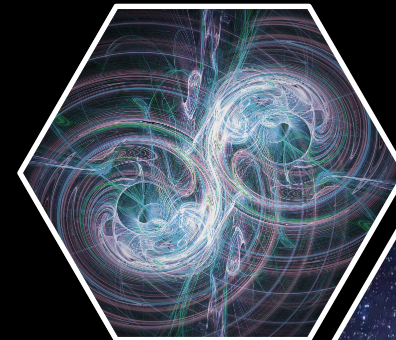
Superheavy Elements in Kilonovae



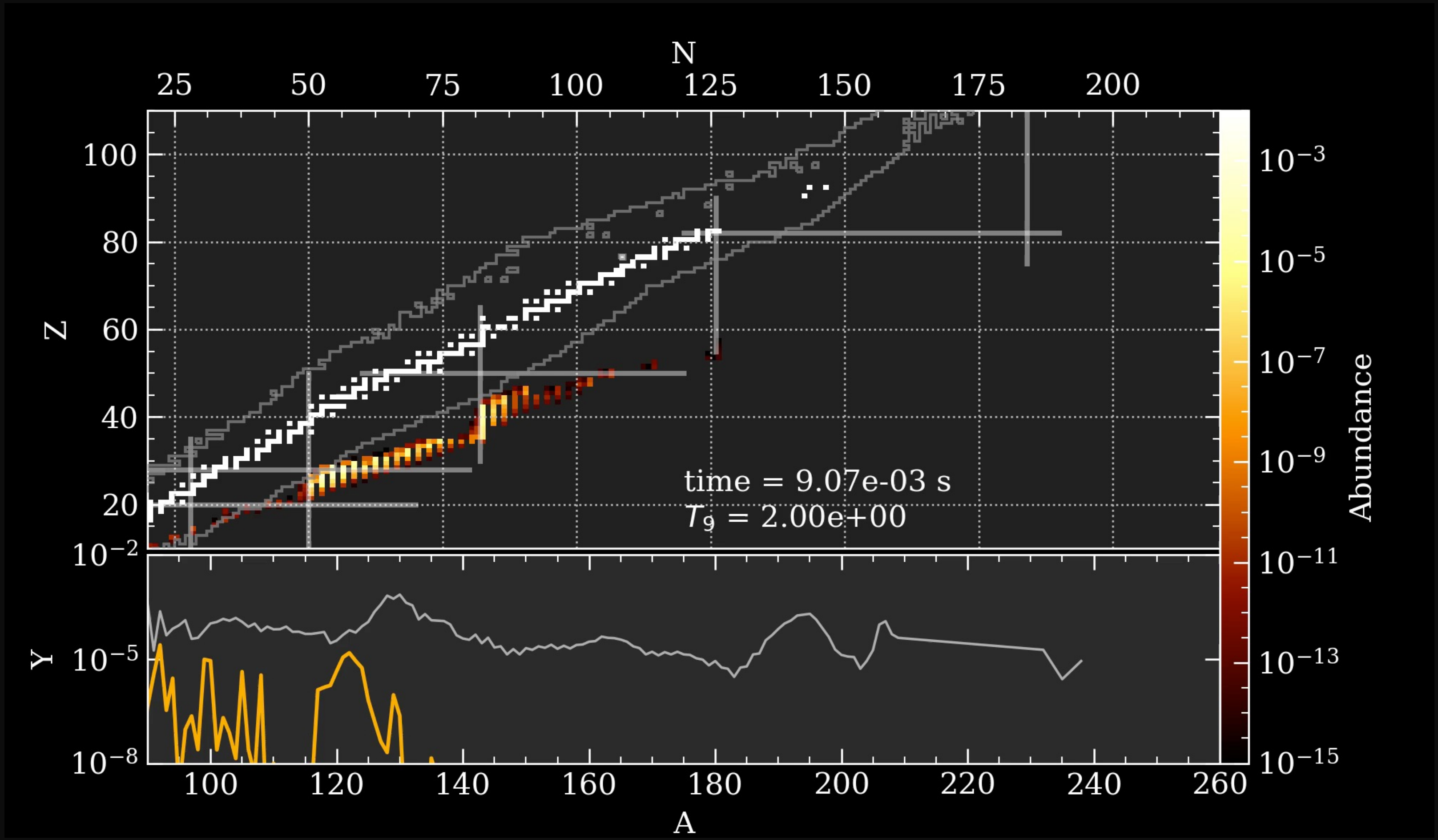
Erika M. Holmbeck[†]
J. Barnes, K.A. Lund, T.M. Sprouse, G.C. McLaughlin, M.R. Mumpower
ApJL, 951, L13 (2023)

Institute for Nuclear Theory | 31 July 2023
[†]NHFP Hubble Fellow | eholmbeck.github.io

NASA Hubble Fellowship Program

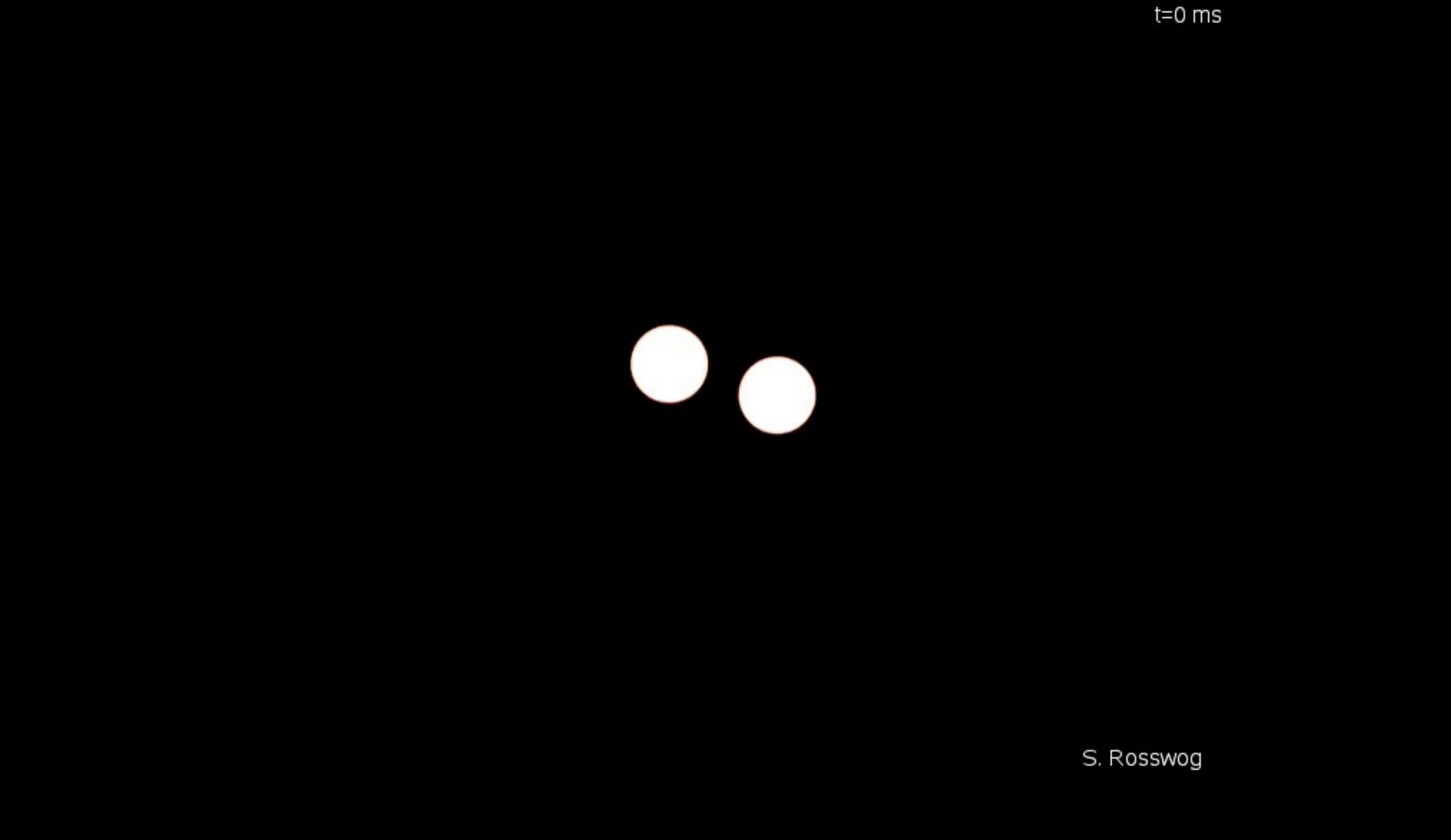
Carnegie Science

The **rapid neutron-capture process** visualized

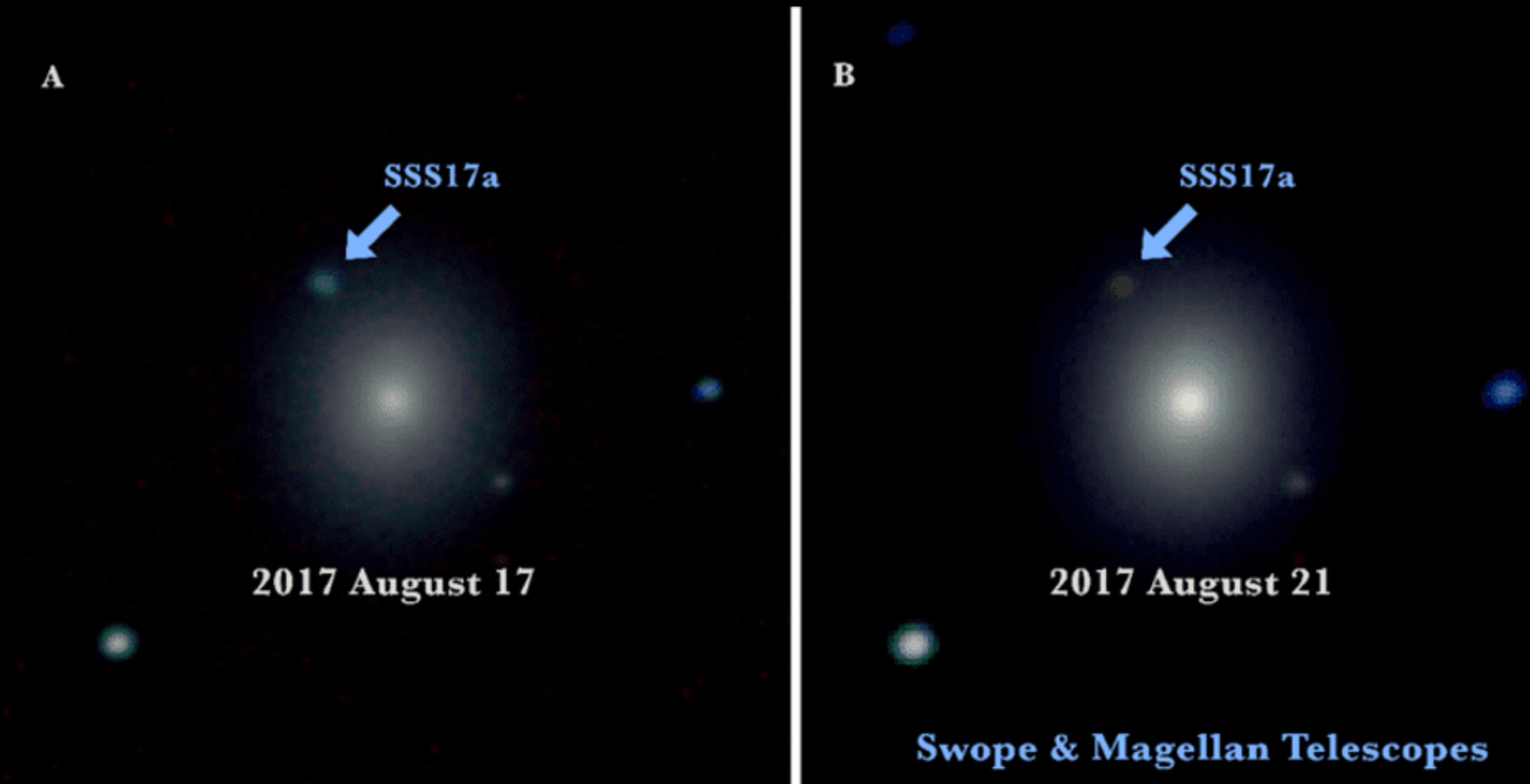


PRISM (Sprouse & Mumpower)

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

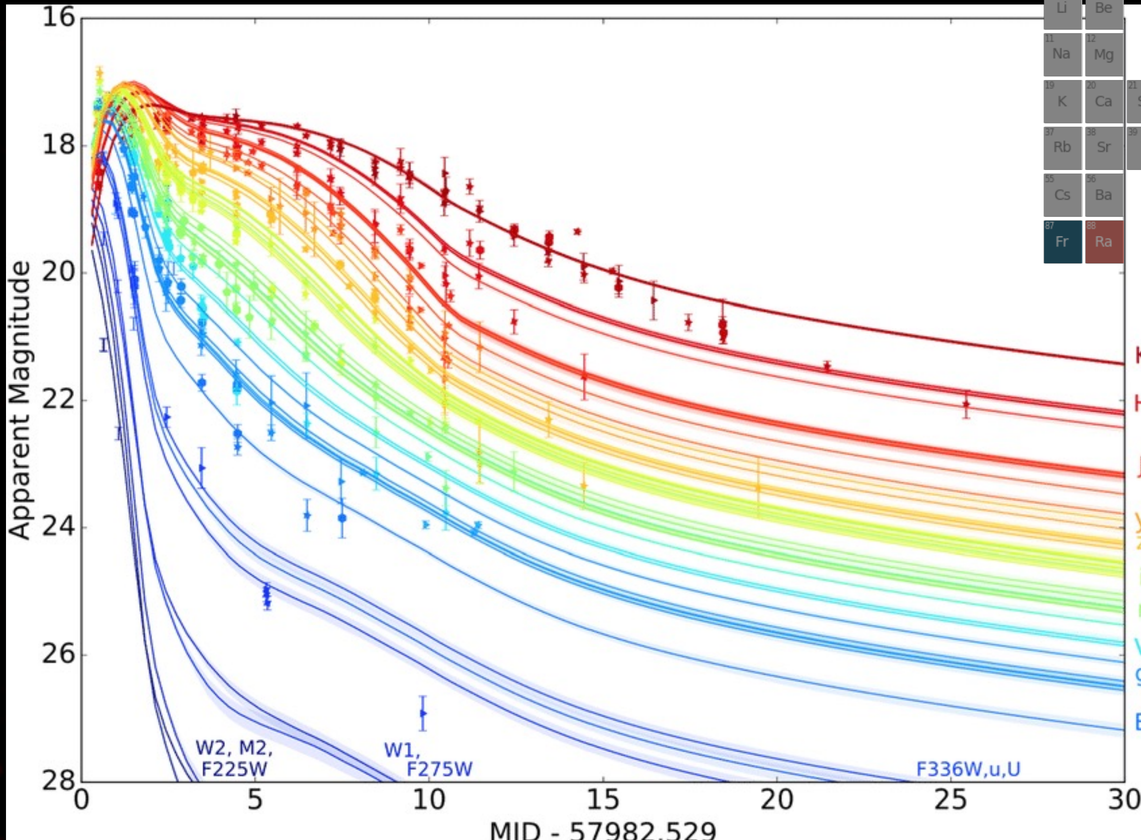


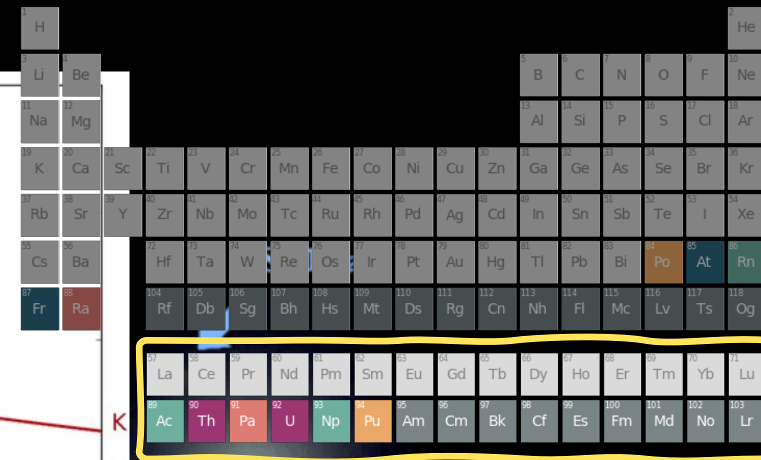
GW170817 and its associated “**kilonova**”

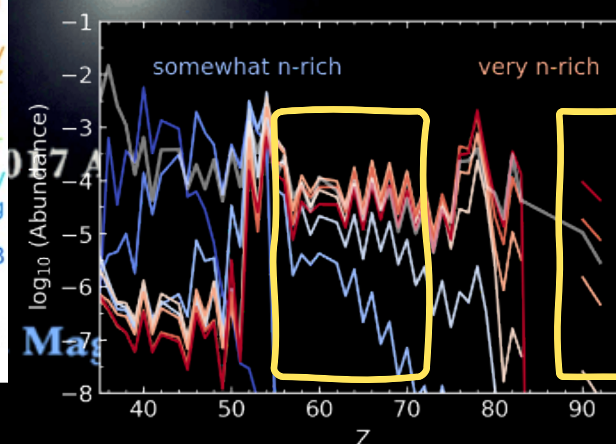


Drout+ (2017)

