The *r*-process: nature's rare isotope facility

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TRIUMF Theory Group

FRIB-TA Topical Program:

Theoretical Justifications and Motivations for Early High-Profile FRIB Experiments,

May 23, 2023

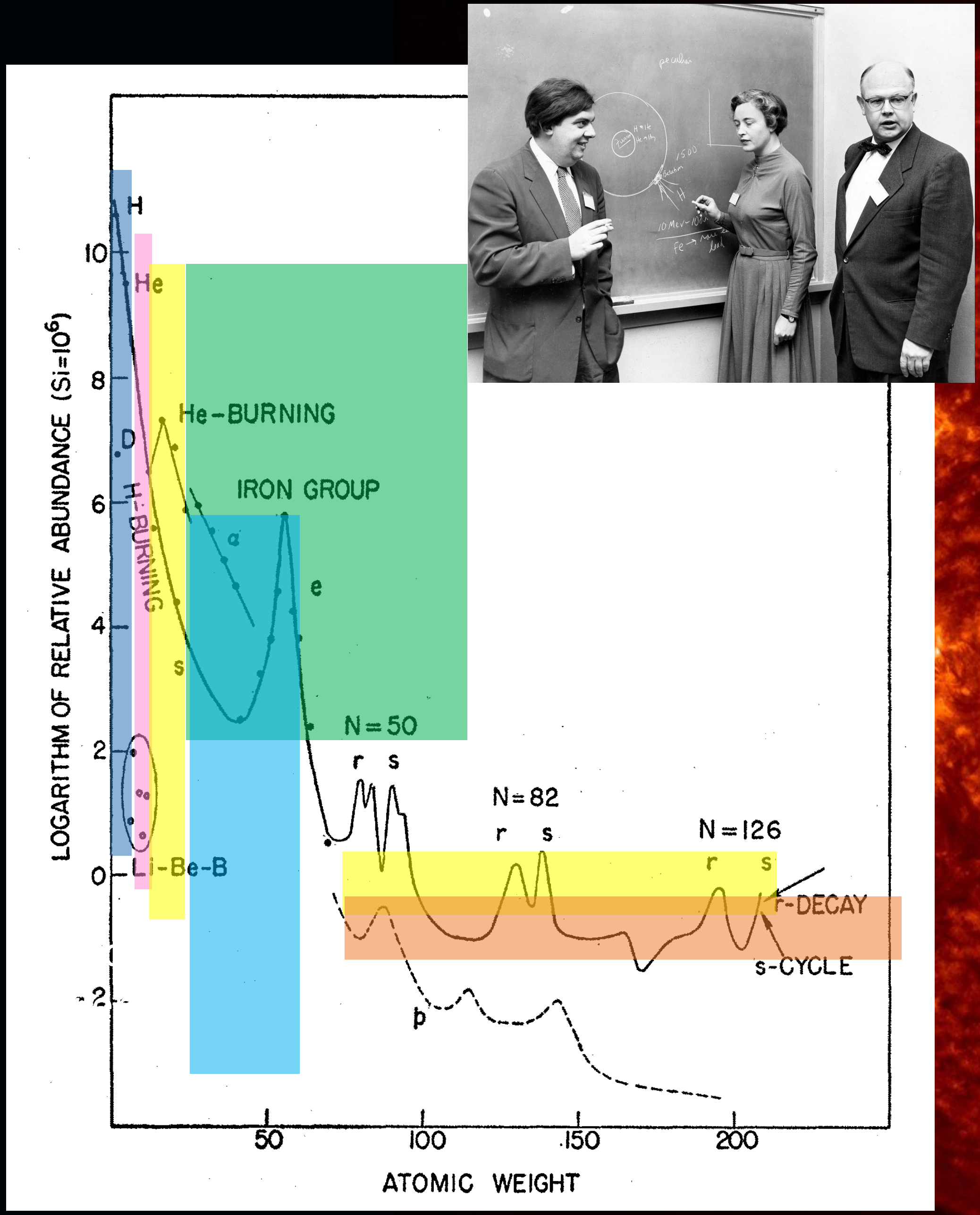
TRIUMF

FRIB Theory Alliance

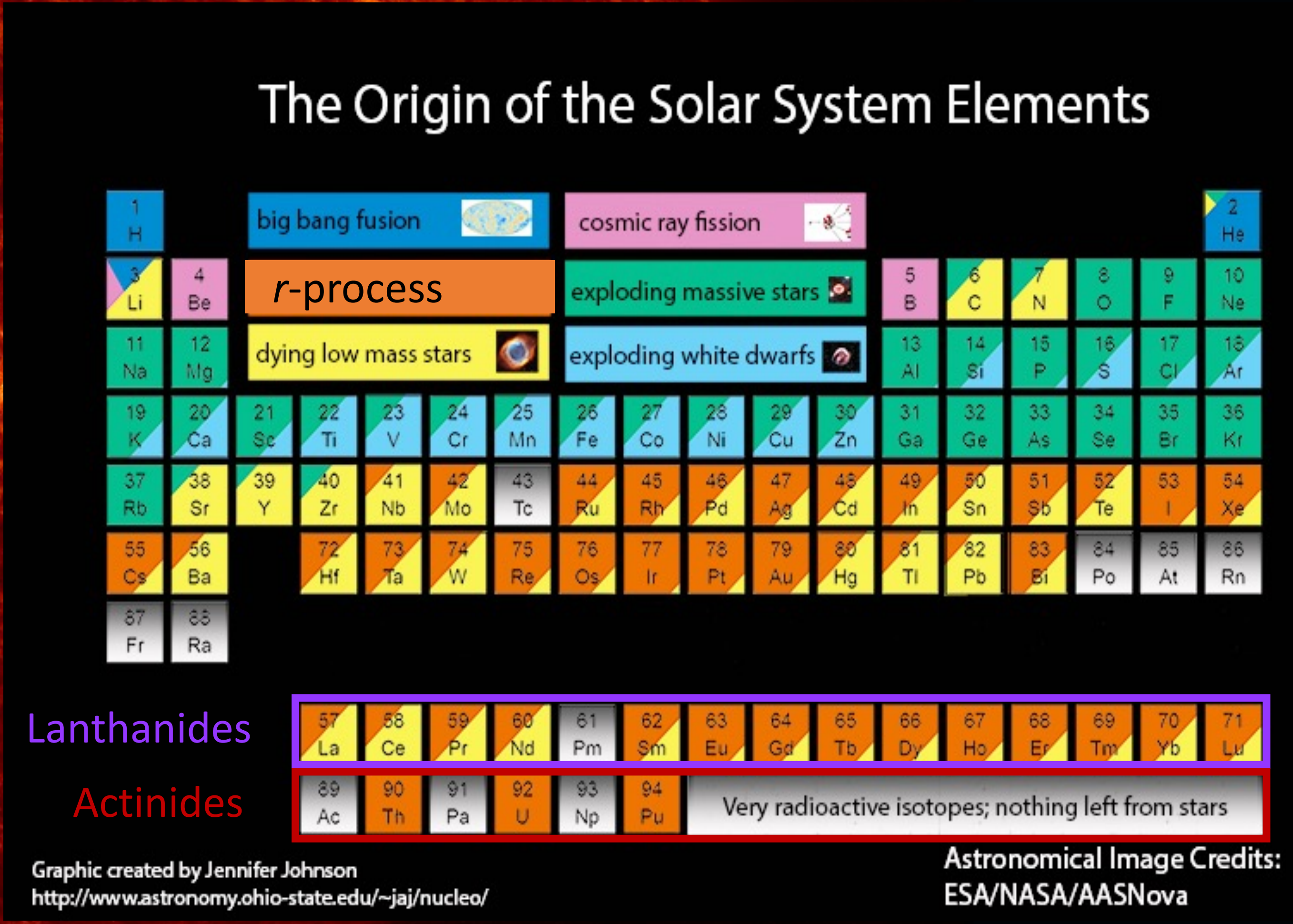
NSERC CRSNG

65 years of nuclear astrophysics

The solar composition shows signatures of many processes
→ enriched by multiple nucleosynthesis sites

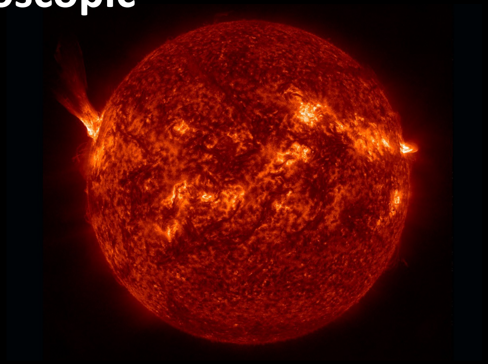


Burbidge, Burbidge, Fowler and Hoyle (1957)

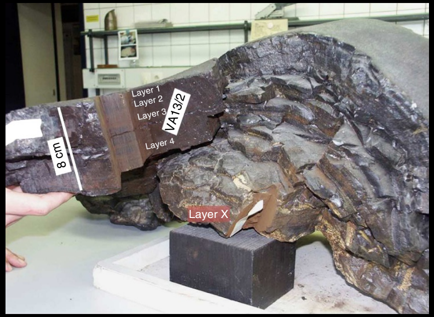


Many observables tied to distinct time epochs and event types

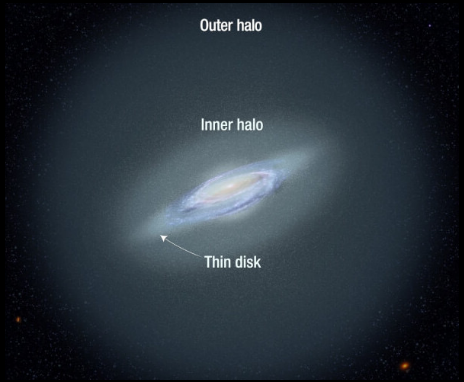
Solar Spectroscopic Abundances



Meteorites



Deep-sea ocean crusts



Stellar abundances in the Milky Way and nearby galaxies

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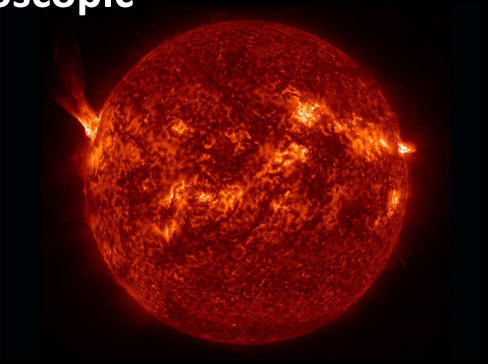

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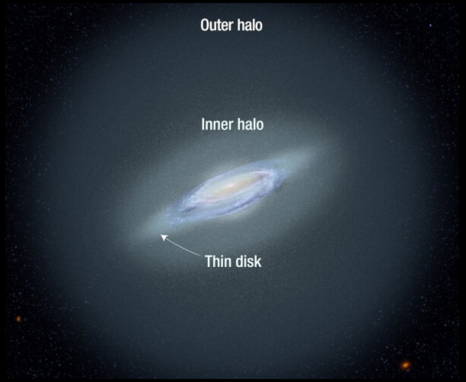
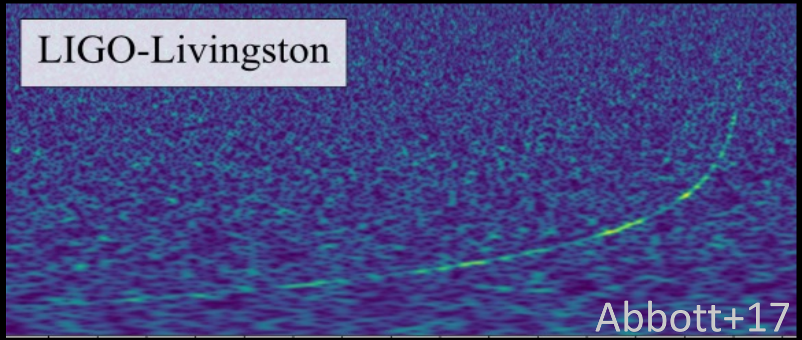


Stellar abundances in the Milky Way and nearby galaxies

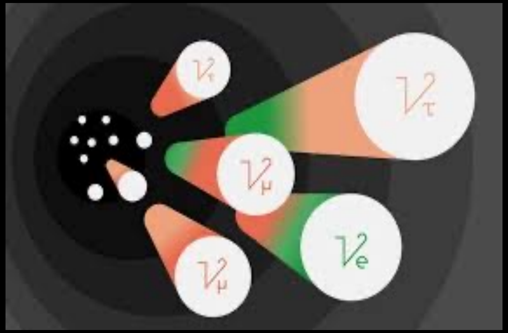
Can now see supernova and neutron star mergers in real time

Electromagnetic Emission: Light curves and γ-rays (UV, IR, Radio, X-ray, optical…)

Gravitational Waves



Neutrinos



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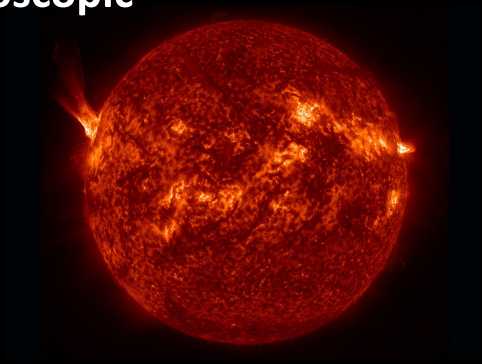

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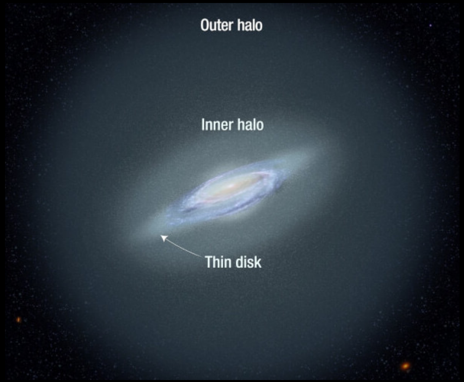


Stellar abundances in the Milky Way and nearby galaxies

Can now see supernova and neutron star mergers in real time

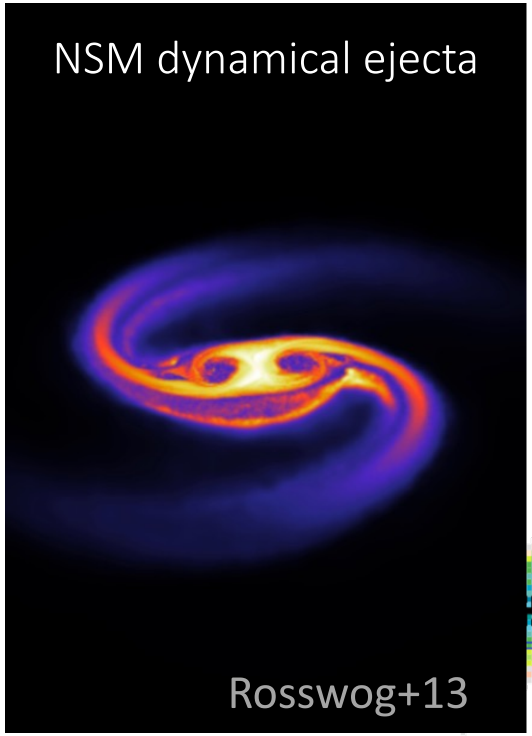
Electromagnetic Emission: Light curves and γ-rays (UV, IR, Radio, X-ray, optical…)

*observed kilonova light curve implies at least lanthanide elements made; no direct evidence for elements beyond such as gold or uranium

*unclear whether NSMs make enough to be Solar System source; still exploring other r-process candidate sites (e.g. MHD SN)

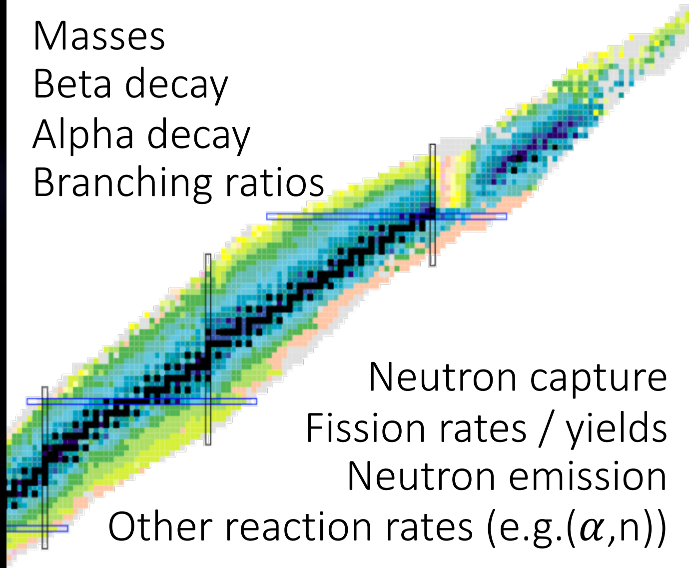
Modeling the *r*-process: nucleosynthesis networks and post-processing

Hydrodynamic simulations provide us with a "trajectory":
density / temperature / position
as a function of time



Both experimental + theoretical nuclear inputs:

Masses
Beta decay
Alpha decay
Branching ratios



Neutron capture
Fission rates / yields
Neutron emission
Other reaction rates (e.g.(α,n))

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- input initial composition dependent on EOS
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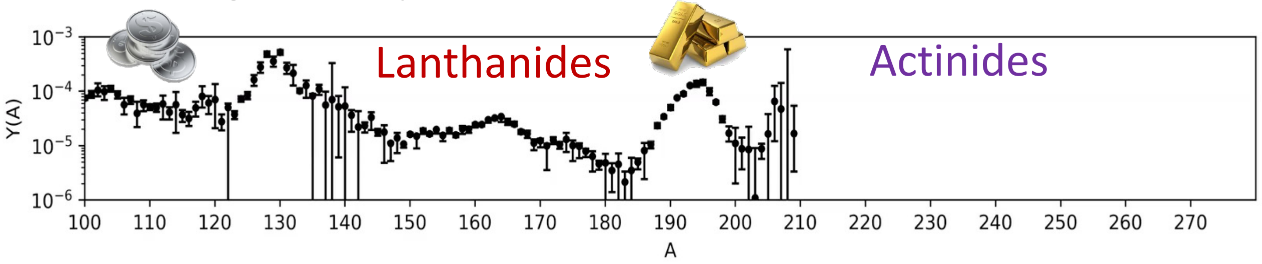

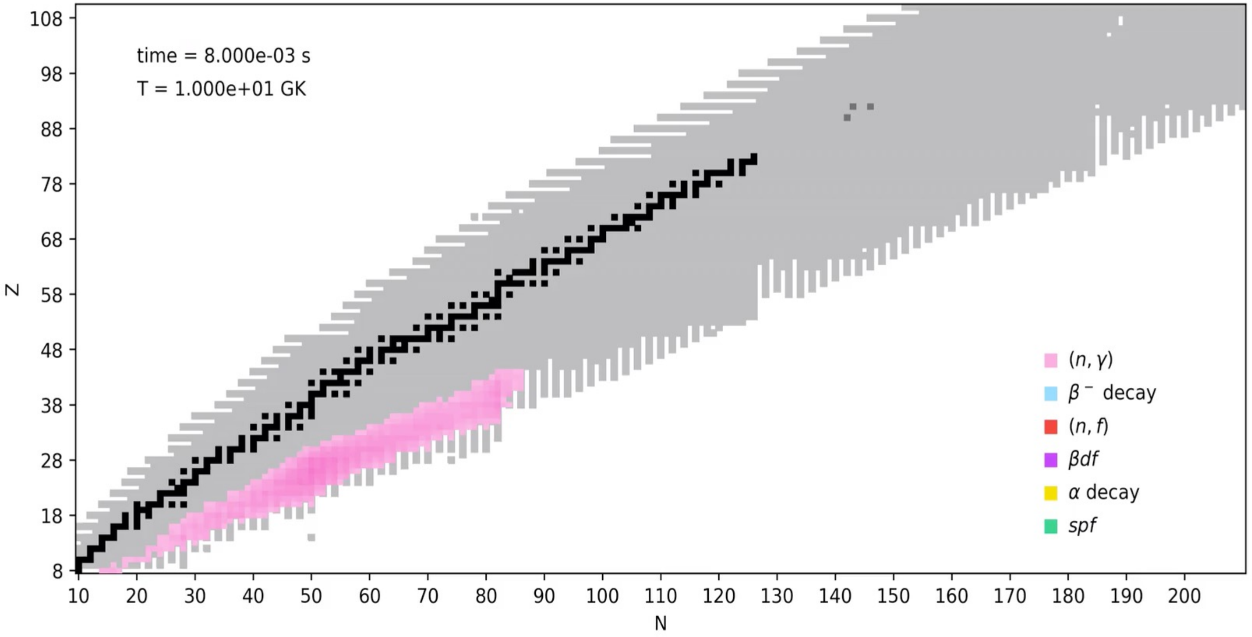

N Vassh

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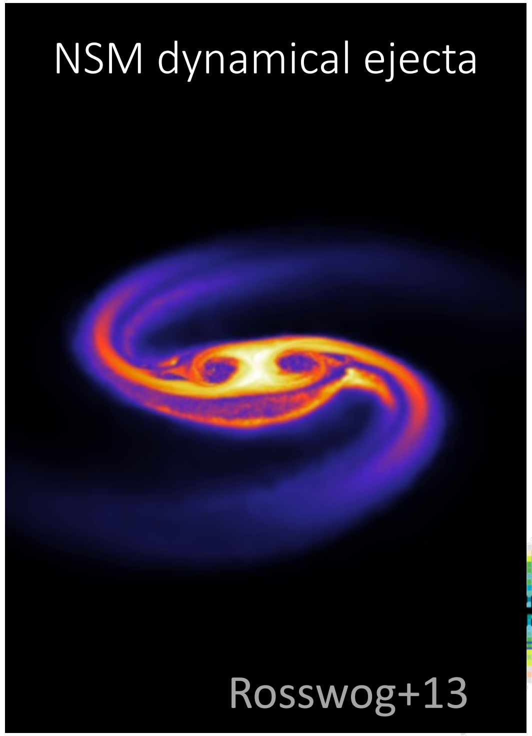

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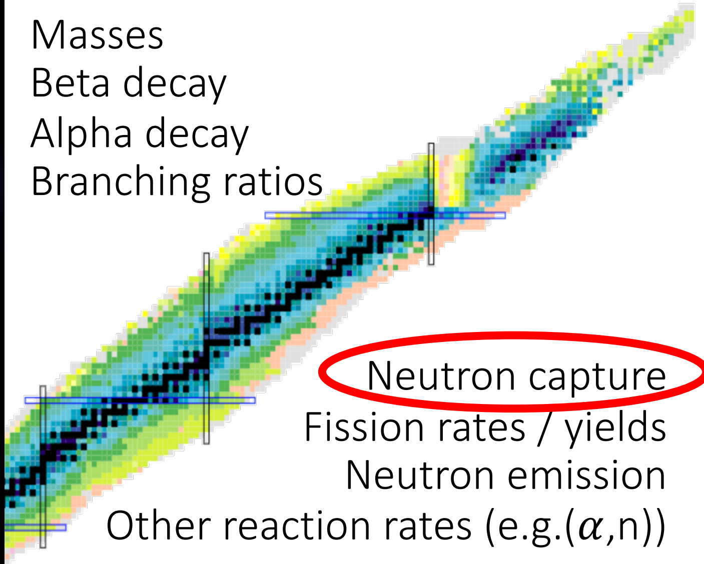

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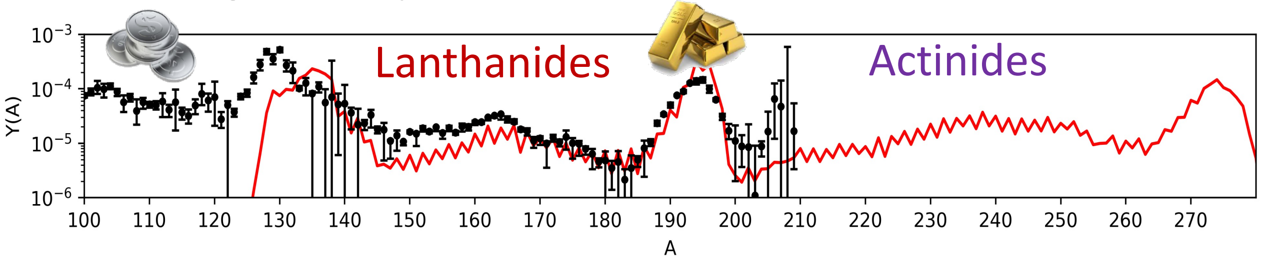

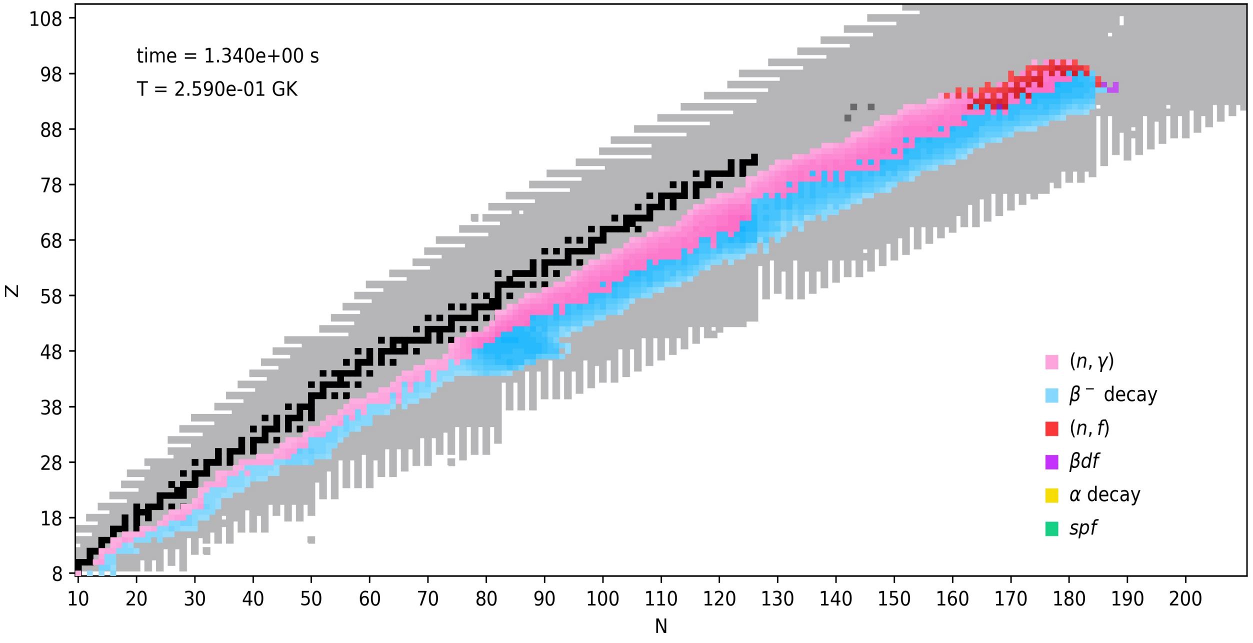

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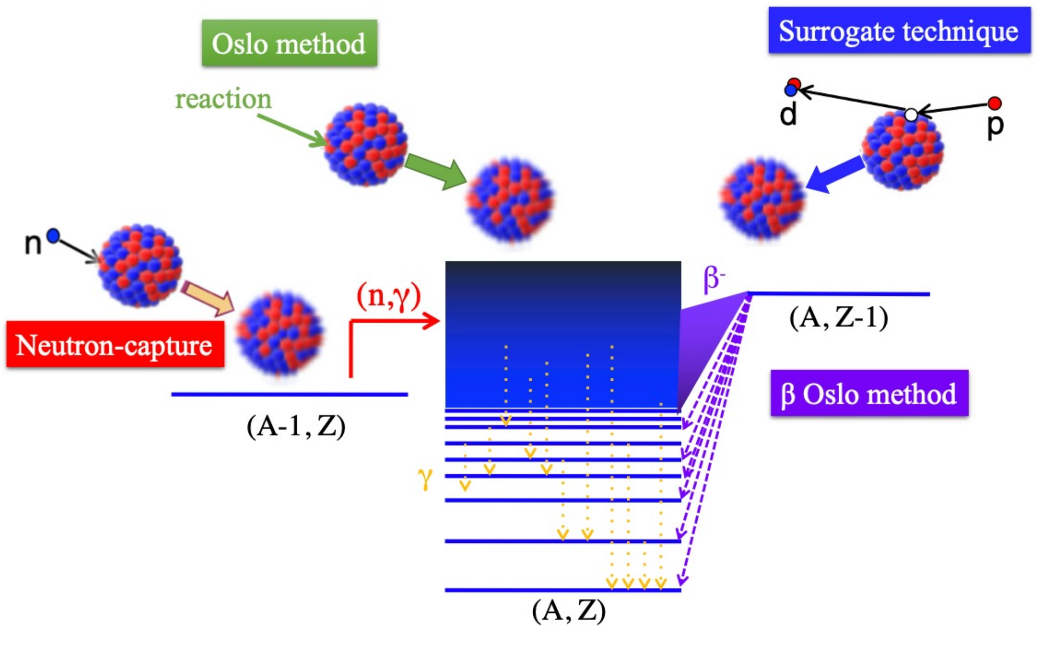
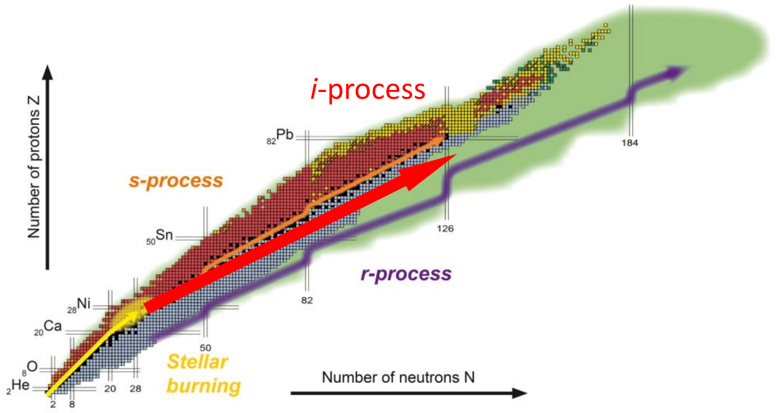
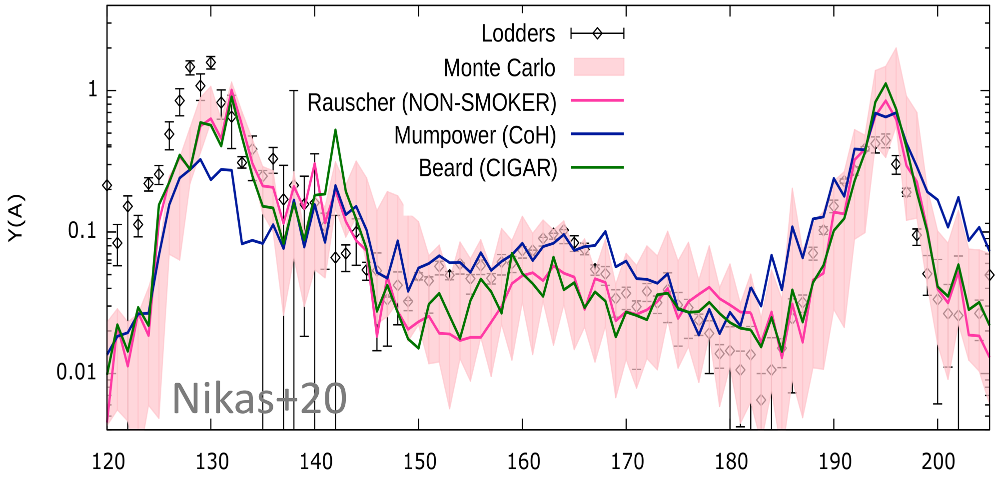
Spotlight on *neutron capture*

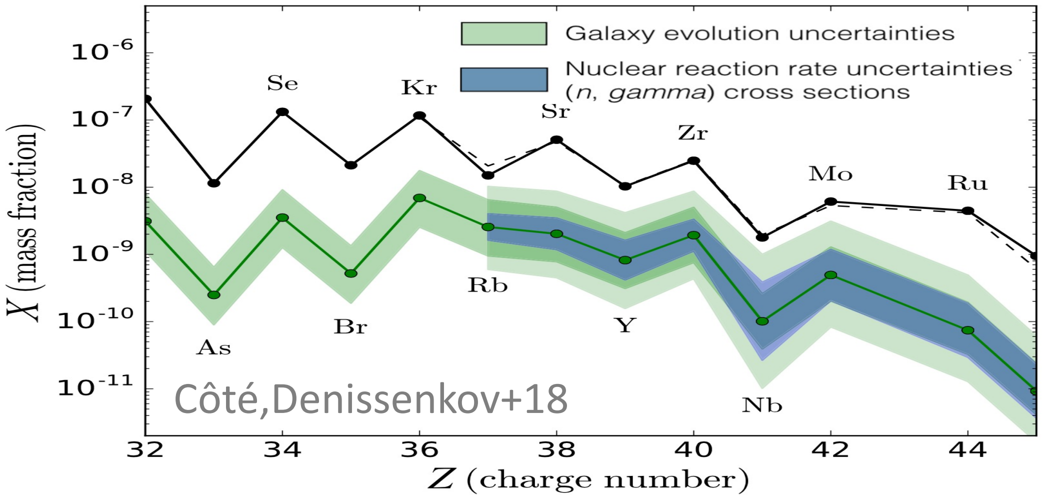
Uncertainties in **γ-strength functions** and **nuclear level densities** propagate to (n,γ) rate predictions affecting astrophysical neutron capture processes (*i*-process and *r*-process)



Schatz+22







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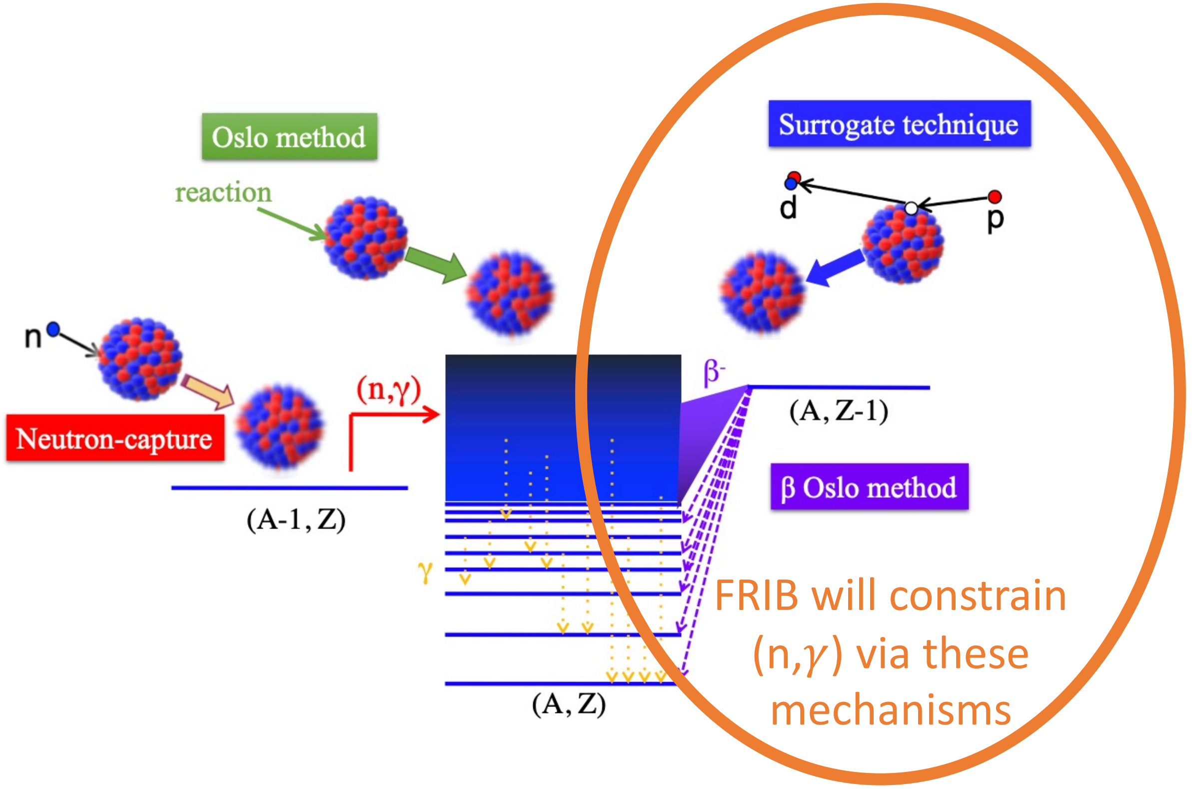

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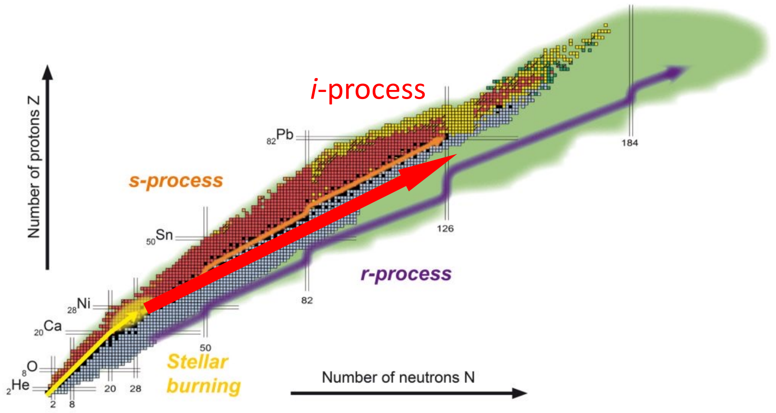

