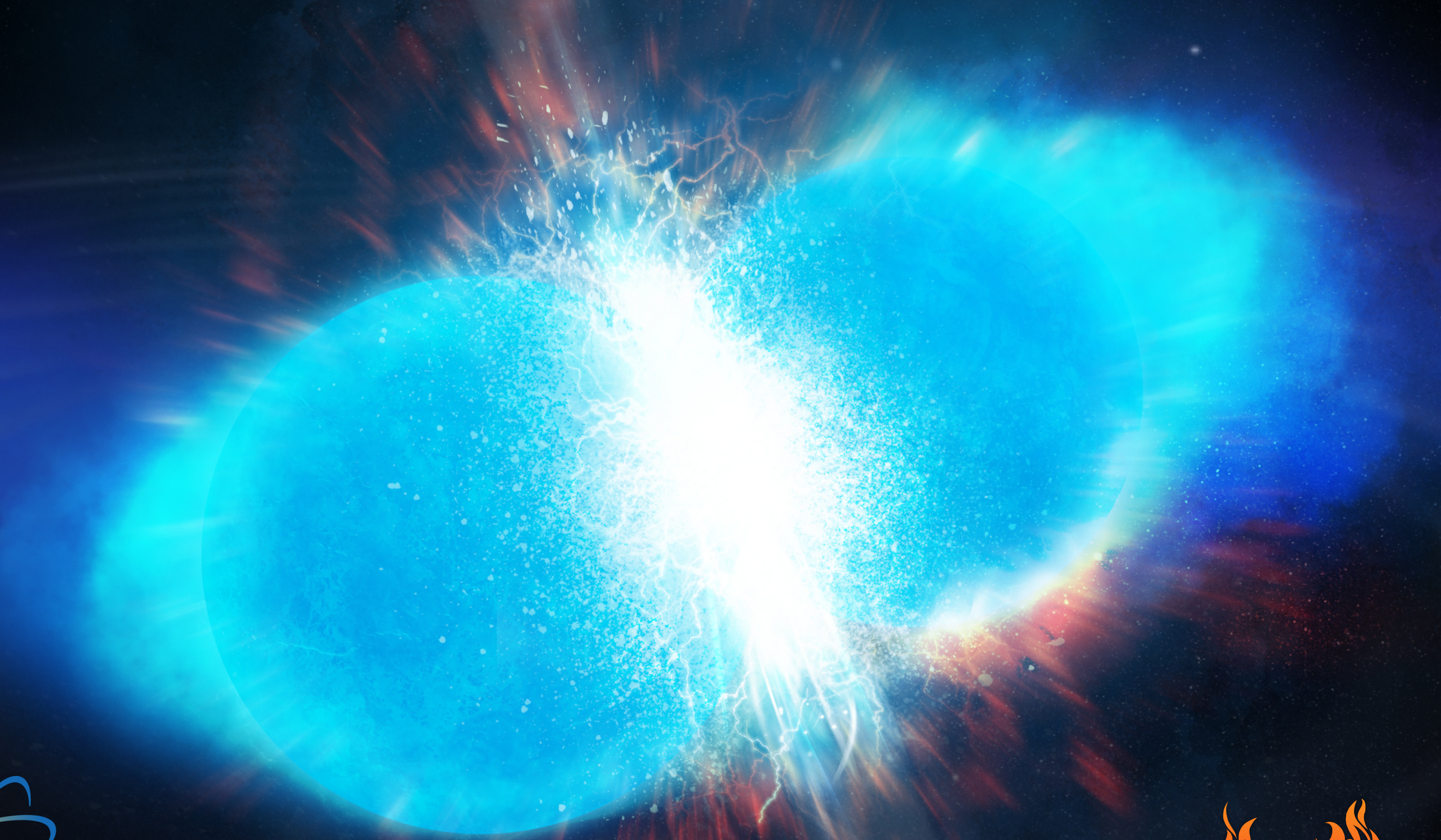
# THE LATEST DEVELOPMENTS OF NUCLEAR THEORY RELATED TO THE $r$-PROCESS

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MATTHEW MUMPOWER


*INT $r$-process / EOS Workshop*

Wednesday May 25$^{th}$ 2022


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.)

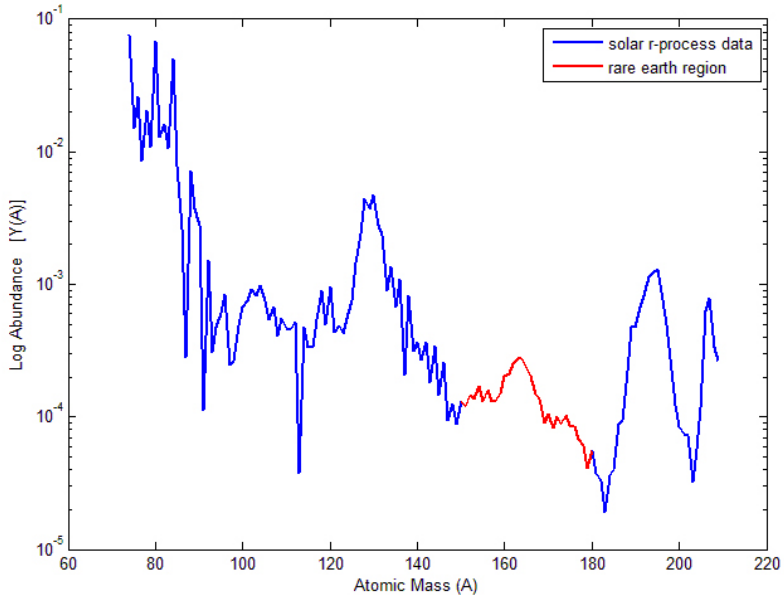
Nuclear theory predictions for exotic nuclei

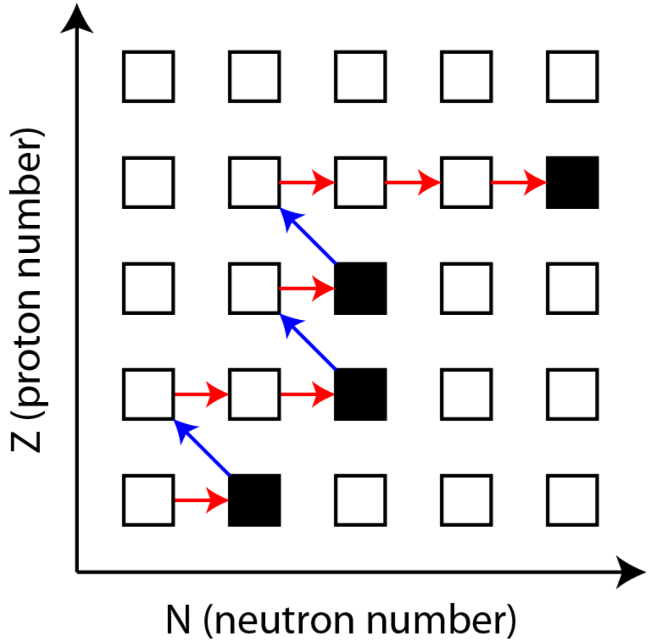
Precision experiments to constrain nuclear theory

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 $\beta$-decays

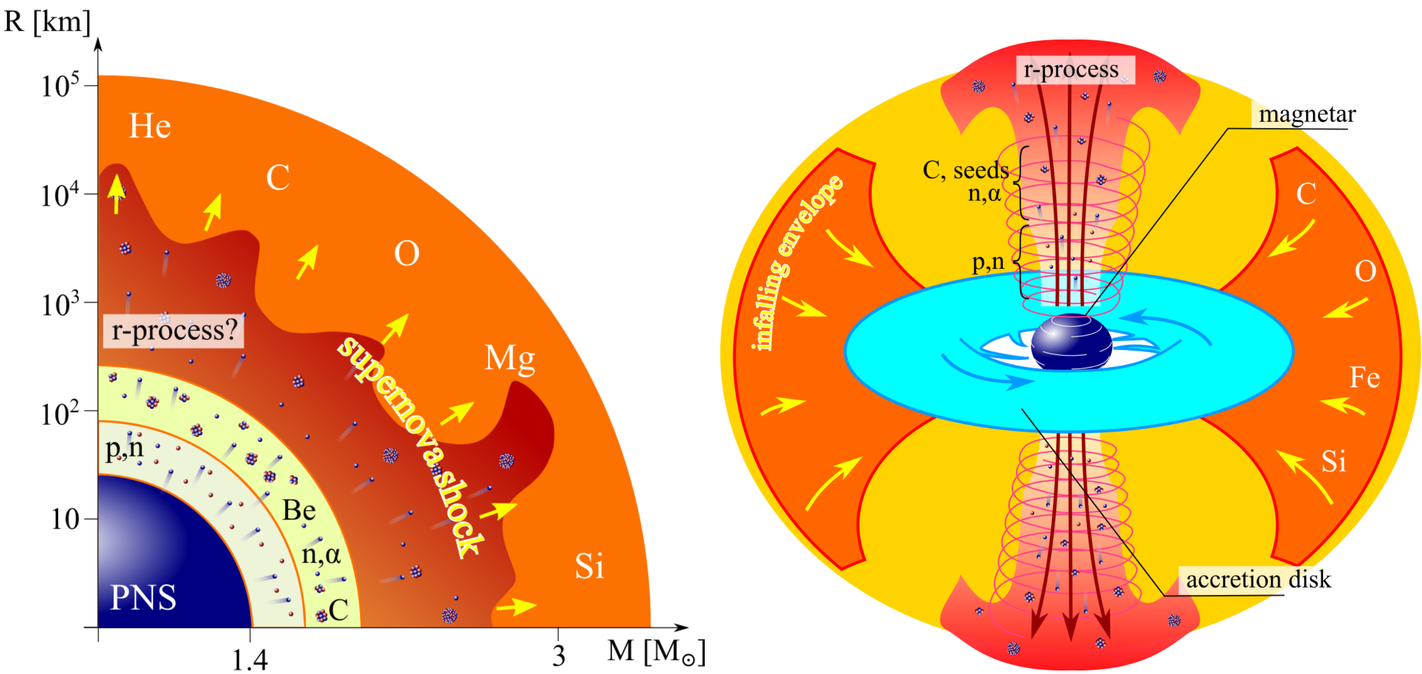
Relative slowdown in the nuclear flow (right) produces peak structures in the observed abundances (left)

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


Horowitz ***et al.*** J Phys G 083001 (2019) • Kajino *et al.* PPNP 107 (2019) • Cowan *et al.* RMP 93 015002 (2021)

# WHERE CAN THE $r$-PROCESS OCCUR?

One possibility is in (rare?) supernovae




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

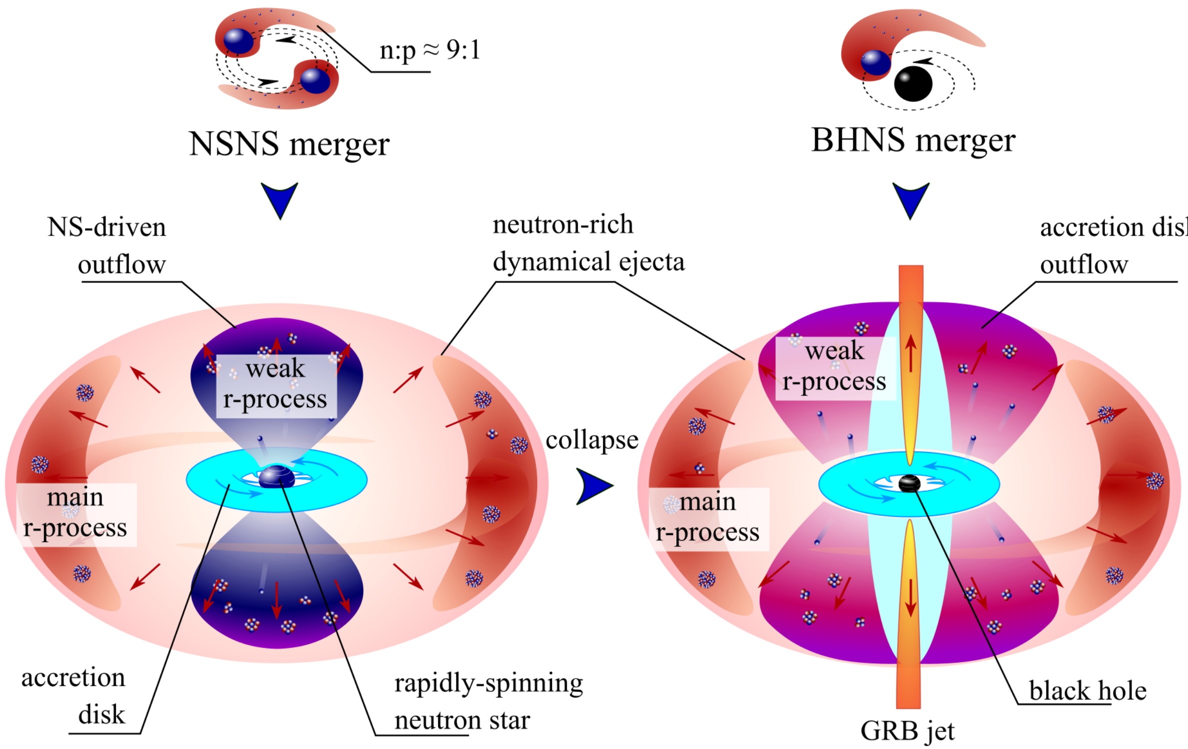
Jets in magnetorotational driven supernovae may also provide the necessary conditions

