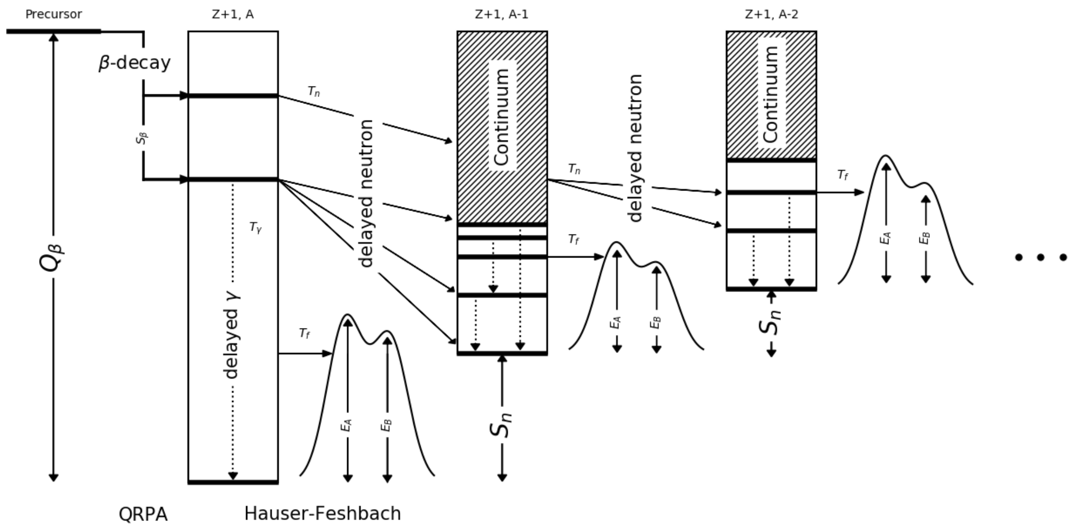
FISSION PROPERTIES RELEVANT FOR GW170817



Nicole Vassh, University of Notre Dame

for

Matthew Mumpower

Los Alamos National Laboratory

Nuclei in the Cosmos 2018

29 June 2018

FIRE Collaboration

Fission In R-process Elements

GW170817 and NSM production of *r*-process nuclei

Much like supernova light curves are powered by the decay chain of ^{56}Ni, kilonovae are also powered by radioactive decays

The kilonova observed following GW170817 suggested the production *r*-process material (lanthanides)

Is there a clear signature from the heaviest, fissioning nuclei (actinides)?

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PHYSICAL REVIEW VOLUME 103, NUMBER 5 SEPTEMBER 1, 1956

Californium-254 and Supernovae*

G. R. BURBIDGE AND F. HOYLE,† *Mount Wilson and Palomar Observatories, Carnegie Institution of Washington, California Institute of Technology, Pasadena, California*

AND

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(Received May 17, 1956)

It is suggested that the spontaneous fission of Cf^{254} with a half-life of 55 days is responsible for the form of the decay light-curves of supernovae of Type I which have an exponential form with a half-life of 55 nights. The way in which Cf^{254} may be synthesized in a supernova outburst, and reasons why the energy released by its decay may dominate all others are discussed. The presence of Tc in red giant stars and of Cf in Type I supernovae appears to be observational evidence that neutron capture processes on both a slow and a fast time-scale have been necessary to synthesize the heavy elements in their observed cosmic abundances.

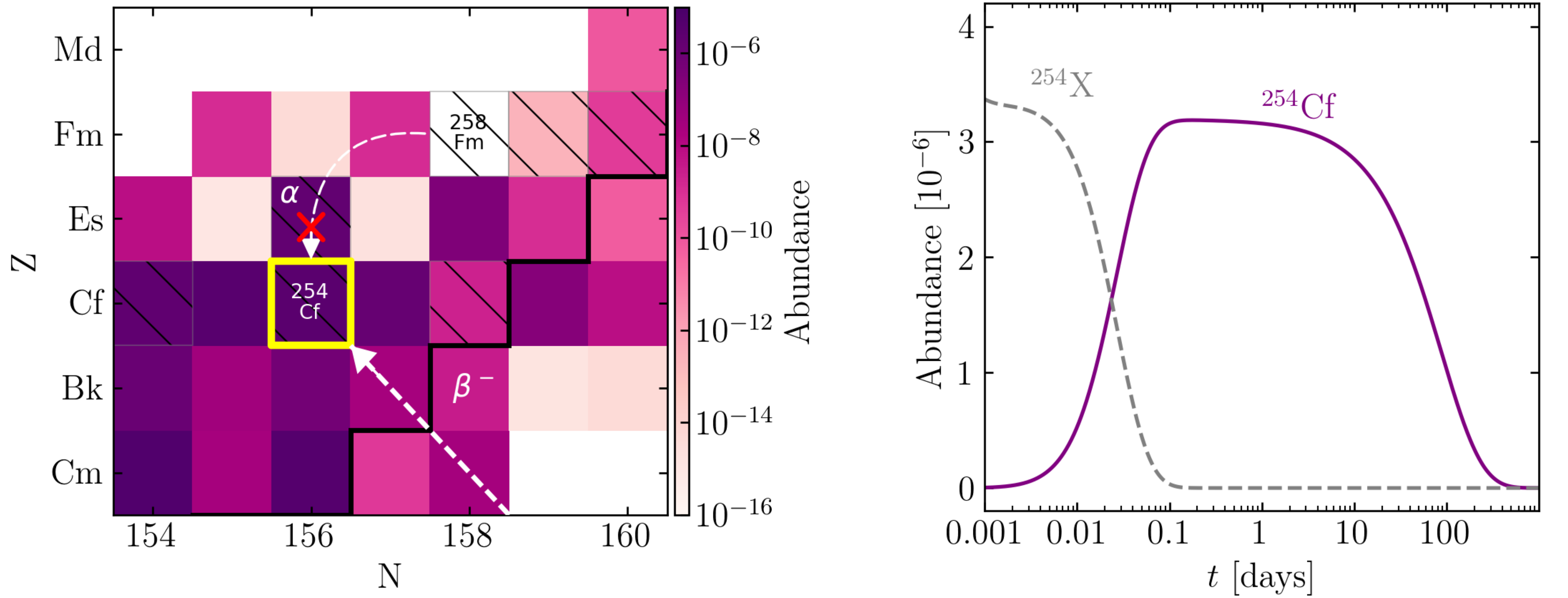
OBSERVATIONAL DATA

A CHARACTERISTIC feature of supernovae of Type I is that after an initial period of 50–100 days the light curve develops an exponential tail corresponding to about 0.0137 magnitudes daily, or a half-life of 55±1 days. Baade has analyzed the records of the supernovae *B* Cassiopeiae and *SN* Ophiuchi,[1] and has shown that their exponential decline is very closely similar to his own observations of the supernova in *IC*

sufficient energy to explain the curve. He suggested that it was built by the endothermic reaction $He^4(\alpha,n)Be^7$, occurring at high temperatures. However, recent work[5–7] suggests that this is most unlikely, since He^4 would be destroyed by the exothermic Salpeter reaction in which C^{12} is produced. An alternative method of production is through spallation reactions of protons (with $E_p \gtrsim 100$ Mev) on C, N, and O, which are known to give large yields of Li, Be, and B.

