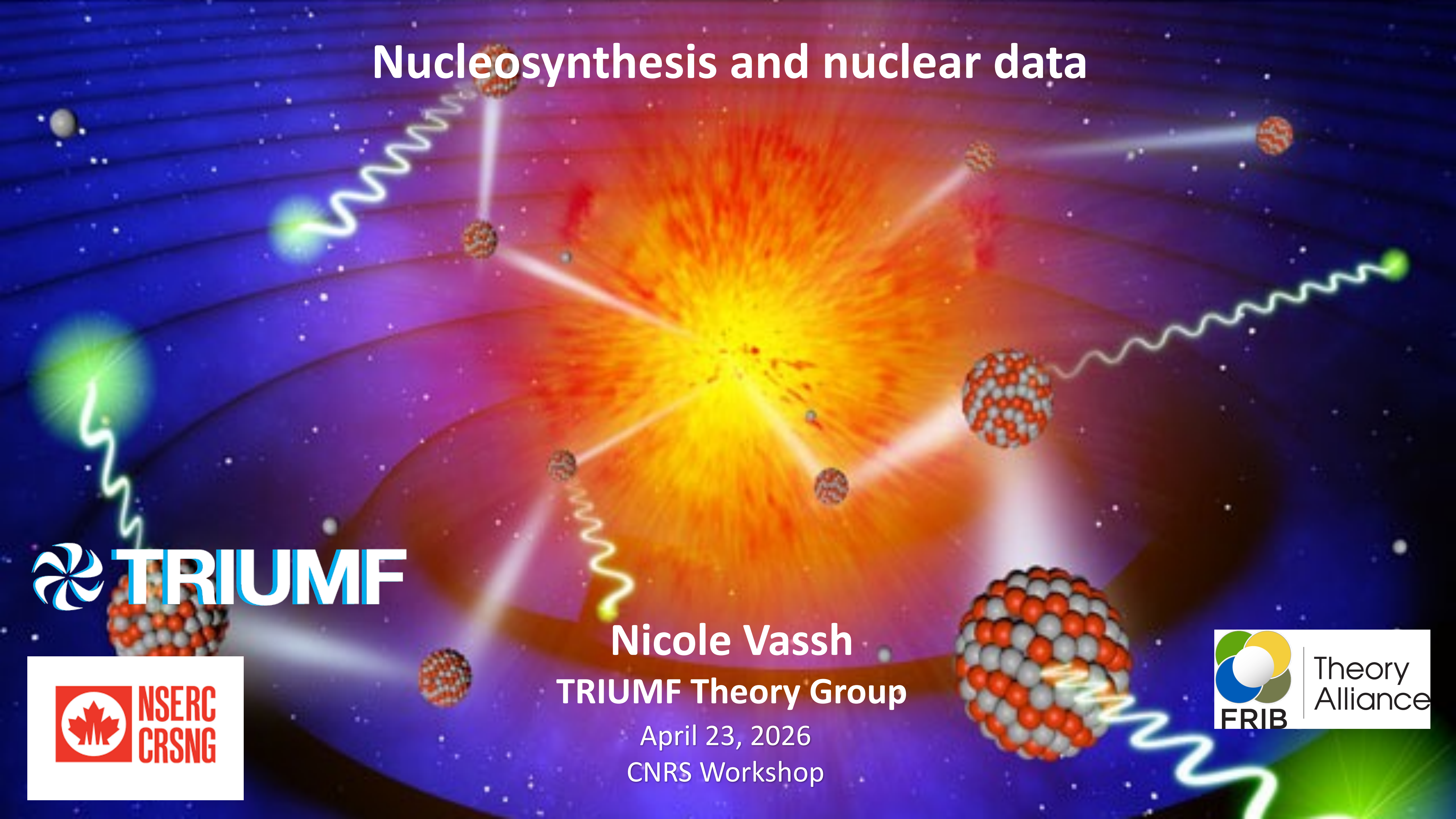


Nucleosynthesis and nuclear data

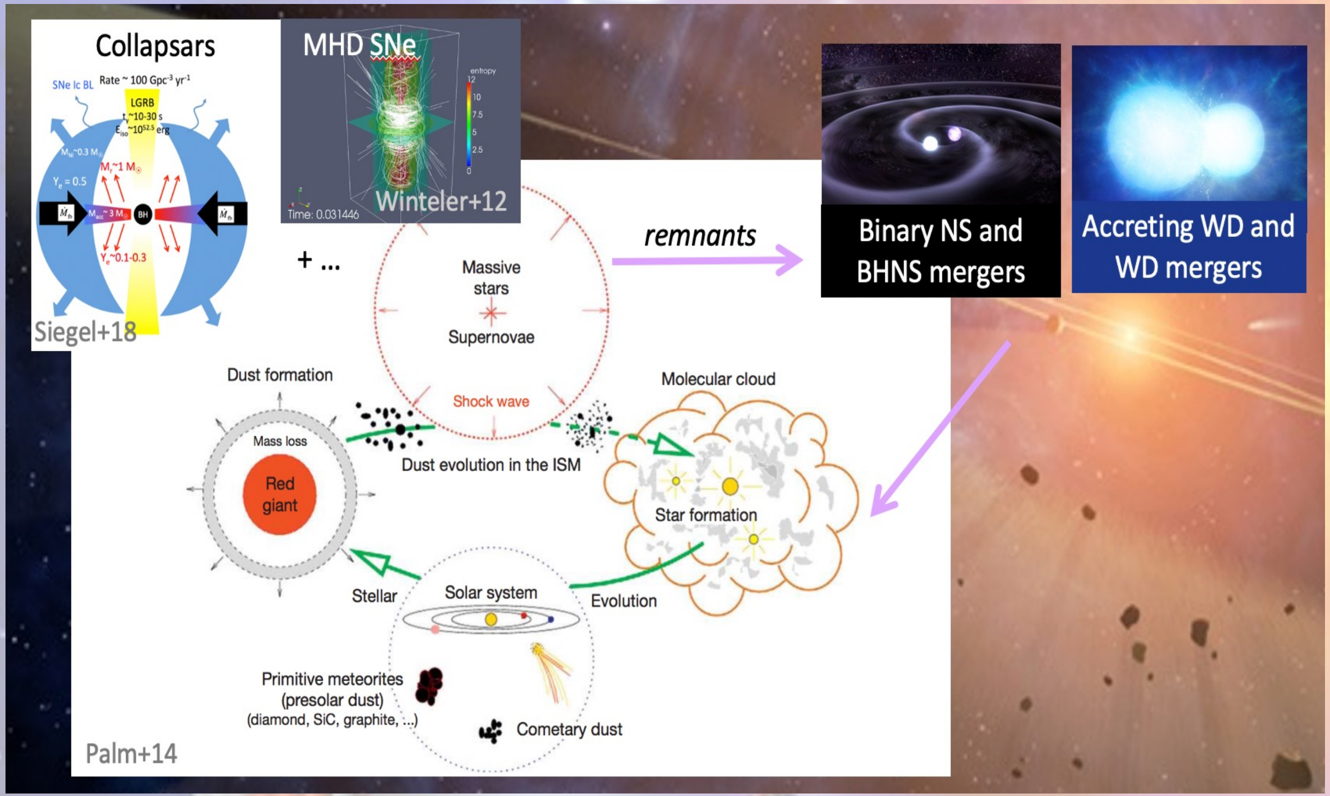
Nicole Vassh

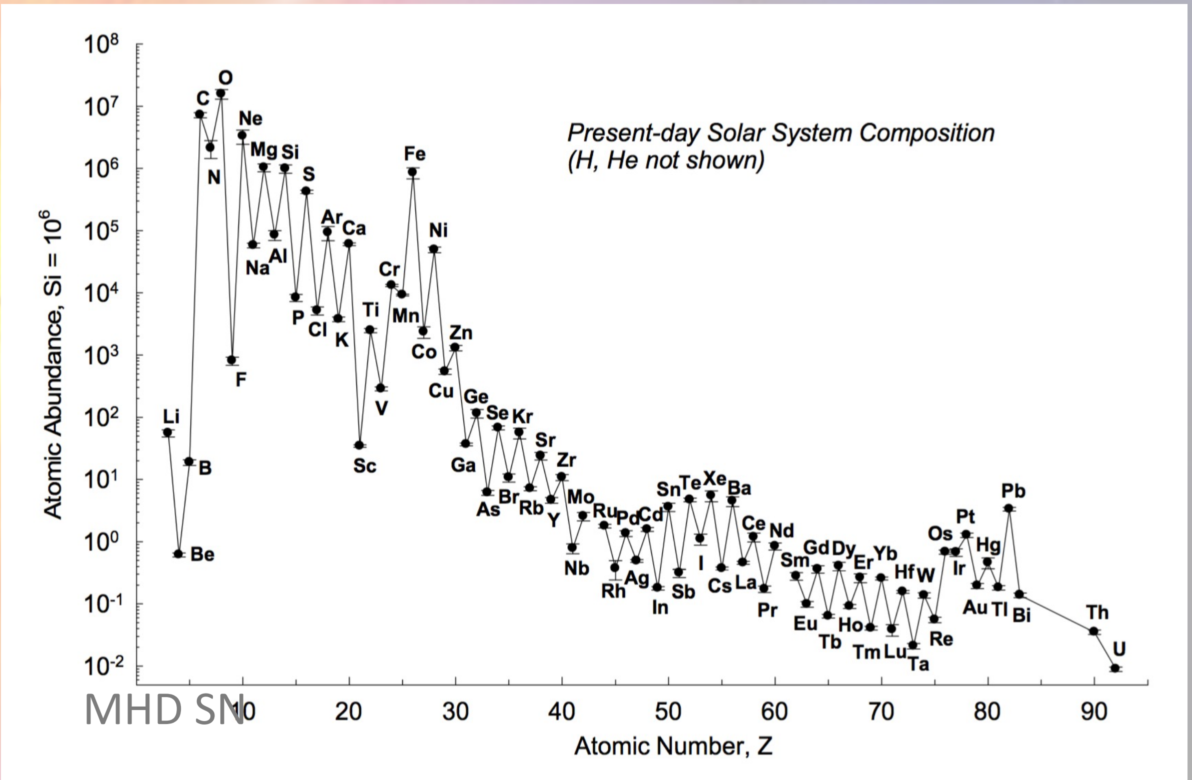
TRIUMF Theory Group

April 23, 2026

CNRS Workshop

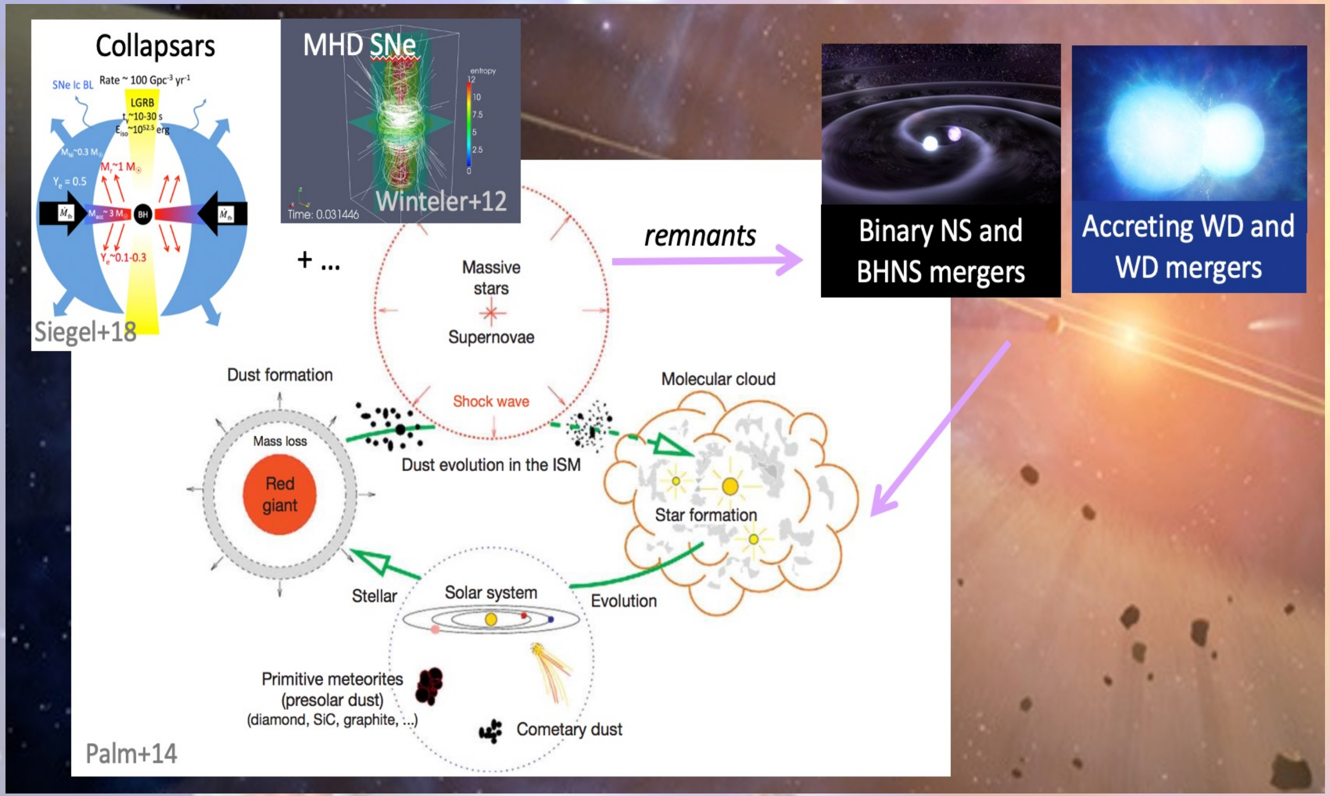
Nuclear physics properties imprinted on astrophysical observables

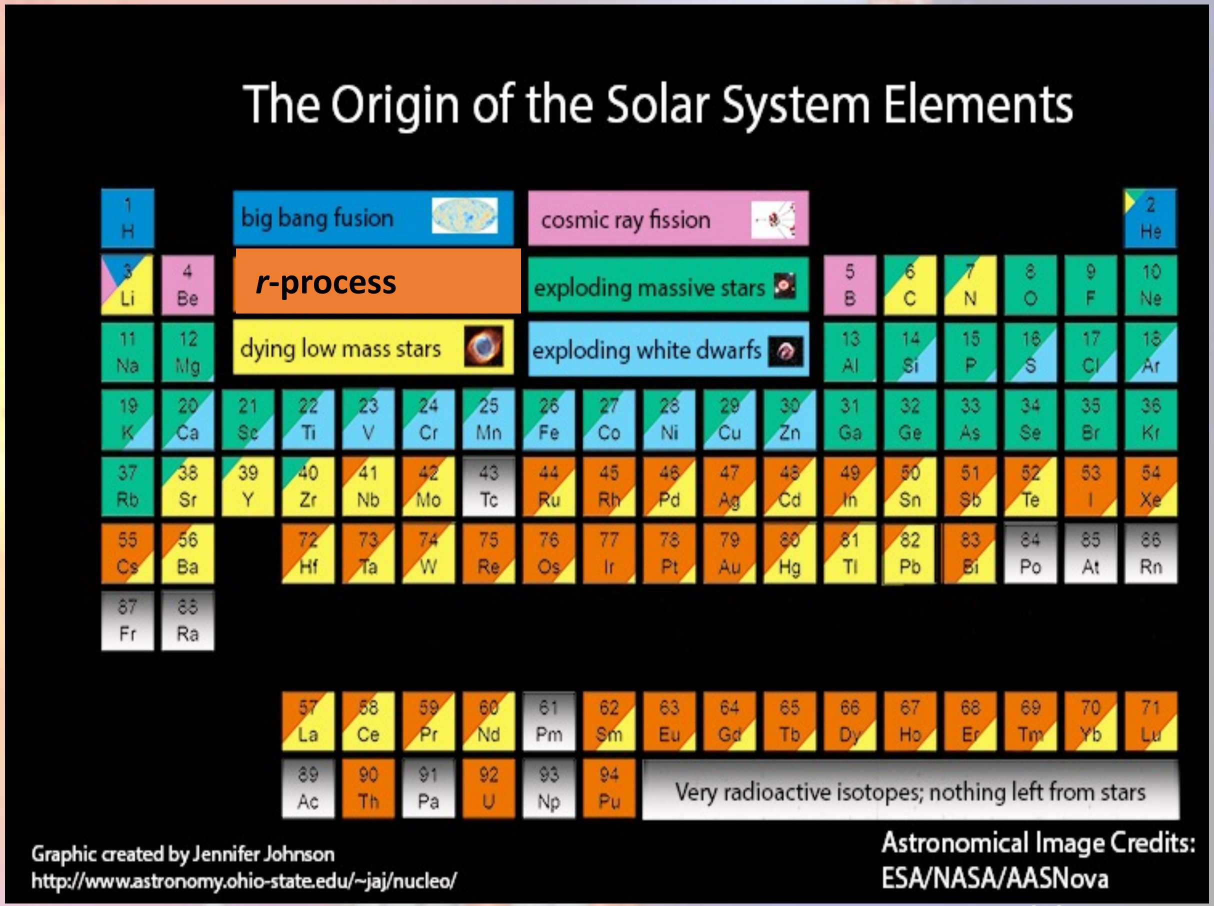




Lodders 10

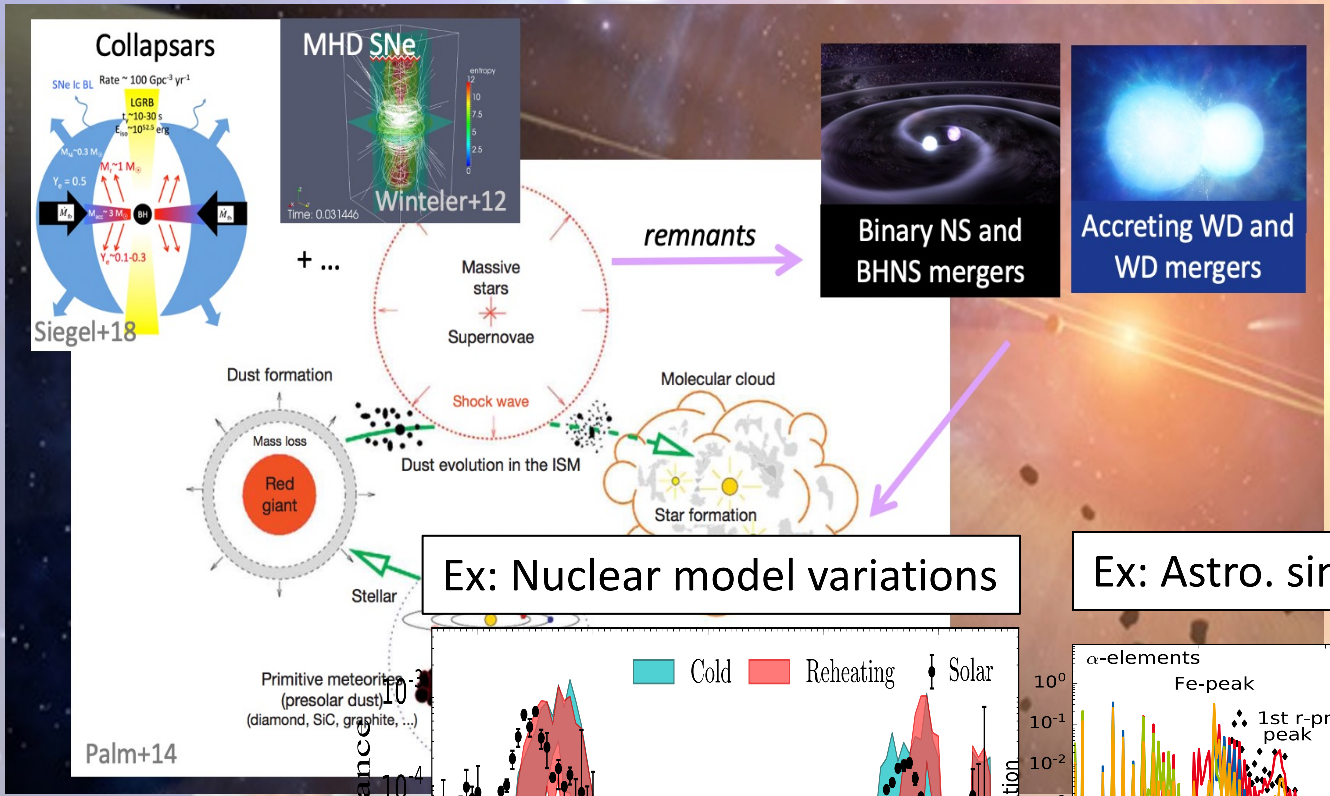
Nuclear physics properties imprinted on astrophysical observables

