UiO : University of Oslo

Progress of the IS559 experiment

The γ-ray strength function and nuclear level density of ^{67}Ni

National Research Foundation 1999-2019

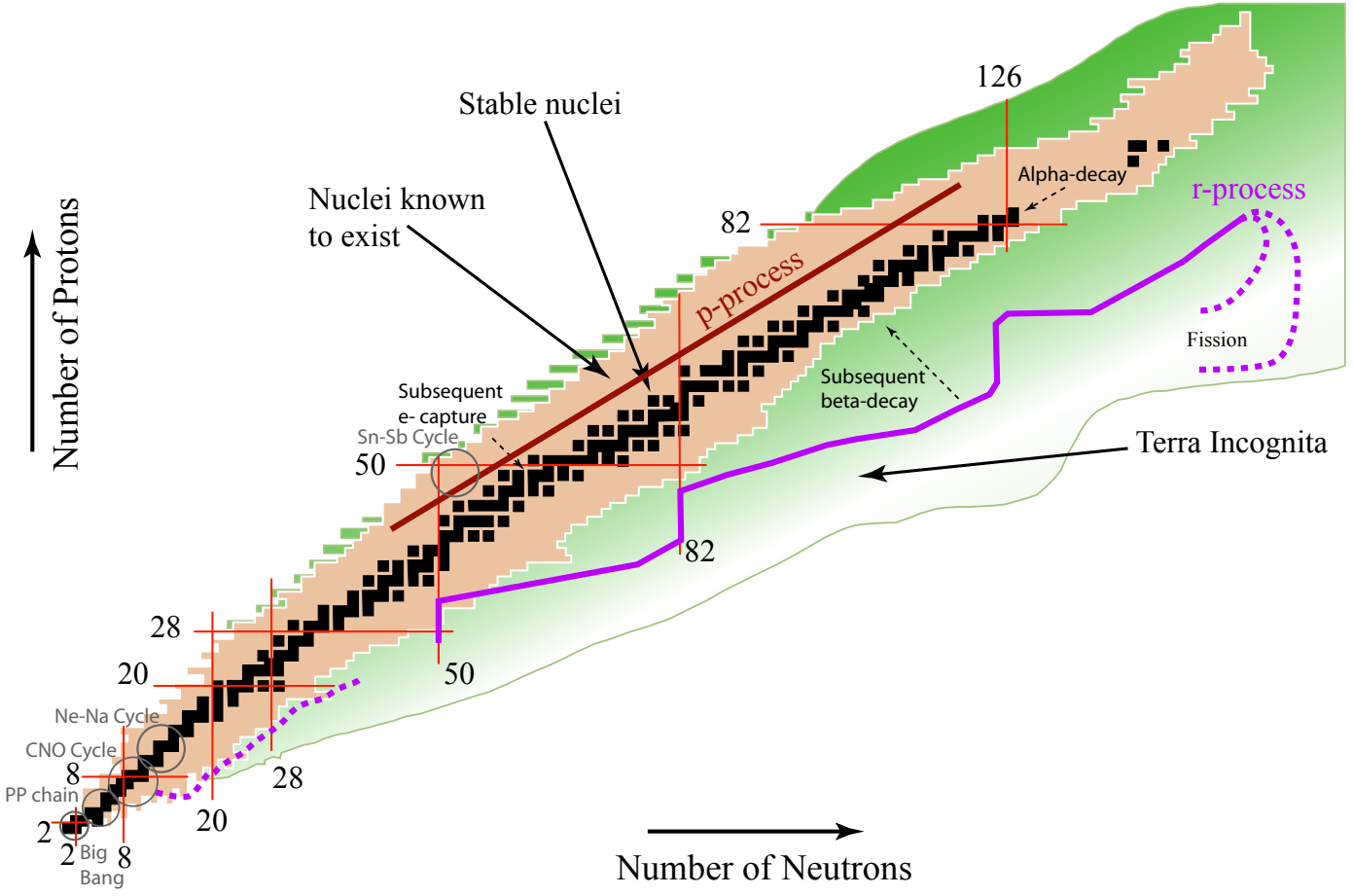
iThemba LABS
Laboratory for Accelerator Based Sciences

Outline

- Motivation
- The IS559 experiments
- Preliminary results
- Summary

Nucleosynthesis – neutron capture process

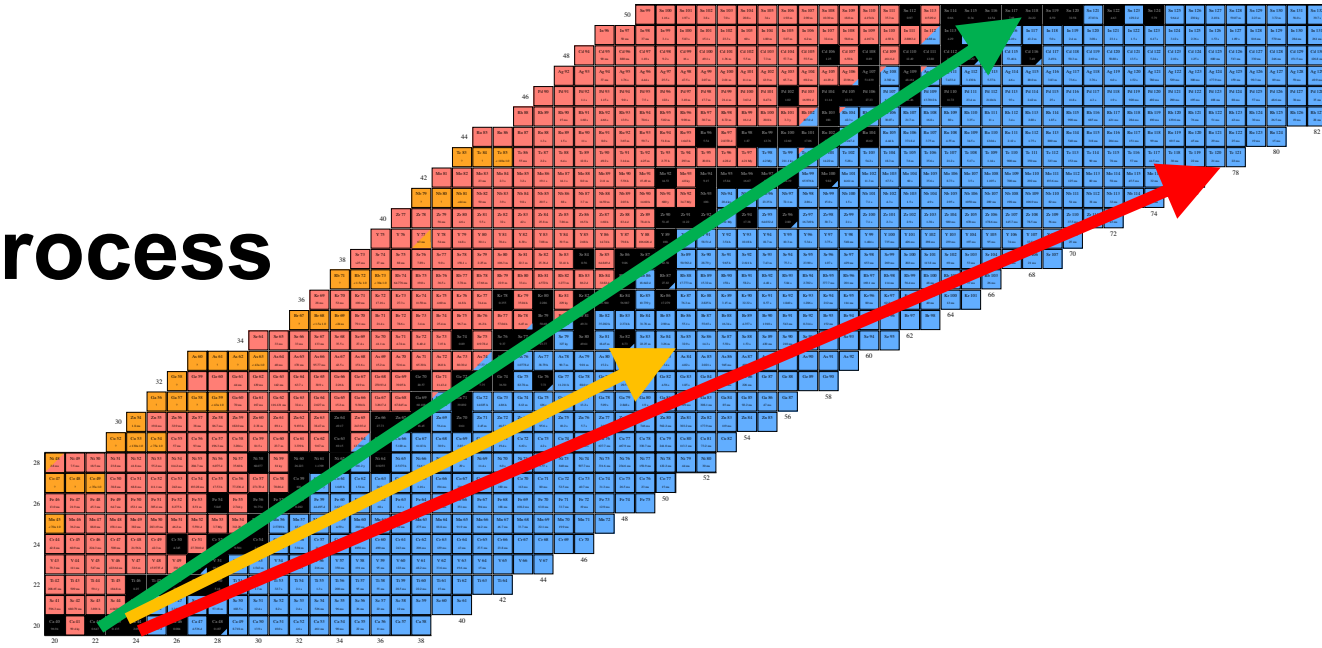
- r- and s-process responsible for production of almost all elements heavier than iron[1]
- r-process known to happen in kilonovas following neutron star mergers[2]
- Abundance calc. needs accurate nuclear input
  - Neutron capture rates
  - Decay rates, masses, etc.



