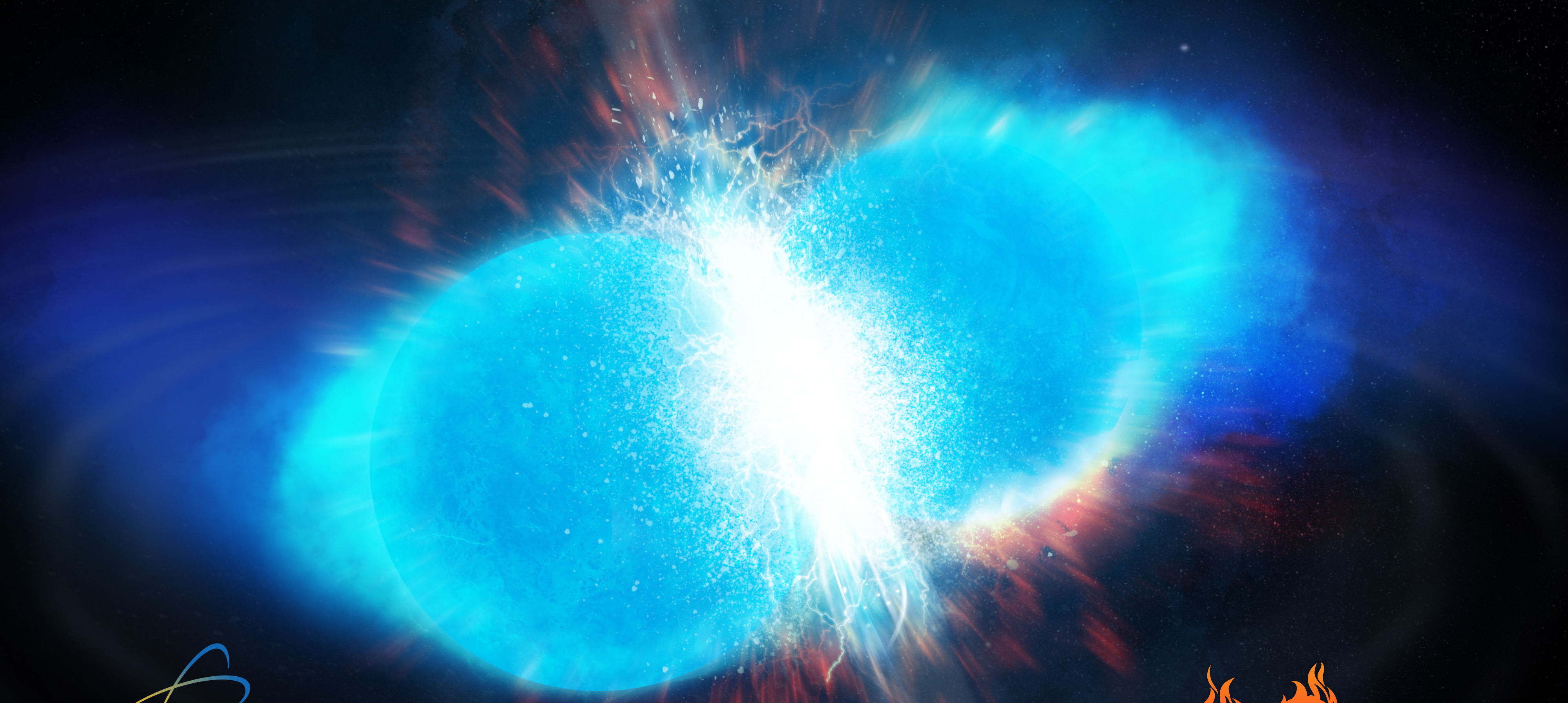
NUCLEAR FISSION FOR THE r-PROCESS IN THE ERA OF MULTI-MESSENGER OBSERVATIONS



Los Alamos NATIONAL LABORATORY EST. 1943

LA-UR-19-23312

MATTHEW MUMPOWER

ECT r-process Workshop*

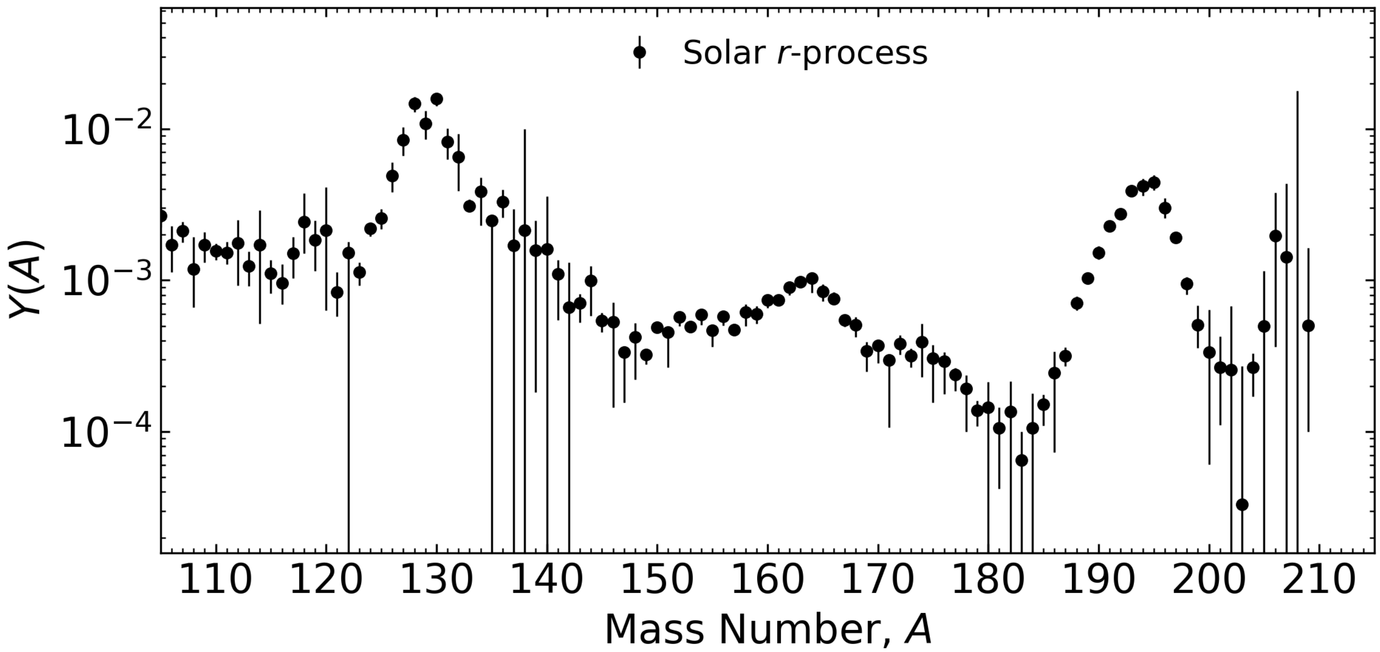
Tuesday July 2nd 2019

FIRE Collaboration

Fission In R-process Elements

WHAT IS THE SITE OF HEAVY ELEMENT FORMATION?

THE ANSWER TO THIS QUESTION REQUIRES



Knowledge of astrophysical conditions (variations in current simulations)

Knowledge of nuclear physics inputs (1000's of unknown species / properties)

(Both are needed to model the nucleosynthesis)

And precise observations!

In other words, the solution is quite difficult...

