FISSION ACROSS THE CHART OF NUCLIDES AND IMPLICATIONS FOR THE r PROCESS

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Workshop on nuclear fission dynamics

Monday Oct. 28^{th} 2019

FIRE Collaboration
Fission In R-process Elements

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.)

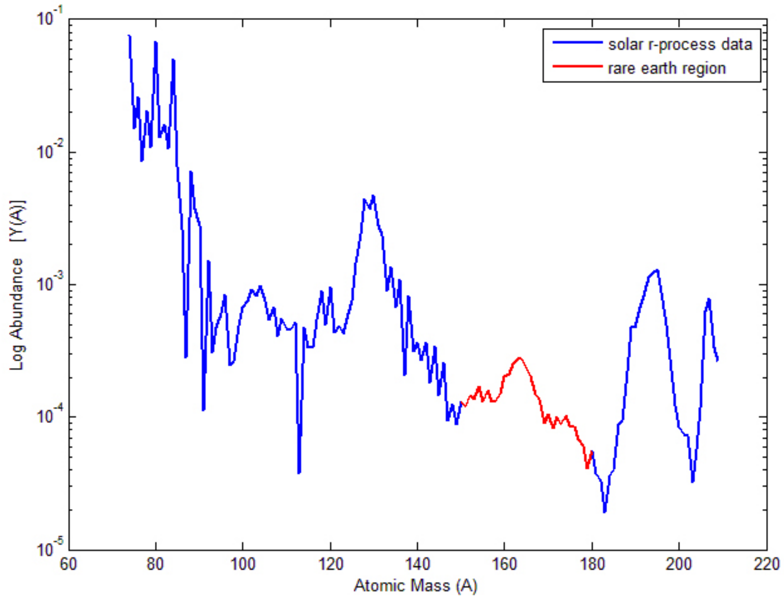
Nuclear theory predictions for exotic nuclei

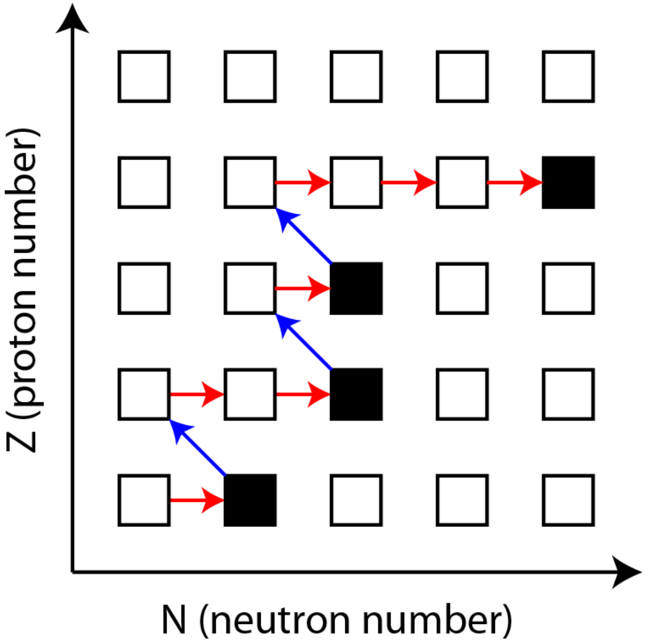
Precision experiments to constrain nuclear theory

Data and observations are limited

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

WHAT IS THE r-PROCESS?





Rapid neutron capture that occurs in astrophysical environments allowing for the production of heavy elements

Neutron captures are initially much faster than β-decays

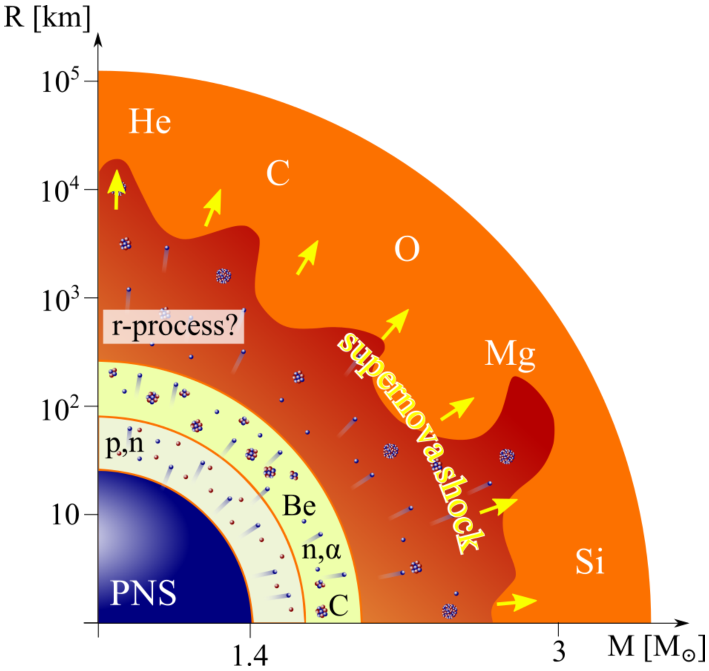
Relative slowdown in the nuclear flow (right) produces peak structures in the observed abundances (left)

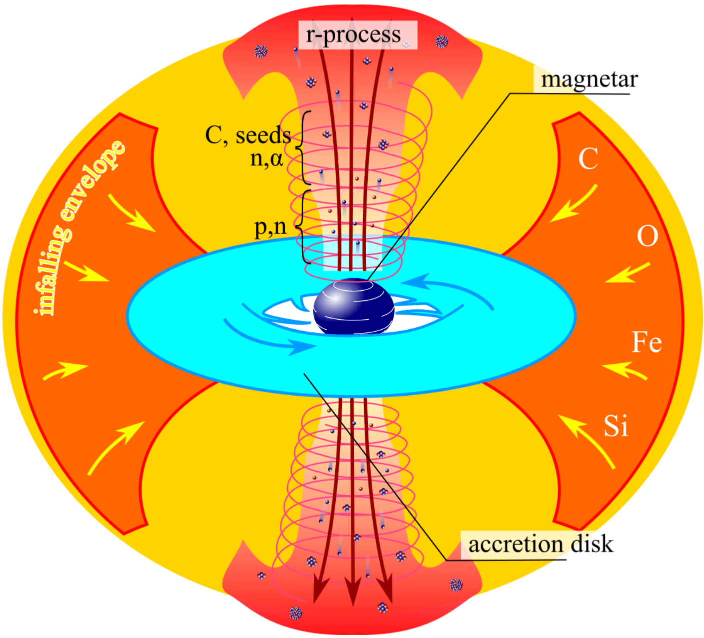
Astrophysical environment must produce a lot of free neutrons in order for this process to proceed

Aprahamian *et al.* (2018) • Horowitz *et al.* J Phys G 083001 (2019)

WHERE CAN THE *r*-PROCESS OCCUR?

One possibility is in (rare?) supernovae





For standard supernovae (left) neutrino physics still needs to be well understood

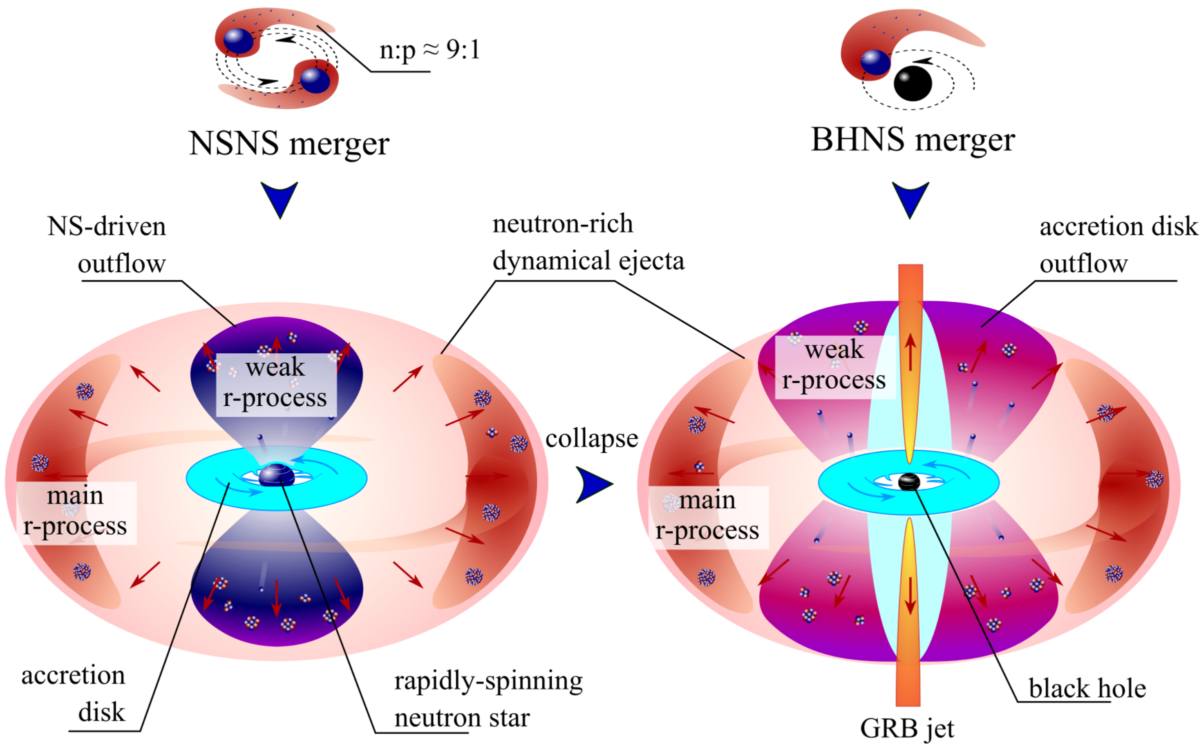
Jets in magnetorotational driven supernovae (right) may also provide the necessary conditions

Another option is the disk winds of collapsars - black hole forms after core collapse of a rapidly rotating star

Meyer ApJ (1989) • MacFadyen & Woosley ApJ (1999) • Figure from **Mumpower** *et al.* in prep. (2019)

WHERE CAN THE r-PROCESS OCCUR?

Another possibility is in compact object mergers



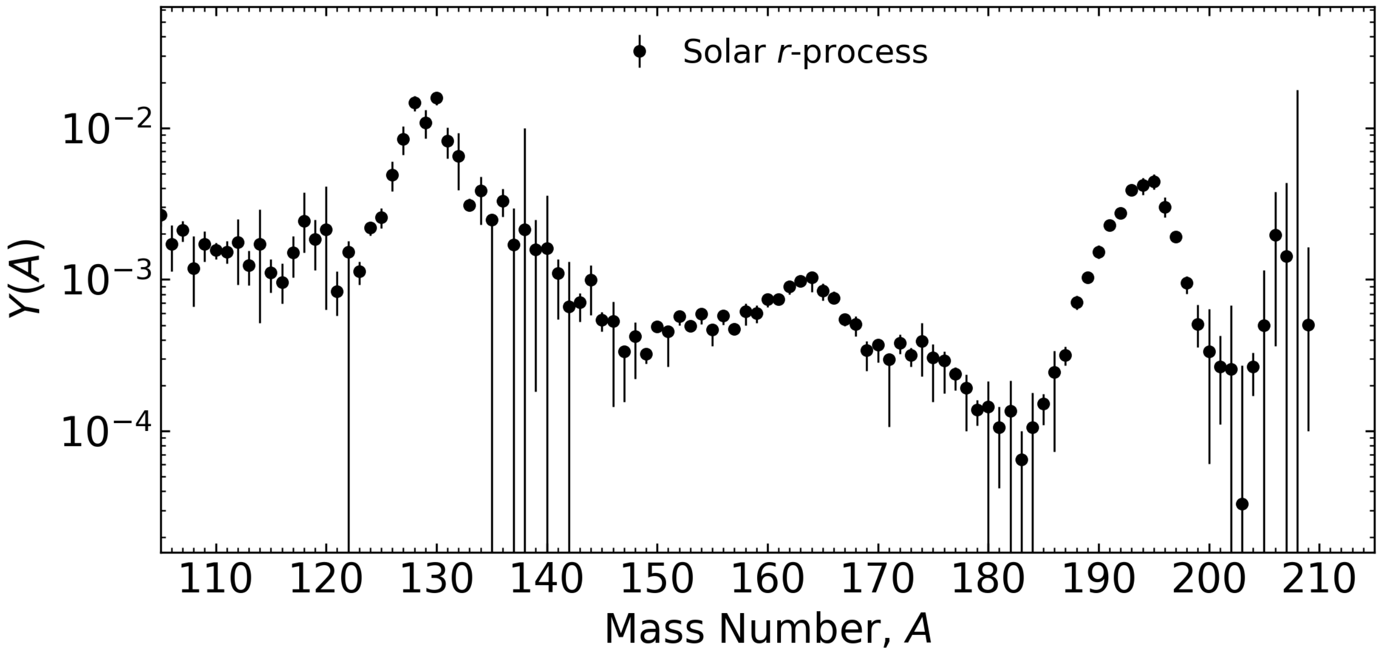
A binary merger of neutron stars is an exciting possibility (some indirect evidence exists)

Another option is in the disk of a black hole neutron star binary

Lattimer & Schramm (1974) • Korobkin *et al.* (2012) • Figure from **Mumpower** *et al.* in prep. (2019)

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)

Mumpower *et al.* PRC (2015) • Côté ***et al.*** ApJ (2018)

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)

r-PROCESS CALCULATION

nuclear physics inputs

(Sn, β-rates, n-cap rates, …)

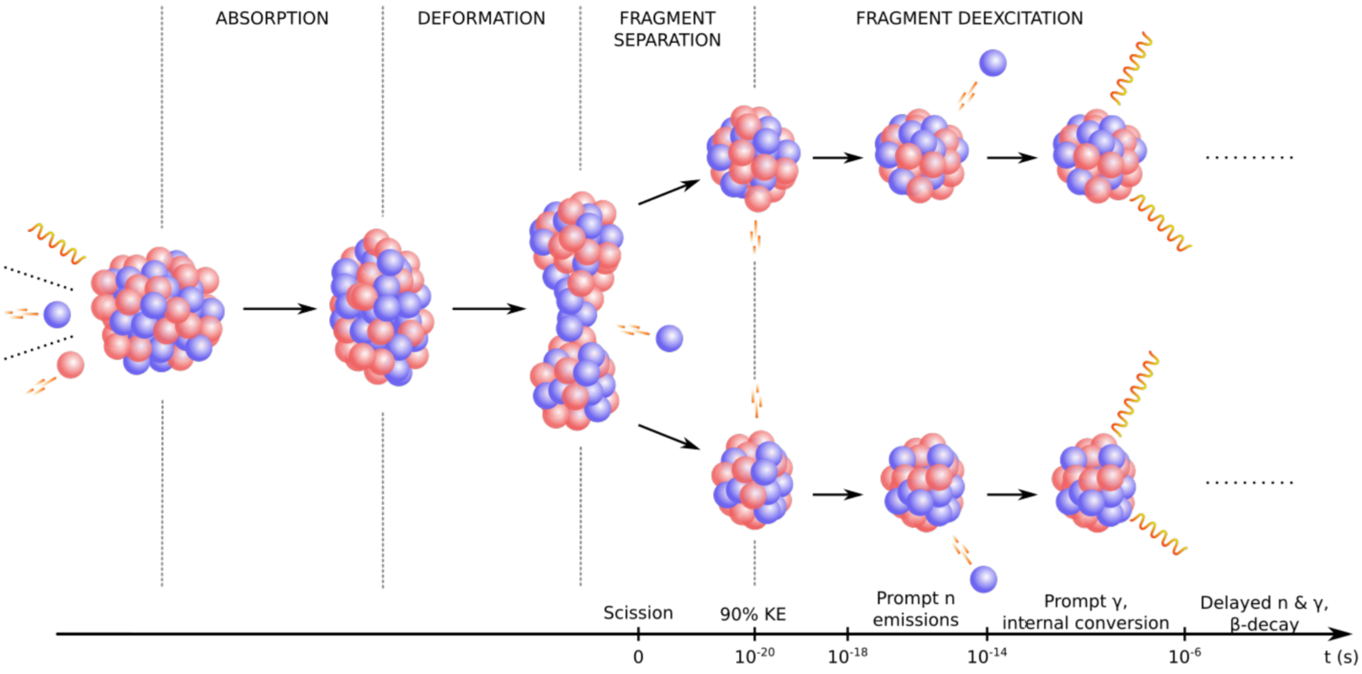
thermodynamic conditions

(temperature, density, ...)