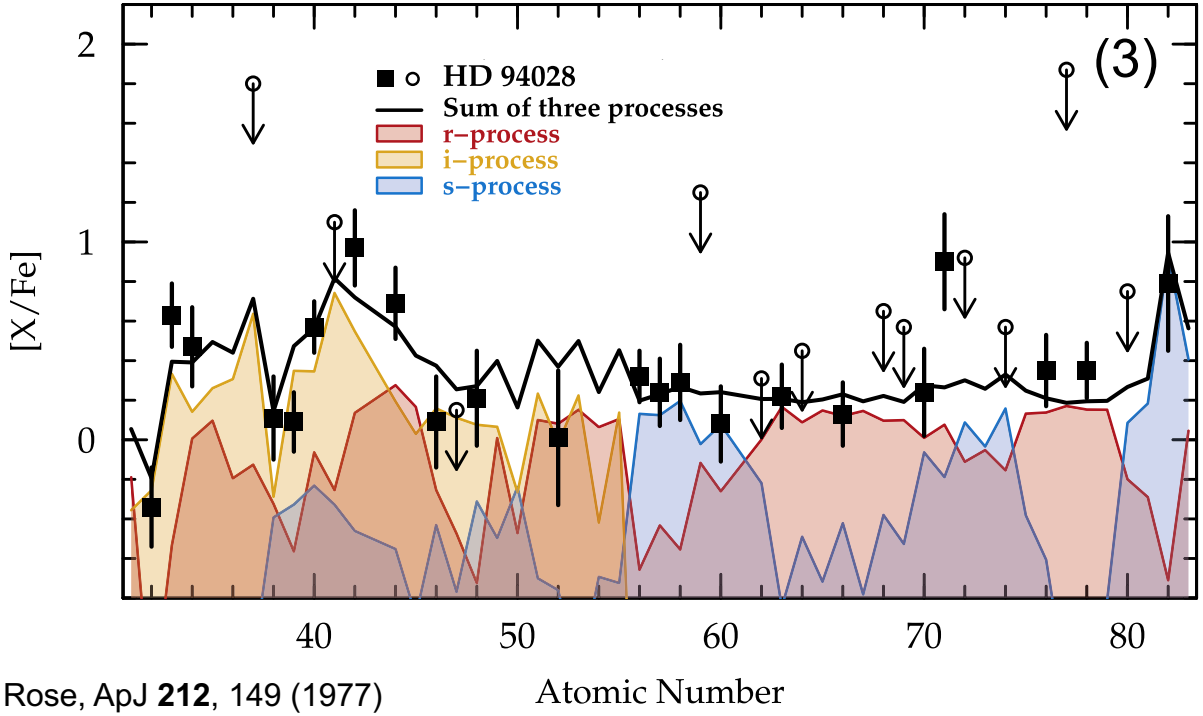
[1] M. Arnould, S. Goriely and K. Takahashi, Phys. Rep. **450**, 97-213 (2007)
[2] D. Kasen *et al.*, Nature **551**, 80-84 (2017)

Figure credit: F. Timmes, http://cococubed.asu.edu/images/nuclide_chart/table_nuclei04.pdf

Nucleosynthesis – i-process



- First suggested in 1977 by Cowan & Rose[1]
- Intermediate neutron flux ~ 10^{13} - 10^{16} cm^{-3}
- Observed in post-AGB star Sakurai's object (V4334 Sagittarii)[2]
- Elemental abundance of HD94028: Cannot be explained with s- and/or r-process alone[3]
  - Weak i-process



[1]J. J. Cowan and W. K. Rose, ApJ **212**, 149 (1977)
[2]M. Aspelund *et al.*, A&A **343**, 507 (1999)
[3]I. U. Roederer *et al.*, ApJ **821,** 37 (2016)

The weak i-process

- Possibly initiated by ingesting of H into a convective He zone
- Terminates quickly
- The ^{66}Ni(n,γ) identified as a major bottleneck
  - Experimental measurements needed!

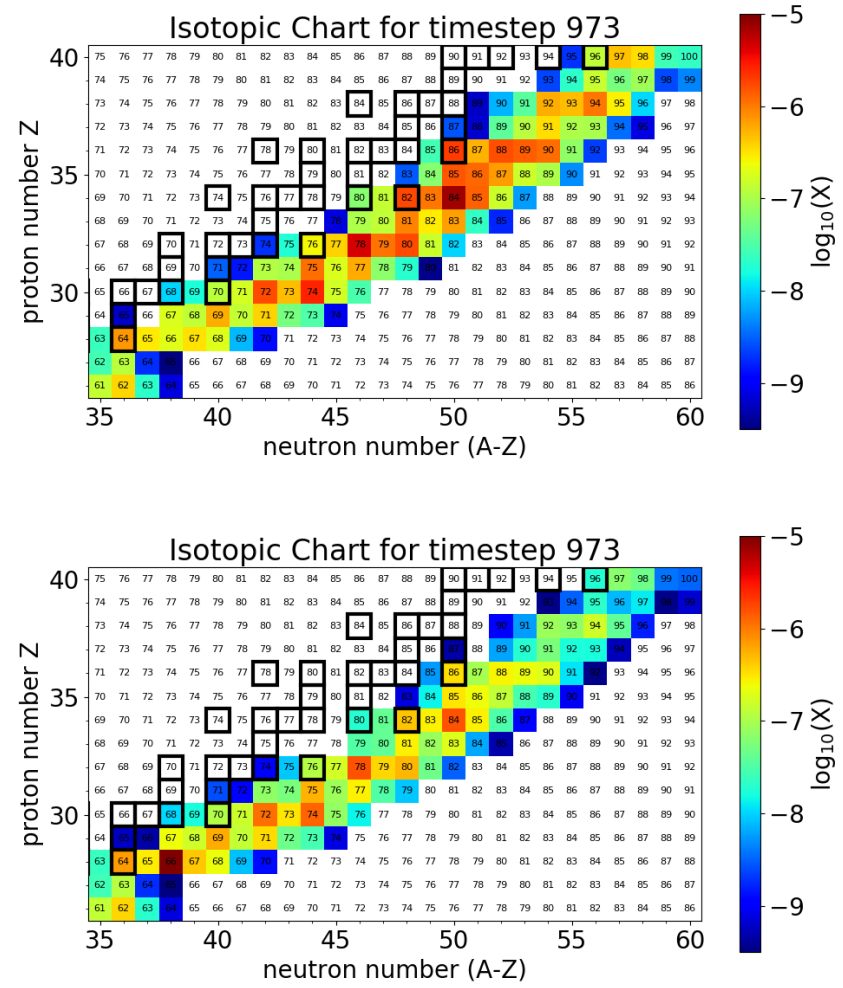
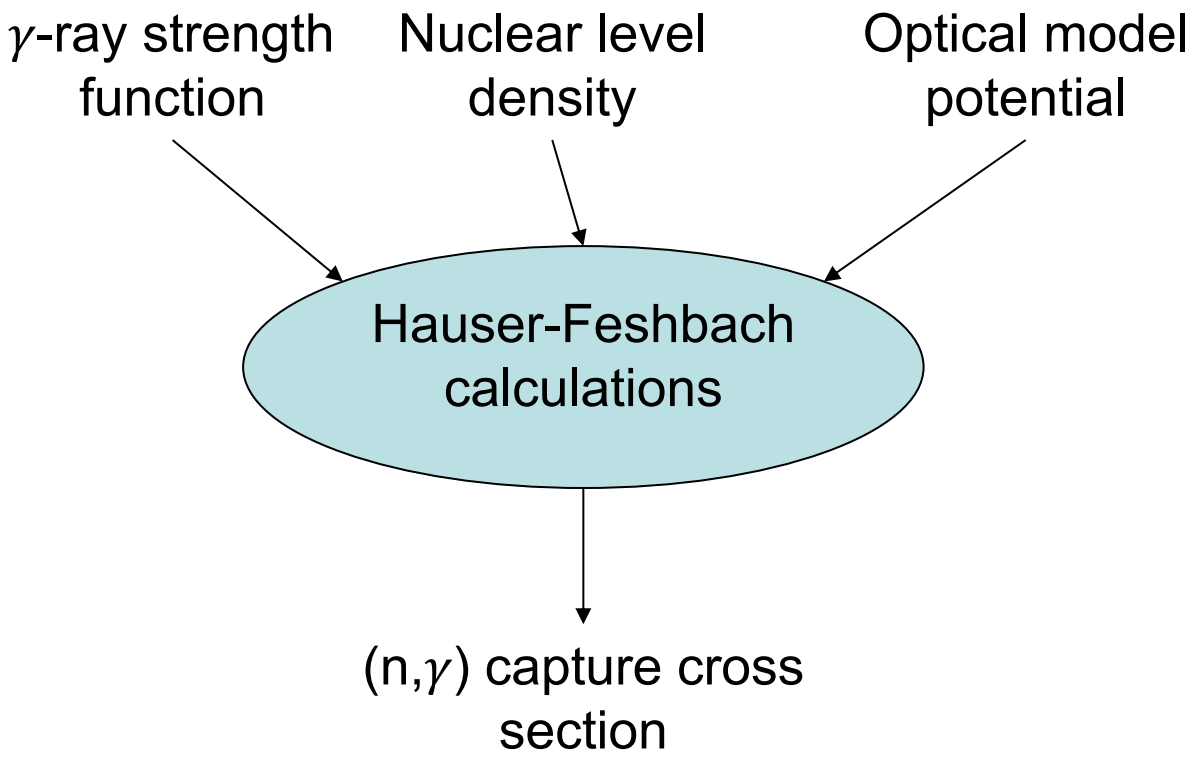