At least lanthanides (*r*-process elements) were made

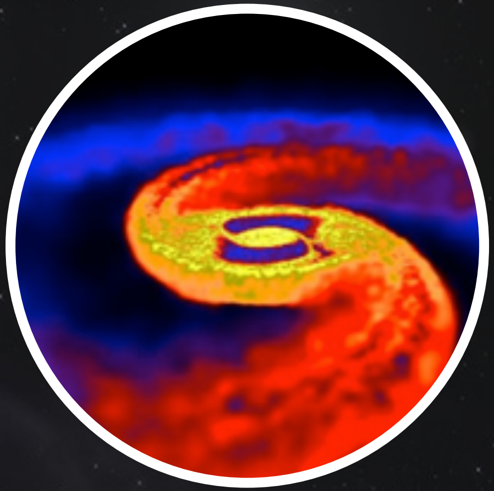


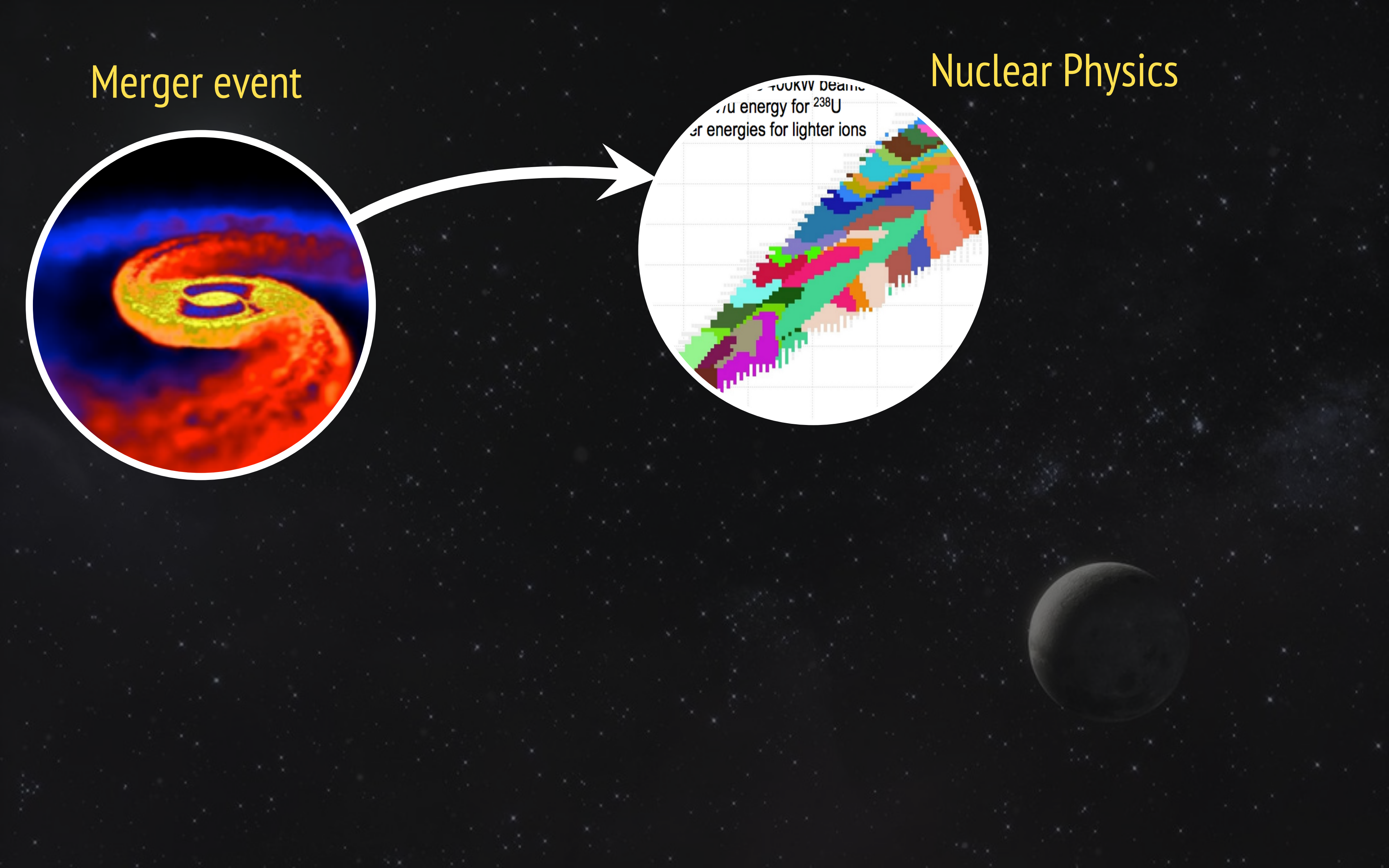


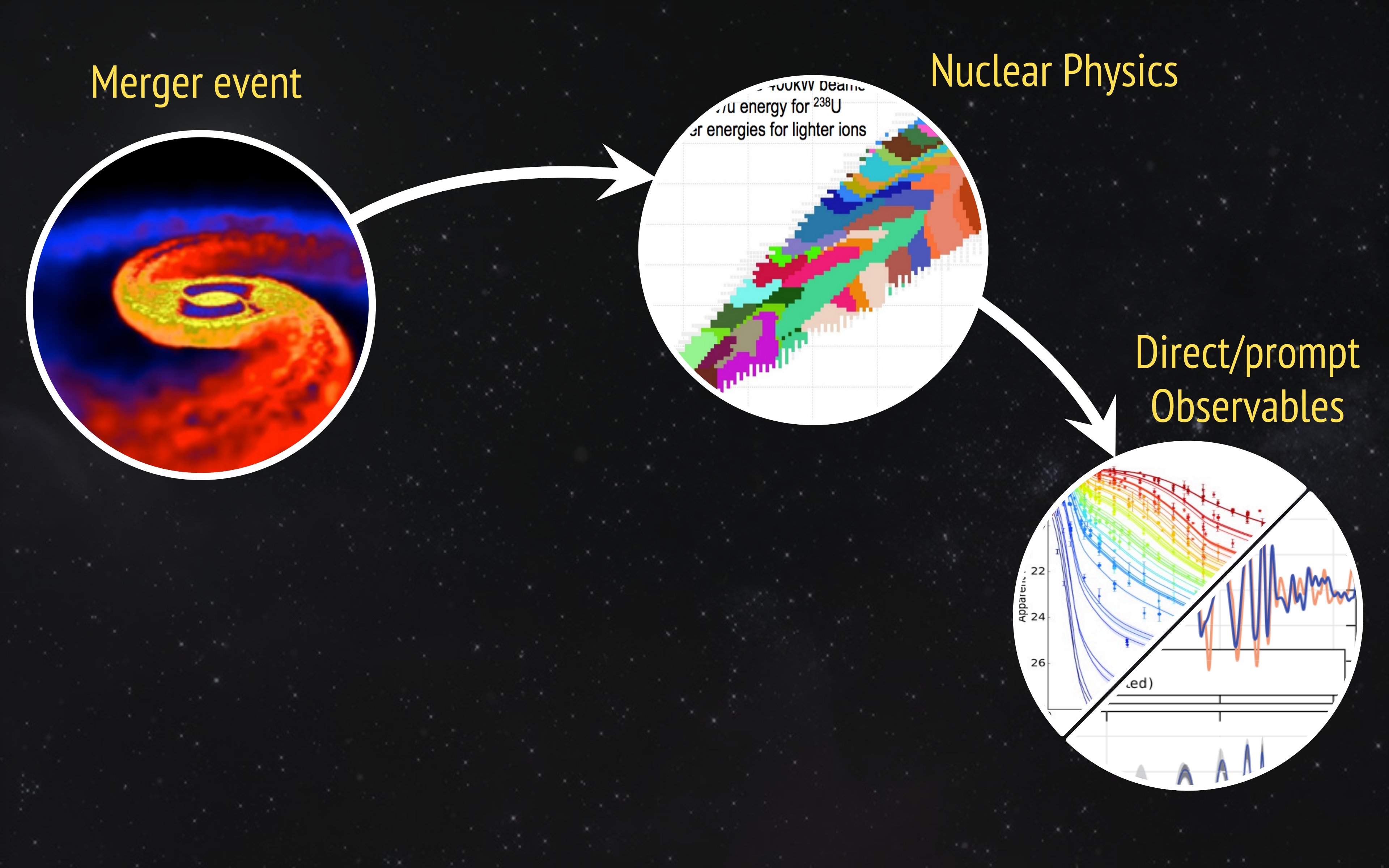


Villar+ (2017)

