Experimental Constraints on Statistical Quantities for Nuclear Astrophysics

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February 27, 2023

LLNL-PRES-845521
This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under contract DE-AC52-07NA27344. Lawrence Livermore National Security, LLC

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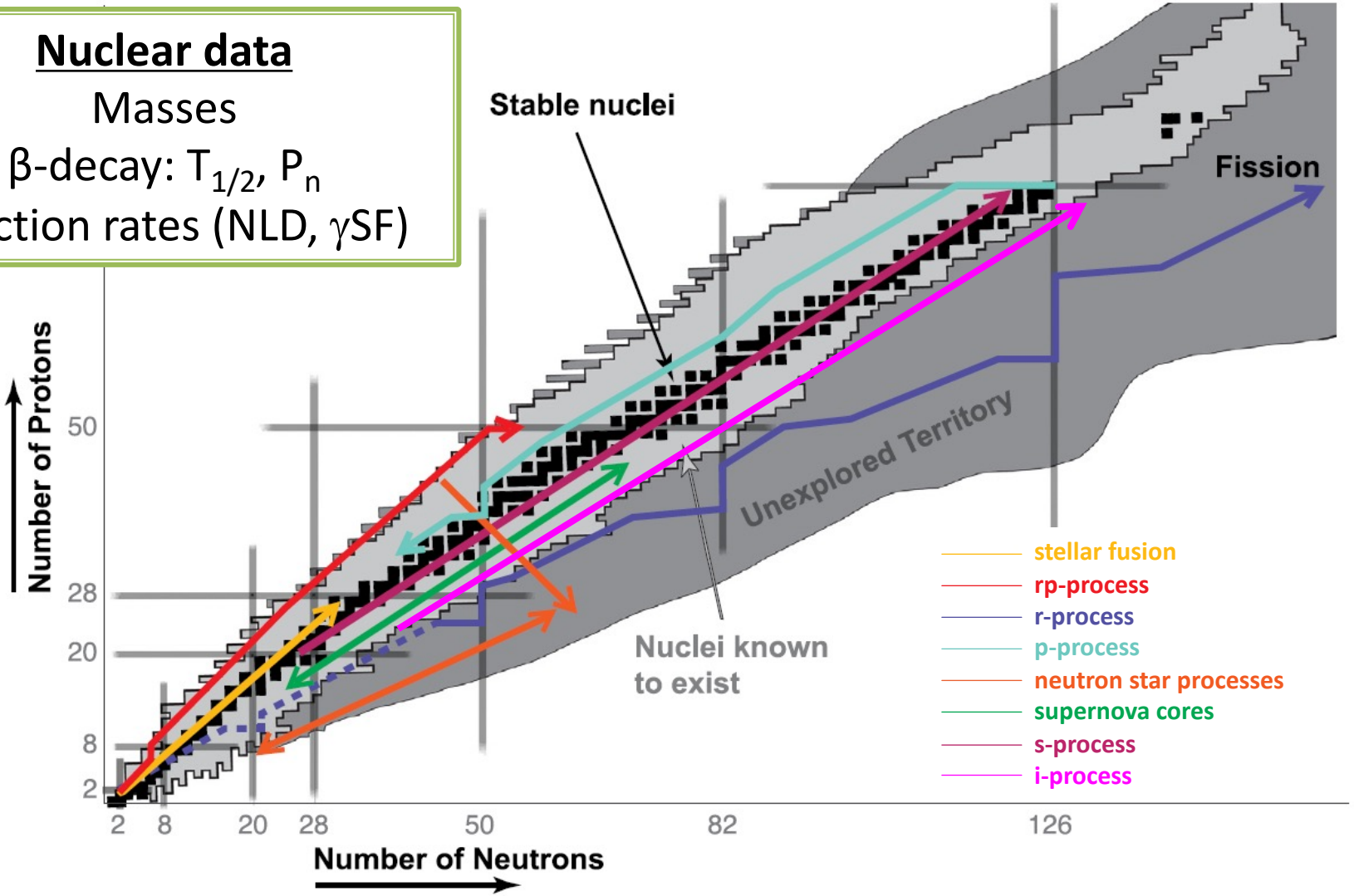
Nucleosynthesis across the Nuclear Landscape

