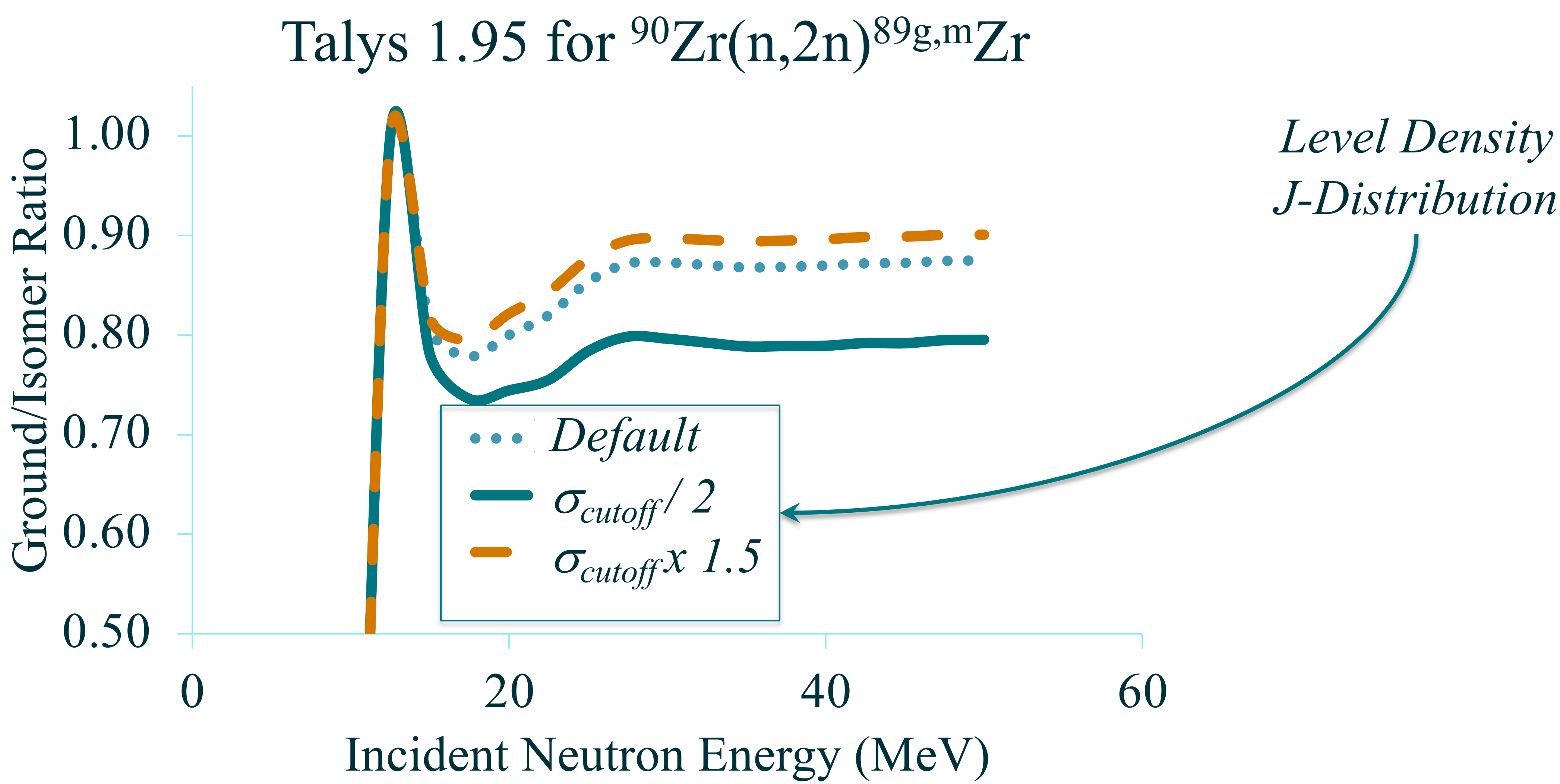
The Effect on the Ground-to-Isomer Ratio is greater

Production of ^{86}Y for medical imaging

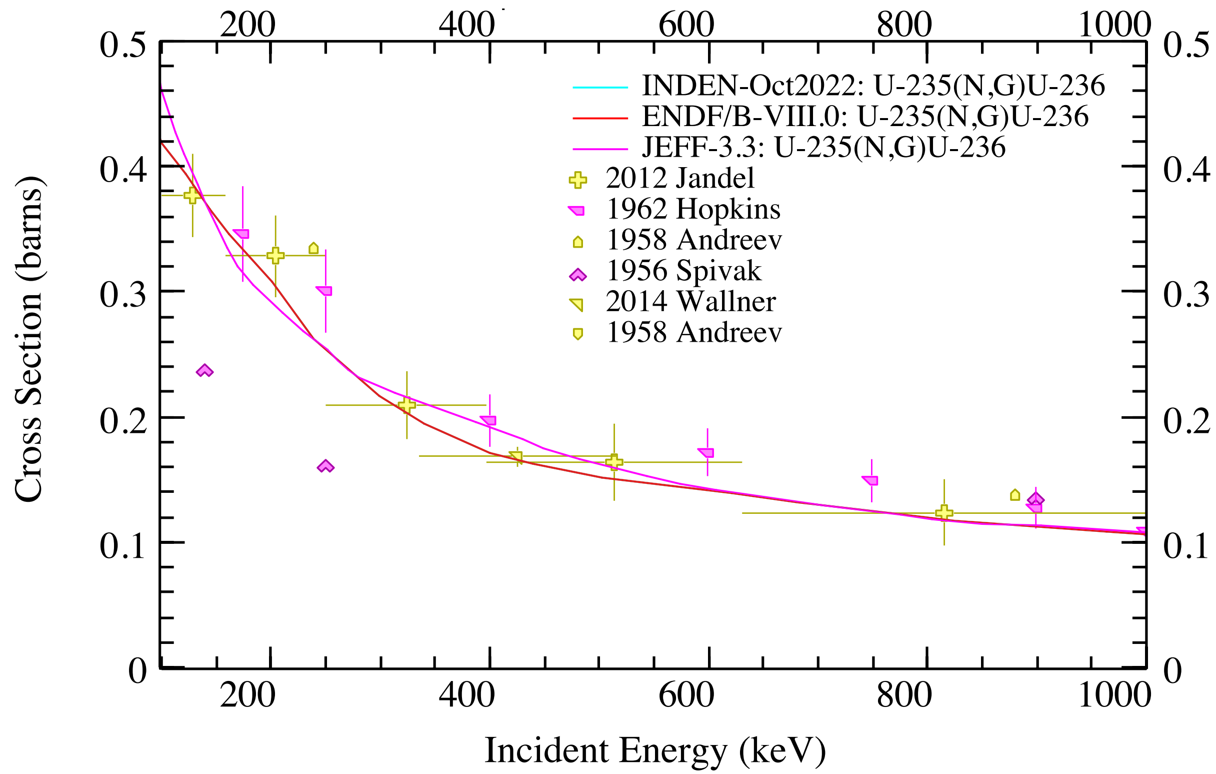


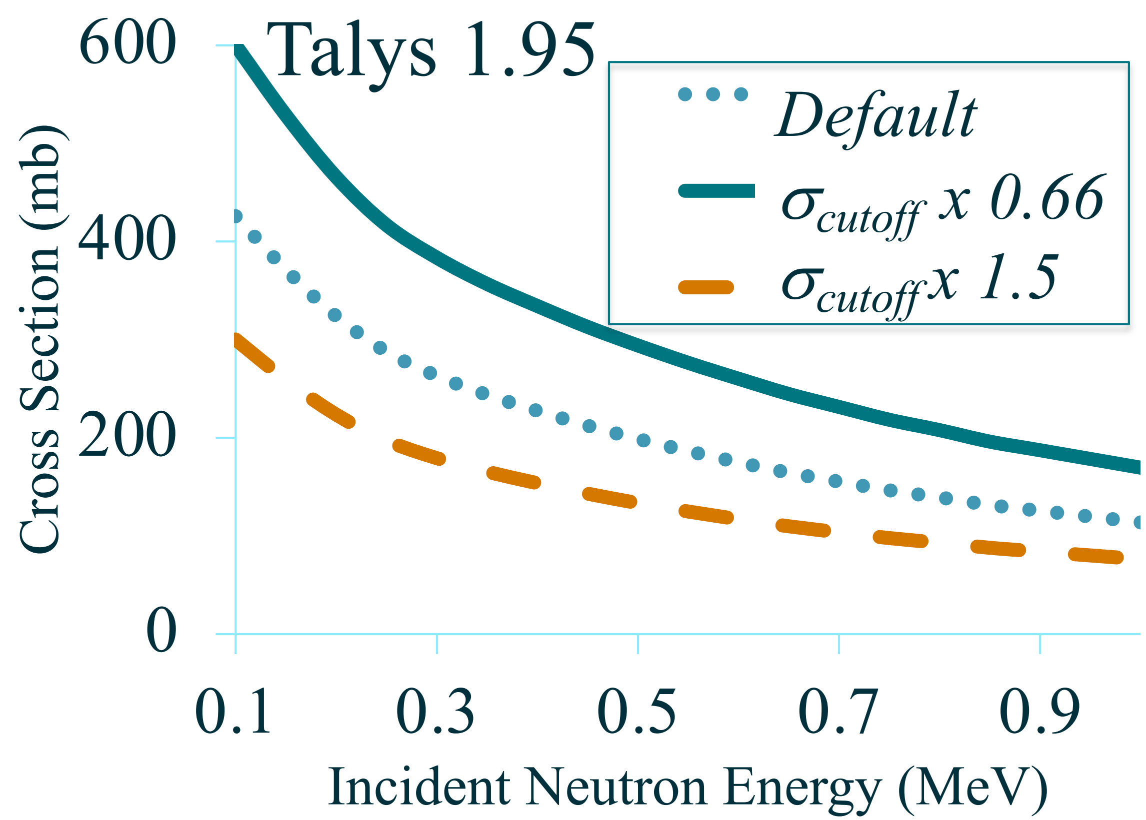
How about an example from NA-11's perspective

$^{89g,m}Zr$ as a radiochemical diagnostic



How about a broadly important reaction?
Dependence of $^{235}U(n,\gamma)$ at Fast Fission Energies on $\rho(J)$





What about the dependence on $F(E_\gamma)$?

