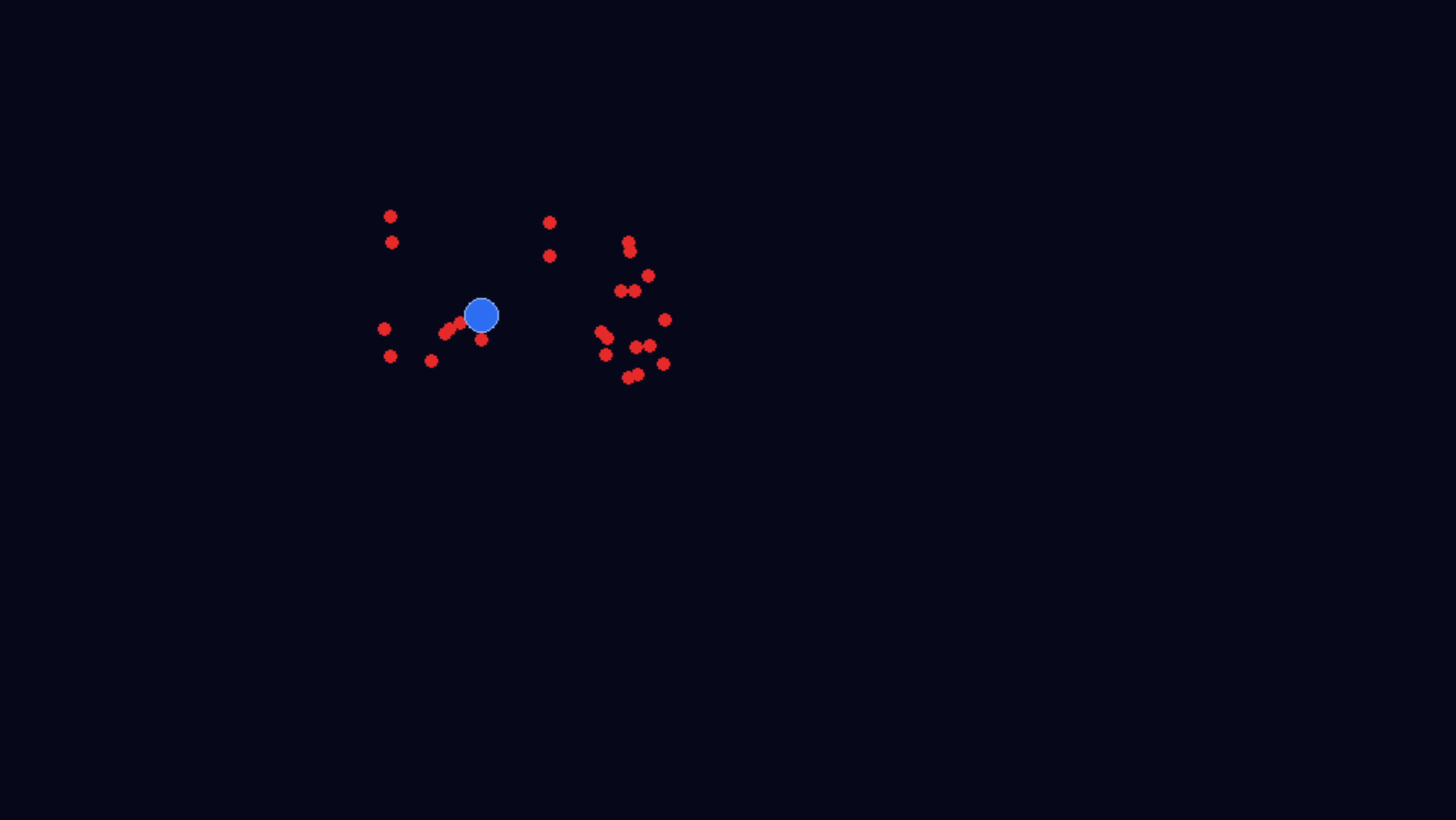
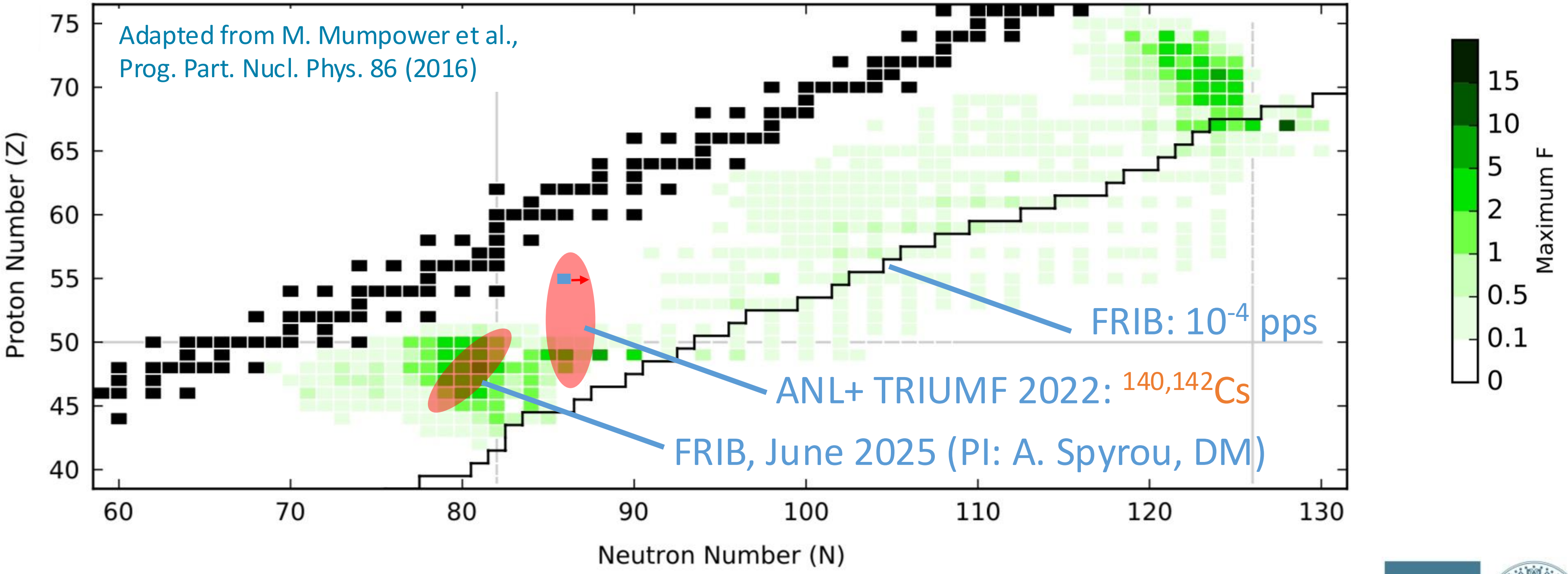
Dennis Mücher (IKP Cologne)

Erich Türk playing
Toccata & Fugue
d-minor, J. S. Bach

Experimental Neutron Capture Rates for the r Process

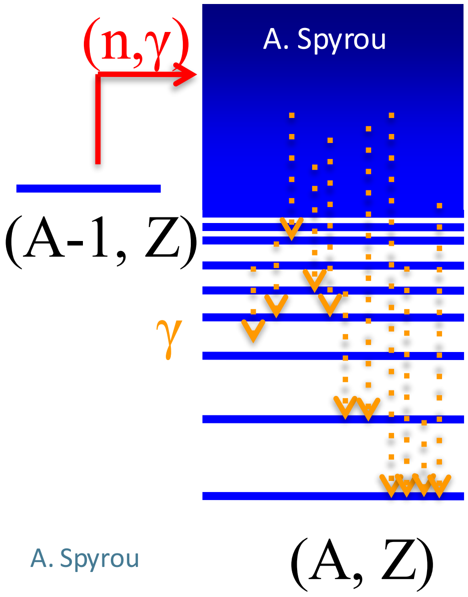


Which Neutron Captures do we want for the r process?



