Heavy-Element Nucleosynthesis in the Multi-Messenger Era

Erika M. Holmbeck*

1st IReNA-UKAKUREN Joint Workshop | 31 August 2023

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Carnegie Science | Observatories

Nuclear Astrophysics

Nuclear Astrophysics

“ to understand the origin of the chemical elements and isotopes, and the role of nuclear energy generation, in cosmic sources such as stars, supernovae, novae, and violent binary-star interactions ”

- Wikipedia

Nuclear Astrophysics

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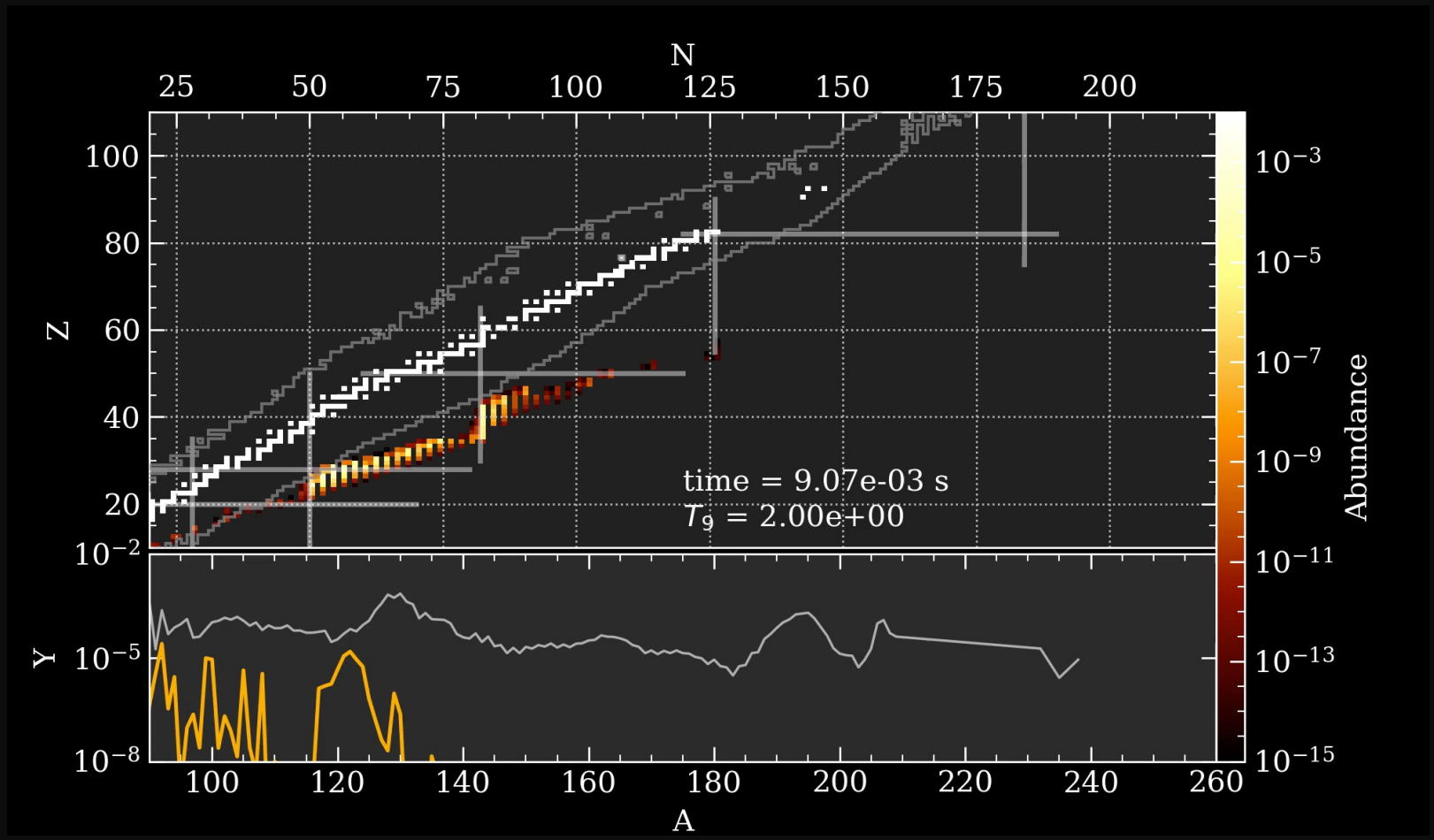
- Wikipedia

by the r-process
(my work)

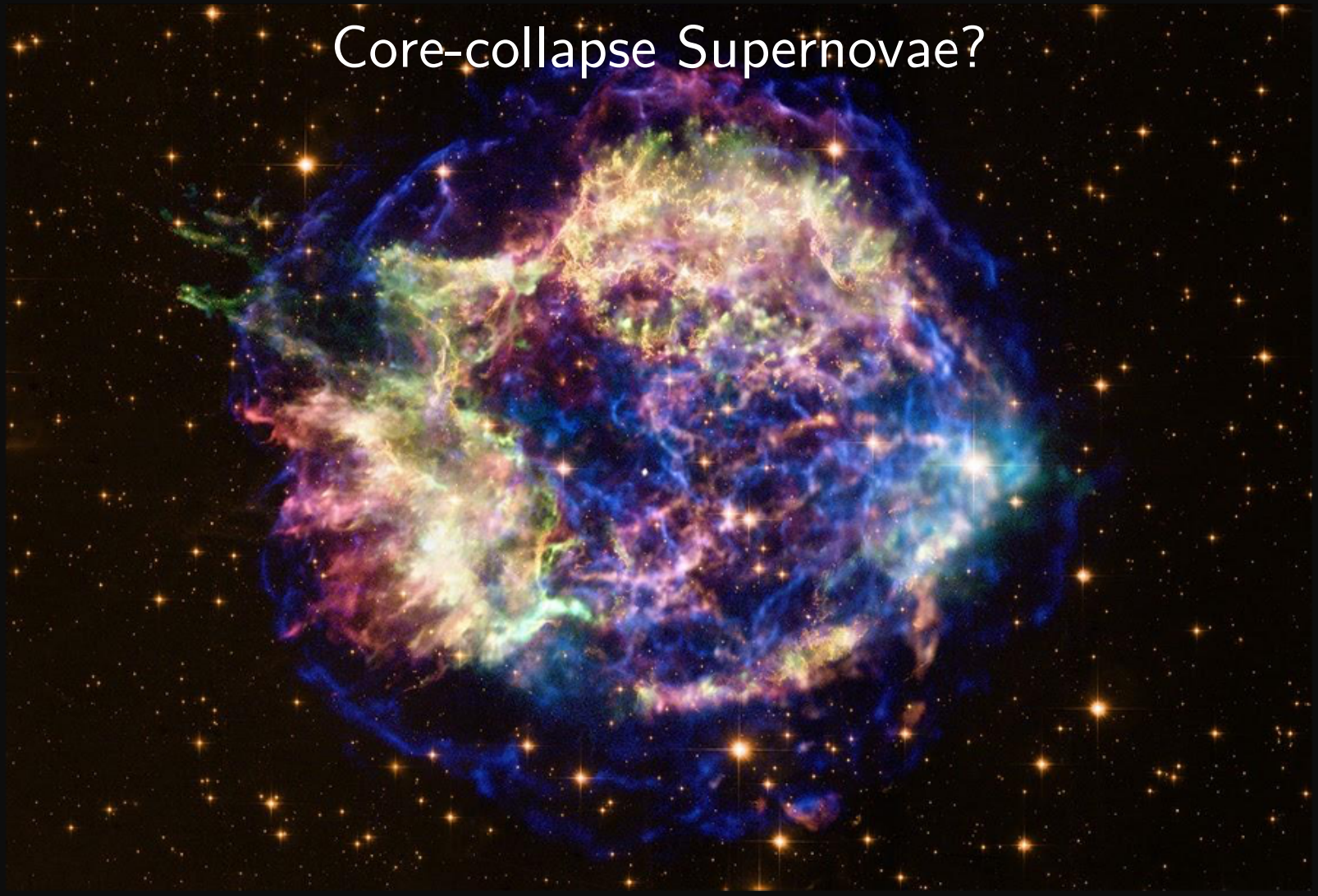
Rapid neutron-capture nucleosynthesis is a major producer of trans-iron elements



PRISM (Sprouse & Mumpower)

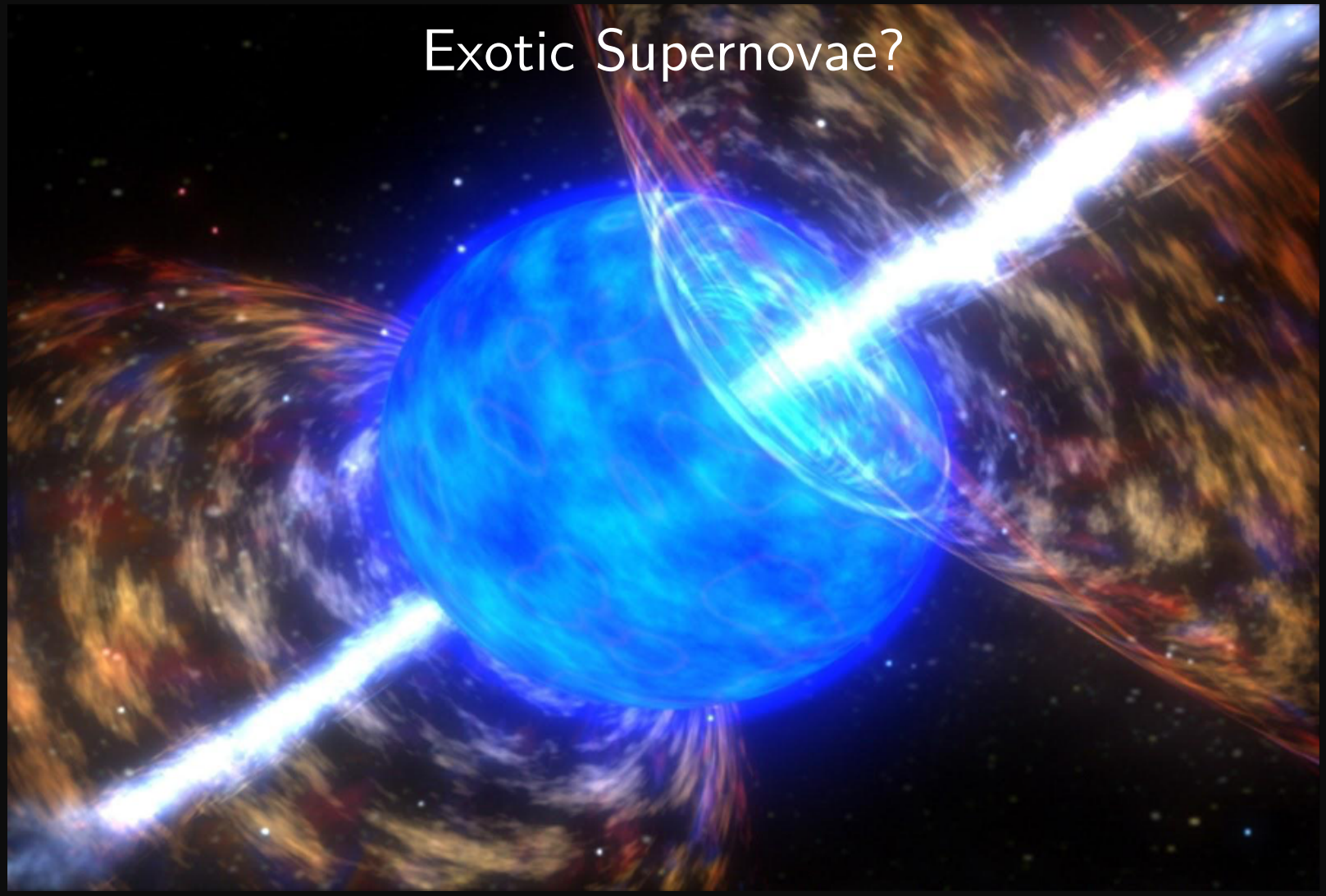
Come to the *r*-process unconference (N. Nishimura)

Core-collapse Supernovae?



NASA / JPL-Caltech

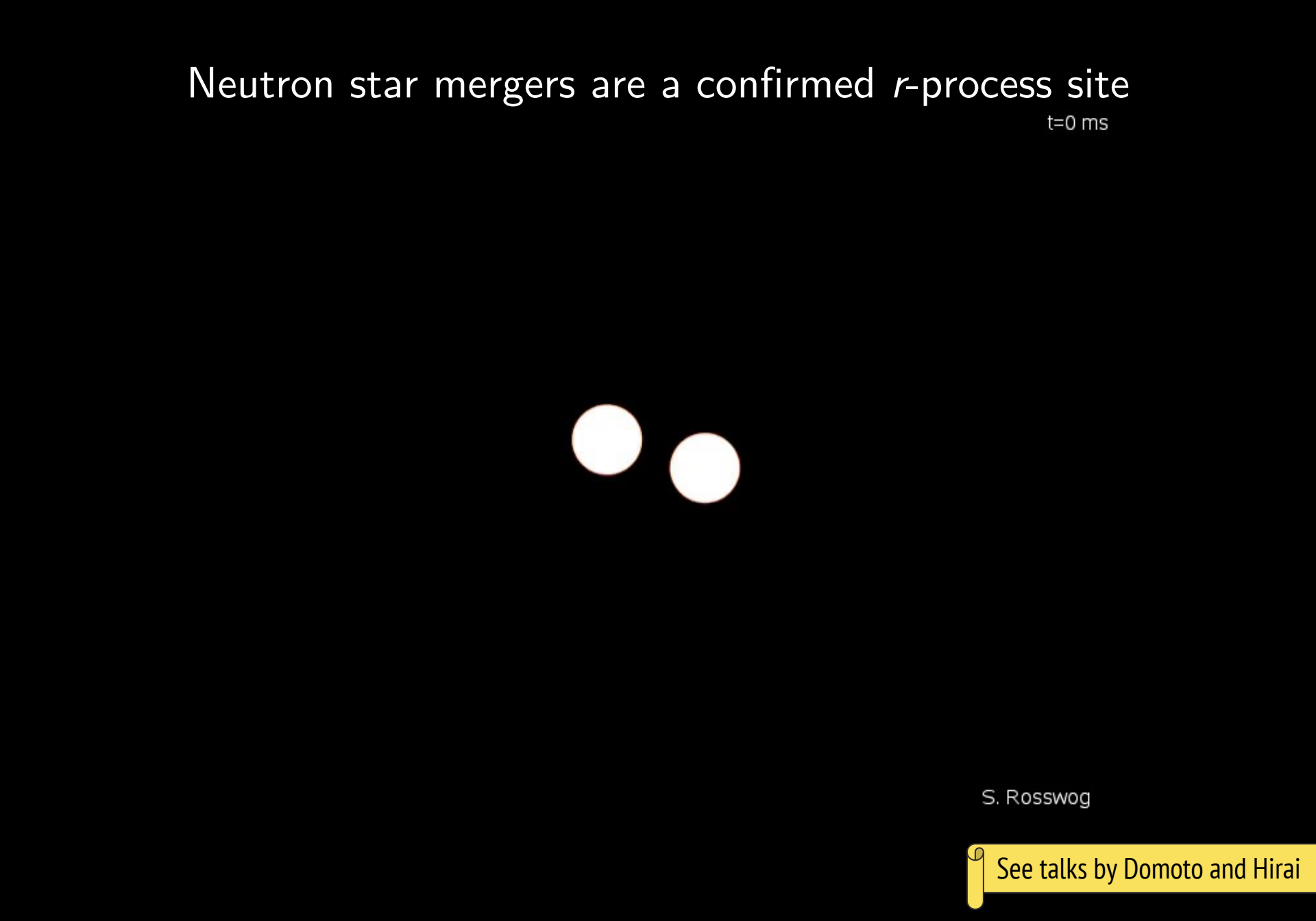
See talk by Hirai



NASA / SkyWork Digital

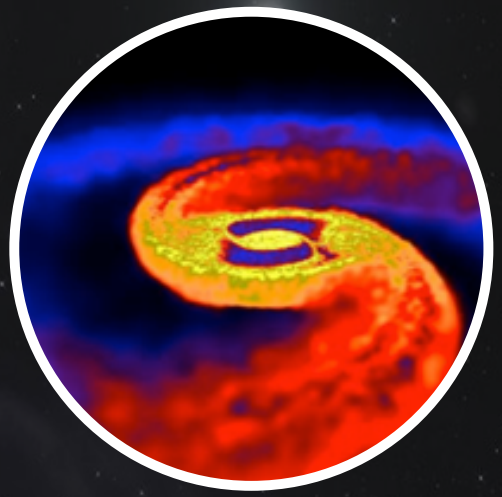
See talk by Hirai

Neutron star mergers are a confirmed *r*-process site



See talks by Domoto and Hirai

r-process nucleosynthesis
(NSMs?)