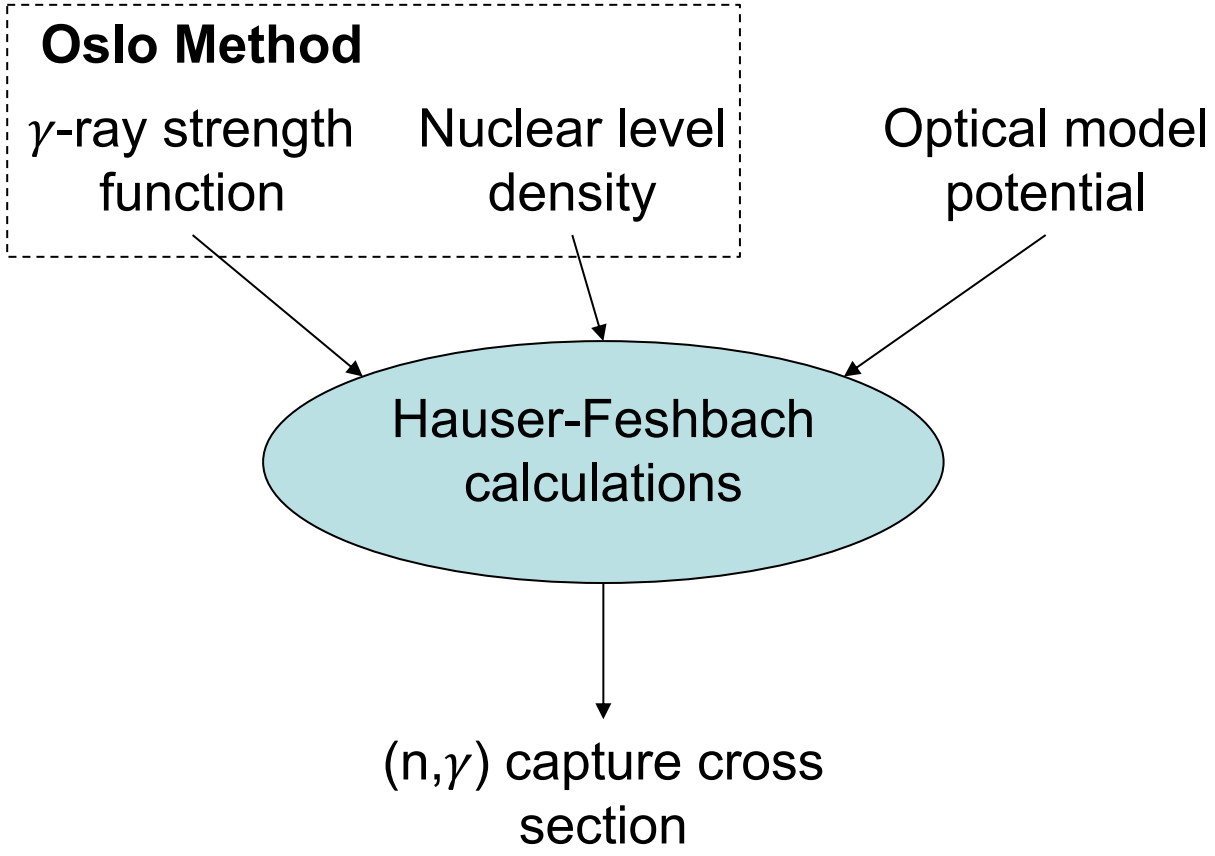
Figure 10. Isotopic abundances from the two additional ppn runs in which only the multiplication factor $f(^{66}\mathrm{Ni})$ was switched between its maximum (top panel) and minimum (bottom panel) values constrained by the Hauser-Feshbach model computations.

J. E. McKay *et al.*, MNRAS *in press.*, arXiv: 1909.07011 (2019)

Hauser-Feshbach model

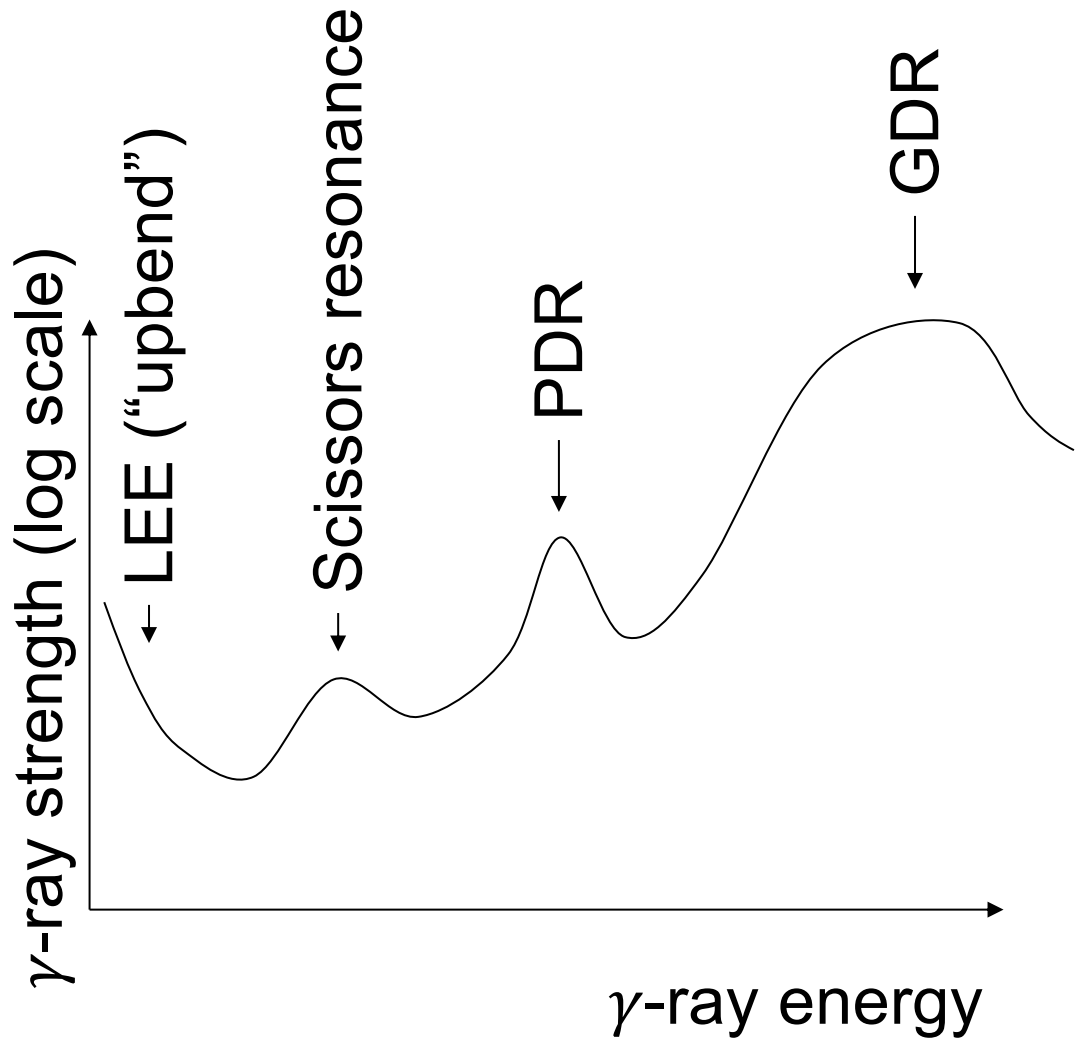


Hauser-Feshbach model



γ-ray Strength Function

- Measure of the electromagnetic interaction of a nucleus
- Dominated by the E1 giant resonance (GDR)
- Low energy enhancement "upbend" (LEE)
- Scissors resonance
- Pygmy dipole resonance (PDR)



Effect of LEE on neutron capture

- Origin of LEE still not well understood
- The LEE can have a huge impact on (n,γ) cross section
- Experimental data is needed to refine theoretical models