Nuclear data

Masses

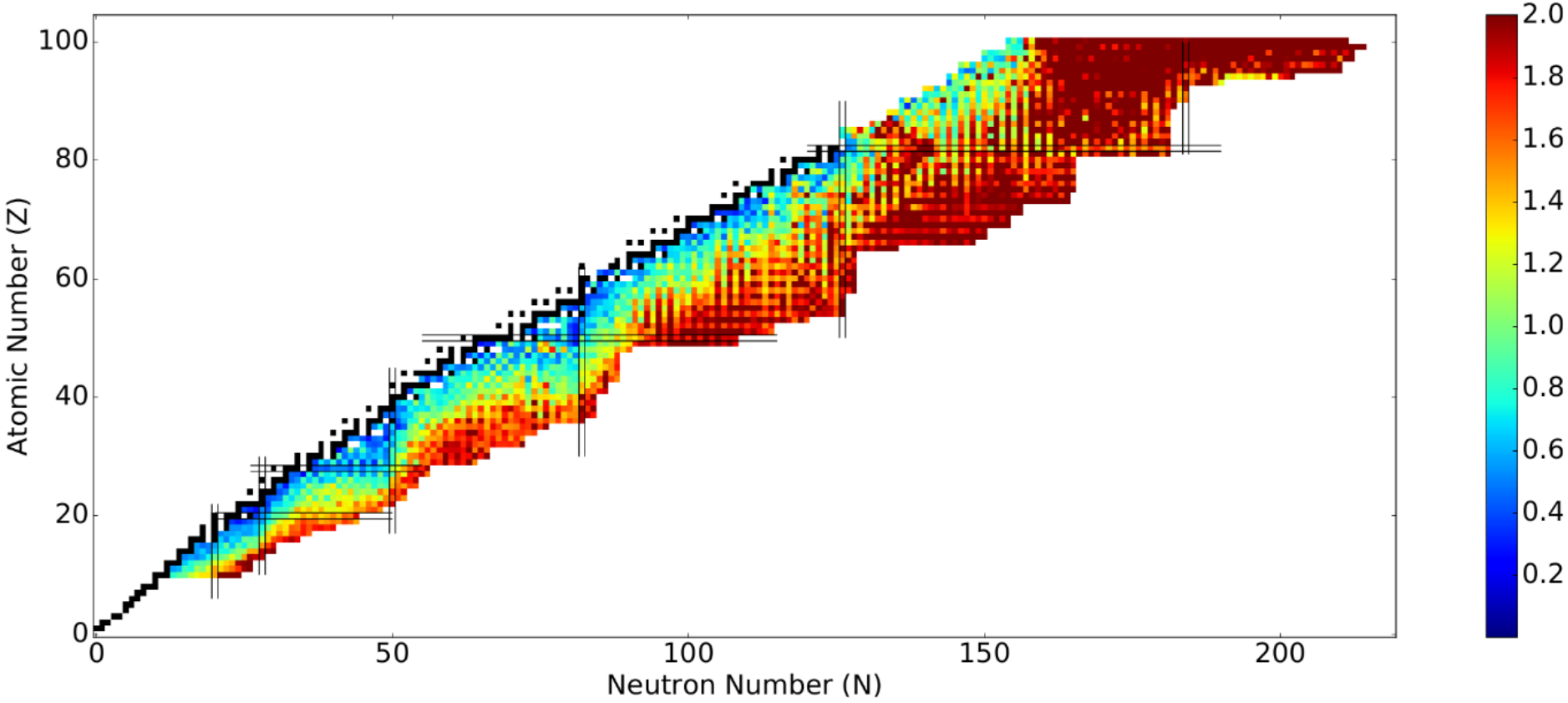
β-decay: $T_{1/2}$, P_n

Reaction rates (NLD, γSF)



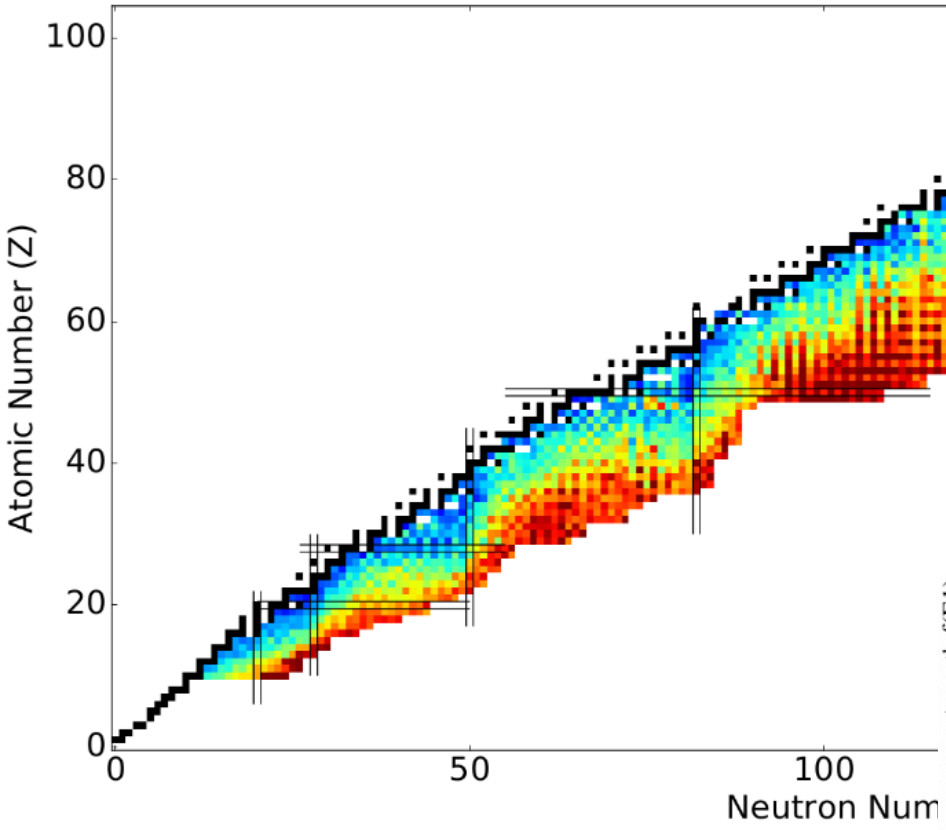
A. Arcones *et al.*, PPNP **94**, 67 (2017) and adapted from Frank Timmes

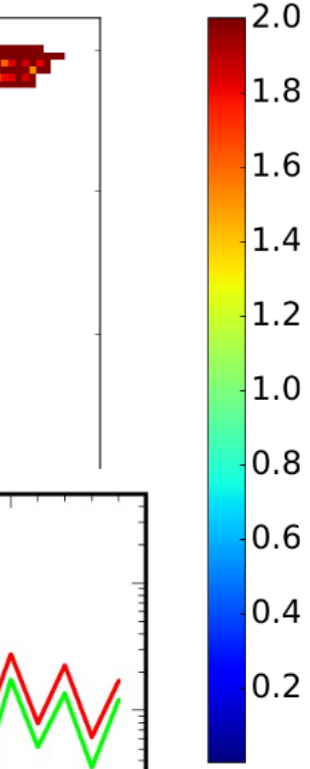
NLD and γSF uncertainties lead to large (n,γ) uncertainties



