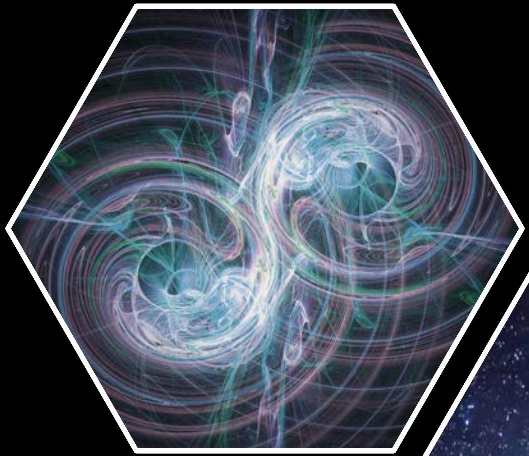
Properties of *r*-Process-Producing Neutron Star Mergers: What We Can Learn from Metal-Poor Stars

Erika M. Holmbeck

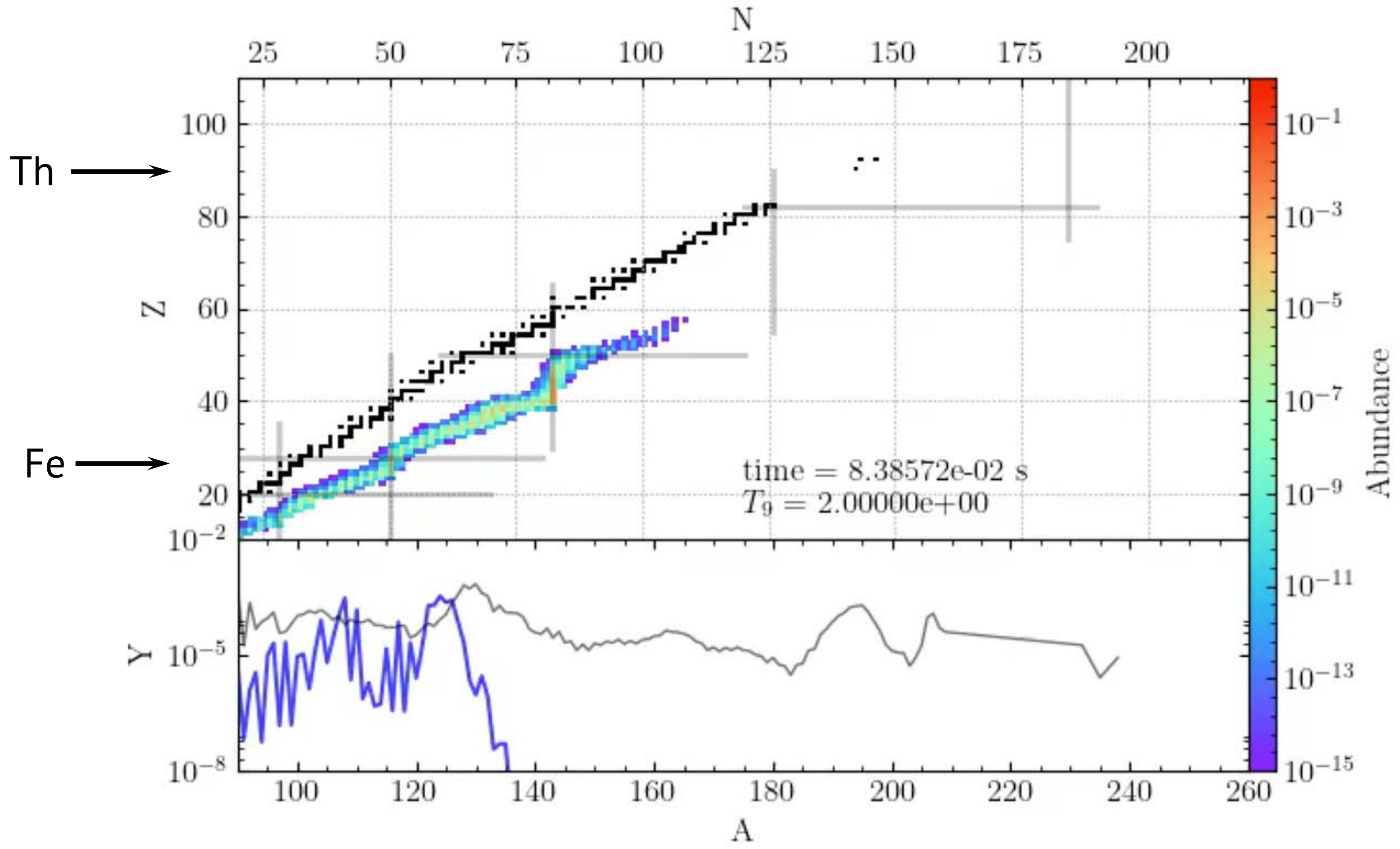
N3AS Seminar | 6 October 2020

arXiv:2010.01621



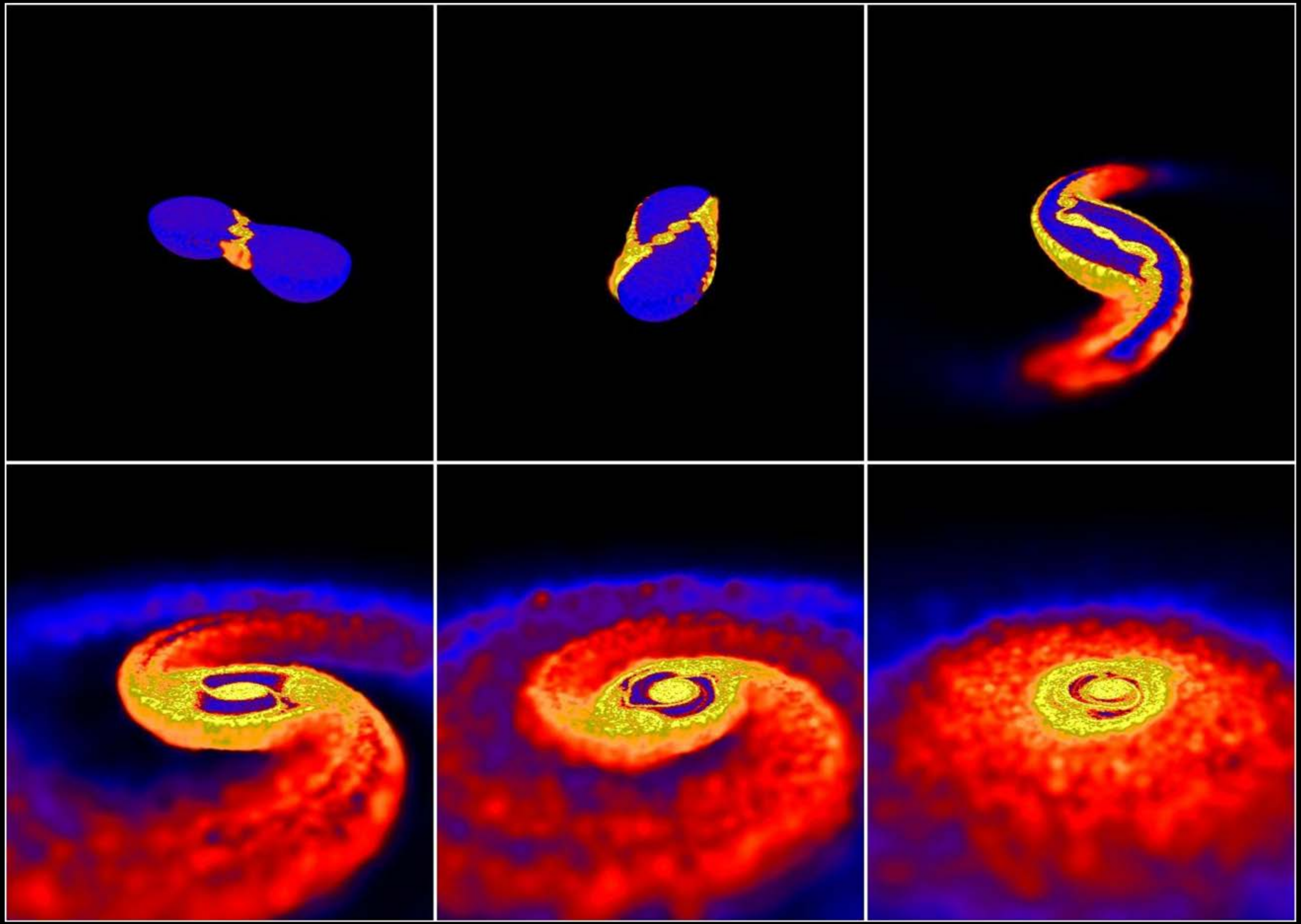
RIT | Rochester Institute of Technology

The ***r*-process** produces the heaviest observable elements, including the actinides, **thorium and uranium**