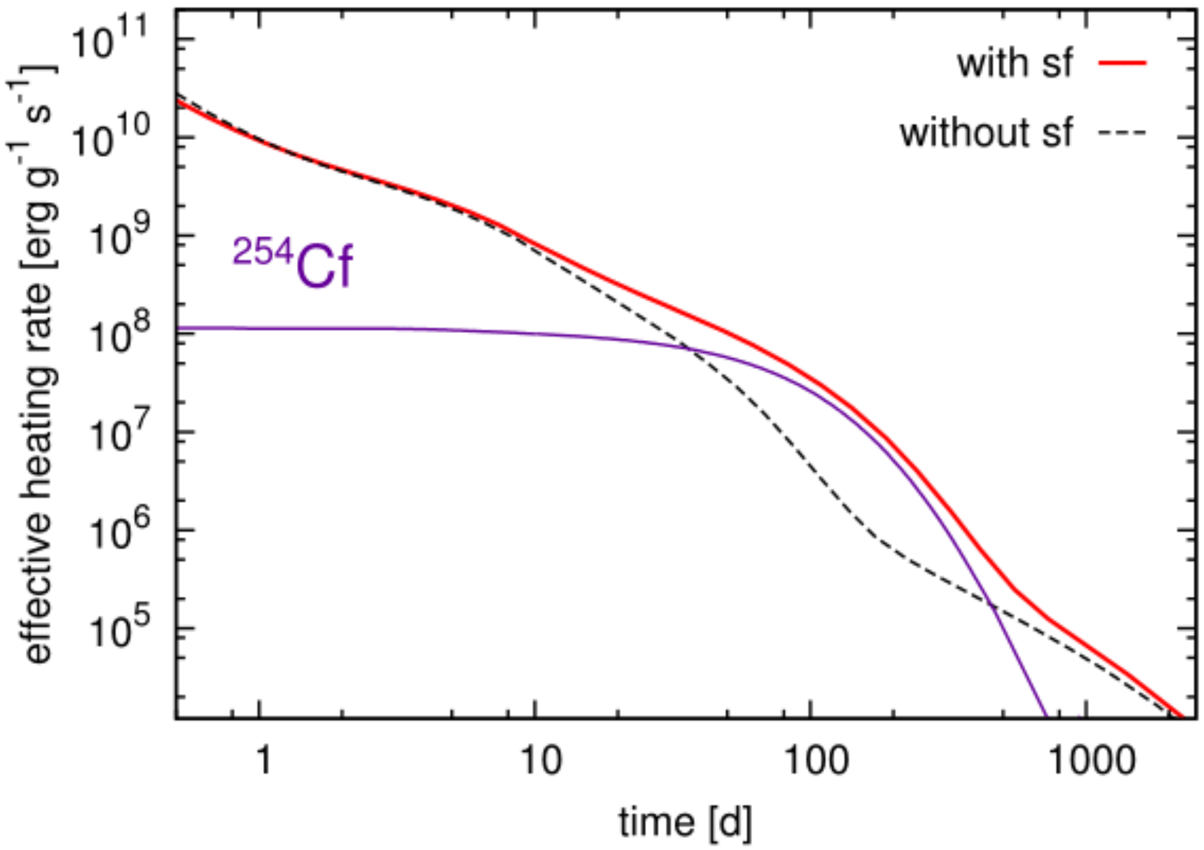
(See also: Baade *et al.* 1956; Huizenga *et al.* 1957; Anders *et al.* 1958…)

^{254}Cf feeding in NSM environments



Zhu, Wollaeger, Vassh, Surman, Sprouse, Mumpower, Möller, McLaughlin, Korobkin, Kawano, Jaffke, Holmbeck, Fryer, Even, Couture, Barnes, submitted 2018 (**arXiv:1806.09724**)

^{254}Cf and effective heating

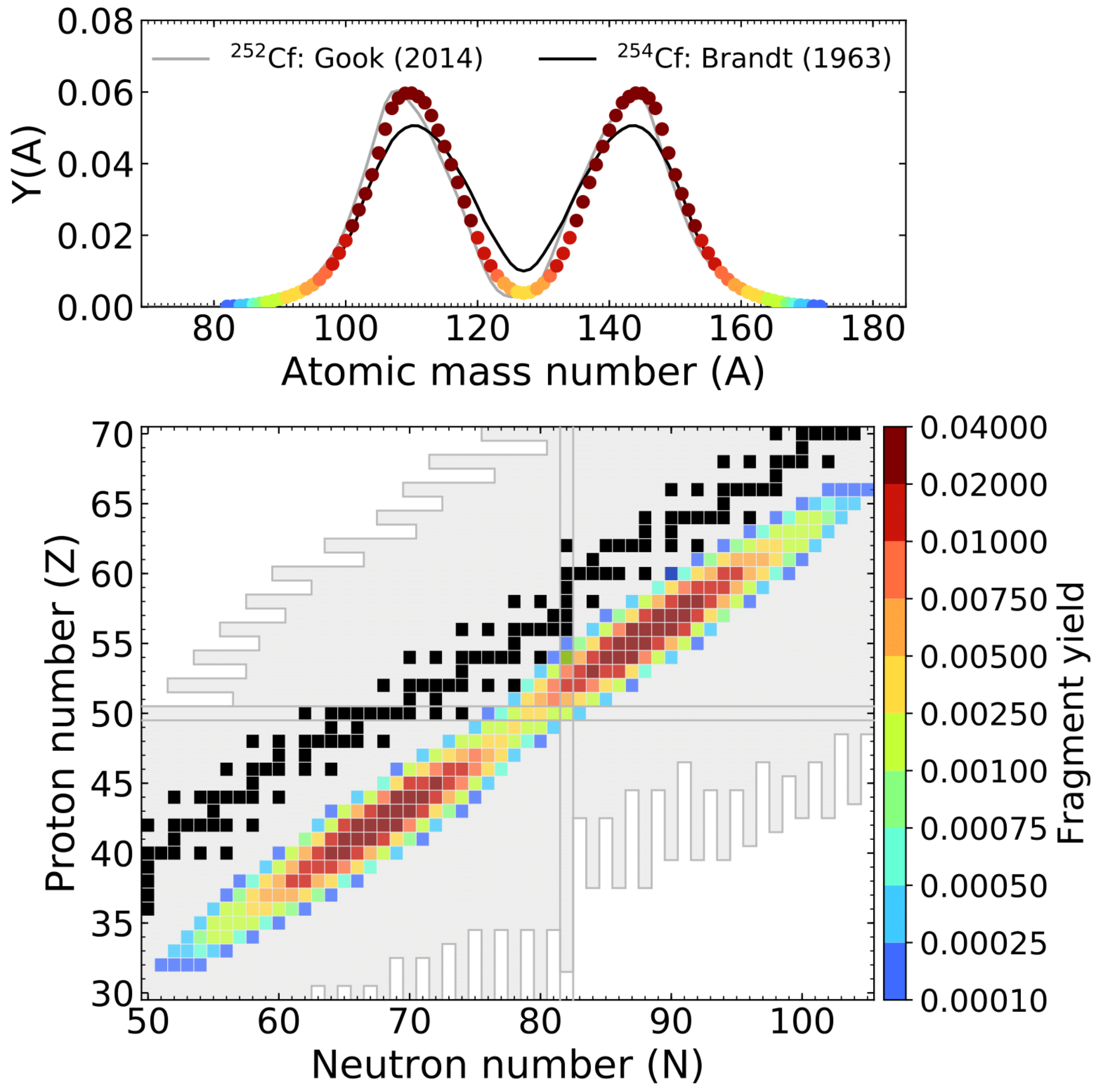


The spontaneous fission of ^{254}Cf is a primary contributor to nuclear heating at late epochs
(See also: Wanajo *et al.* 2014)

Zhu, Wollaeger, Vassh, Surman, Sprouse, Mumpower, Möller, McLaughlin, Korobkin, Kawano, Jaffke, Holmbeck, Fryer, Even, Couture, Barnes, submitted 2018 (**arXiv:1806.09724**)

