ACTINIDES AND THE r-PROCESS

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Workshop on nuclear physics for astrophysical phenomena

Wednesday Oct. 23rd 2019

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LA-UR-19-30941

CTA
Center *for* Theoretical
ASTROPHYSICS

TO UNDERSTAND THE FORMATION OF THE ELEMENTS

Requires deep knowledge of a range of fields, including:

The theoretical modeling of astrophysical environments

Multi-messenger observations (gravitational waves, EM waves, etc.)

Nuclear theory predictions for exotic nuclei

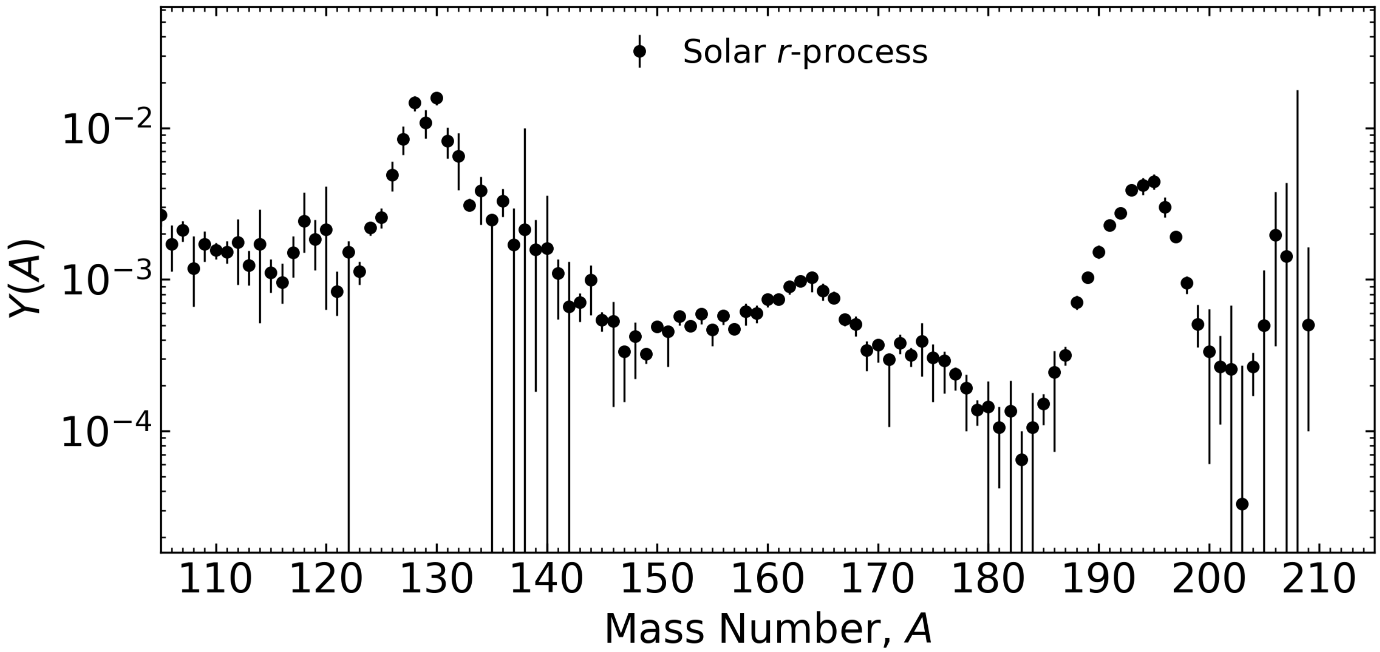
Precision experiments to constrain nuclear theory

Data and observations are limited

We must be clever when deciphering what is going on with nucleosynthesis...

WHEN WE MODEL NUCLEOSYNTHESIS

We want to describe the abundances observed in nature



But there is uncertainty in:

The astrophysical conditions (large variations in current simulations)

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

Arnould *et al.* Phys. Rep. (2007) • Metzger *et al.* MNRAS (2010) • **Mumpower** *et al.* PRC (2015) • Côté ***et al.*** ApJ (2018) • Cowan *et al.* (2019)

INPUTS FROM NUCLEAR PHYSICS

1st order: masses, β-decay rates, reaction rates & branching ratios

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

WHAT DO WE KNOW?

The chart of nuclides

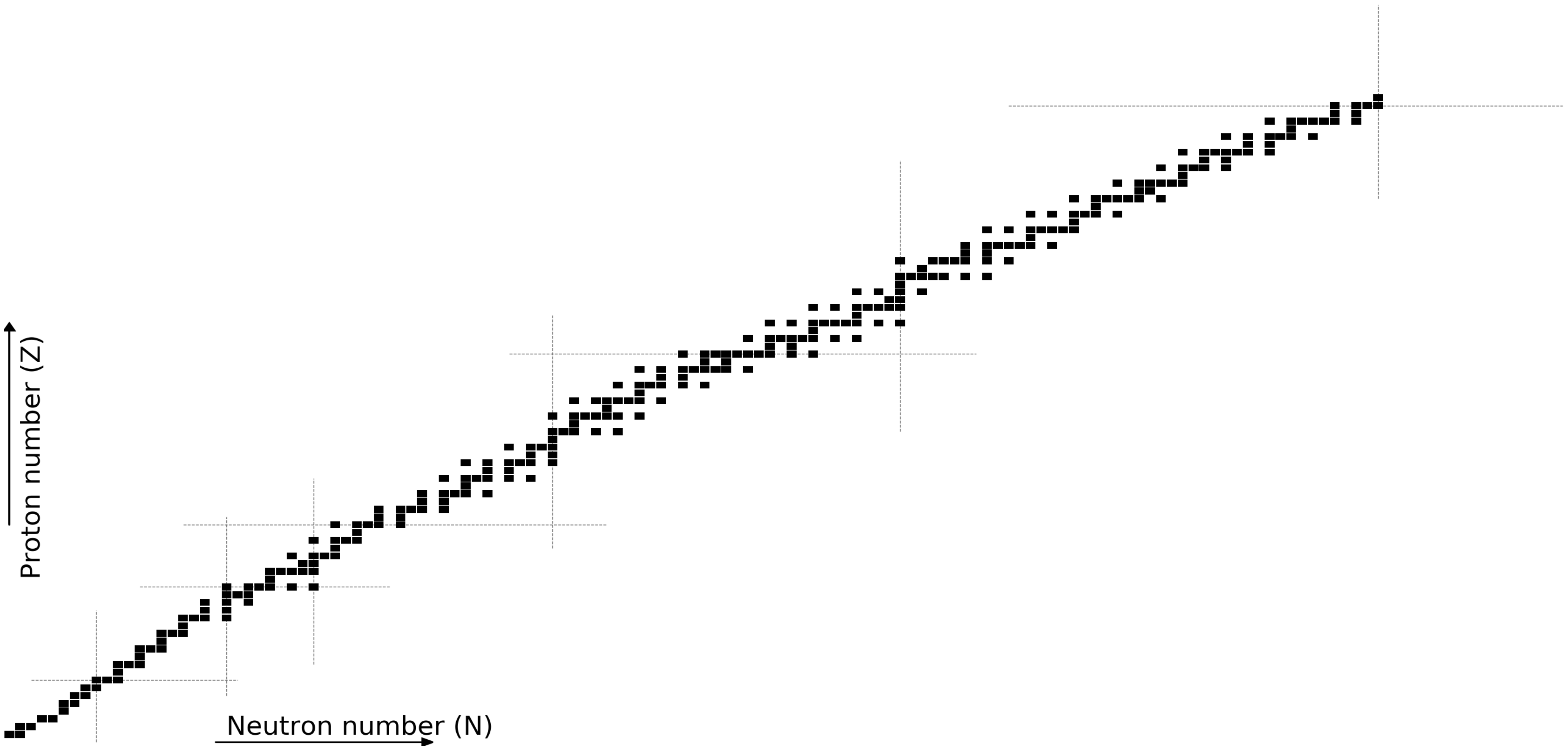


Figure by **Mumpower**

WHAT DO WE KNOW?

All half-lives

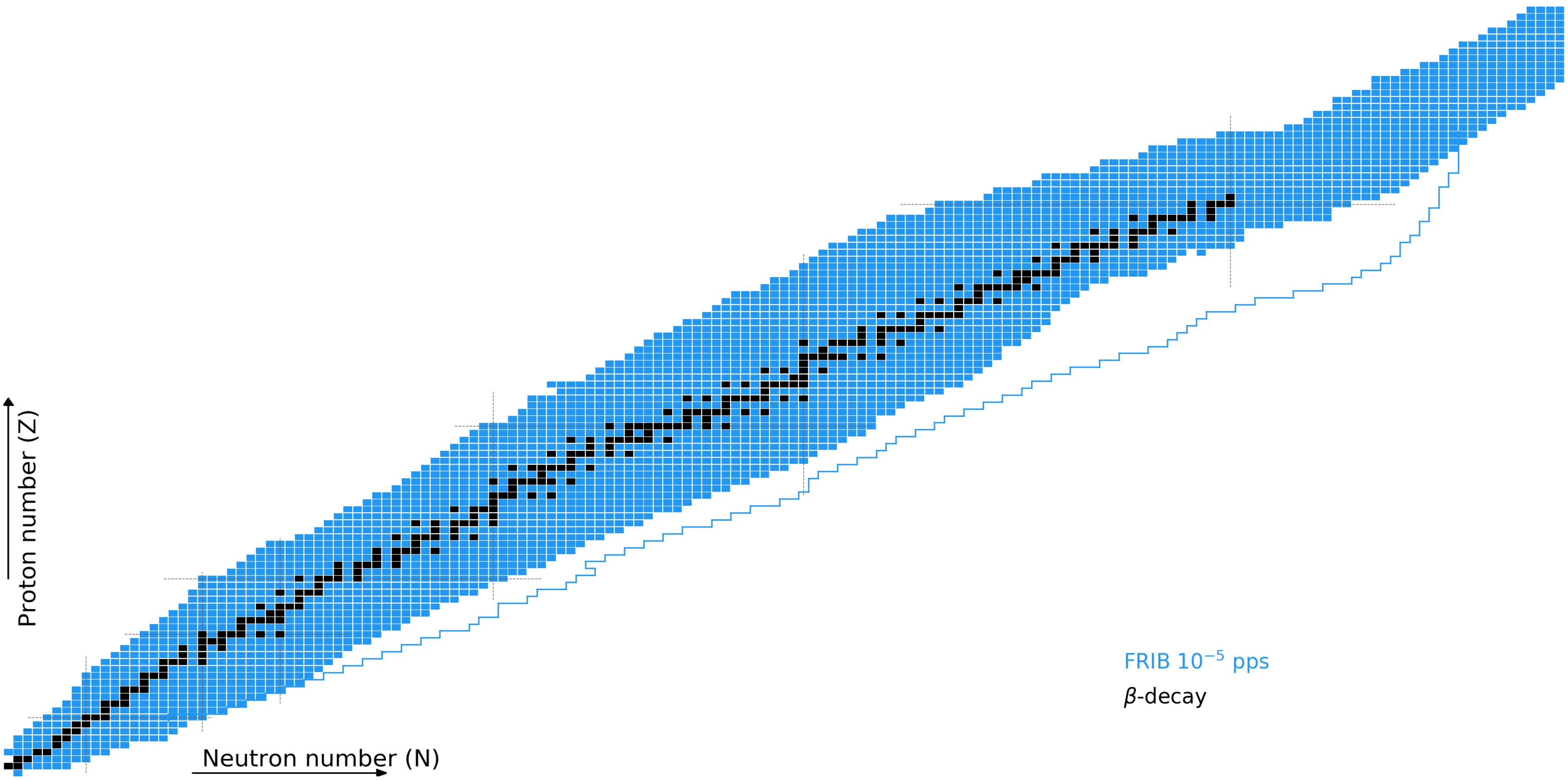


Figure by Mumpower

WHAT DO WE KNOW?