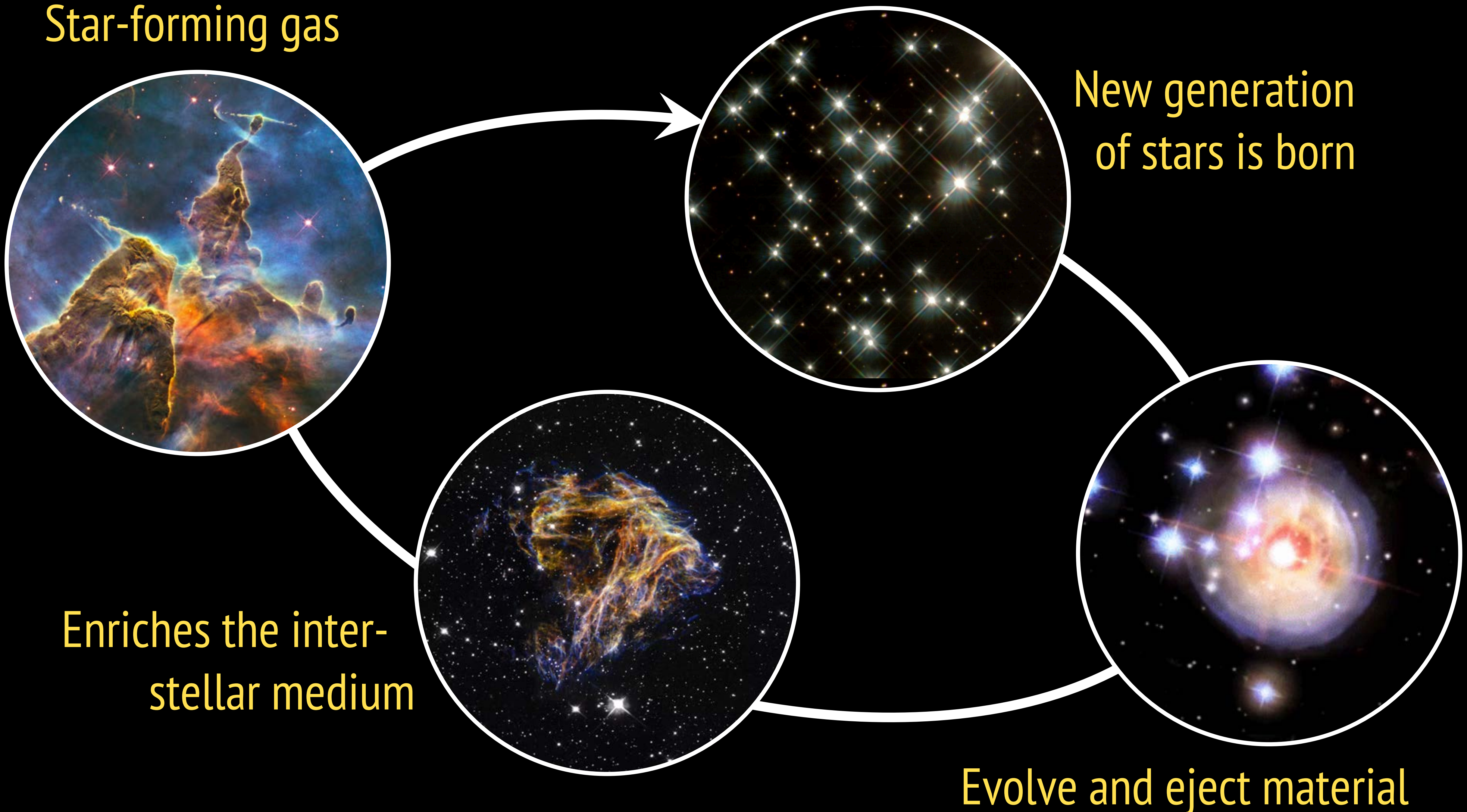


PRISM (Sprouse & Mumpower)

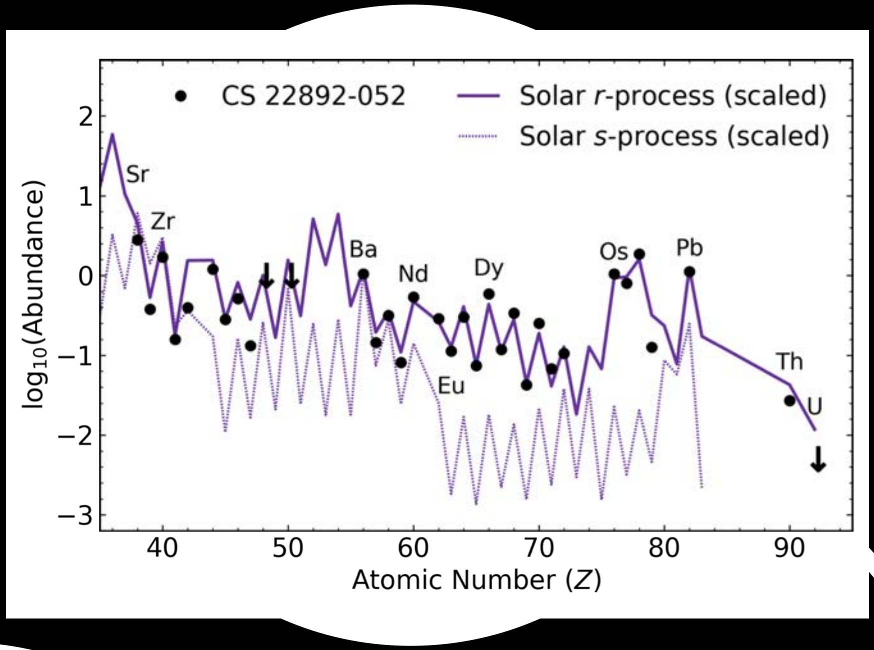
NSMs are one **confirmed** *r*-process site



Price & Rosswog (2006)


Star-forming gas
New generation of stars is born
Evolve and eject material
Enriches the inter-stellar medium

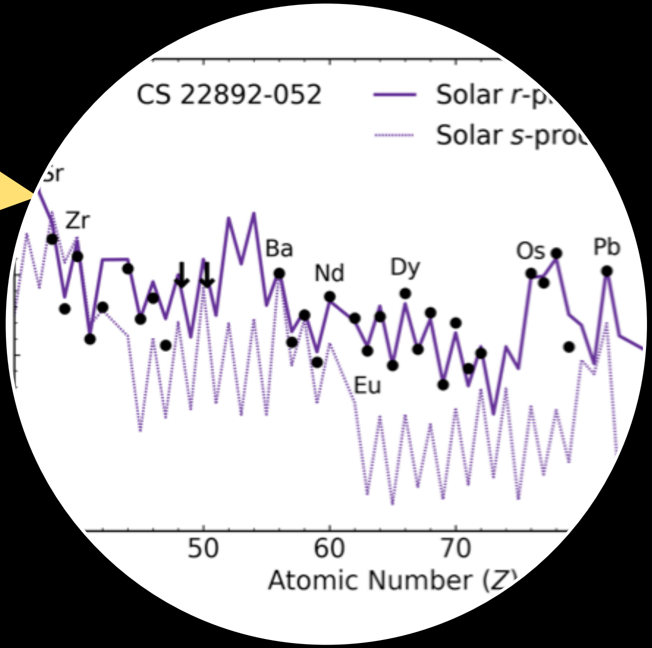
Star-forming gas



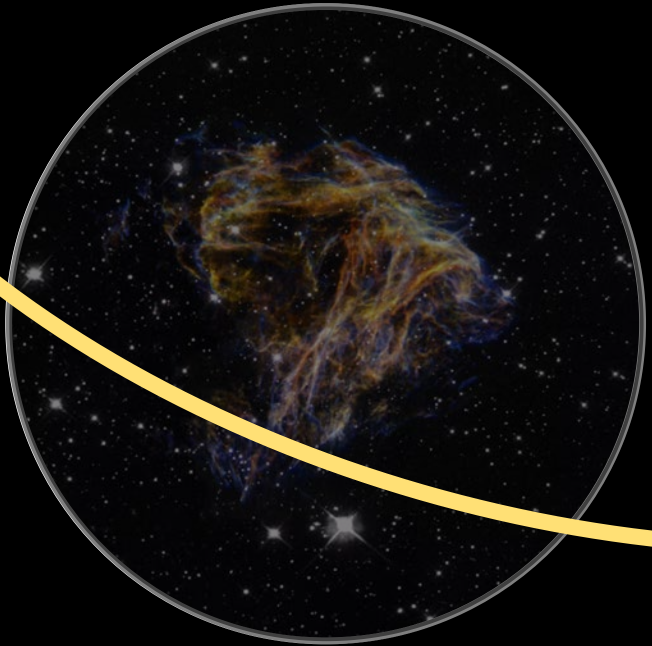
Metal-poor, "*r*- stars"