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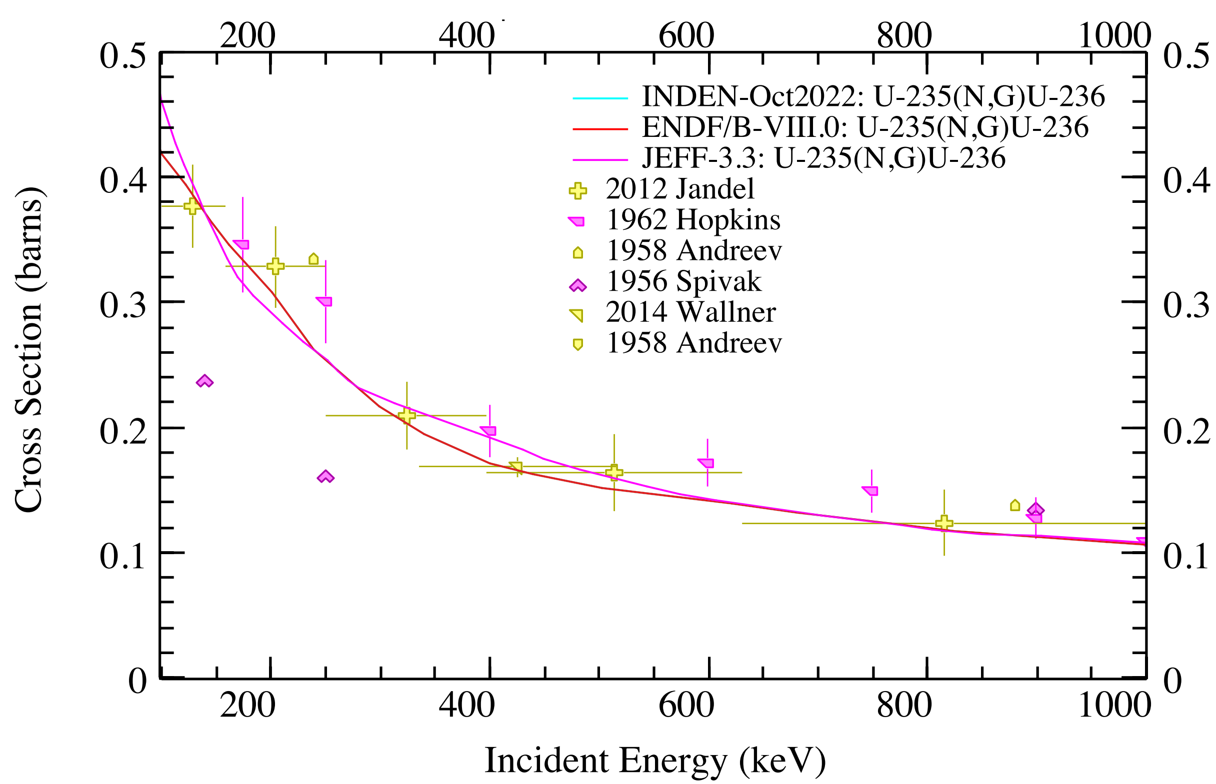
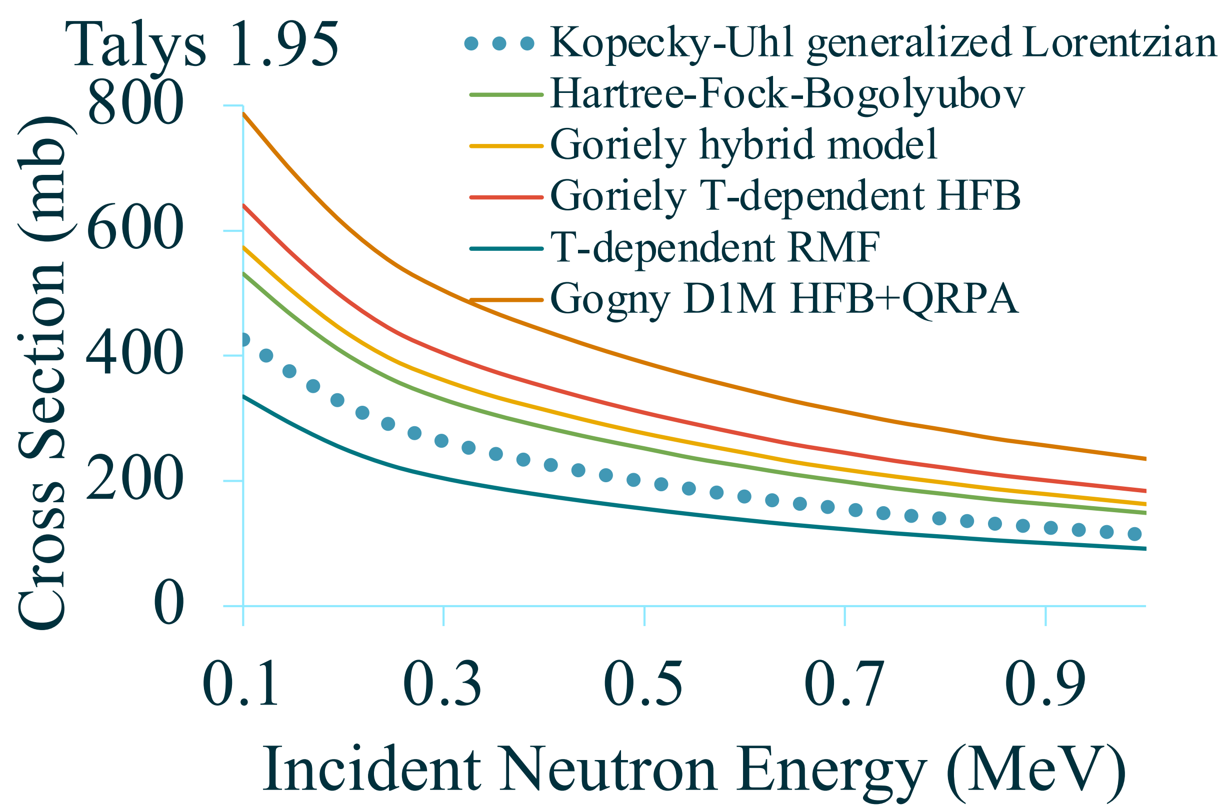
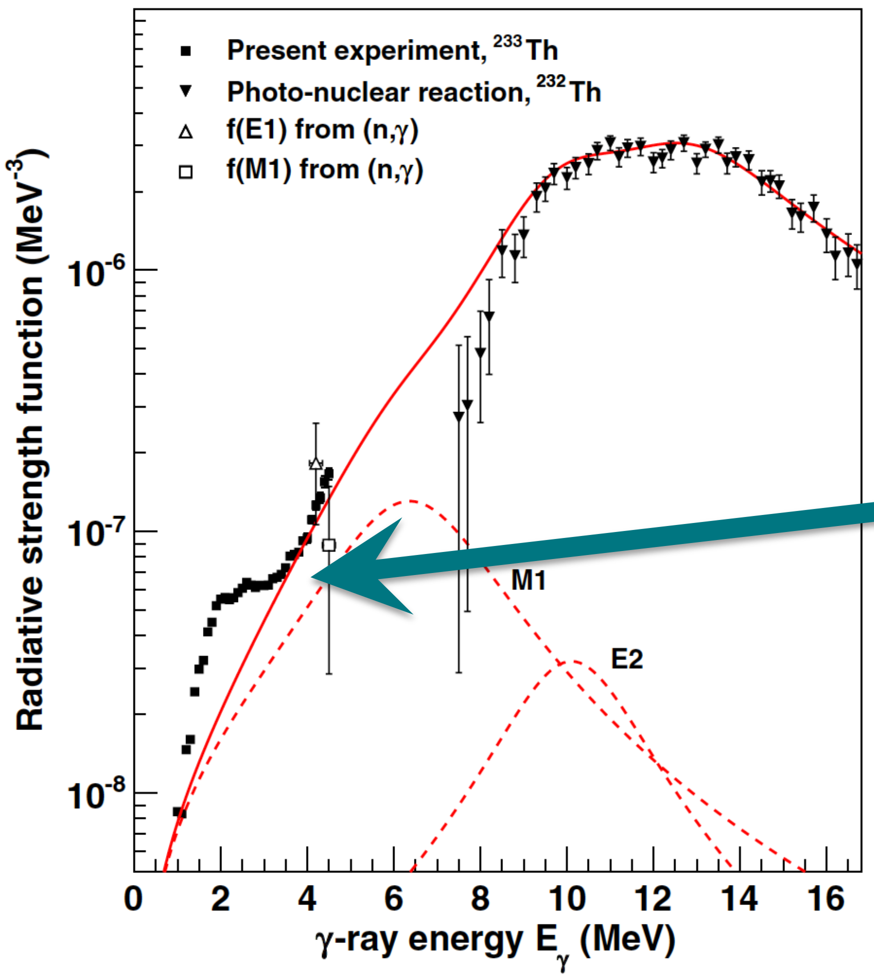