Nuclear masses

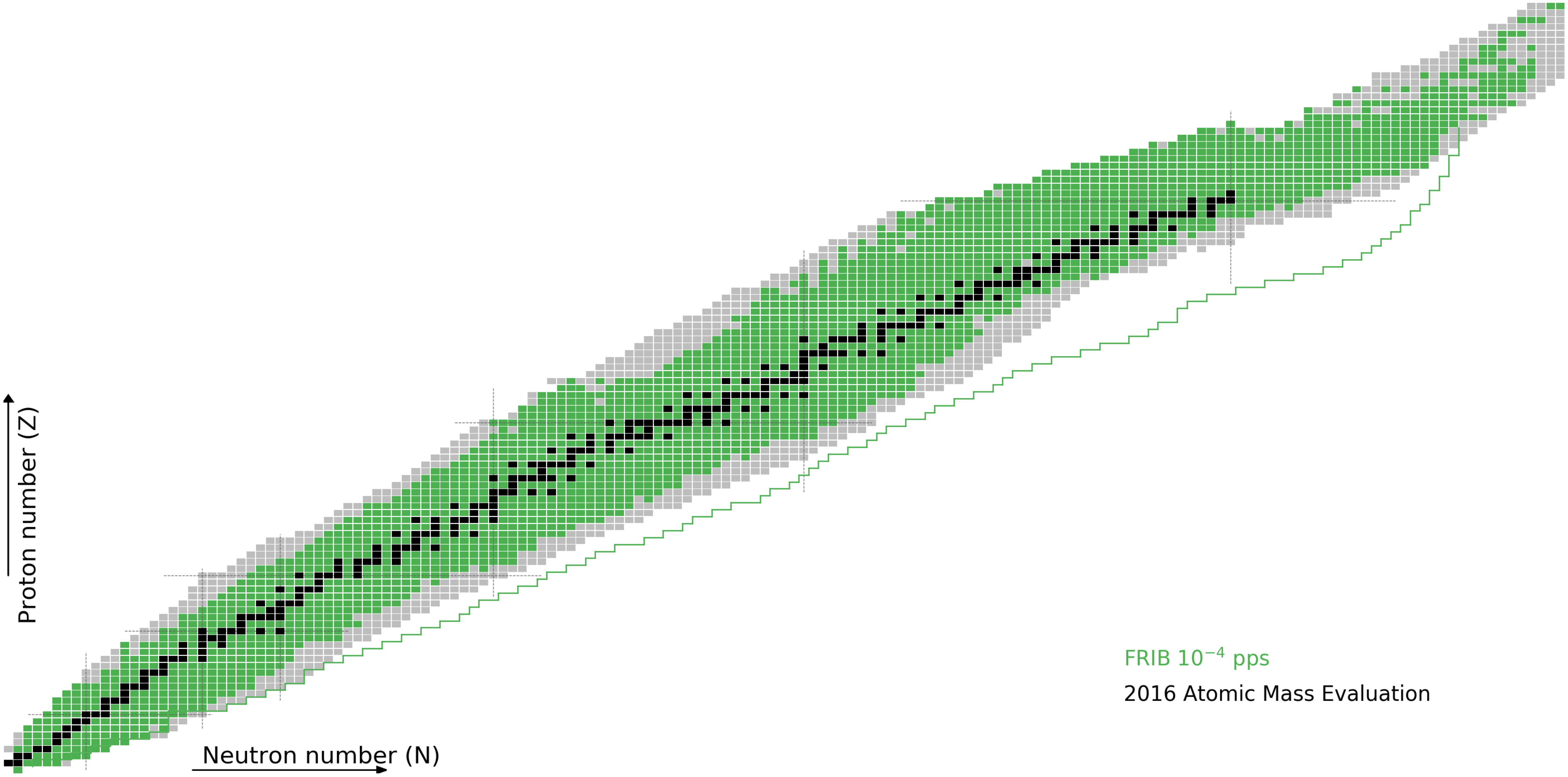


Figure by **Mumpower**

WHAT DO WE KNOW?

Neutron capture rates

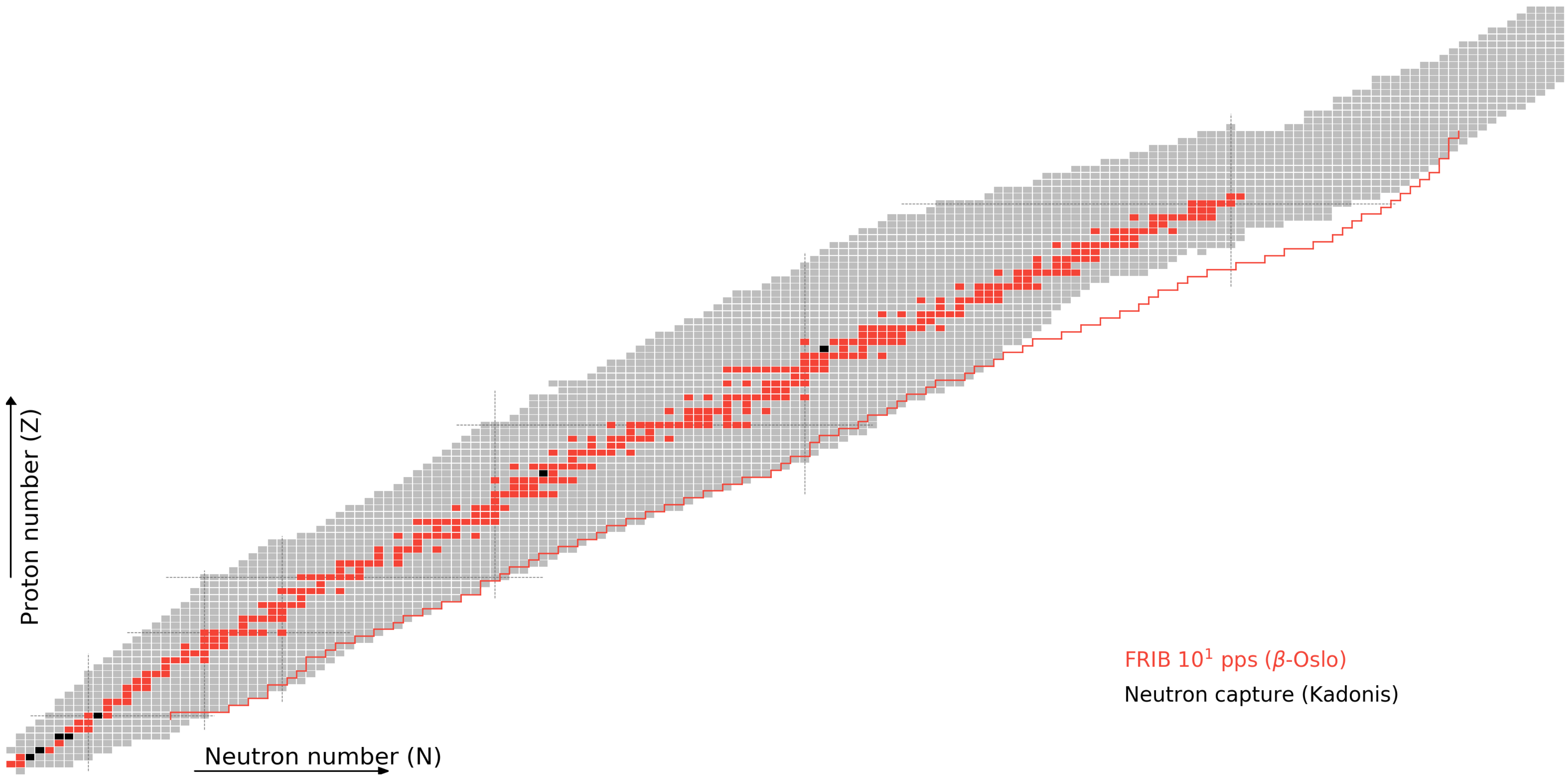


Figure by **Mumpower**

WHAT DO WE KNOW?