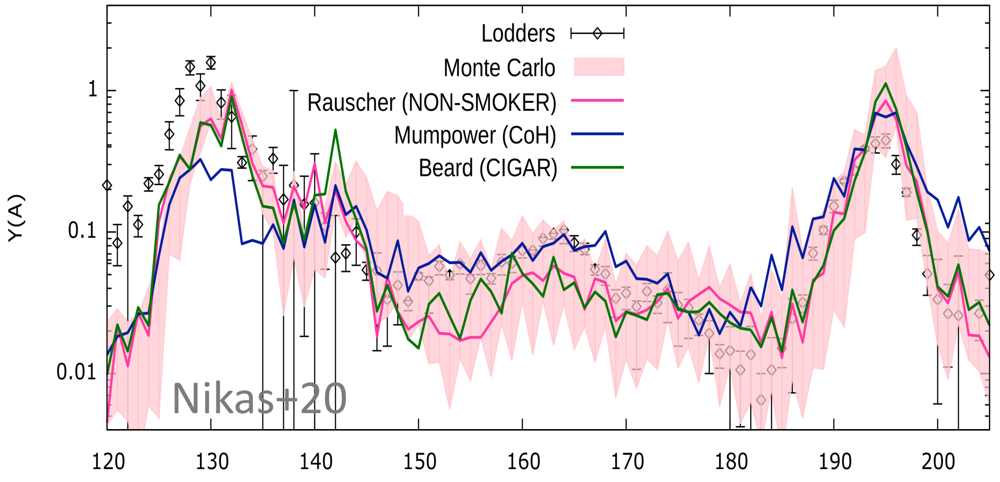

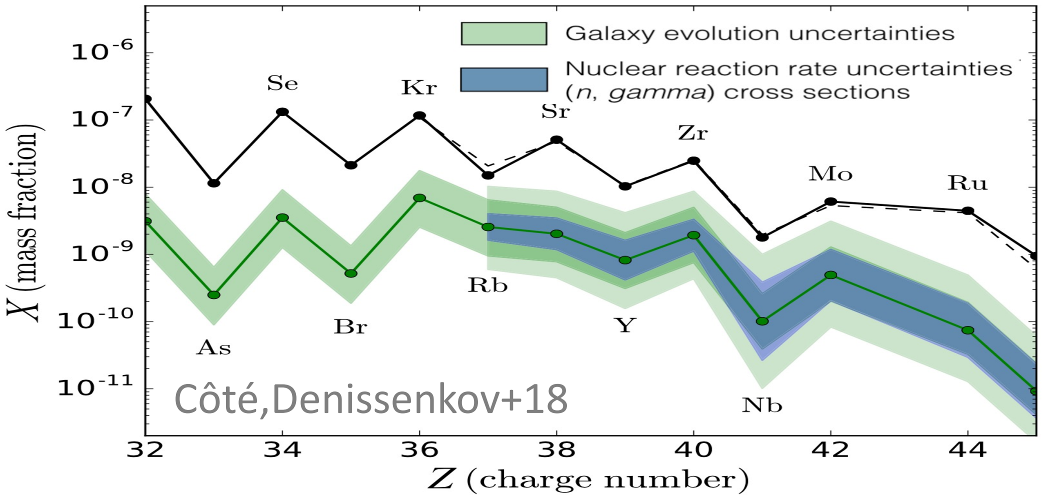

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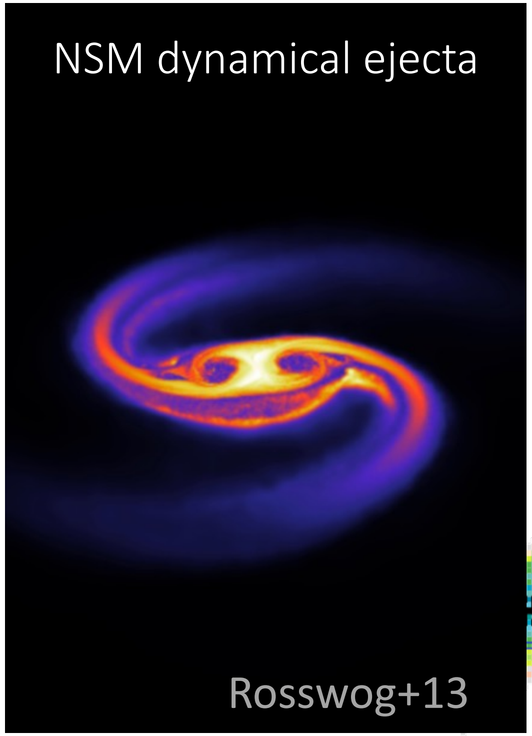

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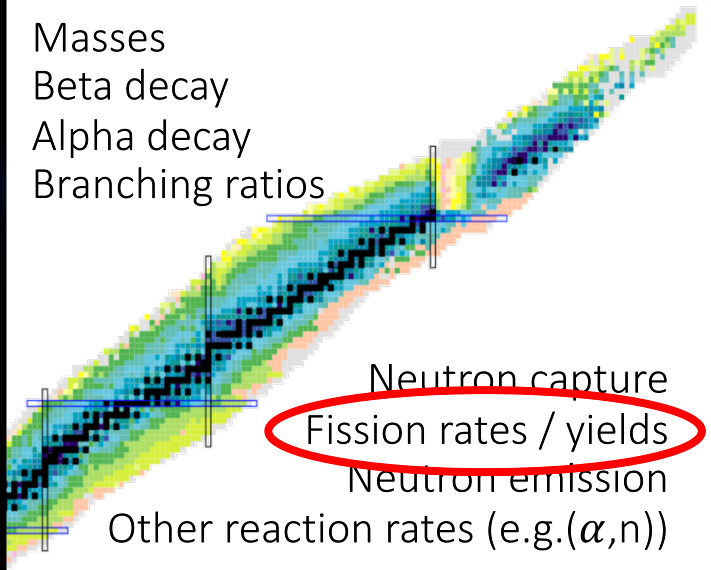

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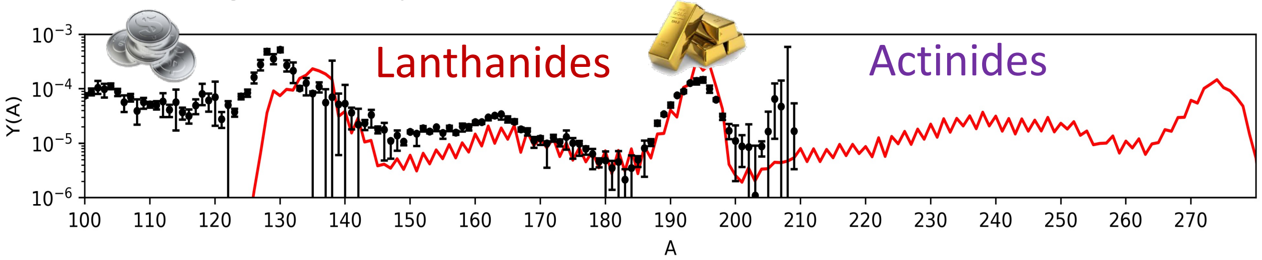
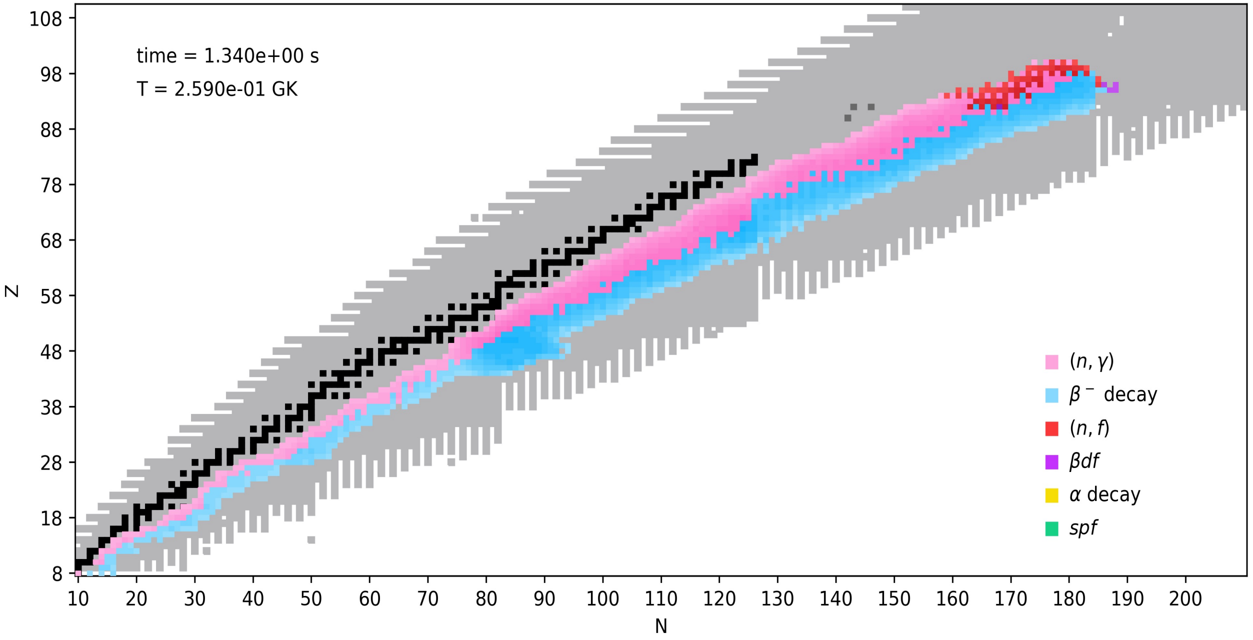




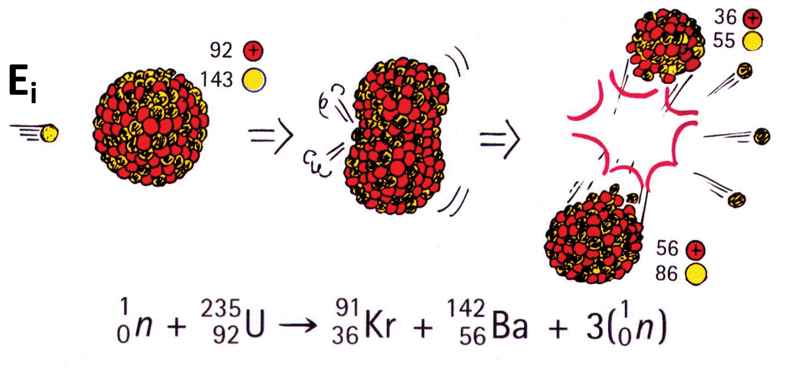
N Vassh

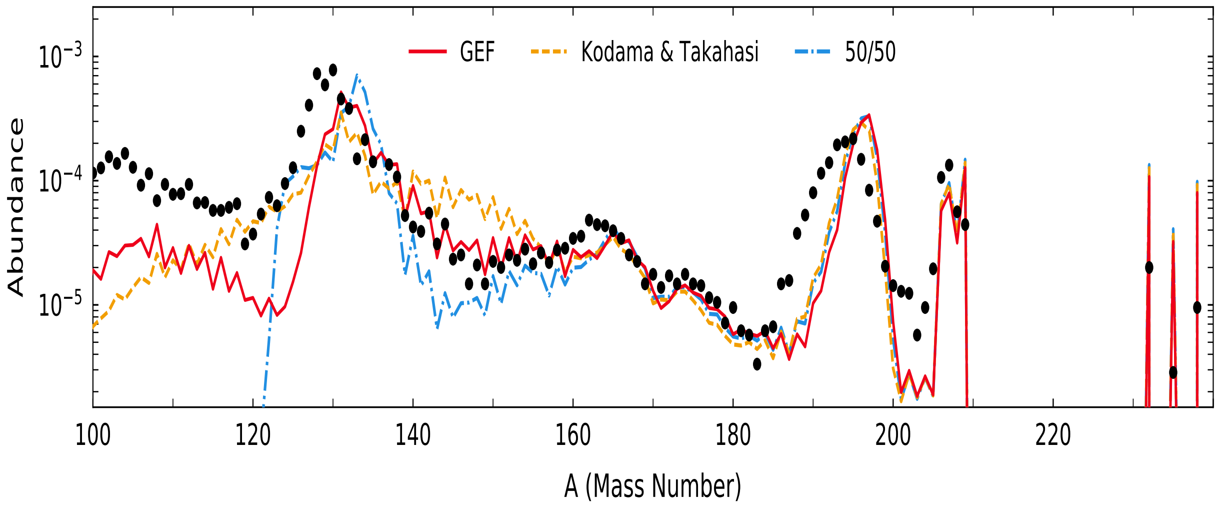
Fission yields and rates for neutron-induced, β-delayed, and spontaneous

Yield dependent on E_i

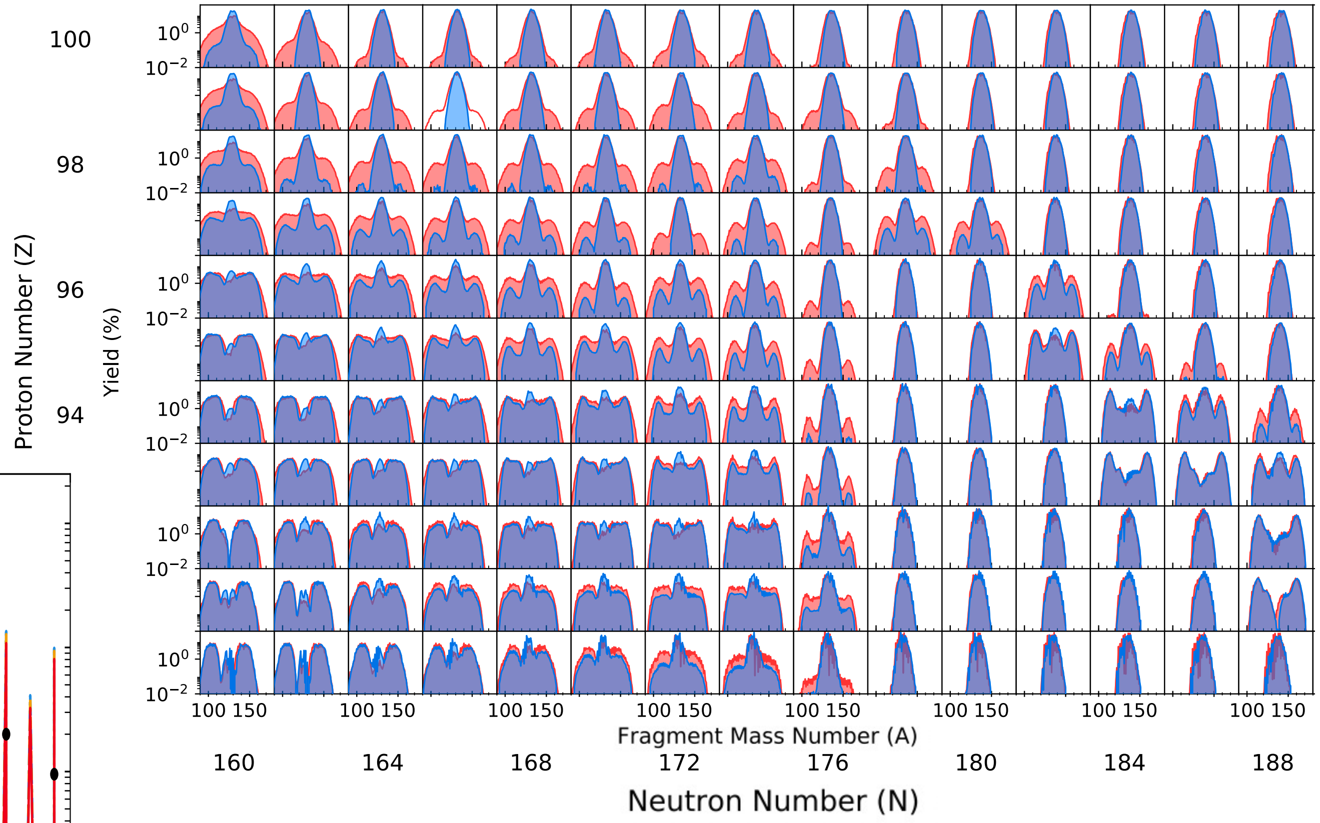
temperature on the order of 1 GK (~0.1 MeV)

important regime for *r*-process





(n,f) yields with excitation energy $E_i + S_n$ differ from sf yields at zero excitation energy (below from GEF 2016)



Vassh+19 (JPhysG)

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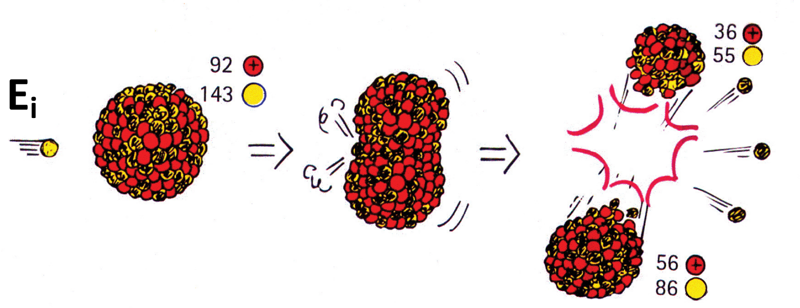
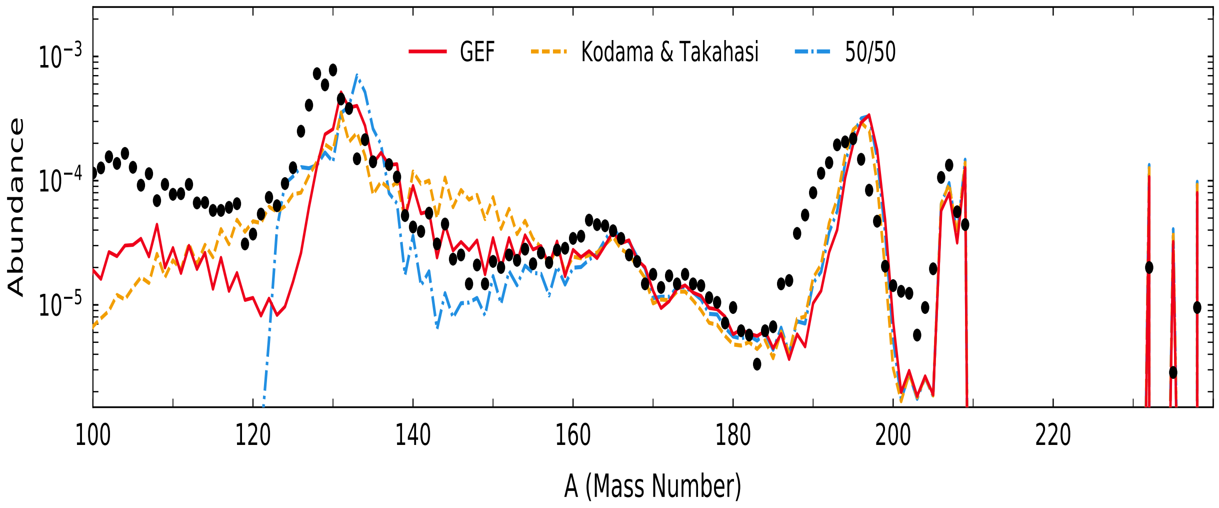
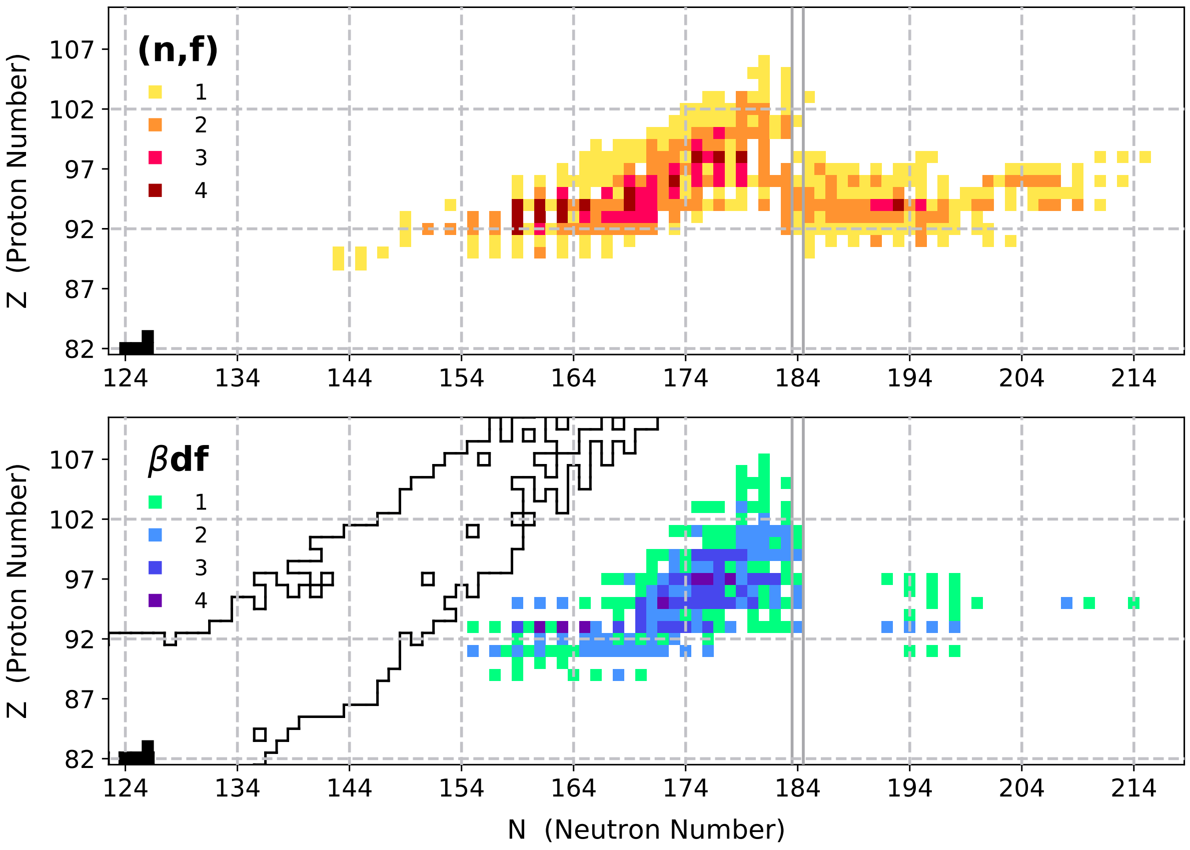


$${}^{1}_{0}n + {}^{235}_{92}U \rightarrow {}^{91}_{36}Kr + {}^{142}_{56}Ba + 3({}^{1}_{0}n)$$



Regions which models commonly predict to fission strongly in *r*-process simulations



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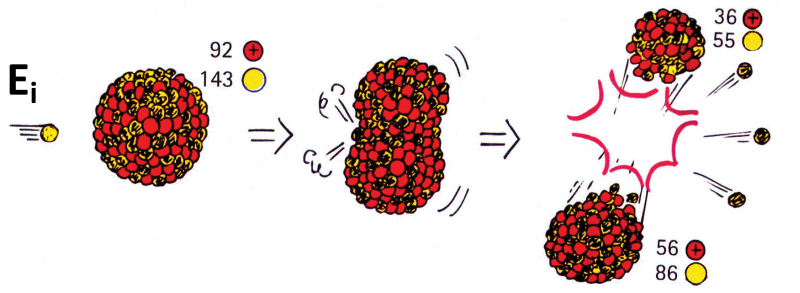

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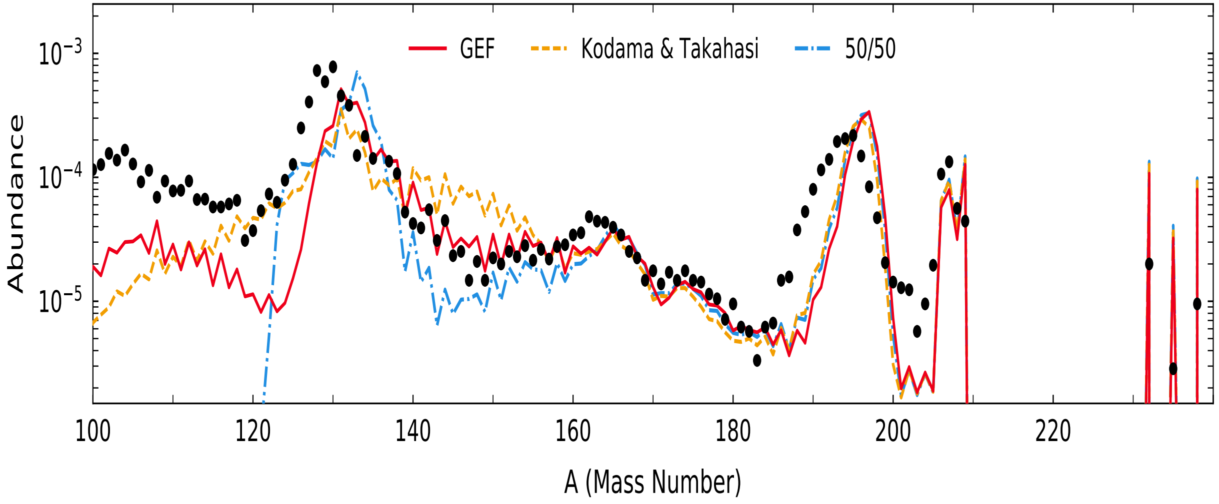

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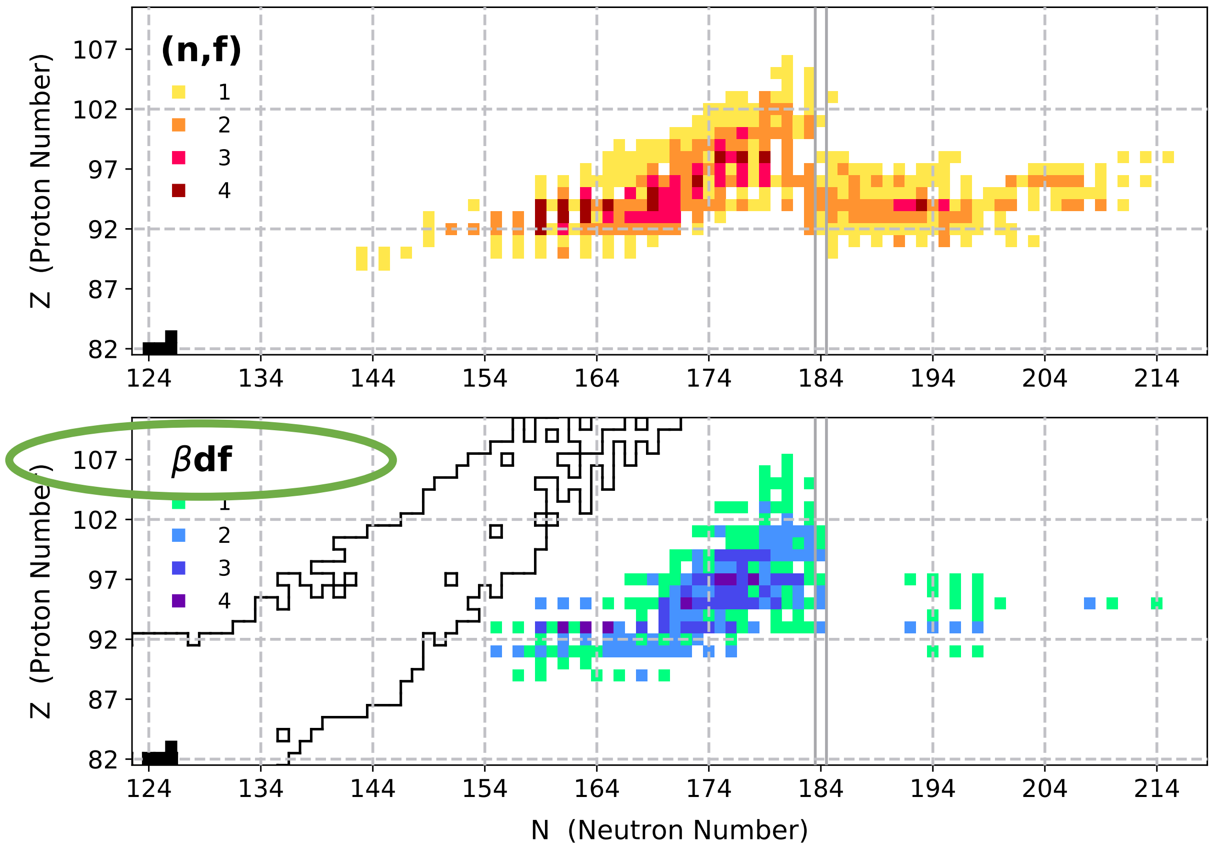
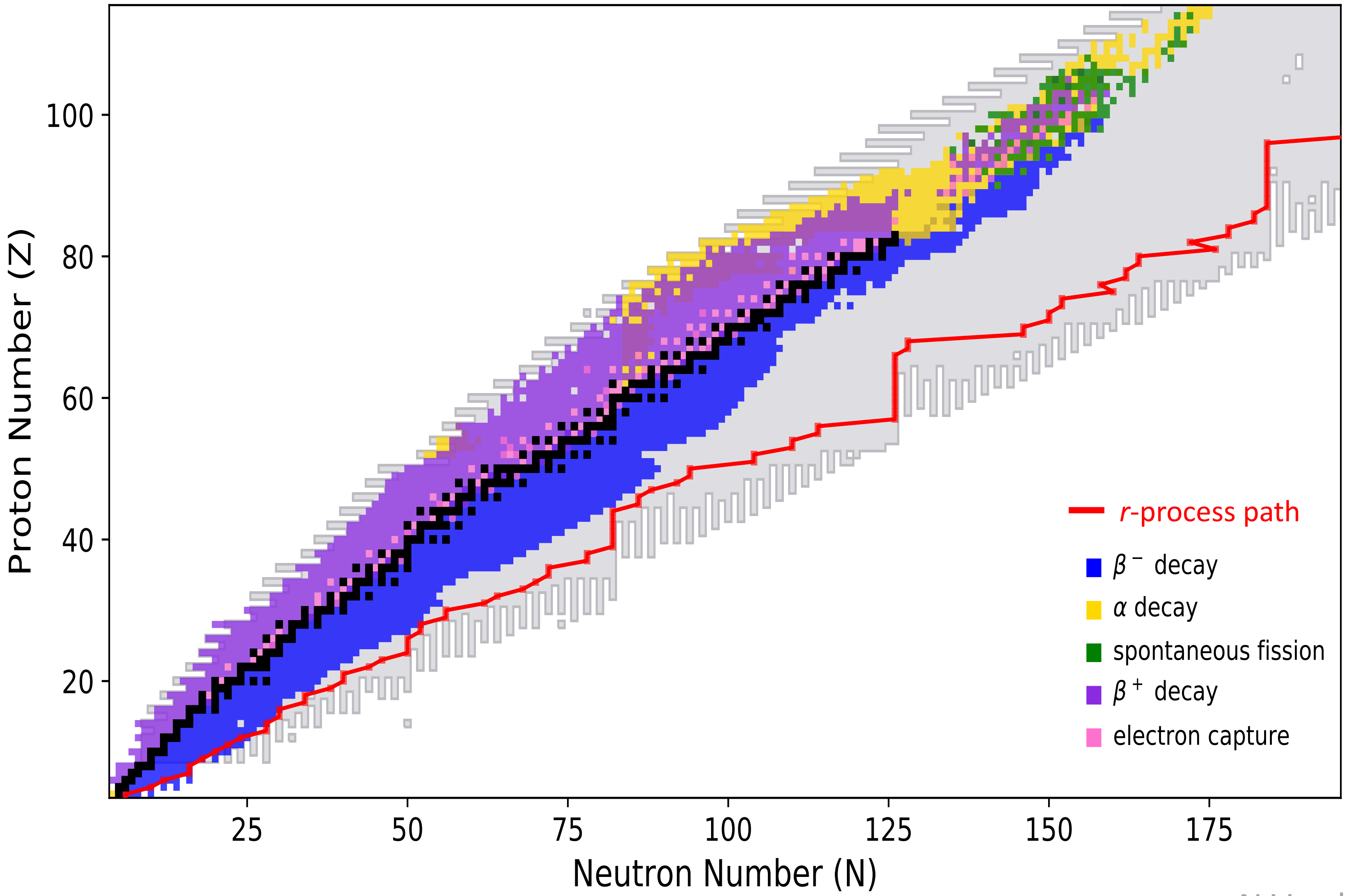


*beta-minus delayed fission has never been experimentally observed, confirmation alone progress (note this is what prevents *r*-process calcs from populating superheavies…)

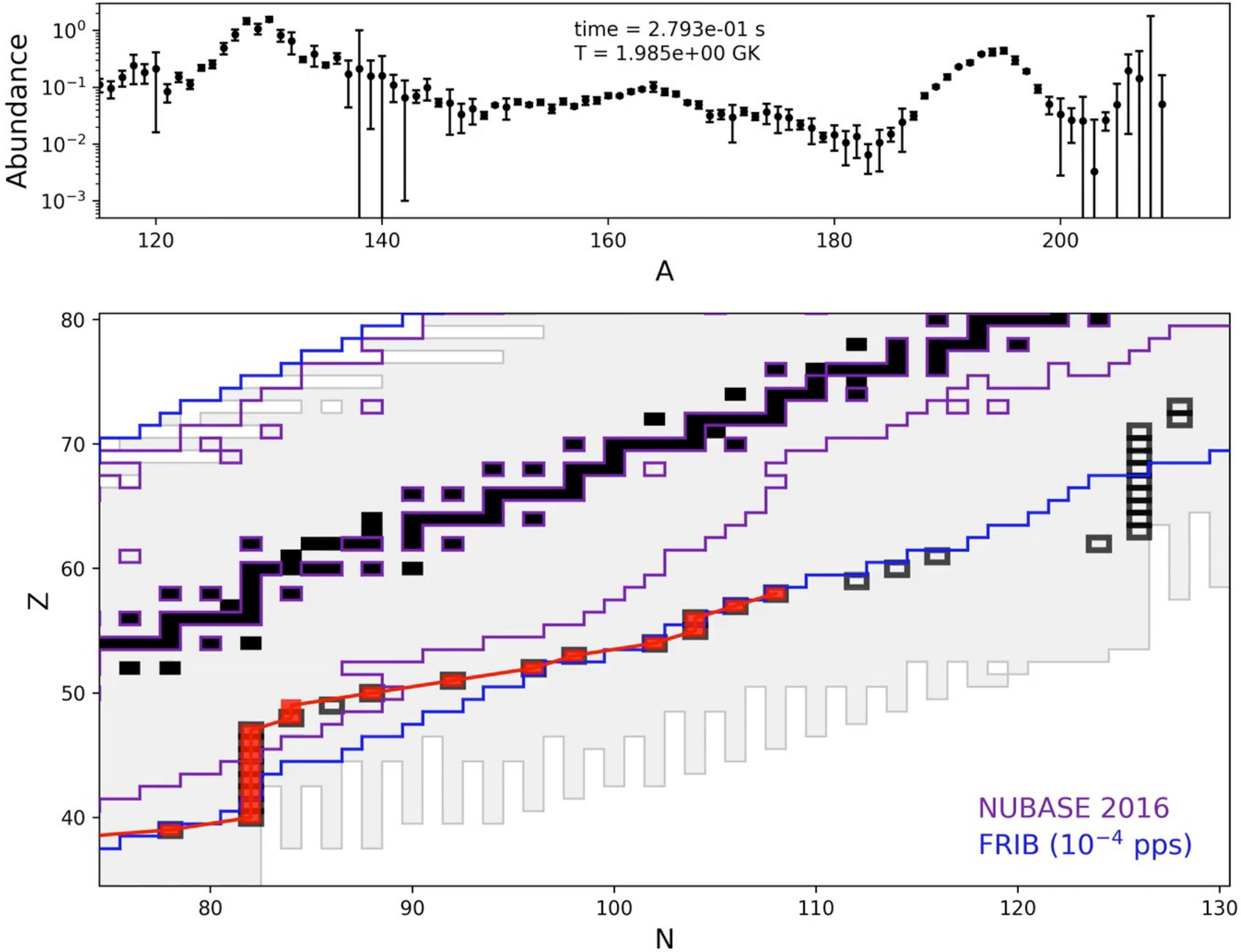
Vassh+19 (JPhysG)

FRIB customers now and for years to come



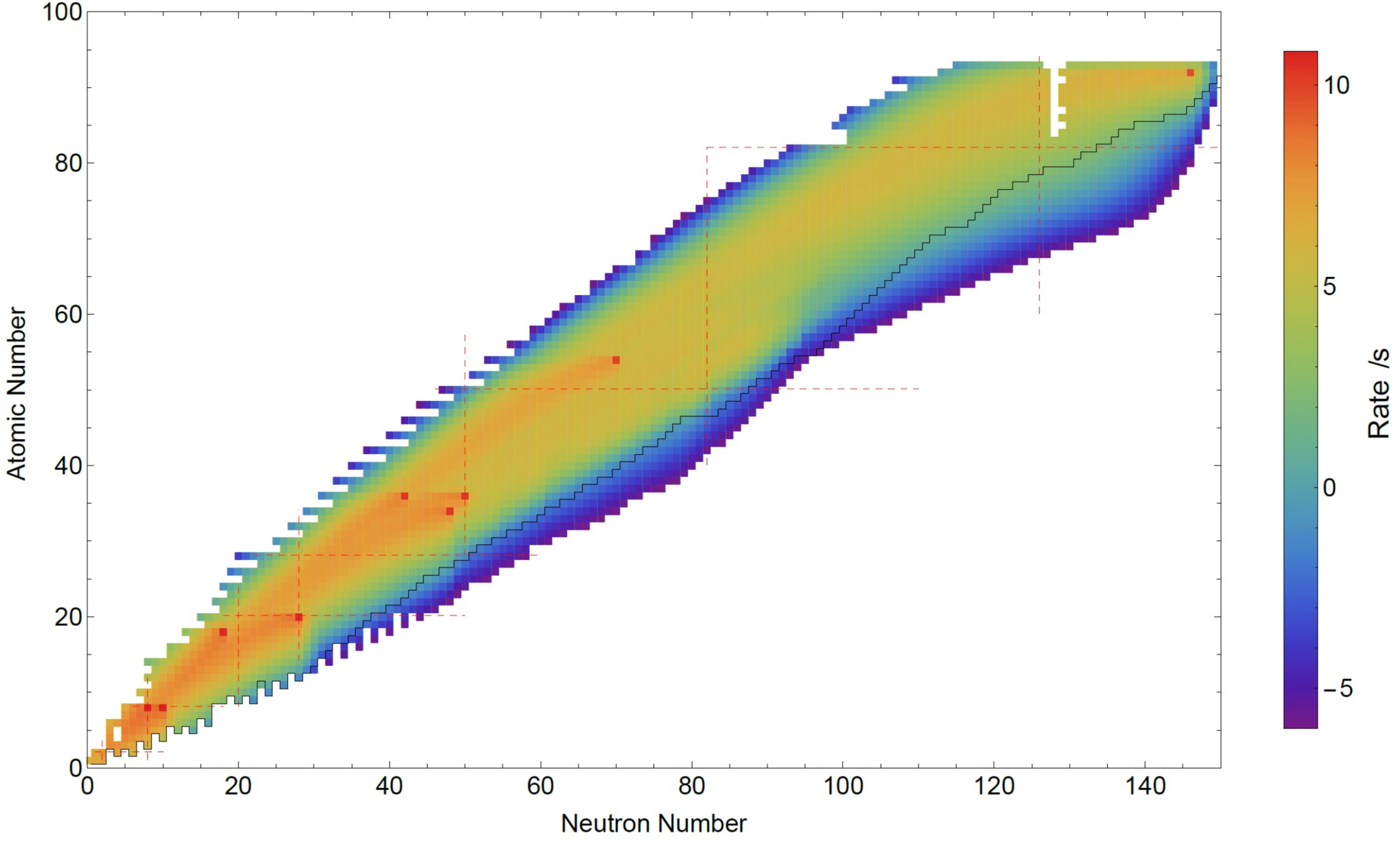
N Vassh

FRIB reach in key regions impacting the evolution of *r*-process abundances



Movie by N. Vassh

r-process studies in the FRIB era



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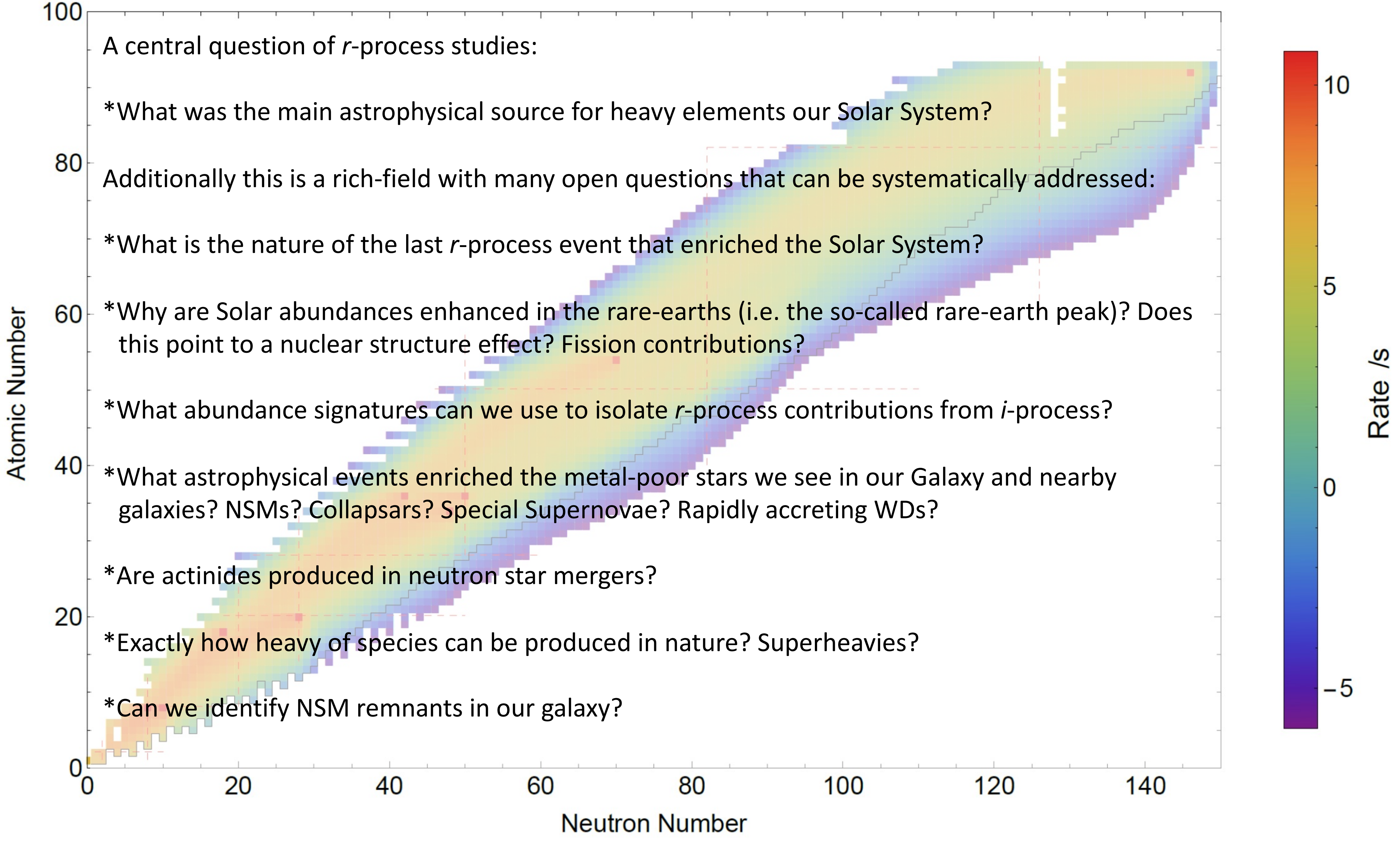

A central question of *r*-process studies:

*What was the main astrophysical source for heavy elements our Solar System?