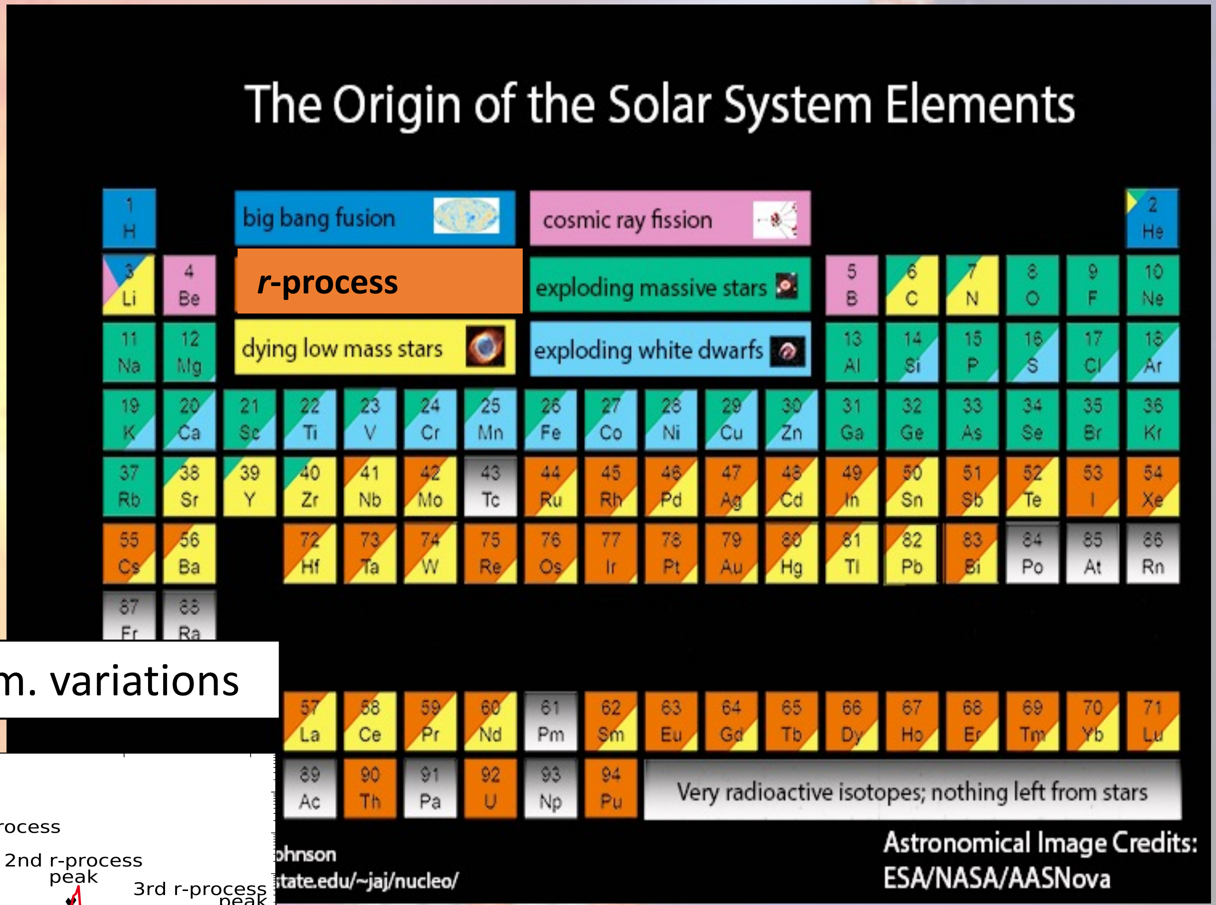




Lodders 10

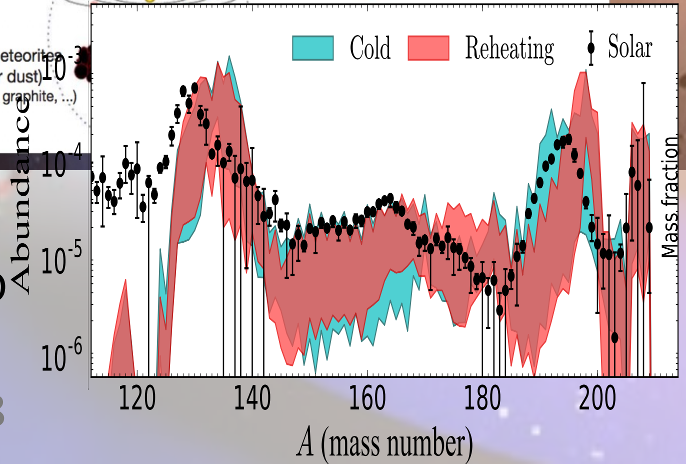
Nuclear physics properties imprinted on astrophysical observables



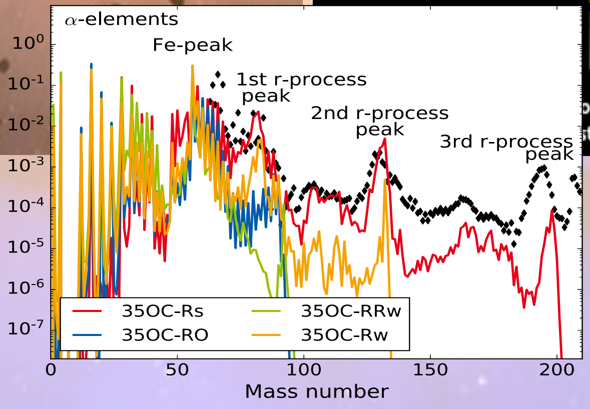


Lodders 10

Ex: Nuclear model variations



Ex: Astro. sim. variations

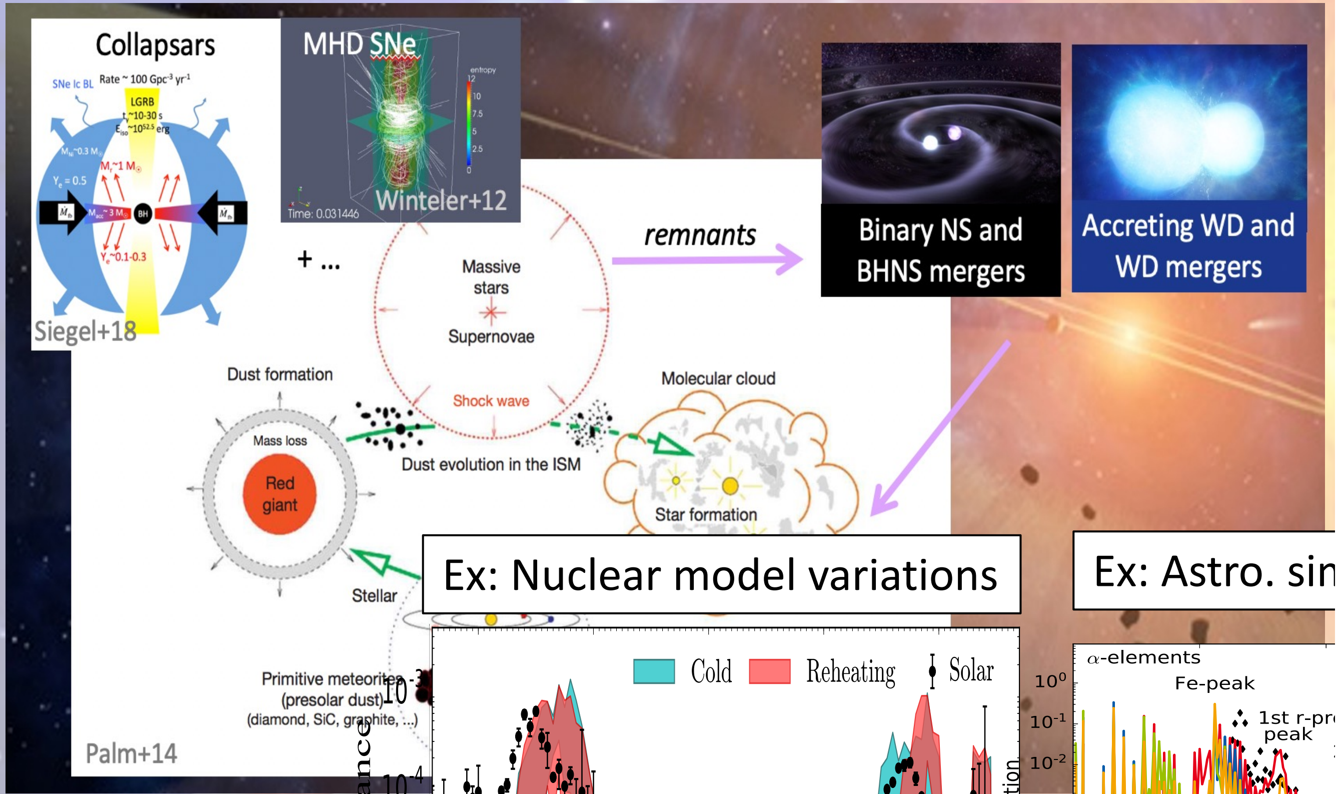


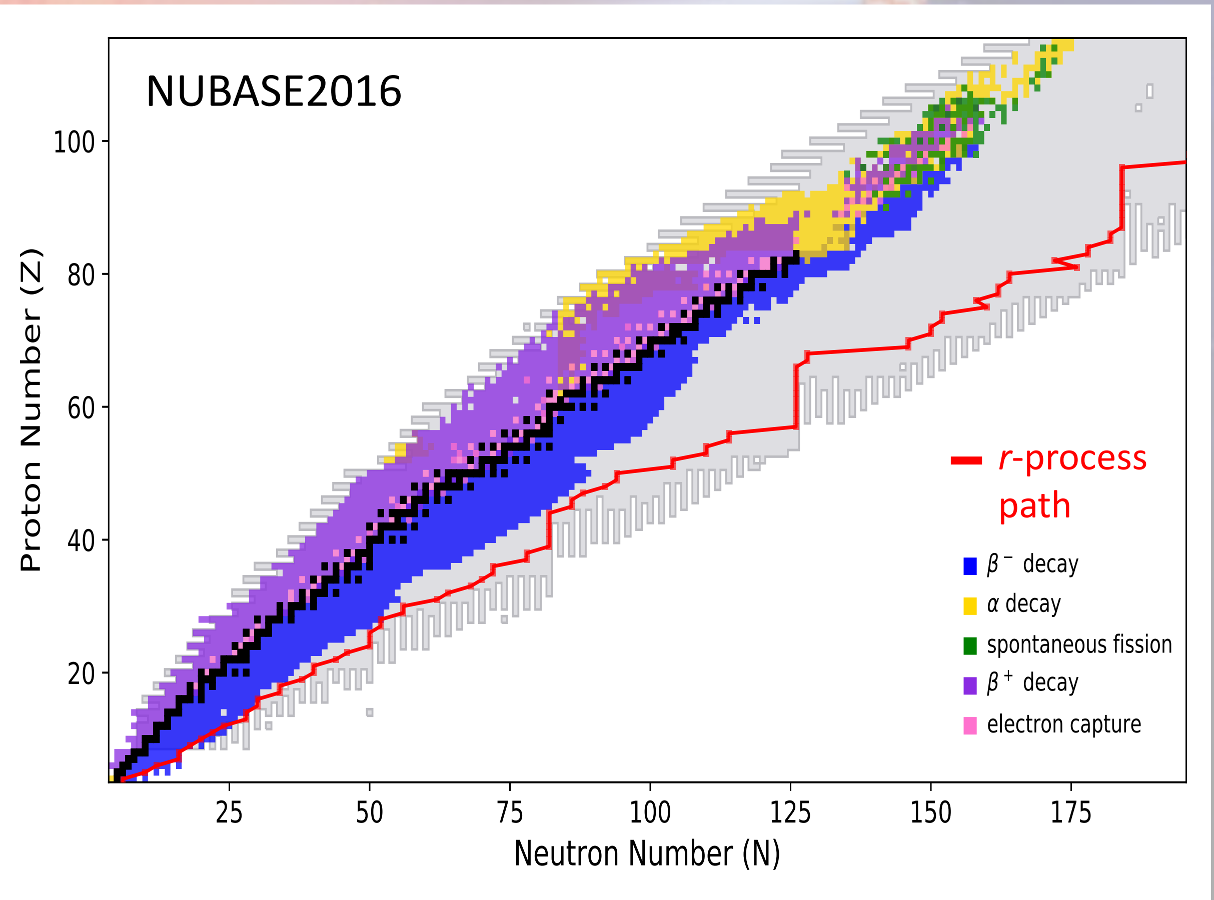
Reichert+21

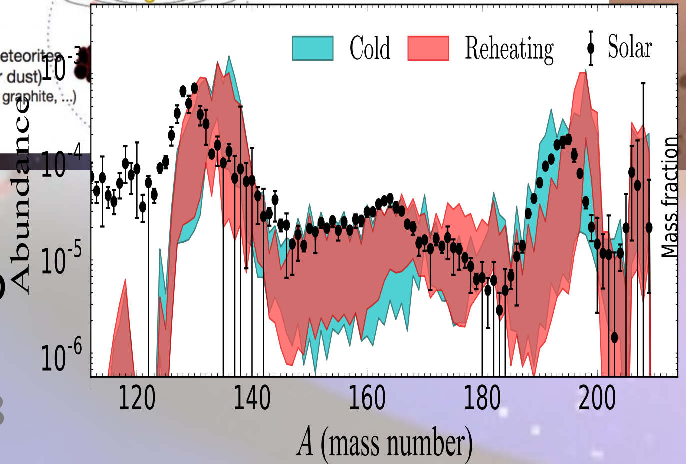
E.g. Neutron star merger and MHD supernova sims

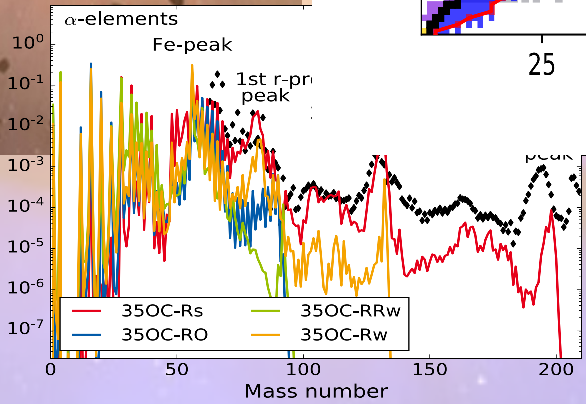
Cote,...,Vassh+18

Nuclear physics properties imprinted on astrophysical observables









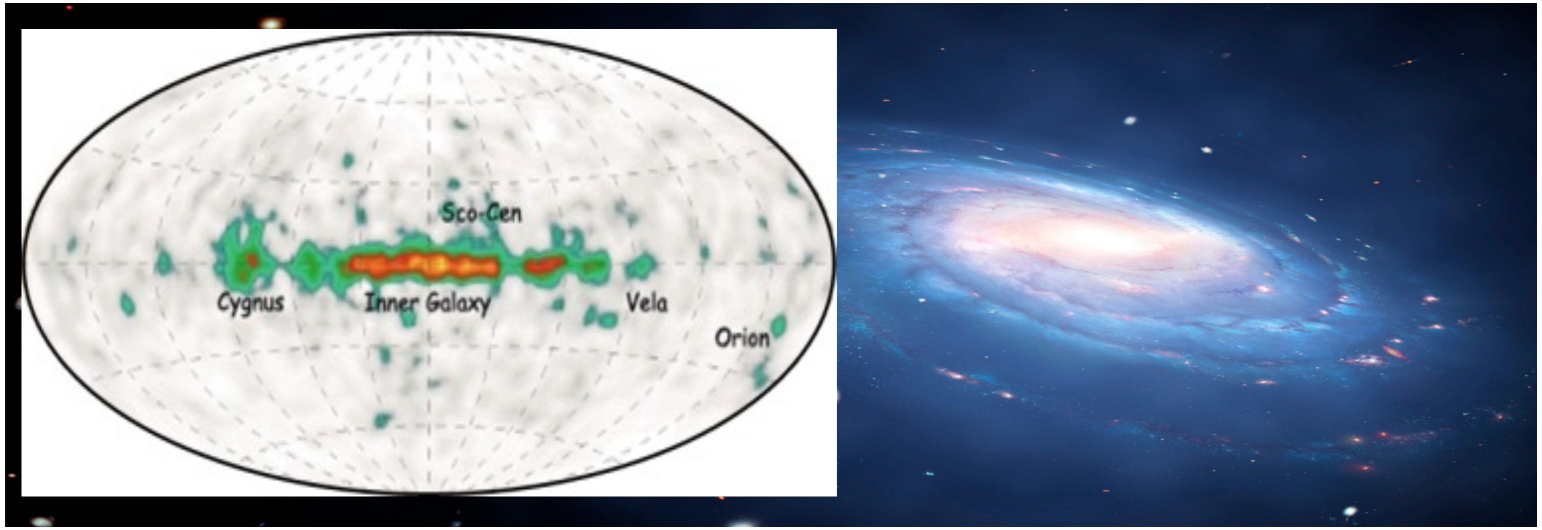
E.g. Neutron star merger and MHD supernova sims

Cote,...,Vassh+18

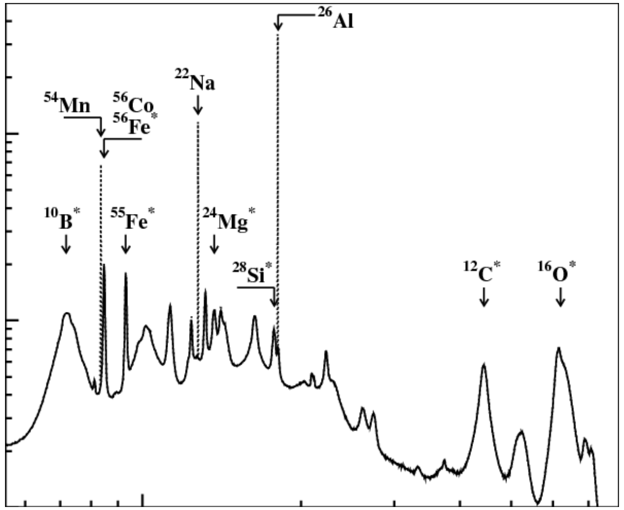
Reichert+21

Lodders 10

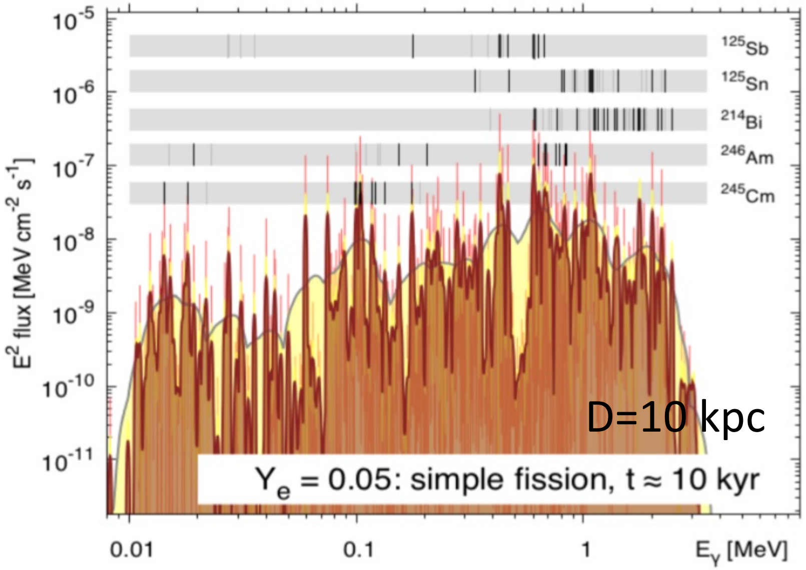
MeV gamma rays as fingerprints of astrophysical isotope production