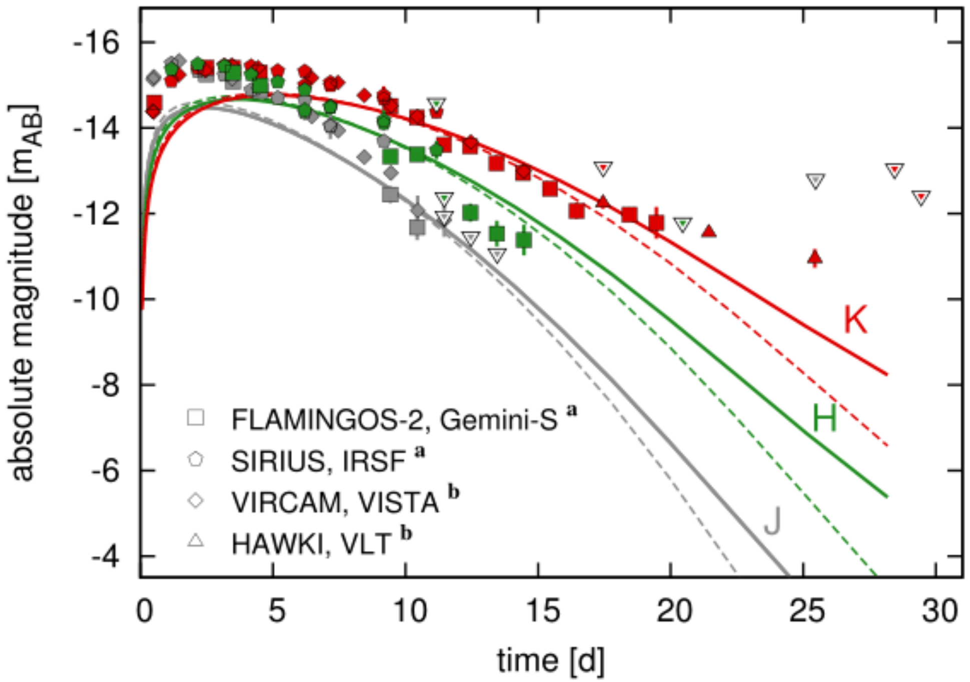
^{254}Cf calculated yields

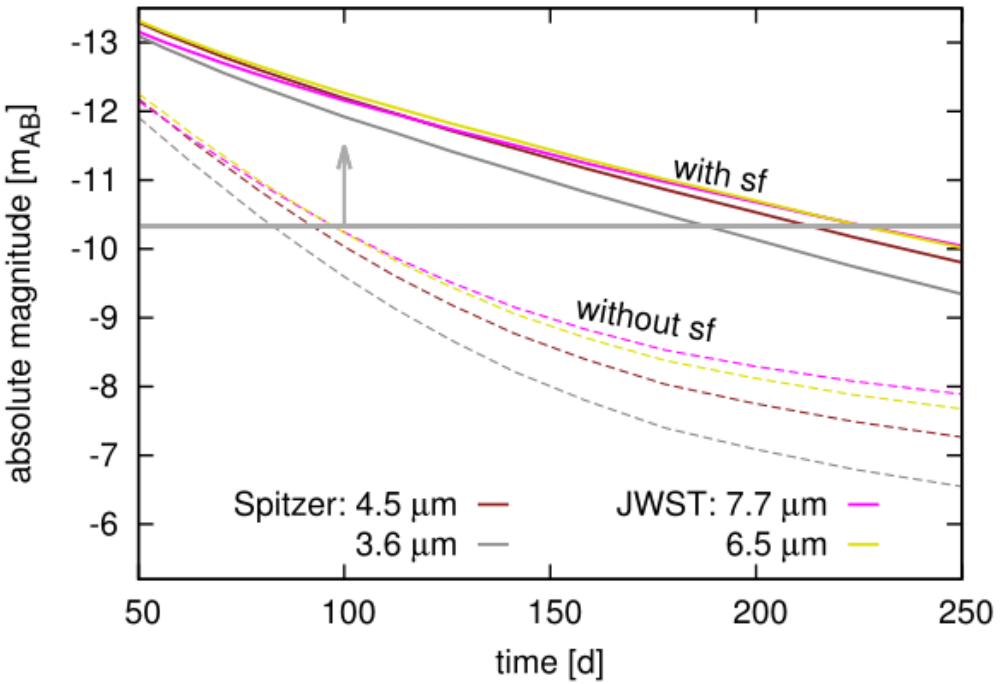
The half-life of ^{254}Cf is known (60 days) but its yield distribution is not



Zhu, Wollaeger, Vassh, Surman, Sprouse, Mumpower, Möller, McLaughlin, Korobkin, Kawano, Jaffke, Holmbeck, Fryer, Even, Couture, Barnes, submitted 2018 (**arXiv:1806.09724**); Jaffke *et al.* in prep.

Observational impact



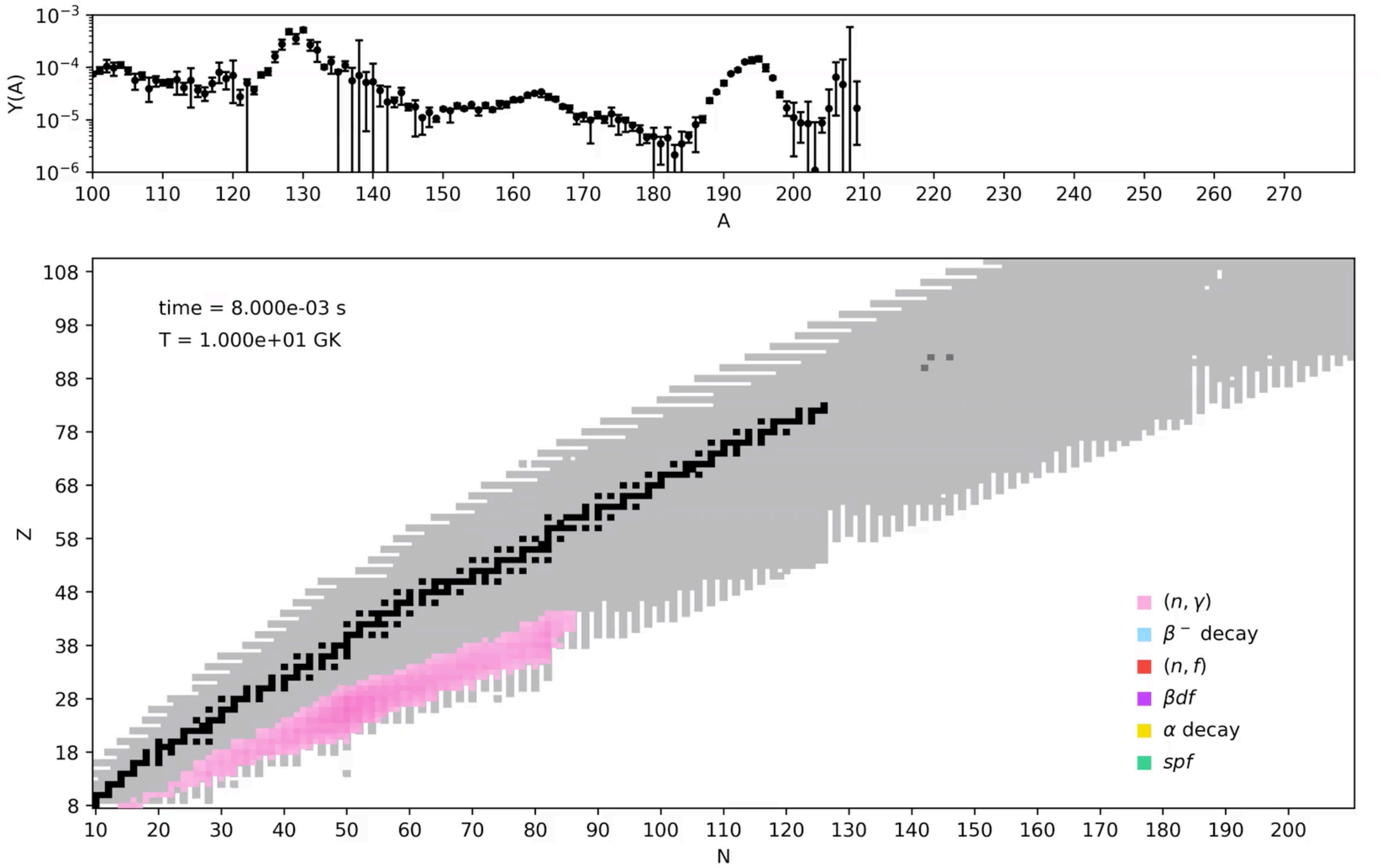


Both near- and middle- IR are impacted by the fission of ^{254}Cf

JWST may be able to detect future kilonovae out to 250 days if actinides are produced in the event