As of today, to varying degrees of accuracy

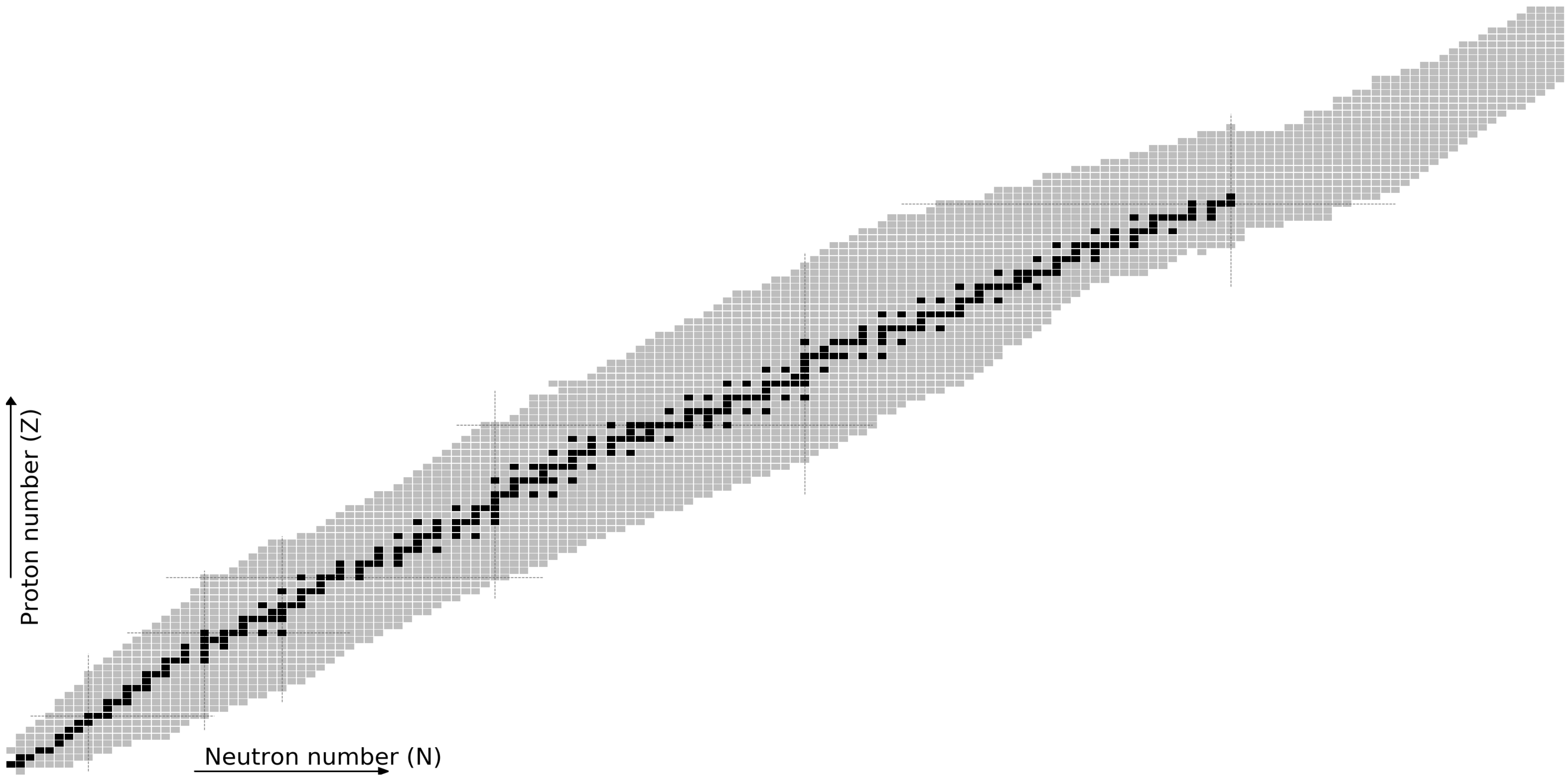


Figure by **Mumpower**

THE R-PROCESS REQUIRES NUCLEAR THEORY

Even in the era of **FRIB**

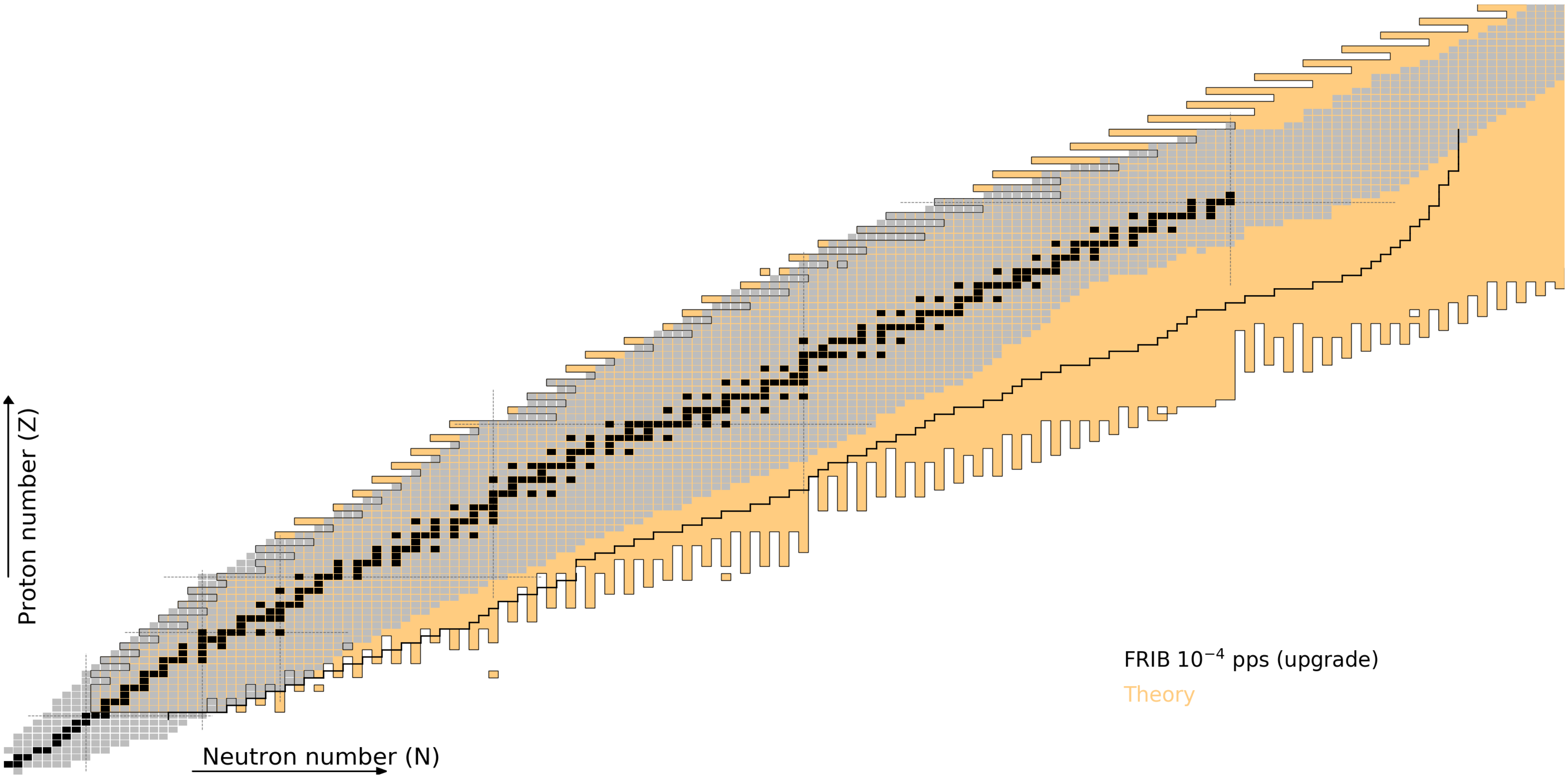


Figure by **Mumpower**

r-PROCESS CALCULATION

nuclear physics inputs

(Sn, β-rates, n-cap rates, …)

thermodynamic conditions

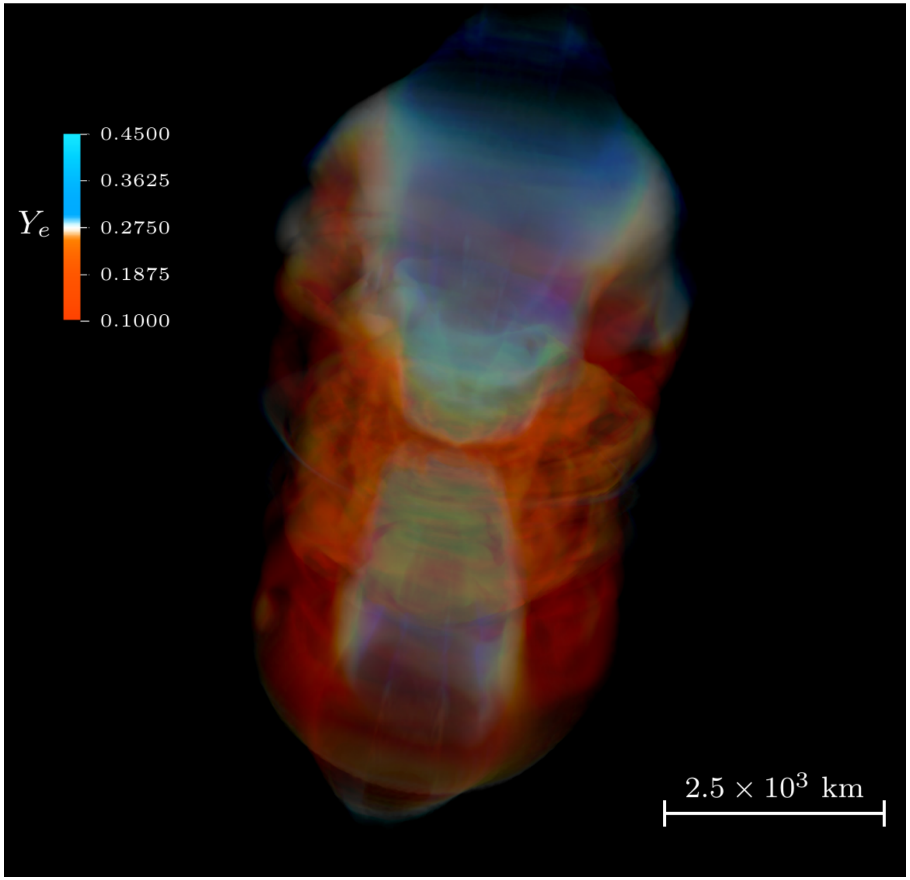
(temperature, density, ...)

PRISM: Portable Routines for Integrated nucleoSynthesis Modeling

Sprouse & **Mumpower** in prep (2019)

ACTINIDE PRODUCTION IN THE r-PROCESS

DISTRIBUTION OF Y_e FOR MERGER DISK



Volume rendering of electron fraction, Y_e for a neutron star merger disk

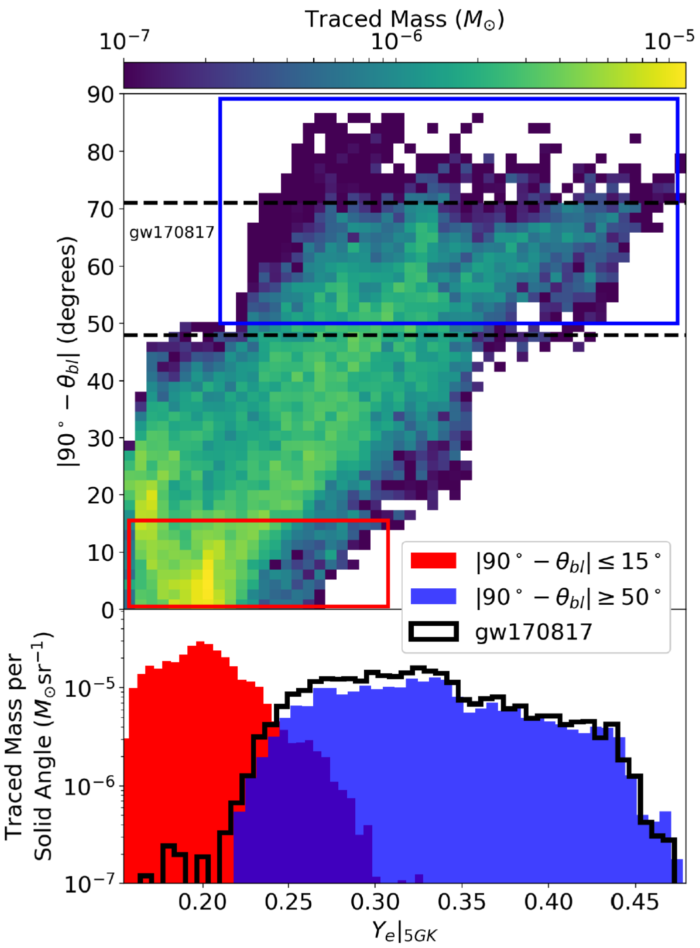
Jet drives material and voids region near azimuthal axis; high Y_e

Miller *et al.* PRD 100 023008 (2019)

MORPHOLOGY OF EJECTA

Miller *et al.* PRD 100 023008 (2019)

ACCRETION DISK



Surrounding a black hole

Viewing angle critical for what composition you see

Measured from the mid-plane of the disk

Our model is consistent with observations of a blue kilonova

Red, full r-process material seen near mid-plane

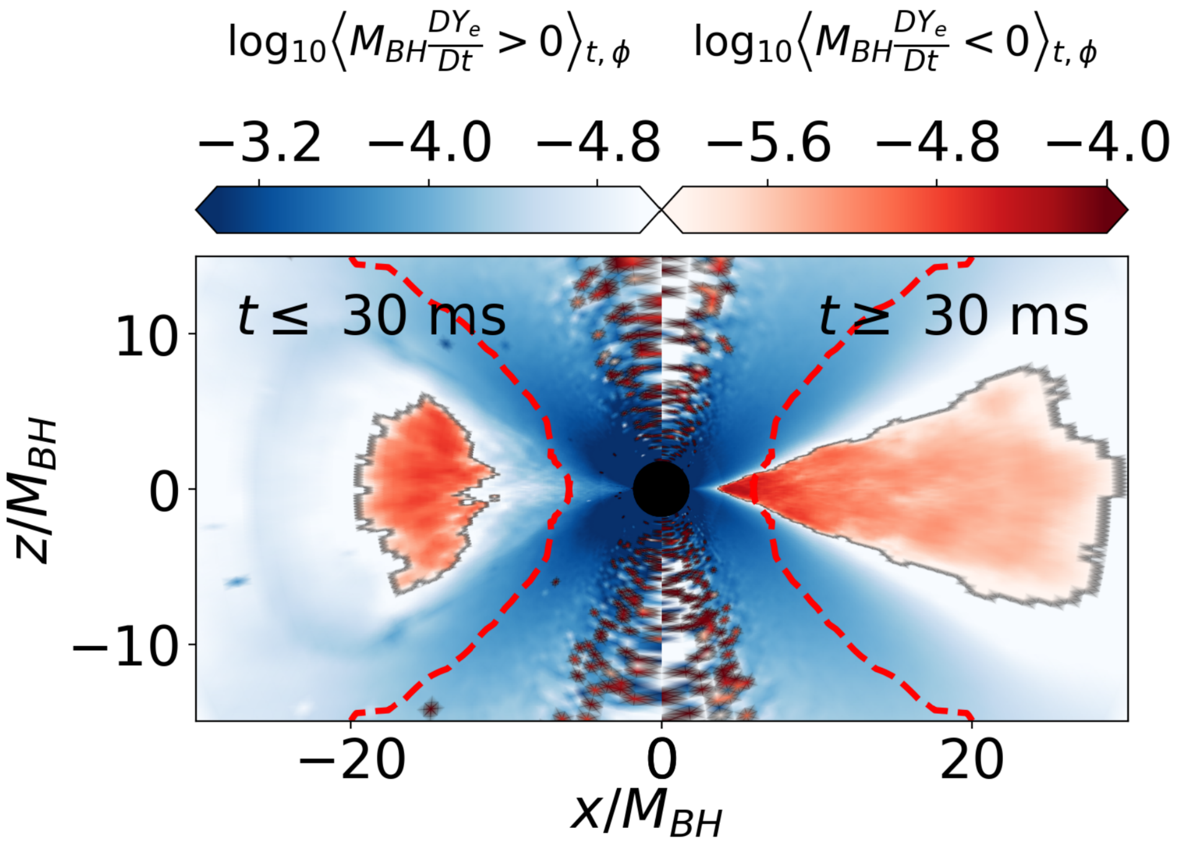
The disk can contain a large amount of material

But exactly how much is gravitationally unbound?