Beers & Christlieb ARAA (2005) • Metzger *et al.* MNRAS (2010) • Barnes *et al.* ApJ (2016) • Côté ***et al.*** ApJ (2018)

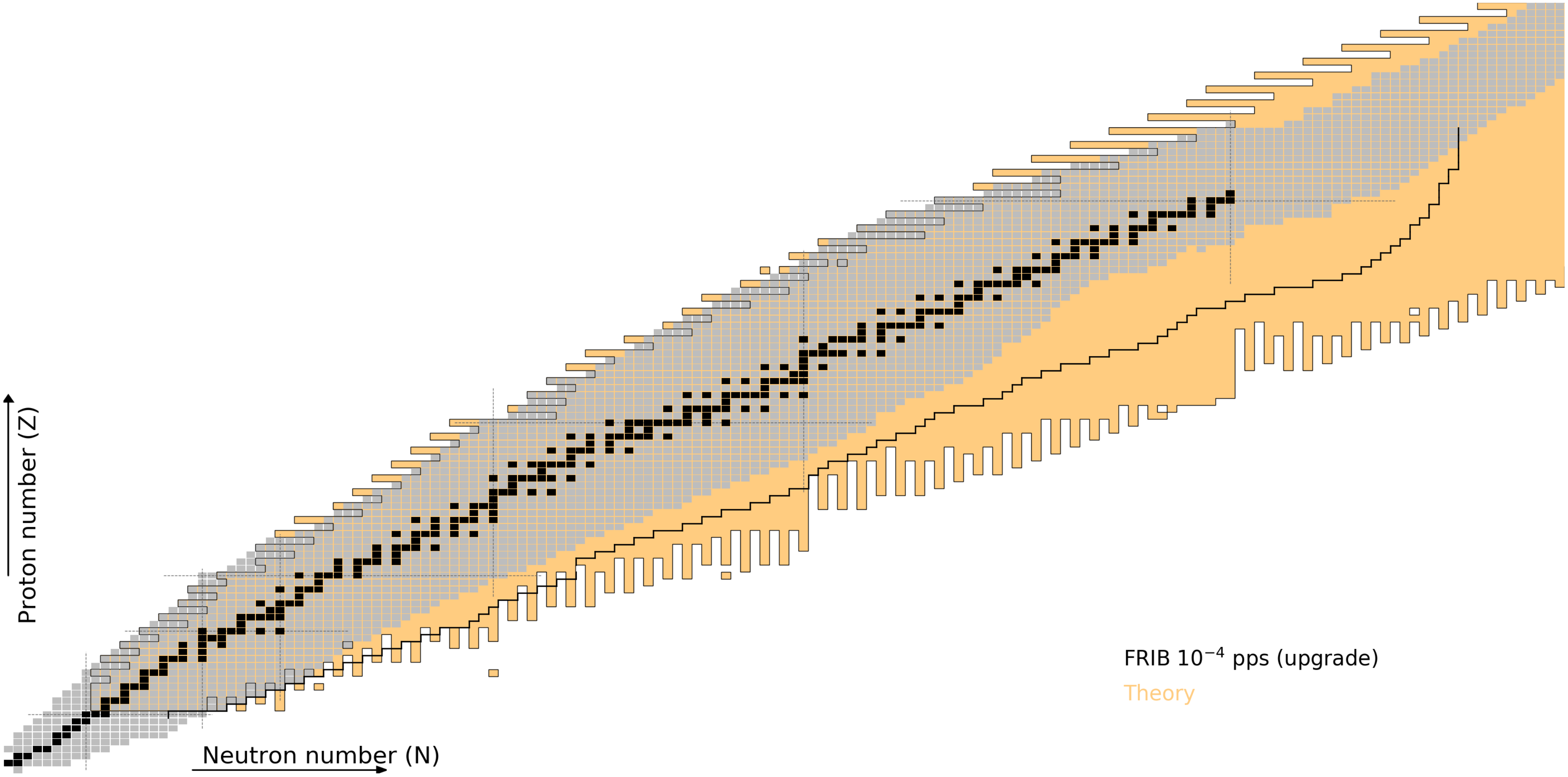
INPUTS FROM NUCLEAR PHYSICS

1st order: masses, β-decay rates, capture rates & fission

Dillmann *et al.* EPJA (2002) • Aprahamian ***et al.*** (2018) • See review paper: **Mumpower** *et al.* PPNP 86 (2016)

MUCH WILL BE MEASURED AT FRIB

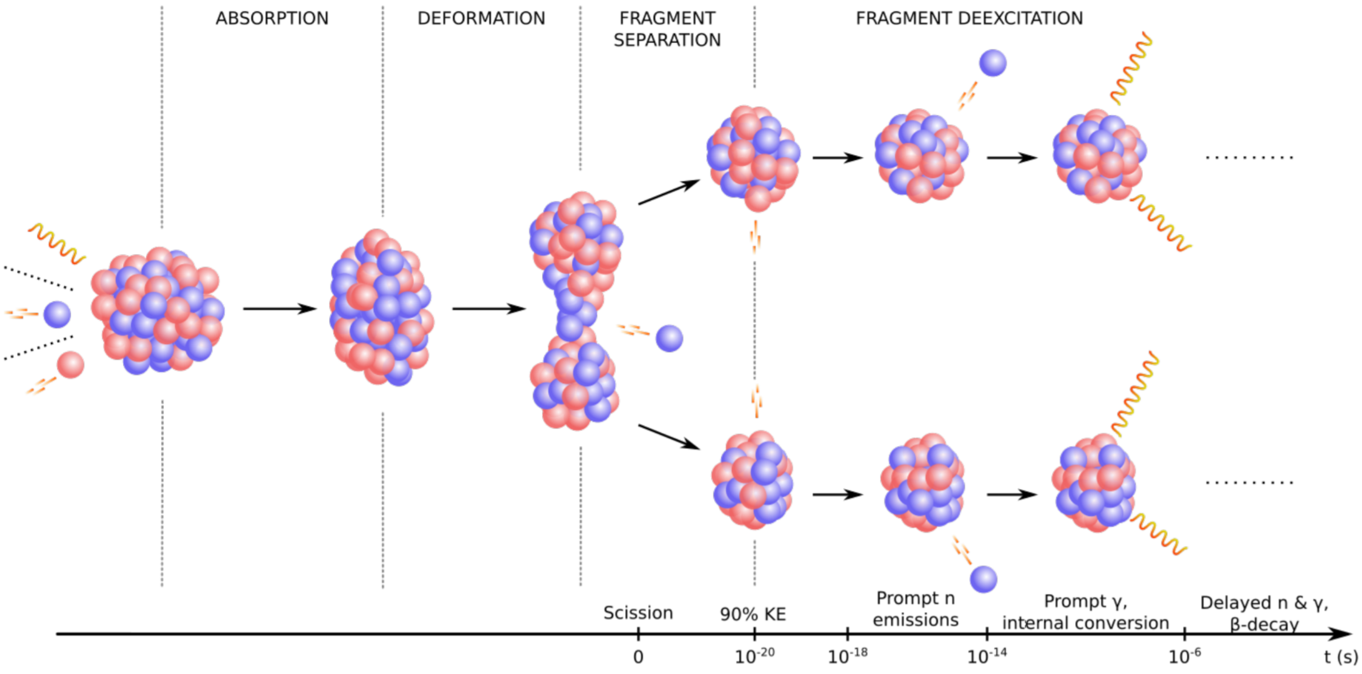
But fission studies will remain relatively inaccessible



∴ Fission theory is critical find any sort of "smoking gun" of heavy element production

Spyrou *et al.* PRL (2016) • Vilen *et al.* • PRL (2018) Orford *et al.* PRL (2018) • Sprouse *et al.* (2019) • Figure by **Mumpower**

NUCLEAR FISSION IN A NUTSHELL



Influence on the *r*-process:

Fission rates and branching determine re-cycling (robustness)

Fragment yields place material at lower mass number; barriers determine hot spots

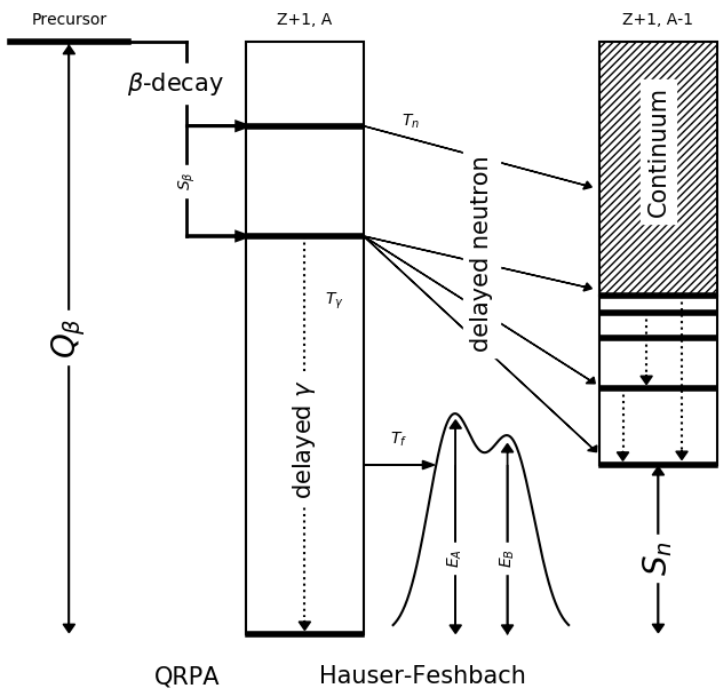
Large Q-value ⇒ impacts thermalization and therefore possibly observations