COMPTEL all-sky image of 26Al 1.8 MeV emission from Galactic disk



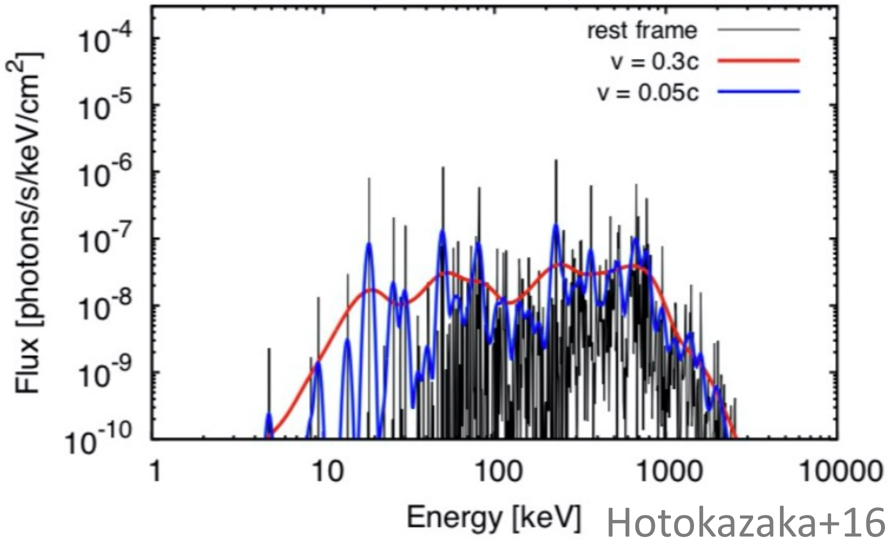
Emission from NSM remnants



Korobkin+19; see also Wu+19

Emission from a nearby mergers

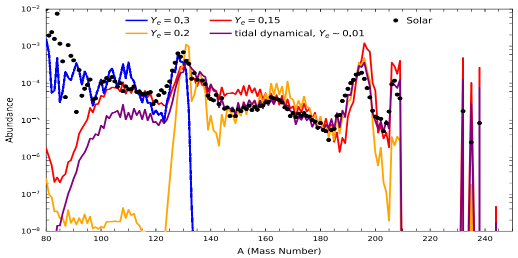
3day, 3Mpc, 0.01Msun

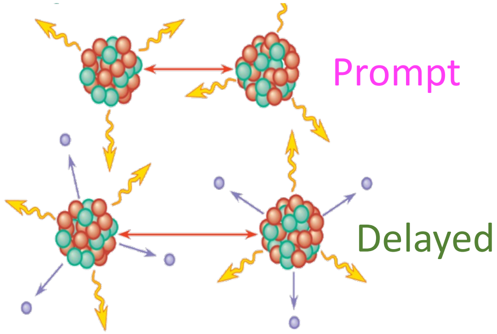


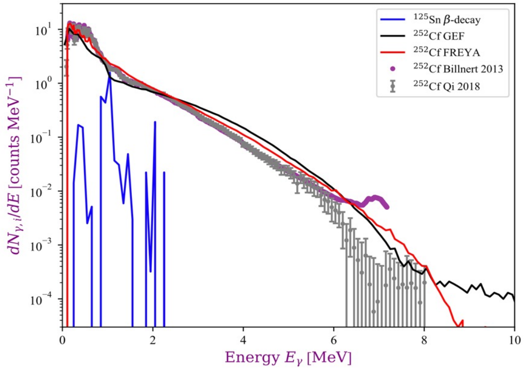
Hotokazaka+16

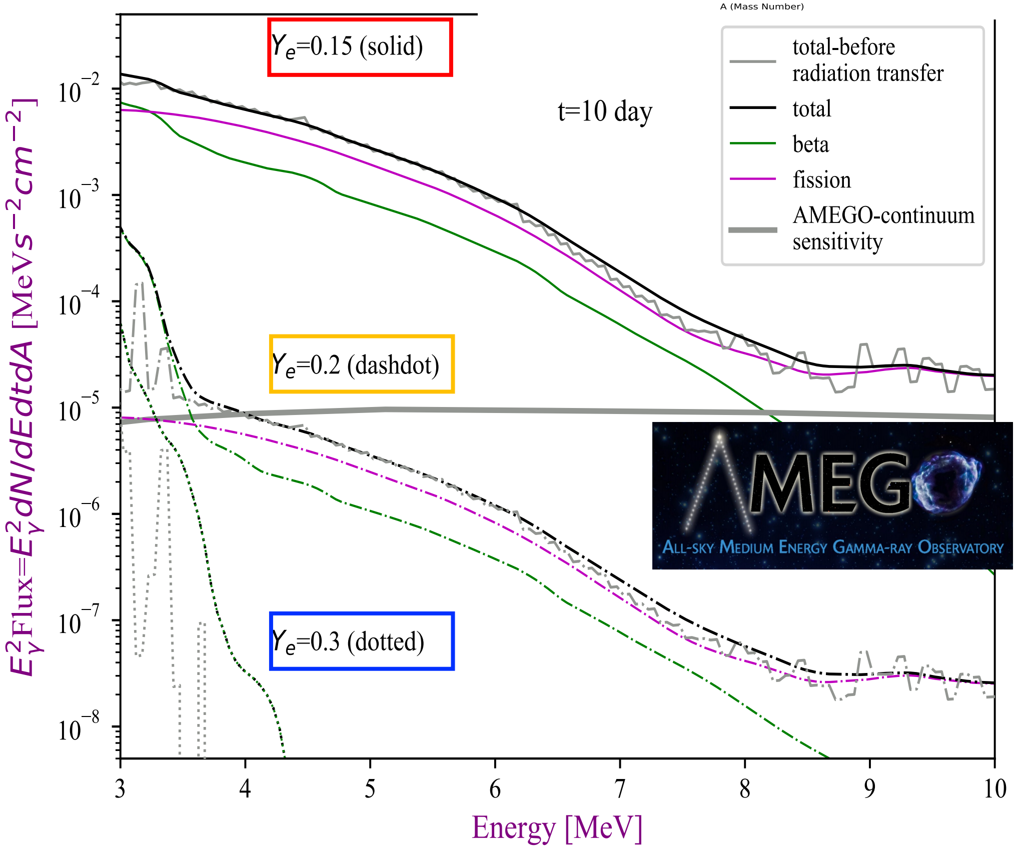
Predictions for observable MeV gamma emission from fission and the decays of neutron-rich nuclei in mergers

Spectrum with significant emission >3.5 MeV signifies that an astro. event produced fissioning species









Wang,Vassh+20 (ApJ Letters 903, L3)

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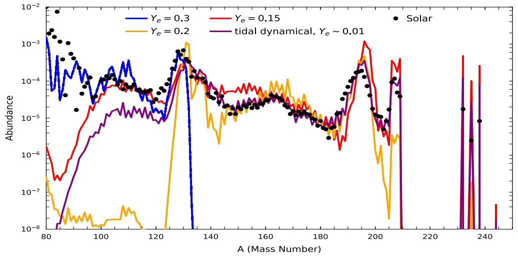
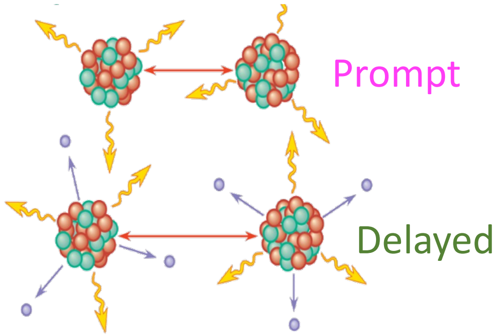
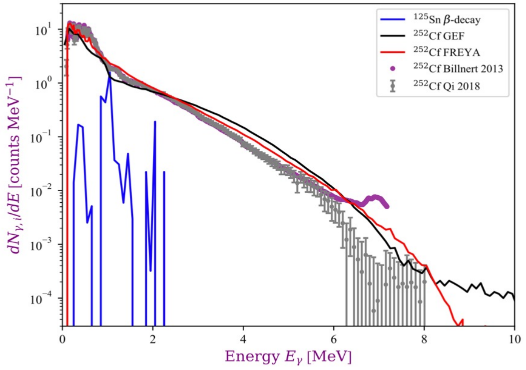
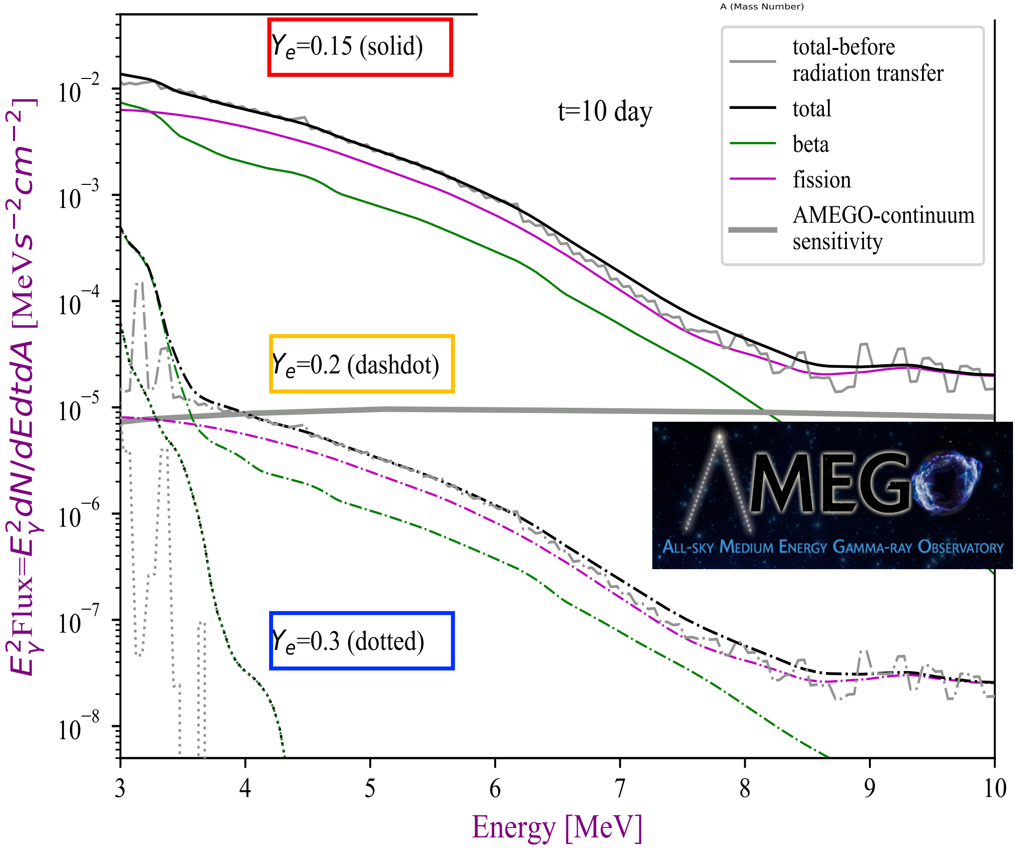


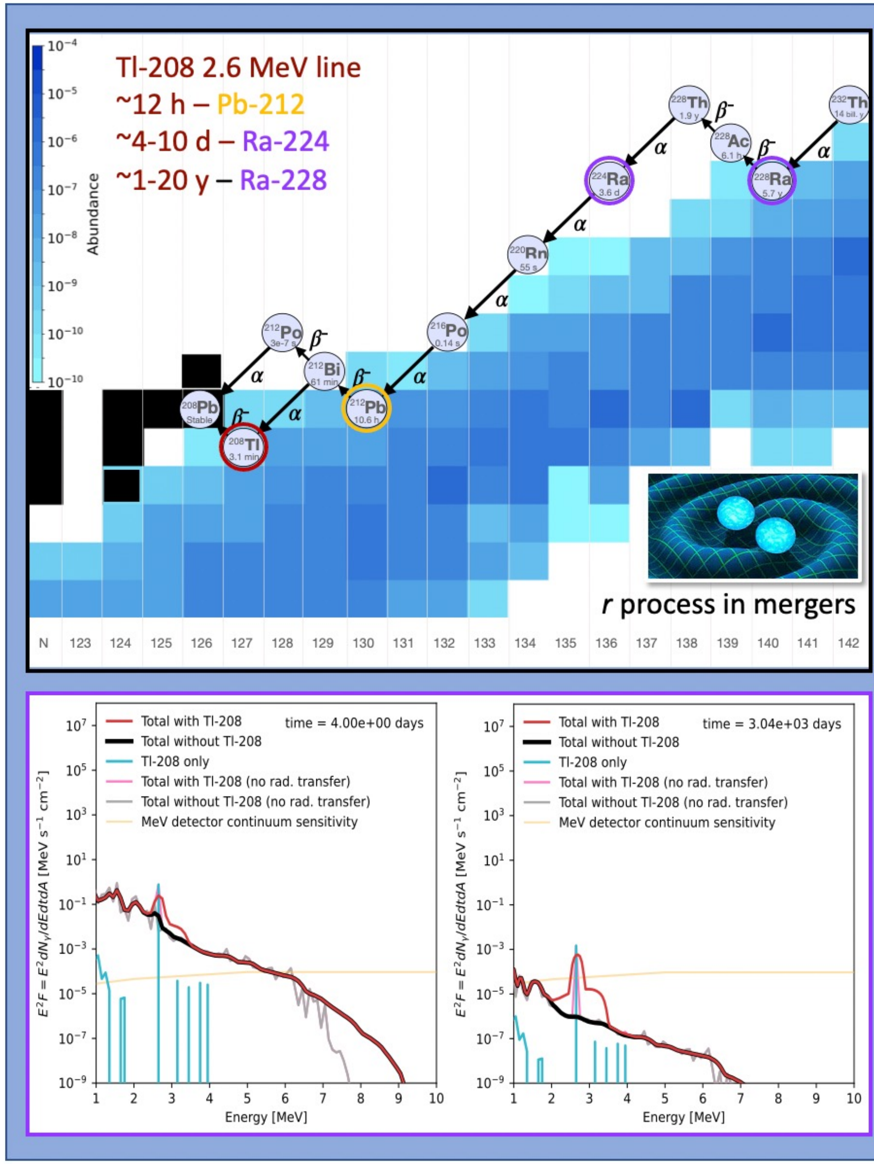




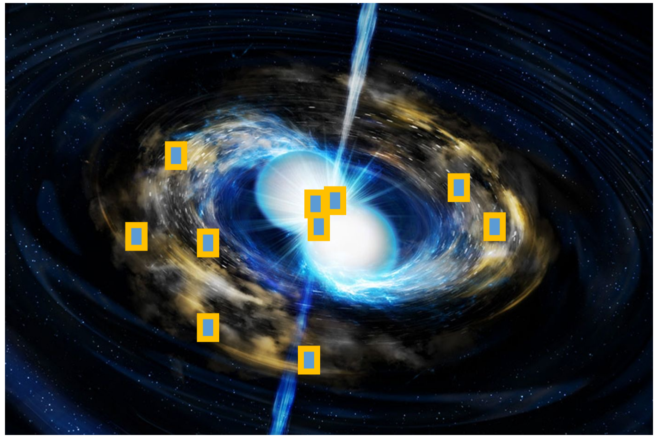


Wang,Vassh+20 (ApJ Letters 903, L3)

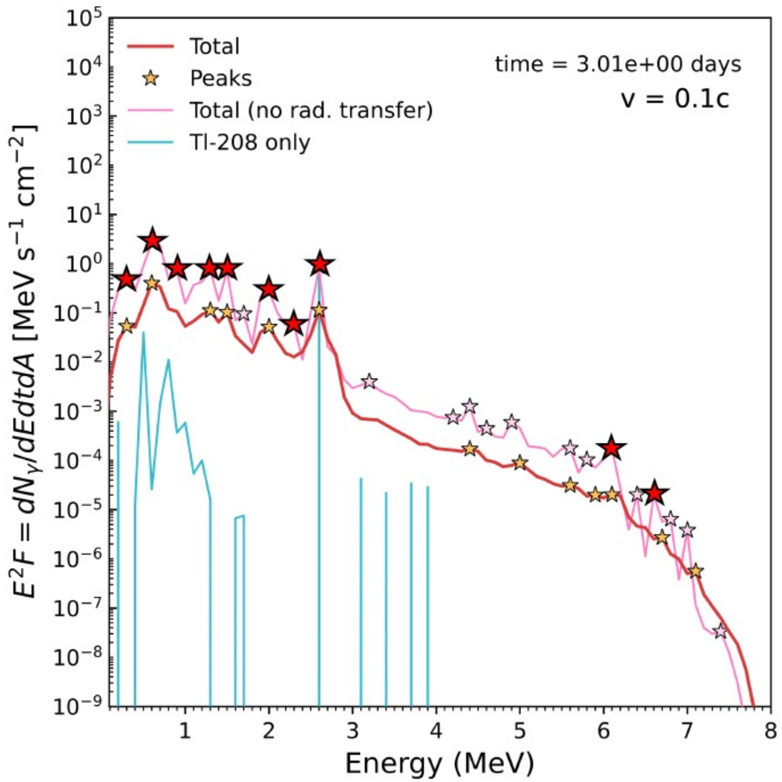
Strong line at 2.6 MeV due to Tl-208 decay indicates at least Pb-212 reached



Vassh, Wang, Larivière+24 (PRL 132, 052701)



- **Consider a mass weighted sum of merger ejecta** from NSM sim. of Radice et al.
- **Apply a peak finding algorithm** to identify when lines from the decay of specific isotopes may be visible in the total predicted spectrum



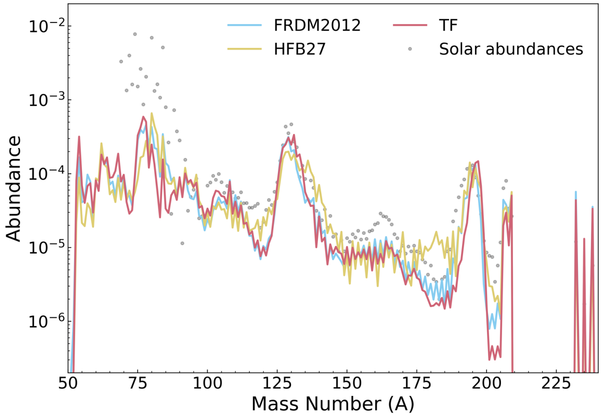
Larivière, Vassh, Wang+26 (in prep)

Remnant timescales (>10 years)

Isotope	Time (years)	E (keV)	Mass models	mkt Betas
K-42	7.49e+01 – 1.40e+02	1525	–	F
Co-60	2.65e+03 – 8.41e+06	1173	*	*
	1.02e+03 – 7.93e+06	1332	*	*
Rh-106	8.25e-01 – 1.24e+01	2366	–	T
In-128	3.77e+01 – 3.86e+01	3520	*F*	–
Sb-125	9.16e-01 – 1.32e+01	**428**, 463	T	FT
	1.90 – 1.94e+01	**601**, 636	FT	FT
Sb-126	5.26e+02 – 2.02e+06	415	*	*
	5.70e+01 – 2.18e+06	**666**, 695, 697	*	*
Sb-134	6.27e-01 – 2.20e+02	6451	–	H
	1.00e-03 – 3.84e+01	6687	*H*	H
	1.00e-03 – 1.53e+01	6820	H	H
I-136	1.64e+02 – 2.09e+02	6104	*H*	H
Ir-194	1.22e+01 – 5.45e+01	328	FT	FT
	7.95 – 3.70e+01	939	–	T
	2.87 – 6.31e+01	**1151**, 1183	FT	FT
	2.29 – 5.32e+01	1469	–	FT
	3.94 – 5.67e+01	1622	–	T
	5.50 – 5.70e+01	1806	*FT*	FT
	7.39 – 5.78e+01	2044	–	FT
Tl-208	4.05e-01 – 1.05e+02	2615	*	*
Tl-209	2.08e+02 – 3.61e+04	1567	*	FT
Ac-228	1.71 – 4.57e+01	**911**, 969	FT	F
	3.26 – 4.67e+01	1588	FT	–
Am-246	8.33e+01 – 3.18e+02	154	–	T

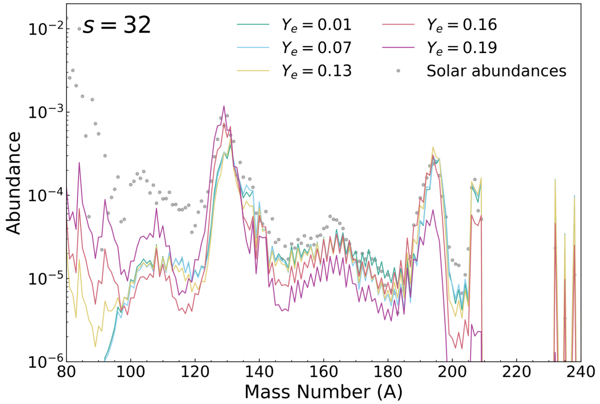
Isotopes with decay lines dominating spectrum some time between 1 day to 1 Gyr

Mass weighted total ejecta from Radice et al. NSM hydrosim



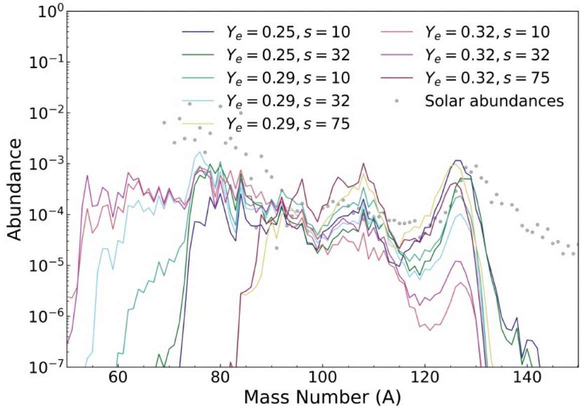
K-42, Fe-59, Co-60, Ga-72, Ge-77, Rb-88, Nb-95, Ru-103, Rh-106, Ag-112, In-128, Sb-125, Sb-126, Sb-128, I-131, I-132, La-140, Pr-144, Eu-156, Ir-194, Tl-208, Tl-209, Ac-228, Am-246

Main r-process variations



Rb-88, Nb-95, Ru-103, Rh-106, Ag-112, Sn-125, Sn-127, Sb-125, Sb-126, Sb-128, Sb-129, I-131, I-132, I-133, I-135, Xe-133, La-140, La-142, Pr-144, Eu-155, Eu-156, Hf-181, Ta-182, Ta-185, Re-188, Ir-194, Tl-208, Tl-209, Pb-211, Pb-214, Ac-228, Pu-243, Am-246