Further... What is the important role of neutrinos?

Miller *et al.* PRD 100 023008 (2019)

NEUTRINOS IMPACT THE NUCLEOSYNTHESIS



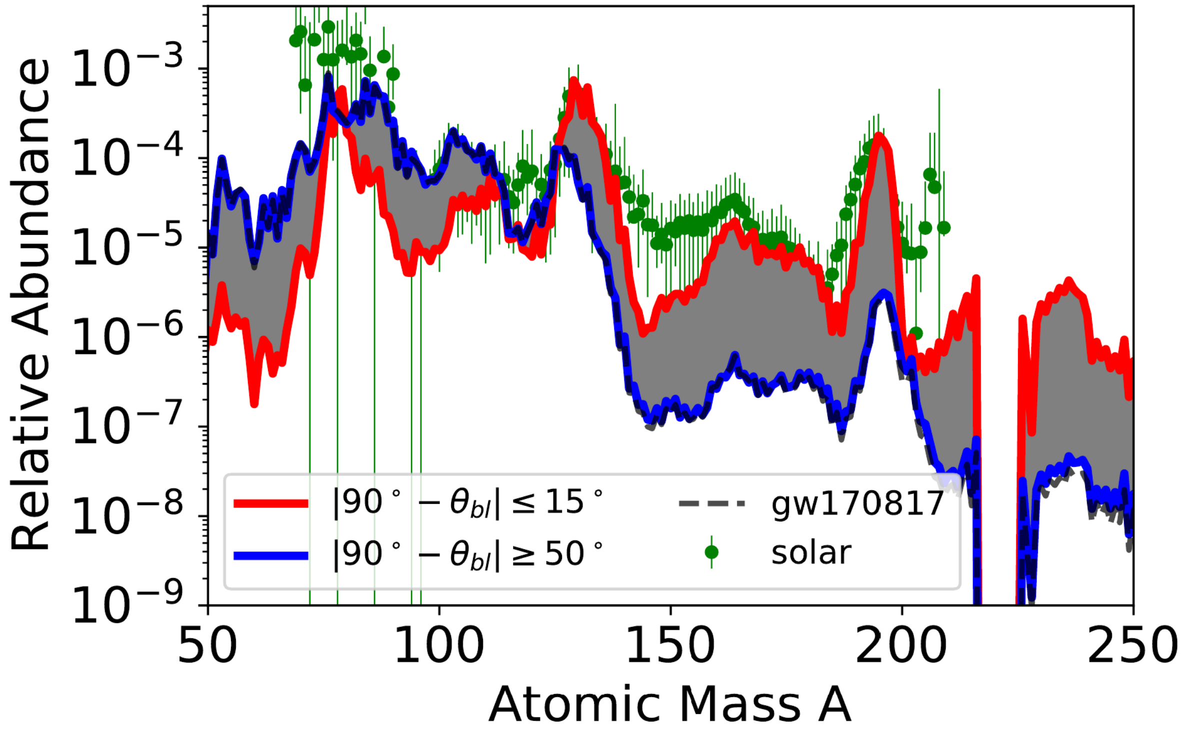
Open question: exactly how is the ejecta processed by neutrinos?

Blue region has high Y_e; red lower Y_e

The transit time away from the disk is crucial

Miller ***et al.*** PRD 100 023008 (2019)

RESULTANT NUCLEOSYNTHESIS



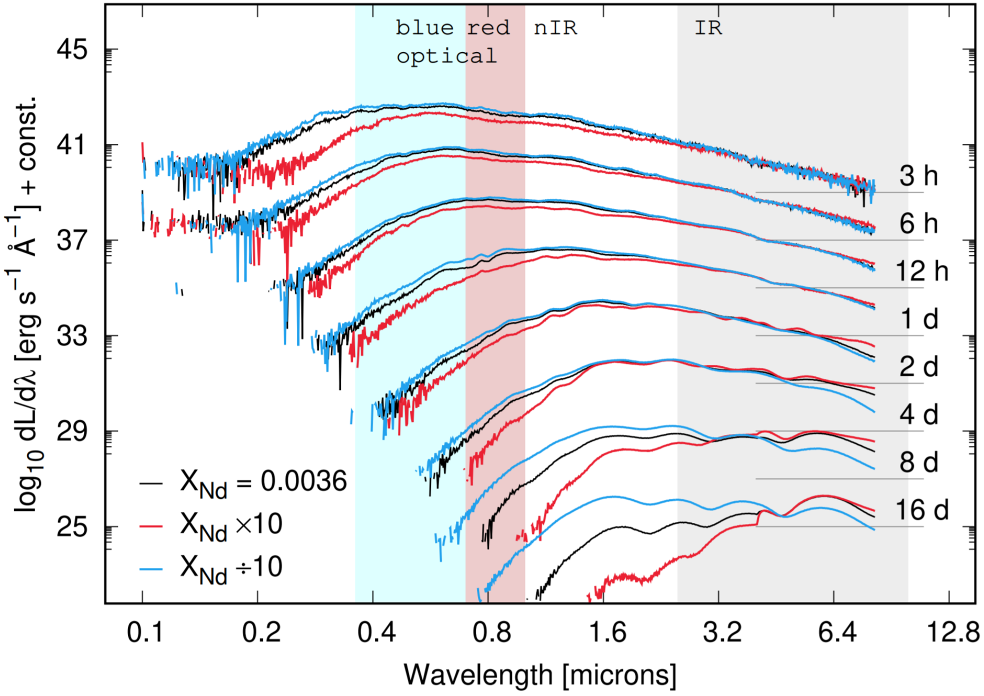
Nucleosynthesis simulation with J. Lippuner's SkyNet

Mass weighted trajectories suggest blue kilonova if viewing angle is similar to GW170817

It is critical to get the full morphology and thereby composition correct...

Miller *et al.* PRD 100 023008 (2019)

INFERRING COMPOSITION IS TRICKY



One way is to find a proxy in the observed light curve spectrum

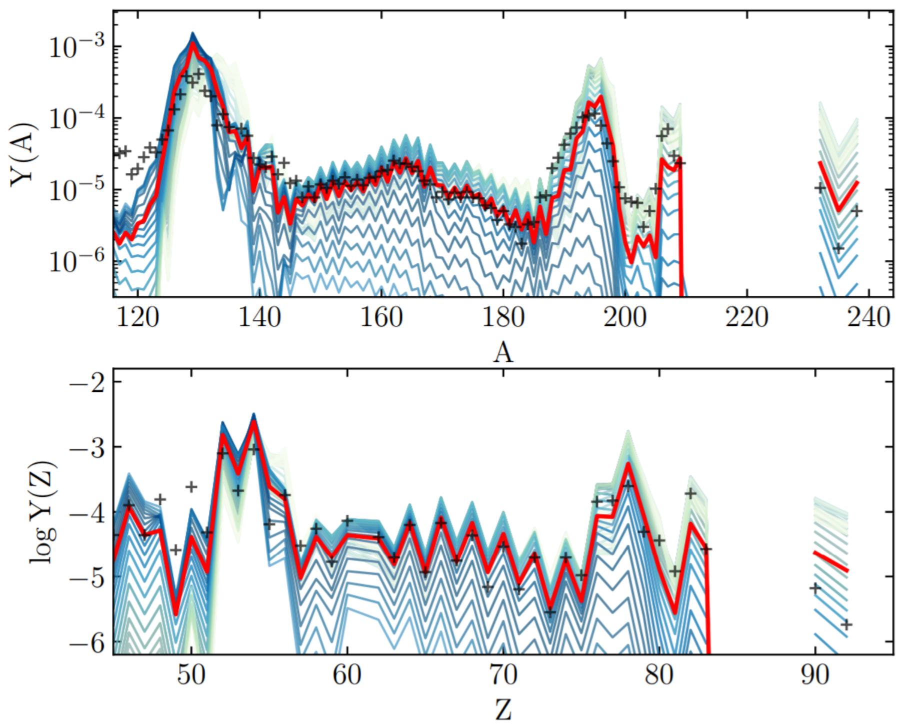
Nd is a good choice because it is a high opacity lanthanide

The amount of Nd is absolutely crucial to the observed light curve

But it is important to remember that there are still many astrophysical model degeneracies as this point...

Kasen *et al.* Nature (2017) • Côté ***et al.*** ApJ (2018) • Even ***et al.*** submitted (2019)

ESPECIALLY FOR SOLAR-LIKE RATIOS



In some simulations actinides seem to be overproduced versus lanthanides

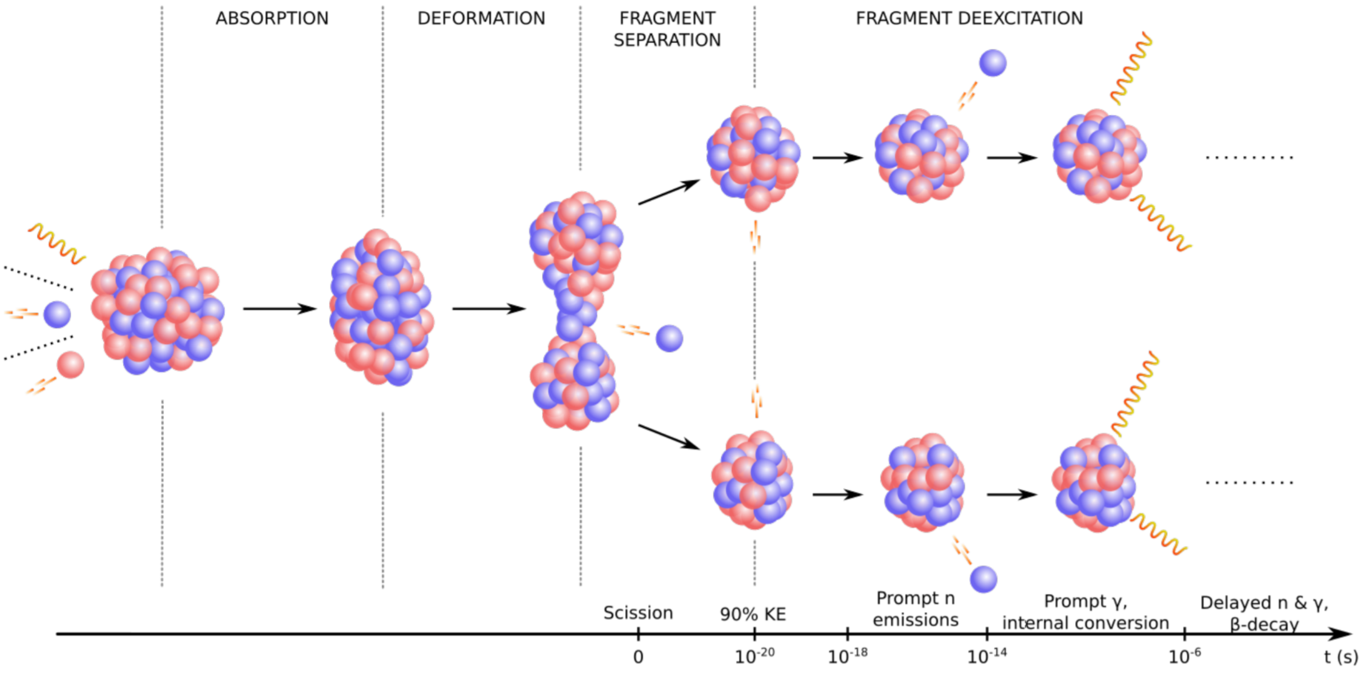
A sufficient amount of dilution with ligher r-process material is required to match the solar isotopic residuals

∴ Fission theory has implications far beyond nucleosynthetic outcomes; e.g. for galactic chemical evolution, etc.