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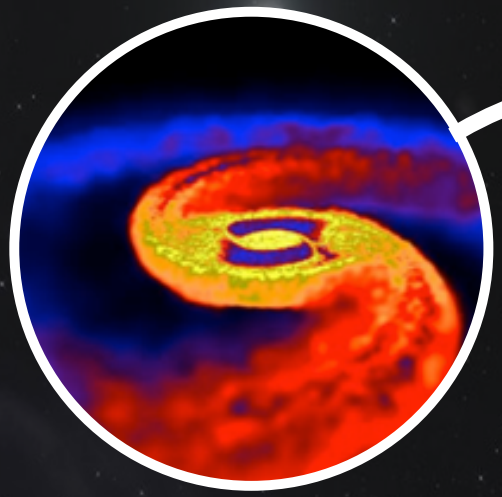
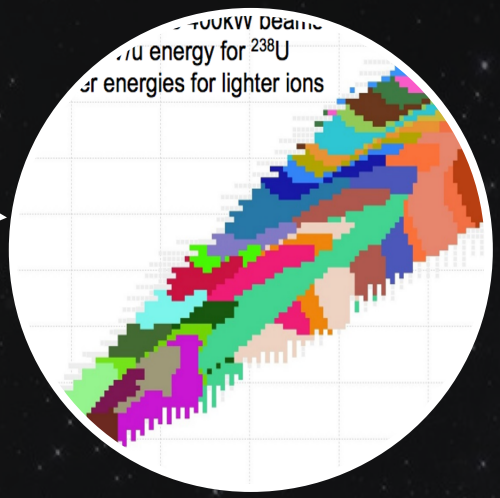
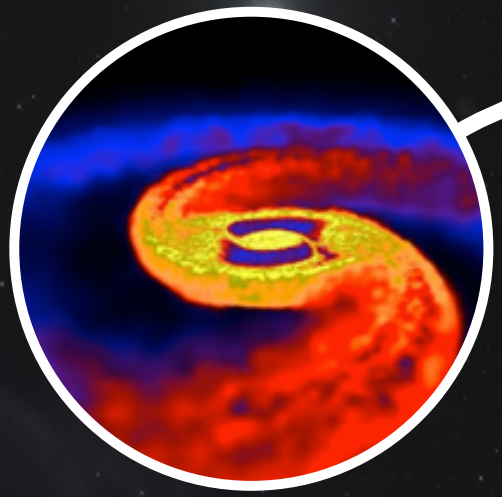
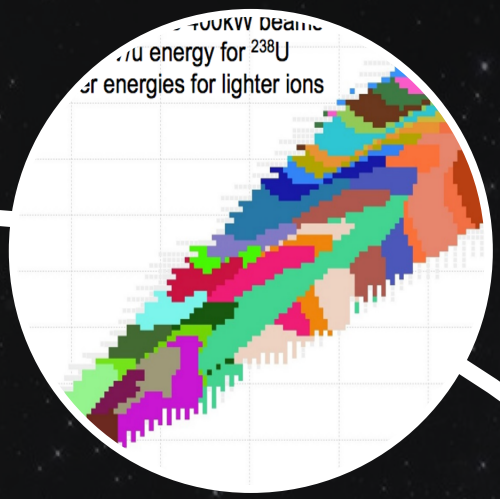




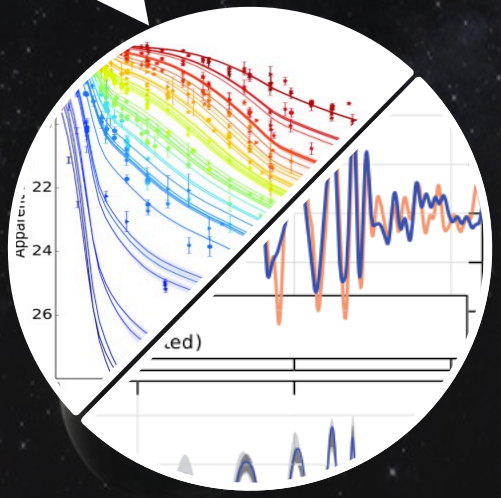
Nuclear Physics

r-process nucleosynthesis (NSMs?)



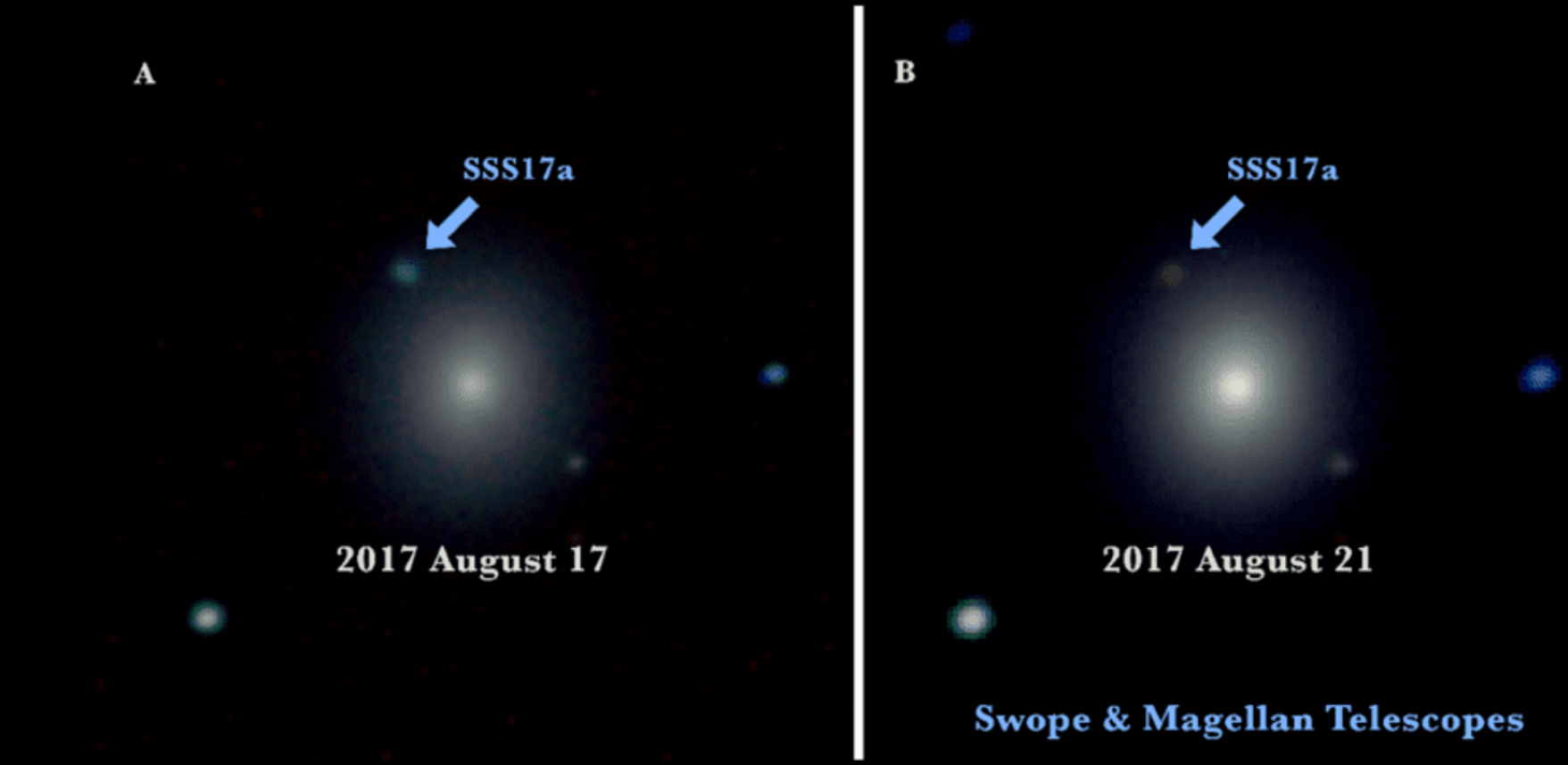


Nuclear Physics



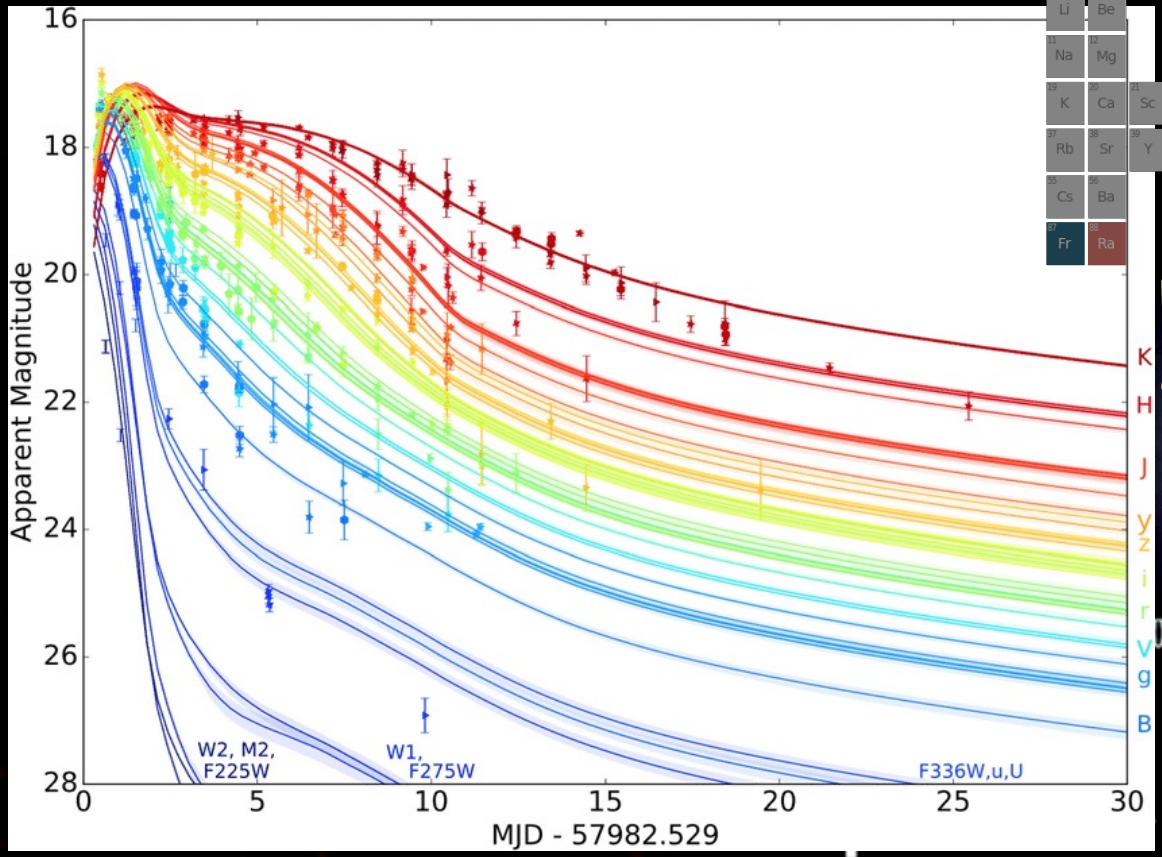
Prompt *r*-process Observables

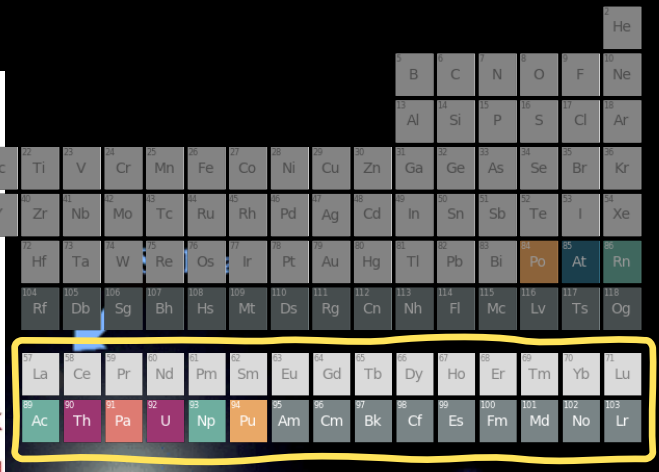
A multi-messenger detection of gravitational waves (GW170817) and an electromagnetic "**kilonova**" (AT2017gfo) from a neutron star merger

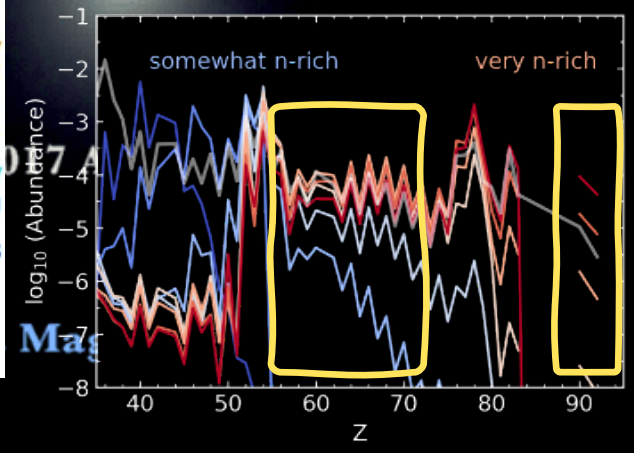


Drout+ (2017)