PRISM: Portable Routines for Integrated nucleoSynthesis Modeling

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

NUCLEAR FISSION IN A NUTSHELL



The fission process:

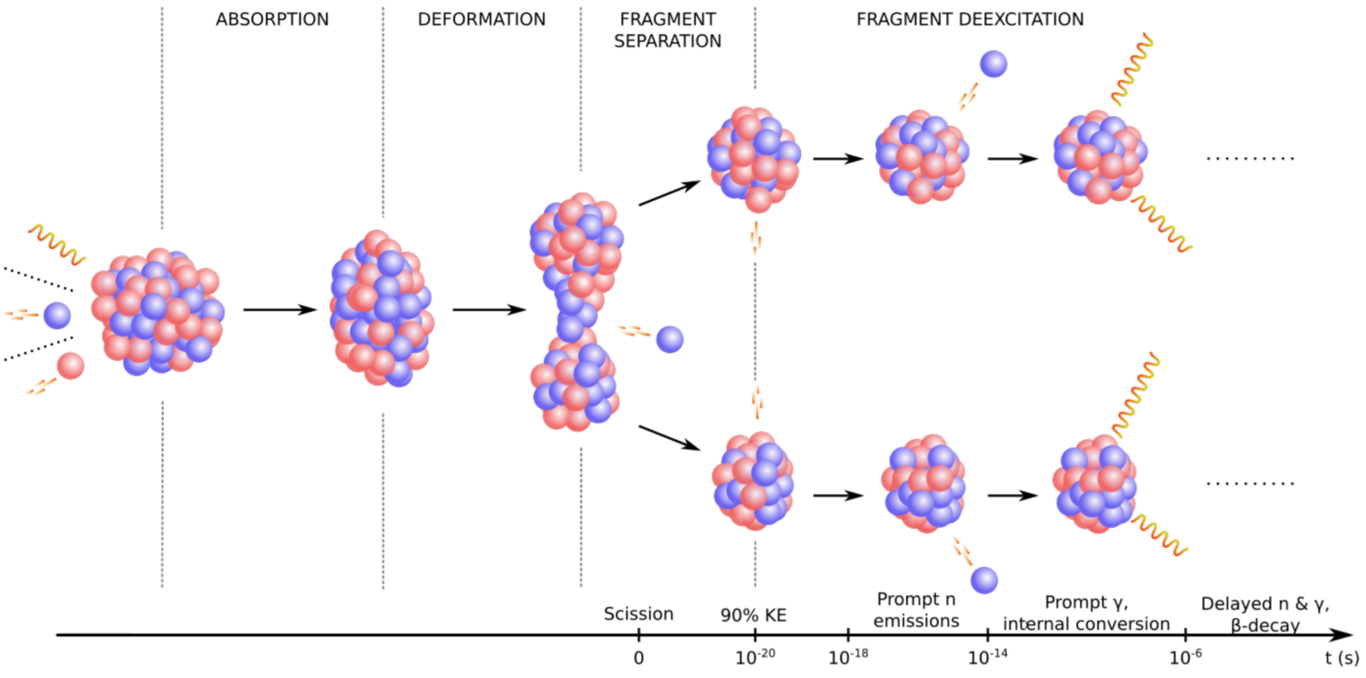
A heavy nucleus splits into two lighter fragments

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

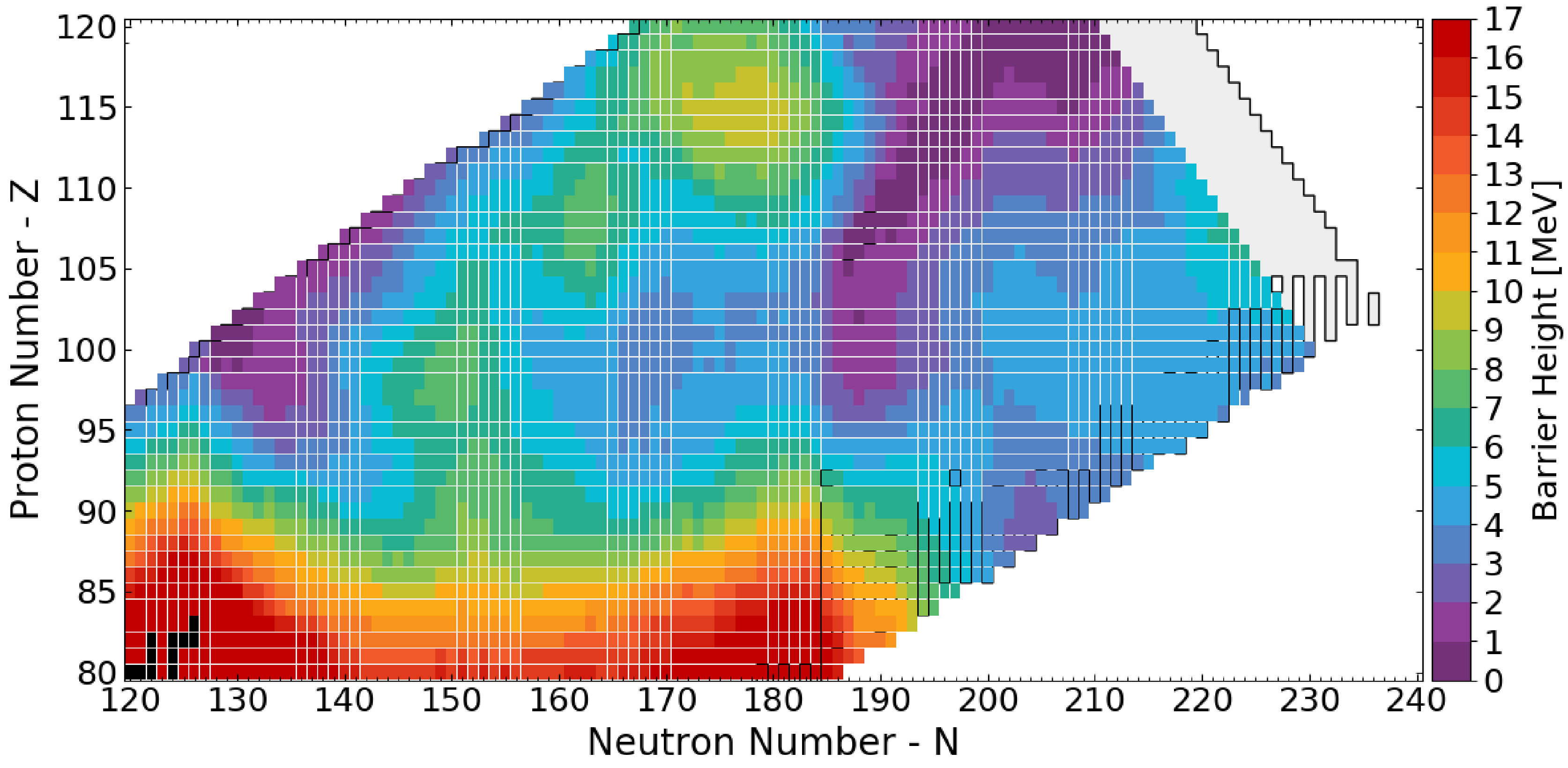
Large Q-value ⇒ impacts thermalization and therefore possibly observations

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)

FISSION BARRIERS

FISSION BARRIER HEIGHTS (FRLDM)



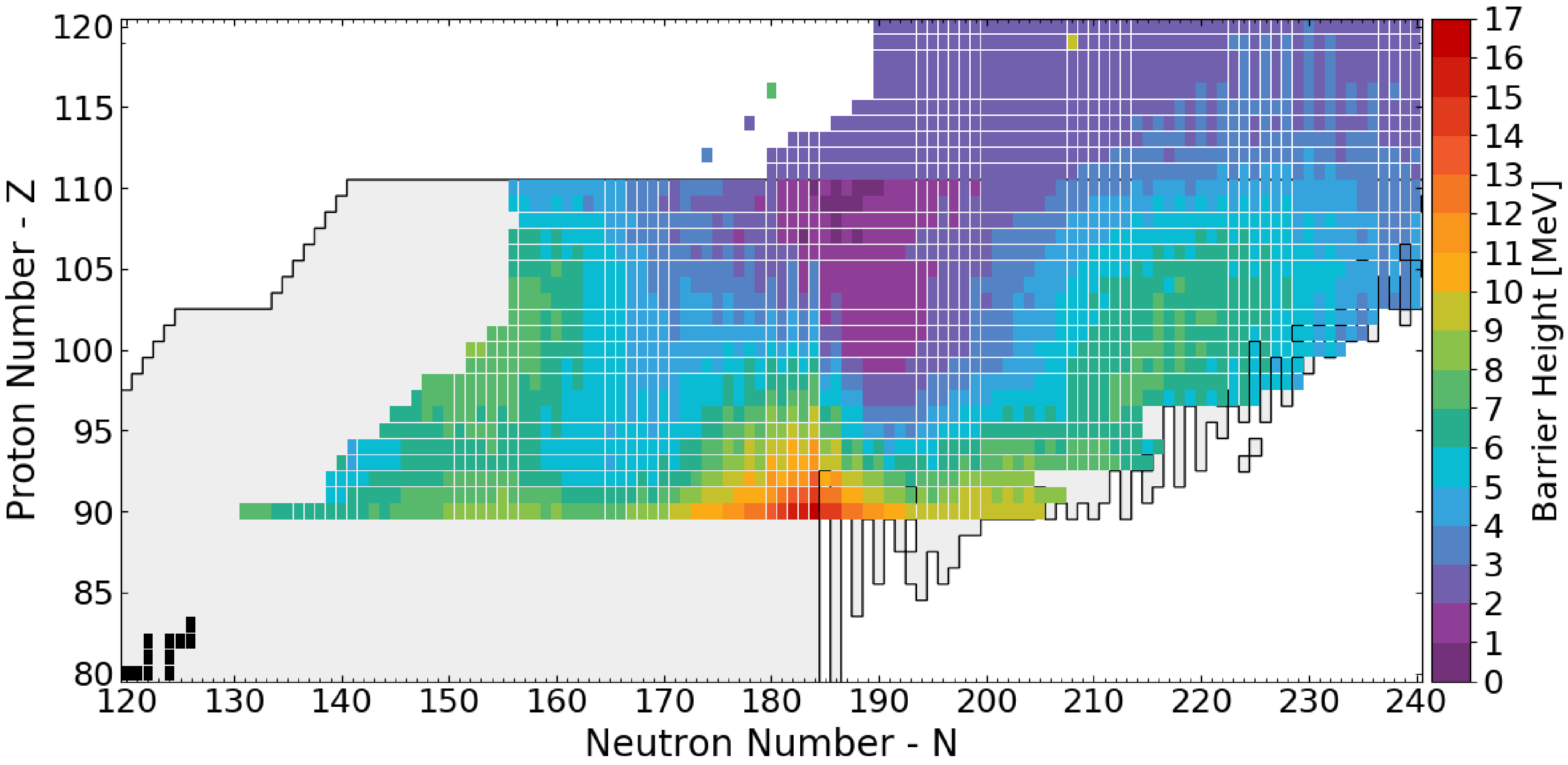
(Maximum) FRLDM Barrier heights

Low barrier ↦ fission ⇑

r-process hot spots follow low barriers

Möller *et al.* PRC 91 024310 (2015)

FISSION BARRIER HEIGHTS (HFB-14)



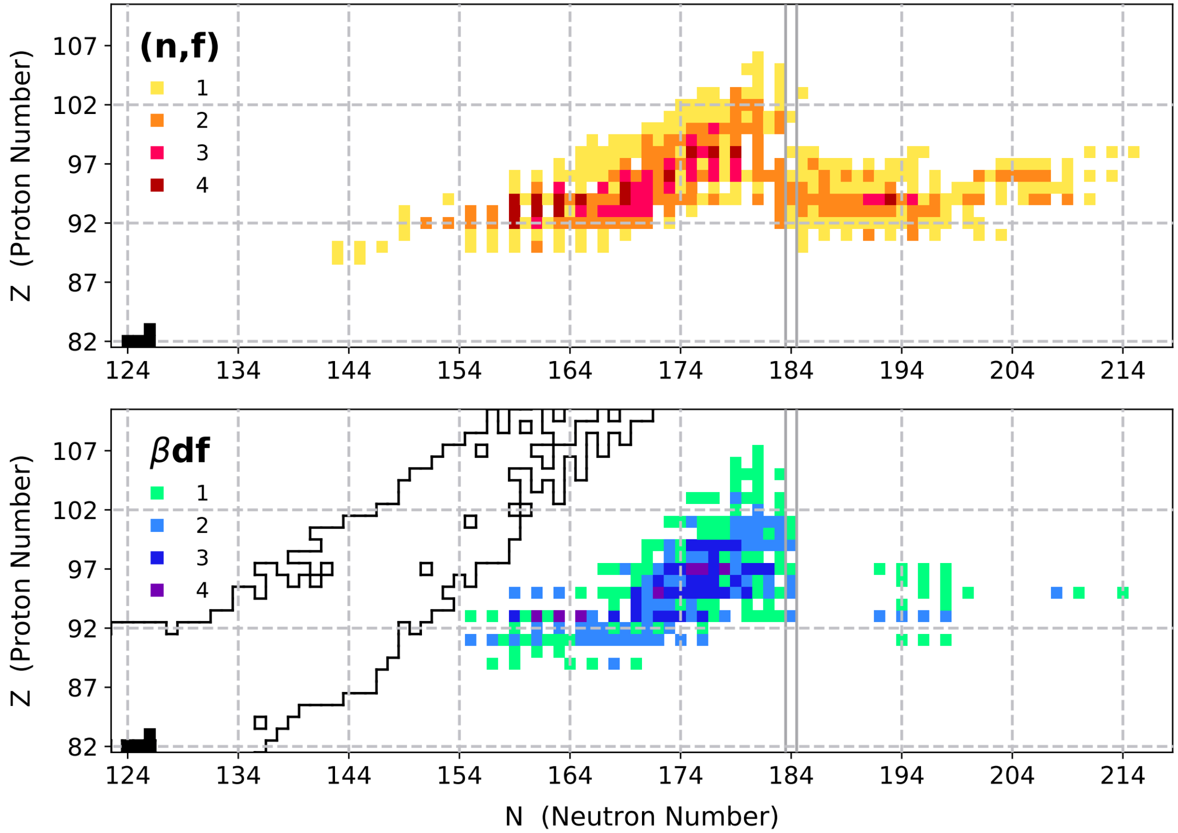
(Maximum) HFB-14 Barrier heights

Low barrier ↦ fission ⇑

Used in (n,f) and βdf calculations

http://www.astro.ulb.ac.be/pmwiki/Brusslib/HomePage

FISSION HOT SPOTS



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

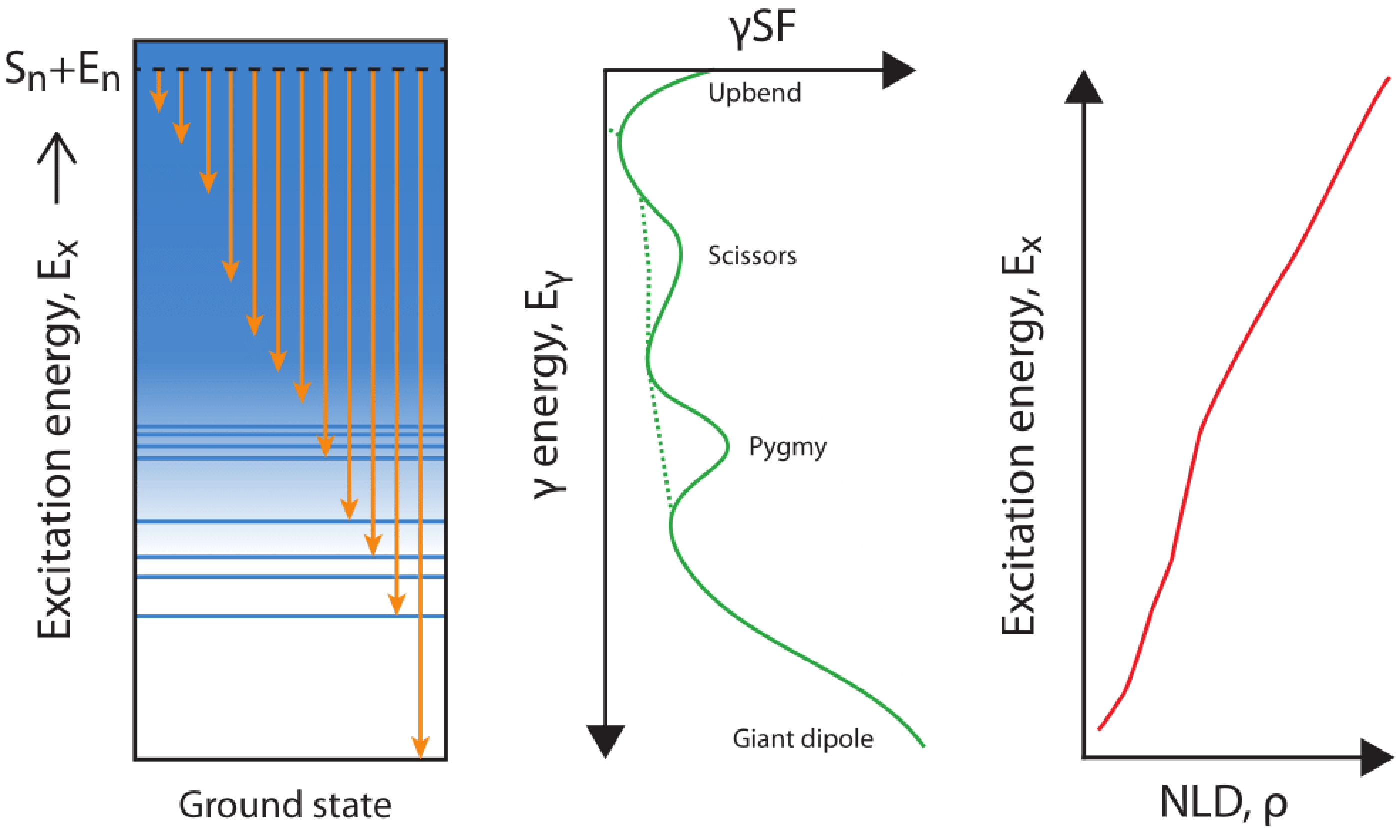
With variations in both astrophysical conditions and nuclear models