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

NUCLEAR FISSION THEORY FOR THE PRODUCTION OF THE HEAVIEST ELEMENTS

NUCLEAR FISSION IN A NUTSHELL



The fission process:

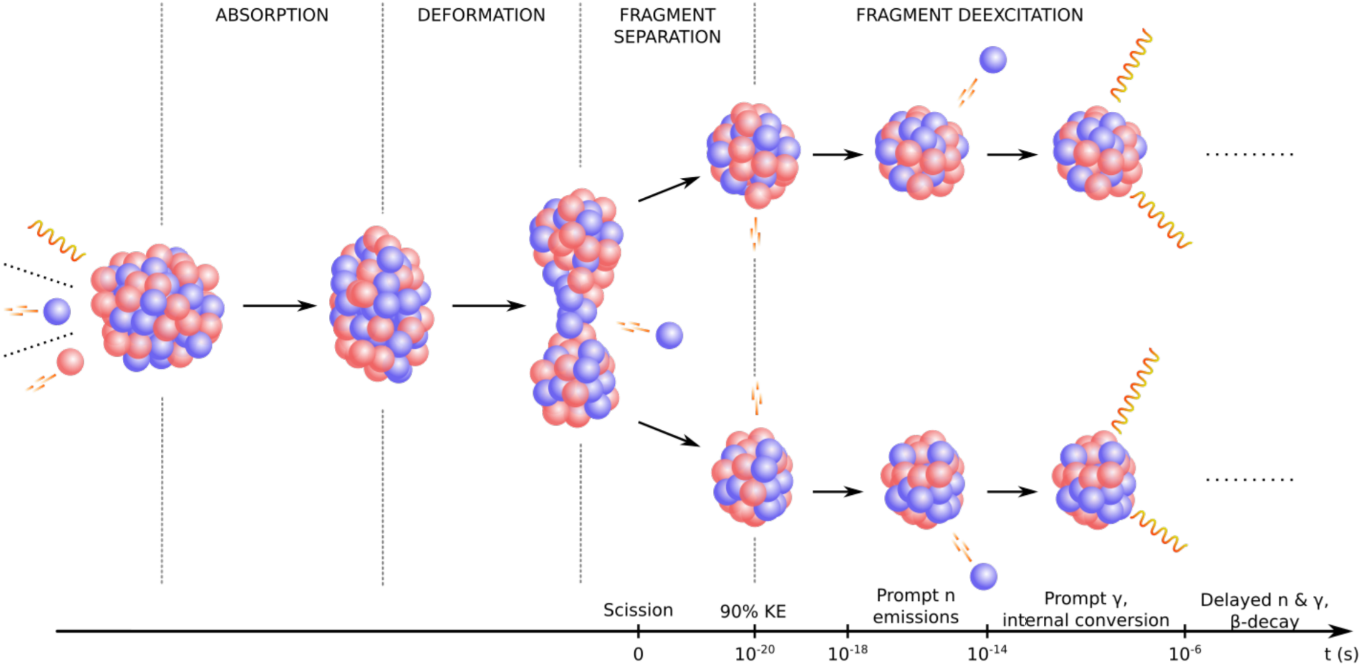
A heavy nucleus splits into two lighter fragments

Subsequent particle emission and decays then occur

Many events gives rise to fission yield

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

NUCLEAR FISSION FOR THE r-PROCESS



Influence on the r-process:

Fission rates and branching determine re-cycling (robustness)

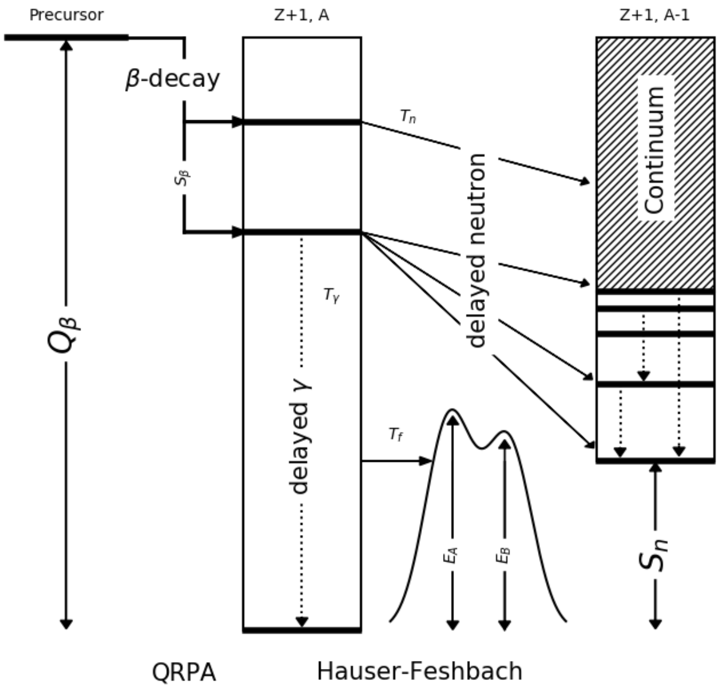
Fragment yields place material at lower mass number; barriers determine hot spots

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"

Holmbeck *et al.* ApJ 870 1 (2019) • Vassh *et al.* J. Phys. G (2019) • Figure from Verriere *et al.* in prep. (2019)

β -DELAYED FISSION



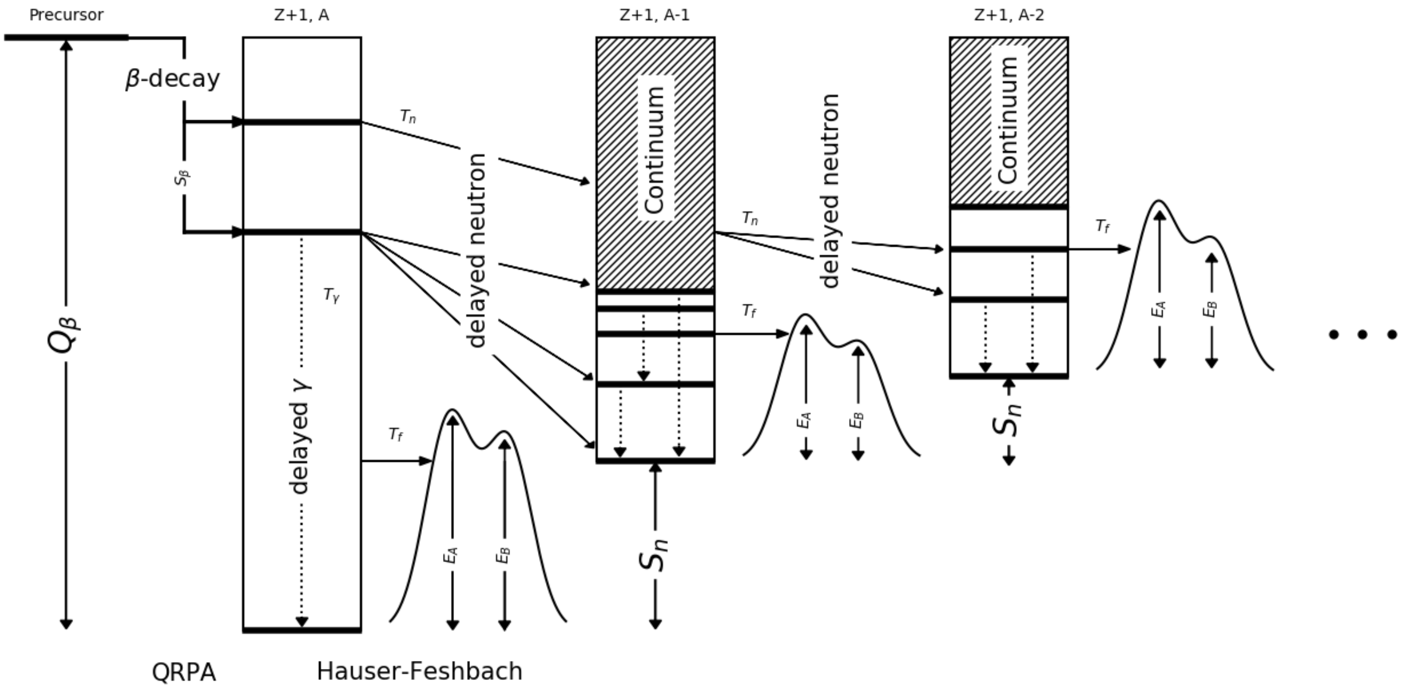
We have recently extended our QRPA+HF model to describe β-delayed fission (βdf)

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

Assumes a Hill-Wheeler form for fission transmission

Mumpower *et al.* PRC 94 064317 (2016) • Spyrou ***et al.*** PRL (2016) • Möller ***et al.*** ADNDT 125 (2019)
Yokoyama *et al.* PRC (2019) • **Mumpower** *et al.* ApJ (2018)

MULTI-CHANCE β DF



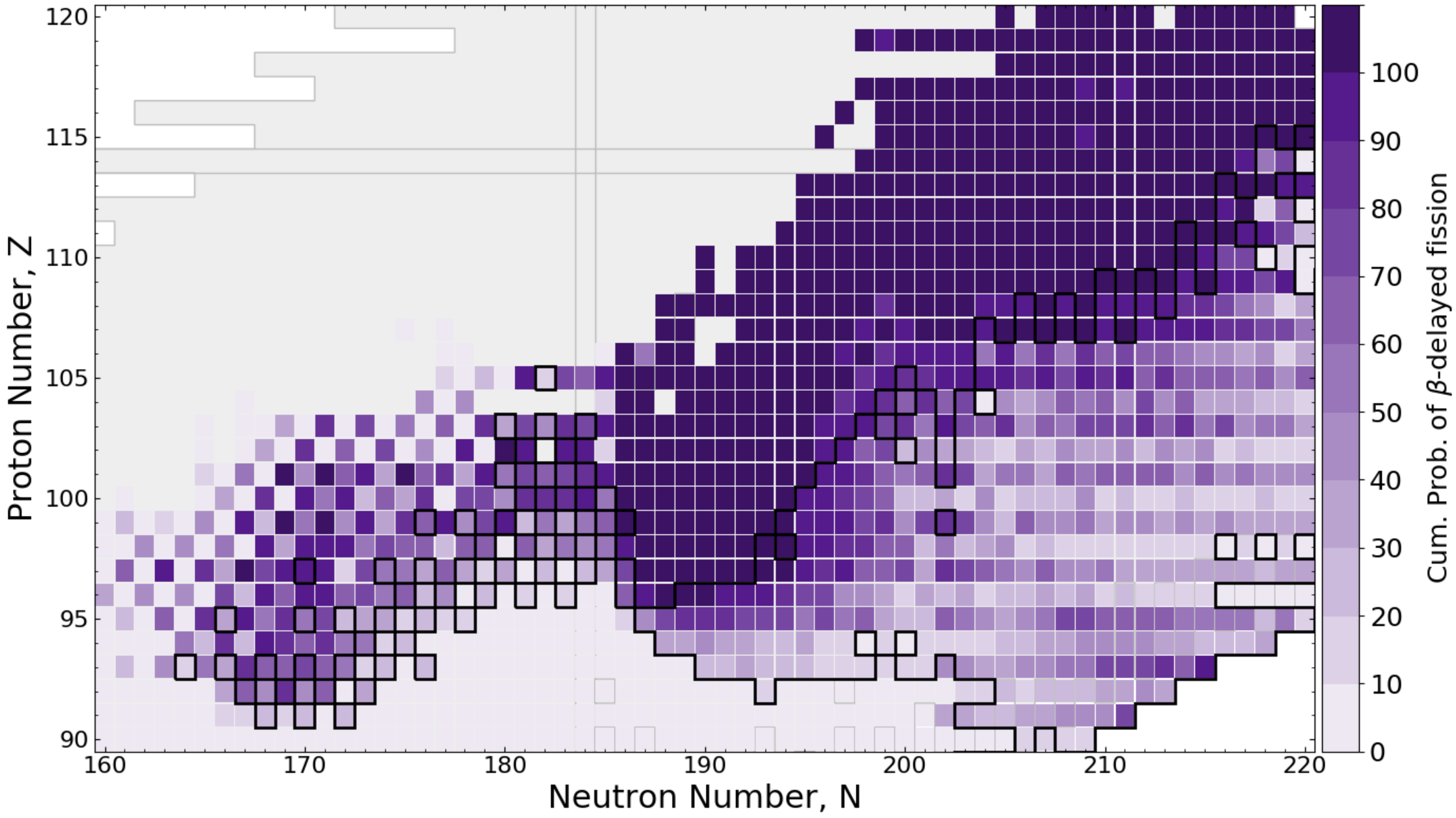
Recall: Near the dripline Q_{beta} ⇡ S_n ⇣