We saw that at least **lanthanides** were made

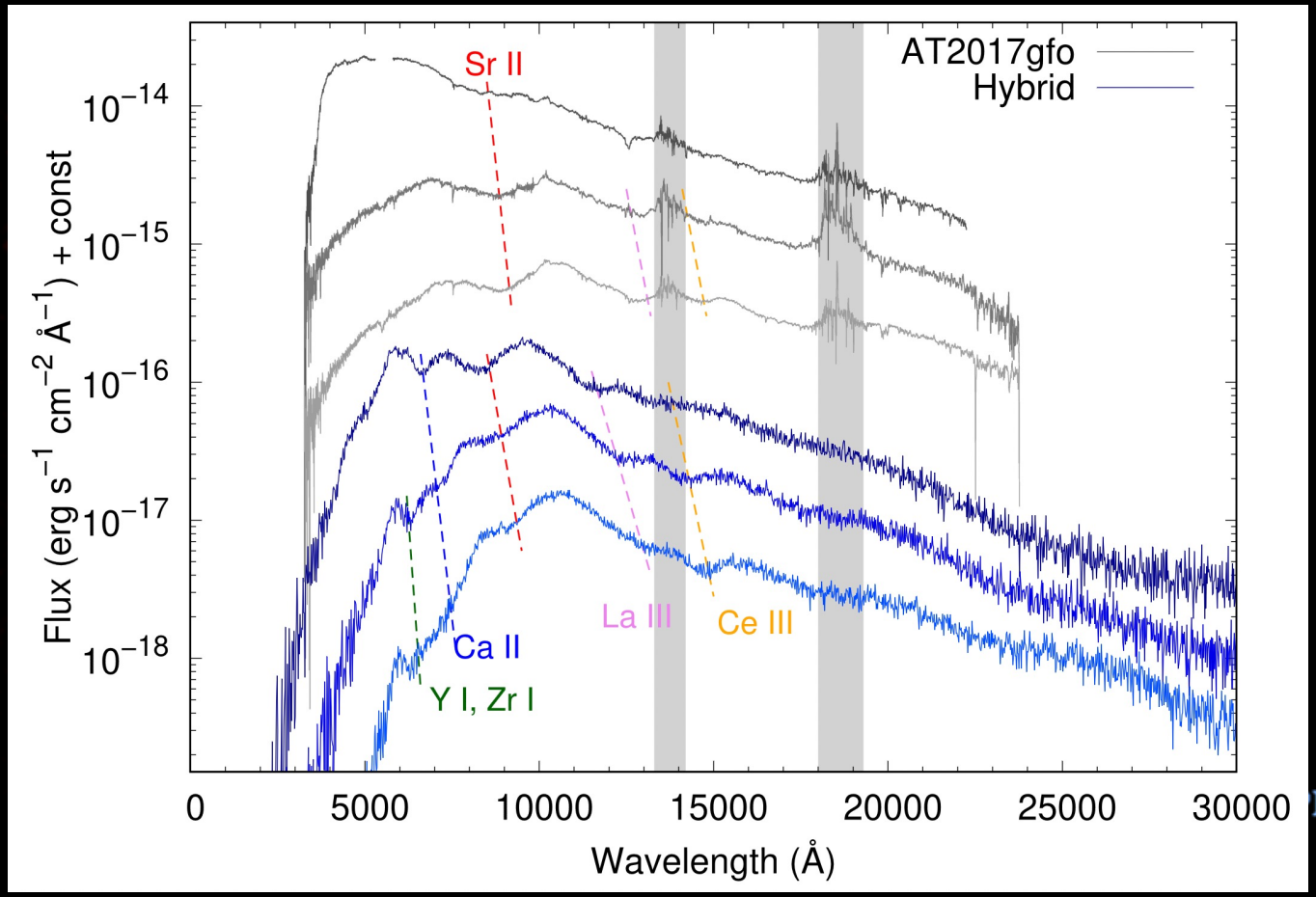






Villar+ (2017)

Elements are exceedingly difficult to measure in kilonova spectra (and we only have data for one event so far)



Domoto+ (2022)

See talk by Domoto

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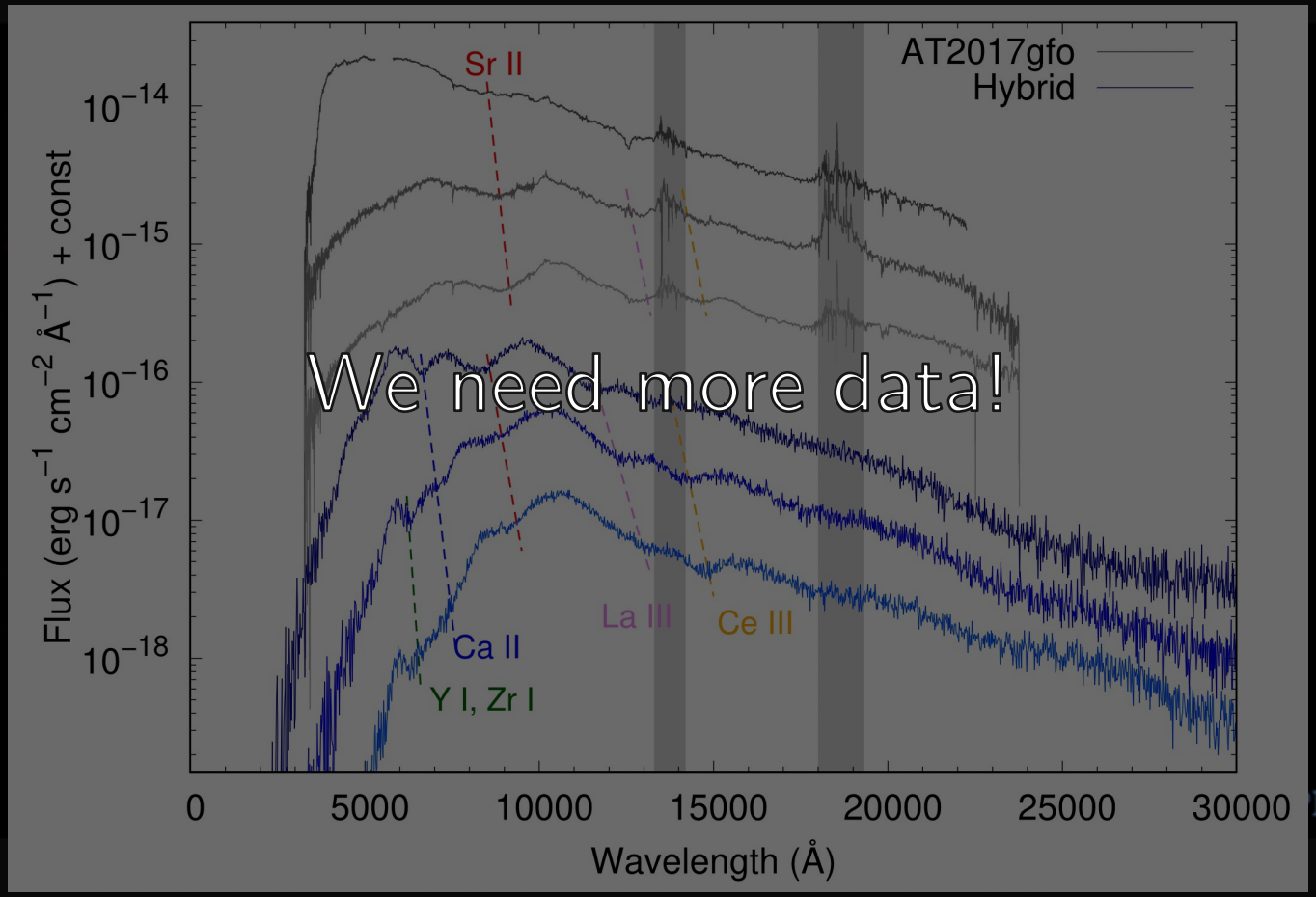

Domoto+ (2022)

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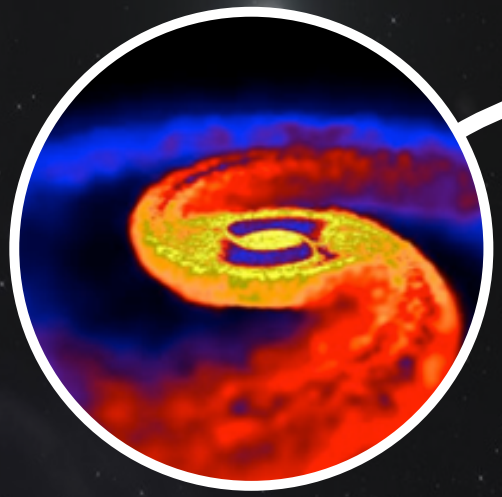
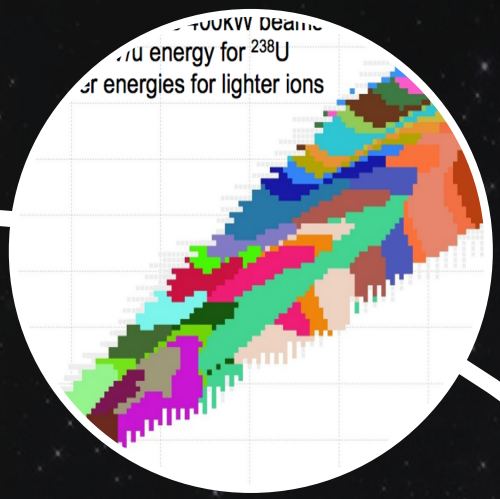
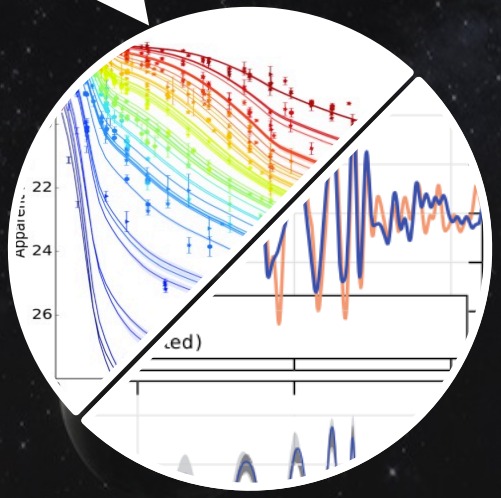
r-process nucleosynthesis (NSMs?)



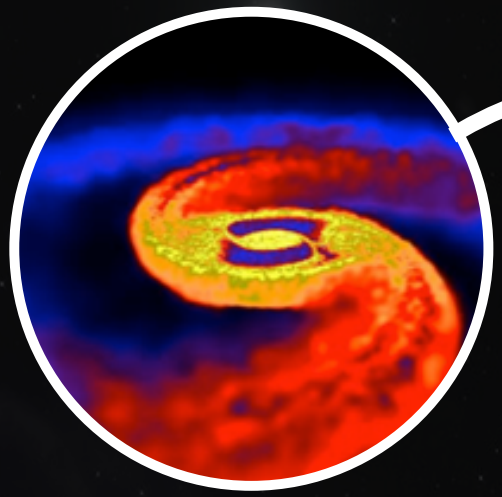


Nuclear Physics

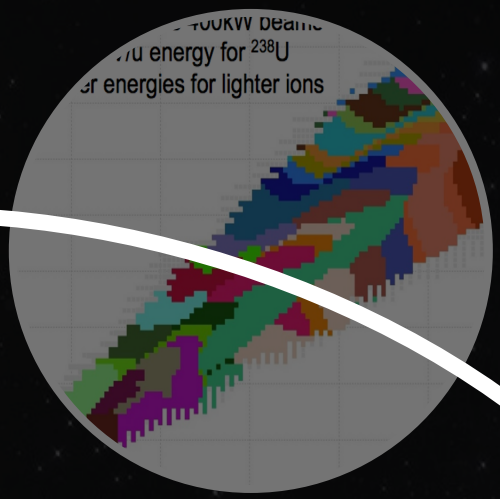


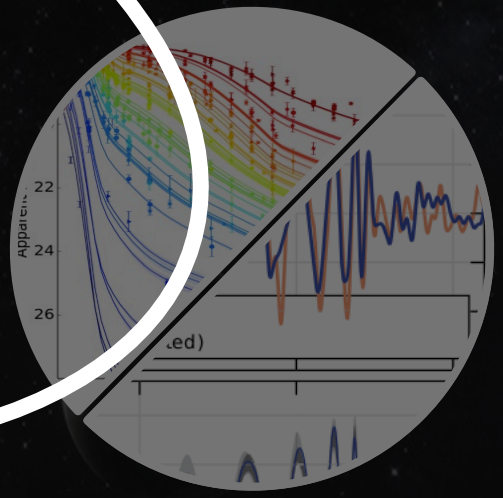
Prompt *r*-process Observables

r-process nucleosynthesis (NSMs?)



Nuclear Physics





Prompt *r*-process Observables

Delayed Observables: Stars enhanced in *r*-process elements

R-Process Alliance


Timothy C. Beers


Rana Ezzeddine


Anna Frebel


Terese T. Hansen


Erika M. Holmbeck


Vinicius M. Placco

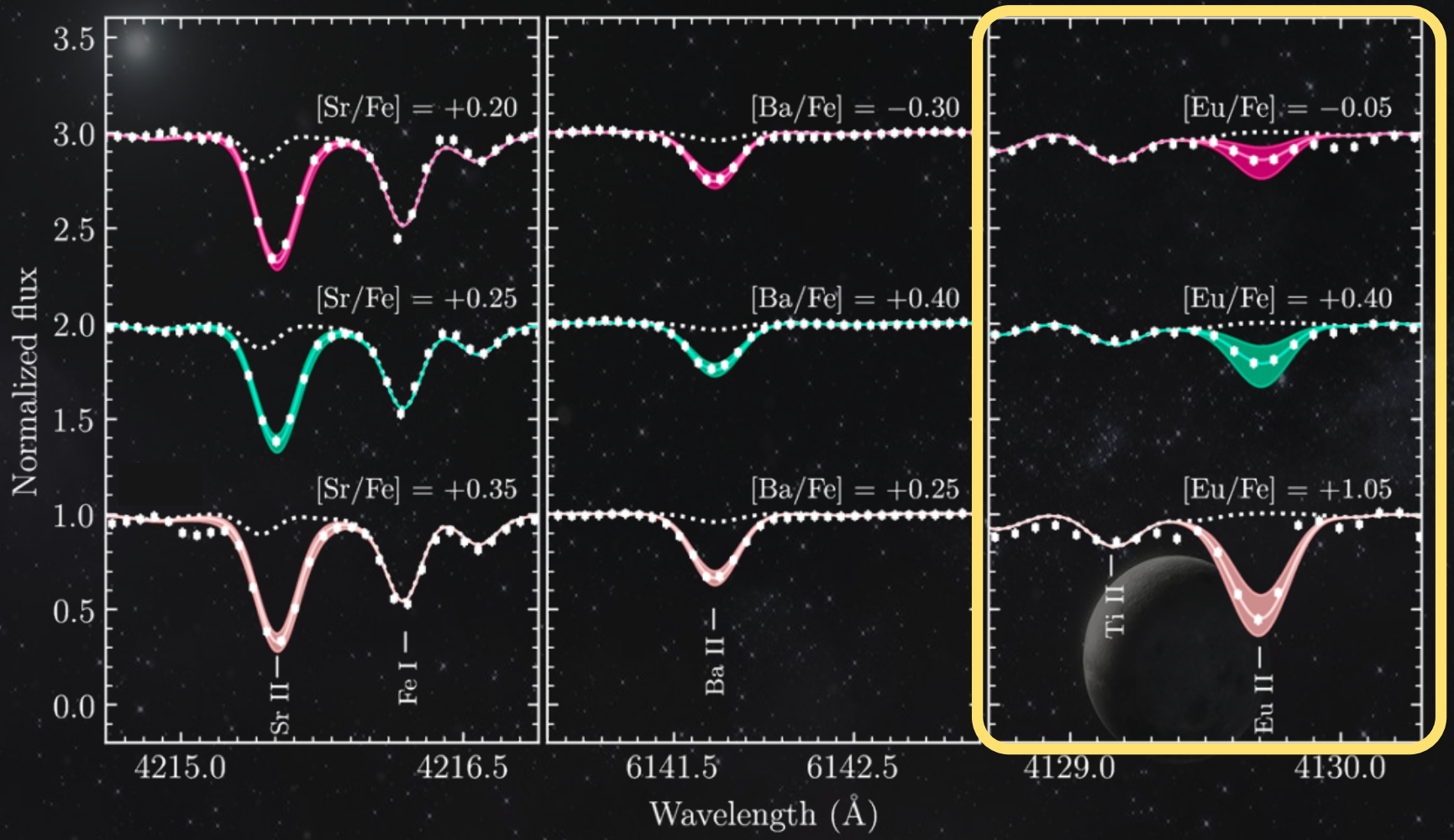

Ian U. Roederer


Charli M. Sakari

+ undergrads, graduate students, postdocs, collaborators...