Responsible for what is left in the heavy mass region when nucleosynthesis is complete ⇒ "smoking gun"

Meitner & Frisch (1938) • Bohr & Wheeler (1939) • Figure from Verriere & **Mumpower** in prep. (2019)

MODELING
β-DELAYED FISSION (βDF)

MODELING β-DELAYED FISSION



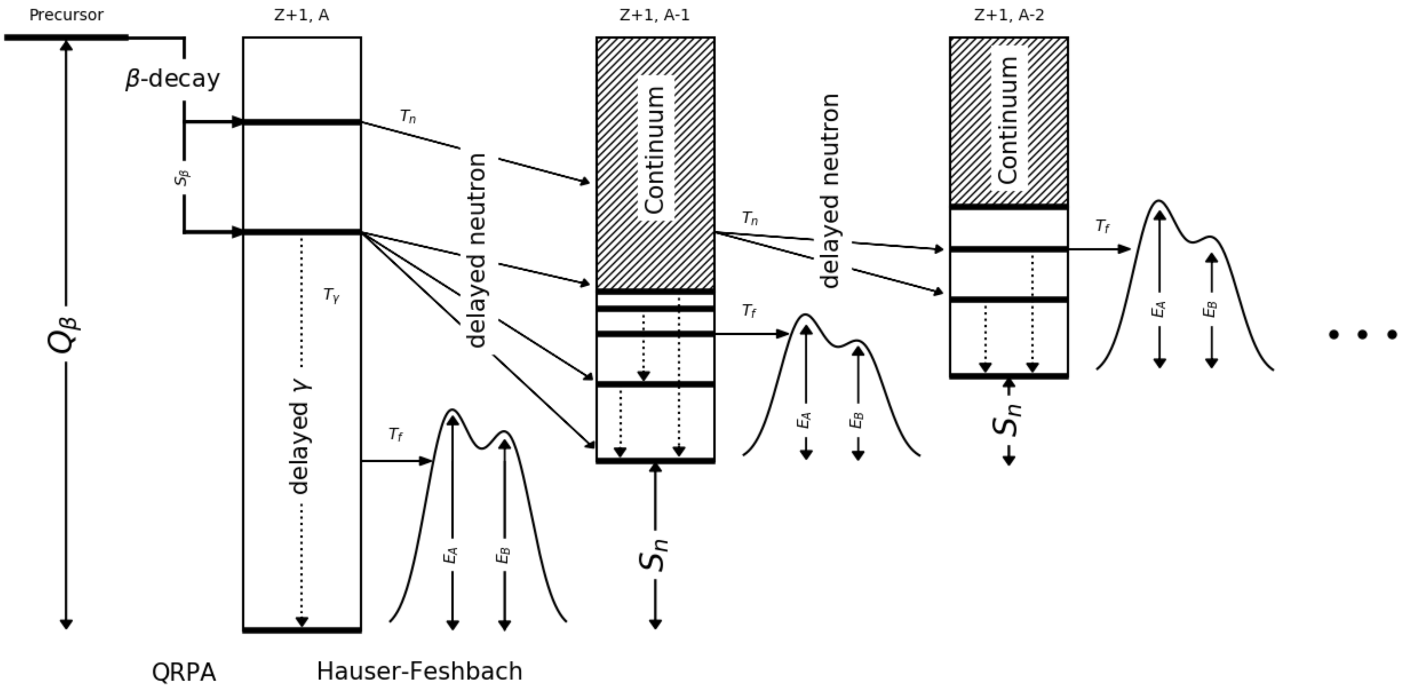
We have a model to describe nuclear de-excitation called QRPA+HF

We have recently extended the our QRPA+HF model to describe β-delayed fission (βdf)

Barrier heights from Möller ***et al.*** PRC 91 024310 (2015)

Kodama & Takahashi (1975) • Thielemann *et al.* (1983) • Shibagaki *et al.* ApJ 816 2 (2016) • **Mumpower** *et al.* ApJ 869 1 (2018)

MULTI-CHANCE β DF



Near the dripline Q_{beta} ⇡ S_n ⇣

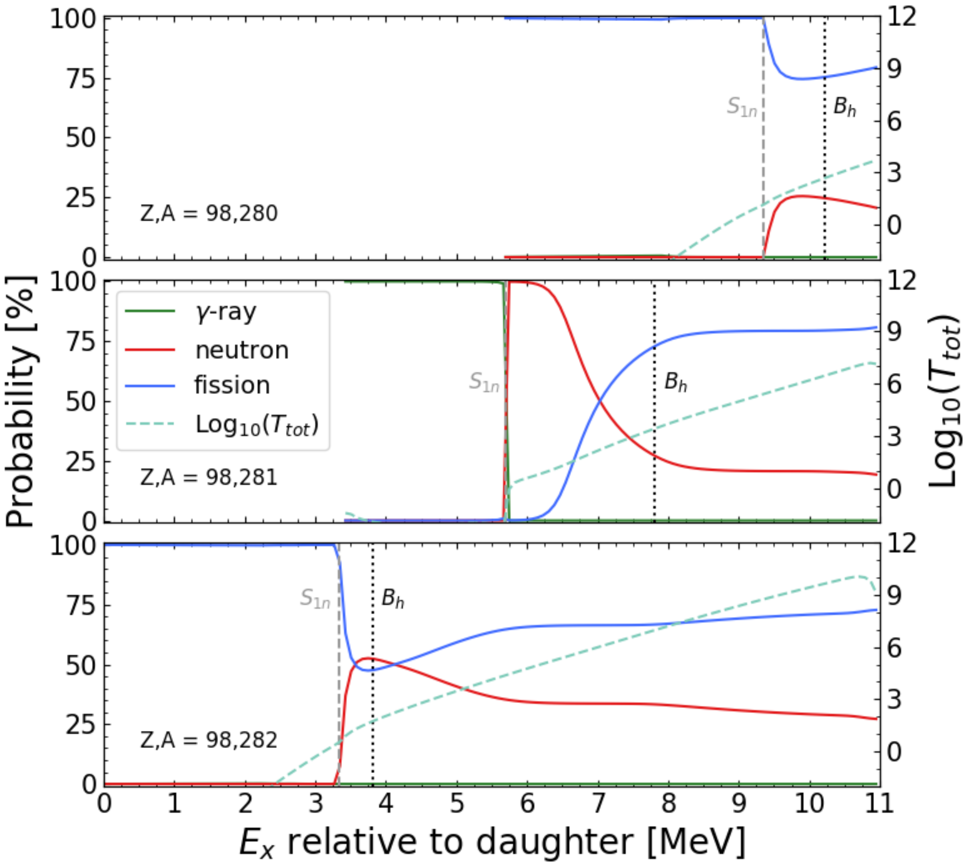
Multi-chance βdf: *each* daughter may fission

New fission channel to consider for r-process calculations

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

Mumpower *et al.* ApJ 869 1 (2018) • **Mumpower** *et al.* in prep (2019)