Multi-chance βdf: <u>*each* daughter may fission</u>

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

Mumpower *et al.* PRC 94 064317 (2016) • Spyrou ***et al.*** PRL (2016) • Möller ***et al.*** ADNDT 125 (2019)
Yokoyama *et al.* PRC (2019) • **Mumpower** *et al.* ApJ (2018)

CUMULATIVE β DF PROBABILITY

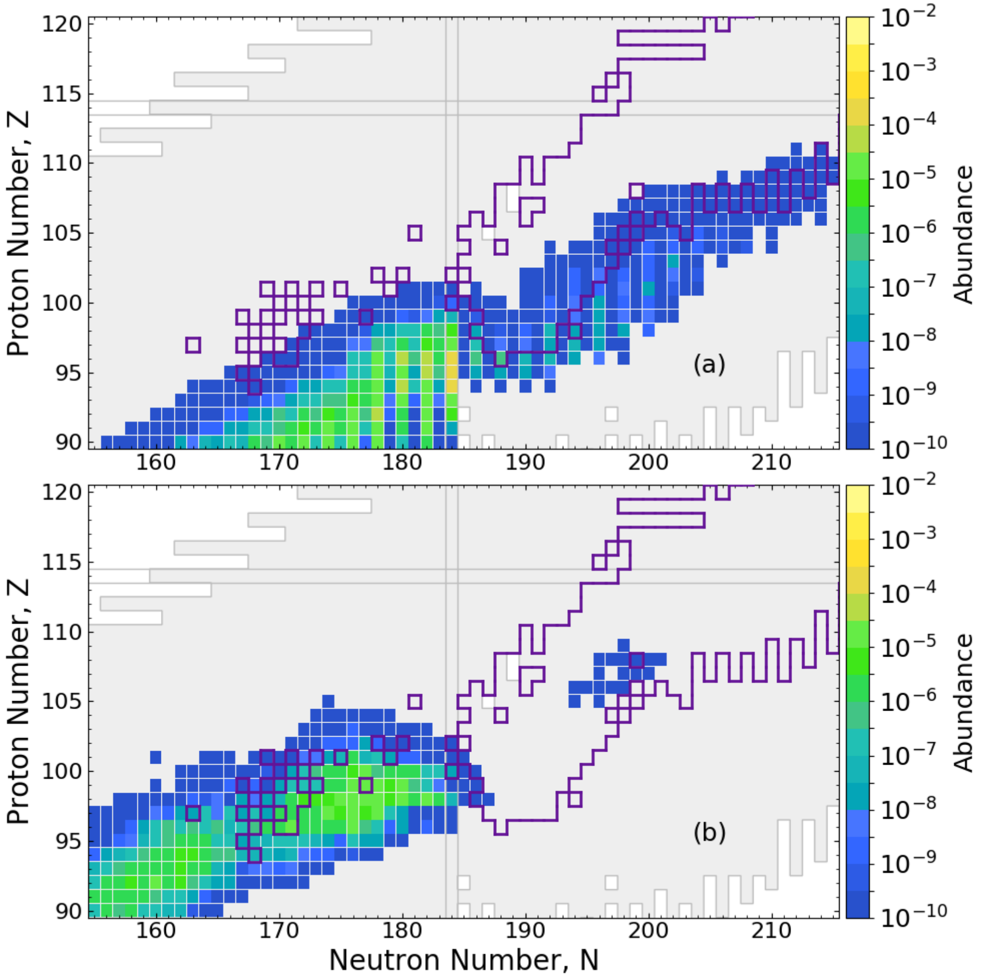


βdf occupies a large amount of real estate in the NZ-plane

Multi-chance βdf outlined in black

Mumpower *et al.* ApJ 869 1 (2018)

APPLICATION TO THE r-PROCESS

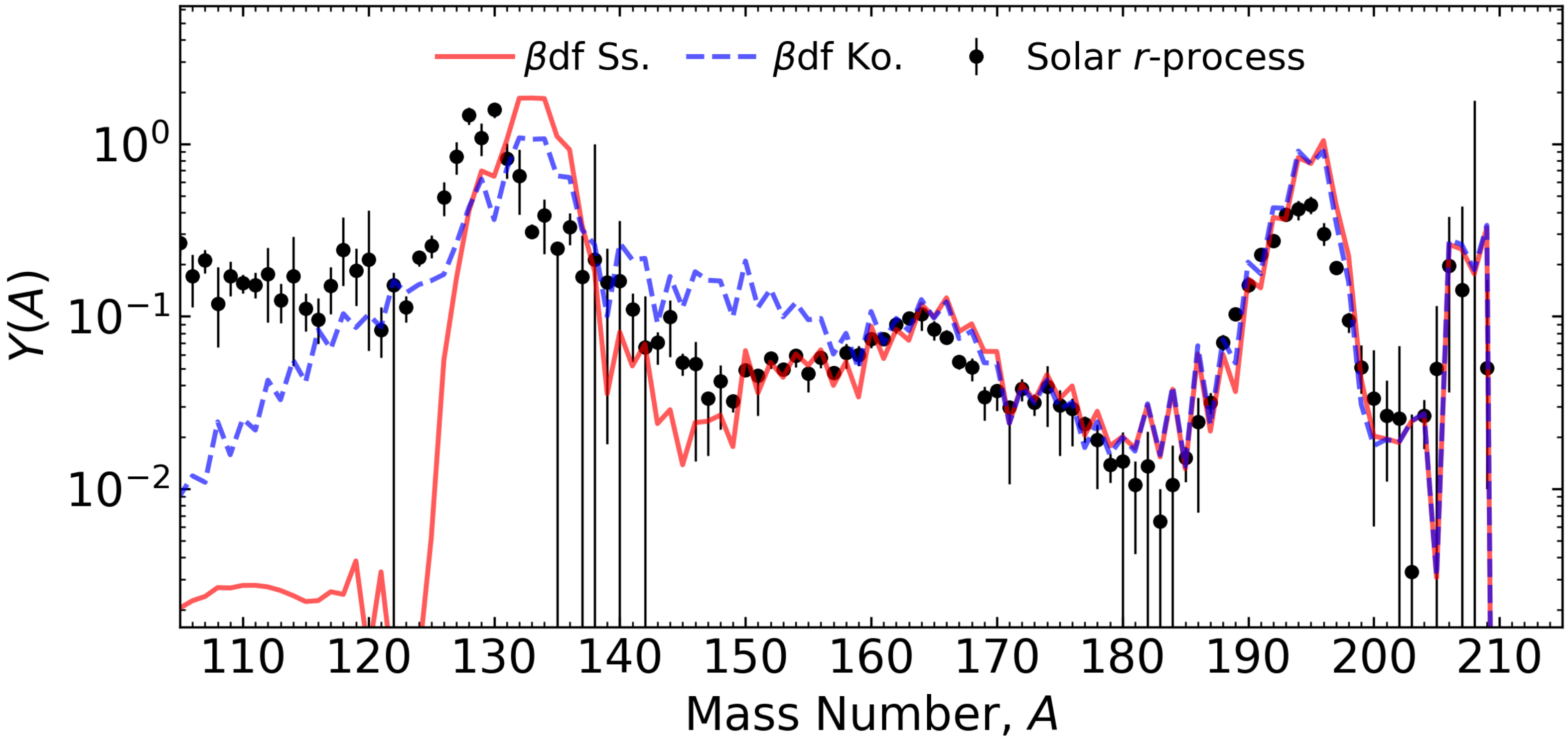


PRISM network calculation of neutron star merger ejecta

βdf alone may prevent the production of superheavy elements in nature

Thielemann *et al.* Zeitschrift fur Physik A Atoms and Nuclei 309 4 (1983) • **Mumpower** *et al.* ApJ 869 1 (2018)

IMPACT ON FINAL ABUNDANCES



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

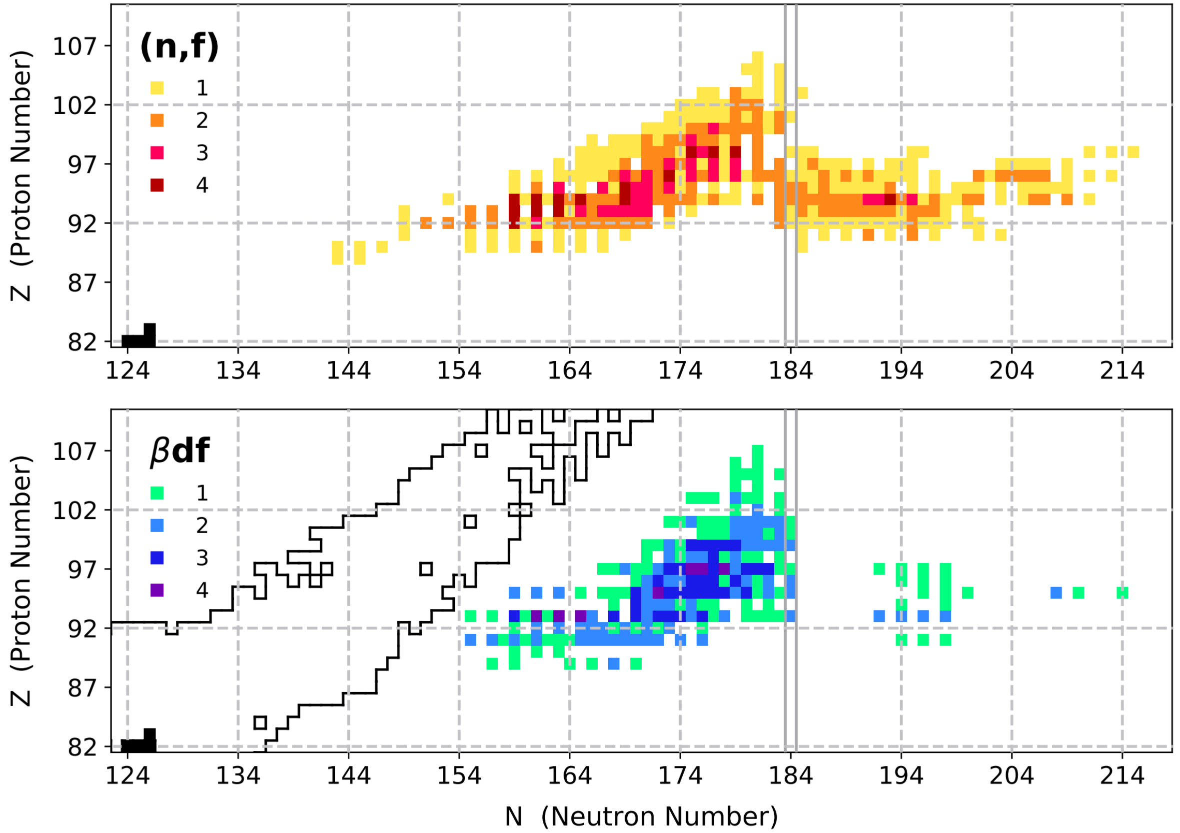
βdf can shape the final pattern near the $A = 130$ peak

This is because of a relatively long fission timescale

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

Kodama & Takahashi (1975) • Shibagaki *et al.* ApJ (2016) • **Mumpower** *et al.* ApJ 869 1 (2018) • Vassh ***et al.*** J. Phys. G (2019)