Enriches the inter-stellar medium

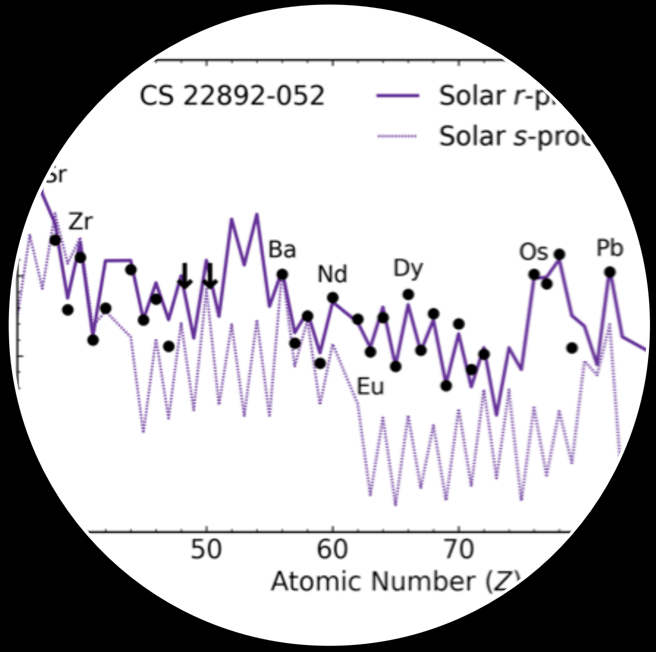
r-Process Event



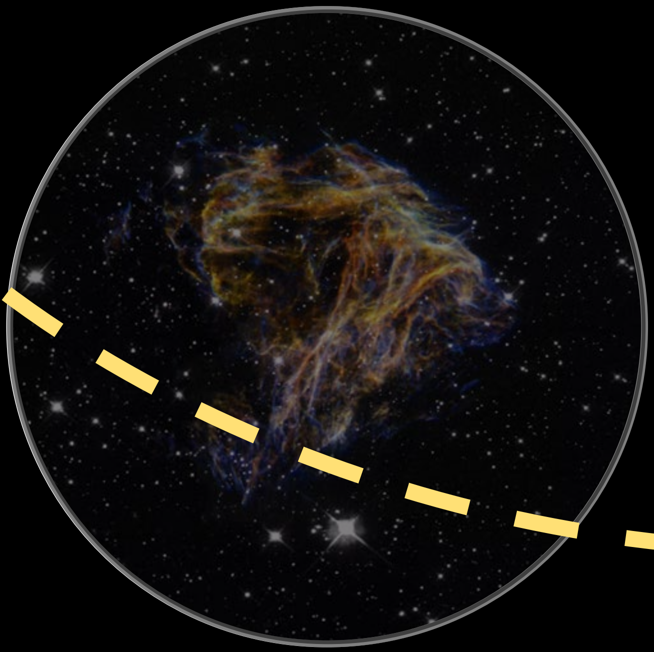
Metal-poor,
“*r*- stars”



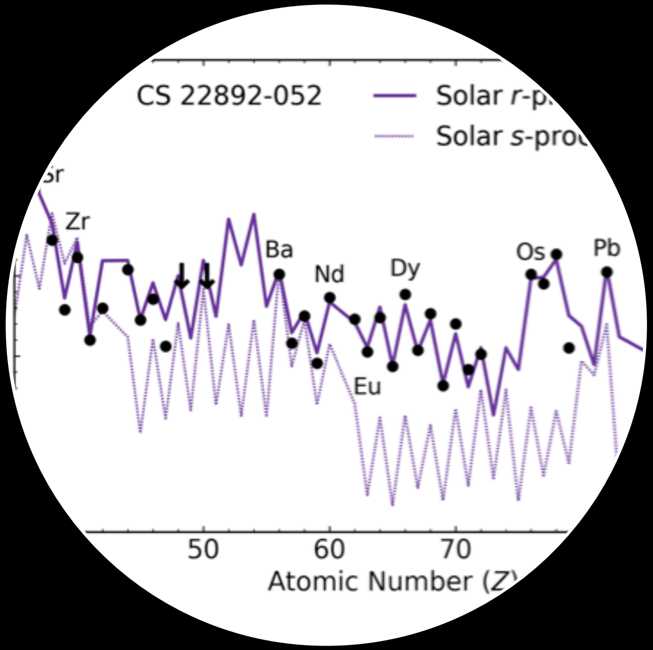
r-Process Event



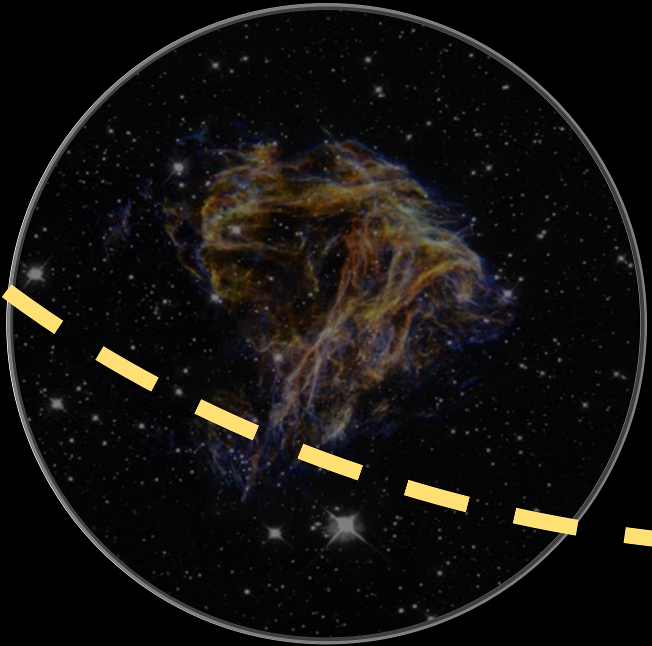
Metal-poor,
"r- stars"

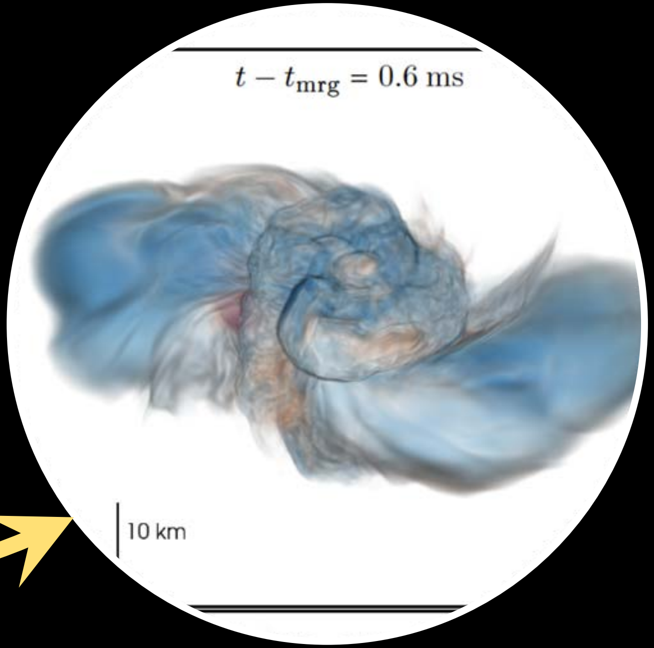


r-Process Event



Metal-poor,
“*r*- stars”