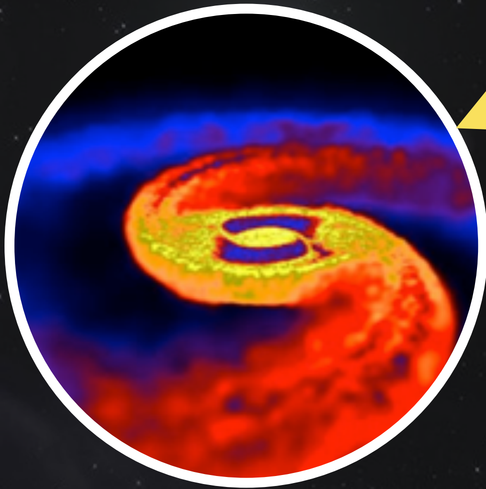
Merger event



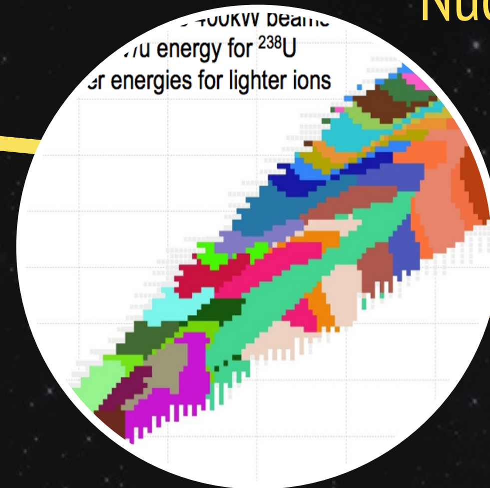

Merger event
Nuclear Physics


Merger event
Nuclear Physics
Direct/prompt Observables

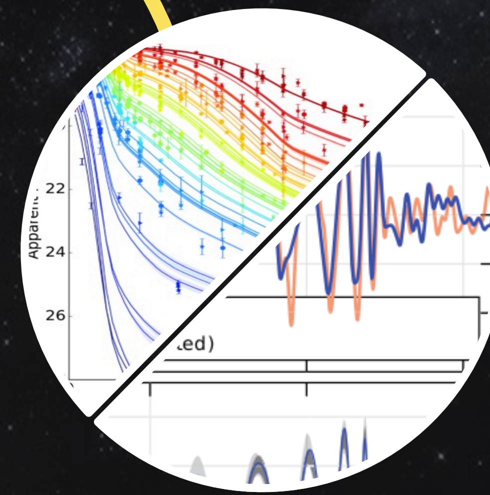
Merger event



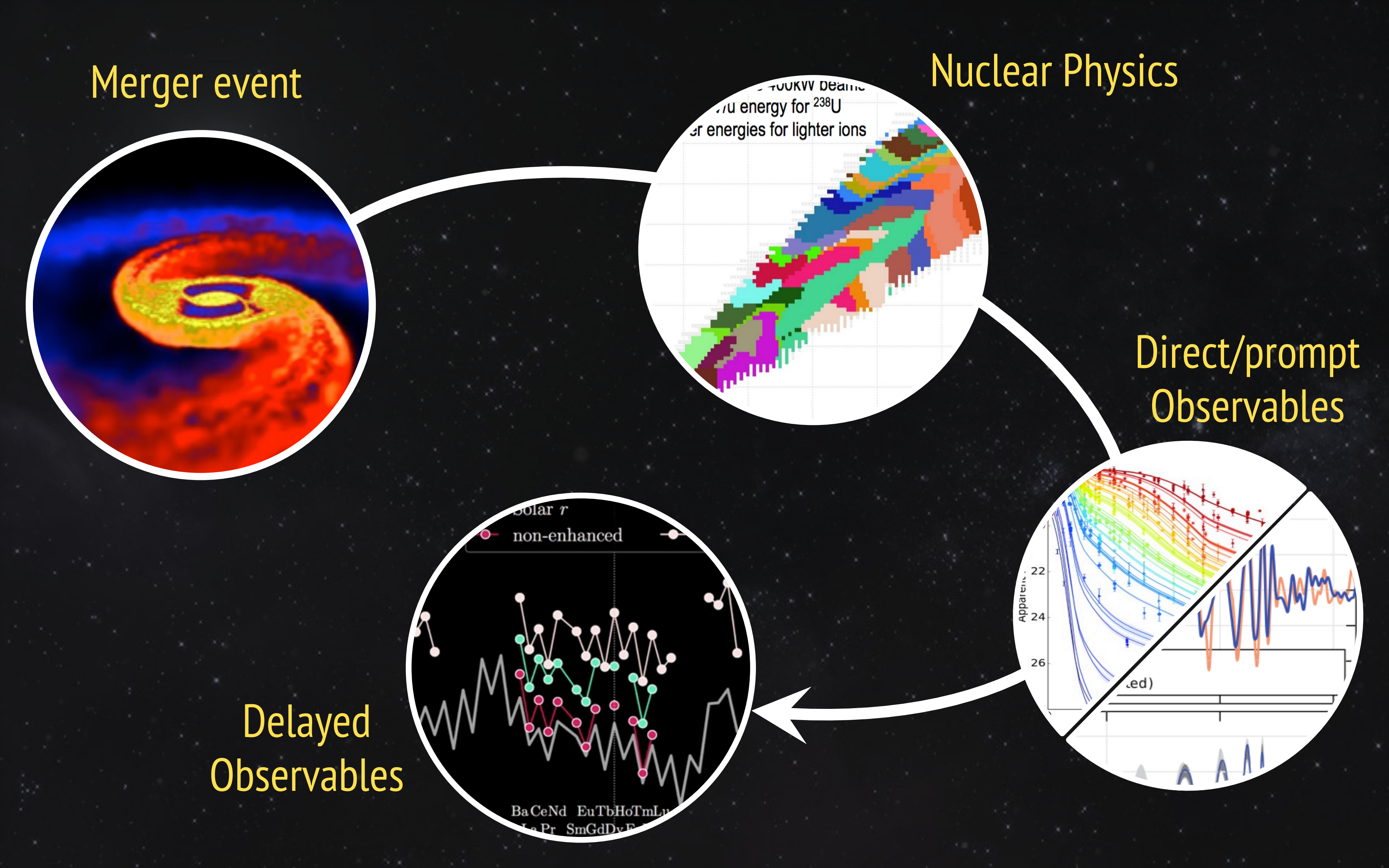
Nuclear Physics

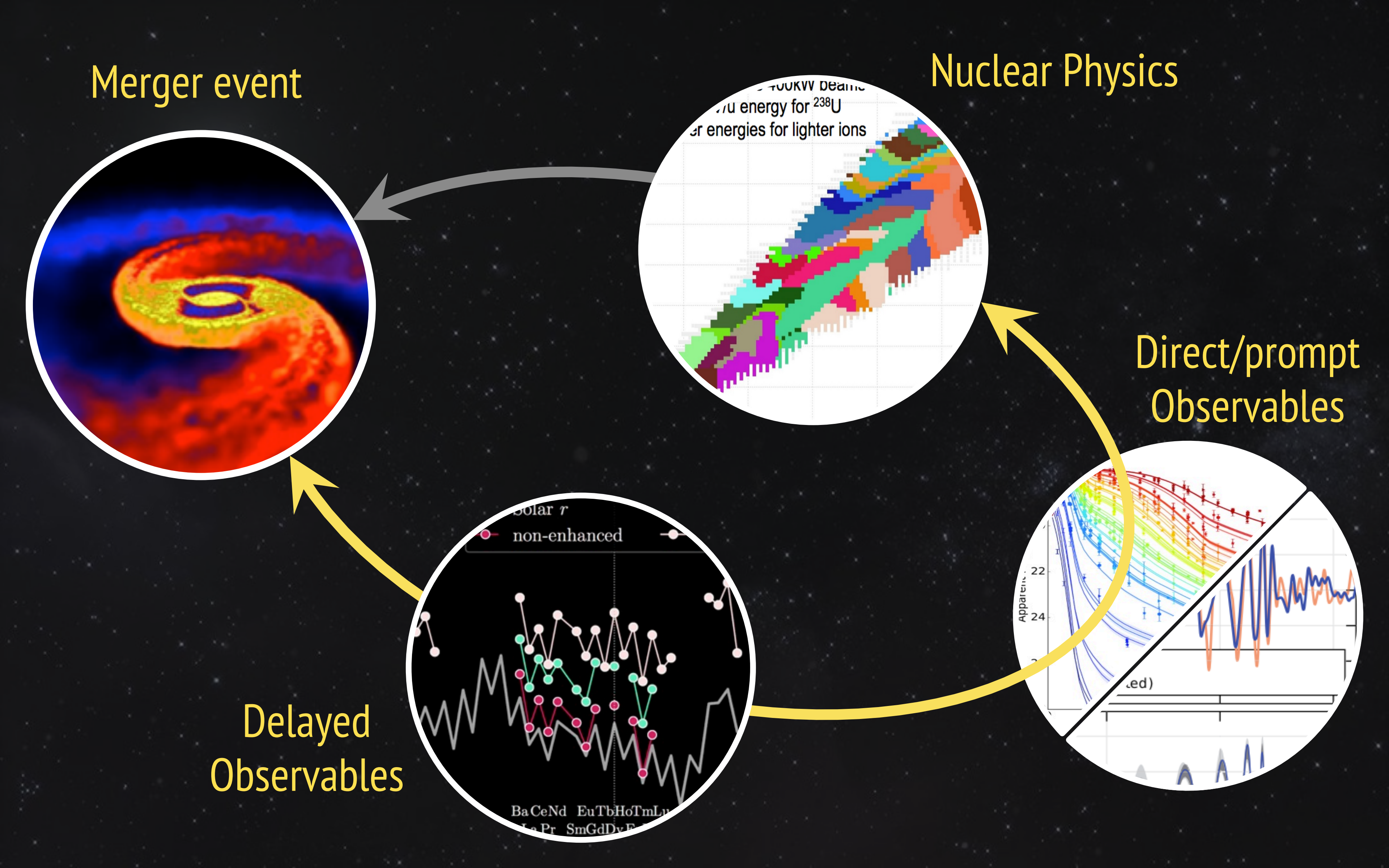


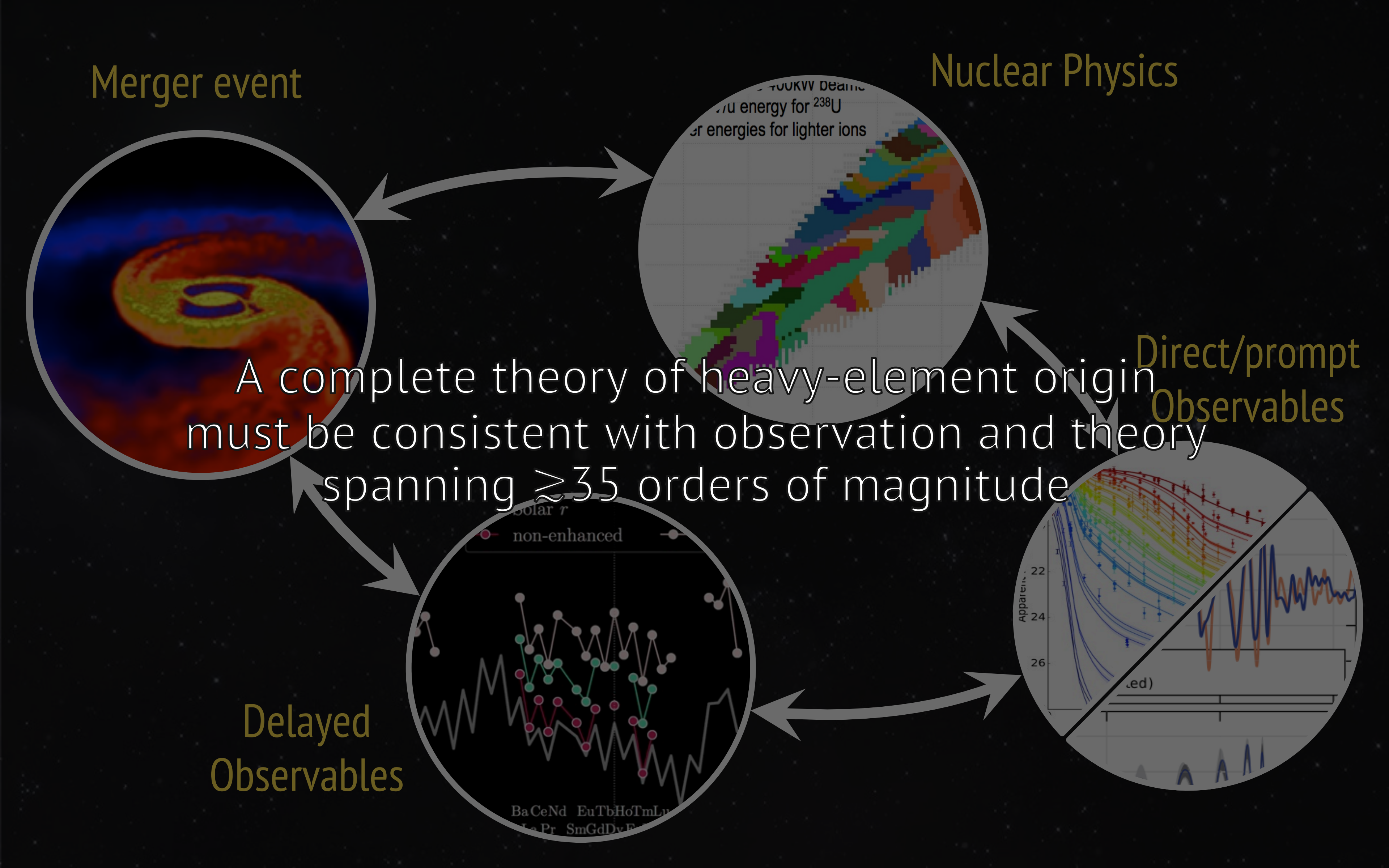
Direct/prompt Observables

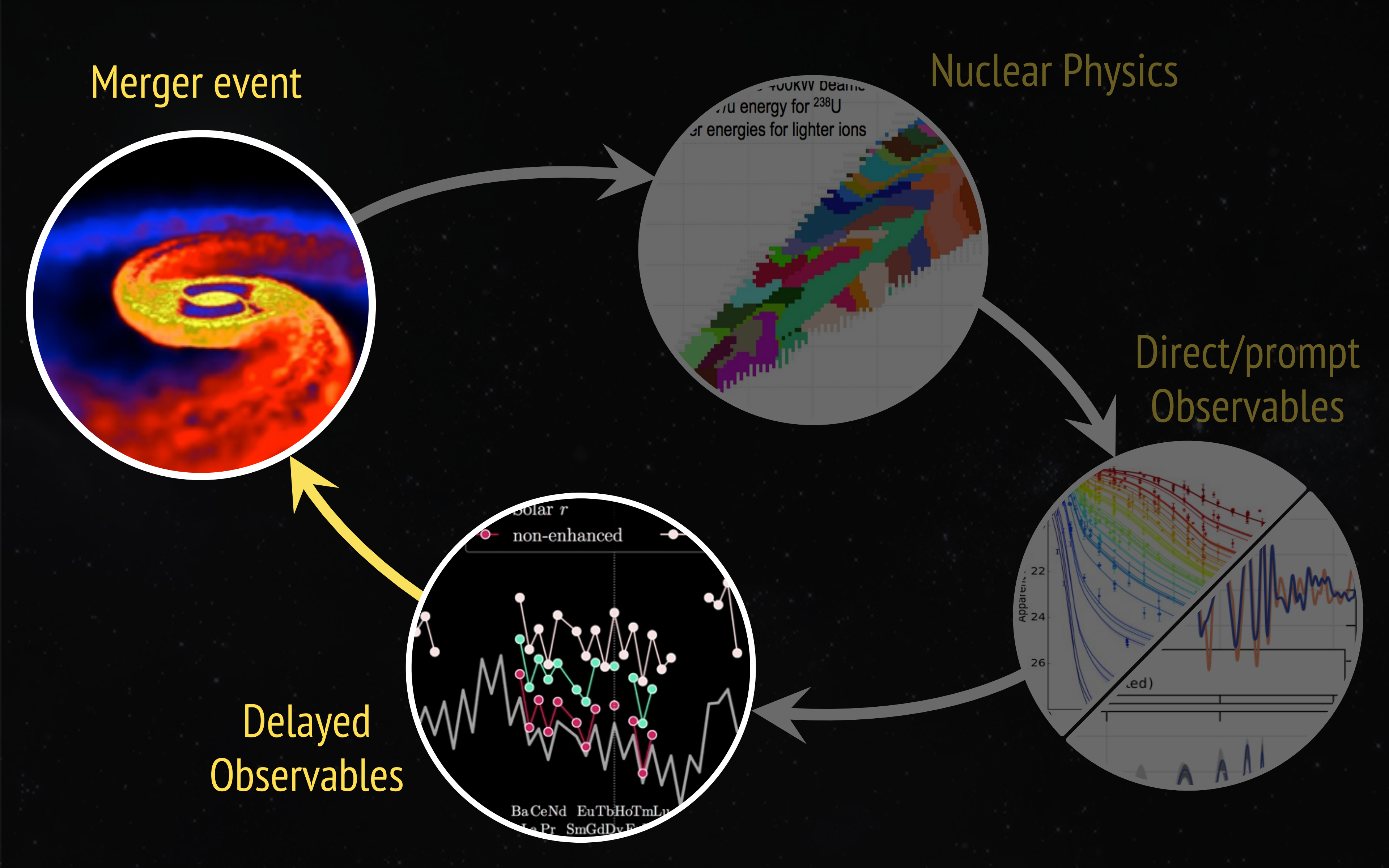


Using observations to say something about nuclear physics, compact object mergers, etc.

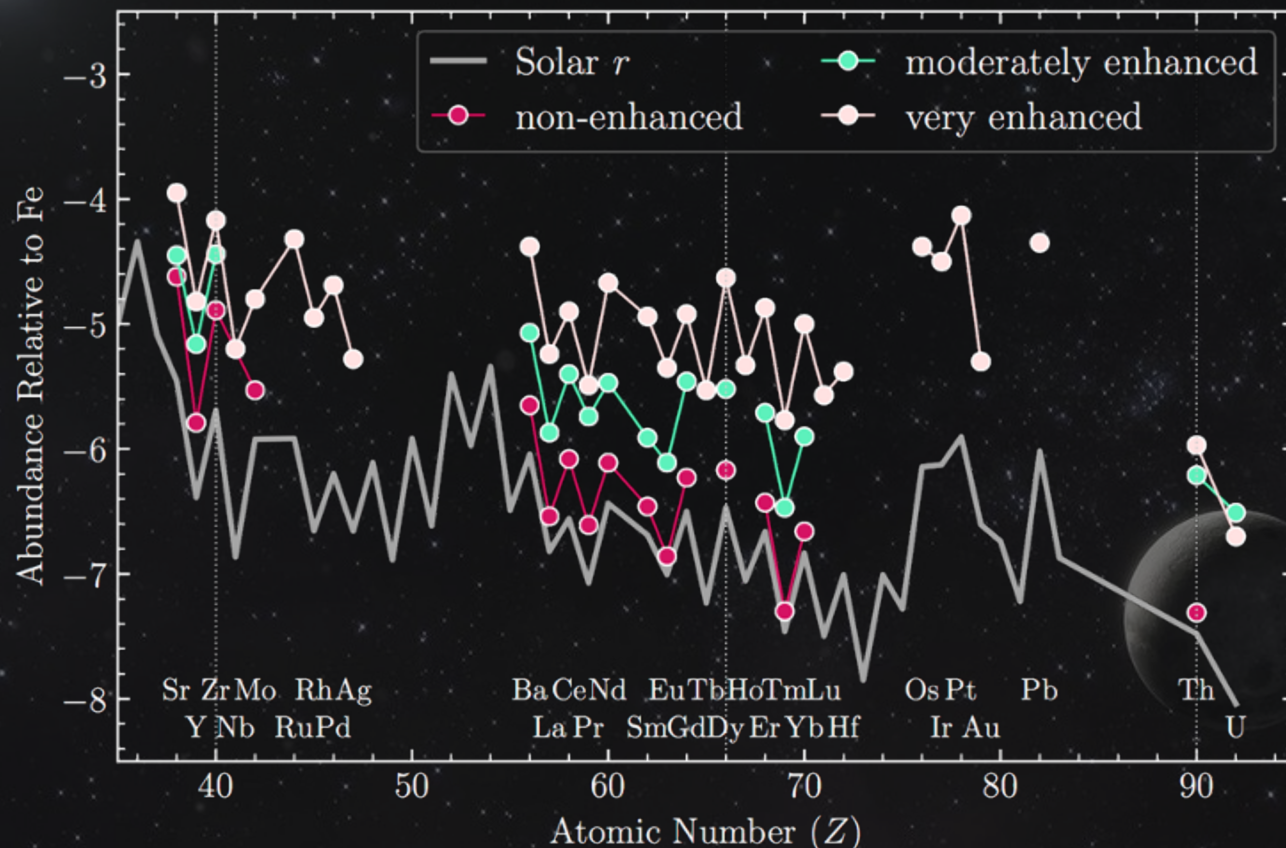

Merger event
Nuclear Physics
Direct/prompt
Observables
Delayed
Observables
non-enhanced


Merger event
Nuclear Physics
Direct/prompt Observables
Delayed Observables
non-enhanced

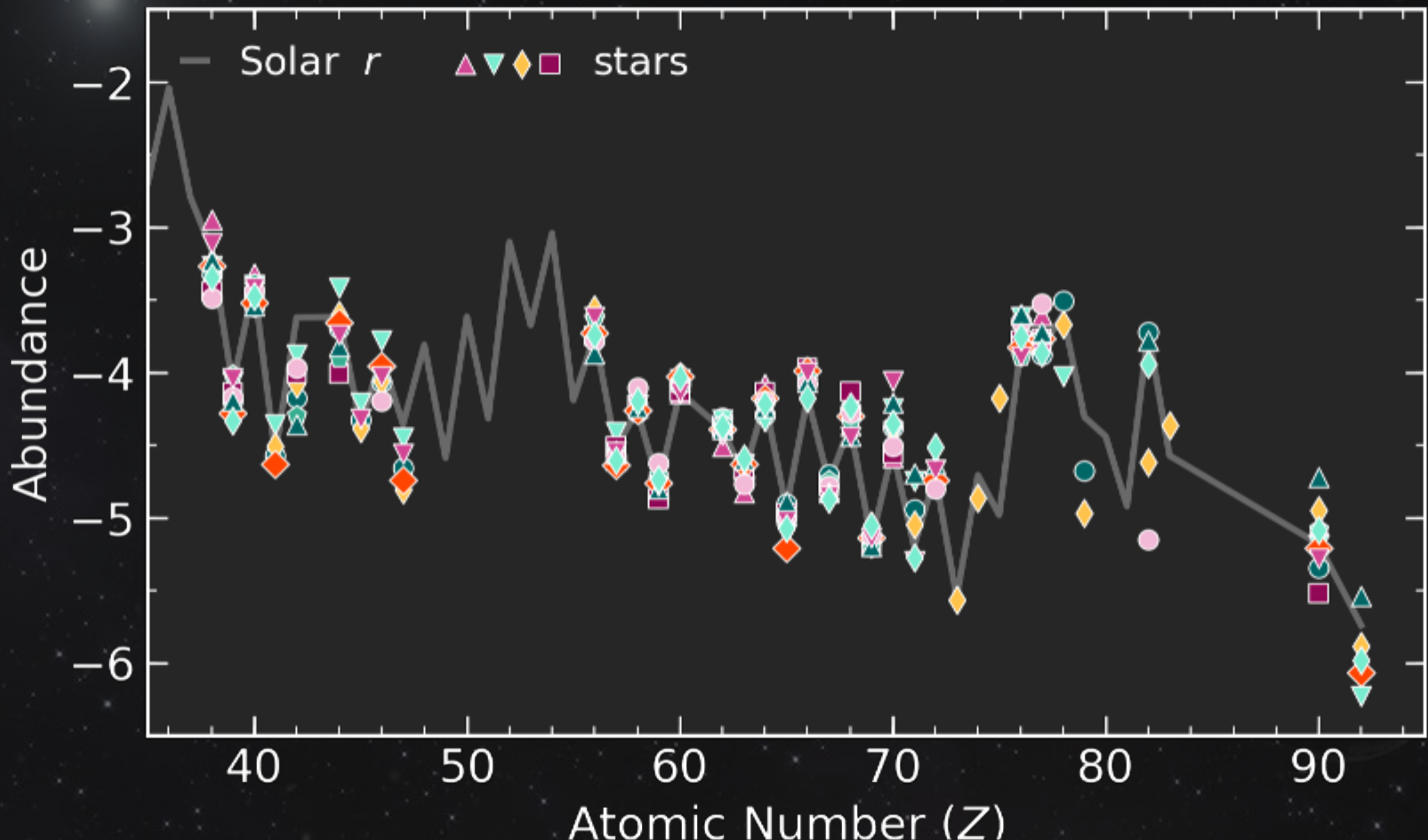

Merger event
Nuclear Physics
Direct/prompt Observables
Delayed Observables
non-enhanced
A complete theory of heavy-element origin must be consistent with observation and theory spanning ≳35 orders of magnitude


Merger event
Nuclear Physics
Direct/prompt
Observables
Delayed
Observables
non-enhanced

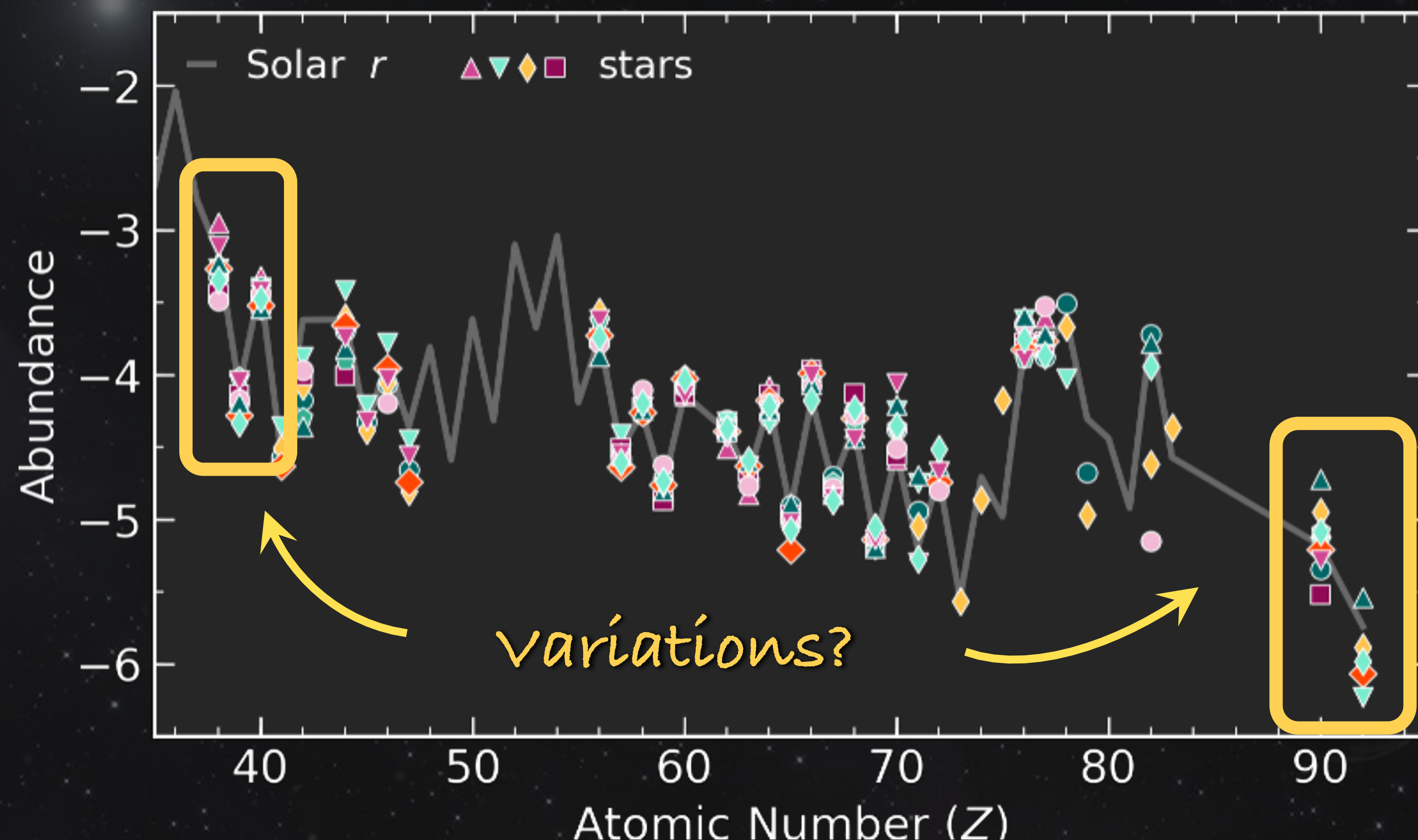
Metal-poor ([Fe/H]< -2) stars with *r*-process elements are considered some of the first descendents of ancient events



Their patterns are strikingly similar

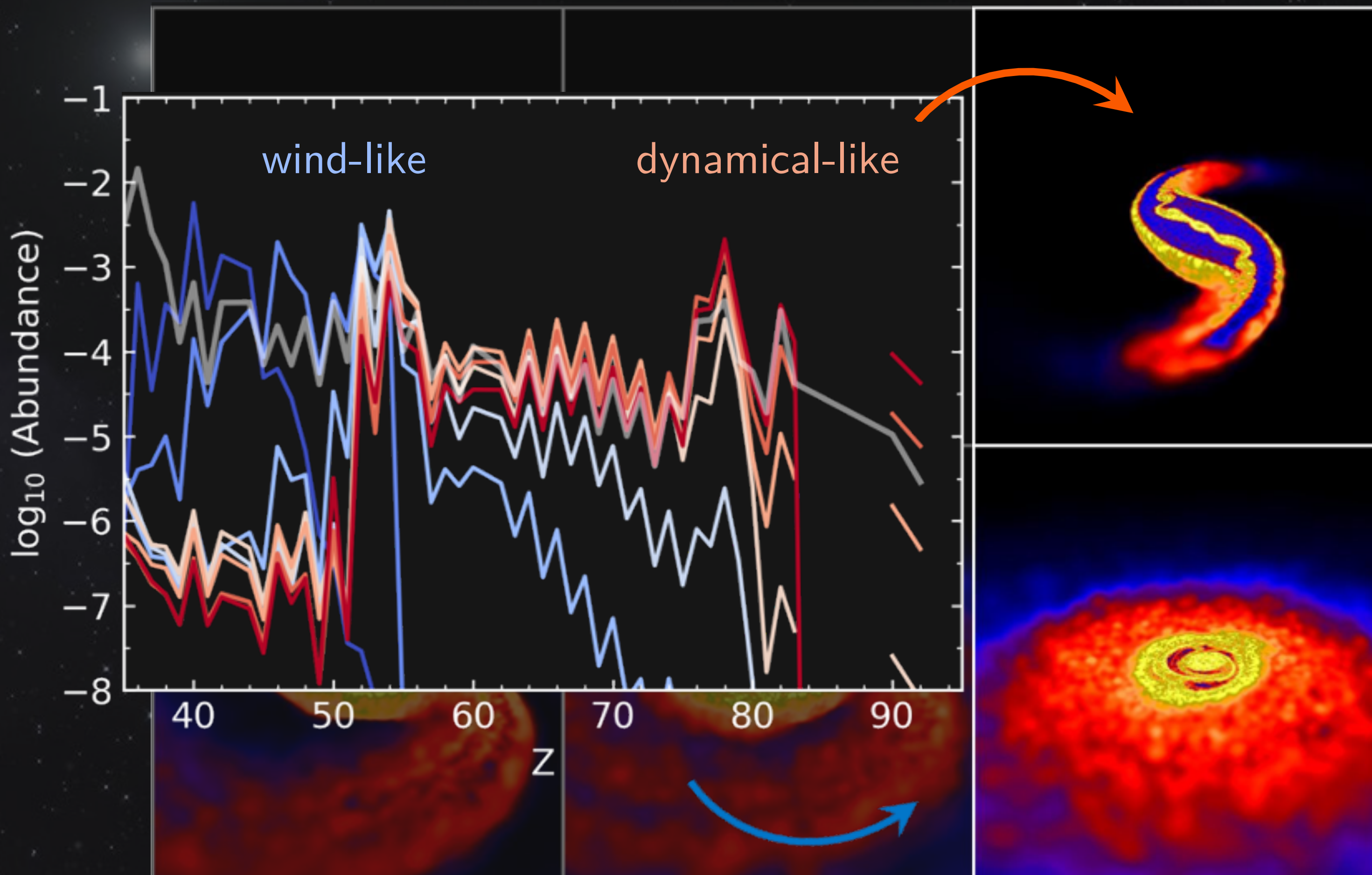


...or are they?