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

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

NEUTRON-INDUCED FISSION

NEUTRON-INDUCED FISSION THEORY

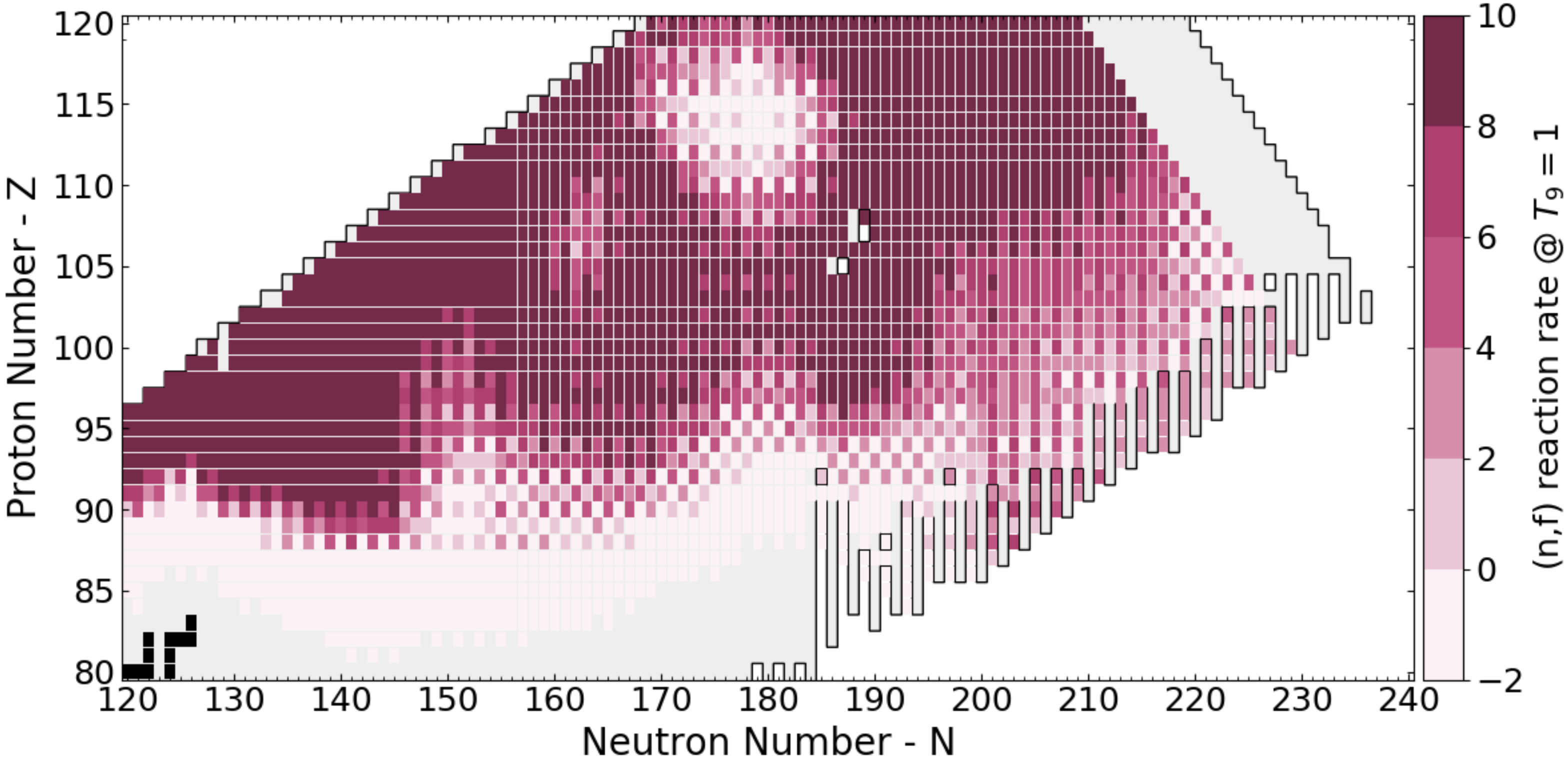


We use statistical Hauser-Feshbach theory updated to account for fission transmission

Model inputs: nuclear level density, γ-ray strength functions, optical model potentials and fission barriers

Kawano *et al.* PRC 94 014612 (2016) • **Mumpower** & Kawano in prep. (2019)

NEUTRON-INDUCED FISSION



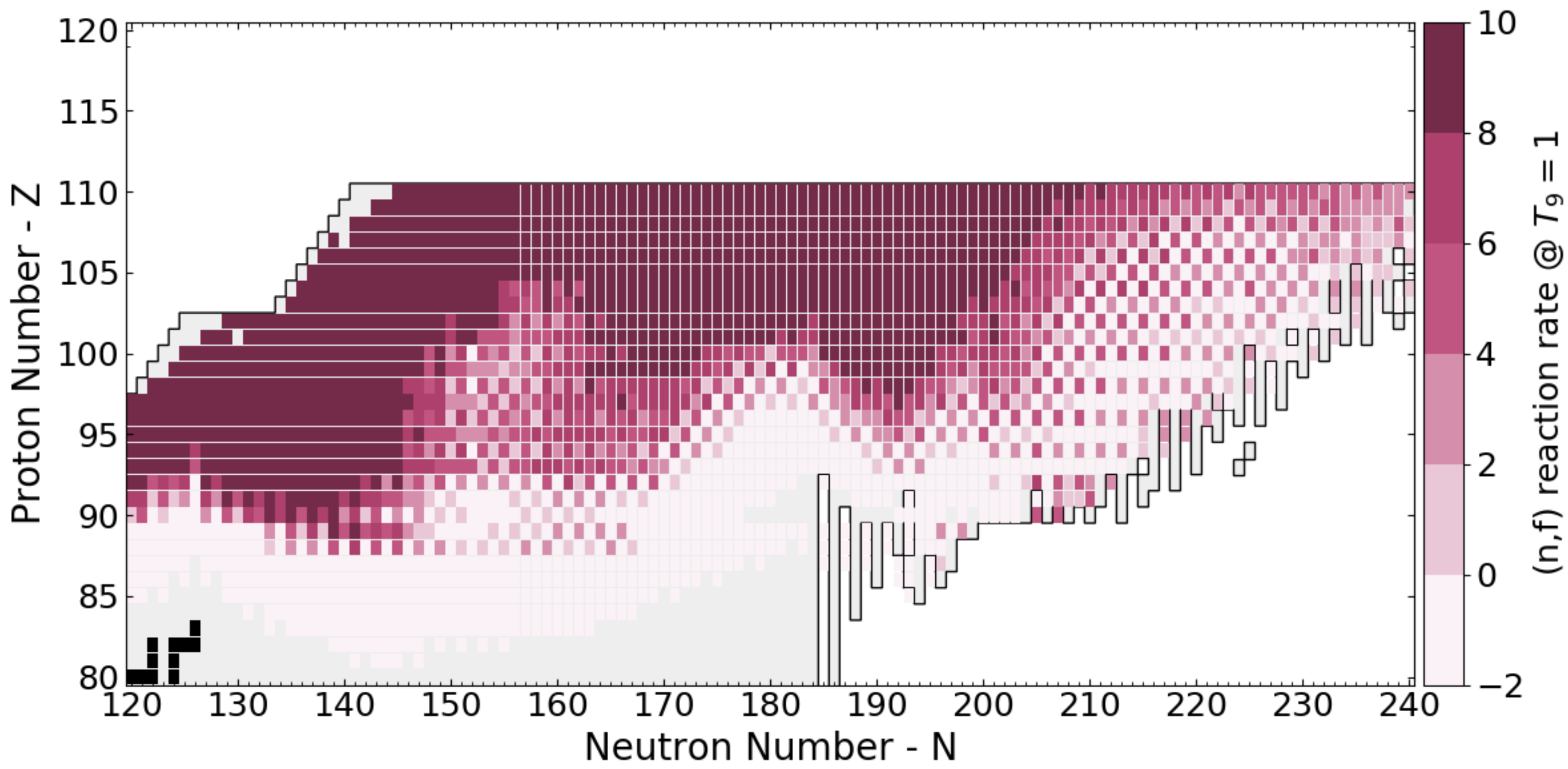
Use statistical Hauser-Feshbach for competition between neutrons, γs and fission

Barrier heights Möller (2015) / FRDM2012 masses

Large region that will fission cycle r-process

Mumpower & Kawano in prep. (2019)

NEUTRON-INDUCED FISSION



Use statistical Hauser-Feshbach for competition between neutrons, γs and fission

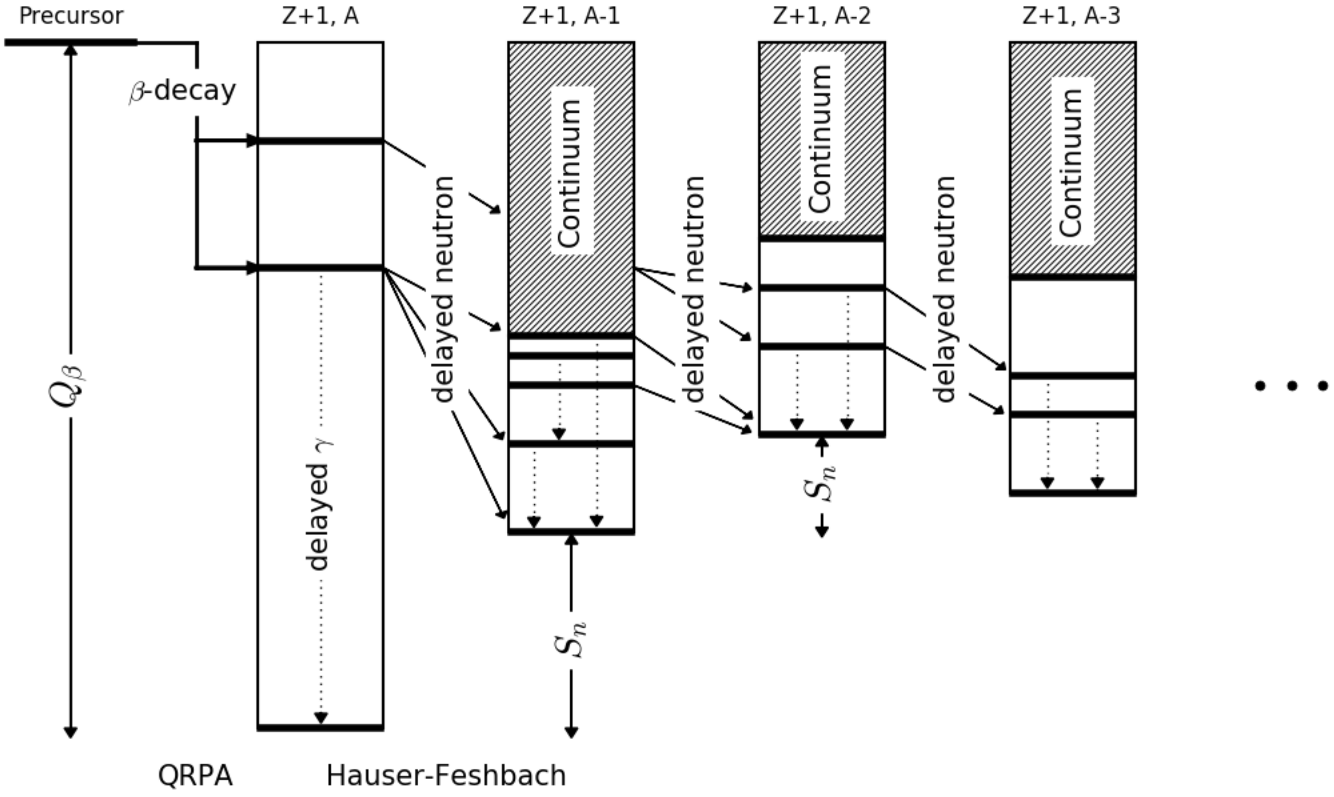
Barrier heights from HFB-14 / HFB-17 masses

Similar results are obtained for other nuclear models

Mumpower & Kawano in prep. (2019)

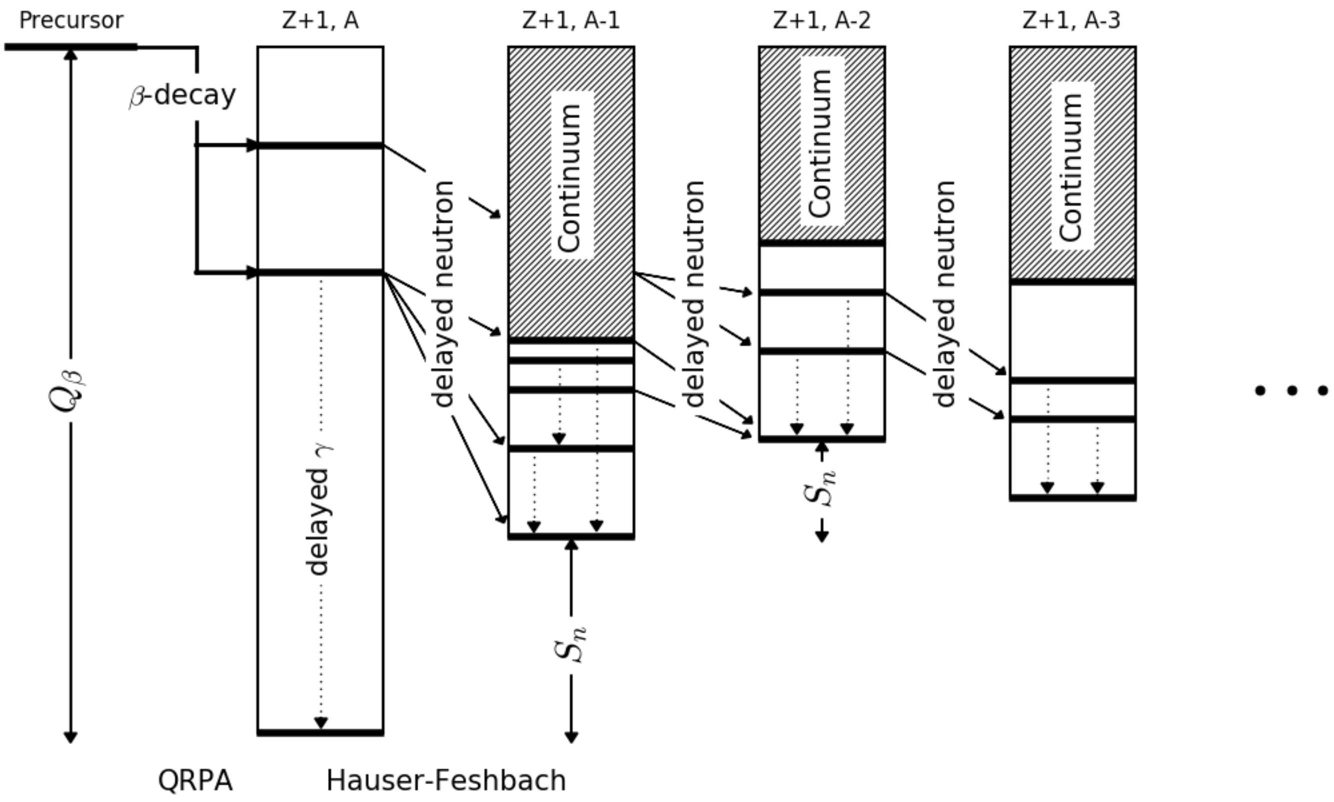
β-DECAY & β-DELAYED FISSION

COMBINING QRPA + HF



Möller *et al.* PRC (1997 & 2003) • Kawano *et al.* PRC 94 014612 (2016) • **Mumpower** *et al.* PRC 94 064317 (2016)

COMBINING QRPA + HF



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

Möller *et al.* PRC (1997 & 2003) • Kawano *et al.* PRC 94 014612 (2016) • **Mumpower** *et al.* PRC 94 064317 (2016)