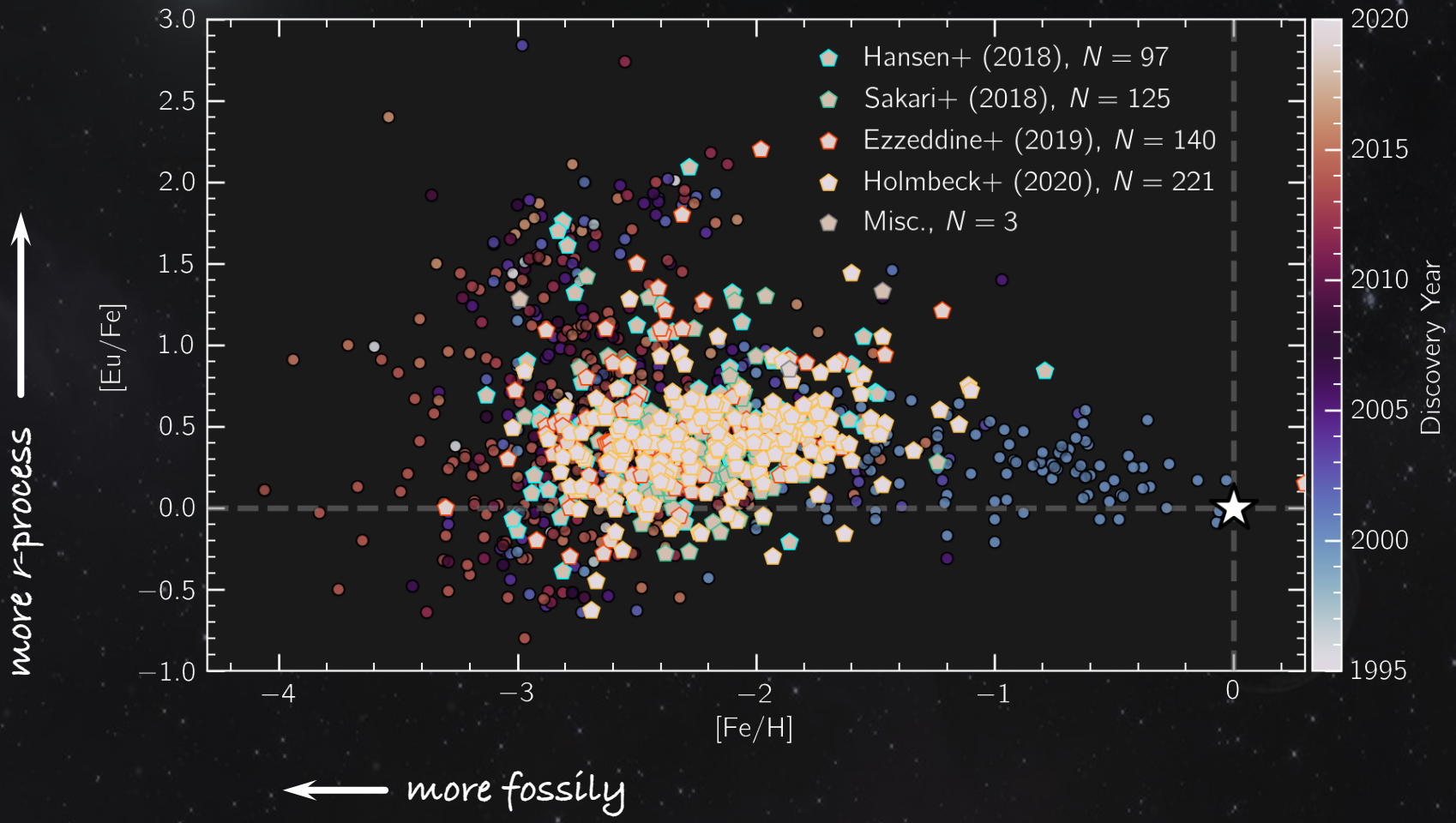
sites.google.com/view/rprocessalliance

Eu (lanthanide):
r-process element

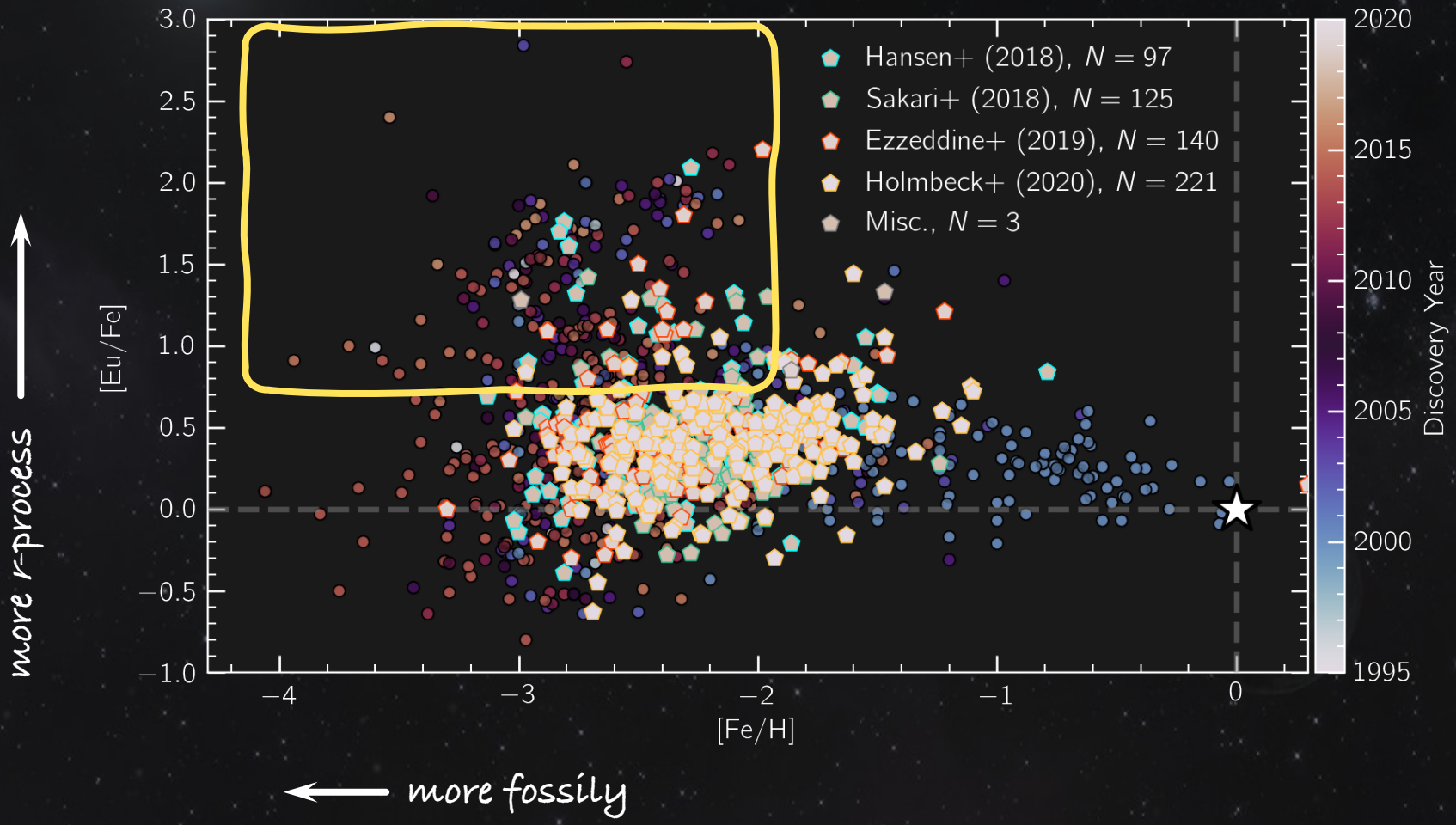


Hansen+ (2017); **Holmbeck**+ (2020a)

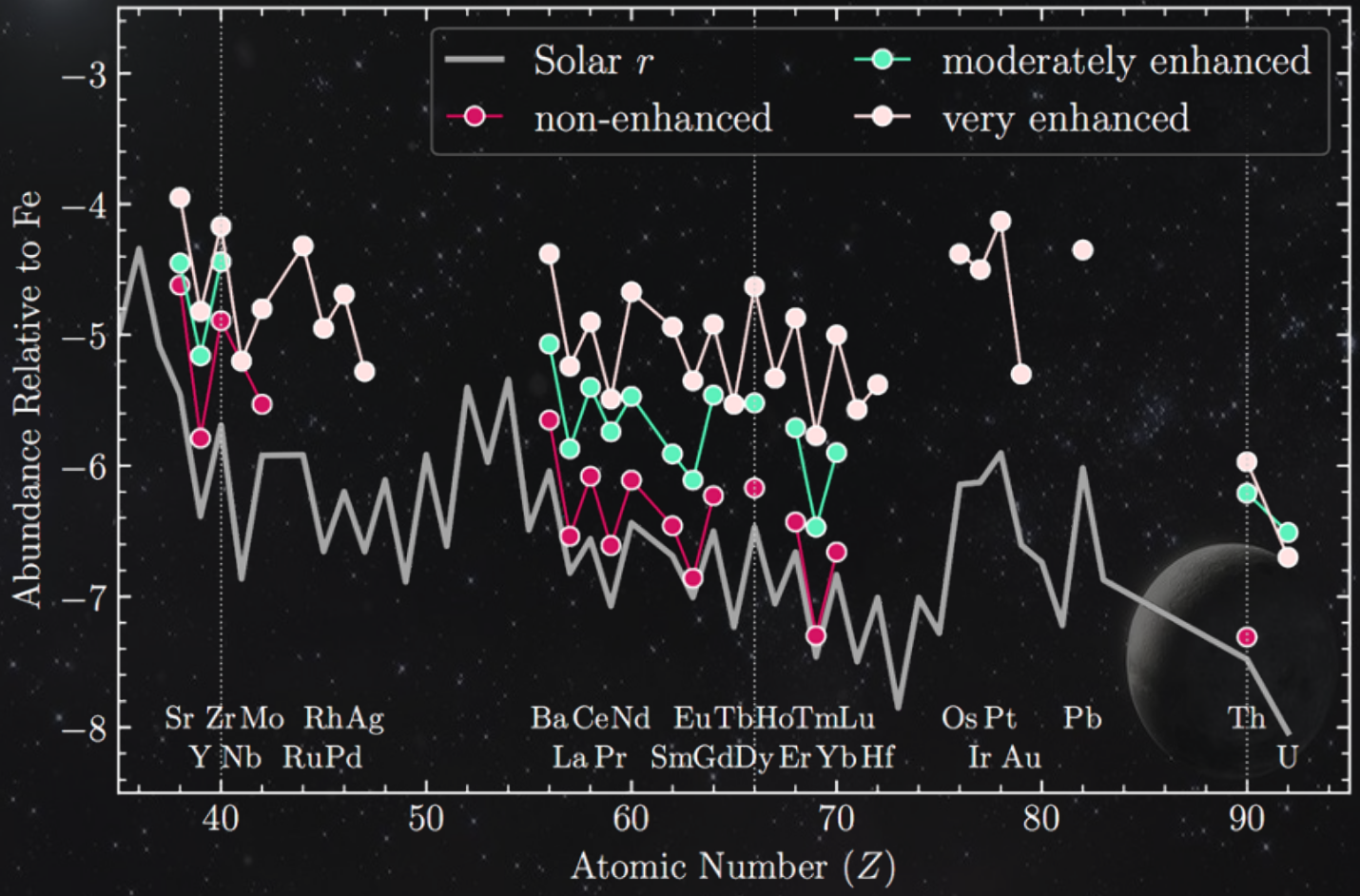
The RPA has *r*-process measurements for 586 new stars



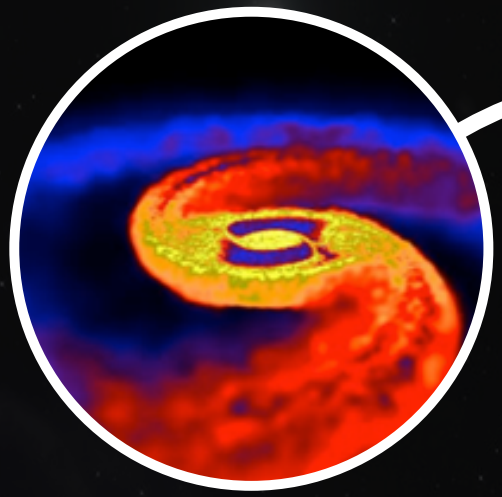
The oldest (most metal-poor) and most *r*-process enhanced are great tracers of past events

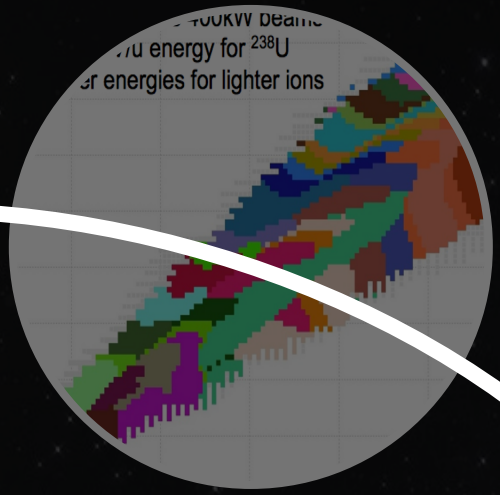


Metal-poor ([Fe/H]< -2) stars with *r*-process elements are considered some of the first descendents of ancient events

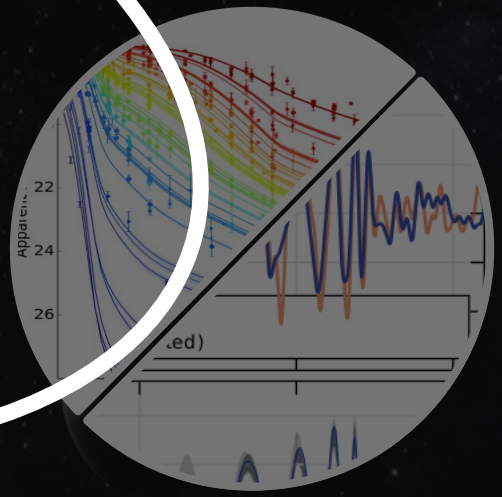


r-process nucleosynthesis (NSMs?)