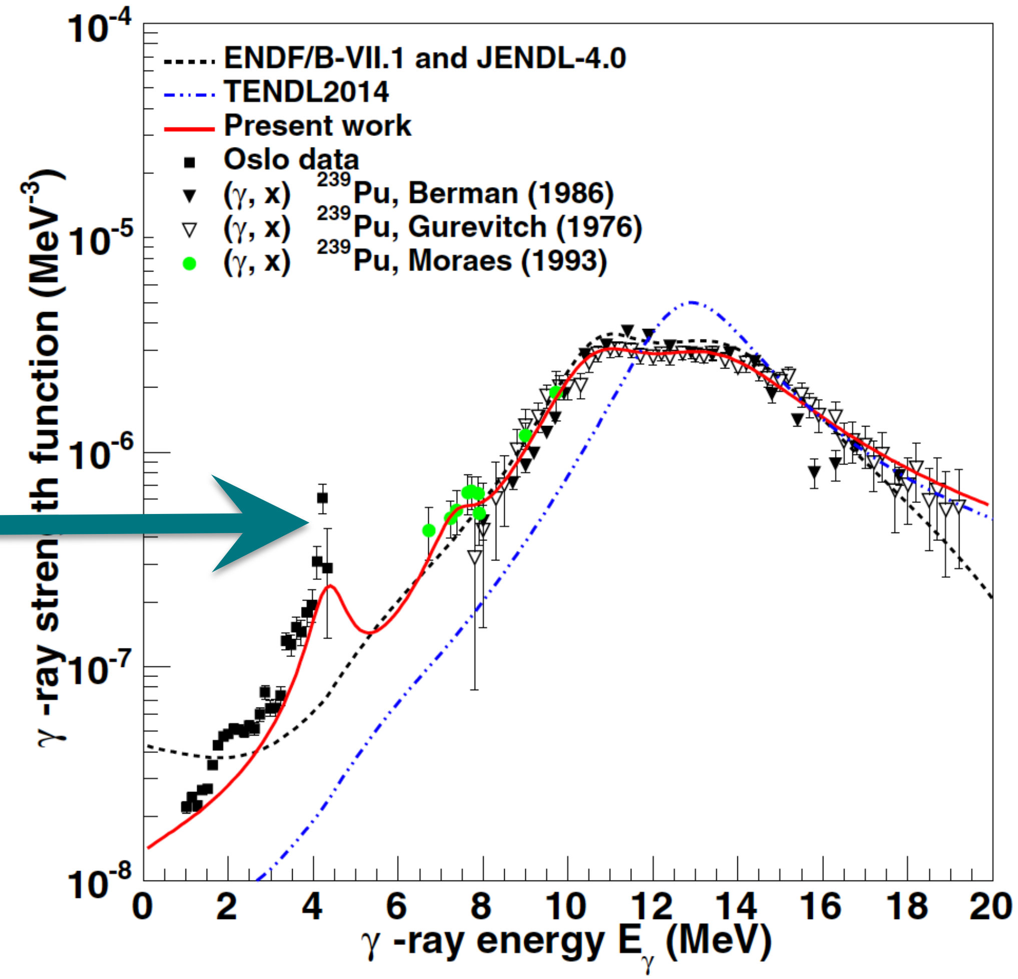


We can ignore this, but we do so at our peril

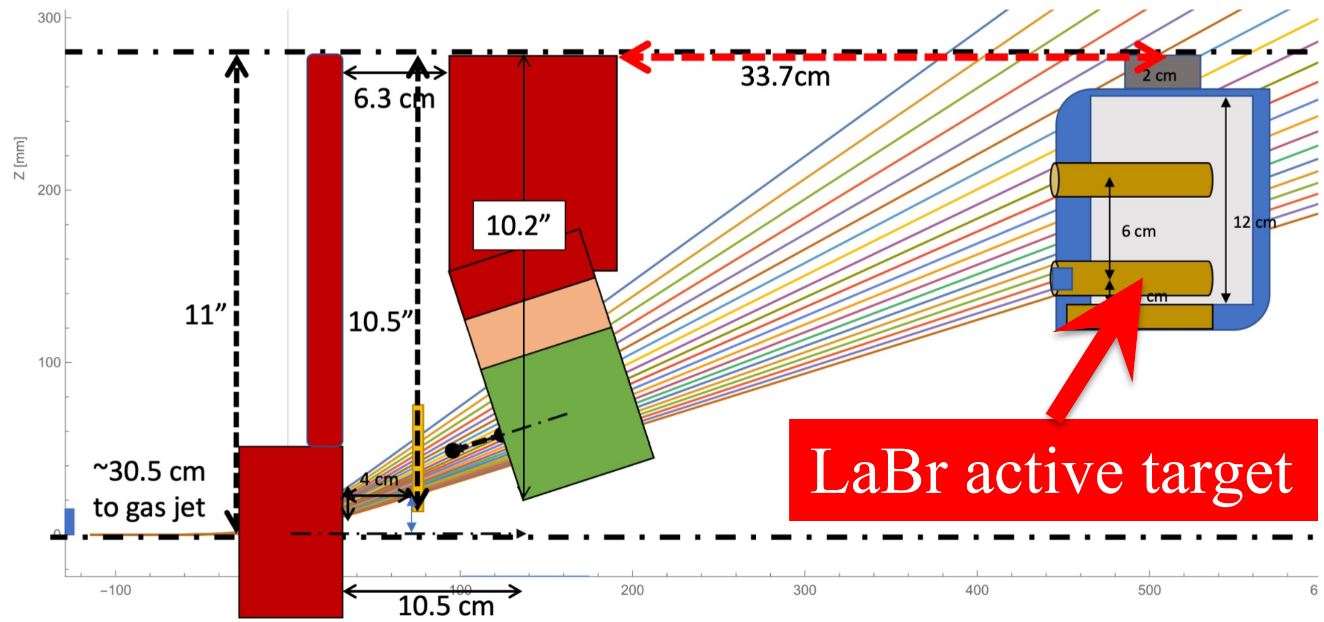
Examples of recent $F(E_\gamma)$ data in Actinide nuclei



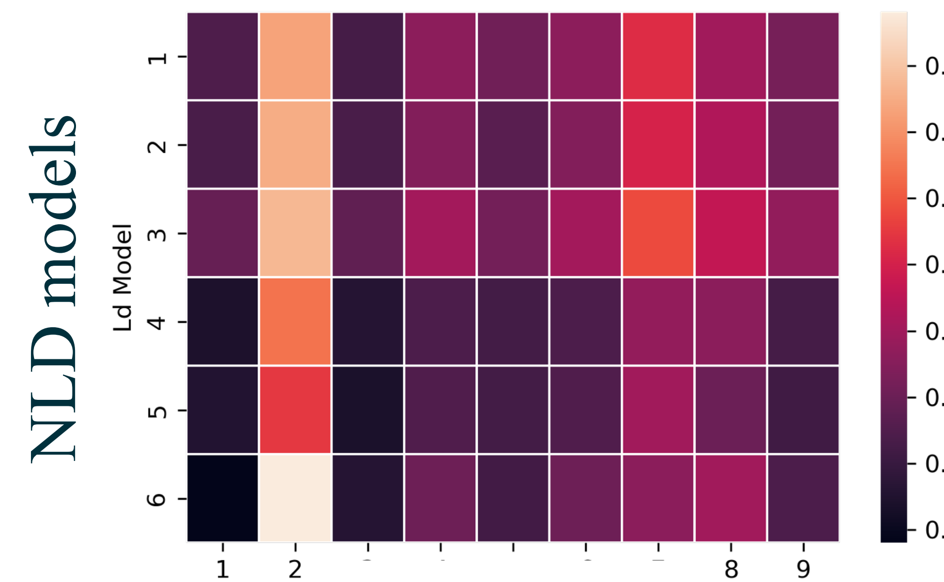
A great deal of data is showing that there's significant strength at low E_γ

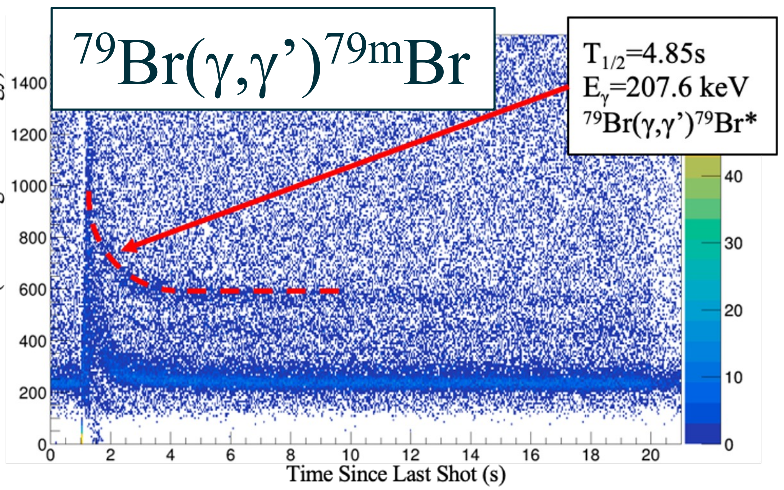


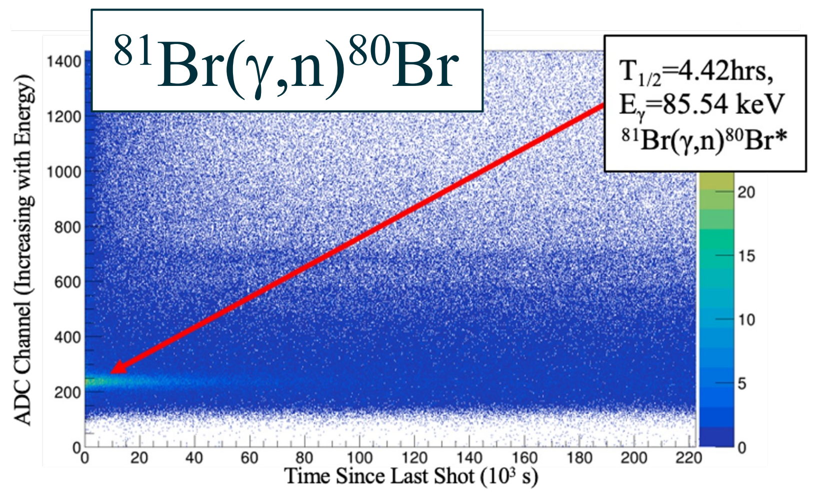
Photoexcitation of Br using the BELLA short-pulse laser facility (supported by Google)