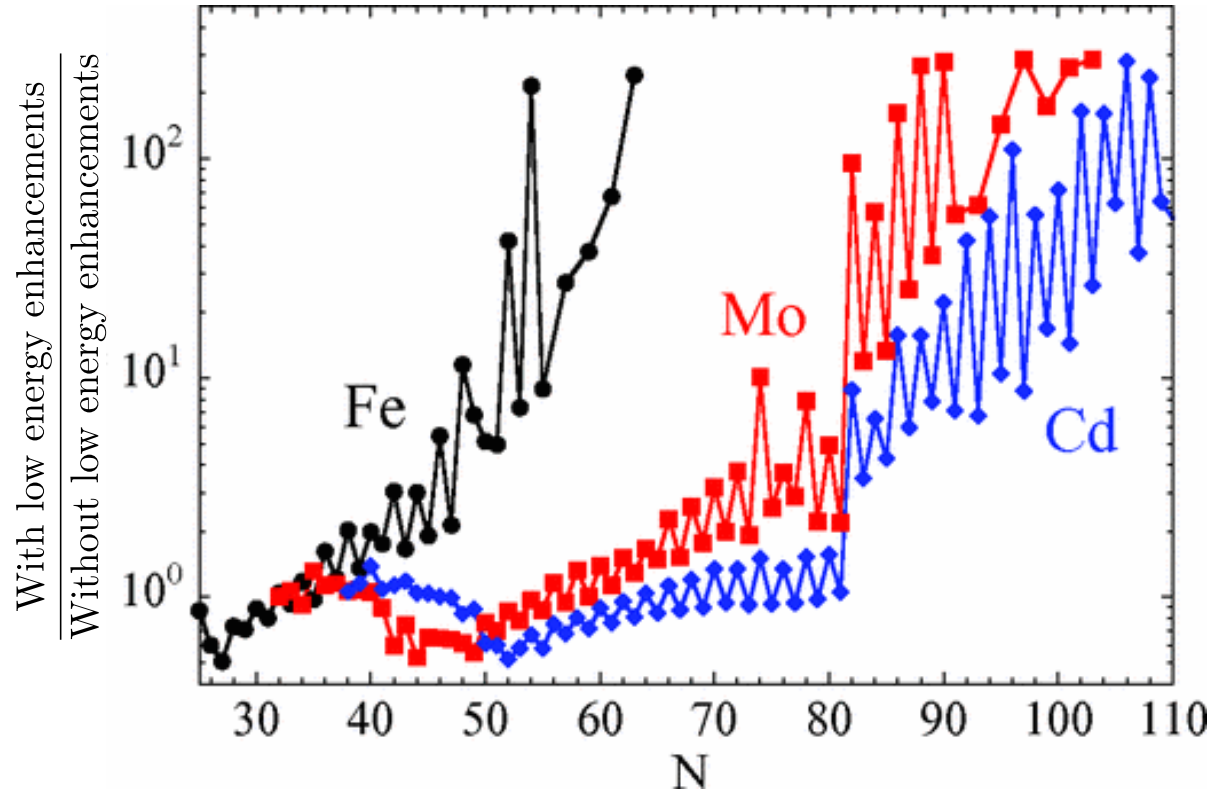


Figure credit: A. C. Larsen and S. Goriely, Phys. Rev. C **82**, 014318 (2010)

The Oslo Method

- Simultaneous measurement of the γ-ray strength function and nuclear level density
- Starting point: Eγ vs Ex matrices
  - Reactions with light ions
  - TAS of beta-decay
  - **Inverse kinematics**

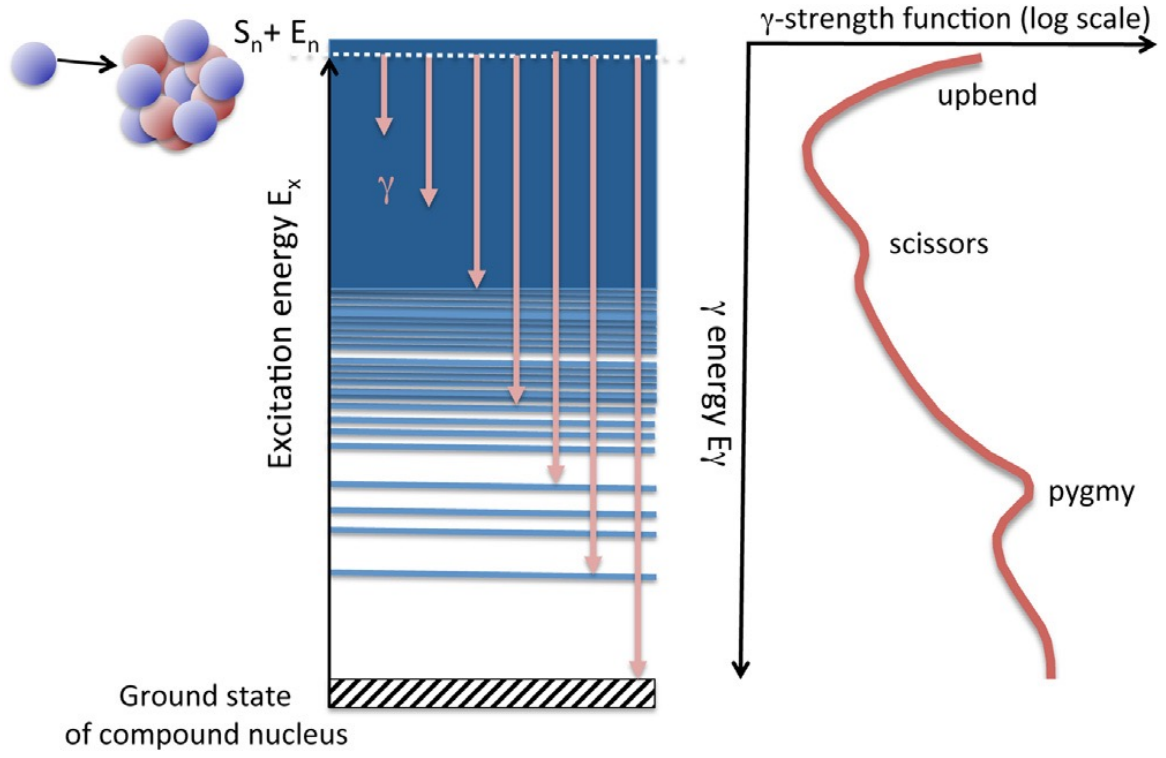
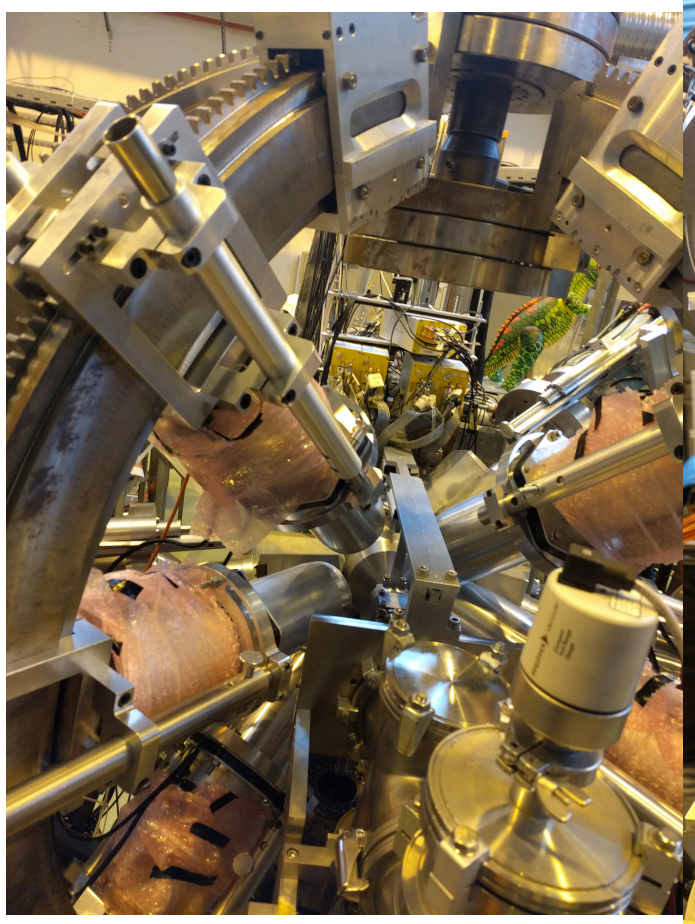
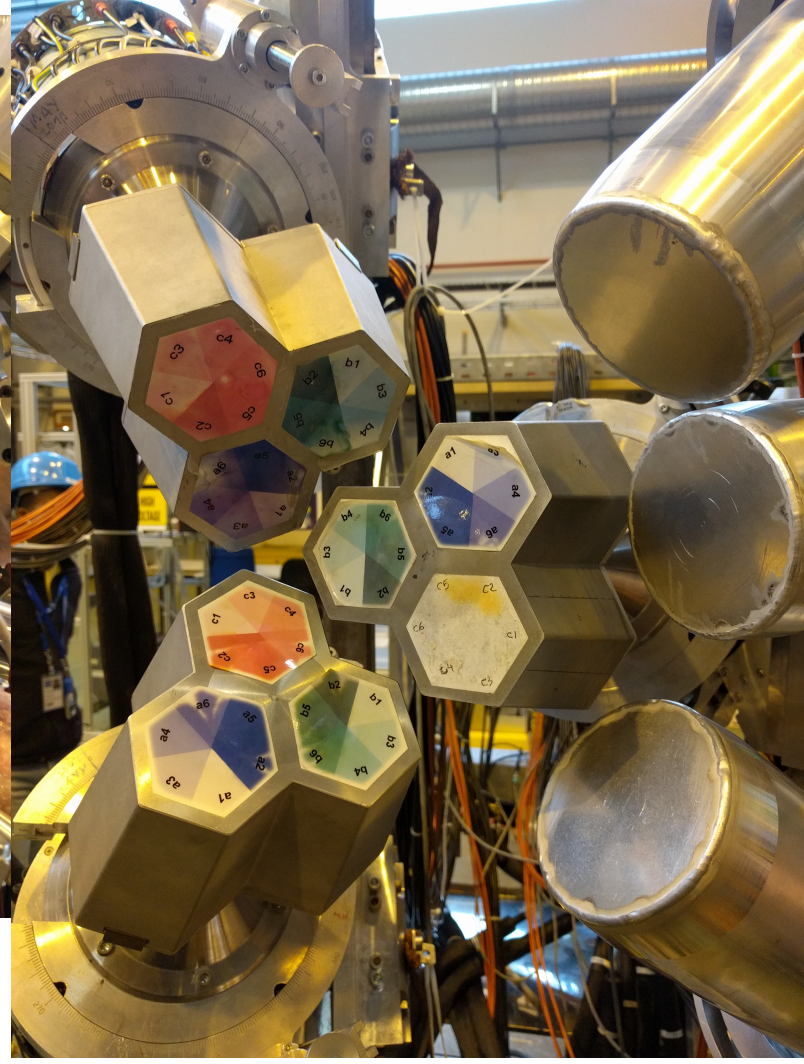