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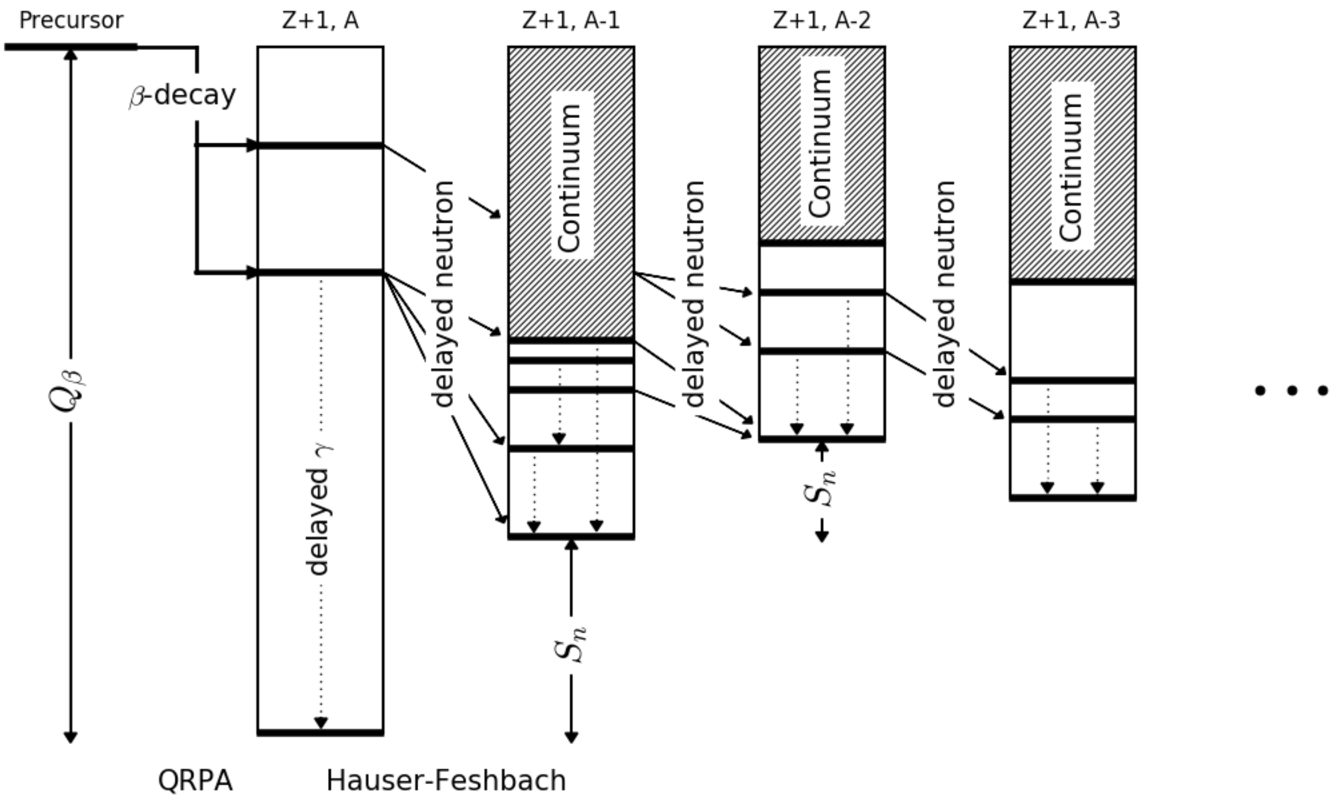
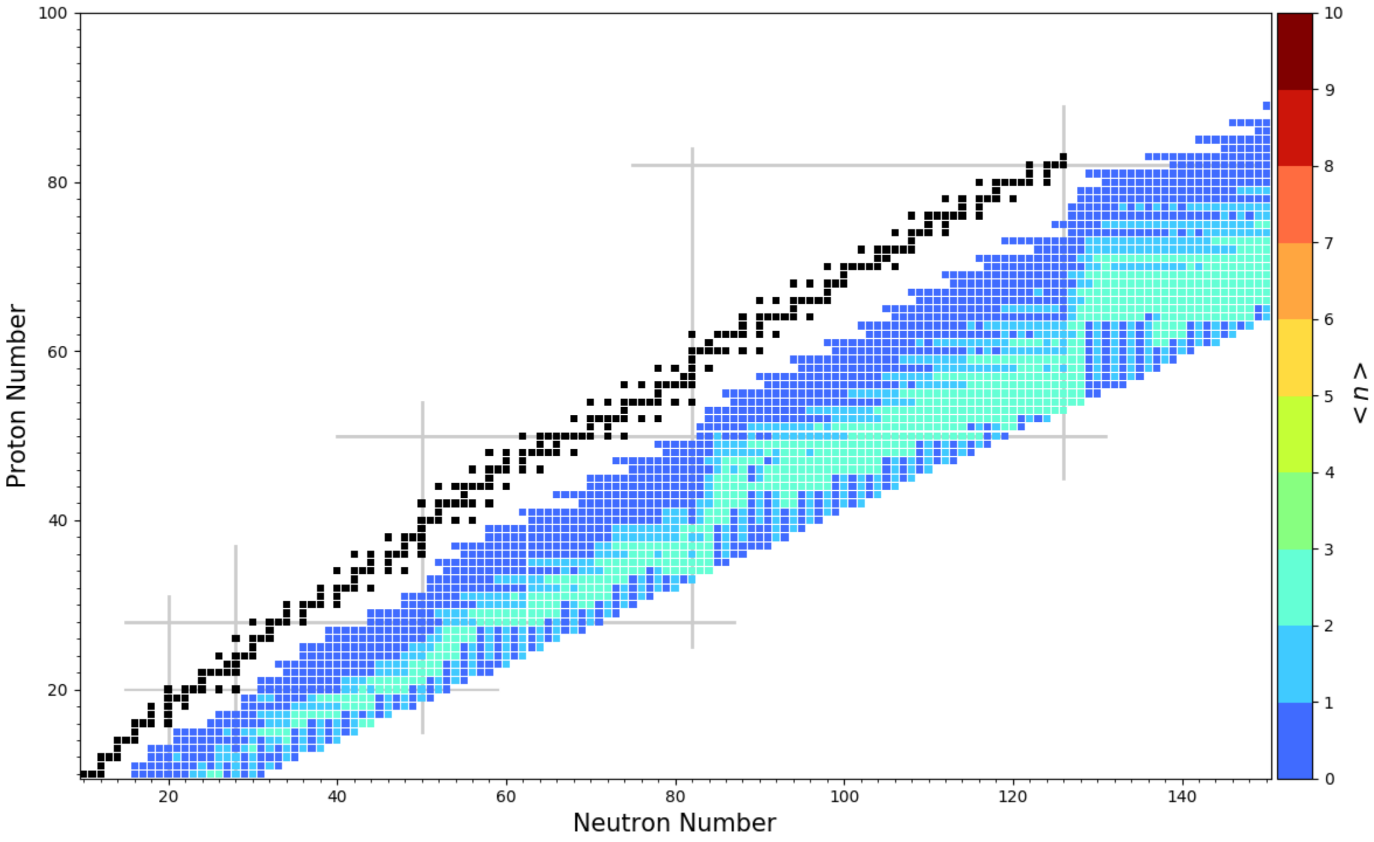


Initial population from the β-decay strength function from P. Möller's QRPA

Follow the statistical decay until all excitation energy is exhausted

Möller *et al.* PRC (1997 & 2003) • Kawano *et al.* PRC 94 014612 (2016) • **Mumpower** *et al.* PRC 94 064317 (2016)

AVERAGE NEUTRON EMISSION

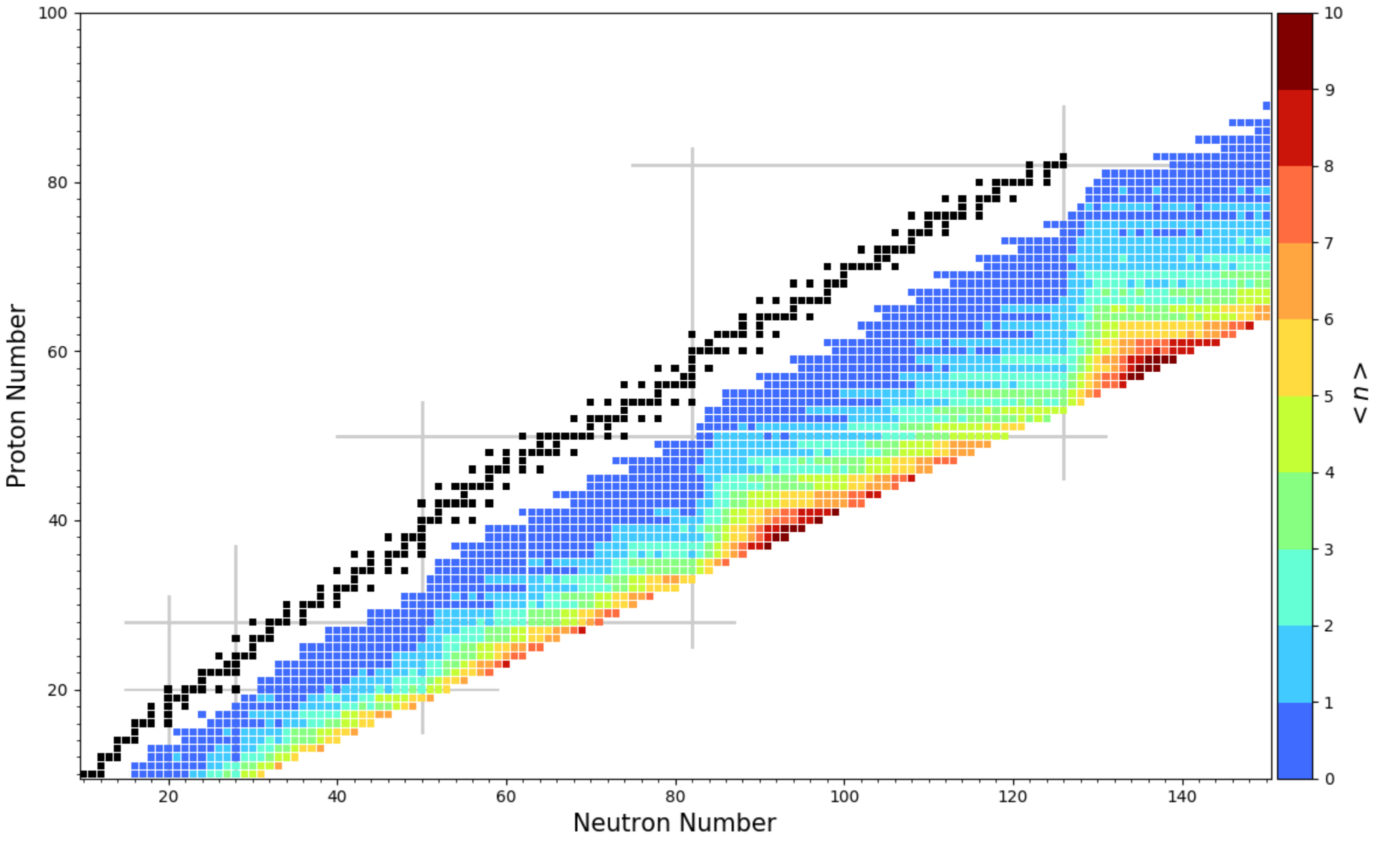


Apply energy window method to the entire chart of nuclides

Problem with describing very neutron-rich nuclei

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

AVERAGE NEUTRON EMISSION



Apply the QRPA+HF method to the entire chart of nuclides

Problem with neutron-rich nuclei goes away

Mumpower *et al.* PRC 94 064317 (2016) • Möller ***et al.*** ADNDT (2018)

EXTENSIVE BENCHMARKING

Spyrou ***et al.*** PRL 117 142701 (2016) • **Mumpower** *et al.* PRC 94 064317 (2016) • Wu *et al.* PRL 118, 072701 (2017)

EXTENSIVE BENCHMARKING

QRPA+HF GT-only β-strength are within 15% of measured P_{1n} values

Spyrou ***et al.*** PRL 117 142701 (2016) • **Mumpower** *et al.* PRC 94 064317 (2016) • Wu *et al.* PRL 118, 072701 (2017)

EXTENSIVE BENCHMARKING

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Adding FF transitions improves the match to measured data by 3%

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This yields a roughly 9% global model uncertainty to measured P_{1n} values

The best in the business!

Spyrou ***et al.*** PRL 117 142701 (2016) • **Mumpower** *et al.* PRC 94 064317 (2016) • Wu *et al.* PRL 118, 072701 (2017)

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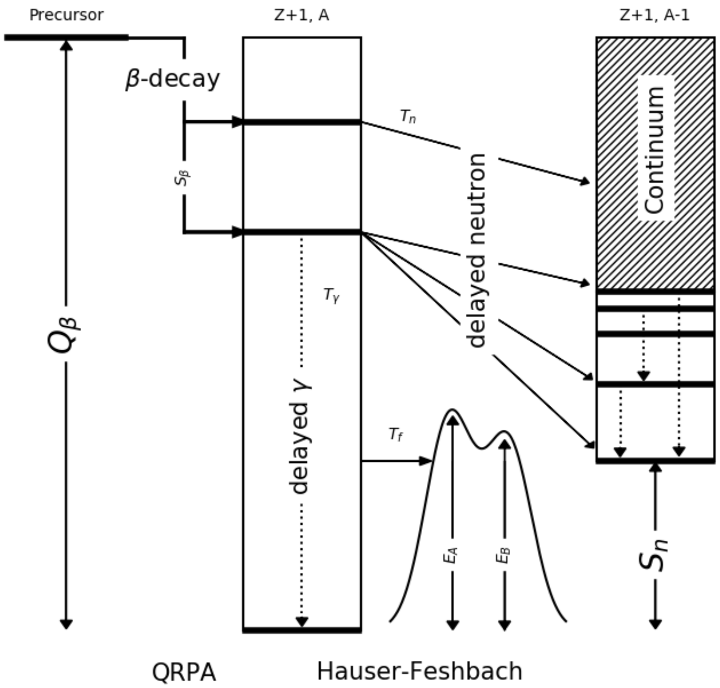
Can we extend this model to other phenomena ... fission?

Spyrou ***et al.*** PRL 117 142701 (2016) • **Mumpower** *et al.* PRC 94 064317 (2016) • Wu *et al.* PRL 118, 072701 (2017)

β -DELAYED FISSION



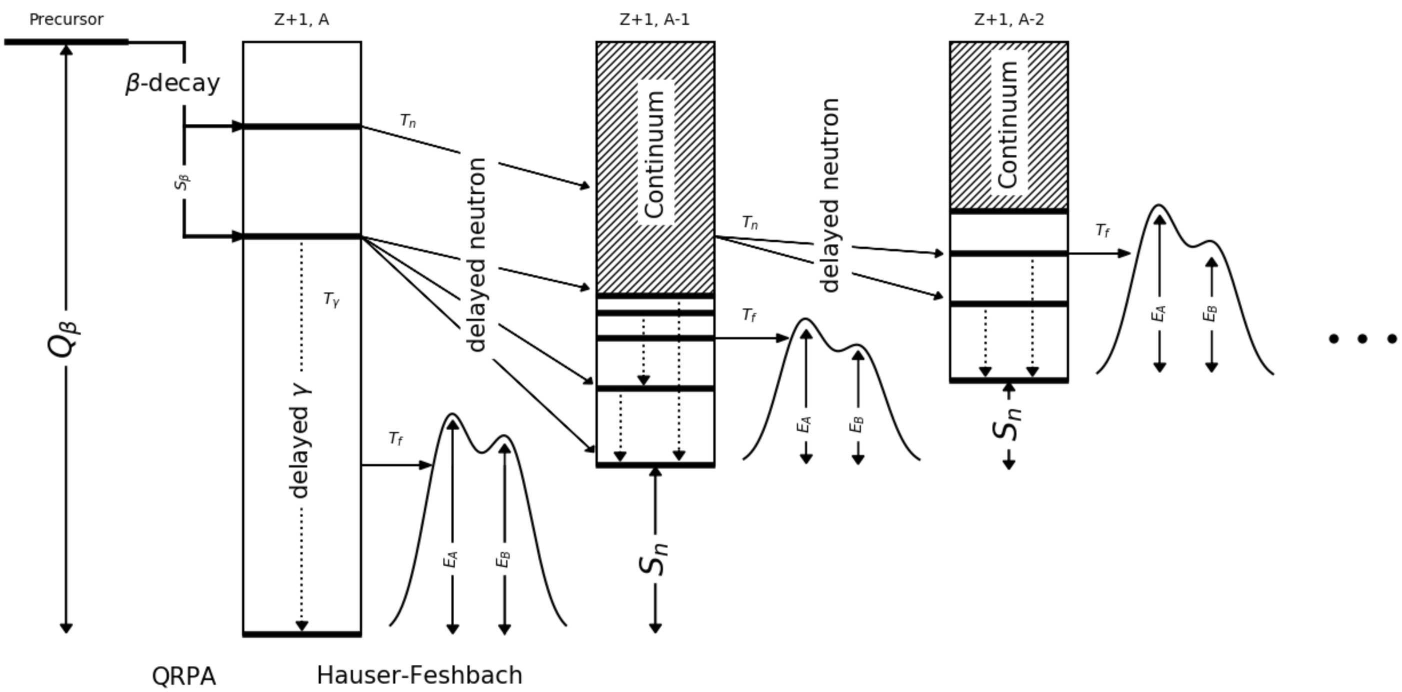
We have recently extended our QRPA+HF model to describe β-delayed fission (βdf)

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



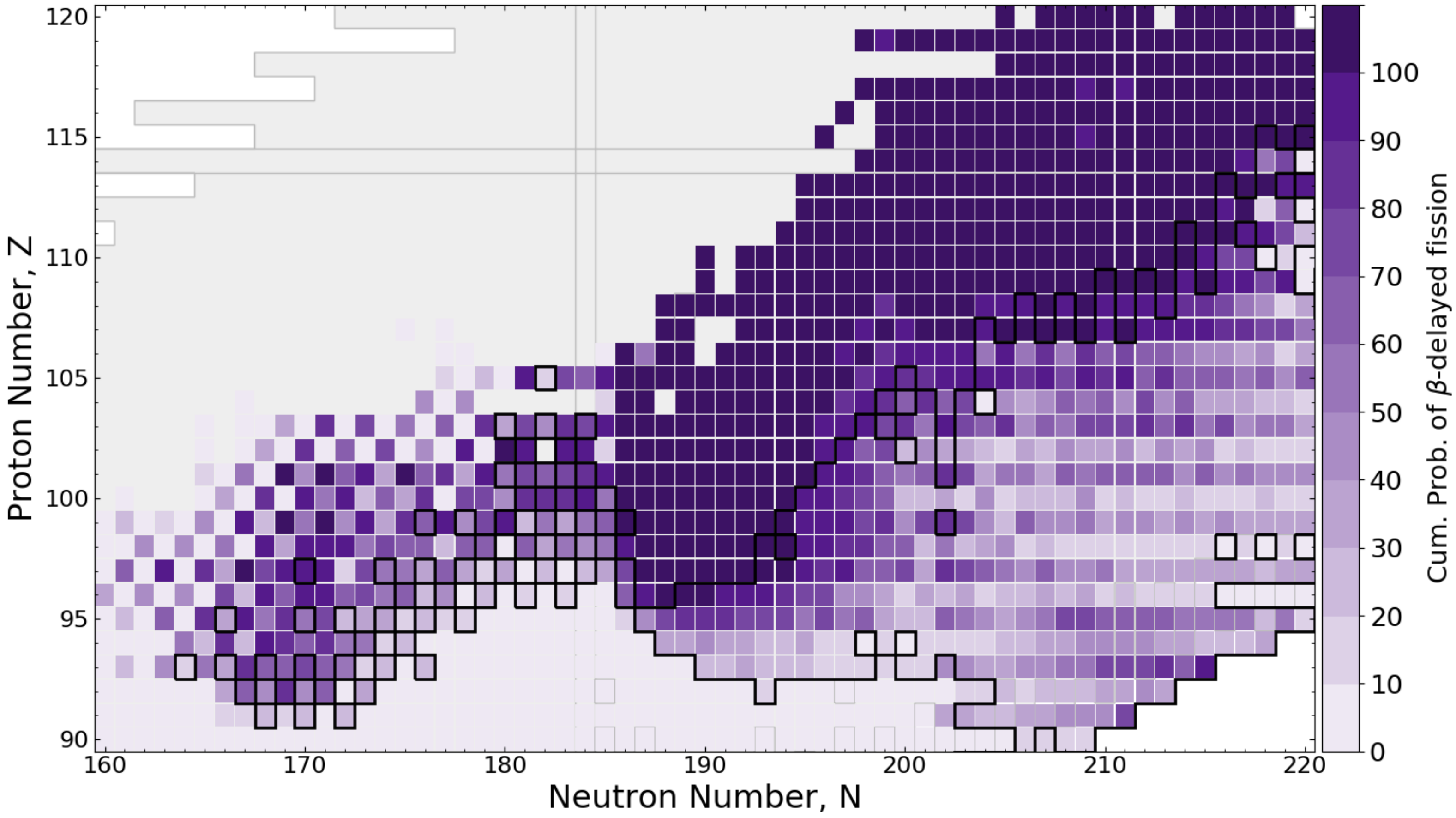
Recall: Near the dripline Q_{beta} ⇡ S_n ⇣

