Probing stellar enrichment with modern tools and refined nuclear data

Nicole Vassh

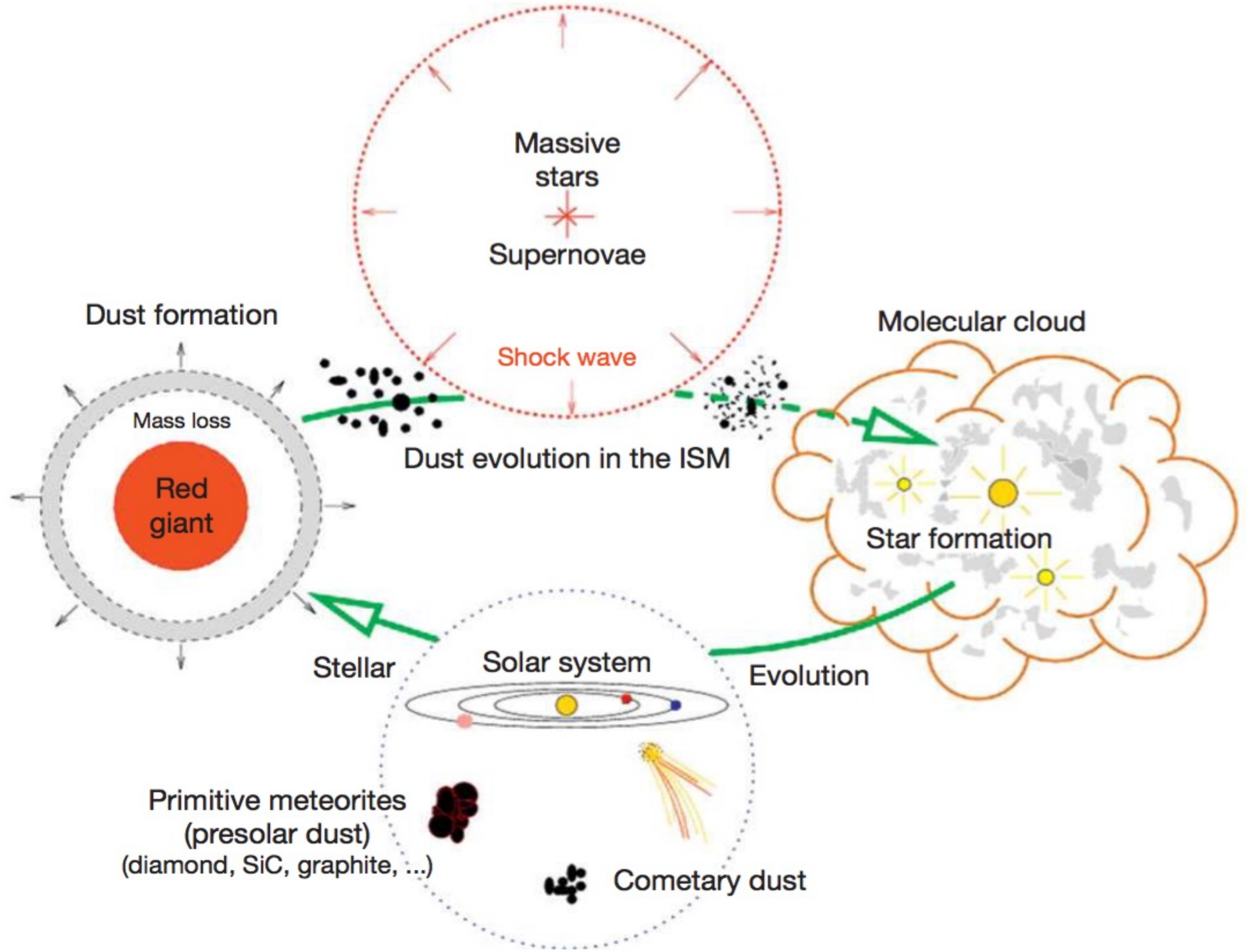
TRIUMF Theory Group

June 9, 2025

CIPANP

UW-Madison

Where *and when* were the elements we see in stars produced?



Palm+14

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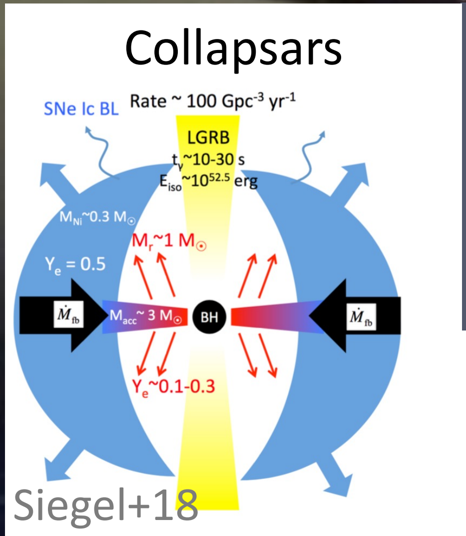
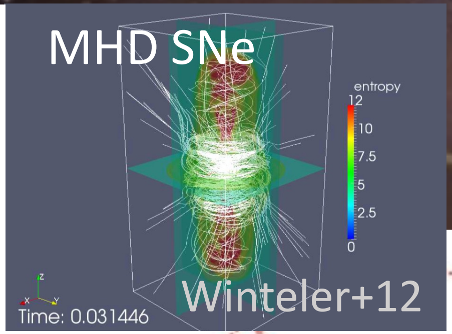
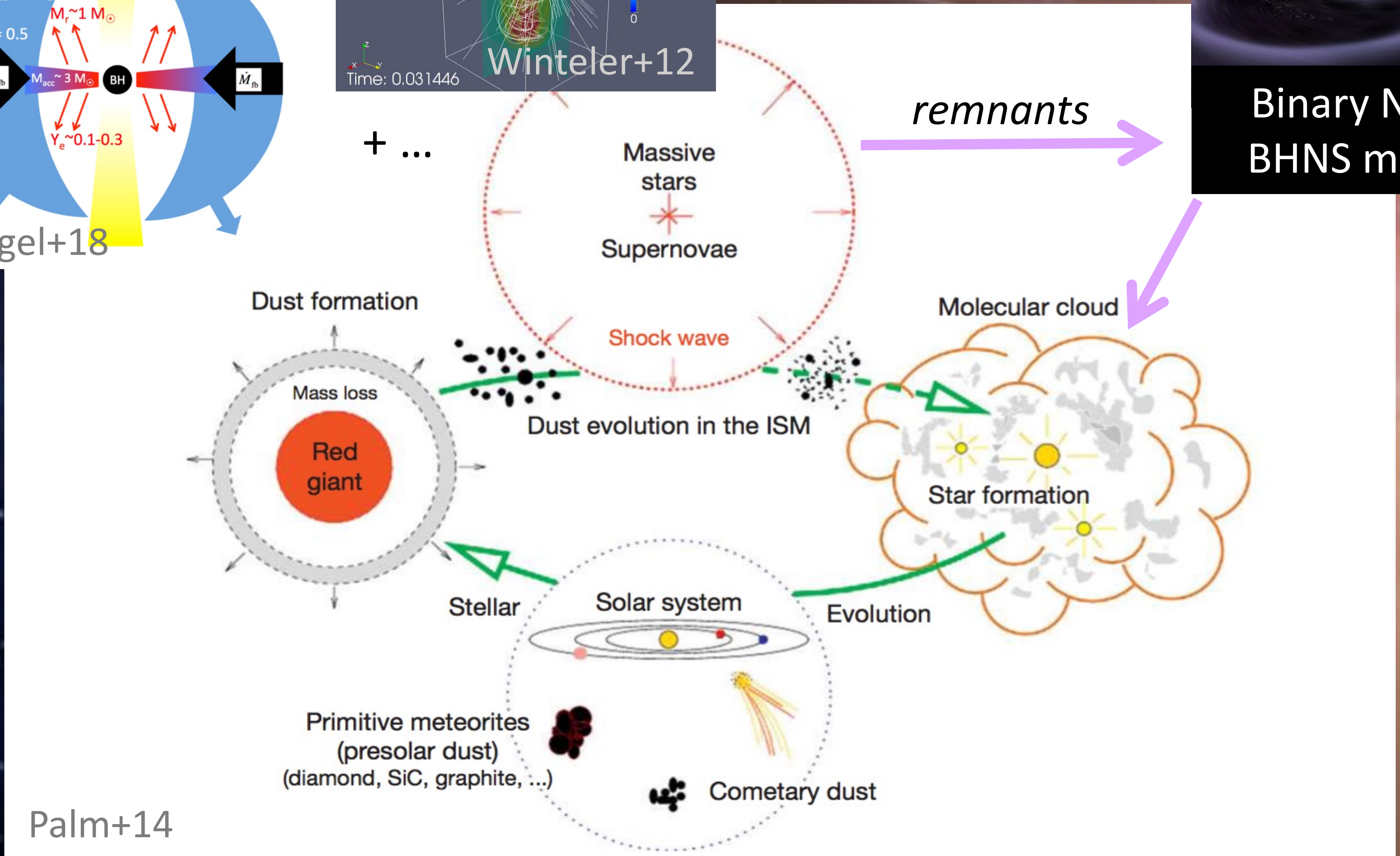




+ ...



remnants

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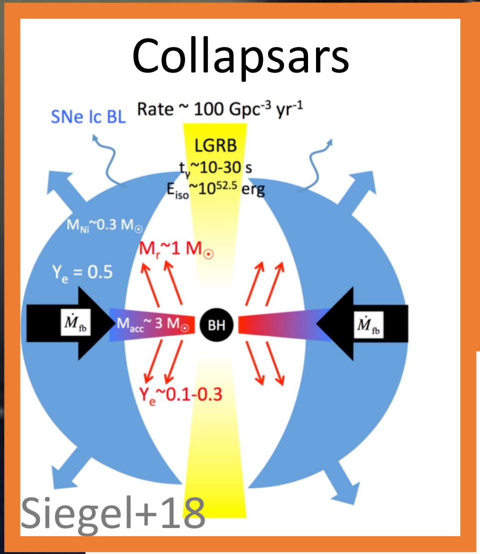

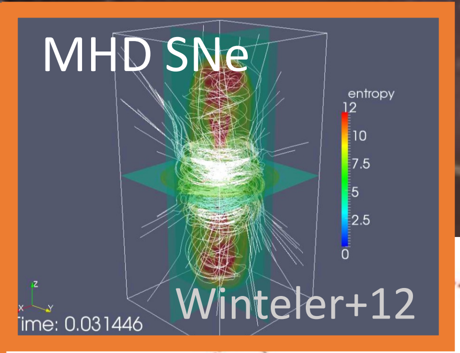

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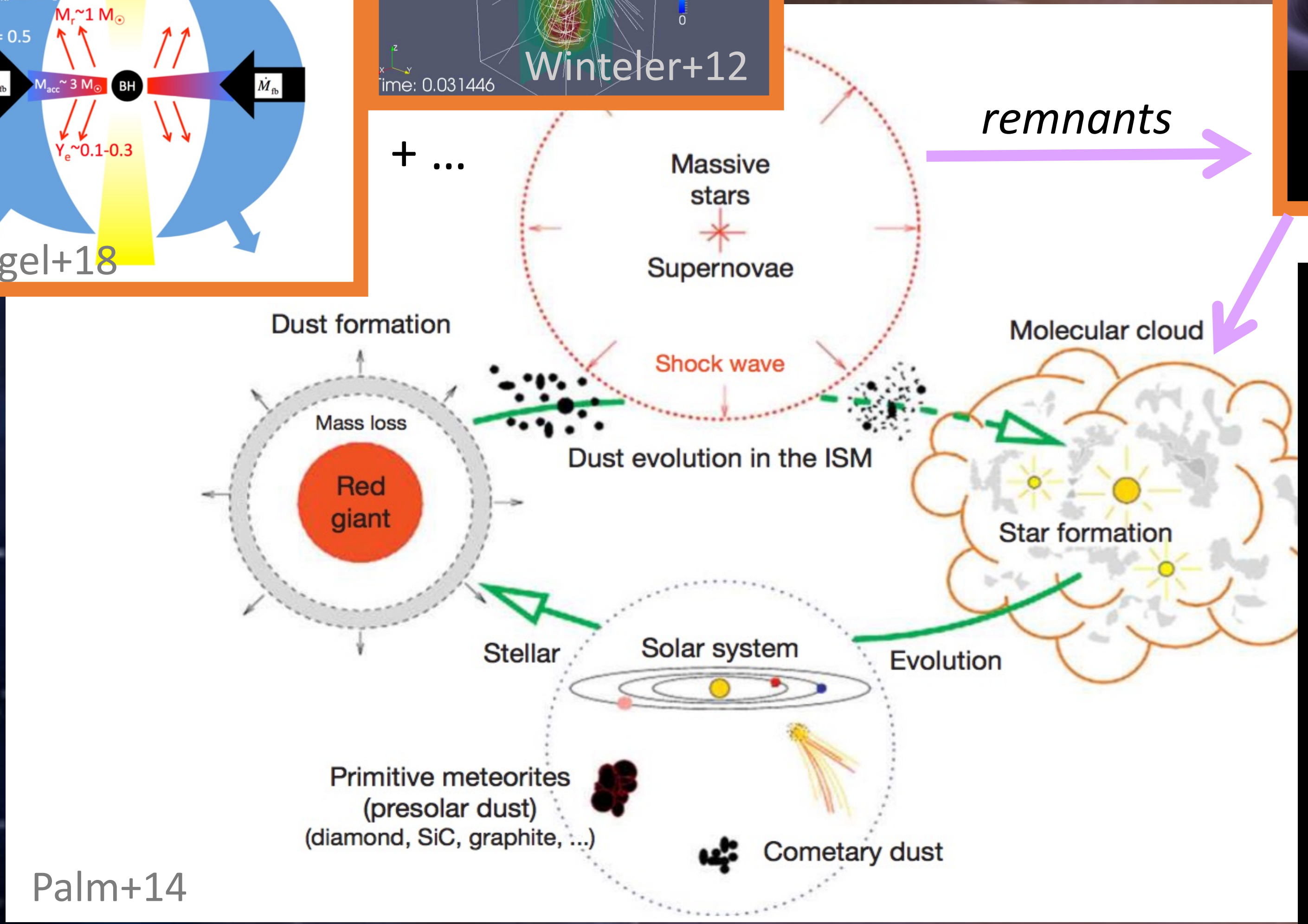
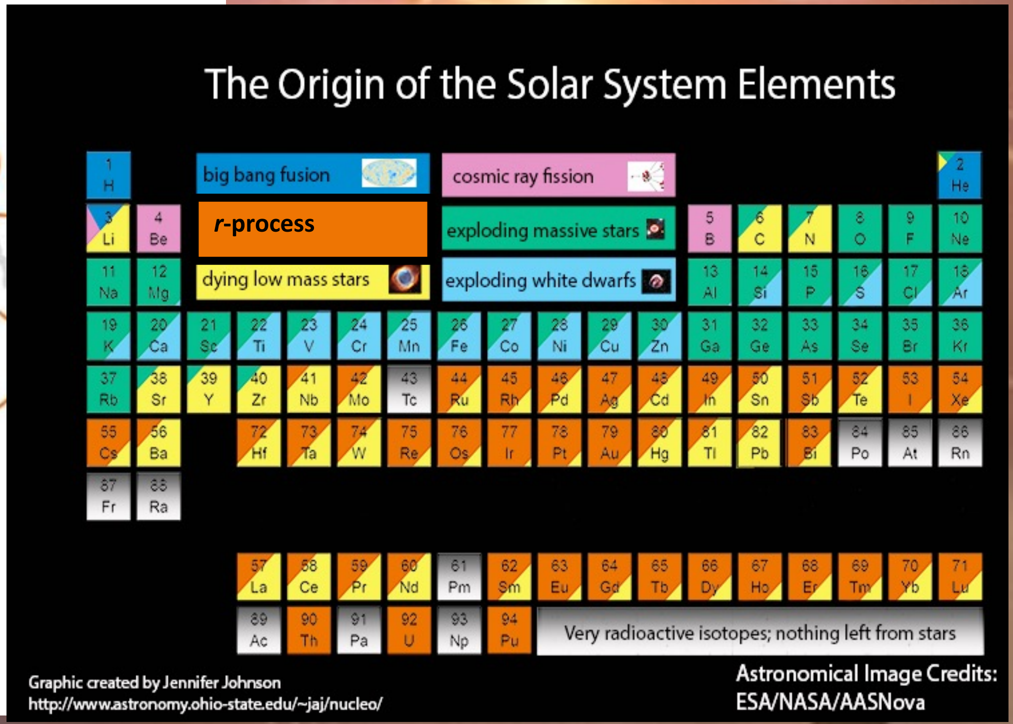
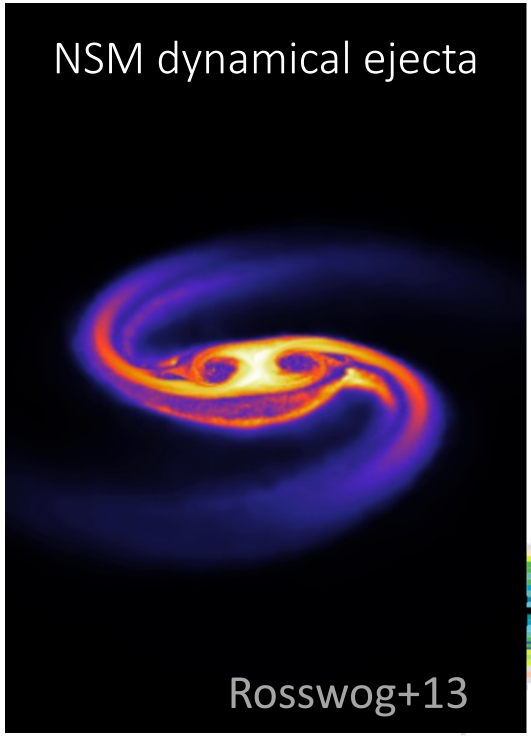




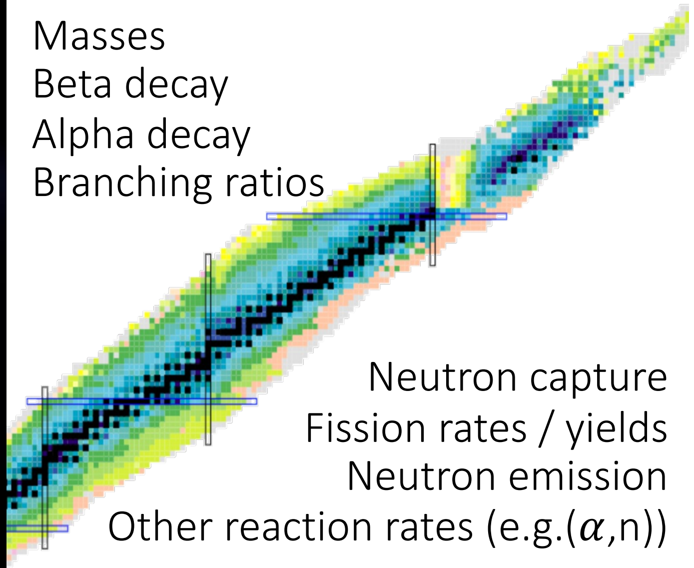
Modeling the *r*-process in neutron star mergers

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))

The need for nuclear inputs is not isolated to reactions and decays in the network:

- input initial composition dependent on EOS
- outputs are post-processed to evaluate nuclear heating, light curves, gamma spectra…

