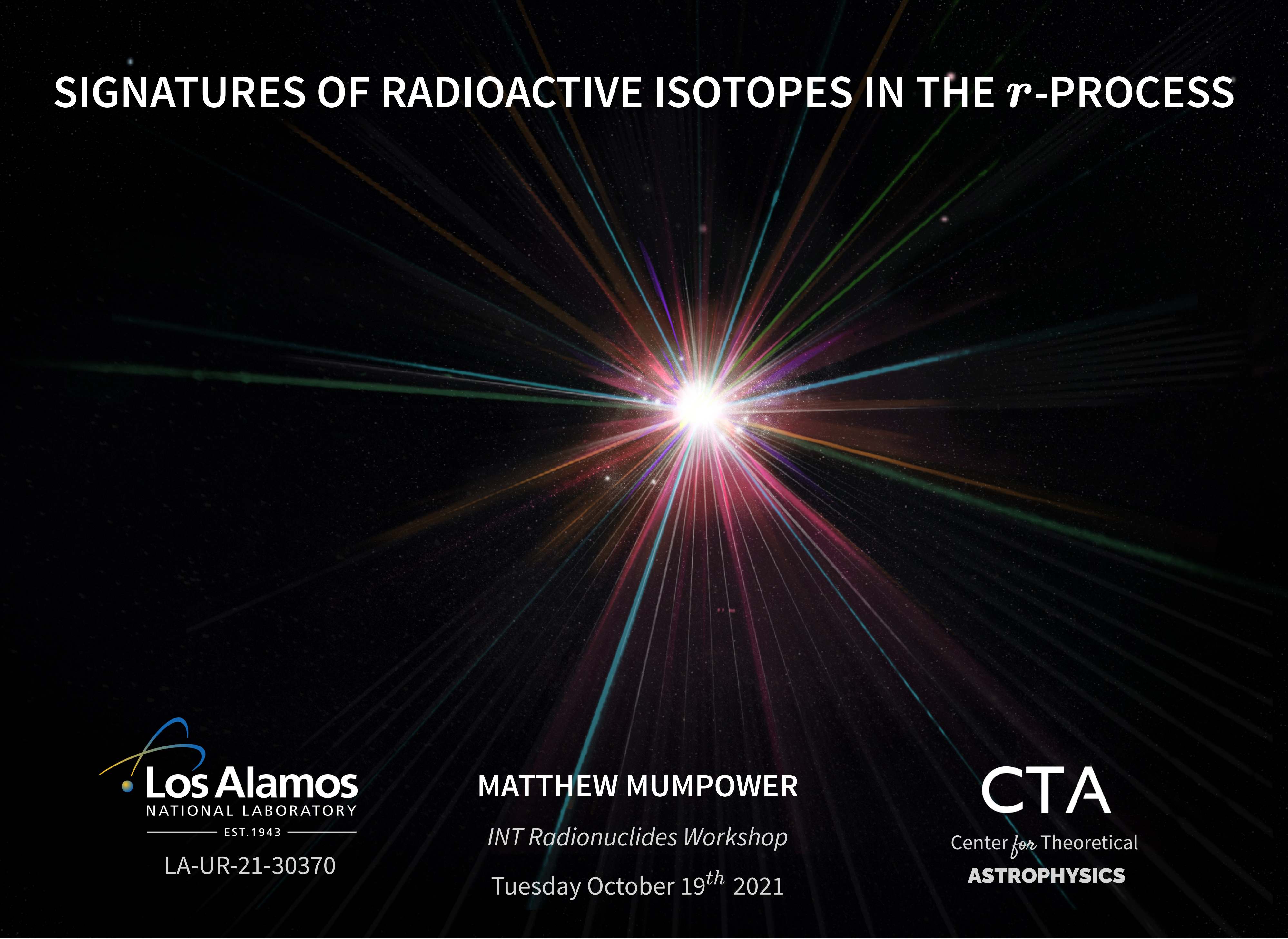
SIGNATURES OF RADIOACTIVE ISOTOPES IN THE r-PROCESS



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LA-UR-21-30370

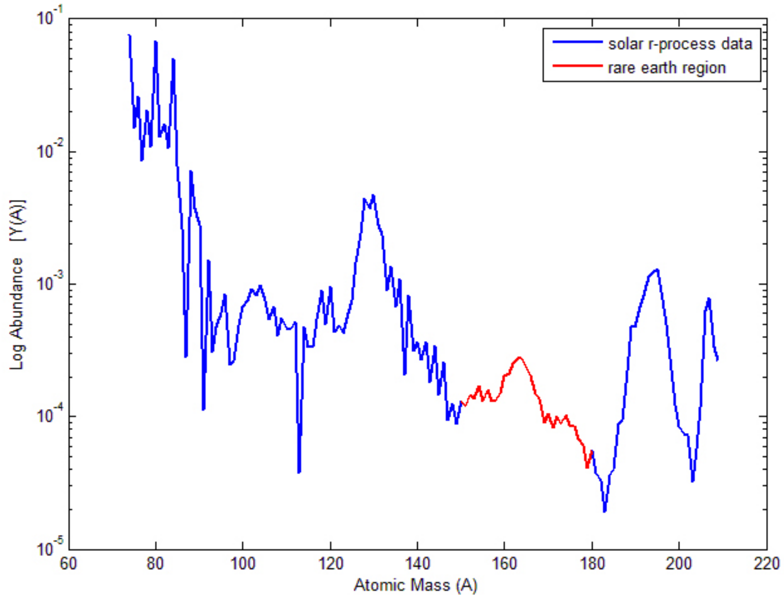
MATTHEW MUMPOWER

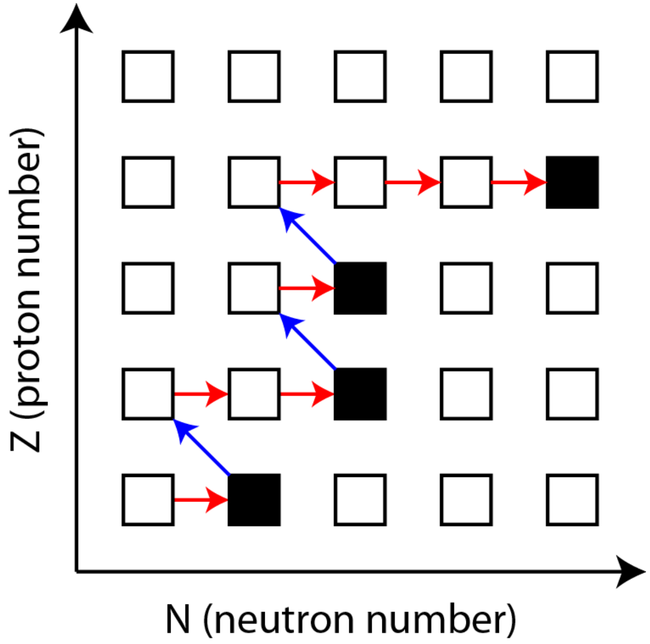
INT Radionuclides Workshop

Tuesday October 19th 2021

CTA
Center *for* Theoretical
ASTROPHYSICS

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

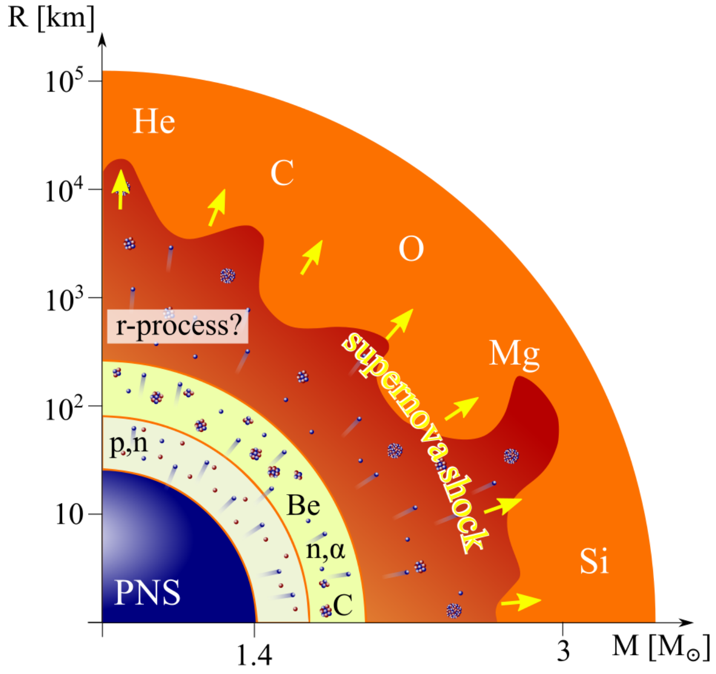
Relative slowdown in the nuclear flow (right) produces peak structures in the observed abundances (left)

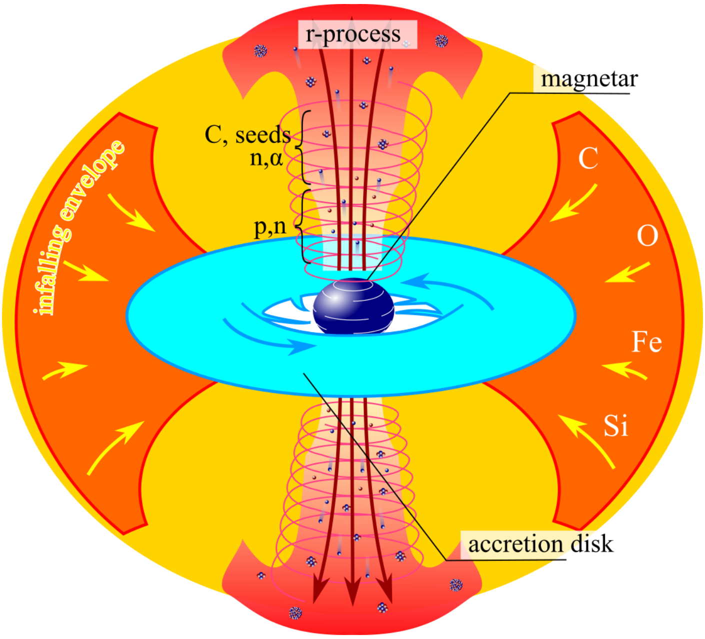
Astrophysical environment must produce a lot of free neutrons in order for this process to proceed

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

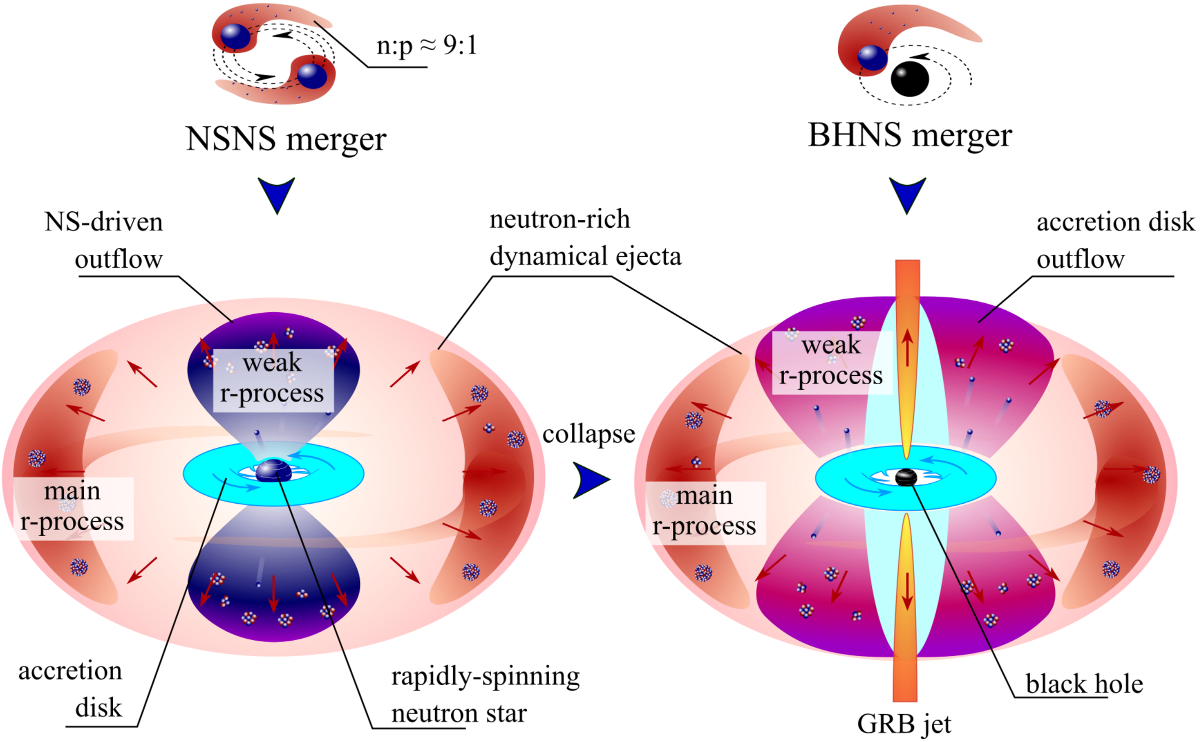
Jets in magnetorotational driven supernovae (right) may also provide the necessary conditions

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 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