Figure credit: A. C. Larsen, A. Spyrou S. N. Liddick and M. Guttormsen, Prog. In Part. And Nucl. Phys. **107**, 69-108 (2019)

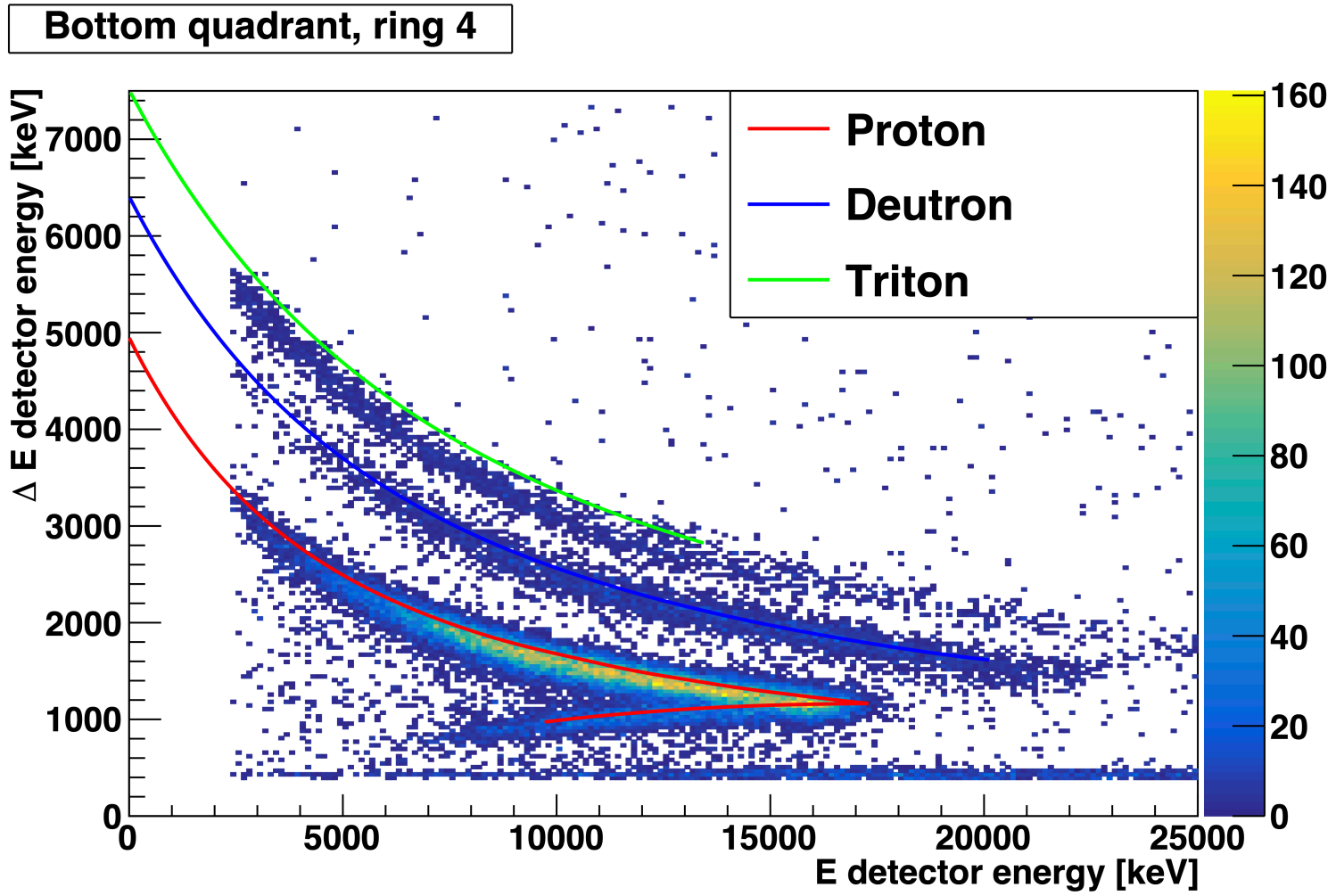
Experiment

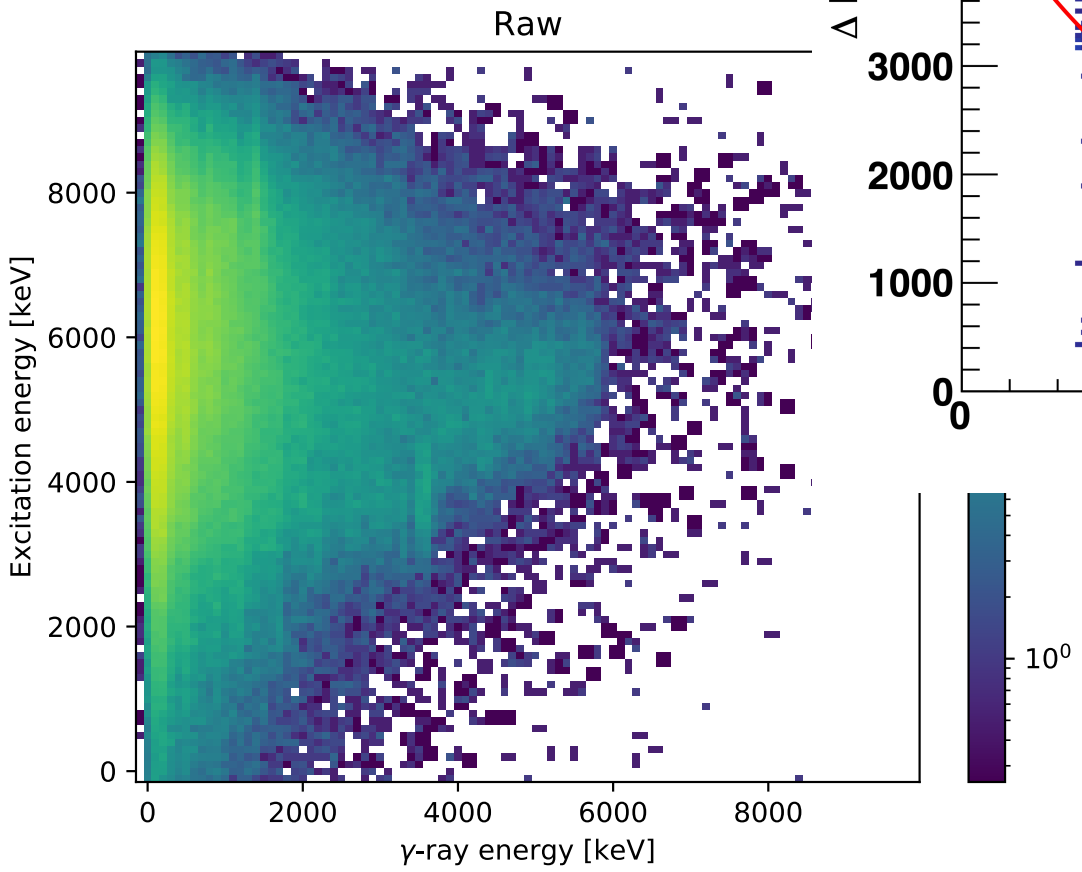
- ^{66}Ni beam @ 4.5 MeV/u
- ≈ 11 pA for ~ 140 hours
- 669 ug/cm^2 C_2D_4 target
- Six Miniball clusters
- Six large volume (3.5x8”) LaBr3:Ce detectors
- C-REX particle array
- > 240k coincidences after BG subtraction
- First Oslo Method in inverse kinematics with radioactive beam!