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 by O. Korobkin

# WHERE CAN THE $r$-PROCESS OCCUR?

Another possibility is in compact object mergers



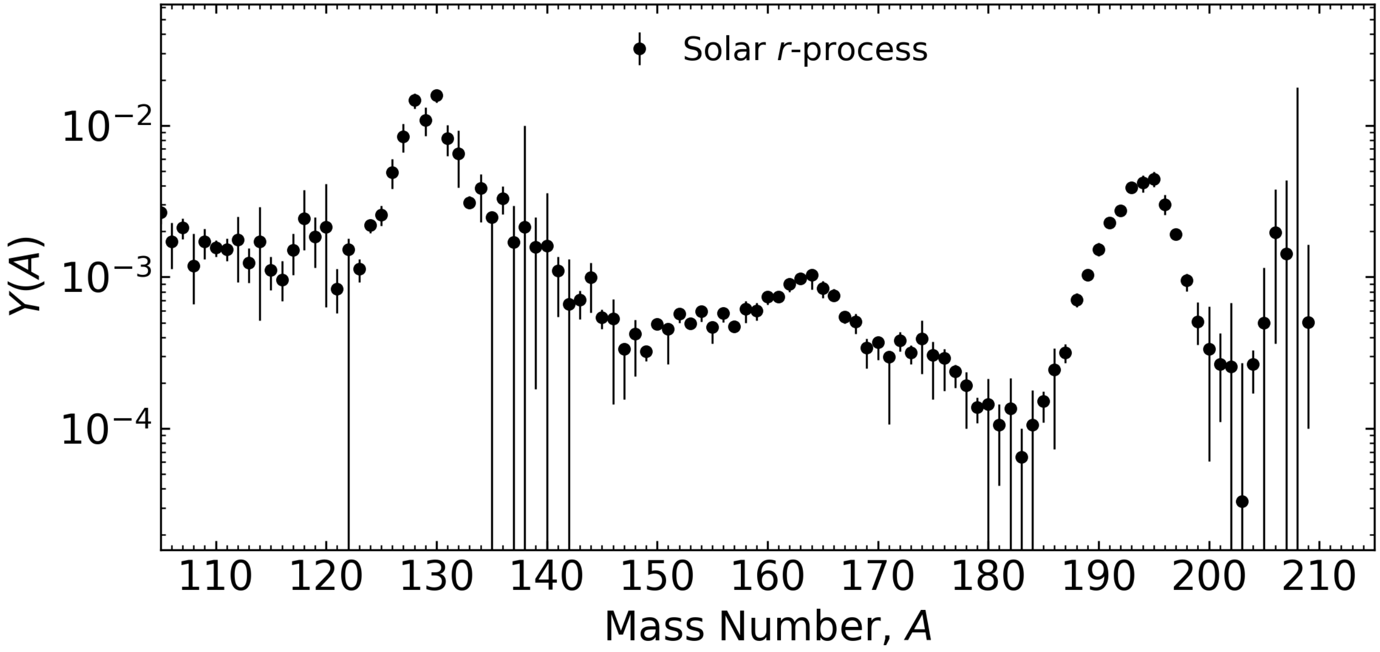

A binary merger of neutron stars is an exciting possibility (some indirect evidence exists)

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

Lattimer & Schramm (1974) • Freiburghaus *et al.* ApJ 525 (1999) • Korobkin *et al.* (2012) • Figure by O. Korobkin

# WHEN WE MODEL NUCLEOSYNTHESIS

We want to describe the abundances observed in nature



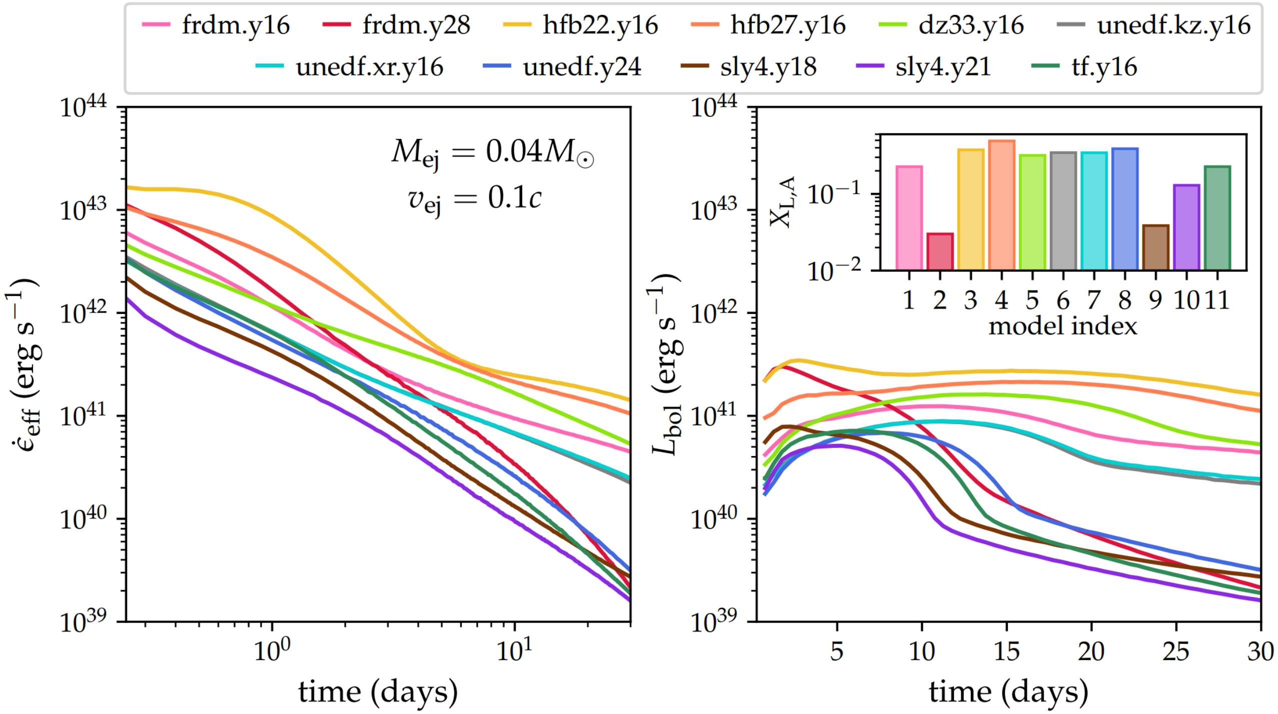

But there is uncertainty in:

The astrophysical conditions (large variations in current simulations)

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

See e.g. Goriely EPJA (2015) • Côté *et al.* ApJ (2018)

# AN EXAMPLE: KILONOVA IMPACTED BY NUCLEAR UNCERTAINTIES




Lanthanide / actinide production can vary drastically using different nuclear models

This in turn impacts heating, thermalization and light curves even for fixed ejected mass & velocity

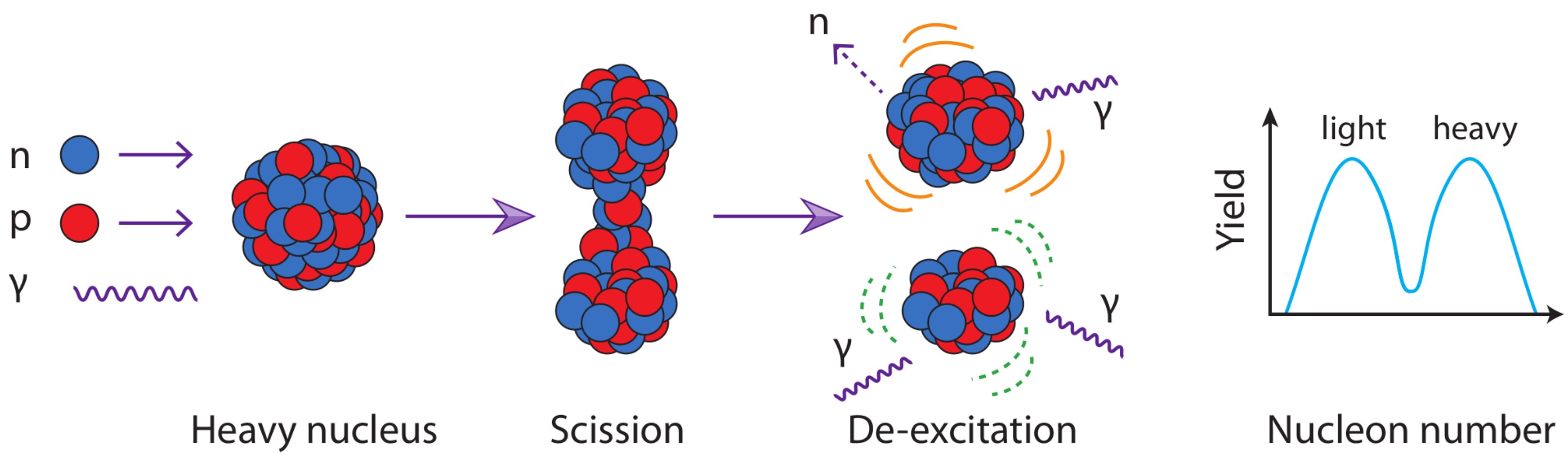
Y. Zhu ***et al.*** ApJ 906 94 (2021) • J. Barnes ***et al.*** ApJ 918 44 (2021)

# INPUTS FROM NUCLEAR PHYSICS

**1st order:** masses, $\beta$-decay rates, reaction rates & branching ratios


Dillmann *et al.* PRL 91 162503 (2003) • Aprahamian ***et al.*** AIP Adv. 4 041101 (2014) • See review paper: **Mumpower** *et al.* PPNP 86 (2016)

# NUCLEAR FISSION IN A NUTSHELL




**The fission process:**

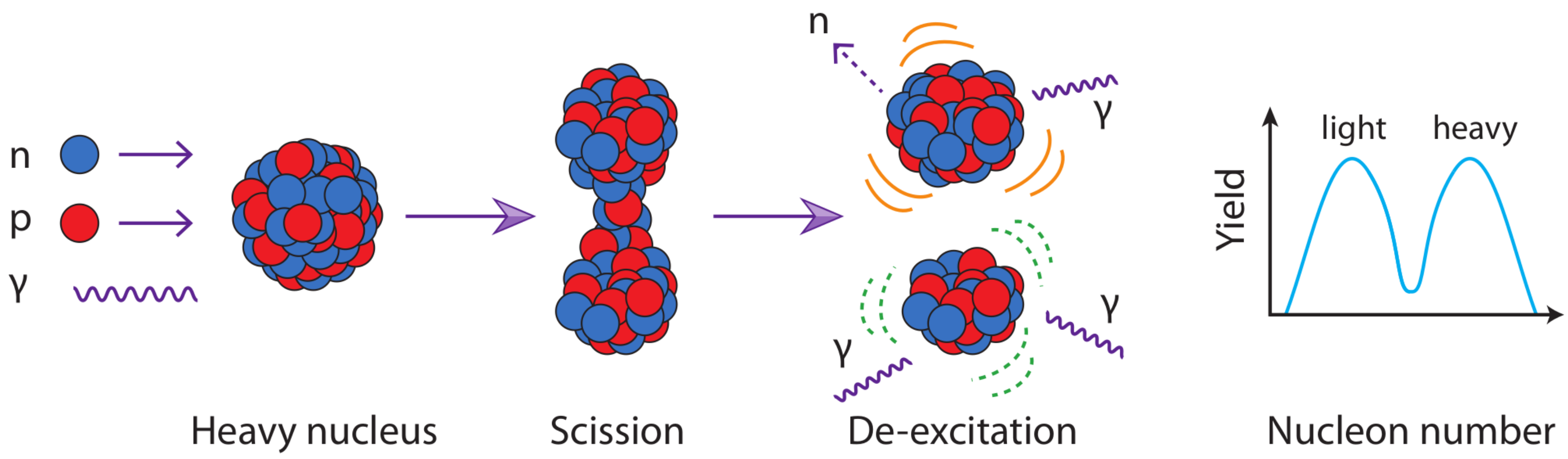
A heavy nucleus splits into lighter fragments