FISSION HOT SPOTS



We've taken a look at the region where fission seems to occur the most

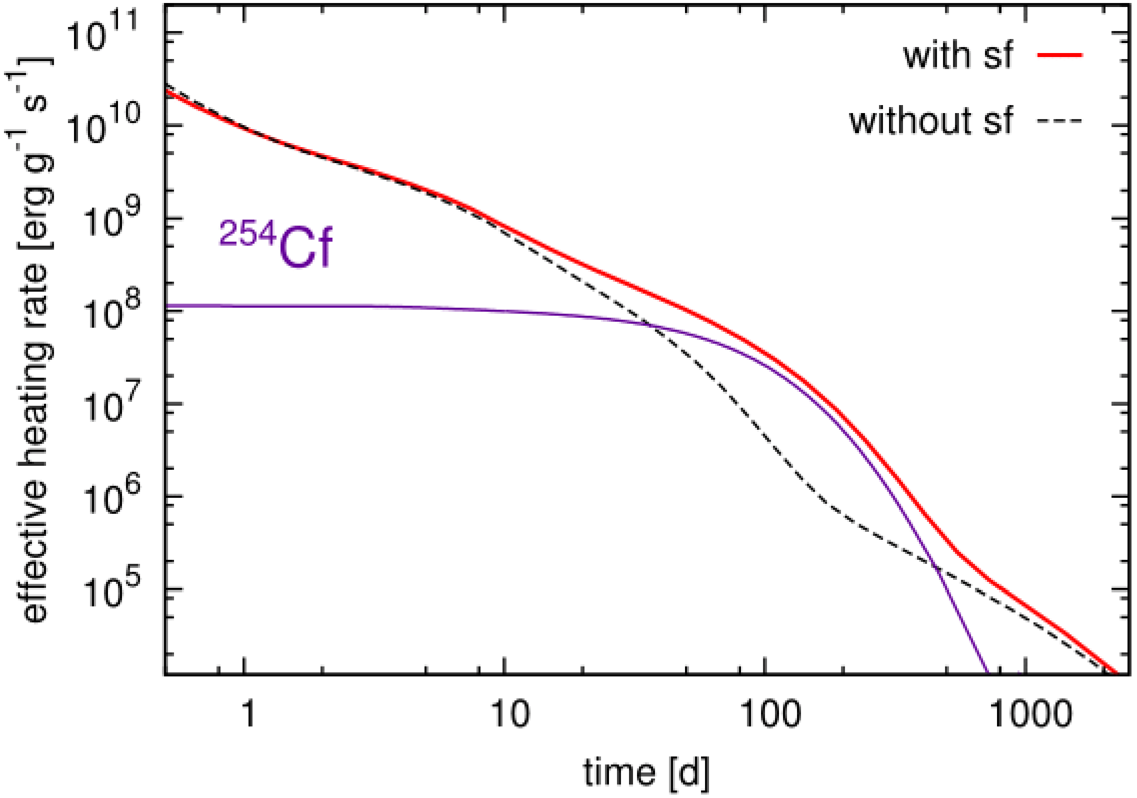
With variations in both astrophysical conditions and nuclear models

Nuclei which influence the final abundances are colored for (n,f) and (β,f)

Vassh ***et al.*** J. Phys. G (2019)

CAN WE OBSERVE ACTINIDE PRODUCTION?

ONE EXAMPLE: ^{254}CF(Z=98)



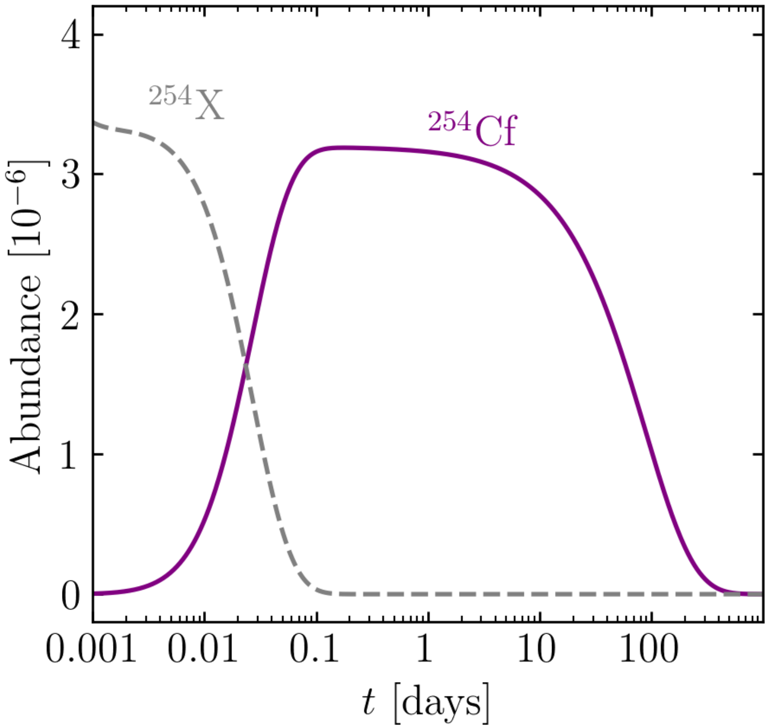
Is there any possible precursor to show that actinide nucleosynthesis has occurred in an event?... Maybe!

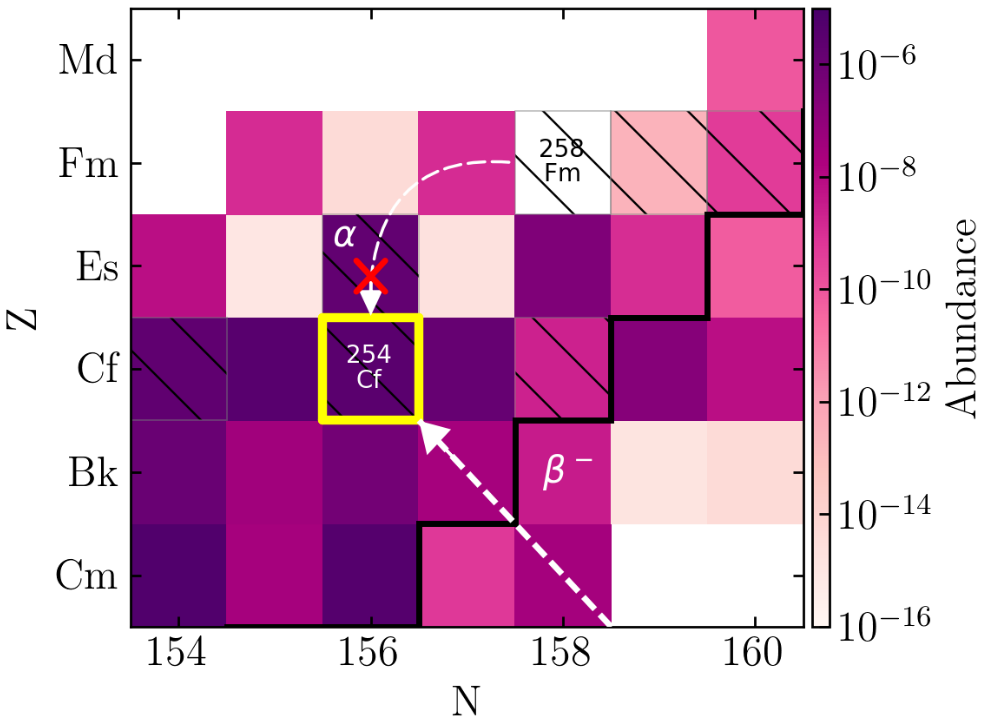
The spontaneous fission of ^{254}Cf can be a *primary* contributor to nuclear heating at late-time epochs

The $T_{1/2} \sim 60$ days; found from nuclear weapons testing

Baade *et al.* PASP (1956) • Conway *et al.* JOSA (1962) • Wanajo *et al.* ApJL (2014) • Y. Zhu ***et al.*** ApJL 863 2 (2018)
Vassh ***et al.*** J. Phys. G (2019)

PRODUCTION OF ^{254}CF(Z=98)





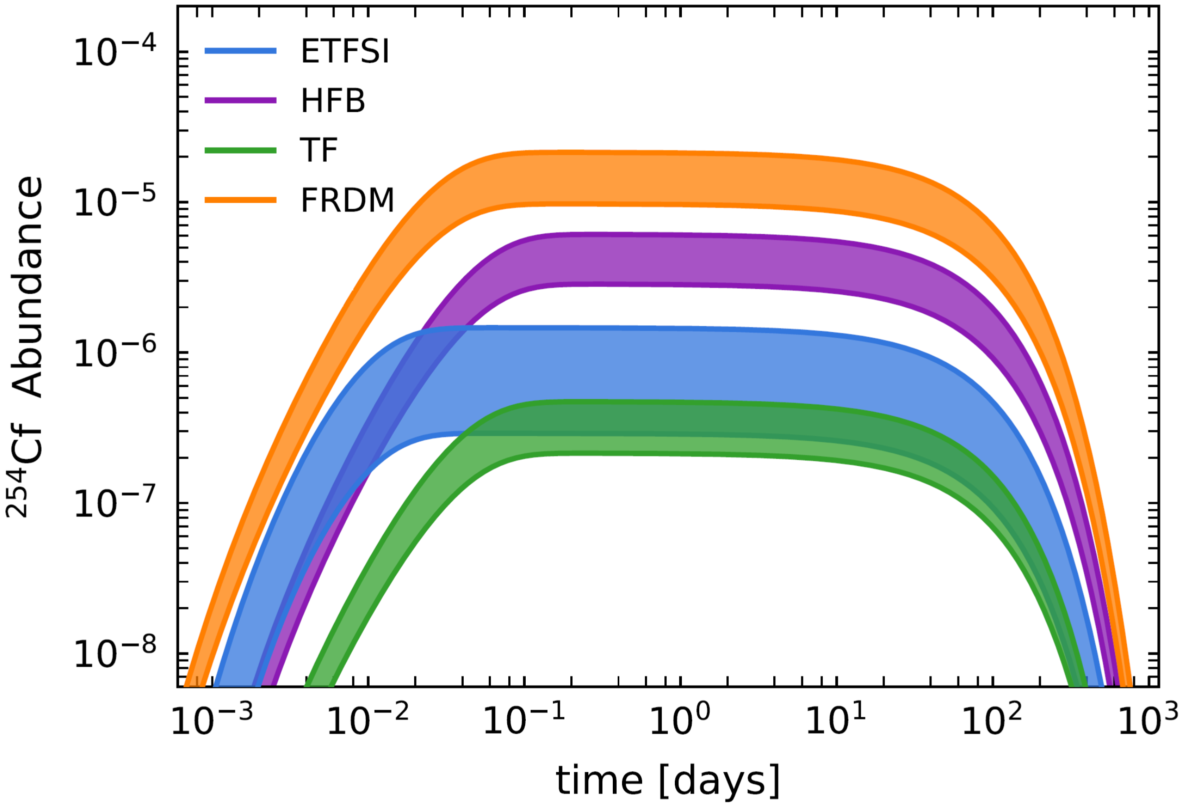
Primary feeder seems to be from β-decay

Production of this nucleus been explored over a range of nuclear models; some high - some low

Remains to be seen if we can disentangle from other late-time heating sources (e.g. puslar or accreetion fallback)

Wanajo *et al.* (2014) • Y. Zhu ***et al.*** ApJL 863 2 (2018) • Vassh ***et al.*** J. Phys. G (2019) • Wollaeger ***et al.*** ApJ (2019) • Wu *et al.* PRL (2019)

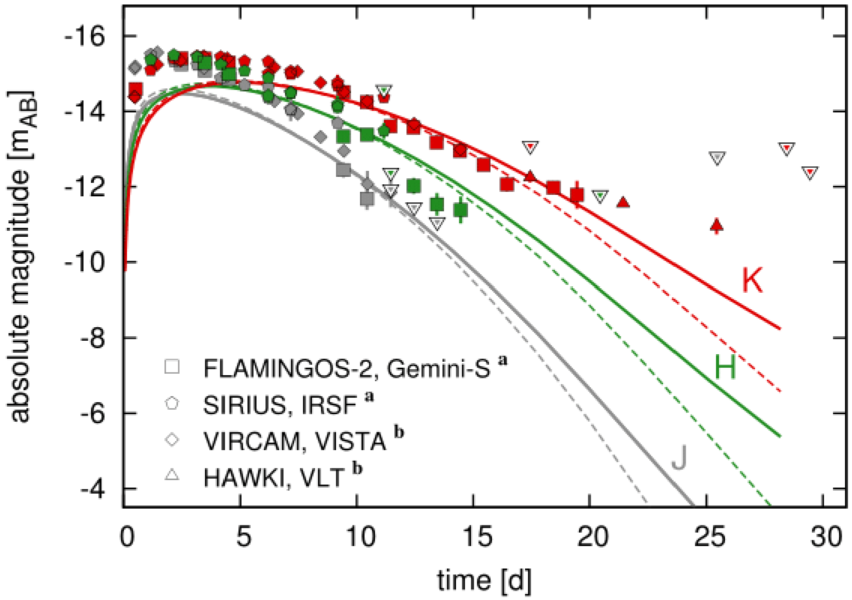
PRODUCTION OF ^{254}CF(Z=98)