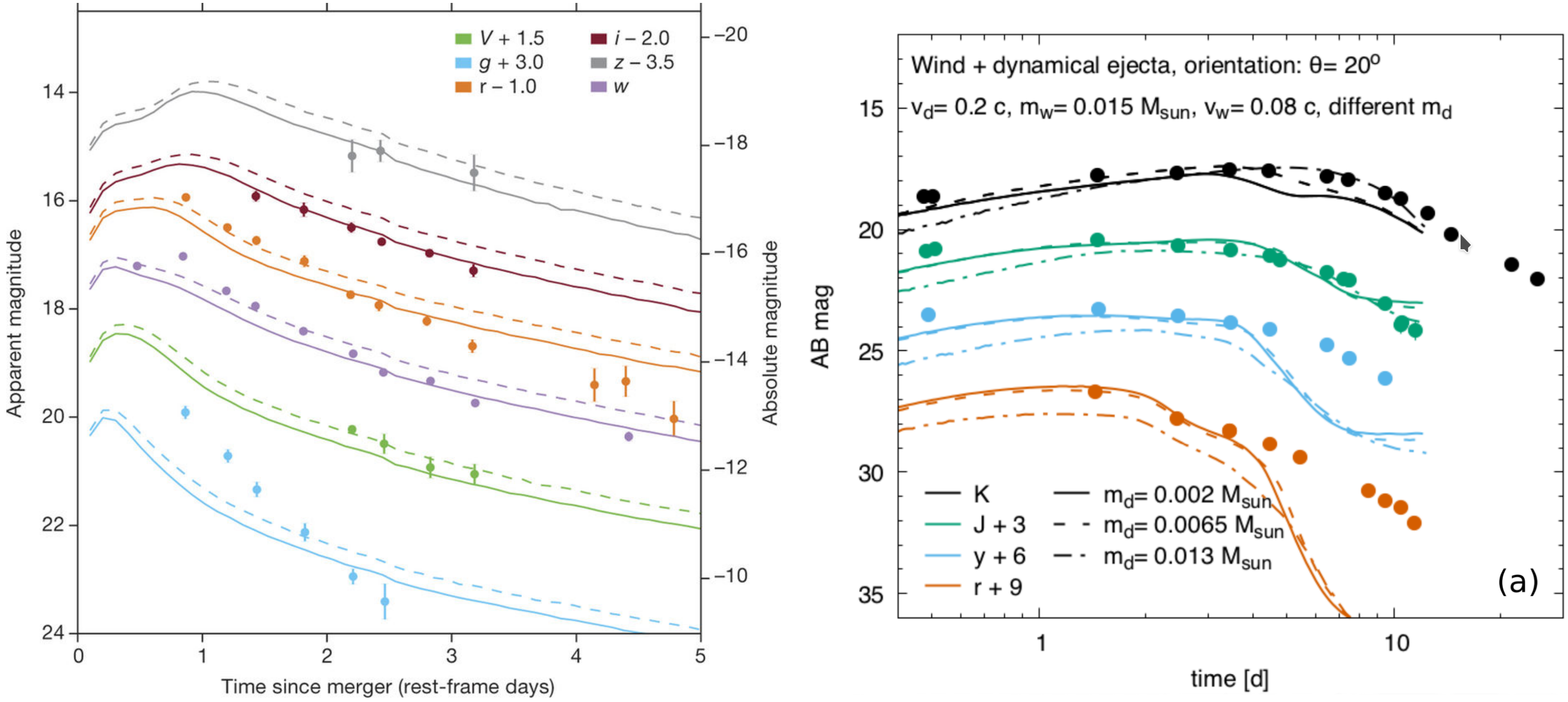
Lattimer & Schramm (1974) • Korobkin *et al.* (2012) • Figure by O. Korobkin

HOW CAN WE OBSERVE THE r-PROCESS?

Gravitational waves are emitted by explosive events (can be detected by LIGO)

Electromagnetic signals may be detected from the radioactive decay of heavy nuclei

The problem with EM signals is that we can only detect them if the event is close



(left) Low lanthanide fraction (right) high lanthanide fraction → major degeneracies in the model space

Arcavi *et al.* Nature 551 64 (2017) • Tanvir *et al.* ApJL 848 2 (2017)

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...

Especially if we want to find the fingerprints of heavy element formation!

NUCLEAR PHYSICS EFFORTS @ LANL HAVE BEEN FOCUSED ON

Creating tools for the community to use to understand the r-process

Here's a few that will be featured today...

NEXUS

(A computational toolkit for synthesizing nuclear data & modeling relevant nuclear physics properties)

URSA: Unified Reaction Structures for Astrophysics

(A novel way to incorporate the latest nuclear data in astrophysical simulations)

PRISM: Portable Routines for Integrated nucleoSynthesis Modeling

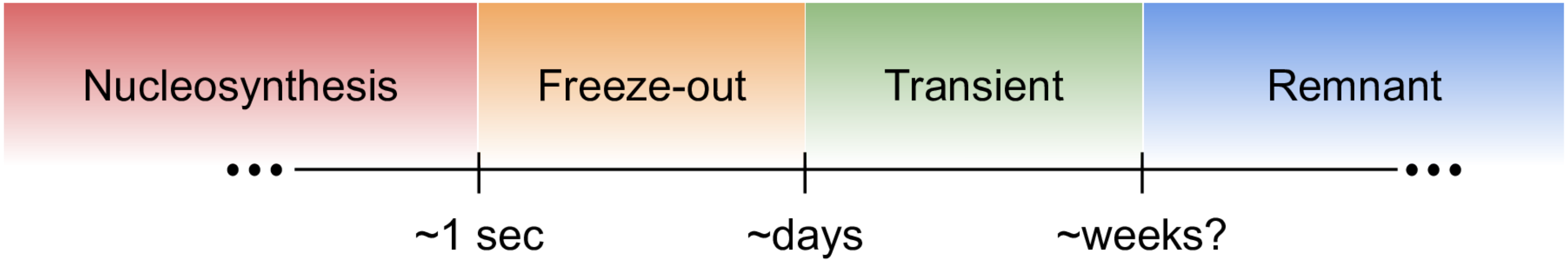
(A state-of-the-art nuclear reaction network)

JADE

(A state-of-the-art decay network for modeling late-time behavior)

Open source releases are available / forth coming!

RADIONUCLIDES IN THE r-PROCESS



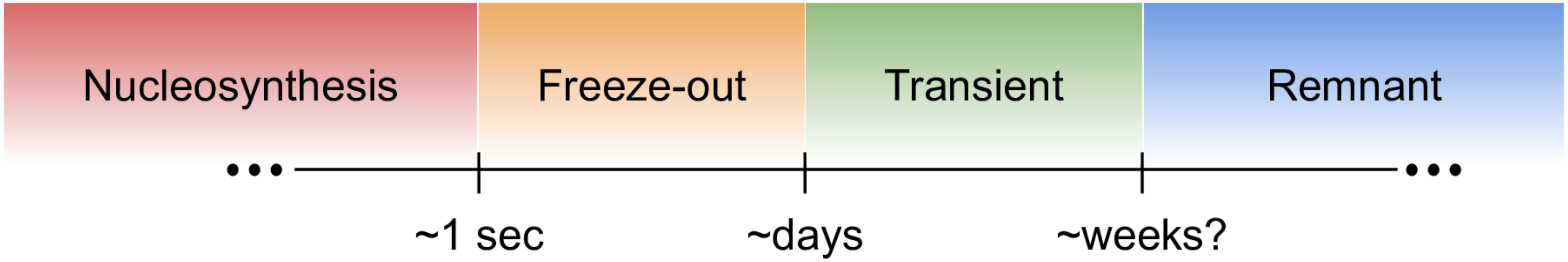
While the nucleosynthesis of the r-process is short-lived (~1 second)

The creation of radionuclides spans half-lives from microseconds to near-stable

Different epocs have unique and interesting radioactive nuclei present along with associated signatures

Figure by **Mumpower**

NUCLEOSYNTHESIS EPOCH ($\tau \sim 1$ SECOND)



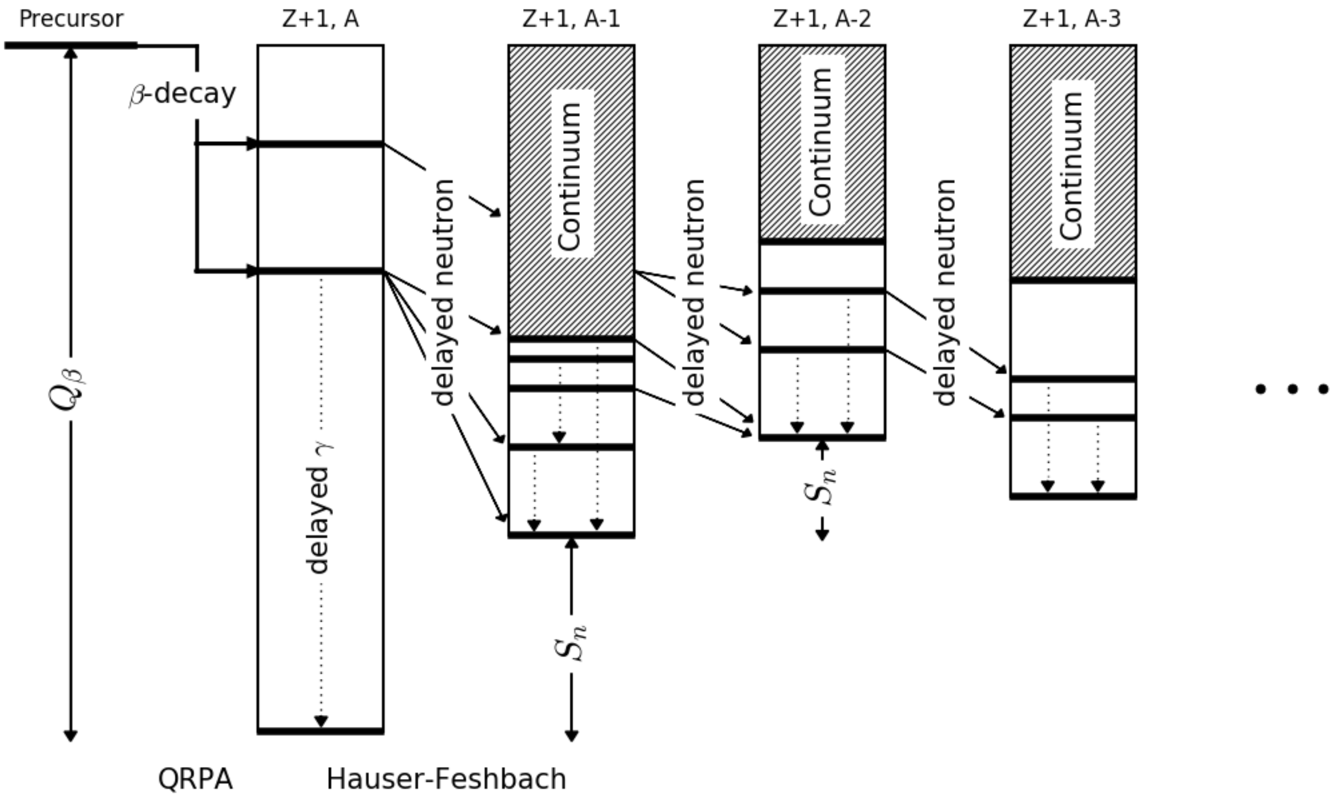
The most uncertain part of the r-process

How high up in mass number (A) can this process achieve?

We need reliable nuclear theory calculations to address such open questions... (NEXUS / URSA / PRISM)

Figure by **Mumpower**

NOVEL DESCRIPTION OF β-DECAY: QRPA + HF

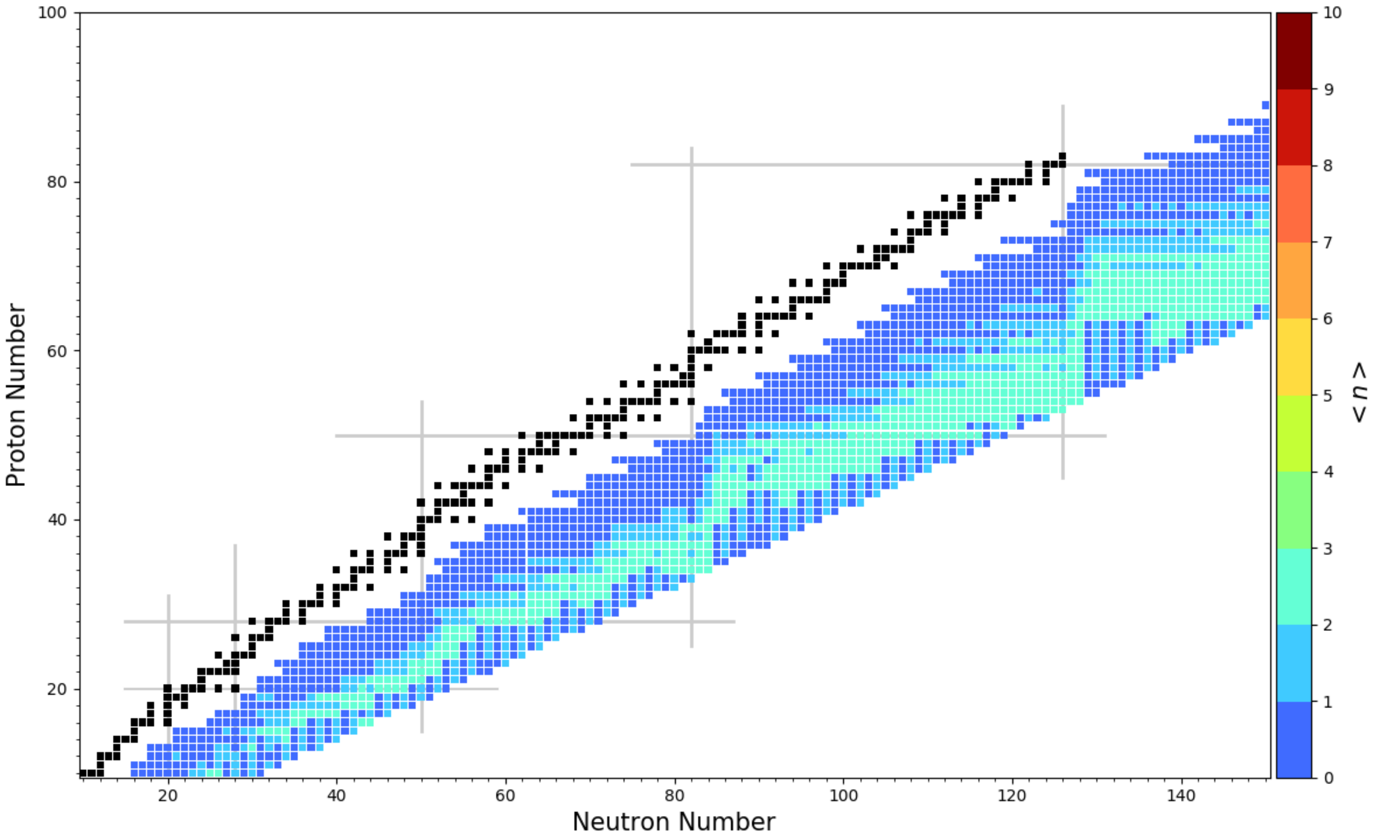


Initial population from the β-decay strength function from QRPA

Follow the statistical decay via Hauser-Feshbach until all excitation energy is exhausted

Mumpower *et al.* PRC 94 064317 (2016) • Spyrou ***et al.*** PRL 117 142701 (2016)
Wu *et al.* PRL 118, 072701 (2017) • **Mumpower** *et al.* ApJ 869 1 (2018) • Möller ***et al.*** ADNDT 125 (2019)