Additionally this is a rich-field with many open questions that can be systematically addressed:

*What is the nature of the last *r*-process event that enriched the Solar System?

*Why are Solar abundances enhanced in the rare-earths (i.e. the so-called rare-earth peak)? Does this point to a nuclear structure effect? Fission contributions?

*What abundance signatures can we use to isolate *r*-process contributions from *i*-process?

*What astrophysical events enriched the metal-poor stars we see in our Galaxy and nearby galaxies? NSMs? Collapsars? Special Supernovae? Rapidly accreting WDs?

*Are actinides produced in neutron star mergers?

*Exactly how heavy of species can be produced in nature? Superheavies?

*Can we identify NSM remnants in our galaxy?

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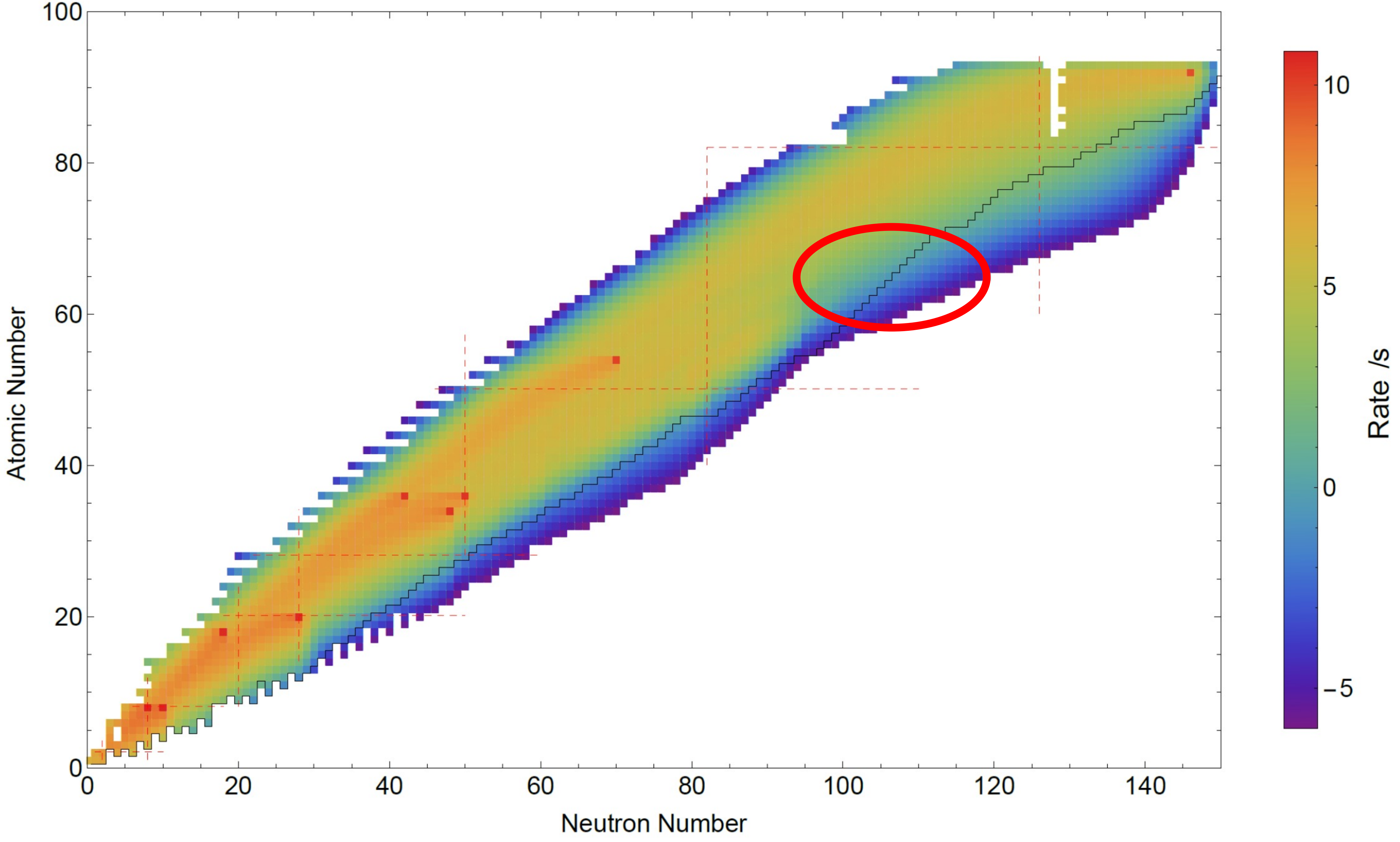
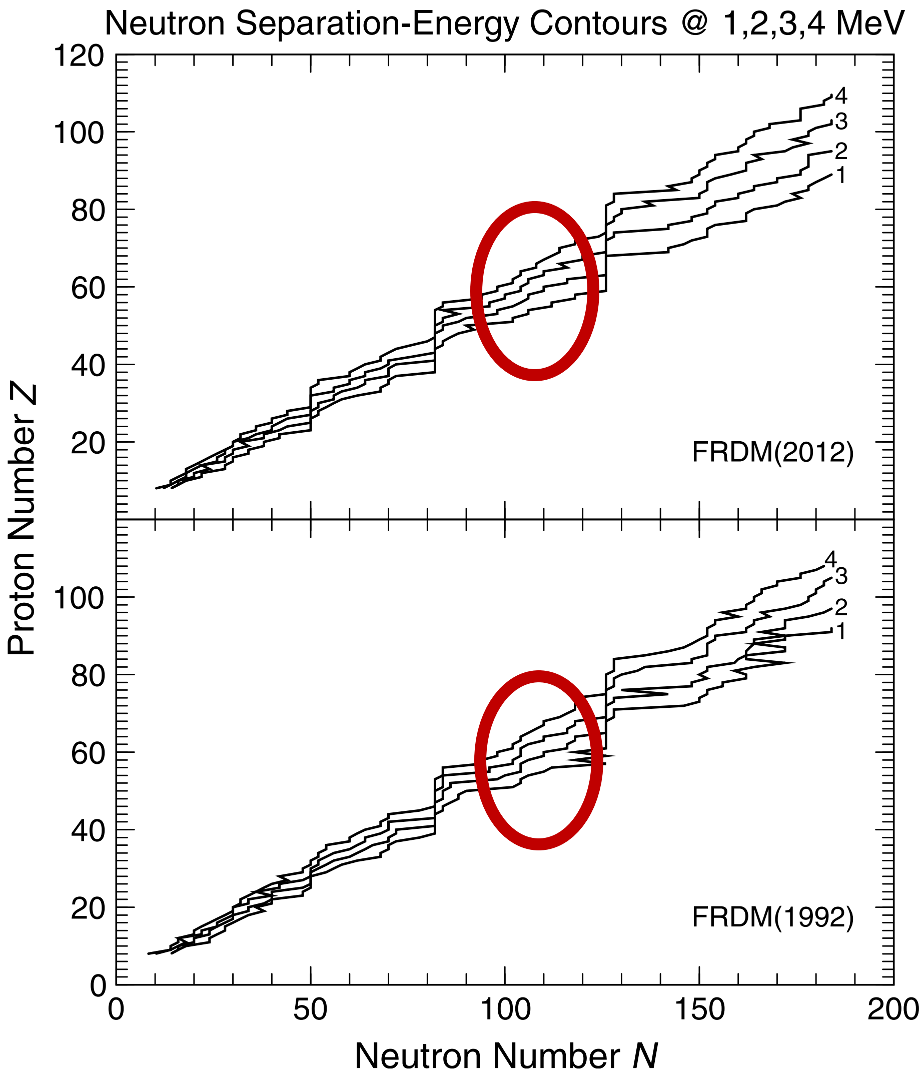
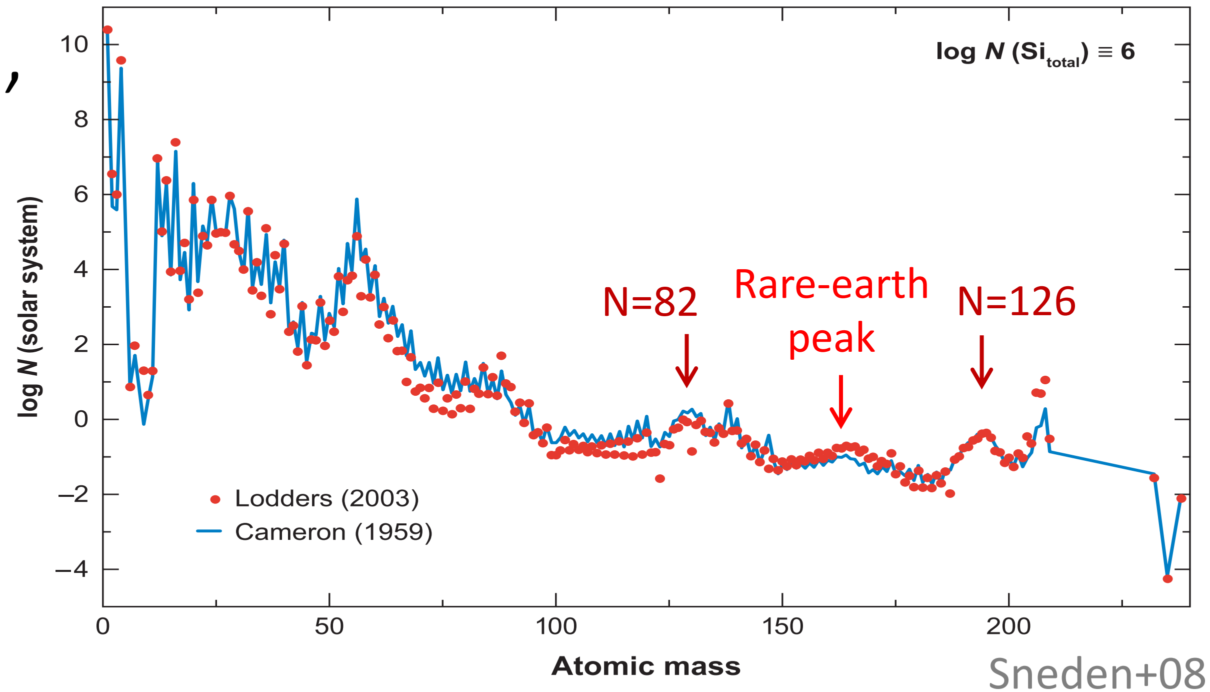


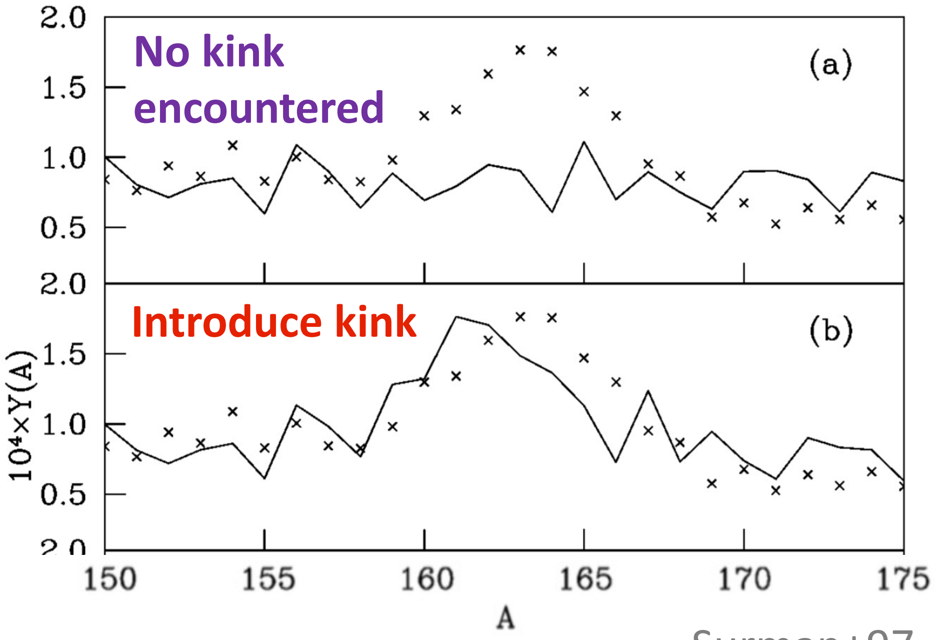
Nuclear masses, nuclear structure, and the rare-earth peak



Möller+12



Sneden+08



Surman+97

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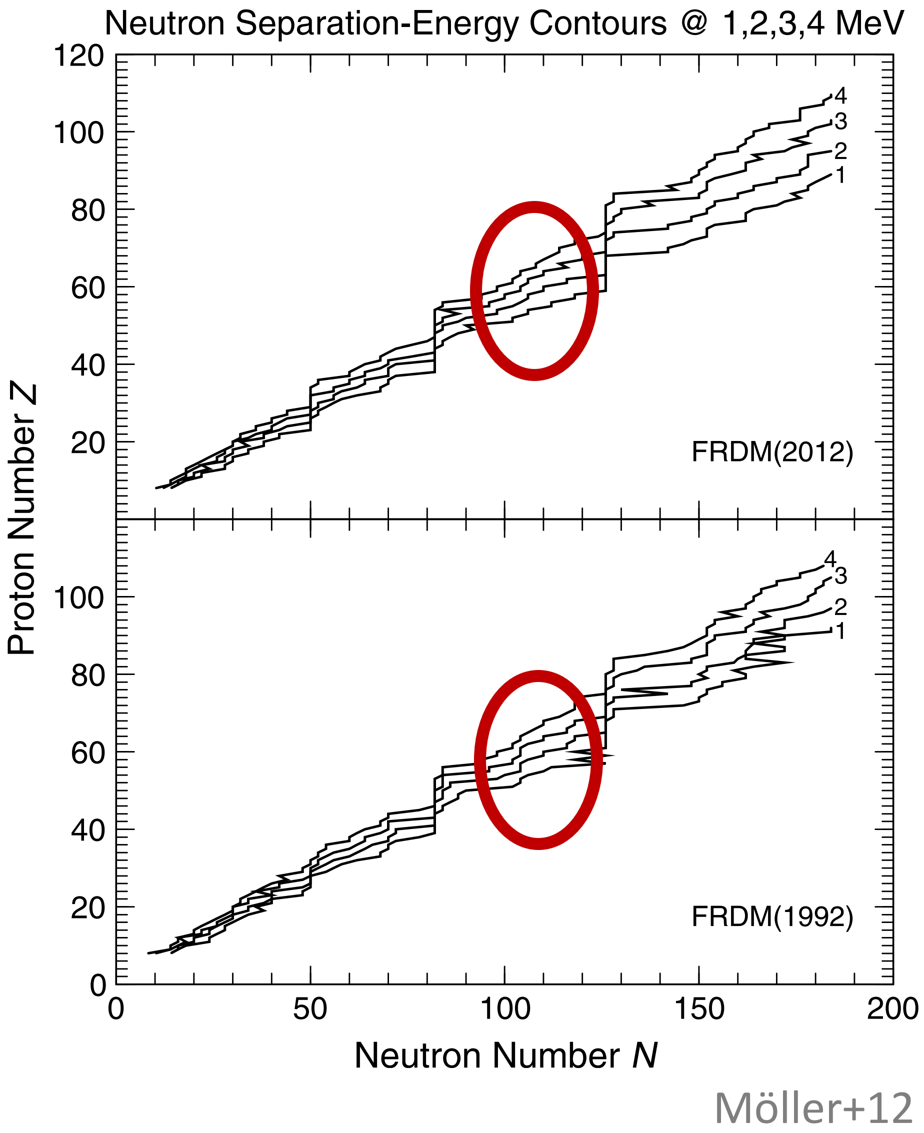
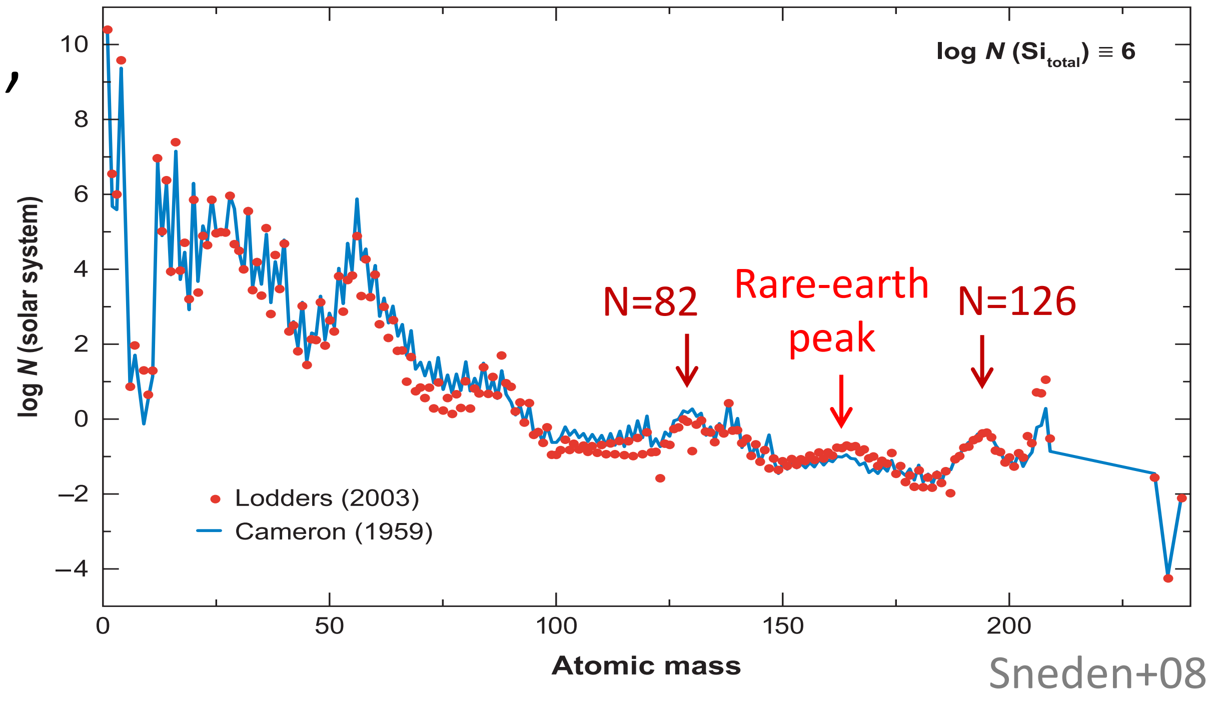
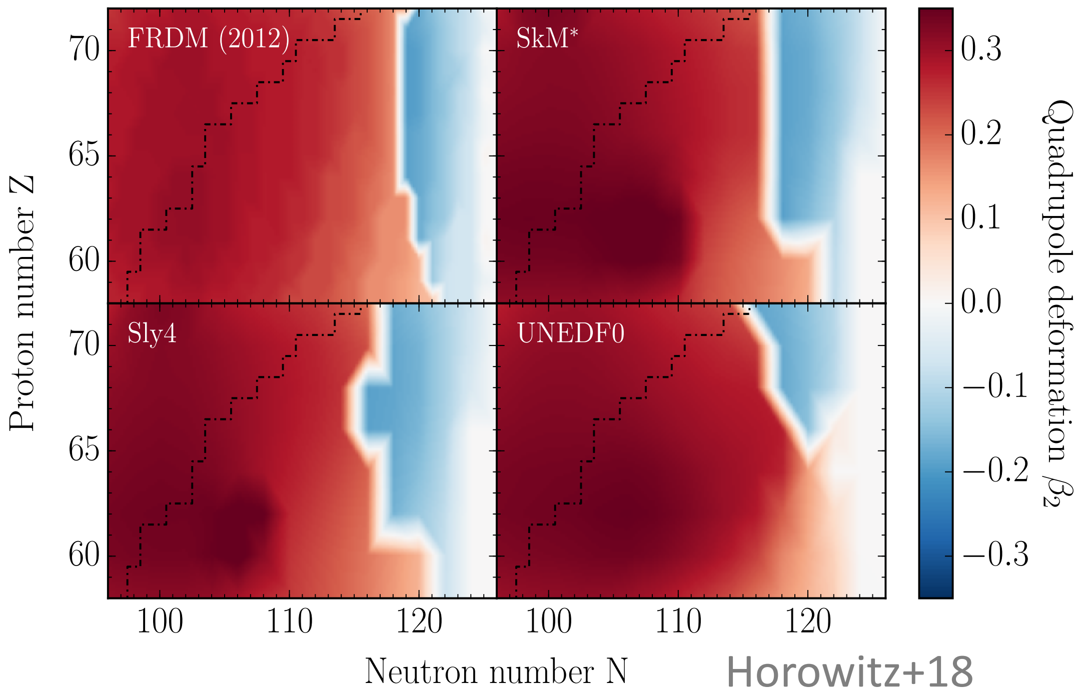






Markov Chain Monte Carlo (MCMC):

Uses observational data to discern nuclear properties such as masses as well as constrain the conditions present at nucleosynthesis sites

- Monte Carlo mass corrections

$$M(Z,N) = M_{DZ}(Z,N) + a_N e^{-(Z-C)^2/2f}$$

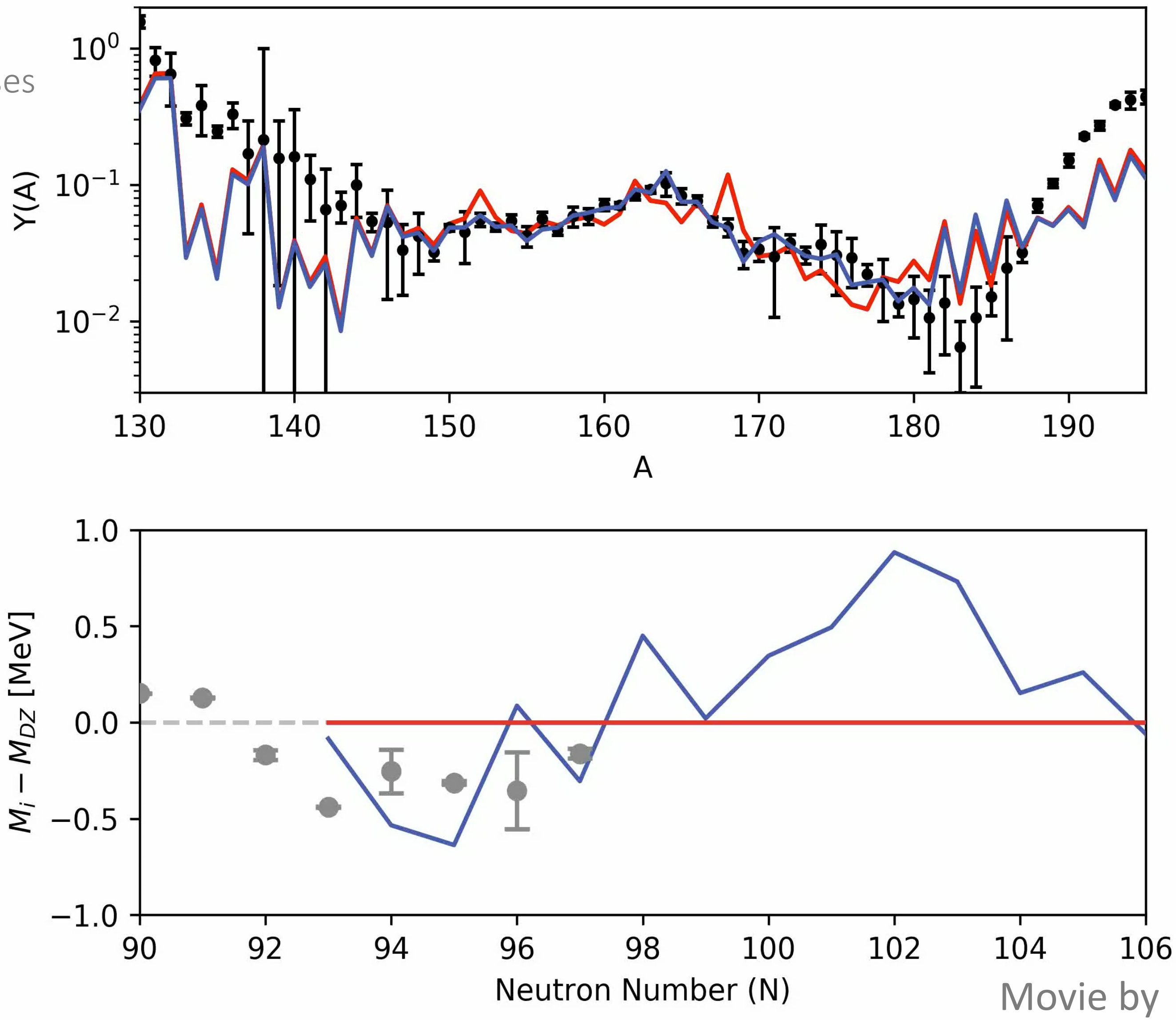
- Calculate: $\sigma^2_{\text{rms}}(M_{\text{AME12}}, M) \leq \sigma^2_{\text{rms}}(M_{\text{AME12}}, M_{DZ})$
- Calculate:

$$D_n(Z,A) = (-1)^{A-Z+1}\big(S_n(Z,A+1) - S_n(Z,A)\big) > 0$$

- Update nuclear quantities and rates
- Perform nucleosynthesis calculation
- Calculate $\chi^2 = \sum_{A=150}^{180} \frac{\left(Y_{\odot,r}(A) - Y(A)\right)^2}{\Delta Y(A)^2}$
- Update parameters OR revert to last success

$$\mathcal{L}(\mathrm{m}) = \exp\left(-\frac{\chi^2(\mathrm{m})}{2}\right) \rightarrow \alpha(\mathrm{m}) = \frac{\mathcal{L}(\mathrm{m})}{\mathcal{L}(\mathrm{m}-1)}$$

See Orford,Vassh+18 (PRL), Vassh+21 (ApJ), Orford,Vassh+22 (PRC Letters), Vassh+22 (Frontiers in Phys.)



Movie by N. Vassh

Black – solar abundance data
Grey – AME 2012 data
Red – values at current step
Blue – best step of entire run

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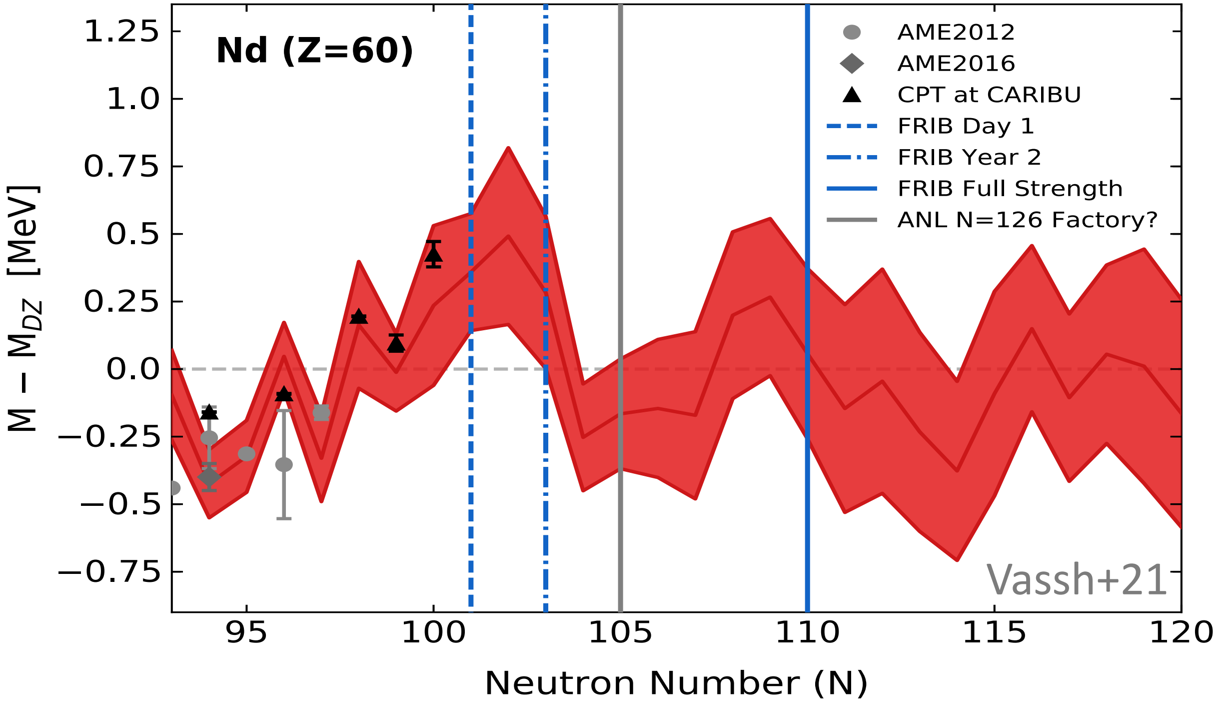
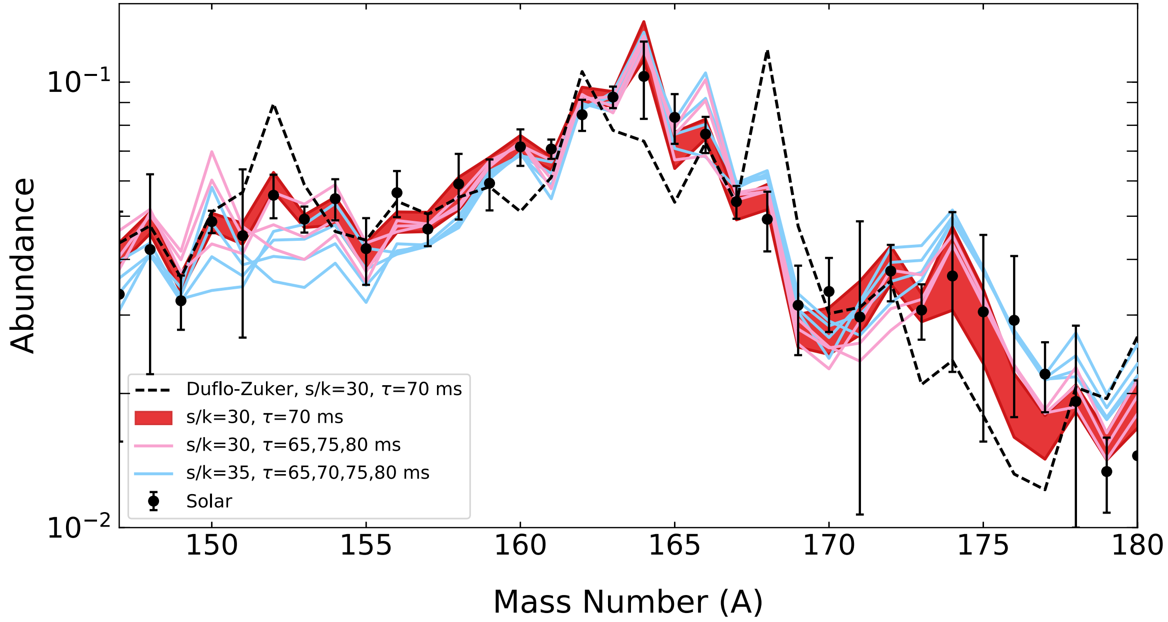
hot low entropy accretion disk wind (moderately n-rich)