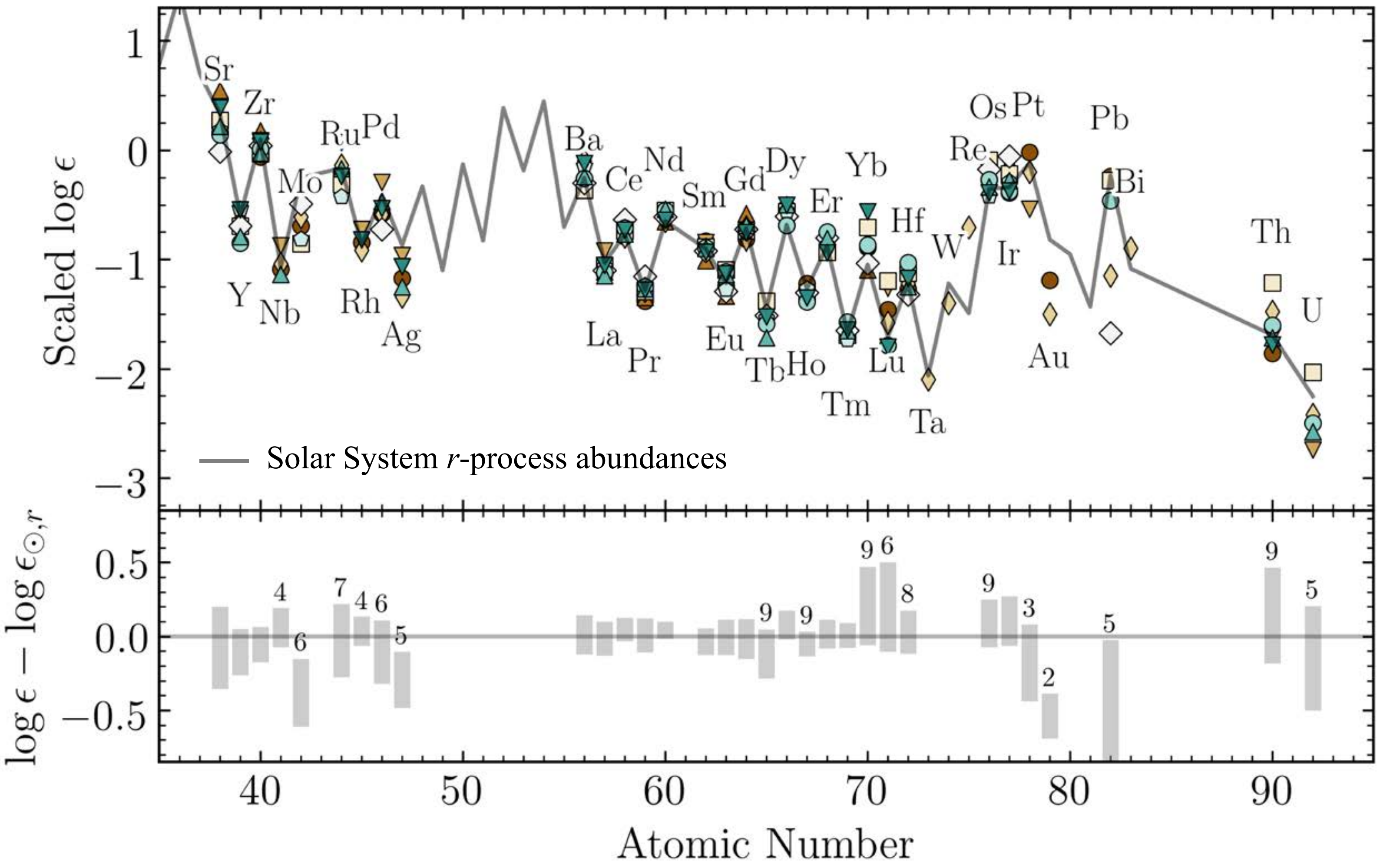




NSM Details

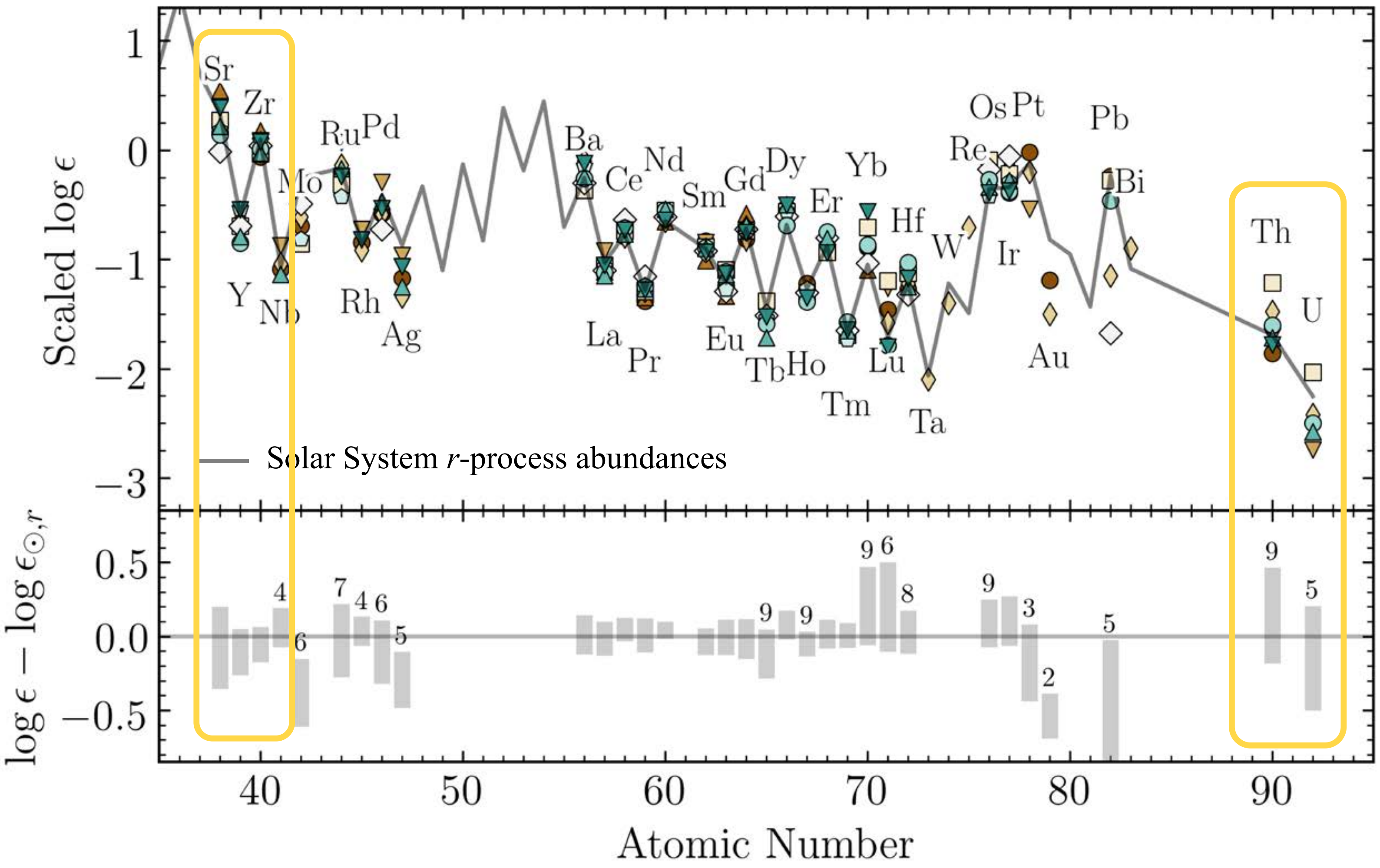
What can we learn about NSMs from metal-poor stars?