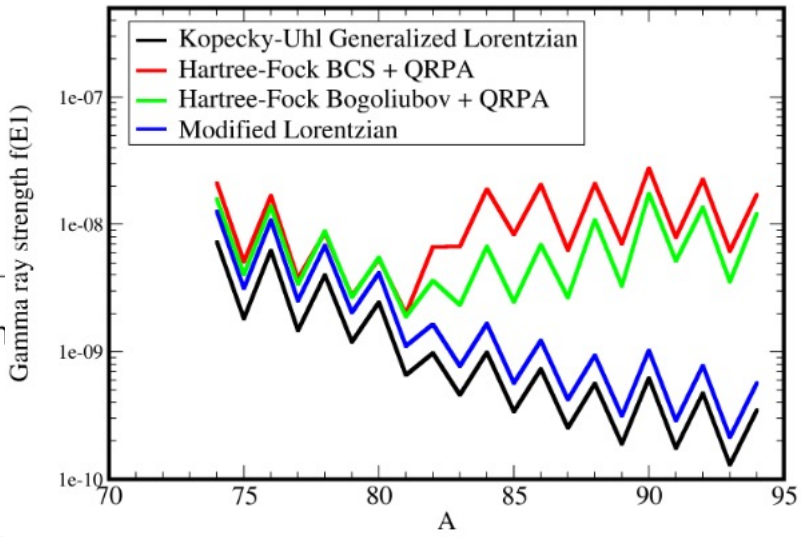
S. Nikas, arXiv:2010.01698
R. Lewis, private comm.

NLD and γSF uncertainties lead to large (n,γ) uncertainties





Ga isotopic chain



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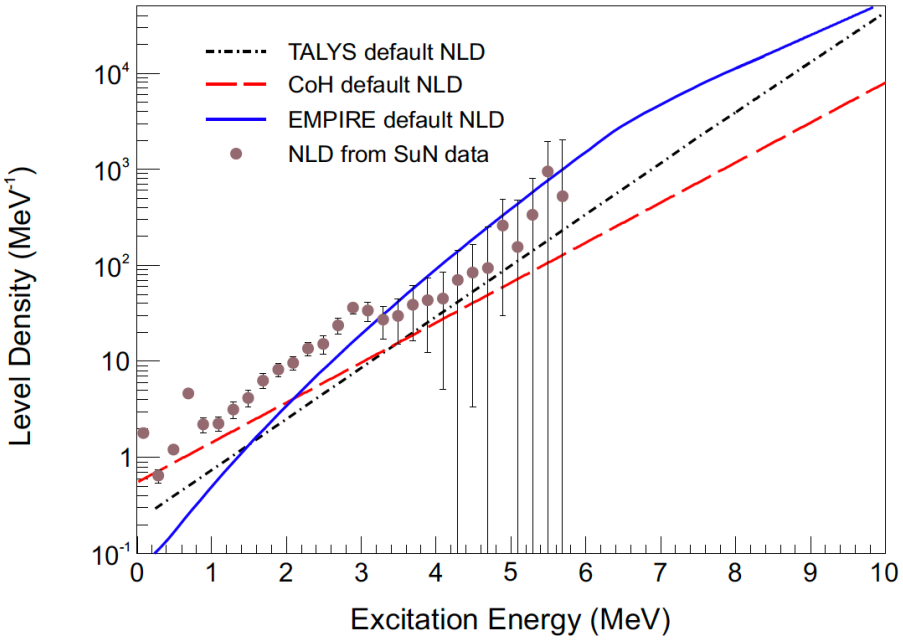
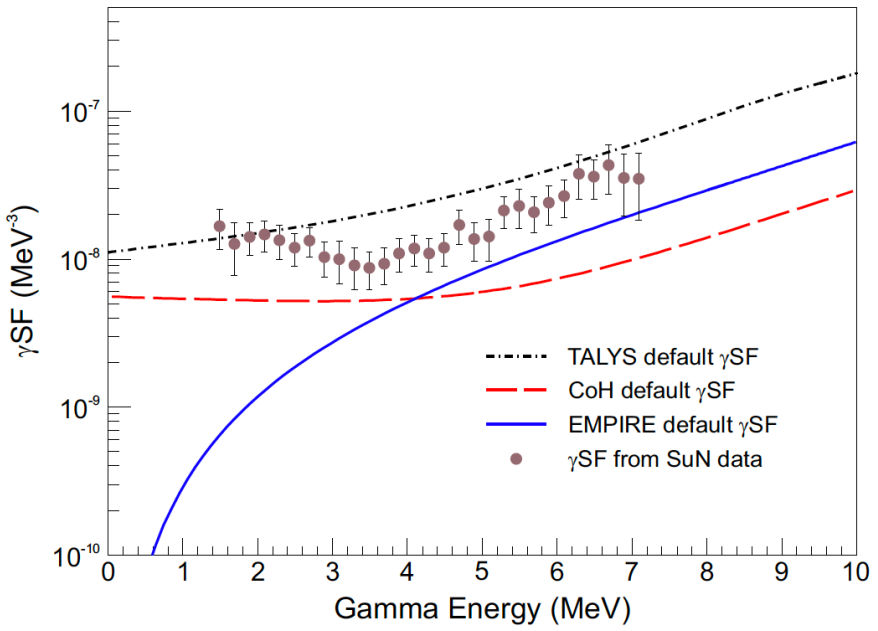
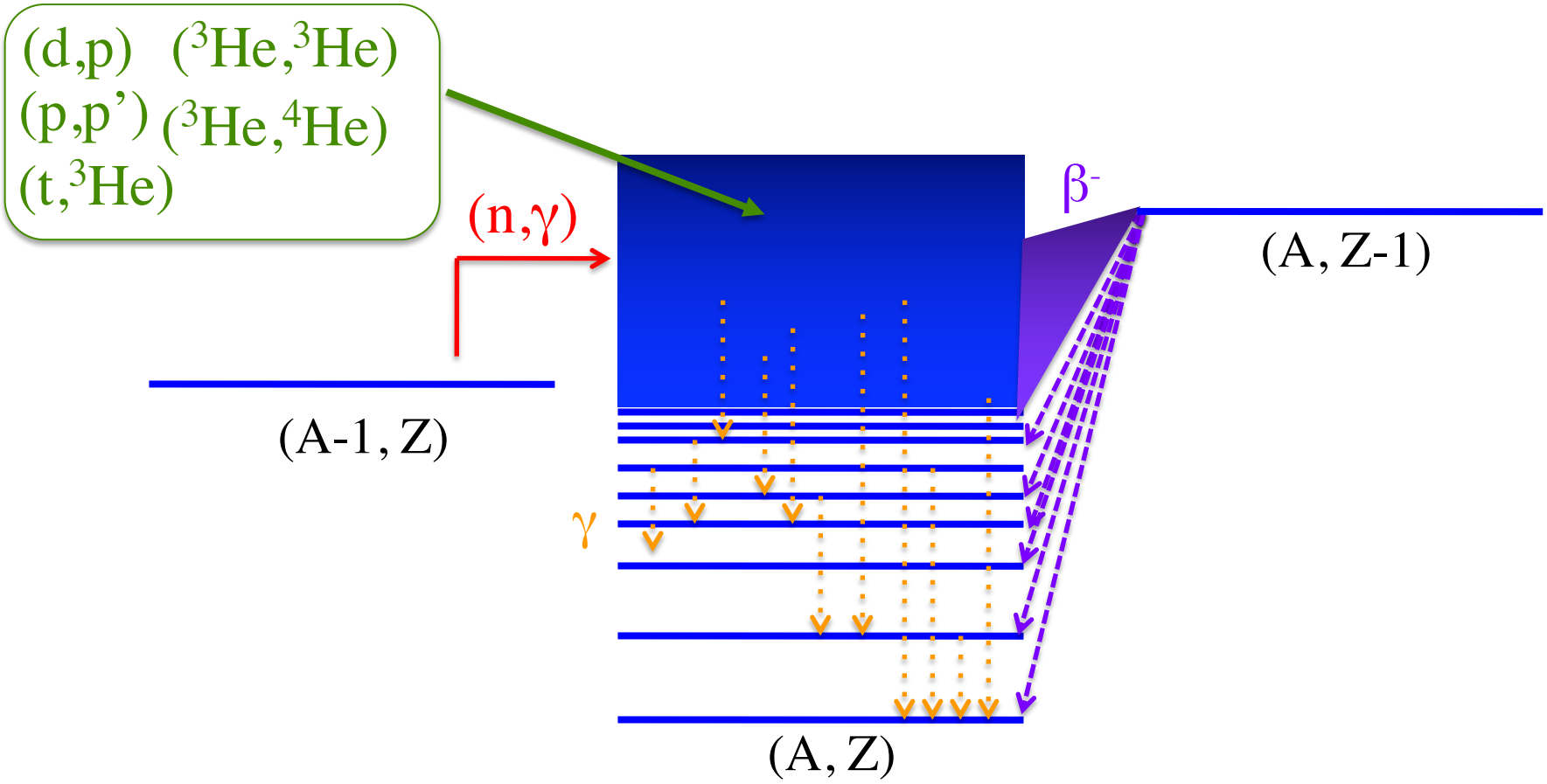