Universität zu Köln

Hauser-Feshbach: Statistical Approach to Neutron Captures



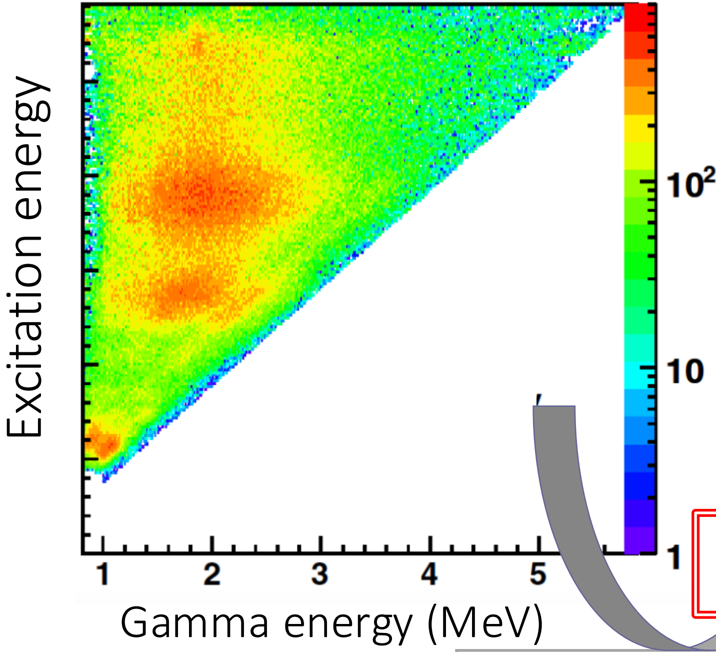
A. Spyrou

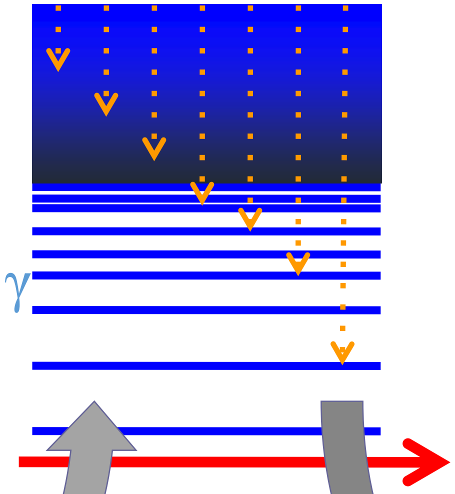
Required input:
- Nuclear Level Density (NLD)
- γ-ray strength function (γSF)
- Optical model potential

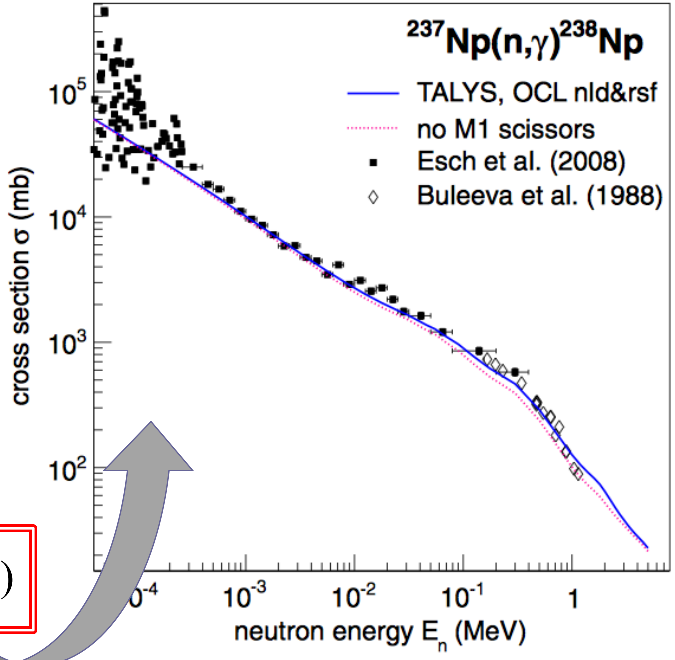
\+ Direct capture contributions can play a role

- In unstable nuclei the γSF and optical model parameters can in principle be measured or well constrained via inverse kinematics experiment
- First method to directly measure the absolute NLD in short-lived nuclei: "Shape method"

Oslo Method: Constraining neutron capture rates







$$\boxed{P(E_\gamma, E_x) \sim \rho(E_x - E_\gamma)\mathcal{T}(E_\gamma)}$$

Unfolding
Iterative subtraction

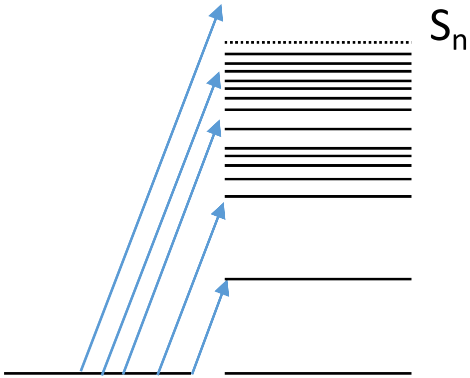
Normalization

T.G. Tornyi, M. Guttormsen,et al., PRC2014

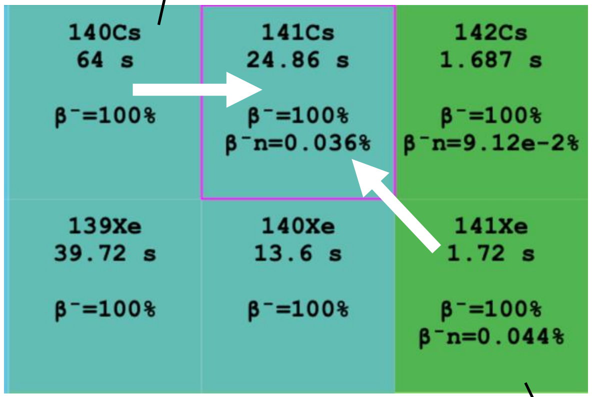
Oslo vs Beta-Oslo

A. Spyrou et. al, Phys. Rev. Lett. **113**, 232502

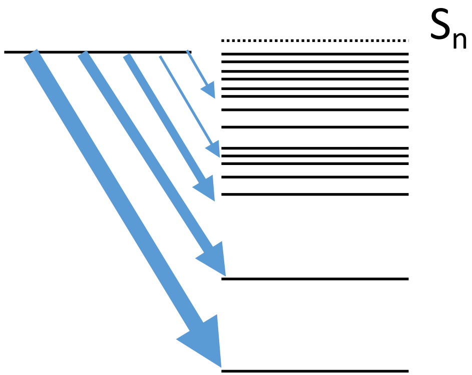
1.2· 10^4 pps (reaccelerated)



One-neutron transfer (or similar)



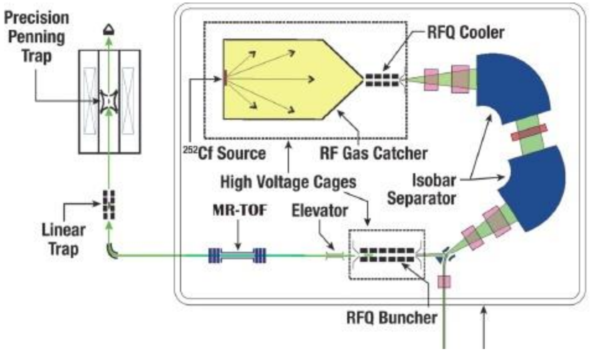
2.7· 10^4 pps
(low energy)



β-decay

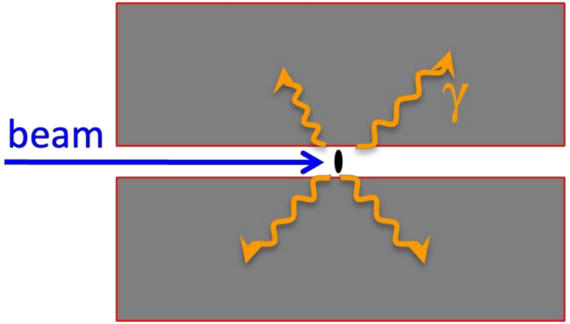
- In general, β-Oslo is the (far) more sensitive method in terms of how exotic we can go
- In certain cases, β-Oslo cannot be applied because of Q-value and/or spin restrictions

^{141}Cs using CARIBU & SuN @ Argonne Nat. Lab.