(n,γ,f) COMPETITION

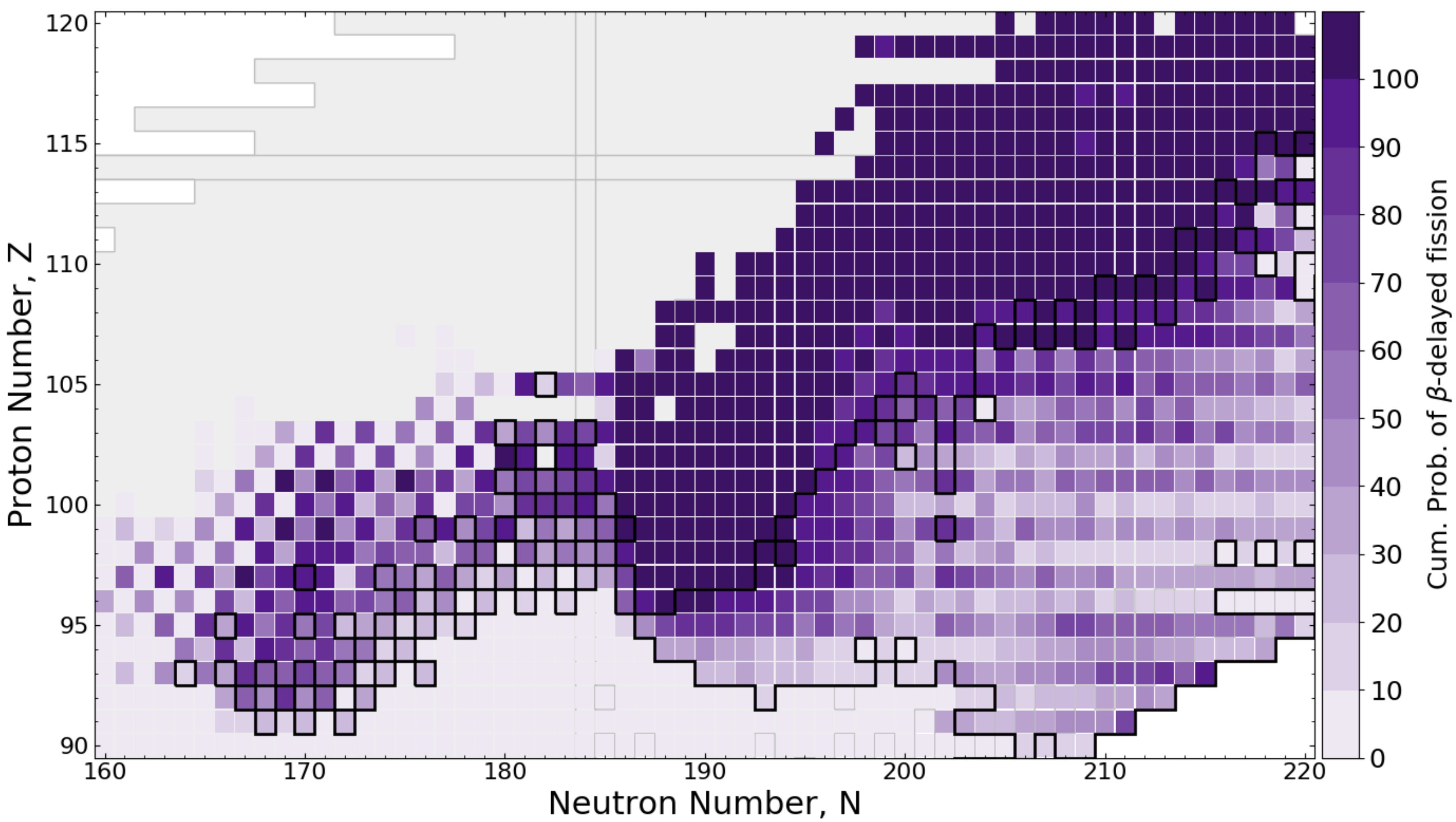


Fission can successfully compete with γ-rays and neutrons

Particle spectra also produced which are of interest for observations

Mumpower et al. PRC (2016) • **Mumpower** *et al.* ApJ 869 1 (2018) • Möller ***et al.*** ADNDT 125 (2019) • **Mumpower** *et al.* in prep (2019)

CUMULATIVE β DF PROBABILITY

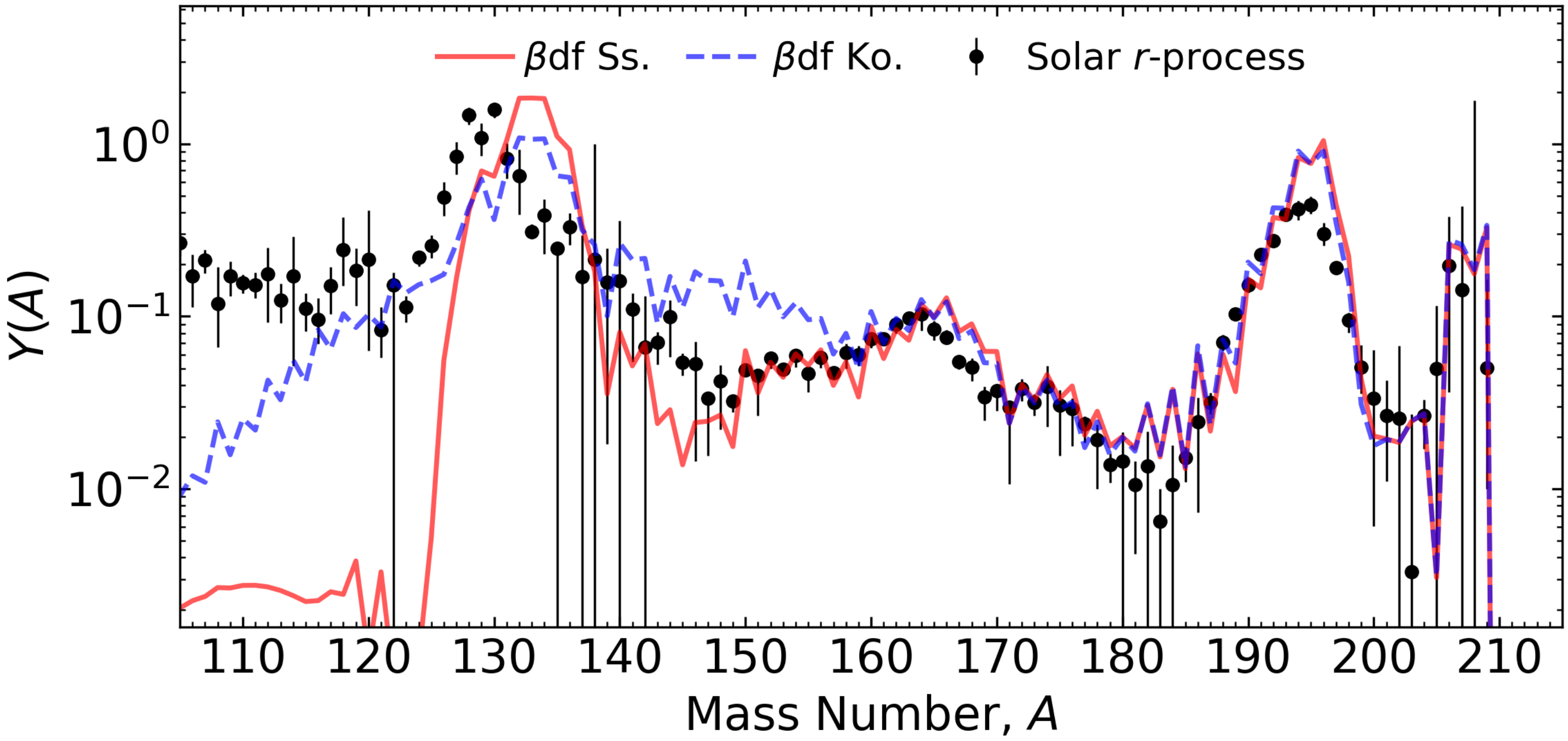


βdf occupies a large amount of real estate in the NZ-plane

Multi-chance βdf outlined in black

Mumpower *et al.* ApJ 869 1 (2018) • **Mumpower** *et al.* in prep (2019)

IMPACT ON FINAL ABUNDANCES



Network calculation of tidal ejecta from a neutron star merger (FRDM2012)