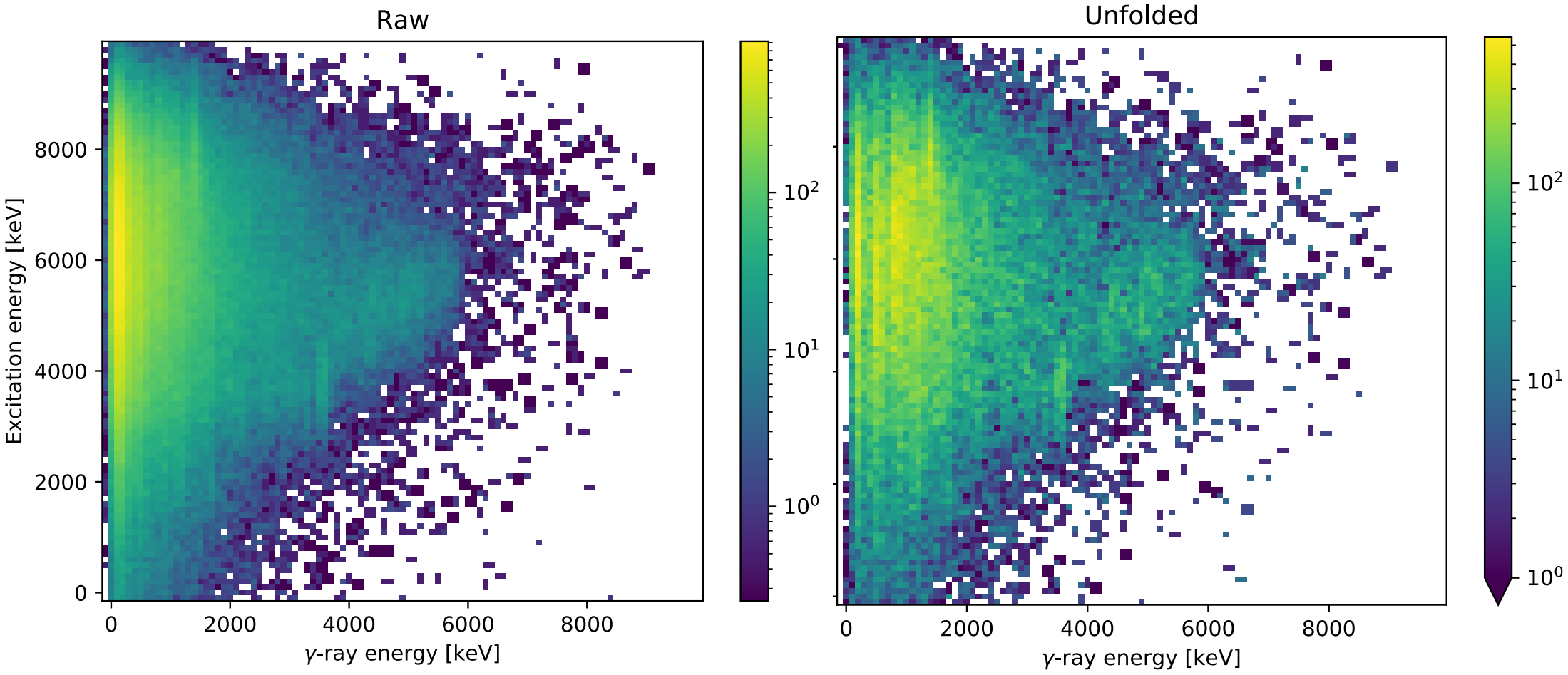


Results

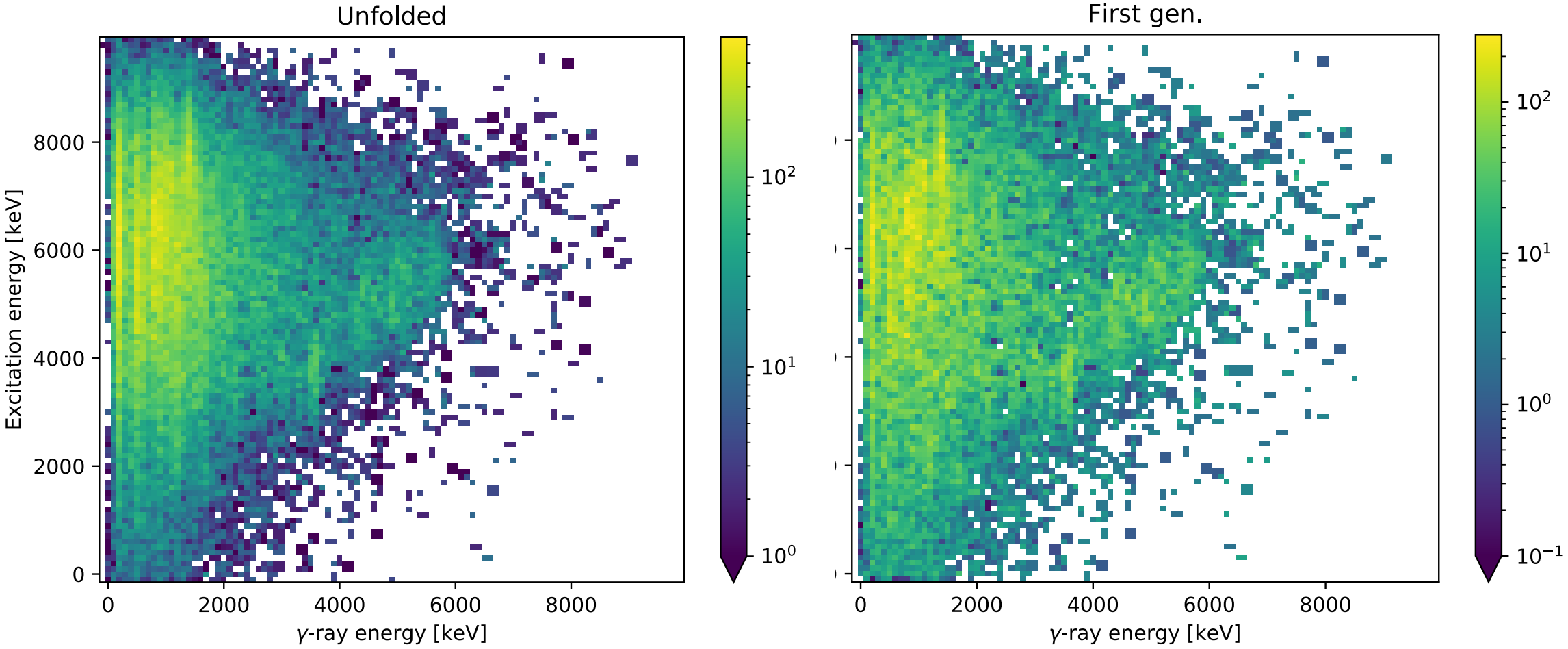

Bottom quadrant, ring 4
Proton
Deutron
Triton
Δ E detector energy [keV]
E detector energy [keV]
0
1000
2000
3000
4000
5000
6000
7000
0
5000
10000
15000
20000
25000
0
20
40
60
80
100
120
140
160