^{80}Br/ ^{79m}Br ratio

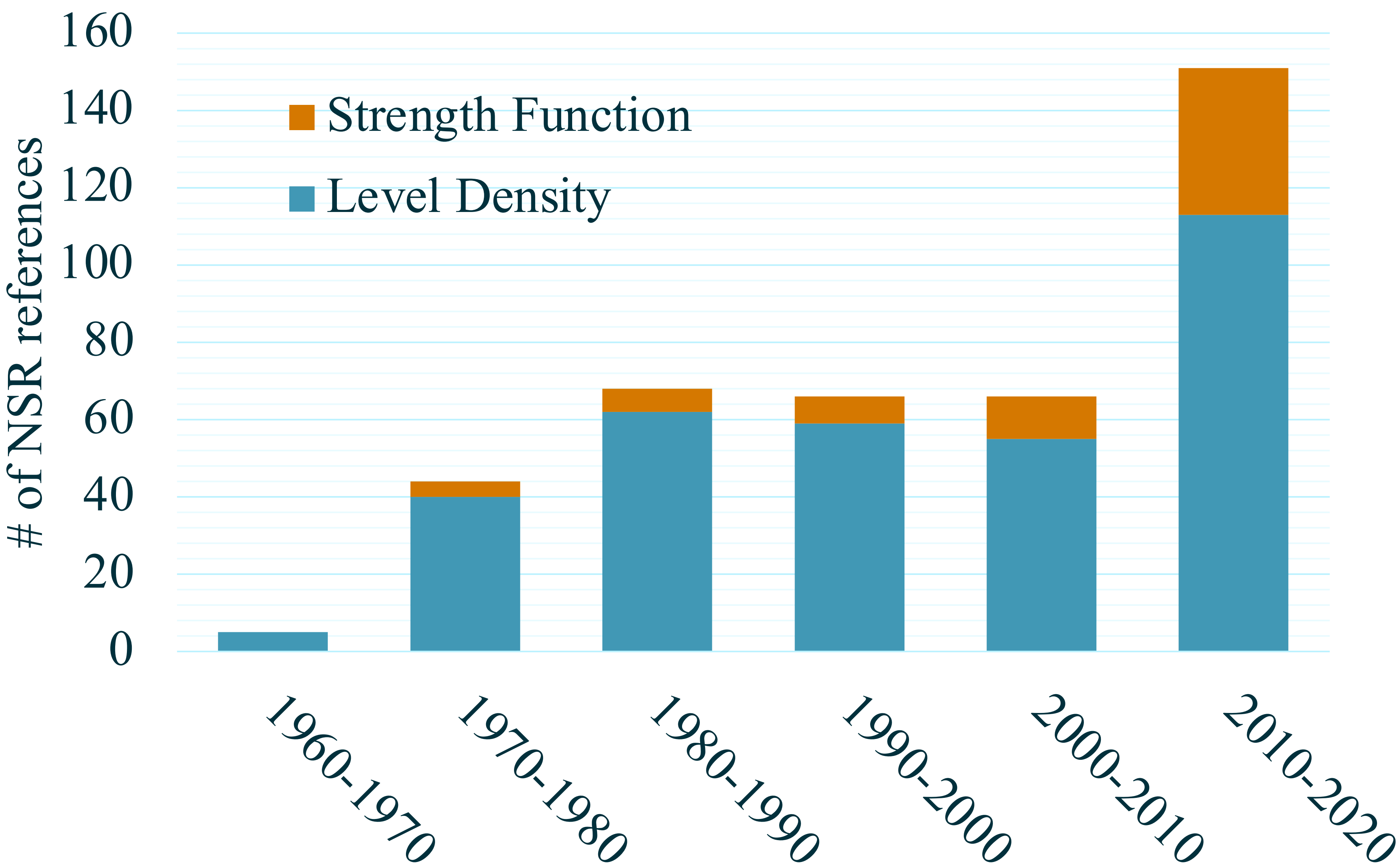






Irradiation Cases	Population Ratios (#/Shot)
Brem. Photons 79/80	0.023±0.0024
Electrons 79/80	0.033±0.0015
Brem. 79/Electrons 79	0.503±0.0515
Brem. 80/Electrons 80	0.719±0.0326

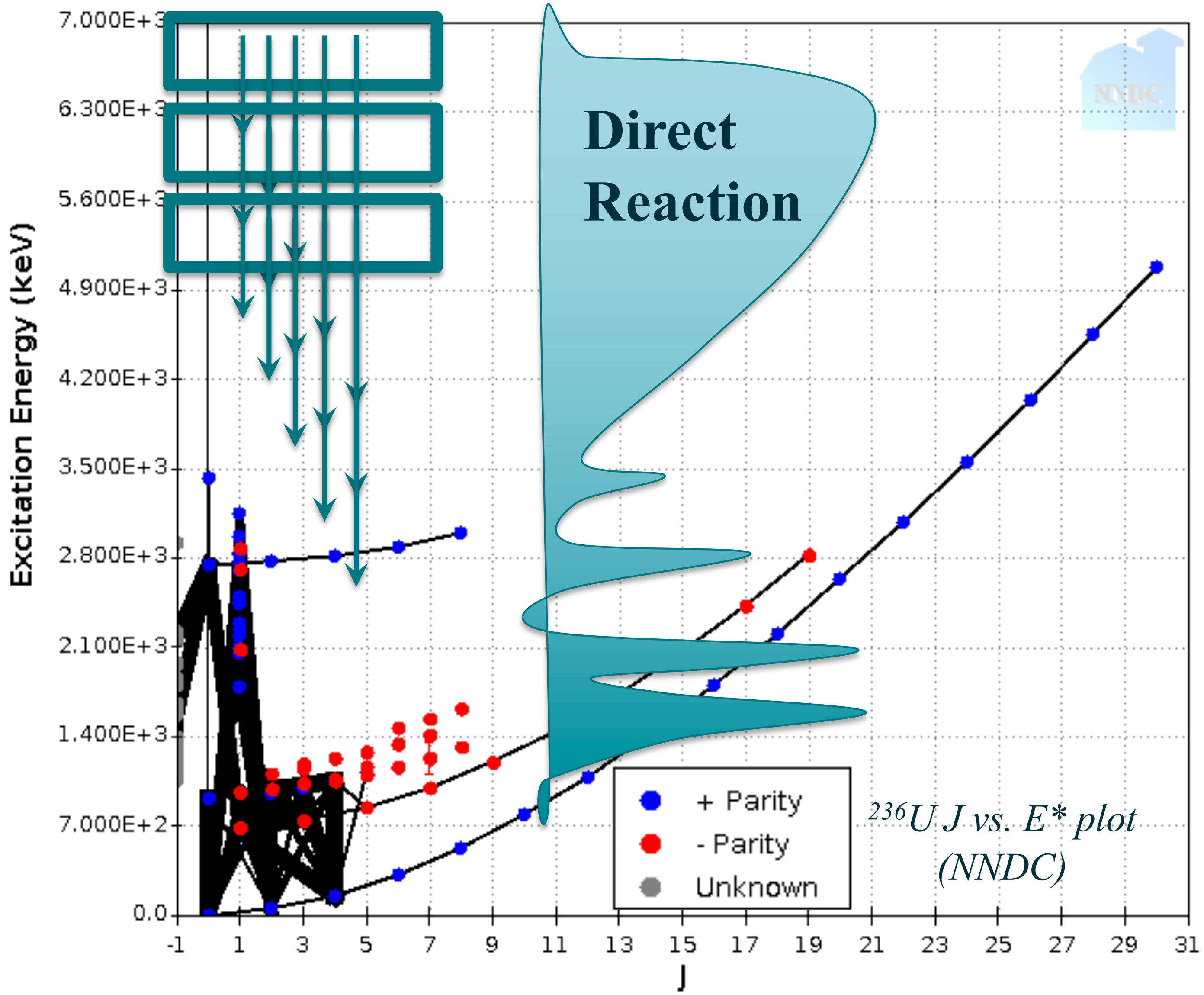
The publication rate of QC Data is on the rise



- This probably a radical underestimation the actual number of articles since QC properties are often not indexed properly in NSR!

Side note: We need Natural Language Processing to compile all of the available data!

There are a wealth of source of experimental data on QC properties



^{236}U J vs. E plot (NNDC)*

1. Energy-Indexing approaches:
   - Direct Reaction + γ-ray coincidence: Uses outgoing particle energy to iteratively obtain a Level Density and Photon strength from a "1st Generation γ-ray spectrum" ($\Gamma_i(E_\gamma)$) for an E slice i :

$$\Gamma_i(E_\gamma) = F(E_\gamma)\rho(E_x - E_\gamma)$$

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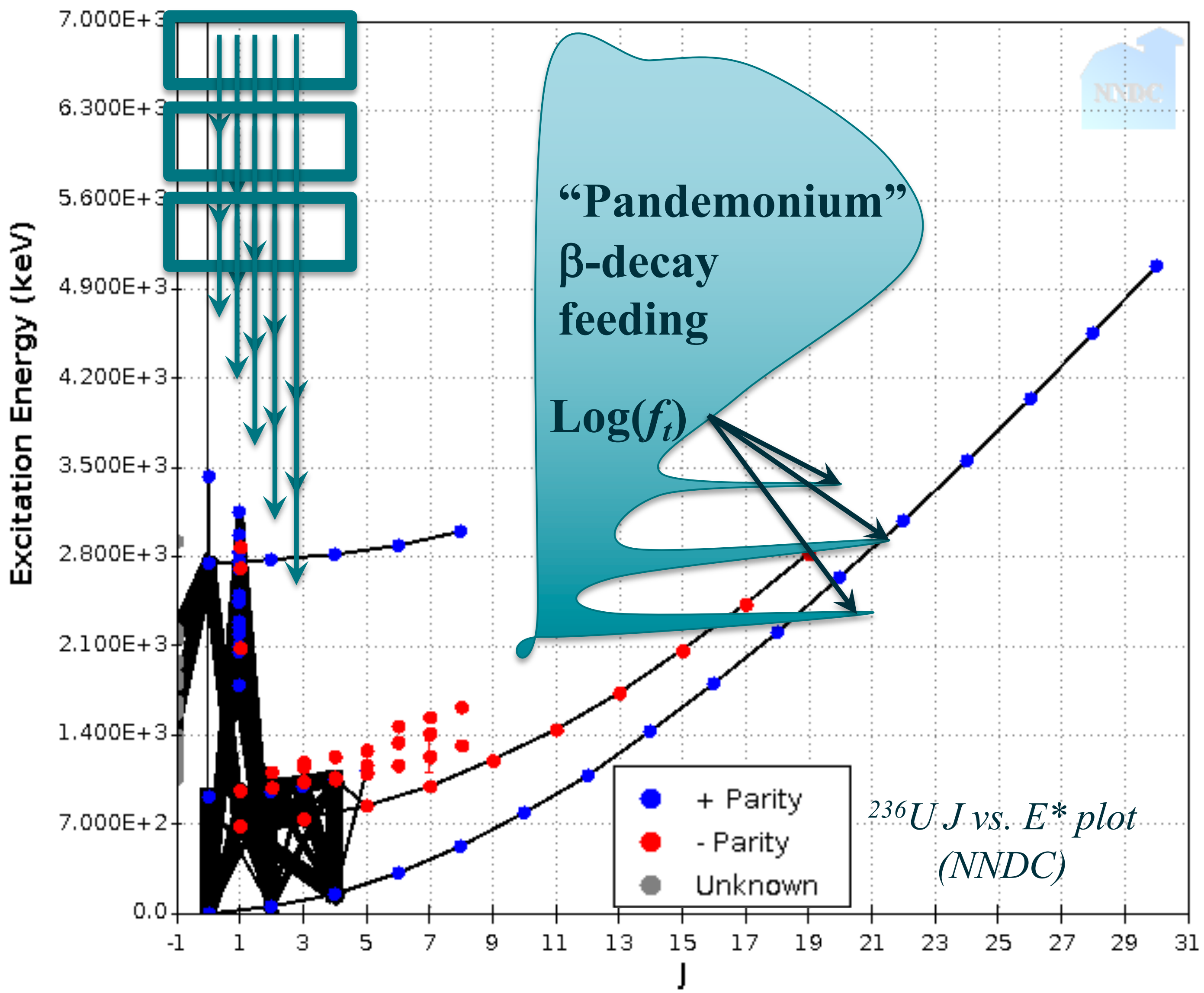