Subsequent particle emission and decays then occur

Many events gives rise to fission yield

Meitner & Frisch (1938) • Bohr & Wheeler (1939) • Figure by **Mumpower**

# 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

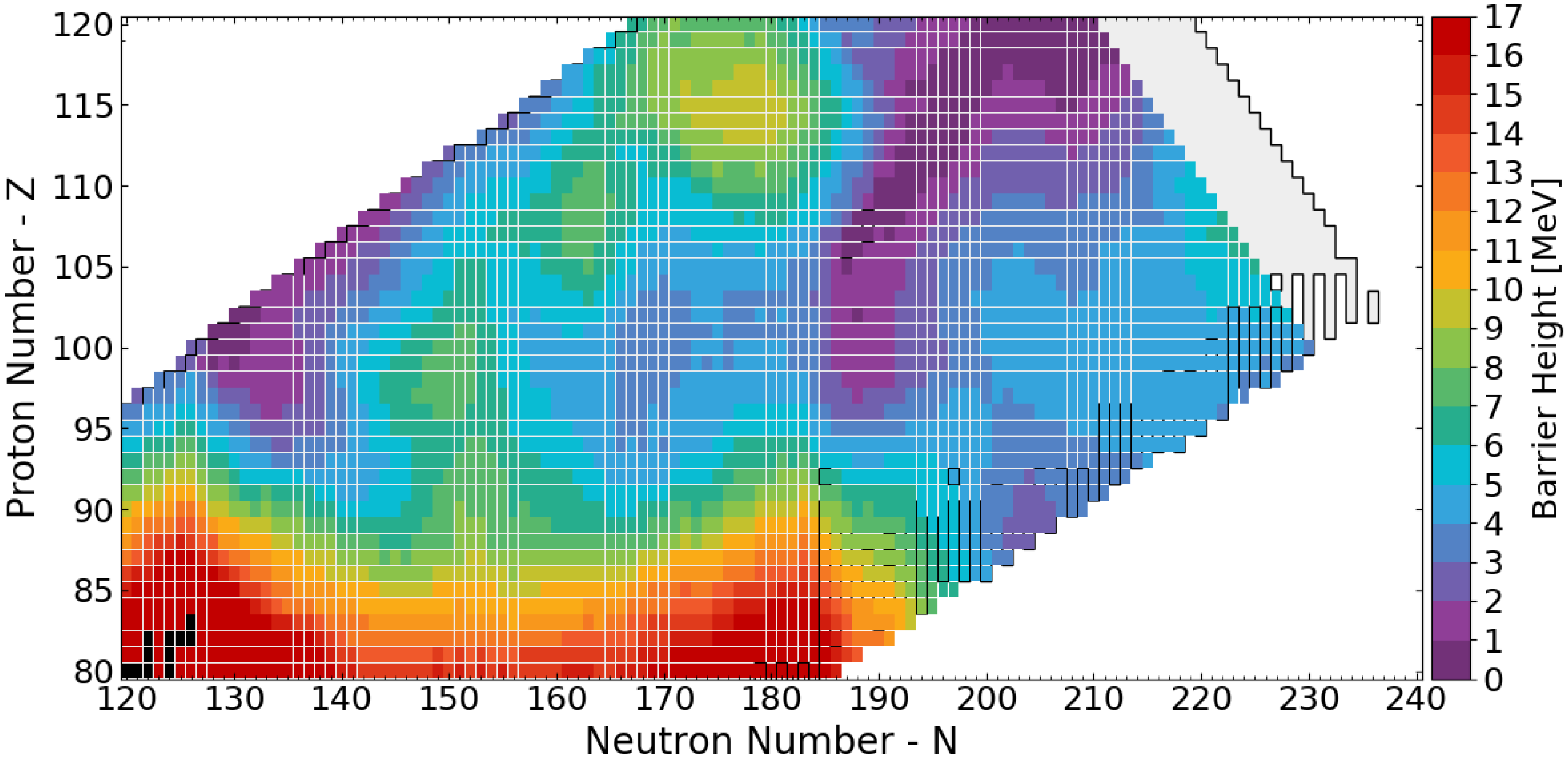
Large Q-value ⇒ impacts thermalization and therefore possibly observations

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 by **Mumpower**

# FISSION BARRIERS

# FISSION BARRIER HEIGHTS (FRLDM)



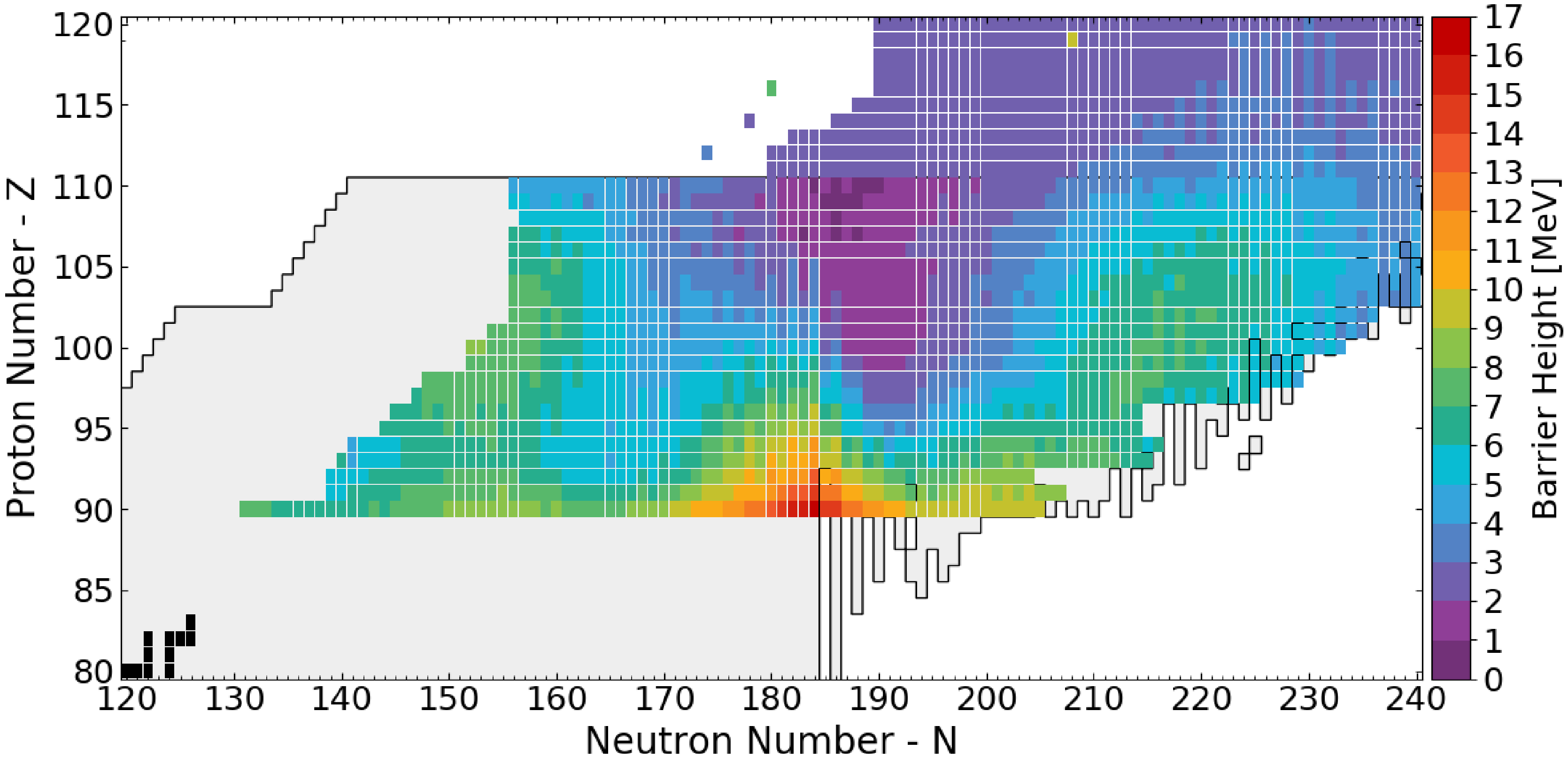

(Maximum) FRLDM Barrier heights

Low barrier ↦ fission ⇑

$r$-process hot spots follow low barriers

Möller **et al.** PRC 91 024310 (2015) • Giuliani *et al.* PRC 97 034323 (2018)