Codes used to calculate NLD and γSF show large variations

S. Nikas, arXiv:2010.01698
R. Lewis, private comm.

Multiple techniques are required to address this question!

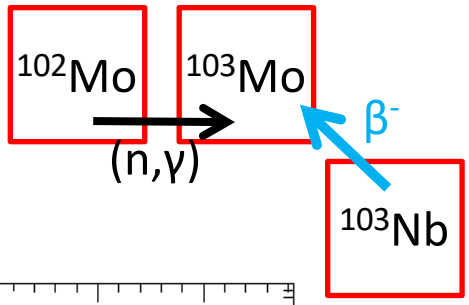


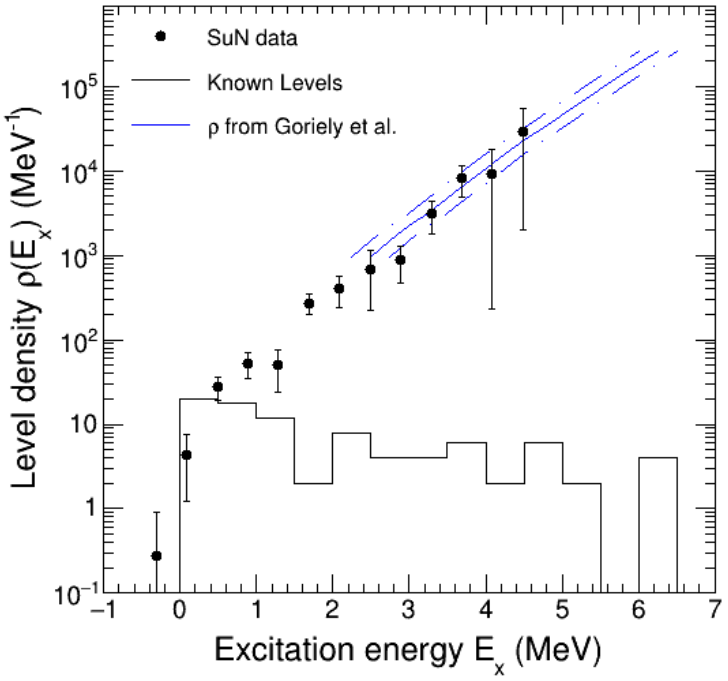
- Need many pathways to constrain statistical properties for short-lived nuclei
- Several techniques developed: **β-Oslo Method**, Inverse-Oslo Method, **Surrogate Reaction Method**