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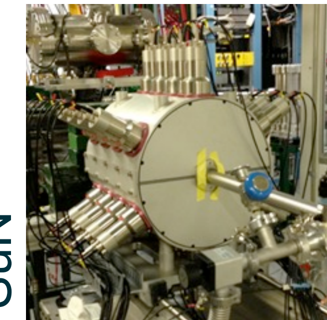
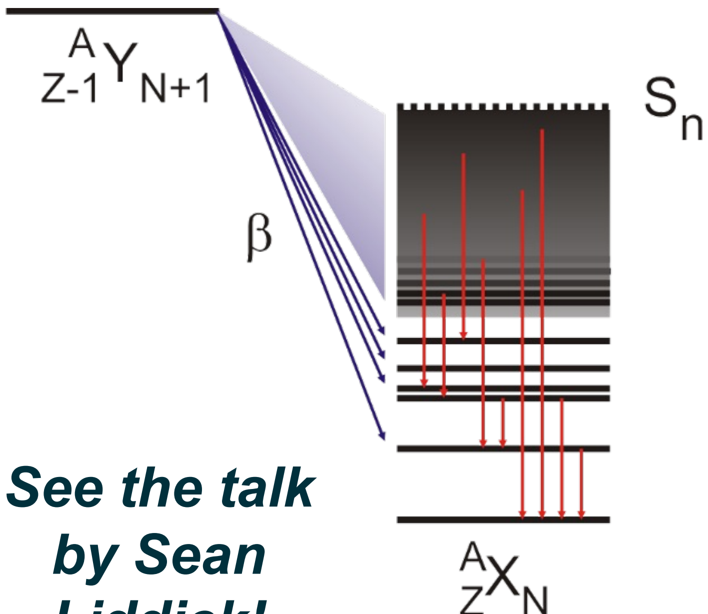
   - High Q-value β-decay using a segmented Total Absorption Spectrometer (TAS). Already used with CARIBU. FRIB will provide data on nuclei far from stability.

Using beta decay and total absorption spectroscopy to infer critical nuclear data *(Thanks to S. Liddick & A. Spyrou!)*

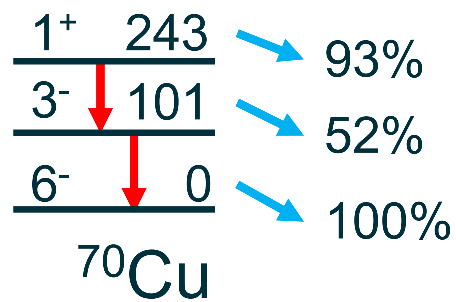
- Measure beta decay of nucleus using TAS.
- Extract critical QC structure, astrophysics, and stockpile stewardship
  - I_β
  - avg. e^-/γ energy
  - n/γ competition
  - nuclear level density, γ-ray strength,
  - Tests $F(E_\gamma)$ independence of J^π *(Brink-Axel Hypothesis)*
  - neutron capture cross section

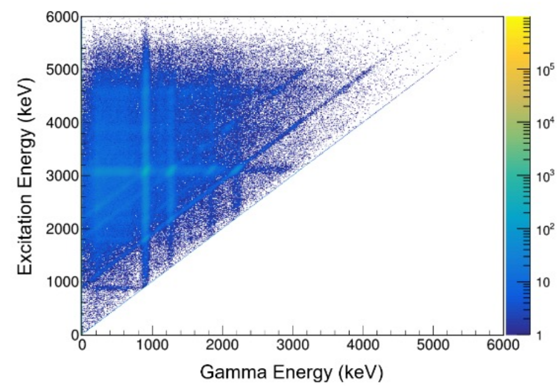
SuN

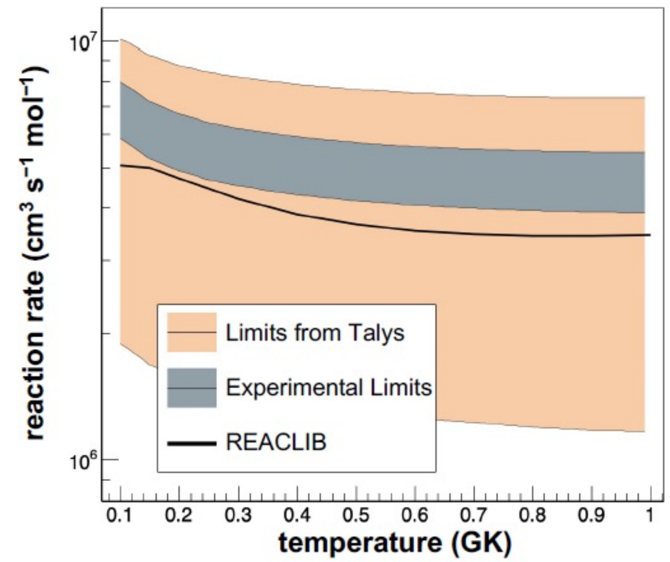




See the talk by Sean Liddick!



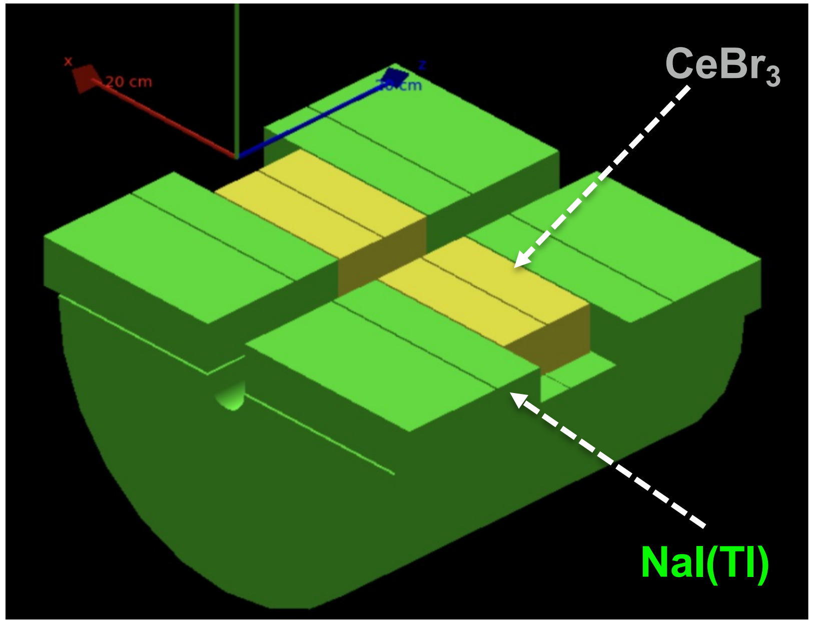




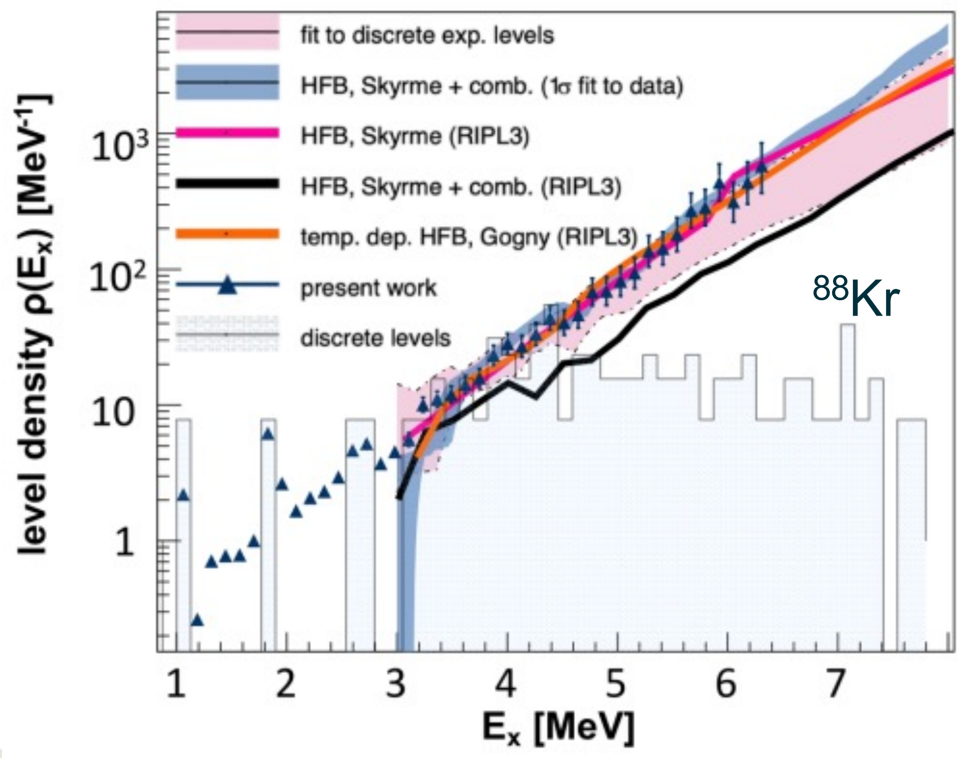
^{139}Ba$(n,\gamma)^{140}$Ba submitted

A.C.Larsen, A.Spyrou, S.N.Liddick, M.Guttormsen, Prog.Part.Nucl.Phys. 107, 69 (2019)
S.N.Liddick, A. Spyrou et. al., PRL, 116, 242502 (2016)
A. Spyrou, S.N.Liddick et al., PRL 117, 142701 (2016)
A.C.Larsen etl al., PRC 97, 054329 (2018)

Continual improvement in hardware and software technique to advance the state-of-the-art *(Thanks to S. Liddick & A. Spyrou!)*