Weak r-process variations



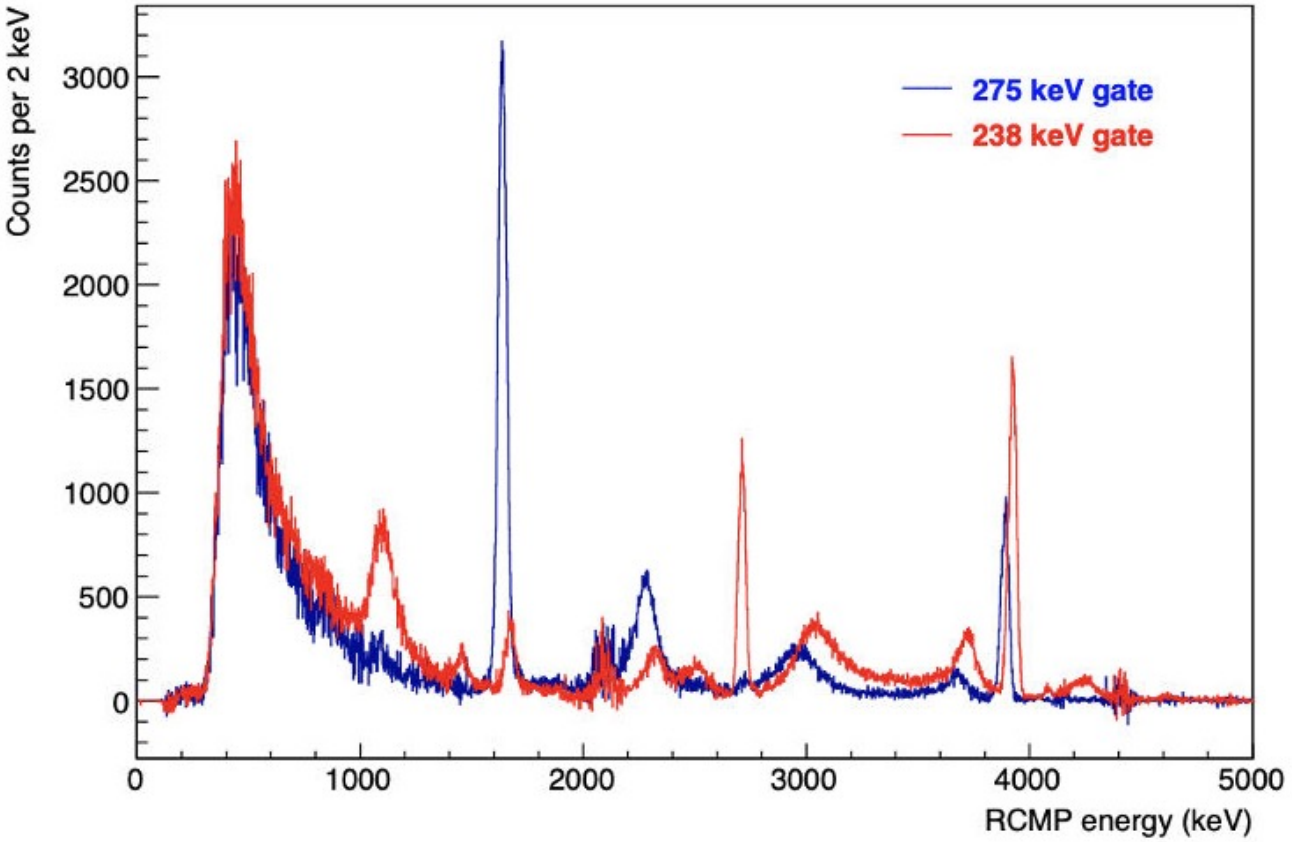
Na-24, K-42, Fe-59, Co-60, Cu-66, Cu-67, Zn-72, Ga-72, Ge-77, Kr-85, Kr-88, Rb-88, Y-91, Zr-95, Nb-95, Ru-103, Rh-106, Ag-112, Sn-125, Sb-125, Sb-126, Sb-127, Sb-128, Sb-129, I-131, I-132, La-140

* Overall, find Fe-59, Co-60, Ga-72, Ge-77, Rb-88, Zr-95, Nb-95, Ru-103, Rh-106, Ag-112, Sn-125, Sb-125, Sb-126, Sb-128, I-131, I-132, La-140, Eu-156, Ir-194, Tl-208, Tl-209, Pb-214, Ac-228 most frequently reported across calculation variations

Larivière, Vassh, Wang+26 (in prep)

GRIFFIN obs. this 1.6 MeV line in 20Mg decay for the first time in 2024…

… how many more strong lines are unknown?

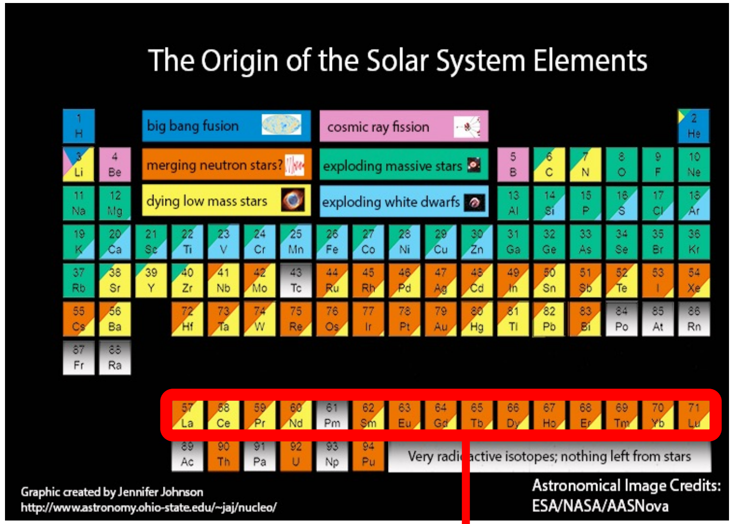


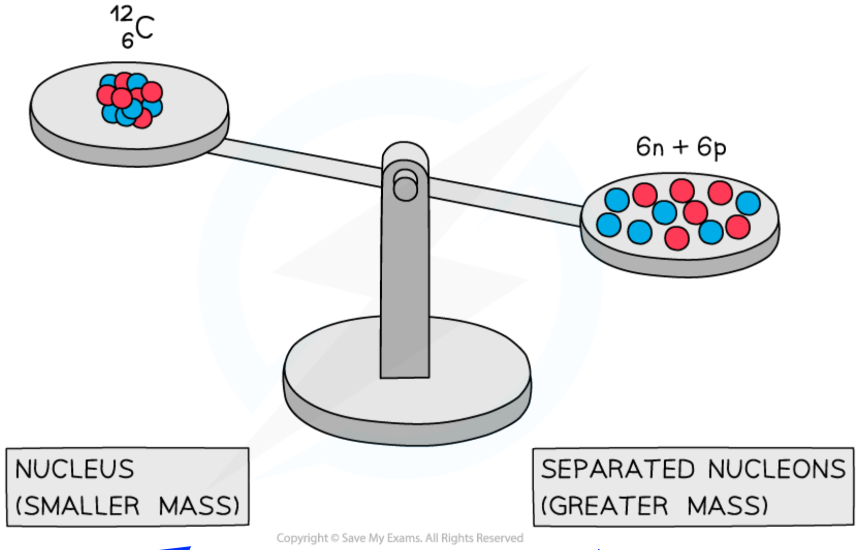
CINP Nuclear Phys Brief for the Canadian SAP LRP
C. Andreoiu, et al 2025

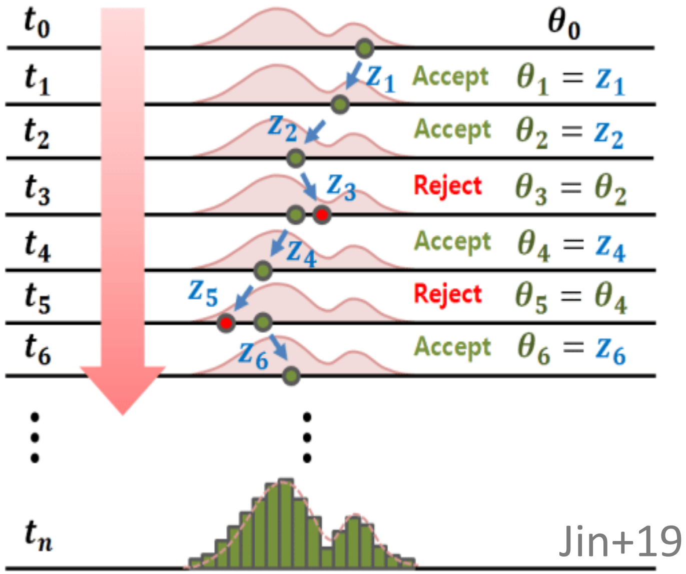
* Recommend remeasurements of the decay spectrum of species currently predicted to be identifiable in the merger spectrum listed on last slide (e.g. Fe-59, Co-60, Ga-72, Ge-77, Rb-88, Zr-95, Nb-95, Ru-103, Rh-106, Ag-112, Sn-125, Sb-125, Sb-126, Sb-128, I-131, I-132, La-140, Eu-156, Ir-194, Tl-208, Tl-209, Pb-214, Ac-228)

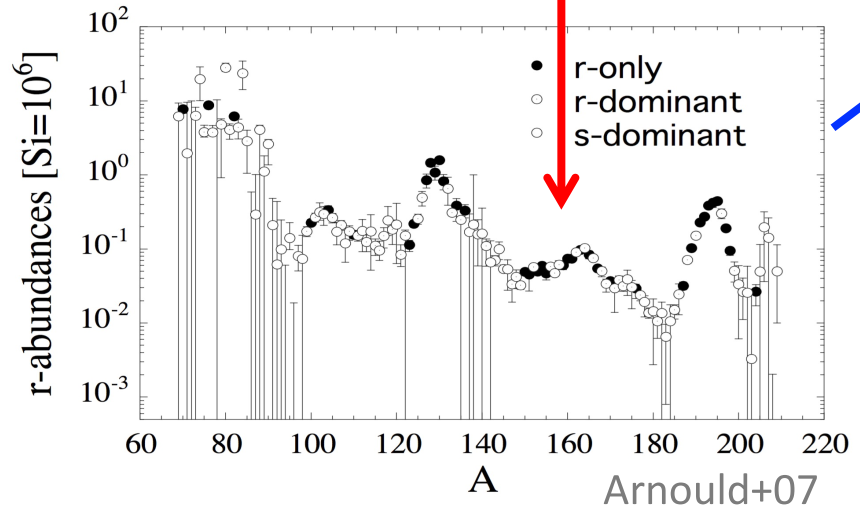
* Reconsider the species with β-decay half-lives within astro. observation window of ~days+ which are pop. during our calcs. but currently nothing in their spectrum strong enough reported with our approach of searching total spectrum for peaks (e.g. Cs-135,136,137, Pm-147,149,151, Eu-154,155,156 …)

Markov Chain Monte Carlo (MCMC) and the Solar rare-earth peak







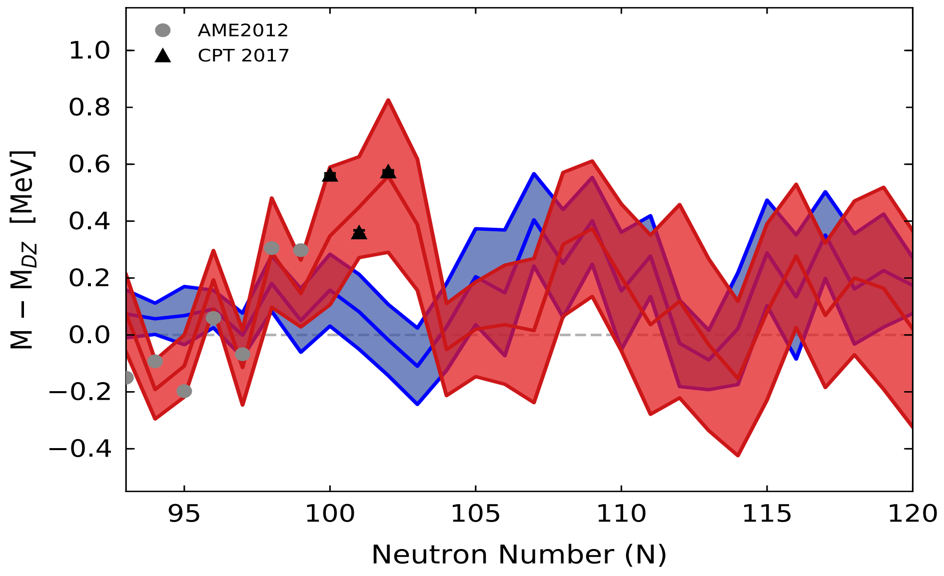


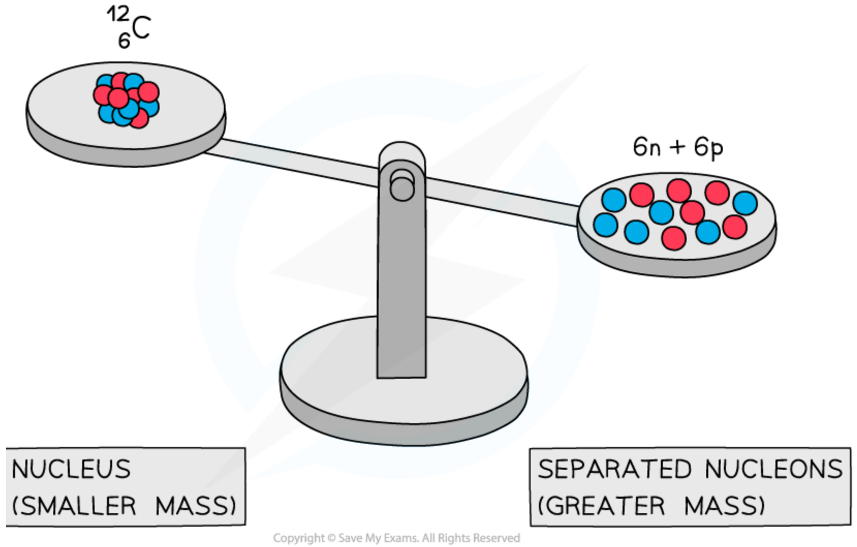
The nuclear structure responsible for abundance features (shell closures, deformation…) affects masses; masses are a key input for reaction and decay rates; thus changes in masses affect abundances

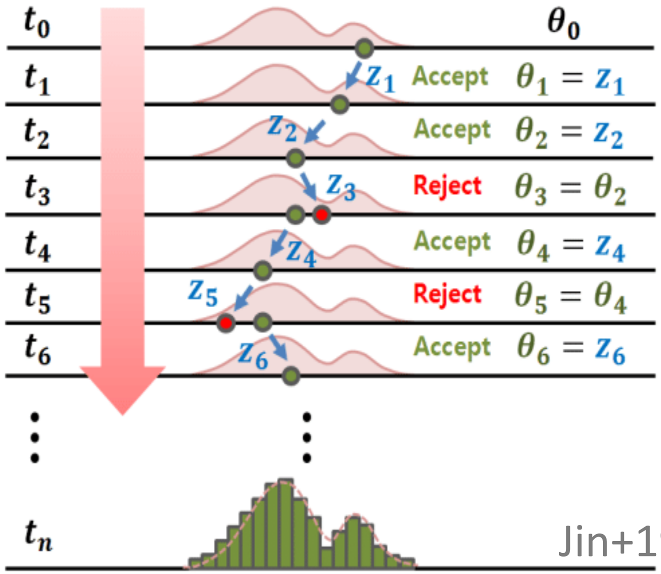
- Monte Carlo mass corrections
  $$M(Z,N) = M_{DZ}(Z,N) + a_N e^{-(Z-C)^2/2f}$$
- Update nuclear quantities and rates
- Perform nucleosynthesis calculation
- Calculate $\chi^2 = \Sigma_{A=150}^{180} \frac{(Y_{\odot,r}(A) - Y(A))^2}{\Delta Y(A)^2}$
- Update parameters / revert to last
  $$\mathcal{L}(\mathrm{m}) = \exp\left(-\frac{\chi^2(\mathrm{m})}{2}\right) \rightarrow \alpha(\mathrm{m}) = \frac{\mathcal{L}(\mathrm{m})}{\mathcal{L}(\mathrm{m}-1)}$$

* Use observation to discern which masses accommodate data for a given astrophysical condition

Markov Chain Monte Carlo (MCMC) and the Solar rare-earth peak







Jin+19

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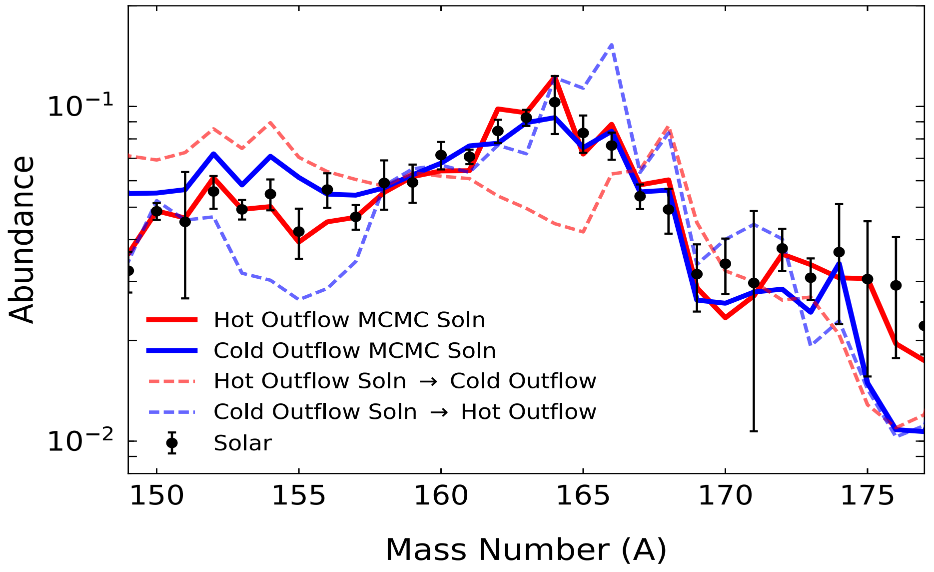
Considering two distinct moderately n-rich ejecta components from mergers



Orford,Vassh+18 (PRL); Vassh+21 (ApJ)

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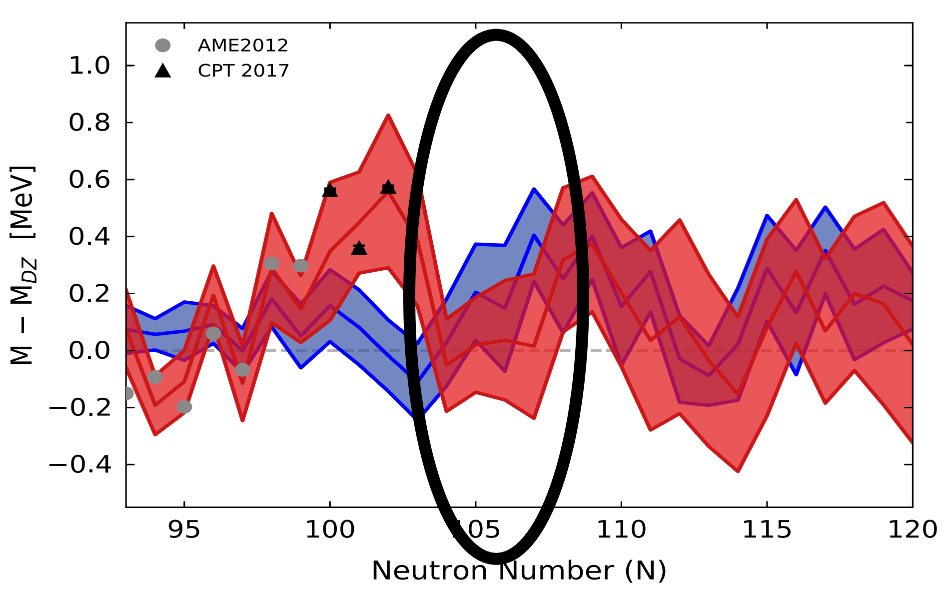