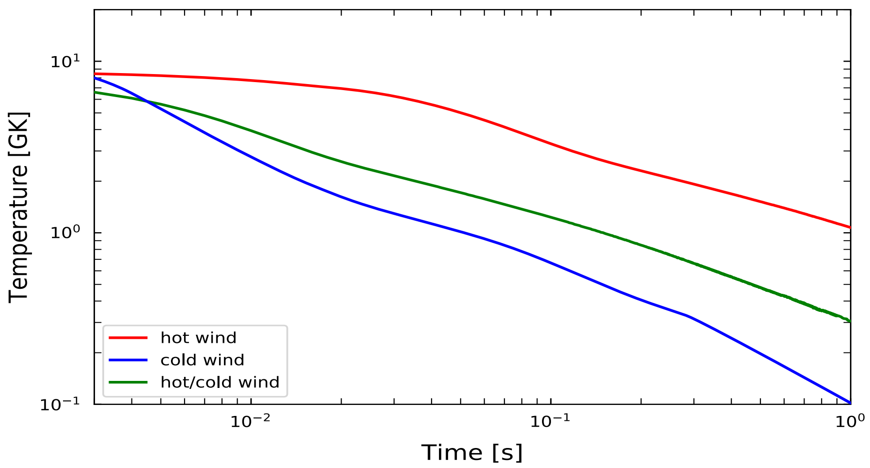


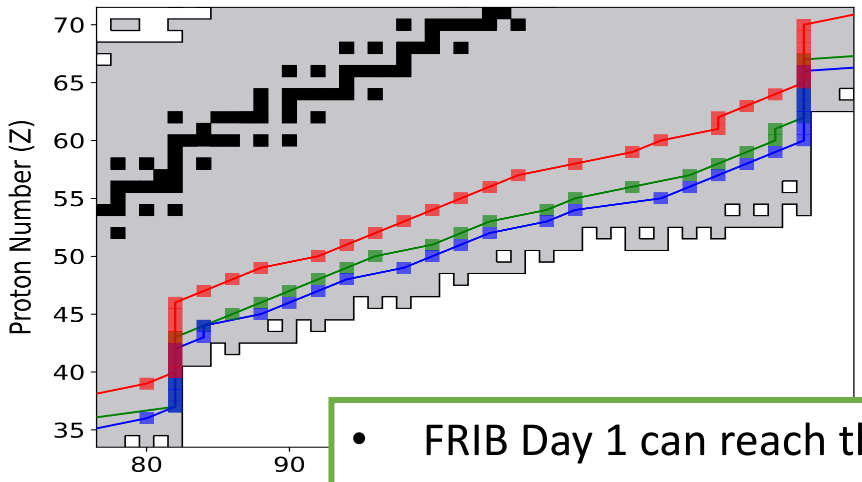


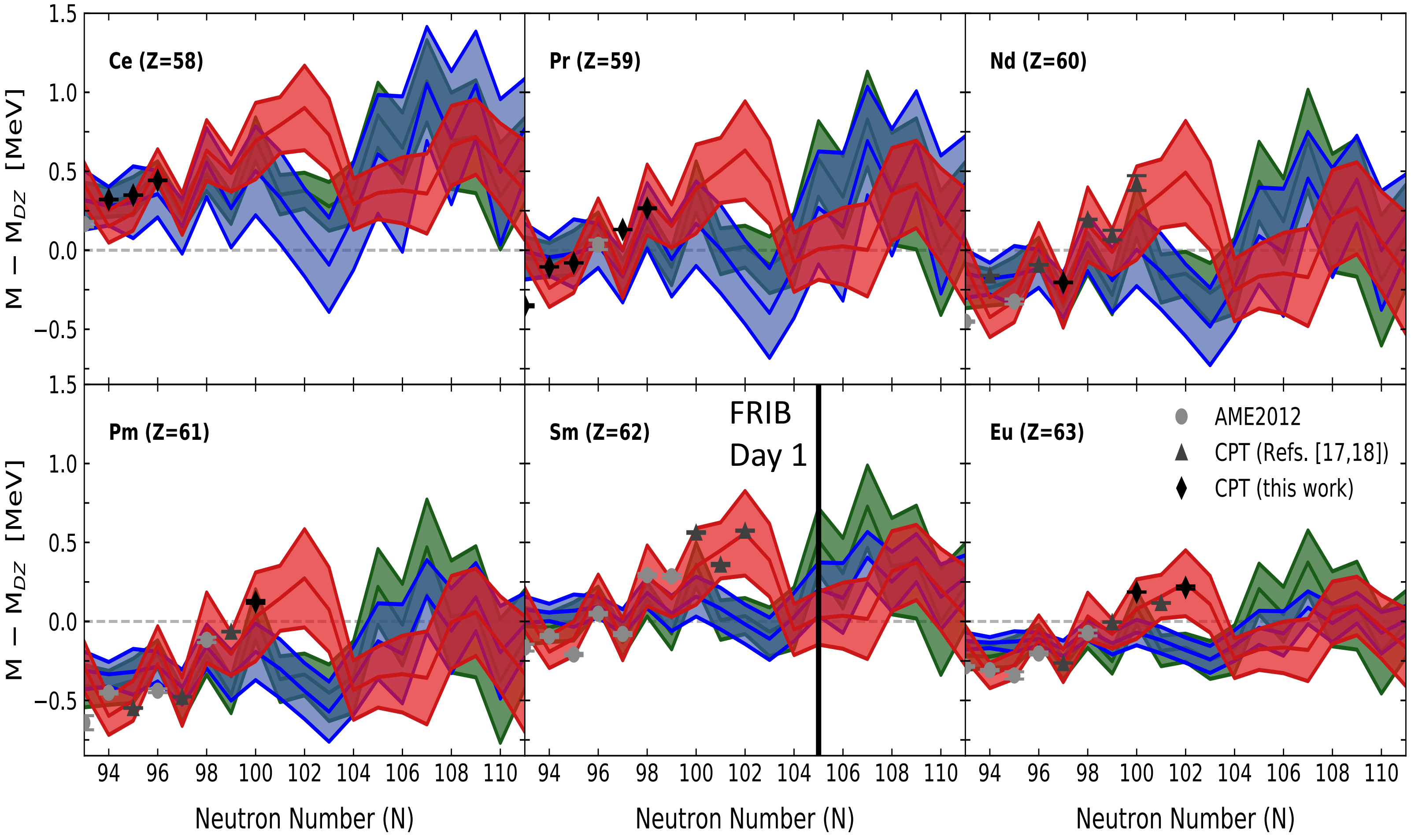
hot vs cold low entropy accretion disk winds (moderately n-rich)

Ejecta Outflow Parameters

Outflow Type	Entropy (s/k_B)	Timescale (ms)	Y_e
Hot	30	70	0.2
Hot/cold	20	10	0.2
Cold	10	3	0.2





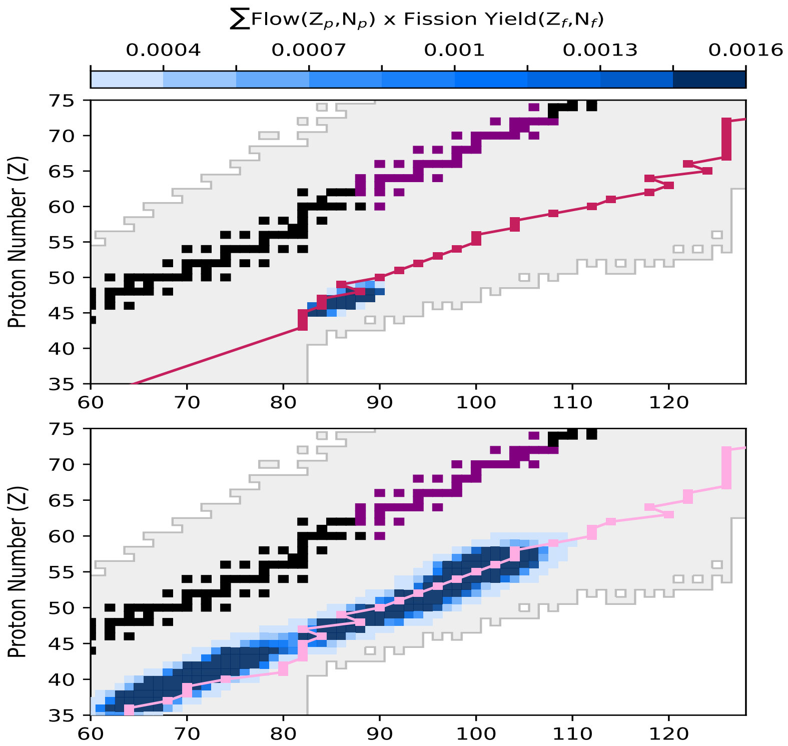


Orford,Vassh+22 (PRC Letters)

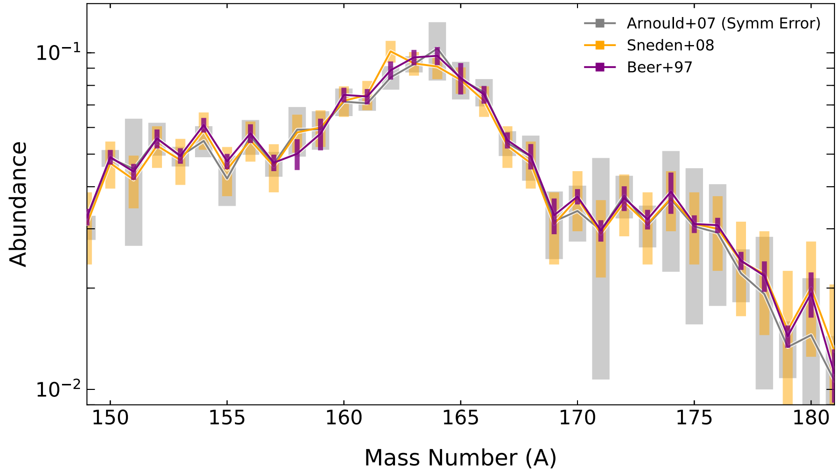
- FRIB Day 1 can reach the N=104 feature forming the peak in hot conditions
- Future FRIB reach will cover the N=108 and N=106 features utilized with cold and in between dynamics

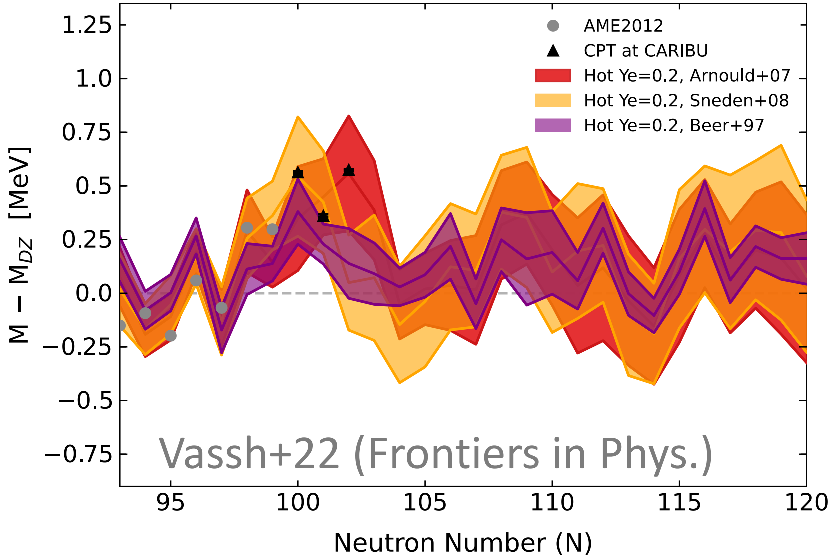
Recent work:

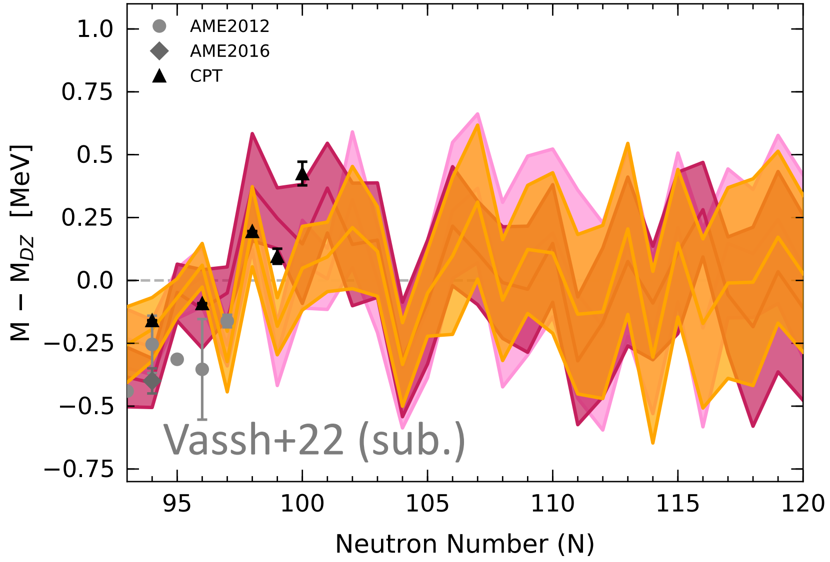
Very n-rich conditions with fission deposition



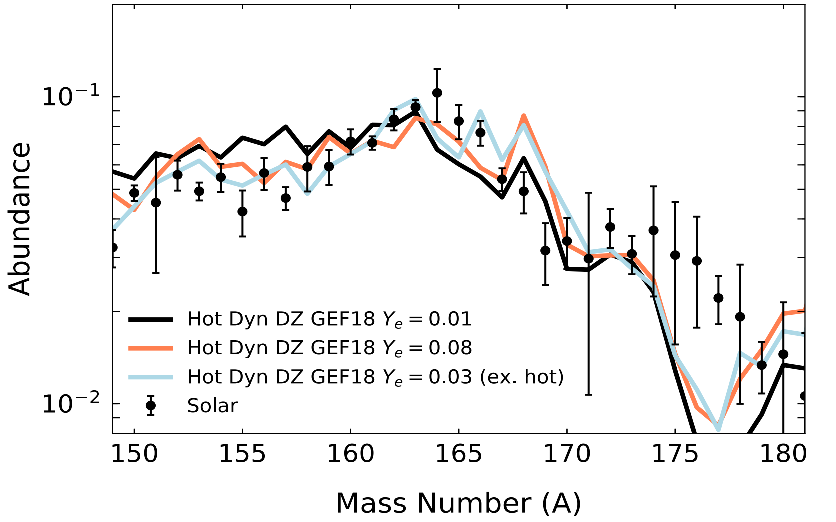
Solar abundance variations

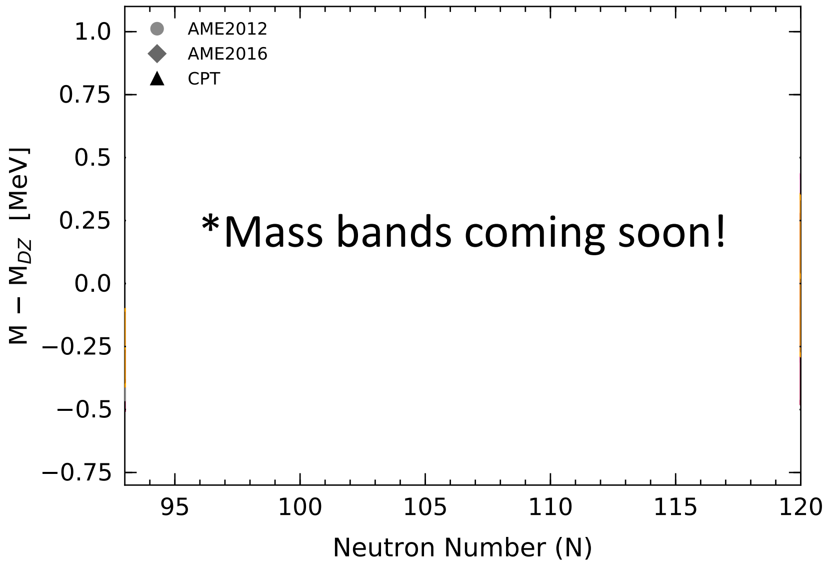






A wider variety of n-richness





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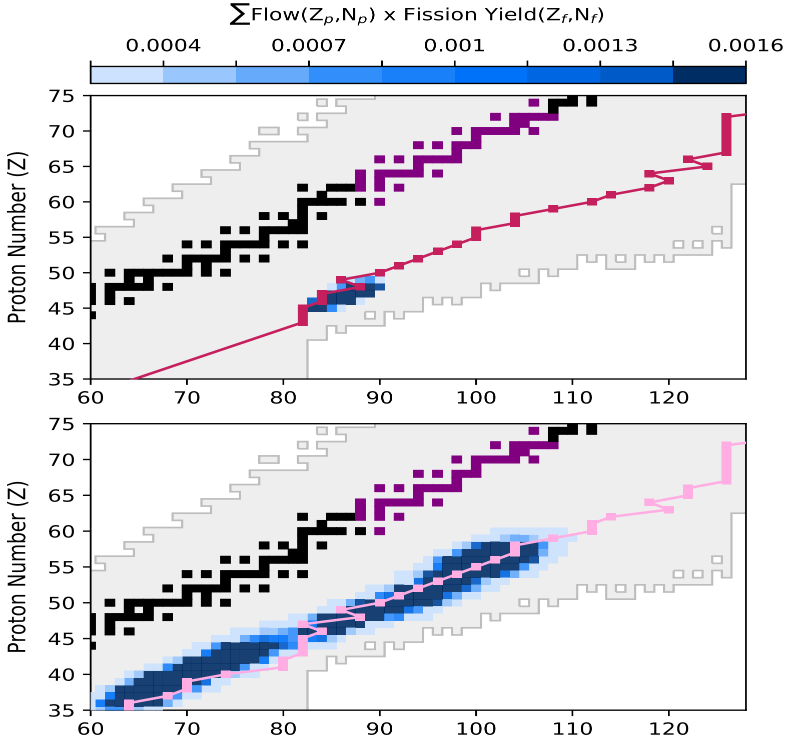

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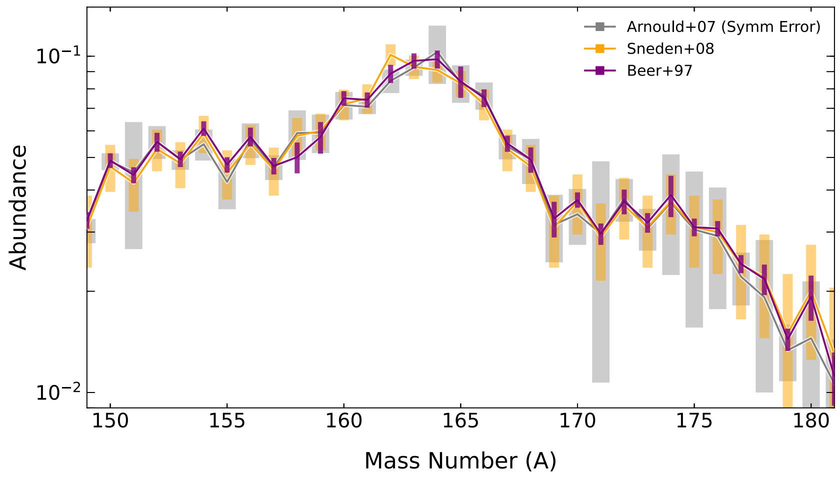

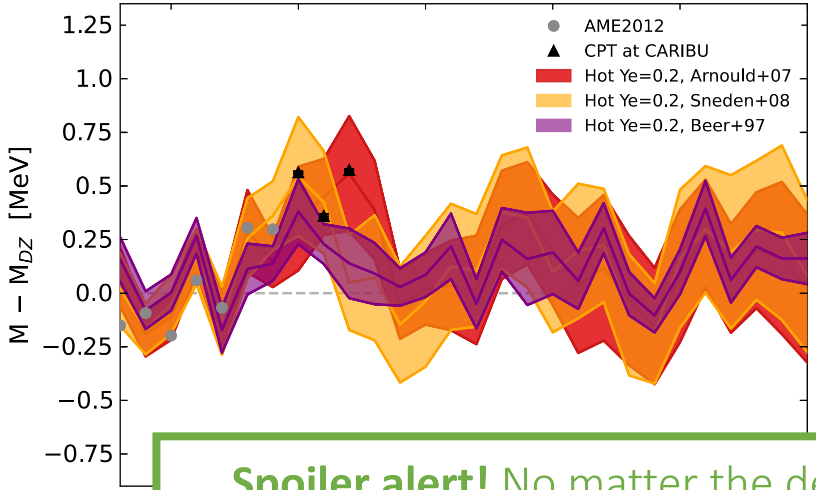

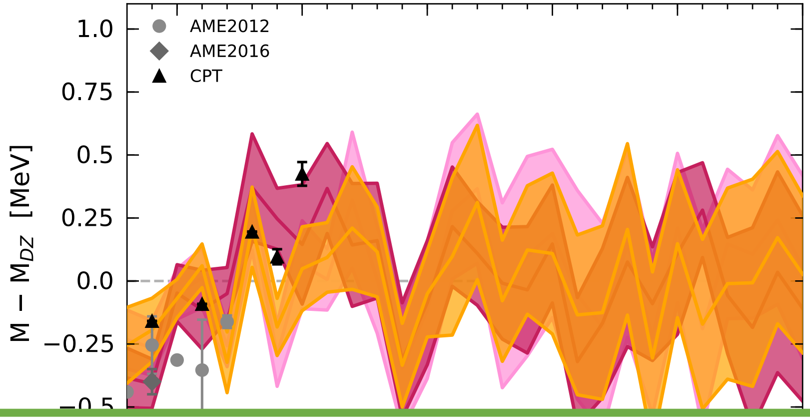

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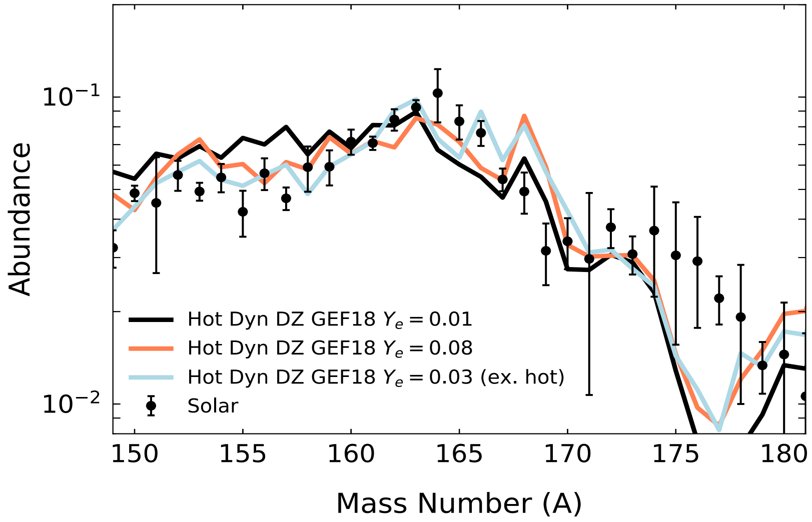
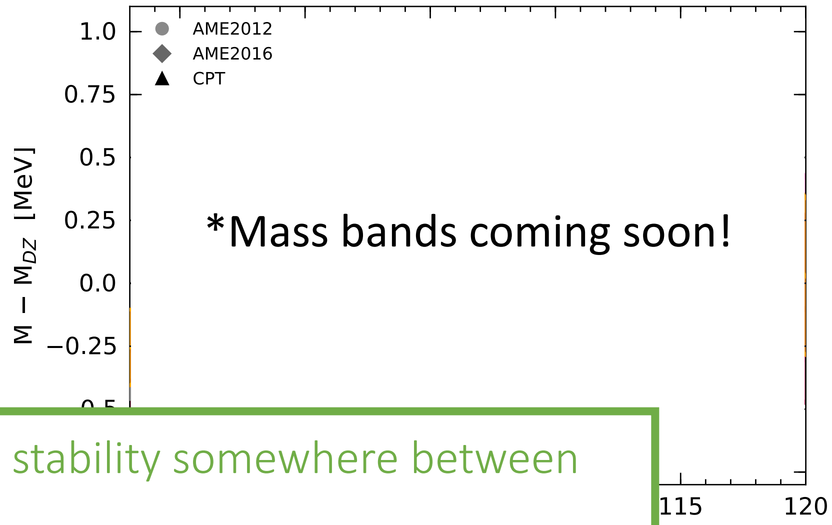
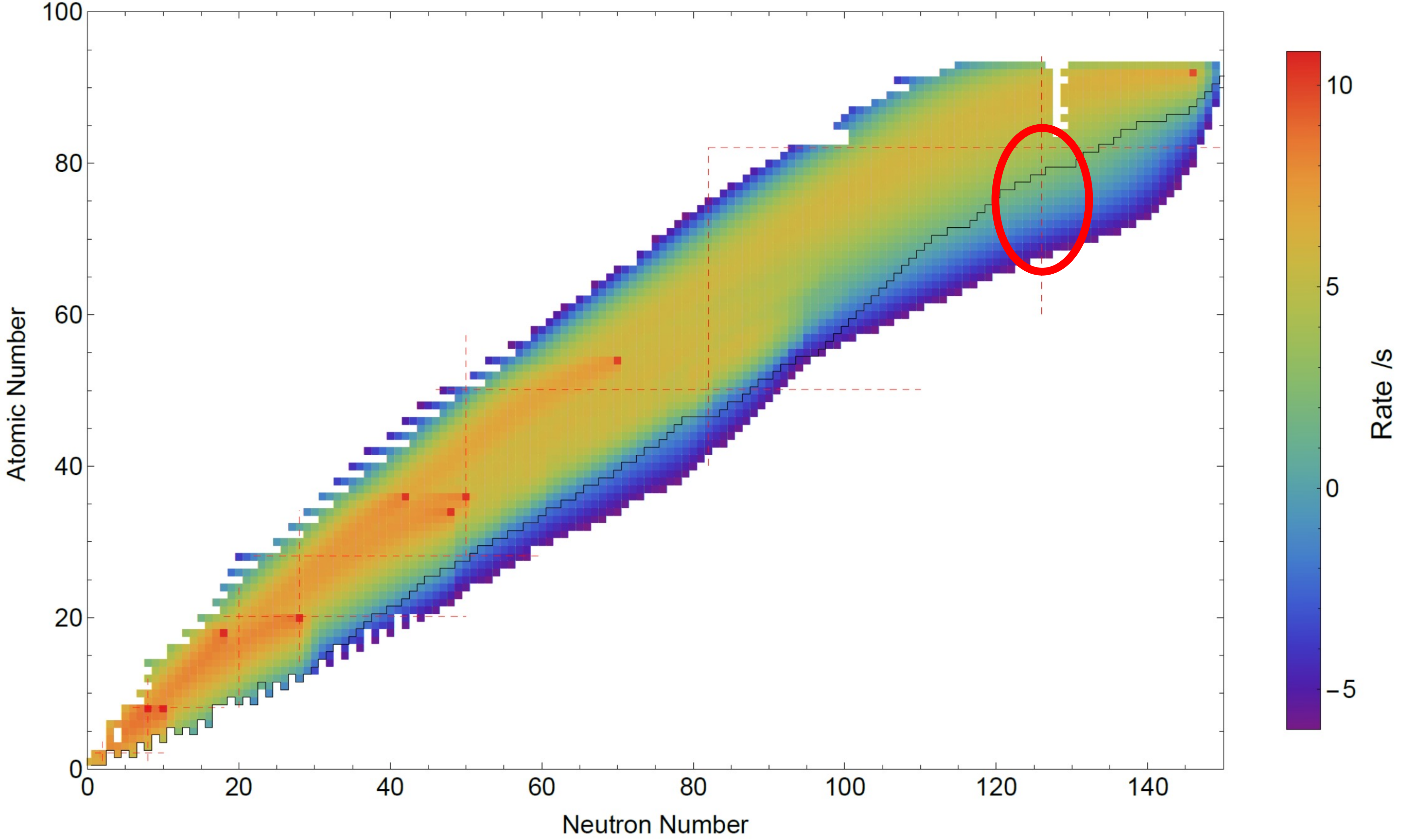


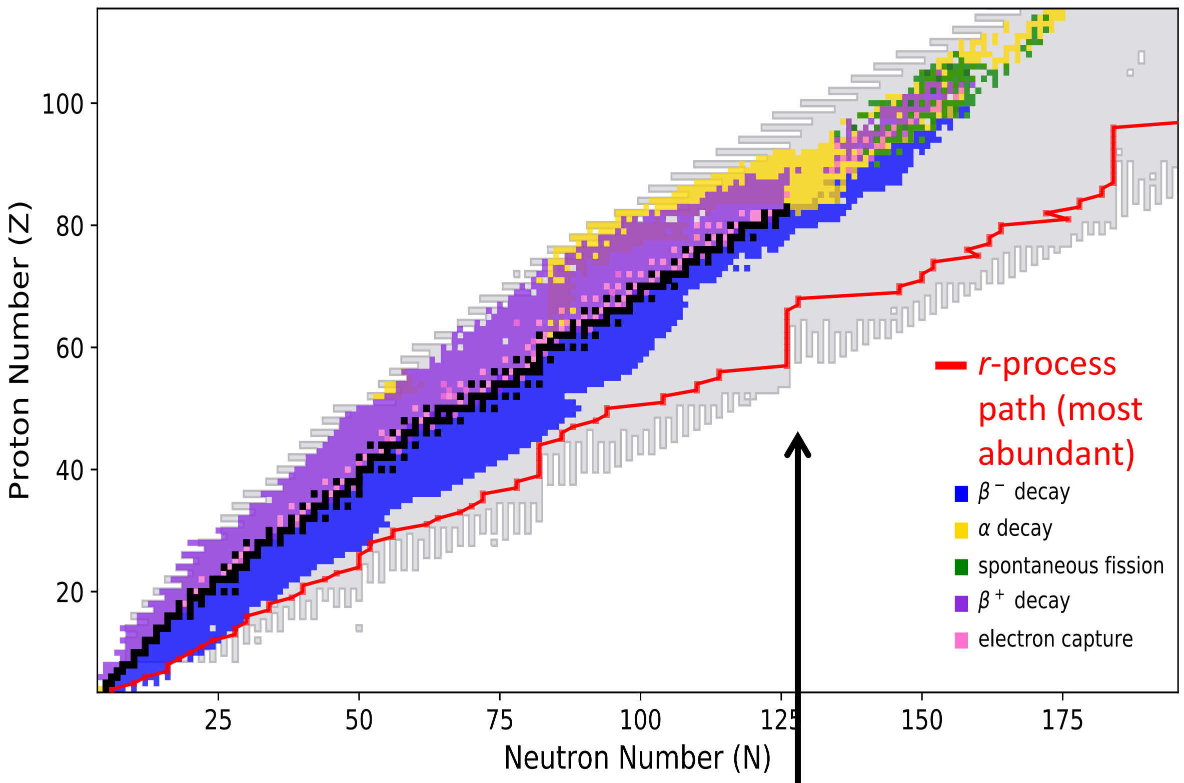


Spoiler alert! No matter the details we almost always need a local enhanced stability somewhere between N=104-108 in the isotopic chains of Z~57-63

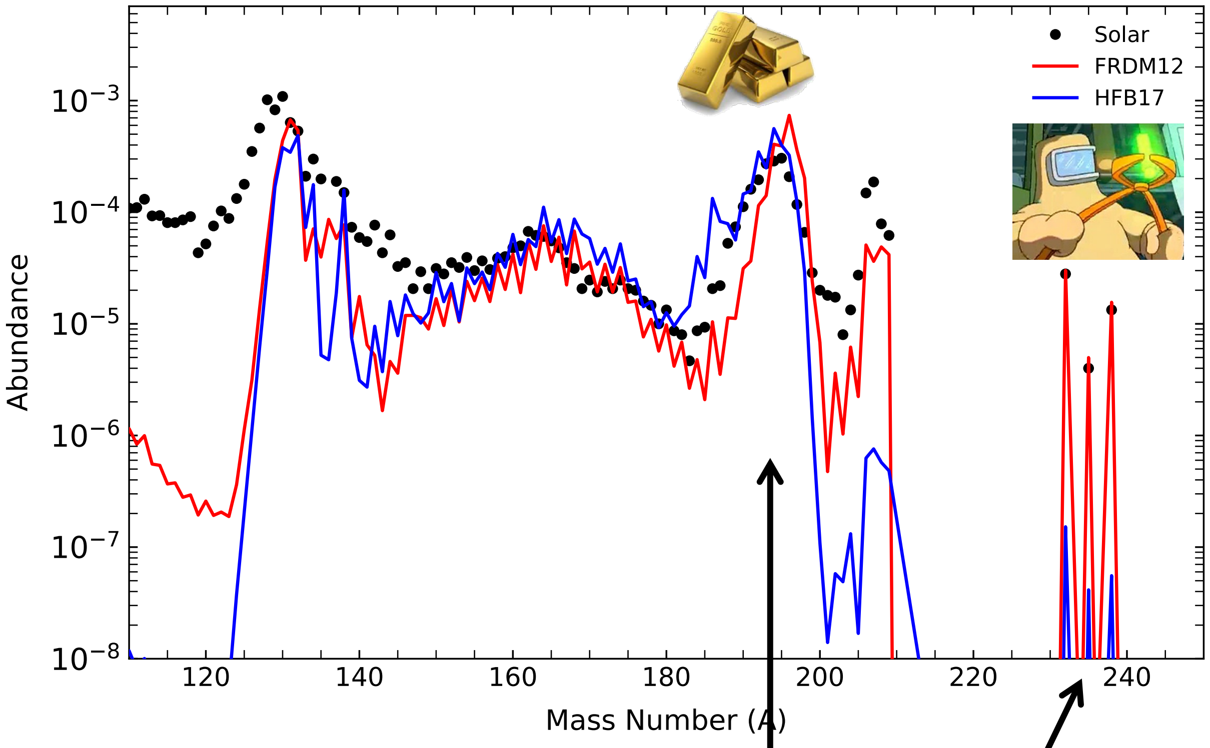
r-process studies in the FRIB era



Current state of the *r*-process N=126 peak



Little to no experimental data on the neutron-rich side at N=126

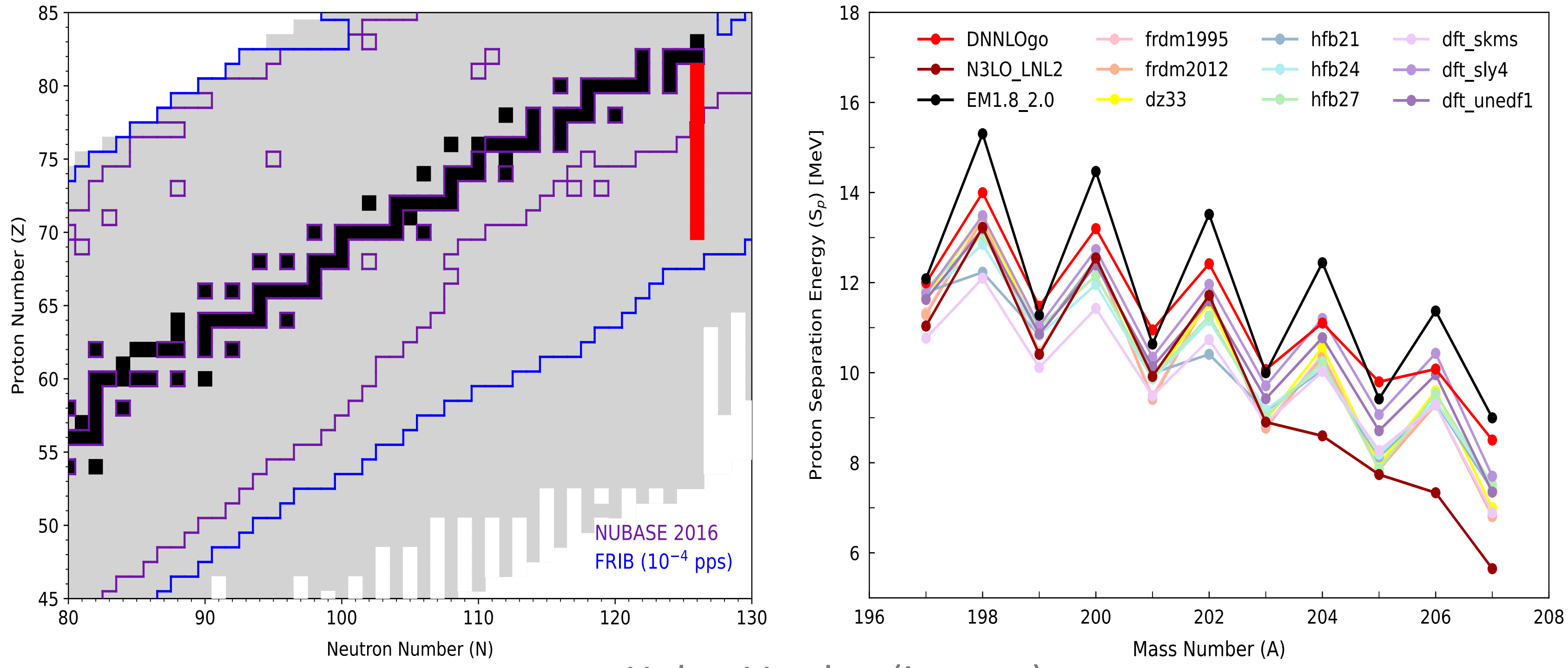


*Nuclear mass models predict different shell closure strengths = different amounts of elements like Au, Pt

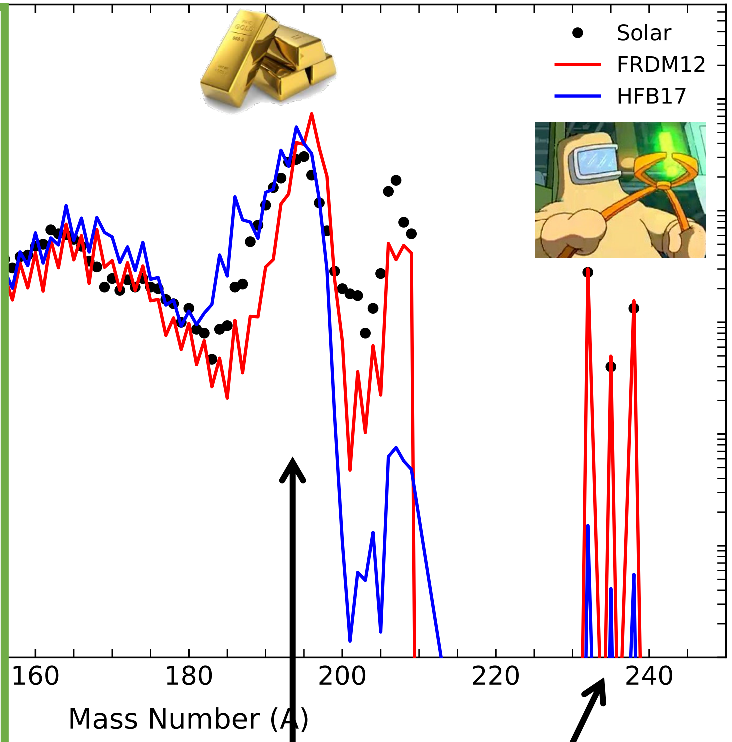
*The N=126 shell closure is the “gateway” to the actinides: e.g. affects production of uranium-238, etc.