- SuN++ currently under development (new 12 NaI and 8 $CeBr_3$).
- Smaller segments help to identify the direction of the electron and reduce electron background
- Better energy resolution with $CeBr_3$ segments to identify low-lying discrete levels

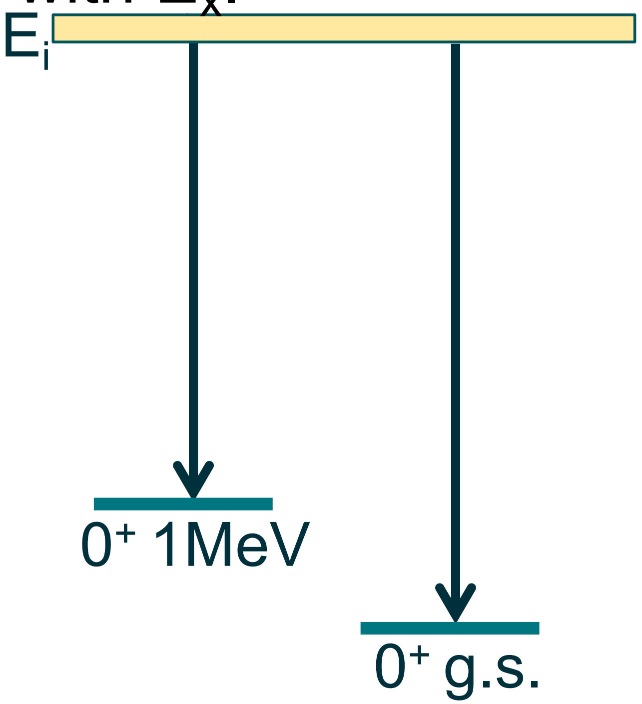


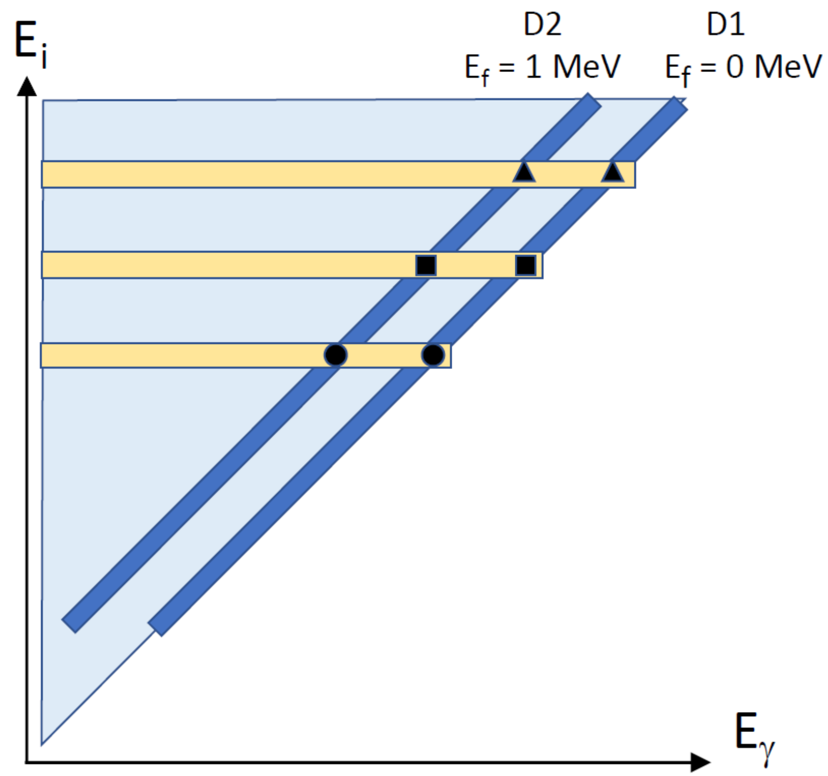
- Application of shape method with β–Oslo.
- Provides a model independent nuclear level density for populated states in nuclei far from stability.
- Constrained NLD leads to a reduction in predicted neutron capture cross section uncertainty of an order of magnitude

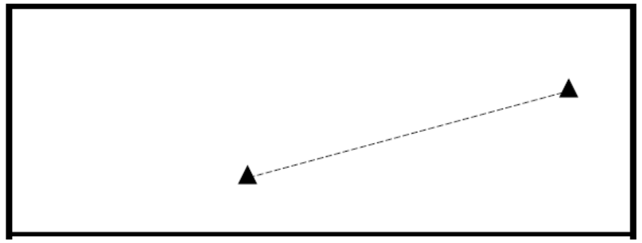
D.Mucher et al., PRC 107, L011602 (2023)

Combining the Shape and β-Oslo Methods at FRIB offers a chance to address improve reaction rate calculations for unstable nuclei

Primaries from intercepts of diagonals with E_x.







Pair of data points internally normalized and proportional to PSF.

Thanks to Mathis Wiedeking iThemba Labs!

Independent normalization for γ-ray strength functions: The shape method, M. Wiedeking, M. Guttormsen, A. C. Larsen, F. Zeiser, A. Görgen, S. N. Liddick, D. Mücher, S. Siem, and A. Spyrou Phys. Rev. C **104**, 014311 – Published 12 July 2021

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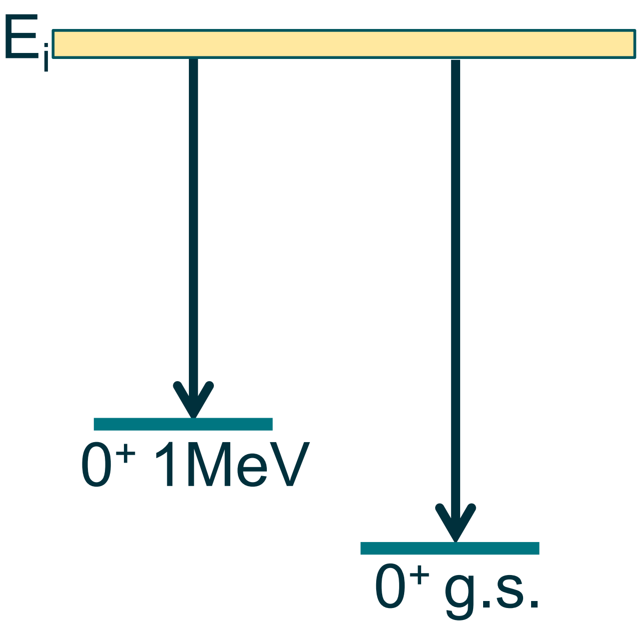

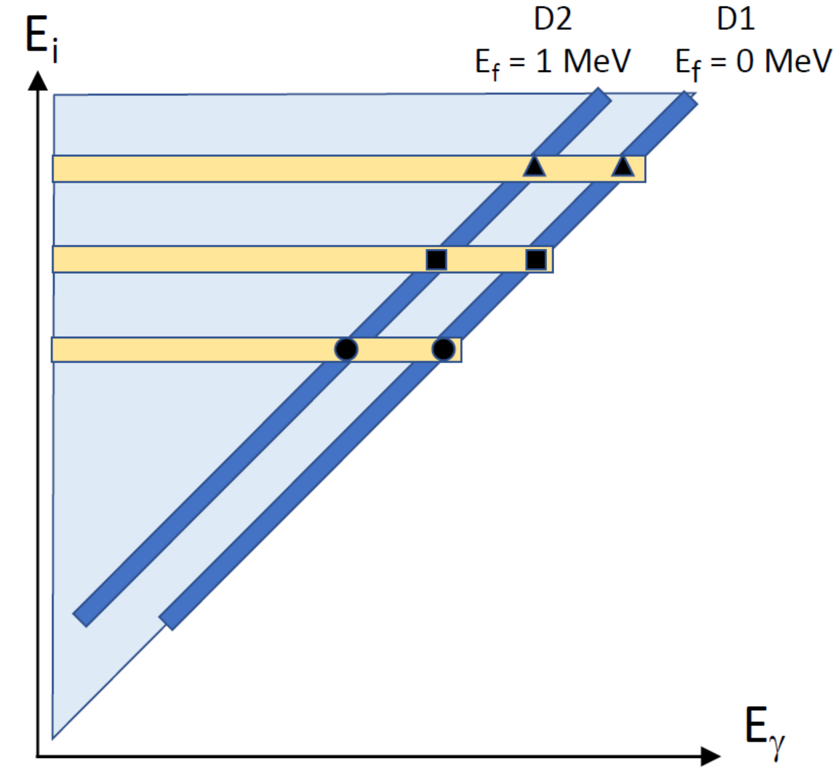

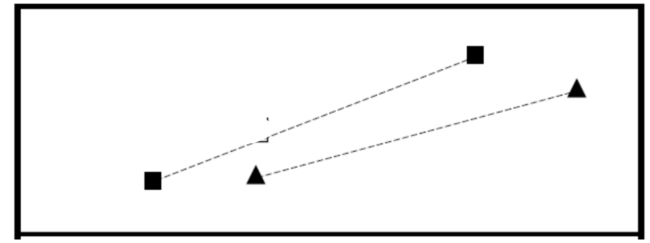

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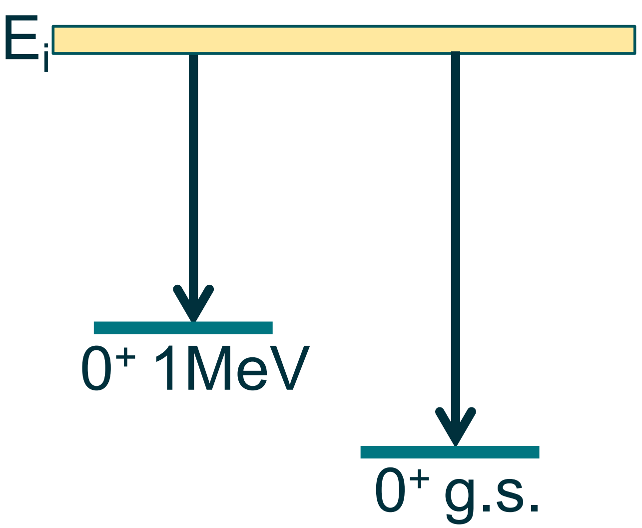