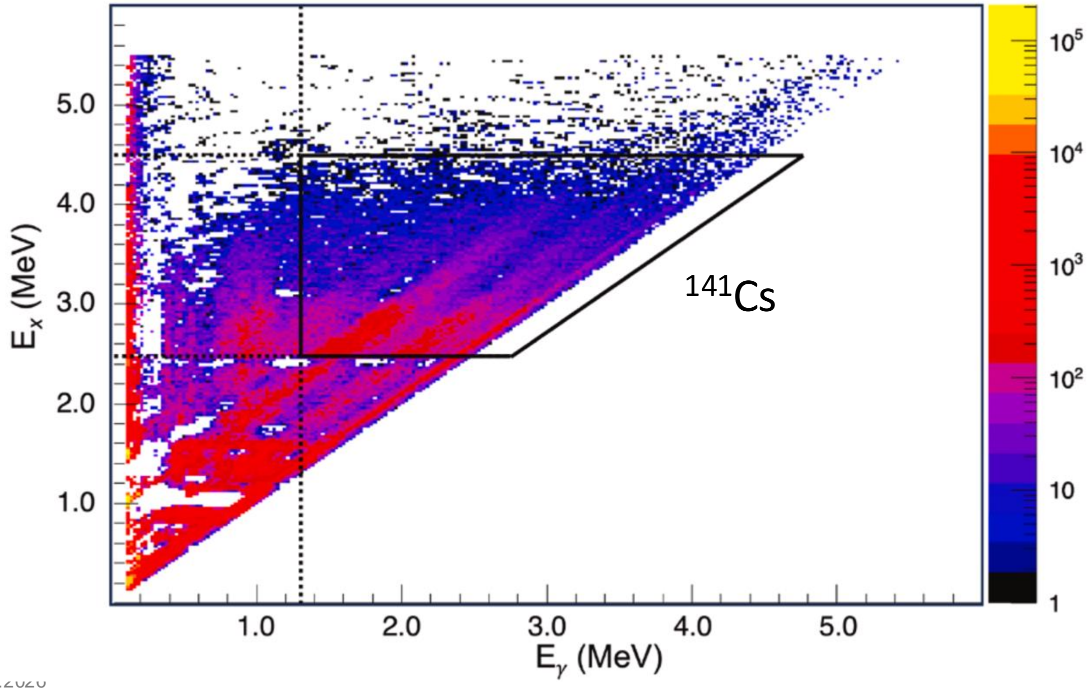


Beau Greaves, now postdoc at LNL INFN

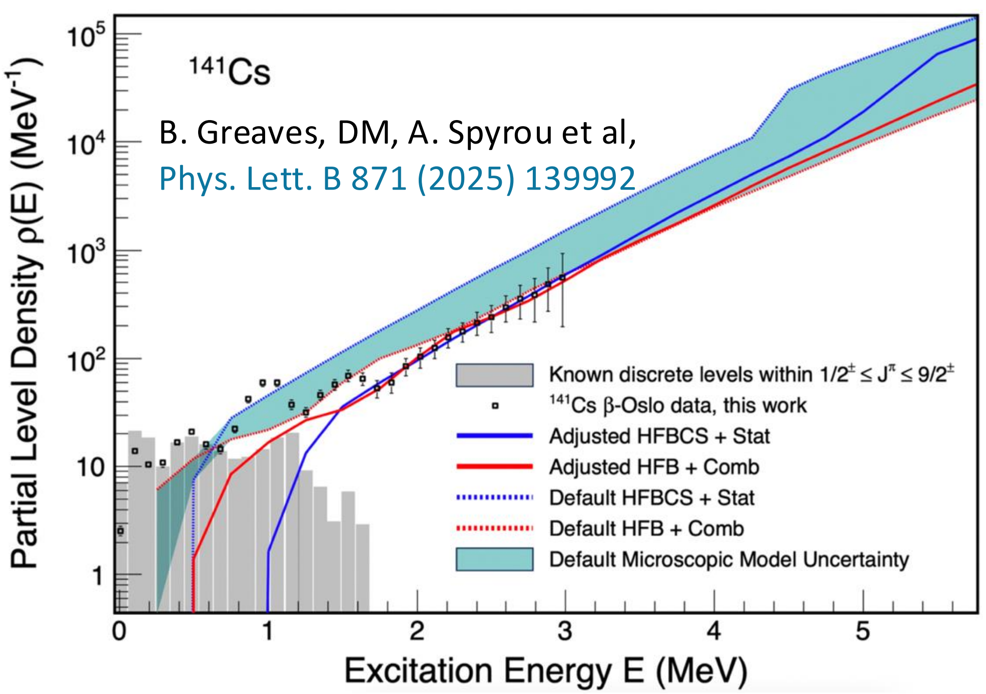
SuN- Total Absorption Spectrometer: A. Simon et al., NIM B 703 (2013) 16-21