# FISSION BARRIER HEIGHTS (HFB-14)

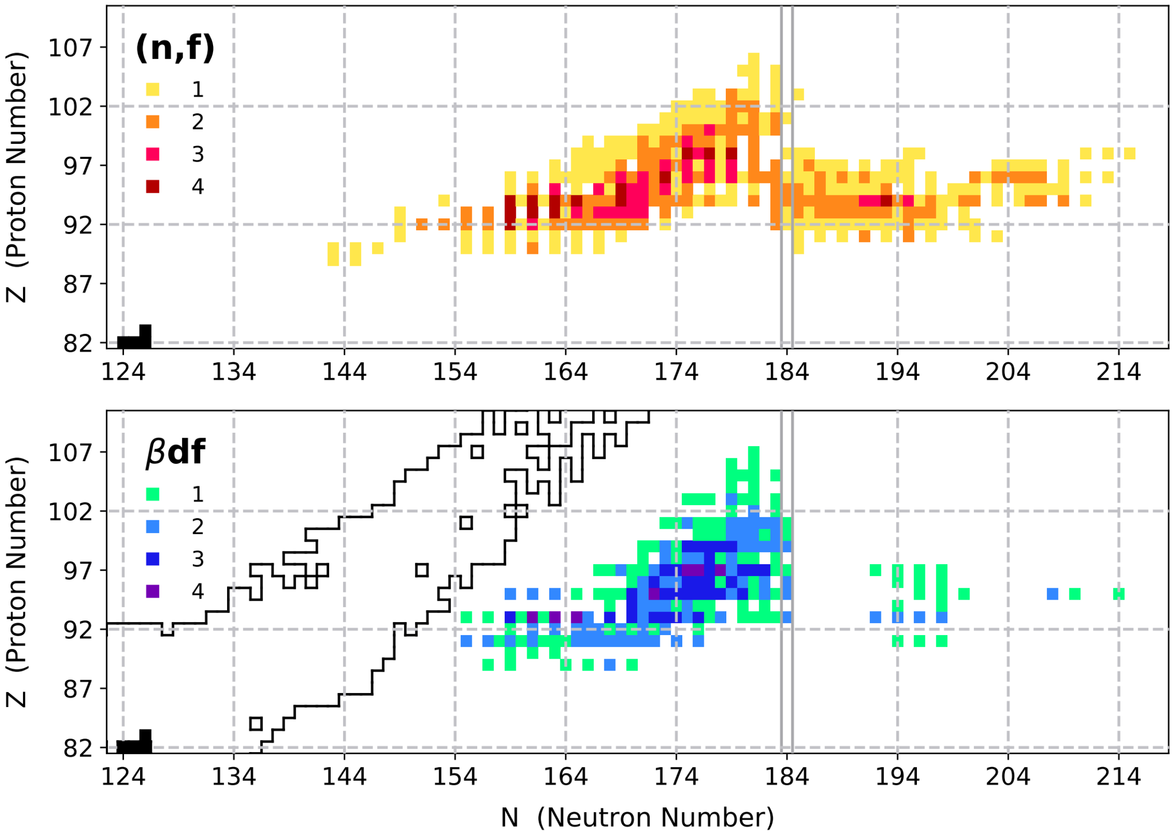



(Maximum) HFB-14 Barrier heights

Low barrier ↦ fission ⇑

Used in (n,f) and $\beta$df, spontaneous fission calculations

# FISSION HOT SPOTS




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

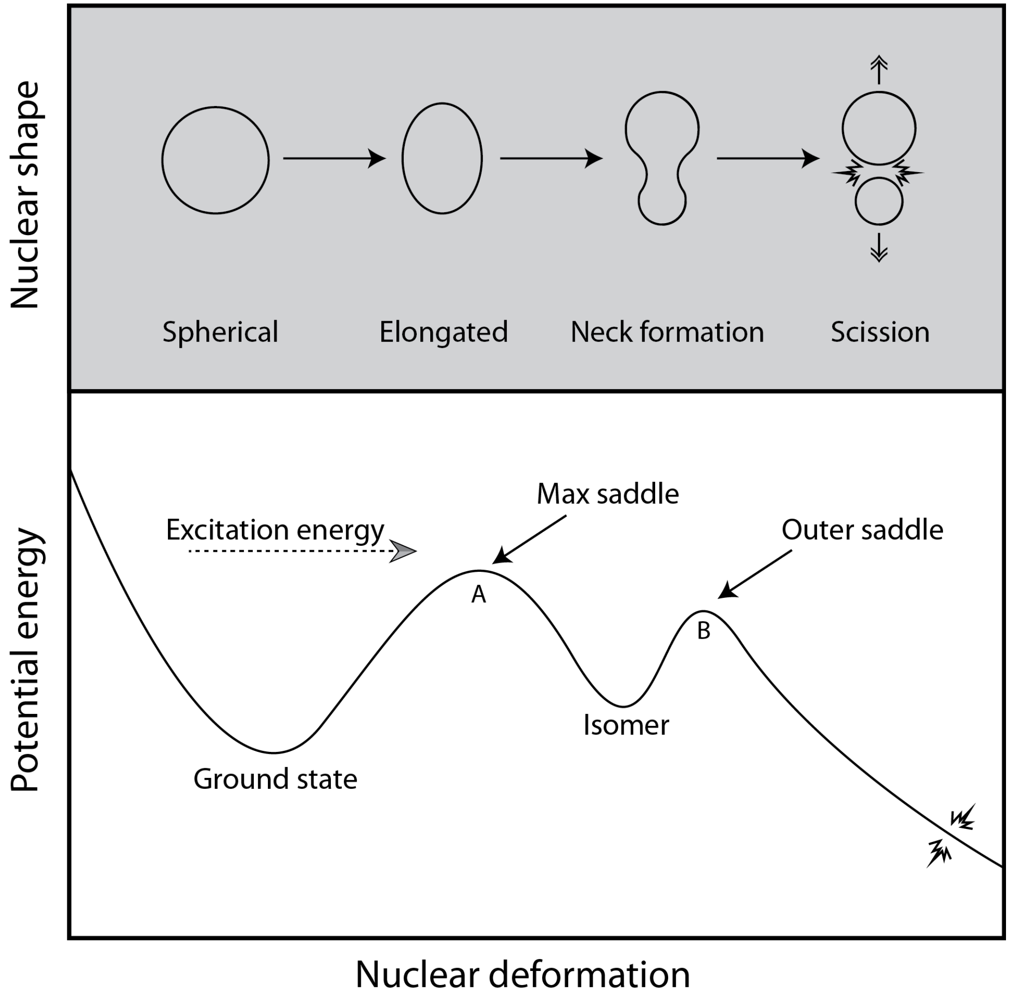
With variations in both astrophysical conditions and nuclear models

Nuclei which influence the final abundances are colored for (n,f) and ($\beta$,f)

Vassh *et al.* J. Phys. G (2019) • Giuliani *et al.* PRC 102 045804 (2020)

# FISSION YIELDS

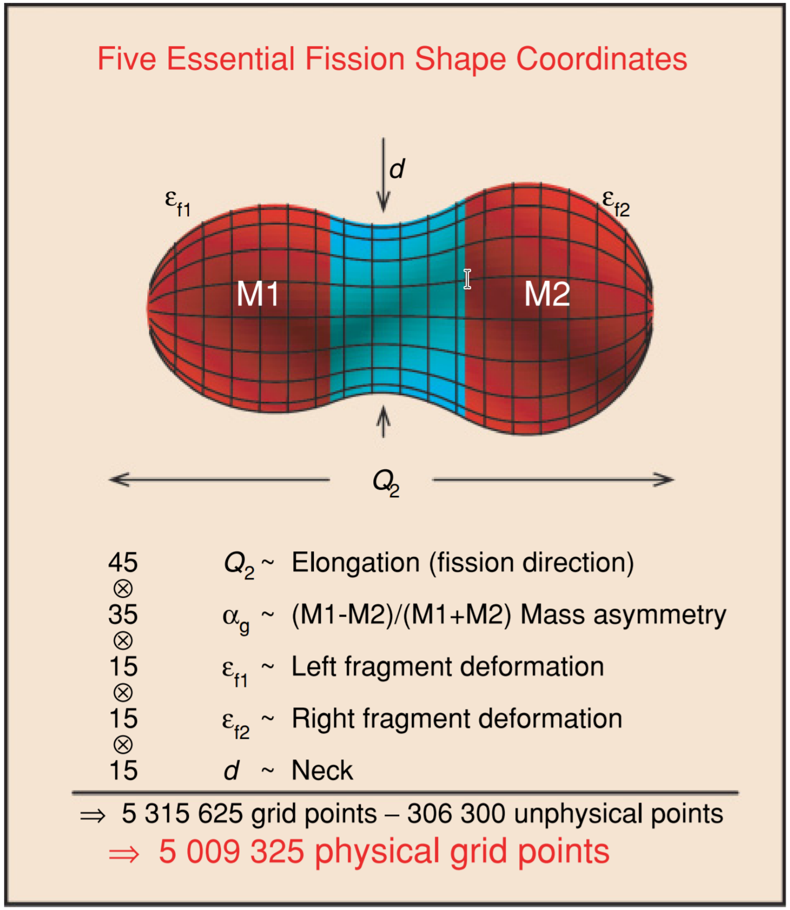
# A SIMPLE PICTURE OF FISSION




Follow progression of the nucleus from compact to highly elongated shapes

**Mumpower** *et al.* PRC 101 054607 (2020)

# FINITE-RANGE LIQUID-DROP MODEL




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

Möller *et al.* PRC 79 064304 (2009) • Möller ***et al.*** PRC 91 044316 (2015)

# HOW DO WE CALCULATE FRAGMENT YIELDS WITH THIS MODEL?

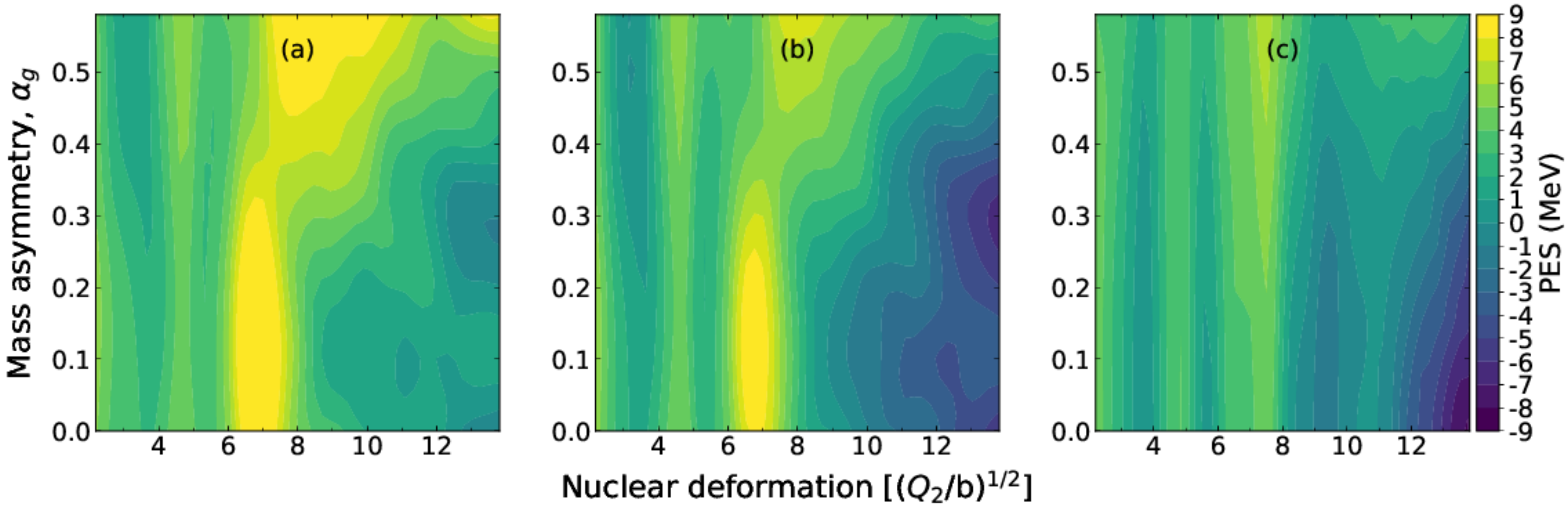
Change in nuclear shape acts as a driving force for bulk rearrangement of material

This results in a collective kinetic energy

The macroscopic shape degrees of freedom couple to individual nucleonic motion

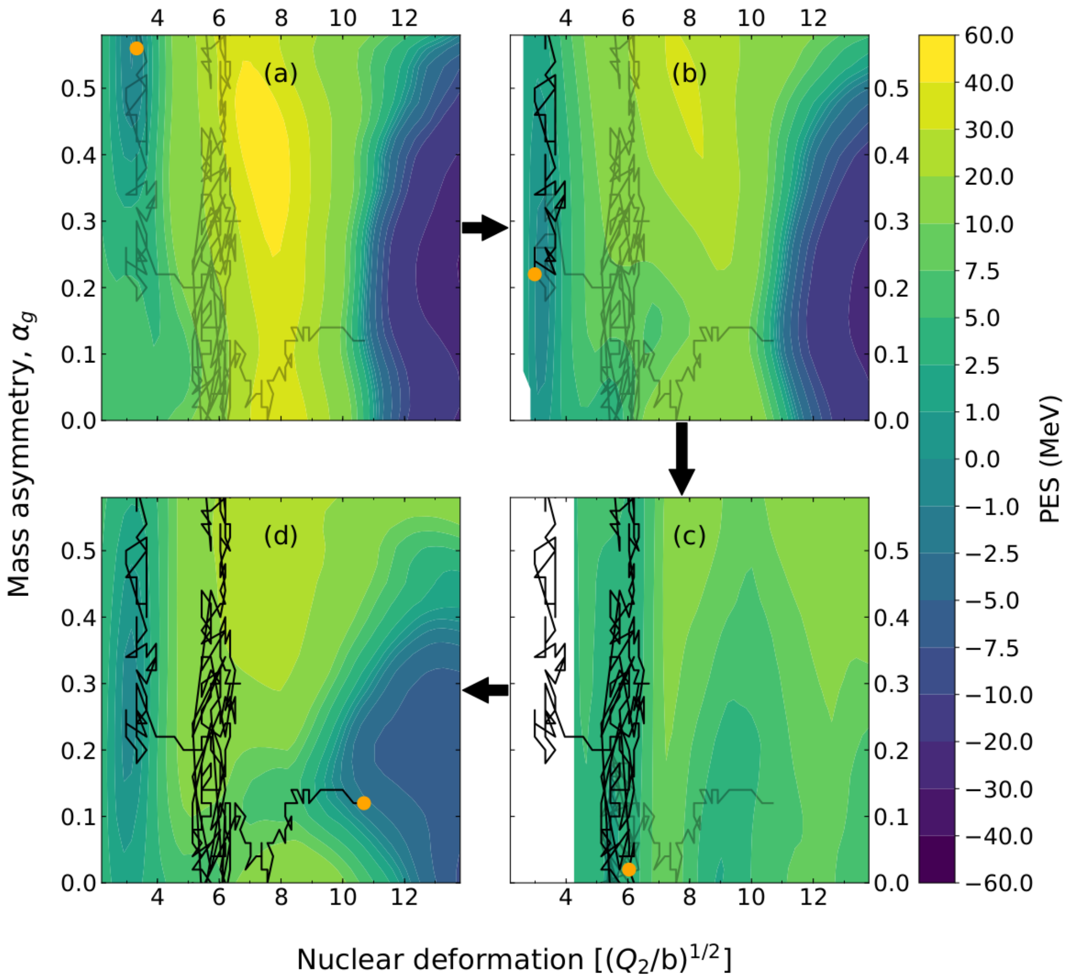
Resulting in an evolution that is both damped and diffuse