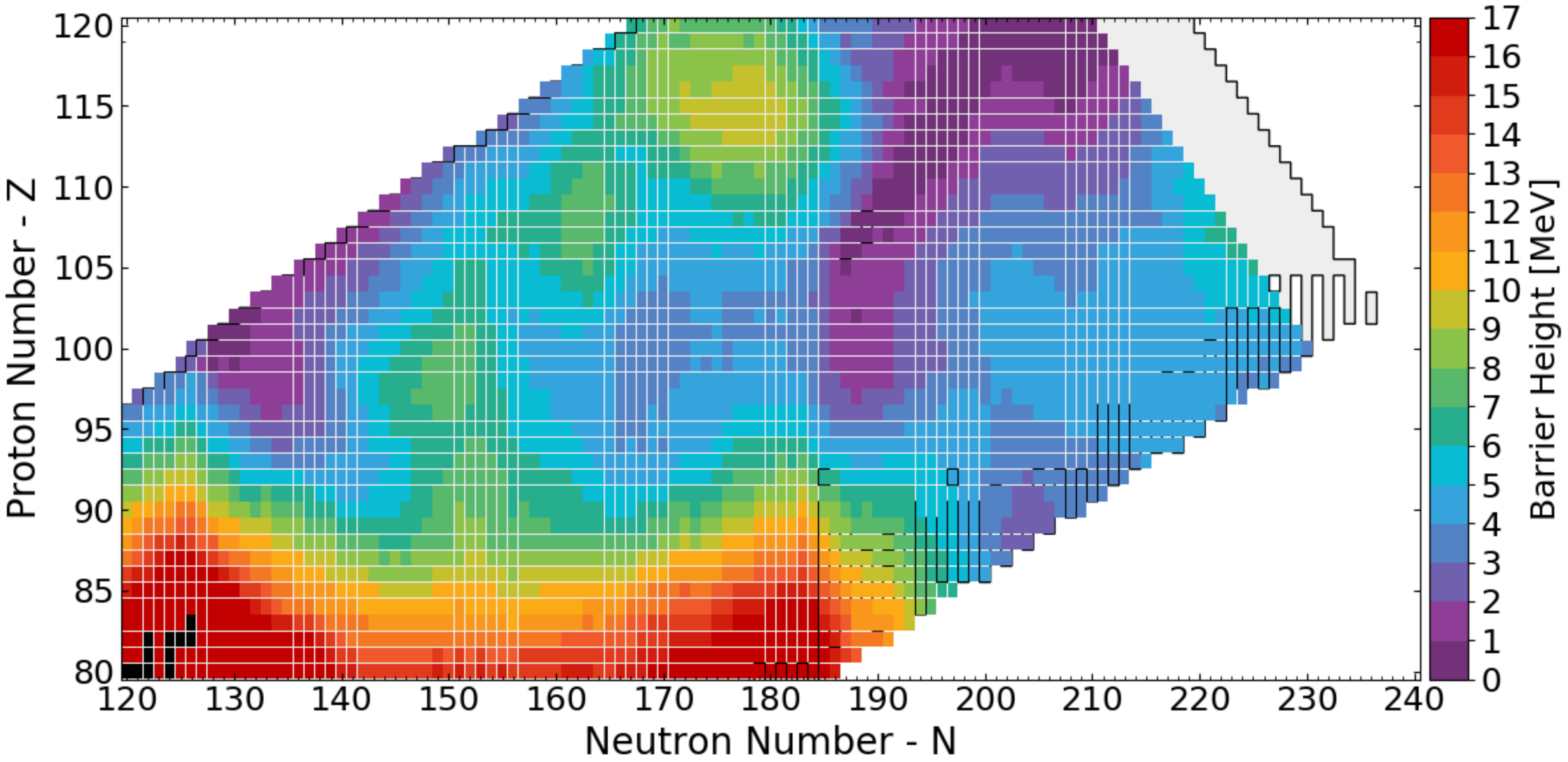
Zhu, Wollaeger, Vassh, Surman, Sprouse, Mumpower, Möller, McLaughlin, Korobkin, Kawano, Jaffke, Holmbeck, Fryer, Even, Couture, Barnes, submitted 2018 (**arXiv:1806.09724**)

Fission and *r*-process abundances



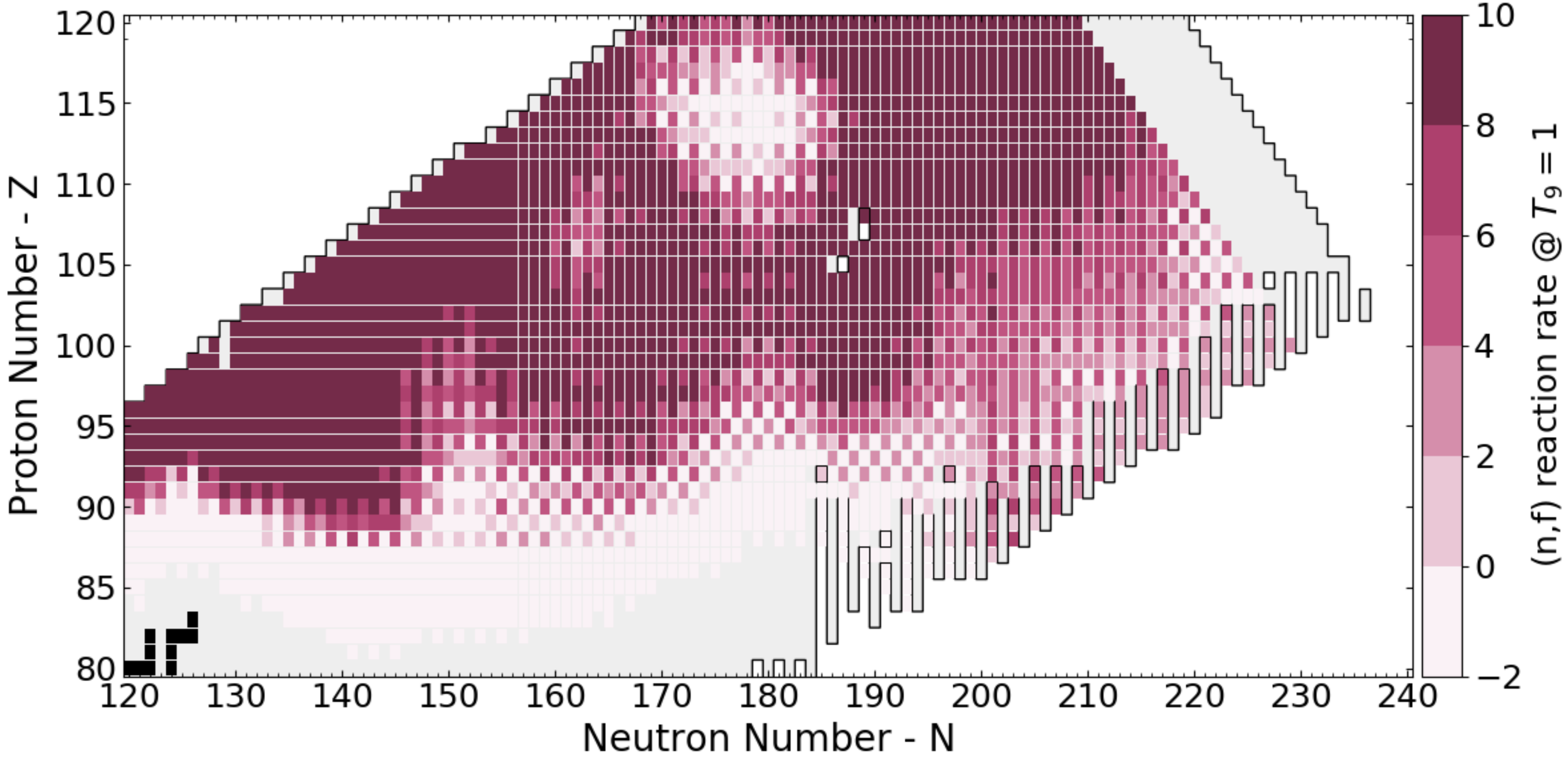
Movie by
N. Vassh

FRLDM estimated barrier heights



Möller et al PRC 91 024310 (2015)

Neutron-induced fission rates



Uses LANL statistical Hauser-Feshbach code and FRLDM barriers

Kawano *et al.* PRC 94 014612 (2016), Mumpower *et al.* in prep

β–delayed neutron emission and fission

Motivation: We want to describe the neutron, γ, and fission competition during de-excitation