Solar r
stars
Abundance
−2
−3
−4
−5
−6
40
50
60
70
80
90
Atomic Number (Z)
variations?

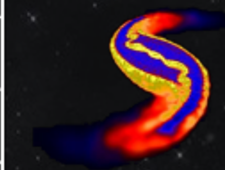
Different elements can be created within the same NSM

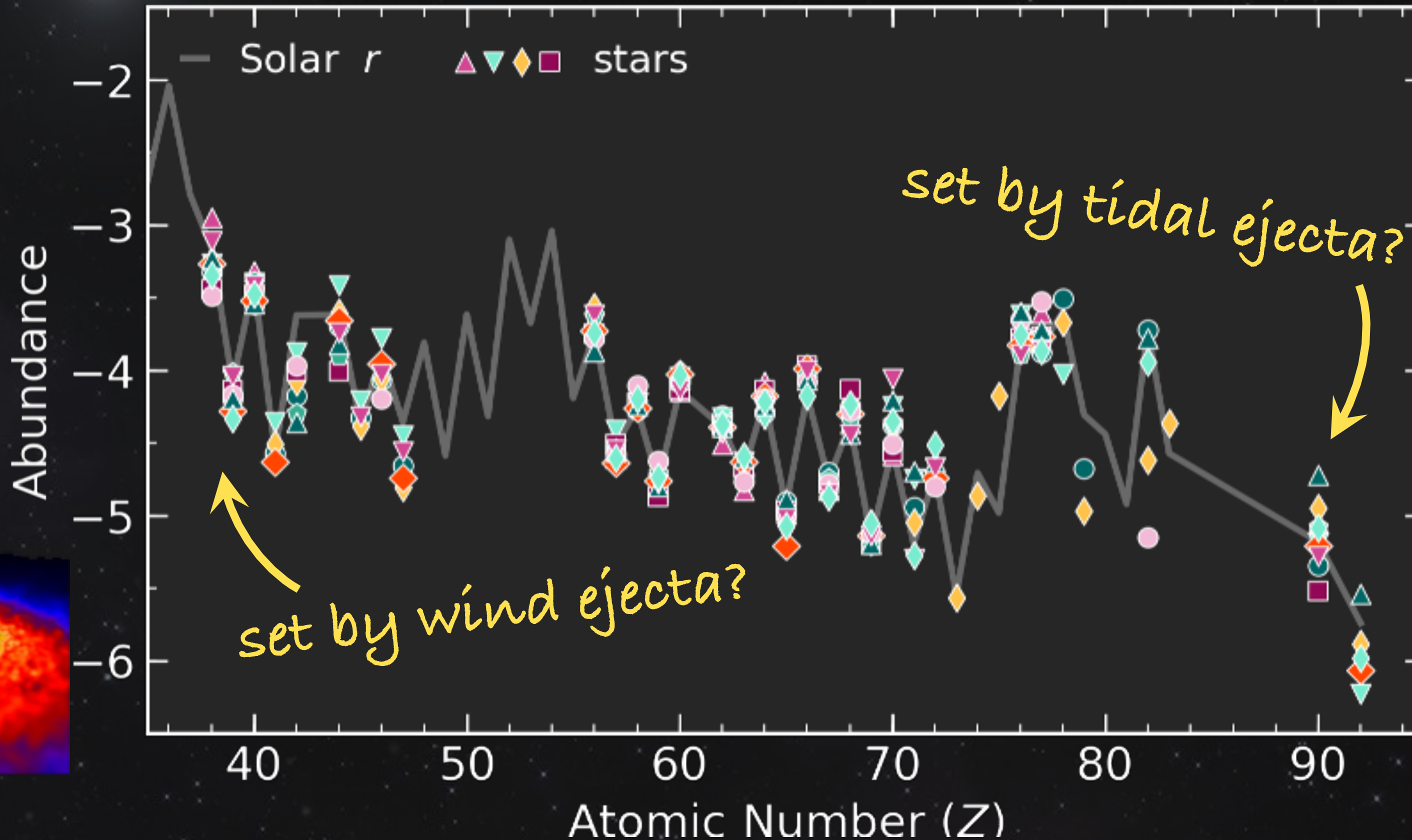


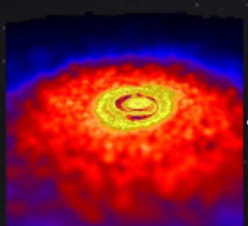
Price & Rosswog (2006)

PRISM

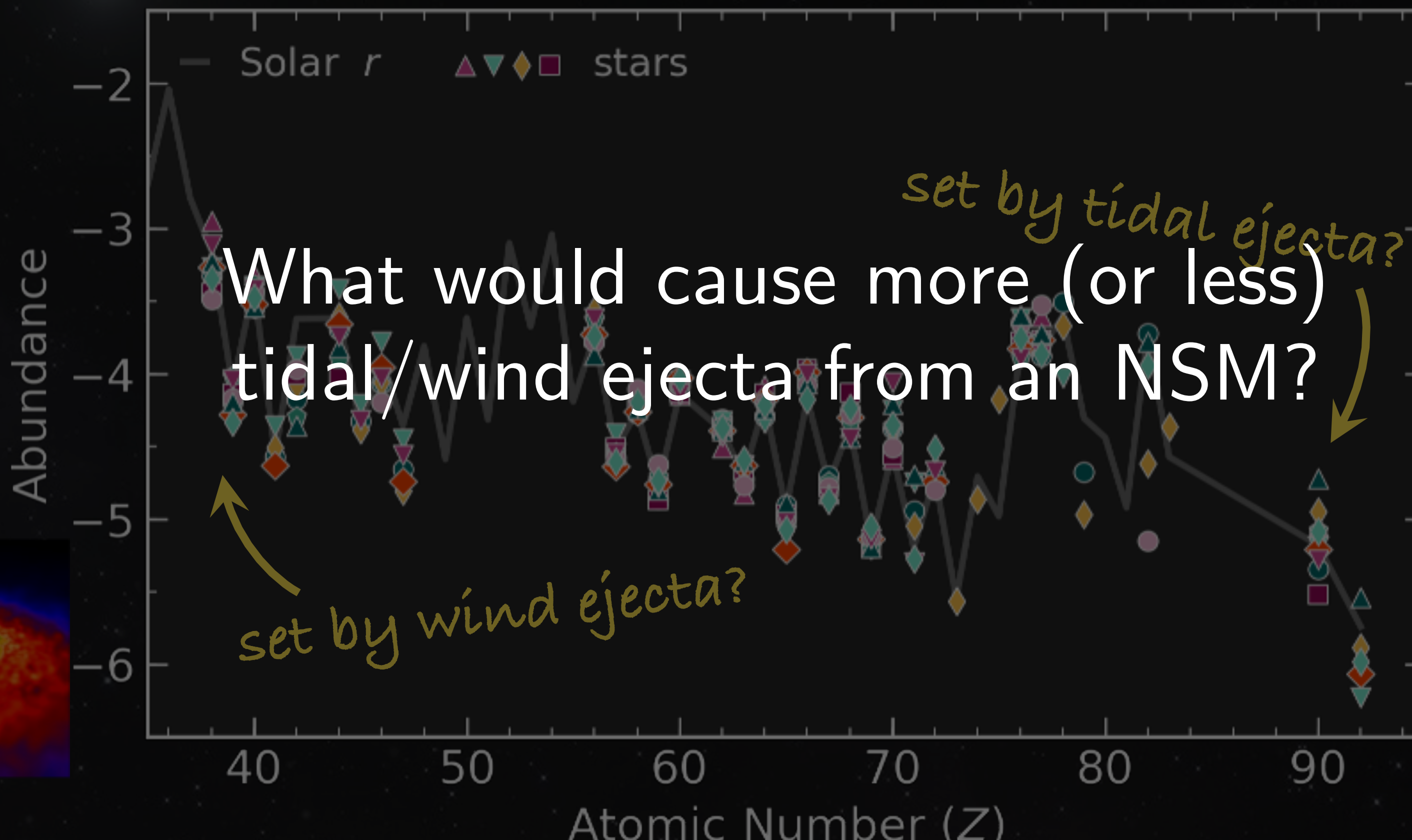
Elemental variations can be explained by differences in NSM ejecta

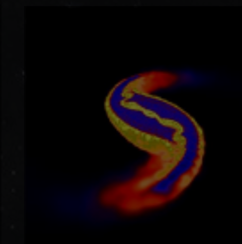


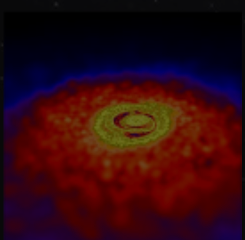




Elemental variations can be explained by differences in NSM ejecta

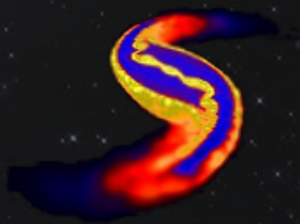




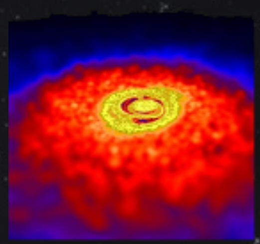


What would cause more (or less) tidal/wind ejecta from an NSM?

Ejecta masses depend on the *neutron star* masses and radii (EOS)



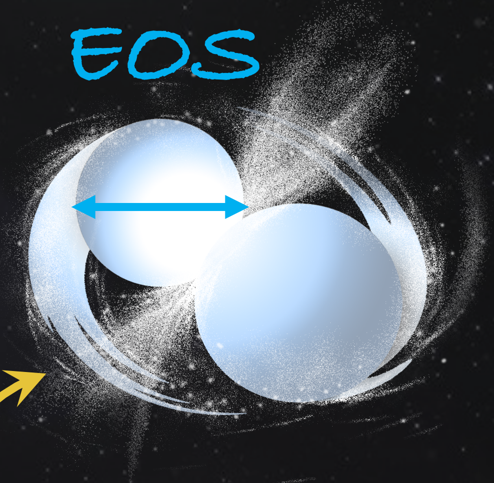
$$\frac{m_{\rm dyn}}{10^{-3}M_\odot} = \left[\frac{a}{\mathcal{C}_1} + b\left(\frac{M_2}{M_1}\right)^n + c\,\mathcal{C}_1\right]M_1 + [1 \leftrightarrow 2]$$



$$\log_{10}(m_{\rm disk}) = \max\left\{-3,\ a\left(1 + b\tanh\left[\frac{c - M_{\rm tot}/M_{\rm thr}}{d}\right]\right)\right\},$$

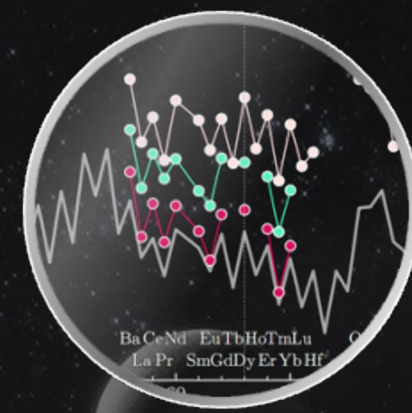
Can we find the EOS that bridges a **theoretical** neutron-star population with **observed** stellar abundances?

EOS



M_1 & M_2

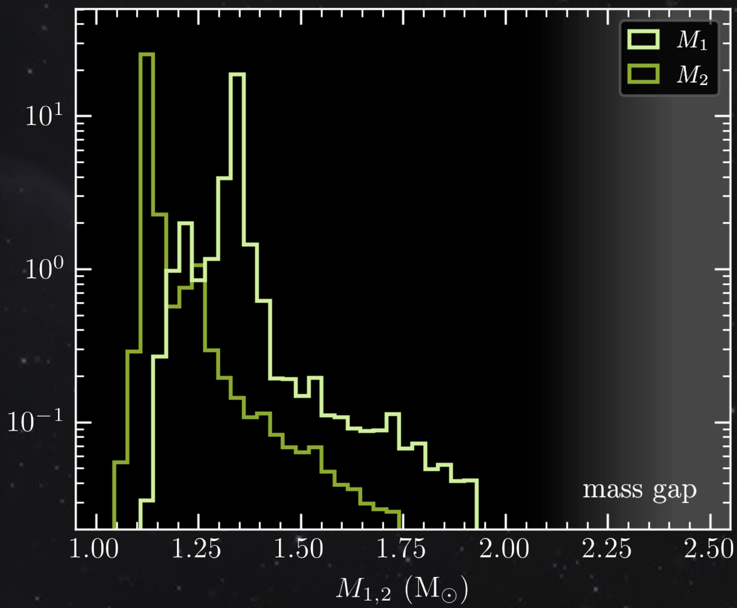
$$f\,(M_{1,2},\,\mathrm{EOS})$$



Metal-poor
r-rich stars

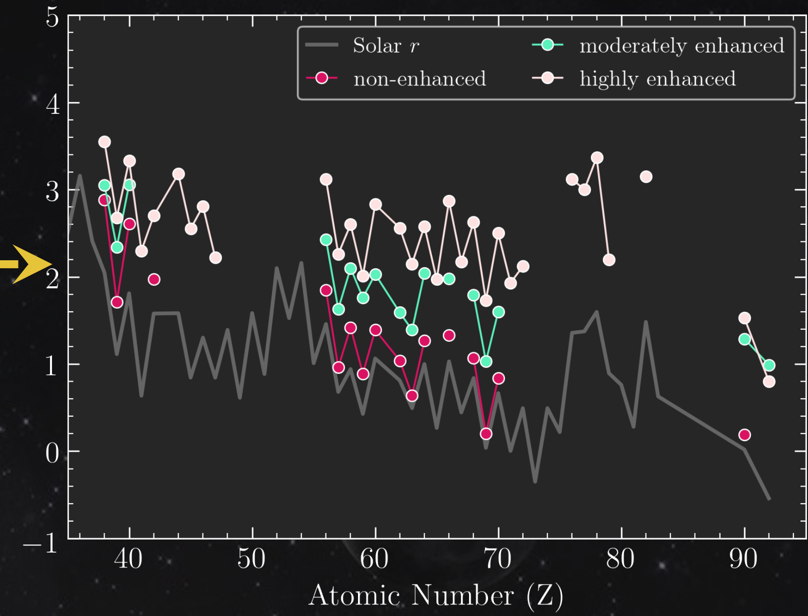
Can we find the EOS that bridges a **theoretical** neutron-star population with **observed** stellar abundances?

NSM population



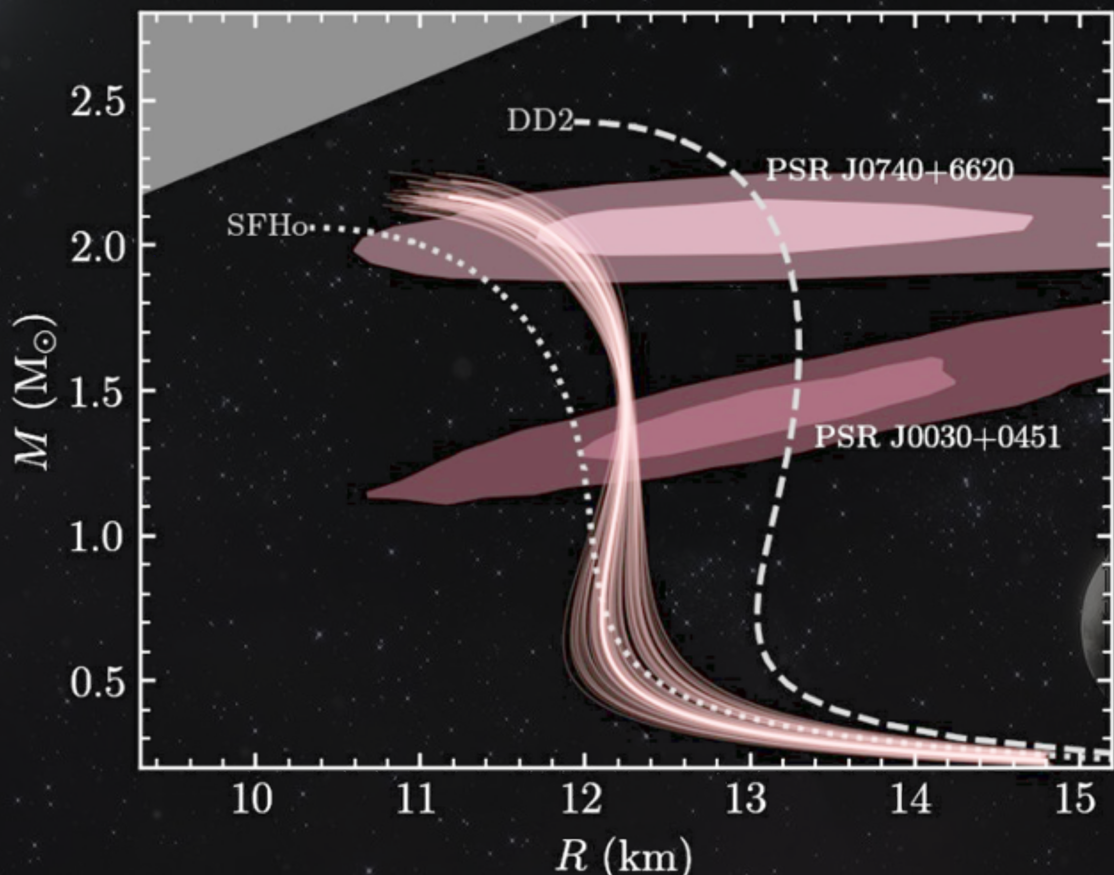
f(EOS)

Observations



EMH+ (2022)

Neutron star mass-radius relationship derived from *r*-process patterns of **metal-poor stars**