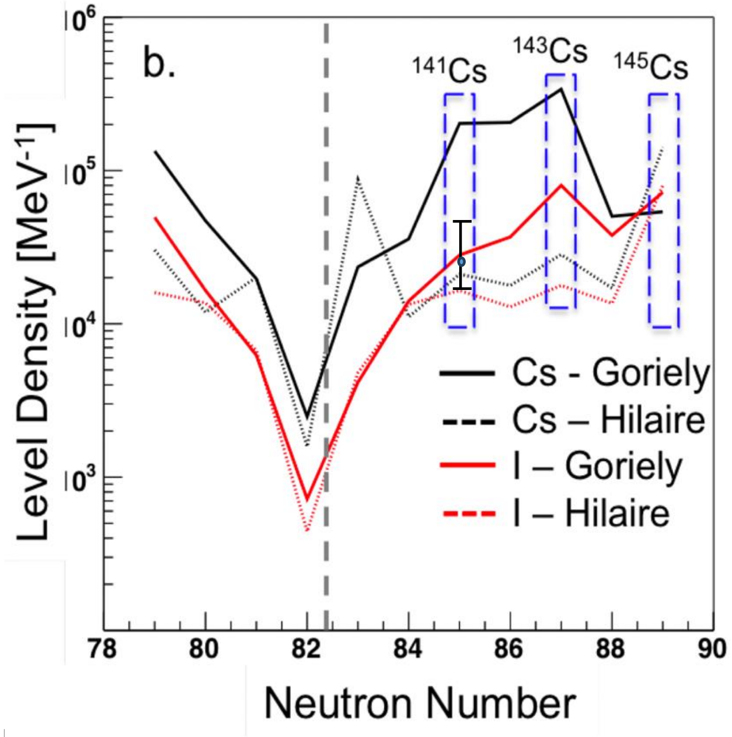


$$E_x = E_{\gamma 1} + E_{\gamma 2} + E_{\gamma 3} + E_{\gamma 4} + \ldots$$



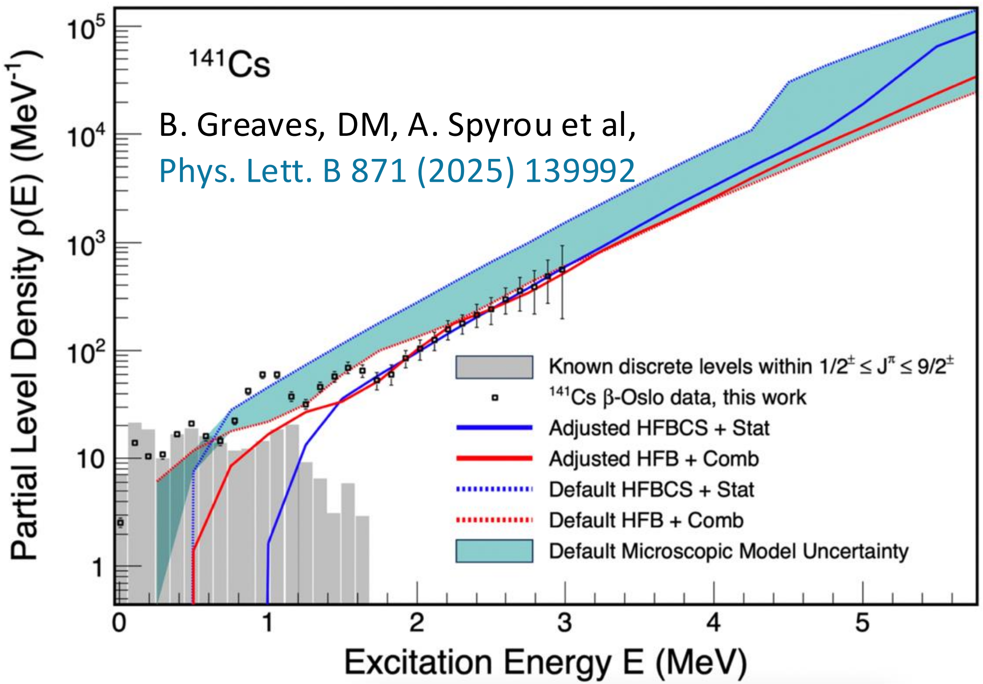
^{141}Cs: low level density at neutron separation energy





- Our data suggest that NLDs in the A=140 region tend to be smaller than expected by some models

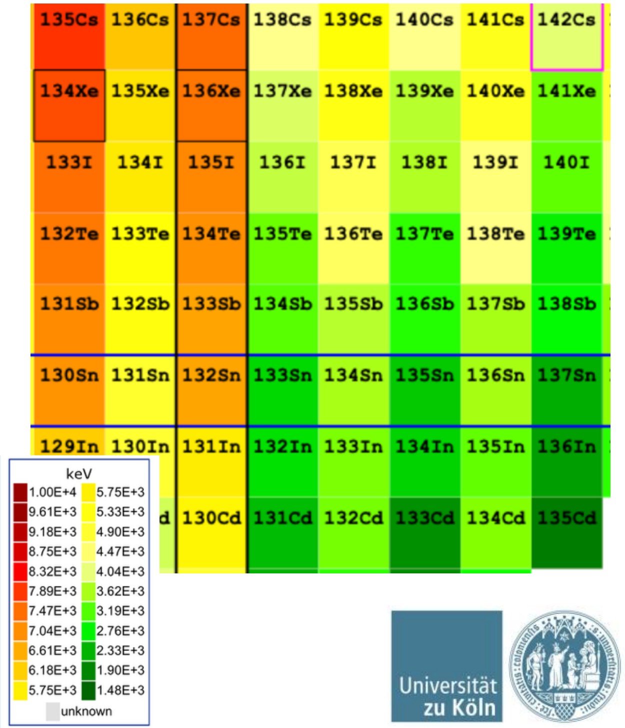
141Cs: low level density at neutron separation energy



B. Greaves, DM, A. Spyrou et al,
Phys. Lett. B 871 (2025) 139992

- Our data suggest that NLDs in the A=140 region tend to be smaller than expected by some models

Lower NLD has impact on validity of Hauser-Feshbach model



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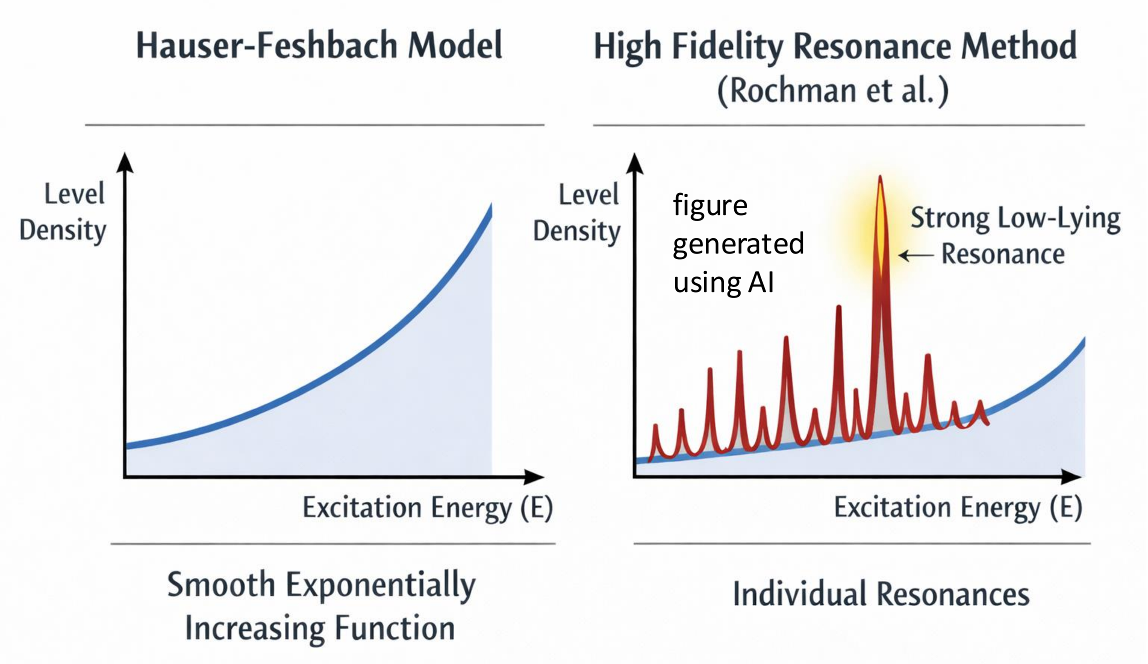
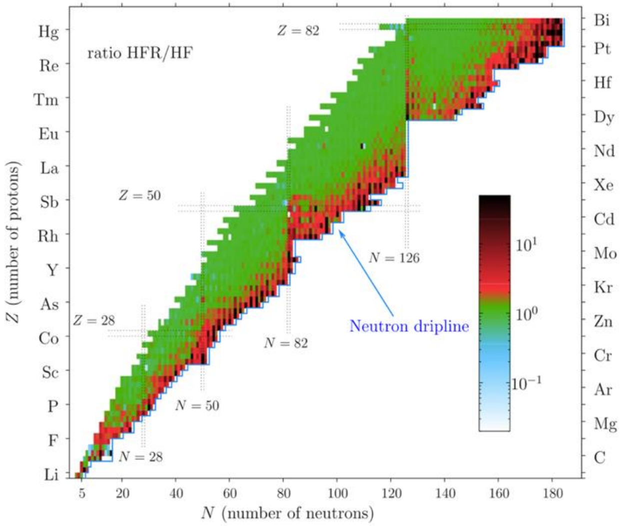
Probing the Limit of the Statistical Regime: The High-Fidelity Resonance Model