Modeling the *r*-process in neutron star mergers

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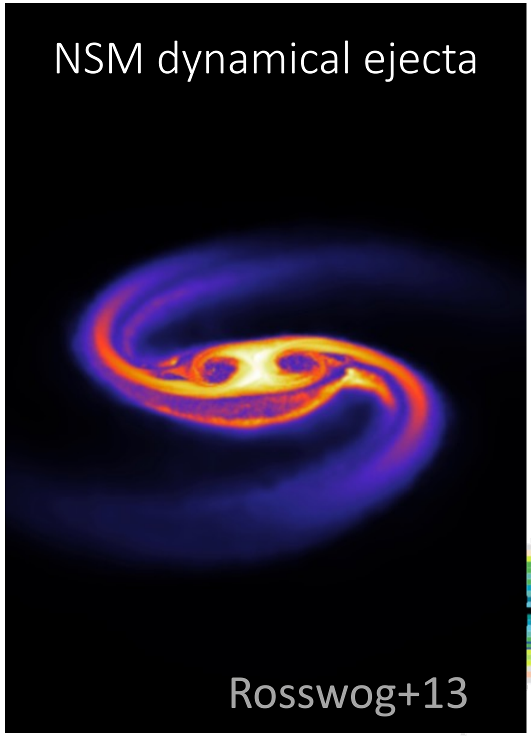

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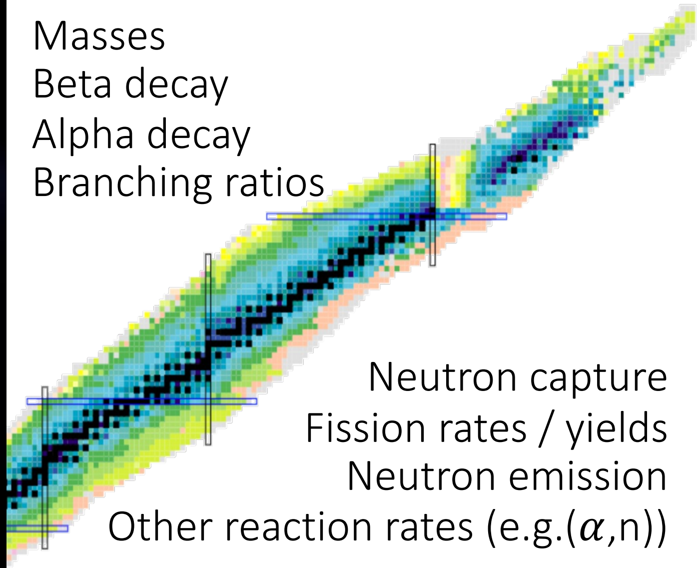

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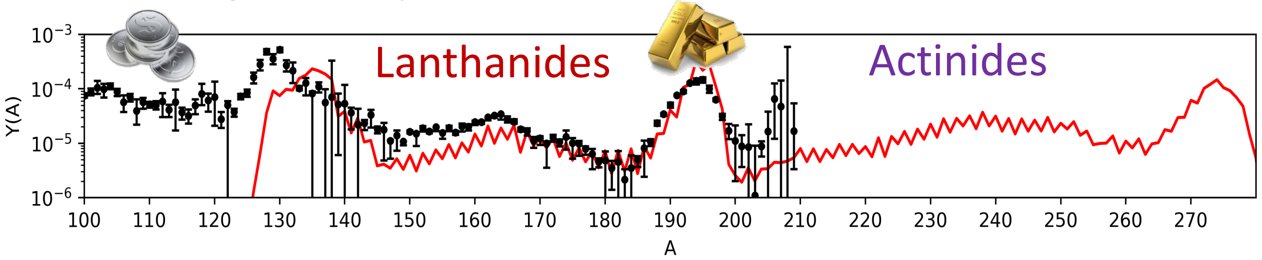
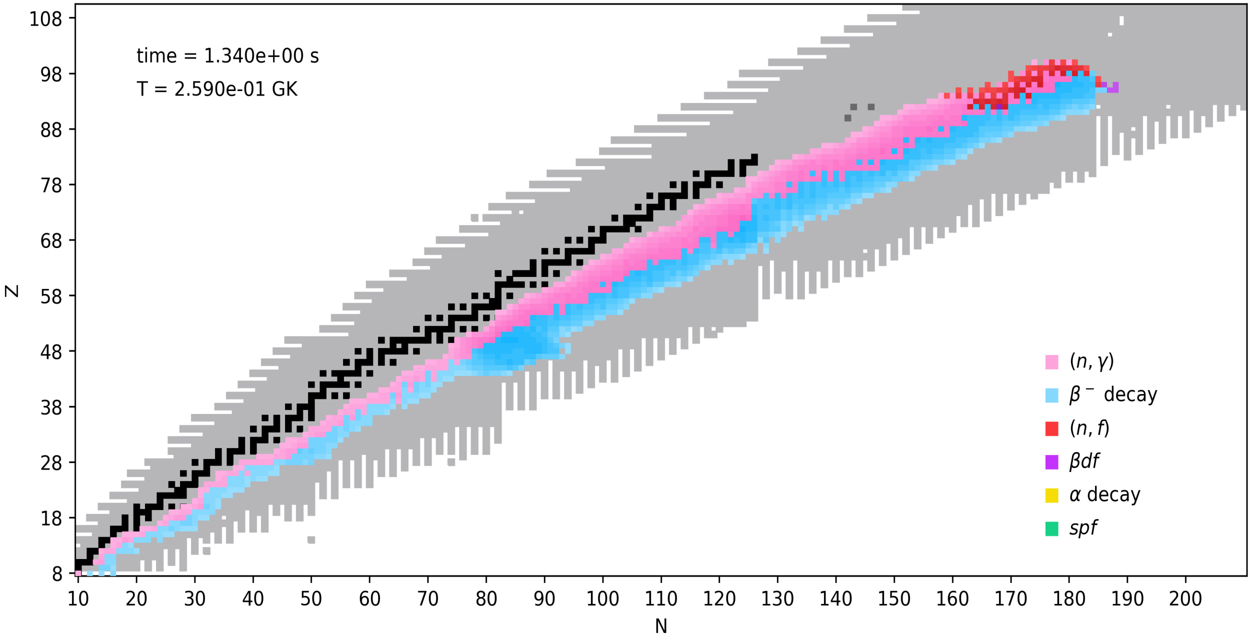
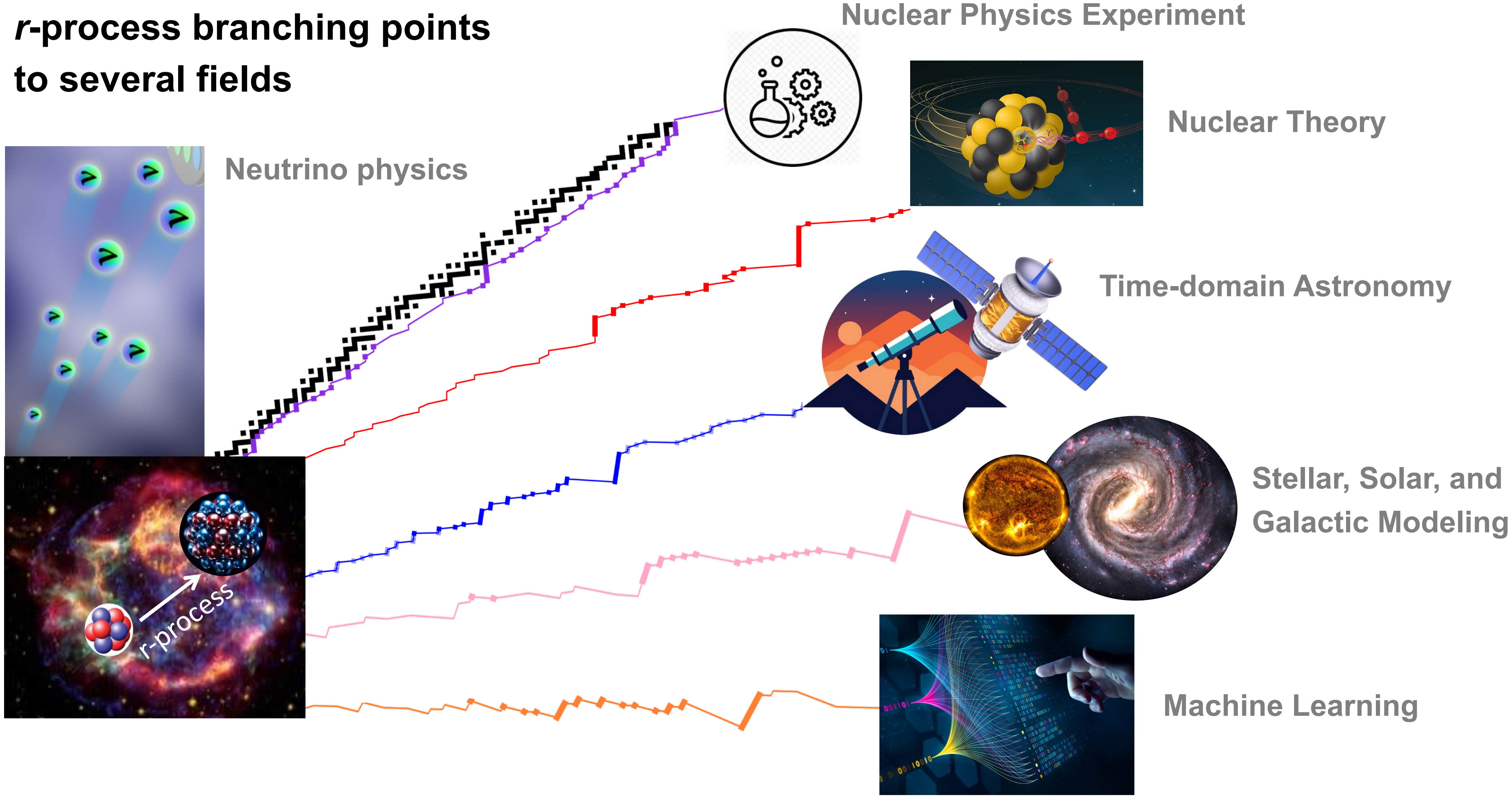
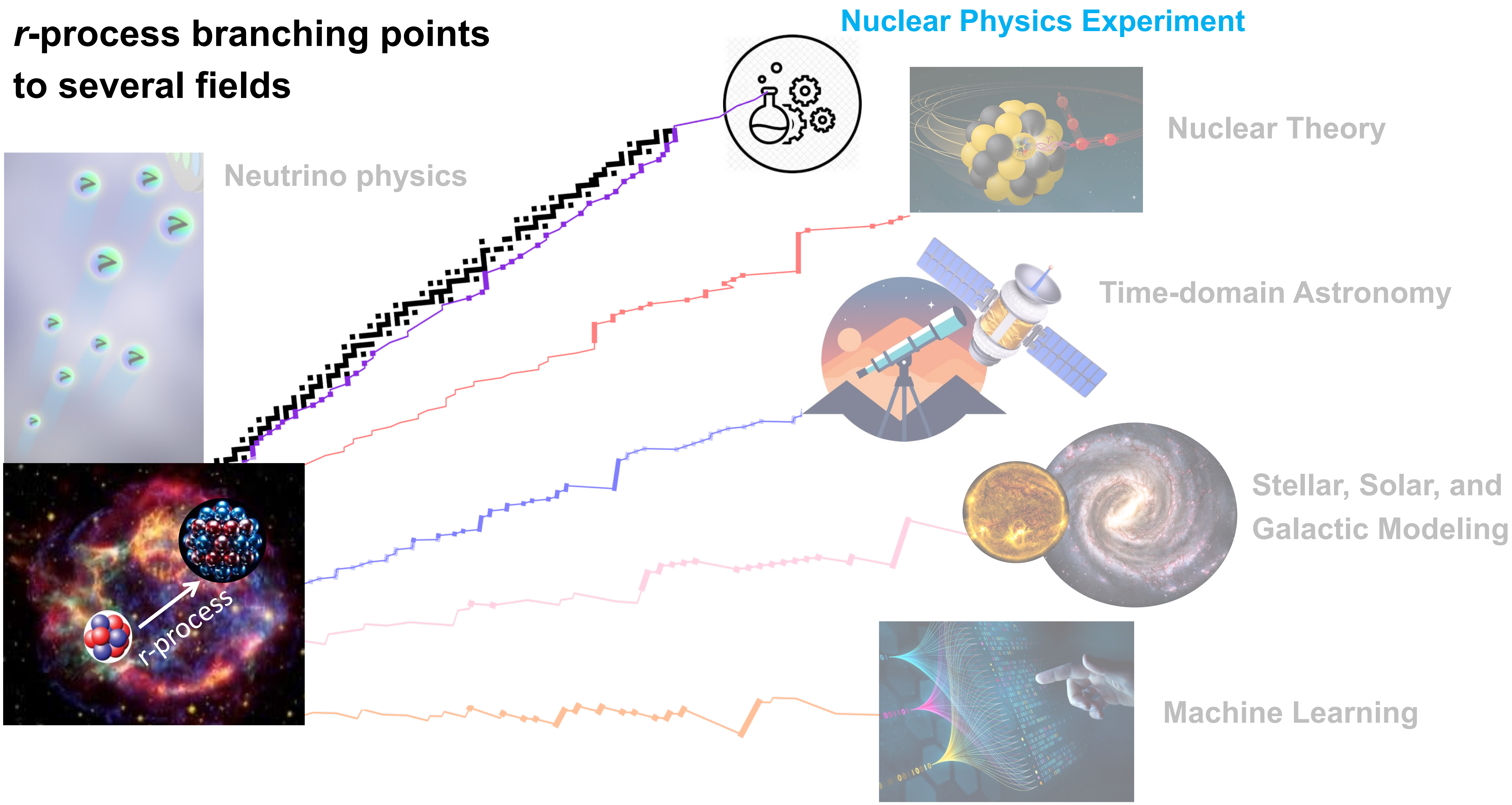




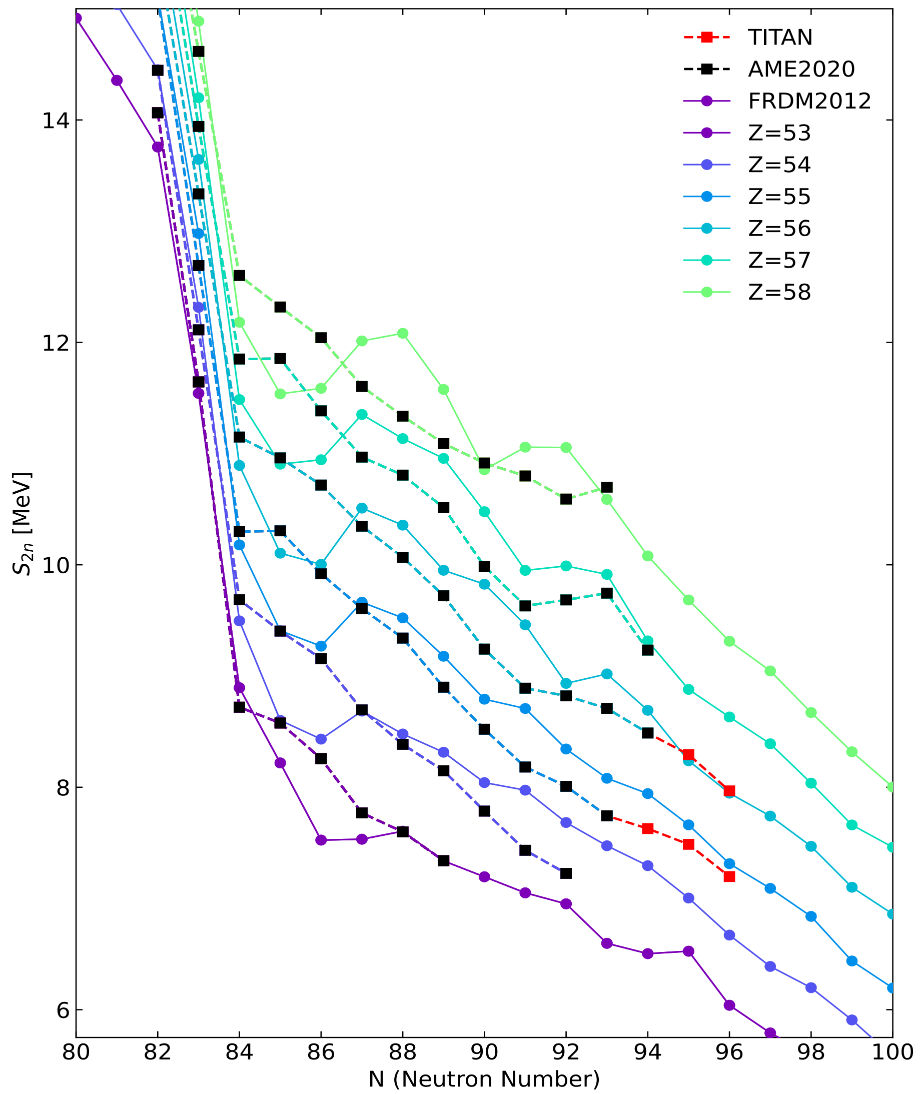
N Vassh


r-process branching points
to several fields
Nuclear Physics Experiment
Nuclear Theory
Neutrino physics
Time-domain Astronomy
Stellar, Solar, and
Galactic Modeling
Machine Learning
r-process

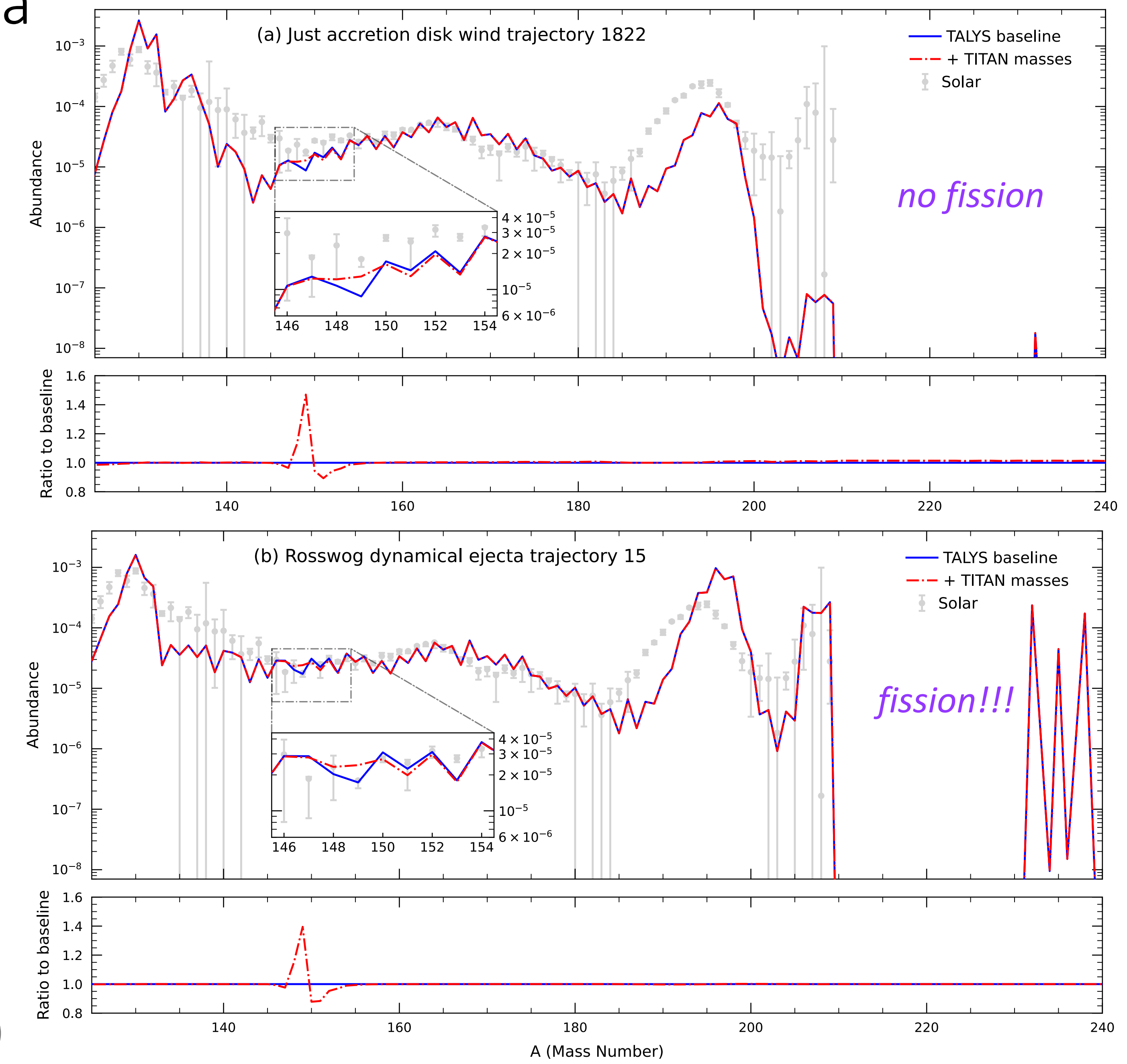
r-process branching points to several fields