EMH+ (2022); data from LIGO/Virgo and NICER teams

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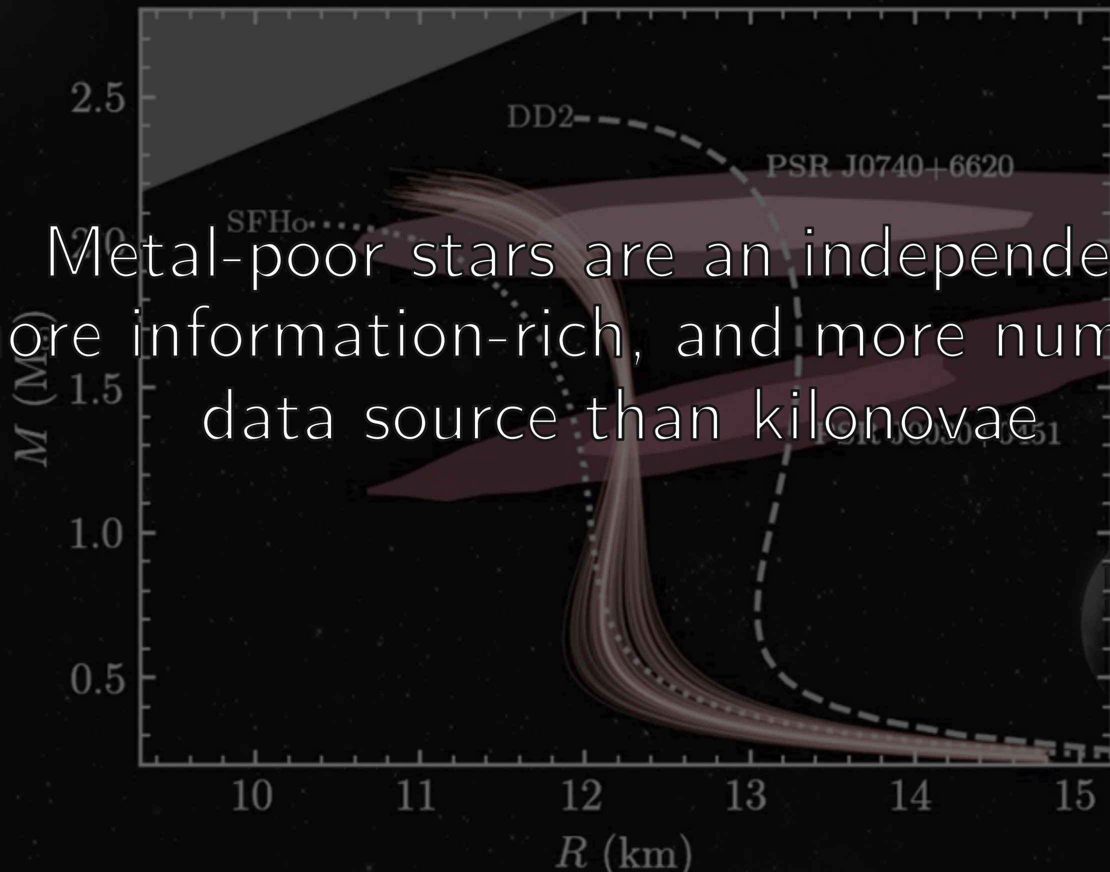
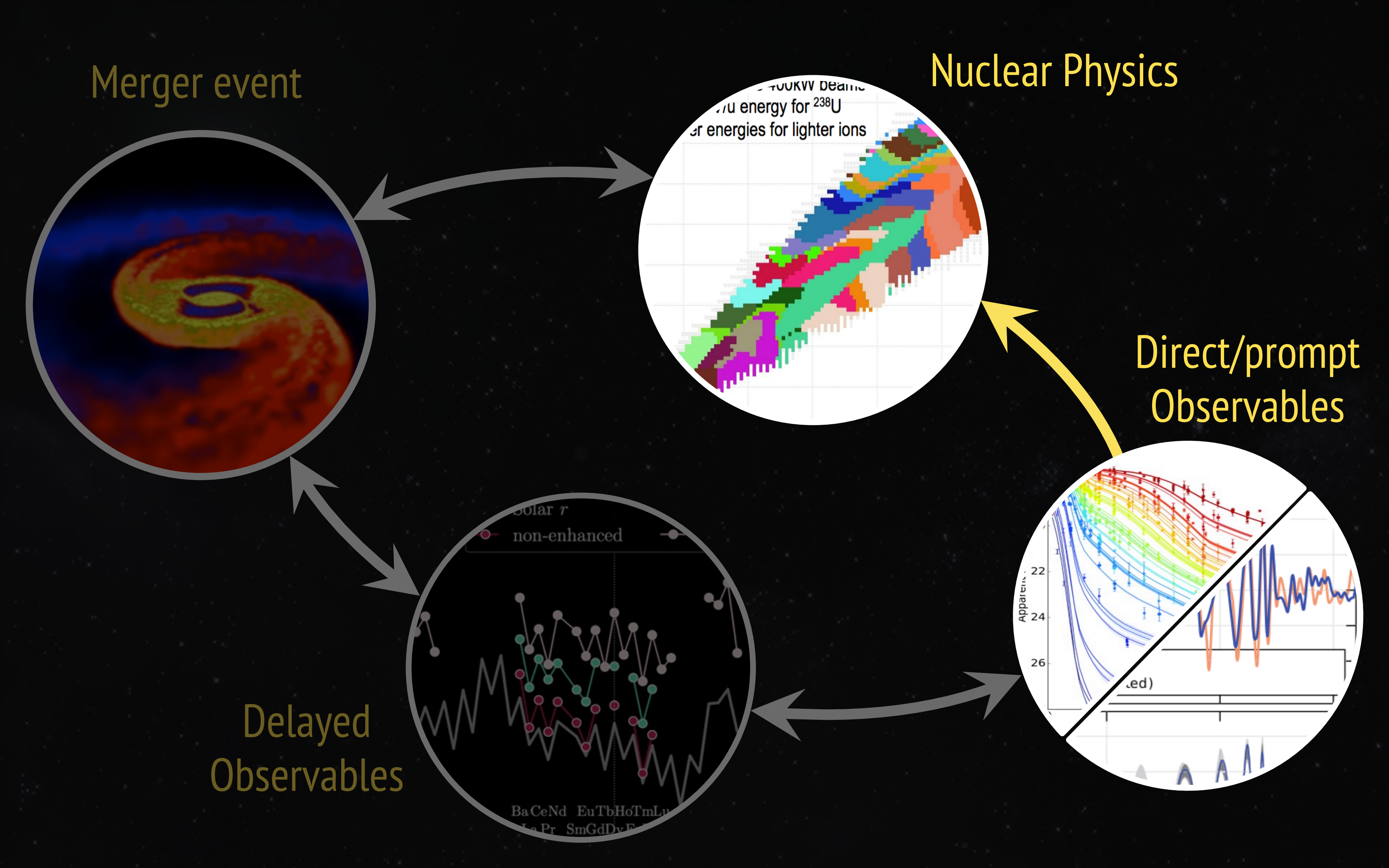
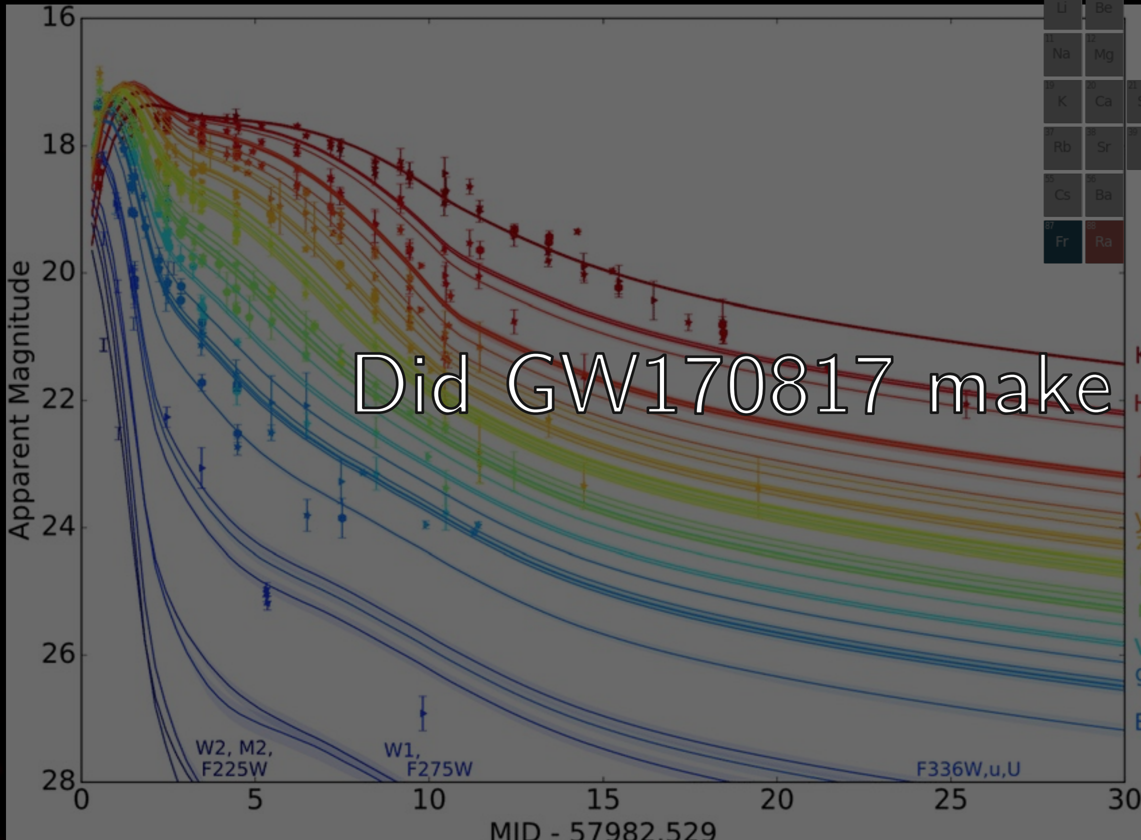


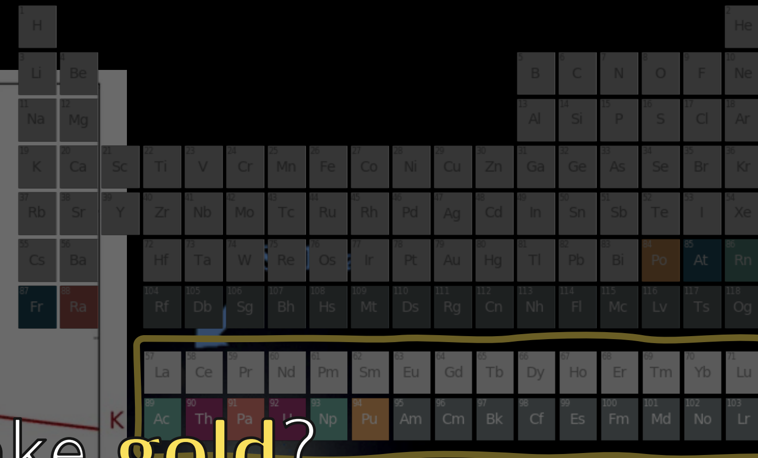
Metal-poor stars are an independent, more information-rich, and more numerous data source than kilonovae

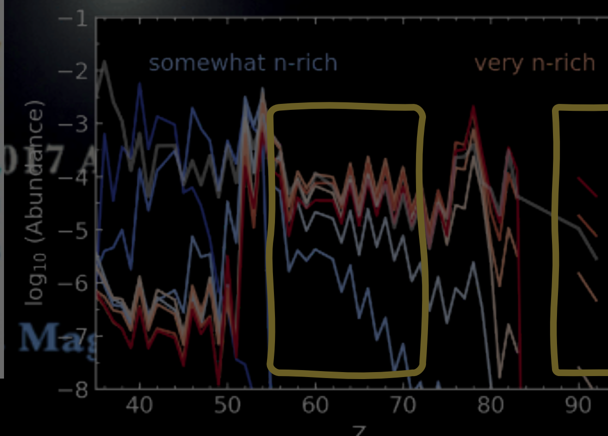
EMH+ (2022); data from LIGO/Virgo and NICER teams


Merger event
Nuclear Physics
Direct/prompt
Observables
Delayed
Observables
energy for ^{238}U
energies for lighter ions
non-enhanced

At least lanthanides (r-process elements) were made



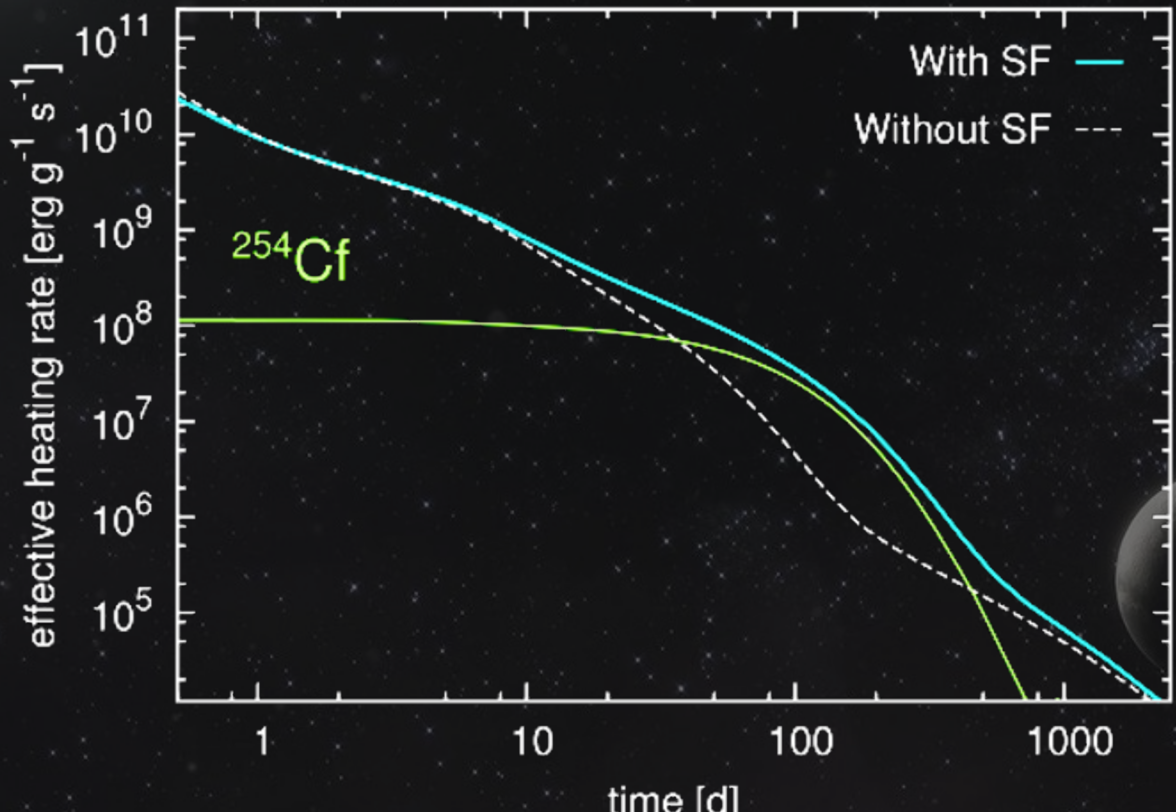




Did GW170817 make **gold**?

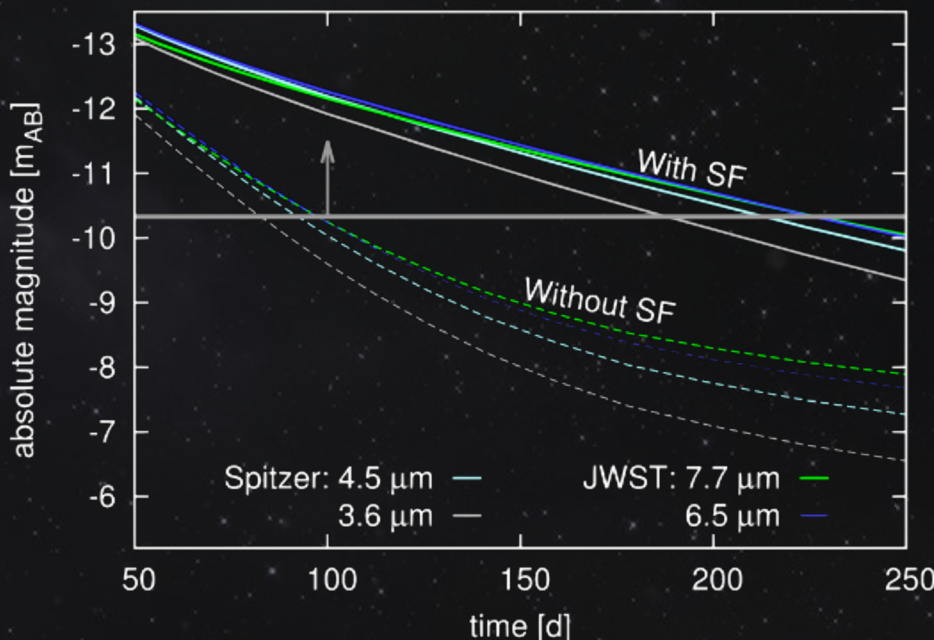
Villar+ (2017)

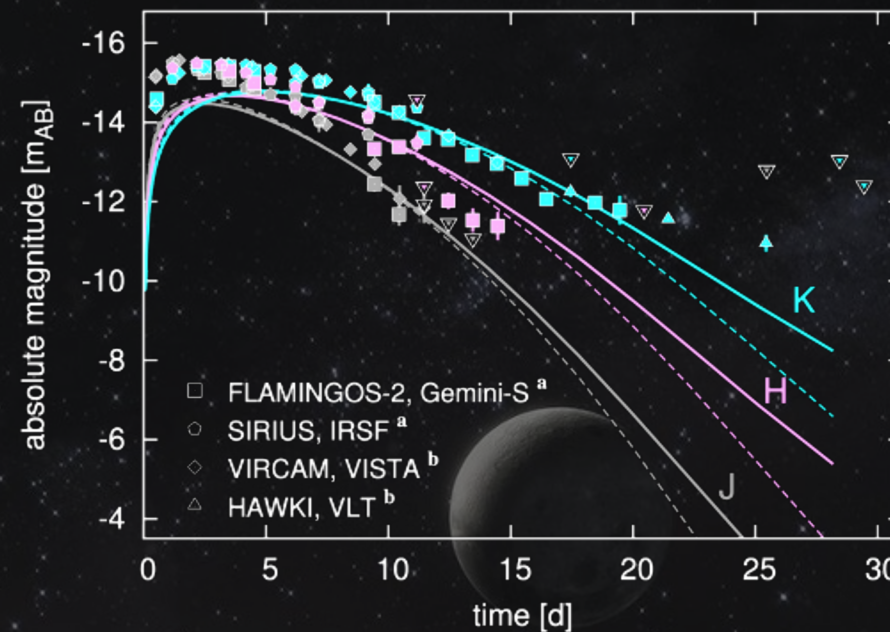
Possibly a lower limit for the extent of heavy-element production



Zhu, Wollaeger, Vassh+ (2018)