AVERAGE NEUTRON EMISSION

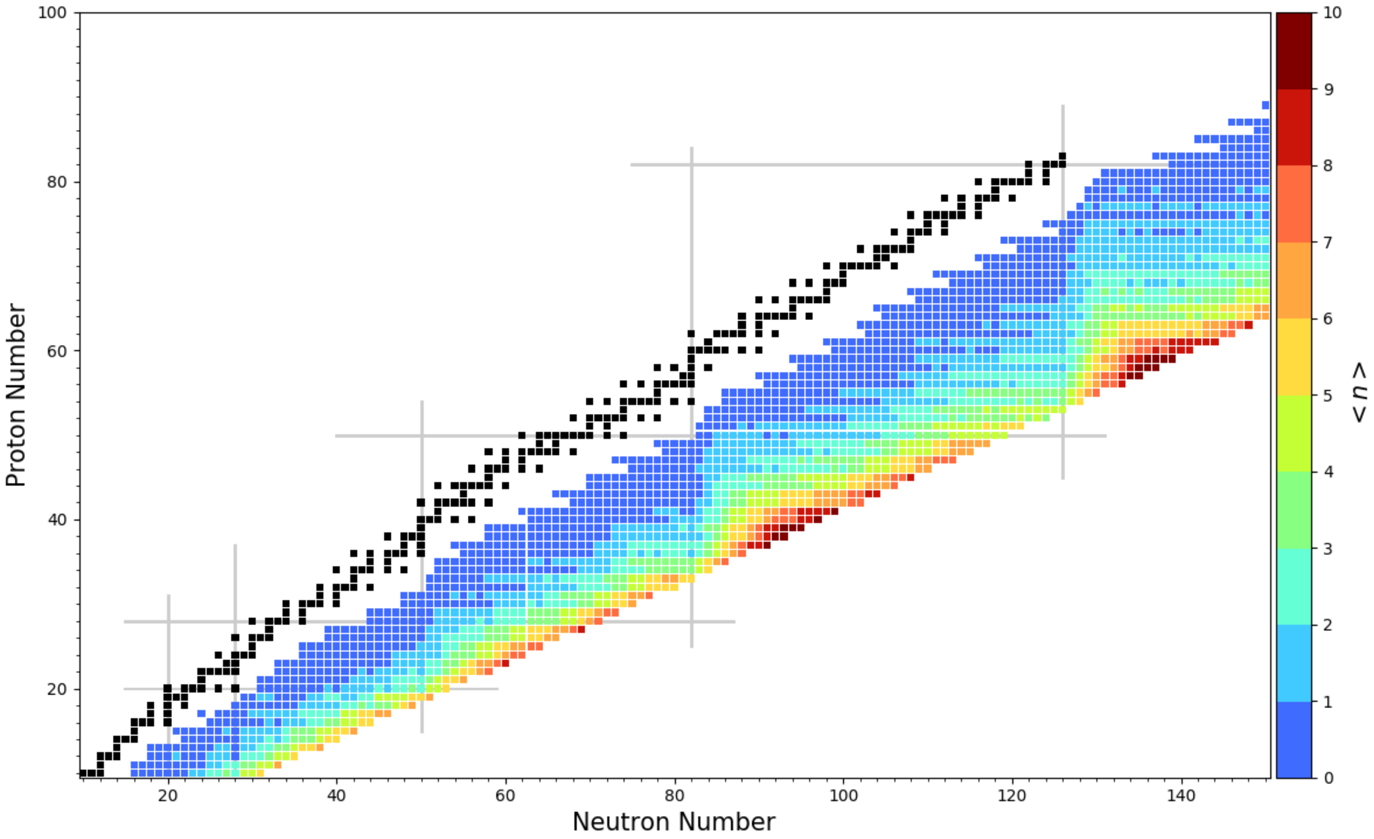


Apply energy window method to the entire chart of nuclides

Problem with describing very neutron-rich nuclei

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

AVERAGE NEUTRON EMISSION

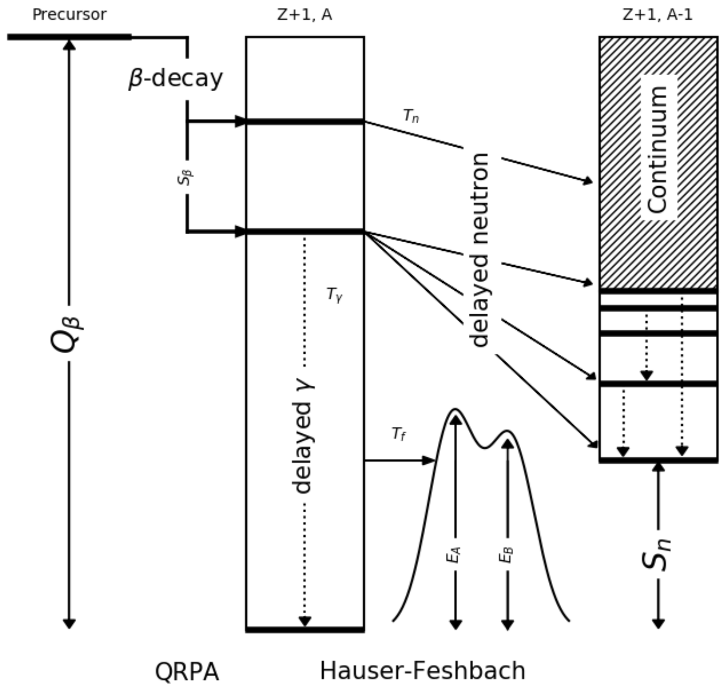


Apply the QRPA+HF method to the entire chart of nuclides

Problem with neutron-rich nuclei goes away

Mumpower *et al.* PRC 94 064317 (2016) • Möller ***et al.*** ADNDT 125 (2019)

β -DELAYED FISSION



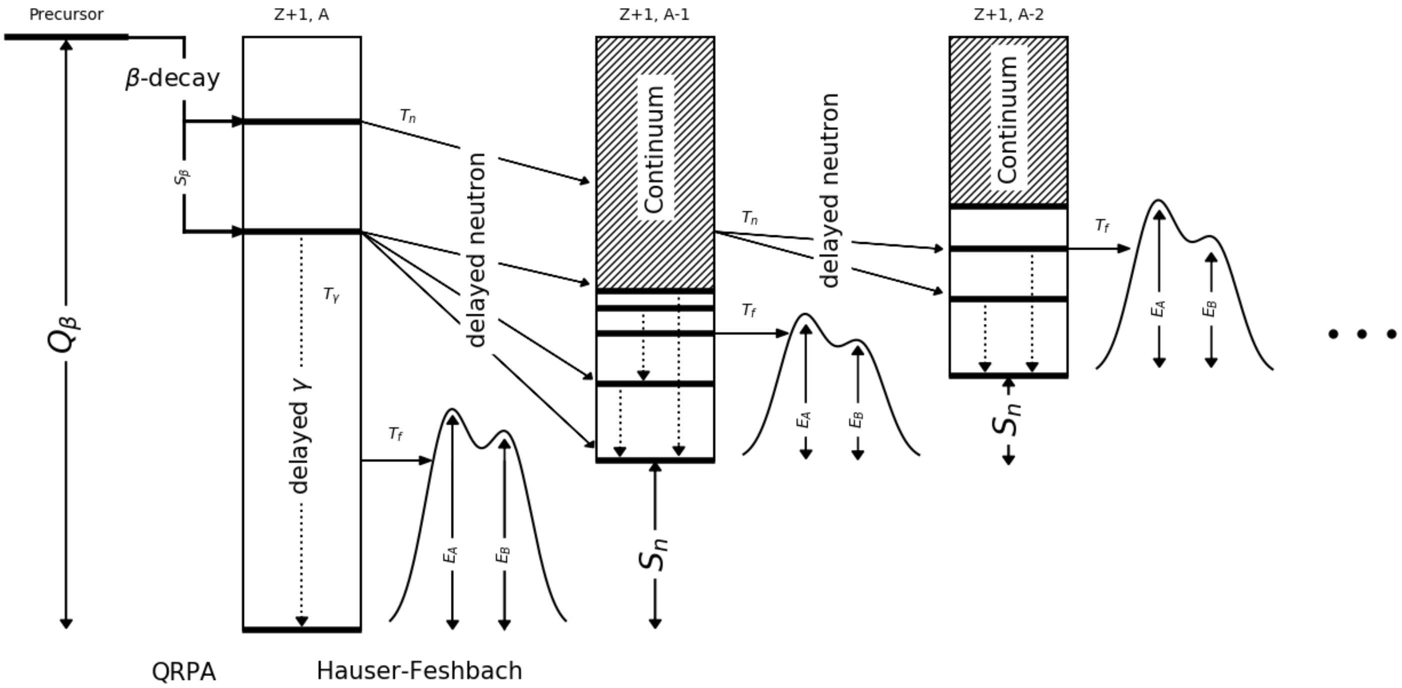
We have recently extended our QRPA+HF model to describe β-delayed fission (βdf)

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



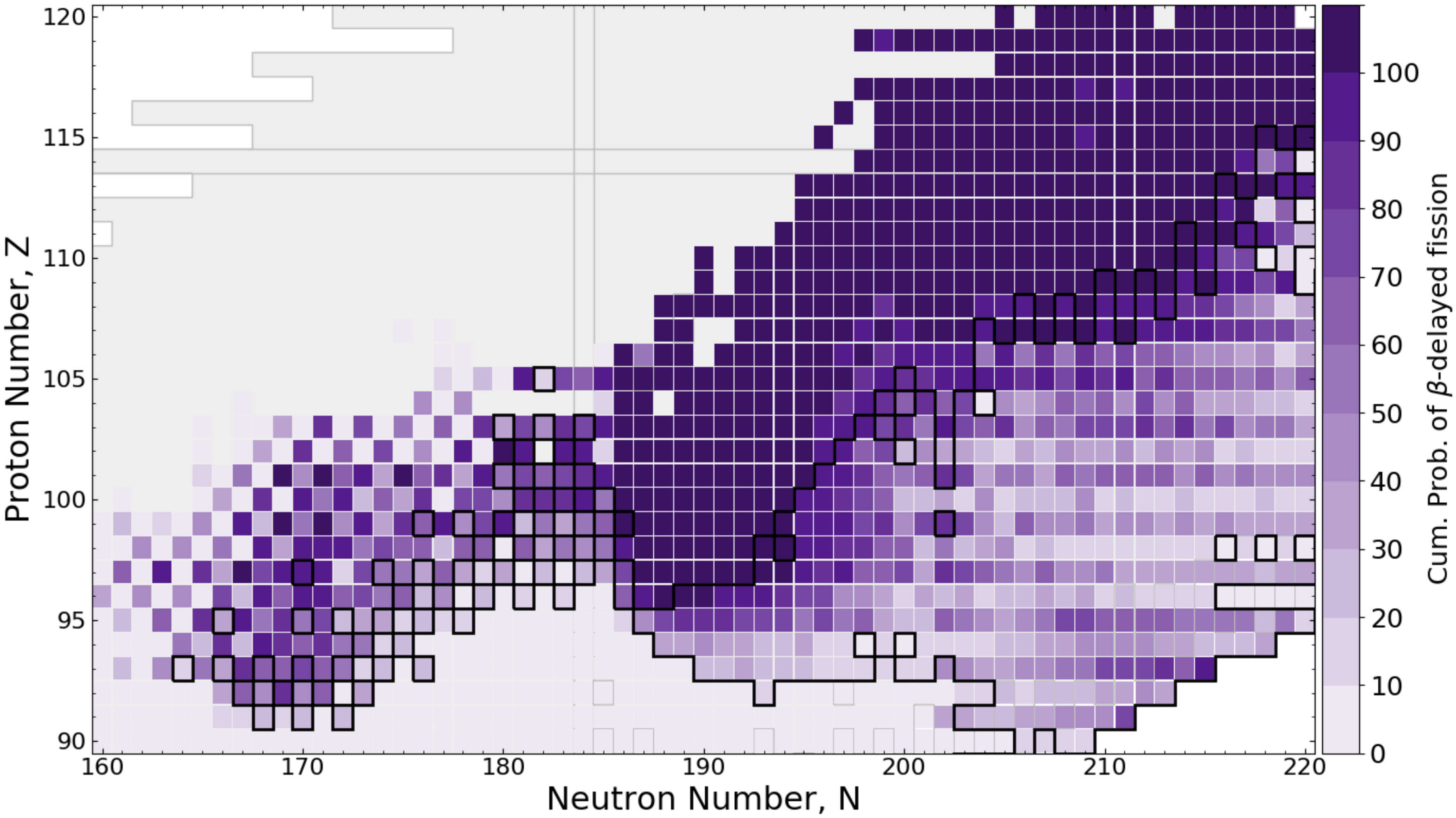
Recall: Near the dripline Q_{beta} ↑ S_n ↓