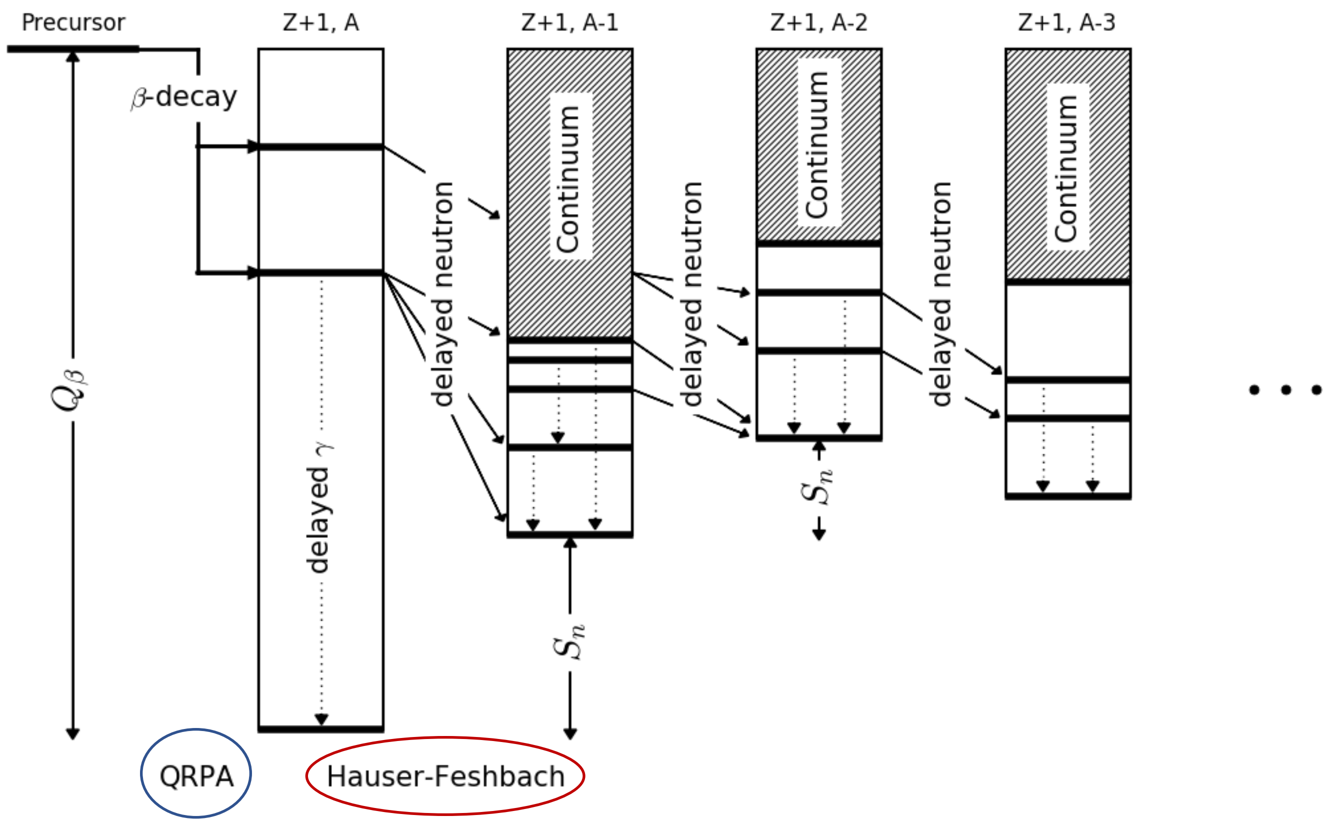
We combine both Quasi-particle Random Phase Approximation (QRPA) and Hauser-Feshbach (HF) theory

This will allow for the calculation of ground state production probabilities, particle multiplicity, and particle spectra

To do this we make use of the Bohr independence hypothesis of compound nucleus formation

Mumpower *et al.* PRC 94 064317 (2016)

Combining QRPA + HF

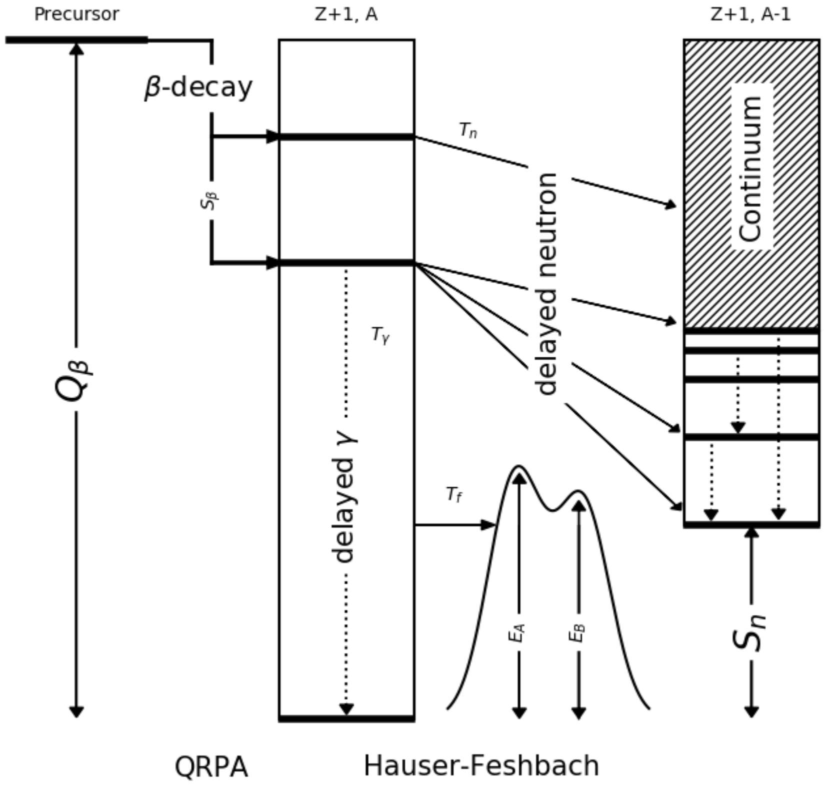


Initial population from the β-decay strength function from P. Möller's QRPA

Follow the statistical decay until all excitation energy is exhausted

Mumpower *et al.* PRC 94 064317 (2016)

QRPA + HF extension to βdf



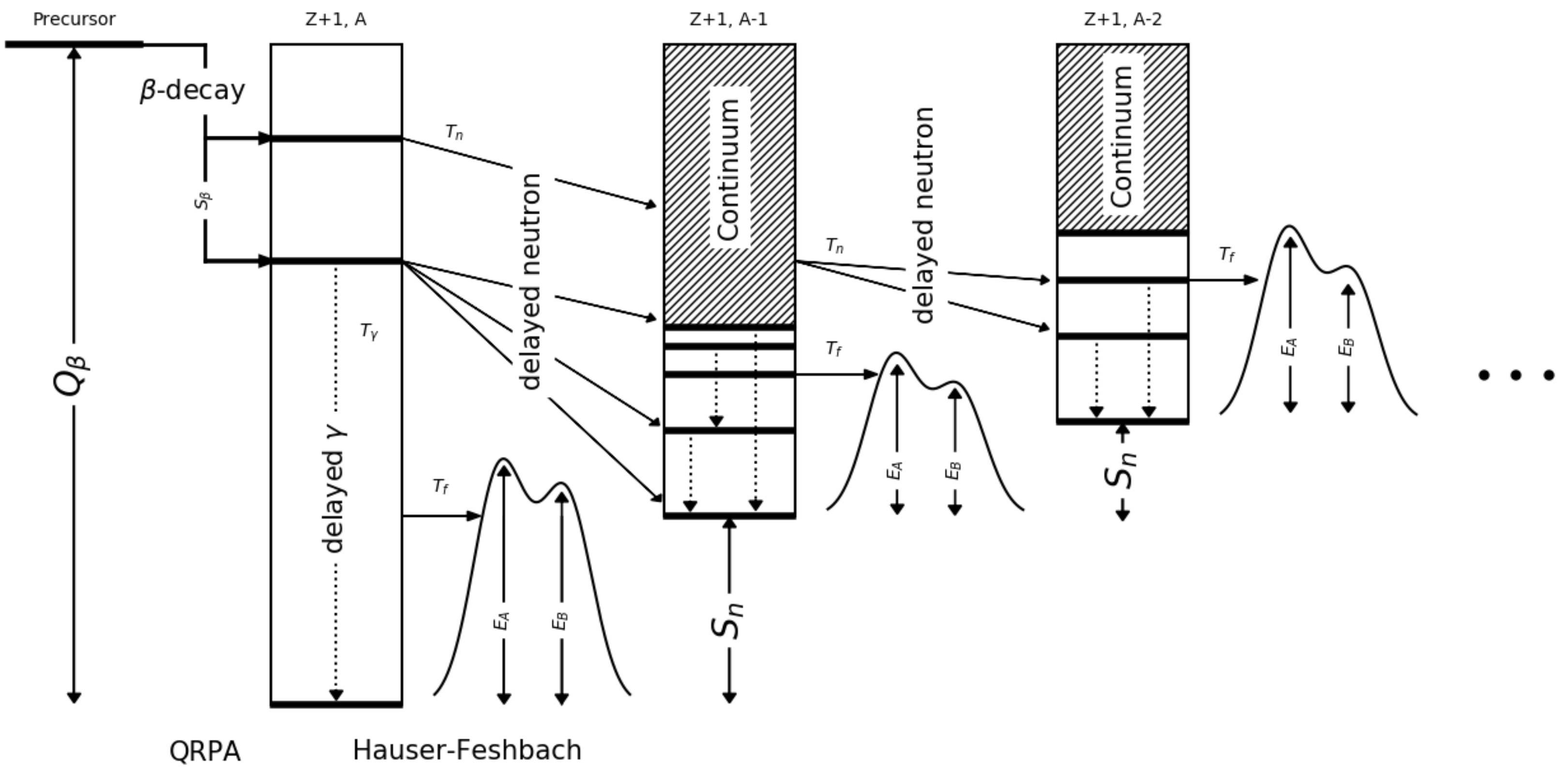
Extend the model to describe β-delayed fission (βdf)