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)

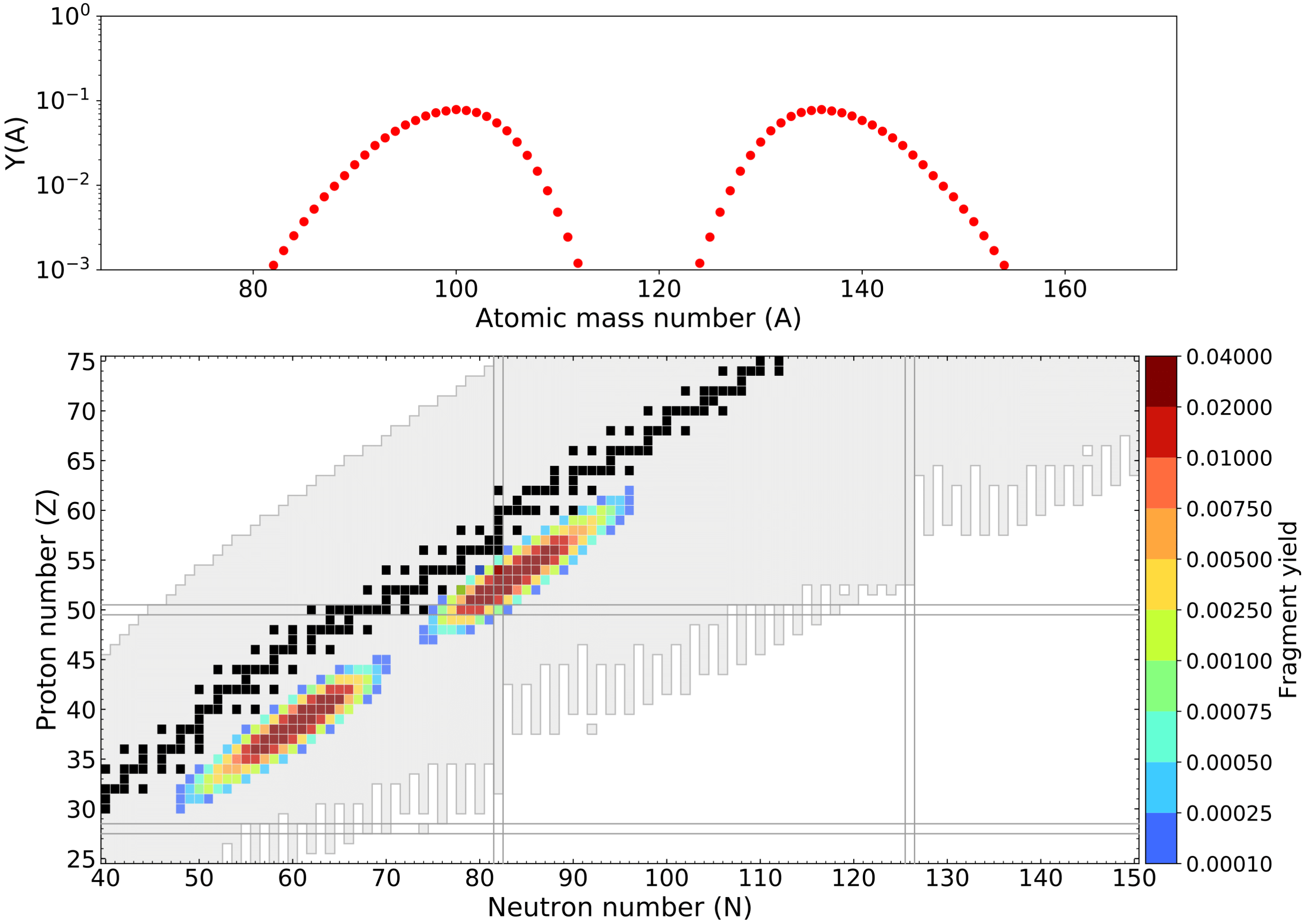
# FISSION EVOLUTION




Amounts to random walk across potential energy surface

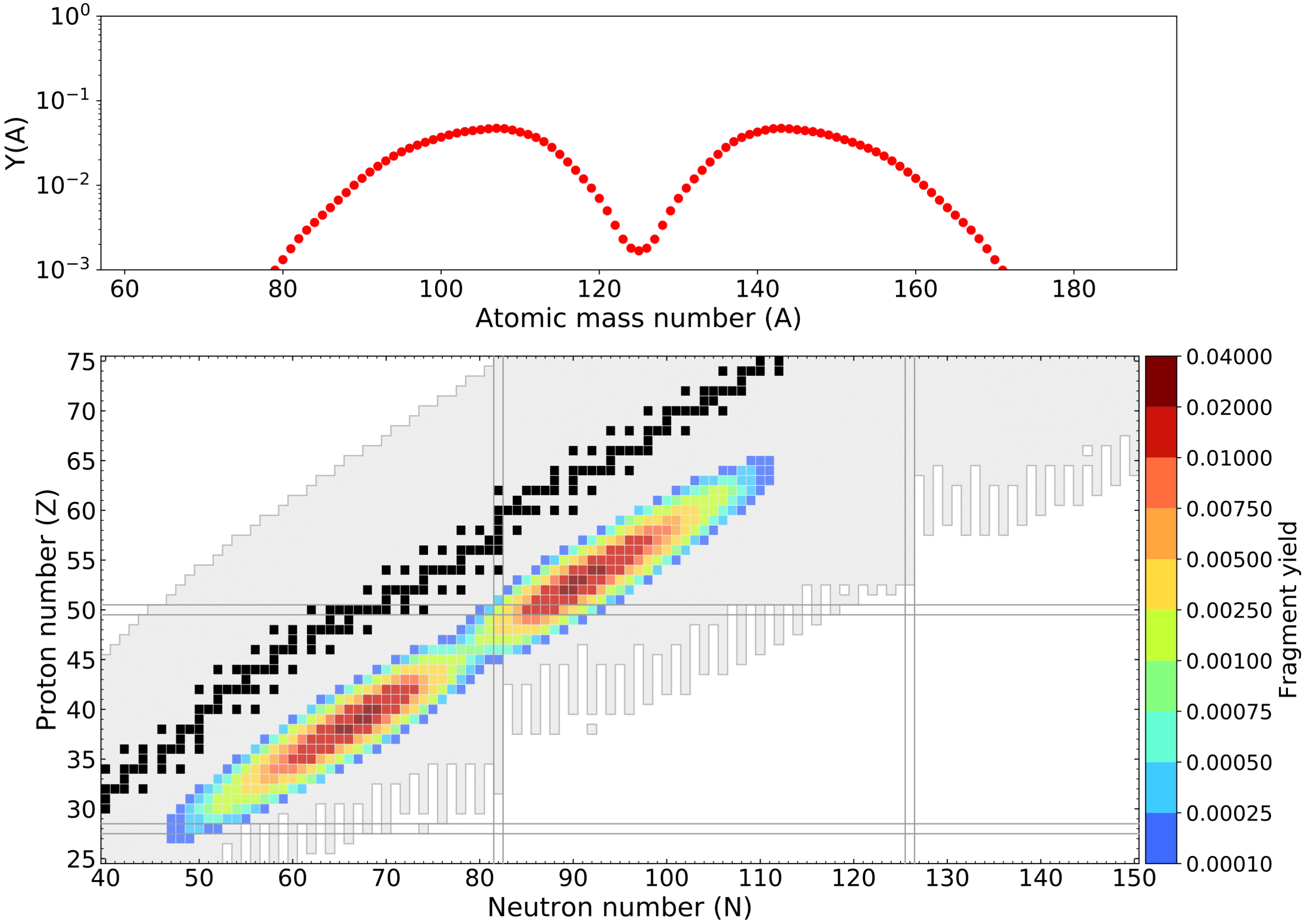
**Mumpower** *et al.* PRC 101 054607 (2020)