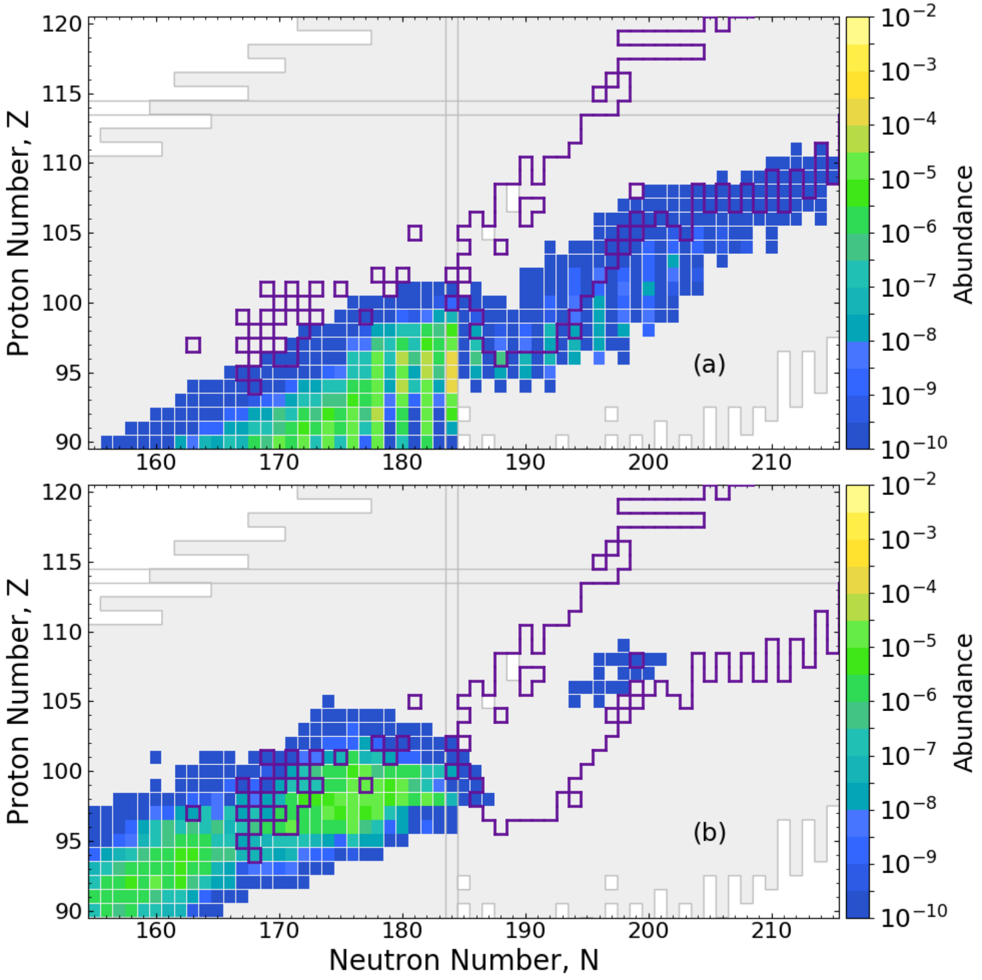
βdf can shape the final pattern near the $A = 130$ peak

This is because of a relatively long fission timescale

Conclusion ⇒ we need a good description of fission yields to understand abundances near $A \sim 130$.

Mumpower *et al.* ApJ 869 1 (2018) • Möller, **Mumpower** *et al.* ADNDT (2019) • **Mumpower** *et al.* in prep (2019)

A SECOND CONSEQUENCE OF βDF

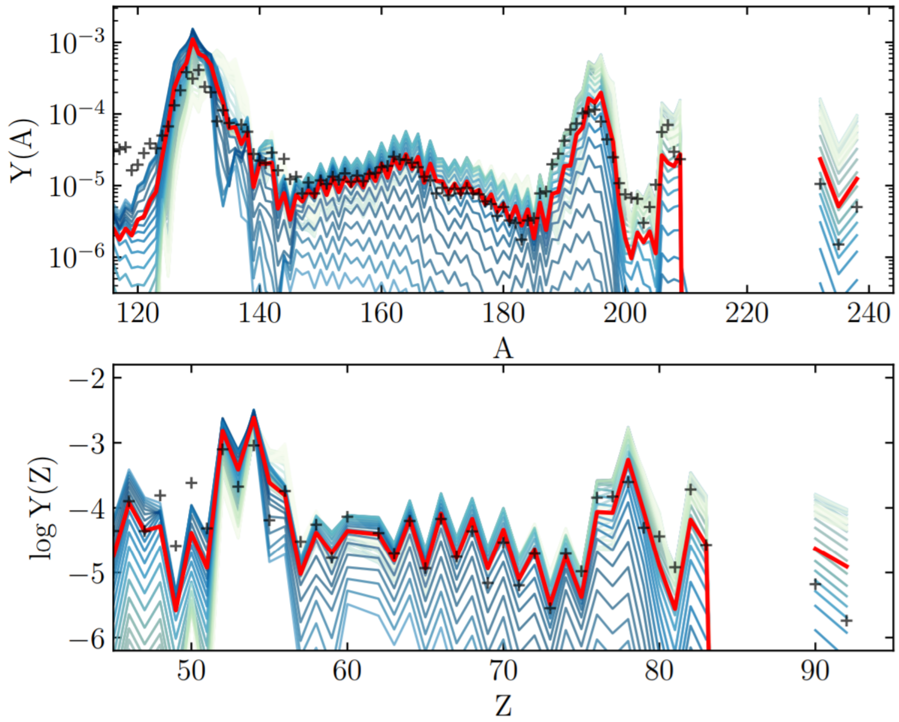


Network calculation of tidal ejecta from a neutron star merger (FRDM2012)

βdf alone prevents the production of superheavy elements in nature

Mumpower *et al.* ApJ 869 1 (2018) • Vassh ***et al.*** J. Phys. G (2019)

LONG-LIVED ACTINIDES



With careful fission treatments: if actinides are produced, they are usually overproduced versus lanthanides

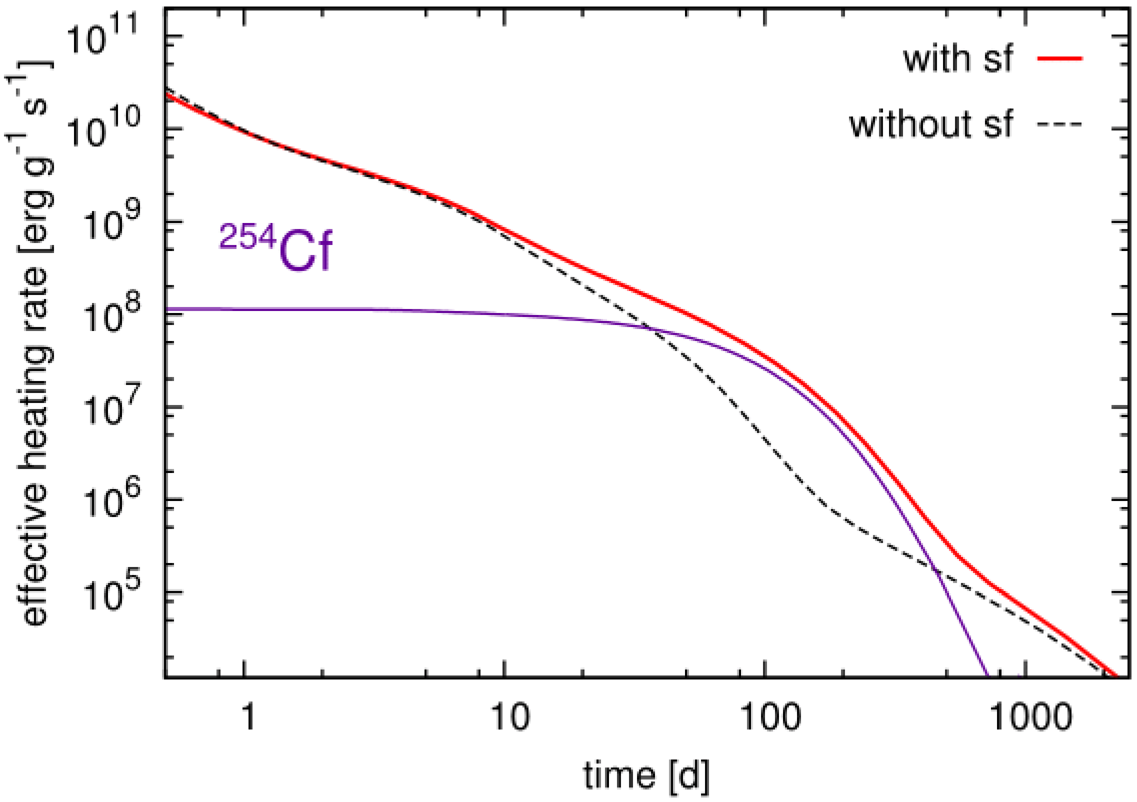
A sufficient amount of dilution with ligher r-process material is required to match the solar isotopic residuals

∴ Fission theory has implications for galactic chemical evolution, etc.