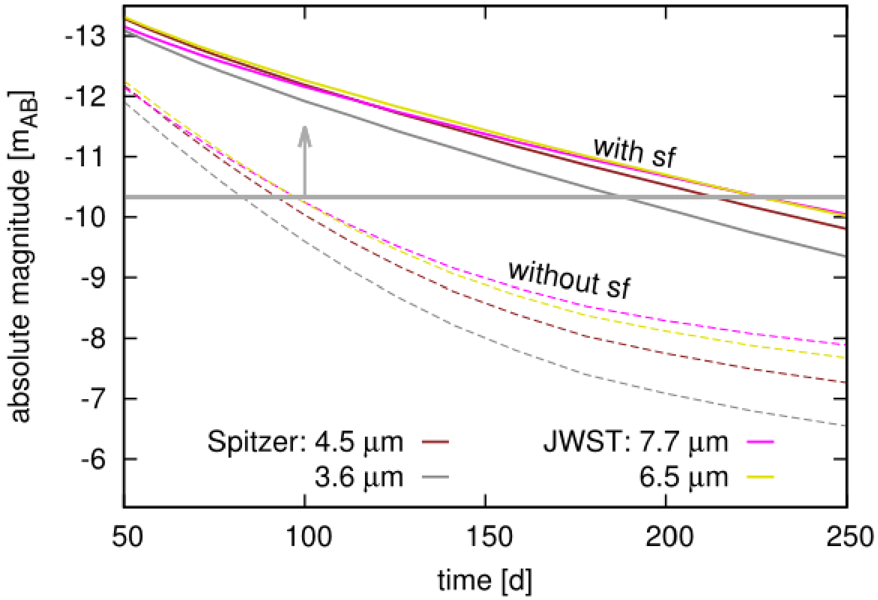


We have also looked at the variation of production in this element with change in fission barriers

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

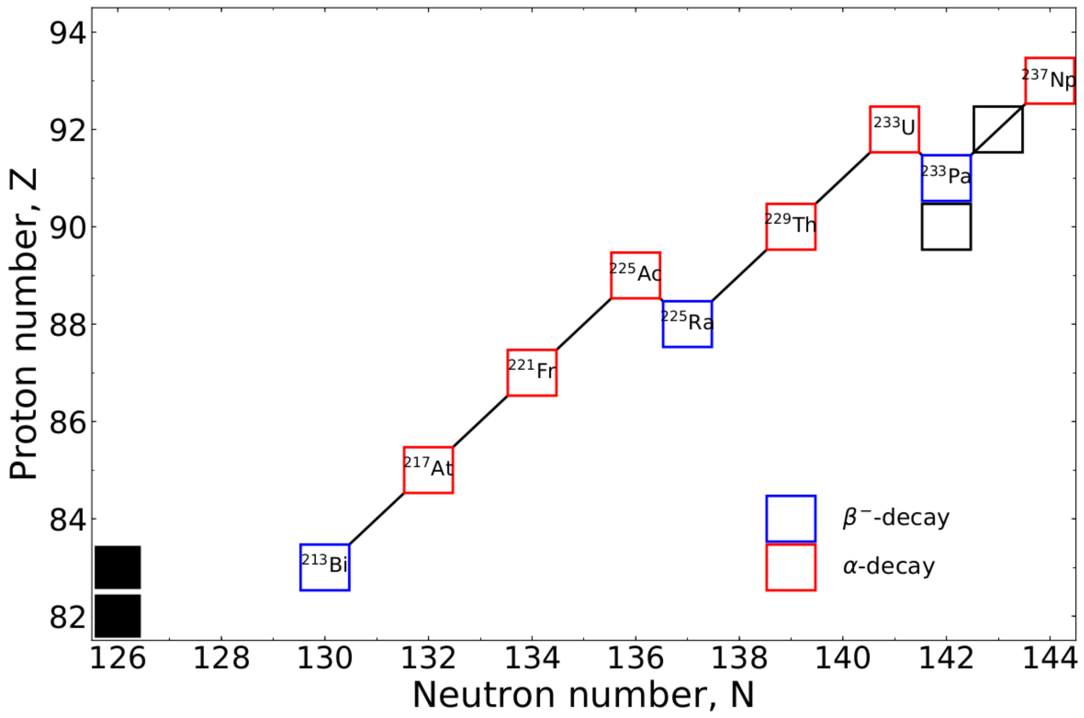
This also has implications for merger morphology...

Wanajo *et al.* (2014) • Y. Zhu ***et al.*** ApJL 863 2 (2018) • Vassh ***et al.*** J. Phys. G (2019) • Wollaeger ***et al.*** ApJ (2019) • Wu *et al.* PRL (2019)

MERGER γ-RAYS

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

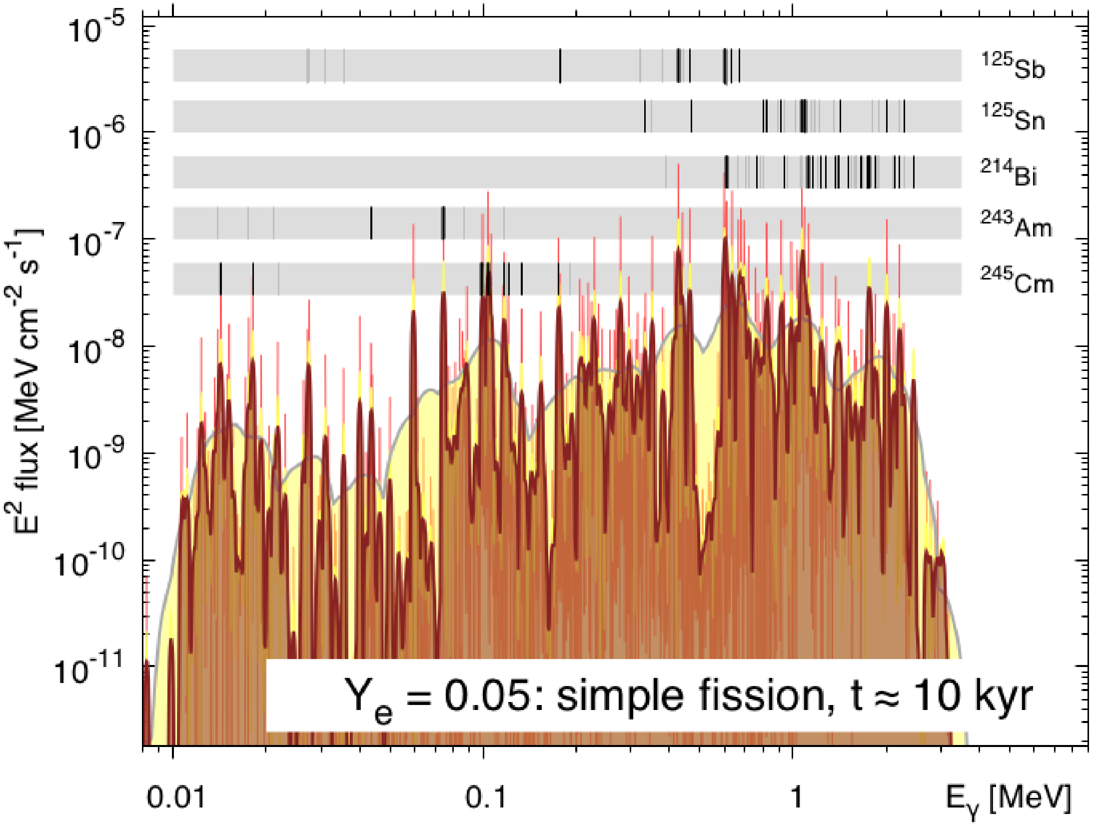
For the r-process we should search for signatures of actinides...



This involves following potentially complex decay chains...

Wu *et al.* ApJ (2019) • Korobkin ***et al.*** accepted ApJ (2019)

γ-RAY SPECTRUM AT 10 KYR



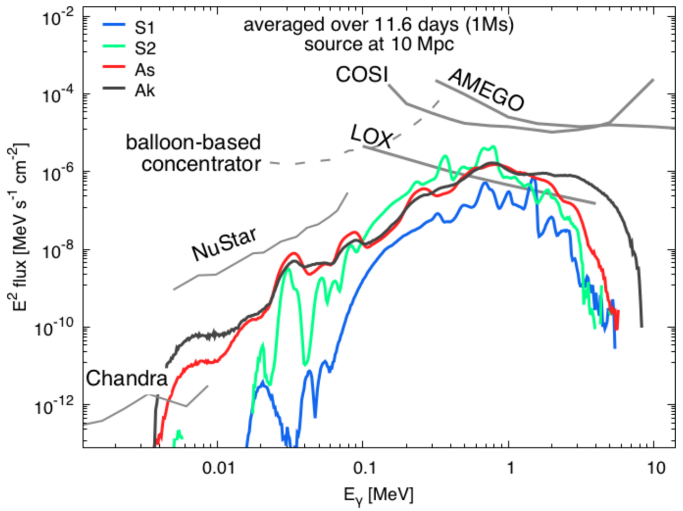
Distinct signatures do arise; despite line broadening

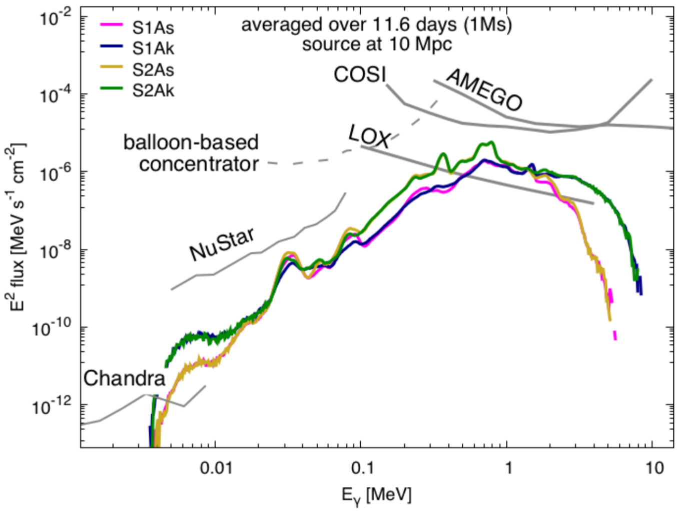
This depends sensitively on observational timescale

Can we do this with future space missions?

Wu *et al.* ApJ (2019) • Korobkin ***et al.*** accepted ApJ (2019)

OBSERVING γ-RAYS





Differing composition may be able to be ascertained, but the event has to be close (10 Mpc or less)

Possible candidates:

The Lunar Occultation Explorer (LOX)

Compton Spectrometer and Imager (COSI)

All-sky Medium Energy Gamma-ray Observatory (AMEGO) may all be promising

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

SPECIAL THANKS TO

My collaborators

A. Aprahamian, J. Barnes, A. Burrows, J. Clark, B. Côté, J. Dolance, W. Even, C. Fontes, C. Fryer, E. Holmbeck, A. Hungerford, P. Jaffke, T. Kawano, O. Korobkin, J. Lippuner, G. C. McLaughlin, J. Miller, W. Misch, P. Möller, R. Orford, J. Randrup, G. Savard, T. Sprouse, R. Surman, N. Vassh, M. Verriere, R. Vogt, R. Wollaeger, Y. Zhu

& many more...

■ Student ■ Postdoc ■ CTA Staff ■ FIRE PI

SUMMARY

The production of actinides in the r-process requires a *deep understanding* of nuclear physics

Recent insights include:

modeling of astrophysical environments ▲ Multi-messenger observations
Nuclear theory predictions

FRIB, etc. will help to constrain nuclear models, but the heaviest elements will remain relatively inaccessible

We therefore need to keep developing and studying theoretical models of nuclear physics

Nuclear modeling is absolutely crucial if we want to prove definitively that heavy elements such as the actinides were made in an event

Results / Data / Papers @ MatthewMumpower.com