Multi-chance βdf: *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

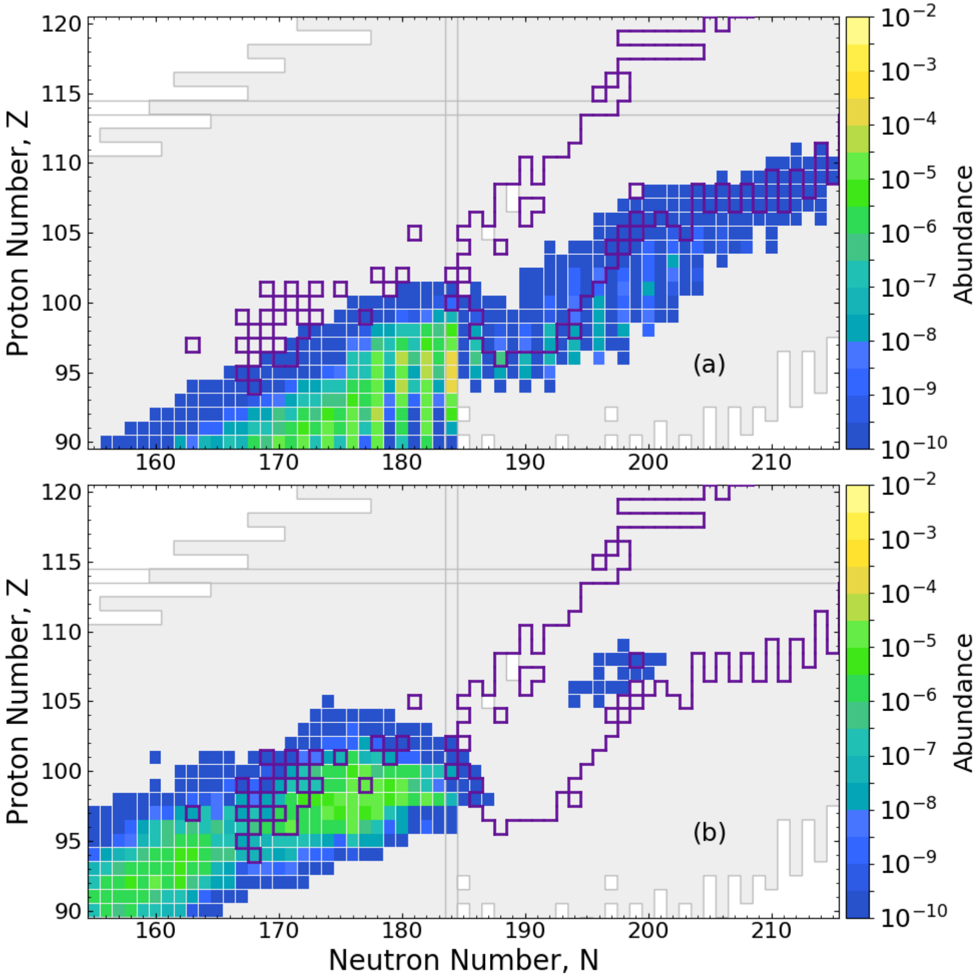


βdf occupies a large amount of real estate in the NZ-plane

Multi-chance βdf outlined in black

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

SUPERHEAVIES IN THE r-PROCESS

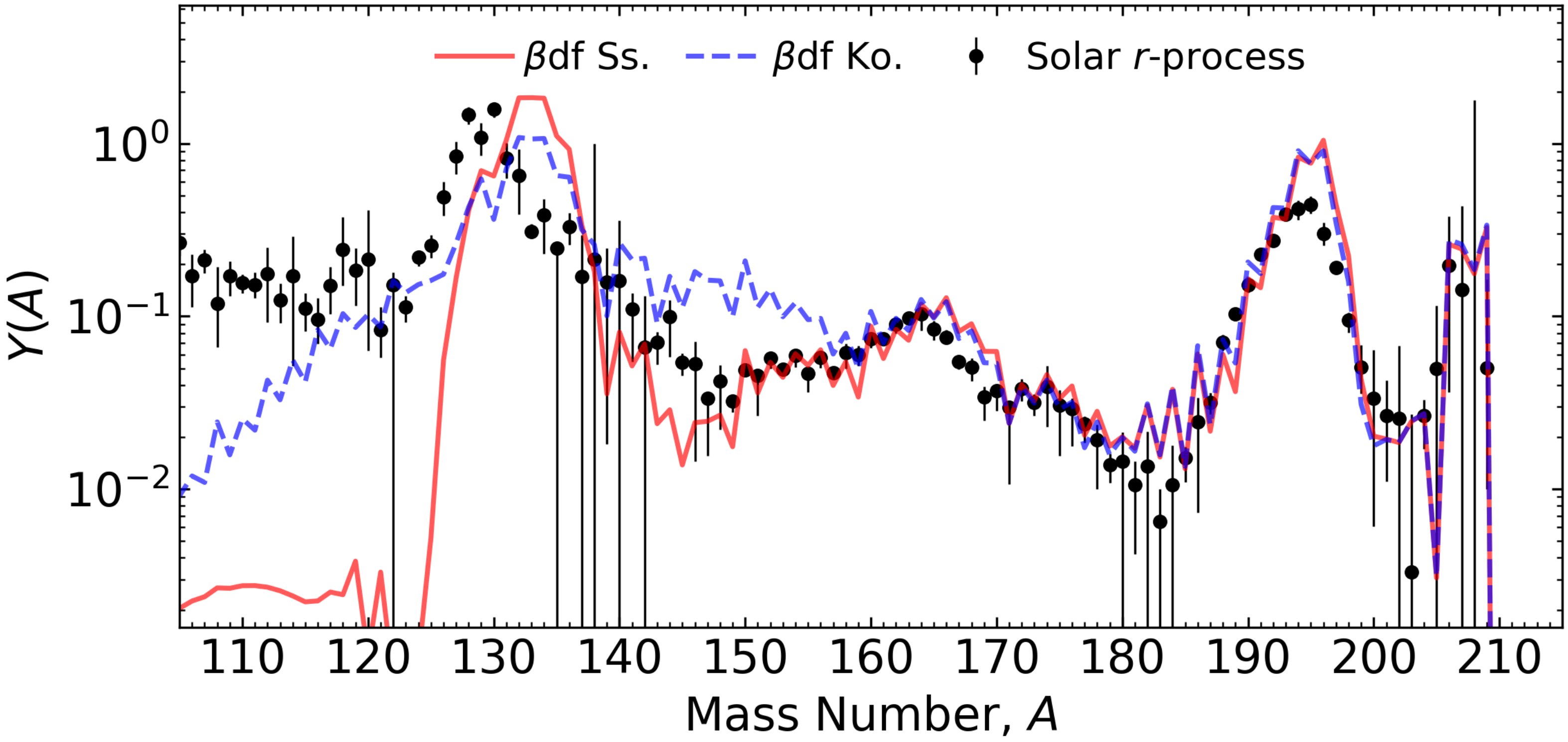


Network calculation of tidal neutron star merger ejecta

βdf alone may prevent the pathway from neutron-rich nuclei to the island of stability

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

FISSION CAN IMPACT FINAL ABUNDANCES



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

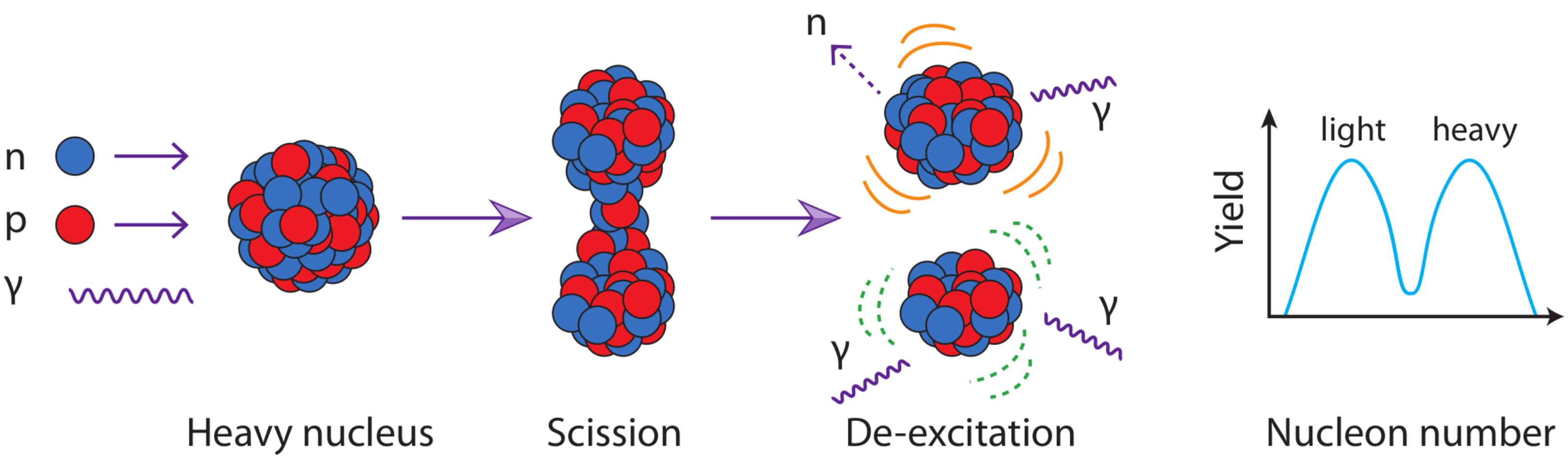
βdf can shape the final pattern near the $A = 130$ peak

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)

NUCLEAR FISSION



We're also interested in describing the mass and charge yields that arise from nuclear fission

Fission is a complex process in which a heavy nucleus splits into lighter fragments

Fission rates and branching determine re-cycling (robustness)

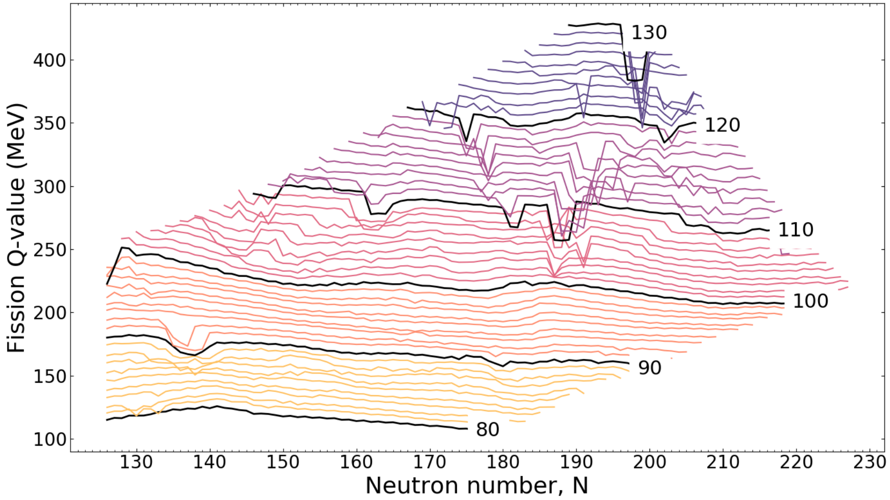
Fragment yields place material at lower mass number; barriers determine hot spots

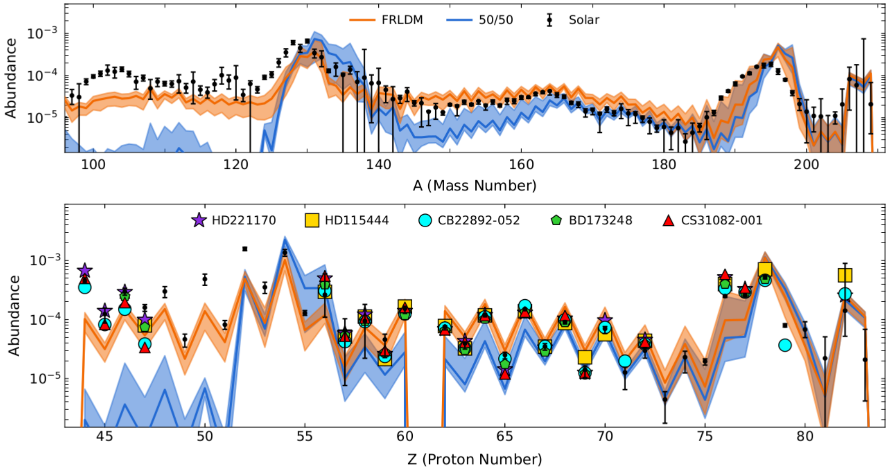
Large Q-value ⇒ impacts thermalization and therefore possibly observations

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

Eichler *et al.* APJ (2015) • Goriely *et al.* EPJA (2015) • Holmbeck ***et al.*** ApJ 870 1 (2019) • Vassh ***et al.*** J. Phys. G (2019) • Figure by **Mumpower**

FRLDM FISSION YIELDS





Left panel: A complete description of fission yields suggests energy release depends mostly on fissioning system charge number

This is important for predictions of early time heating in the r-process

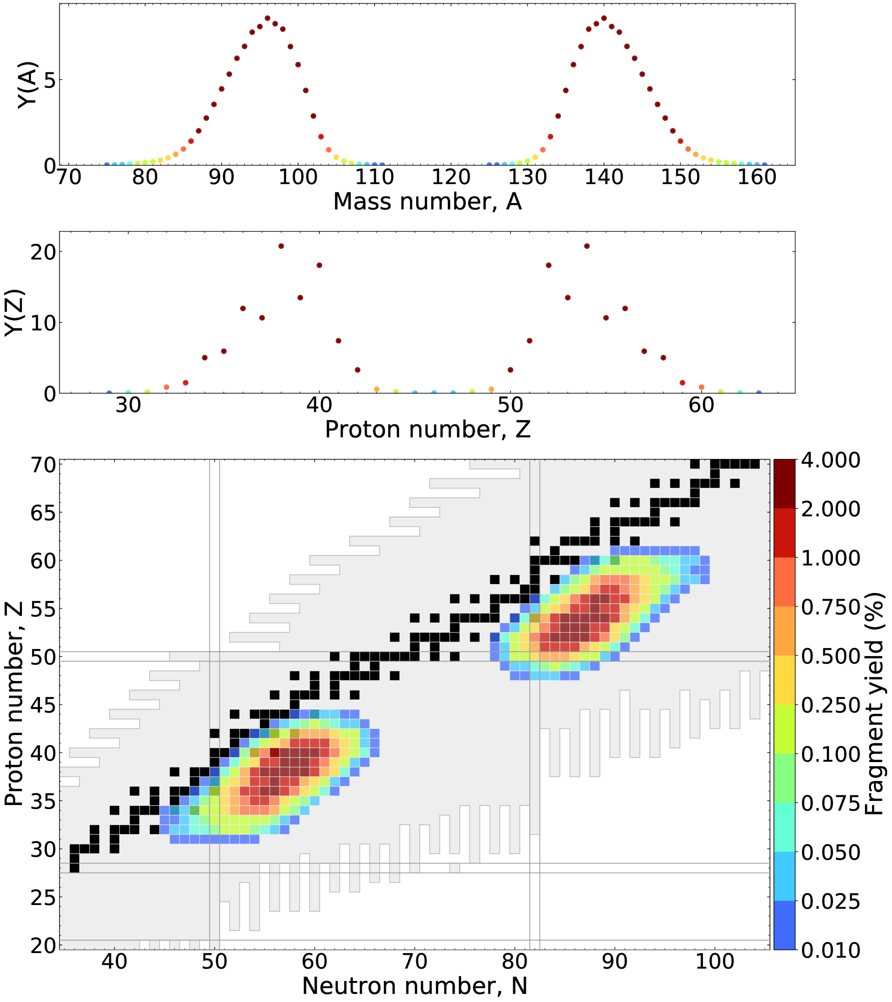
Right panel: Fission might be responsible for the extension of universality down to the precious metals

More complete observations with metal poor stars would be very helpful!