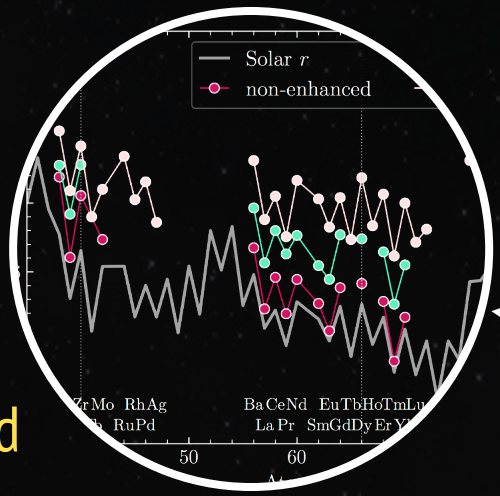




Nuclear Physics

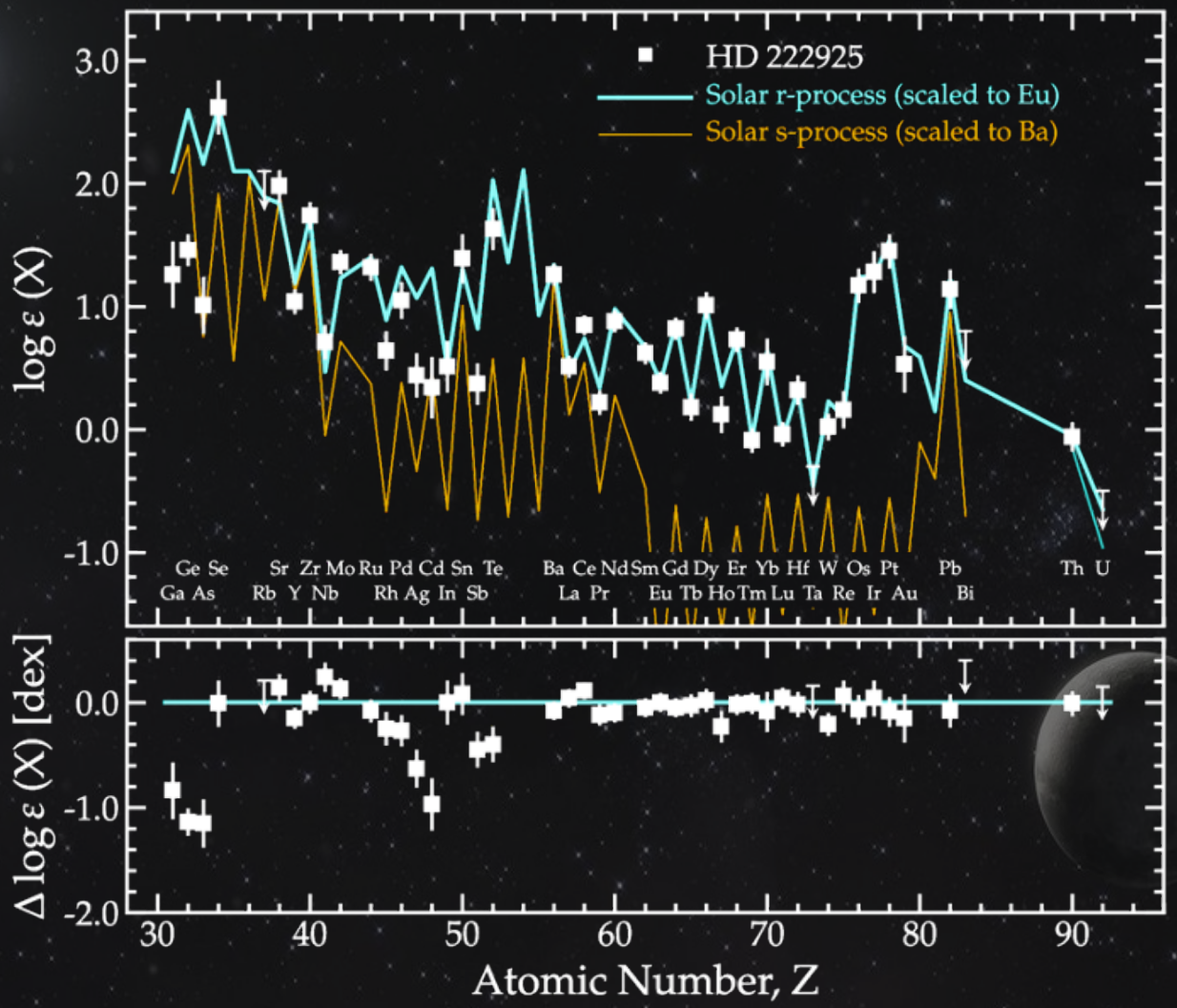


Prompt *r*-process Observables



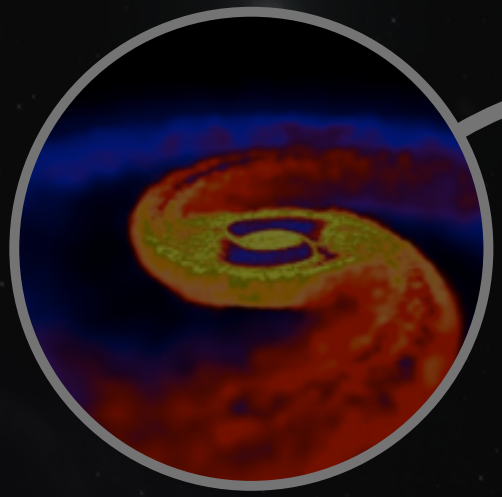
The RPA is finding many of these “delayed observables”

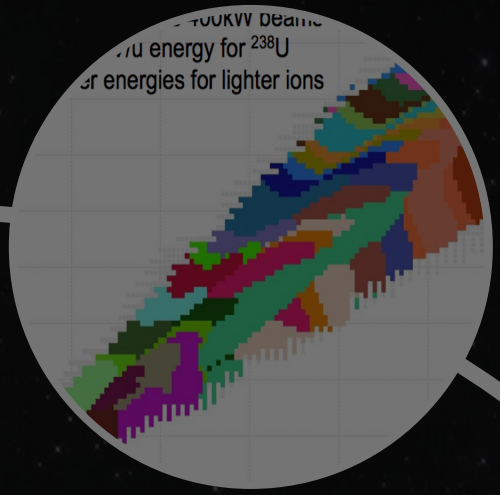
One of these stars has 42 *r*-process elements measured!



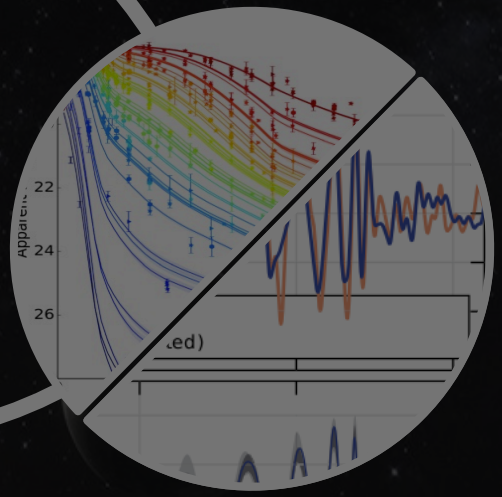
Roederer+ (2022)

r-process nucleosynthesis (NSMs?)





Nuclear Physics



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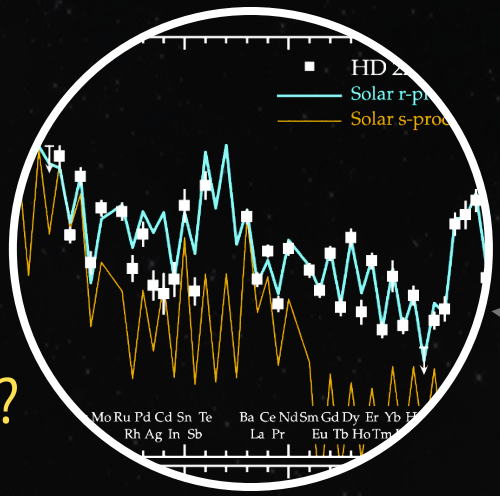
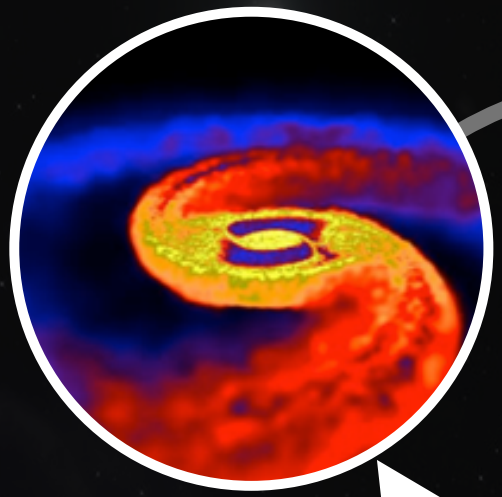
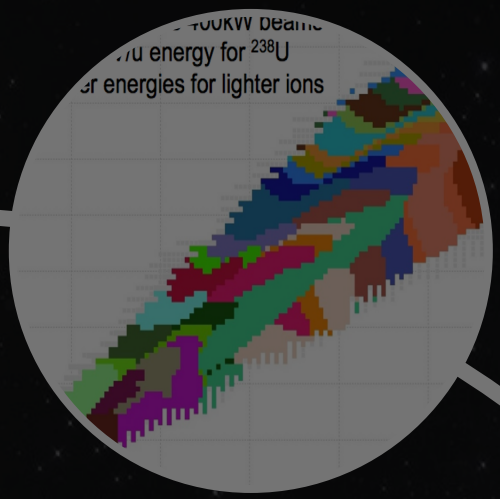


HD 222925: Product of an NSM?

r-process nucleosynthesis (NSMs?)



Nuclear Physics



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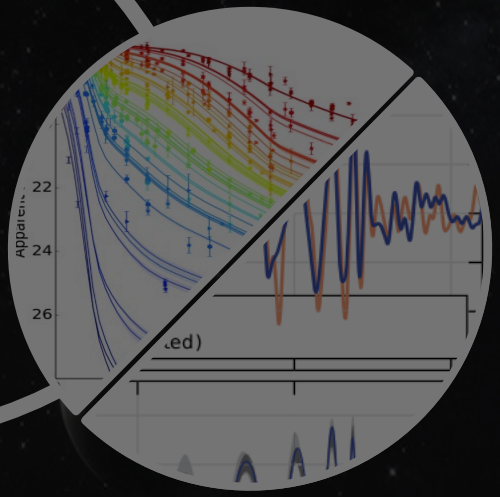

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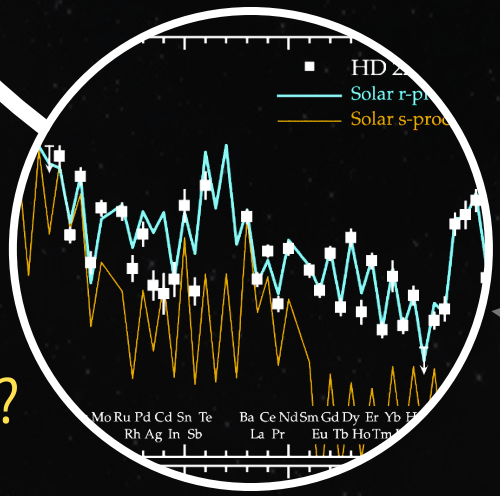
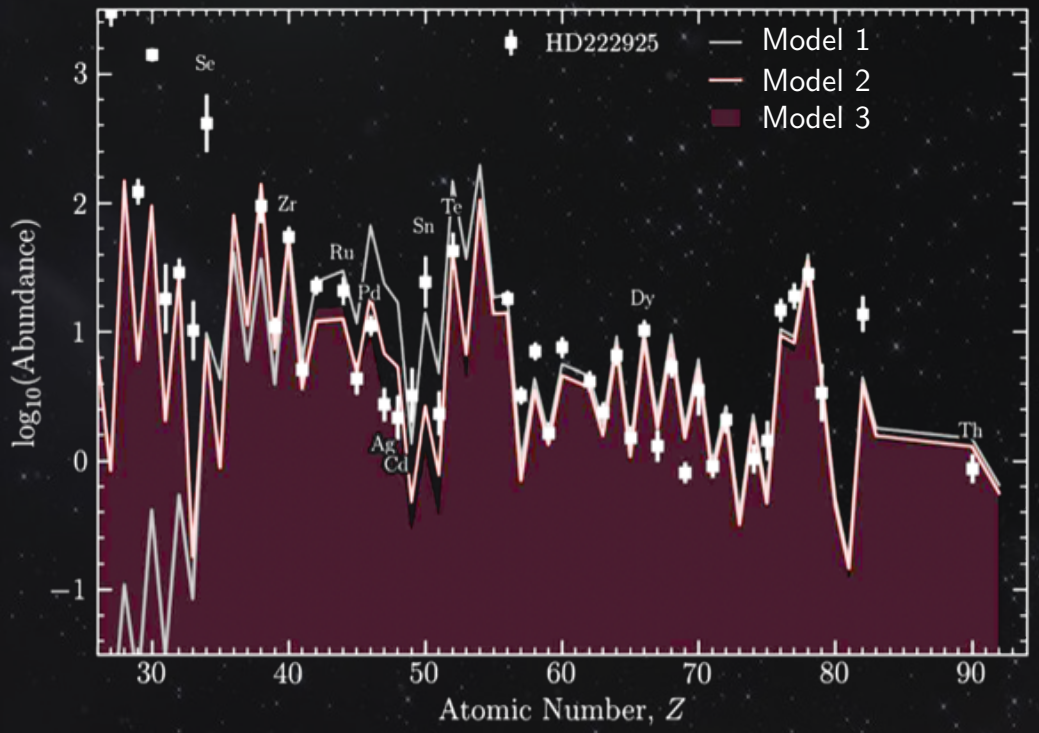
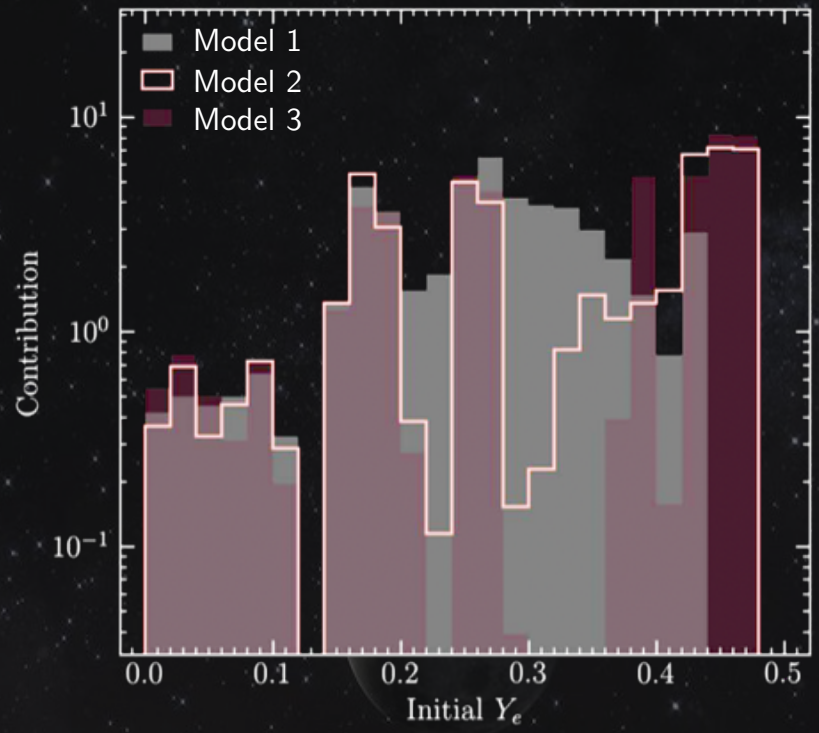