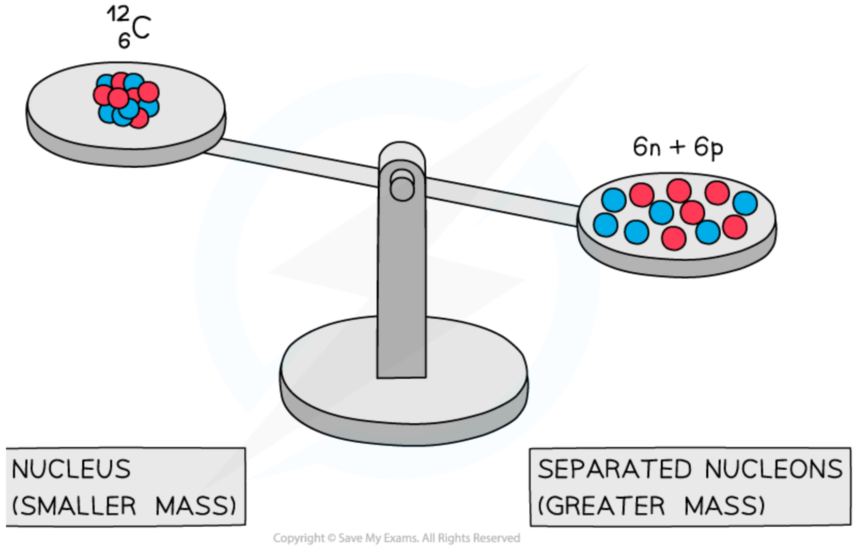

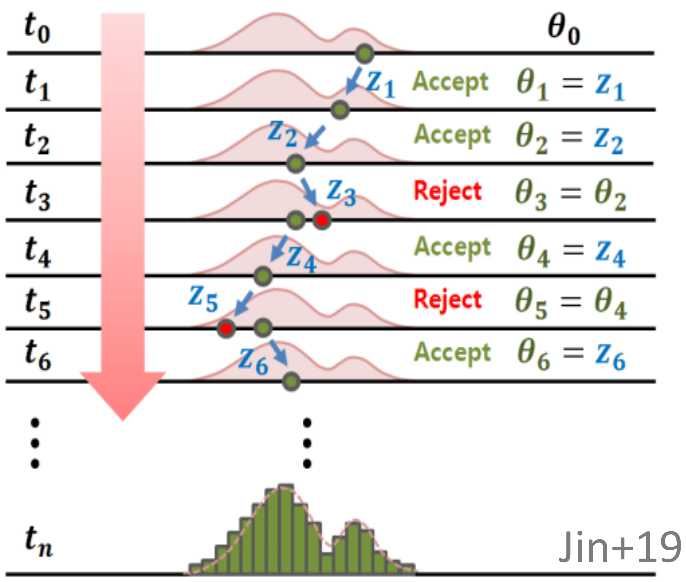

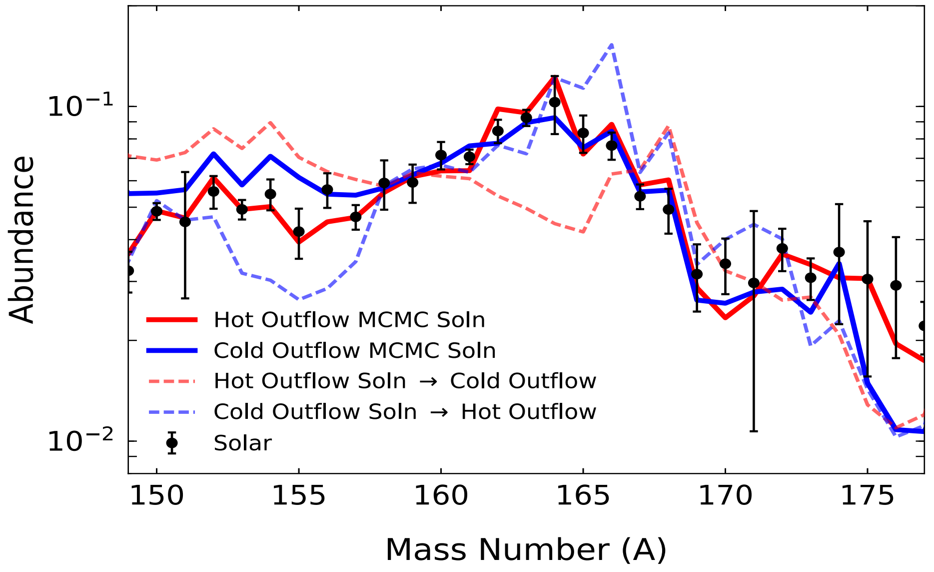

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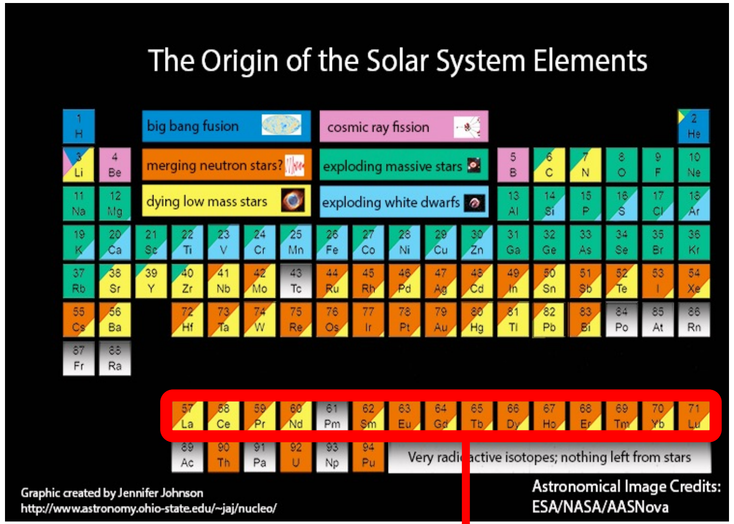

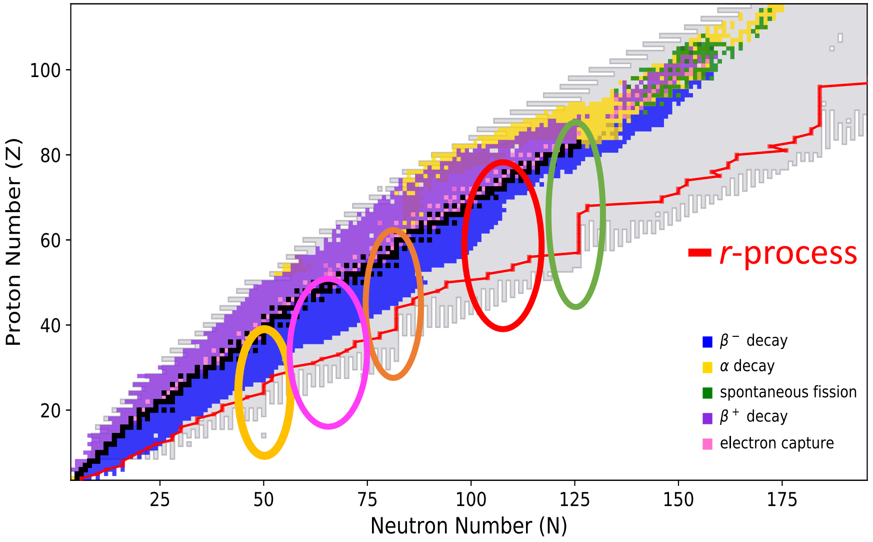

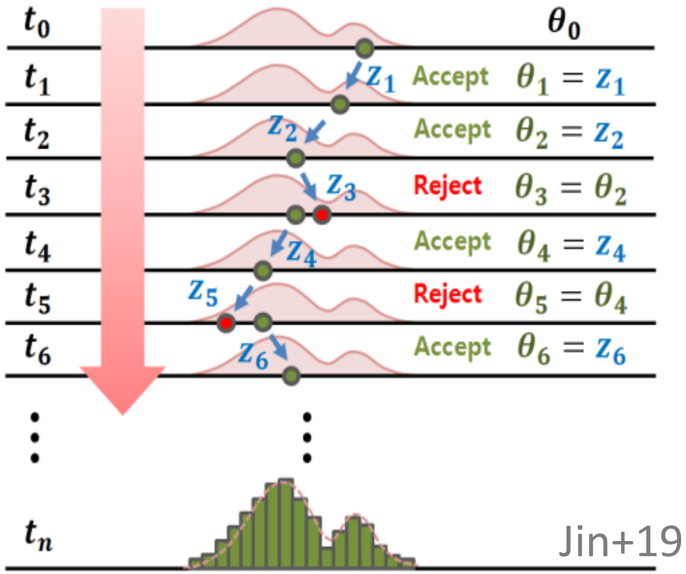

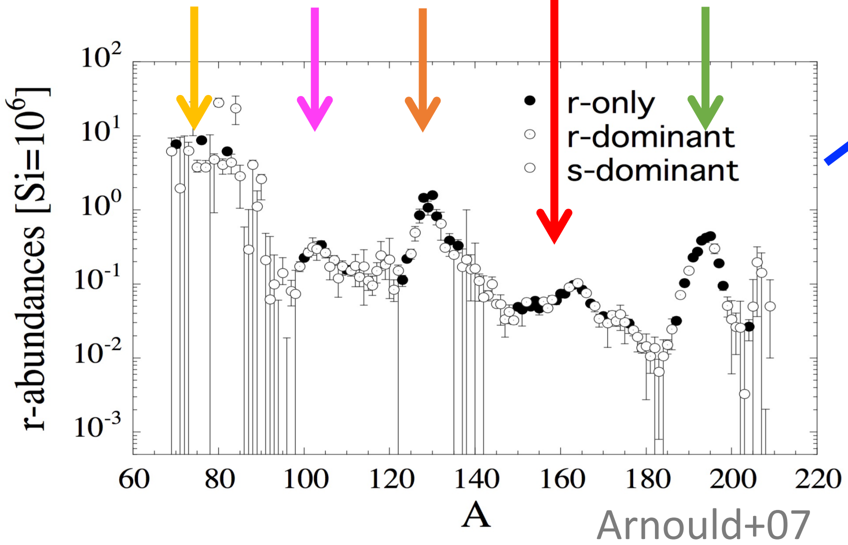

There are more peaks that can be used to inform us about other regions of the nuclear chart

UBC/TRIUMF co-op student Aiden Magor

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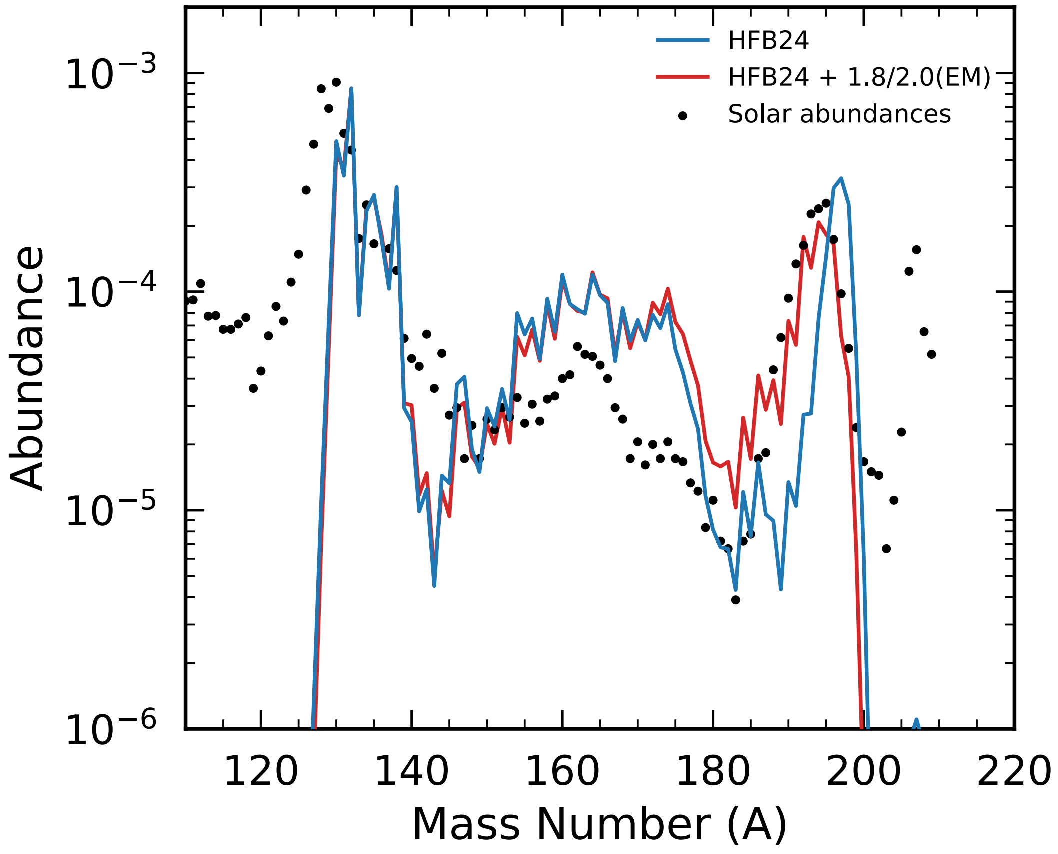
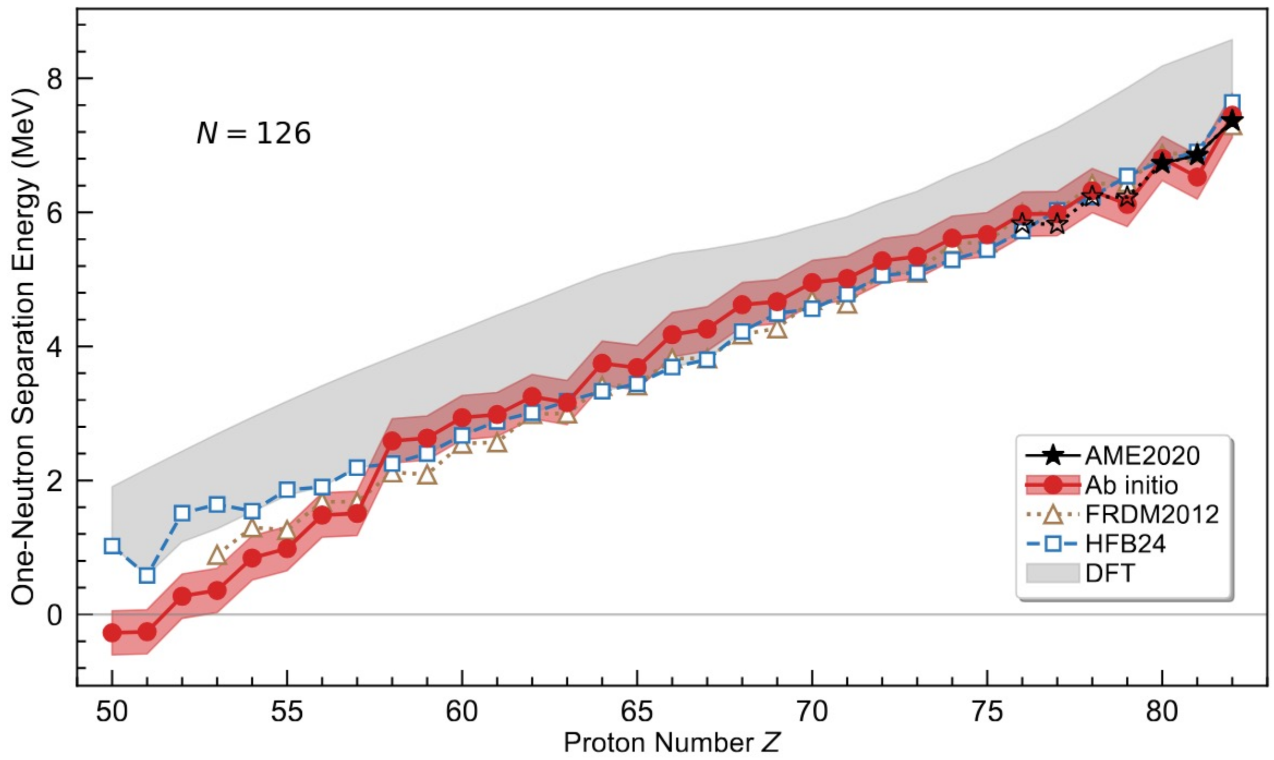
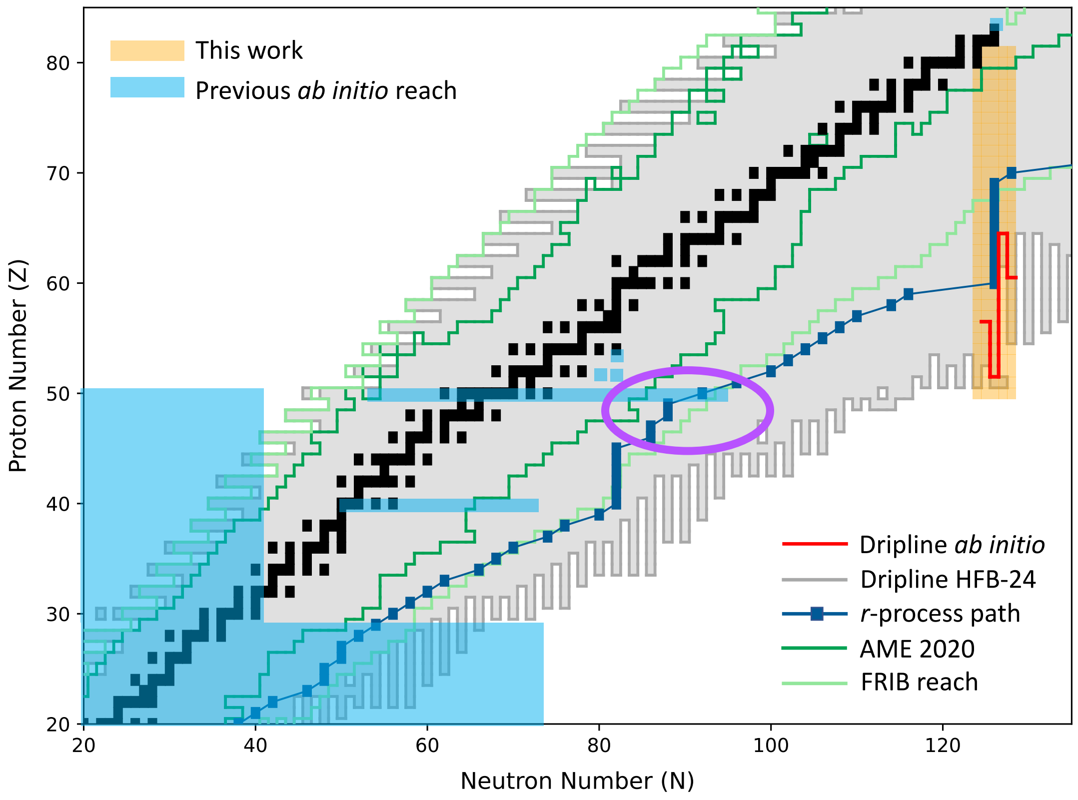
Ab initio nuclear theory predictions at N=124,125,126,127,128: predicted dripline and separation energies for *r*-process nuclei

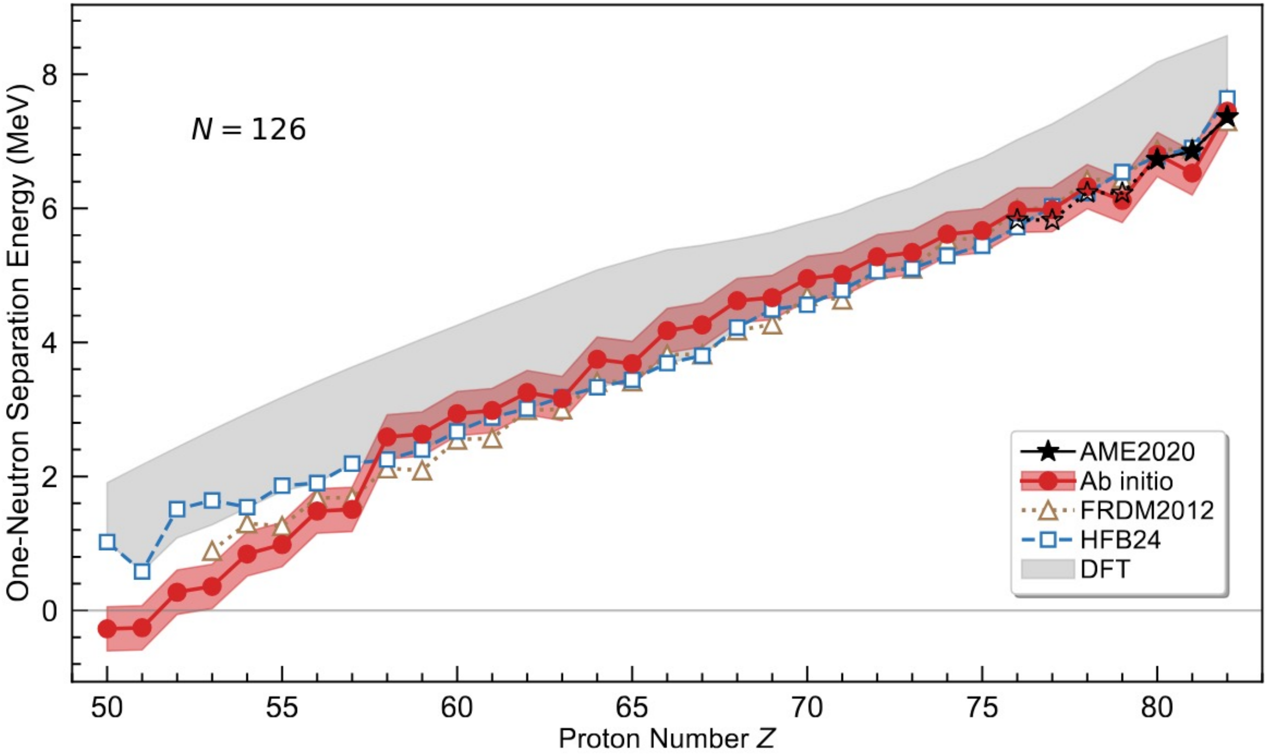




Hu, Larivière, Vassh, Holt, et al. (in prep)