Possibly a lower limit for the extent of heavy-element production





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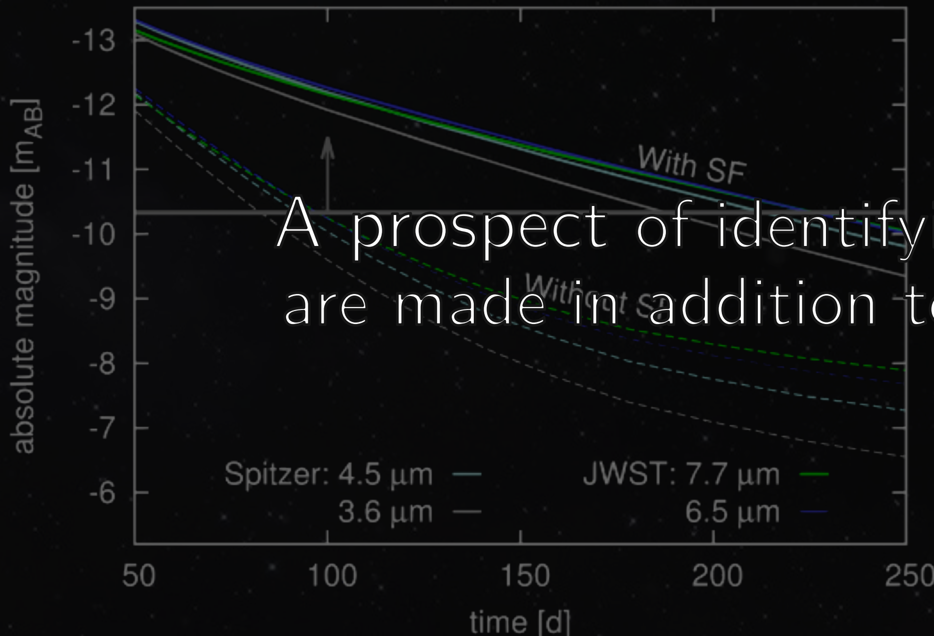
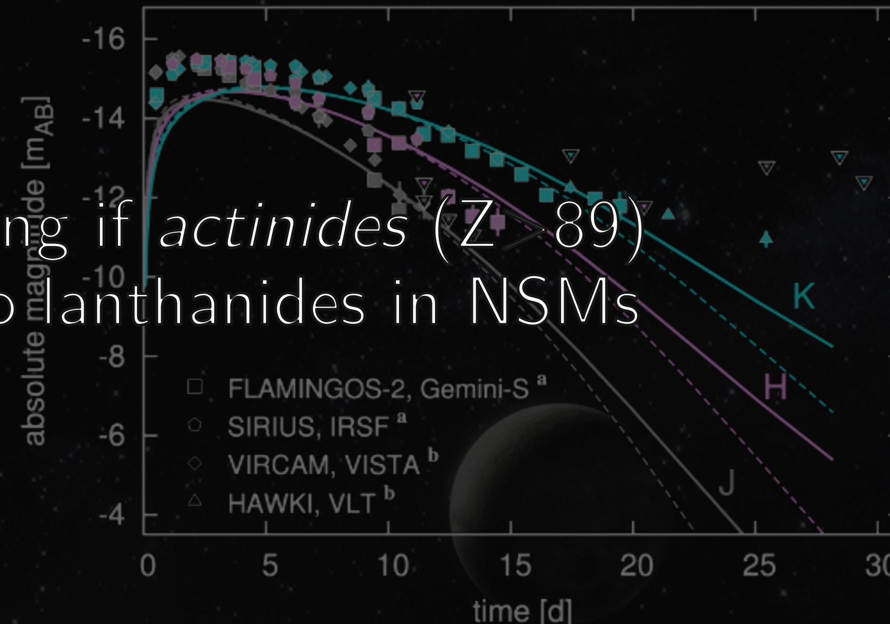
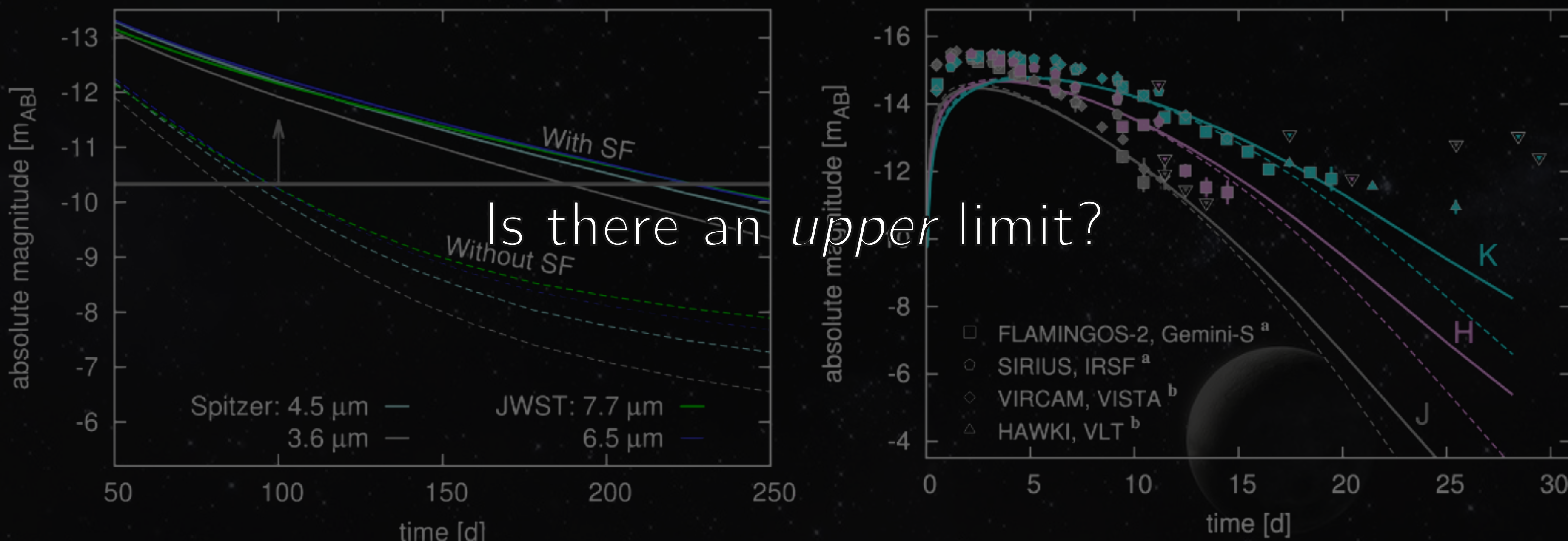




A prospect of identifying if *actinides* ($Z > 89$) are made in addition to lanthanides in NSMs

Zhu, Wollaeger, Vassh+ (2018)

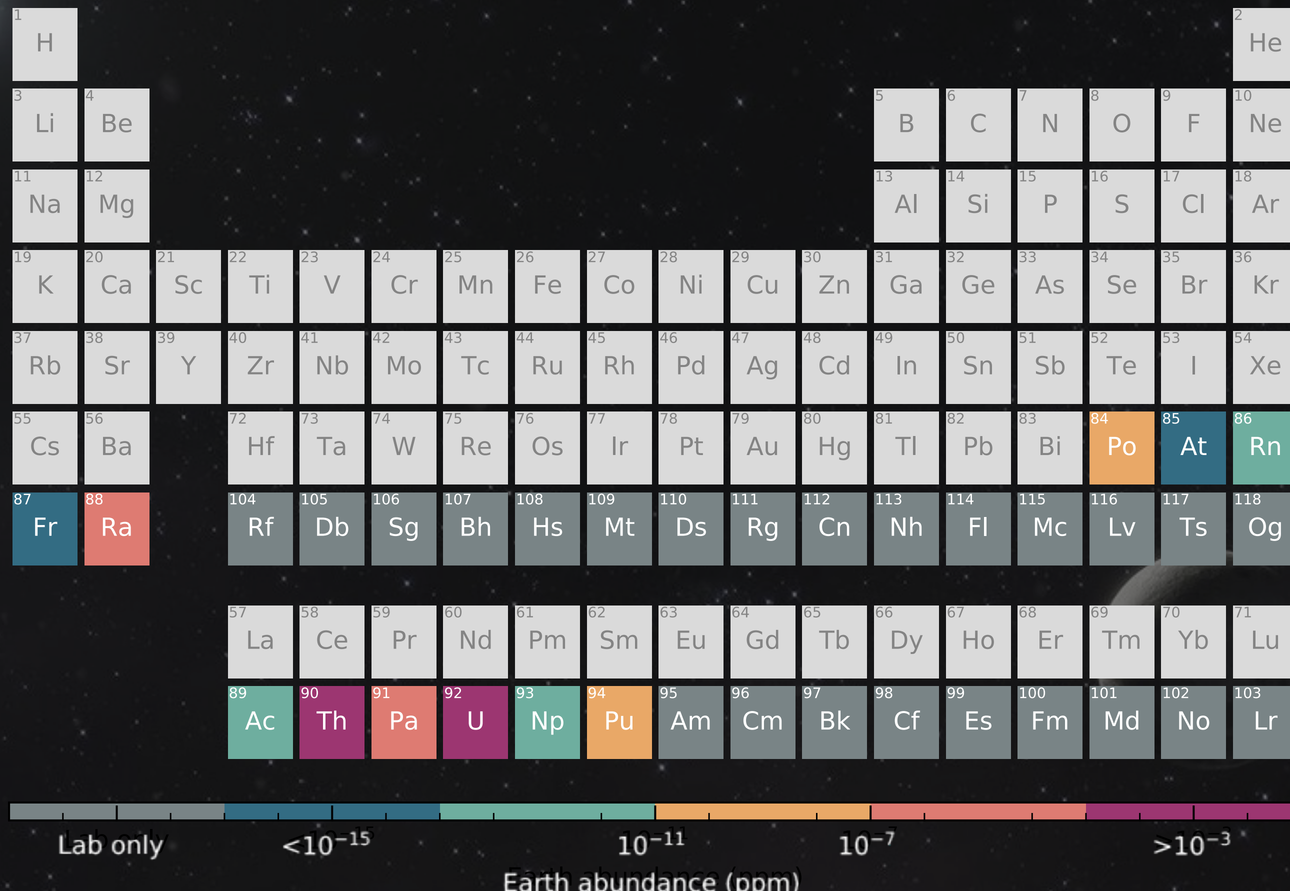
Possibly a lower limit for the extent of heavy-element production



Is there an *upper* limit?

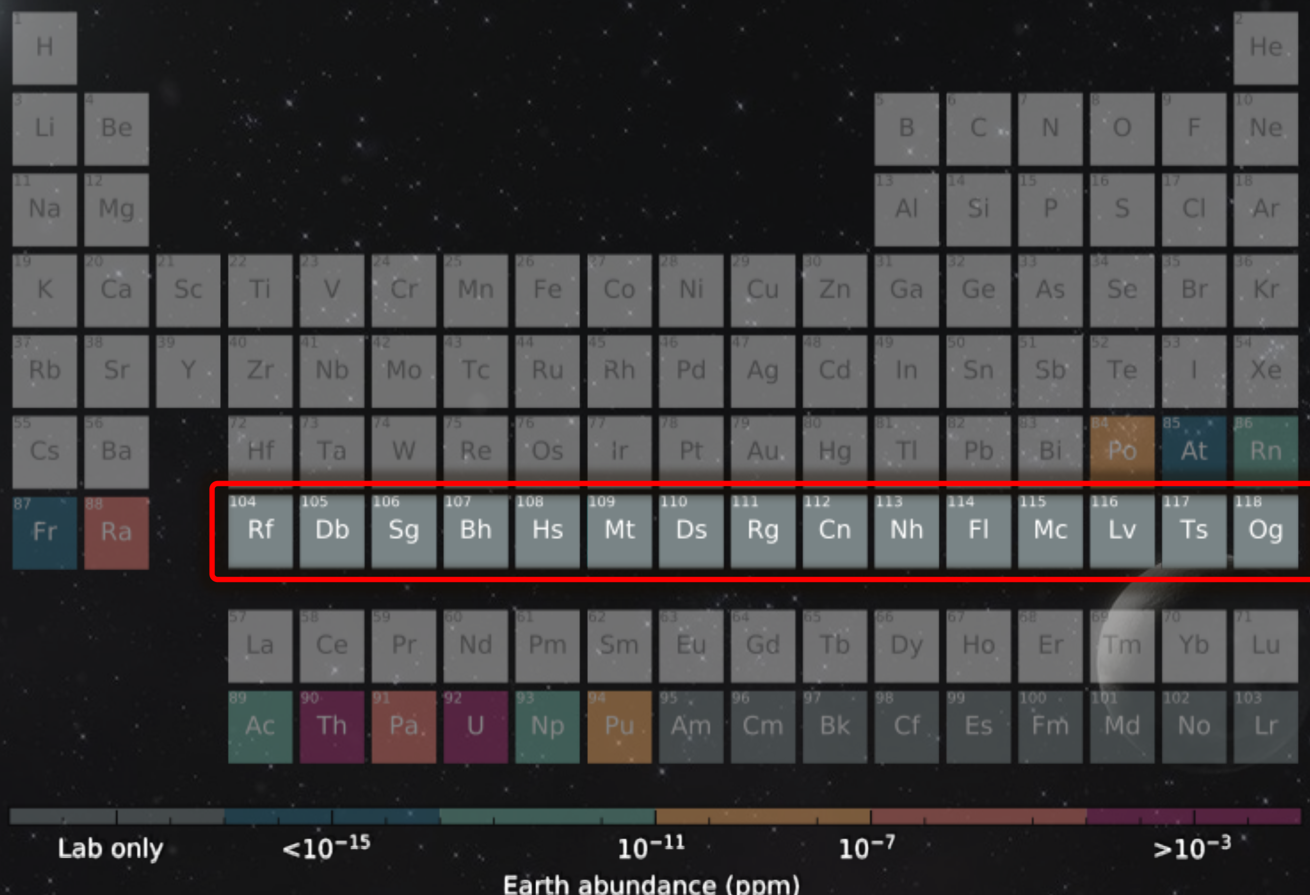
Zhu, Wollaeger, Vassh+ (2018)

Can the ***superheavy*** elements be made naturally?



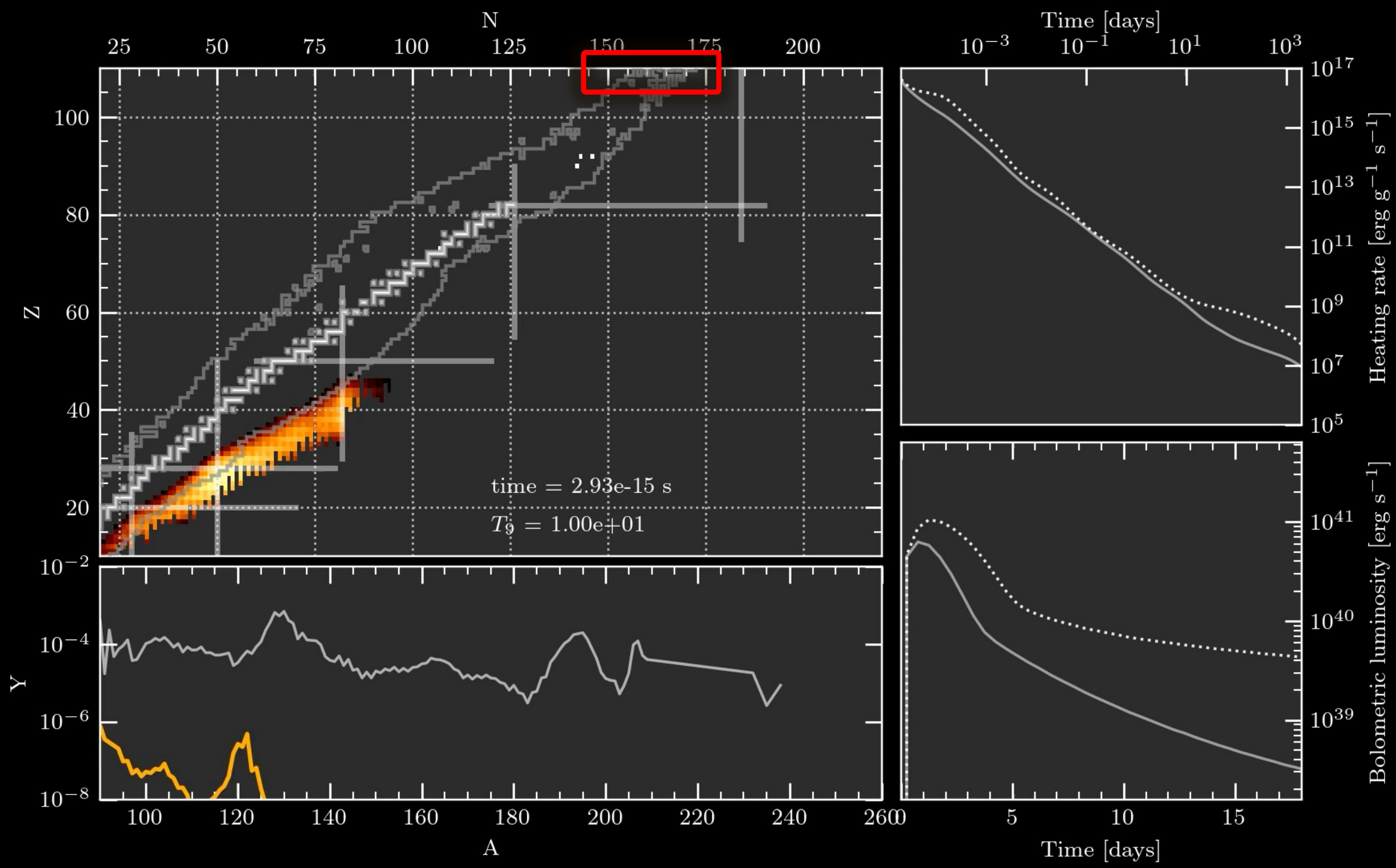
EMH+ (2023a)

Can the ***superheavy*** elements be made naturally?