Current state of the *r*-process N=126 peak

The new reach of *ab initio* nuclear theory: N=126 masses



Holt + Vassh + (in prep)



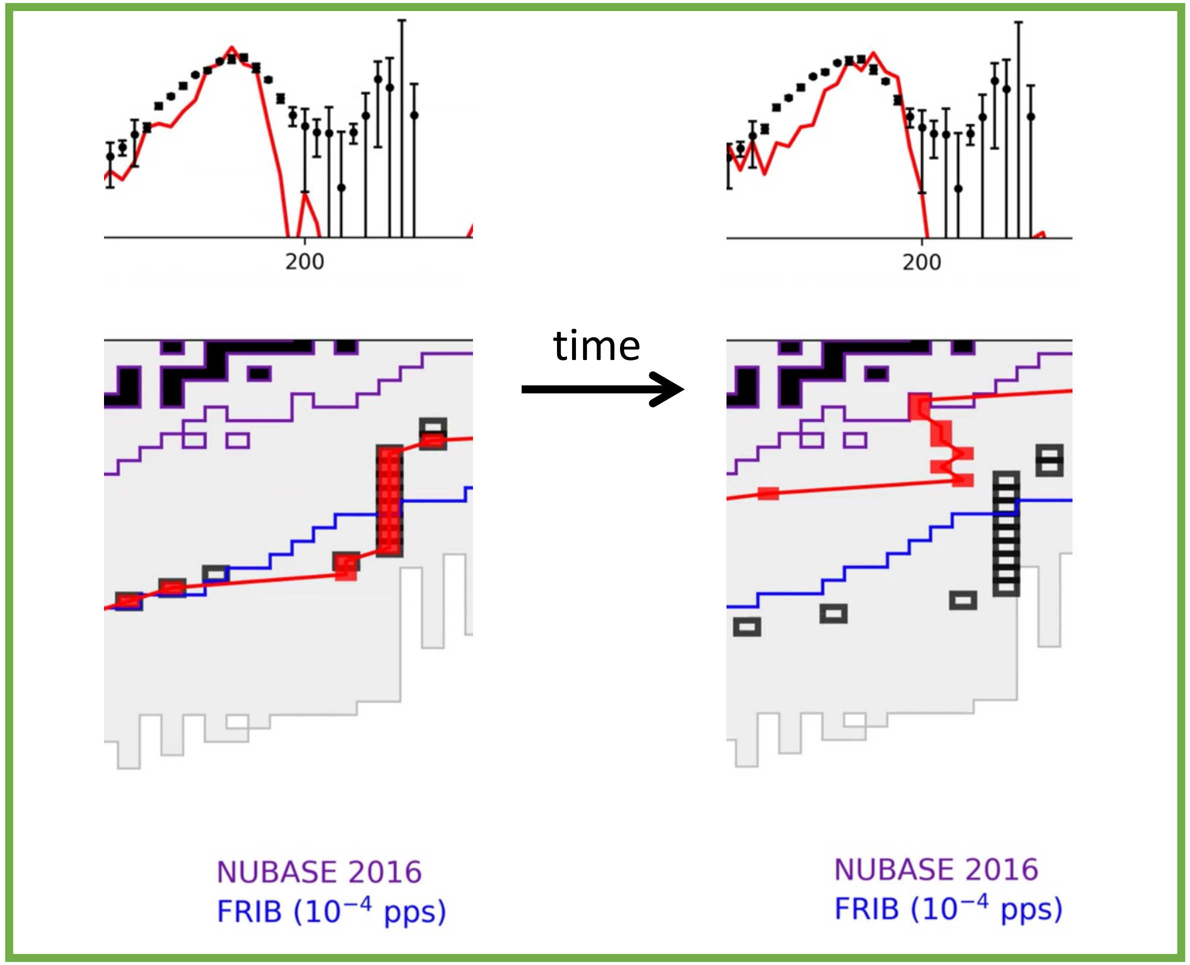
models predict different shell closure strengths = different amounts of elements like Au, Pt

*FRIB can constrain the separation energies that determine the how strongly nuclei "pile-up" at N=126 in the *r*-process and how difficult it is to capture beyond into the actinides

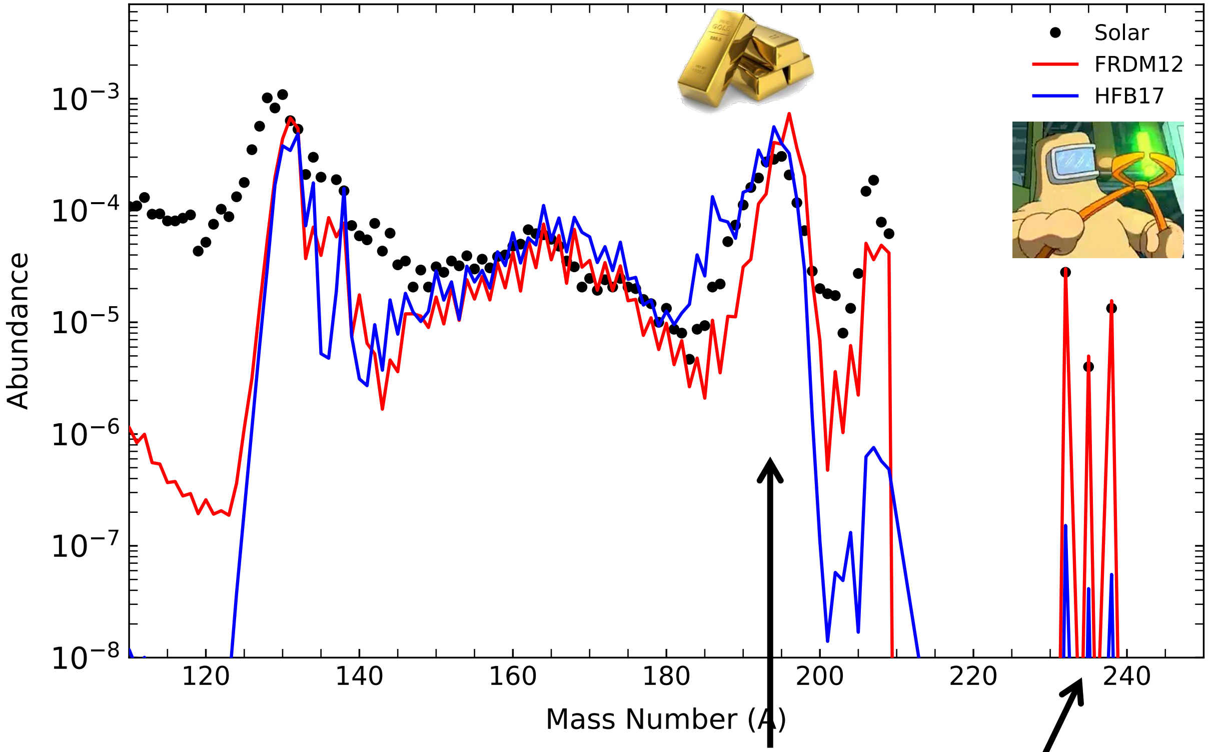
*The N=126 shell closure is the "gateway" to the actinides: e.g. affects production of uranium-238, etc.

Current state of the *r*-process N=126 peak

Local β-decay and neutron capture competition near N=126 can shift and narrow the peak



*FRIB can constrain the beta-decay properties (half-lives, neutron emission, strength functions…) responsible for peak structure



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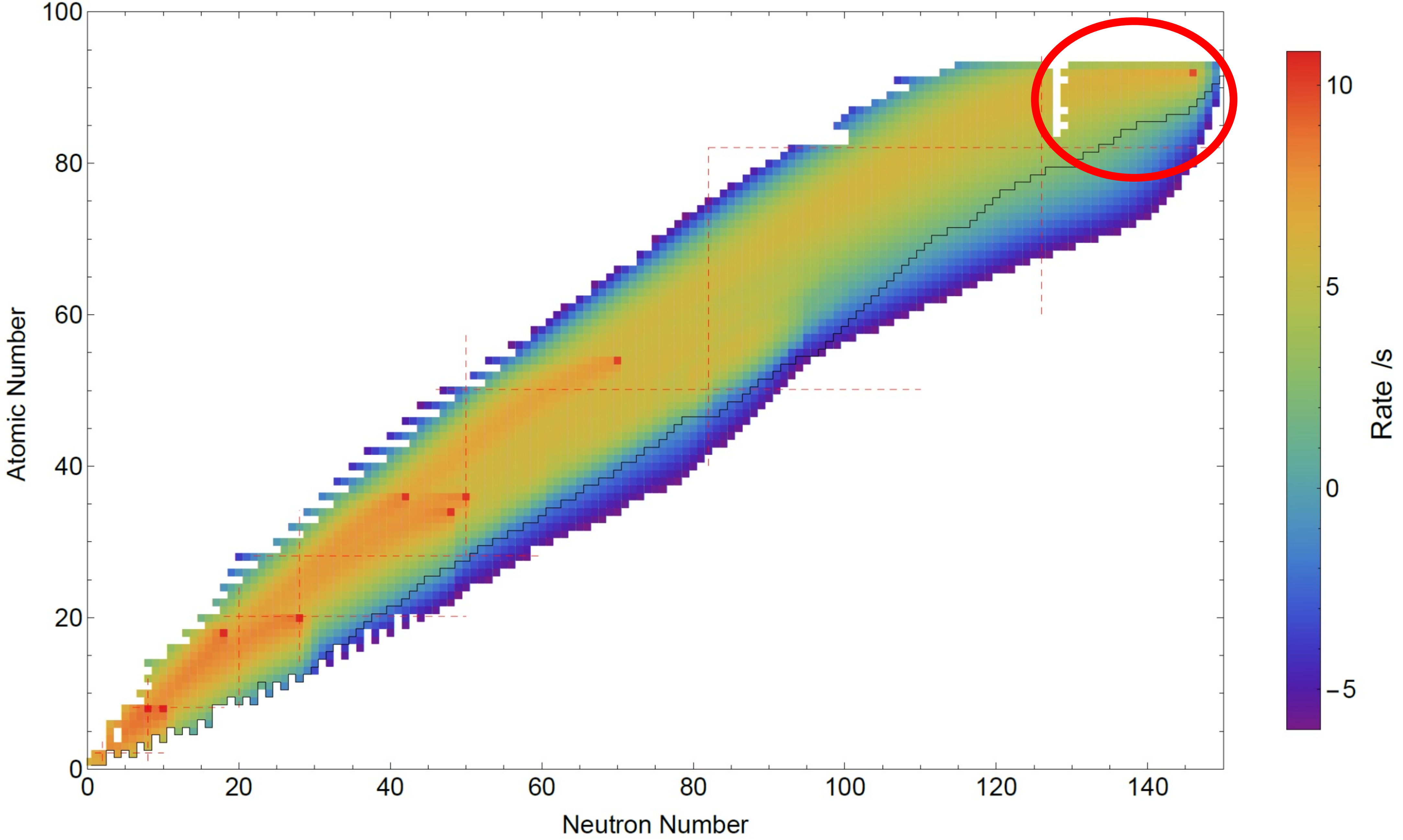
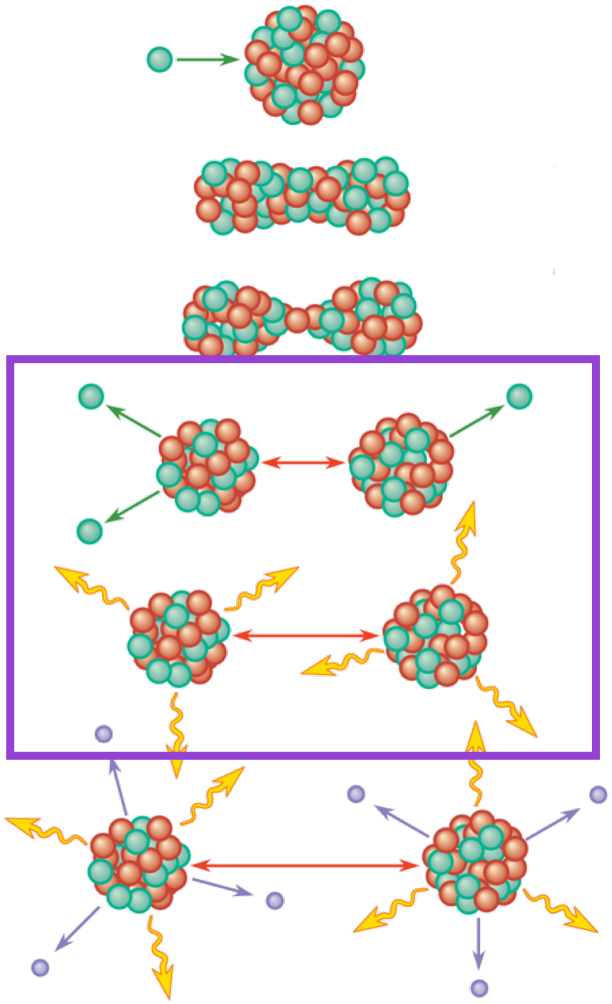


Are actinides produced in neutron star mergers?



Fission heating can greatly impact light curves

PHYSICAL REVIEW VOLUME 103, NUMBER 5 SEPTEMBER 1, 1956

Californium-254 and Supernovae*

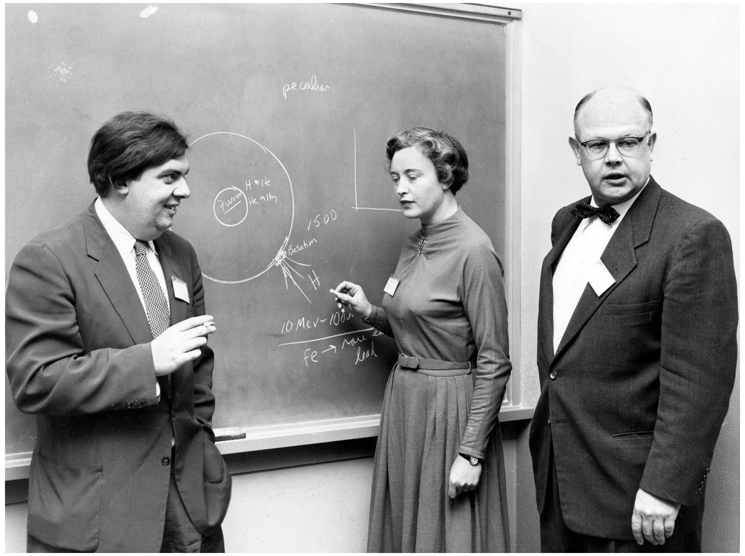
G. R. Burbidge and F. Hoyle,† *Mount Wilson and Palomar Observatories, Carnegie Institution of Washington, California Institute of Technology, Pasadena, California*

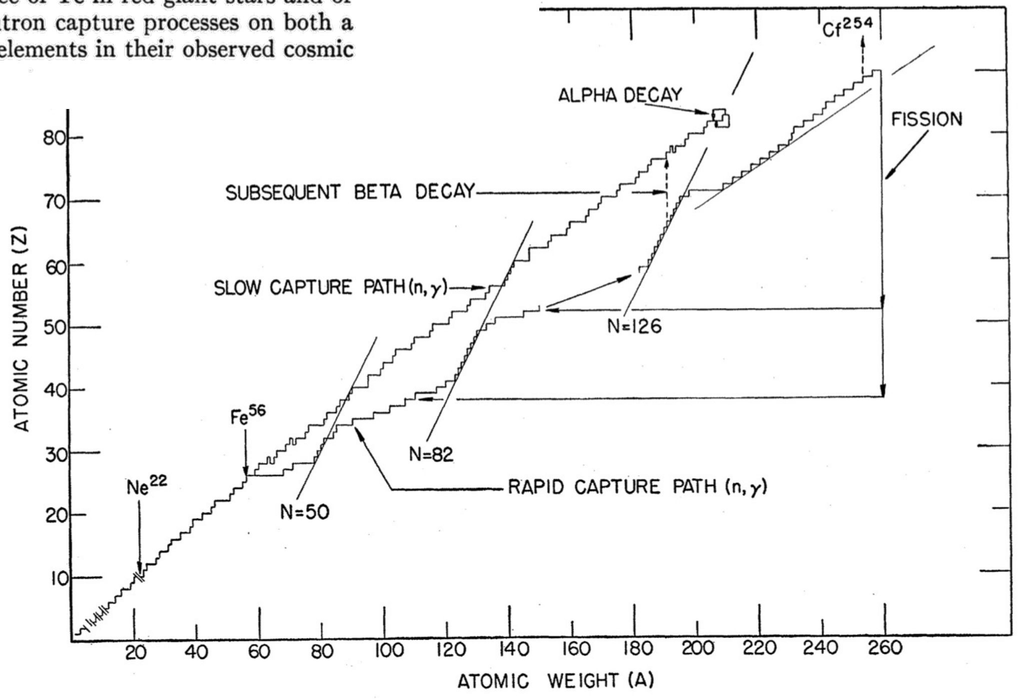
AND

E. M. Burbidge, R. F. Christy, and W. A. Fowler, *Kellogg Radiation Laboratory, California Institute of Technology, Pasadena, California*

(Received May 17, 1956)

It is suggested that the spontaneous fission of Cf^{254} with a half-life of 55 days is responsible for the form of the decay light-curves of supernovae of Type I which have an exponential form with a half-life of 55 nights. The way in which Cf^{254} may be synthesized in a supernova outburst, and reasons why the energy released by its decay may dominate all others are discussed. The presence of Tc in red giant stars and of Cf in Type I supernovae appears to be observational evidence that neutron capture processes on both a slow and a fast time-scale have been necessary to synthesize the heavy elements in their observed cosmic abundances.





Burbidge, Burbidge, Fowler and Hoyle (1957)

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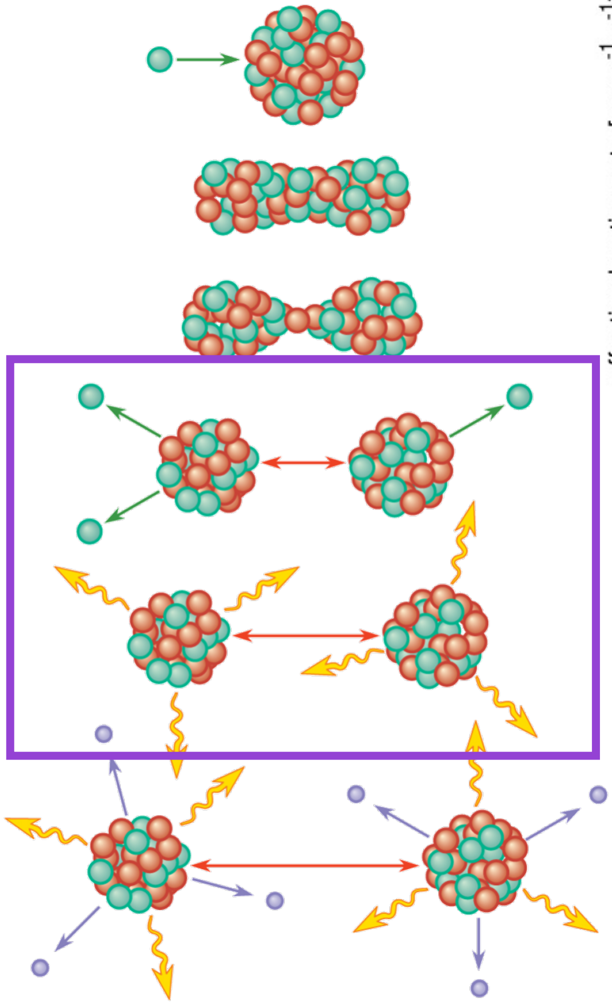

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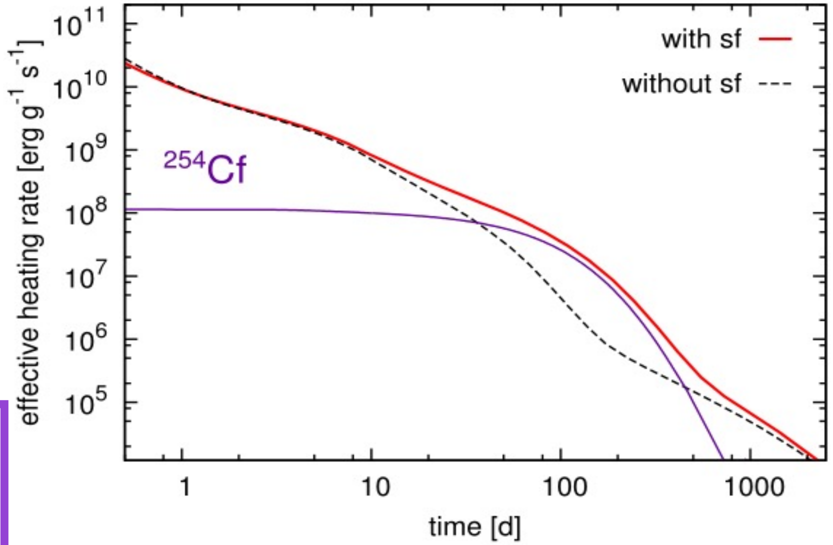
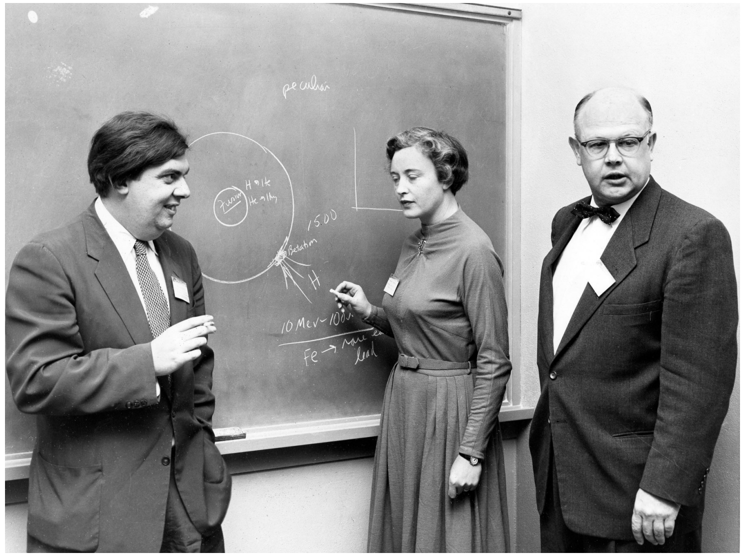
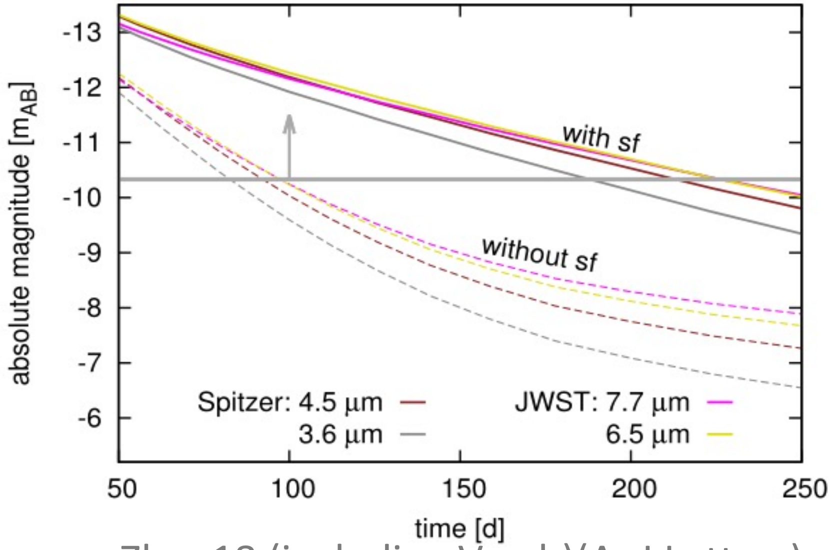
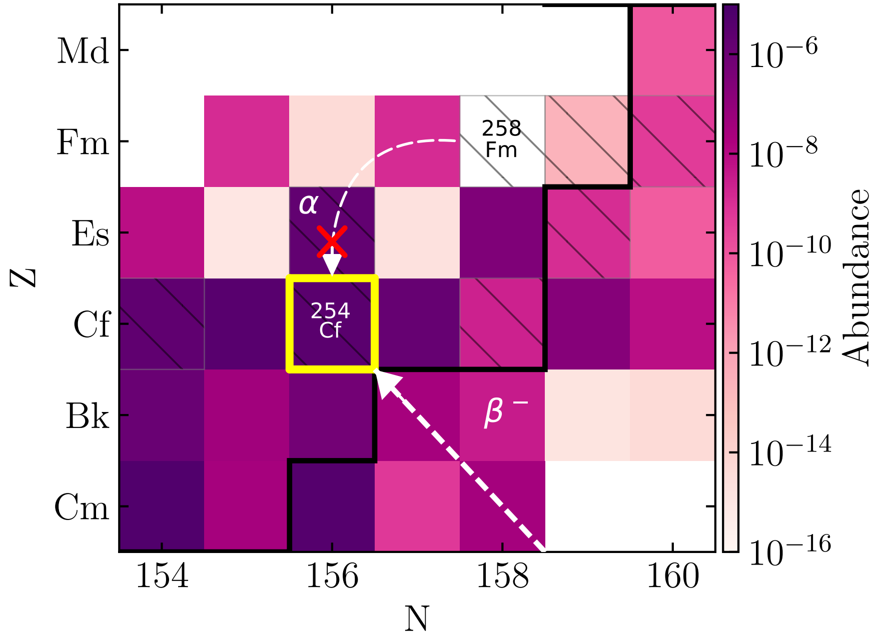






Zhu+18 (including Vassh)(ApJ Letters)



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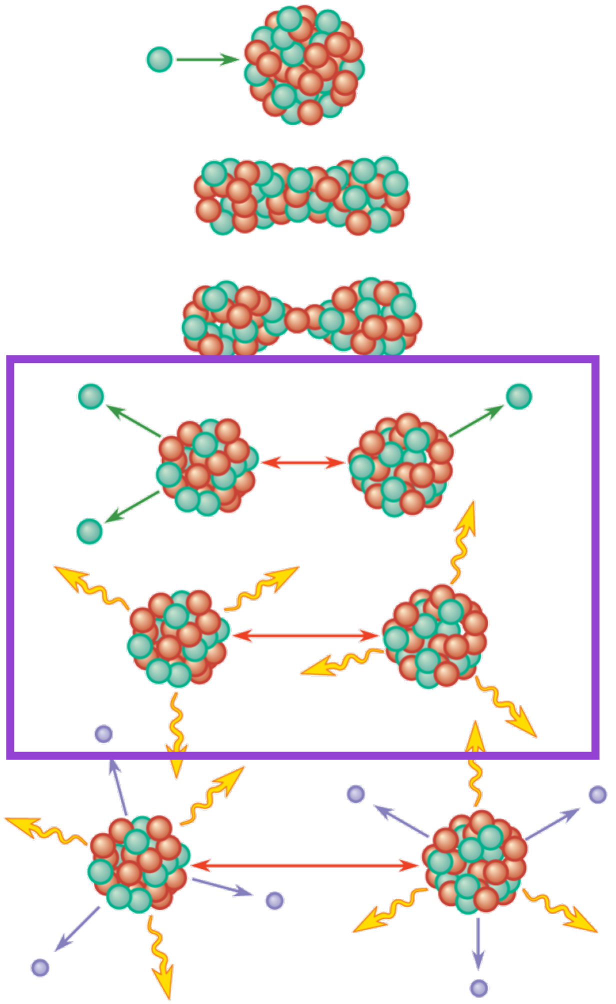

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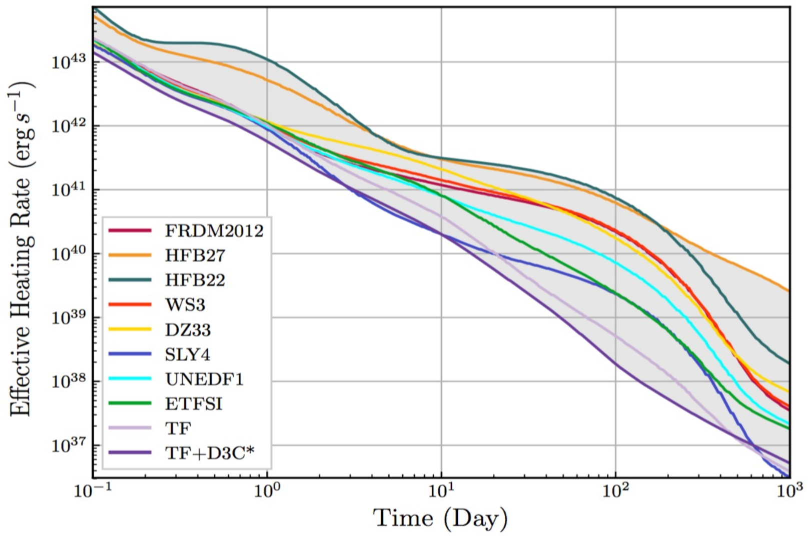
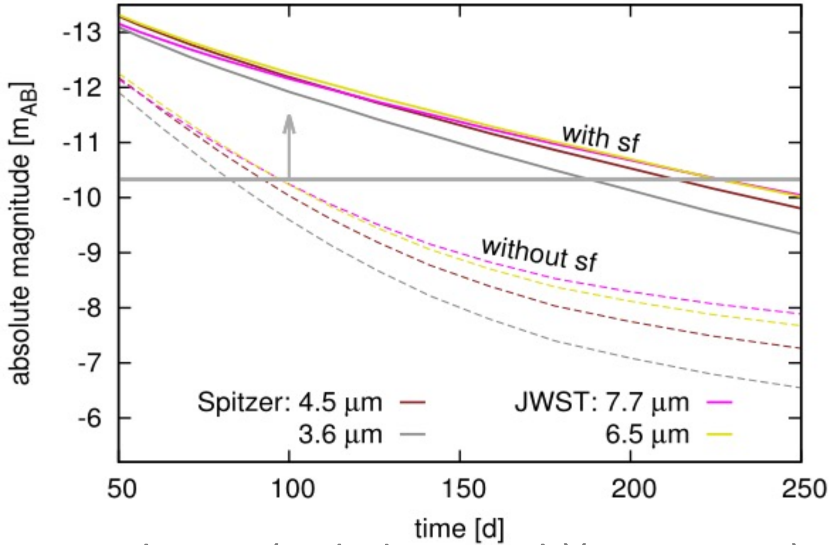


Zhu+21 (including Vassh)(ApJ)



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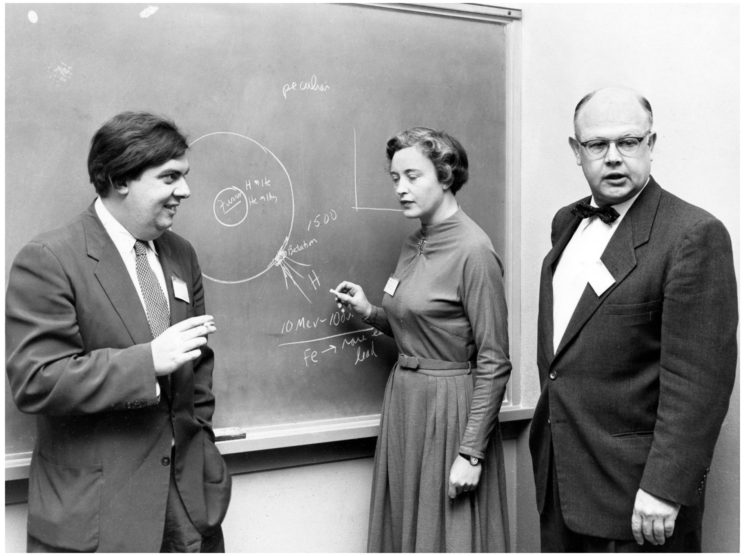

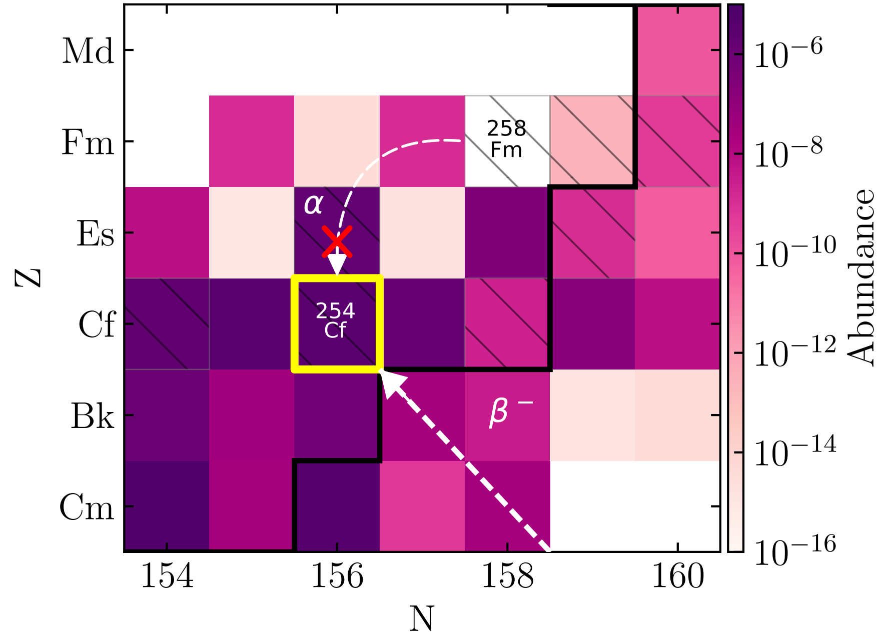

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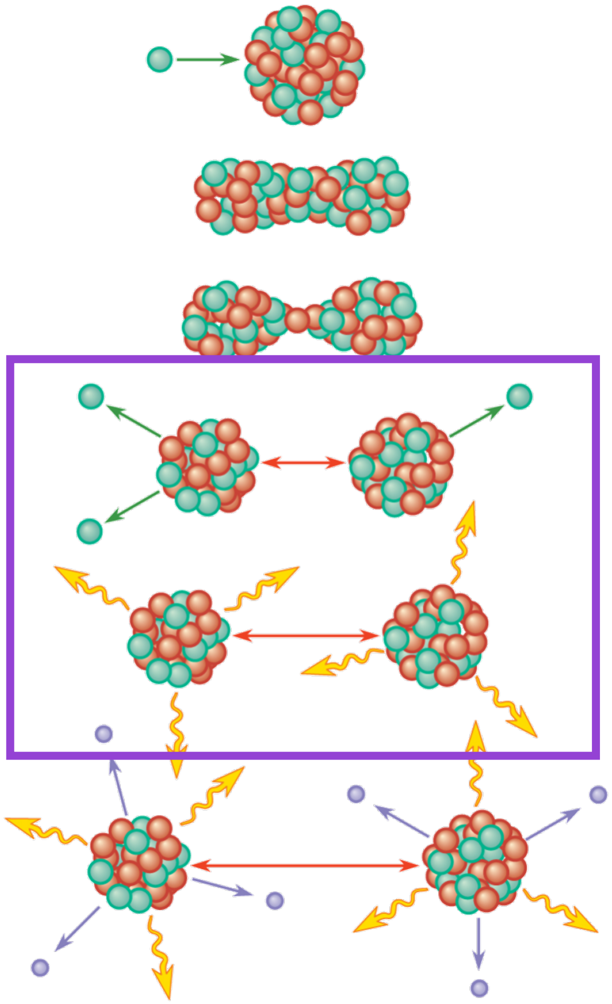

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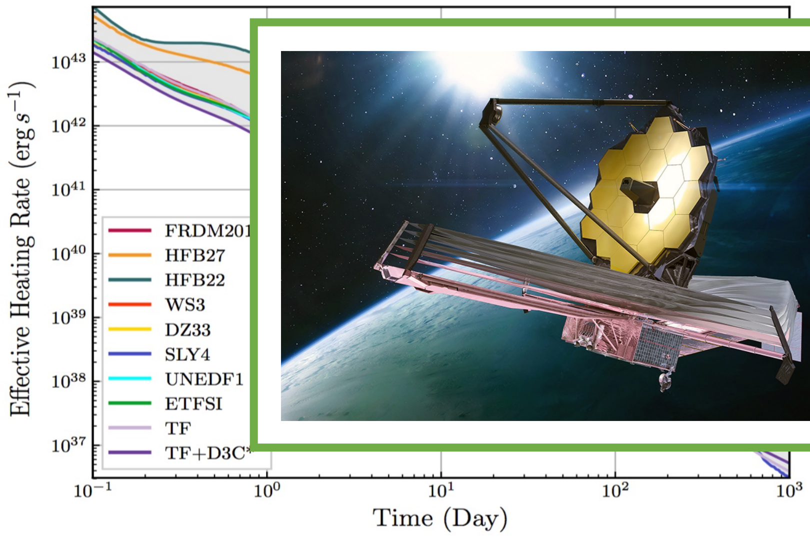
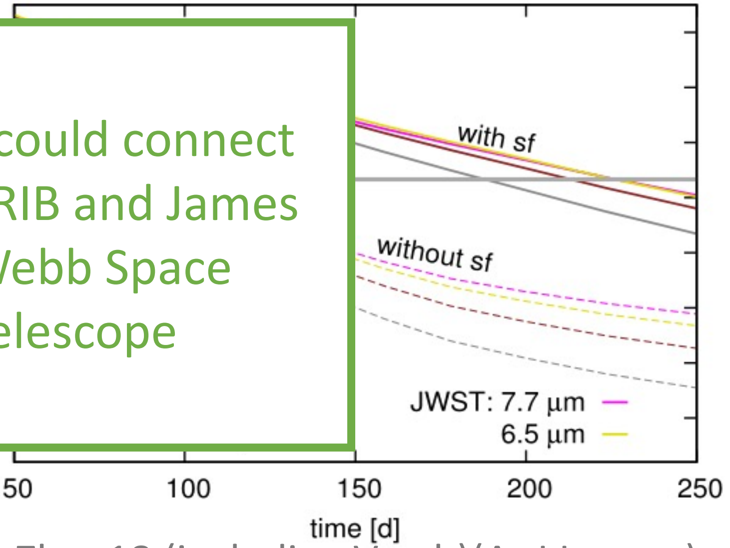


*could connect FRIB and James Webb Space Telescope



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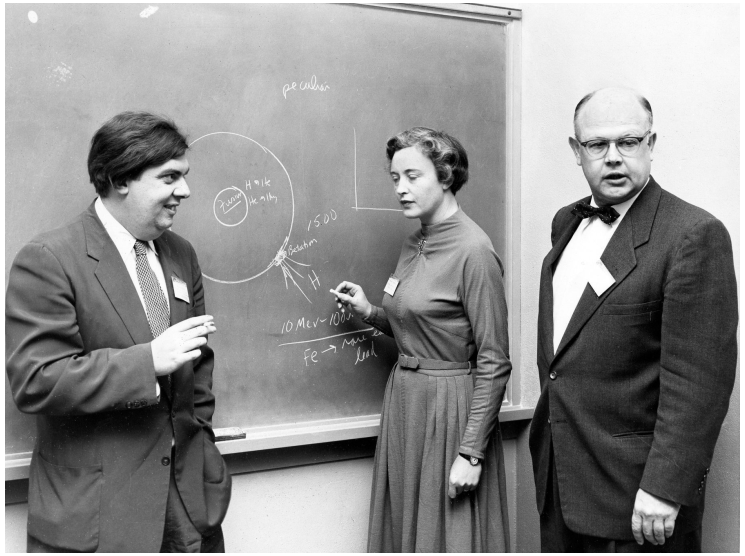