See Nicole's presentation on Thursday for more lanthanide & actinide signatures!

Mumpower et al. PRC 101 054607 (2020) • Vassh ***et al.*** ApJ 896 1 (2020)

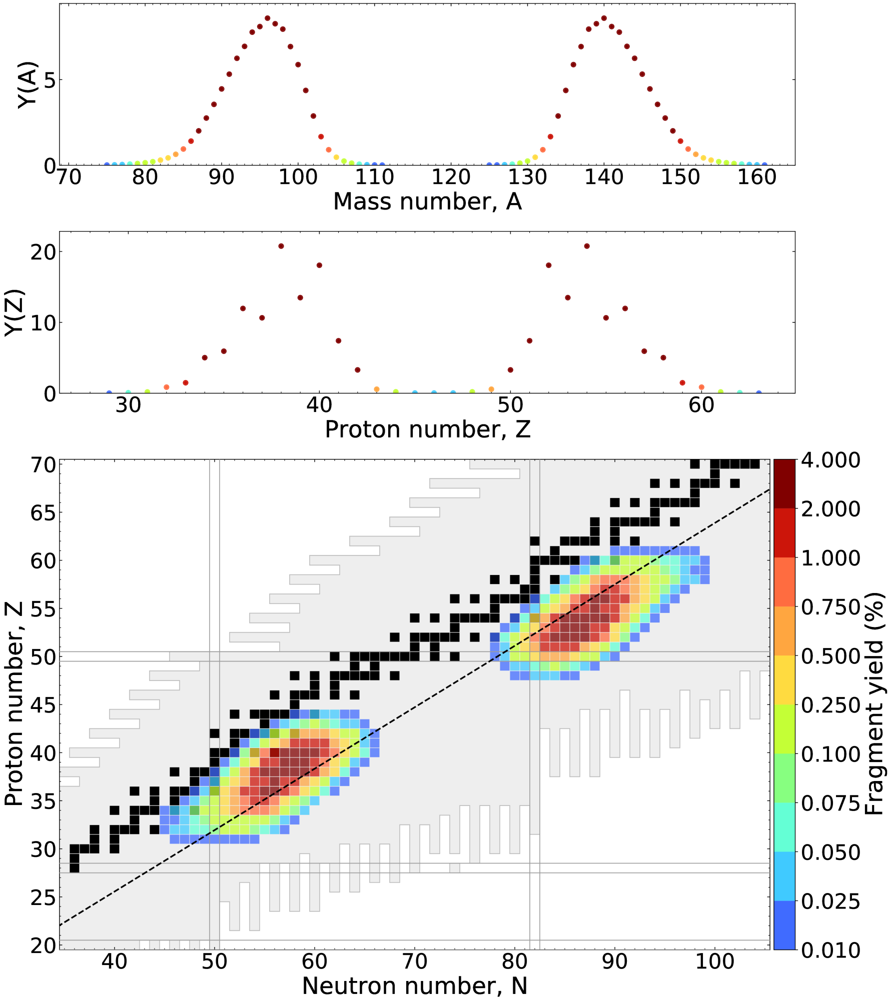
eFRLDM RESULTS: ^{235}U + n_{therm}



We recently improved our fission modeling and can now describe Y(A), Y(Z) and Y(Z,A) simultaneously

Verriere *et al.* PRC 100 024612 (2019) • Verriere & **Mumpower** PRC 103 034617 (2020)

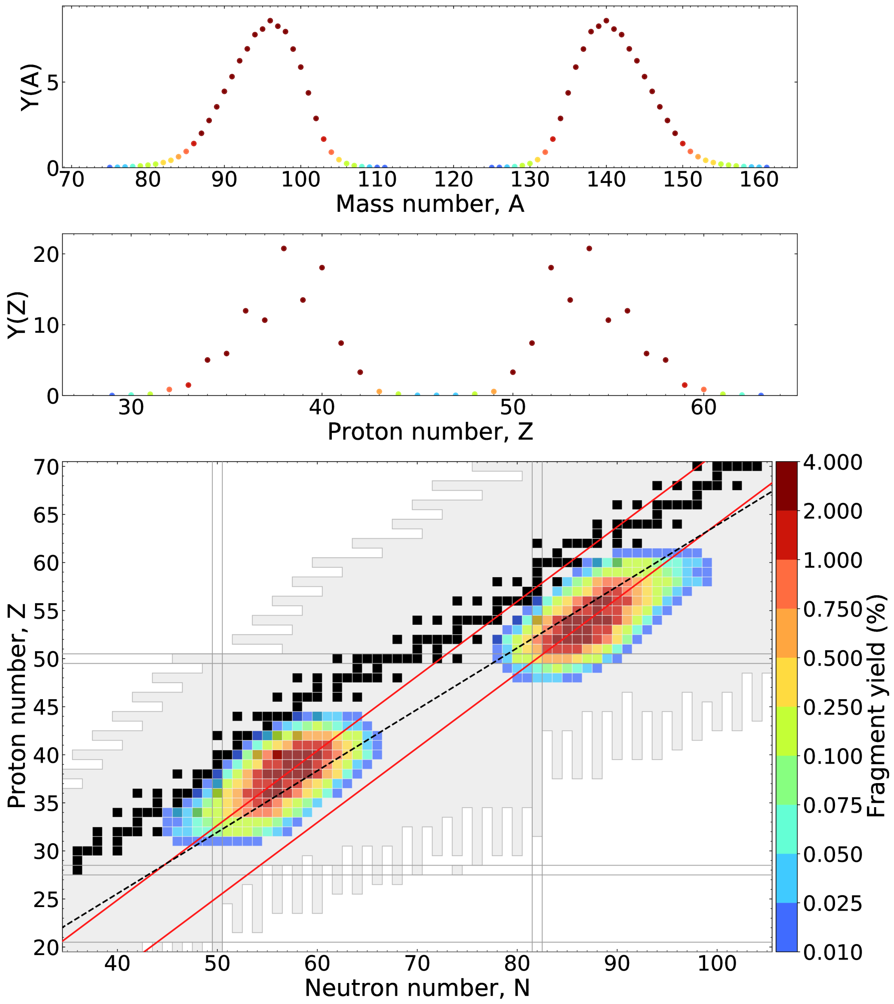
eFRLDM RESULTS: $^{235}\mathrm{U} + n_{\mathrm{therm}}$



Fragment yields no longer follow unchanged charge distribution (UCD) assumption (Blacked dashed line)

Verriere *et al.* PRC 100 024612 (2019) • Verriere & **Mumpower** PRC 103 034617 (2020)

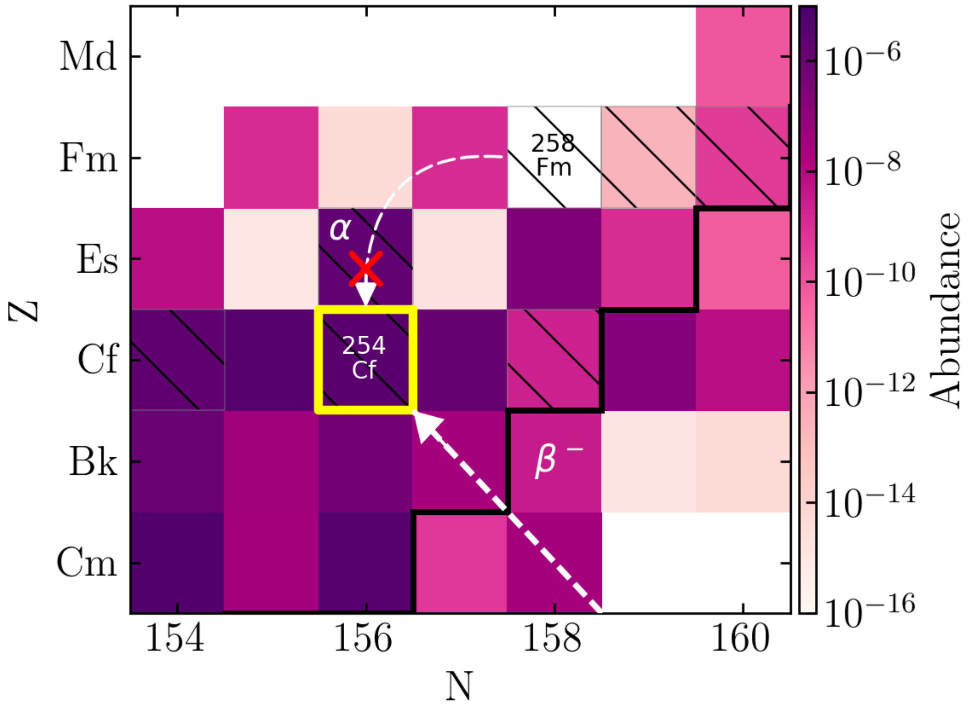
eFRLDM RESULTS: ^{235}U + n_{therm}



Charge polarization offset predicted and in agreement with experimental measurements (red lines)

Verriere *et al.* PRC 100 024612 (2019) • Verriere & **Mumpower** PRC 103 034617 (2020)

AN EXAMPLE CASE: ^{258}FM ($Z = 100$)



^{258}Fm is a nucleus with a half-life of several hundred microseconds (populated in the nucleosynthesis epoch)

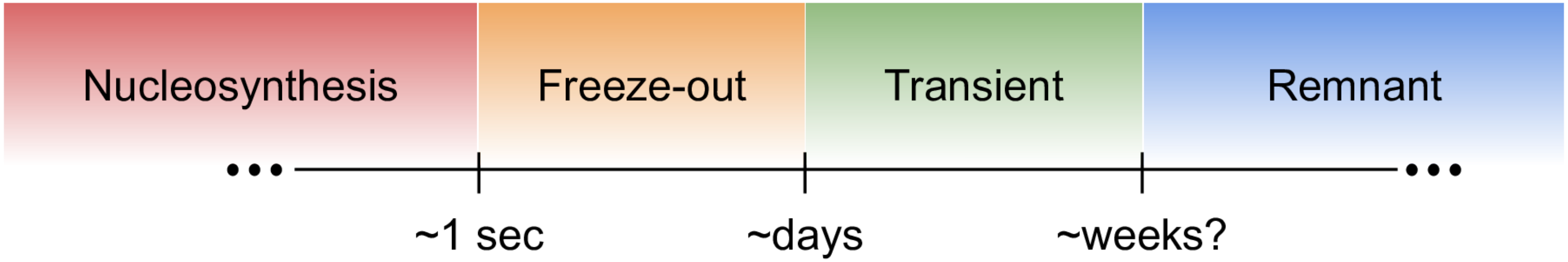
^{258}Fm has a small, but potentially non-trivial α-decay branching to ^{254}Cf; it primarily spontaneously fissions

To fully understand the potential implications of ^{254}Cf production we need to have better measurements of ^{258}Fm

We'll return to the importance of ^{254}Cf soon (trasient epoch)...

Zhu *et al.* ApJL 863 2 (2018)

FREEZE-OUT EPOCH ($\tau \sim$ SECONDS TO DAYS)



Nuclear transmutations are better constrainted; but we still lack information on excited states & particle spectra

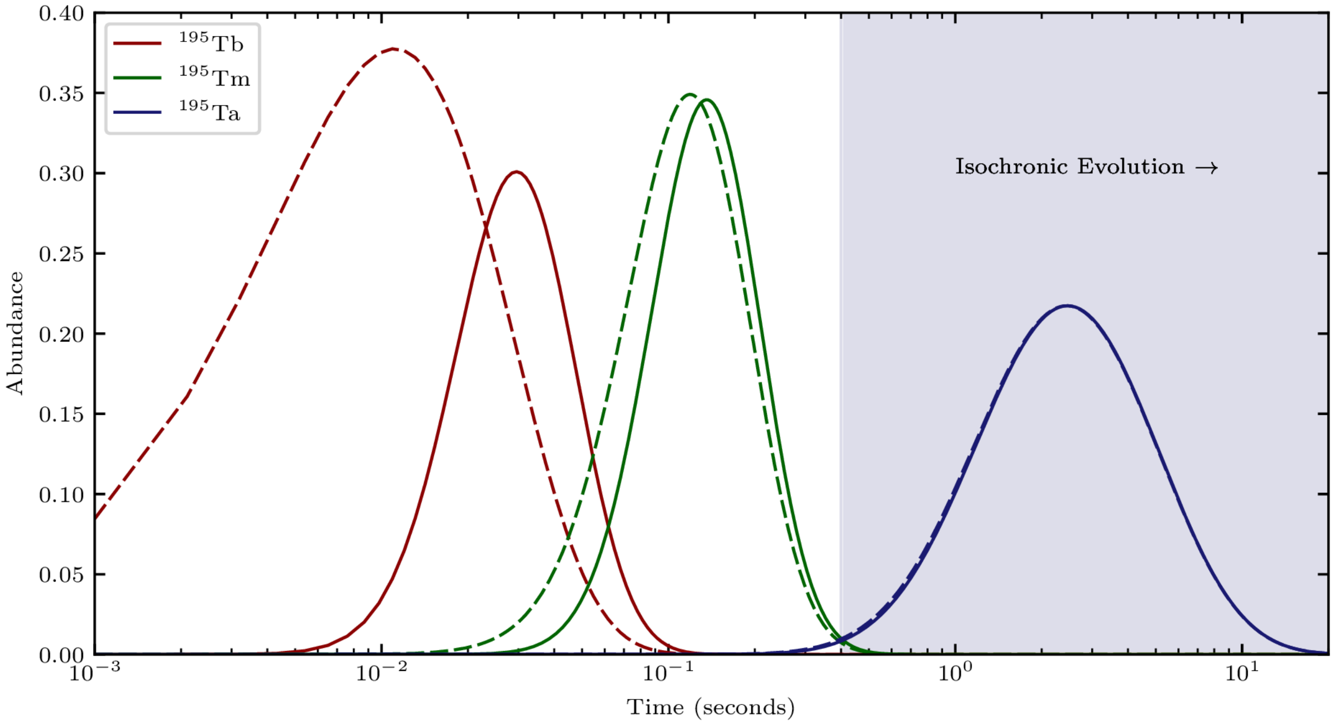
Longer lived isomers are potentially populated and interesting ('*astromers*')

Some nuclei are strong contributors to the radioactive heating

A decay network is ideal for describing the physics of this timescale... (PRISM / JADE)