Elemental **variations** exist between the abundance patterns of metal-poor stars



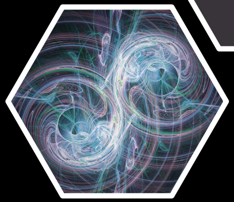
Holmbeck+ (2020a; arXiv: 2001.08792)

Elemental **variations** exist between the abundance patterns of metal-poor stars



* "limited-r"

Holmbeck+ (2020a; arXiv: 2001.08792)

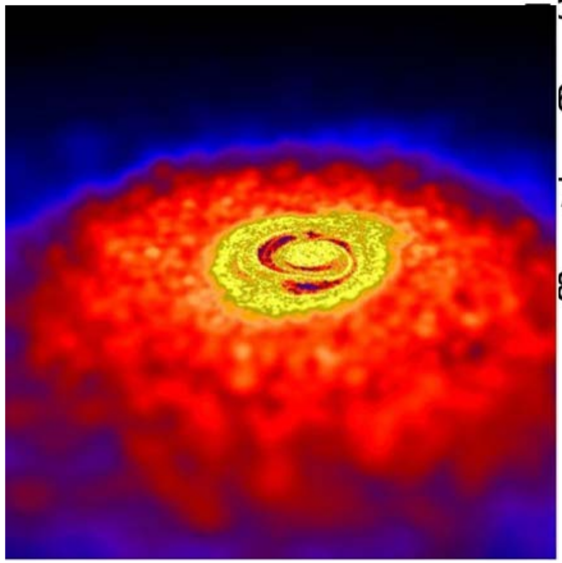


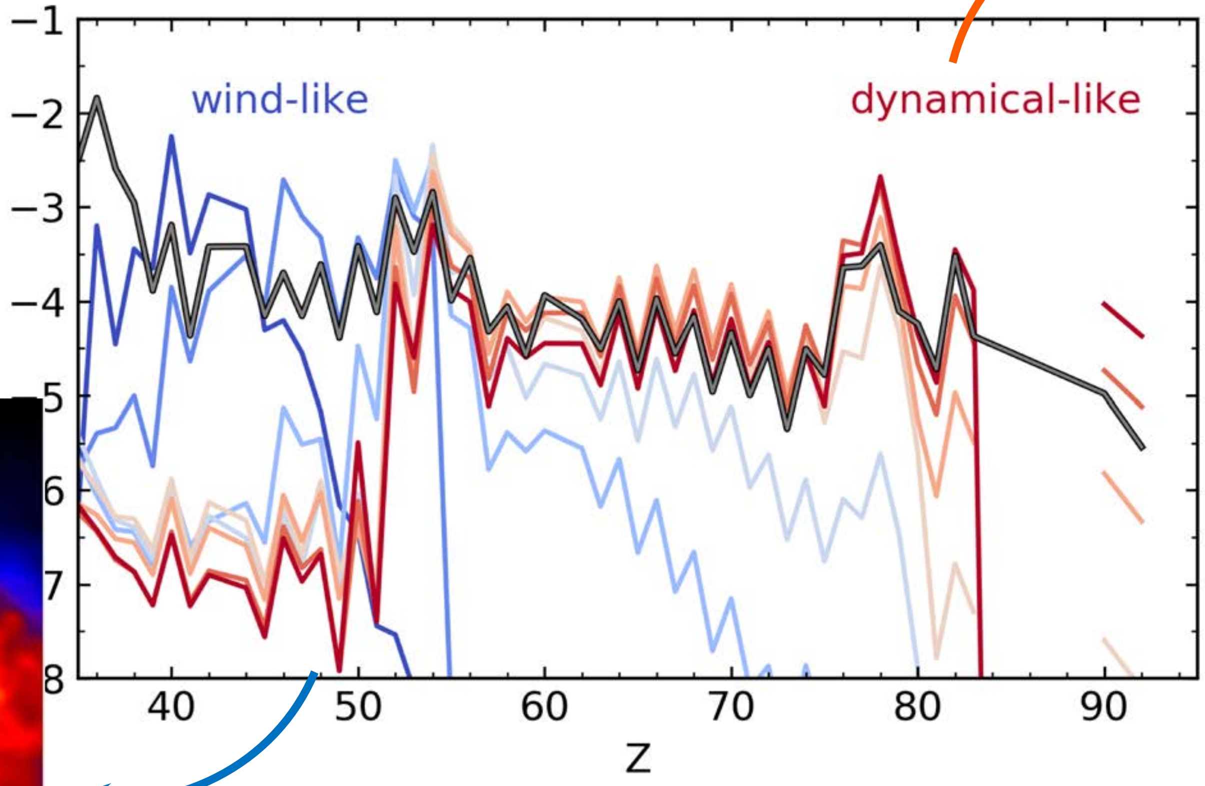
Hypothesis

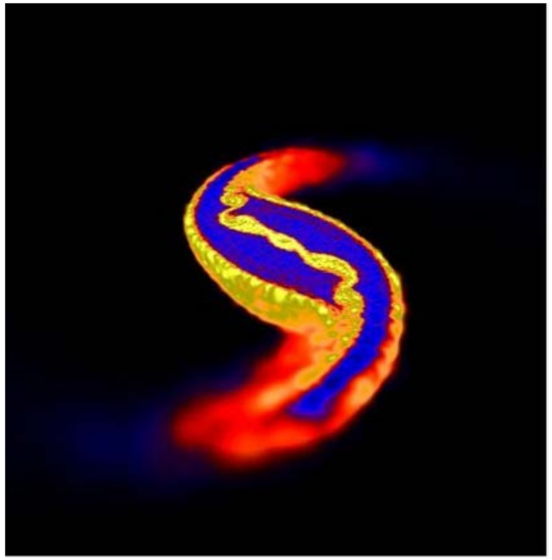
The actinide and limited-*r* abundances differences are signatures of **physically different** NS-NS binaries

The moderate neutron-richness of the disk wind ejecta and the extreme neutron-richness of the dynamical ejecta produce **characteristic abundances**

Wind:
moderately *n*-rich
(Y_e ~ 0.2-0.4)