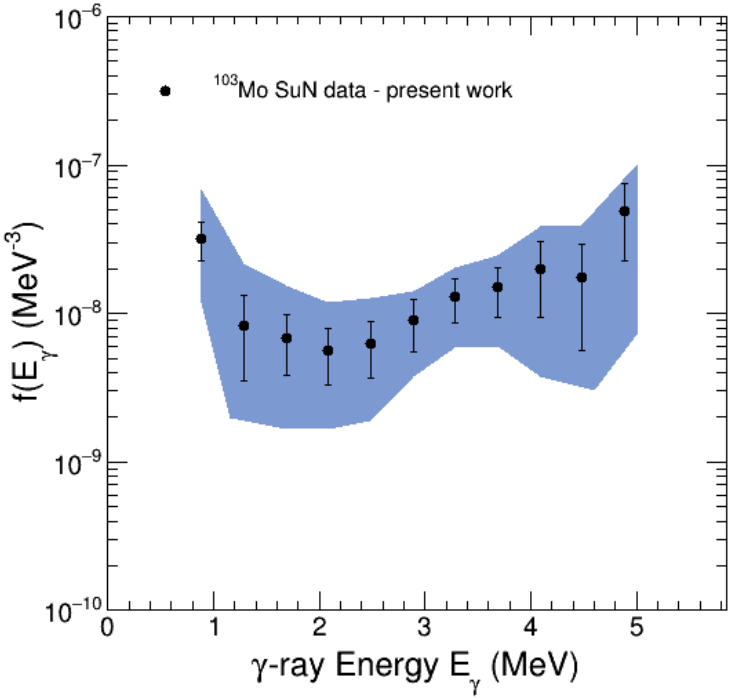
Image Credit: A. Spyrou

β-Oslo Method used to constrain the ^{102}Mo(n,γ)^{103}Mo reaction

- β-decay of radioactive ^{103}Nb beam at the NSCL
- Extraction of NLD, γSF, and (n,γ) rates following Oslo Analysis

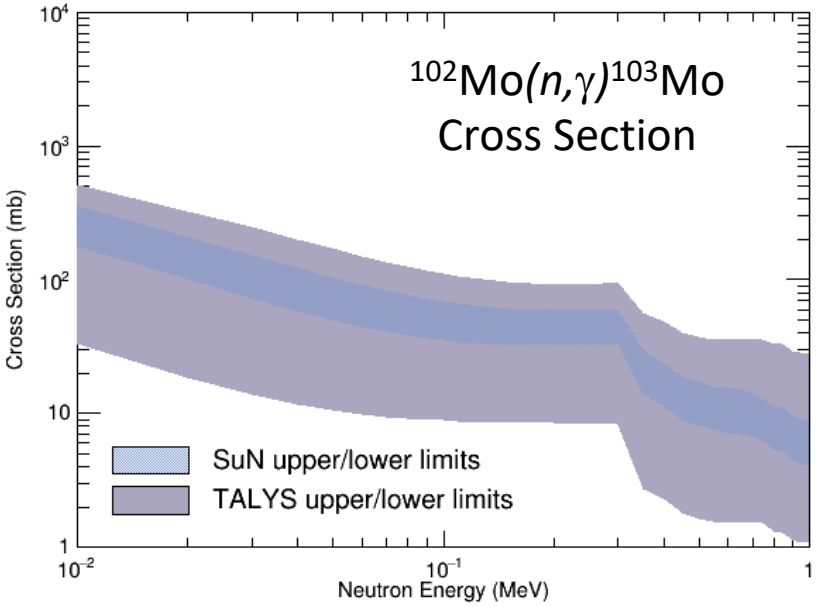


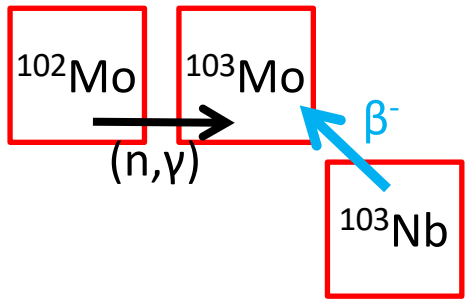




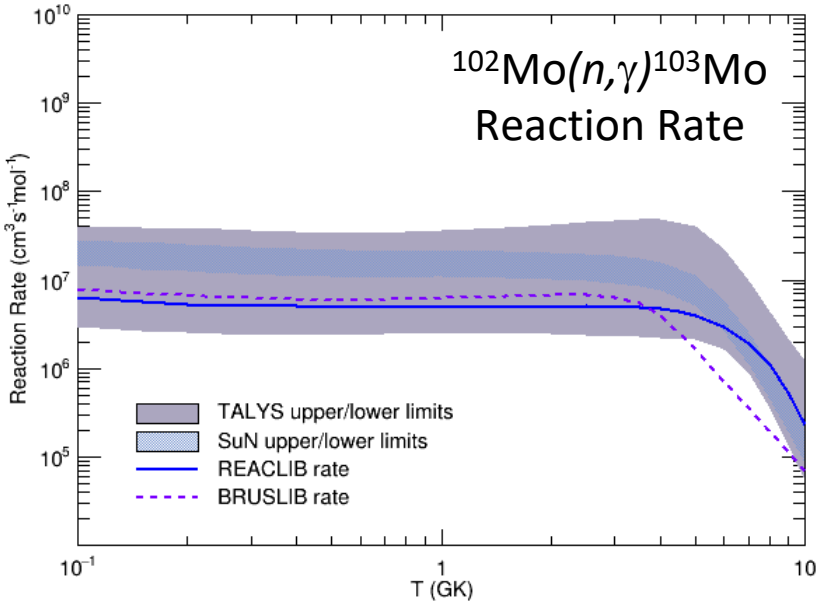
Big consideration: where do the external normalizations come from?
We need new techniques (experiment and theory), nuclear data, and systematic studies!