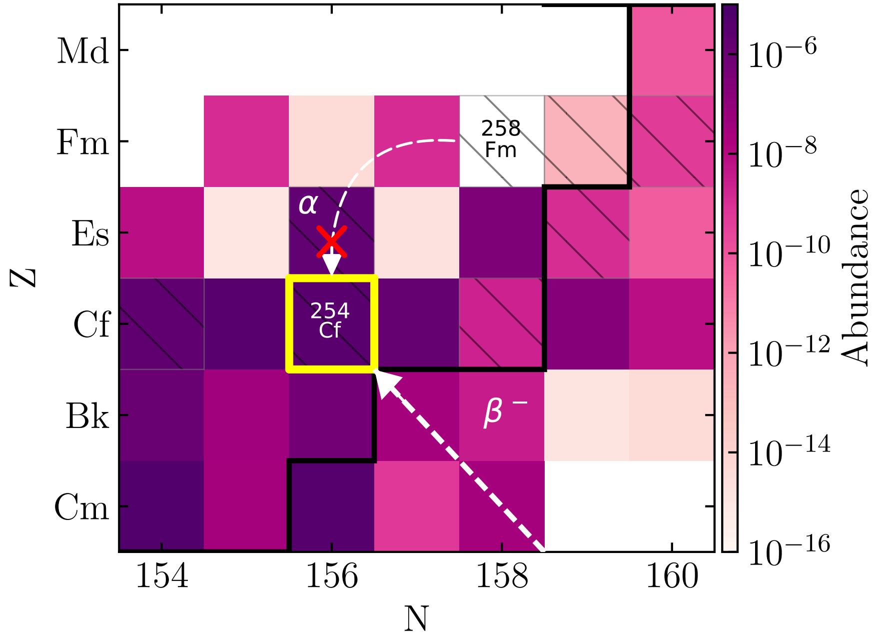

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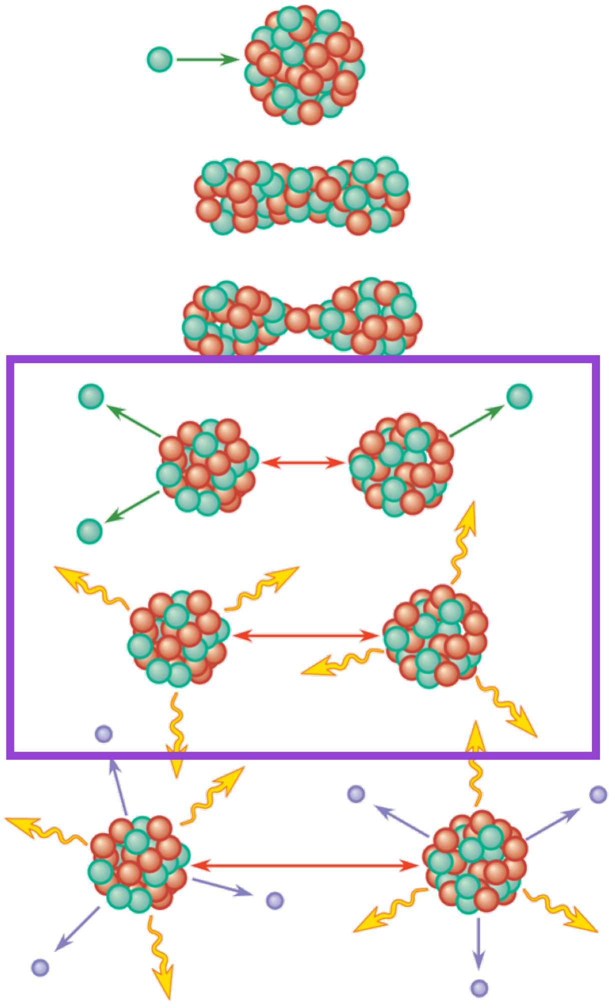

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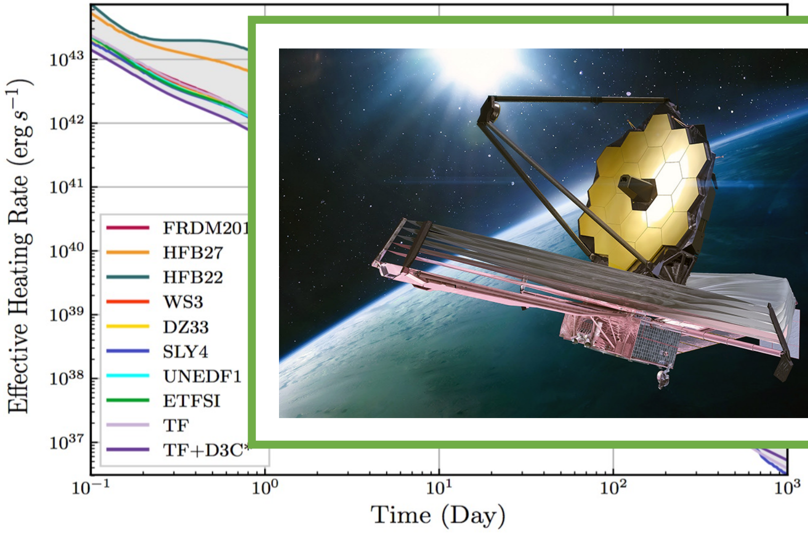

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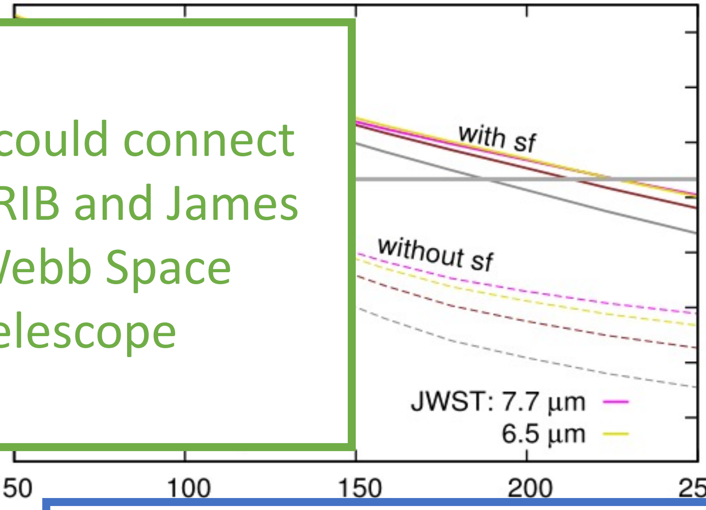
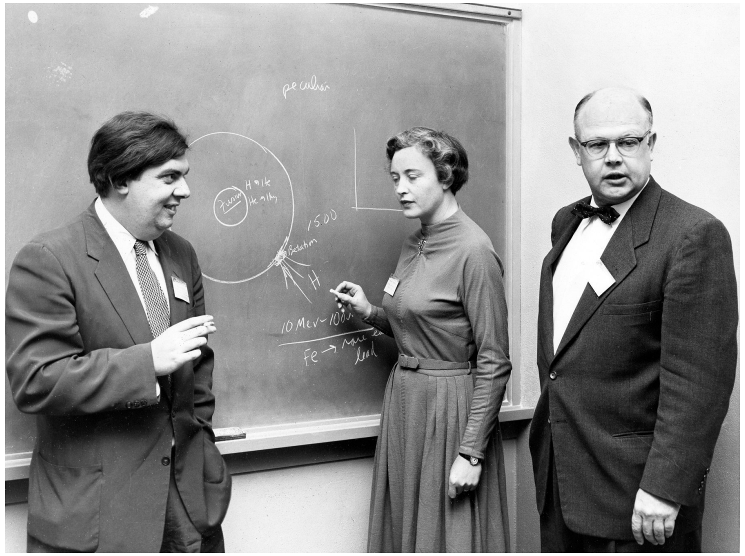
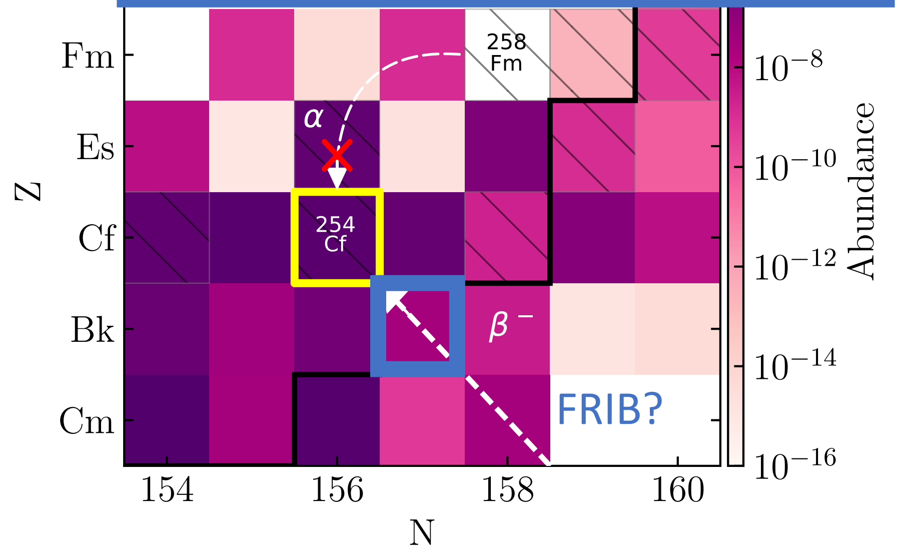




*Decay rate and branching ratios (β?βdf?α?) of 254Bk unknown (only mechanism to populate 254-Cf!)



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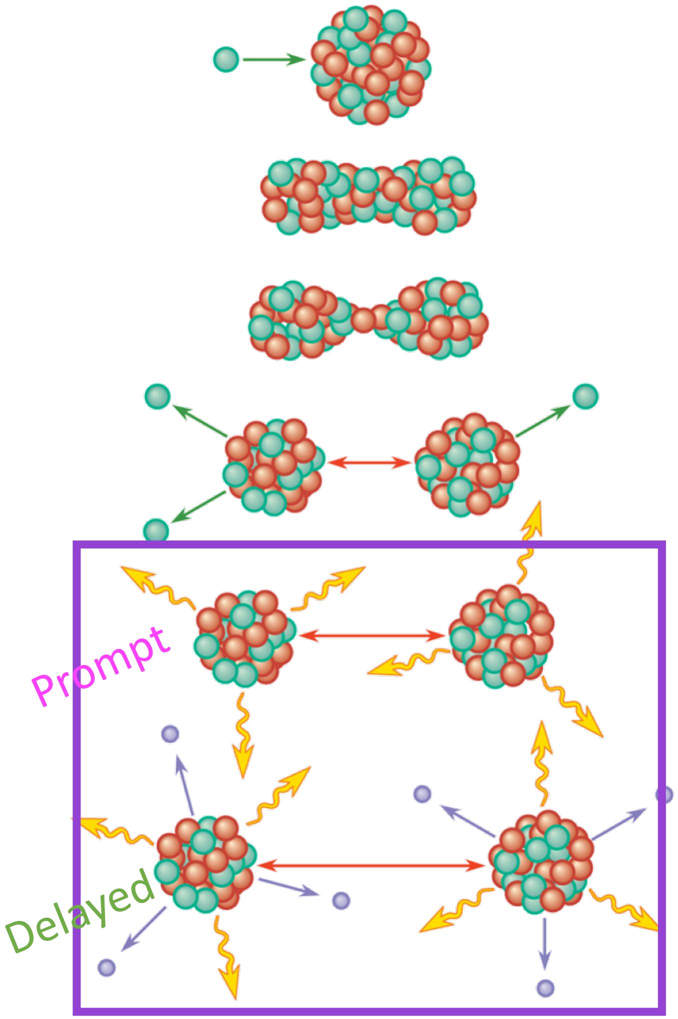
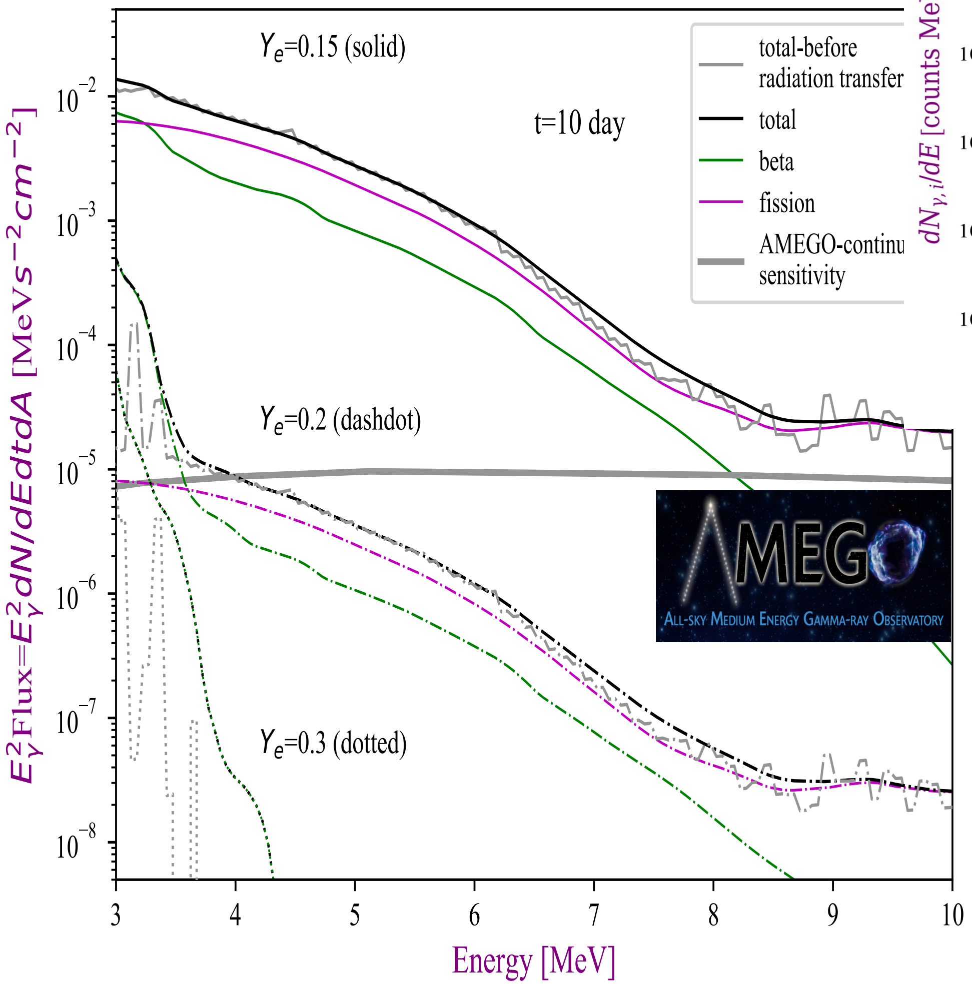
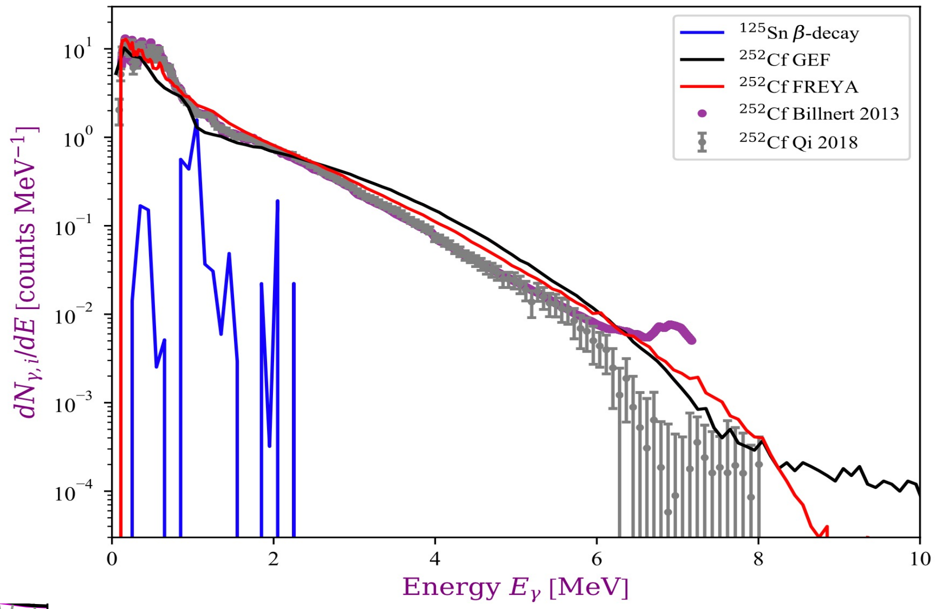


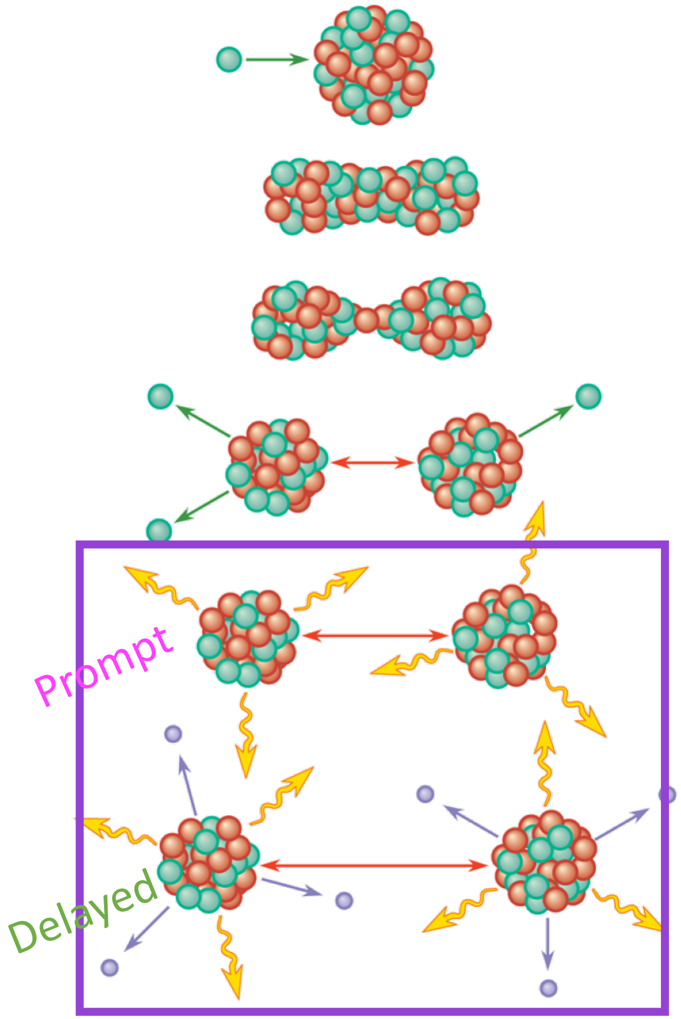


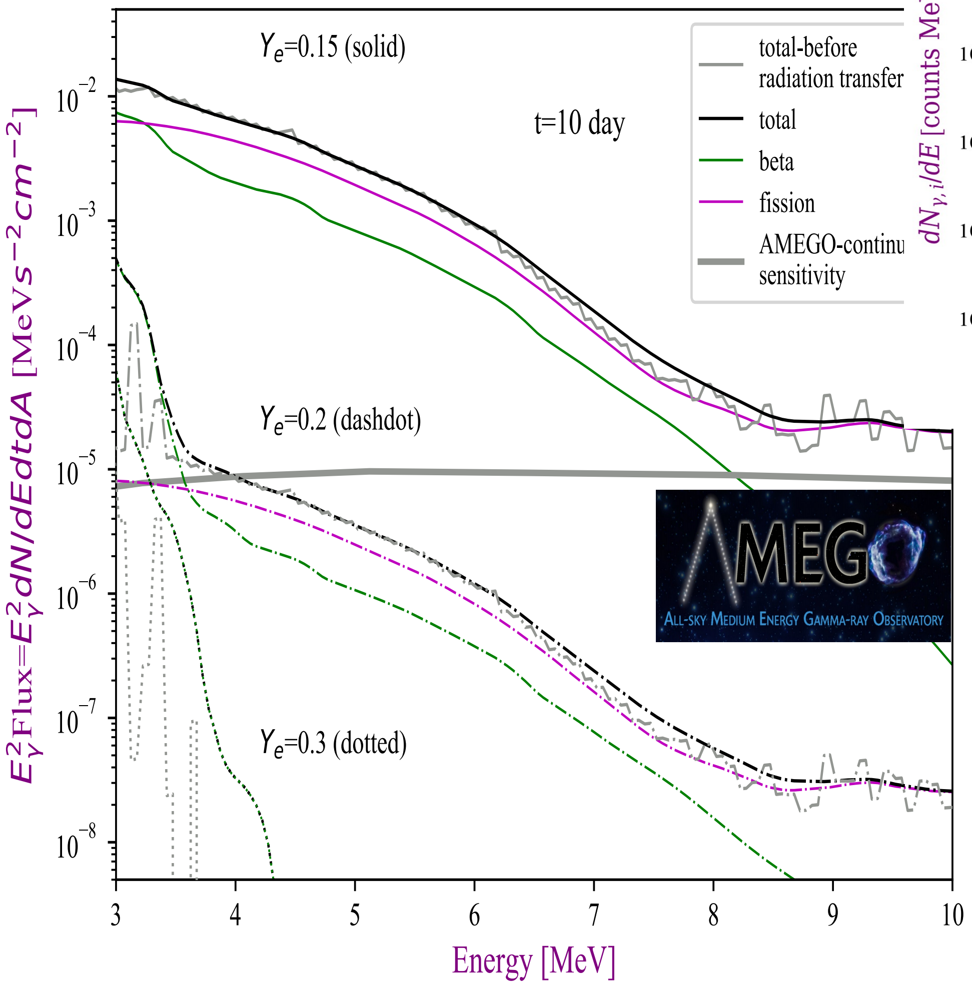


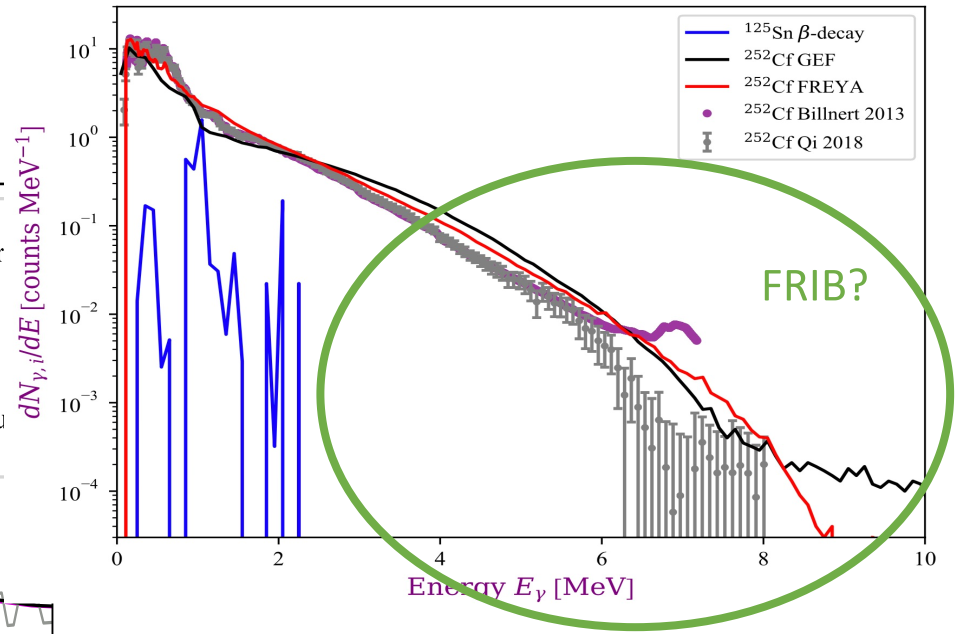
Wang,Vassh+20 (ApJ Letters); nuclear model variations being explored in Wang,Vassh+23 (in prep)

Gammas > 3.5 MeV: signature of prompt and delayed fission gammas in a merger event!

Are actinides produced in neutron star mergers?







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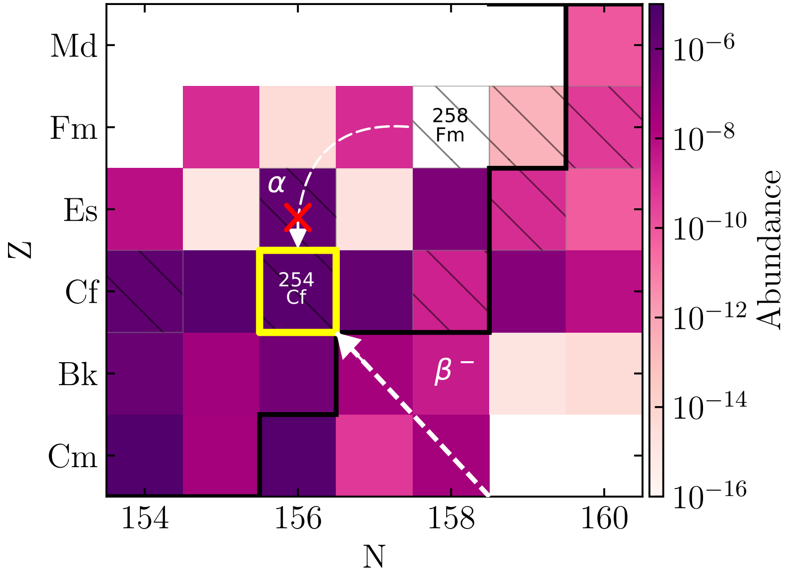
FRIB measurements of fission gamma spectra for 254Cf and other long-lived nuclei which undergo sf?

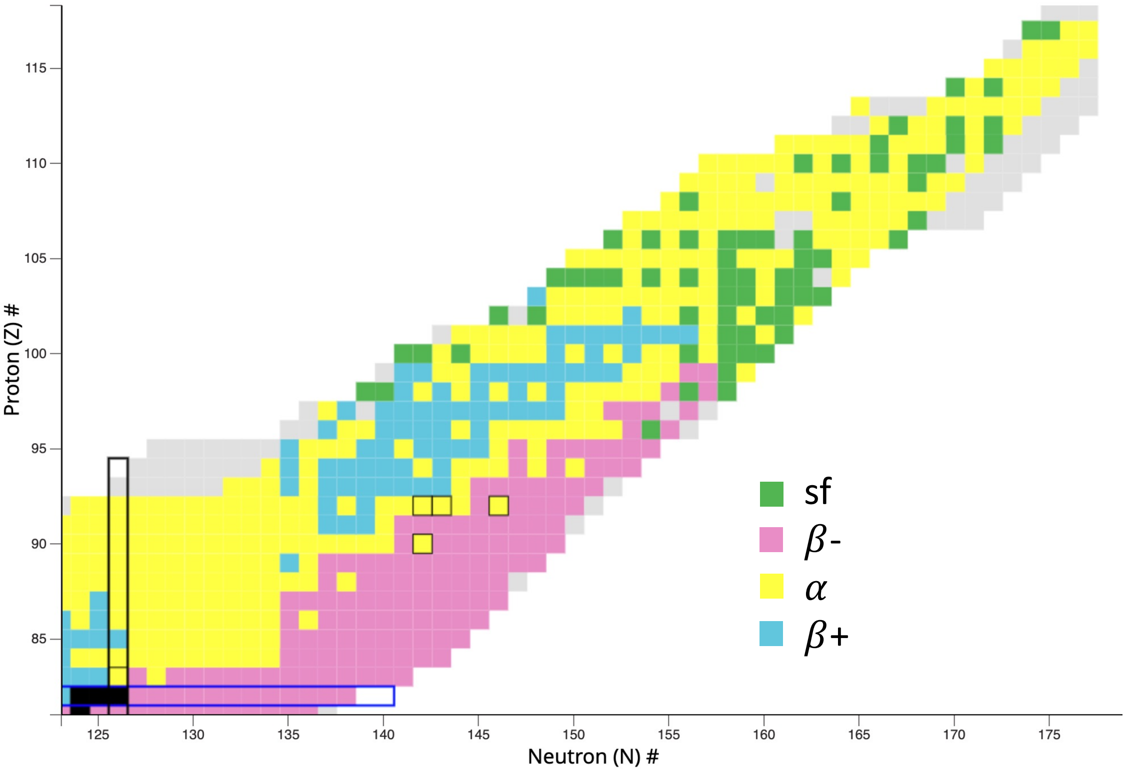
More reasons to map out actinide branching ratios

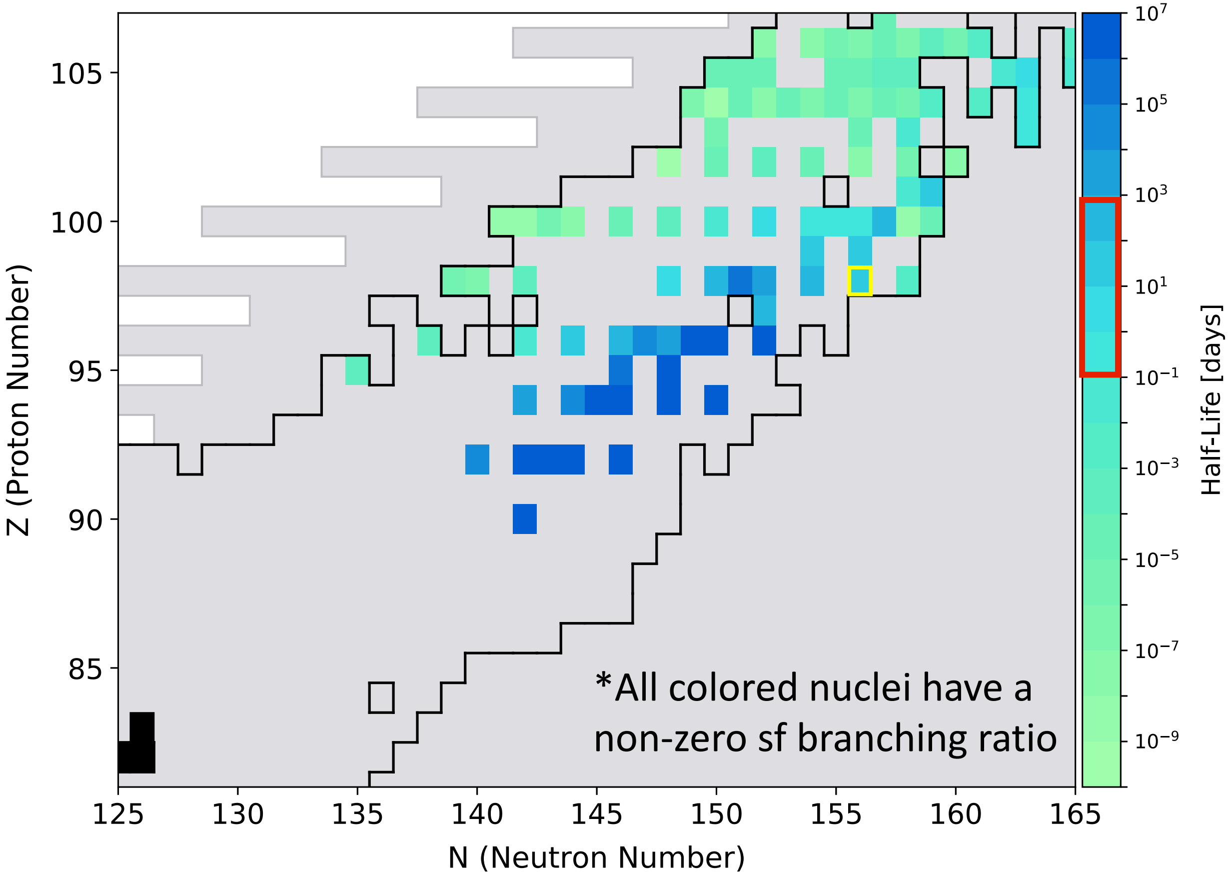
Zhu+18 (including Vassh)(ApJ Letters)



Other sf fission on the order of days?

This is largely unexplored territory, maybe ^{254}Cf not so "anomalous" (e.g. 271Rf has theoretical sf $T_{1/2}$~7 days)





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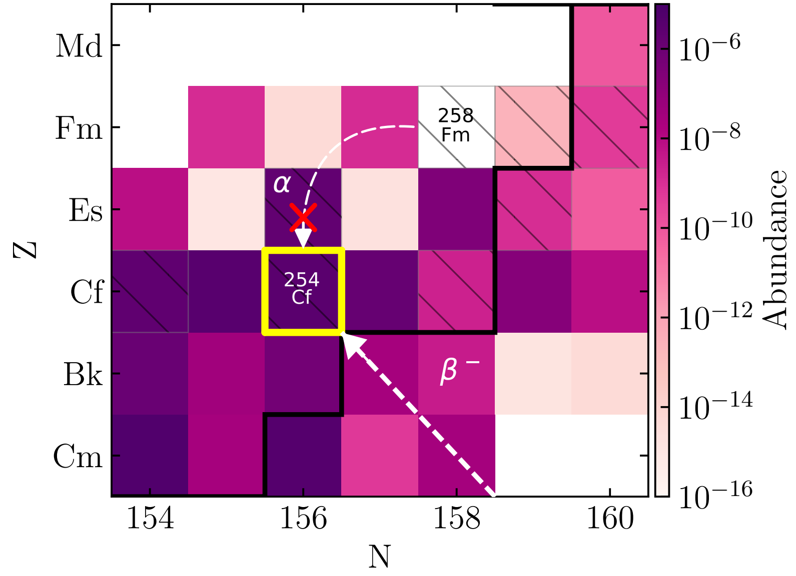

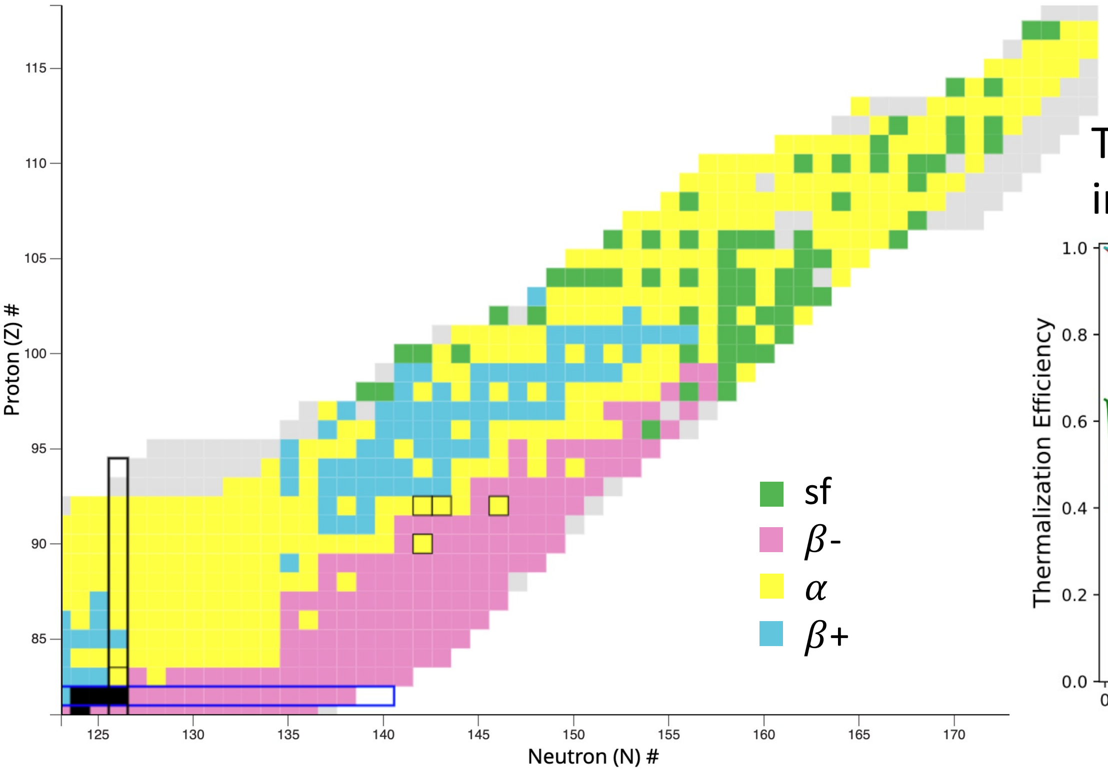

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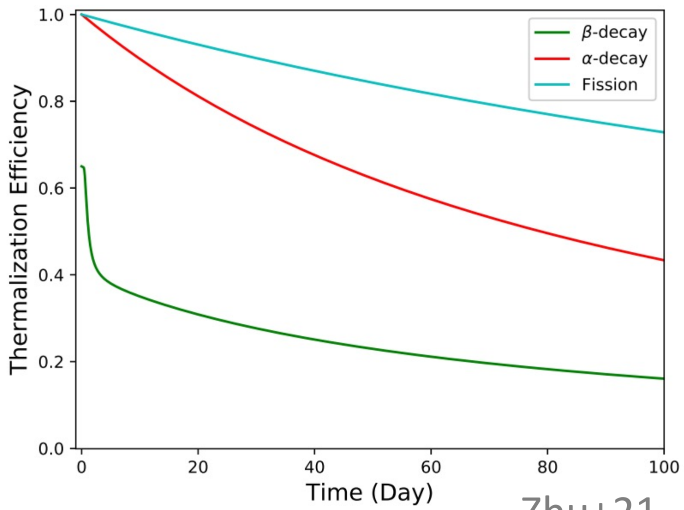
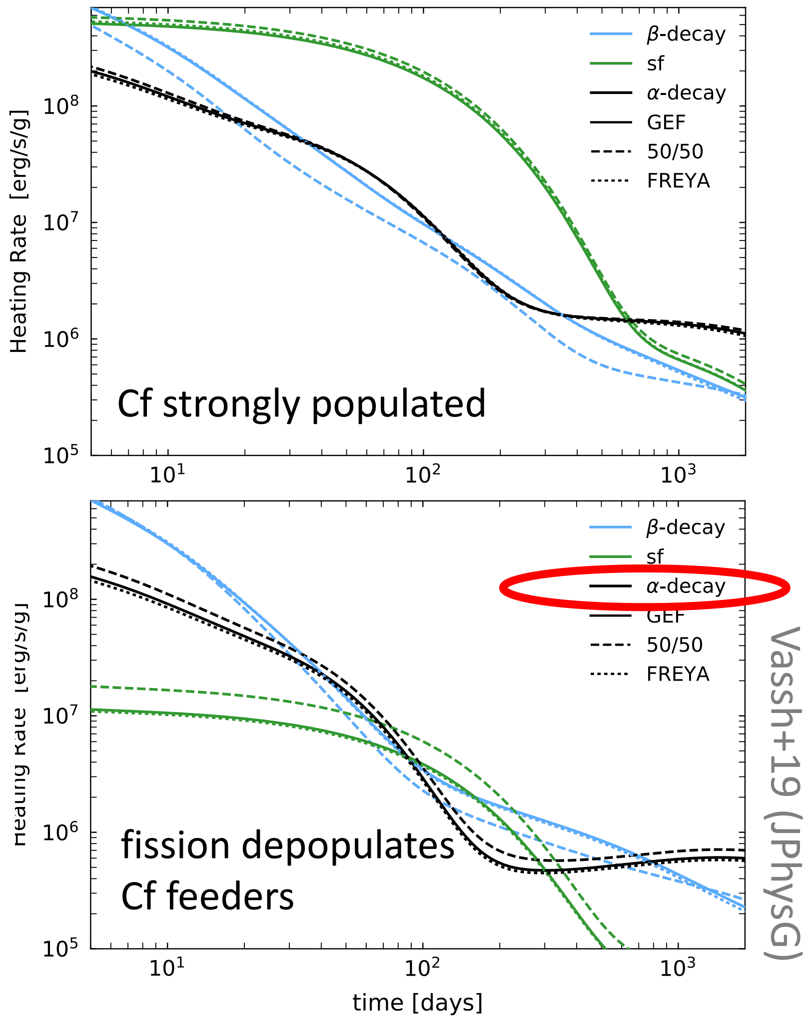
Thermalization efficiency in kilonovae