Ab initio nuclear theory predictions at N=124,125,126,127,128: predicted dripline and separation energies for *r*-process nuclei

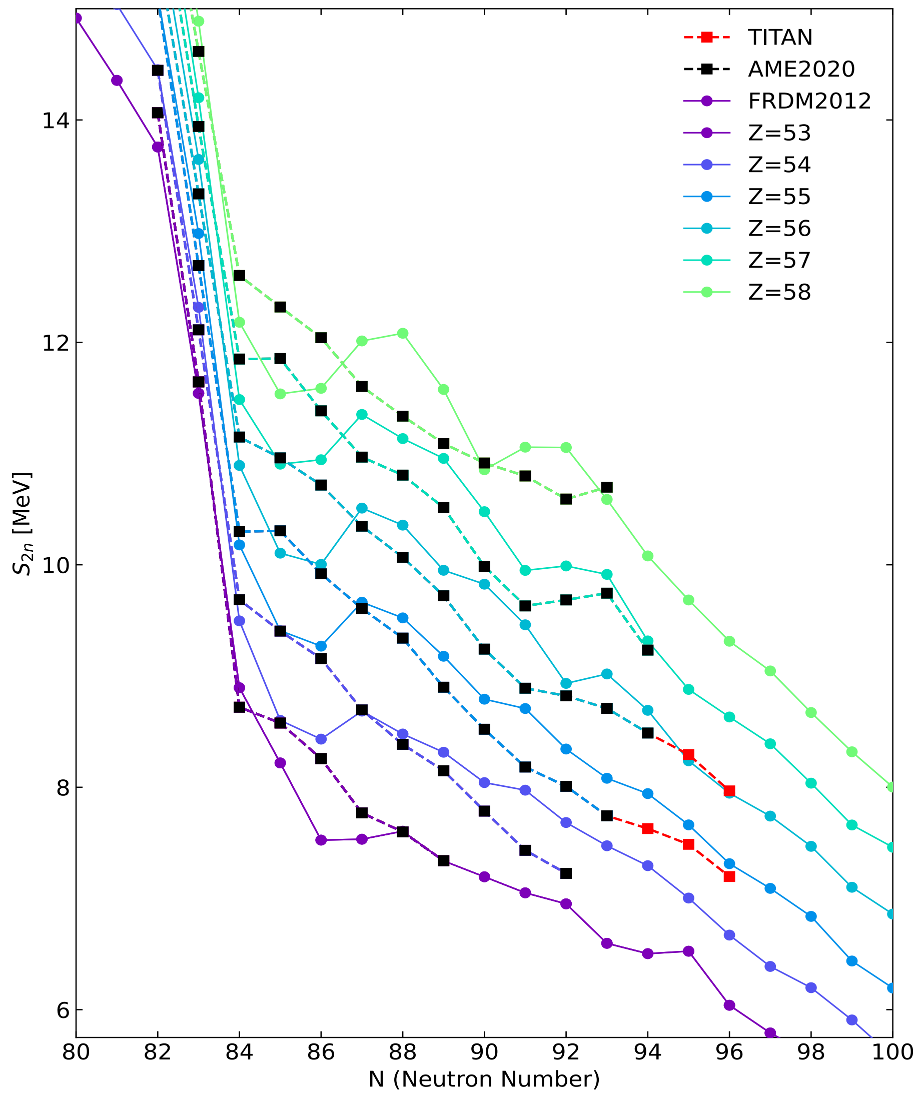




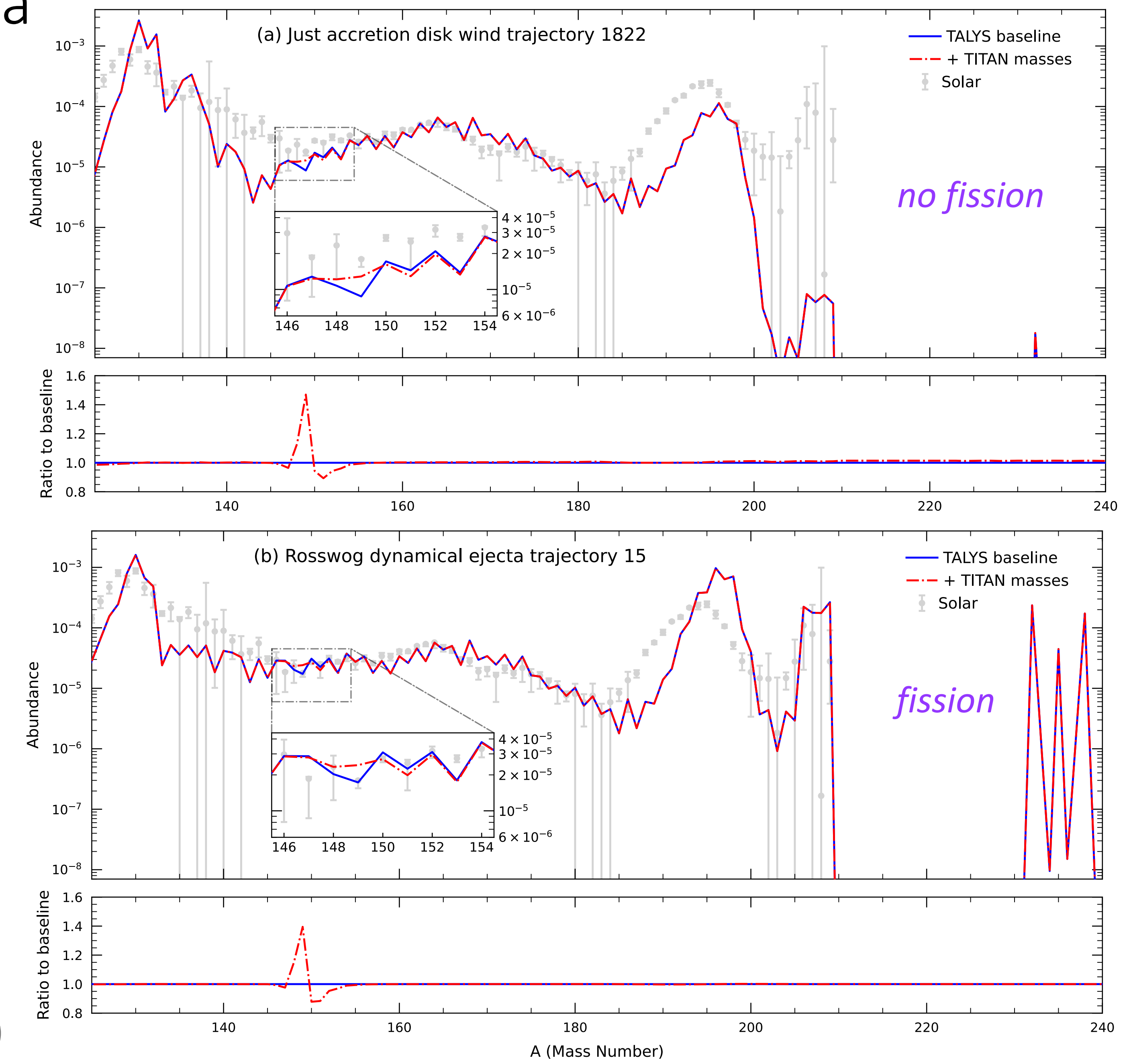
Kuske, Miyagi, Arcones, Schwenk recent results

Hu, Larivière, Vassh, Holt, et al. (in prep)

TITAN mass measurements: Cs, Ba



Solar abundance comparison

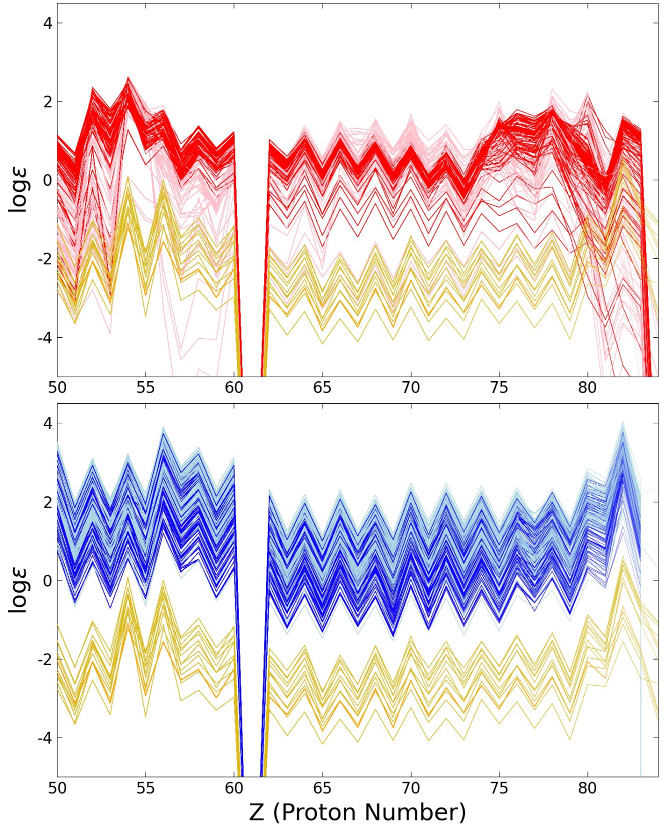


*impact study led by TRIUMF postdoc Tsung-Han Yeh

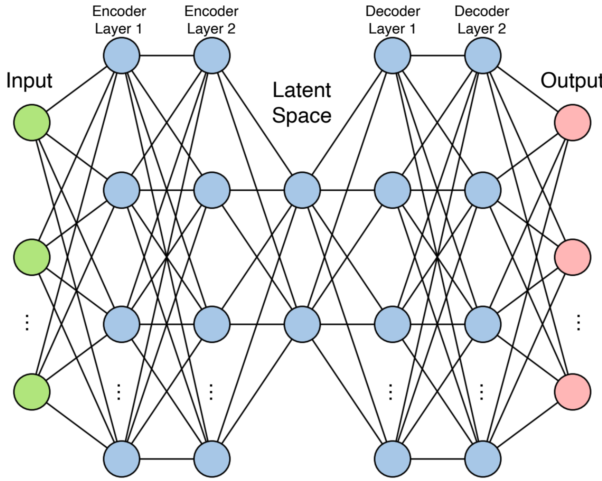
Yeh, Cordova, Wang, et al (including Vassh), et al (in prep)

Example of bridging nuclear physics and astro. using ML:
stellar classification feature importance as a new kind of “sensitivity study”

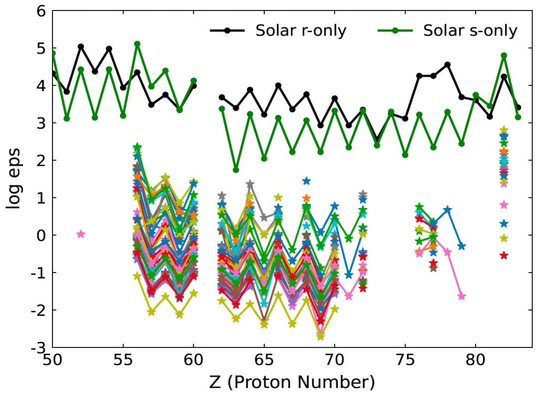
(1) Calculations for abundance patterns of s-process and r-process nucleosynthesis



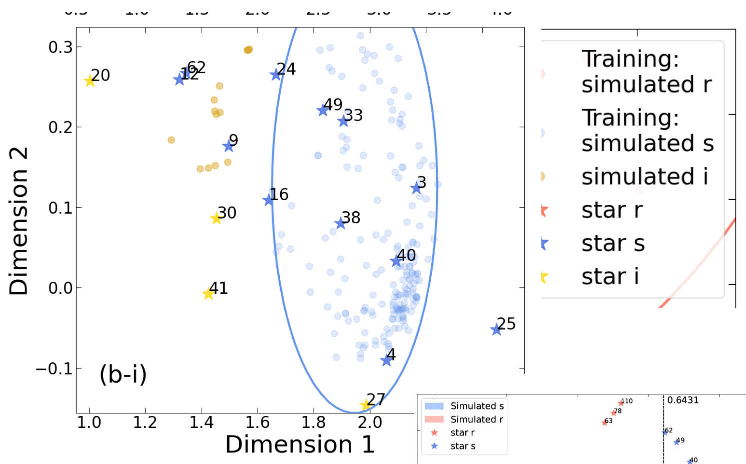
(2) Train an autoencoder on s *or* r groups / train a classifier on s *and* r)

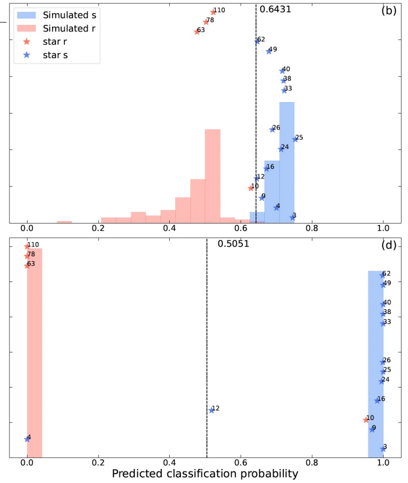


(3) Expose trained ML model to unseen data such as the stellar abundances



(4) Examine latent space values or class. prob. for stars and other unseen data (e.g. i-process calcs) as compared to training data





* This application demonstrated that *some stars recently labeled to be of i-process origins are actually compatible with r or s groups* BUT *some stars were not found to belong to either group* → **first ML predictions of a process beyond r and s**

N. Vassh, Y. Wang, R. Woloshyn, et al. 2025, Astrophysical Journal 992, 36

Example of bridging nuclear physics and astro. using ML: stellar classification feature importance as a new kind of "sensitivity study"

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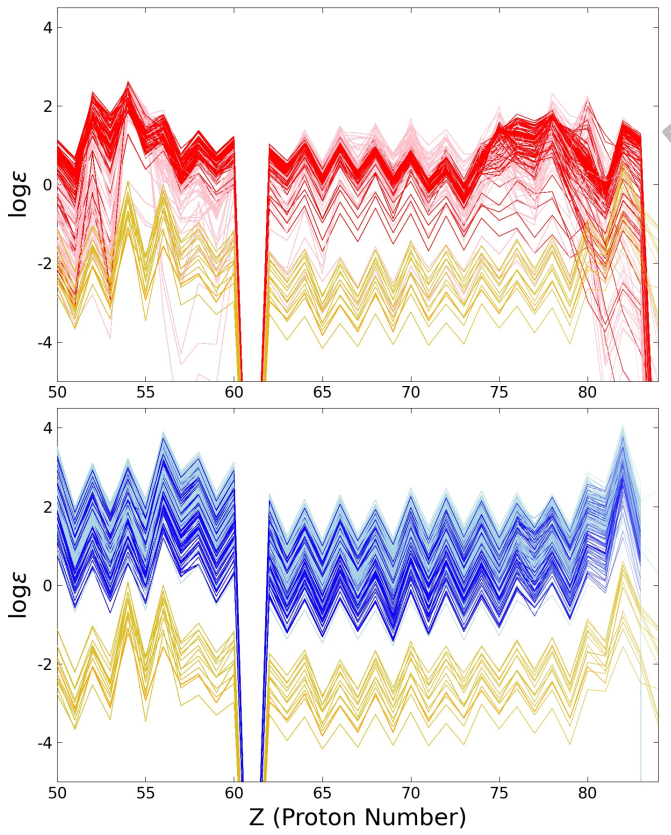
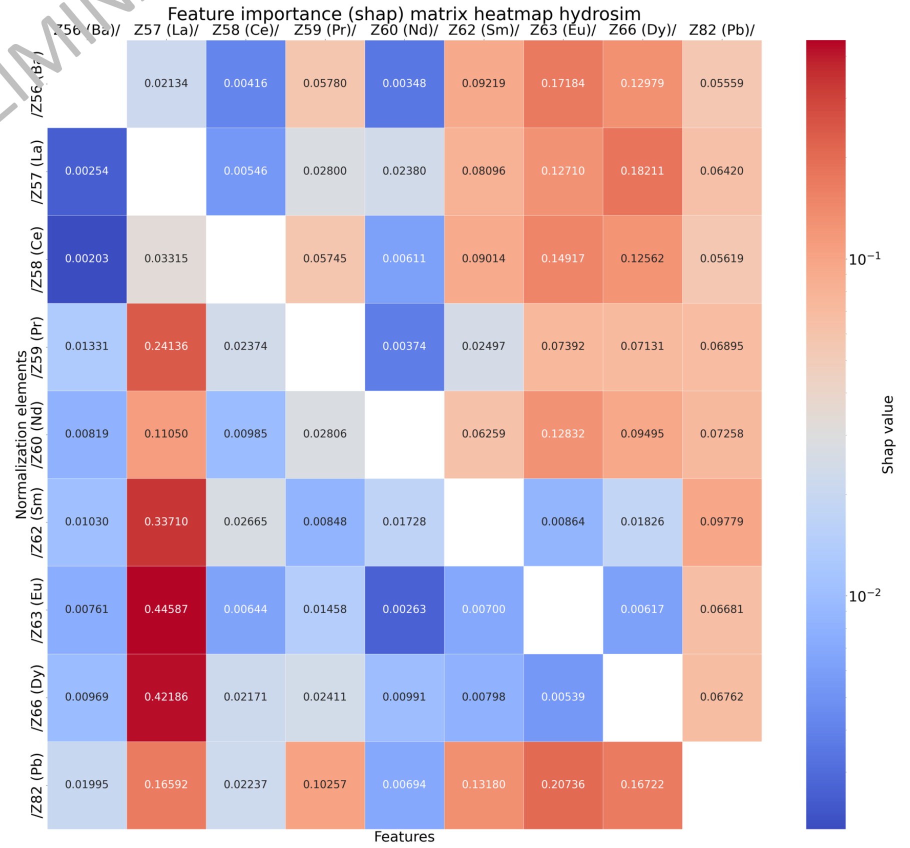