Multi-chance βdf: *each* daughter may fission

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

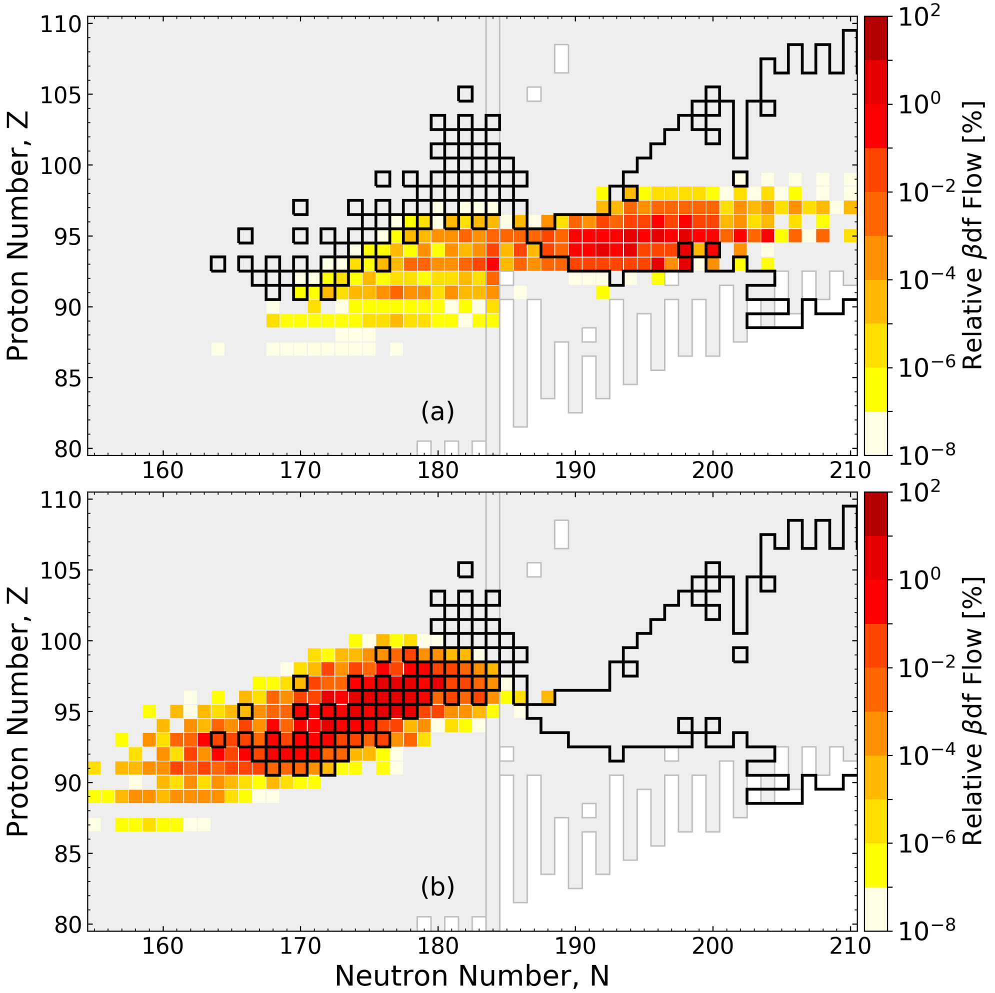


βdf occupies a large amount of real estate in the NZ-plane

Multi-chance βdf outlined in black

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

MULTI-CHANCE β DF CONTRIBUTION

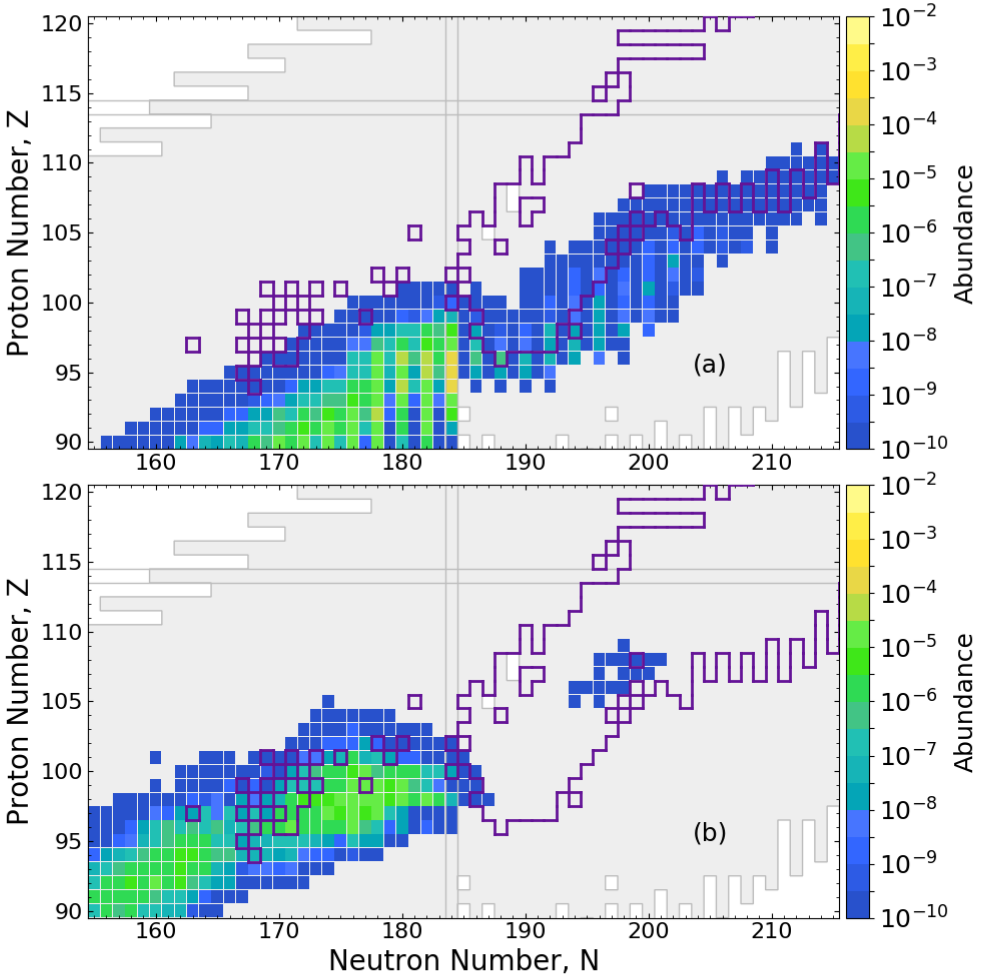


Network calculation of neutron star merger ejecta; FRDM2012 inputs

Multi-chance βdf contributes at both early and late times

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

APPLICATION TO THE r-PROCESS

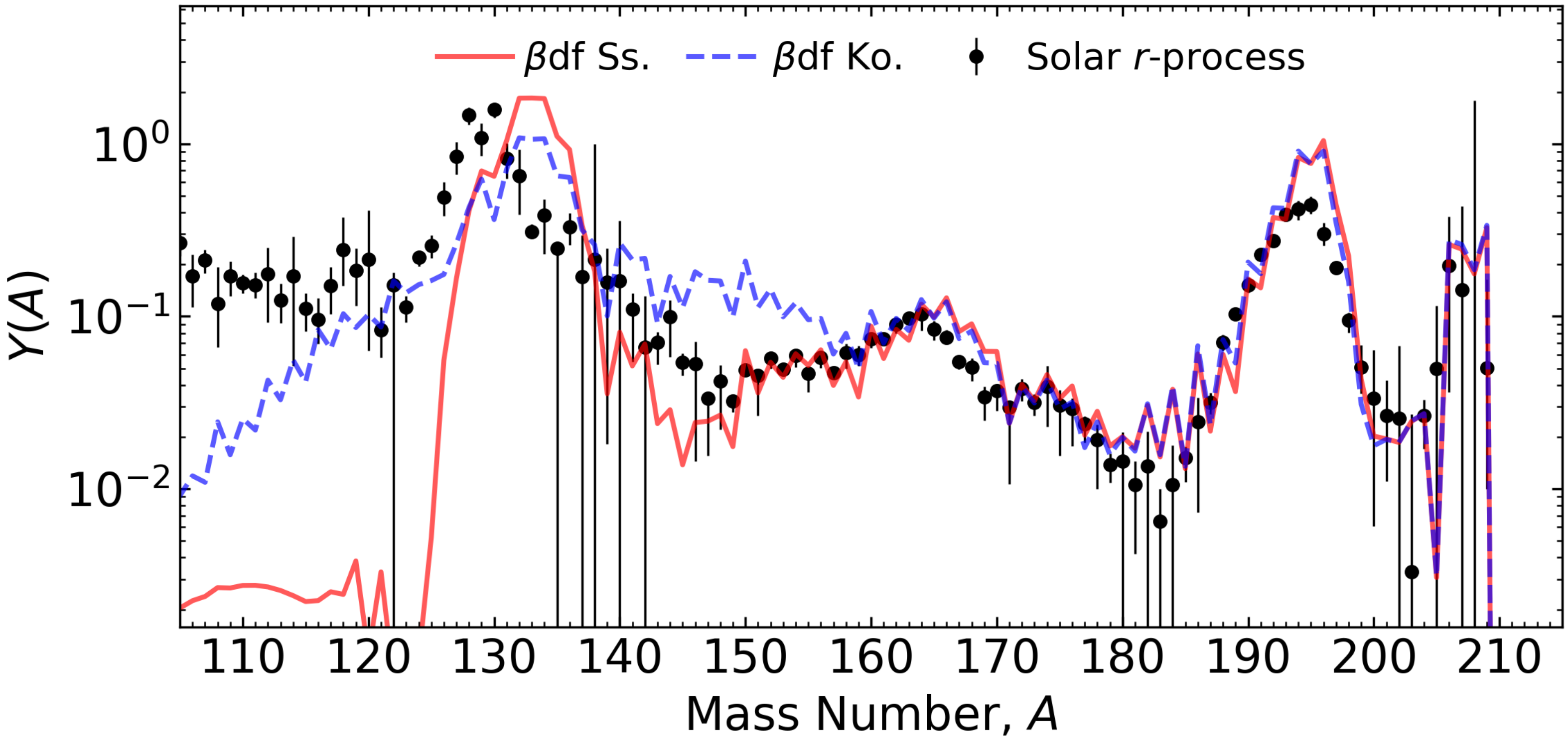


PRISM network calculation of neutron star merger ejecta

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

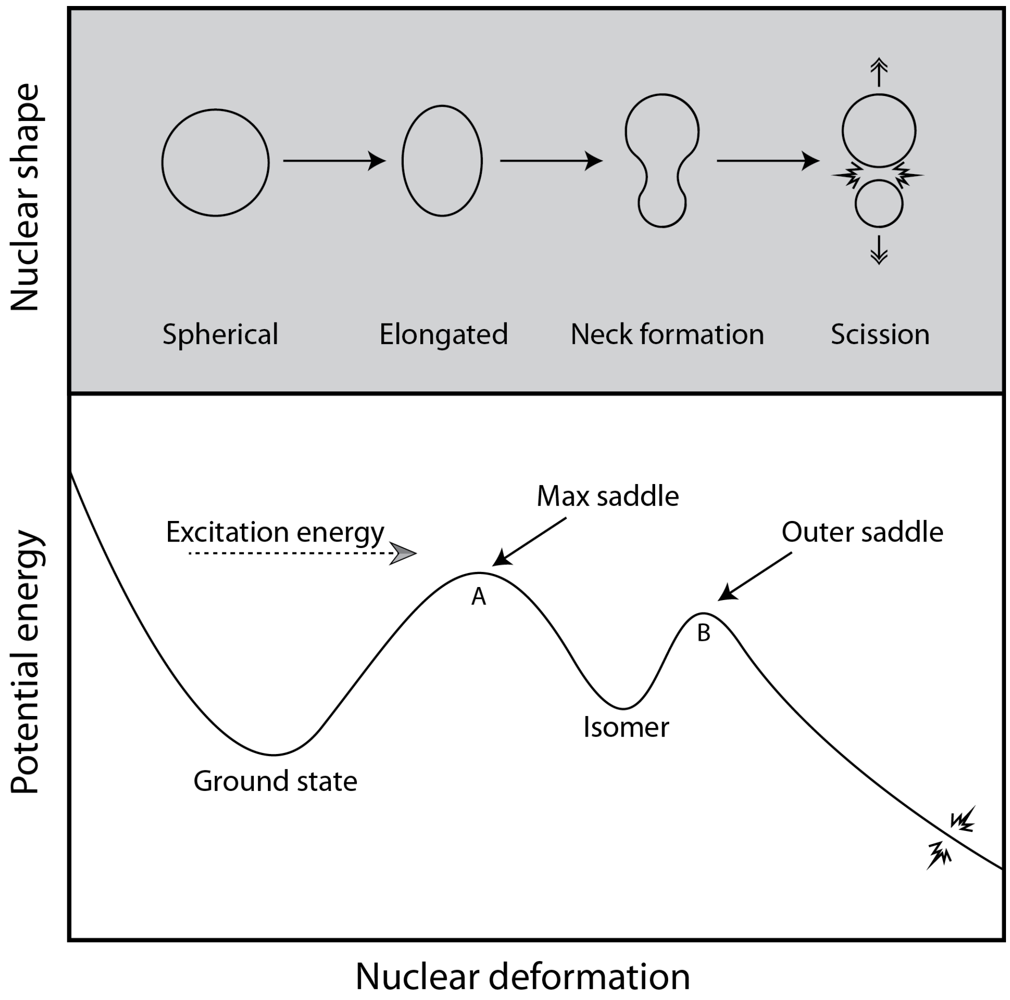
This is because of a relatively long fission timescale

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 YIELDS

A SIMPLE PICTURE OF FISSION

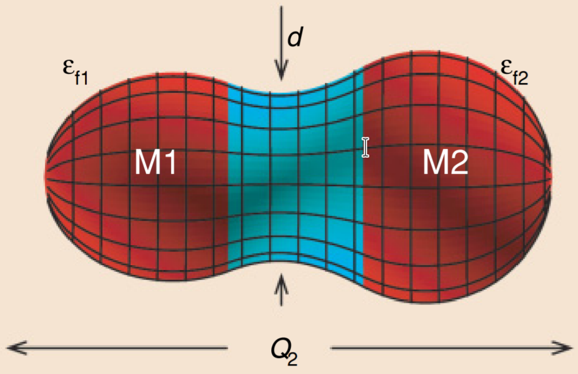


Follow progression of the nucleus from compact to highly elongated shapes

Mumpower *et al.* in prep. (2019)

FINITE-RANGE LIQUID-DROP MODEL

Five Essential Fission Shape Coordinates



45	Q_2	~	Elongation (fission direction)
⊗			
35	α_g	~	(M1-M2)/(M1+M2) Mass asymmetry
⊗			
15	ε_{f1}	~	Left fragment deformation
⊗			
15	ε_{f2}	~	Right fragment deformation
⊗			
15	d	~	Neck

⇒ 5 315 625 grid points – 306 300 unphysical points

⇒ 5 009 325 physical grid points

Many possible shape degrees of freedom - but we have to isolate the most important

Möller *et al.* PRC (2009) • Möller ***et al.*** PRC (2015)

HOW DO WE CALCULATE FRAGMENT YIELDS WITH THIS MODEL?