Raw
Excitation energy [keV]
γ-ray energy [keV]
0
2000
4000
6000
8000
10^0

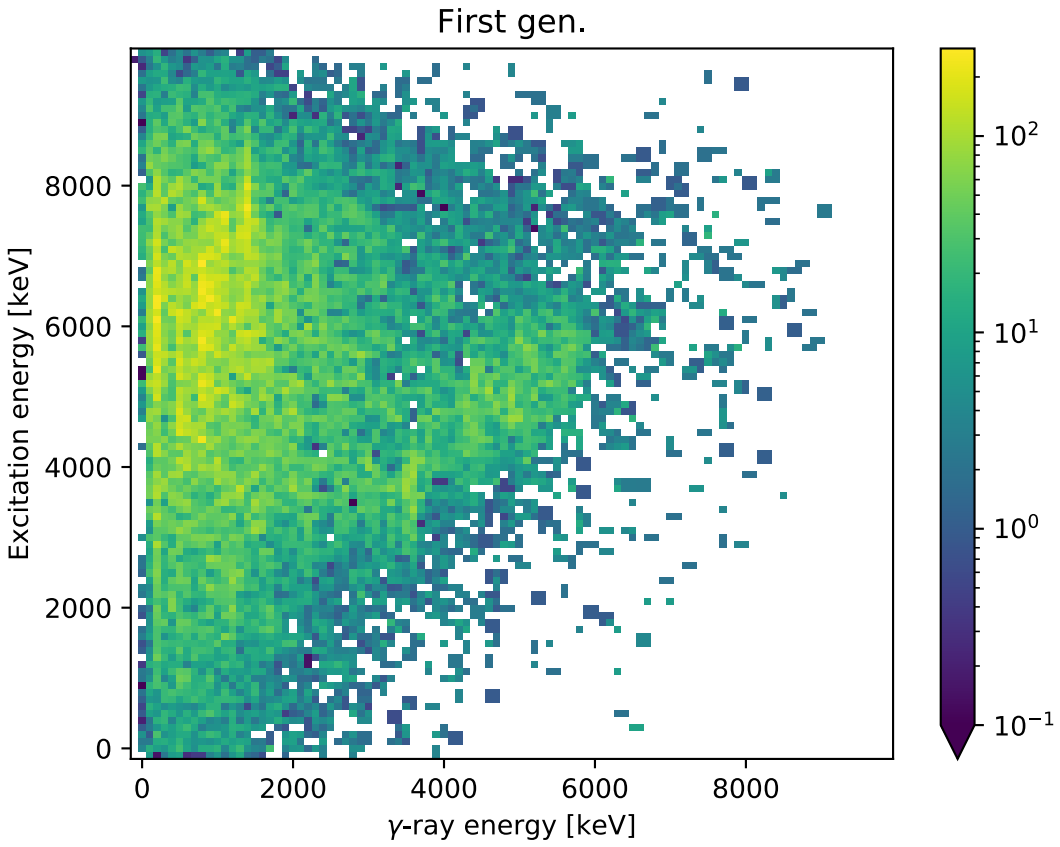
Oslo Method Analysis - Unfolding



Oslo Method Analysis – First generation



Oslo Method Analysis – extraction of gSF & NLD



$$\Gamma(E_x, E_\gamma) \propto \mathcal{T}(E_\gamma)\rho(E_x - E_\gamma)$$

$$\Gamma_{\text{theo.}}(E_x, E_\gamma) = \frac{\mathcal{T}(E_\gamma)\rho(E_x - E_\gamma)}{\sum_{E_\gamma = E_\gamma^{\min}}^{E_x} \mathcal{T}(E_\gamma)\rho(E_x - E_\gamma)}$$

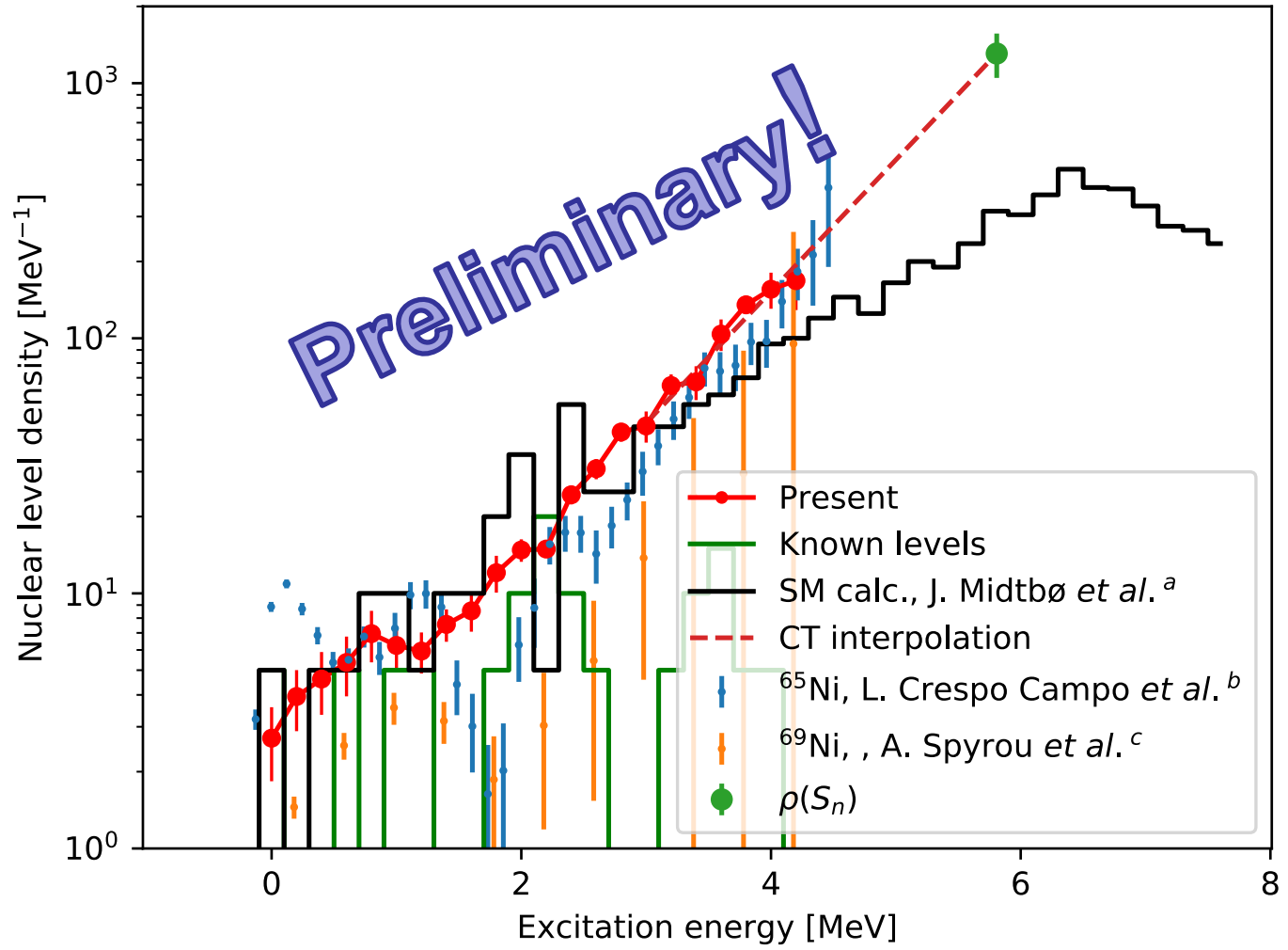
$$f(E_\gamma) = \frac{1}{2\pi E_\gamma^3}\mathcal{T}(E_\gamma)$$

$$\rho(E_x) = A\tilde{\rho}(E_x)e^{\alpha E_x}$$

$$\mathcal{T}(E_\gamma) = B\tilde{\mathcal{T}}(E_\gamma)e^{\alpha E_\gamma}$$

The Oslo Method – normalization of NLD

- Known discrete levels
  - ENSDF
  - XNSDF
- NLD at S_n
  - Systematics
- Fixes slope parameter α and absolute value A