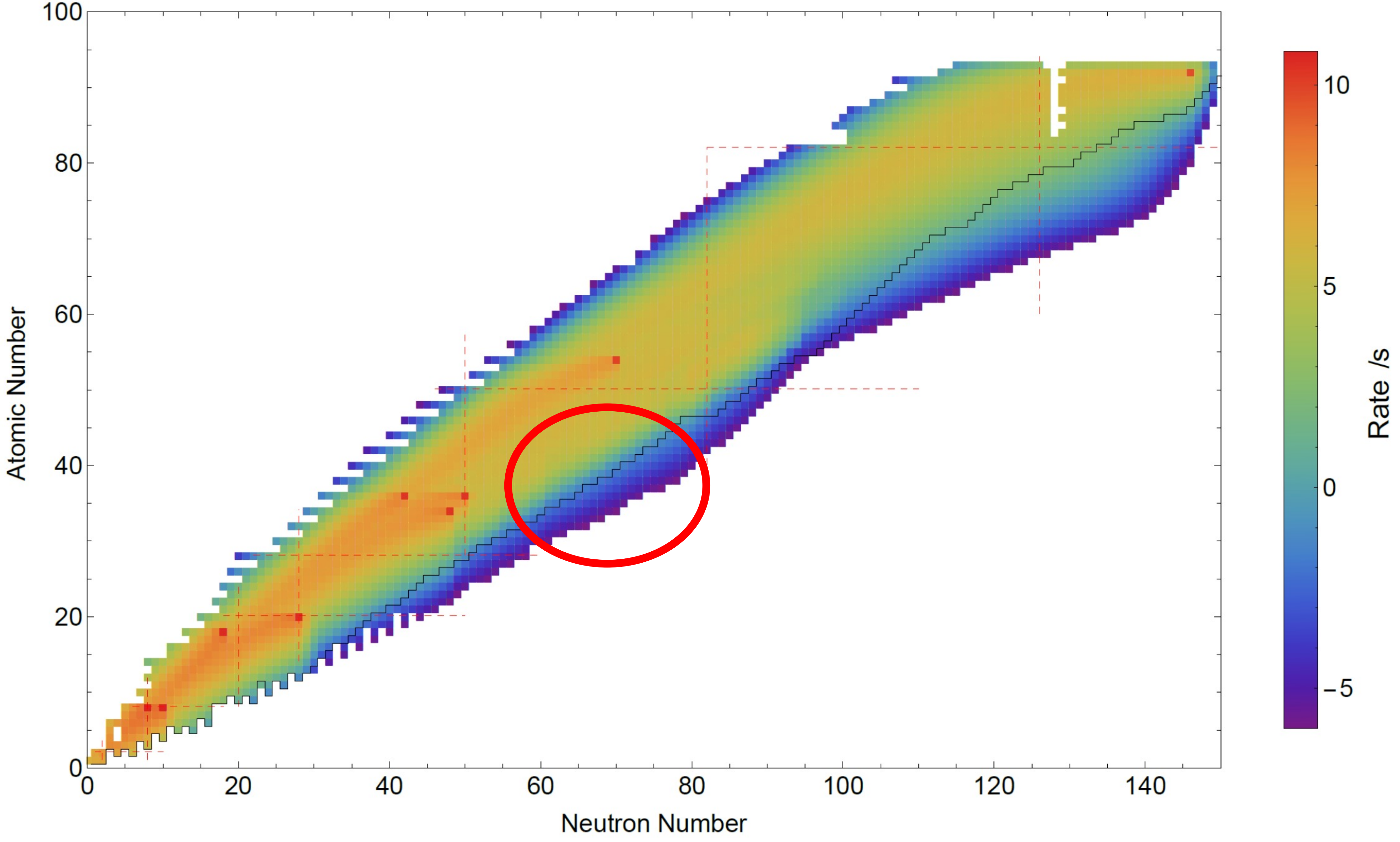
Zhu+21

α-decay a source of nuclear heating affecting kilonova light curves

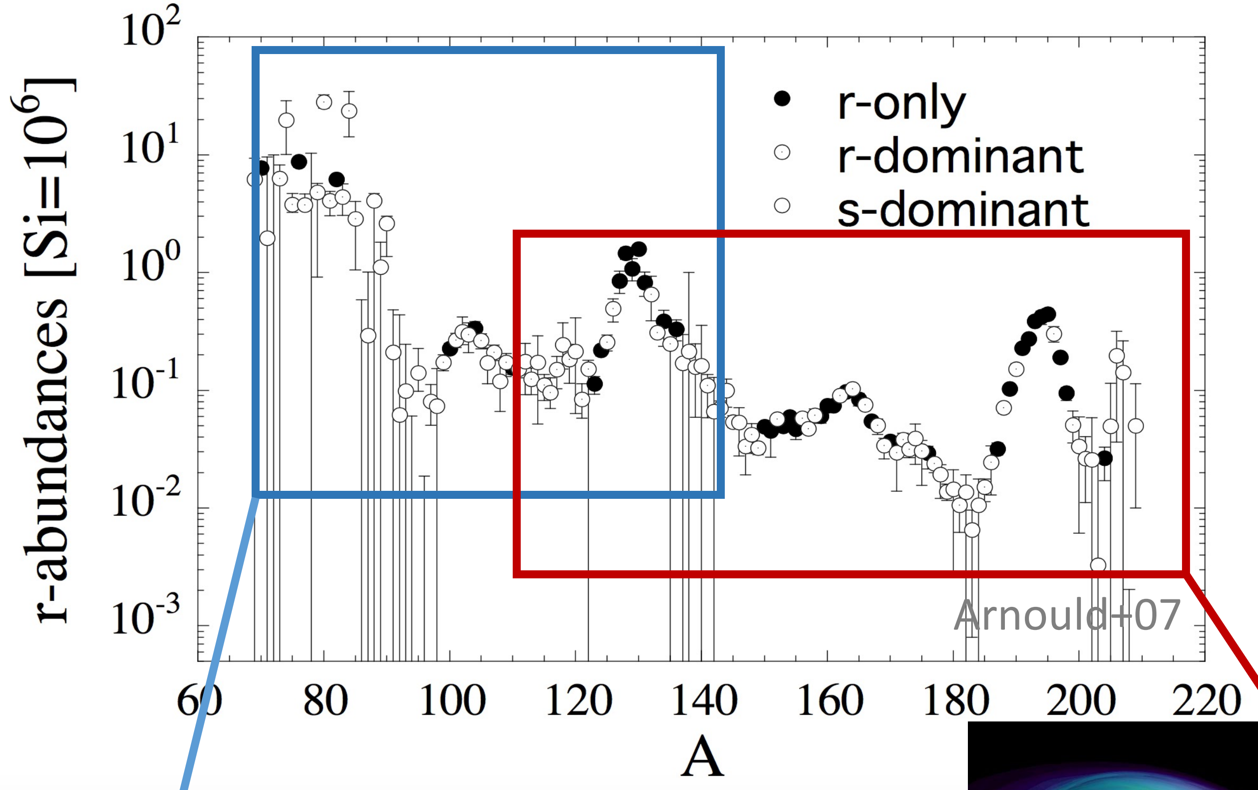


Vassh+19 (JPhysG)

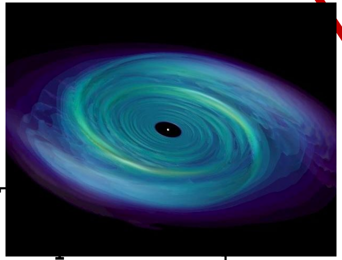
r-process studies in the FRIB era

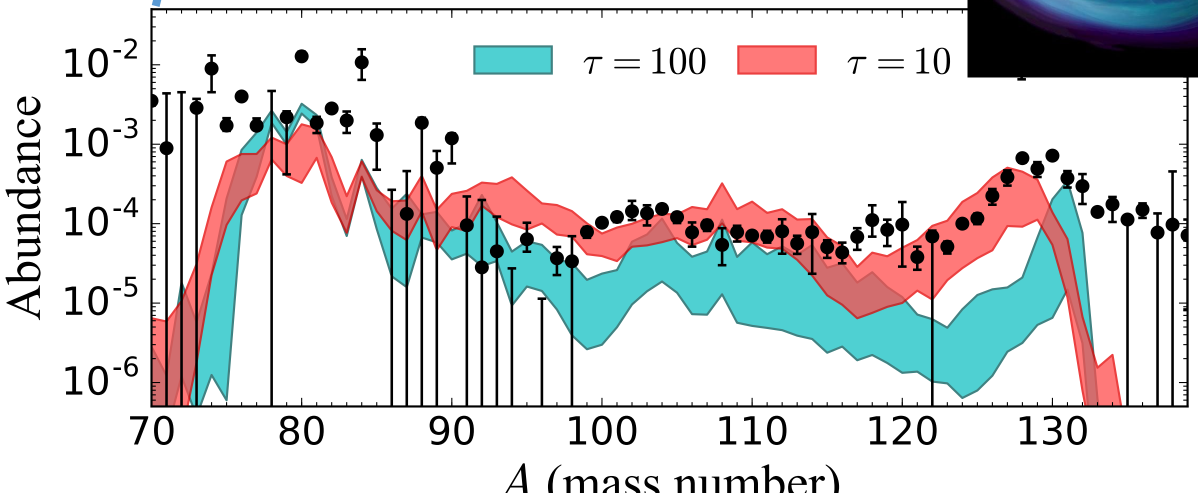


“Weak” *r*-process:
multiple astrophysical sites produce these nuclei

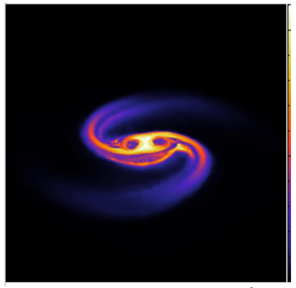


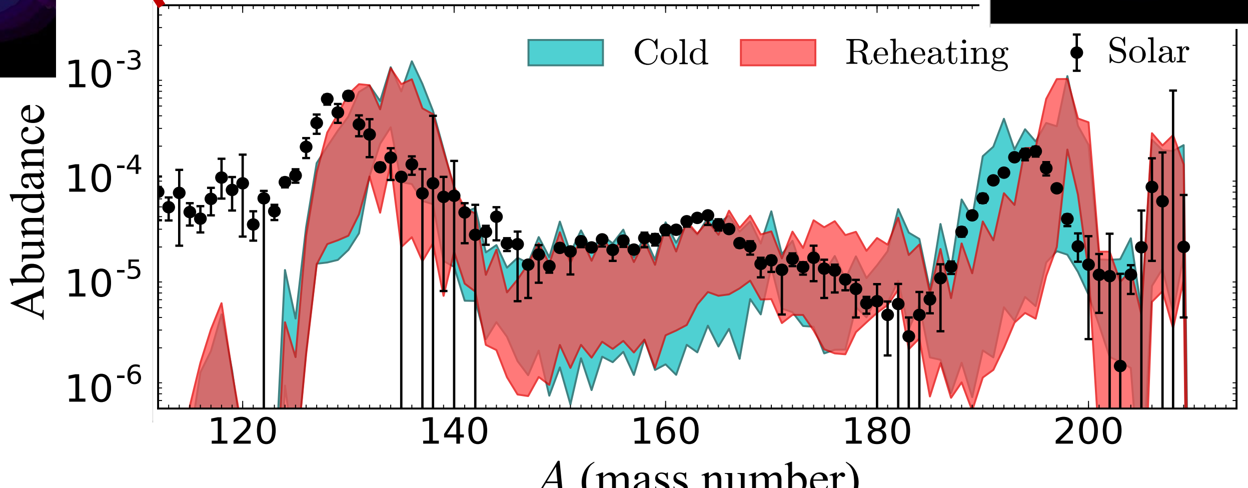
Wind ejecta (s/k=10, Y_e=0.27)



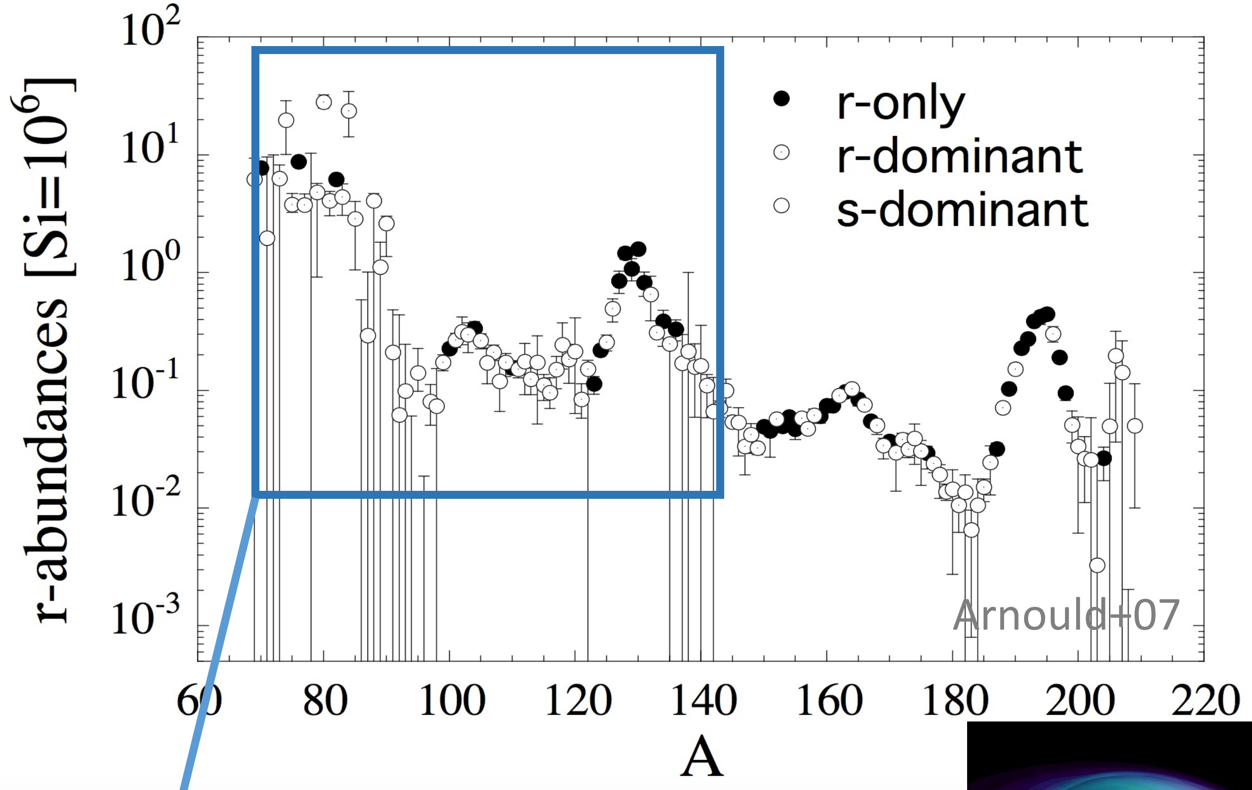


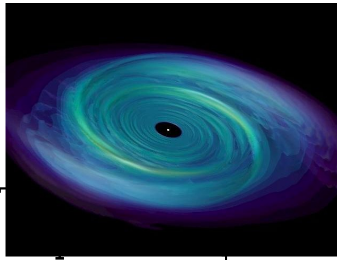
Very n-rich **dynamical** ejecta



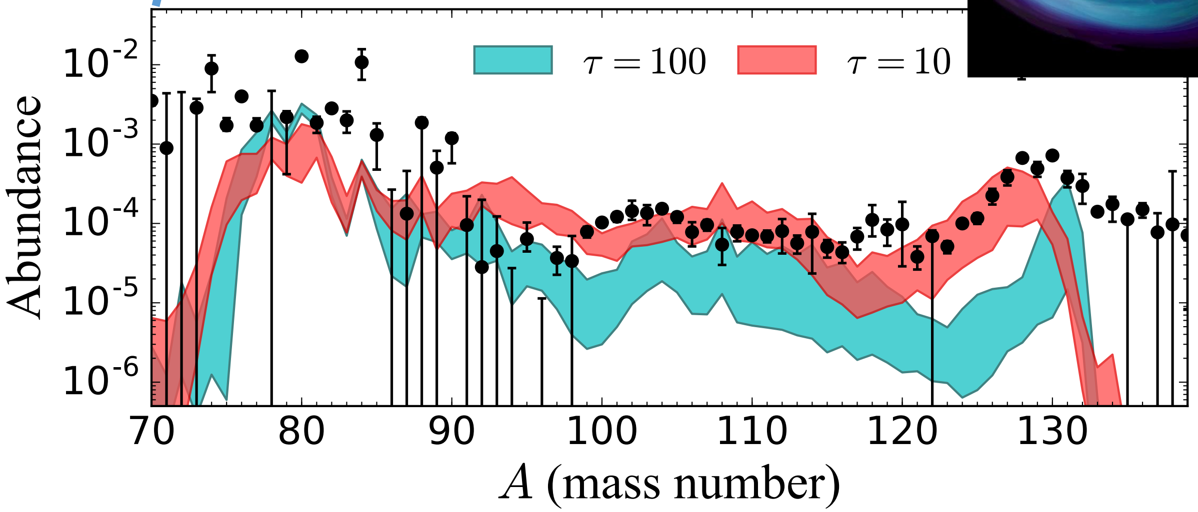


"Weak" *r*-process: multiple astrophysical sites produce these nuclei



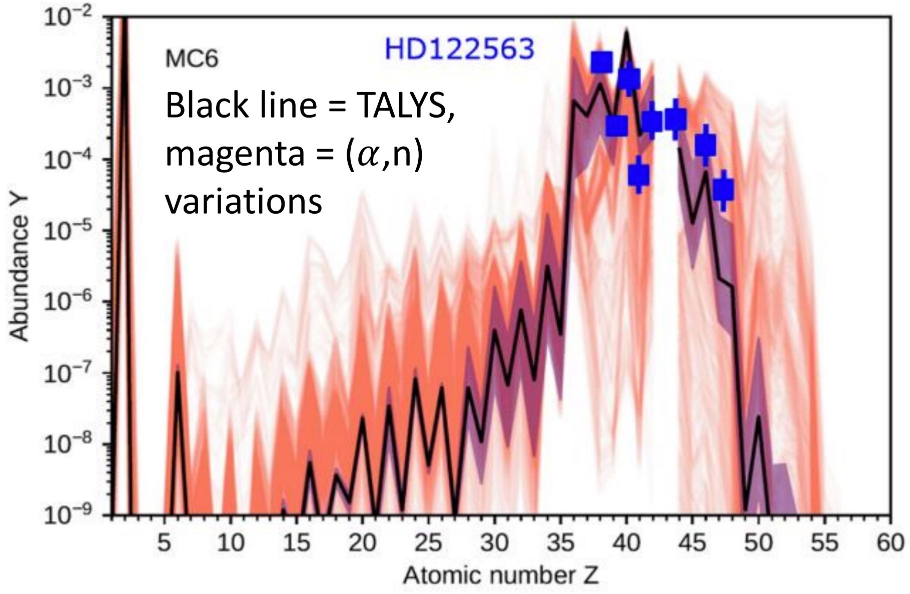


Wind ejecta (s/k=10, Y_e=0.27)



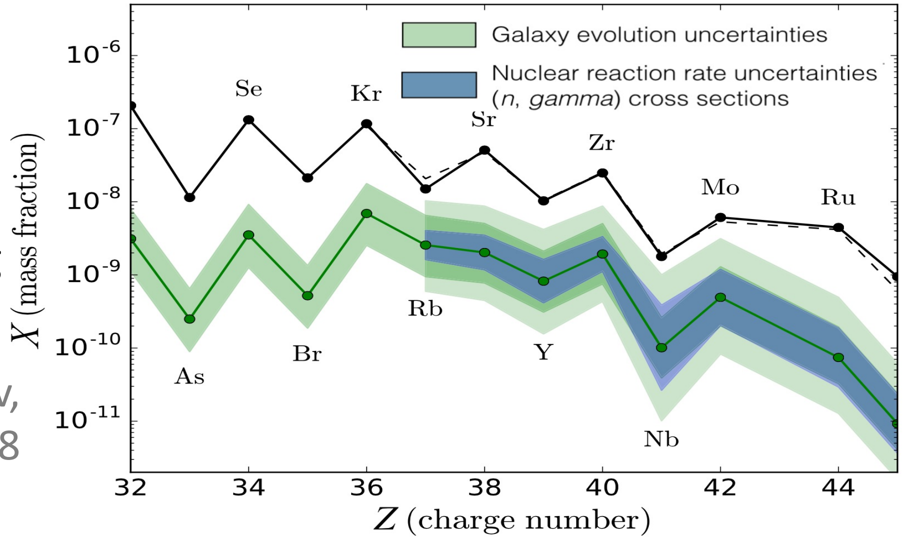
Core-collapse Supernovae

Pereira+20



i-process in rapidly accreting white dwarfs

Côté, Denissenkov, Herwig+18



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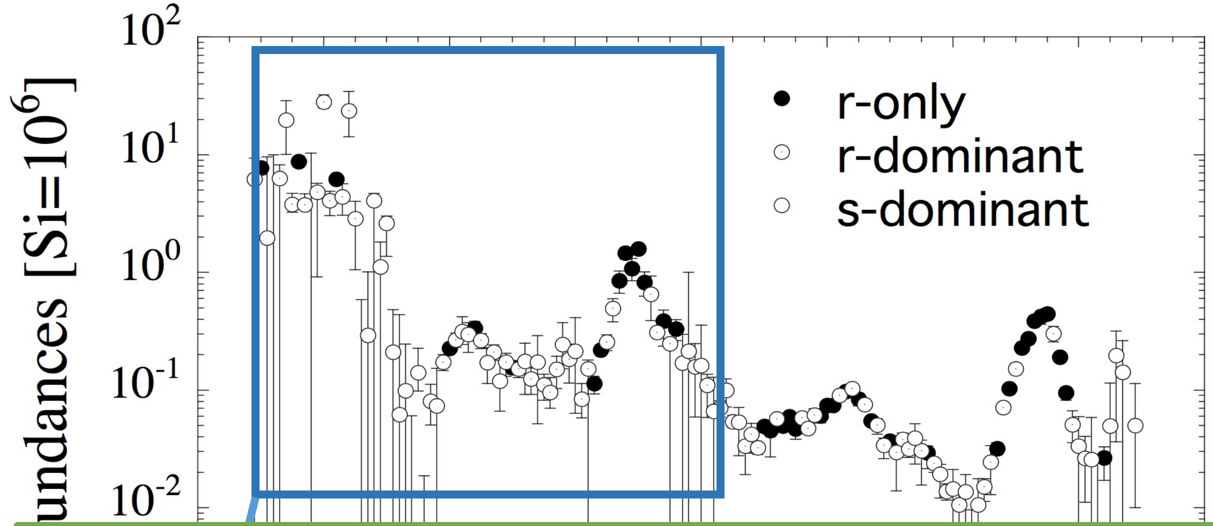
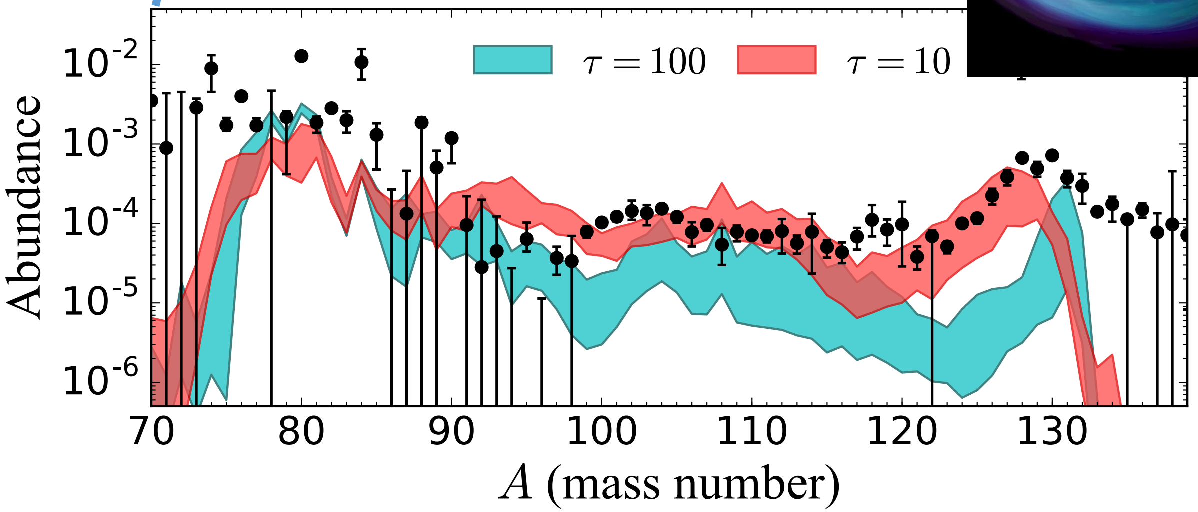
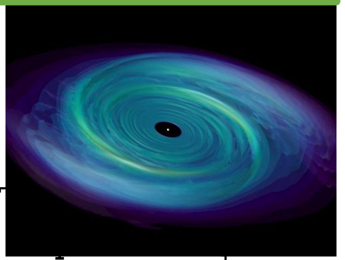


“Correlation of Triaxial Deformation with Inertial Dynamics, Masses and r-Process Nucleosynthesis”,
FRIB PAC1 exp 21035 (J. Almond+ (including Vassh))

Wind ejecta (s/k=10, Y_e=0.27)





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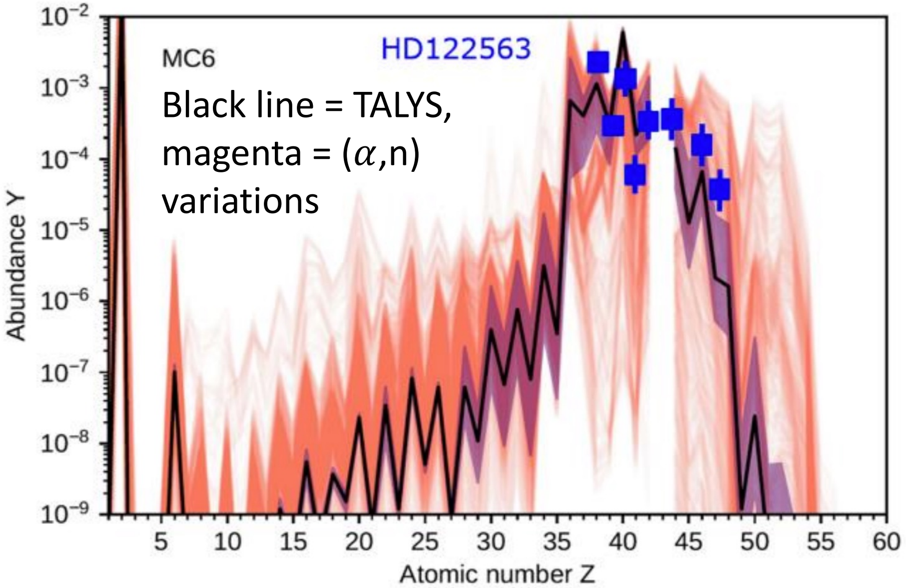

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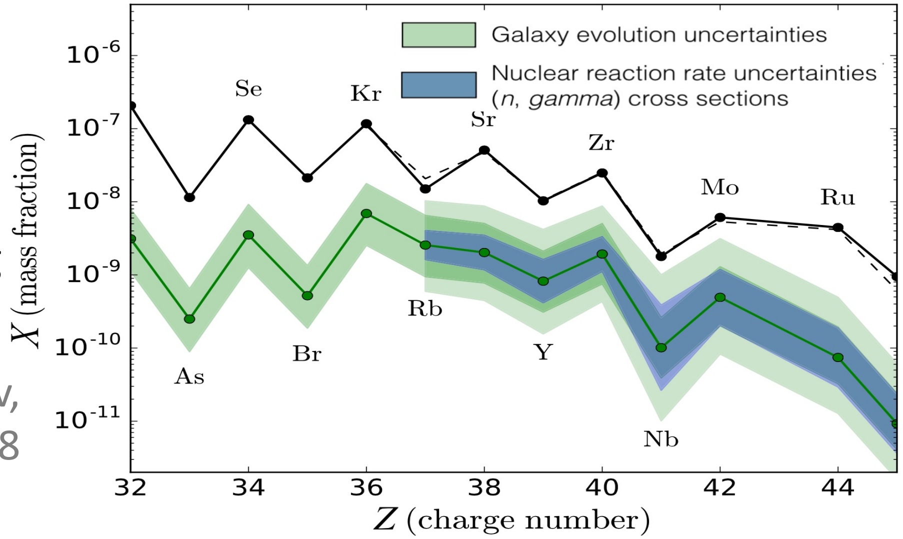
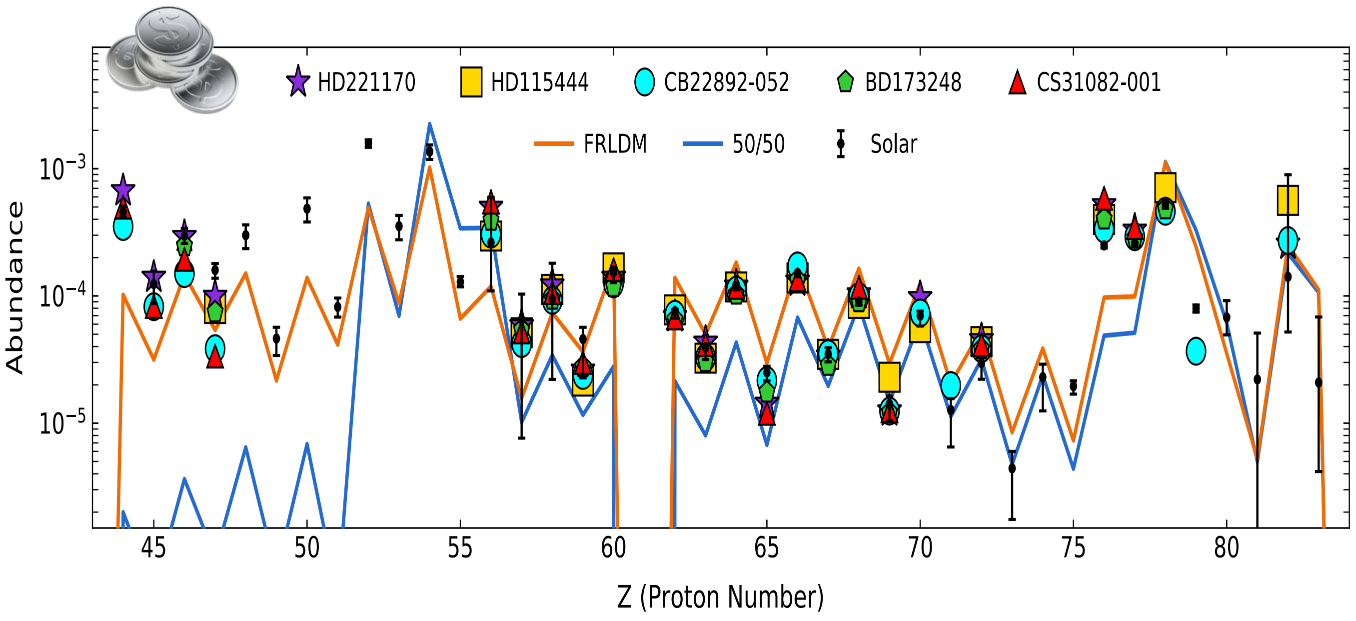


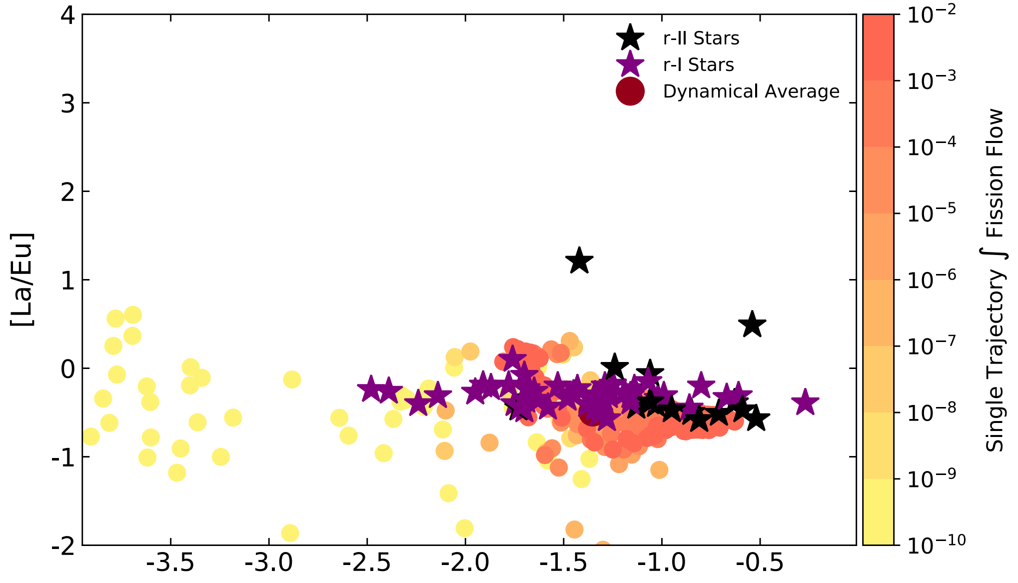
"Universality" or "robustness" of *r*-process abundances

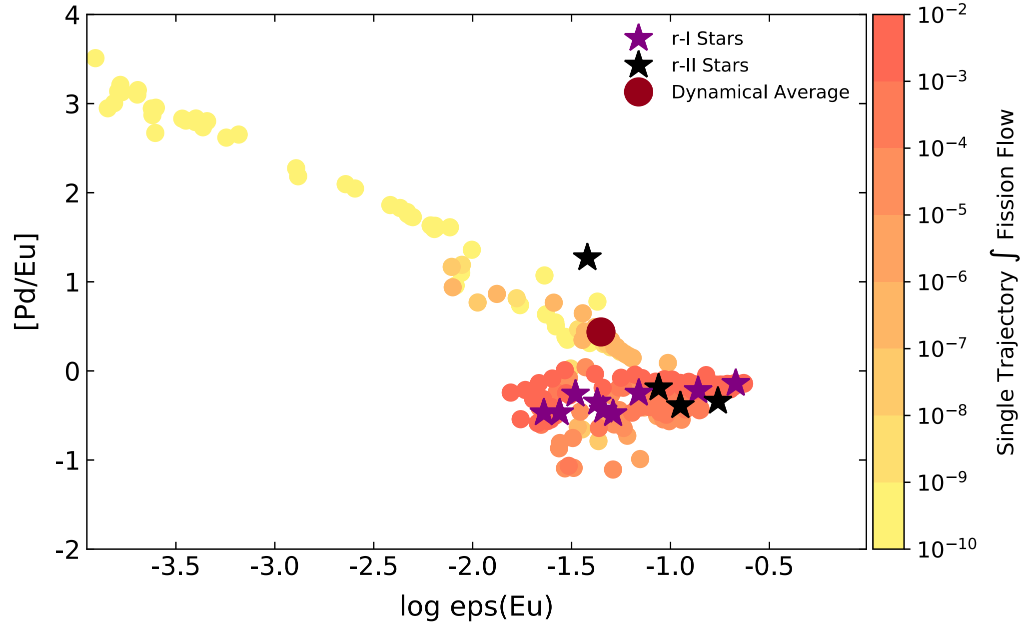
10 *r*-process rich halo stars compared to solar: similar lanthanide abundance ratios

and light precious metal (Ag,Pd)



1.2-1.4 $M_\odot$ NSM dynamical ejecta
(hydro simulation Rosswog+13)
with theoretical fission yields from LANL





Vassh+20 (ApJ)
See also Roederer,Vassh+23 (submitted to Science)