Figure by **Mumpower**

ISOCHRONIC EVOLUTION



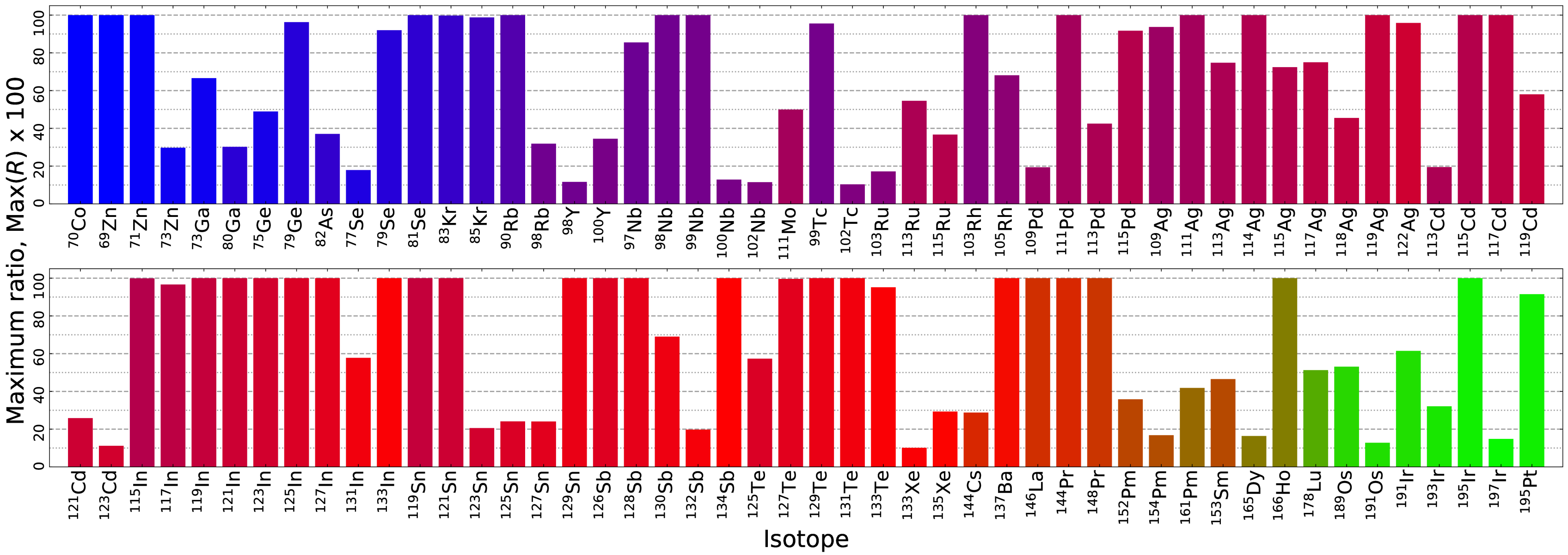
If you wait long enough the evolution of abundances is *isochronic*

This means: two different distributions (solid vs dashed) early on later converge to the same curve; memory of initial state is lost

The bulk of r-process ejecta will undergo such an evolution; fission complicates this picture...

Sprouse ***et al.*** submitted (2021)

ASTROPHYSICALLY METASTABLE NUCLEAR ISOMERS (ASTROMERS)



Isomers are dynamically populated in the r-process

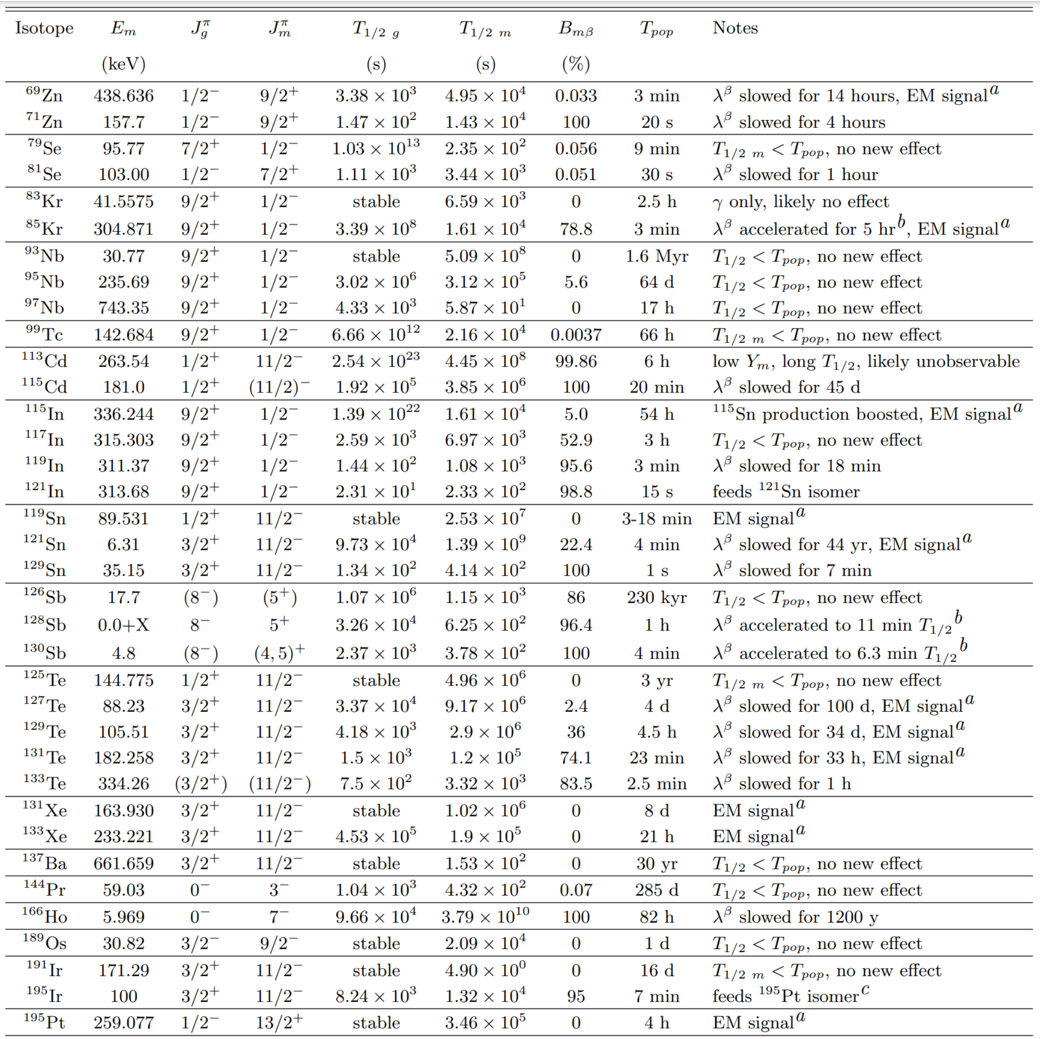
Their contributions to heating, light curves and observations can be quantified

Work pioneered by LANL postdocs: G. W. Misch (see Friday's presentation) & T. M. Sprouse

Nuclear databases are incomplete - there are certainly even more populated in the r-process!

Misch ***et al.*** ApJS 252 2 (2021) • Misch ***et al.*** ApJL 913 L2 (2021) • Misch ***et al.*** Symmetry 13 1831 (2021)

ASTROPHYSICALLY METASTABLE NUCLEAR ISOMERS (ASTROMERS)

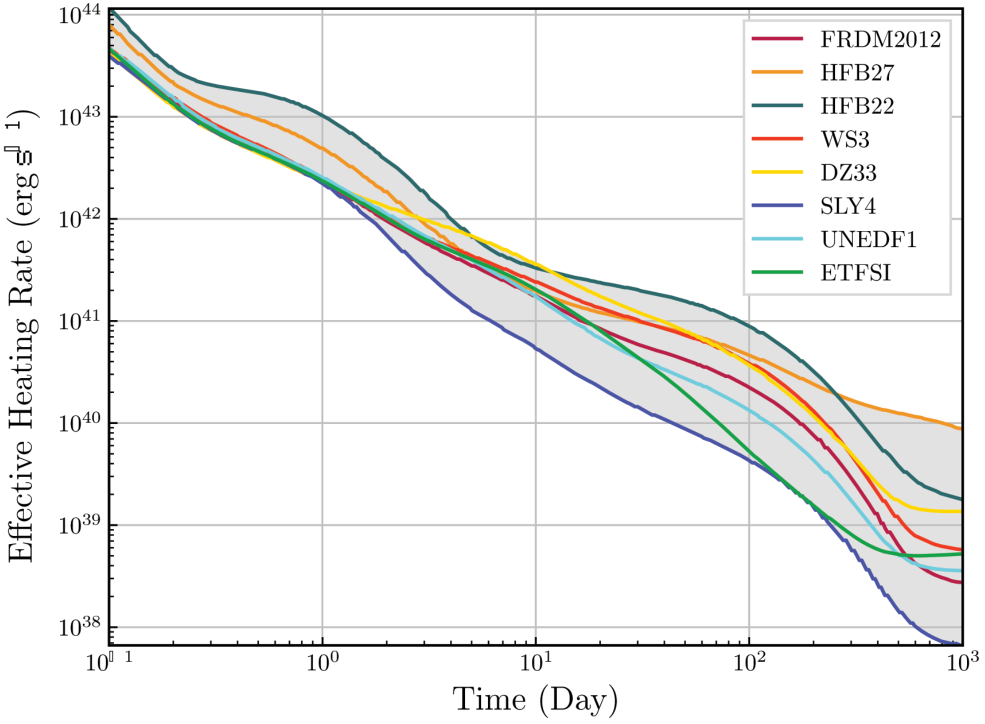


Isotope	E_m	J_g^π	J_m^π	$T_{1/2\ g}$	$T_{1/2\ m}$	$B_{m\beta}$	T_{pop}	Notes
	(keV)			(s)	(s)	(%)		
^{69}Zn	438.636	$1/2^-$	$9/2^+$	3.38×10^3	4.95×10^4	0.033	3 min	λ^β slowed for 14 hours, EM signal[a]
^{71}Zn	157.7	$1/2^-$	$9/2^+$	1.47×10^2	1.43×10^4	100	20 s	λ^β slowed for 4 hours
^{79}Se	95.77	$7/2^+$	$1/2^-$	1.03×10^{13}	2.35×10^2	0.056	9 min	$T_{1/2\ m} < T_{pop}$, no new effect
^{81}Se	103.00	$1/2^-$	$7/2^+$	1.11×10^3	3.44×10^3	0.051	30 s	λ^β slowed for 1 hour
^{83}Kr	41.5575	$9/2^+$	$1/2^-$	stable	6.59×10^3	0	2.5 h	γ only, likely no effect
^{85}Kr	304.871	$9/2^+$	$1/2^-$	3.39×10^8	1.61×10^4	78.8	3 min	λ^β accelerated for 5 hr[b], EM signal[a]
^{93}Nb	30.77	$9/2^+$	$1/2^-$	stable	5.09×10^8	0	1.6 Myr	$T_{1/2} < T_{pop}$, no new effect
^{95}Nb	235.69	$9/2^+$	$1/2^-$	3.02×10^6	3.12×10^5	5.6	64 d	$T_{1/2} < T_{pop}$, no new effect
^{97}Nb	743.35	$9/2^+$	$1/2^-$	4.33×10^3	5.87×10^1	0	17 h	$T_{1/2} < T_{pop}$, no new effect
^{99}Tc	142.684	$9/2^+$	$1/2^-$	6.66×10^{12}	2.16×10^4	0.0037	66 h	$T_{1/2\ m} < T_{pop}$, no new effect
^{113}Cd	263.54	$1/2^+$	$11/2^-$	2.54×10^{23}	4.45×10^8	99.86	6 h	low Y_m, long $T_{1/2}$, likely unobservable
^{115}Cd	181.0	$1/2^+$	$(11/2)^-$	1.92×10^5	3.85×10^6	100	20 min	λ^β slowed for 45 d
^{115}In	336.244	$9/2^+$	$1/2^-$	1.39×10^{22}	1.61×10^4	5.0	54 h	^{115}Sn production boosted, EM signal[a]
^{117}In	315.303	$9/2^+$	$1/2^-$	2.59×10^3	6.97×10^3	52.9	3 h	$T_{1/2} < T_{pop}$, no new effect
^{119}In	311.37	$9/2^+$	$1/2^-$	1.44×10^2	1.08×10^3	95.6	3 min	λ^β slowed for 18 min
^{121}In	313.68	$9/2^+$	$1/2^-$	2.31×10^1	2.33×10^2	98.8	15 s	feeds ^{121}Sn isomer
^{119}Sn	89.531	$1/2^+$	$11/2^-$	stable	2.53×10^7	0	3-18 min	EM signal[a]
^{121}Sn	6.31	$3/2^+$	$11/2^-$	9.73×10^4	1.39×10^9	22.4	4 min	λ^β slowed for 44 yr, EM signal[a]
^{129}Sn	35.15	$3/2^+$	$11/2^-$	1.34×10^2	4.14×10^2	100	1 s	λ^β slowed for 7 min
^{126}Sb	17.7	(8^-)	(5^+)	1.07×10^6	1.15×10^3	86	230 kyr	$T_{1/2} < T_{pop}$, no new effect
^{128}Sb	0.0+X	8^-	5^+	3.26×10^4	6.25×10^2	96.4	1 h	λ^β accelerated to 11 min $T_{1/2}$[b]
^{130}Sb	4.8	(8^-)	$(4,5)^+$	2.37×10^3	3.78×10^2	100	4 min	λ^β accelerated to 6.3 min $T_{1/2}$[b]
^{125}Te	144.775	$1/2^+$	$11/2^-$	stable	4.96×10^6	0	3 yr	$T_{1/2\ m} < T_{pop}$, no new effect
^{127}Te	88.23	$3/2^+$	$11/2^-$	3.37×10^4	9.17×10^6	2.4	4 d	λ^β slowed for 100 d, EM signal[a]
^{129}Te	105.51	$3/2^+$	$11/2^-$	4.18×10^3	2.9×10^6	36	4.5 h	λ^β slowed for 34 d, EM signal[a]
^{131}Te	182.258	$3/2^+$	$11/2^-$	1.5×10^3	1.2×10^5	74.1	23 min	λ^β slowed for 33 h, EM signal[a]
^{133}Te	334.26	$(3/2^+)$	$(11/2^-)$	7.5×10^2	3.32×10^3	83.5	2.5 min	λ^β slowed for 1 h
^{131}Xe	163.930	$3/2^+$	$11/2^-$	stable	1.02×10^6	0	8 d	EM signal[a]
^{133}Xe	233.221	$3/2^+$	$11/2^-$	4.53×10^5	1.9×10^5	0	21 h	EM signal[a]
^{137}Ba	661.659	$3/2^+$	$11/2^-$	stable	1.53×10^2	0	30 yr	$T_{1/2} < T_{pop}$, no new effect
^{144}Pr	59.03	0^-	3^-	1.04×10^3	4.32×10^2	0.07	285 d	$T_{1/2} < T_{pop}$, no new effect
^{166}Ho	5.969	0^-	7^-	9.66×10^4	3.79×10^{10}	100	82 h	λ^β slowed for 1200 y
^{189}Os	30.82	$3/2^-$	$9/2^-$	stable	2.09×10^4	0	1 d	$T_{1/2} < T_{pop}$, no new effect
^{191}Ir	171.29	$3/2^+$	$11/2^-$	stable	4.90×10^0	0	16 d	$T_{1/2\ m} < T_{pop}$, no new effect
^{195}Ir	100	$3/2^+$	$11/2^-$	8.24×10^3	1.32×10^4	95	7 min	feeds ^{195}Pt isomer[c]
^{195}Pt	259.077	$1/2^-$	$13/2^+$	stable	3.46×10^5	0	4 h	EM signal[a]