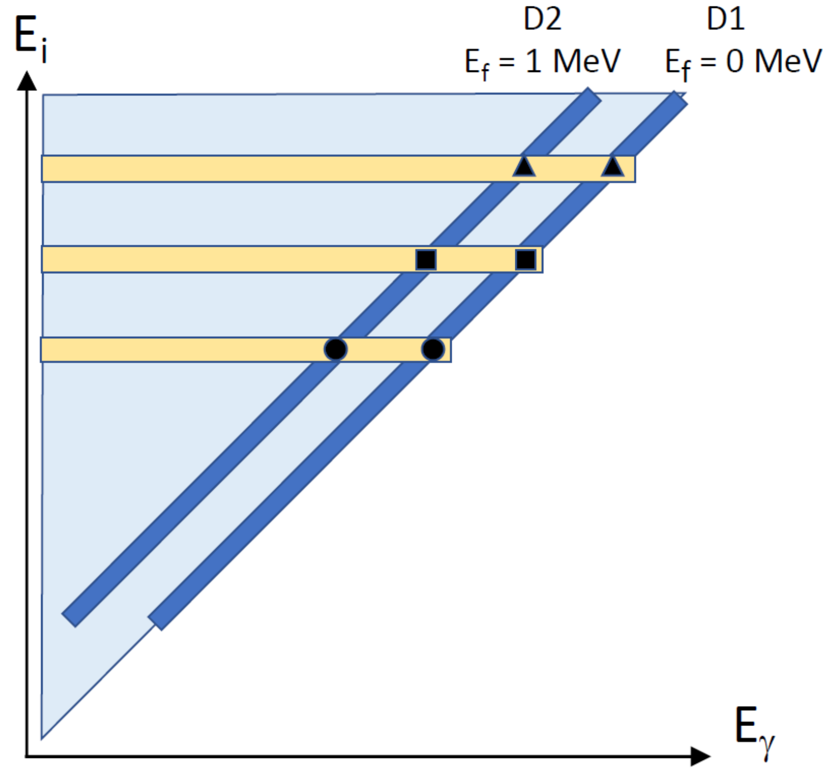

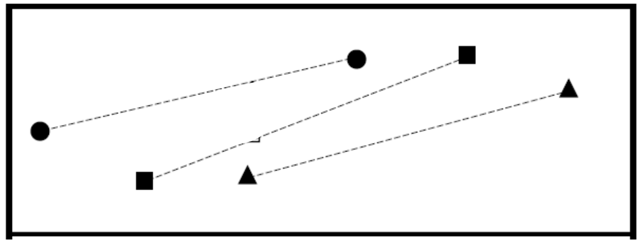

Pair of data points internally normalized and proportional to PSF.

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Independent normalization for γ-ray strength functions: The shape method, M. Wiedeking, M. Guttormsen, A. C. Larsen, F. Zeiser, A. Görgen, S. N. Liddick, D. Mücher, S. Siem, and A. Spyrou Phys. Rev. C **104**, 014311 – Published 12 July 2021

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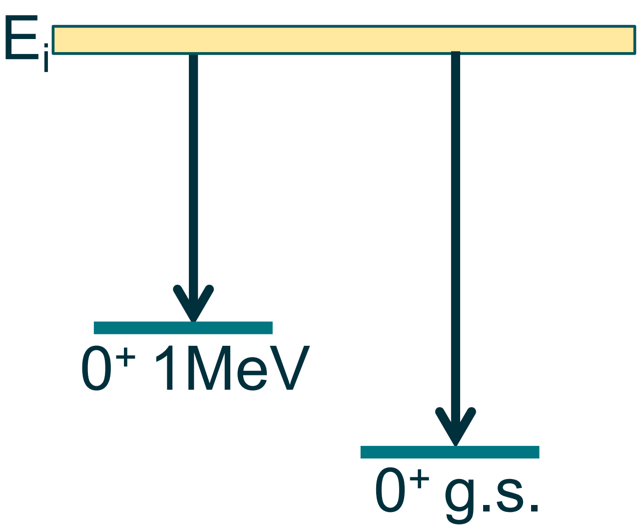
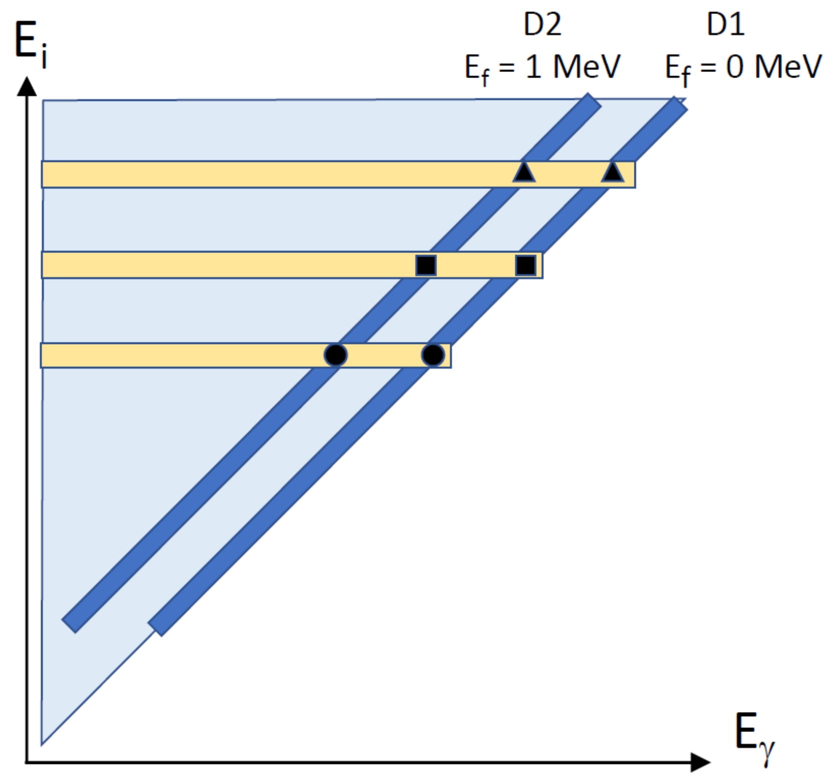
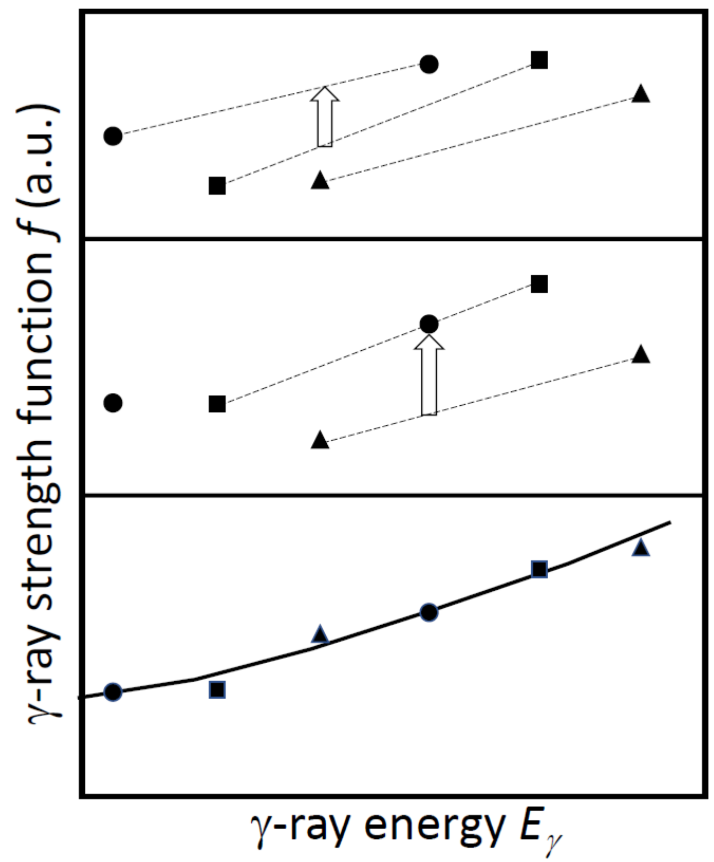
Combining the Shape and β-Oslo Methods at FRIB offers a chance to address improve reaction rate calculations for unstable nuclei

Primaries from intercepts of diagonals with E_x.







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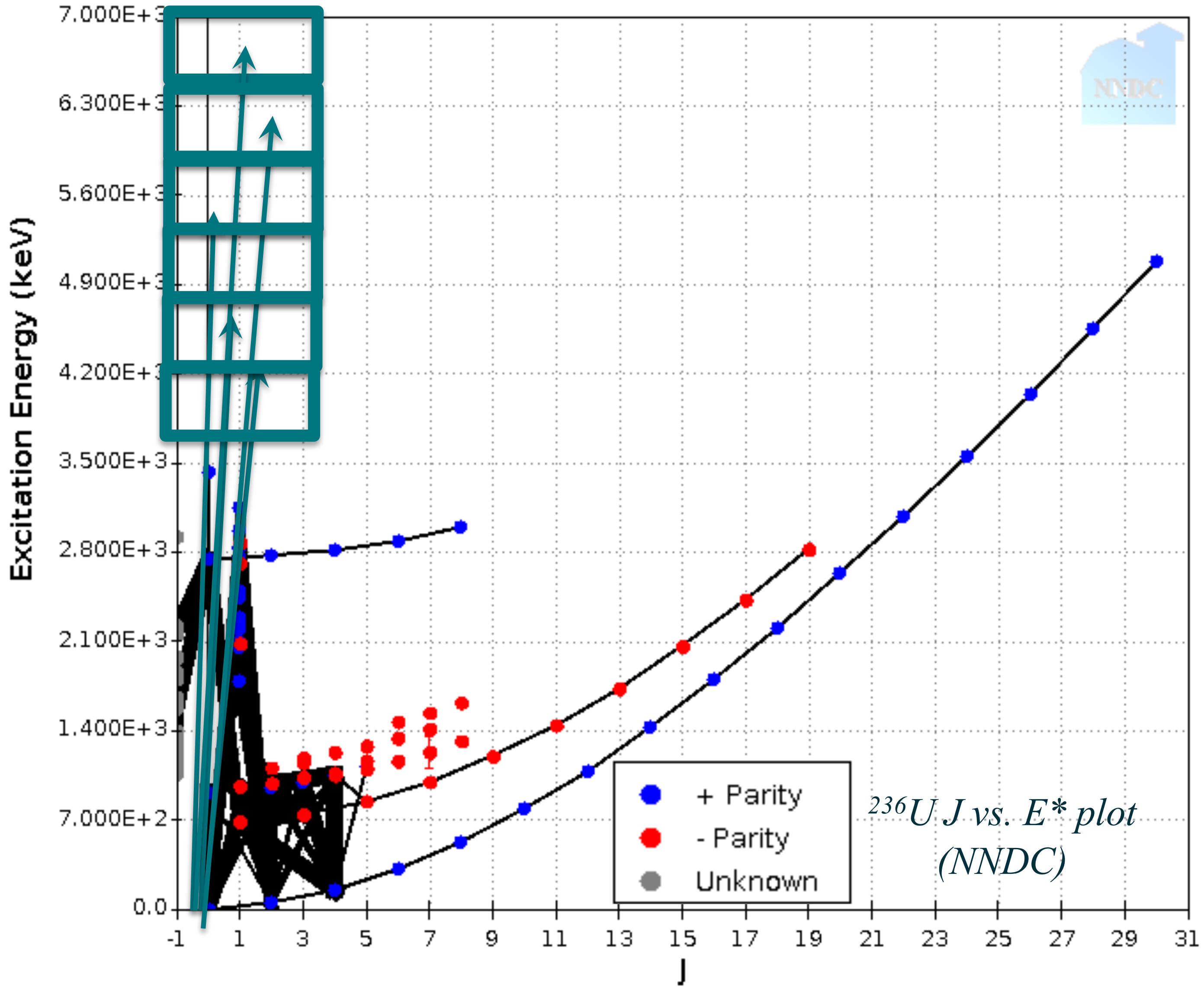
There are also a wealth of source of experimental data on QC properties