Experimental constraints on the NLD and γSF reduce uncertainties on (n,γ) cross sections



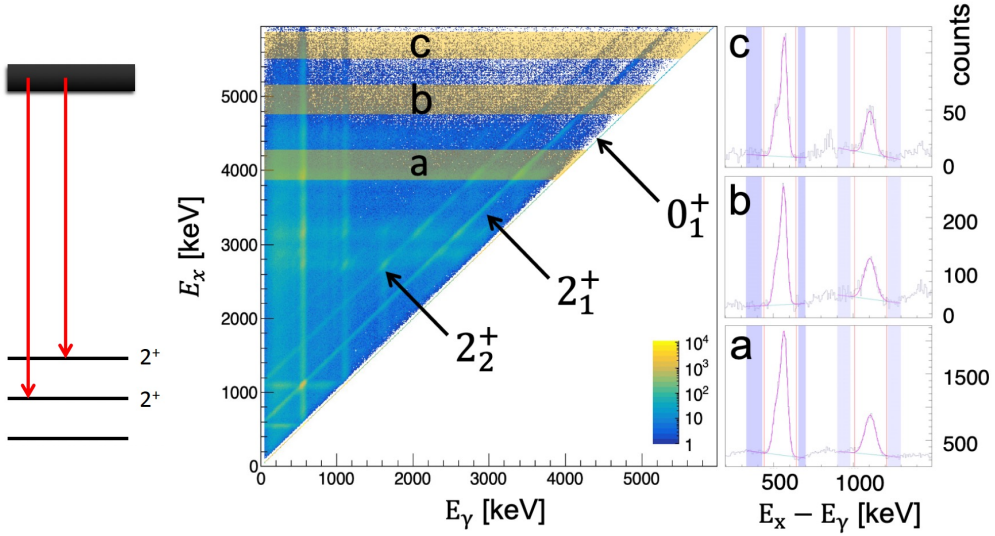


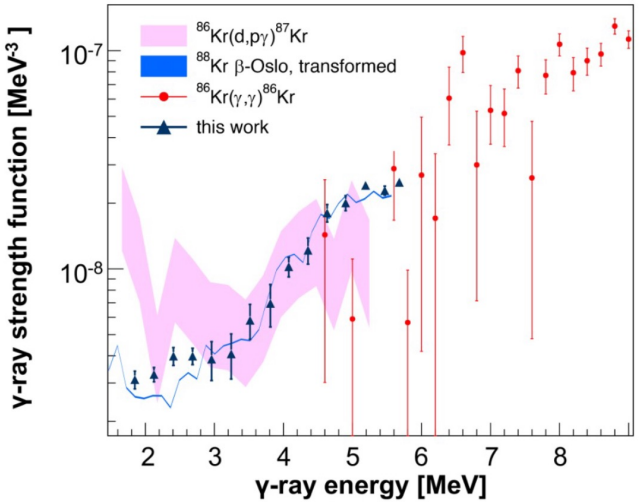
- Reaction rate higher than default values used in astrophysical calculations
- Impacts production of Ru, Rh in stellar environments

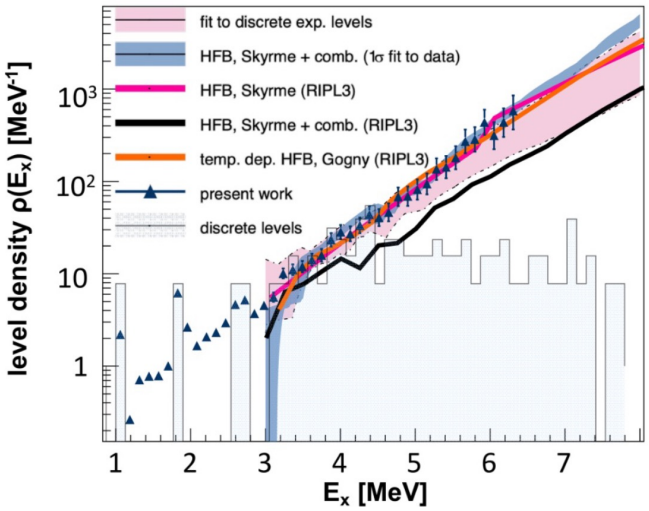


Shape Method: shape of γSF from data

- New normalization technique work is in progress
  - Shape Method (M. Weideking, *et al.* PRC **104**, 014311 (2021)) for Oslo/inverse-Oslo data and ShapeIt for β-Oslo (D. Muecher, A. Spyrou *et al.*, PRC **107**, L011602 (2023))
- Relies on diagonals in the E_x vs. E_γ matrix to extract the shape of the γSF
  - Use γSF in β-Oslo analysis to extract a model-independent level density