TITAN mass measurements: Cs, Ba



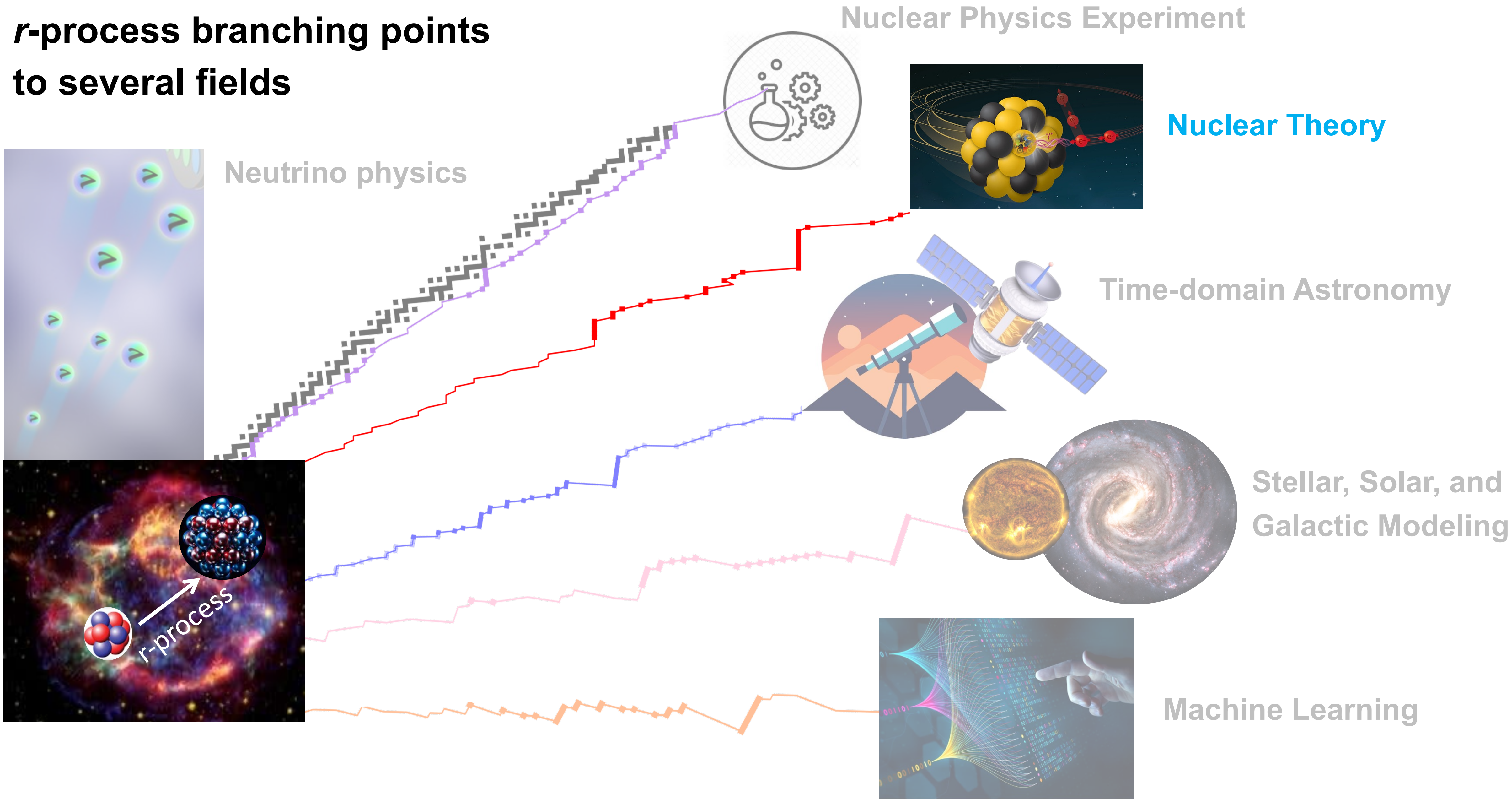
Solar abundance comparison



*impact study led by TRIUMF postdoc Tsung-Han Yeh

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

r-process branching points to several fields



Ab initio nuclear theory: new reach into *r*-process nuclei

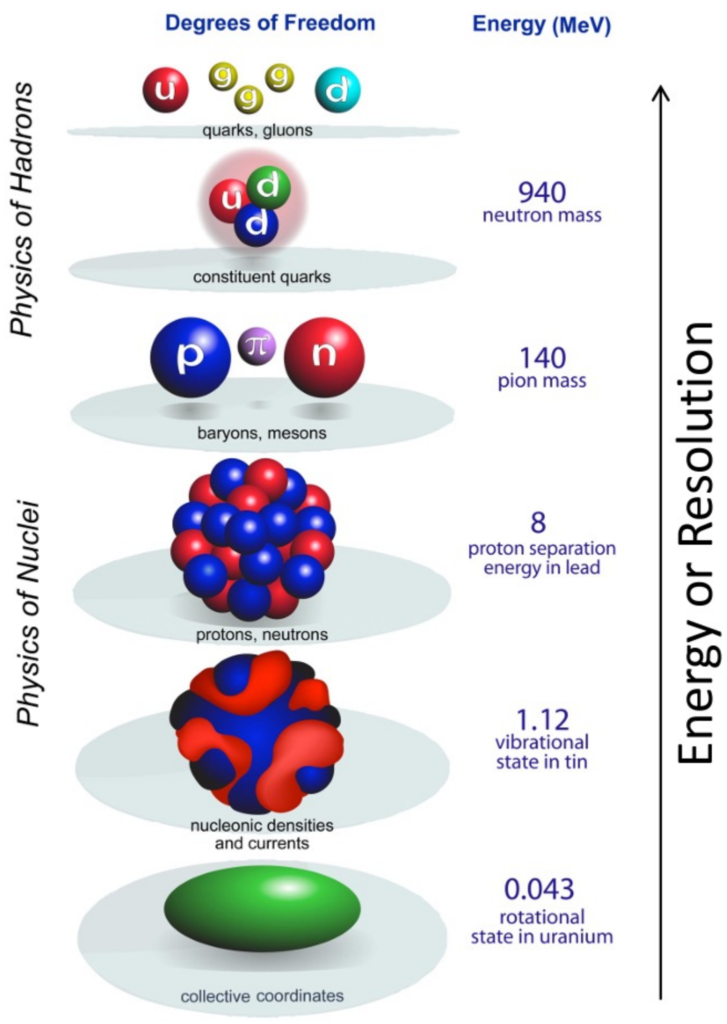
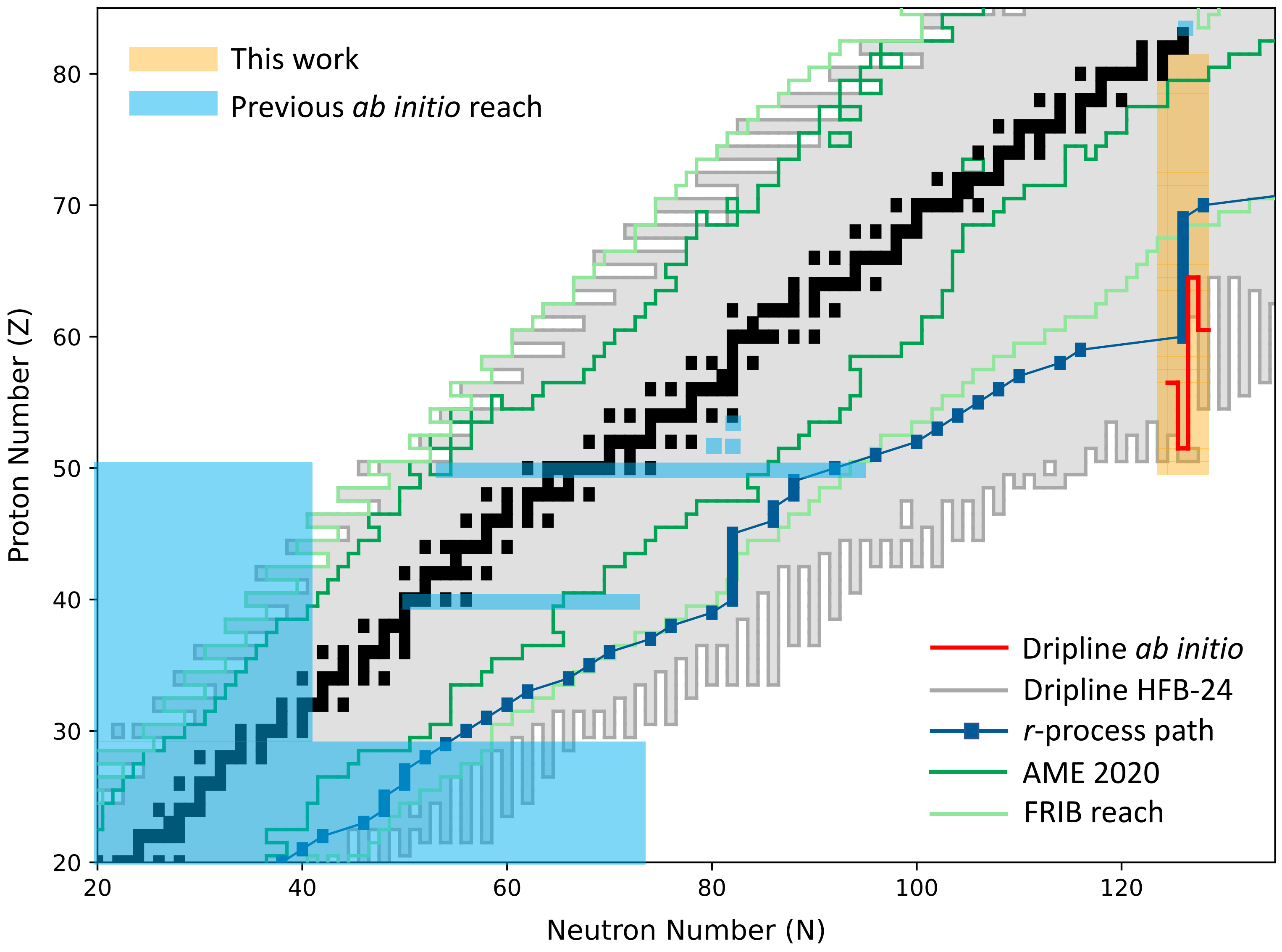


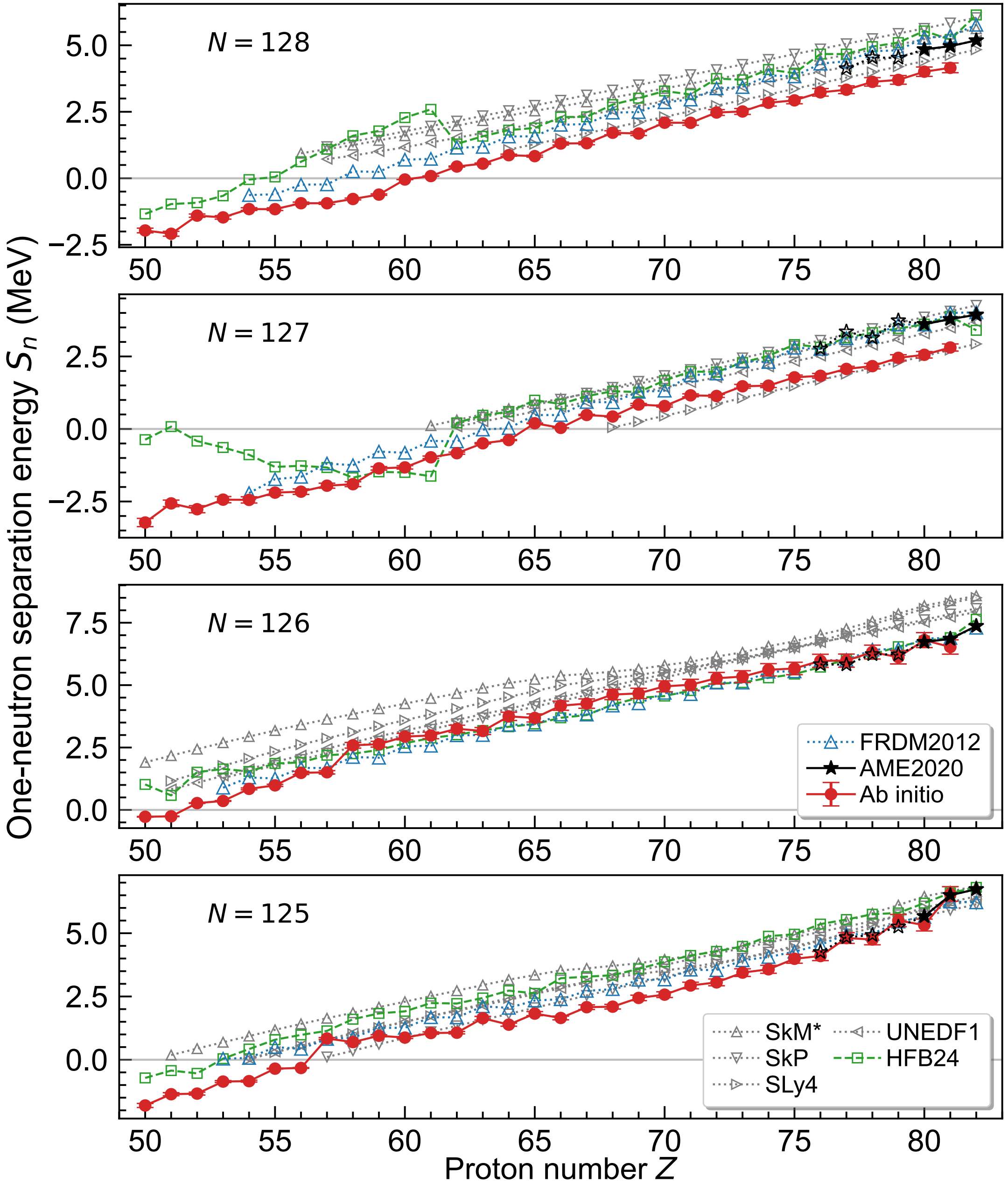
Fig.: Bertsch, Dean, Nazarewicz (2007)

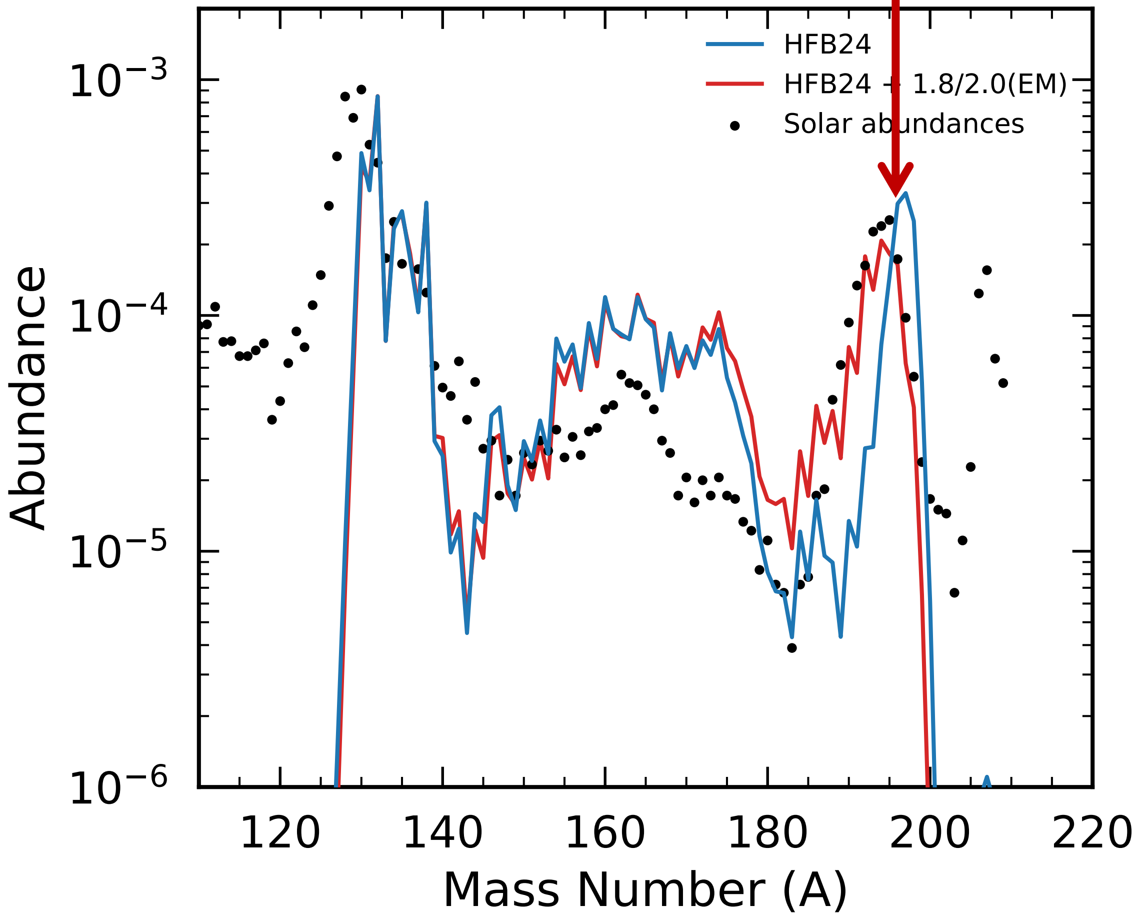


Hu, Larivière, Vassh, Holt, Yeh, Arcones, Schwenk, et al. (in prep)

Ab initio nuclear theory:

New *ab initio* masses change predictions of key heavies like Pt, Au





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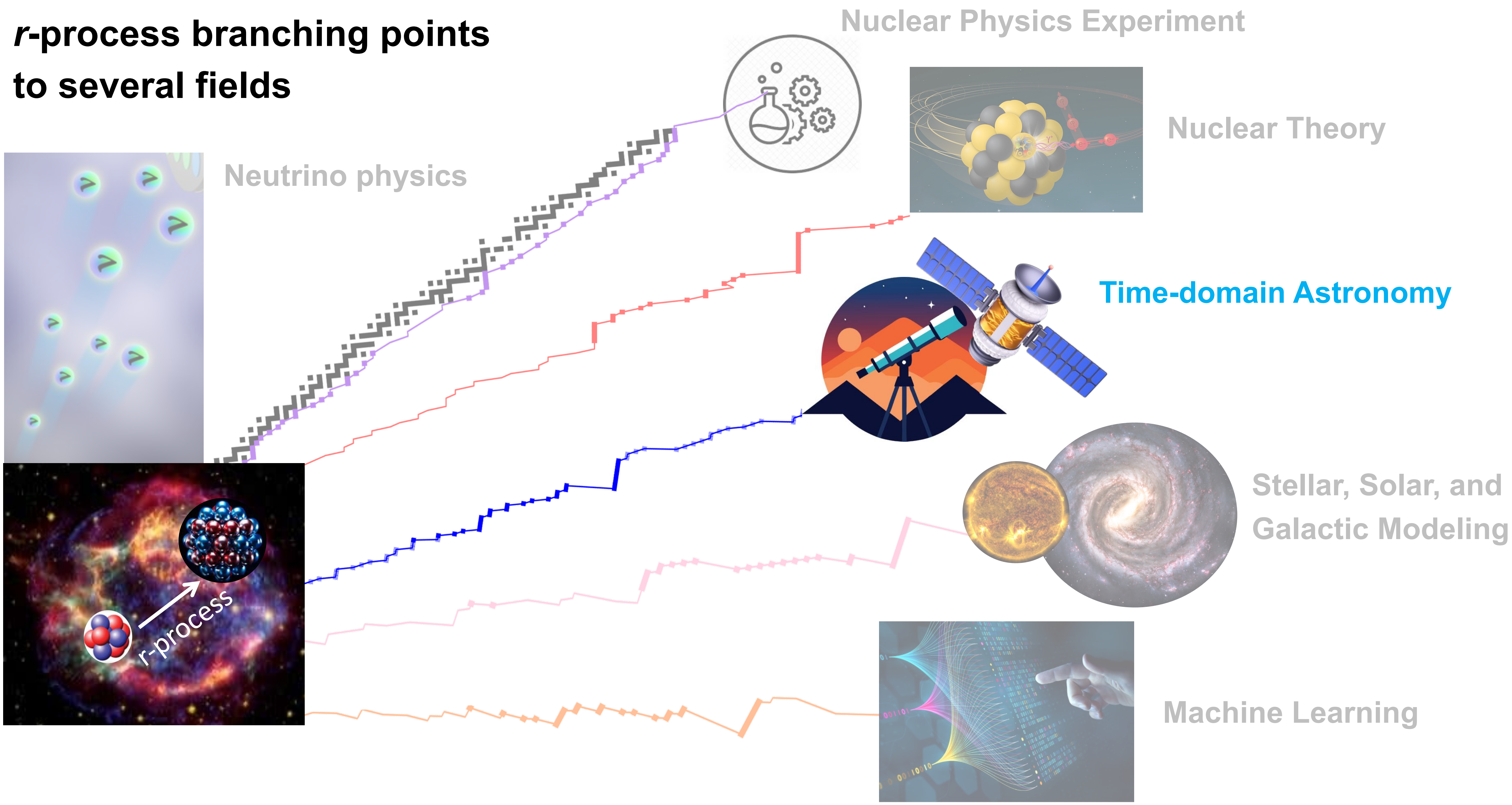
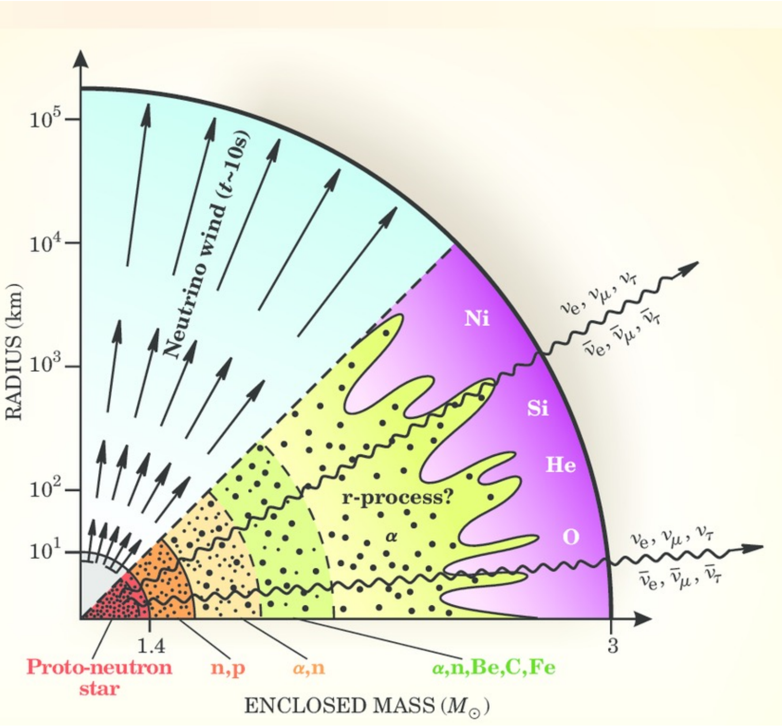


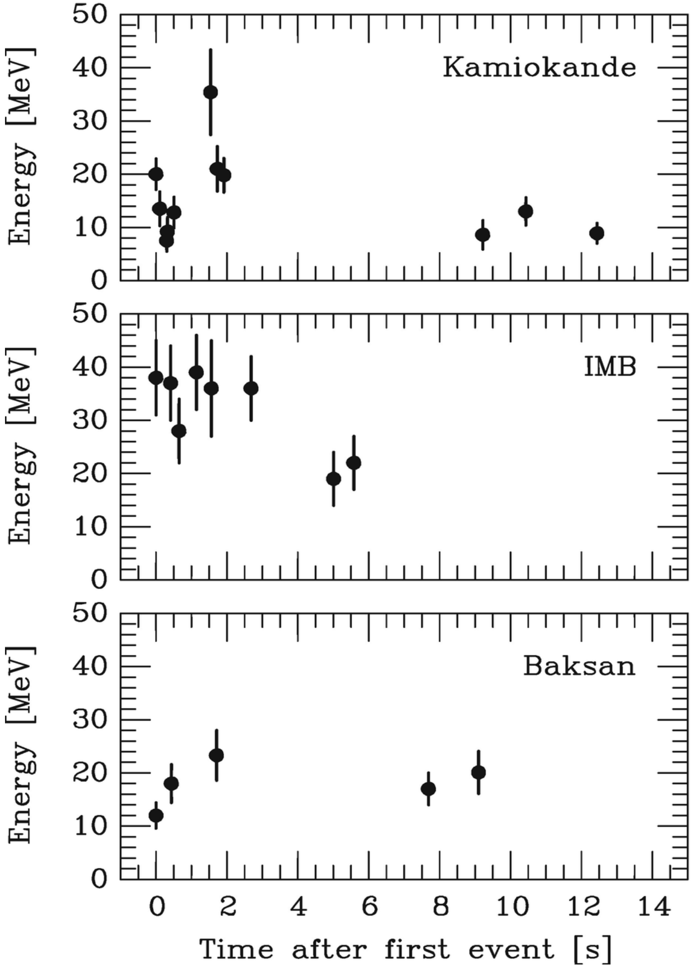
Multi-messenger events: Supernovae

SN1987A:
A famous core-collapse supernova

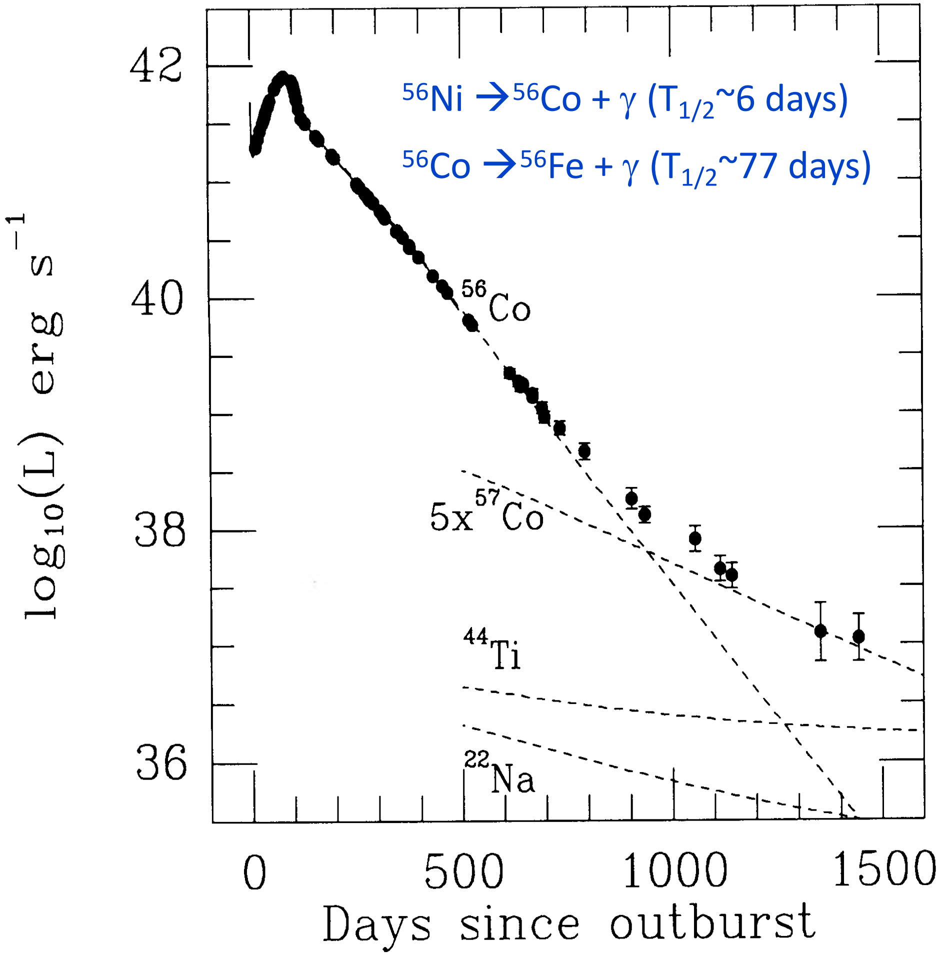


Woosley&Janka 06

Neutrinos



Light curve

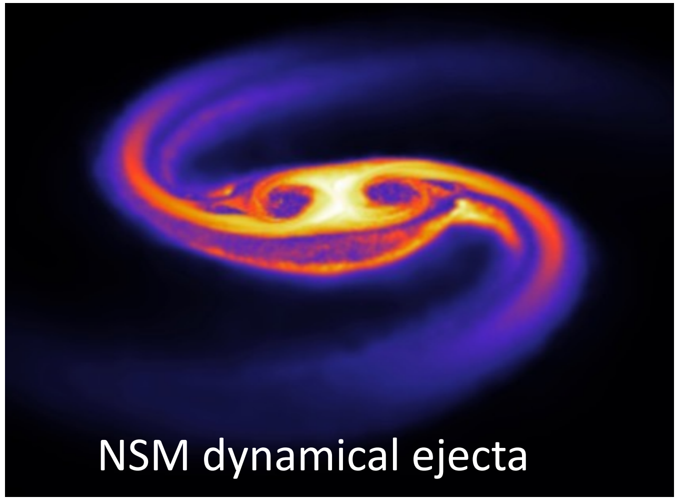


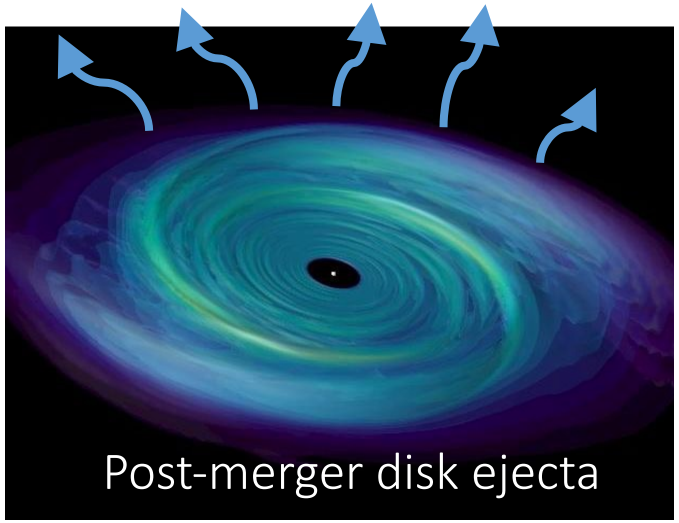
Suntzeff+92

Multi-messenger events: Neutron star mergers

GW170817 & AT2017gfo:
Binary neutron star merger

Neutron-rich ejecta from neutron star mergers predicted for > 40 years
(see e.g. Lattimer&Schramm 74, Lattimer+77)



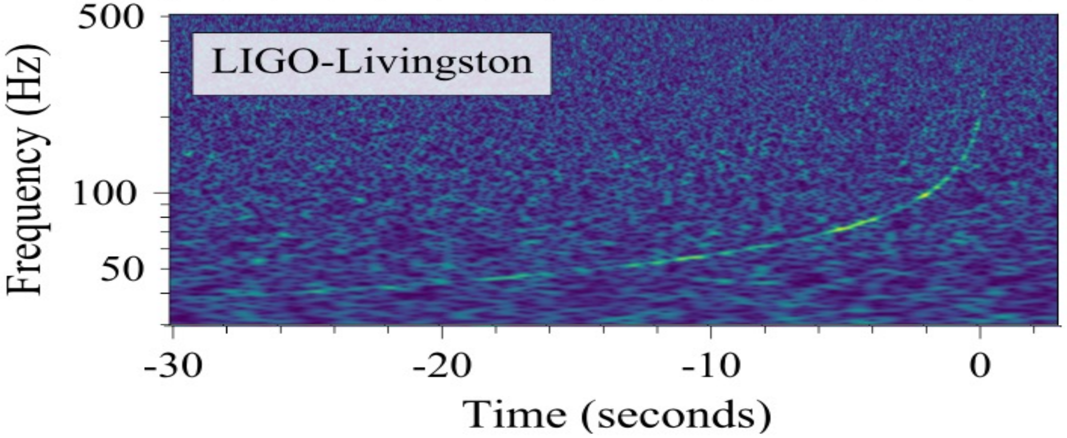


See Rosswog+13,Wanajo+14, Bovard+17, Radice+19, Perego+19, Foucart+20….

See Just+16, Miller+19, Most+21, Sprouse+23, Fernandez+23…

Over ~70 observing teams (~1/3 of the worldwide astronomical community) followed up on the merger event!

Gravitational waves

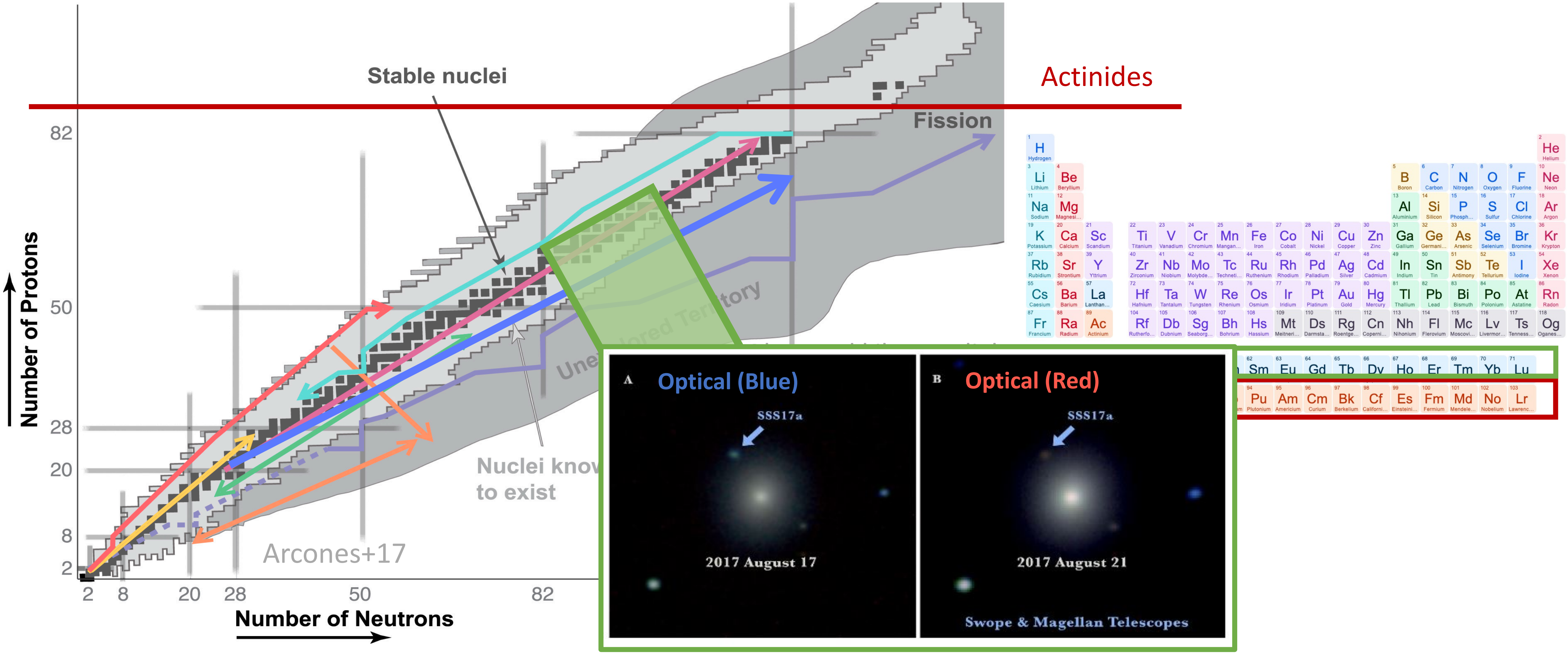


Abbott+17

Optical (Blue) **Optical (Red)**

Hurt/Kasliwal/Hallinan, Evans, and the GROWTH collab.

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

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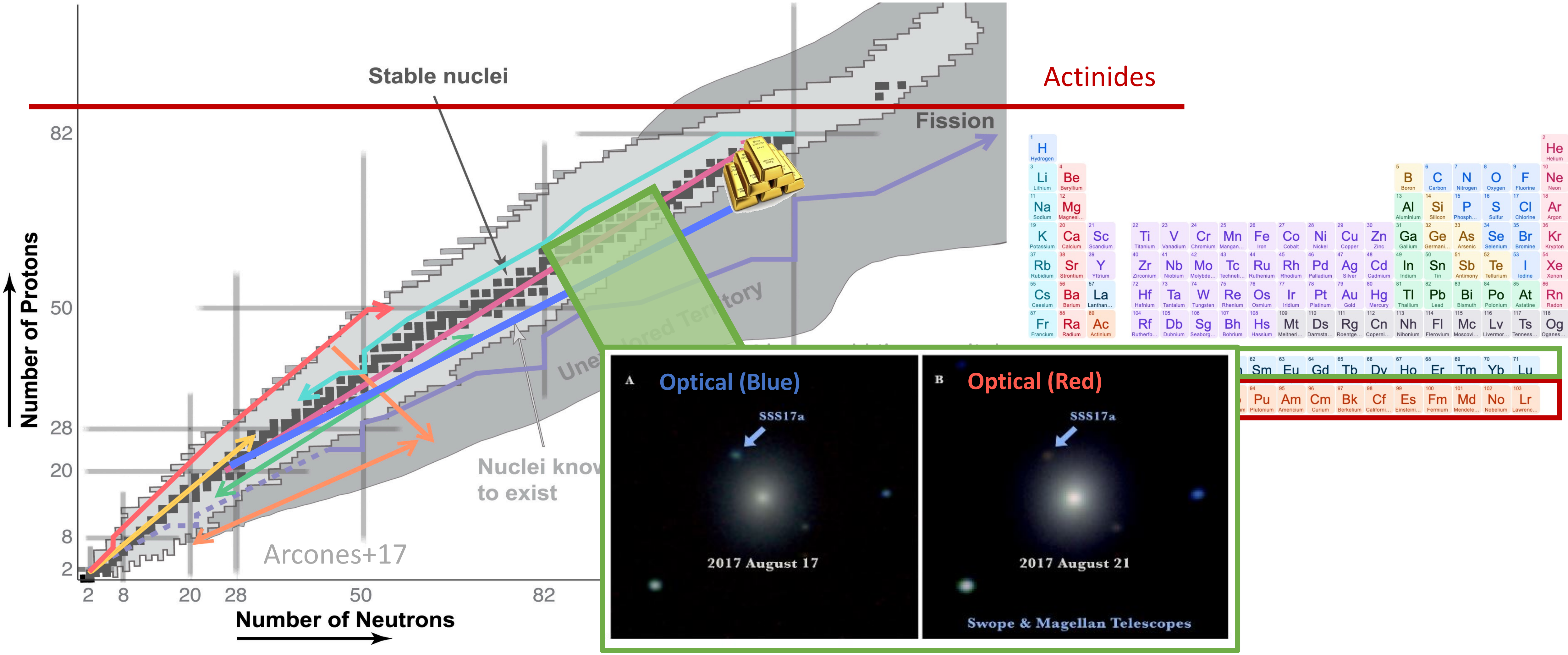