Holmbeck *et al.* ApJ 870 1 (2019) • Vassh *et al.* J. Phys. G (2019)

CONNECTING TO MULTI-MESSENGER ASTROPHYSICS

DIGGING DEEPER...



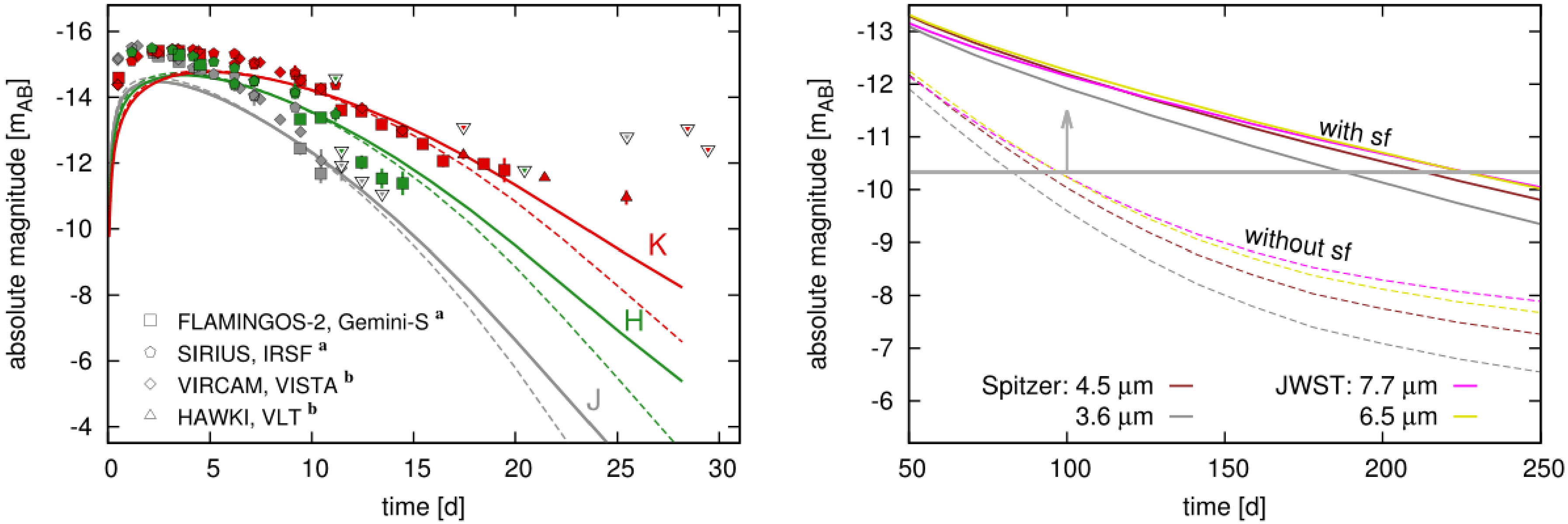
Is there any possible precursor to show that actinide nucleosynthesis has occurred in an event?... Maybe!

The spontaneous fission of ^{254}Cf is a *primary* contributor to nuclear heating at late-time epochs

The $T_{1/2} \sim 60$ days but yield distribution is not well constrained

Y. Zhu ***et al.*** ApJL 863 2 (2018) • Vassh ***et al.*** J. Phys. G (2019)

OBSERVATIONAL IMPACT OF CALIFORNIUM



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

Late-time epoch brightness can be used as a proxy for actinide nucleosynthesis

Future JWST will be detectable out to 250 days with the presence of ^{254}Cf

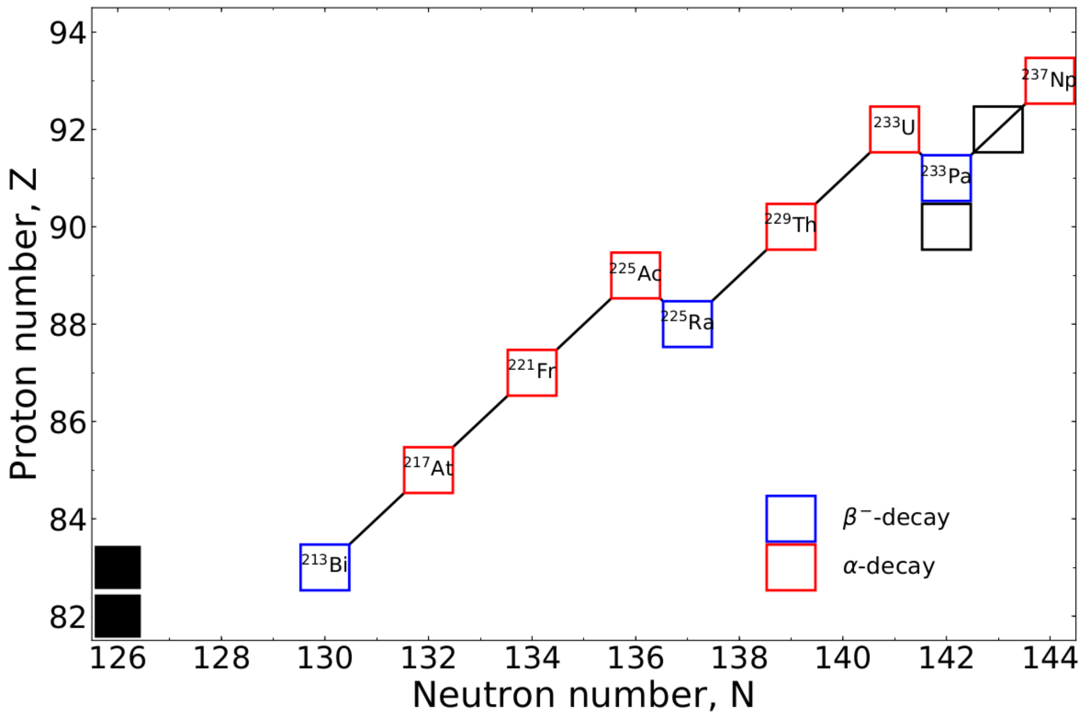
This also has implications for merger morphology...

Y. Zhu *et al.* ApJL 863 2 (2018) • Miller *et al.* accepted PRD (2019) • Korobkin *et al.* submitted ApJ (2019)

MERGER γ-RAYS

Another possible (yet very difficult) option is to attempt to observe the spectra from transients / remnants

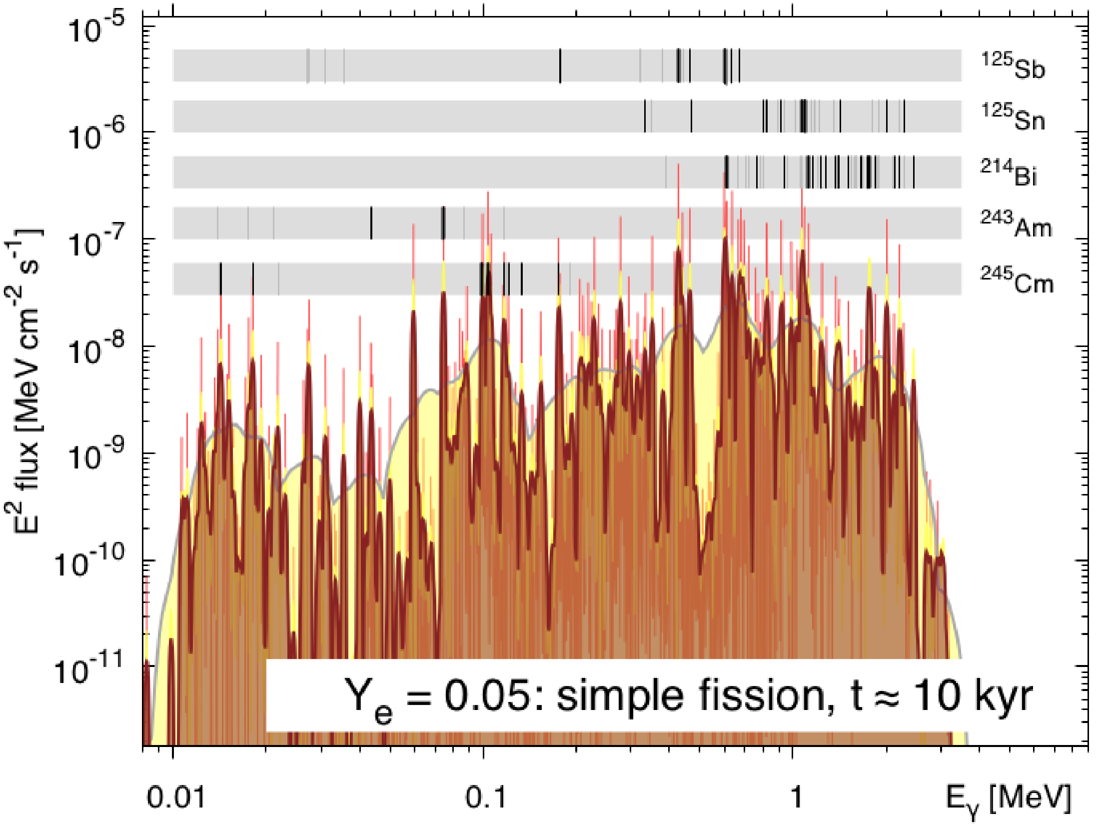
For the r-process we should search for signatures of actinides...