^{236}U J vs. E plot (NNDC)*

1. Energy-Indexing approaches (Oslo, β-Oslo):
   - Direct Reaction + γ-ray coincidence: Uses outgoing particle energy to iteratively obtain a Level Density and Photon strength from a "1st Generation γ-ray spectrum" ($\Gamma_i(E_\gamma)$) for an E slice i :
     $$\Gamma_i(E_\gamma) = F(E_\gamma)\rho(E_x - E_\gamma)$$
   - High Q-value β-decay using a segmented Total Absorption Spectrometer (TAS). Already used with CARIBU. FRIB will provide data on nuclei far from stability.
2. Photo-absorption (HIγS, Brehmsstrahlung)
   - Measures $F(E_\gamma)$ from ground to 1$^-$ states.

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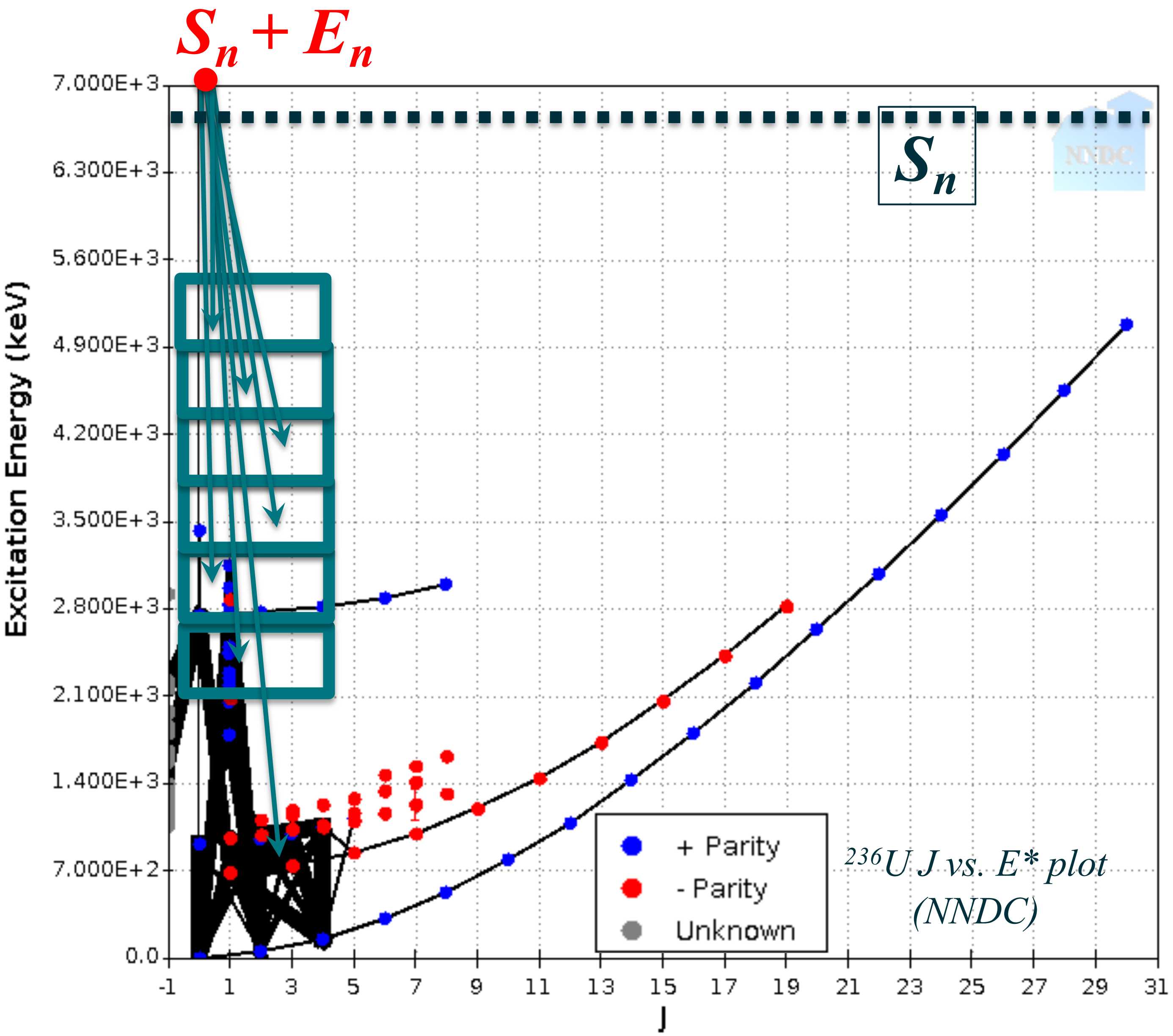

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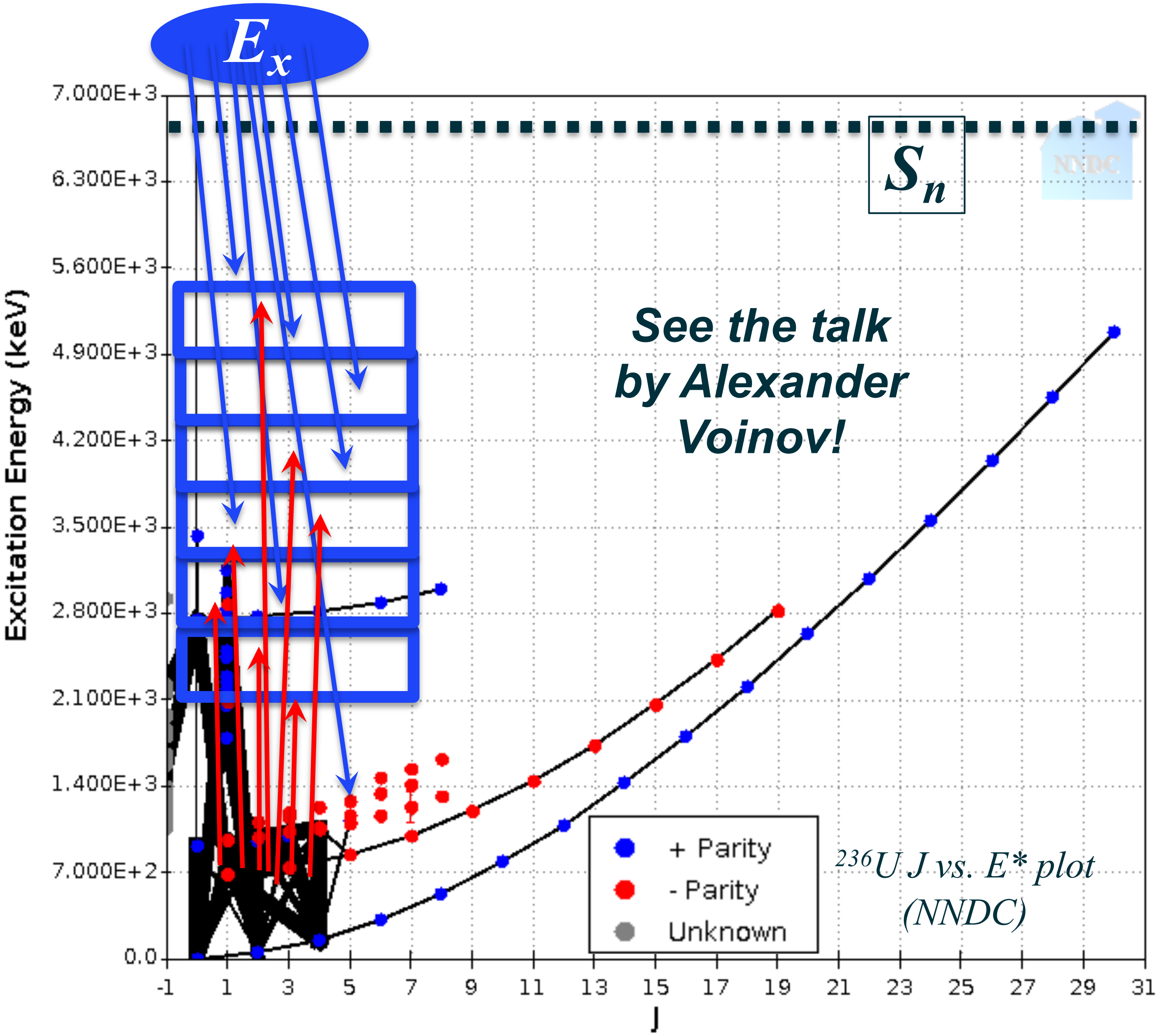

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4. (n,n'γ) & Neutron evaporation spectra
   - Measures $\rho(E_x)$ by determining $kT_{nuclear}$

Summary

1. Nuclear Level Densities and Gamma Strength functions are key inputs for reaction modeling needed for applied and basic nuclear science.
2. There is a wealth of new data being generated using both stable and radioactive ion beam facilities
3. A new evaluation effort is needed the couples structure and reaction data to provide nominal values and uncertainties for NLD and RSF.

Thanks for your attention!