A wide variety of nuclei are found with unique signatures

Misch ***et al.*** ApJS 252 2 (2021) • Misch ***et al.*** ApJL 913 L2 (2021) • Misch ***et al.*** Symmetry 13 1831 (2021)

RADIOACTIVE HEATING

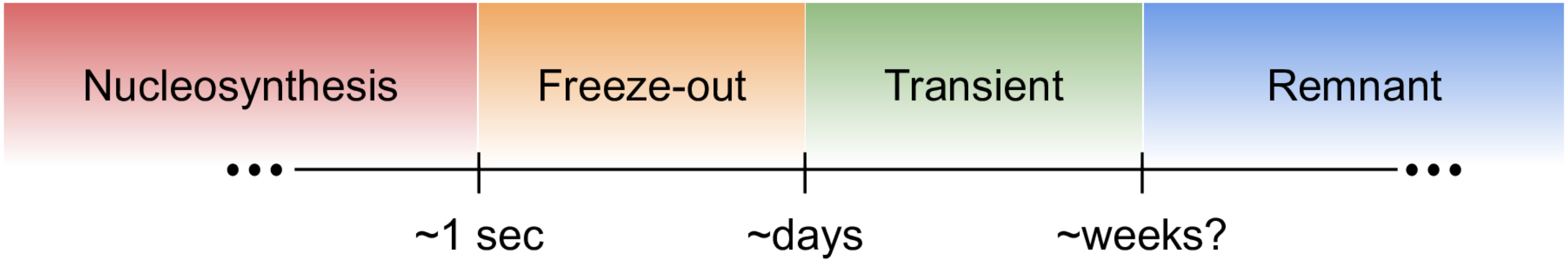


Variation in radioactive heating from uncertainties in nuclear binding

Interesting nuclei can control energy release on characteristic timescales... e.g. I, La, Rf isotopes
(see Kelsey's presentation)

Zhu *et al.* ApJ 906 94 (2021) • Barnes *et al.* ApJ 918 44 (2021) • Lund *et al.* in prep. (2021)

TRANSIENT EPOCH ($\tau \sim$ DAYS TO WEEKS?)



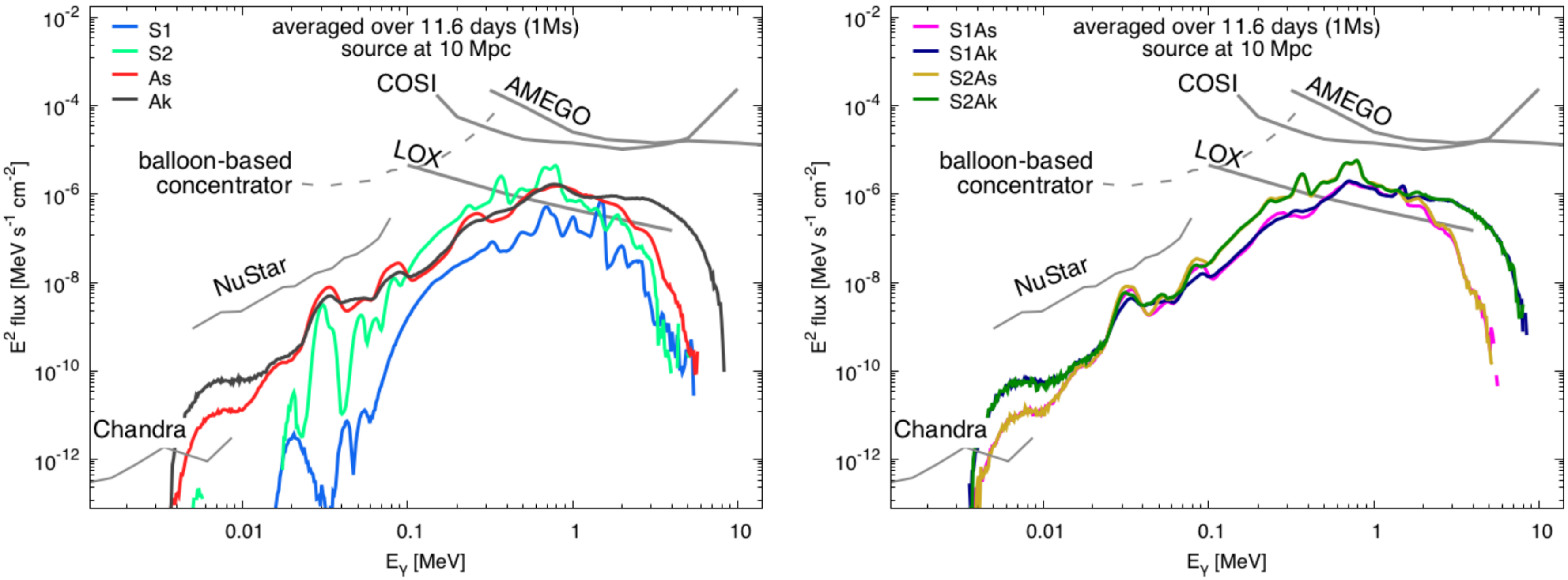
Observationally interesting time period for a nascient r-process event

We must blend astrophysical simulations, nuclear physics and atomic physics to describe observables

Nebular phase requires non-LTE physics (hard!)

Figure by **Mumpower**

γ-RAYS FROM MERGERS

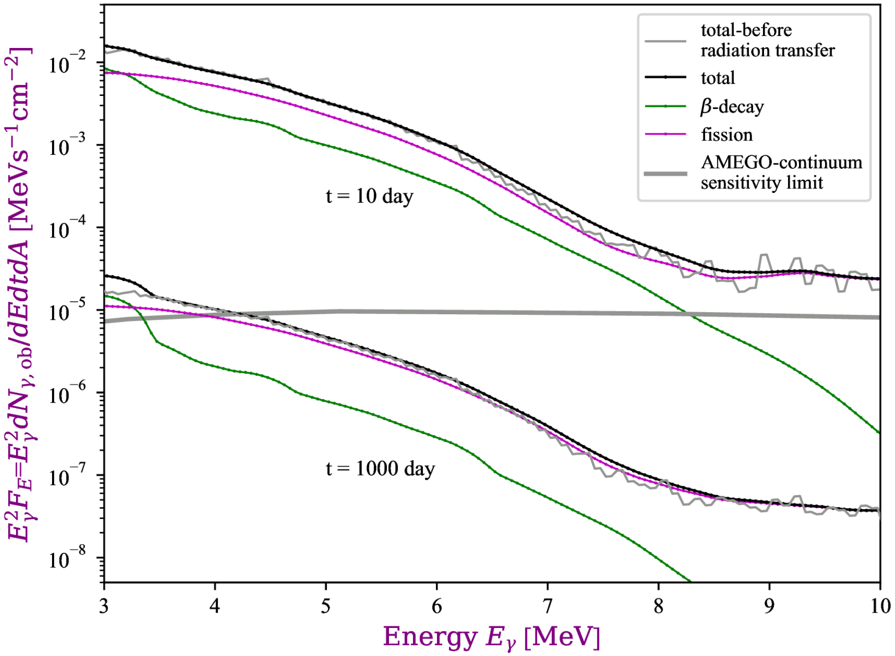


If the r-process source is very close we might disentangle different compositions (colored lines)

Signatures of major emitters can come through (many second peak elements: e.g. isotopes of I, Sb, Sn)

Korobkin ***et al.*** ApJ 889 2 (2020)

FISSION γ-RAYS FROM MERGERS



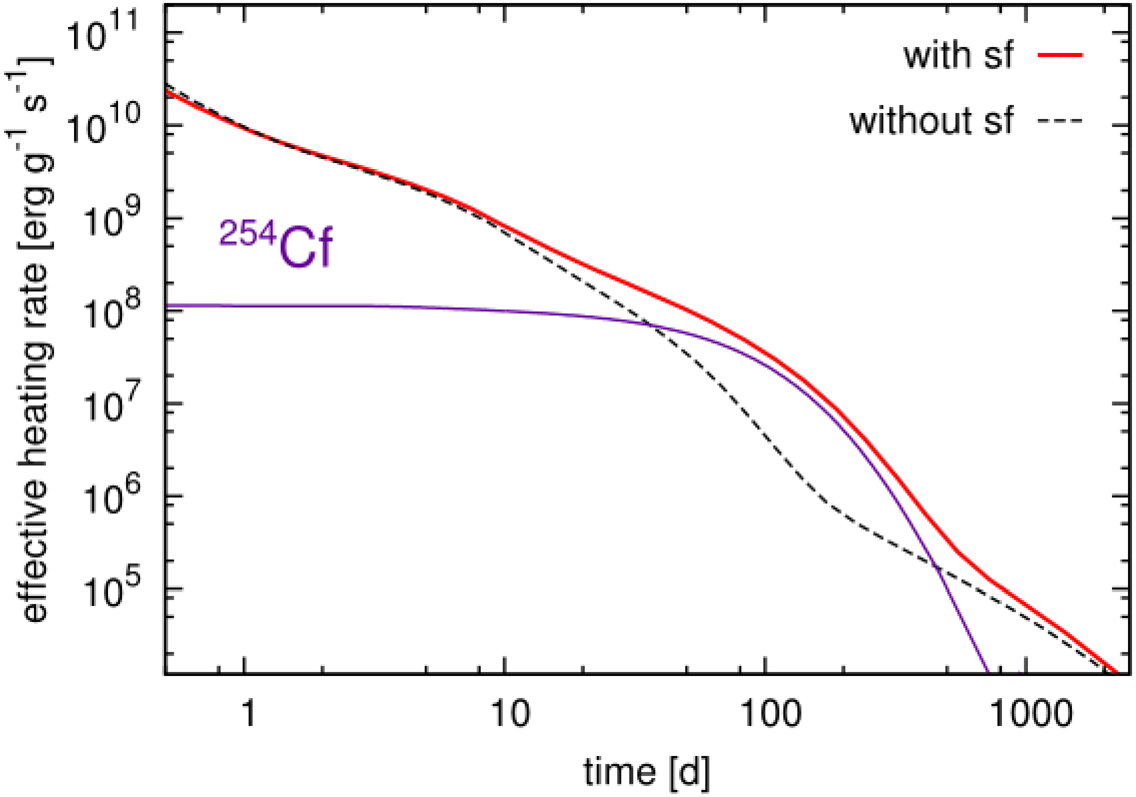
γ-rays from fission have a distinct (higher energy) spectra

Spectra is smooth; cannot detect presence of individual radionuclides

It is however indicative of fission occuring (no other process can create such high energy γ's)

Wang ***et al.*** ApJL 903 1 (2020)

RETURNING TO ^{254}CF



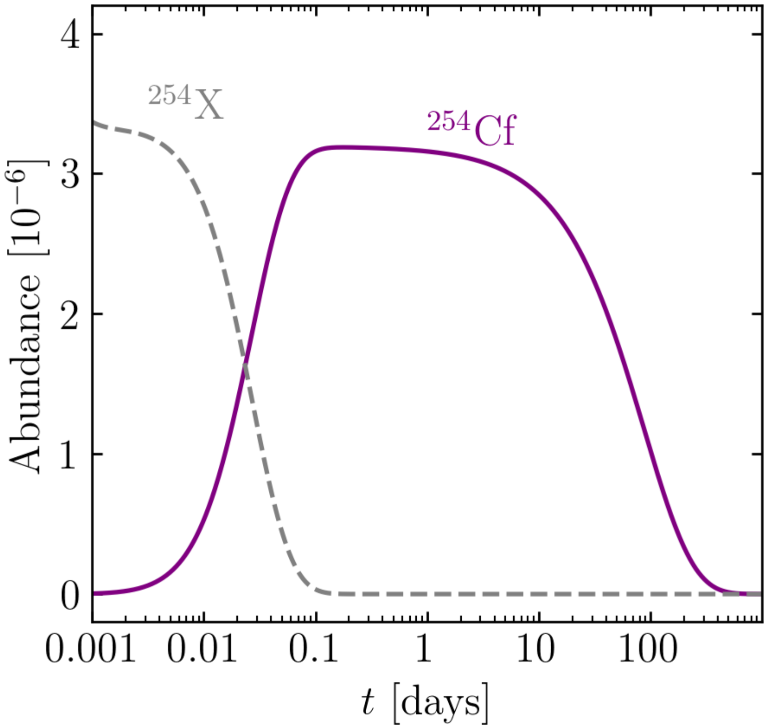
Can we prove that all of heavy elements nucleosynthesis has occurred in an event?... Maybe!