Lower NLD has impact on validity of Hauser-Feshbach model

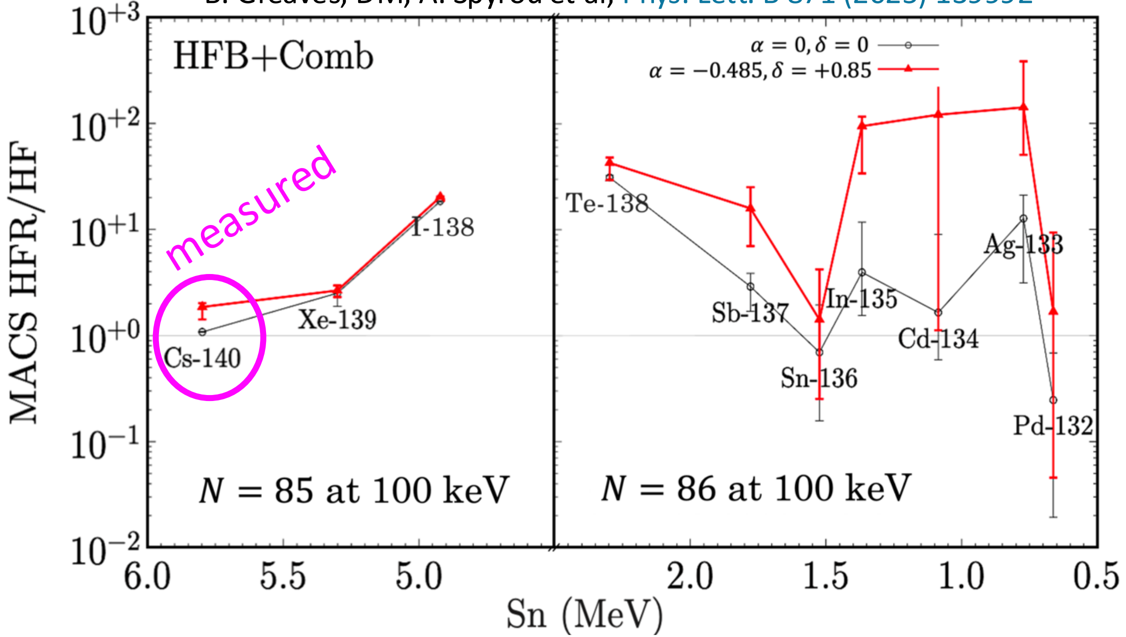


D. Rochman, S. Goriely et al, Physics Letters B 764 (2017)

Universität zu Köln

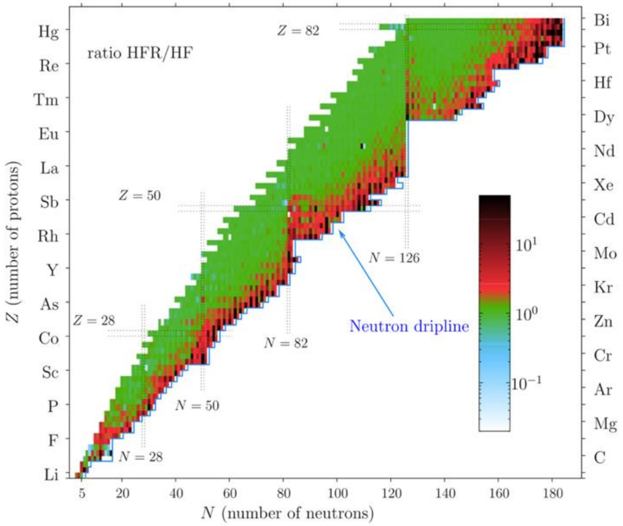
Hauser-Feshbach vs. Individual Resonances

B. Greaves, DM, A. Spyrou et al, Phys. Lett. B 871 (2025) 139992



- We have already experimentally reached the limit of the statistical regime
- General trend: Hauser-Feshbach underpredicts (n,γ) rates

Lower NLD has impact on validity of Hauser-Feshbach model



D. Rochman, S. Goriely et al, Physics Letters B 764 (2017)

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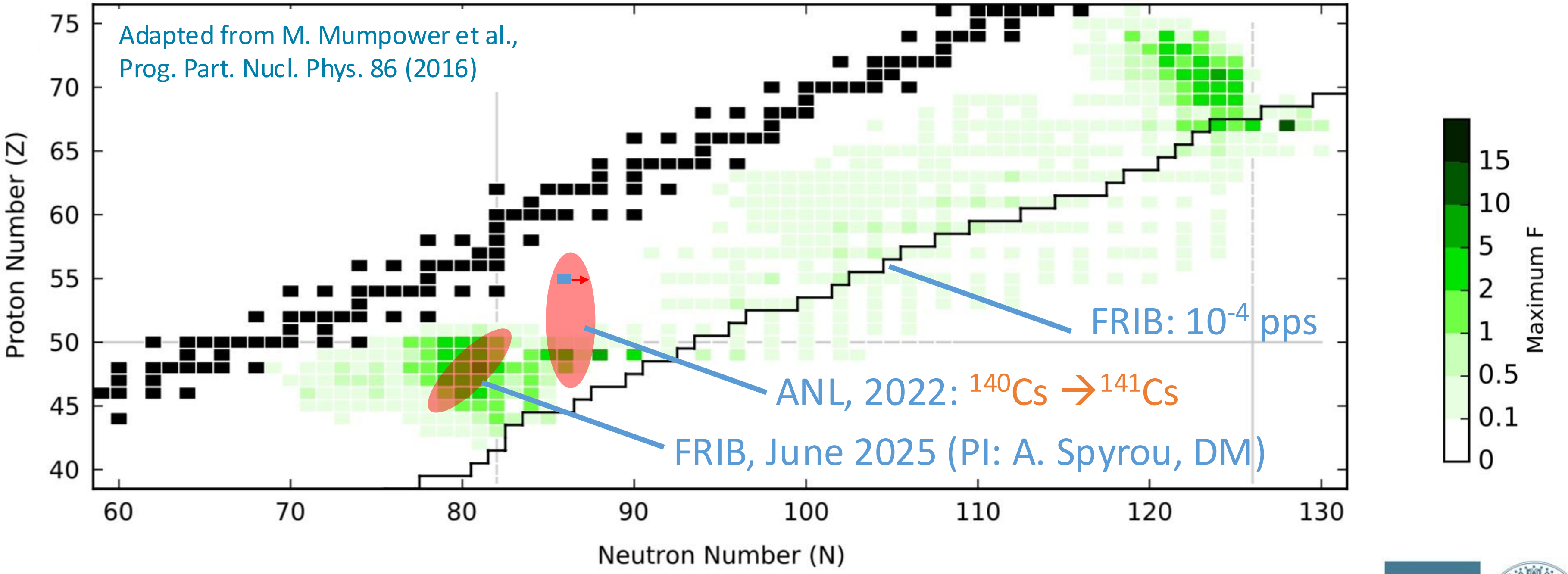
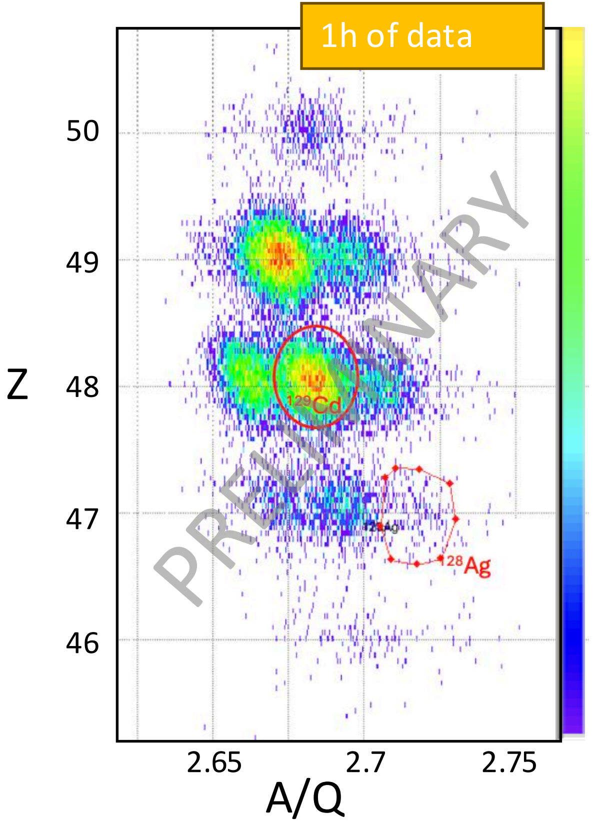
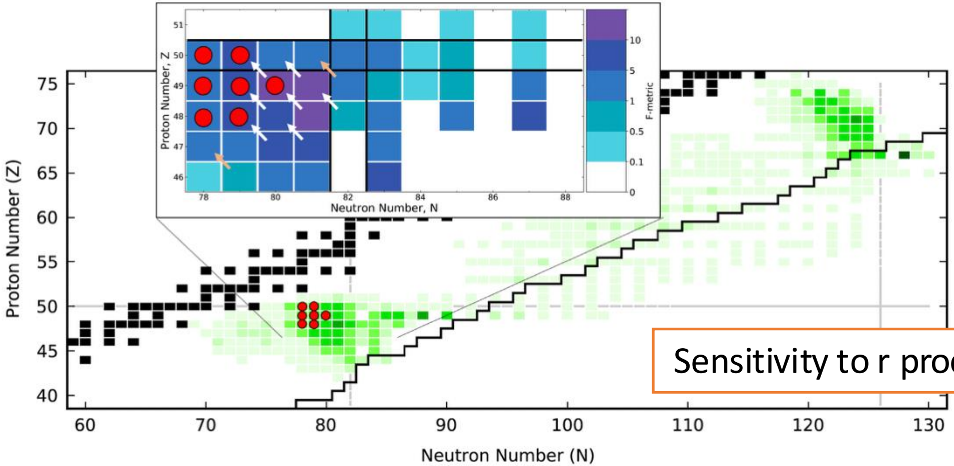
The rapid neutron capture process