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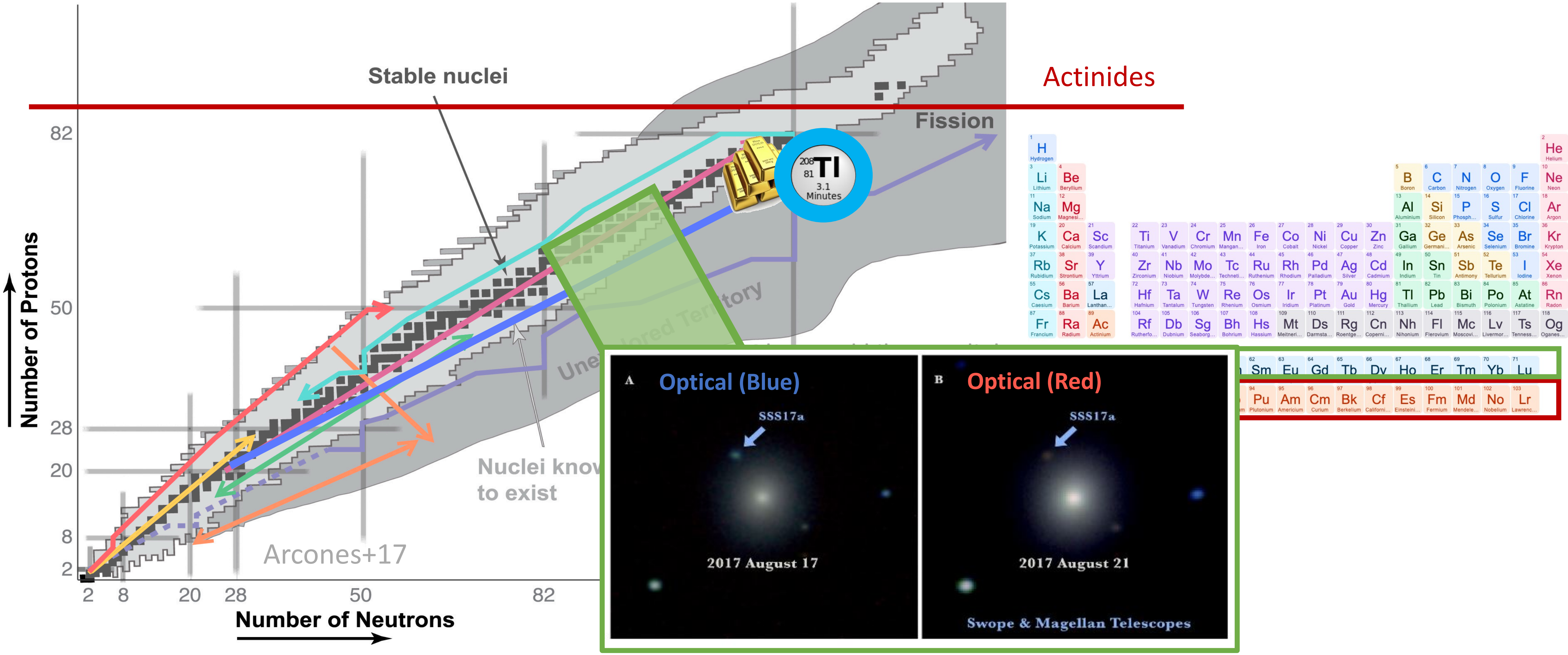
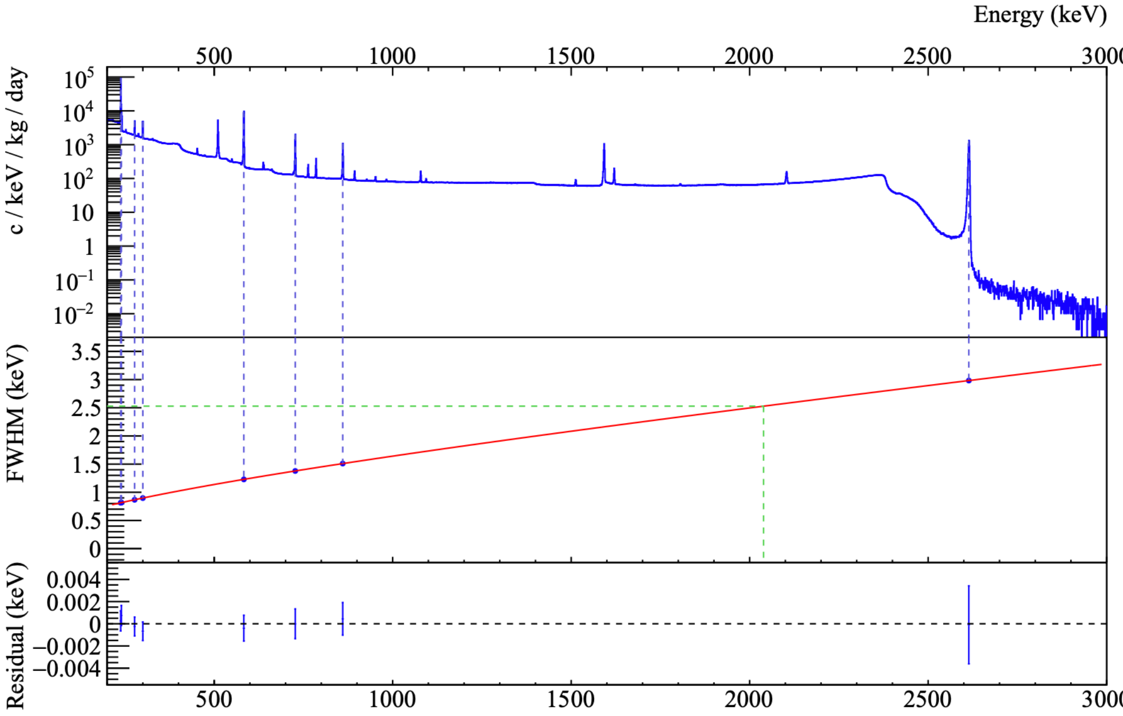


Kilonova emission -> IR with longer duration light curve implies high-opacity lanthanide elements

The 2.6 MeV gamma-ray line of Tl-208 and the Th-232 decay chain



Alvis+19

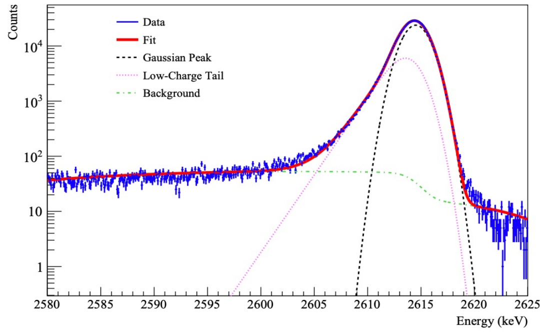
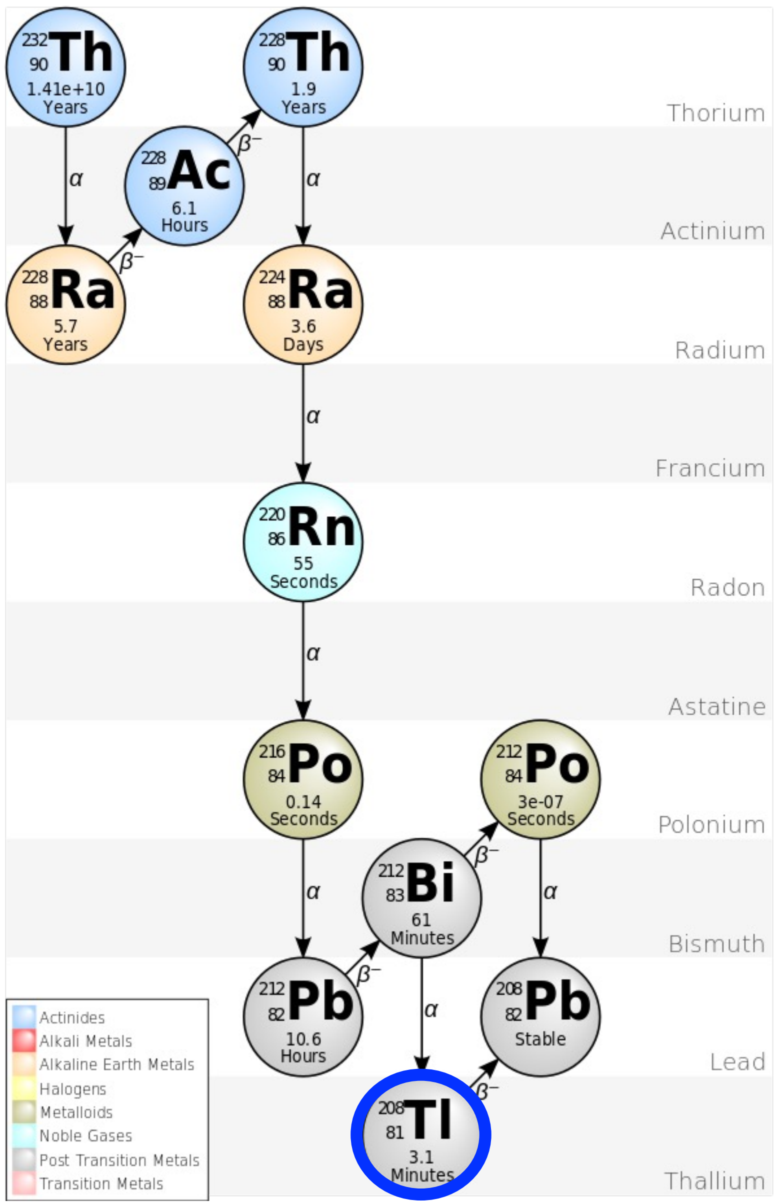
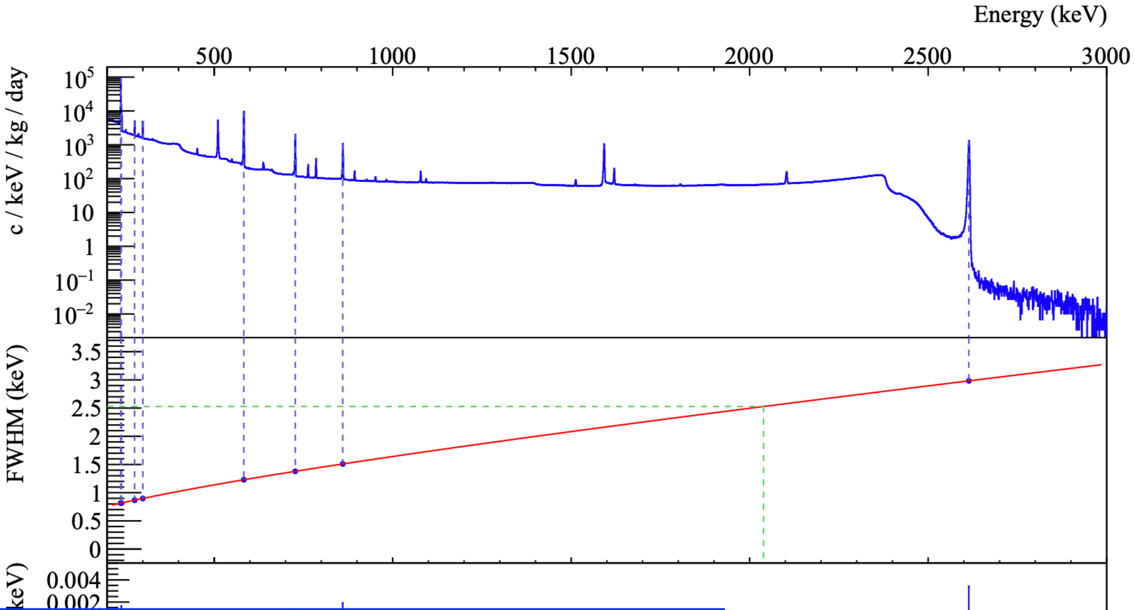


FIG. 3. Color online. The 2615 keV peak from ^{208}Tl in calibration data with all detectors combined is shown in the blue points with statistical error bars.

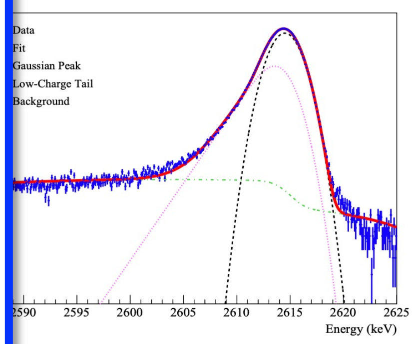
Majorana demonstrator
(^{76}Ge neutrinoless double β-decay search)



The 2.6 MeV gamma-ray line of Tl-208 and the Th-232 decay chain



And many more! e.g.:
Exp. background: SNO+,
Nuclear safeguards: detect shielded enriched U-232,
Nuclear medicine: Clinical imaging studies using 224Ra α-particle therapy
Geology: aerial surveys to map out terrestrial Th,
Soil and Hydrological Sciences: studies of soil and water content….



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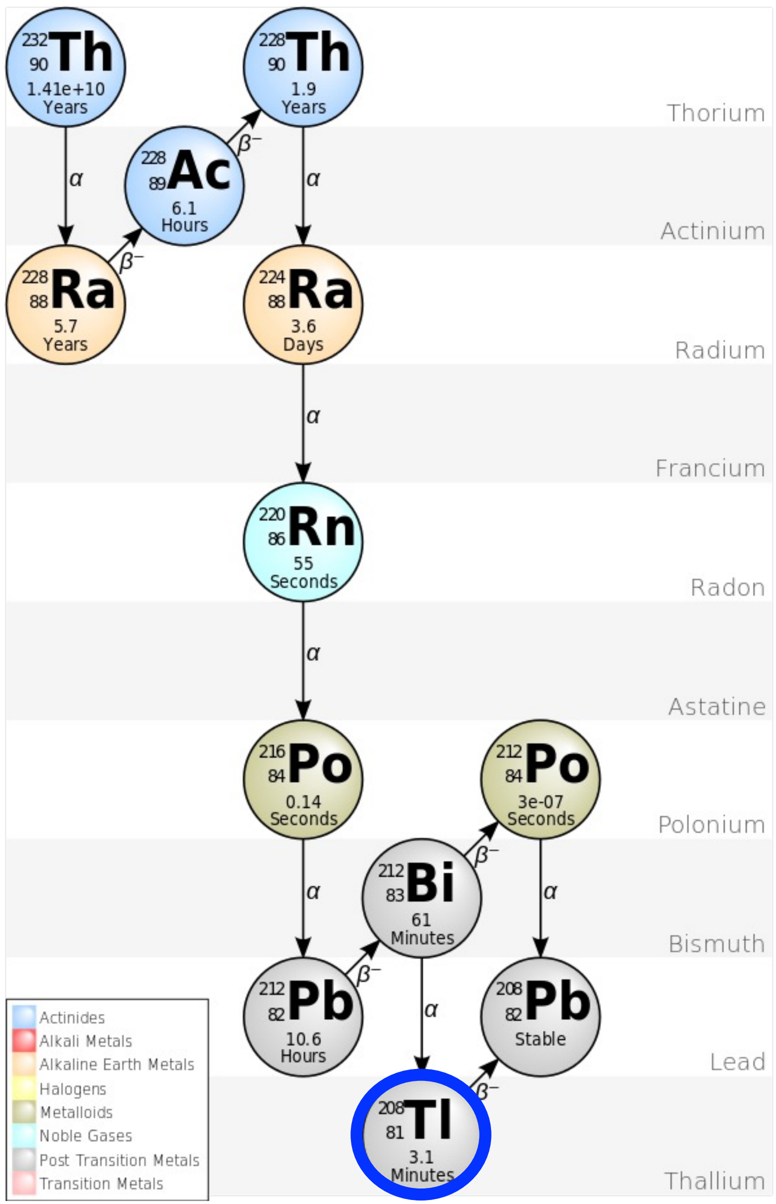
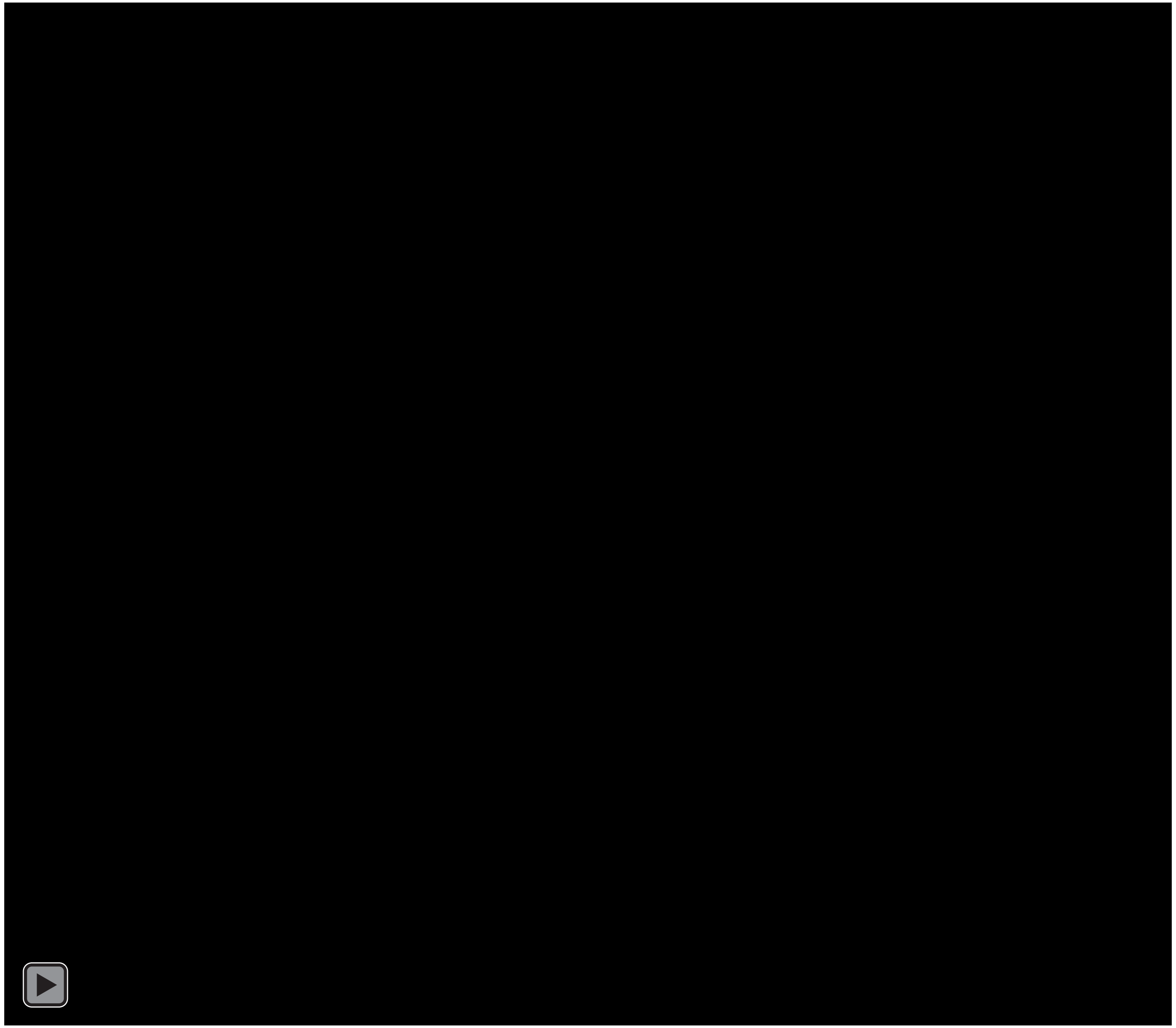


r process in neutron star mergers: MeV gamma rays emitted from the β-decay of neutron-rich isotopes