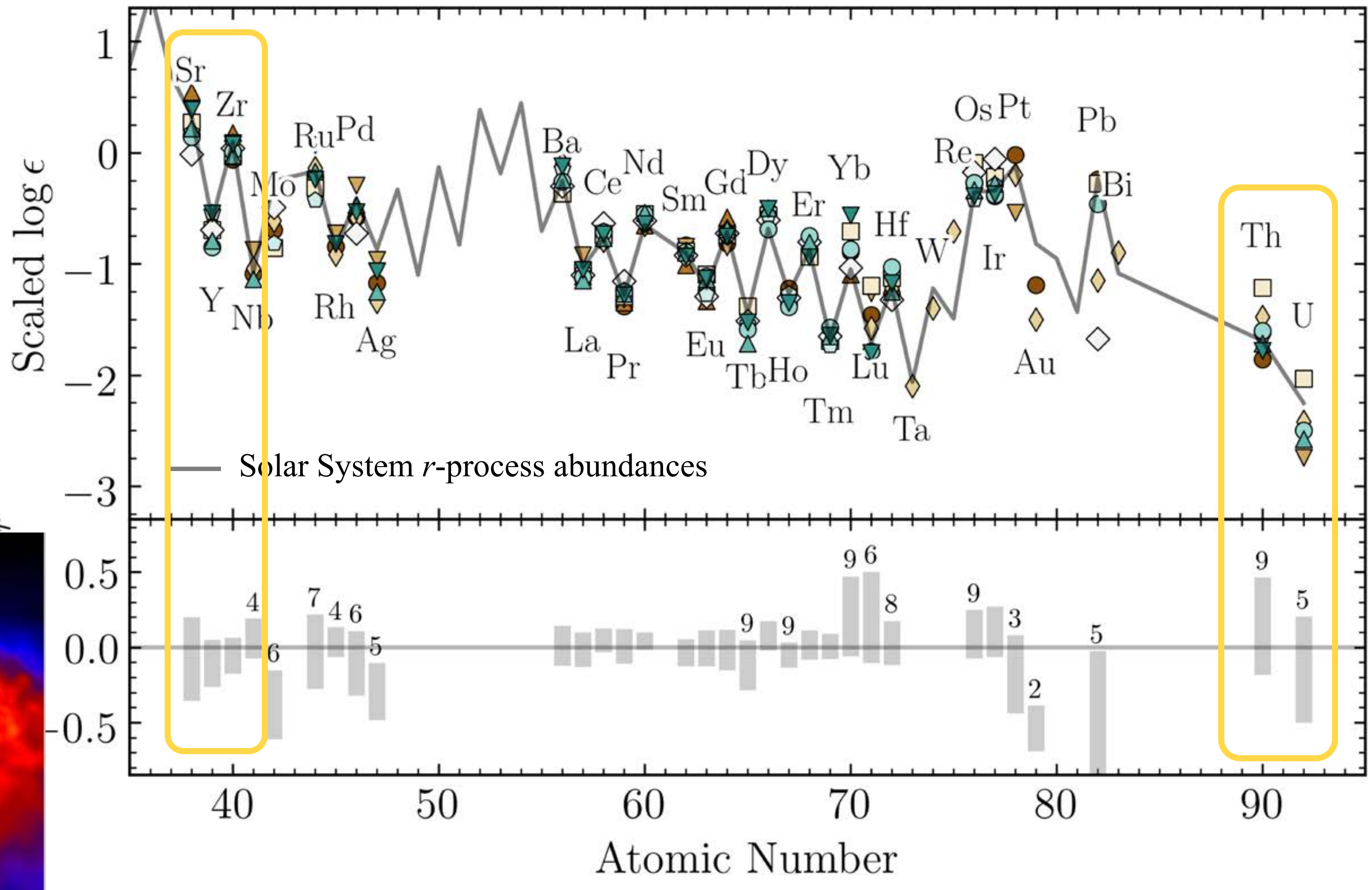


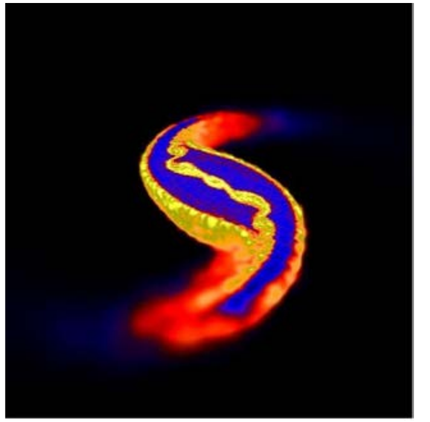


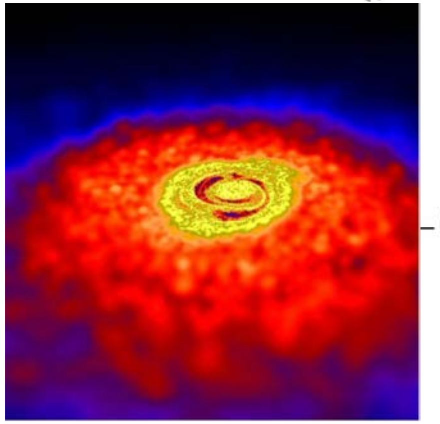
Dynamical:
very *n*-rich
(Y_e < 0.2)

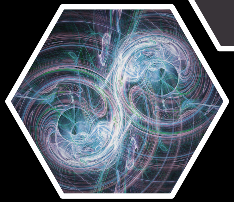
Price & Rosswog (2006)

Are the variations in metal-poor stars reflective of different merger conditions?



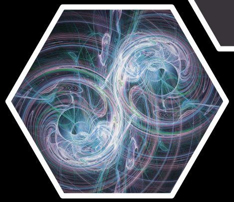






Project Goal

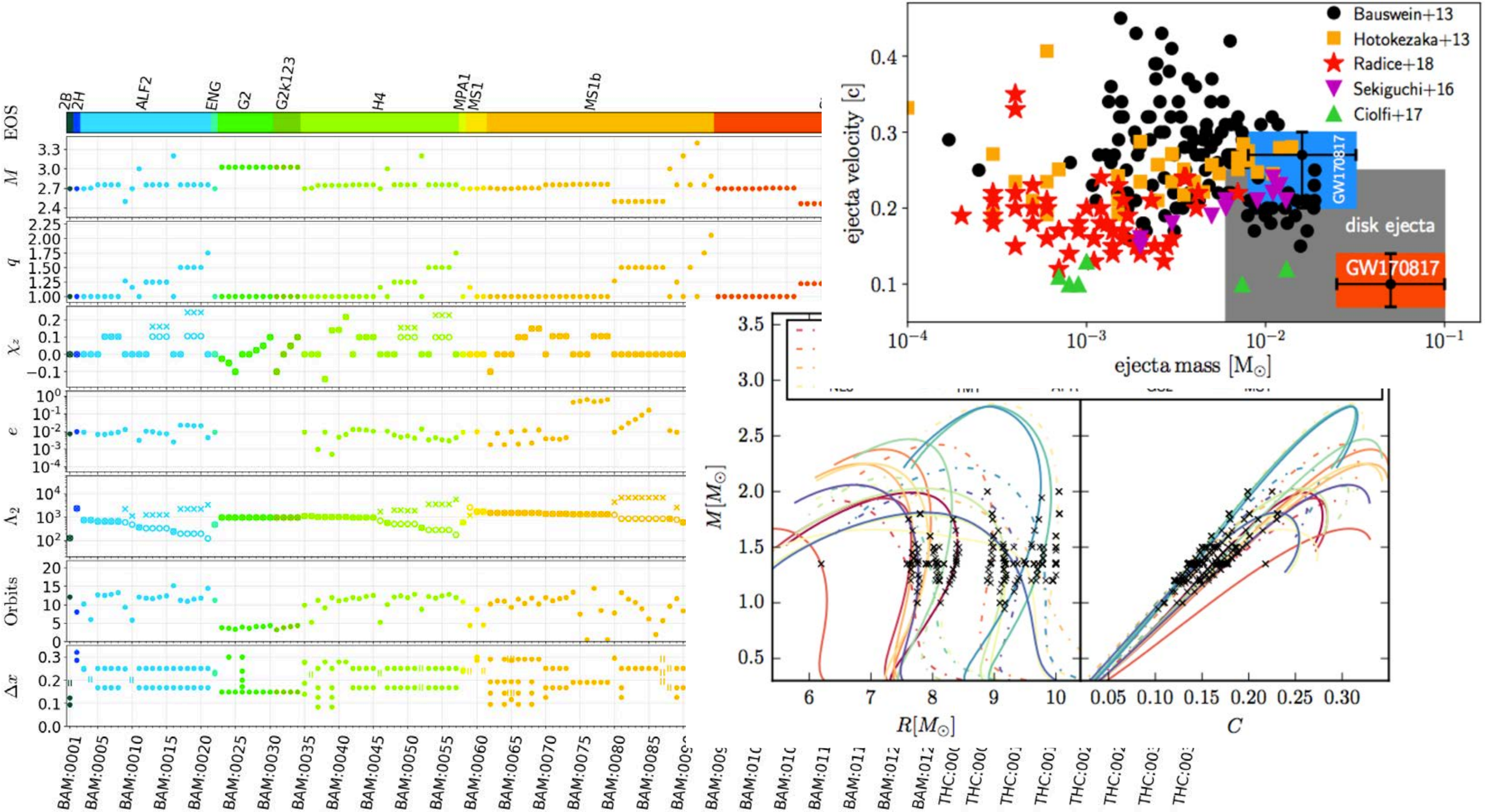
Reconstruct the **masses of the NSs** that merged to produce the elements in metal-poor stars **from their *r*-process abundance patterns**



(How) Can these ejecta components be **parameterized** in terms of the binary properties?