Simplification: one dimensional barrier penetration

Hill-Wheeler form for fission transmission

Mumpower, Kawano, Sprouse, Vassh, Holmbeck, Surman, Möller arXiv:1802.04398 (2018)

Multi-chance βdf



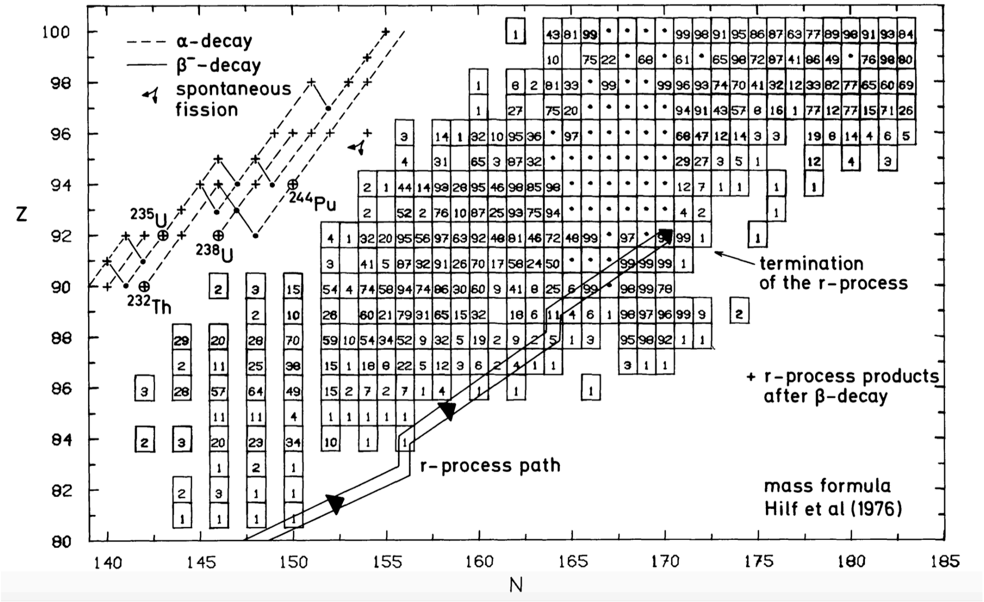
Near the dripline Q_β increases, S_n decreases

Multi-chance βdf: each daughter may fission

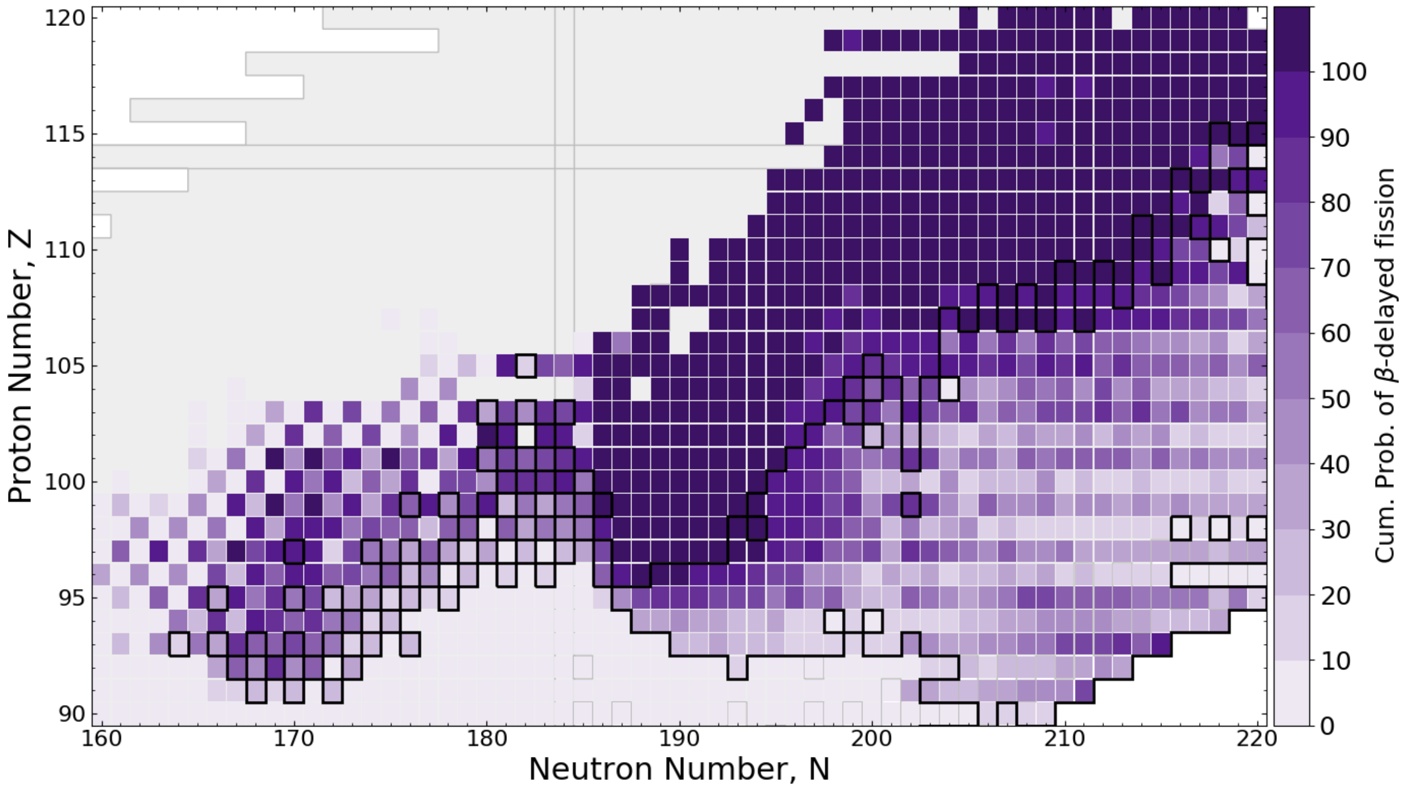
The yields in this decay mode are a convolution of many fission yields!

Mumpower, Kawano, Sprouse, Vassh, Holmbeck, Surman, Möller arXiv:1802.04398 (2018)

Cumulative βdf probability



Thielemann, Metzinger, and Klapdor (1983)



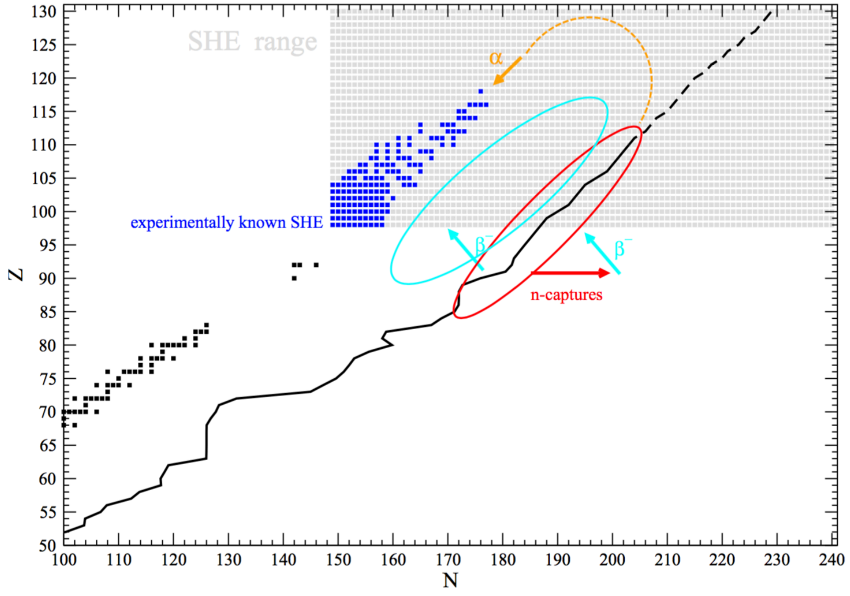
βdf occupies a large amount of real estate in the NZ-plane