PRELIMINARY



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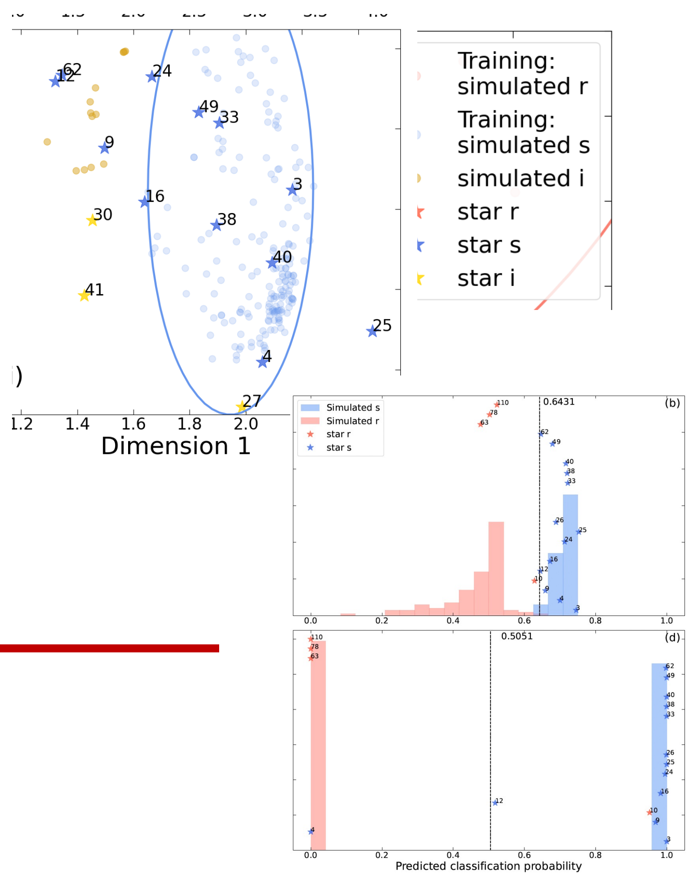
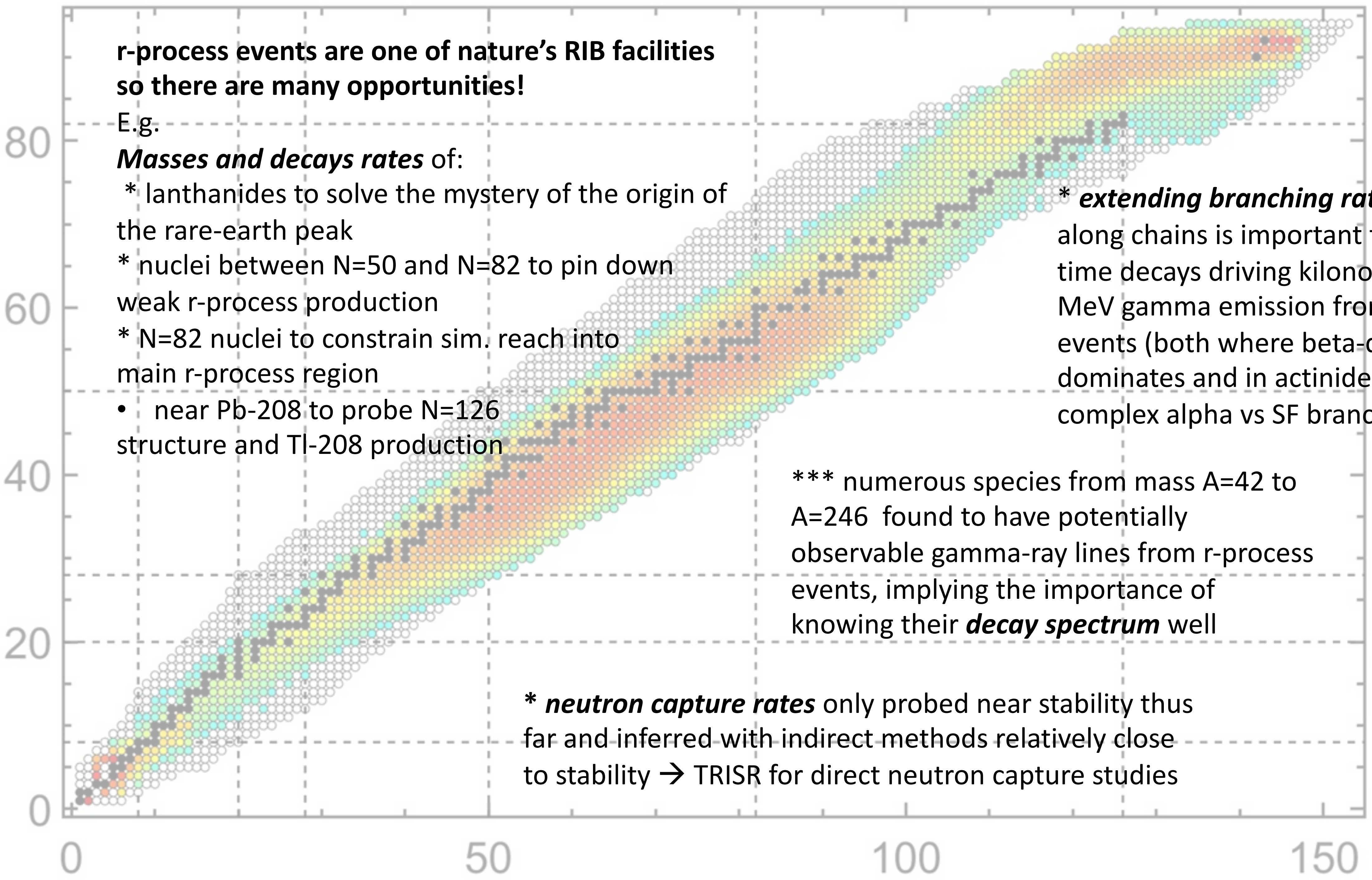


Y. Wang, N. Vassh, R. Woloshyn, et al. (in prep.)

* Examining SHAP value and other metrics for **feature importance** find which elemental abundances most impact ML stellar classification to: (1) motivate stellar abundance observations, (2) motivate nuclear phys. measurements, (3) explore updated definitions of stellar classification schemes which currently use thresholds on elemental ratios such as Ba/Eu



r-process events are one of nature's RIB facilities so there are many opportunities!

E.g.

Masses and decays rates of:

* lanthanides to solve the mystery of the origin of the rare-earth peak
* nuclei between N=50 and N=82 to pin down weak r-process production
* N=82 nuclei to constrain sim. reach into main r-process region
- near Pb-208 to probe N=126 structure and Tl-208 production

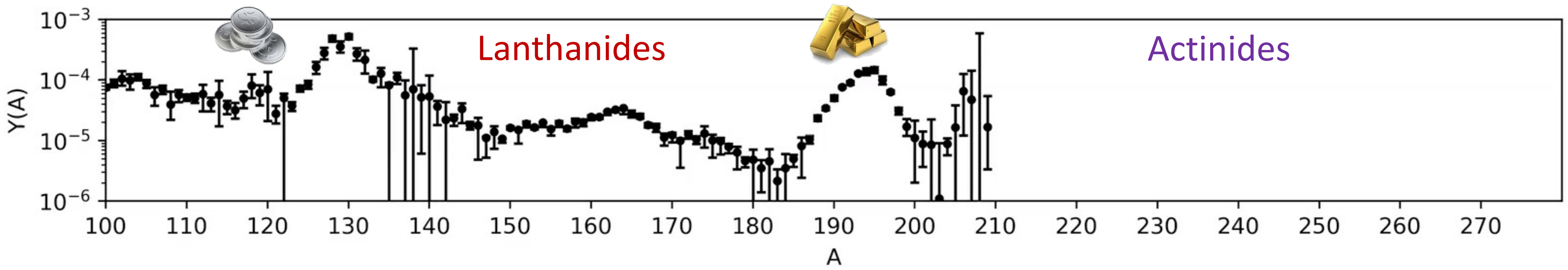
* ***extending branching ratio data*** along chains is important for late-time decays driving kilonova and MeV gamma emission from merger events (both where beta-decay dominates and in actinides with complex alpha vs SF branchings)

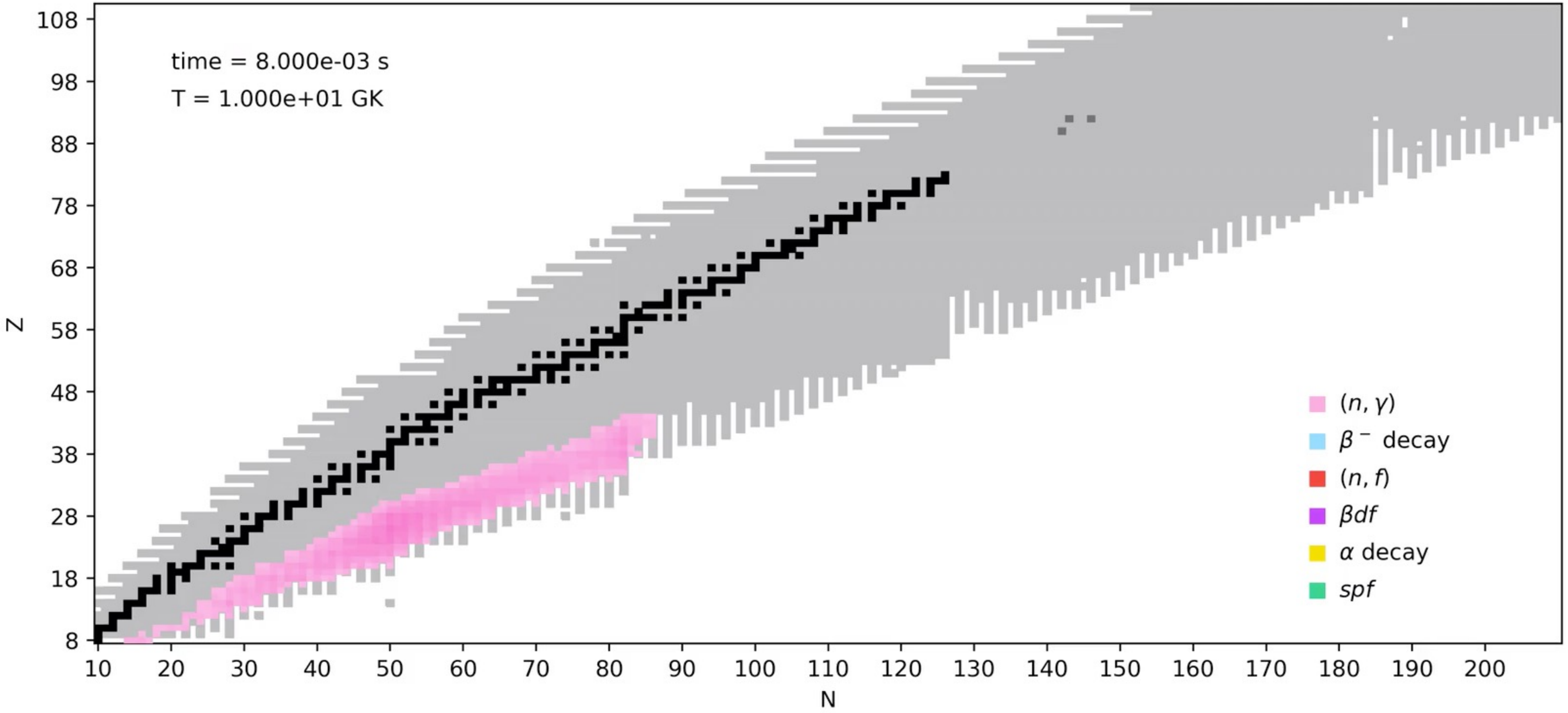
*** numerous species from mass A=42 to A=246 found to have potentially observable gamma-ray lines from r-process events, implying the importance of knowing their ***decay spectrum*** well

* ***neutron capture rates*** only probed near stability thus far and inferred with indirect methods relatively close to stability → TRISR for direct neutron capture studies

Back up

Modeling *r*-process nucleosynthesis

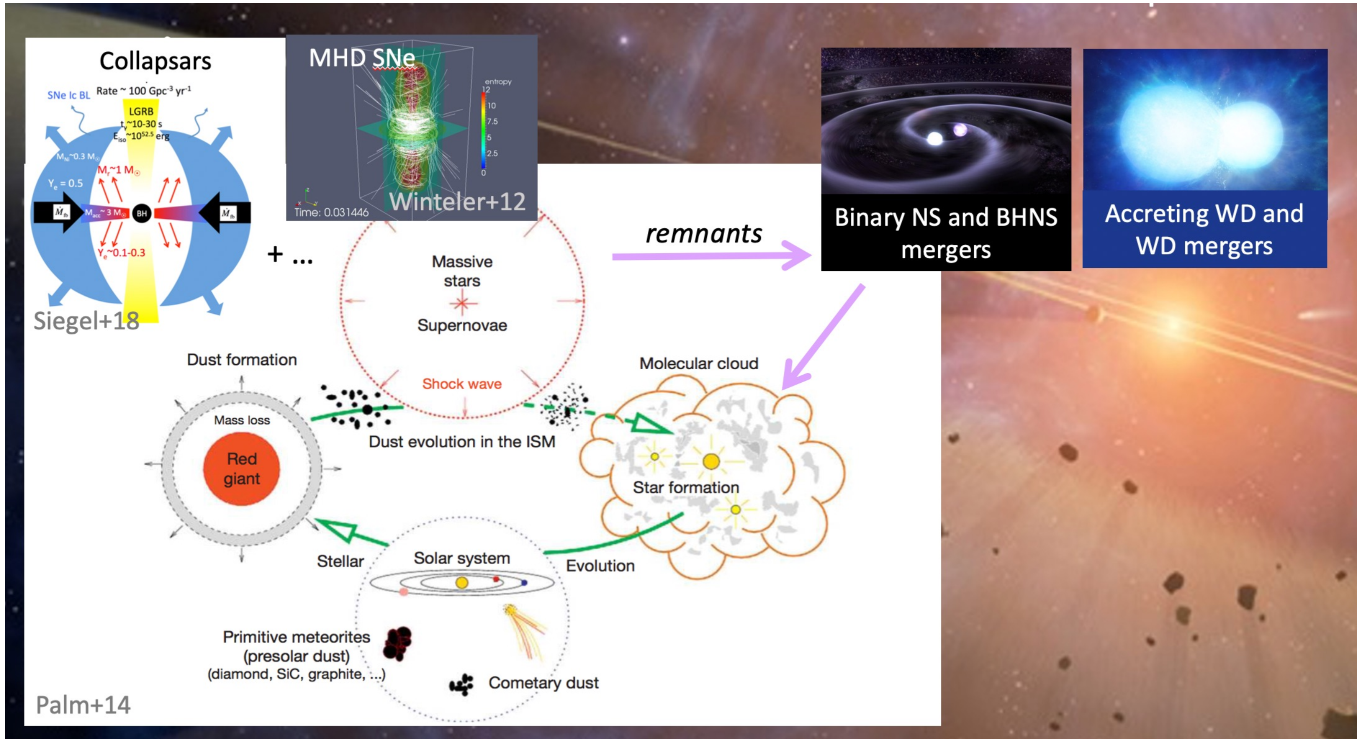




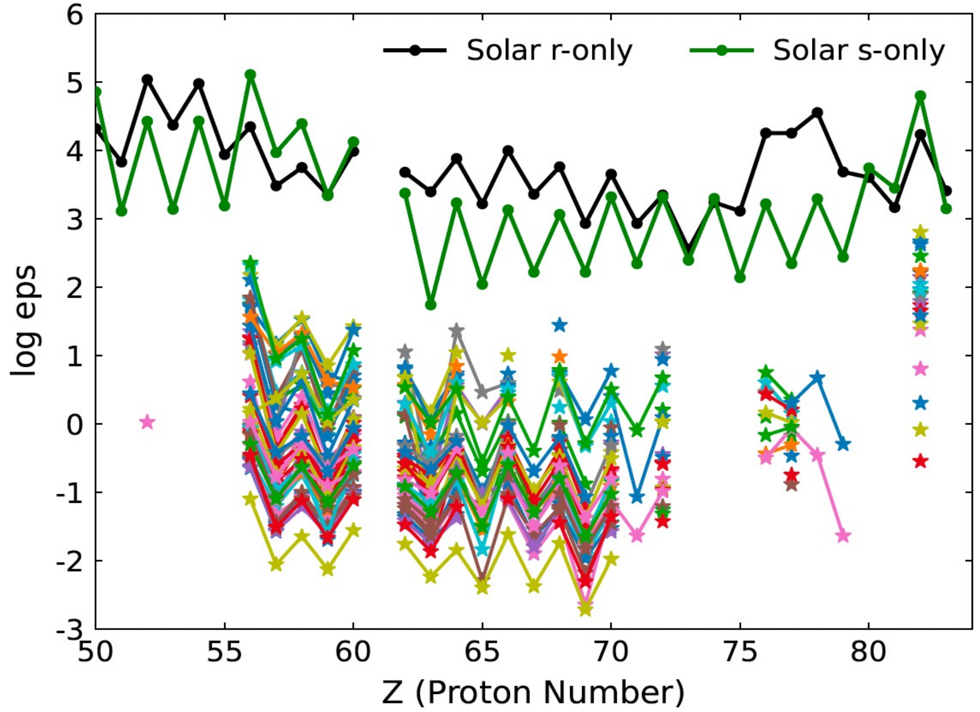
Movie by Vassh

Current classification method: thresholds on elemental ratios

Metal-poor stars (e.g. low in Fe) likely enriched by one to few events so can probe rare processes such as *r* process



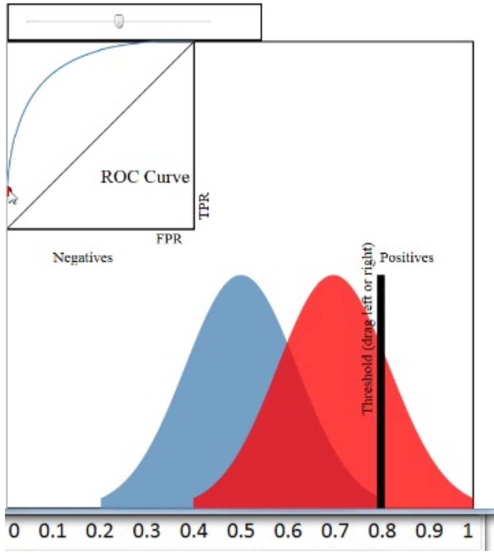
$r-I$: $0.3 \leq$ [Eu/Fe] ≤ 1 and [Ba/Eu] < 0,
$r-II$: [Eu/Fe] > 1 and [Ba/Eu] < 0,
$r-lim$: [Eu/Fe] < 0.3, [Sr/Ba]>0.5, and [Sr/Eu]>0,
s: [Ba/Fe] > 1, [Ba/Eu] > 0.5, and [Ba/Pb]>-1.5.



Ba, La, Ce, Pr, Nd, Sm, Eu, Dy, Er (Z=56, 57, 58, 59, 60, 62, 63, 66, 68) as one feature set. A second feature set with Er replaced by Pb was also considered.

Machine learning to classify metal-poor stars as r or s

Binary classifier
(supervised training on r *and* s)

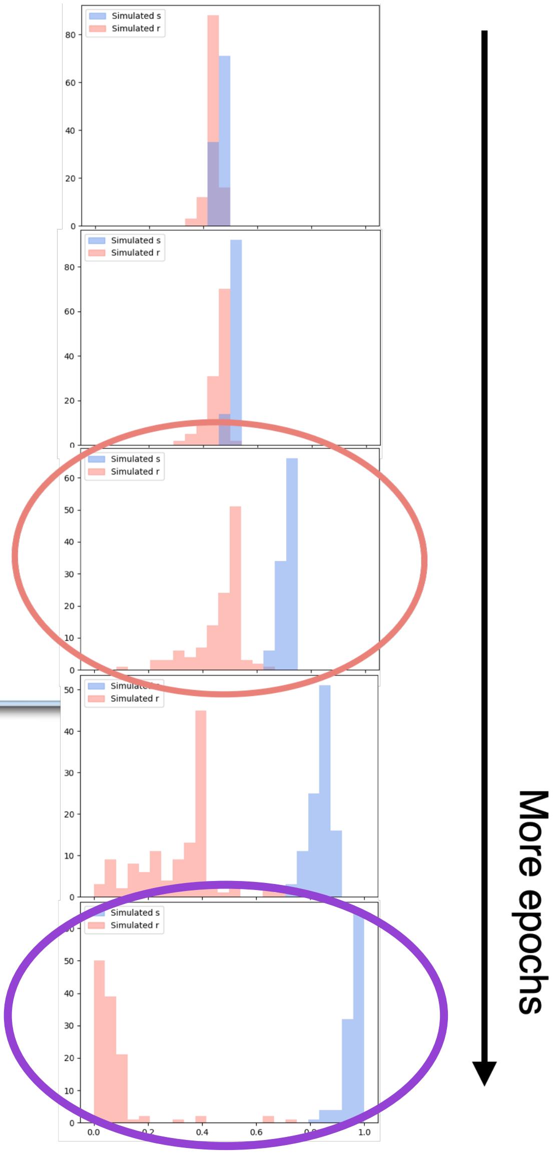


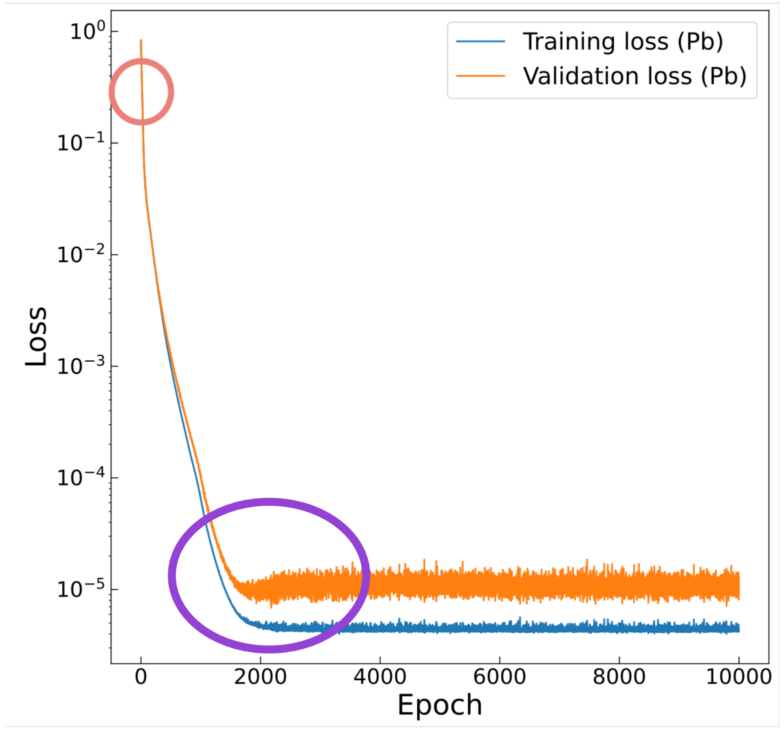
True Positive Rate =
50 / 250 = 0.2

False Positive Rate =
0 / 250 = 0

Plot on ROC Curve:
(x, y) = (0, 0.2)

UBC/TRIUMF PhD student Yilin Wang





Binary Cross Entropy Loss Function

$$\text{BCE} = -\frac{1}{N}\sum_{i=1}^{N}\left[y_i \log(p_i) + (1-y_i)\log(1-p_i)\right]$$