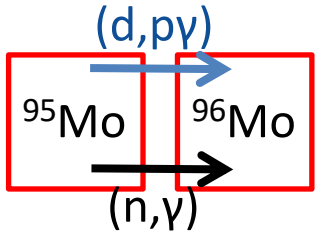


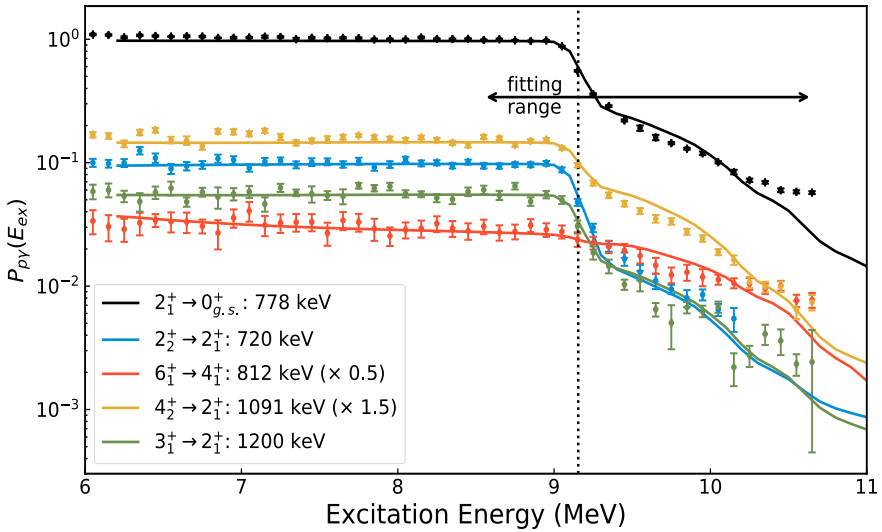




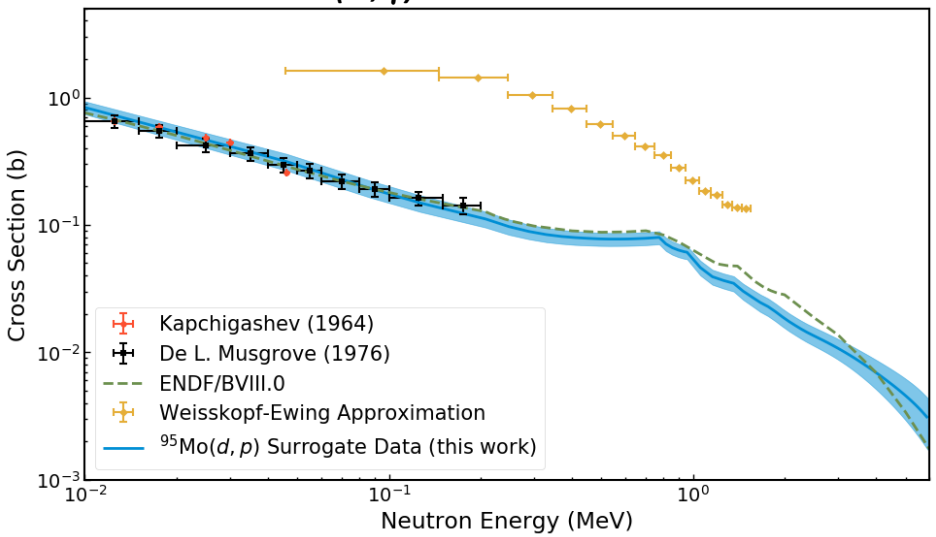
Surrogate Reaction Method

- Particle-γ coincidence measurements in inverse kinematics combined with reaction theory allows for (n,γ) constraints and NLD/γSF soon
- Many inverse kinematics measurements completed, analysis underway



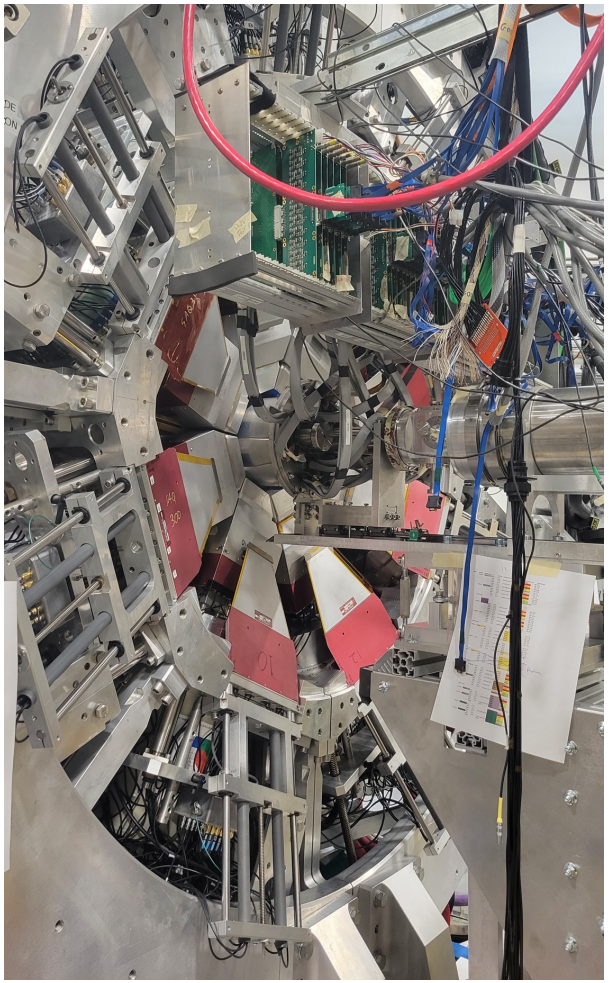


^{95}Mo(*n*,γ)^{96}Mo Cross Section

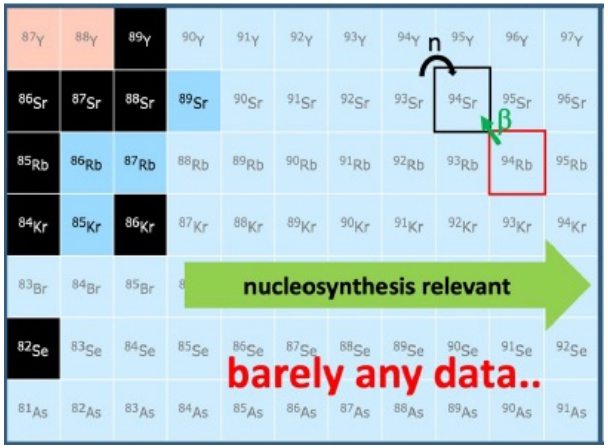


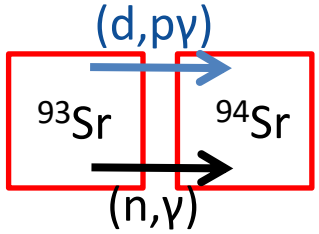
G. Potel *et al.*, PRC 92, 034611 (2015)
J. Escher *et al.*, PRL 121, 052501 (2018)
A. Ratkiewicz, *et al.* PRL 122, 052502 (2019)