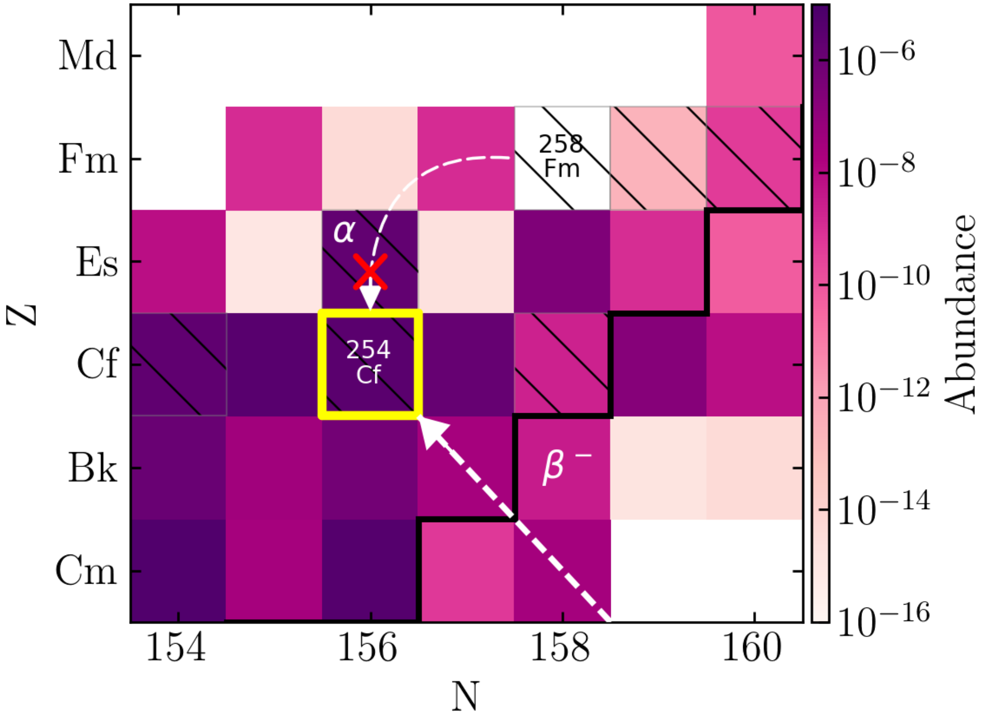
The spontaneous fission of ^{254}Cf can be a *primary* contributor to nuclear heating at late-time epochs

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)





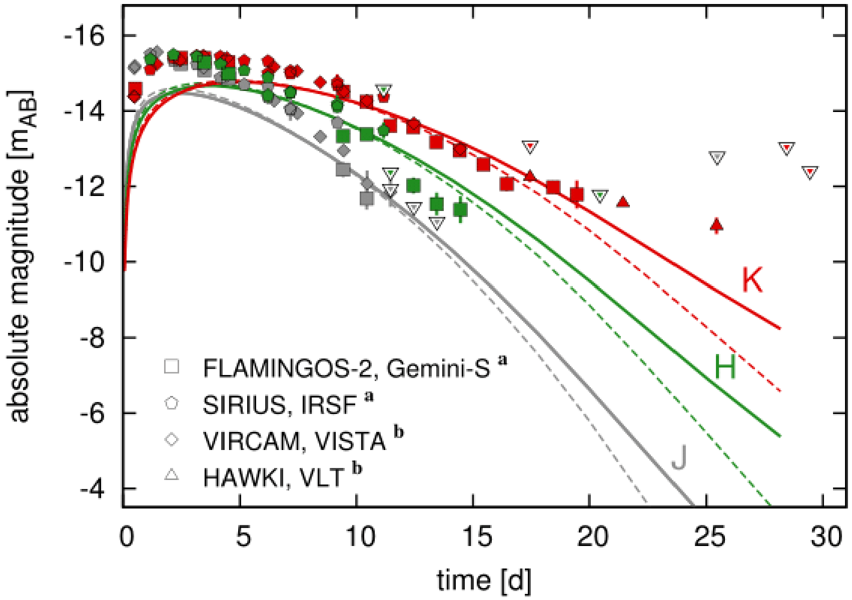
Primary feeder seems to be from β-decay

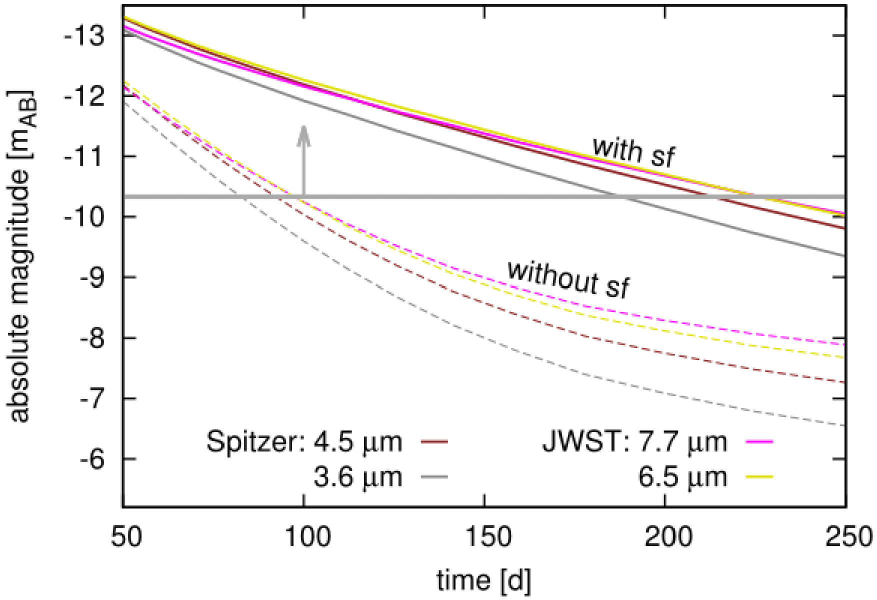
Production of this nucleus been explored over a range of nuclear models; some high - some low

Remains to be seen if we can disentangle from other energy 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)

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 heavy element nucleosynthesis

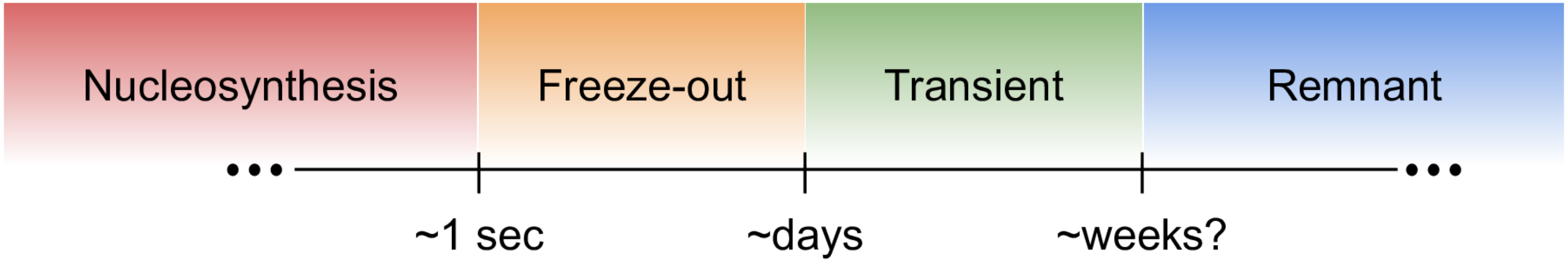
Future JWST mission could detect r-process event out to 250 days with the presence of ^{254}Cf

This also has implications for compact object merger morphology...

Other nuclei remain interesting (e.g. ^{260}Md with $T_{1/2} \sim 30$ days)

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

REMNANT EPOCH ($\tau \sim$ WEEKS? AND LONGER)

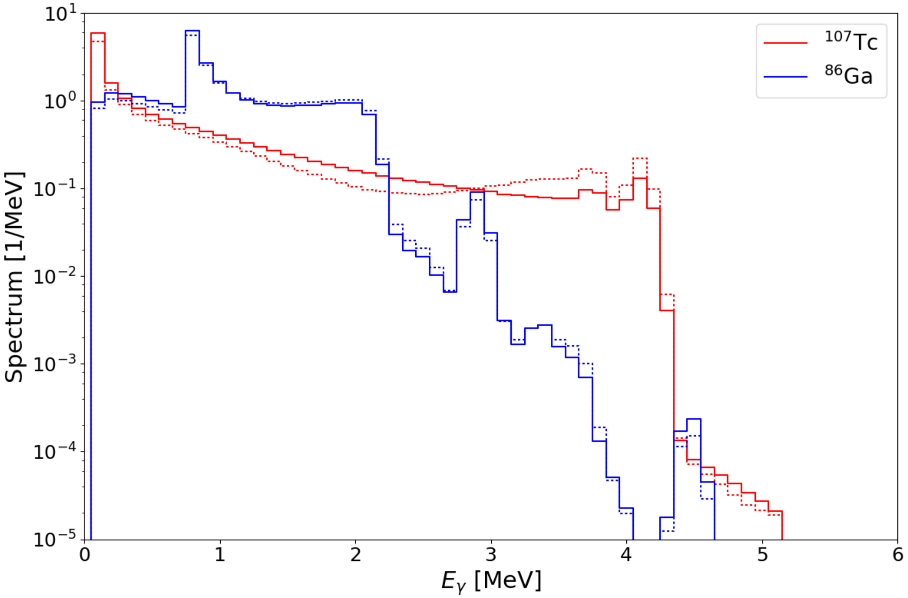


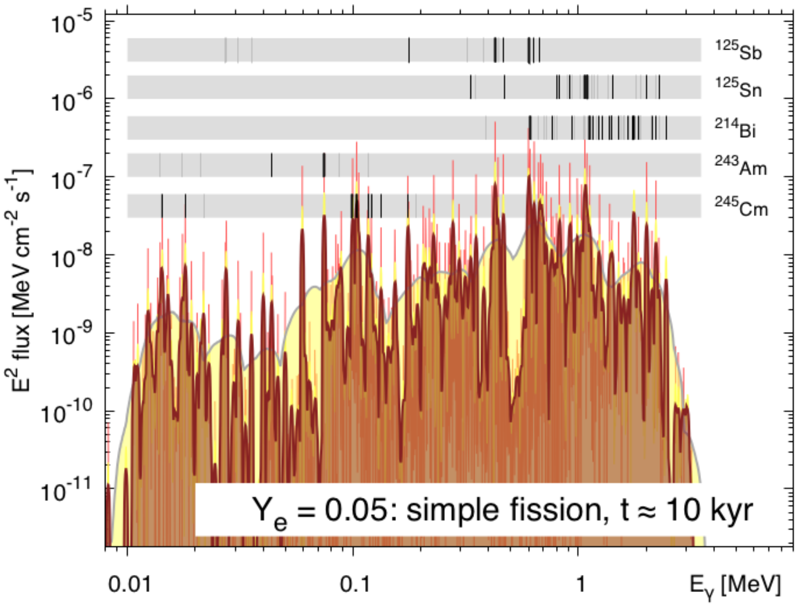
Observationally interesting time period for a long-past r-process event

Longer-lived radionuclides of interest during this epoch

Figure by **Mumpower**

PARTICLE SPECTRA FOR RADIONUCLIDES





Our QRPA+HF model is also capable of producing predictions of particle spectra coupled with evaluations (left)

Benchmarking these quantities provides a more sensitive test of the model beyond integral quantities such as P_n

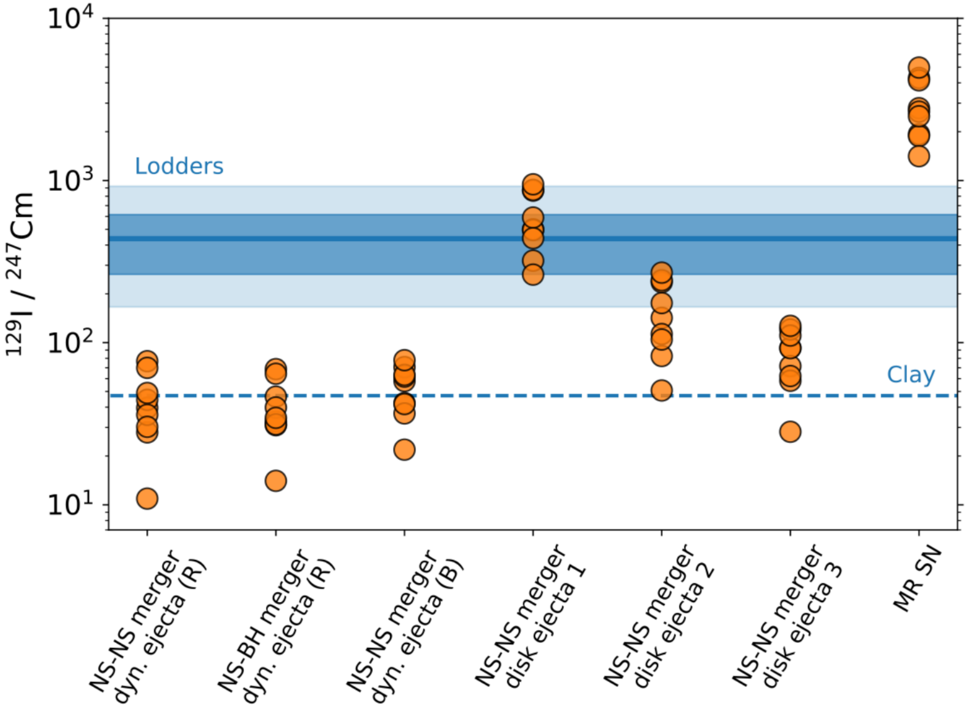
Both theory & data are influential in predicting observational signatures e.g. γ-rays from remnants (right)

Measurements focused on decays can provide a new handle on potential 'smoking gun' r-process nuclei

^{213,214}Bi($Z = 83$) are strong γ-emitters that have short half-lives but can be generated by longer-lived species

Korobkin ***et al.*** 889 2 (2020) • Miller ***et al.*** PRD 100 023008 (2019) • Wu ***et al.*** PRC 101 042801(R) (2020) • **Mumpower** *et al.* in prep. (2021)

ON EVEN LONGER TIMESCALES...



The ^{129}I to ^{247}Cm ratio offers a unique insights into the r-process

These radionuclides have nearly identical half-lives (15 Myrs), but are widely separated in mass

See Benoit's talk on Friday!

Côtè ***et al.*** Science 371 945 (2021)

SPECIAL THANKS TO

My collaborators!

SUMMARY

We need *accurate* nuclear data and *reliable* nuclear physics models to understand r-process nucleosynthesis

Recent advances:

We have developed a state-of-the-art research pipeline for studying nuclear physics in nuclear astrophysics

We have developed theoretical tools to interpret experiments and gauge impact in astrophysical environments

We have recently compiled new mass, reaction, decay and fission predictions across the chart of nuclides

Providing novel insights into radionuclides of the r-process and their associated signatures in various epochs

Results / Data / Papers @ MatthewMumpower.com