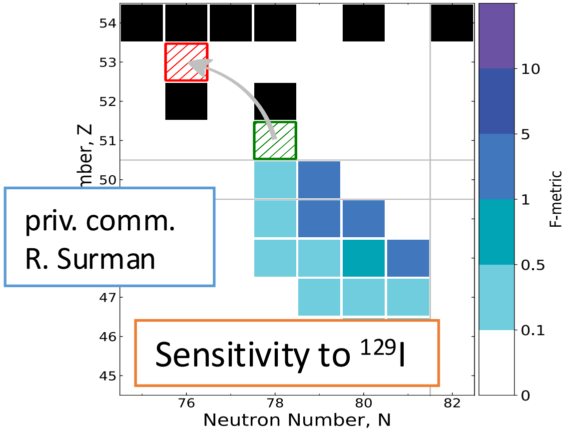


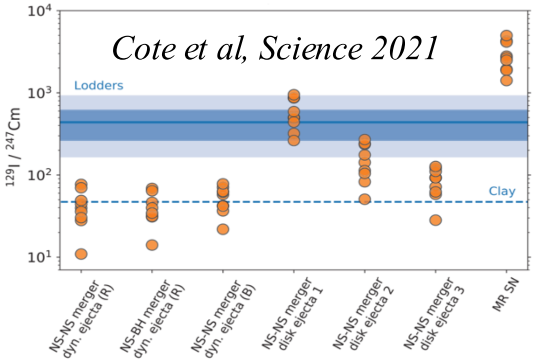
First Results from SuN@FRIB, MSU
June 2025





Artemis Spyrou
FRIB





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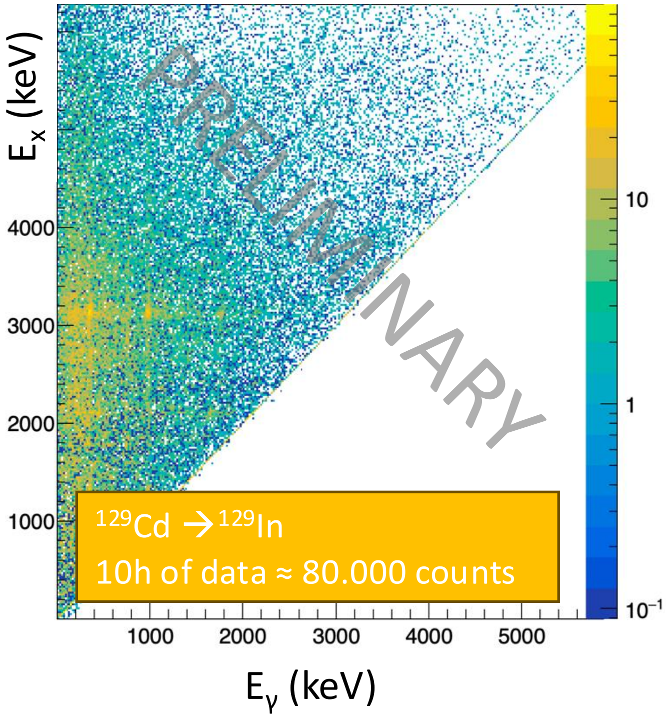
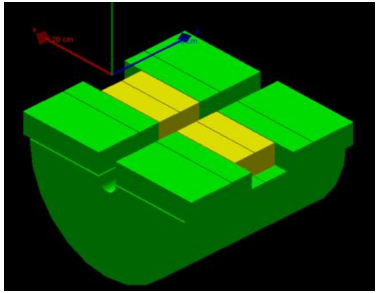
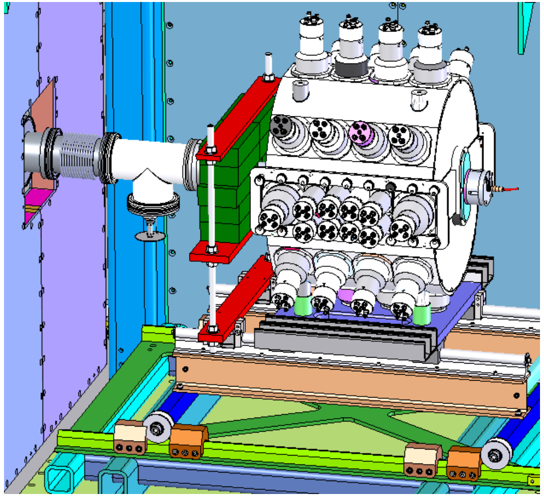


PIs: A. Spyrou, DM
+ S. Liddick + many people





Jessica Berkman
(Liddick group)
MSU

Kostas Bosmpotinis
(Spyrou group)
MSU

Chris Schlaier
(Muecher group)
Univ. Cologne

Setup

- SuN++ TAS (12 NaI, 8 $CeBr_3$)
- seg. implantation DSSD detector (both PiD and β-trigger)
- hosted inside MTAS frame

Results from SuN@FRIB, MSU June 2025

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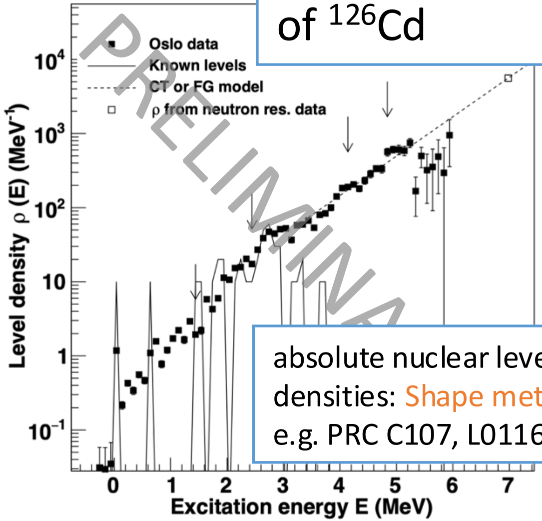
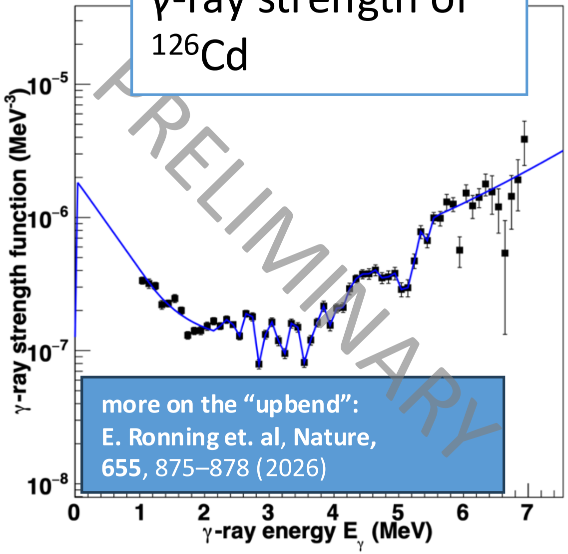
level density of ^{126}Cd



absolute nuclear level densities: Shape method
e.g. PRC C107, L011602

γ-ray strength of ^{126}Cd



more on the "upbend":
E. Ronning et. al, Nature, 655, 875–878 (2026)