This involves following potentially complex decay chains...

Korobkin *et al.* submitted ApJ (2019)

γ-RAY SPECTRUM AT 10 KYR



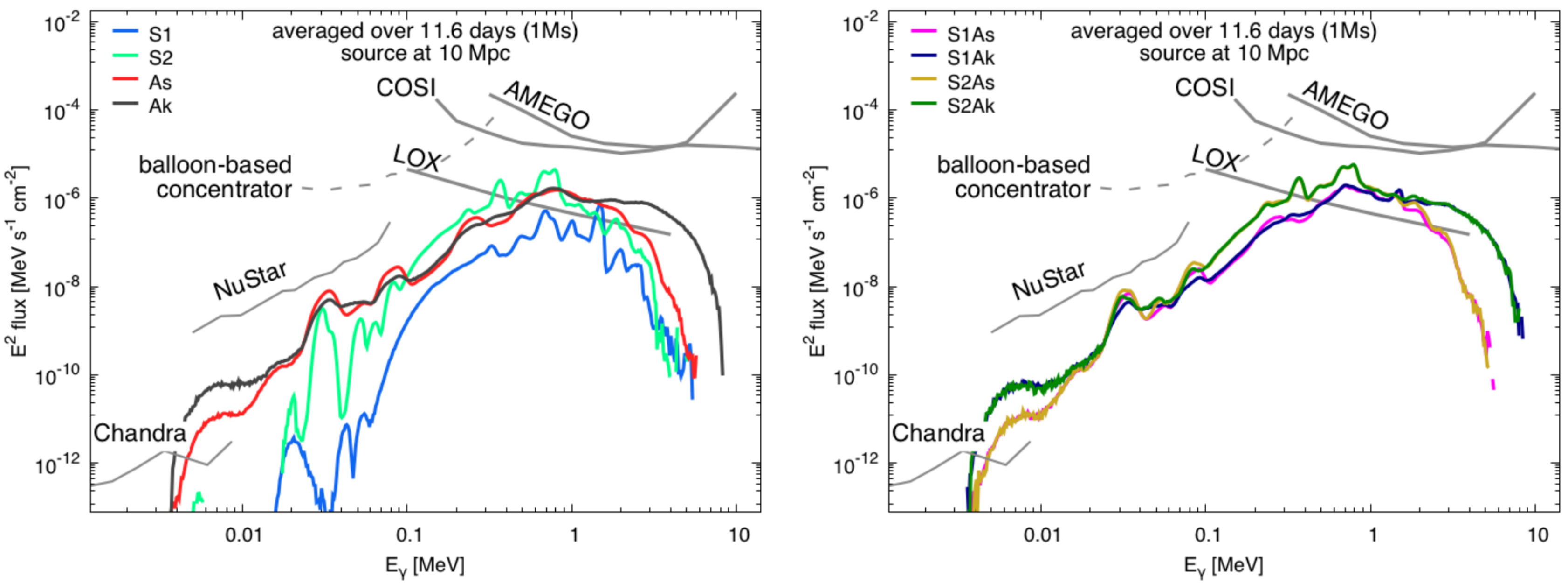
Distinct elements do arise

This depends sensitively on observational timescale

Can we do this with future space missions?

Korobkin *et al.* submitted ApJ (2019)

REMNANT γ-RAY COULD BE OBSERVABLE



Next generation γ-ray (space-based) have a chance to disentangle merger components

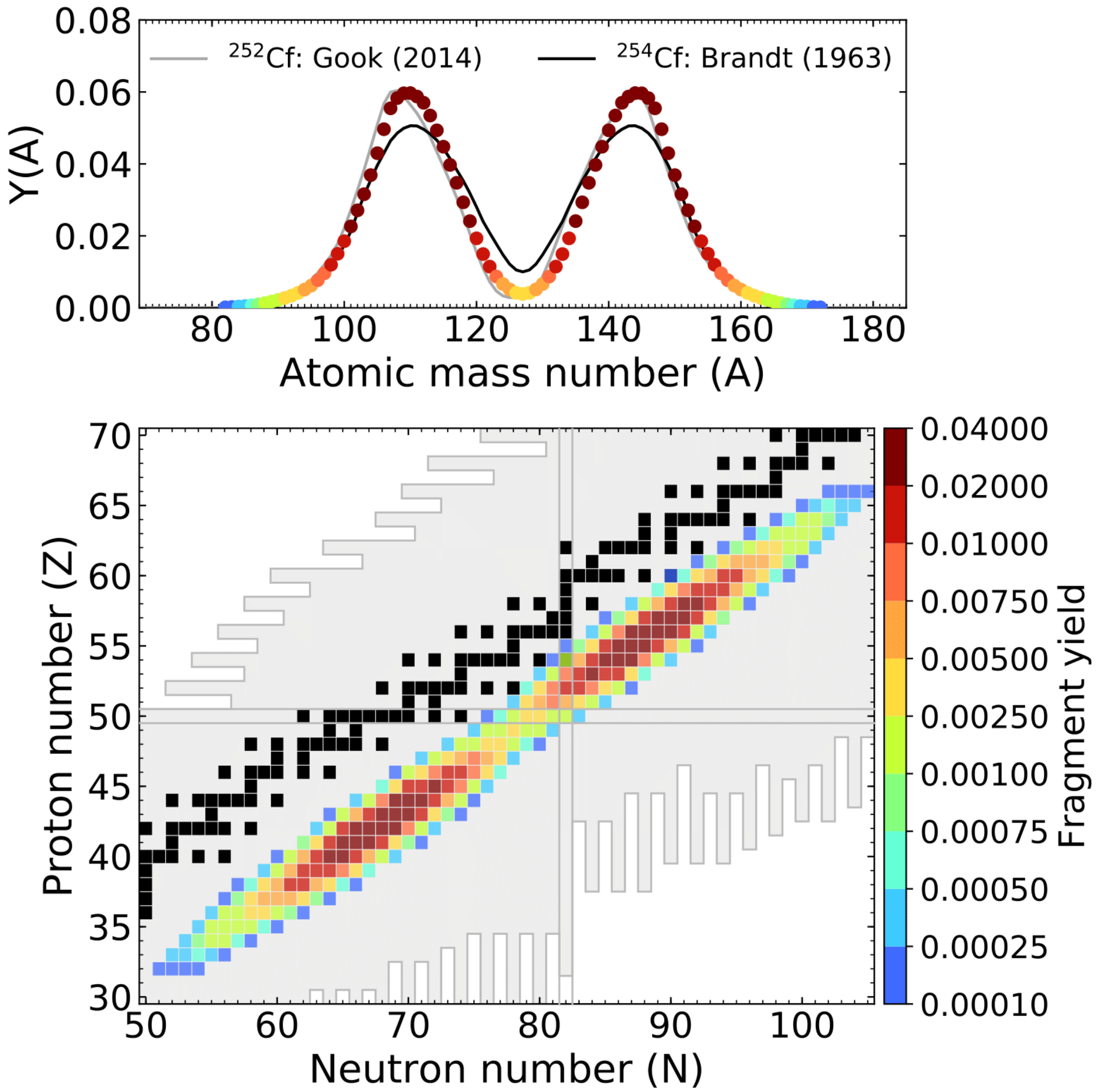
These are tentative numbers from this community