# 236-U Y(Z,A) YIELD



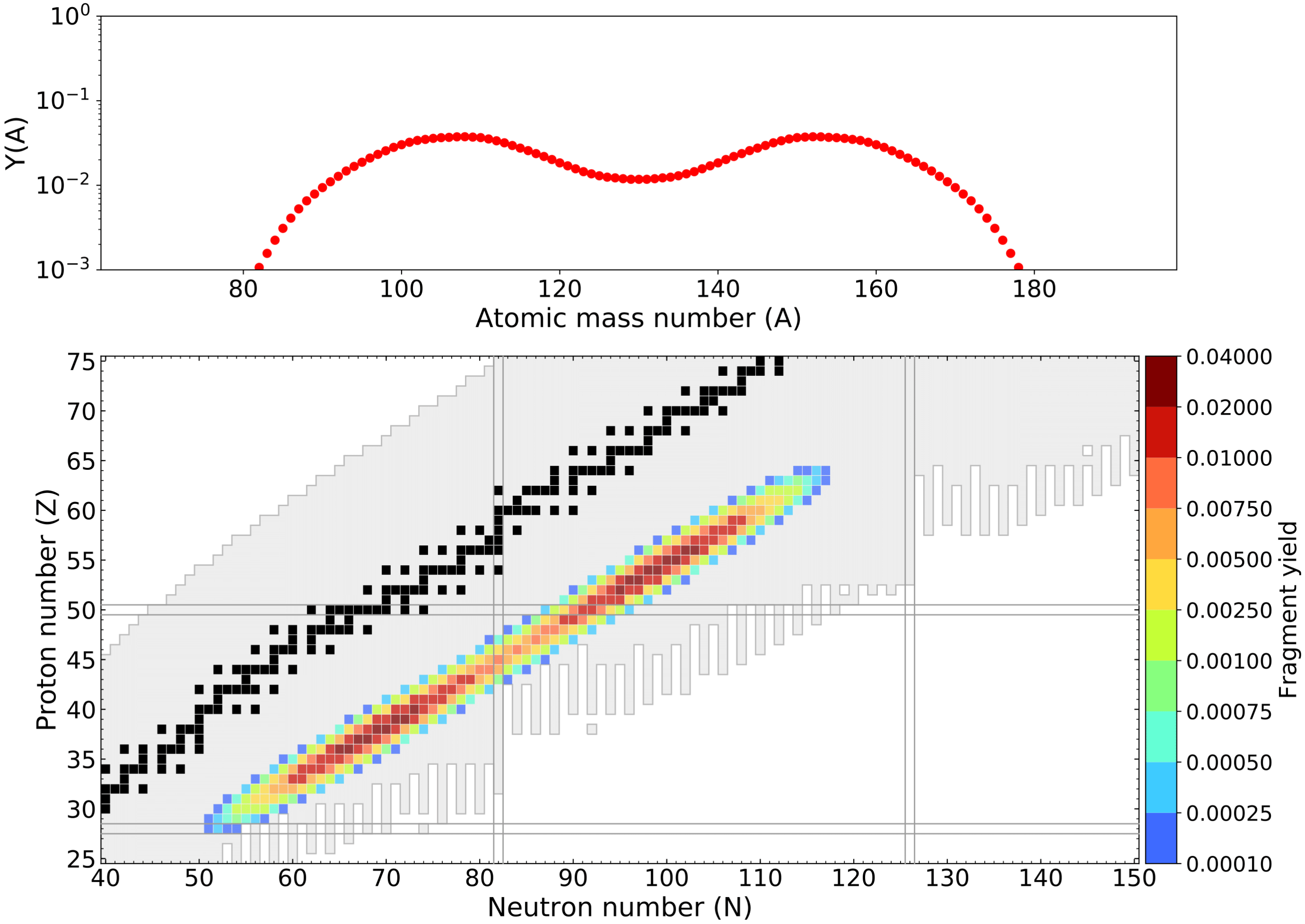

**Mumpower** *et al.* PRC 101 054607 (2020)

# 250-U Y(Z,A) YIELD



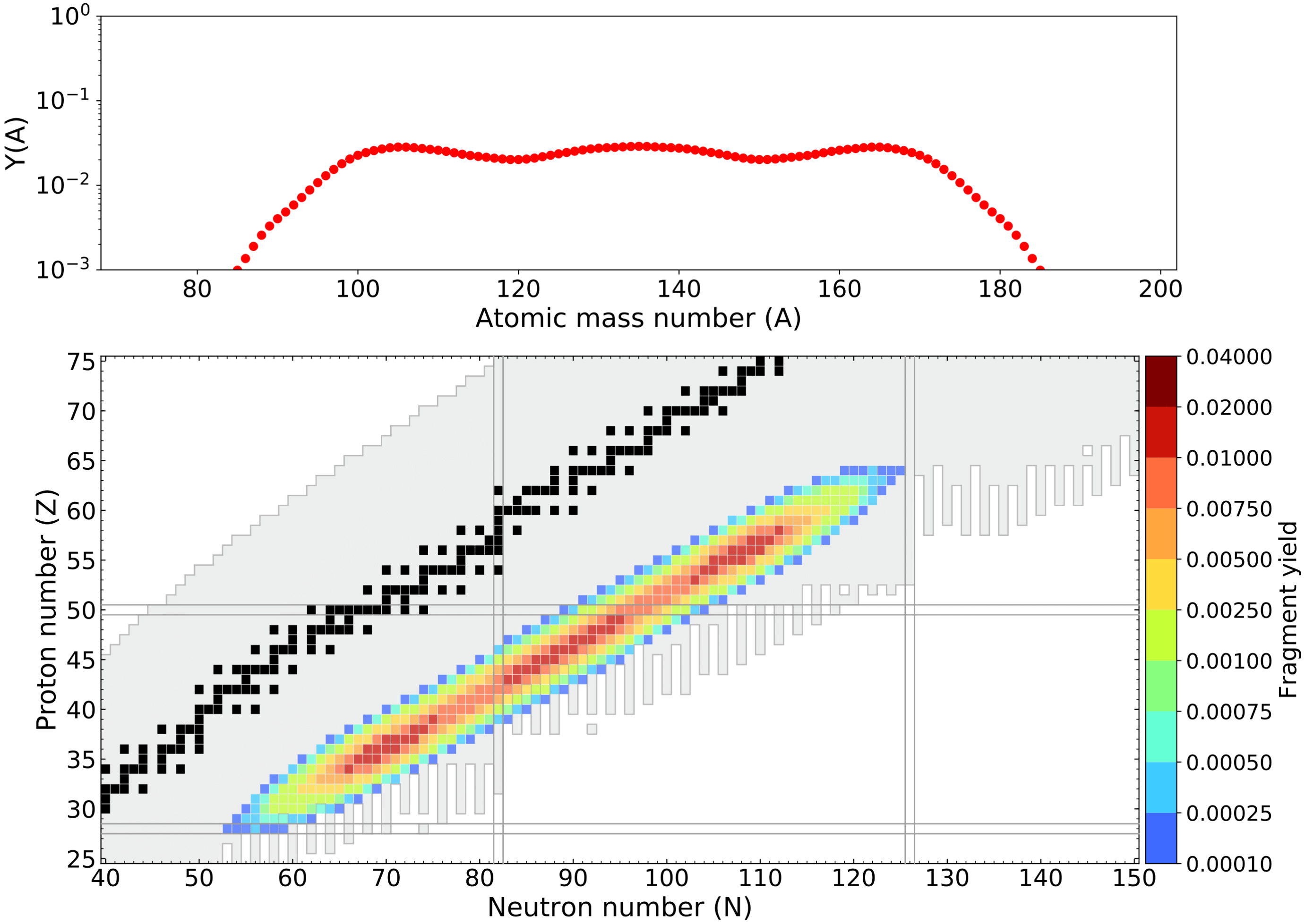

**Mumpower** *et al.* PRC 101 054607 (2020)

# 260-U Y(Z,A) YIELD



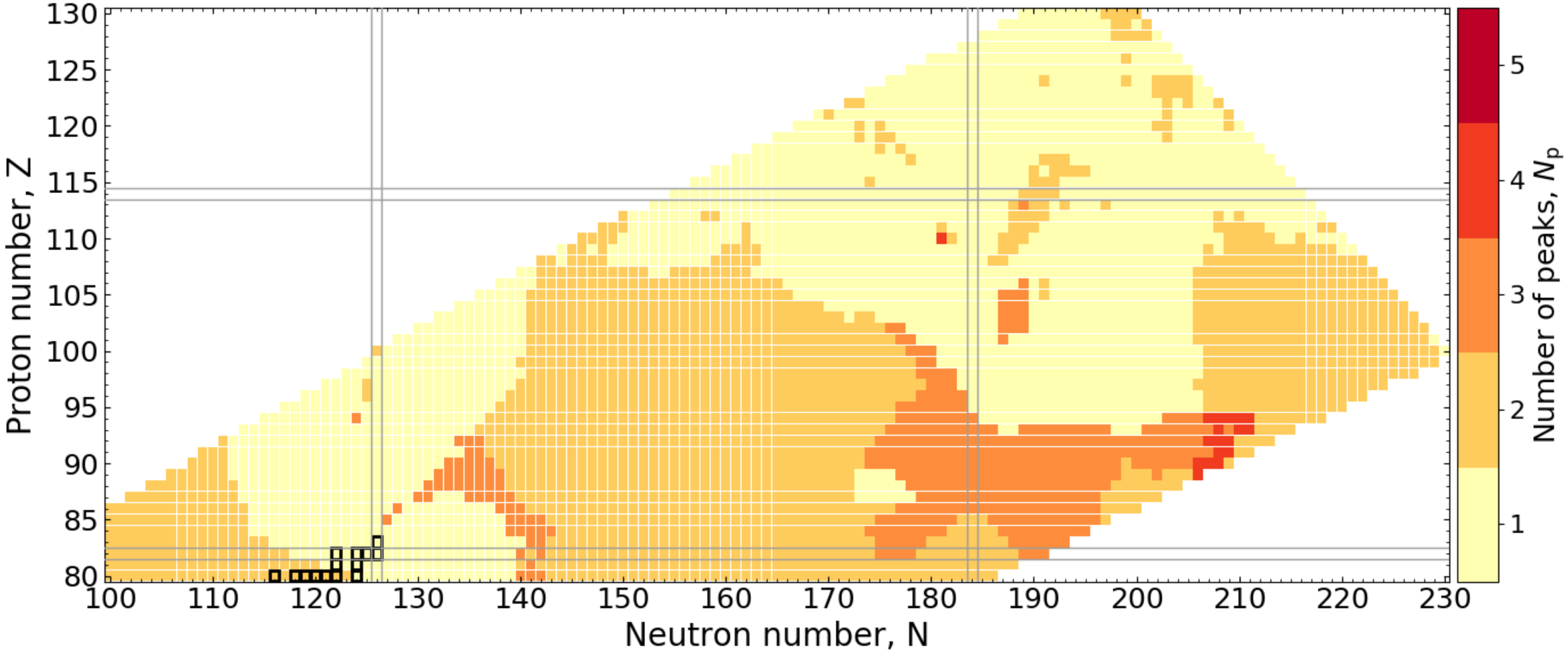

**Mumpower** *et al.* PRC 101 054607 (2020)

# 270-U Y(Z,A) YIELD




**Mumpower** *et al.* PRC 101 054607 (2020)

# NUMBER OF PEAKS



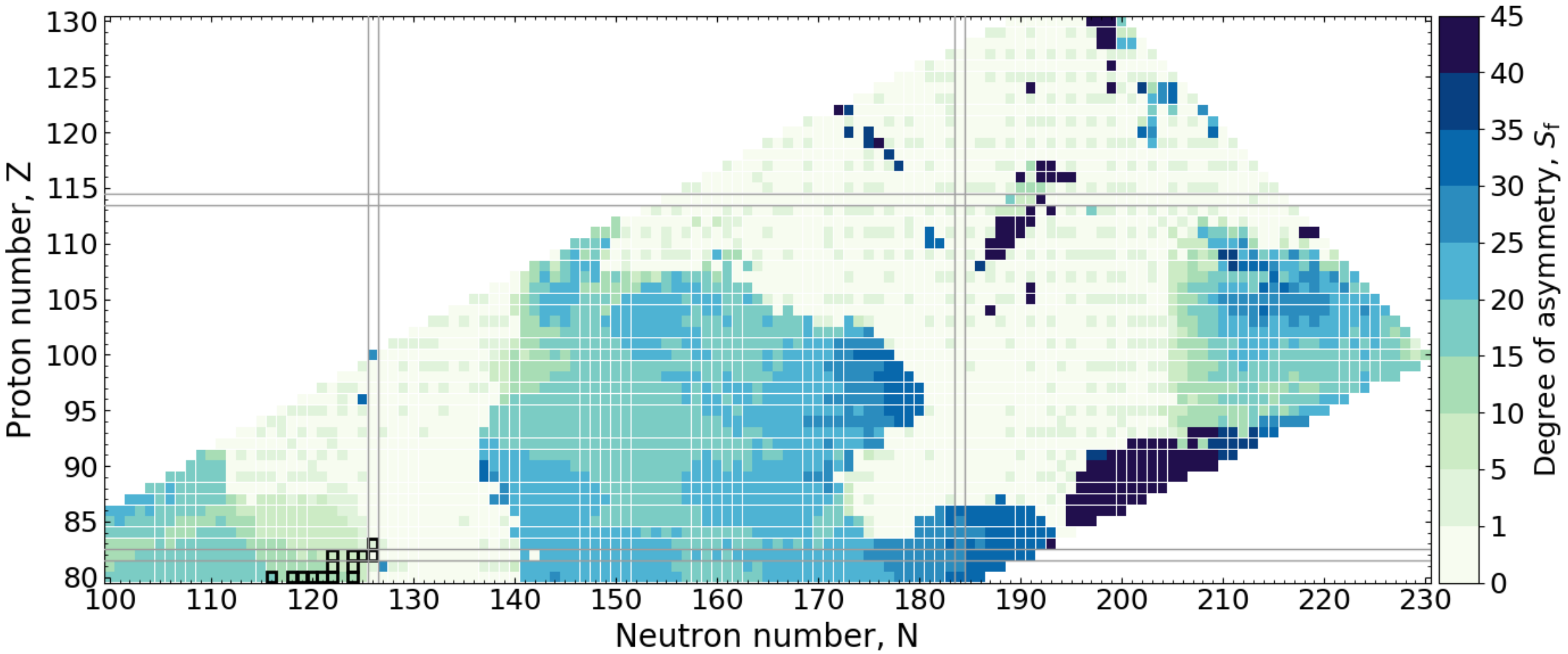

Count the number of peaks in the mass yield, $Y(A)$, distribution

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.* PRC 101 054607 (2020)

# MEASURE OF ASYMMETRY



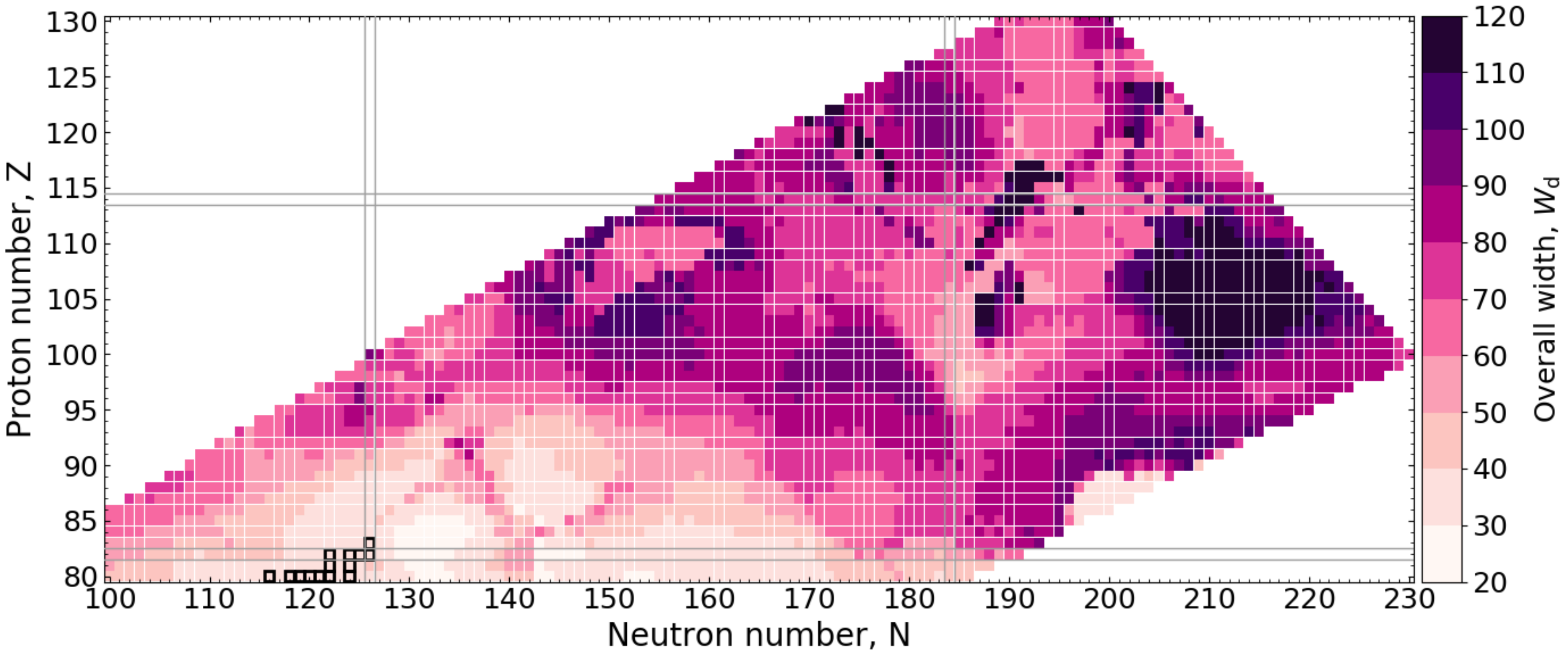

Measure the distance in $A$ between the maxima of $Y(A)$ and $Y(A_f/2)$

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.* PRC 101 054607 (2020)