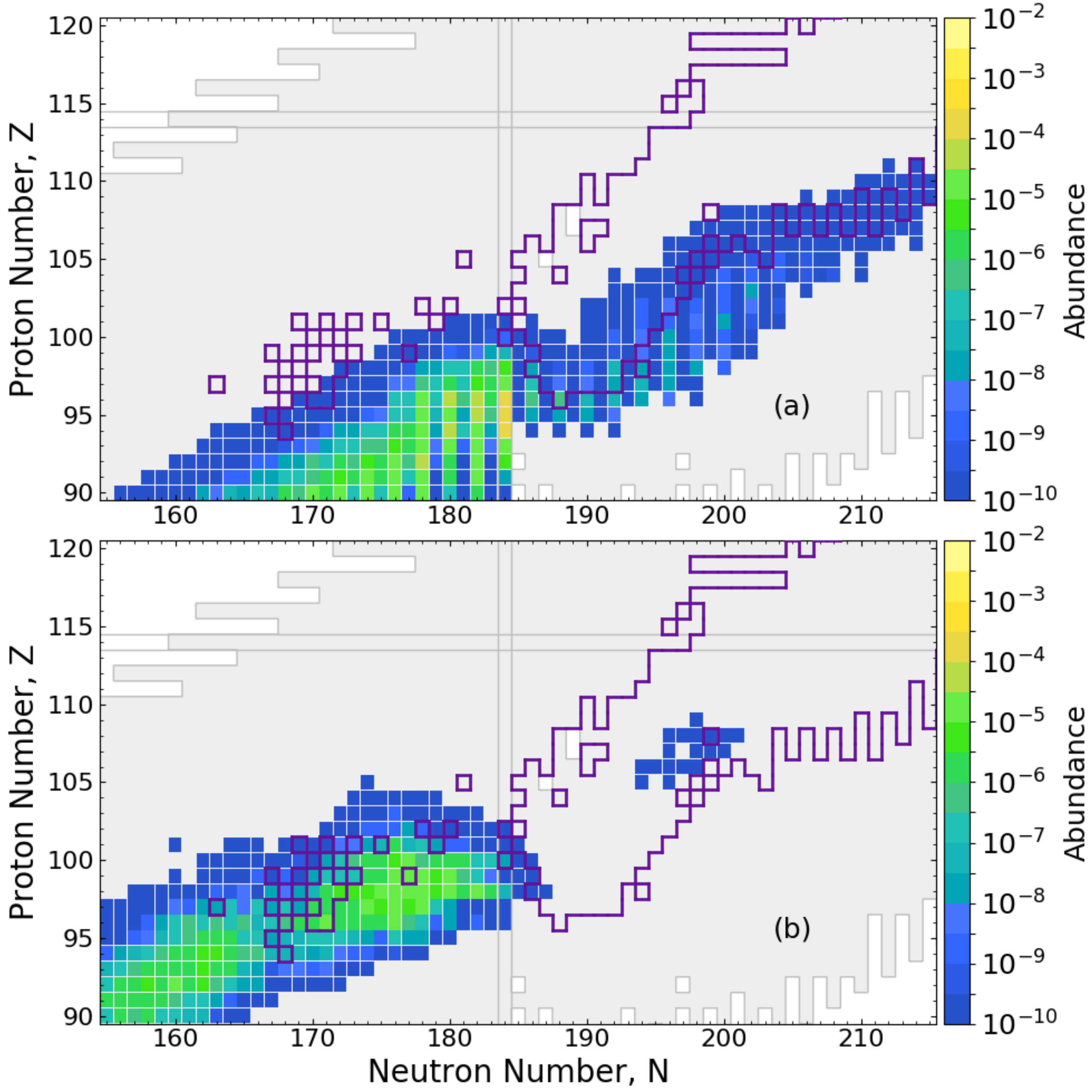
(Multi-chance βdf outlined in black)

Mumpower, Kawano, Sprouse, Vassh, Holmbeck, Surman, Möller arXiv:1802.04398 (2018)

Application to *r* process in NSM ejecta

previous calculations with Z<100 identified possibility to circumvent region with βdf probability ~100% (Petermann et al 2012)

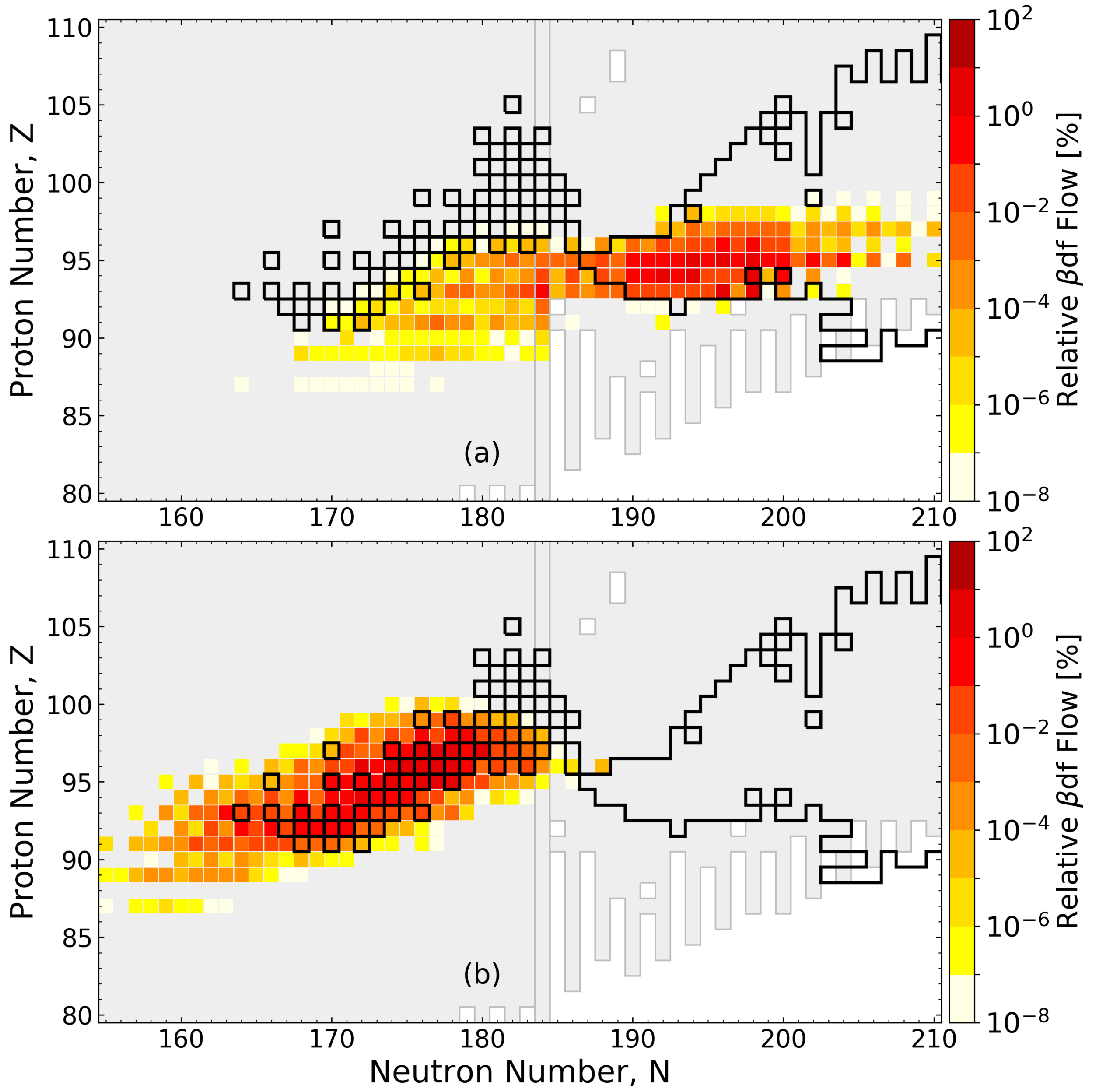




βdf alone can prevent the production of superheavy elements in nature

Mumpower, Kawano, Sprouse, Vassh, Holmbeck, Surman, Möller arXiv:1802.04398 (2018)