Movie by
M. Larivière

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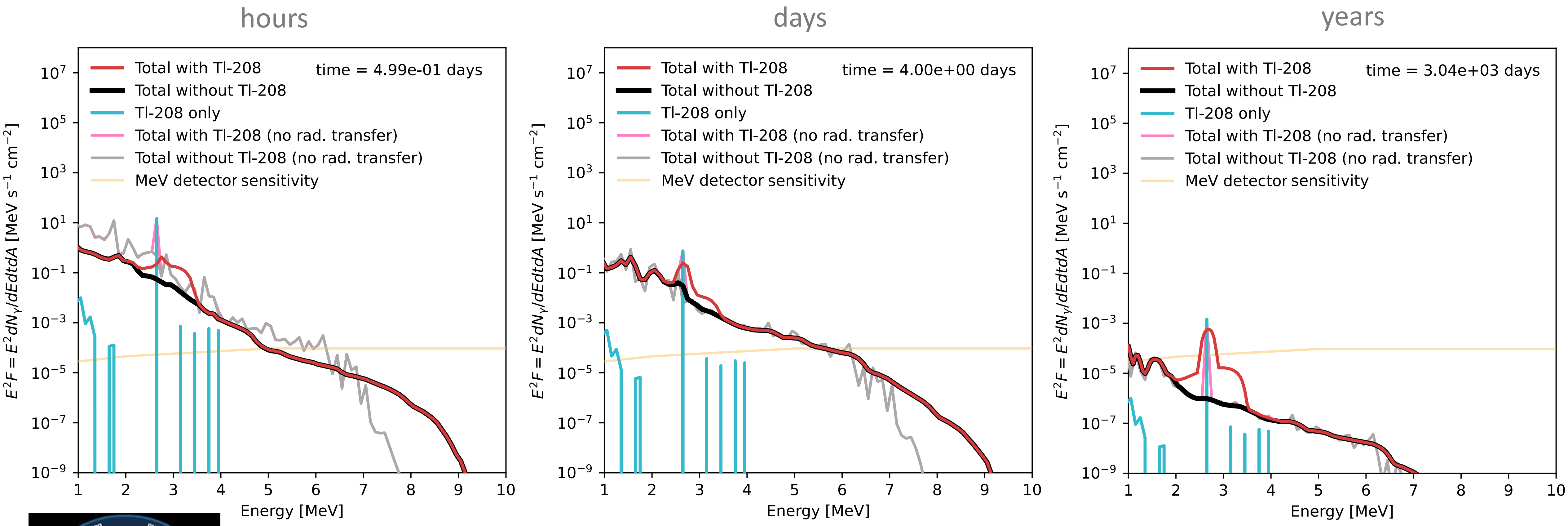


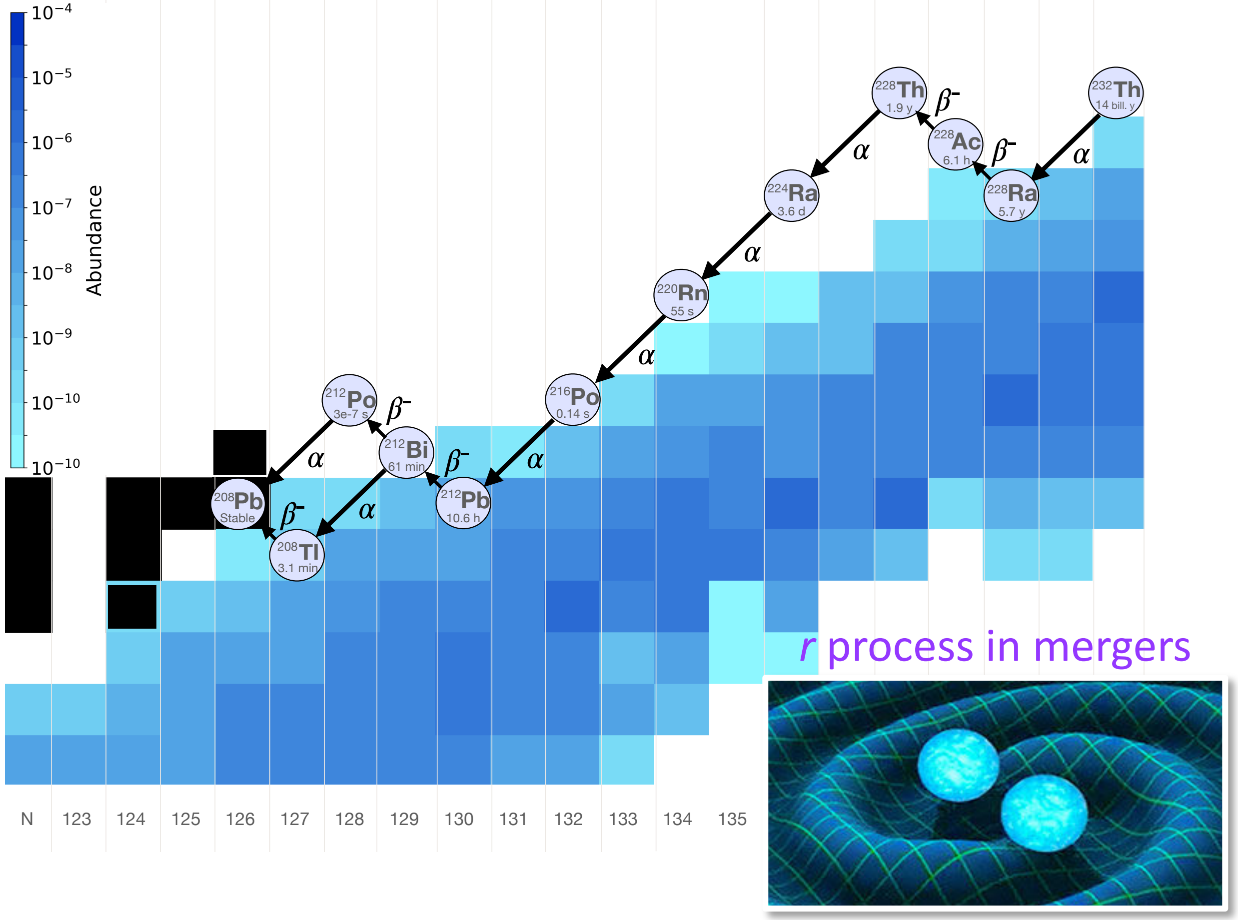
@ 10 kpc (Galactic)

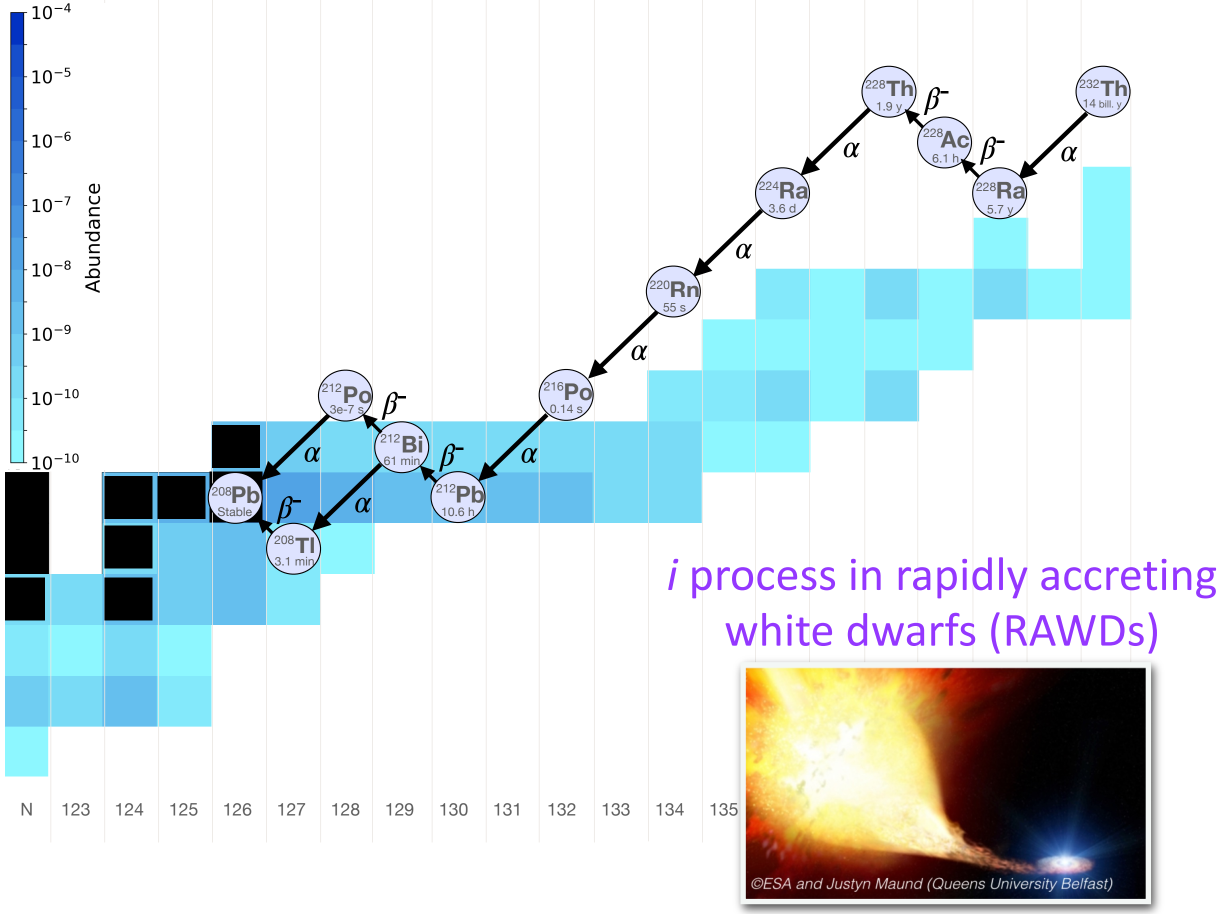
Vassh, Wang, Larivière+24 (PRL 132, 052701)

Thallium-208: a beacon of *in situ* neutron capture nucleosynthesis

Nicole Vassh,[1,*] Xilu Wang,[2,†] Maude Larivière,[1,3] Trevor Sprouse,[4,5] Matthew R. Mumpower,[4,5]
Rebecca Surman,[6] Zhenghai Liu,[7] Gail C. McLaughlin,[7] Pavel Denissenkov,[8,9,10] and Falk Herwig[8,9,10]

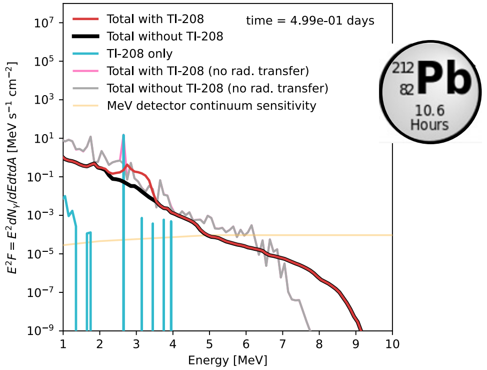
[1] *TRIUMF, 4004 Wesbrook Mall, Vancouver, British Columbia V6T 2A3, Canada*
[2] *Key Laboratory of Particle Astrophysics, Institute of High Energy Physics, Chinese Academy of Sciences, Beijing, 100049, People's Republic of China*
[3] *Department of Physics and Astronomy, University of British Columbia, Vancouver, British Columbia, V6T 1Z1, Canada*

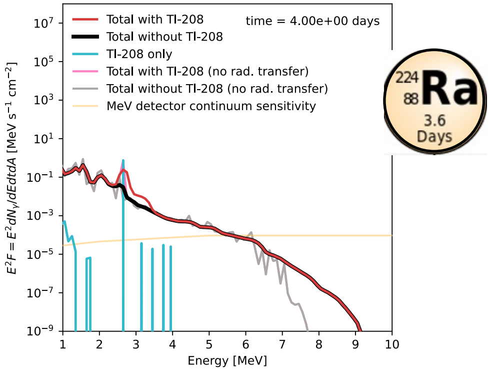


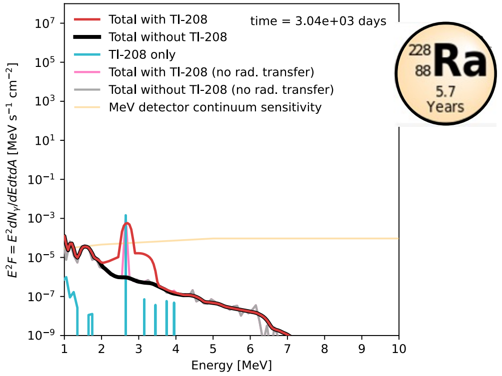


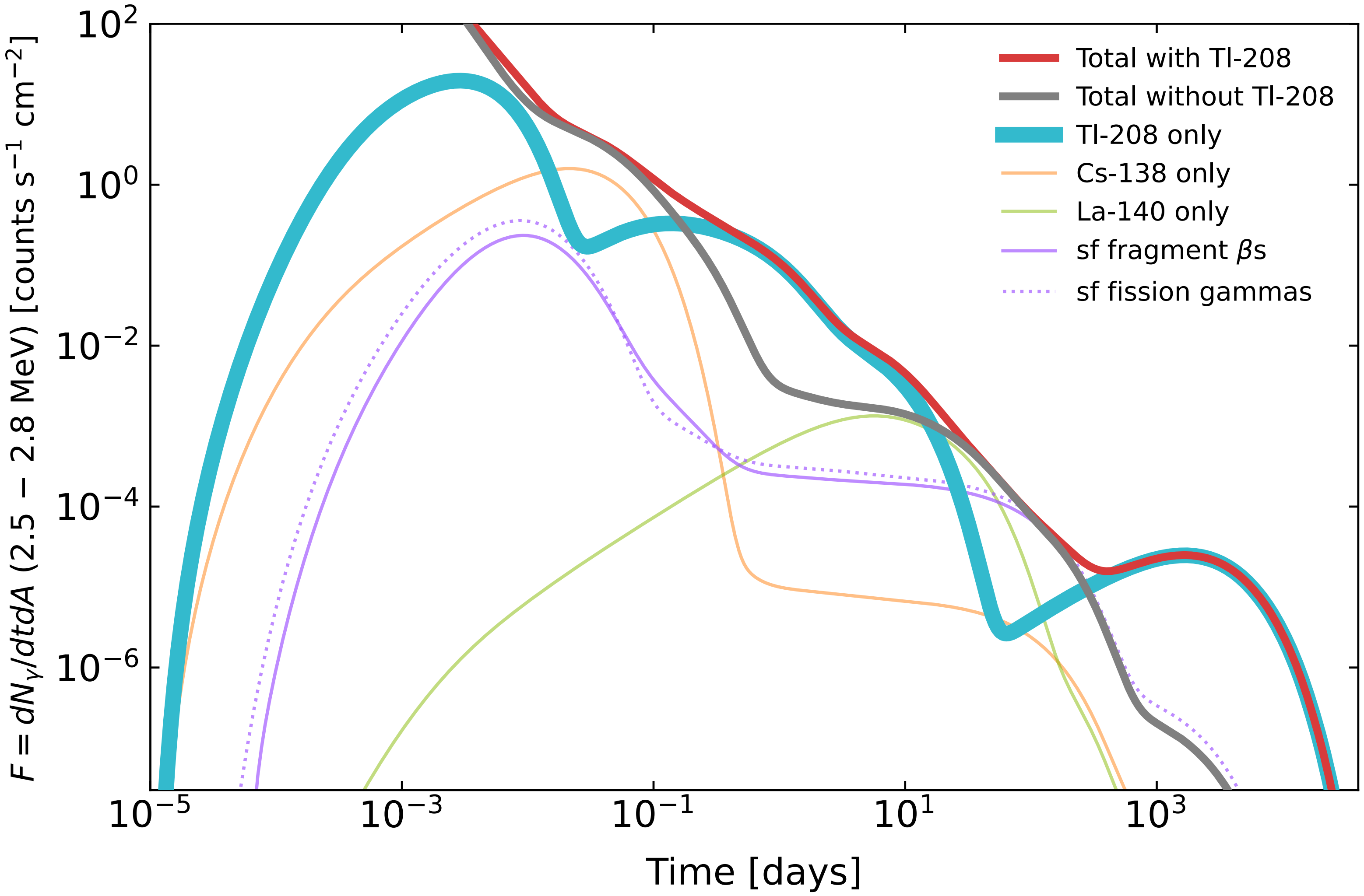
Vassh, Wang, Larivière+24 (PRL 132, 052701)

Comparison with other nuclei with decays emitting in the 2.5-2.8 MeV energy range