Hydrodynamical simulations have been run for a **variety of merger conditions and EOSs**

Dietrich & Ujevic (2017); Dietrich+ (2018); Metzger (2019)

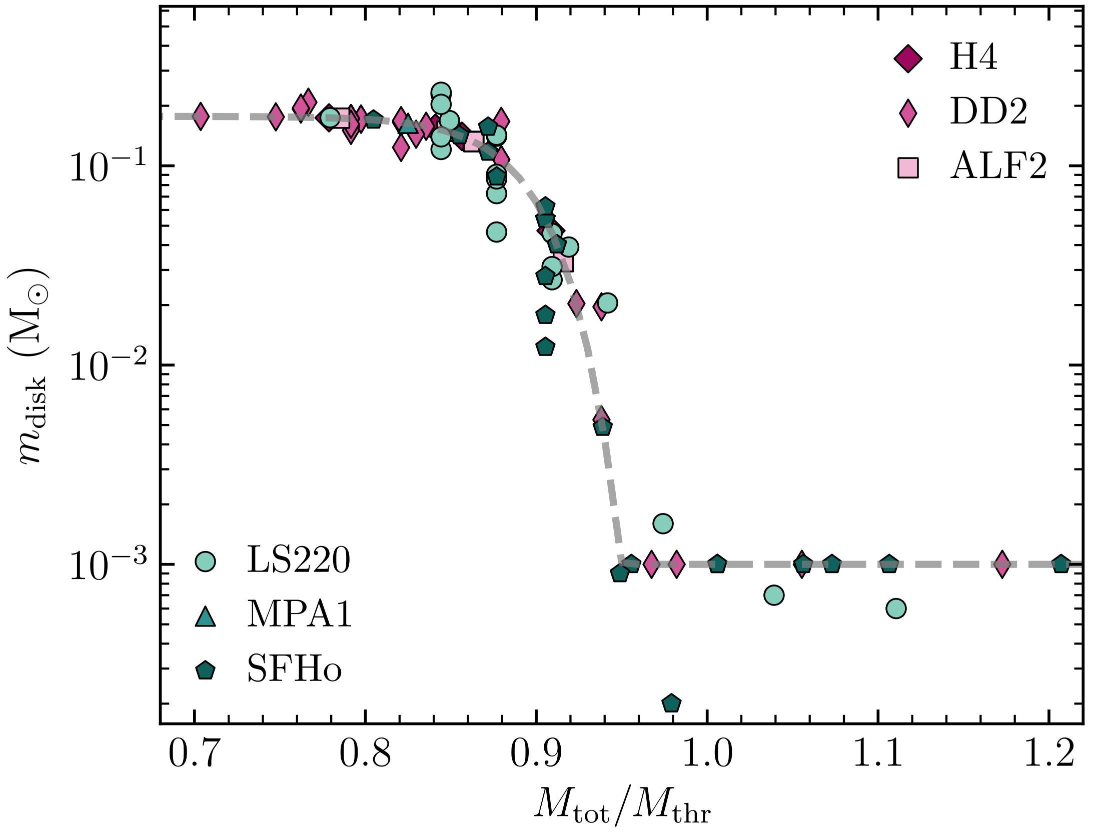


The total disk wind outflow mass primarily depends on the **total binary mass** (M_1+M_2)

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

$$M_{\rm thr} = \underline{M_{\rm TOV}}\left(2.38 - 3.606\,\frac{GM_{\rm TOV}}{\underline{c^2 R_{1.6\,{\rm M}_\odot}}}\right)$$

EOS dependence!



Coughlin+ (2018)

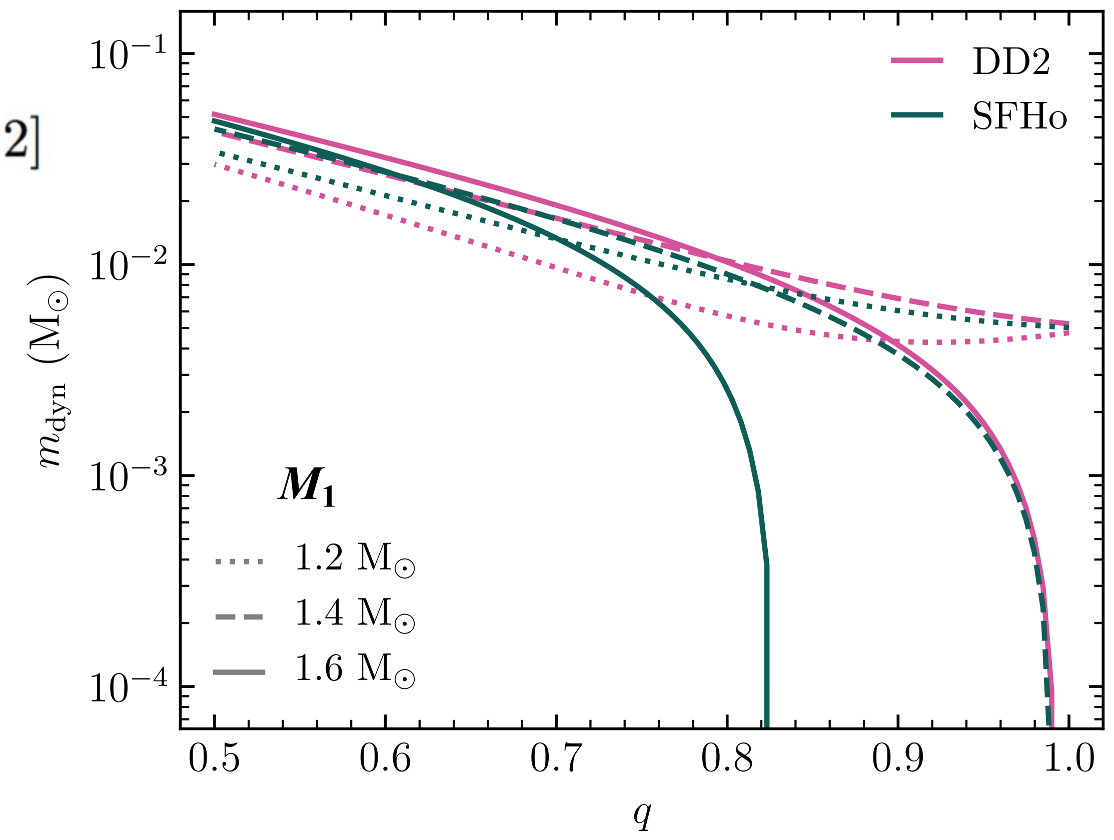
See also: Radice+ (2018), Dietrich+ (2020), Krueger & Foucart (2020)

The total dynamical ejecta mass depends sensitively on the **binary mass ratio** ($q = M_2/M_1$)