- first time we can constrain neutron capture rates in the r process
- level density predictions range from $4\cdot 10^3$ (CT) to $6\cdot 10^5$ (microscopic) MeV^{-1} at S_n!
- we need to work on the normalizations, but the higher level densities seem to be unlikely already at this early stage

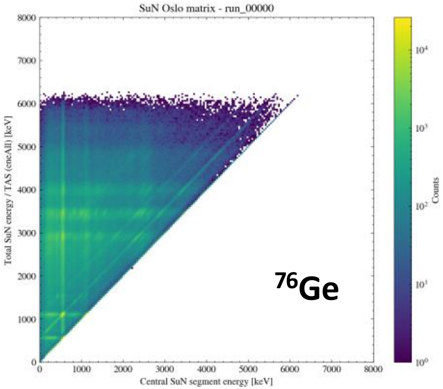
Extracting NLDs and γSFs via AI?

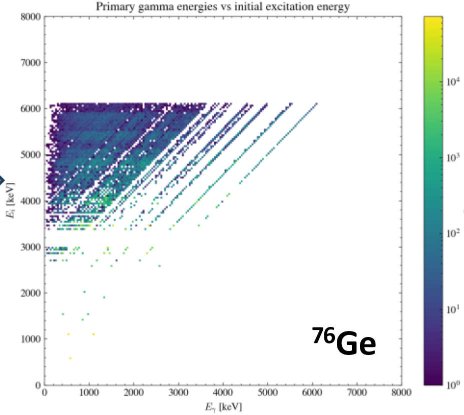
Laila Weisel MSc
student, U. of Cologne

AI approach

Direct unfolding of experimental matrix to primary matrix!

- Treat as **Image-to-Image translation** problem
- Employ established models from **semantic segmentation** with **ResNet** or **U-Net** architecture





© Forschungszentrum Jülich

Computing

- Cooperation with **Stefan Kesselheim** from the **Forschungszentrum Jülich**
- Access to **Supercomputer Jusuf**
  → HPC cluster /136 CPU nodes /128 cores each
- For AI training also prospect of access to **Europe´s fastet Supercomputer Jupiter**

Universität zu Köln

Laila Weisel MSc
student, U. of Cologne

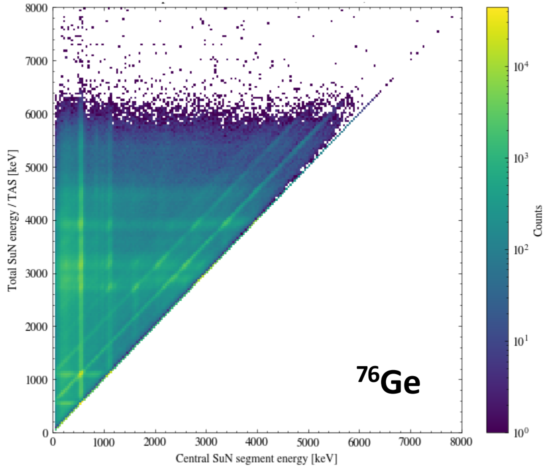
Oslo AI – Data Generation & Forward Approach

Data Generation

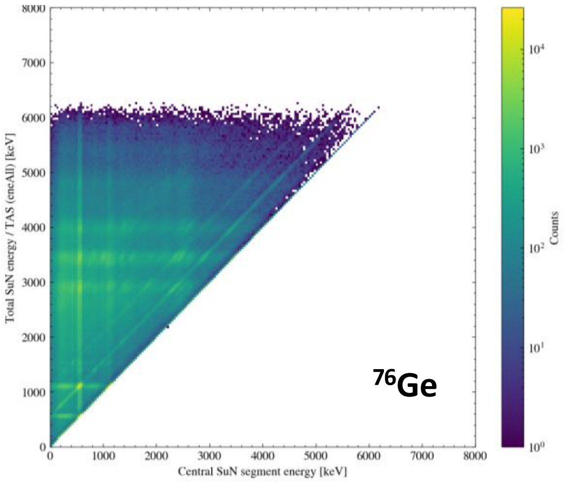
- Generate **10.000 training pairs:**
  primary <-> experimental
  with RAINIER & Geant4 simulation
- Vary model parameters for
- Established a HPC pipeline for automated data generation

→ **Generated 10.000 pairs on 8 nodes of the HPC in only 6.5h!**

Experimental Matrix: SuN spectrometer



Simulated matrix: Default RAINIER parameter



Forward Approach

- Use the 10.000 configurations to search for the best fit with the experimental spectrum
- Extract LD & grsf from the corresponding model parameters

Universität zu Köln

Laila Weisel MSc
student, U. of Cologne

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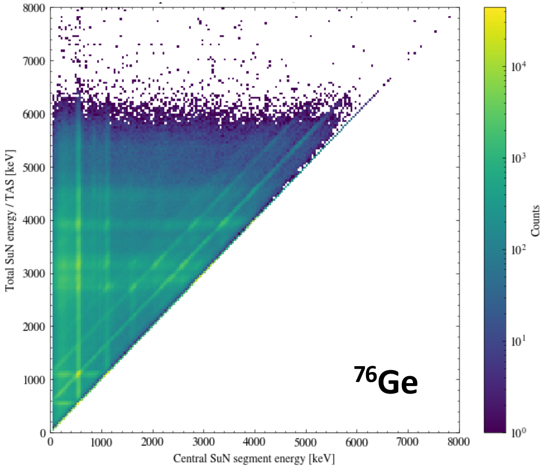
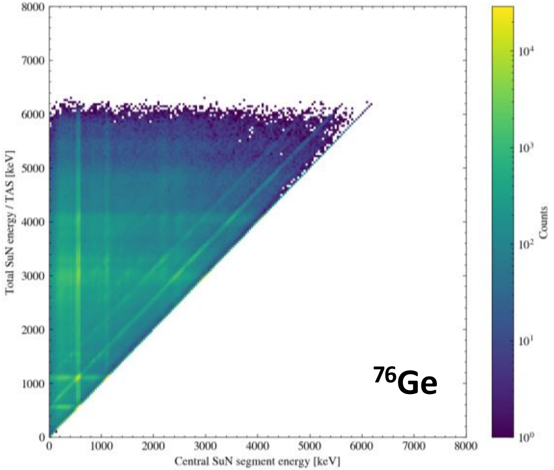


Simulated matrix: Best fit parameters



Forward Approach

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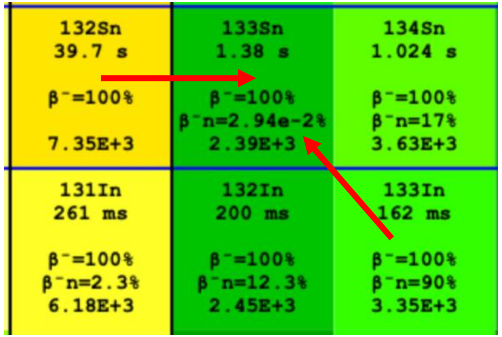
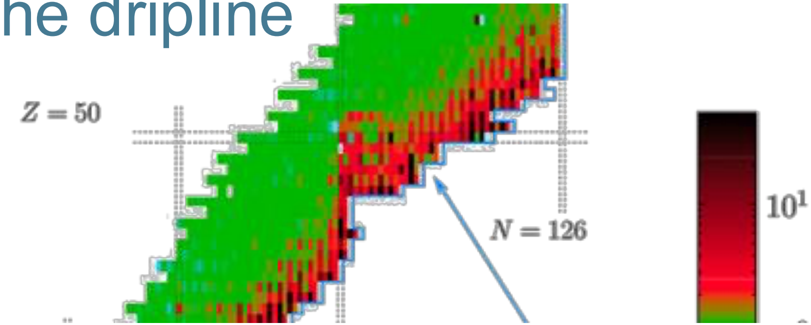
Universität zu Köln