Several ejecta distributions all reproduce the abundances we see in HD 222925



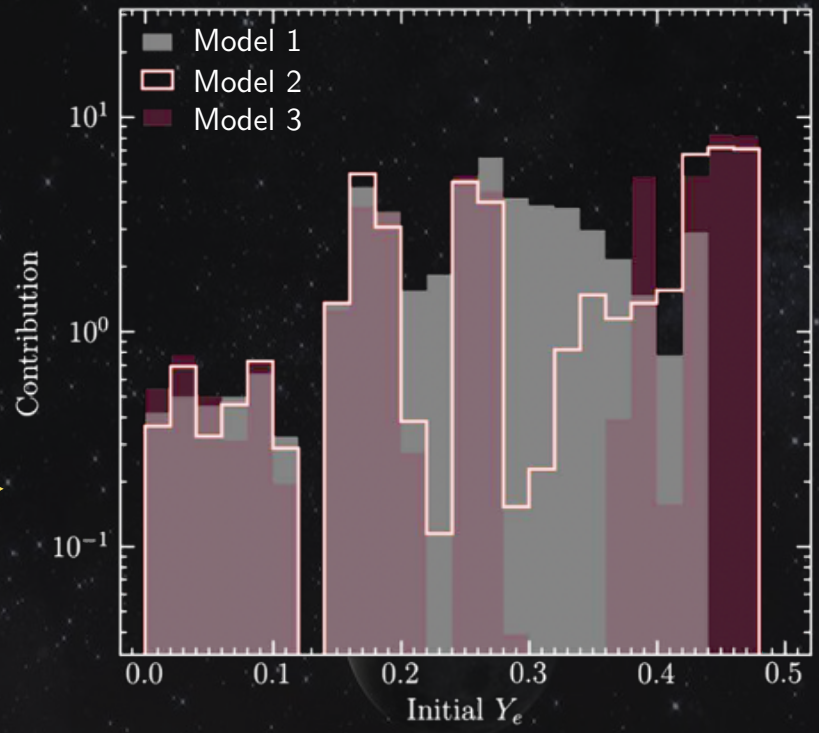


$$Y_e = \frac{n_p}{n_p + n_n}$$

Holmbeck+ (2023)

Several ejecta distributions all reproduce the abundances we see in HD 222925

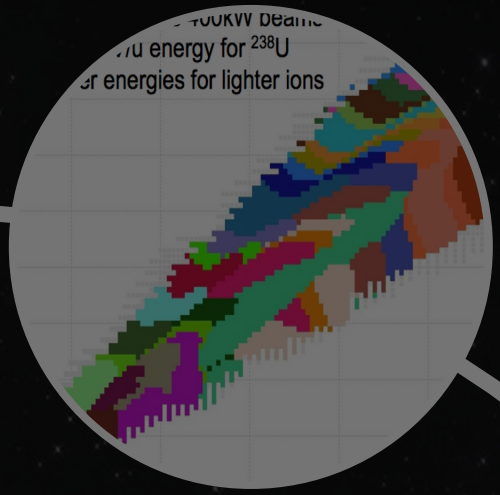
These are very different distributions!

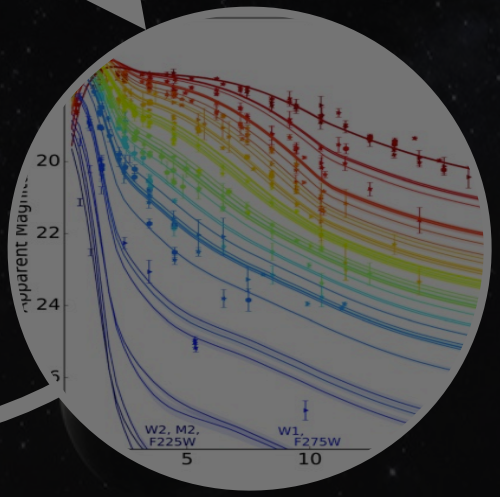


Holmbeck+ (2023)

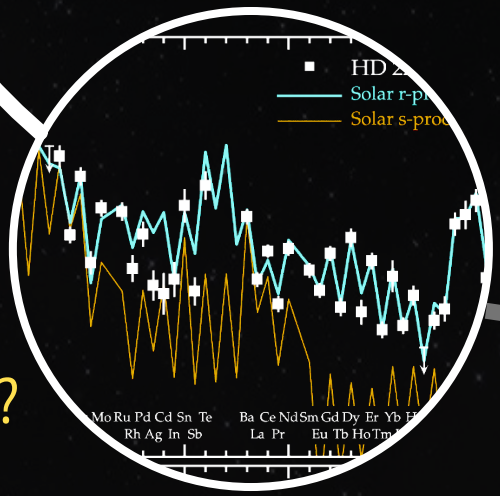
NSM ejecta distribution

Nuclear Physics





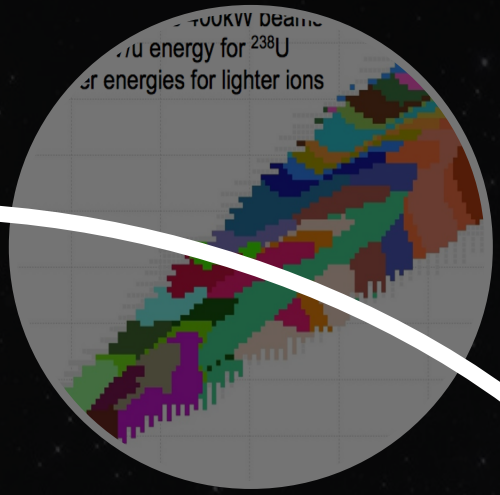
Prompt *r*-process Observables

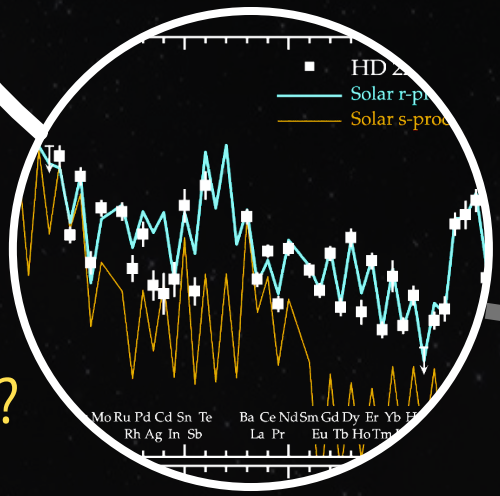


HD 222925:
Product of an NSM?

NSM ejecta distribution

Nuclear Physics





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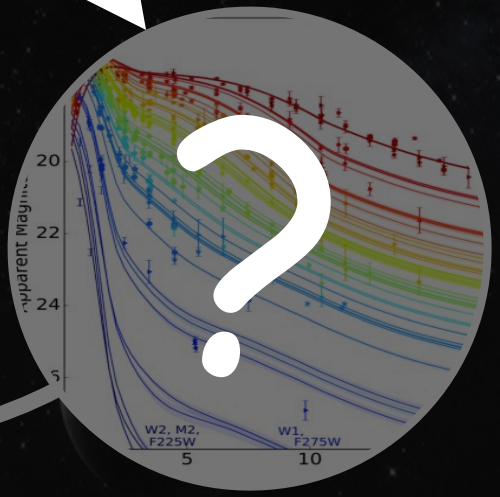
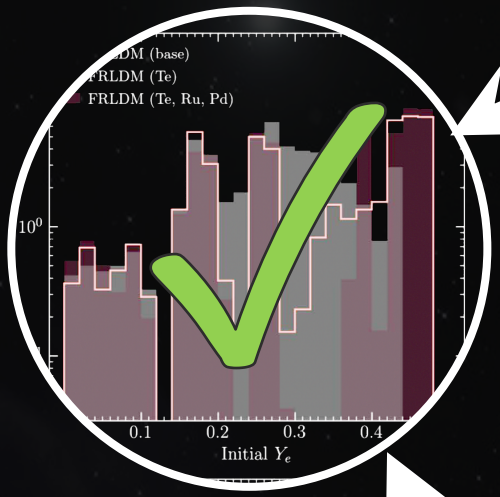
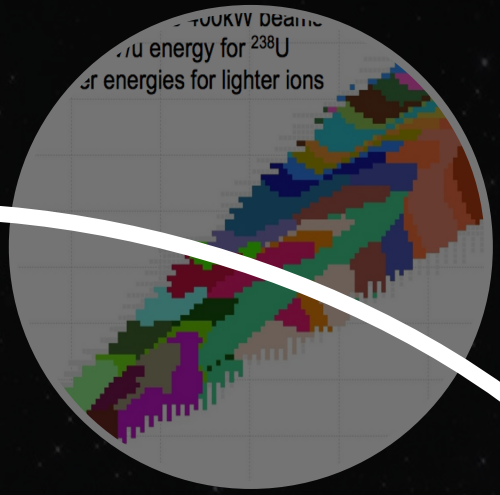


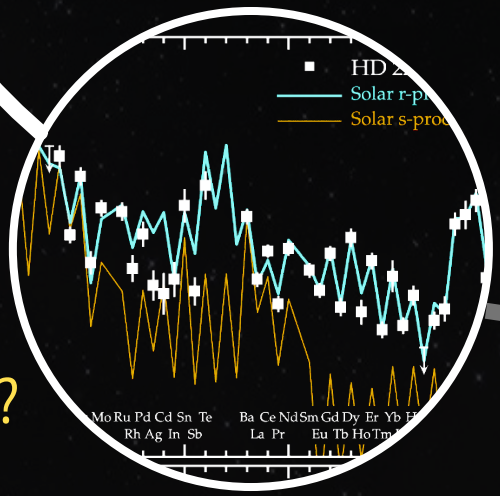
What did HD 222925's kilonova look like?

NSM ejecta distribution



Nuclear Physics





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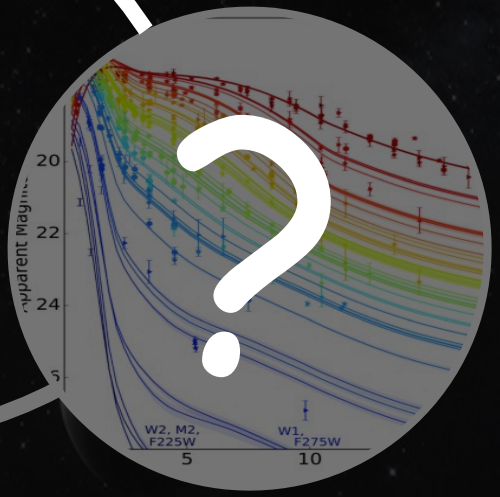

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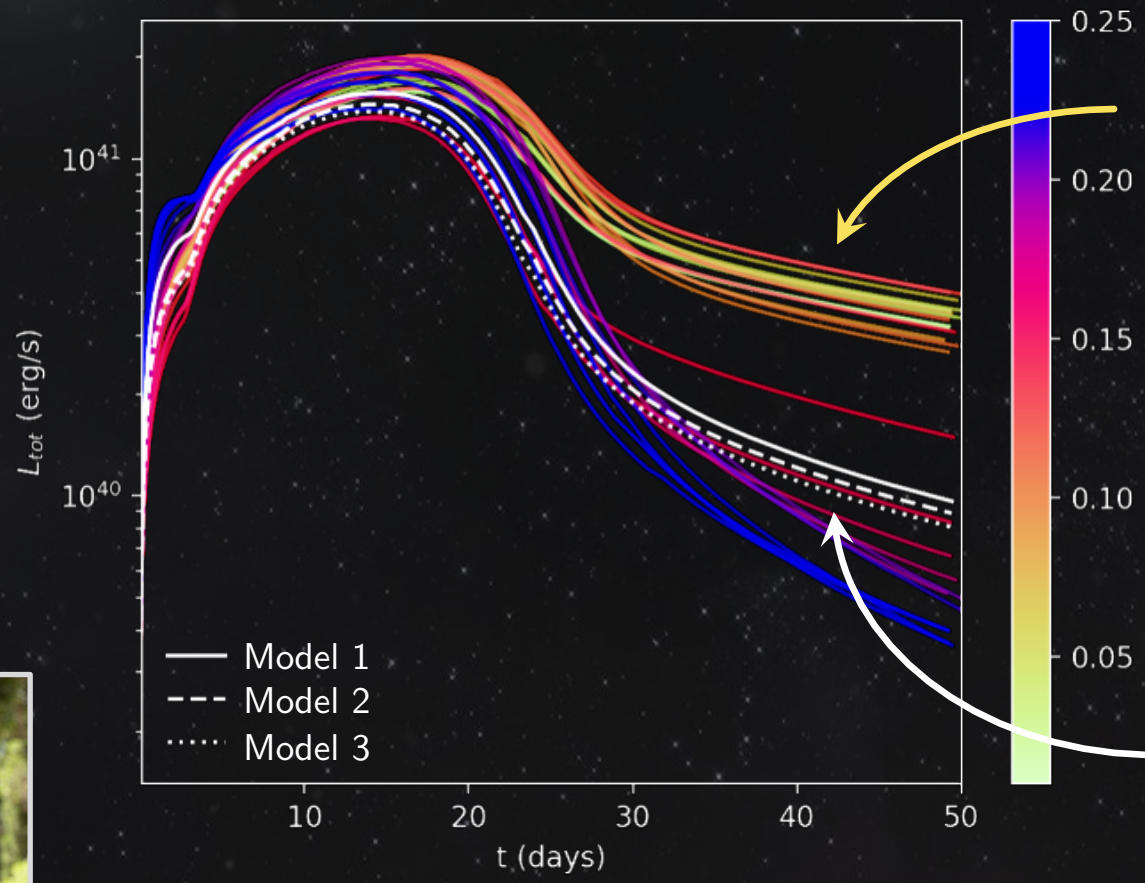
Despite the differences in Y_e distributions, the light curves are observational indistinguishable