Lunar Occultation Explorer (LOX) at this point seems like our best bet for a composition observable

Korobkin ***et al.*** submitted ApJ (2019)

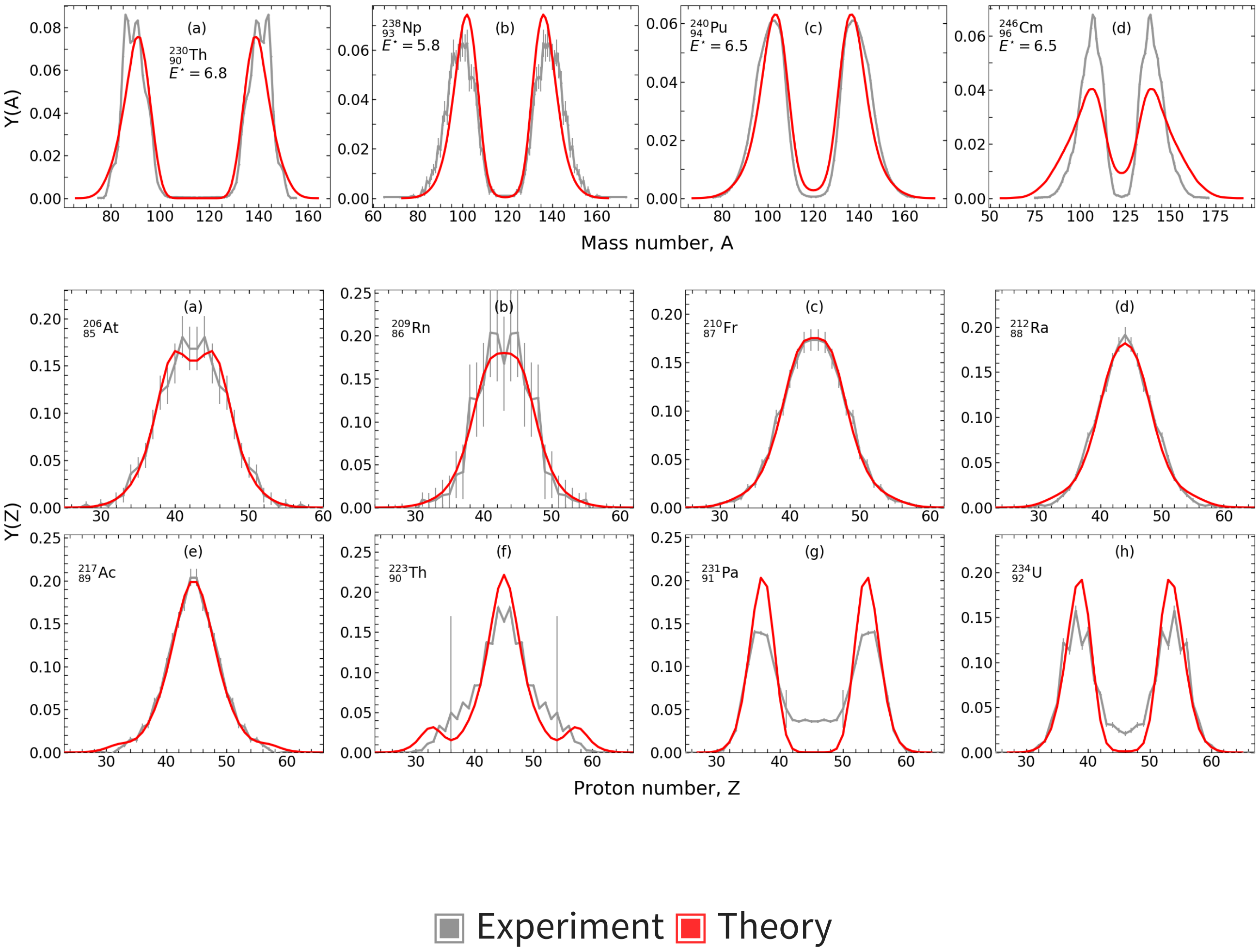
FISSION YIELDS
(COMING SOON)

CALCULATED YIELD (CALIFORNIUM)



Jaffke *et al.* PRC 67 034608 (2018) • Y. Zhu ***et al.*** ApJL 863 2 (2018) • **Mumpower** *et al.* in prep. (2019)

MACROSCOPIC-MICROSCOPIC YIELDS



FRLDM fragment yields have remarkable agreement with known data

Over a range of experiments, evaluations and nuclei!

Verriere & **Mumpower** in prep. (2019) • **Mumpower** *et al.* in prep. (2019)

SPECIAL THANKS TO

My collaborators

A. Aprahamian, J. Clark, E. Holmbeck, P. Jaffke, T. Kawano, O. Korobkin, S. Liddick, G. C. McLaughlin, J. Miller, P. Möller, R. Orford, J. Randrup, G. Savard, A. Sierk, N. Schunck, T. Sprouse, A. Spyrou, I. Stetcu, R. Surman, P. Talou, N. Vassh, M. Verriere, X. Wang, Y. Zhu

& **many more...**

■ Students ■ Postdocs ■ FIRE PIs

SUMMARY

The r-process relies on fission in many ways:

Re-cycling material ▲ Actinide production ▲ Late-time observations

FRIB and other facilities will make a lot of measurements, but fission studies remain relatively inaccessible

Fission theory is crucial to understanding the formation of the heaviest elements (and $A \sim 130$)

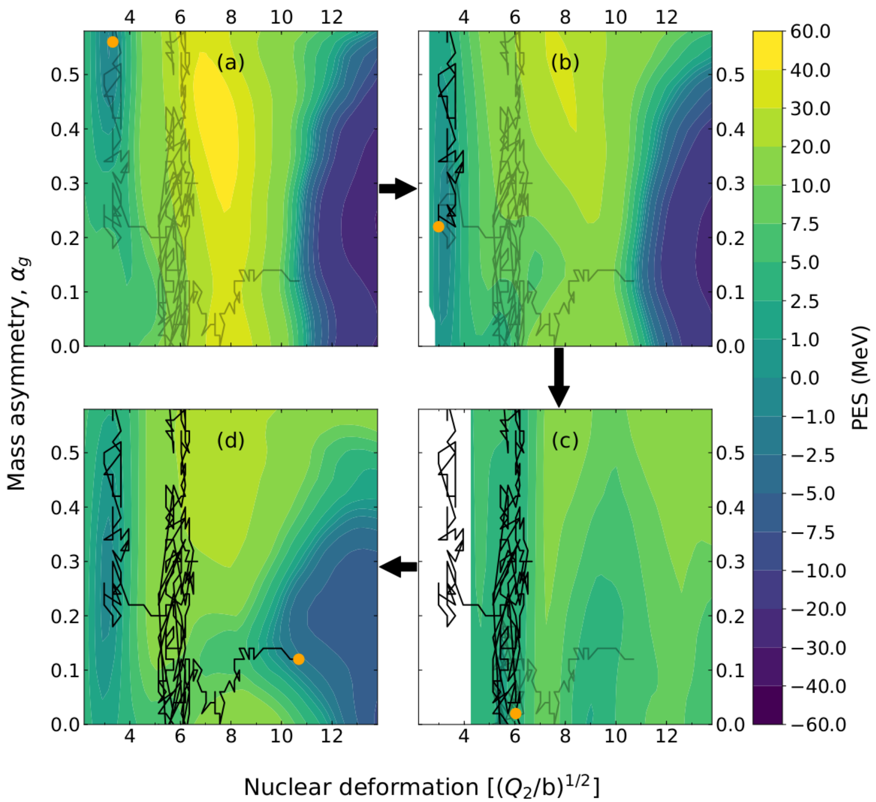
The FIRE Collaboration will soon provide a suite of new fission properties for the community:

Rates • Branchings • Yields • Q-values • Spectra

Results / Data / Papers @ MatthewMumpower.com

EXTRA SLIDES

HOW WE CALCULATE FISSION YIELDS



We use a discrete random walk over a potential energy surface

This assumes strong disspative dynamics

The ensemble of such random walks produces the fission yield

Verriere & **Mumpower** in prep. (2019) • **Mumpower** *et al.* in prep. (2019)