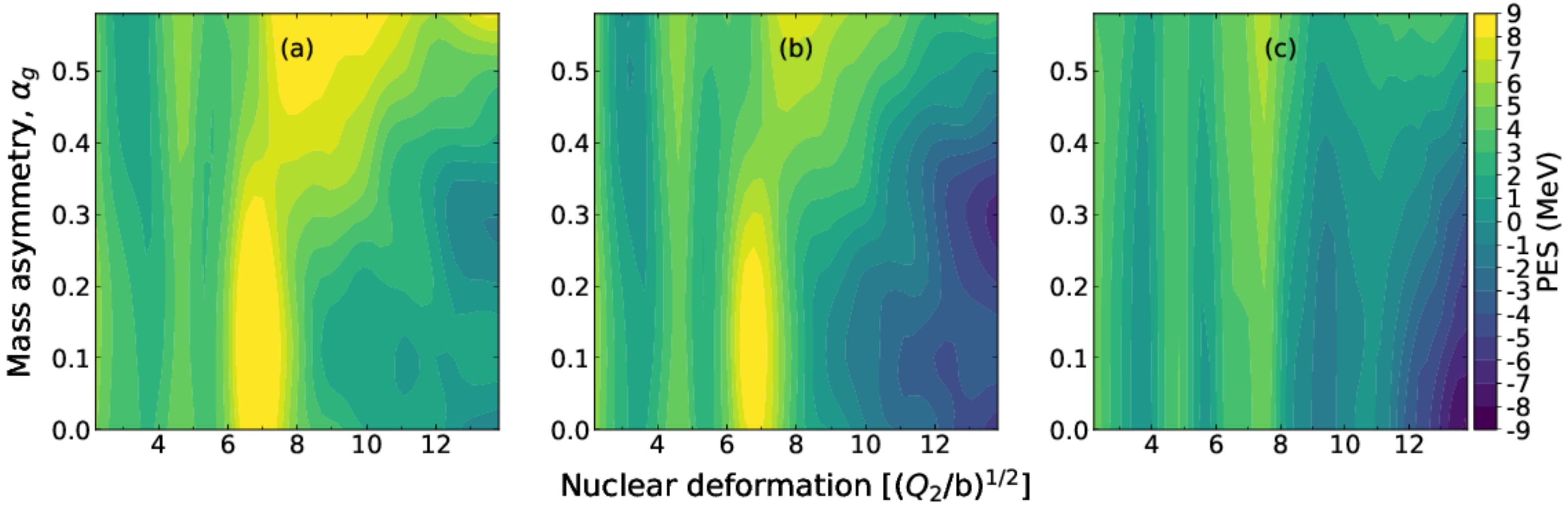
Change in nuclear shape acts as a driving force for bulk rearrangement of material

This results in a collective kinetic energy

The macroscopic shape degrees of freedom couple to individual nucleonic motion

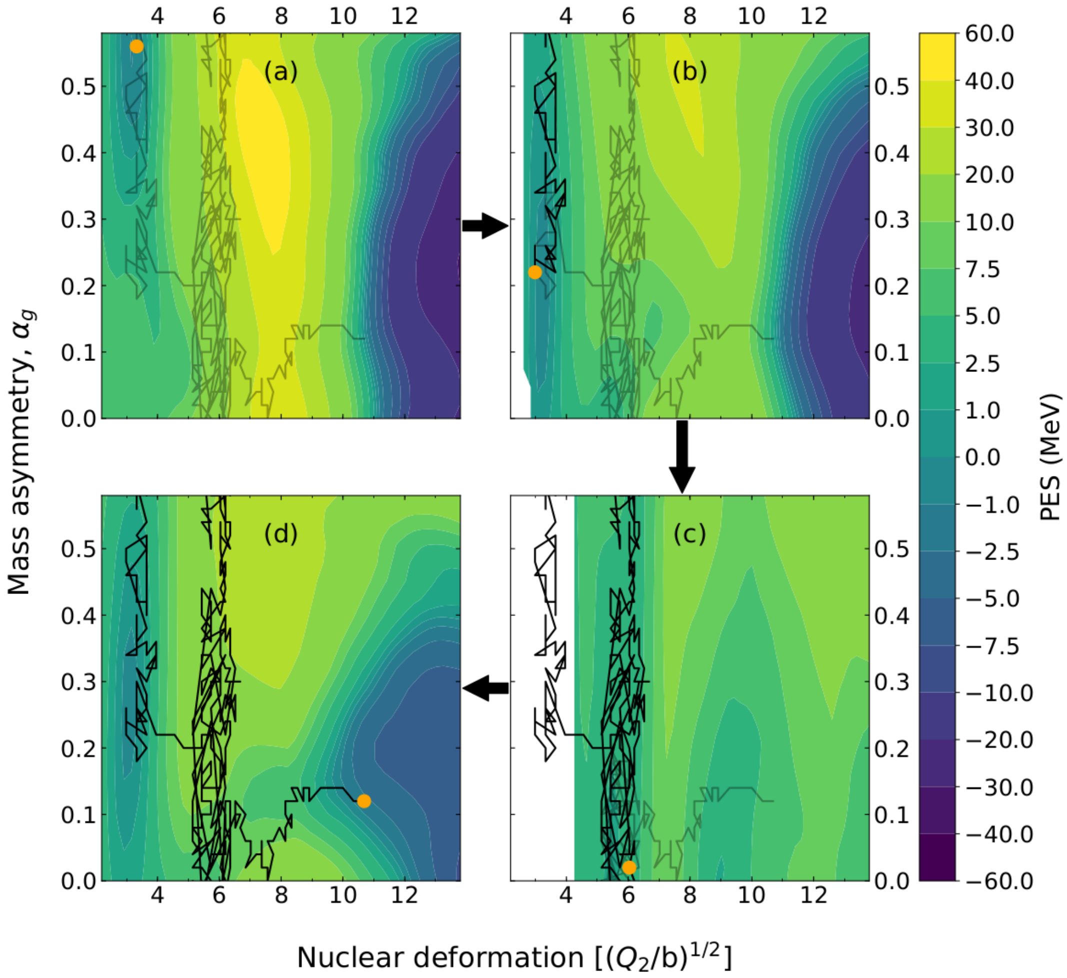
Resulting in an evolution that is both damped and diffuse

This can be approximated as Brownian shape motion



Randrup *et al.* PRL (2011) • Randrup *et al.* PRC (2011) • Randrup *et al.* PRC (2013) • Möller ***et al.*** PRC (2015)

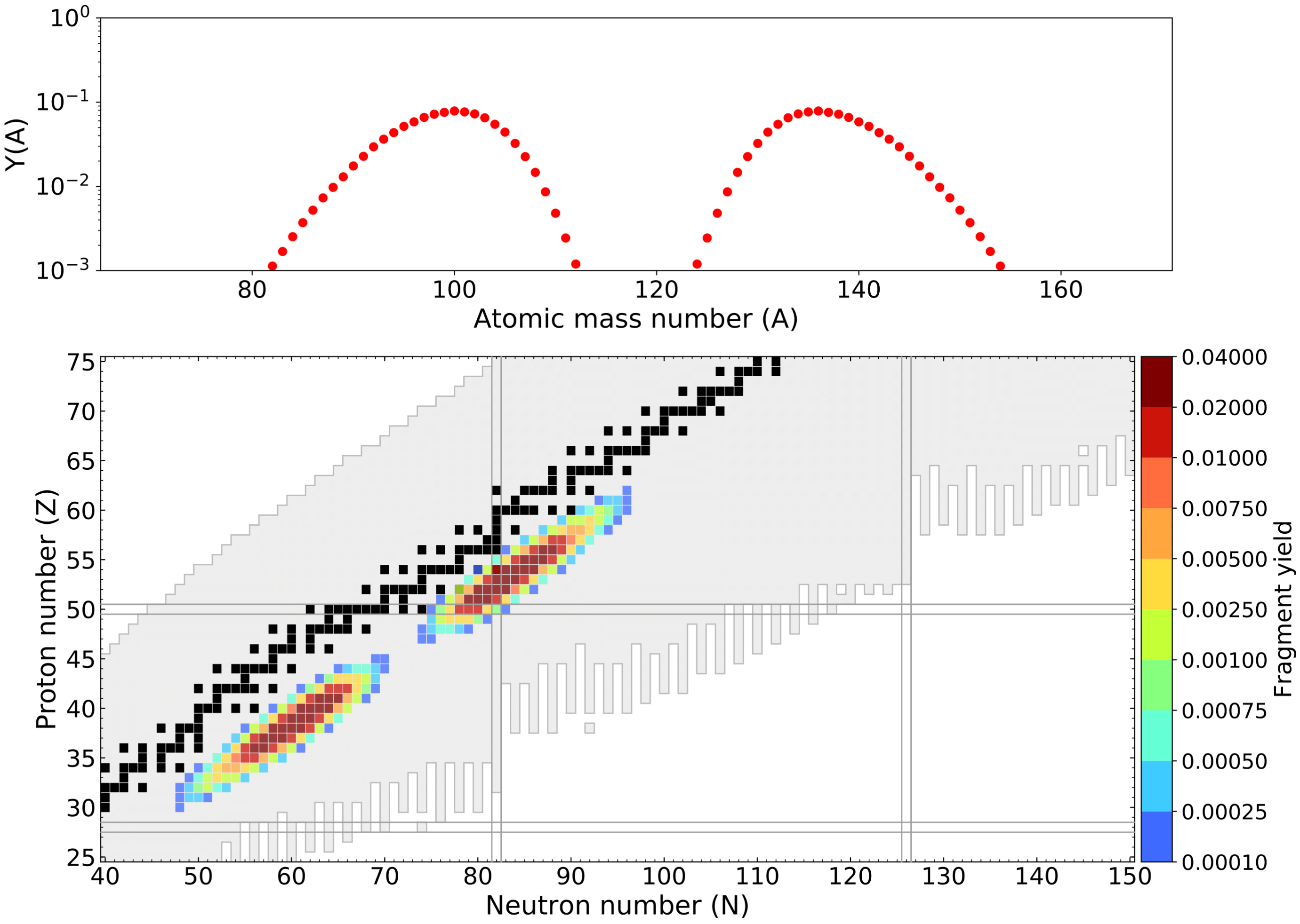
FISSION EVOLUTION



Amounts to random walk across potential energy surface

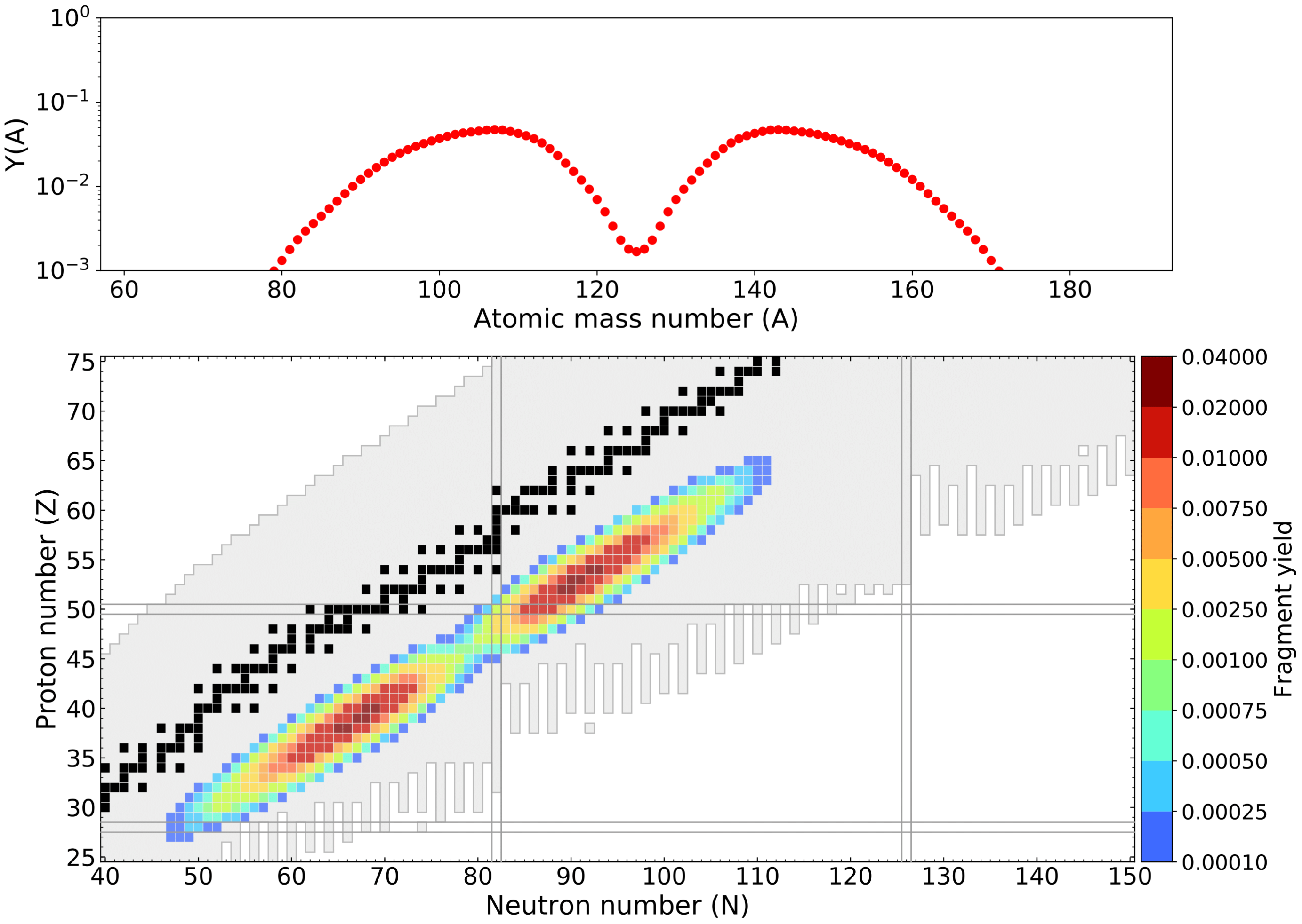
Mumpower *et al.* in prep. (2019)

236-U Y(Z,A) YIELD



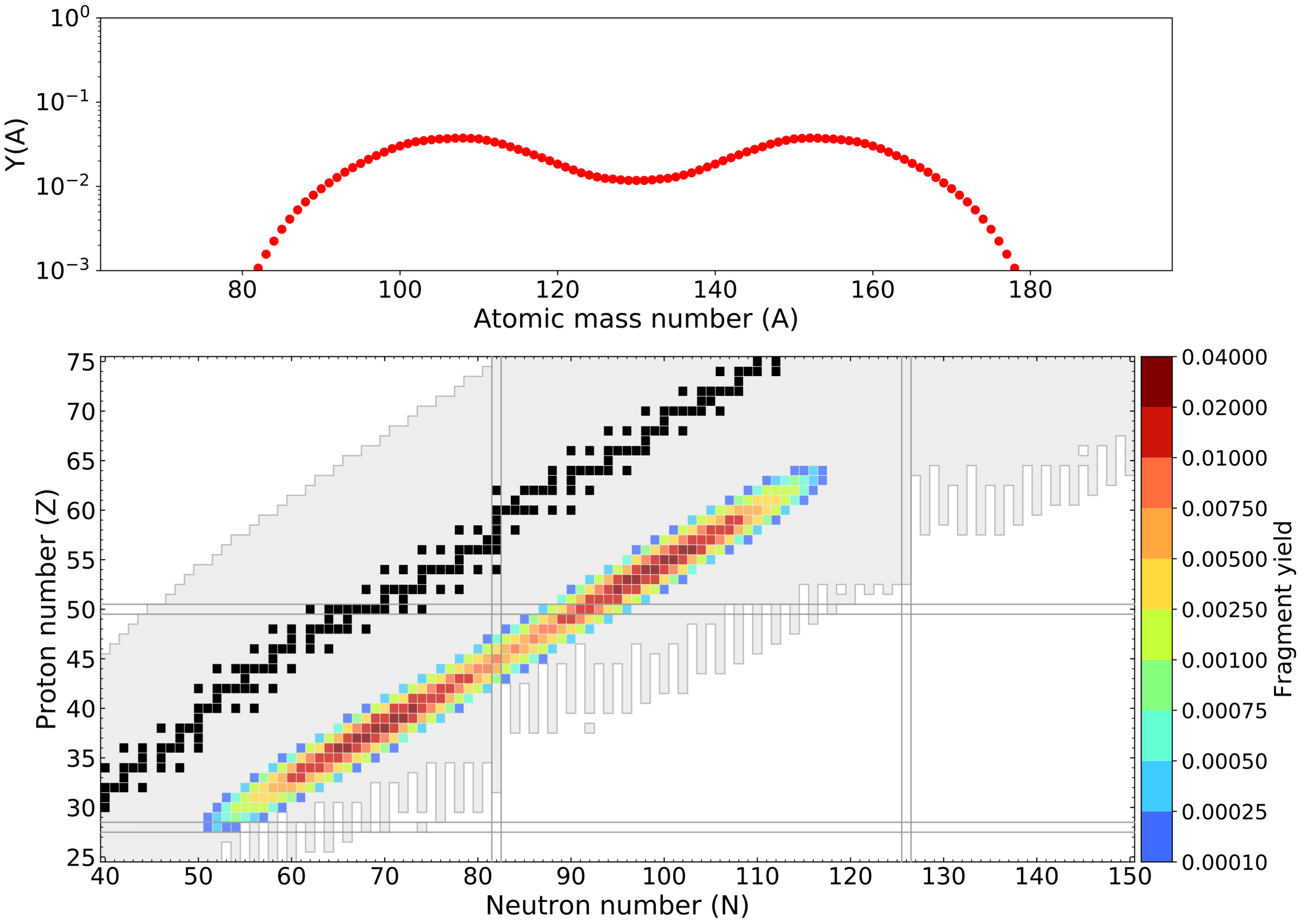
Mumpower *et al.* in prep. (2019)