# EXTENT OF Y(A) DISTRIBUTION



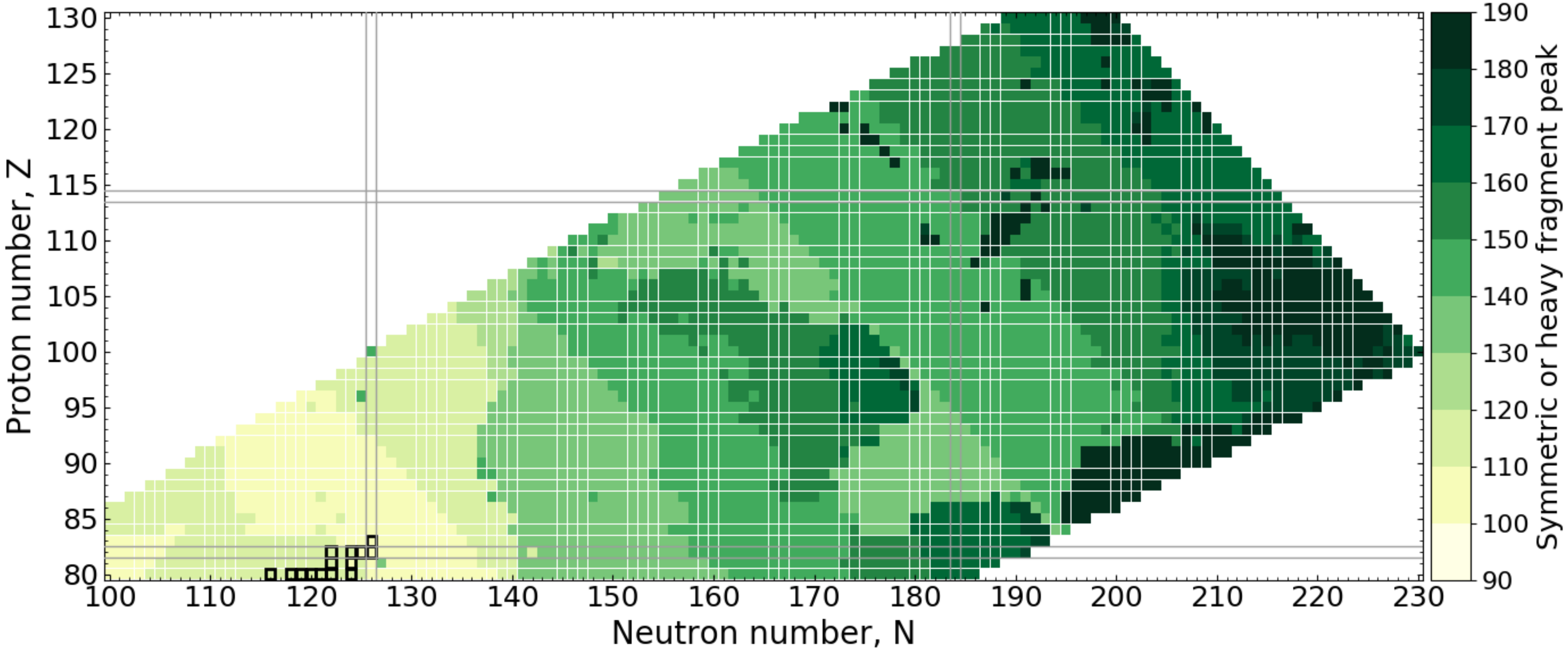

Measure the spread of the daughter products in $A$

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.* PRC 101 054607 (2020)

# PEAK LOCATION (A)



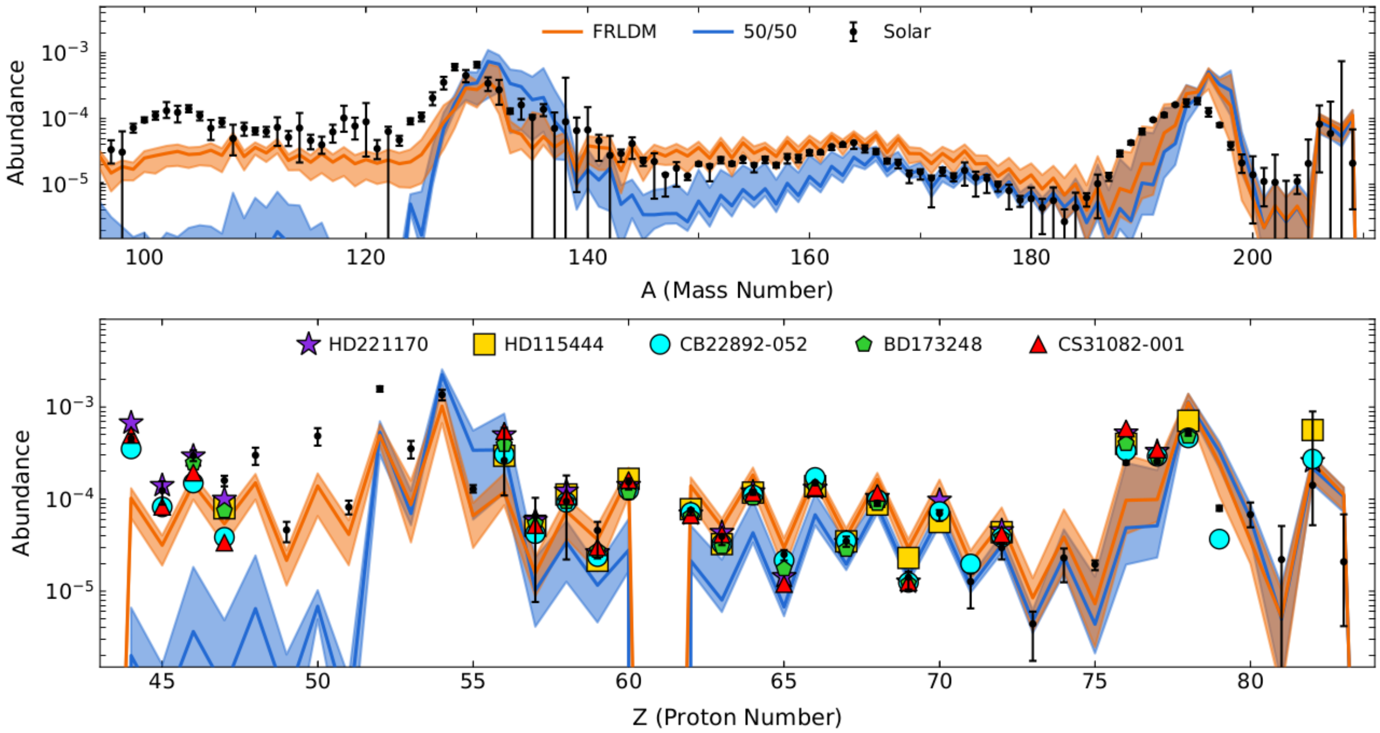

Measure the placement of material of the highest peak in $A$

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.* PRC 101 054607 (2020)

# IMPACT ON THE ABUNDANCES



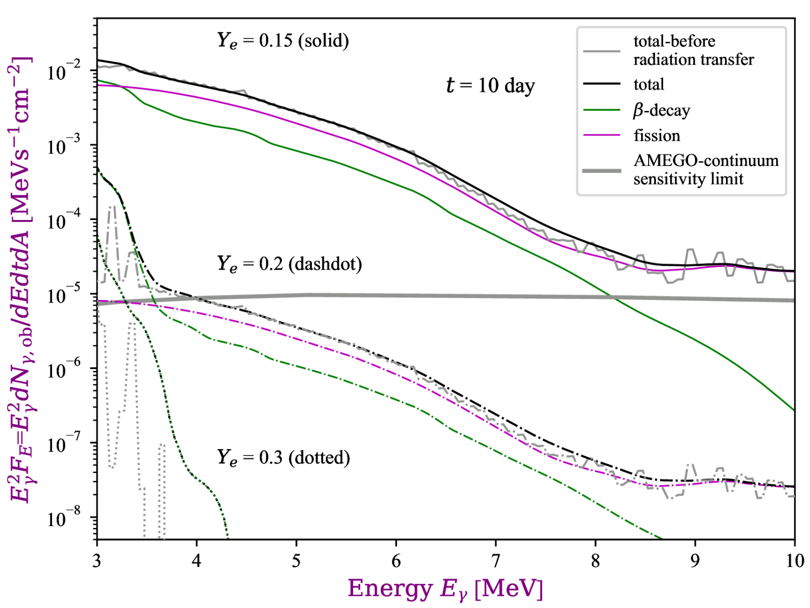

Abundance output using commonly used 50/50 split and new FRLDM model predictions

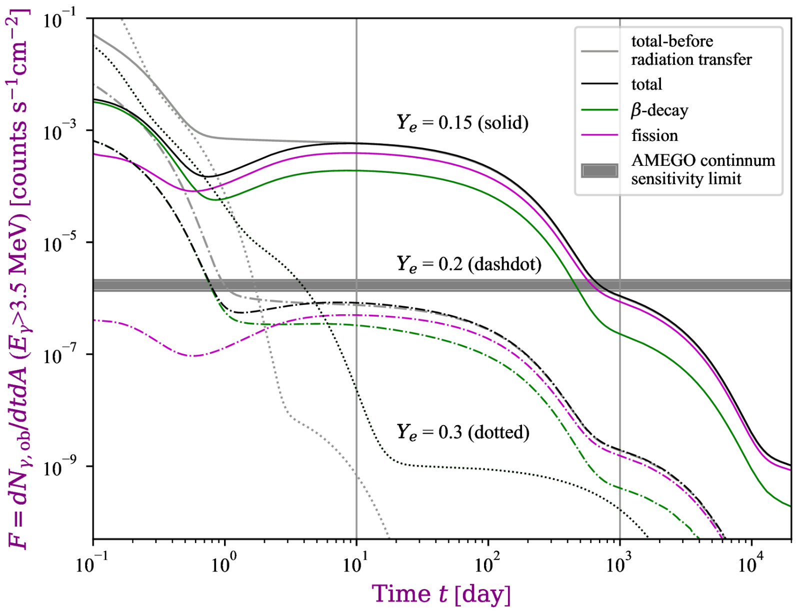
Co-production of light nuclei from $Z \sim 45$ to the actinides (dynamical merger ejecta only!)