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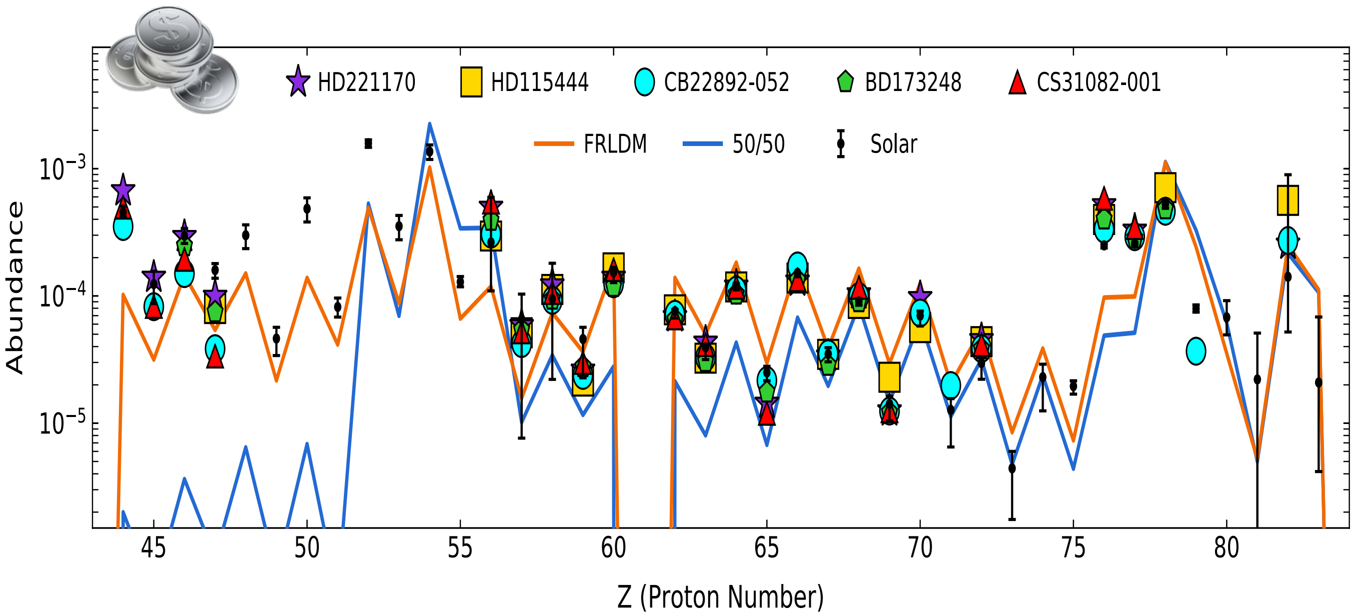

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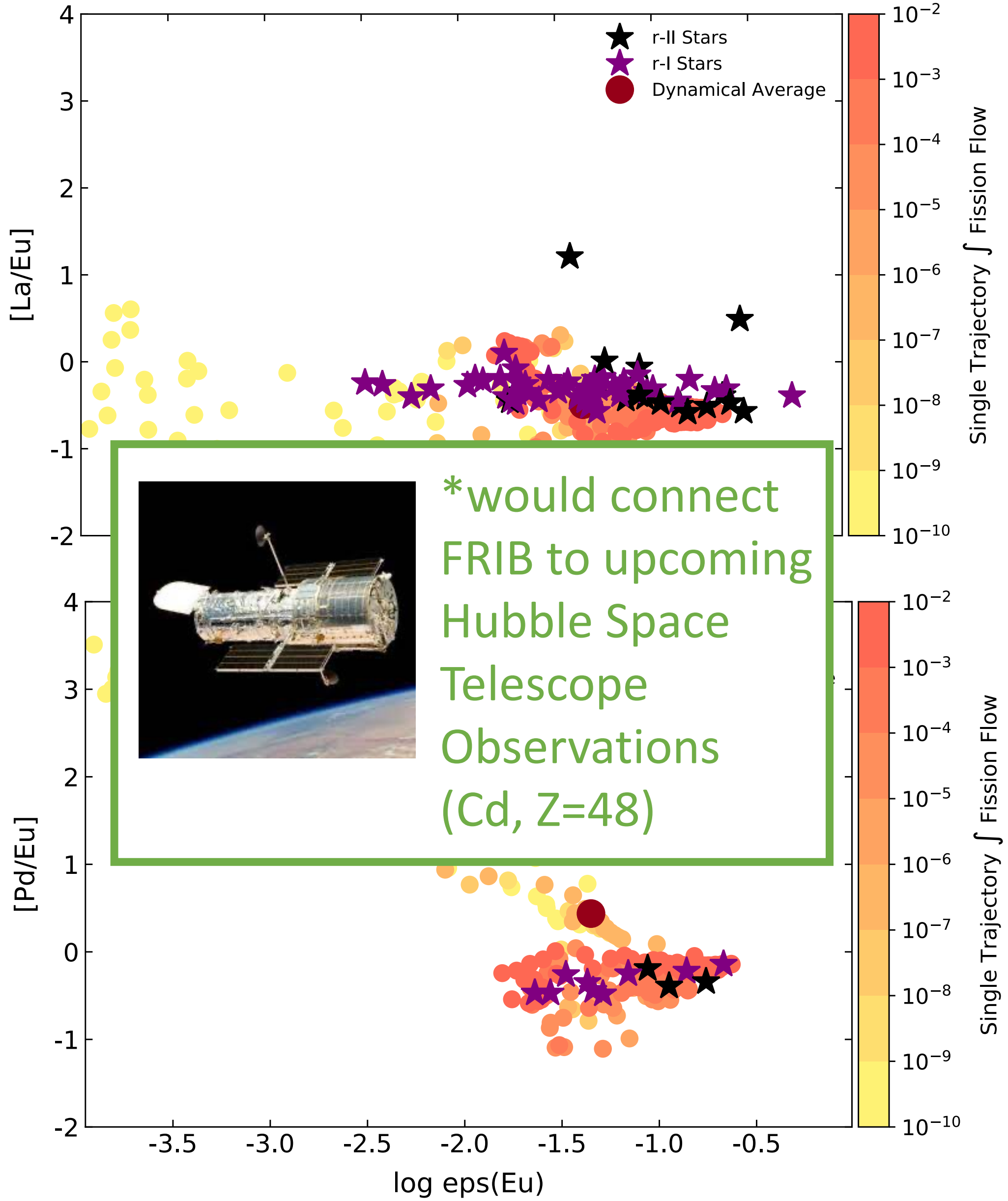
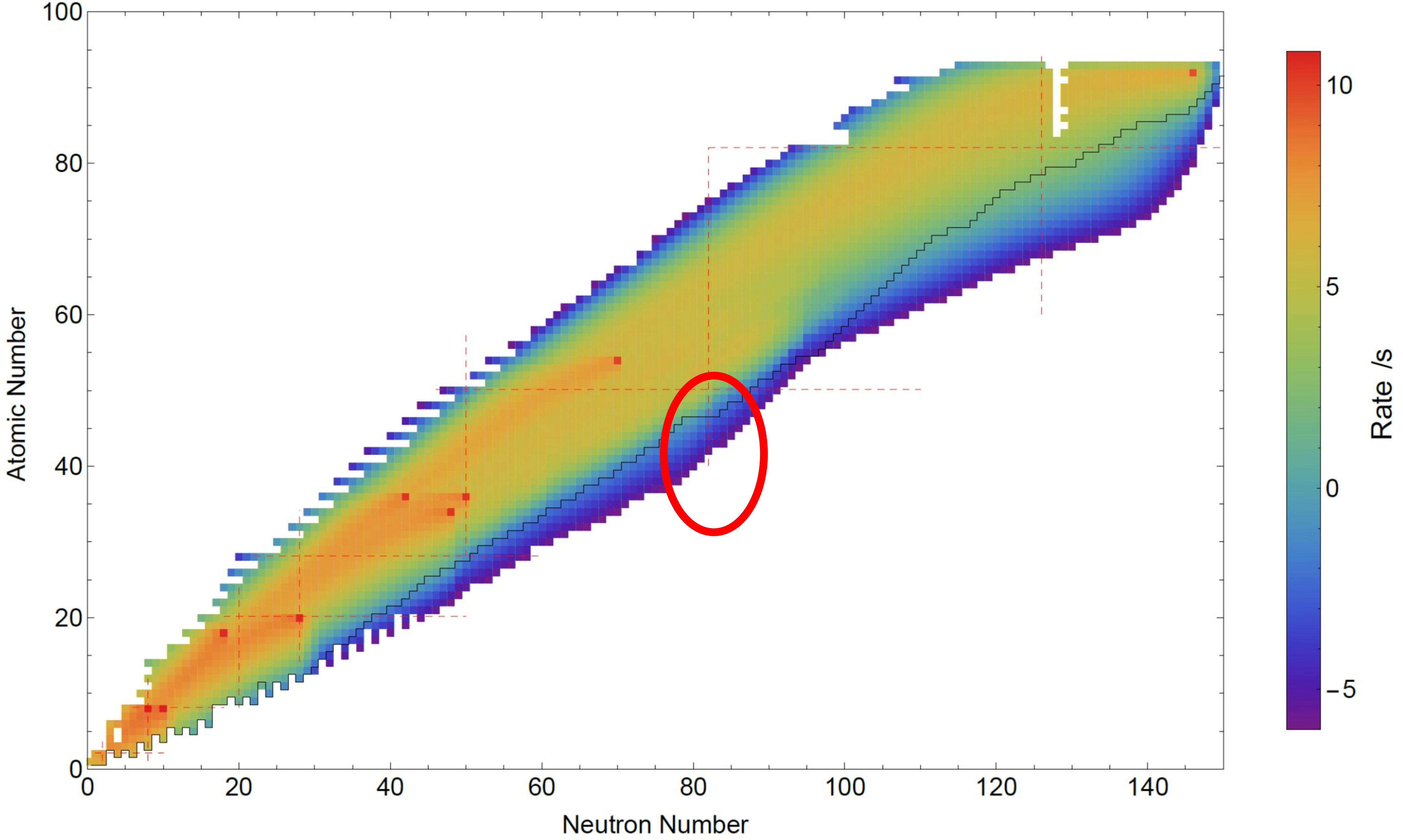


*would connect FRIB to upcoming Hubble Space Telescope Observations (Cd, Z=48)

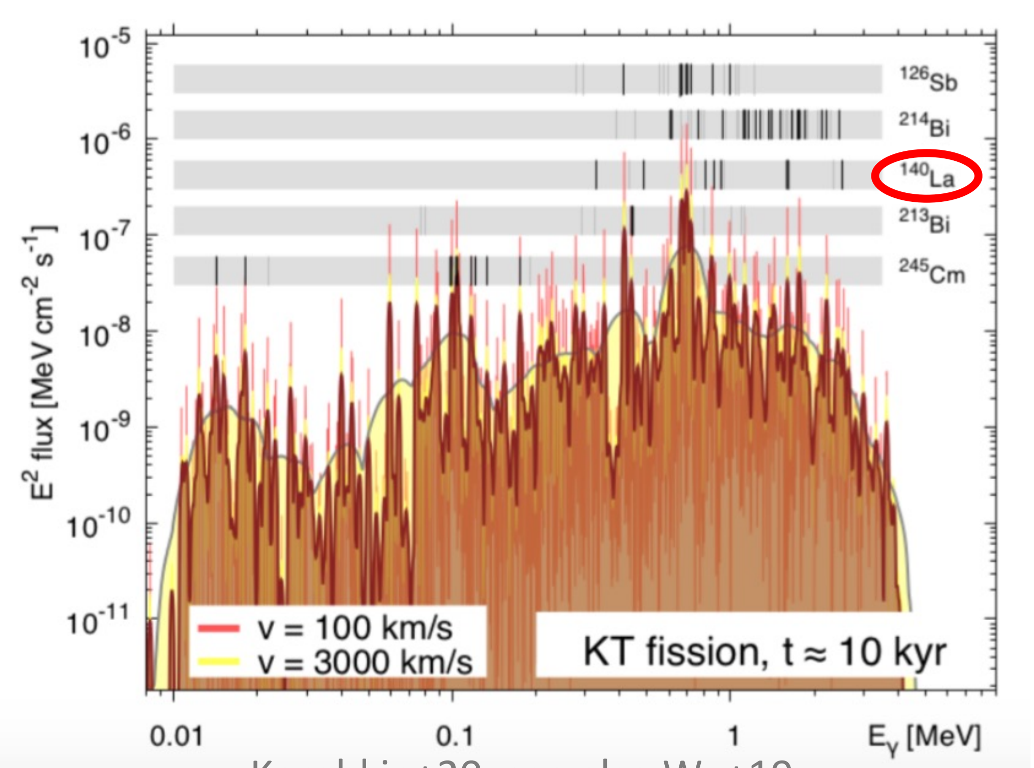
Vassh+20 (ApJ)
See also Roederer,Vassh+23 (submitted to Science)

r-process studies in the FRIB era



Gamma-ray emission and kilonova heating from β-decays near N=82

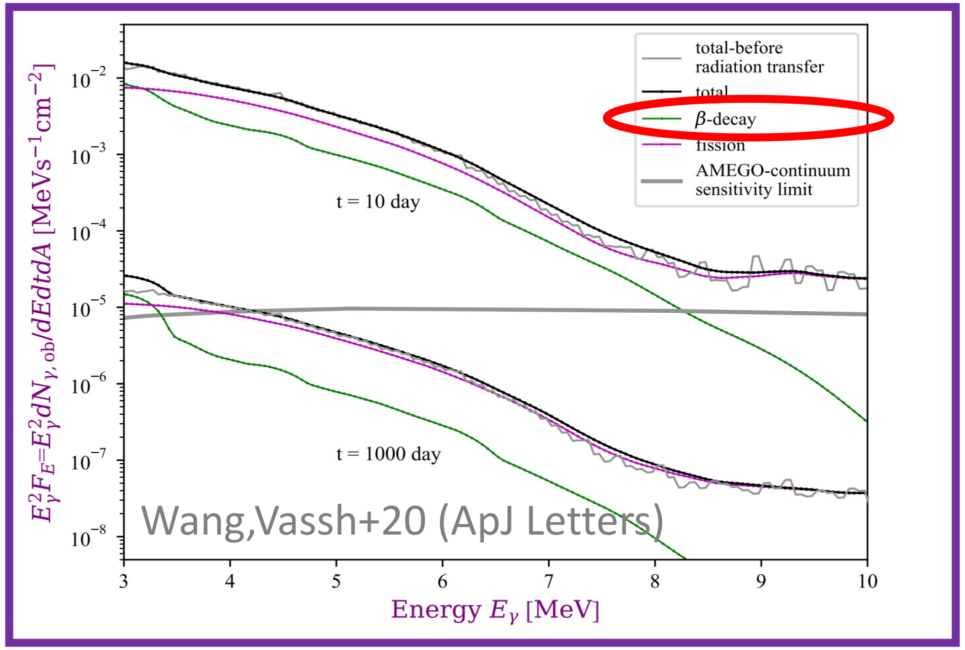
Searching for neutron star merger remnants:
modeling spectral lines from β-decay and α-decay gammas



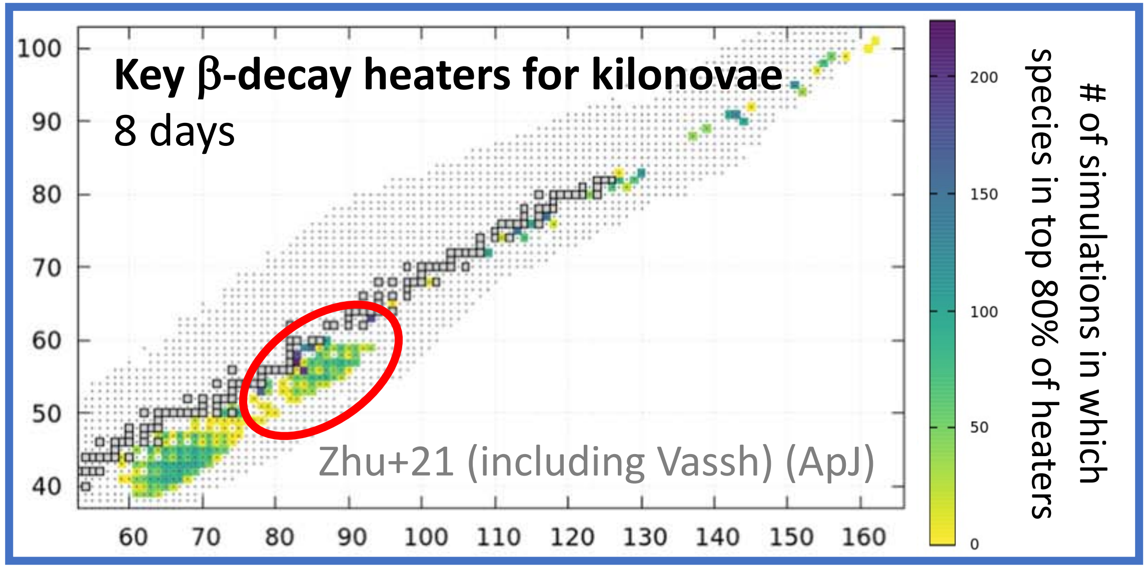
Korobkin+20; see also Wu+19

Both gamma-ray calculations @ 10 kpc (within Milky Way)

Gamma-rays from nearby events and β-decay of n-rich fission fragments: how well are these measured above 3.5 MeV?



Wang,Vassh+20 (ApJ Letters)



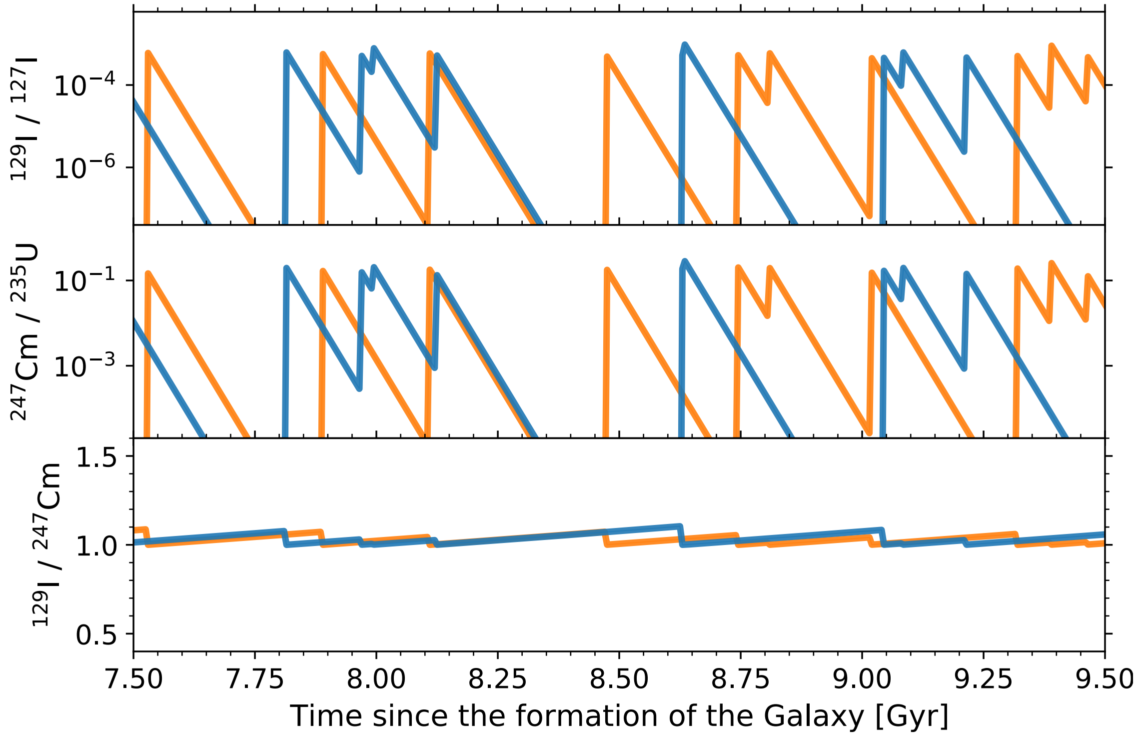
Zhu+21 (including Vassh) (ApJ)

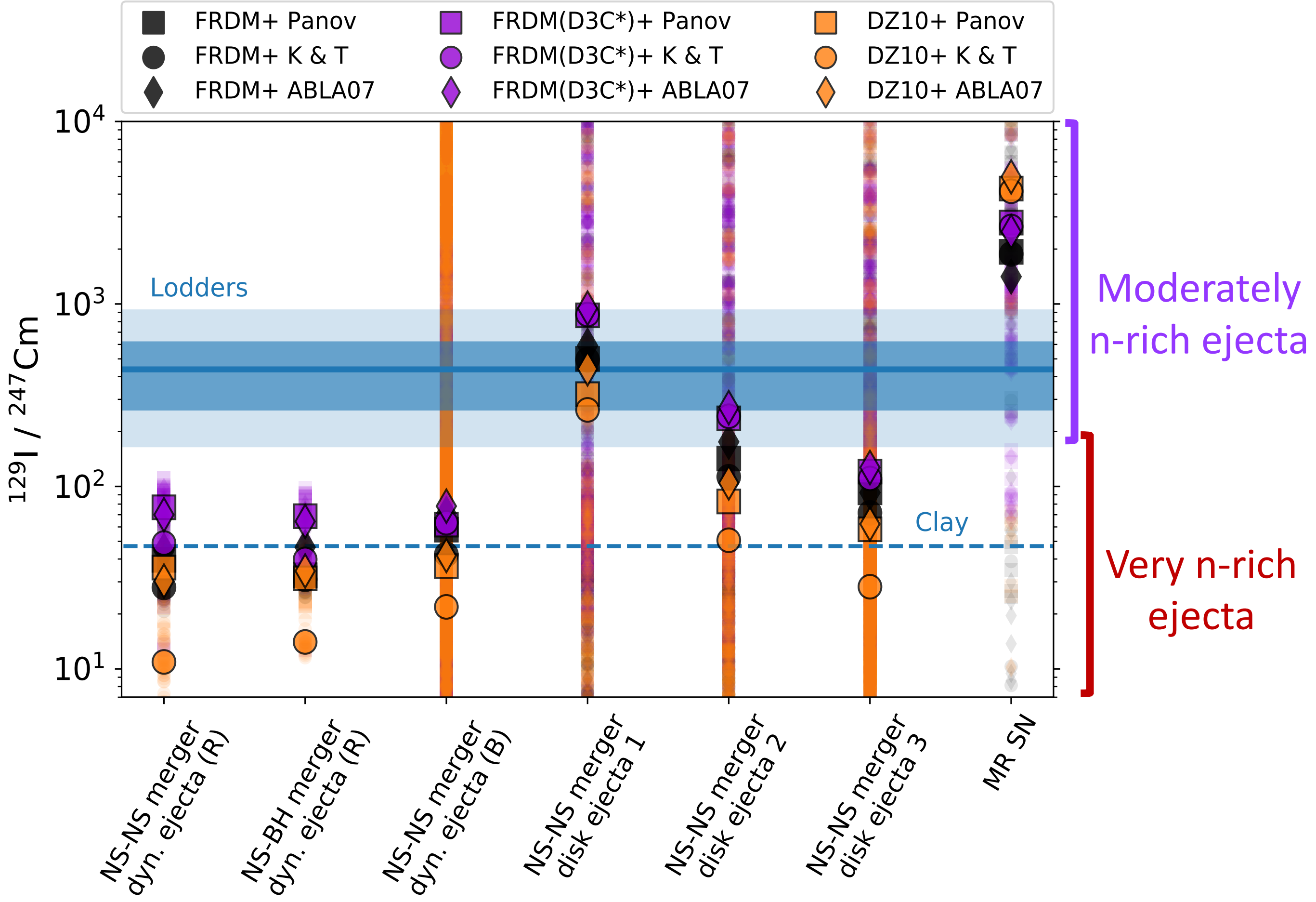
The nature of the *last* *r*-process event that enriched our solar system

"Curious Marie" sample of Allende meteorite shows excess U-235 which is a trace of Cm-247

Only 4 radioactive isotopes in meteorites linked to *r* process with $T_{1/2} < 1$ Gyr:

^{129}I	$T_{1/2}$ = 15.7 Myr	^{244}Pu	$T_{1/2}$ = 80 Myr
^{247}Cm	$T_{1/2}$ = 15.6 Myr	^{235}U	$T_{1/2}$ = 700 Myr





Côté+21 (including Vassh) (Science)

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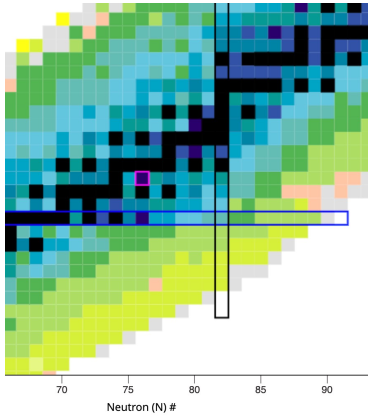
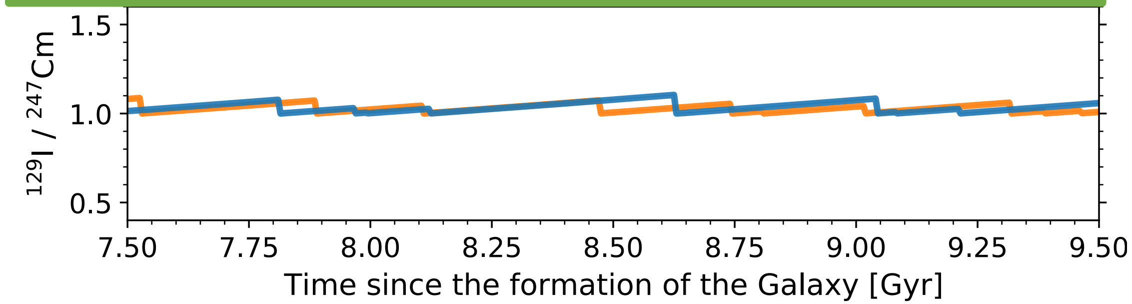
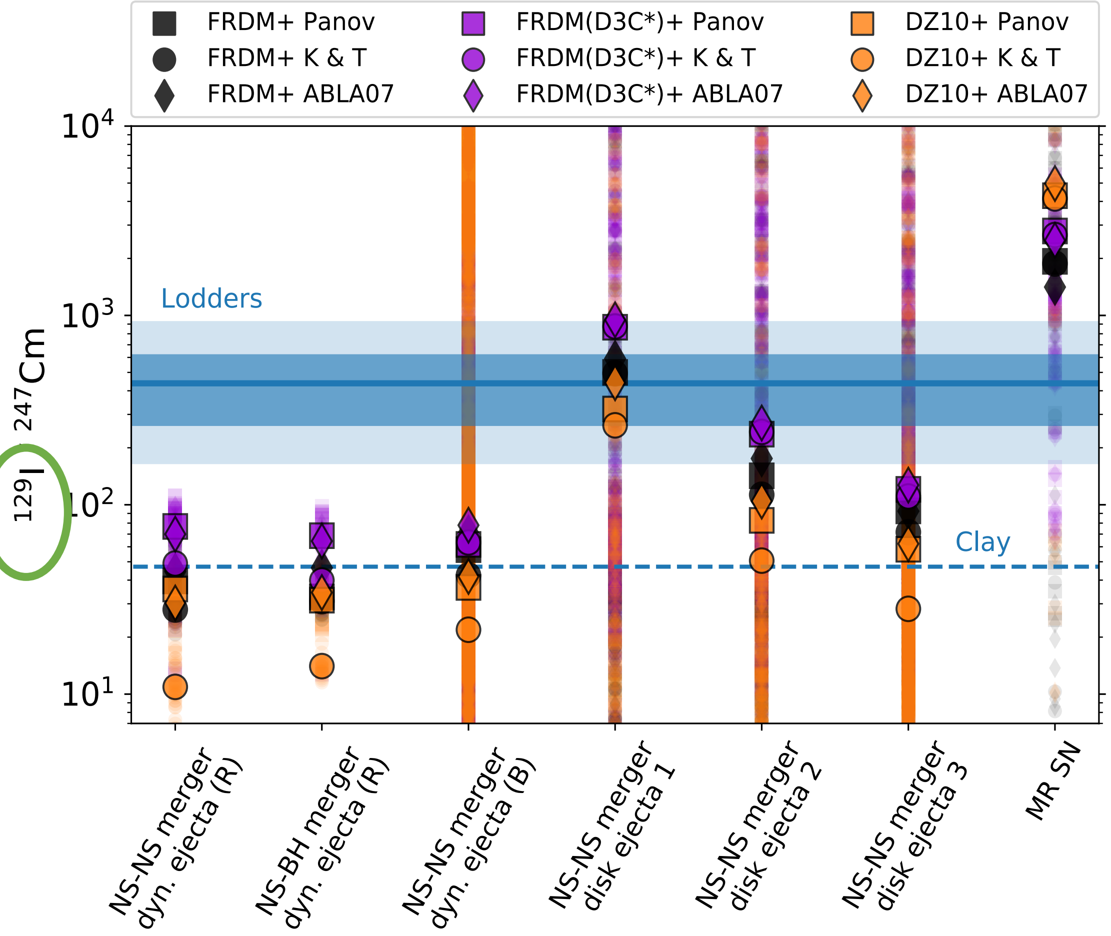
*FRIB can constrain the nuclear properties (masses, beta-decay…) around N=82, Z~47 affecting the abundance of 129I





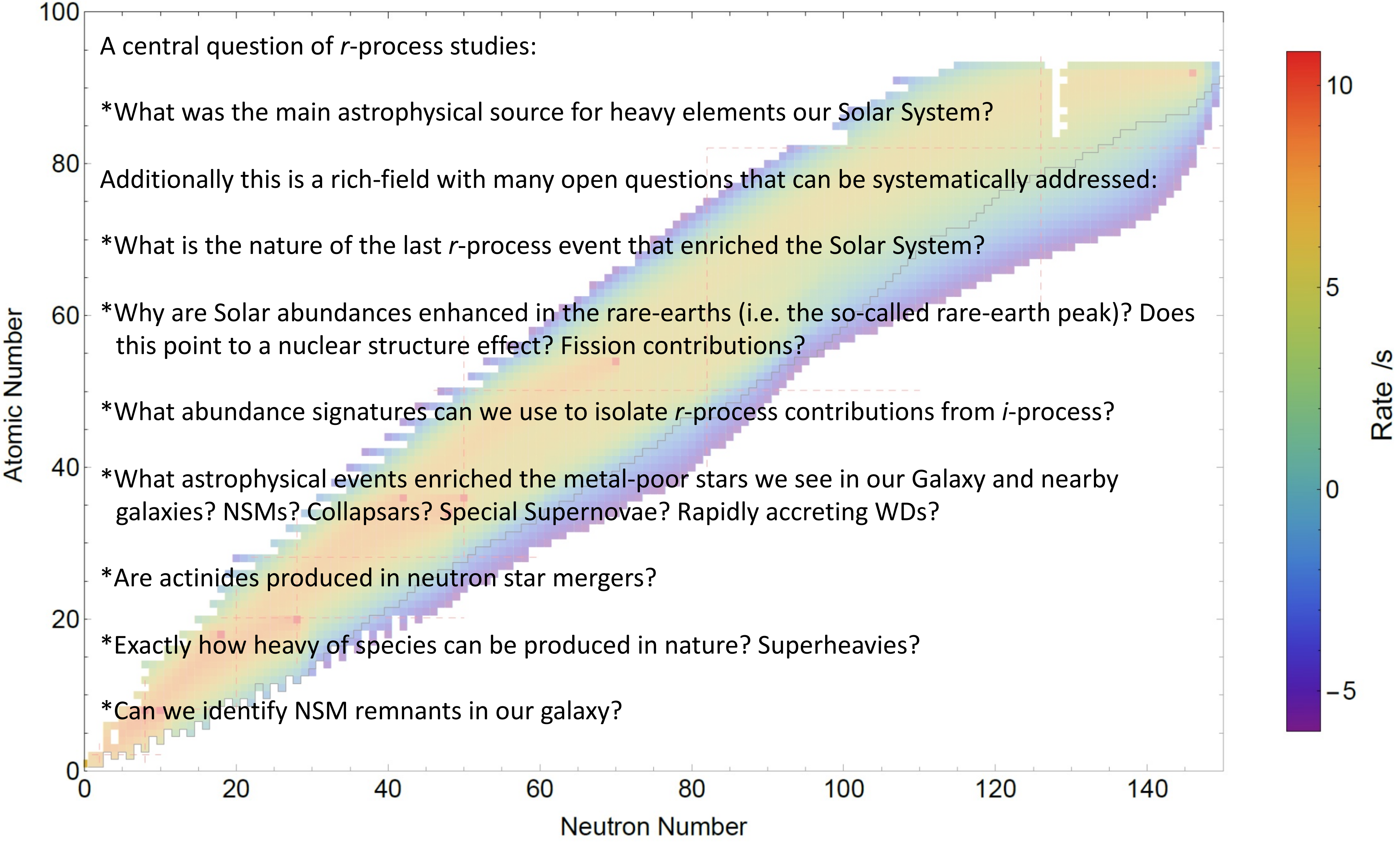


Moderately n-rich ejecta

Very n-rich ejecta

Côté+21 (including Vassh) (Science)

r-process studies in the FRIB era



A central question of *r*-process studies:

*What was the main astrophysical source for heavy elements our Solar System?

Additionally this is a rich-field with many open questions that can be systematically addressed:

*What is the nature of the last *r*-process event that enriched the Solar System?

*Why are Solar abundances enhanced in the rare-earths (i.e. the so-called rare-earth peak)? Does this point to a nuclear structure effect? Fission contributions?

*What abundance signatures can we use to isolate *r*-process contributions from *i*-process?

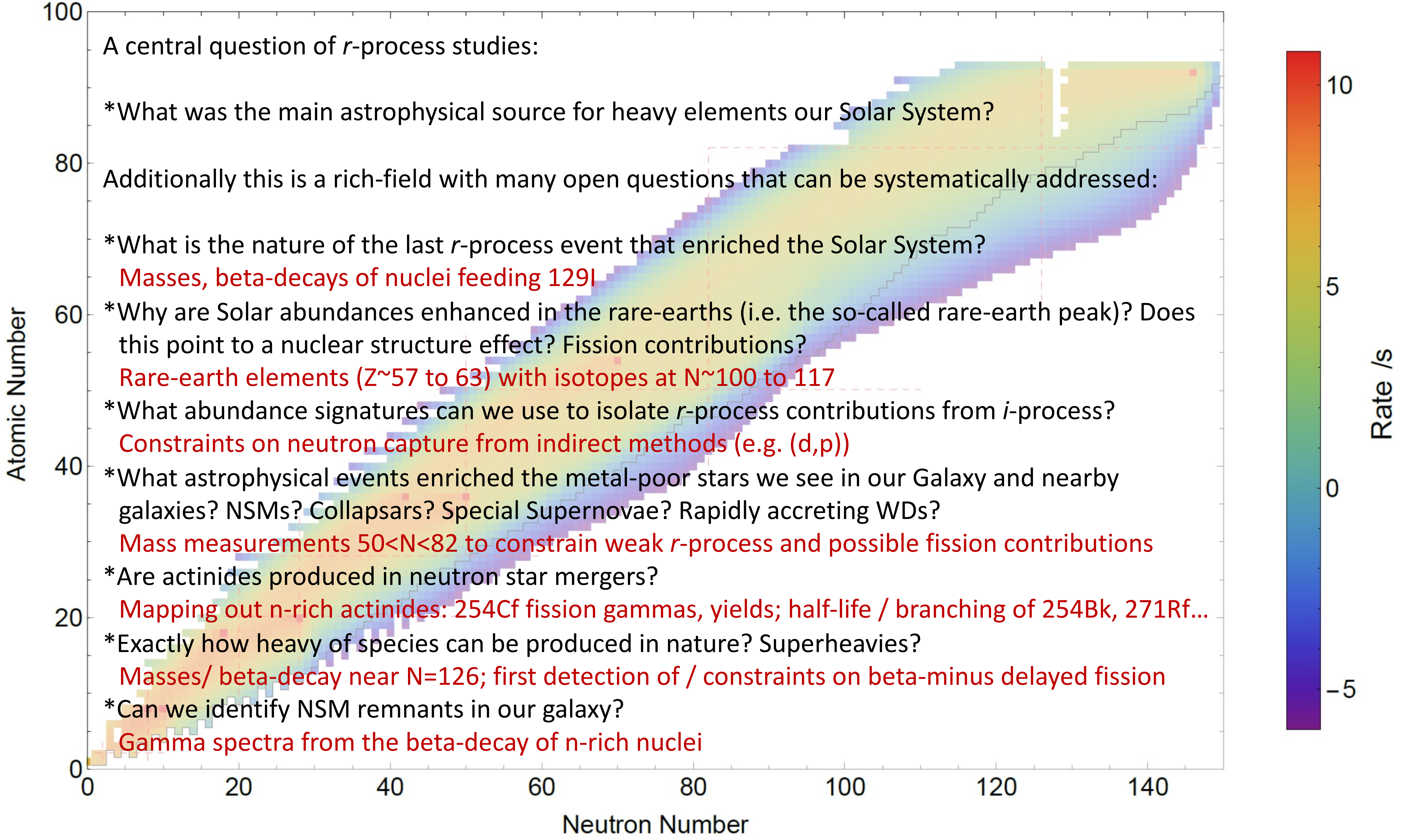
*What astrophysical events enriched the metal-poor stars we see in our Galaxy and nearby galaxies? NSMs? Collapsars? Special Supernovae? Rapidly accreting WDs?

*Are actinides produced in neutron star mergers?

*Exactly how heavy of species can be produced in nature? Superheavies?

*Can we identify NSM remnants in our galaxy?

r-process studies in the FRIB era



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Masses, beta-decays of nuclei feeding 129I

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Rare-earth elements (Z~57 to 63) with isotopes at N~100 to 117

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Constraints on neutron capture from indirect methods (e.g. (d,p))

*What astrophysical events enriched the metal-poor stars we see in our Galaxy and nearby galaxies? NSMs? Collapsars? Special Supernovae? Rapidly accreting WDs?
Mass measurements 50<N<82 to constrain weak *r*-process and possible fission contributions

*Are actinides produced in neutron star mergers?
Mapping out n-rich actinides: 254Cf fission gammas, yields; half-life / branching of 254Bk, 271Rf…

*Exactly how heavy of species can be produced in nature? Superheavies?
Masses/ beta-decay near N=126; first detection of / constraints on beta-minus delayed fission

*Can we identify NSM remnants in our galaxy?
Gamma spectra from the beta-decay of n-rich nuclei