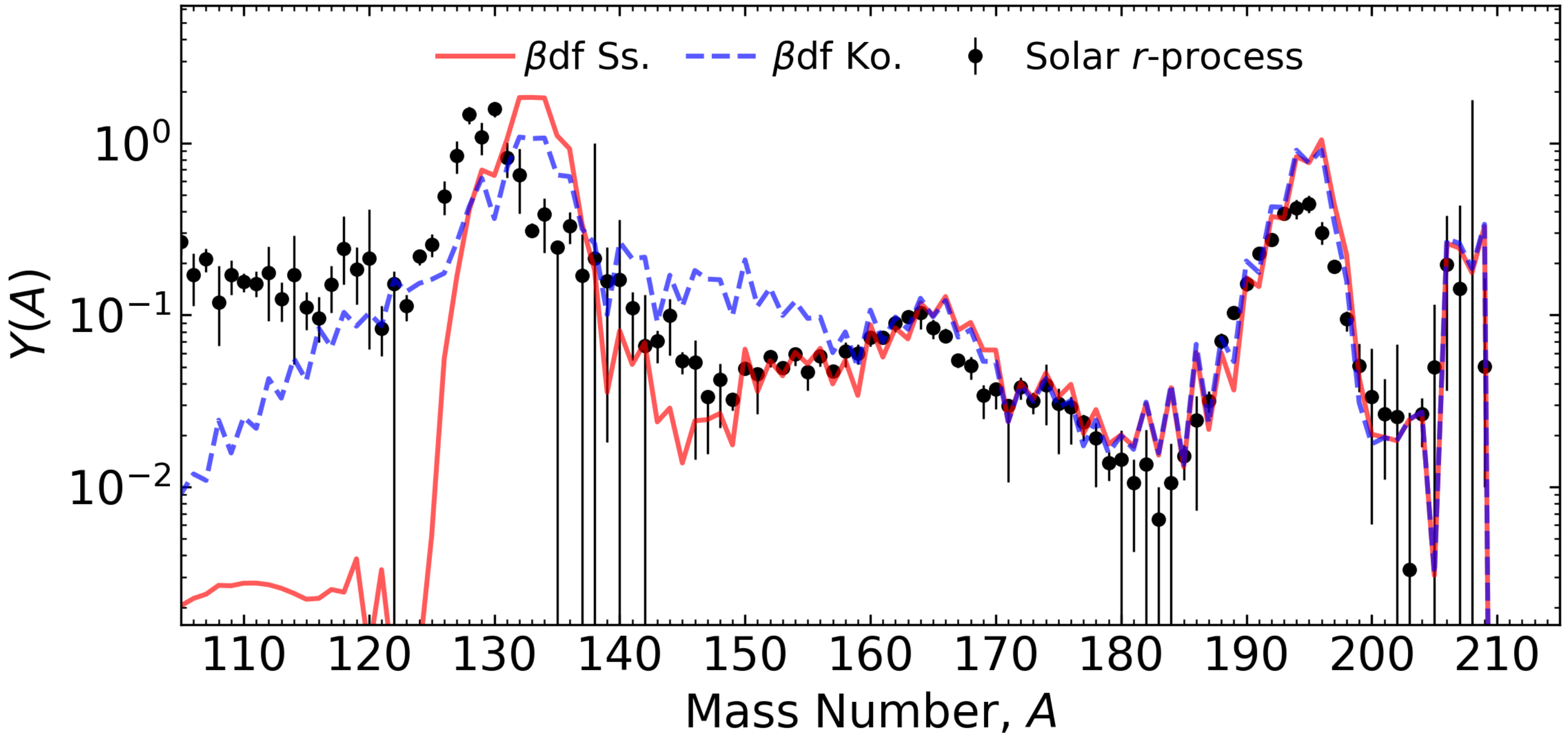
Multi-chance βdf in the *r* process



Multi-chance βdf contributes at both early and late times in neutron star merger ejecta conditions

Mumpower, Kawano, Sprouse, Vassh, Holmbeck, Surman, Möller arXiv:1802.04398 (2018)

βdf Impact on final abundances



Network calculation of neutron star merger ejecta with FRDM2012 inputs

βdf can shape the final pattern near the *A* = 130 peak

Mumpower, Kawano, Sprouse, Vassh, Holmbeck, Surman, Möller arXiv:1802.04398 (2018)

SUMMARY

LANL has made recent progress in describing

neutron-induced fission • β-delayed fission • fission yields

These properties substantially influence nucleosynthetic yields

The production of ^{254}Cf is important for late-time kilonova observations and is tied to the morphology of the ejecta

FRLDM yields *COMING SOON*!

Results at MatthewMumpower.com

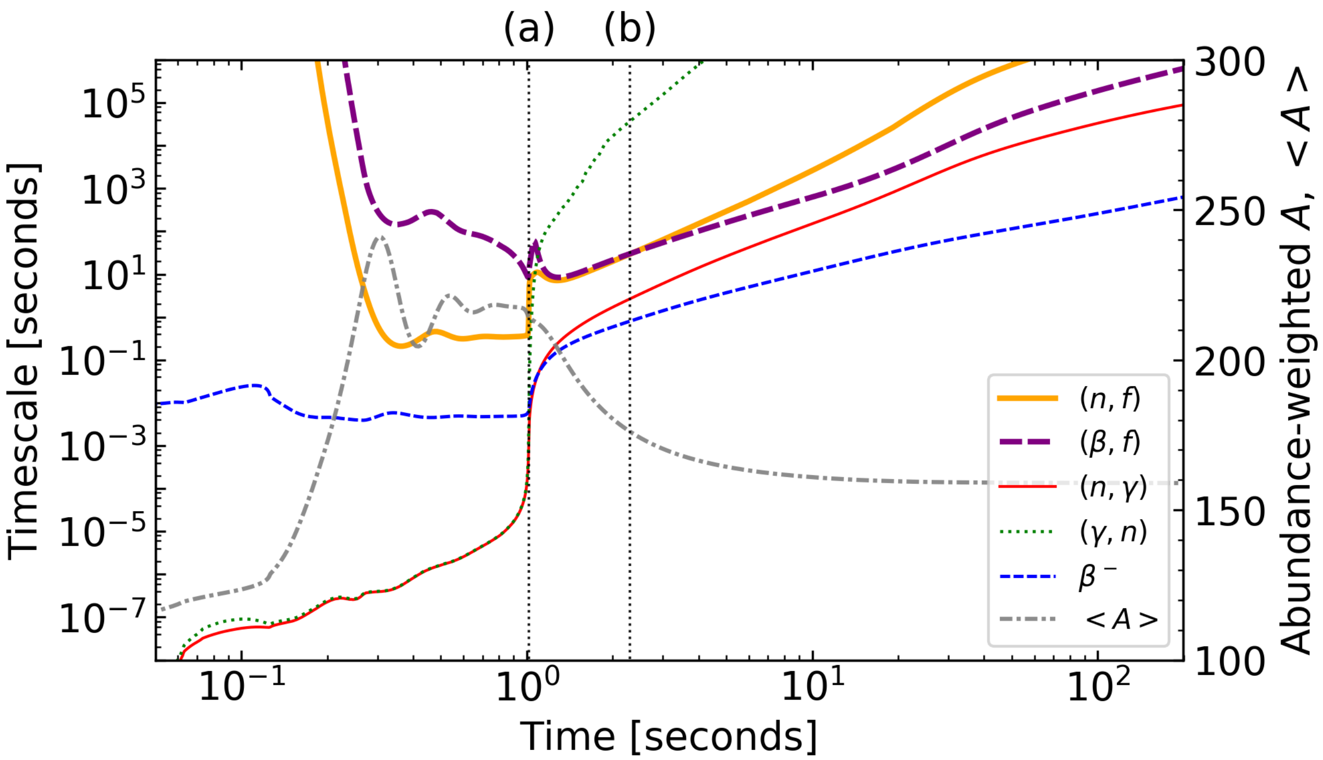
SPECIAL THANKS TO

My collaborators

J. Barnes, A. J. Couture, W. P Even, C. F. Fryer, E. Holmbeck, P. Jaffke, T. Kawano, O. Korobkin, G. C. McLaughlin, P. Möller, T. Sprouse, R. Surman, N. Vassh, M. Verriere & Y. Zhu

■ Students ■ Postdocs

Neutron-induced vs β-delayed fission



βdf overtakes (n,f) during the decay back to stability

High thermalization efficiency and large Q-value → influential for early-epoch nuclear heating

Mumpower, Kawano, Sprouse, Vassh, Holmbeck, Surman, Möller arXiv:1802.04398 (2018)