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

Vassh ***et al.*** ApJ 896 1 (2020) • see also Shibagaki *et al.* ApJ 816 79 (2016) • Lemaitre *et al.* 103 025806 (2021)

# YIELDS ARE ALSO IMPORTANT FOR PROMPT $\gamma$ SPECTRUM




$\gamma$ spectrum calculated with GEF code for neutron star merger event located at 10 kpc

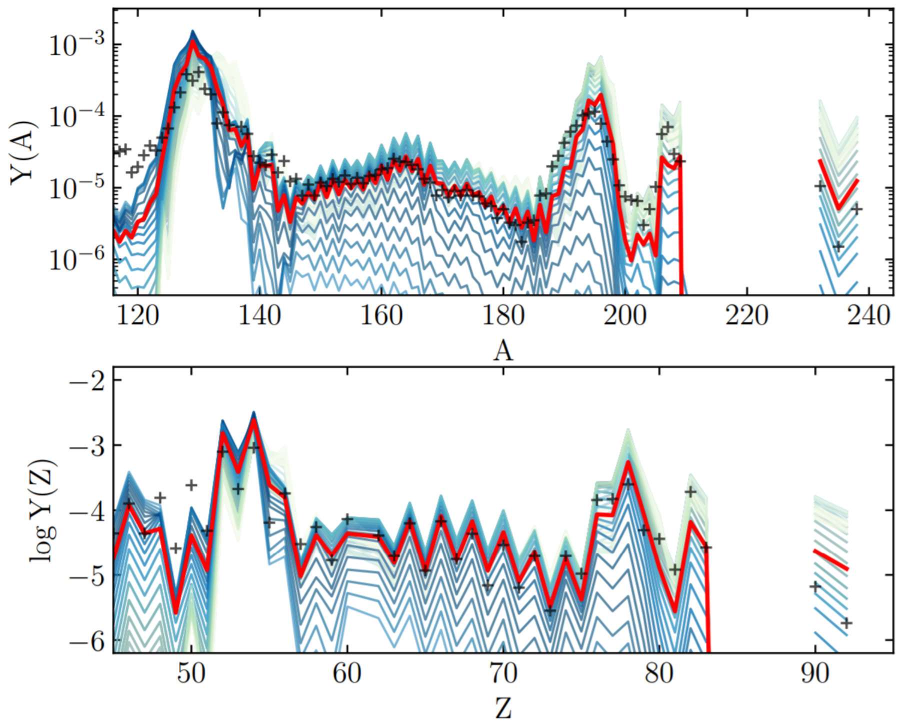
*Observable* high energy $\gamma$'s come 100% from fission (left)

Whether or not this component of the spectrum exists depends on composition (right)

GEF by K.-H. Schmidt: http://www.khschmidts-nuclear-web.eu/GEF.html • X. Wang ***et al.*** ApJL 903 1 (2020)

# WHAT IS LEFT AFTER FISSION?

# LONG-LIVED ACTINIDES



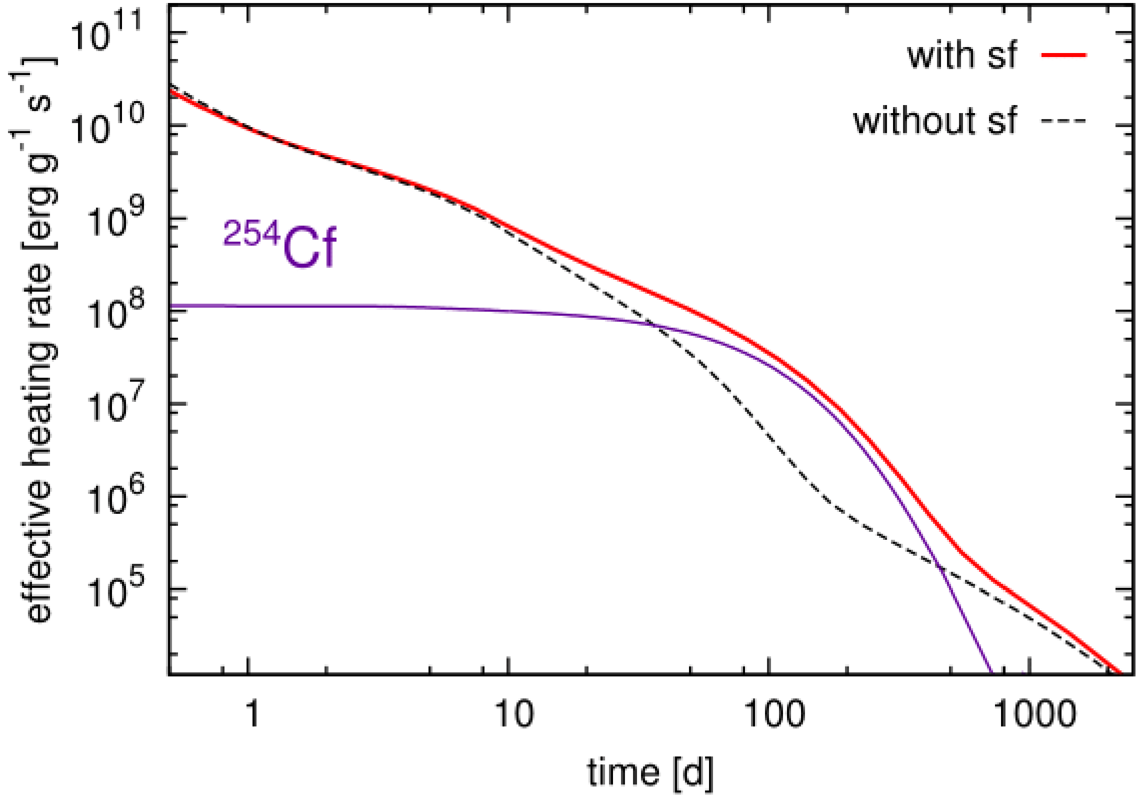

In some simulations actinides seem to be overproduced versus lanthanides (actinide boost)

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)



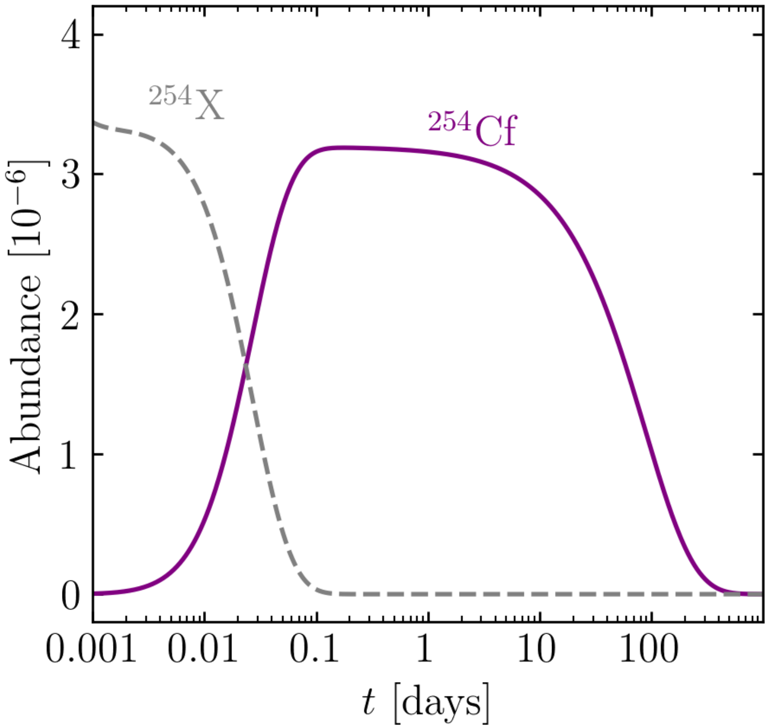

Is there any possible precursor to show that actinide nucleosynthesis has occurred in an event?... Maybe!

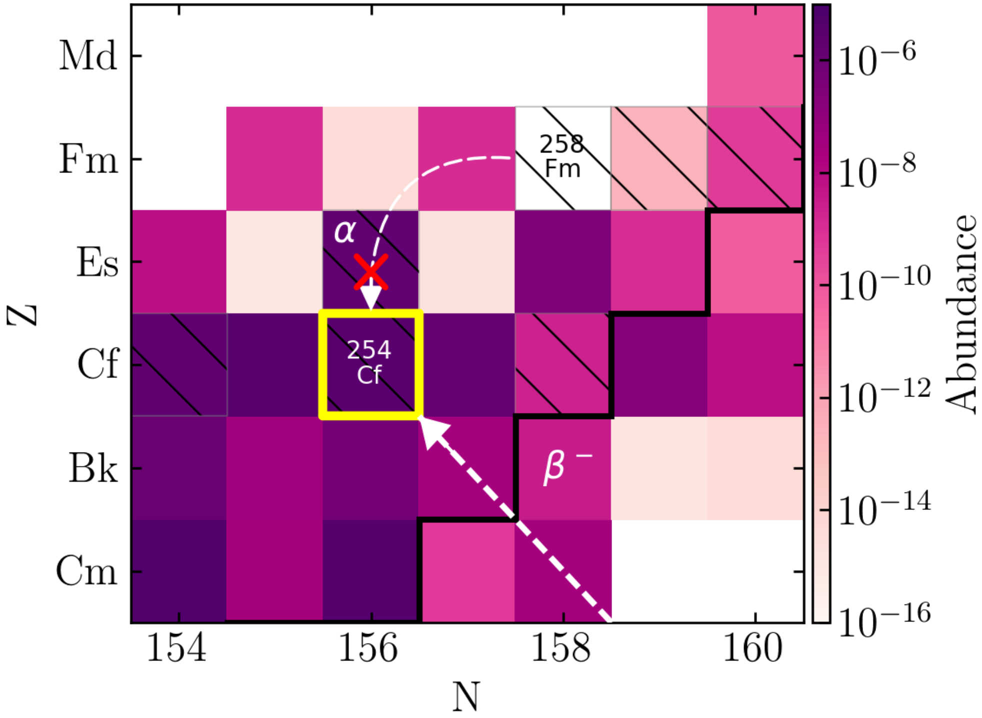
The spontaneous fission of $^{254}$Cf can be a *primary* contributor to nuclear heating at late-time epochs

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)



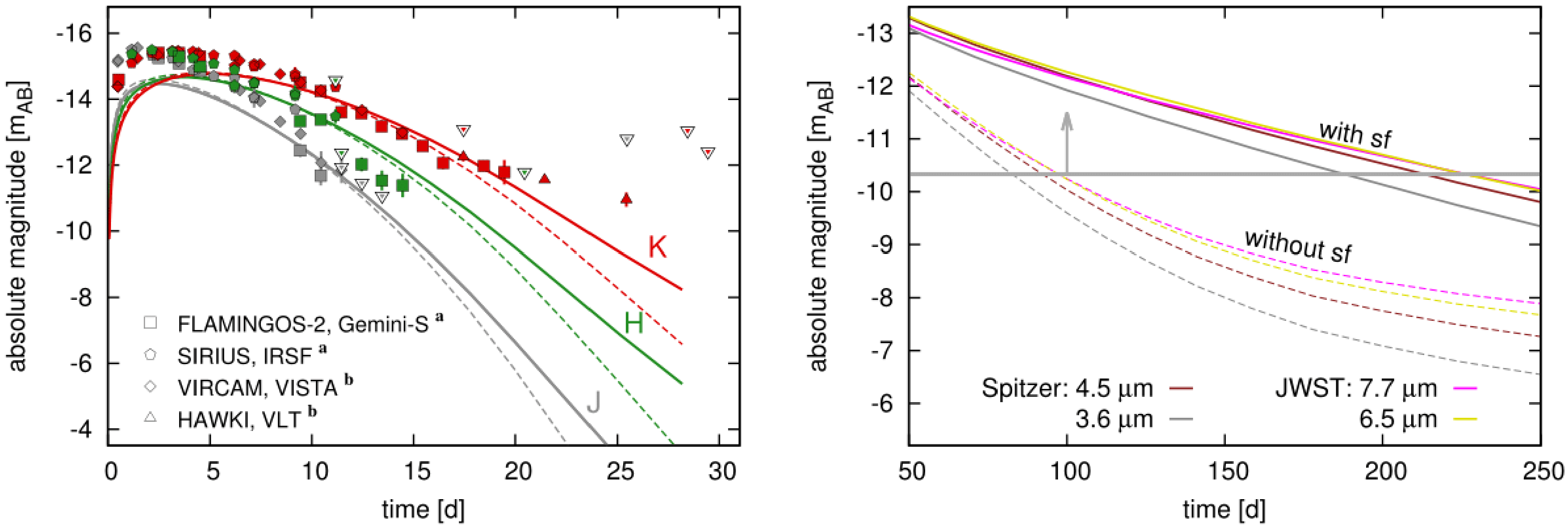

Primary feeder seems to be from $\beta$-decay

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)

# 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