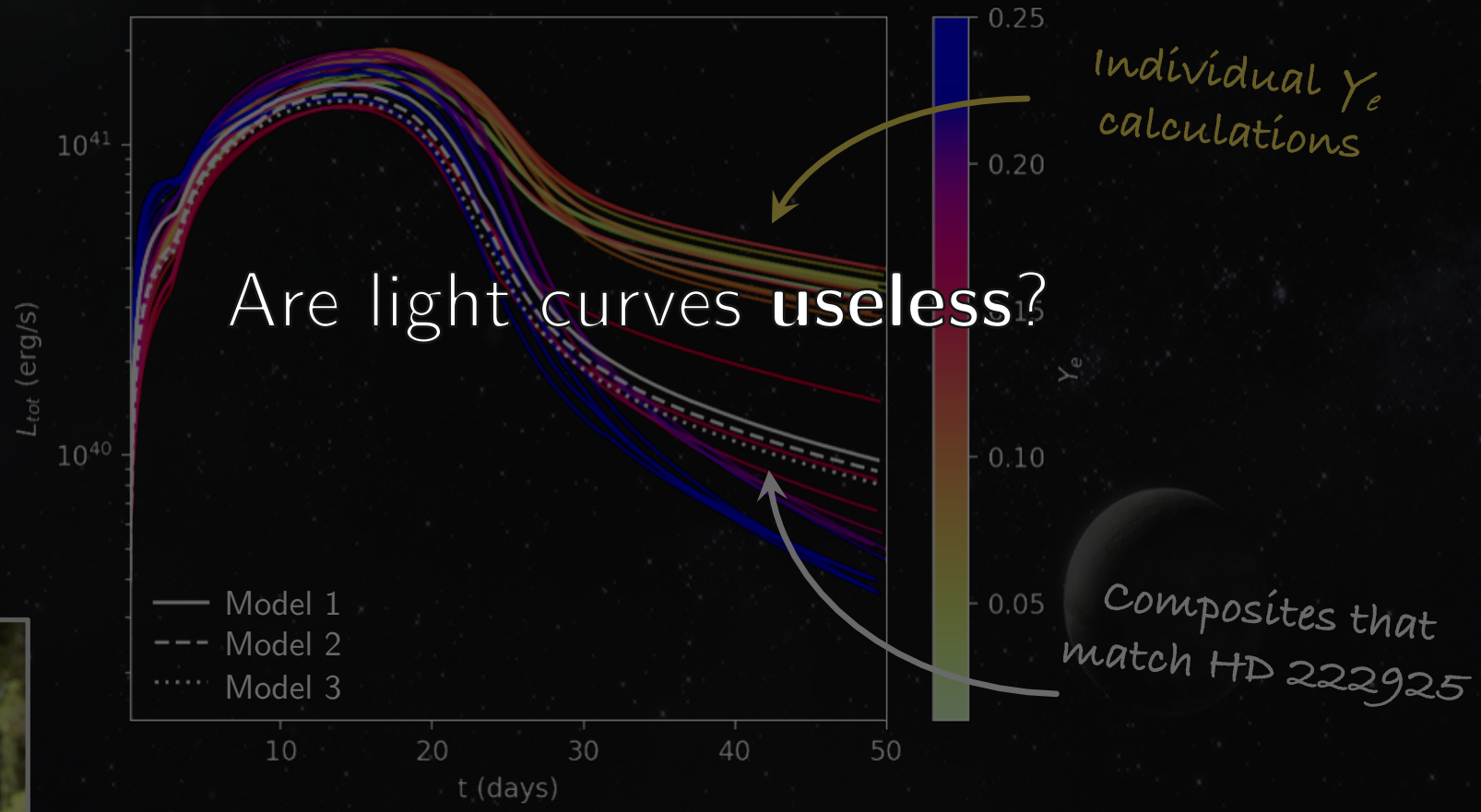


Individual Y_e calculations

Composites that match HD 222925

Ian Johnson (Caltech; 2023 CASSI intern)

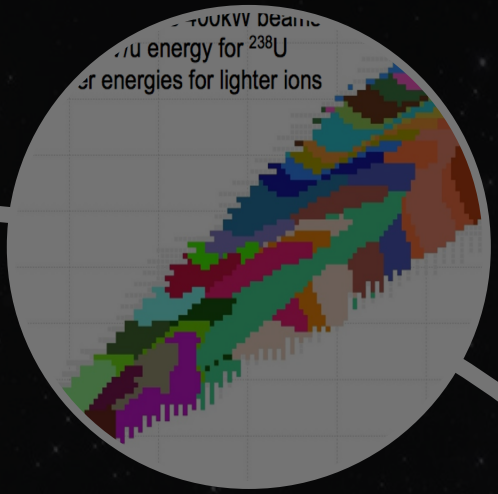
Despite the differences in Y_e distributions, the light curves are observational indistinguishable

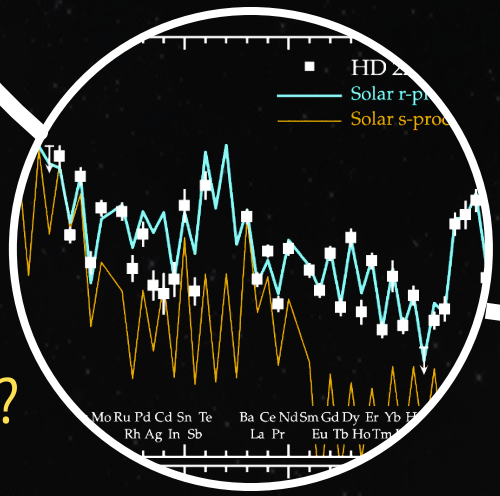


Ian Johnson (Caltech; 2023 CASSI intern)

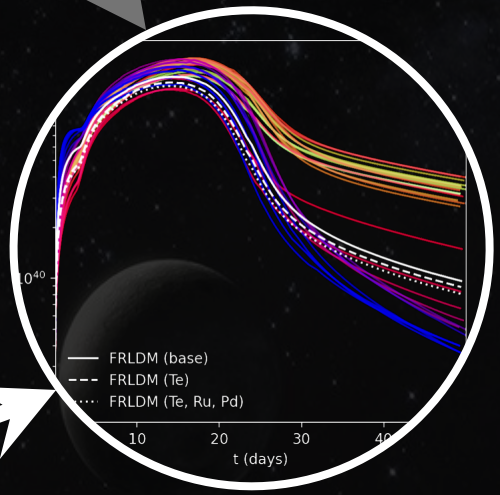
NSM ejecta distribution

Nuclear Physics





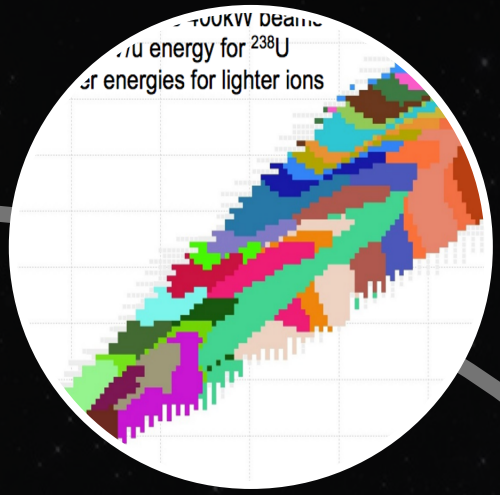
HD 222925:
Product of an NSM?



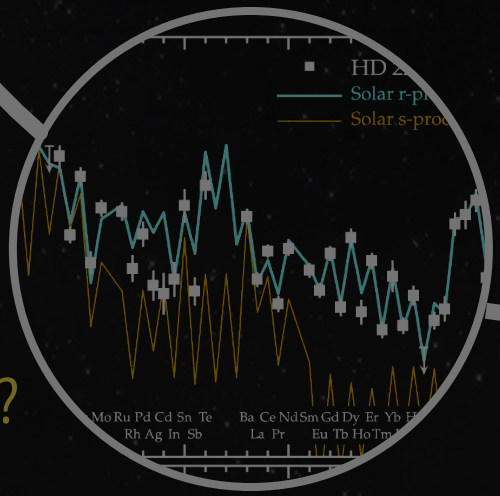
What did HD 222925's kilonova look like?

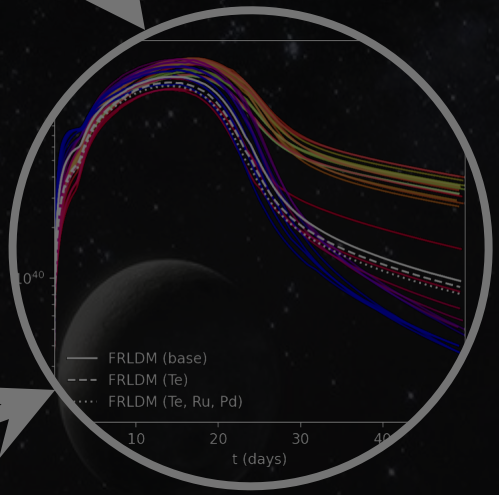
NSM ejecta distribution

Nuclear Physics



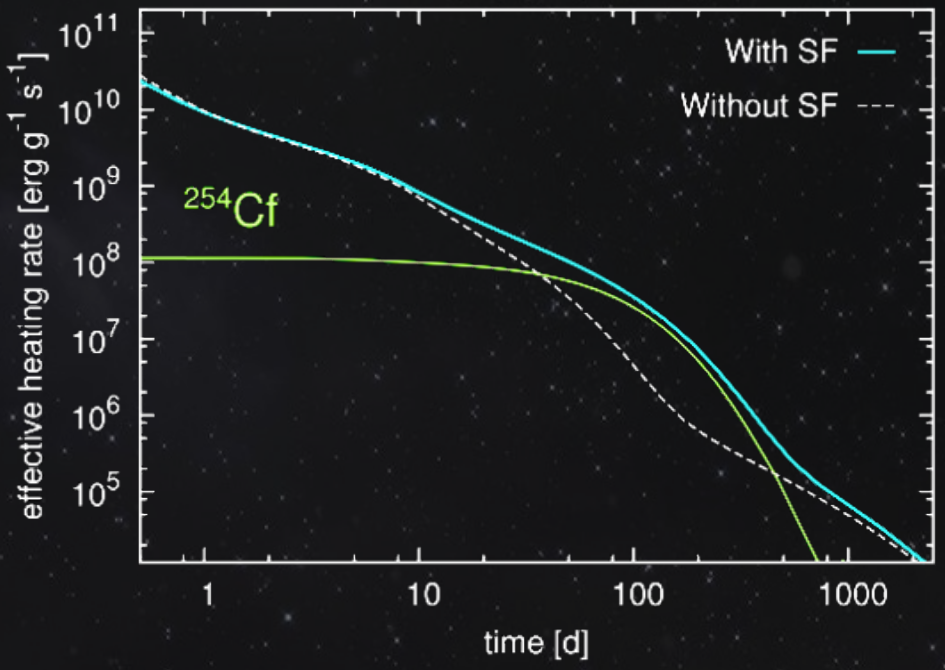
HD 222925:
Product of an NSM?

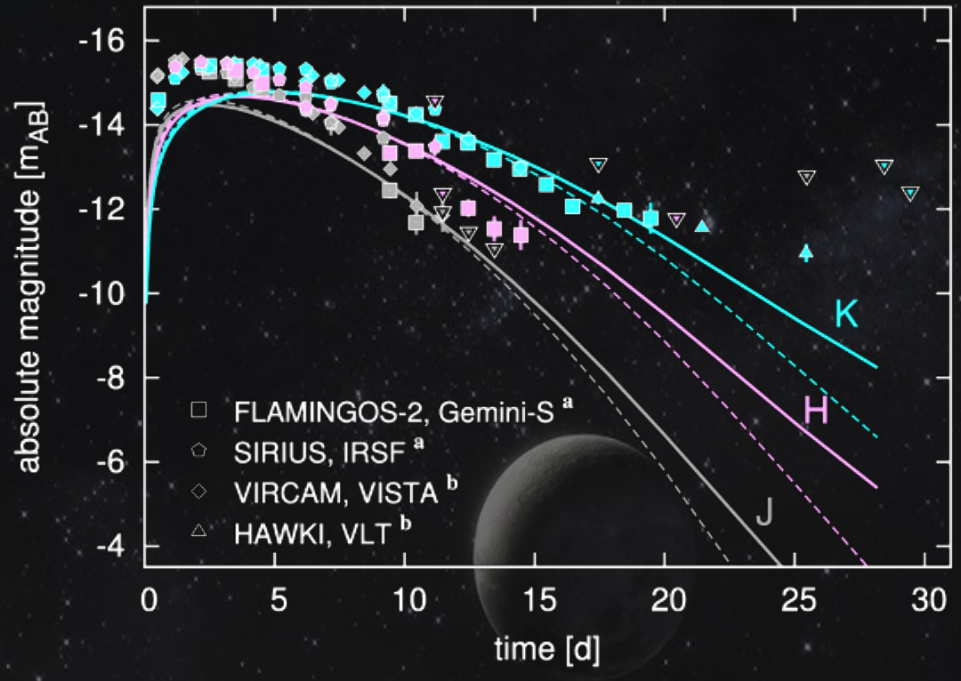




What did HD 222925's
kilonova look like?

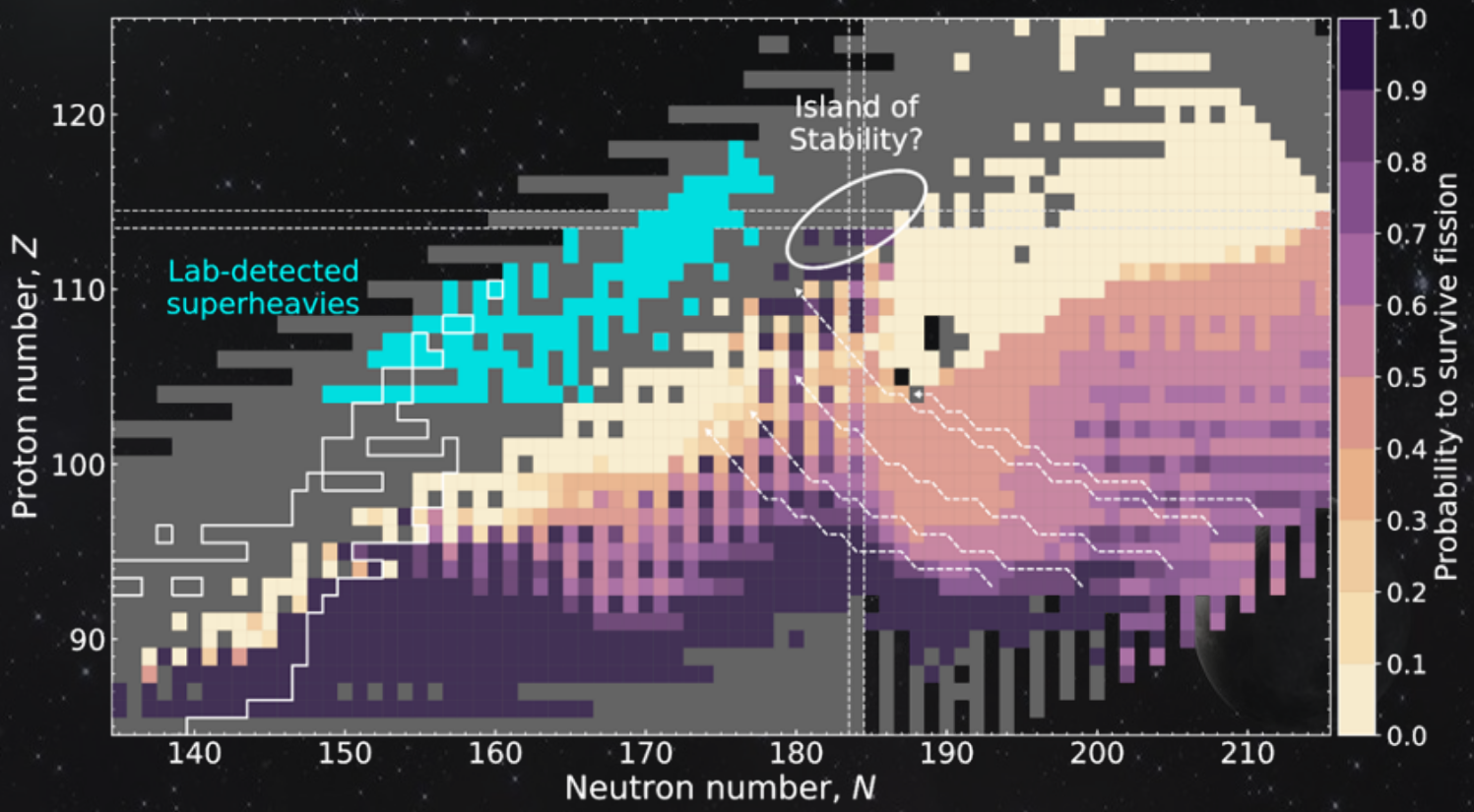
At very late times, **actinide** production can possibly be seen in merger kilonovae (e.g., with JWST)