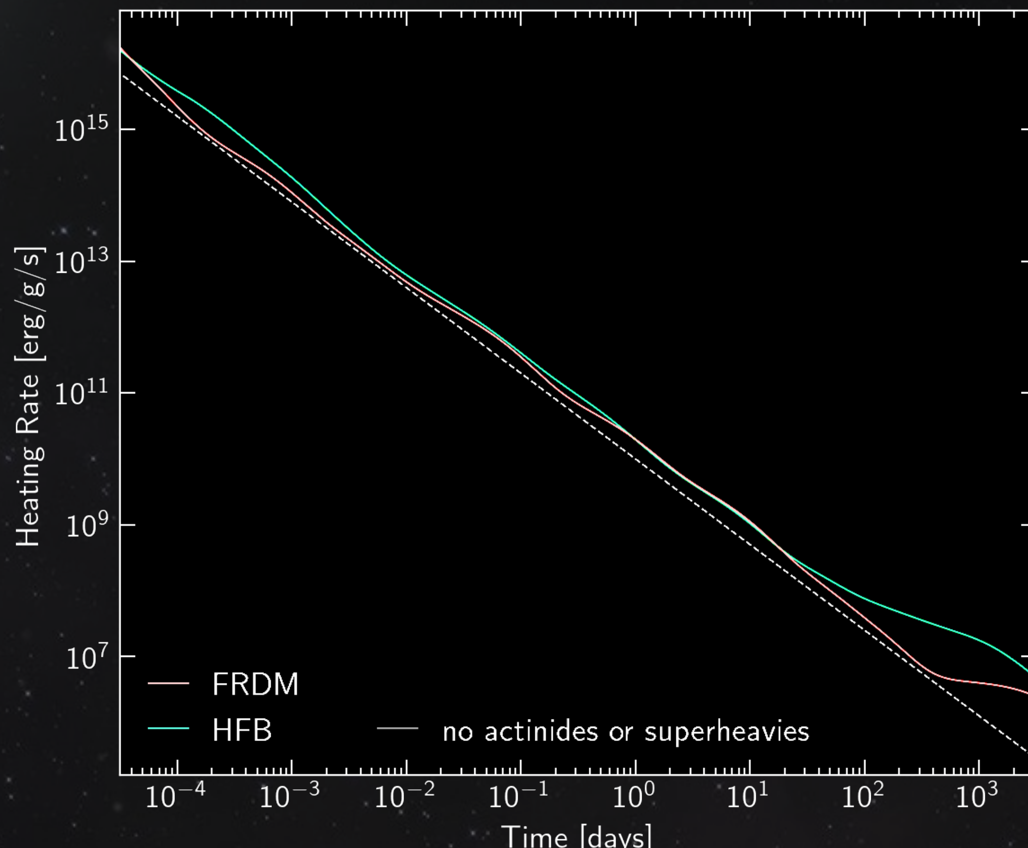


EMH+ (2023a)

The **observable** *r*-process

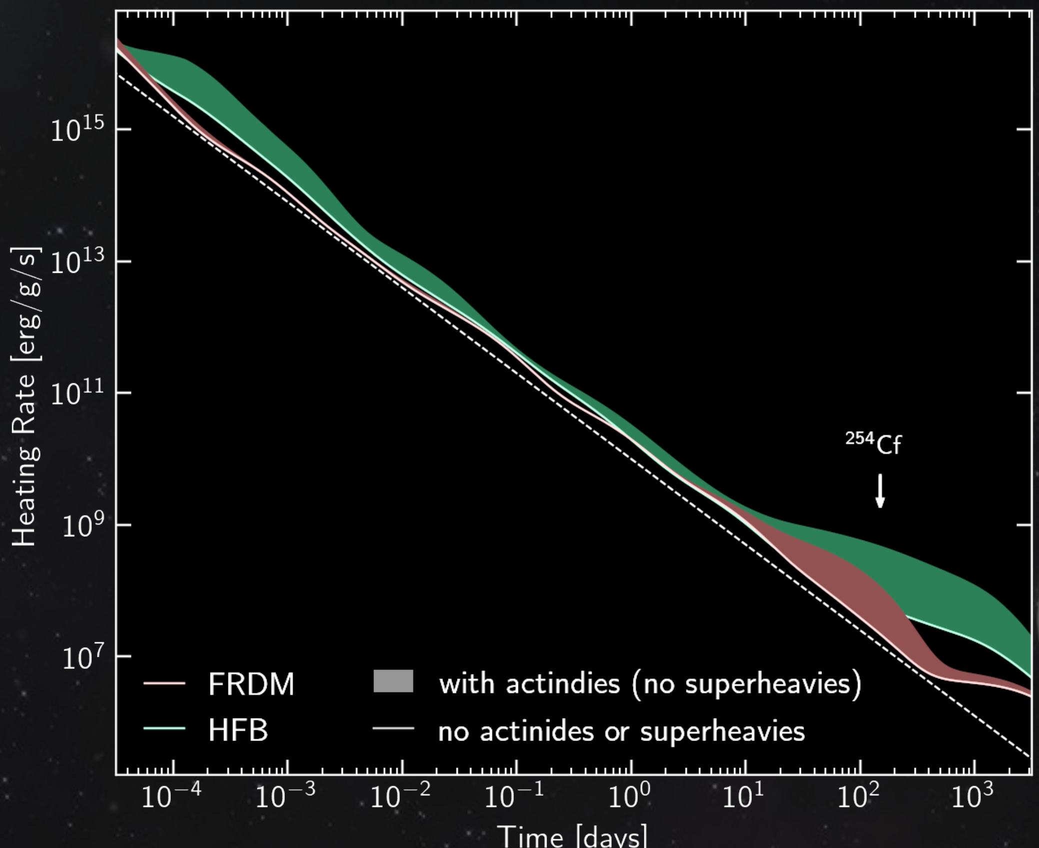


Do the superheavies leave a unique signature like we saw with the actinides?



EMH+ (2023b)

Do the superheavies leave a unique signature like we saw with the actinides?



EMH+ (2023b)

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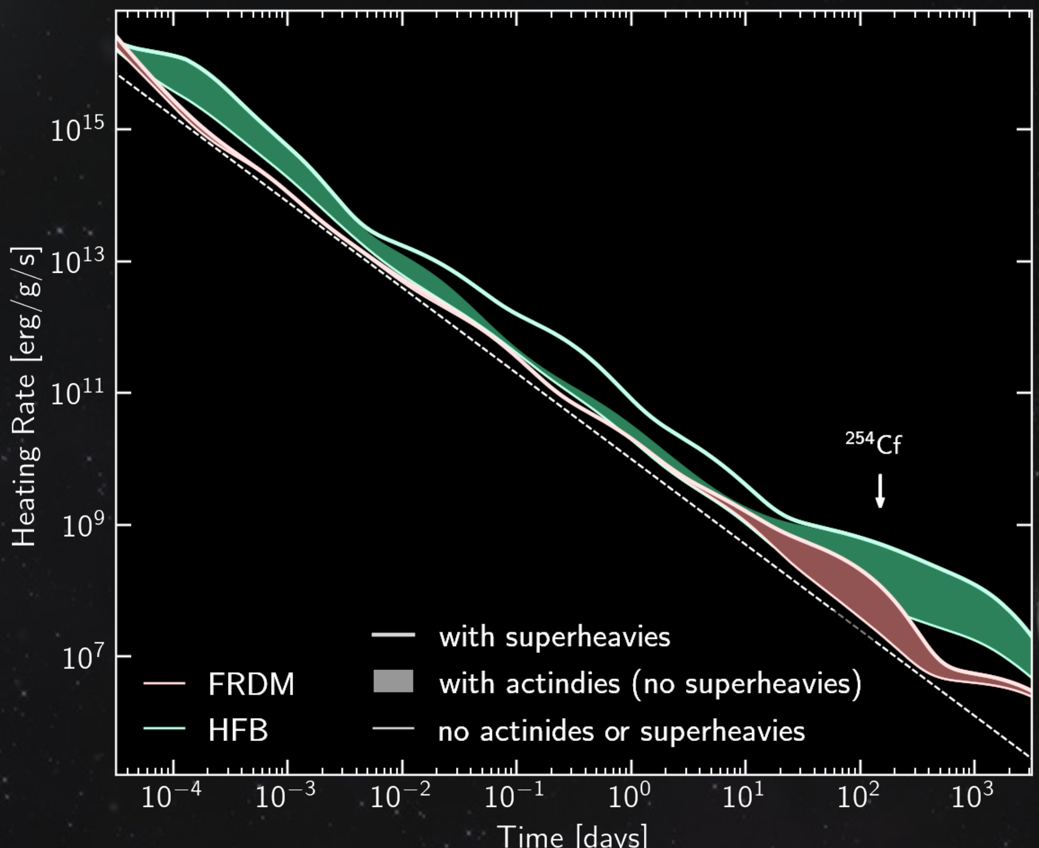
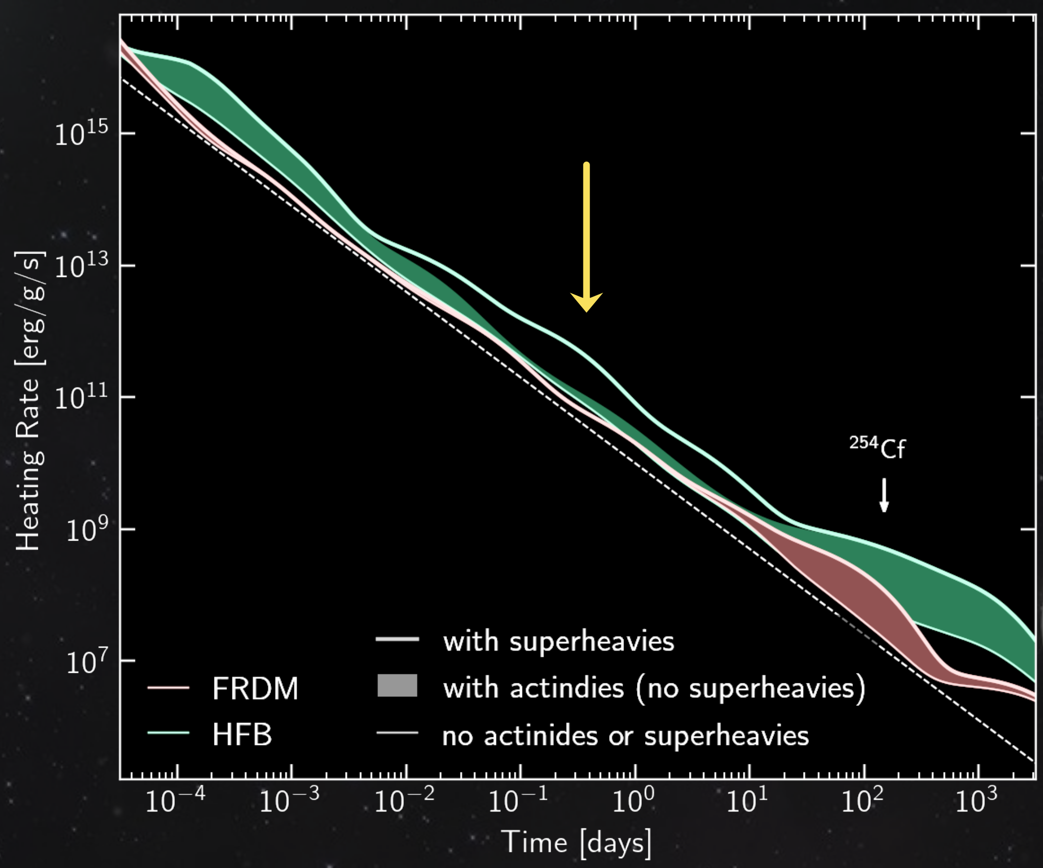


EMH+ (2023b)

A superheavy-unique feature is present at 7.5 hours post-merger!



EMH+ (2023b)

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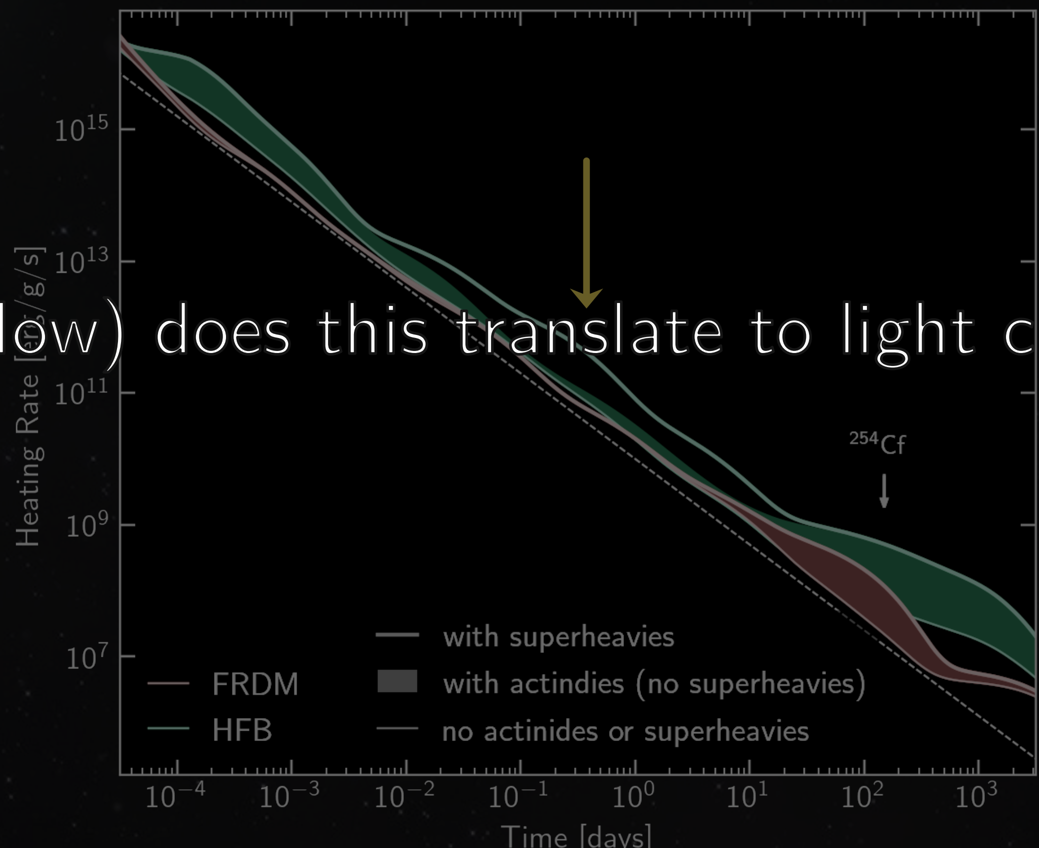
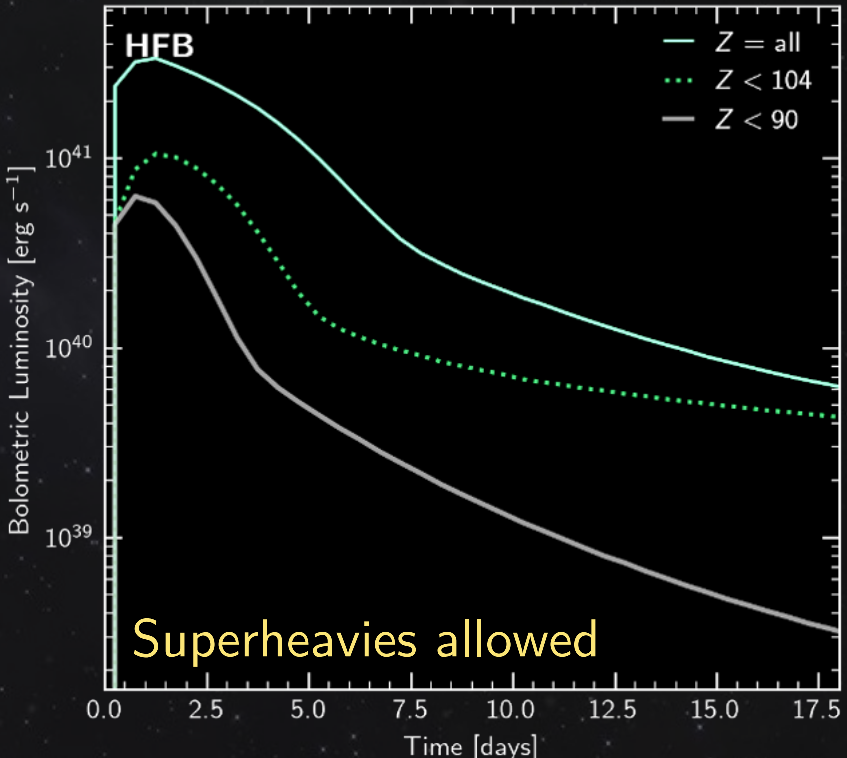
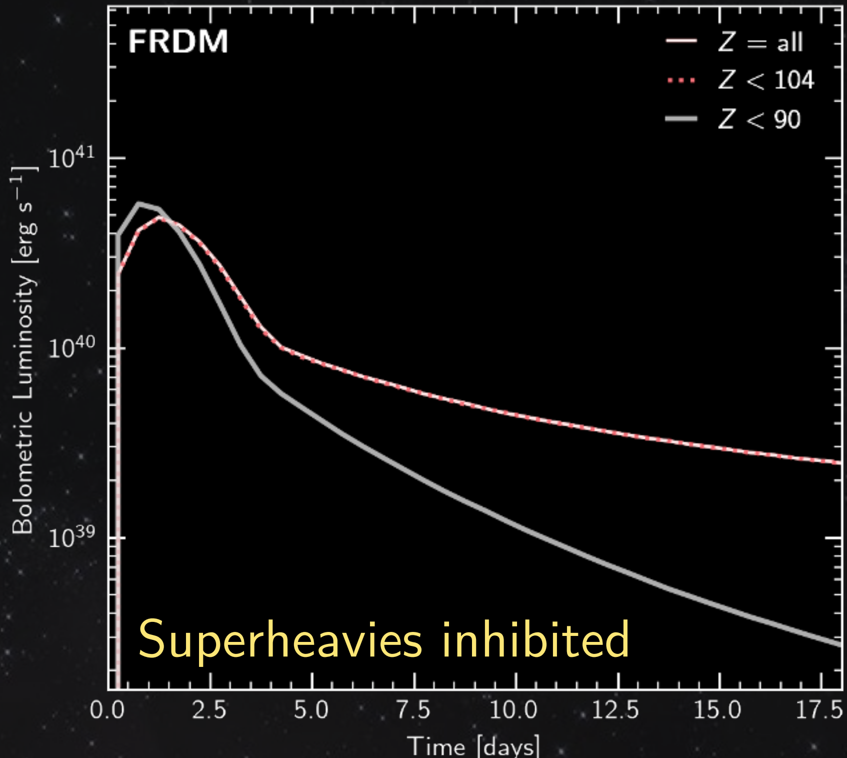


(How) does this translate to light curves?