250-U Y(Z,A) YIELD



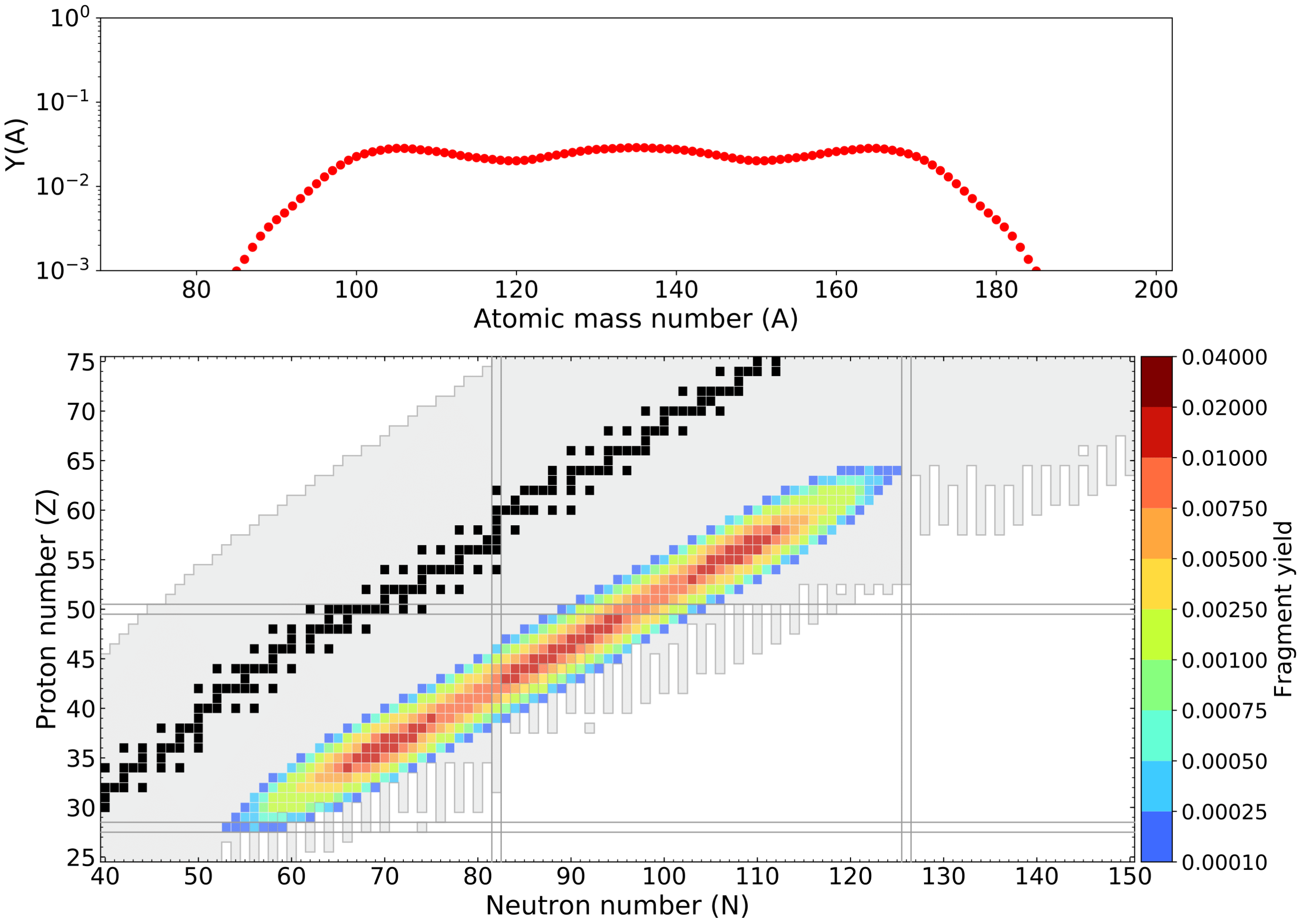
Mumpower *et al.* in prep. (2019)

260-U Y(Z,A) YIELD



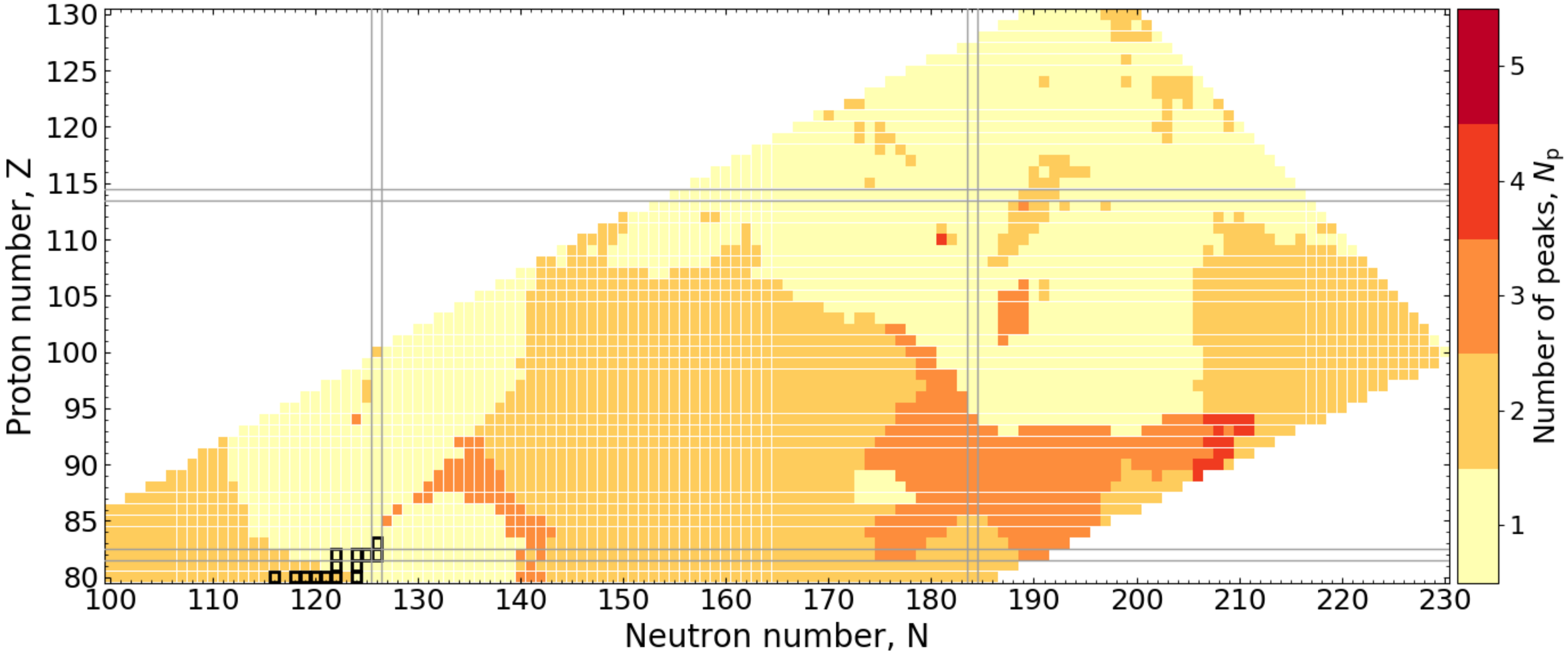
Mumpower *et al.* in prep. (2019)

270-U Y(Z,A) YIELD



Mumpower *et al.* in prep. (2019)

NUMBER OF PEAKS



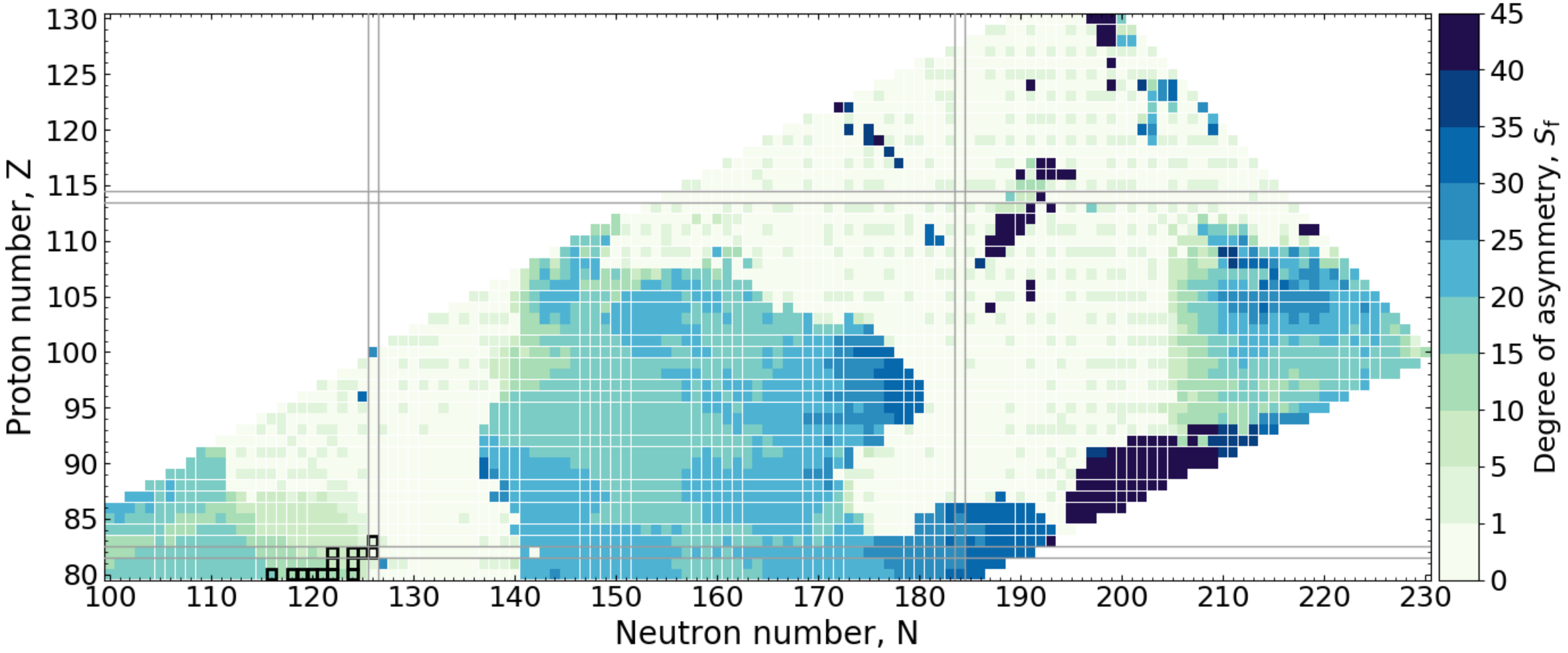
Count the number of peaks in the mass yield, $Y(A)$, distribution

Rather smooth variation in number of peaks across chart of nuclides.

r-process region: 2 or 3 peaks are the norm given our prediction of fission hot spots

Mumpower *et al.* in prep. (2019)

MEASURE OF ASYMMETRY



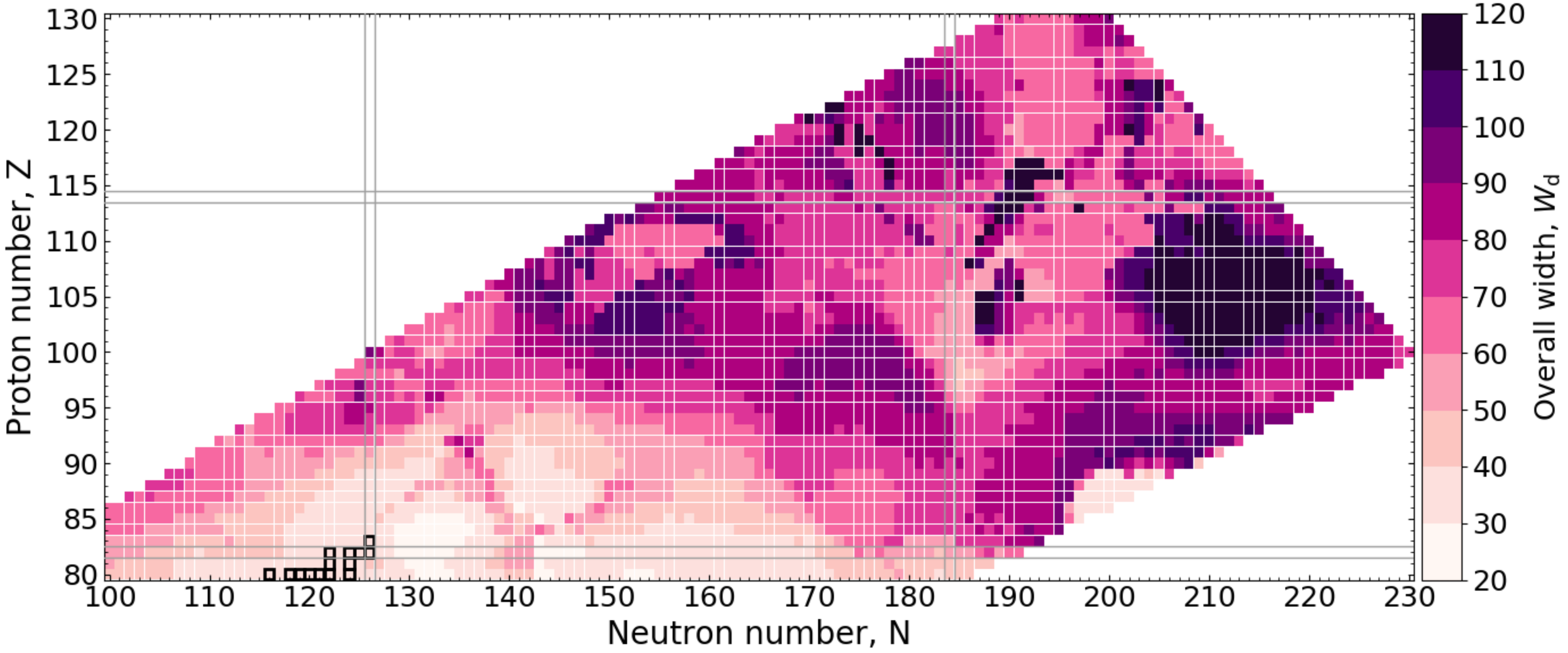
Measure the distance in A between the maxima of $Y(A)$ and $Y(A_f/2)$

Abrupt changes can be seen when the maxima shift from symmetric to asymmetric

Symmetric followed by asymmetric distributions can be expected in r-process simulations

Mumpower *et al.* in prep. (2019)

EXTENT OF Y(A) DISTRIBUTION



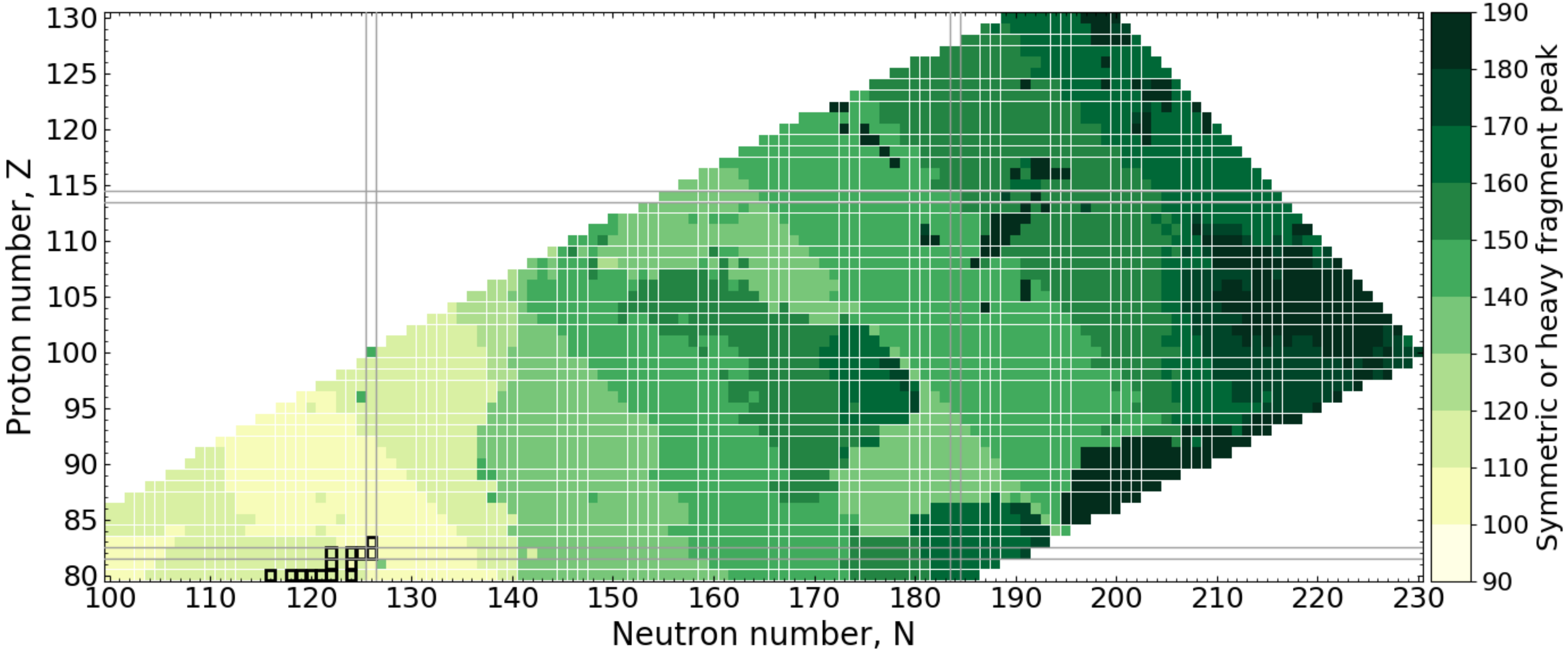
Measure the spread of the daughter products in A

Strong dependence can be seen with the fission system

Wiggles in the yield (number of peaks or asymmetry) don't matter if the distribution is wide!