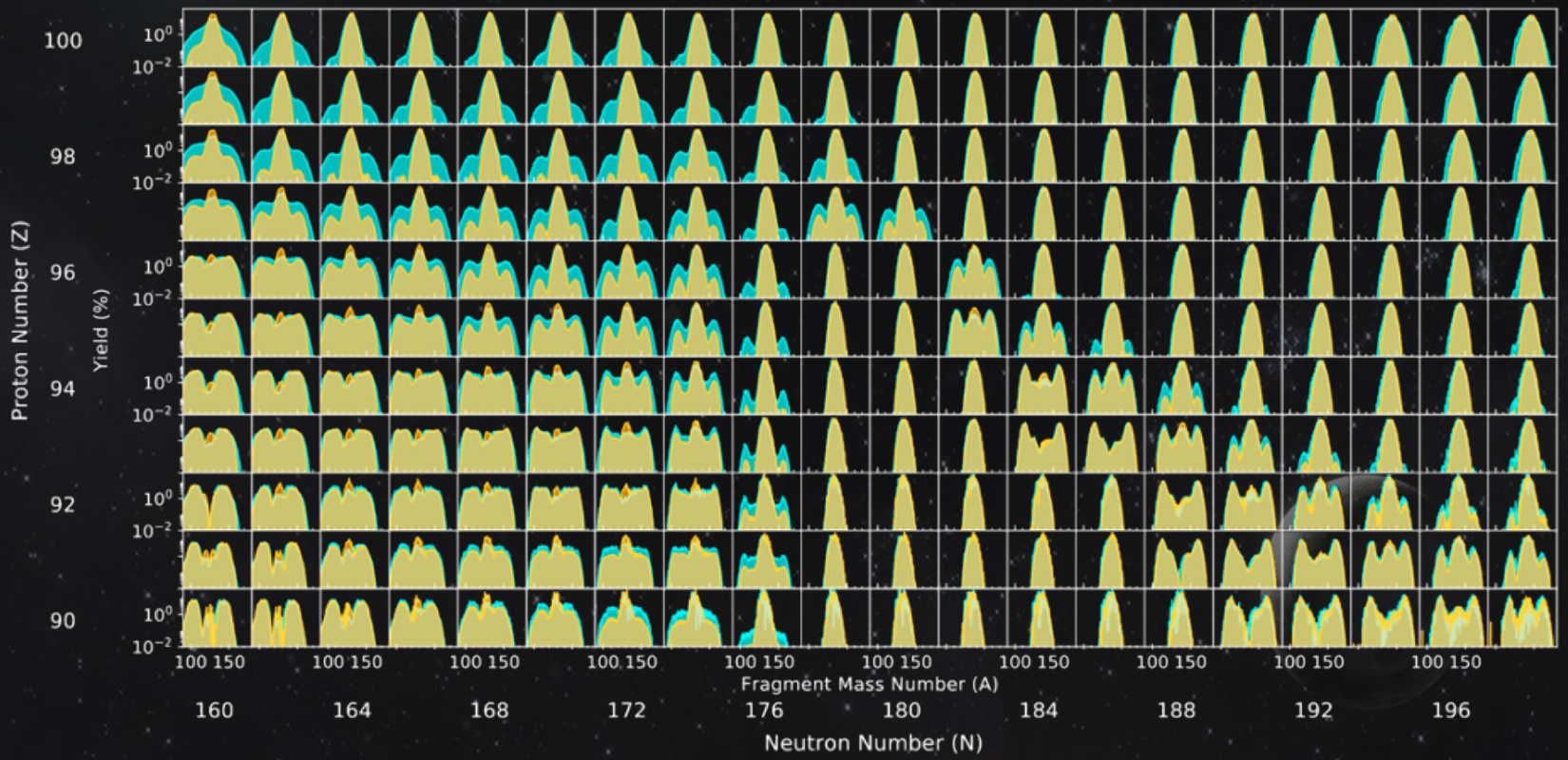
Zhu, Wollaeger, Vassh+ (2018)

Actindes in kilonovae must imply that the material will undergo fission



Holmbeck+ (2023)

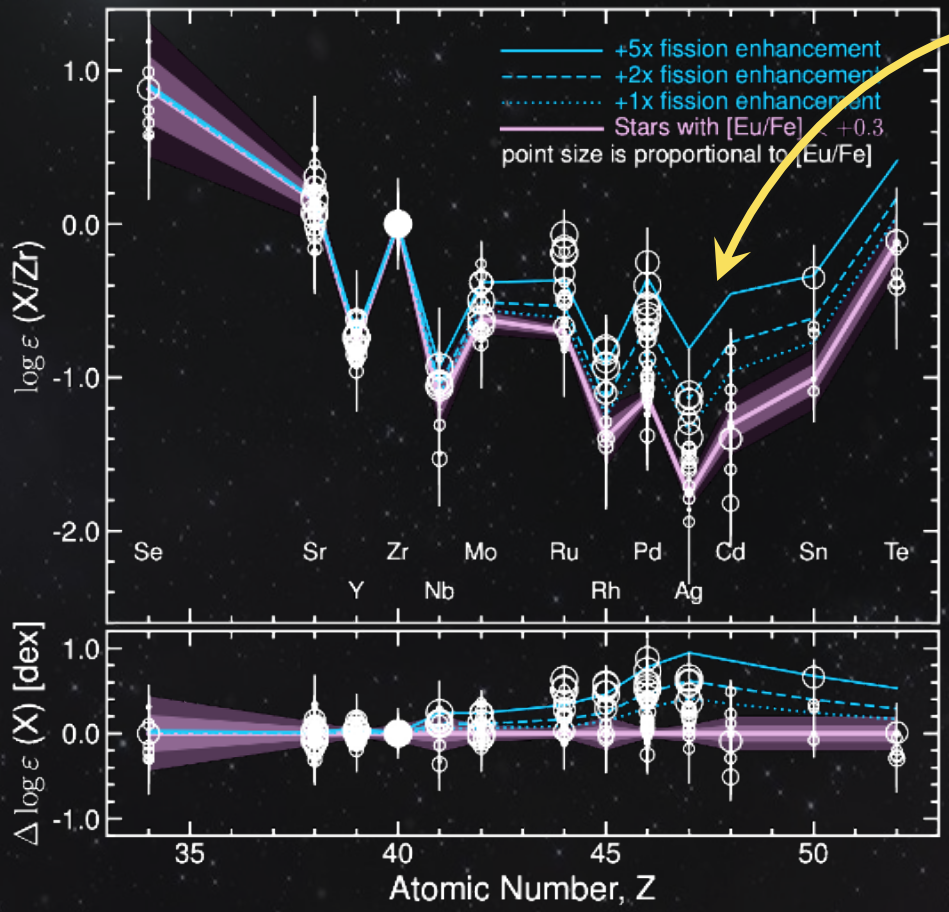
The fission fragment properties of heavy nuclei are unknown

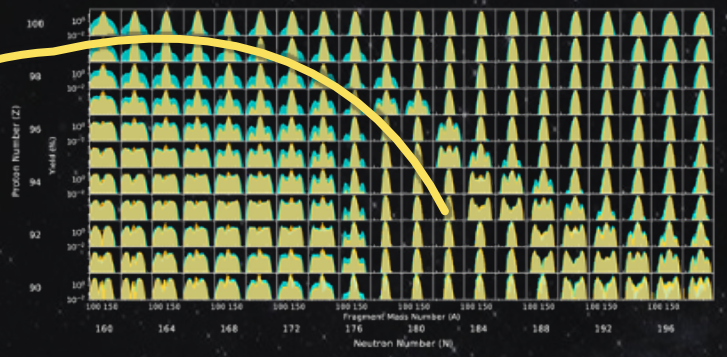


Vassh+ (2019)

See talks by Ito and Chen

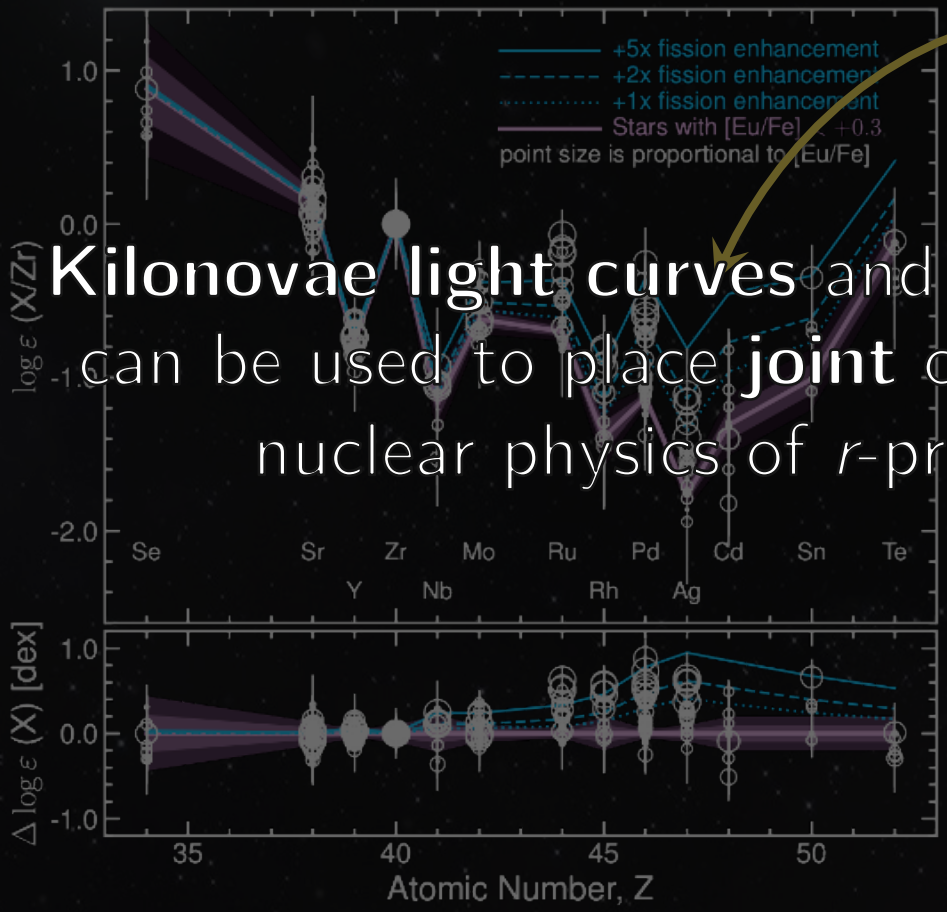
These fission fragments may cause a signature in metal poor stars!

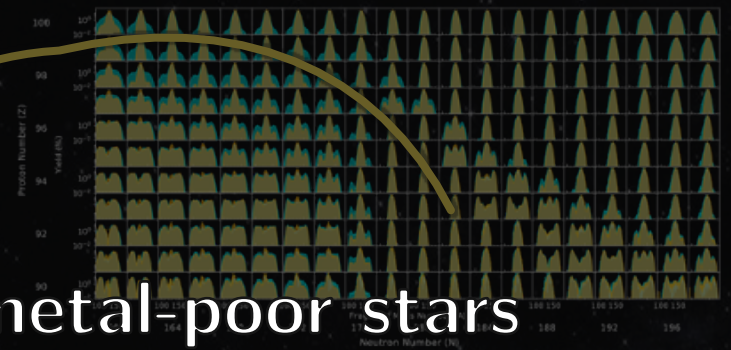




Roederer, Vassh, **Holmbeck**+ (Science, *submitted*)

These fission fragments may cause a signature in metal poor stars!

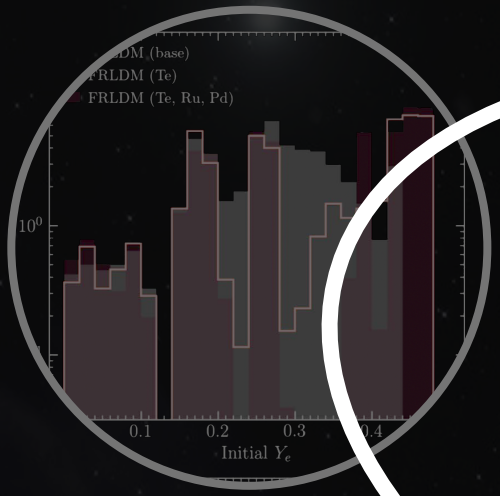




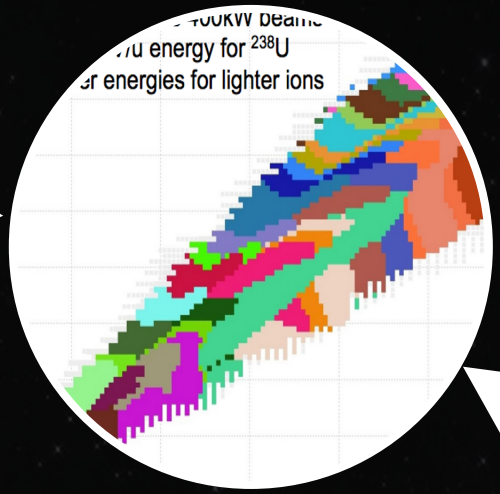
Kilonovae light curves and **metal-poor stars** can be used to place **joint** constraints on the nuclear physics of *r*-process nuclei

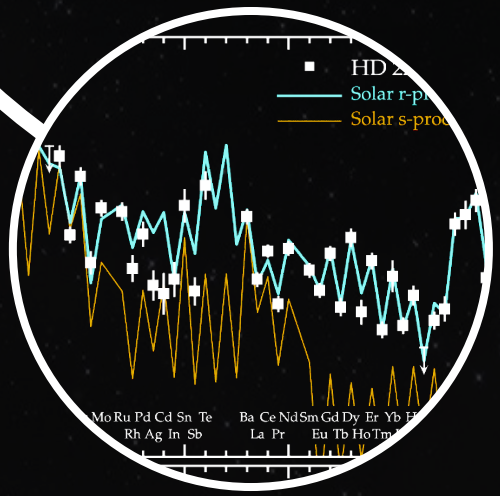
Roederer, Vassh, **Holmbeck**+ (Science, *submitted*)

NSM ejecta distribution

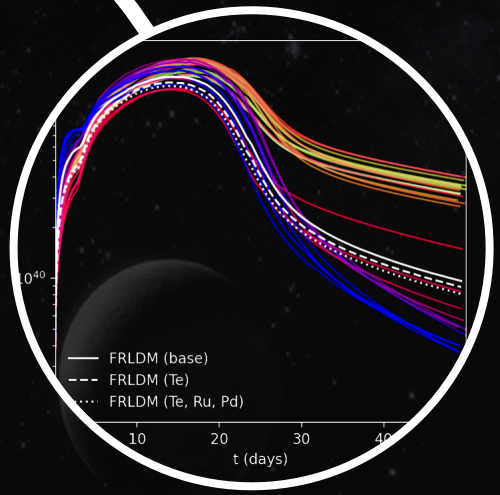


Nuclear Physics





Metal-poor stars



Light curves

NSM ejecta distribution

Nuclear Physics

Heavy-Element Nucleosynthesis in the Multi-Messenger Era

We (probably) cannot: Make robust predictions of neutron star merger ejecta (e.g., Y_e distributions) from light curves

We (probably) can: Place constraints on the nuclear physics of heavy nuclei (e.g., fission properties)

What are we doing now? Identifying stars to be used as chemical records of r-process events

Preparing for the next kilonova!

More experimental and theoretical data for the *r*-process, please!

Delayed *r*-process Observables

Prompt *r*-process Observables

Things I didn't talk about

The source of elemental variations in metal-poor stars

The nuclear equation of state and other nuclear uncertainties

Superheavy elements

ありがとうございます！

質問はありますか？*

*私はまだ日本語初心者です。