EMH+ (2023b)

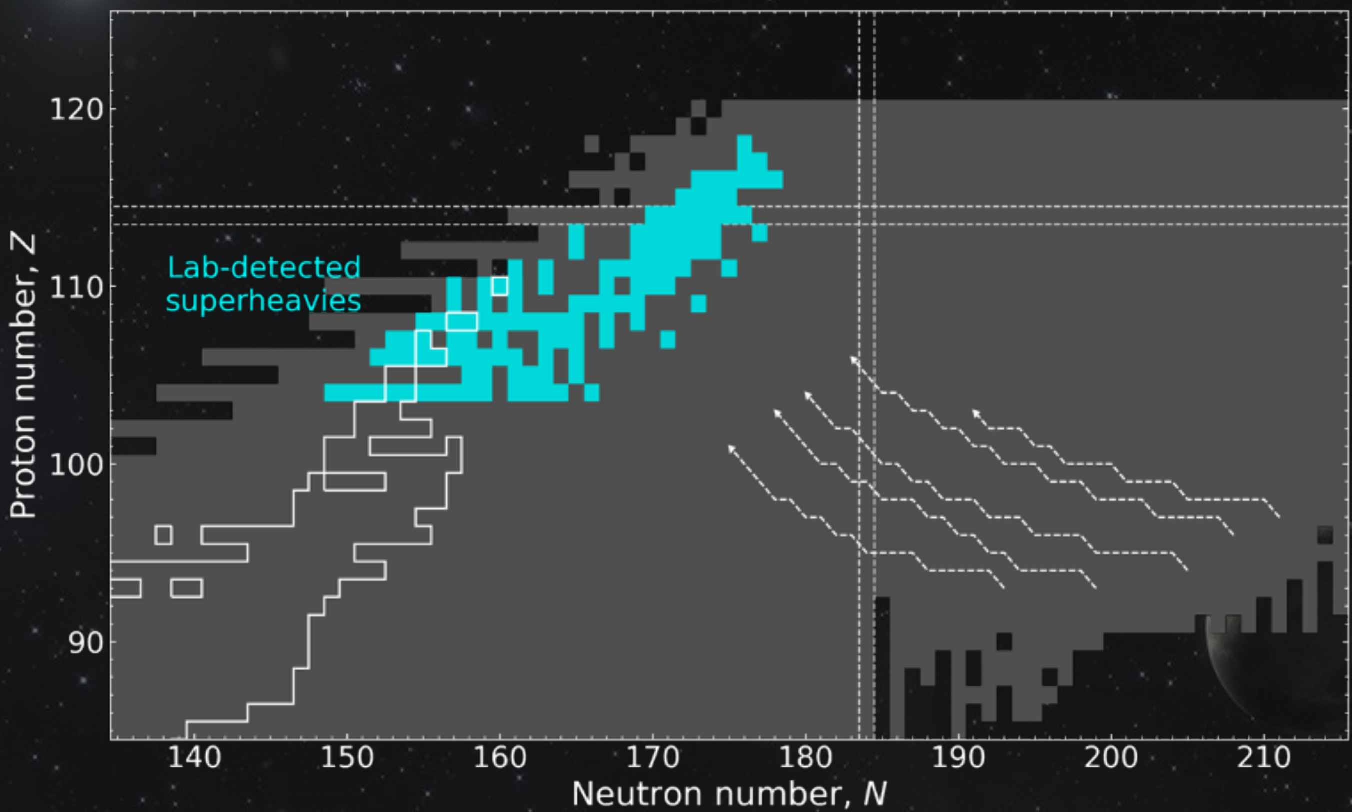
Superheavy elements *can* leave an impression *if* they are made





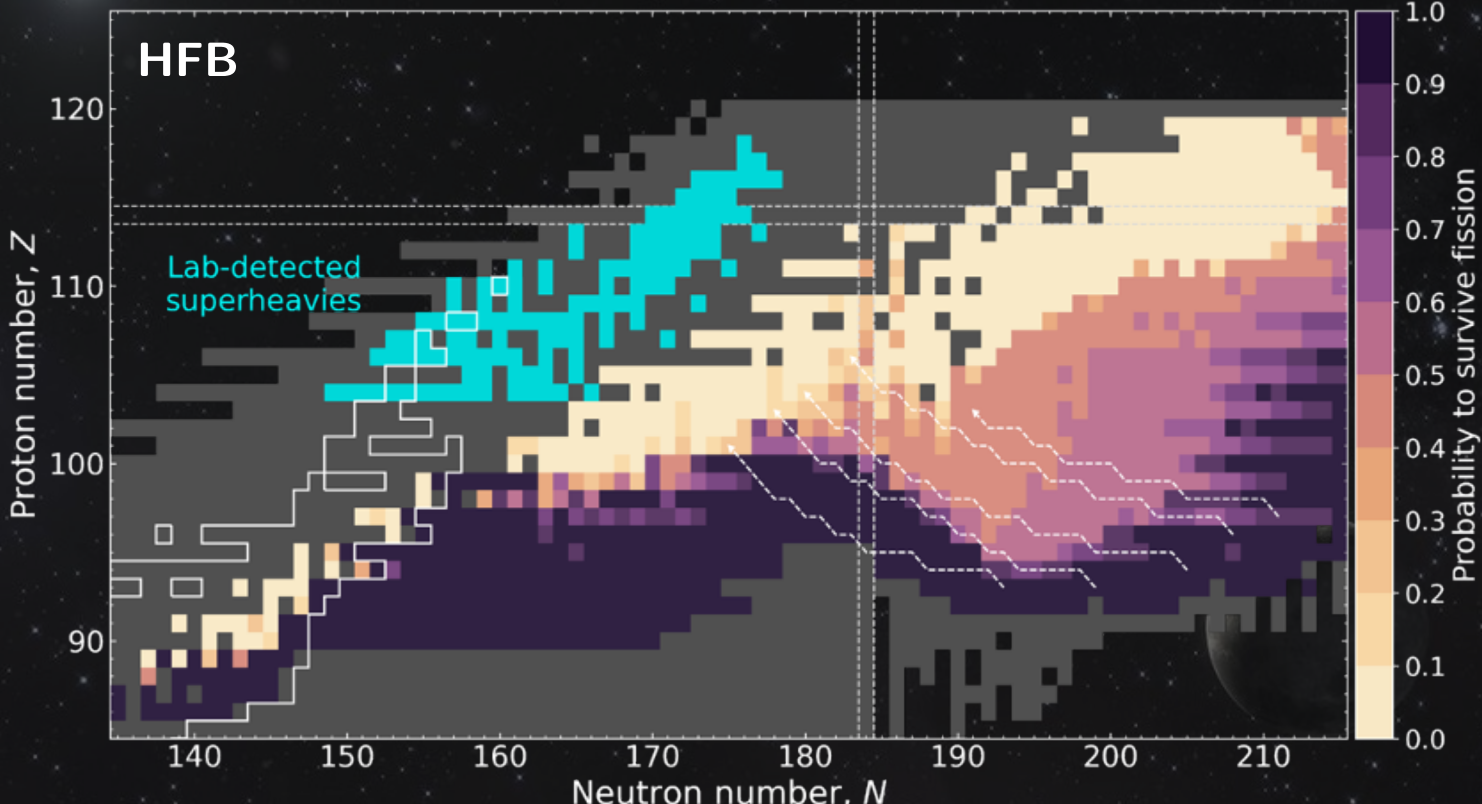
EMH+ (2023b)

The nuclear physics behind superheavy creation in the *r*-process



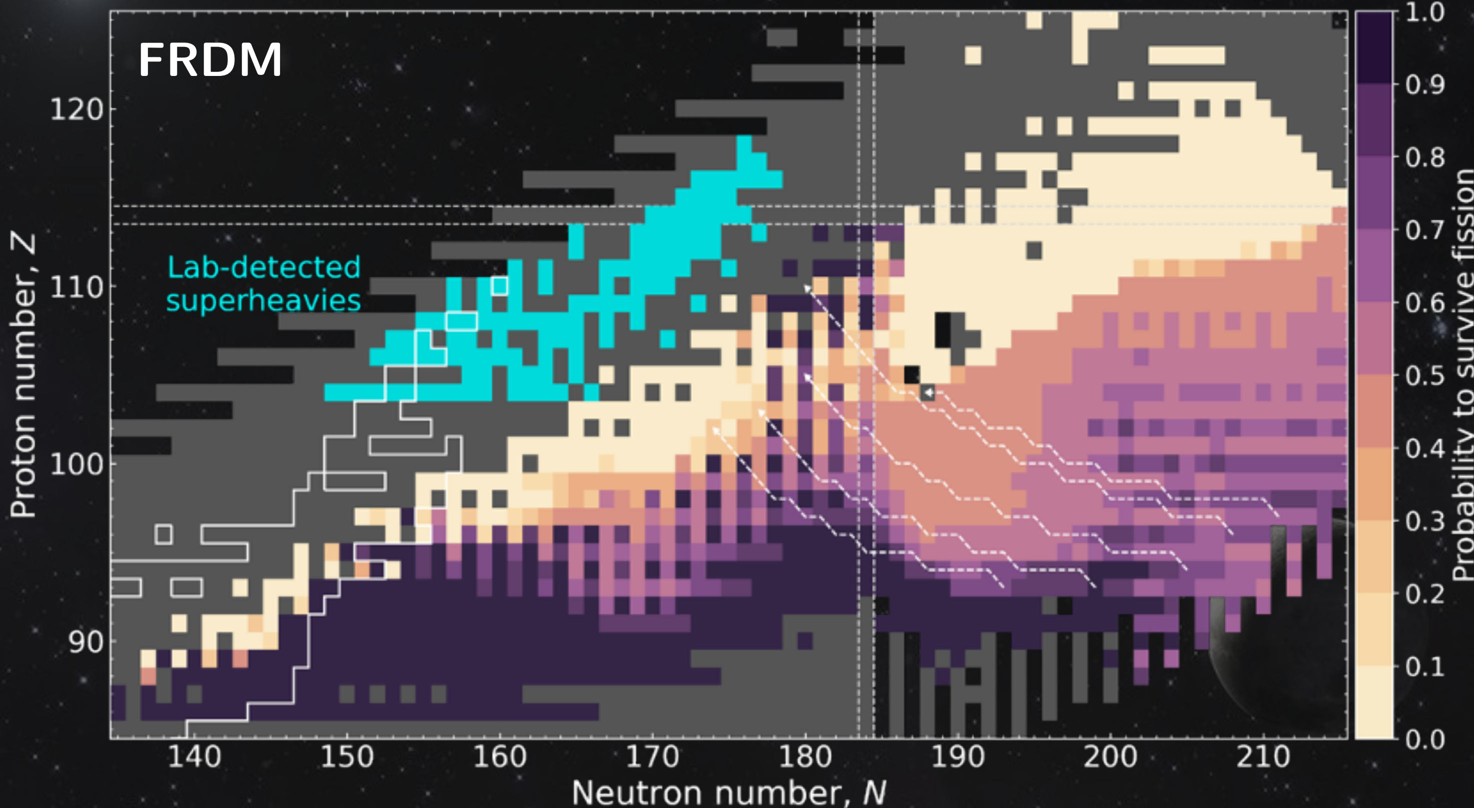
EMH+ (2023a)

The nuclear physics behind superheavy creation in the *r*-process



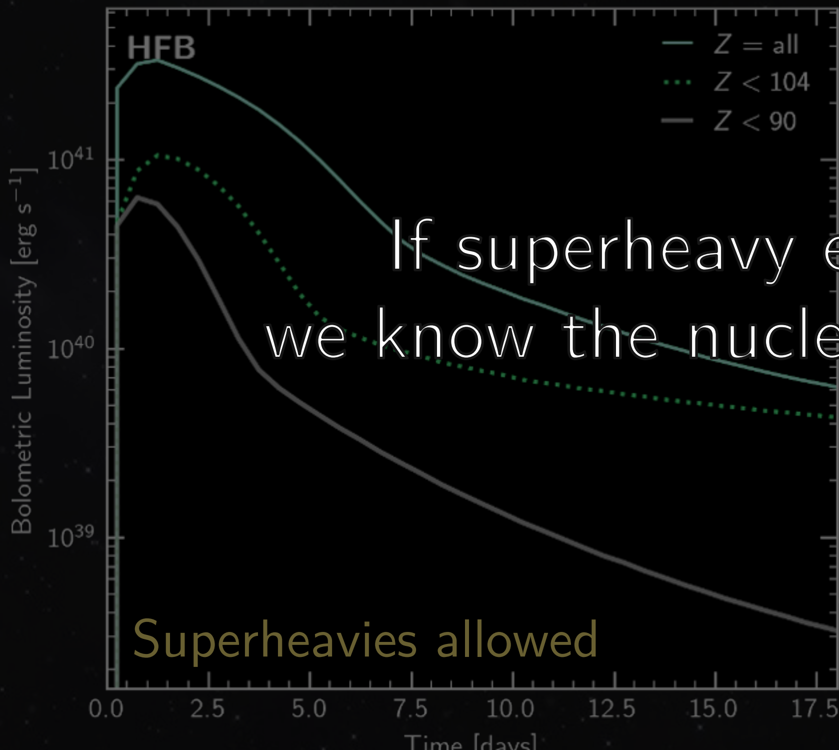
EMH+ (2023a)

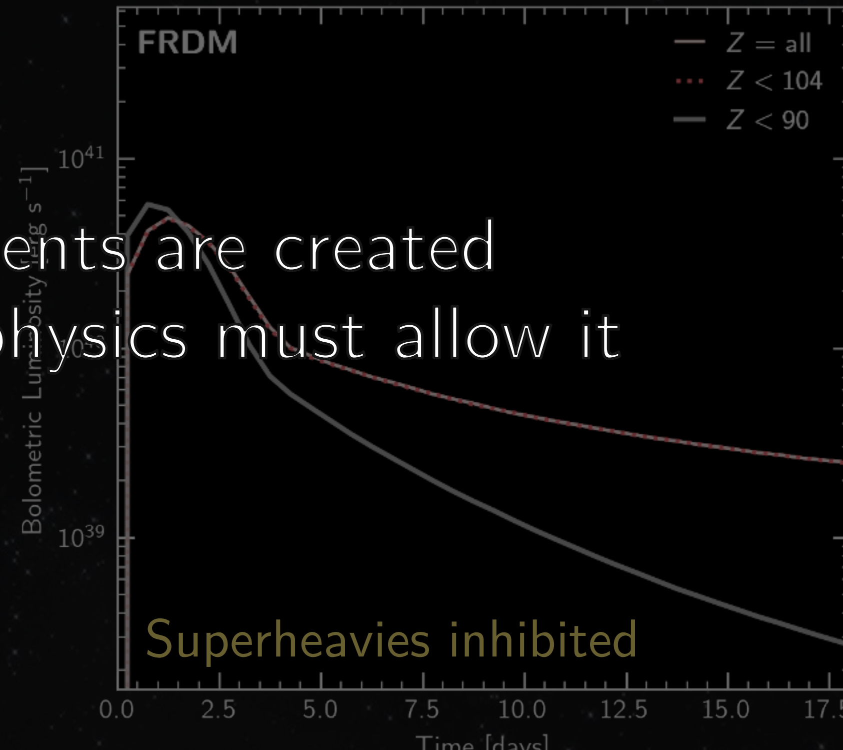
The nuclear physics behind superheavy creation in the *r*-process



EMH+ (2023a)

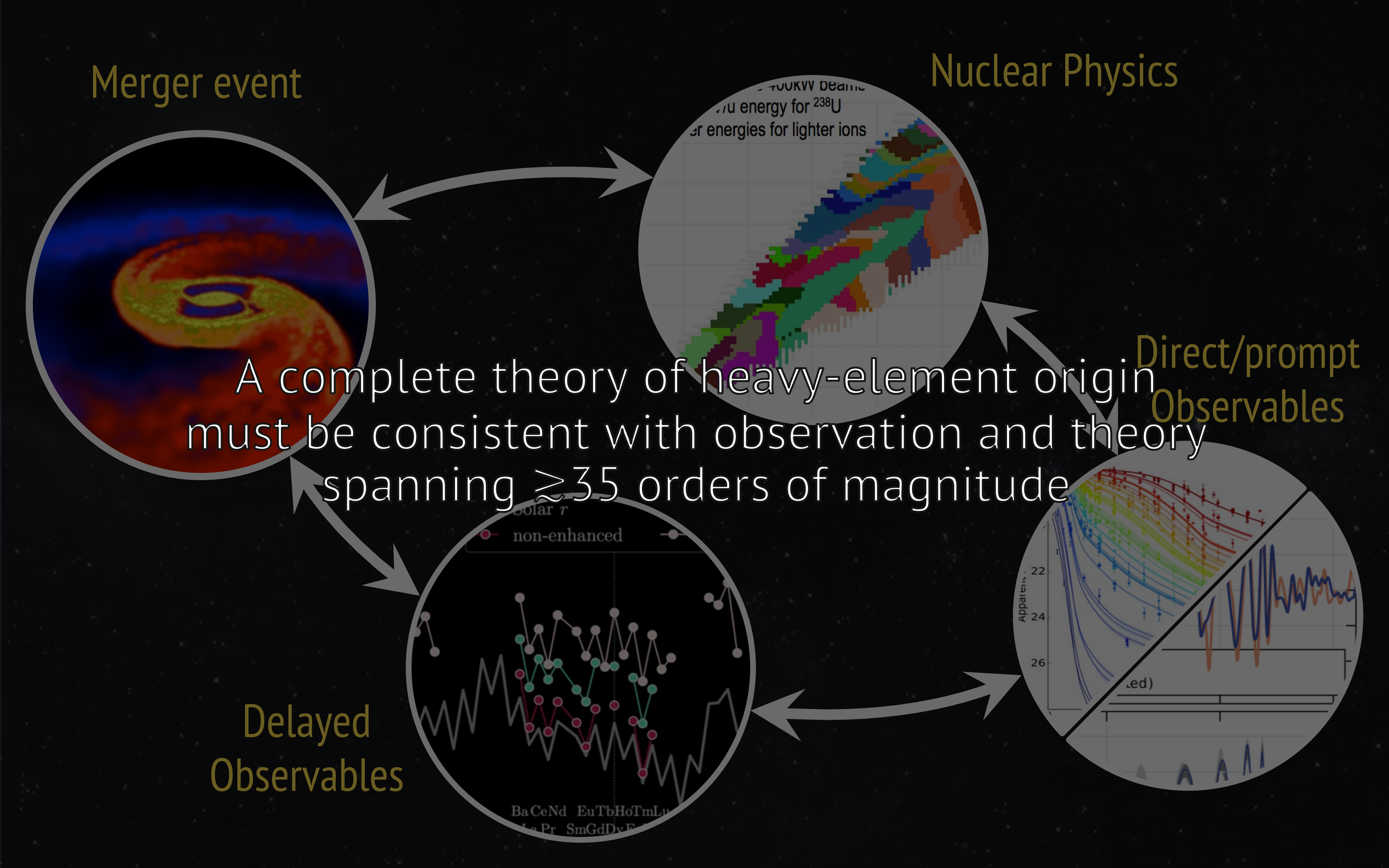
Superheavy elements *can* leave an impression *if* they are made





If superheavy elements are created
we know the nuclear physics must allow it

EMH+ (2023b)


Merger event
Nuclear Physics
Direct/prompt Observables
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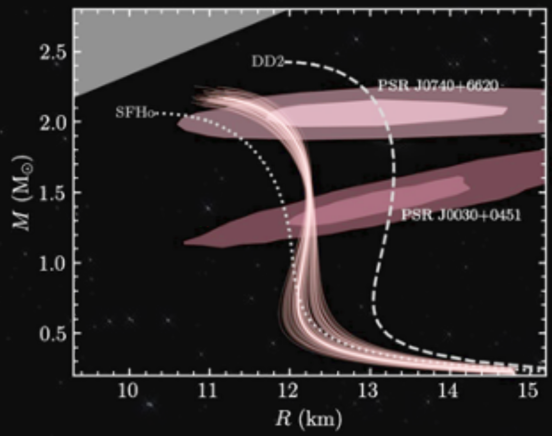
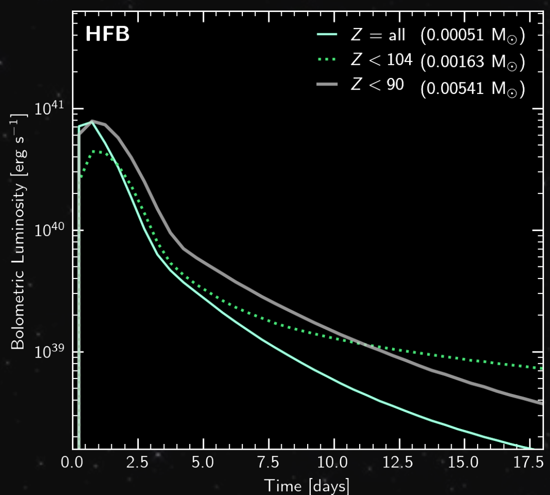
A complete theory of heavy-element origin must be consistent with observation and theory spanning ≳35 orders of magnitude
non-enhanced





In Summary

A comprehensive understanding of NSMs and heavy-element production should explain *r*-process enrichments of ***metal-poor stars***, which are themselves information-rich sources of data

We have an exciting opportunity to observe the in-situ production of the heaviest elements, but beware of ***degeneracies*** and ***uncertainties*** from nuclear physics

Light curves can tell us about the extent of heavy-element production in mergers, providing information for both ***astrophysics*** and ***nuclear physics***

Using all our observations (stars, kilonovae, GWs) together is essential

Thank you!

Lawrence Livermore National Laboratory

Carnegie Science