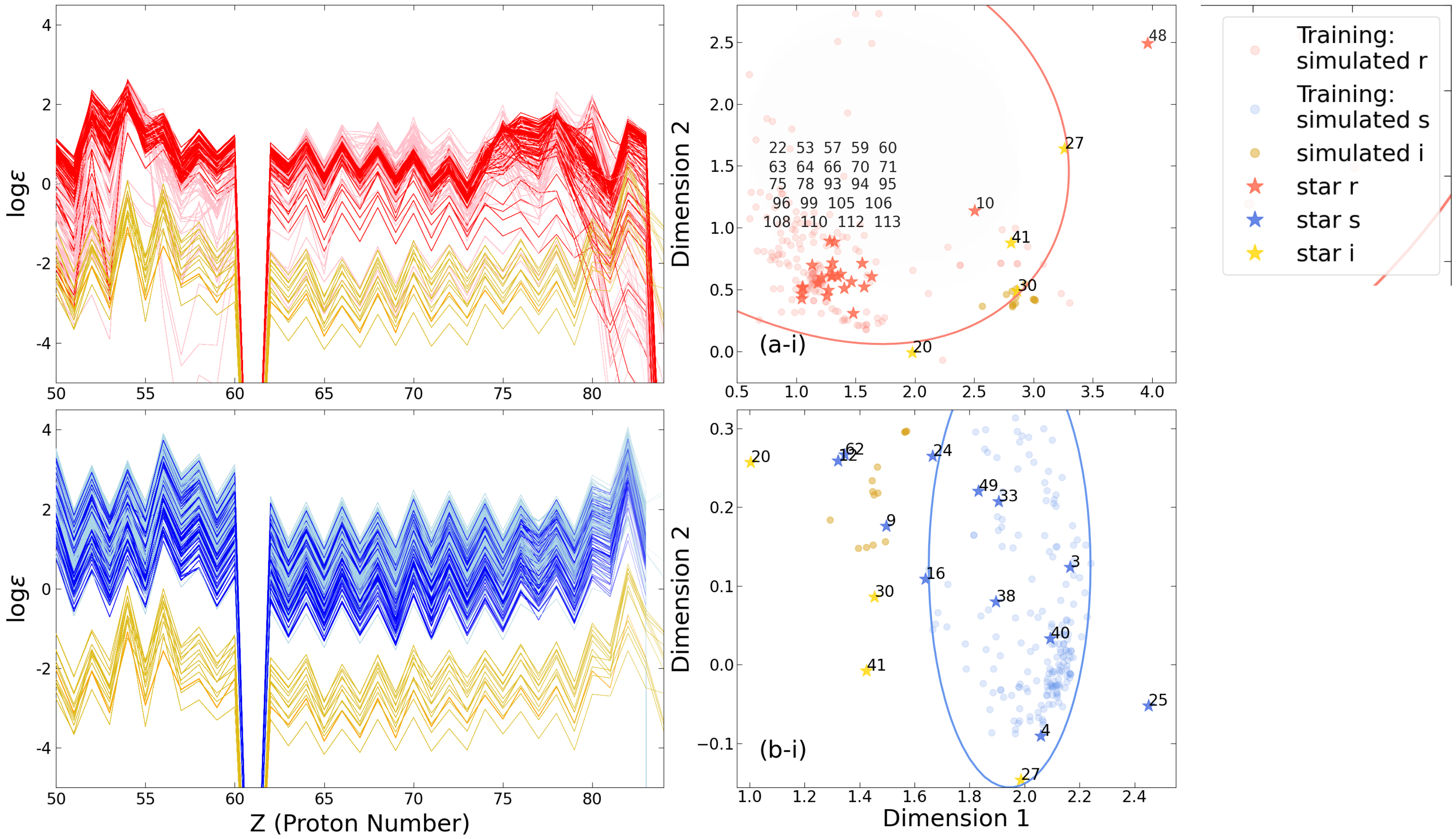
- N is the number of observations
- y_i is the actual binary label (0 or 1) of the i^{th} observation.
- p_i is the predicted probability of the i^{th} observation being in class 1

Vassh, Wang, Woloshyn, Kutchera, Larivière, Majic, Côté (ApJ, 2025, arXiv:2505.14563)

Machine learning to classify metal-poor stars as r or s *or i*

* 2/5 i stars fall into the r or s group

* 3/5 i stars are almost *never* identified as r or s!



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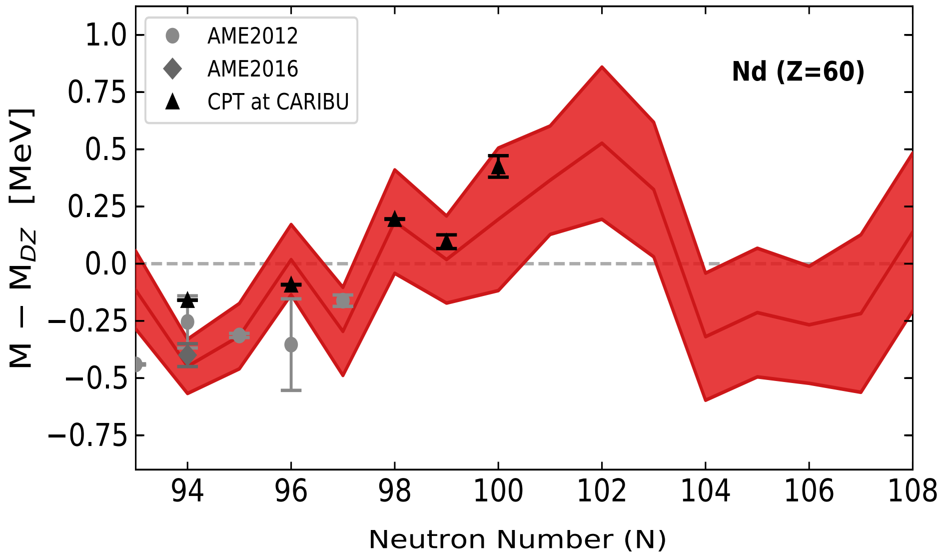
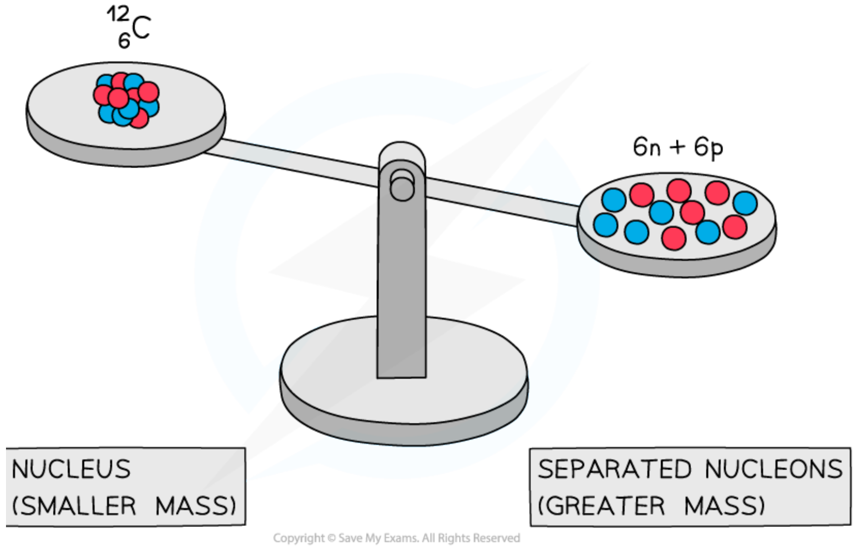
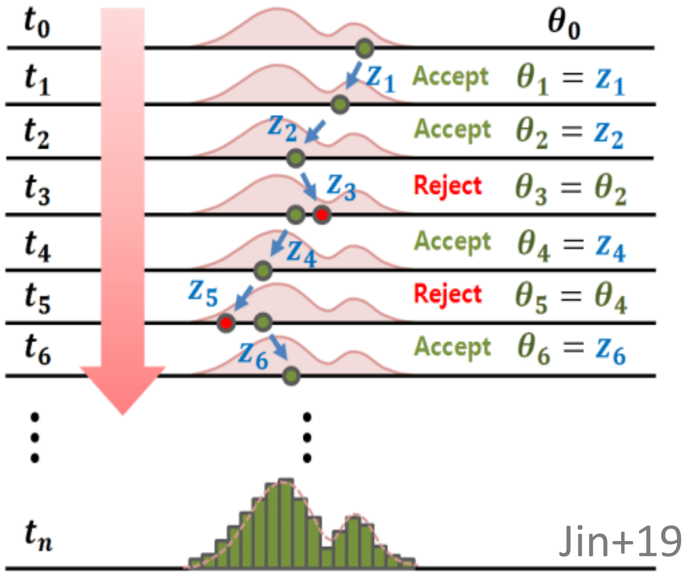
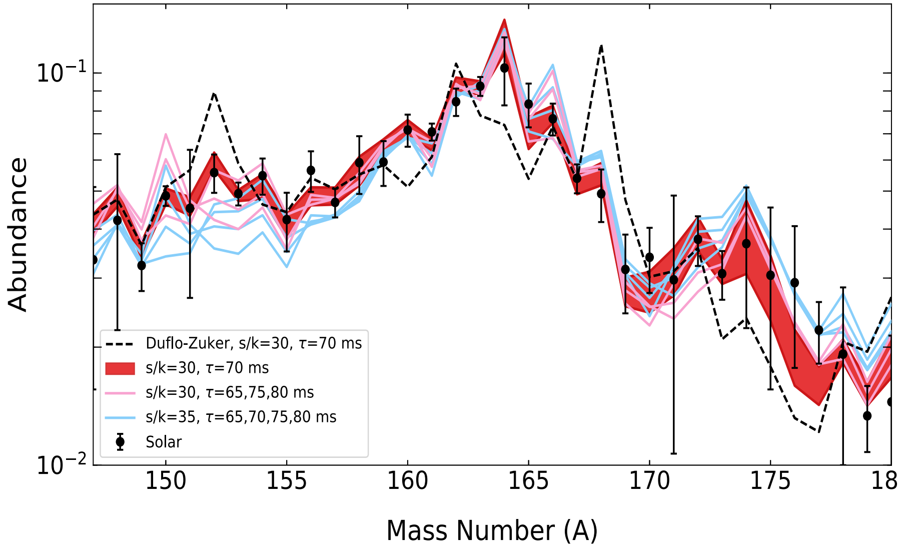
Vassh, Wang, Woloshyn, Kutchera, Larivière, Majic, Côté (ApJ, 2025, arXiv:2505.14563)

Markov Chain Monte Carlo (MCMC) and the Solar rare-earth peak









Orford,Vassh+18 (PRL); Vassh+21 (ApJ)

dotted lines – initial nuclear masses and nucleosynthesis abundances

red – masses and abundances predicted using Markov Chain Monte Carlo

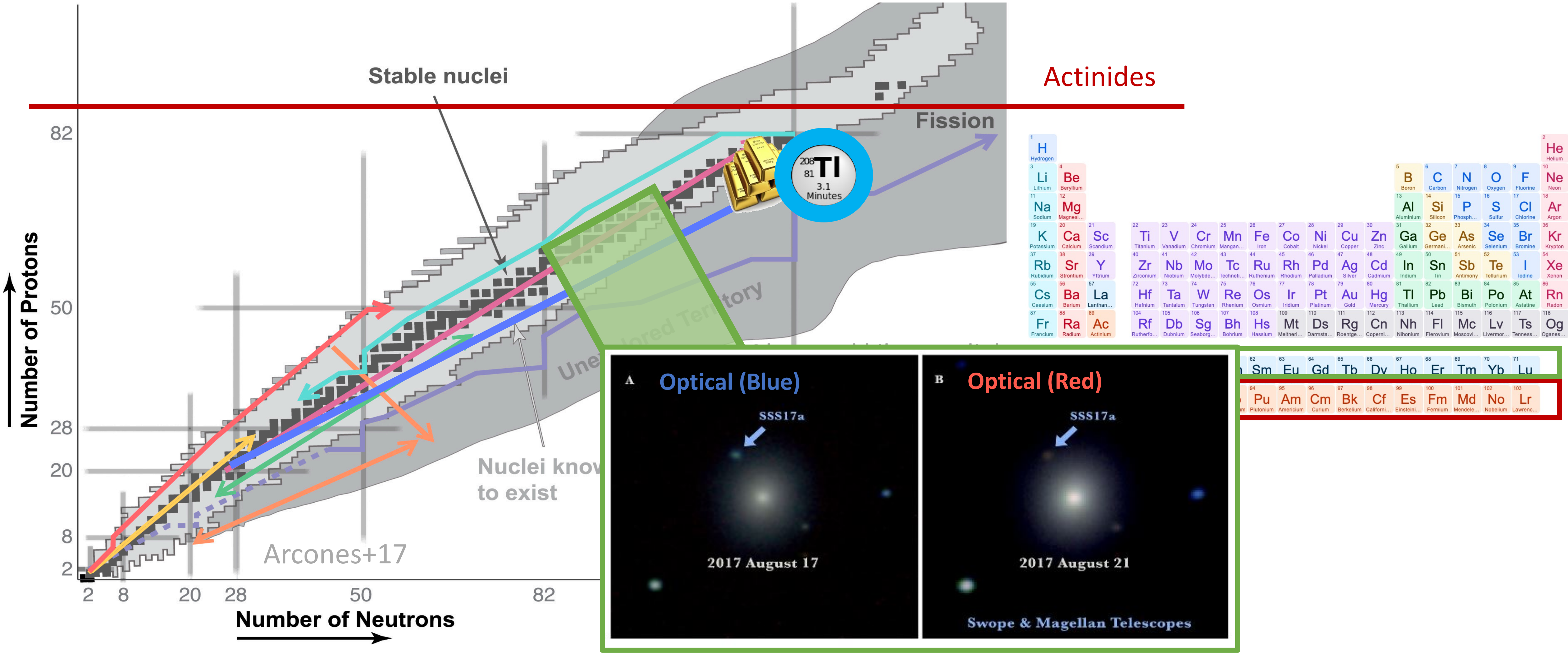
- Monte Carlo mass corrections

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

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

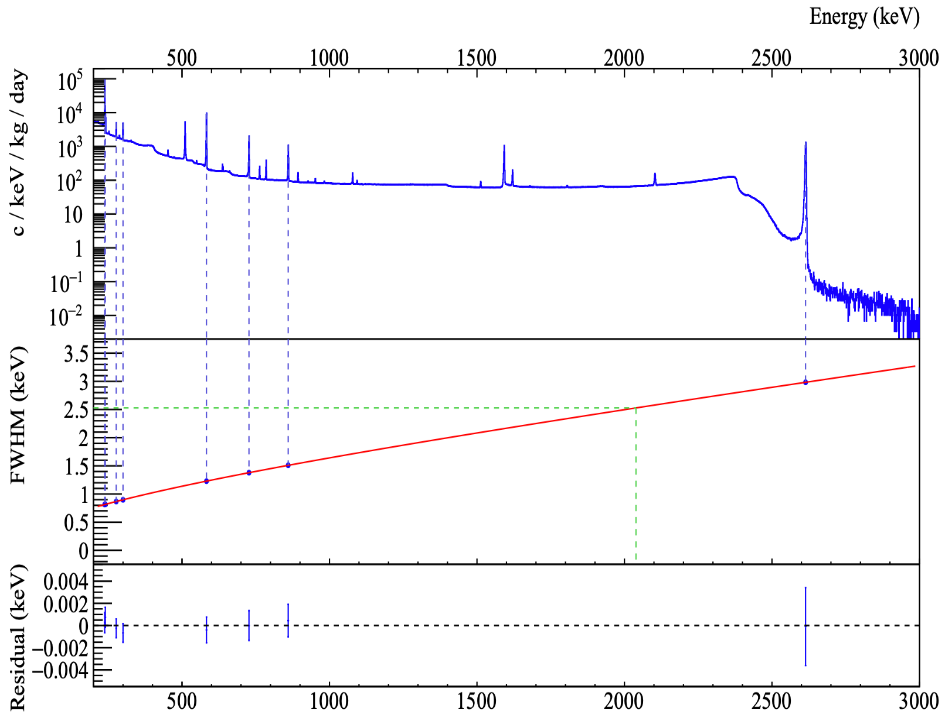
$$\mathcal{L}(\mathrm{m}) = \exp\left(-\frac{\chi^2(\mathrm{m})}{2}\right) \rightarrow \alpha(\mathrm{m}) = \frac{\mathcal{L}(\mathrm{m})}{\mathcal{L}(\mathrm{m-1})}$$

A beacon of *in situ* lead production – Thallium-208's 2.6 MeV emission line

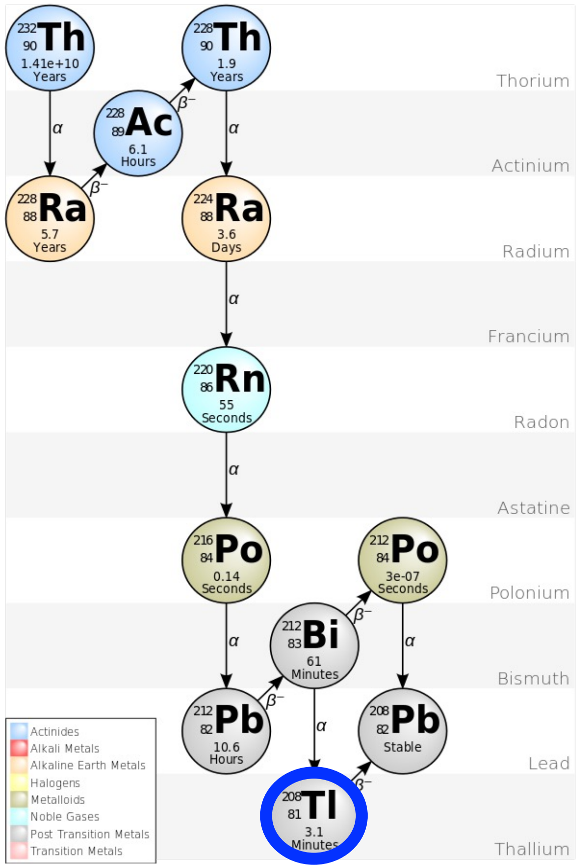


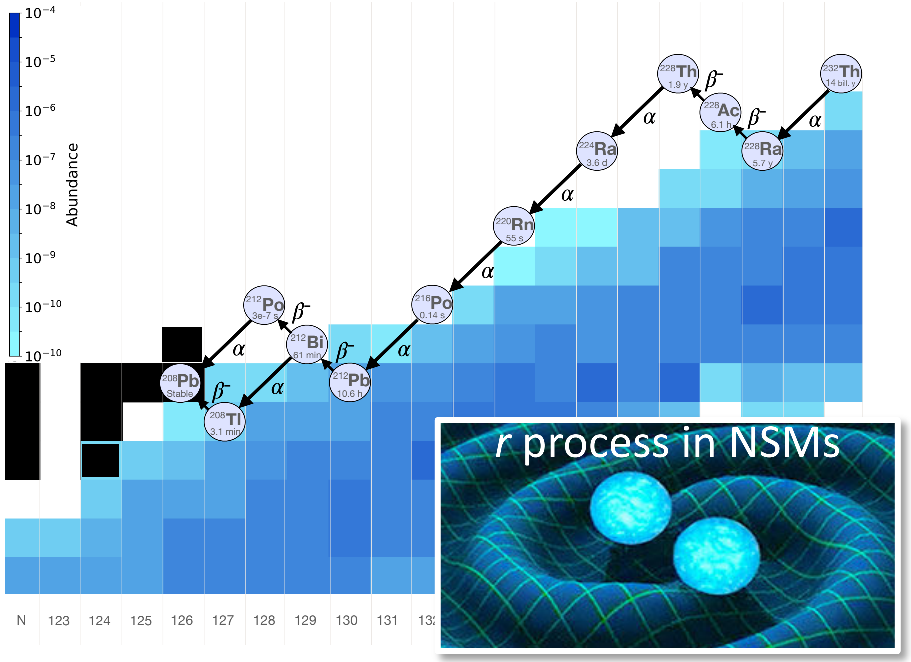
Kilonova emission -> IR with longer duration light curve implies high-opacity lanthanide elements

The 2.6 MeV gamma-ray line from Tl-208 β-decay: a beacon for numerous disciplines and astrophysics



Alvis+19





Majorana demonstrator (^{76}Ge neutrinoless double β-decay search)

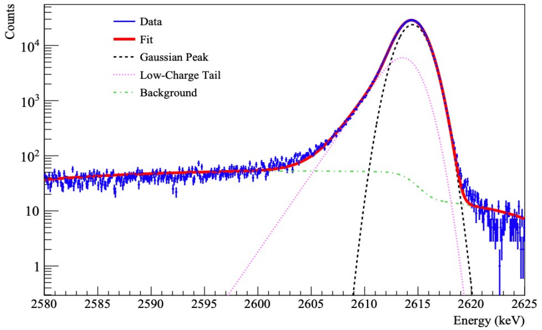


FIG. 3. Color online. The 2615 keV peak from ^{208}Tl in calibration data with all detectors combined is shown in the blue points with statistical error bars.

Vassh, Wang, Larivière+24 (PRL 132, 052701)