Mumpower *et al.* in prep. (2019)

PEAK LOCATION (A)



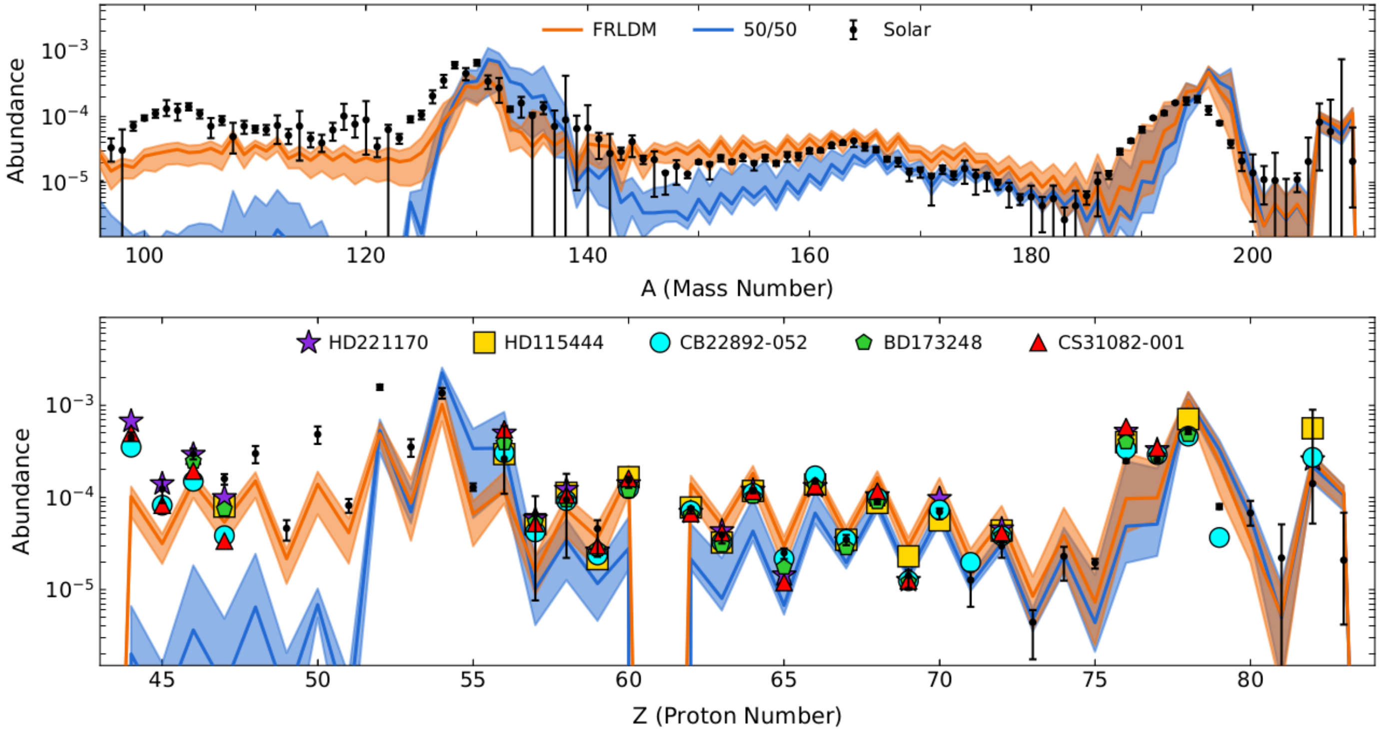
Measure the placement of material of the highest peak in A

Notice the transition between 3 and 2 peaks plays an important role

r-process conditions from astro. simulations suggest population of $A \sim 150$ to ligher nuclei

Mumpower *et al.* in prep. (2019)

IMPACT ON THE ABUNDANCES



Abundance output using common old nuclear fission data and our new model predictions

Co-production of light nuclei from $Z \sim 45$ to the actinides (dynamical merger ejecta only!)

Universality may extend further down to lighter nuclei than commonly accepted in the literature

Vassh ***et al.*** in prep. (2019)

SPECIAL THANKS TO

My collaborators

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& many more...

■ Student ■ Postdoc ■ CTA Staff ■ FIRE PI

SUMMARY

The r-process requires a *deep understanding* of fission

Recent calculations give insight into:

Re-cycling material ▲ Production of heaviest elements ▲ Late-time observations

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

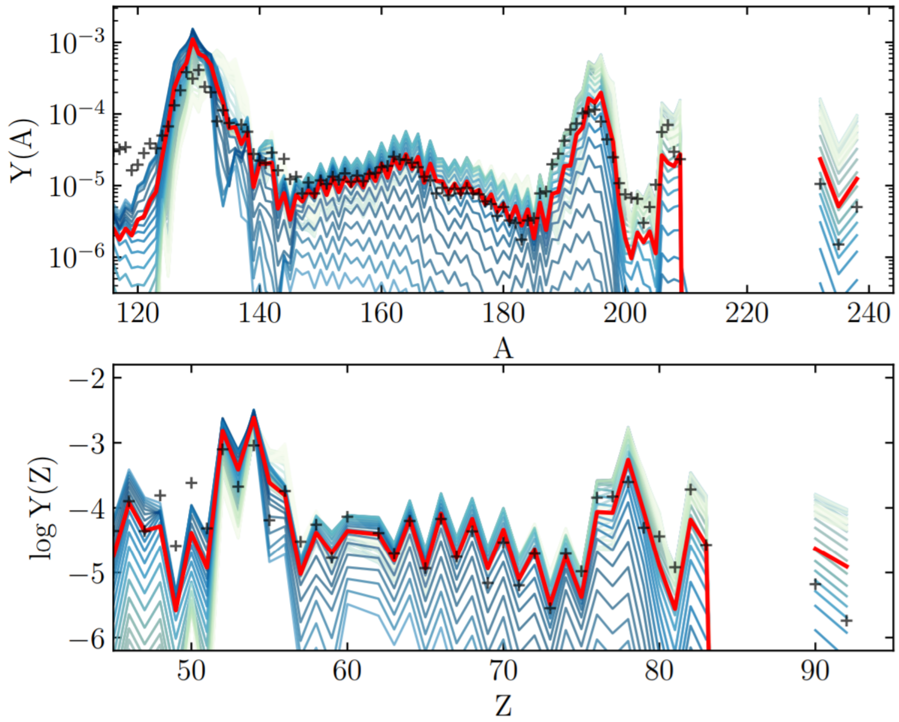
We therefore need to keep developing and studying theoretical models of nuclear physics, especially fission

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

WHAT IS LEFT AFTER FISSION?

LONG-LIVED ACTINIDES



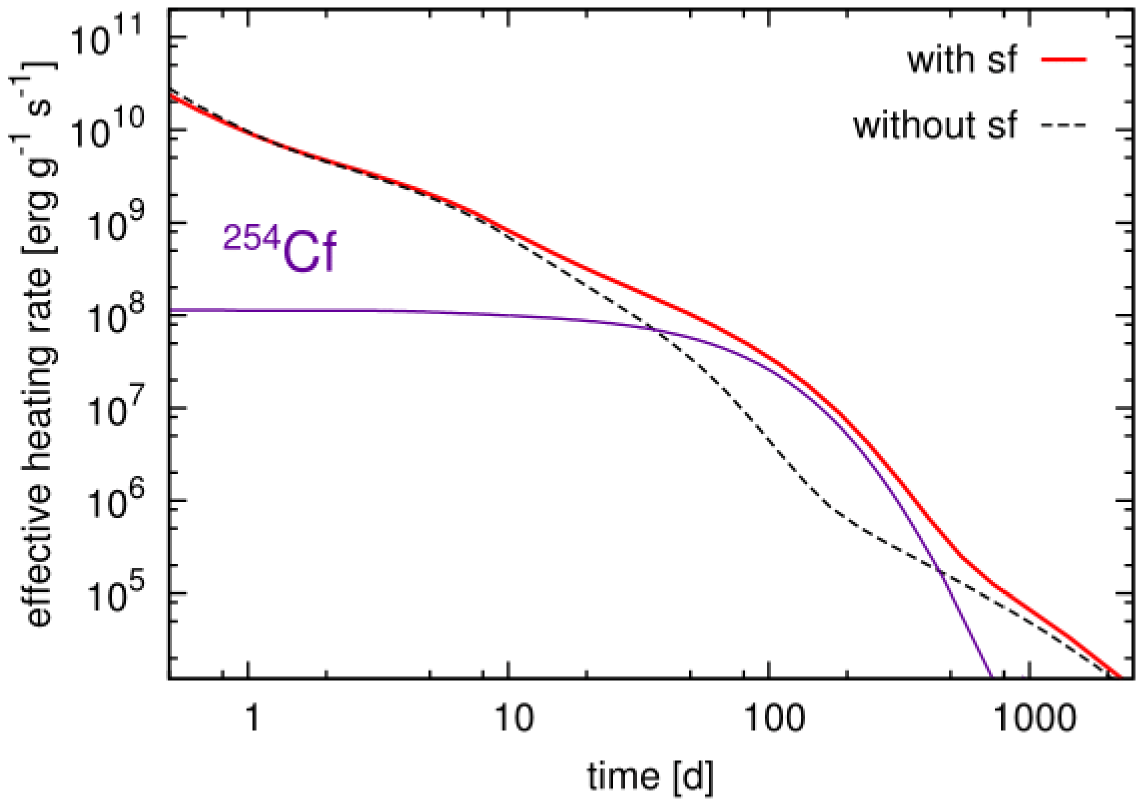
In some simulations actinides seem to be overproduced versus lanthanides

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)

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



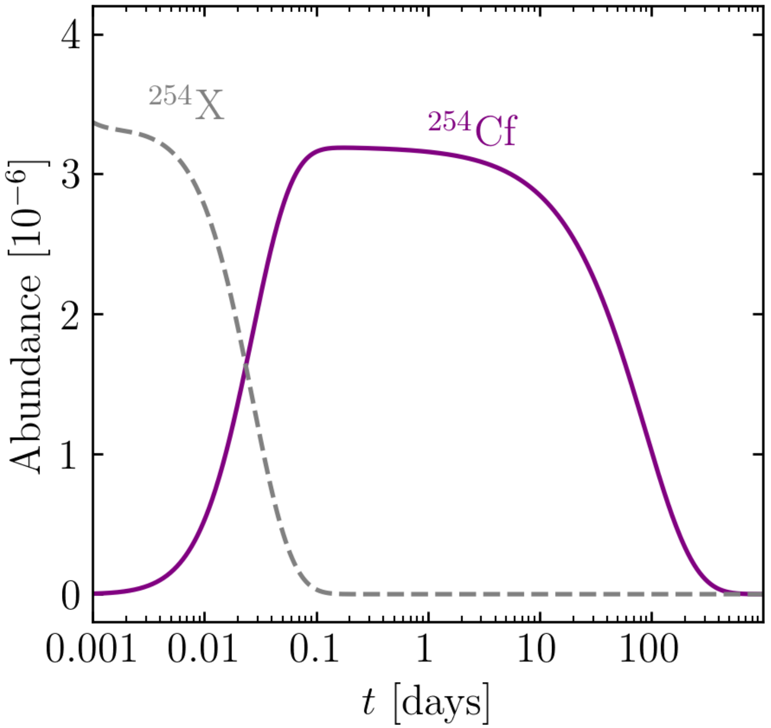
Is there any possible precursor to show that actinide nucleosynthesis has occurred in an event?... Maybe!

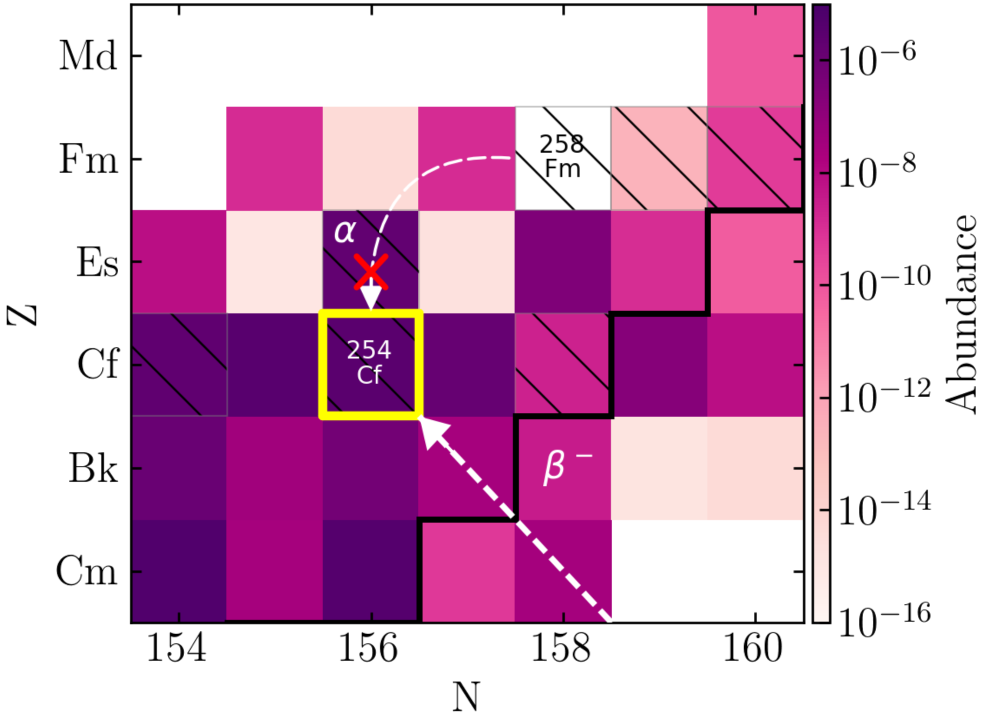
The spontaneous fission of ^{254}Cf can be a *primary* contributor to nuclear heating at late-time epochs

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)





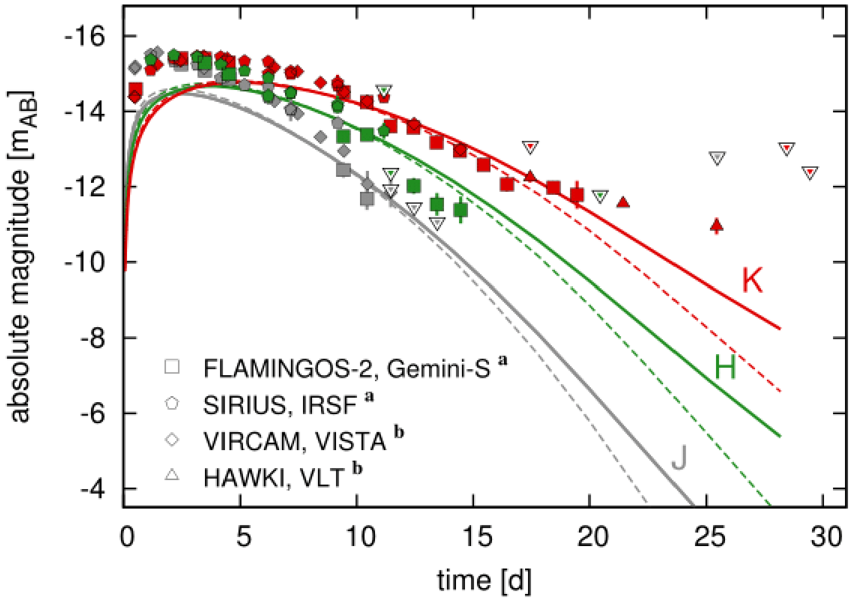
Primary feeder seems to be from β-decay

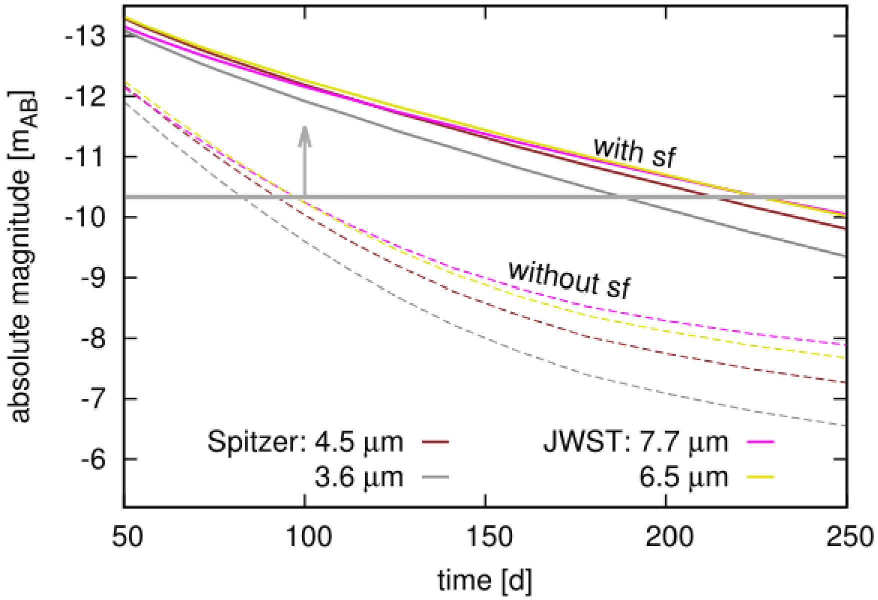
Production of this nucleus been explored over a range of nuclear models; some high - some low

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)

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)