Outlook: Neutron captures towards the dripline

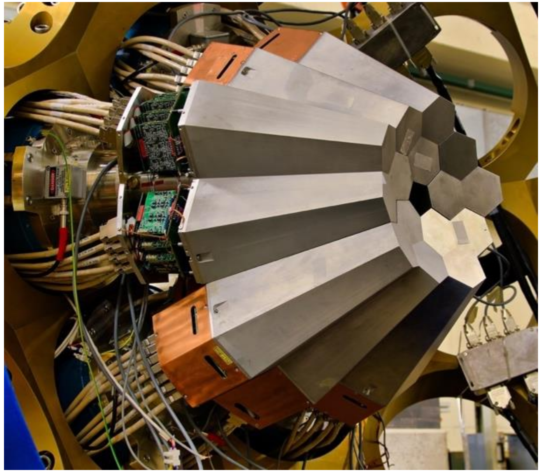
(n,γ): $J^{\pi}=1/2^{+}$





β^{-}, allowed: $J^{\pi}=(1/2^{-}, 3/2^{-})$

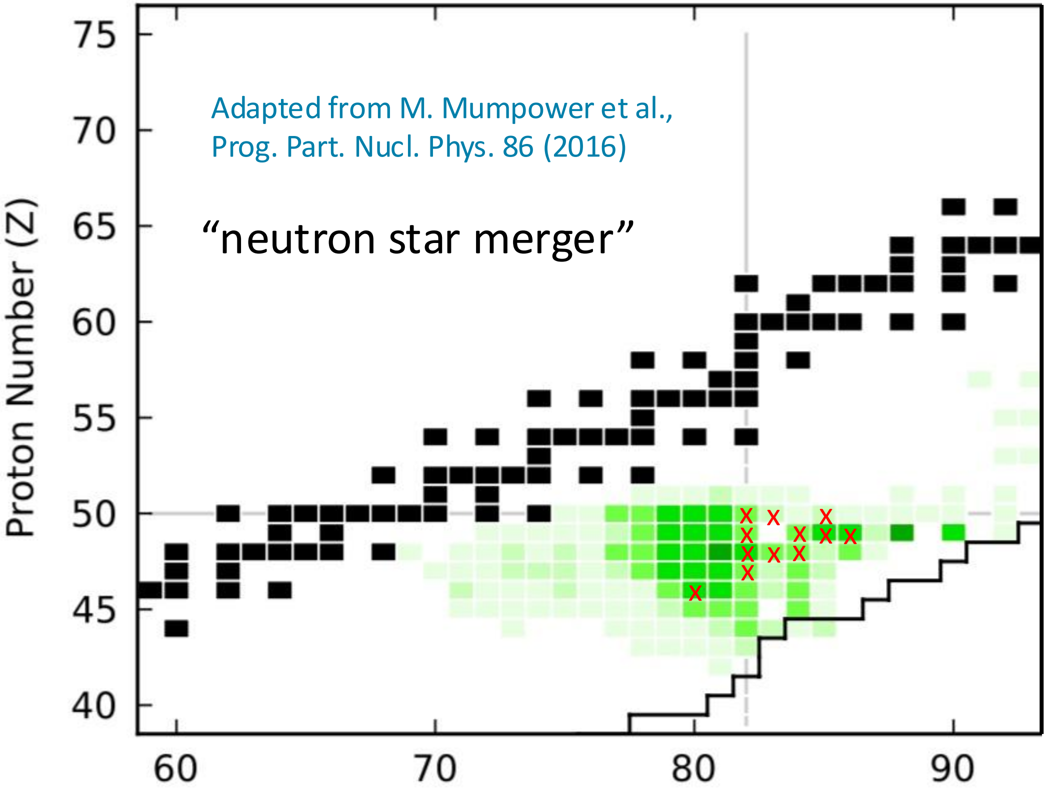
$\rightarrow$(E1): $J^{\pi}=(1/2^{+}, 3/2^{+}, 5/2^{+})$



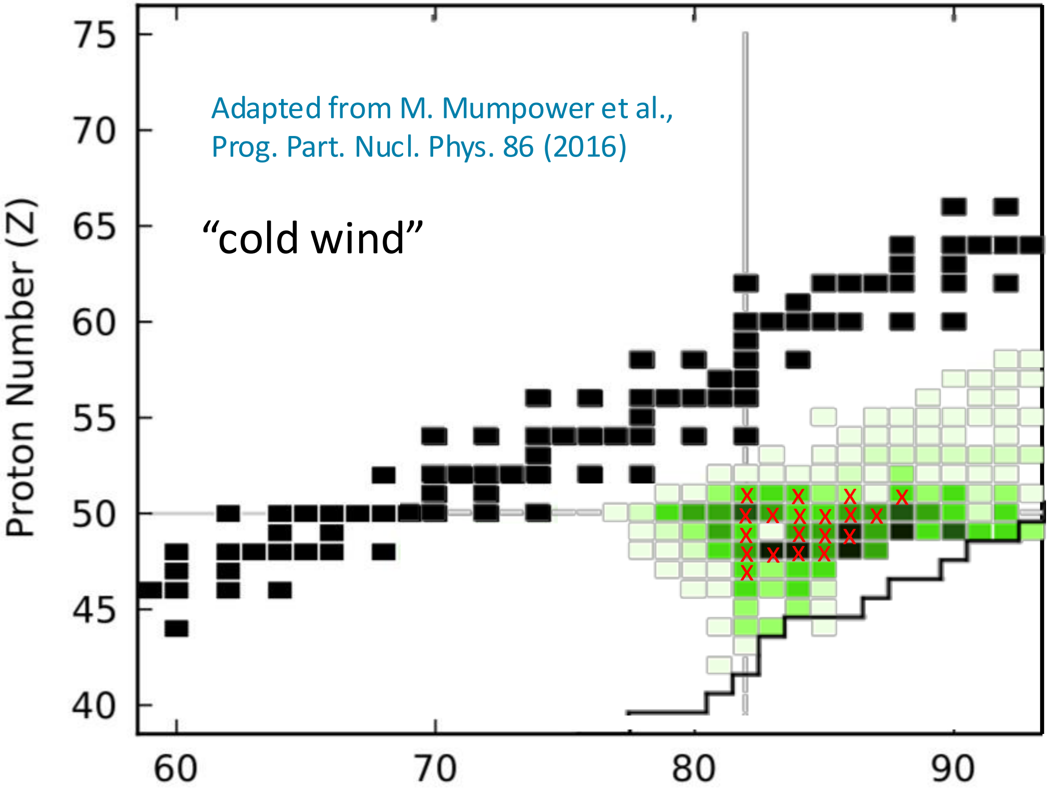
- Idea: use high-resolution γ-array or TAS to directly measure # levels
- total # levels in ^{133}Sn up to S_n: about 50
- total # populated levels: about 10
- Example: using a CeBr TAS (3% energy resolution):

about 20% accuracy to count 100 levels / MeV

Outlook: Neutron captures towards the dripline



Outlook: Neutron captures towards the dripline



Summary + Thank you

- β-Oslo: powerful technique for constraining n-capture rates in exotic nuclei
- First constraint of the $^{140}Cs(n,\gamma)^{141}Cs$ reaction rate at the limit of statistical behaviour
- Successful first experiment for n-capture rates at FRIB below ^{132}Sn

- A. Spyrou, S. Liddick, K. Bosmpotinis, J. Berkman, R. Lubna, S. Uthayakumaar, et. al. (FRIB + MSU)
- B. Greaves (UoGuelph)
- G. Savard, D. Santiago et. al. (Argonne National Lab.)
- S. Goriely (Univ. Brussels)
- D. Rochman (PSI, Villingen)
- C. Schlaier, L. Weisel (IKP Cologne)
- S. Kesselheim (FZ Jülich)