Surrogate Reaction Method

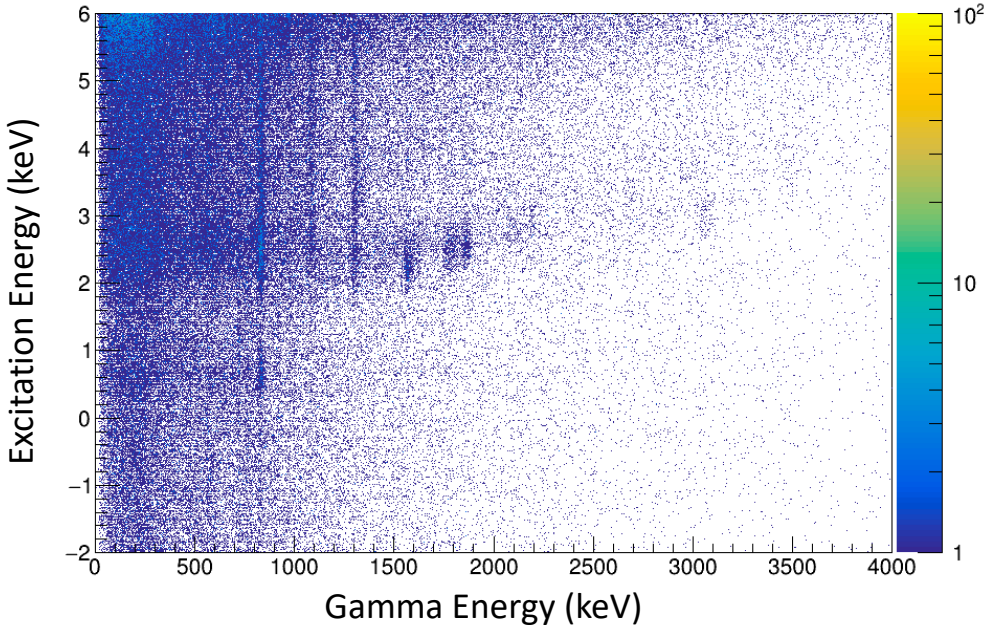


TRIUMF





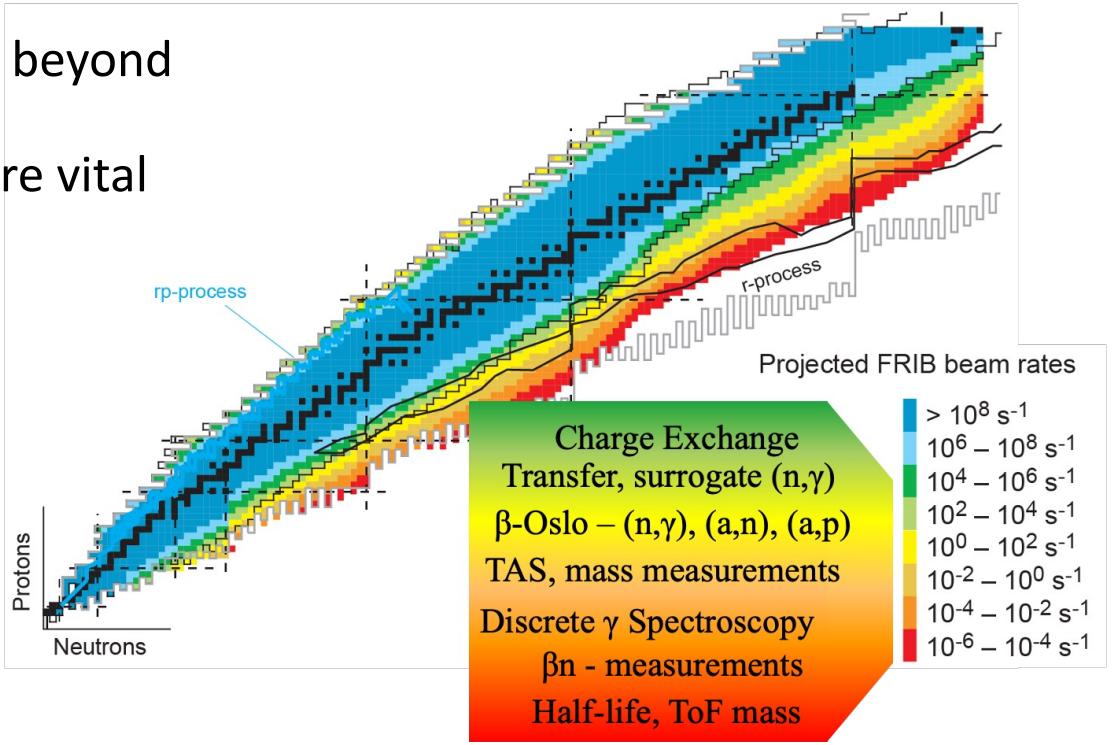
$^{93}Sr(d,p\gamma)^{94}Sr$ to constrain $^{93}Sr(n,\gamma)^{94}Sr$



G. Potel *et al.*, PRC 92, 034611 (2015)
J. Escher *et al.*, PRL 121, 052501 (2018)

Summary and Outlook

- Statistical nuclear properties are needed for astrophysical nucleosynthesis networks and beyond
- Neutron-capture constraints are vital for our understanding of nucleosynthesis, but direct measurements aren't feasible
- β-Oslo method, inverse-Oslo, and Surrogate Reaction Method are indirect techniques for constraining statistical properties far from stability



- Facilities like FRIB and nuCARIBU enable studies of short-lived nuclei far from stability

Image Credit: A. Spyrou

S.N. Liddick, A. Spyrou, *et al.*, Phys. Rev. Lett. **116**, 242502 (2016)

Acknowledgements

Thank you!
Questions?

This work was supported by the US Department of Energy National Nuclear Security Administration through Grant No. DOE-DE-NA0003906 (MSU) and prepared by LLNL under Contract DE-AC52-07NA27344.