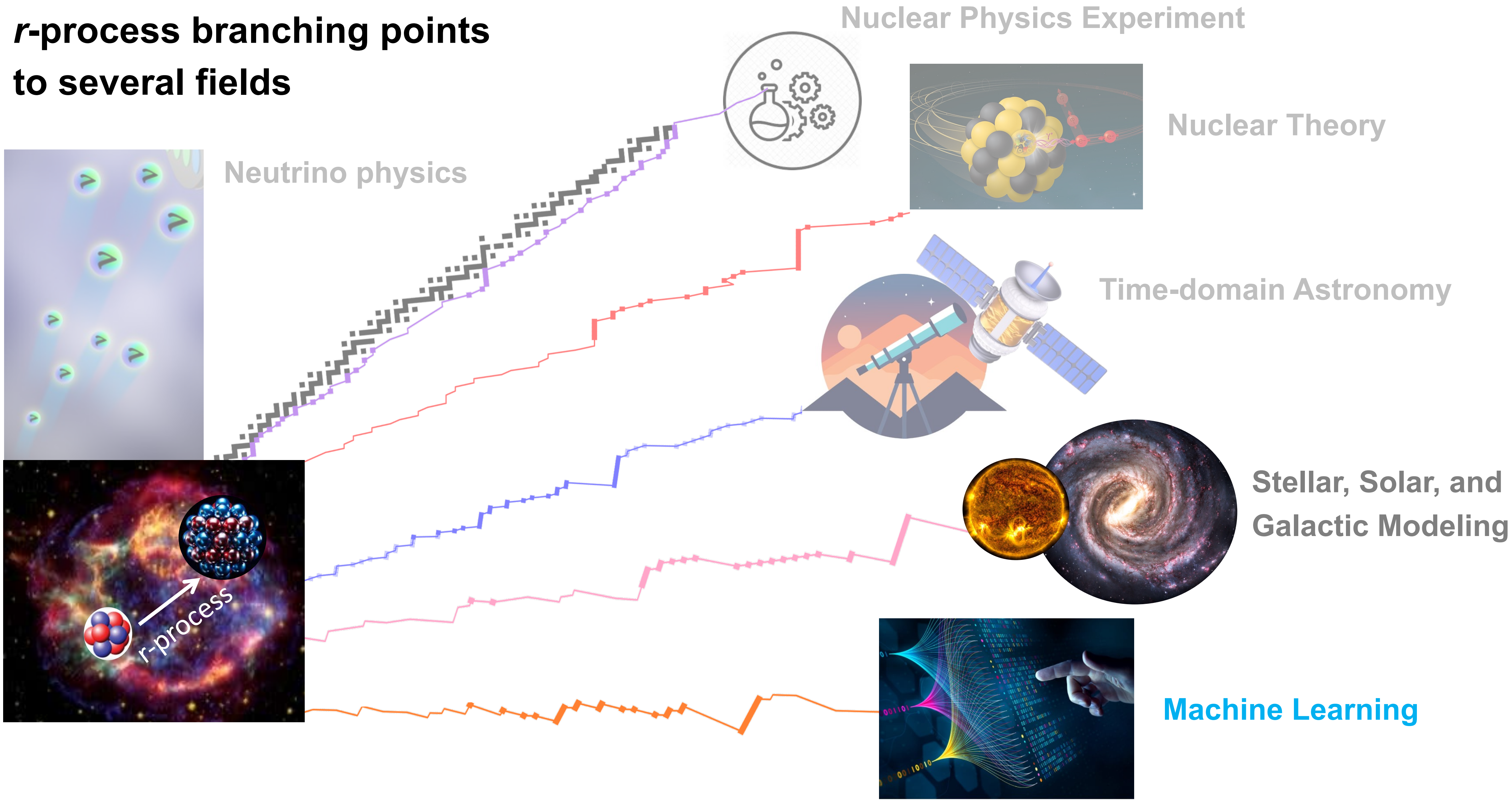


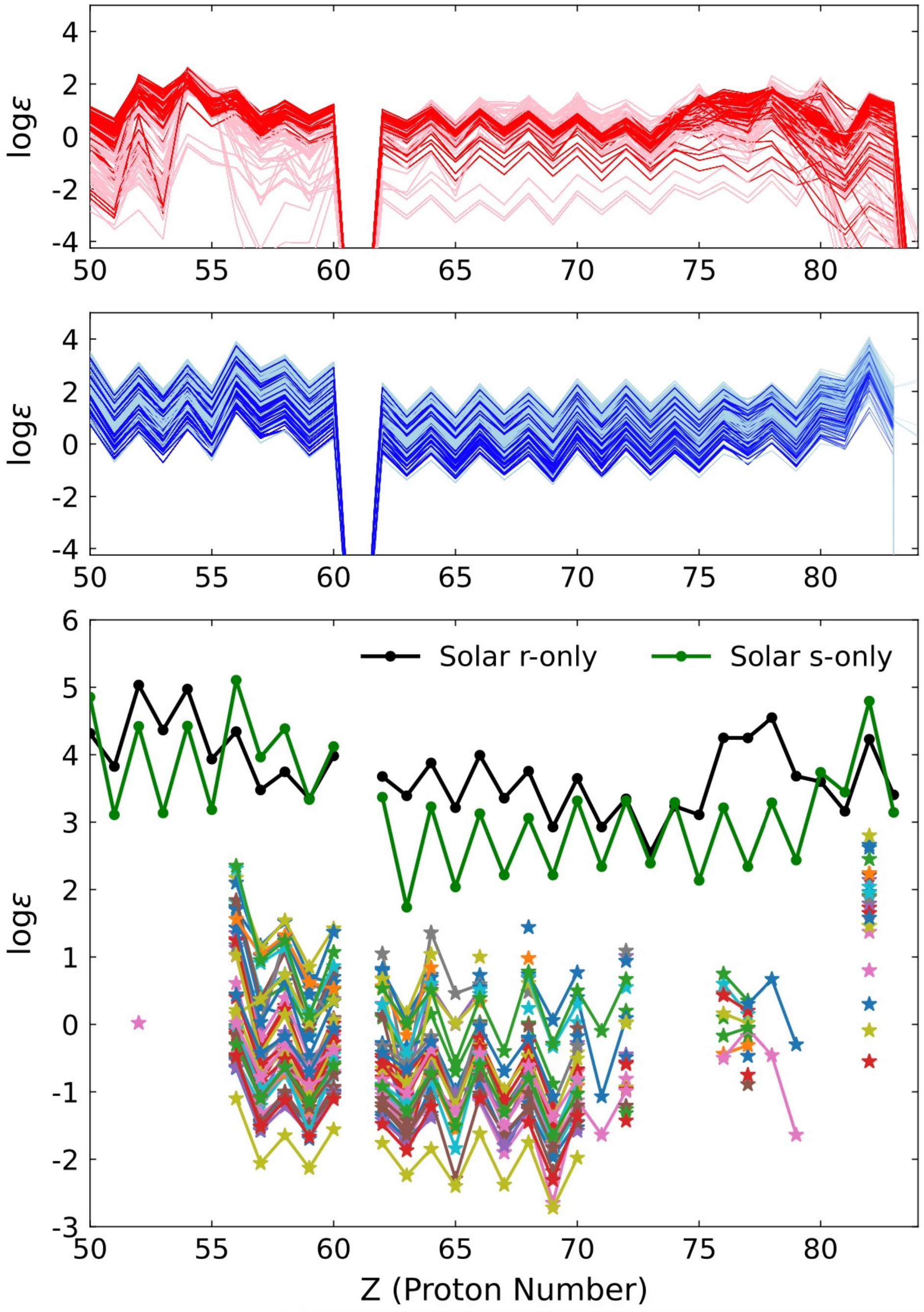




Vassh, Wang, Larivière+24 (PRL 132, 052701)

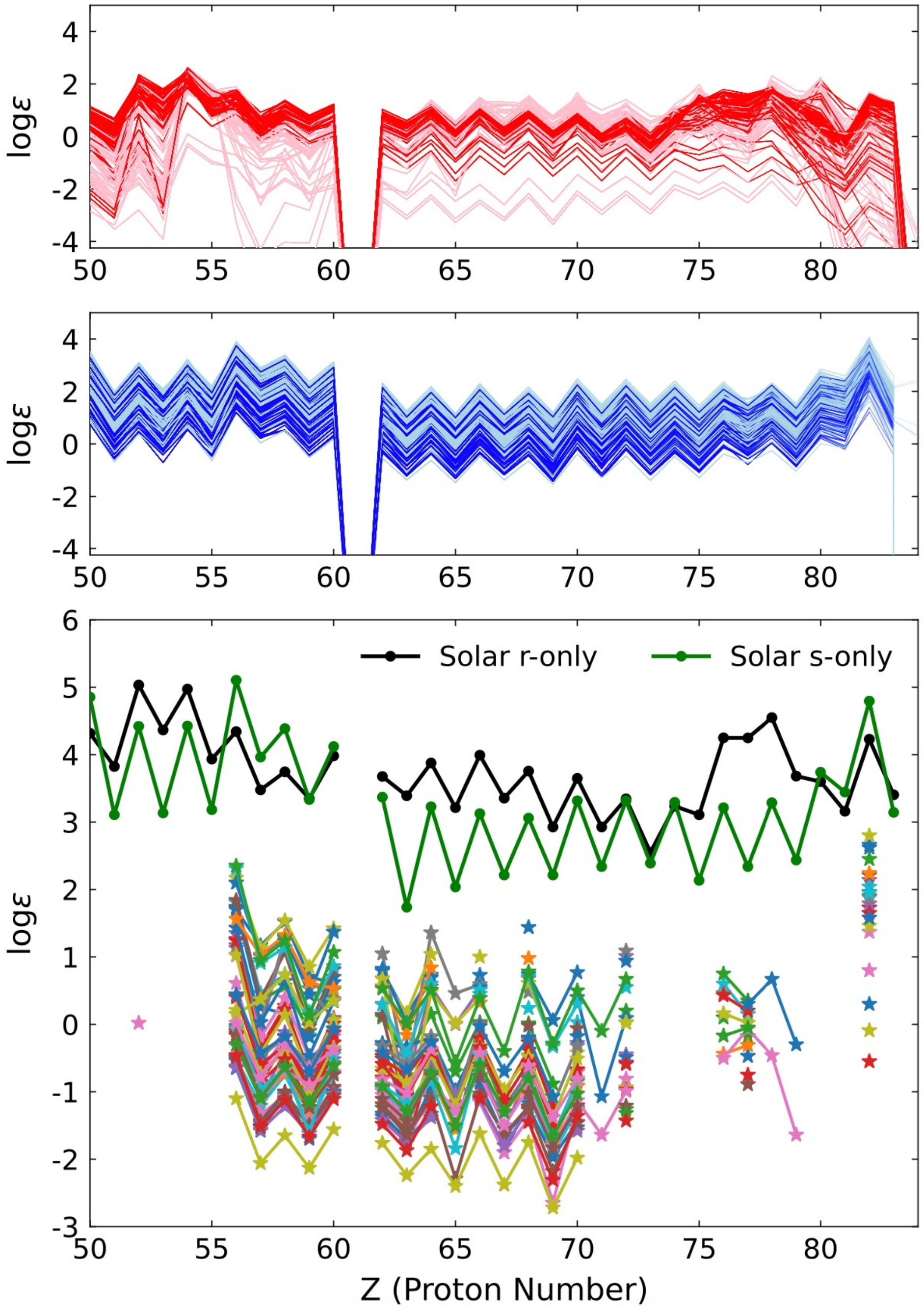
r-process branching points to several fields





Hydrodynamic simulations of r process and s process events show distinct elemental abundance patterns

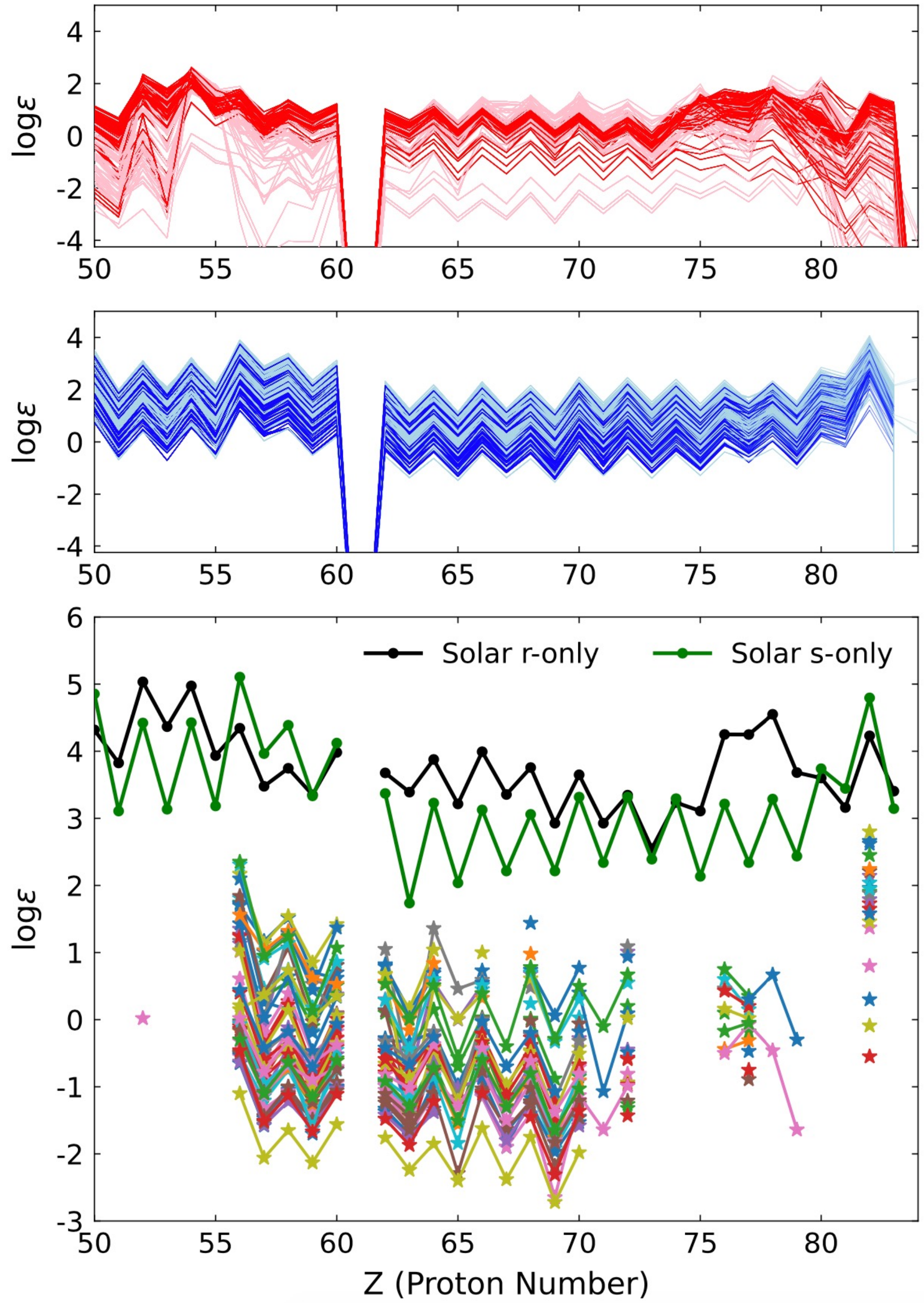
Vassh, Wang, Woloshyn, Kutchera, Larivière, Majic, Côté (submitted, 2025)



Hydrodynamic simulations of r process and s process events show distinct elemental abundance patterns

Stellar abundance patterns are available for > 100 metal-poor stars

Vassh, Wang, Woloshyn, Kutchera, Larivière, Majic, Côté (submitted, 2025)



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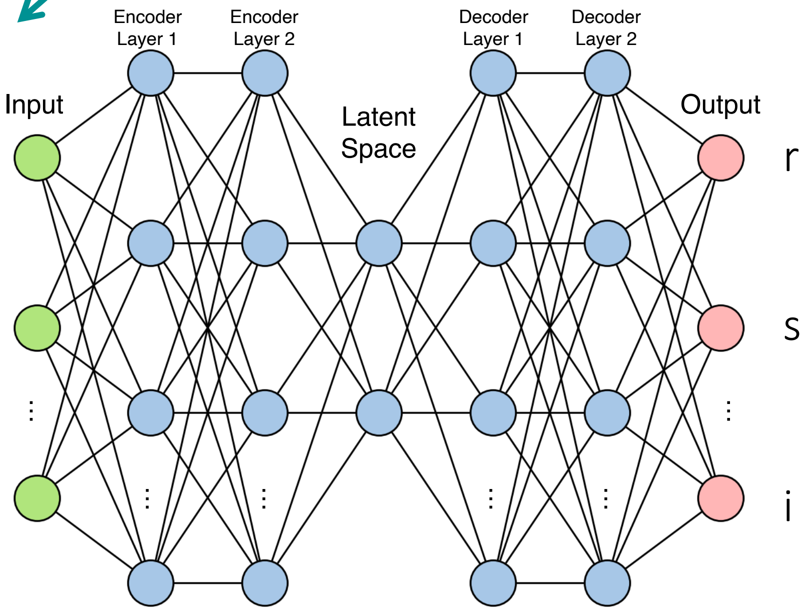


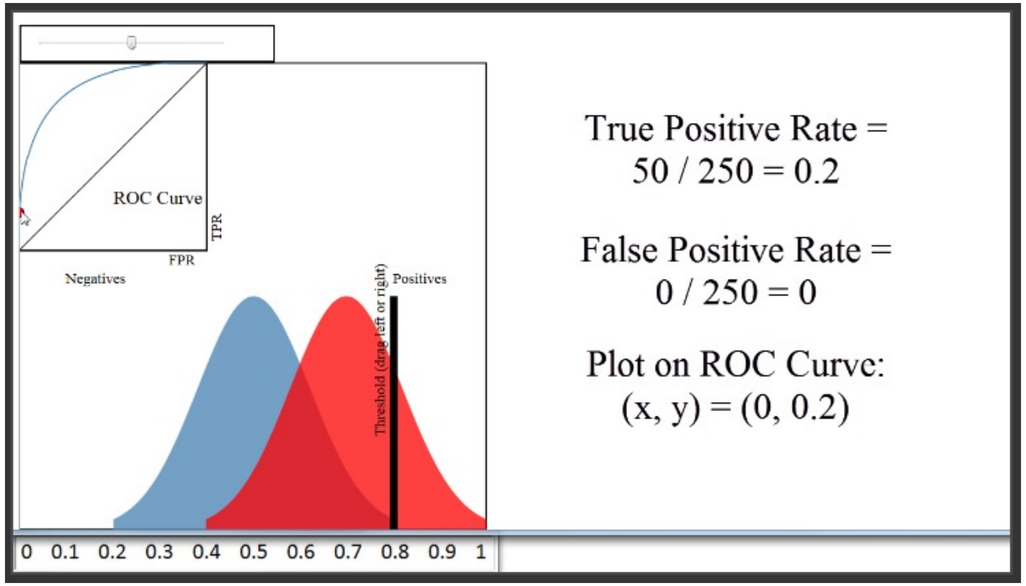
Machine learning can classify patterns = *Machine learning can classify stars*

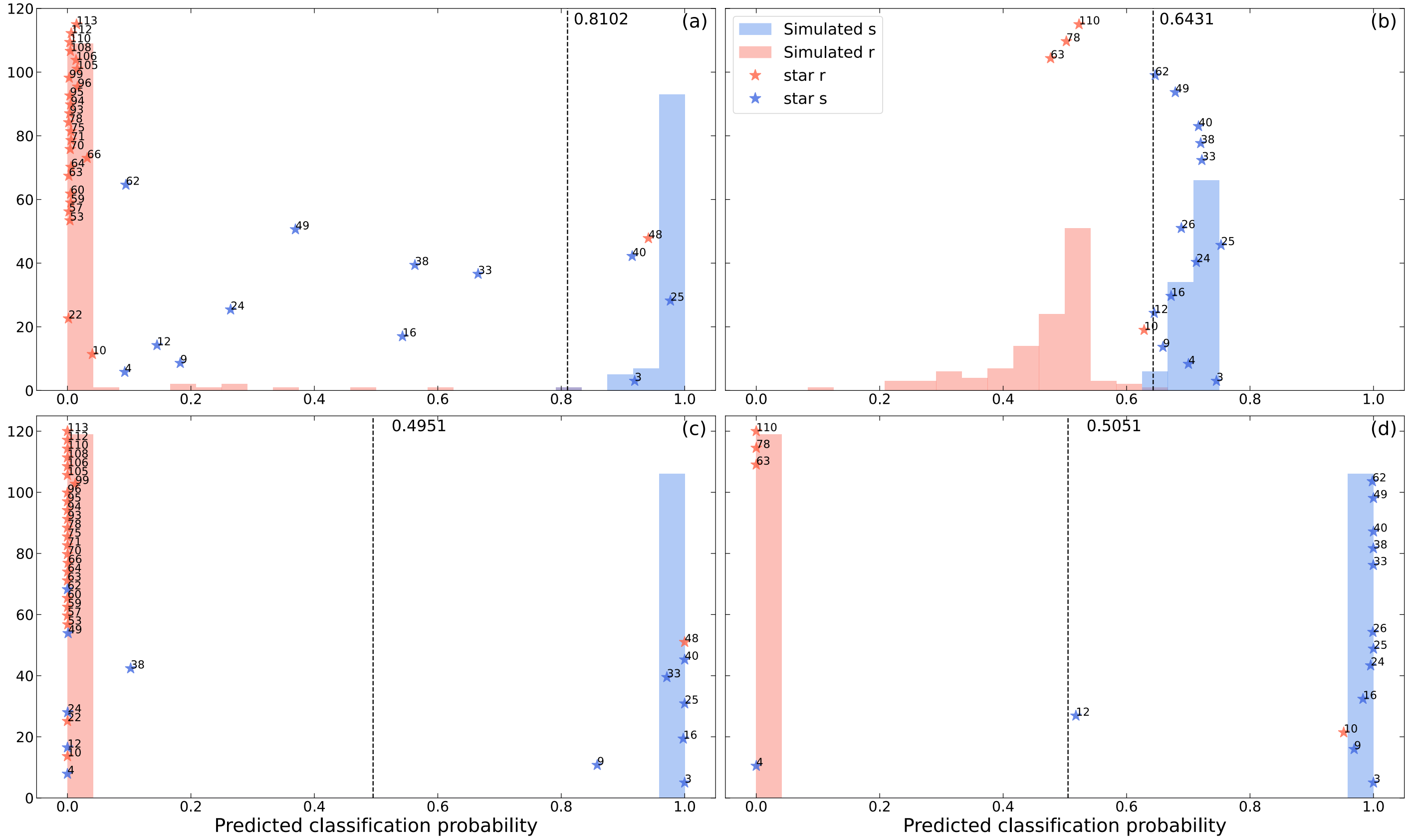
Vassh, Wang, Woloshyn, Kutchera, Larivière, Majic, Côté (submitted, 2025)