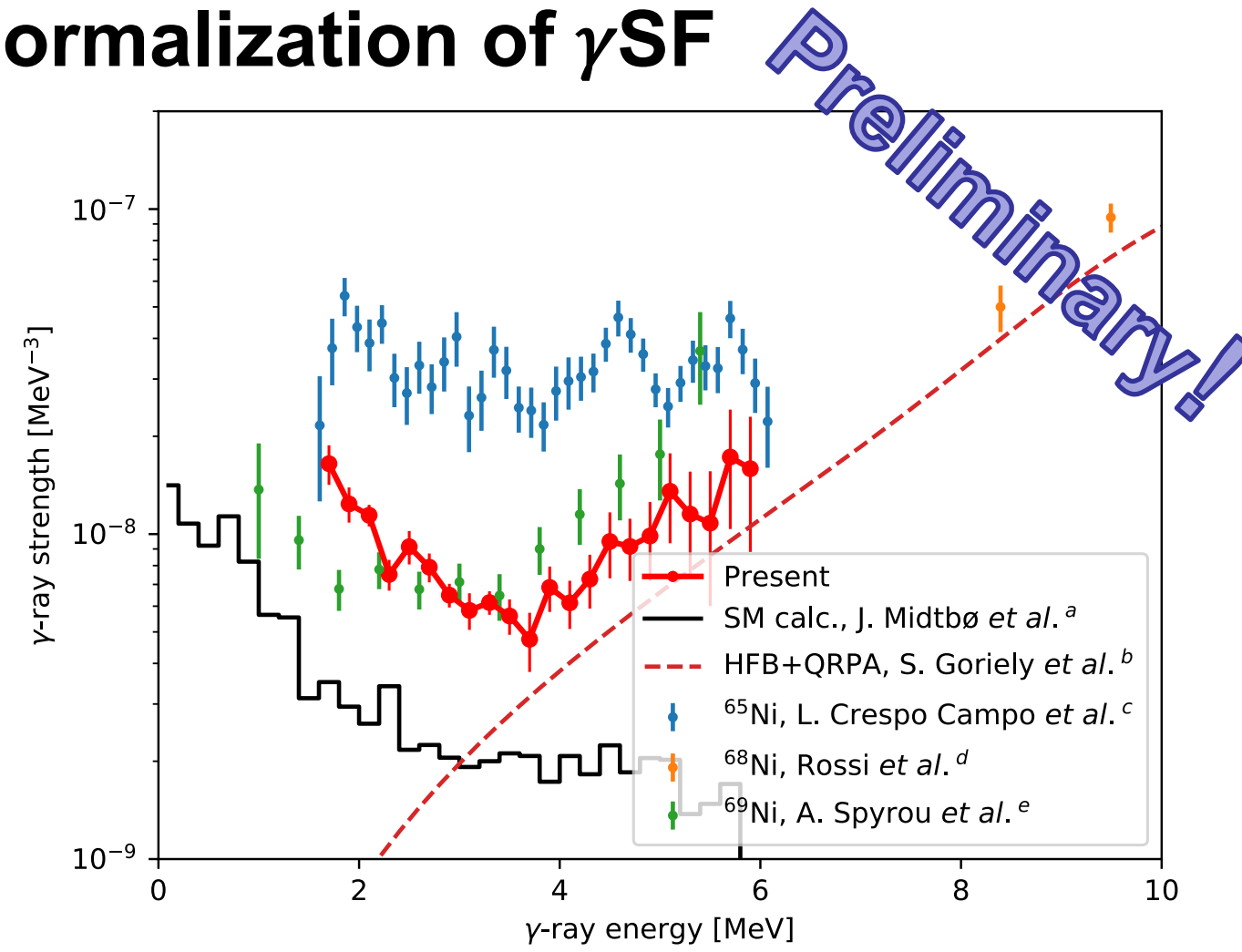


[a] J. Midtbø *et al.*, Phys Rev. C **98**, 064321 (2018)
[b] L. Crespo Campo et al., Phys. Rev. C **96**, 014312 (2017)
[c] A. Spyrou *et al.*, J. Phys. G. Nucl. Part. Phys. **44**, 044002 (2017)

The Oslo Method – normalization of γSF

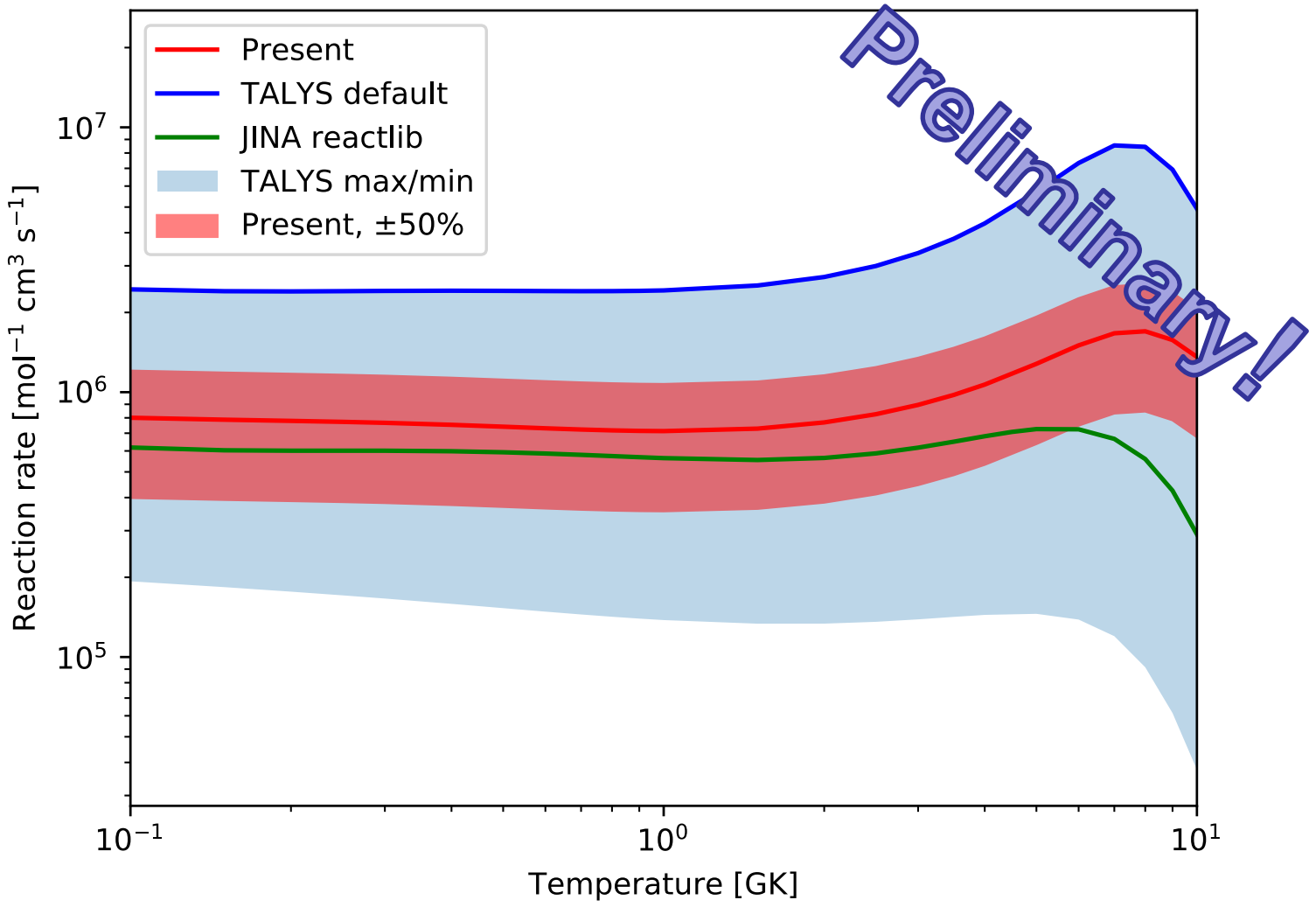
- Slope α fixed by NLD
- Absolute value found by

$$\langle \Gamma_{\gamma 0} \rangle = \frac{B}{2\pi\rho(S_n, J_t^\pi)} \int_0^{S_n} dE_\gamma \mathcal{T}(E_\gamma)\rho(S_n - E_\gamma) \times \sum_{I=-1}^{1} g(S_n - E_\gamma, J_t + I)$$



[a] J. Midtbø *et al.*, Phys Rev. C **98**, 064321 (2018)
[b] S. Goriely and E. Khan, Nucl. Phys. A **706**, 217 (2002)
[c] L. Crespo Campo *et al.*, Phys. Rev. C **96**, 014312 (2017)
[d] D. M. Rossi *et al.*, Phys. Rev. Lett. **111**, 242503 (2013)
[e] A. Spyrou *et al.*, J. Phys. G. Nucl. Part. Phys. **44**, 044002 (2017)

Hauser-Feshbach calculations



Summary

- Preliminary results for the γSF and NLD for ^{67}Ni
- We observe a strong low energy enhancement in the γSF
- Will help our understating the weak i-process
- Oslo Method with inverse kinematics: An important tool for constraining (n,γ) cross sections of unstable nuclei

Acknowledgement

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