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

Ba, lanthanide, and Pb abundances

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



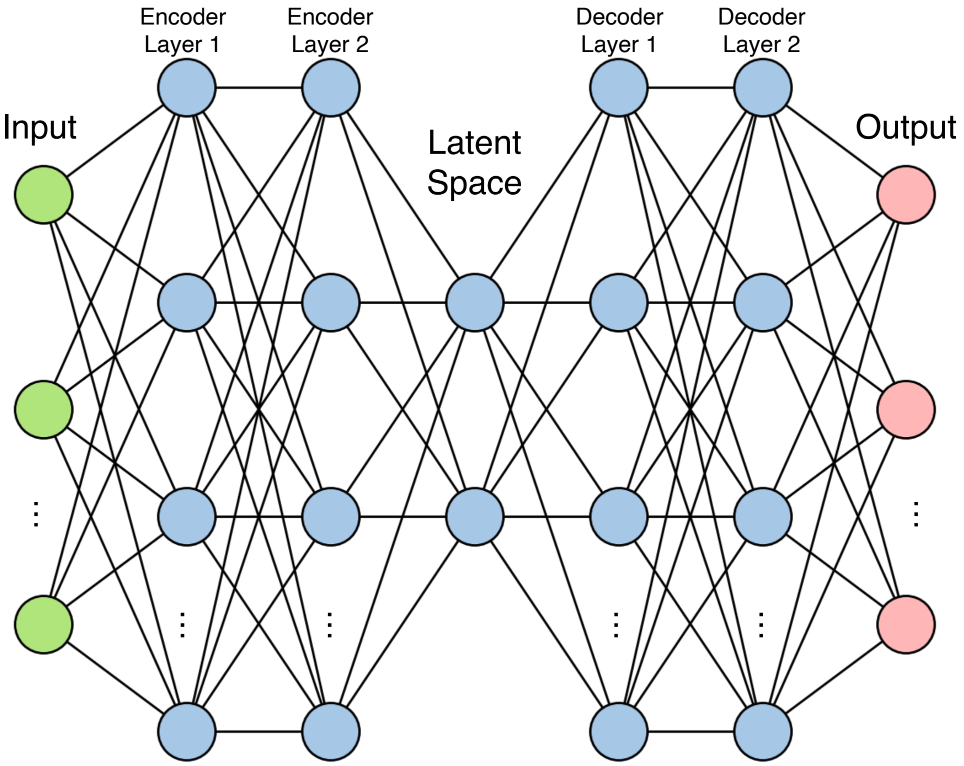


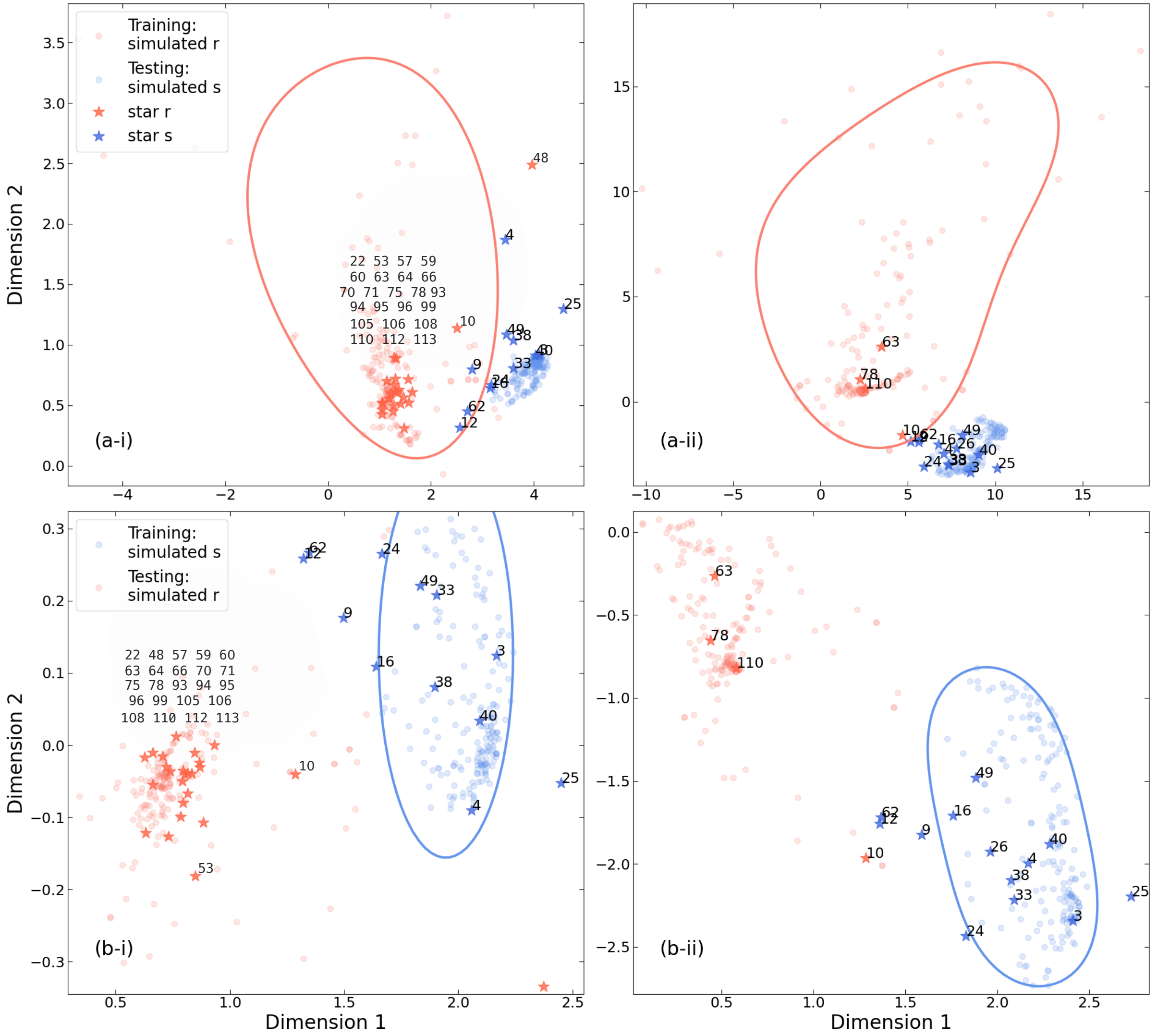
Vassh, Wang, Woloshyn, Kutchera, Larivière, Majic, Côté (submitted, 2025)

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

Ba, lanthanide, and Pb abundances

One-class classifier
(unsupervised training on r *or* s)

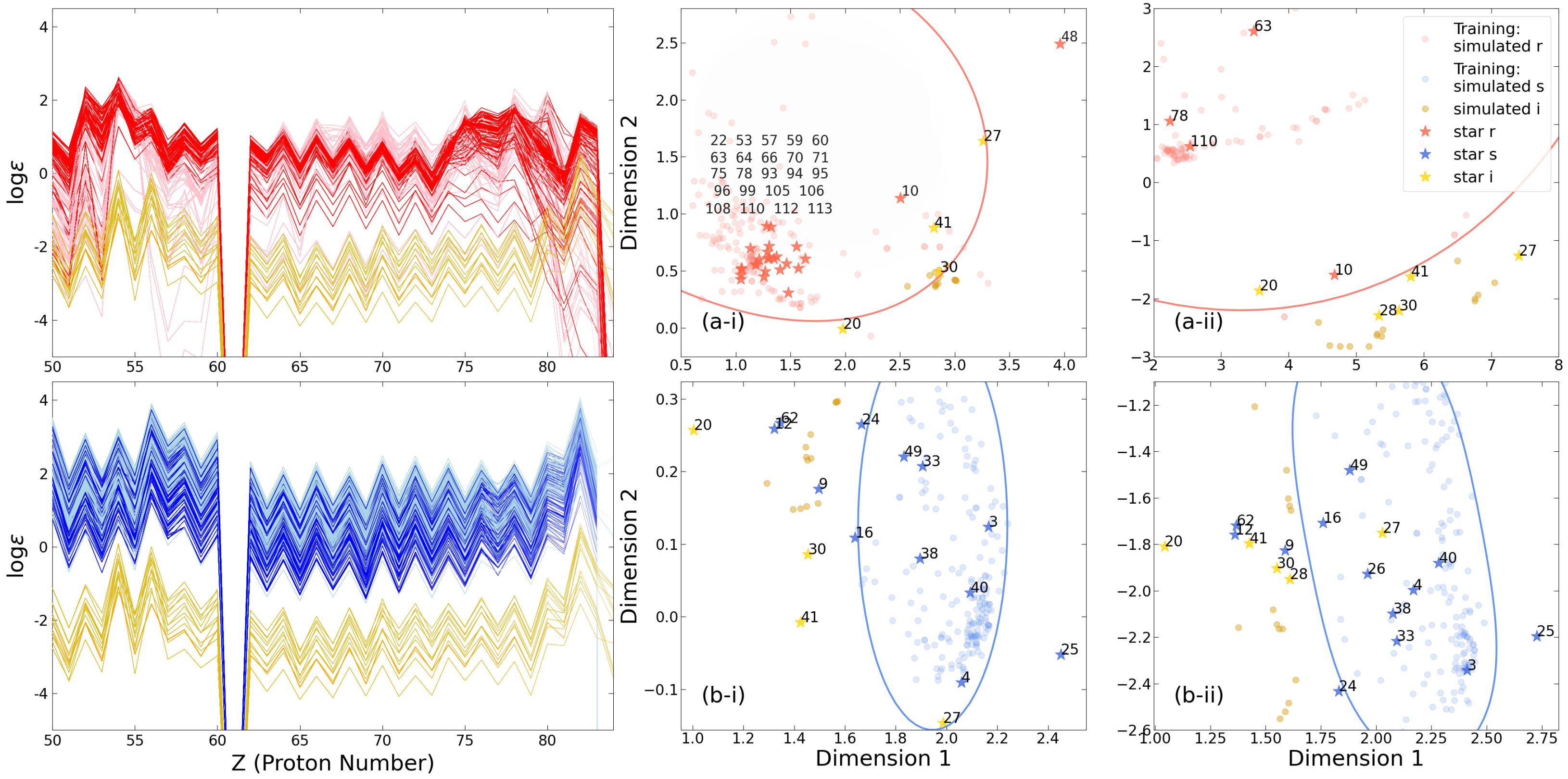




Vassh, Wang, Woloshyn, Kutchera, Larivière, Majic, Côté (submitted, 2025)

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

0.0 < [La/Eu] < 0.6



Stellar classifications with different ML methods							
Star #	Name, Ref.	OCC-L (Er,Pb)	OCC-S (Er,Pb)	OCC-L (Er,Pb)	OCC-S (Er,Pb)	ML Overall	JINA-Base
		Trained on r		Trained on s			
20	HE1405-0822, CUI13	~~r~~,r	r,r	~~s~~,~~s~~	~~s~~,~~s~~	r	i
27	SDSSJ091243.72+021623.7, BEH10	r,~~r~~	~~r~~,~~r~~	s,s	~~s~~,s	s	i
28	HE2148-1247, COH13	-,~~r~~	-,~~r~~	-,~~s~~	-,~~s~~	?	i
30	HE0338-3945, JON06	r,~~r~~	r,~~r~~	~~s~~,~~s~~	~~s~~,~~s~~	?	i
41	HE0243-3044, HAN15	r,~~r~~	r,~~r~~	~~s~~,~~s~~	~~s~~,~~s~~	?	i

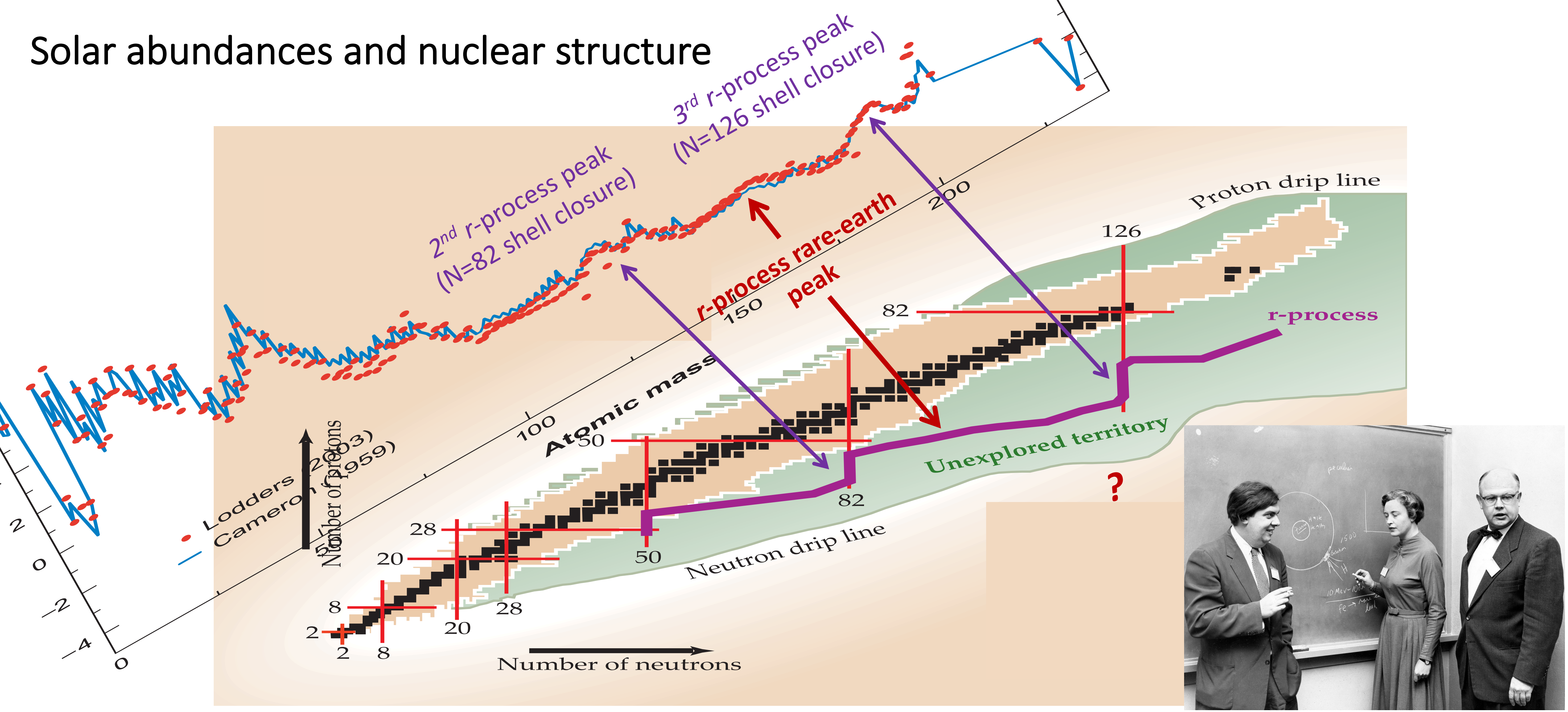
* Some metal-poor stars have been previously found to not be compatible with r or s elemental abundance ratios, points to intermediate neutron capture process (i)

* There are 2/5 i stars the one-class classifier suggests to belong in either the r or s group

* The one-class classifier trained on r or s almost never wants to identify 3/5 i stars as r or s!

Vassh, Wang, Woloshyn, Kutchera, Larivière, Majic, Côté (submitted, 2025)

Solar abundances and nuclear structure



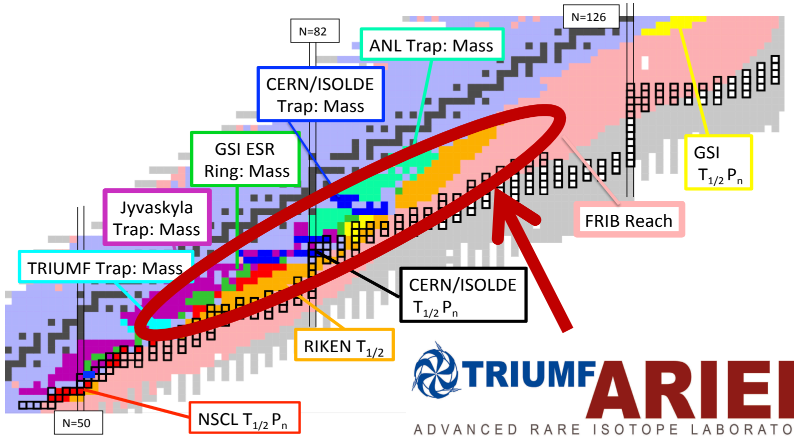
"It has been generally stated that the atomic abundance curve has an exponential decline to A~100 and is approximately constant thereafter. Although this is very roughly true it ignores many details which are important clues to our understanding of element synthesis."

-- Burbidge, Burbidge, Fowler and Hoyle (1957)

An international, multi-disciplinary community is working to understand heavy element origins

There are numerous groups worldwide doing calculations, measurements, and observations relevant for heavy element synthesis!

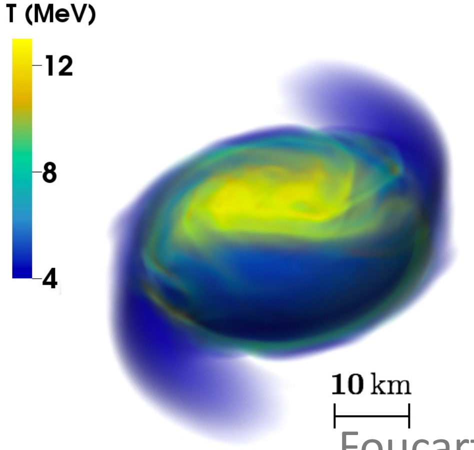
Experimental campaigns



TRIUMF ARIEL
ADVANCED RARE ISOTOPE LABORATORY

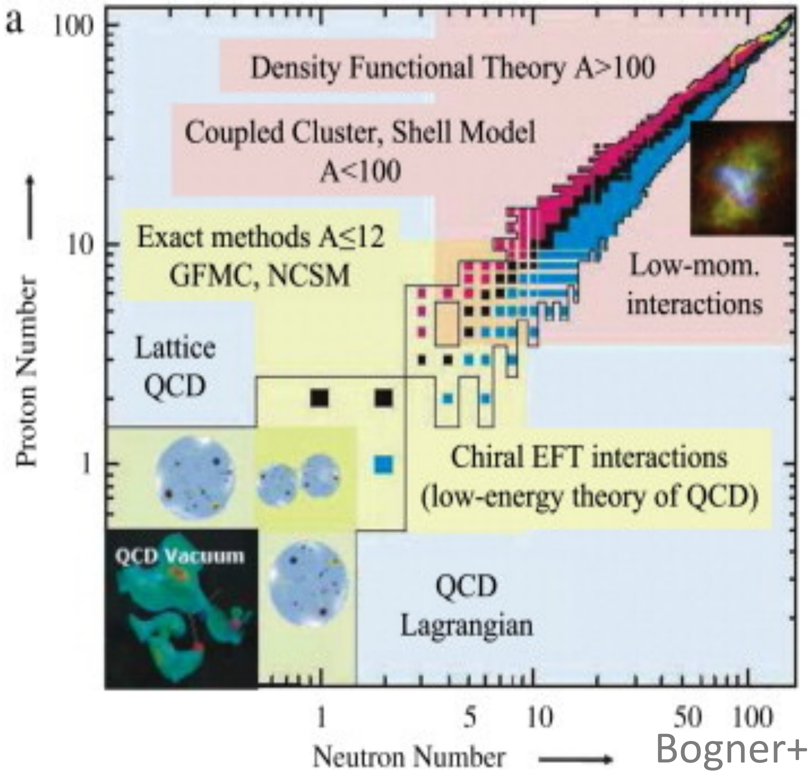
Horowitz+18

Advances in computational simulations



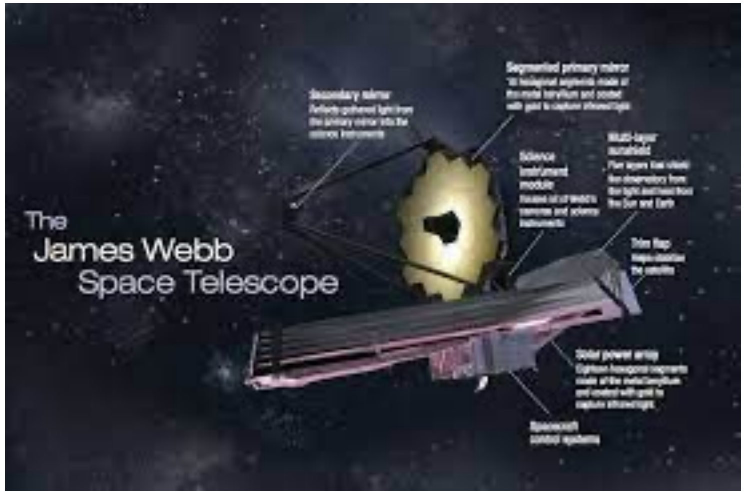
Foucart+16

Advances in nuclear theory



Bogner+

Observational campaigns



LIGO VIRGO