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

$$\underline{\mathcal{C}_i = \frac{GM_i}{c^2 R_i}}$$

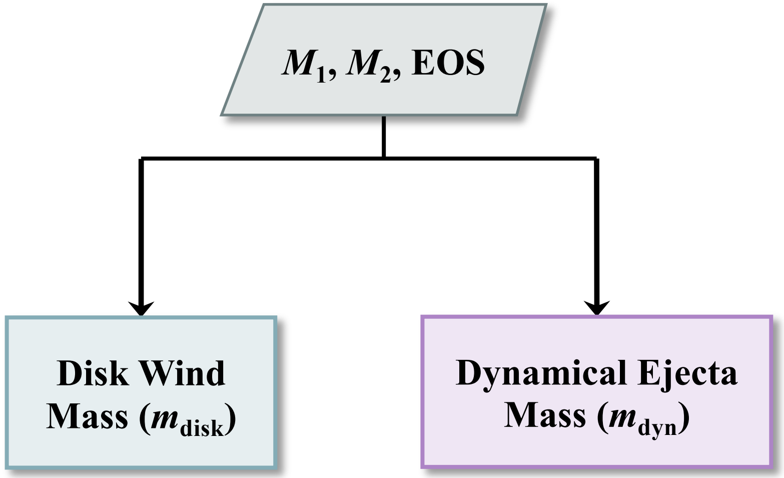
EOS dependence



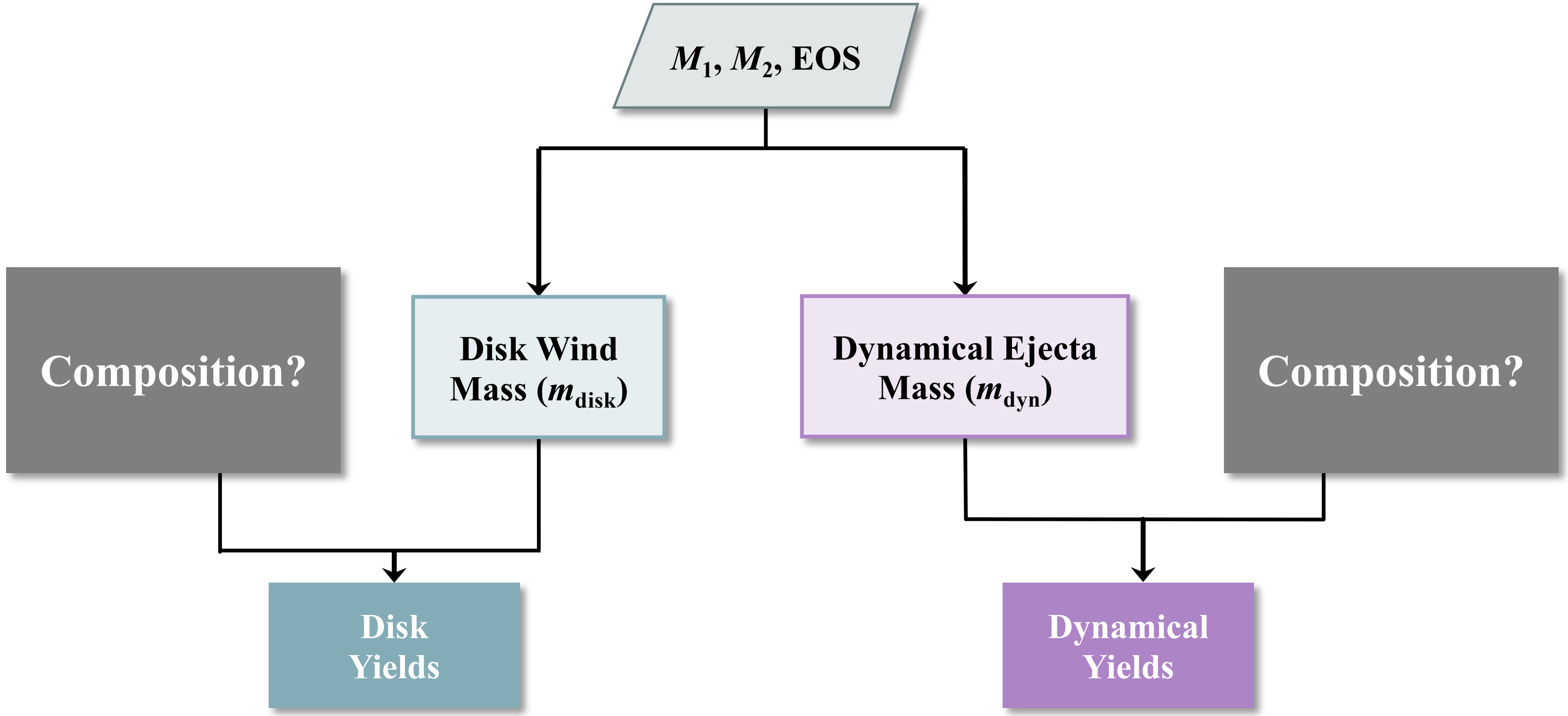
See also: Dietrich & Ujevic (2017), Radice+ (2018), Coughlin+ (2019)

Krueger & Foucart (2020)

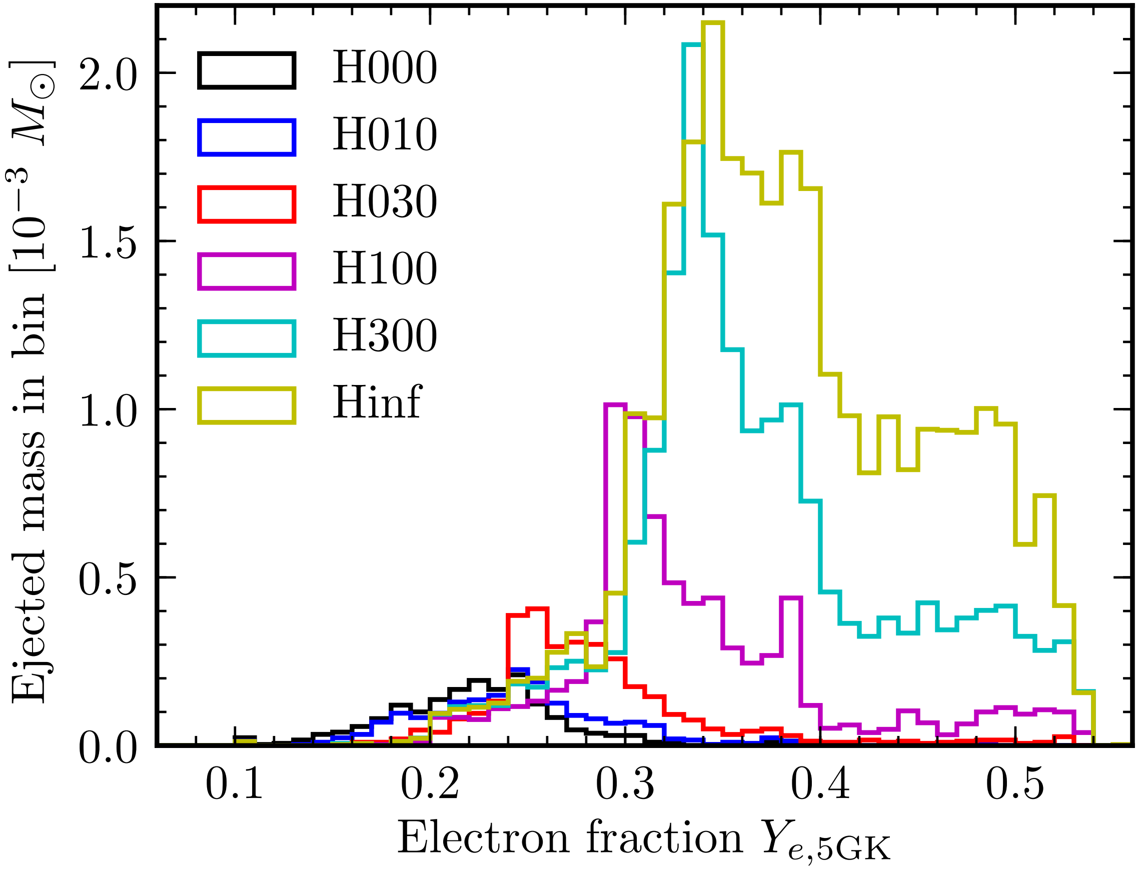
The state so far: the ejecta masses can be described by the binary masses (and an EOS)



If we want the total **elemental** yields, we need to know something about the compositions of these two components

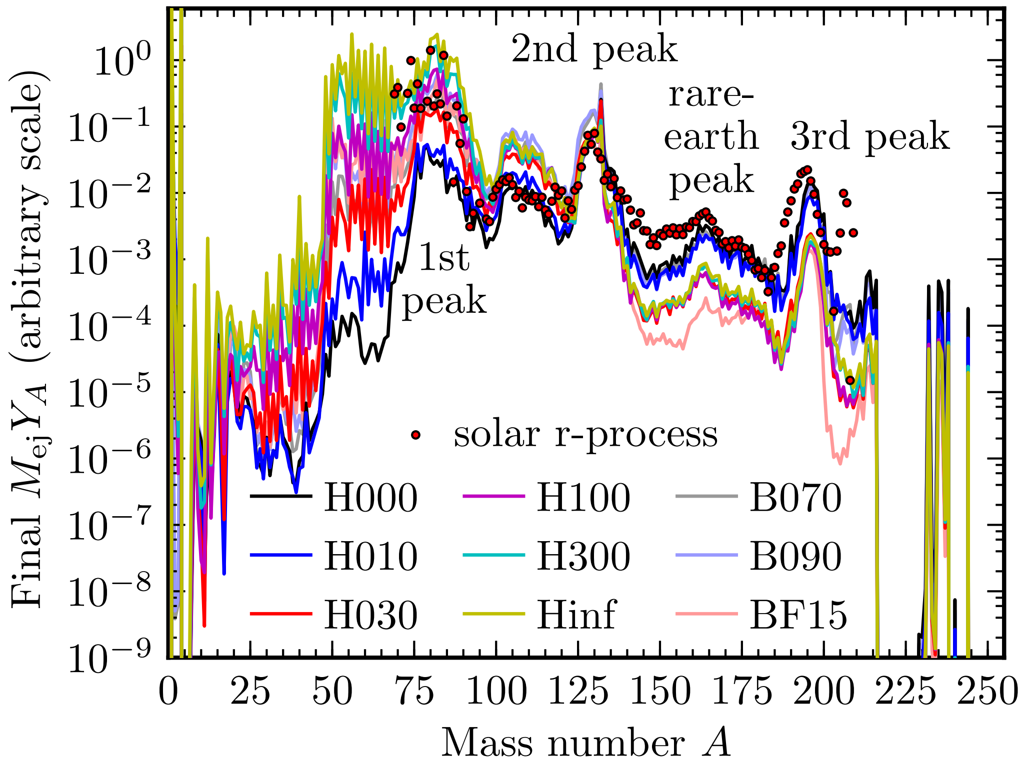


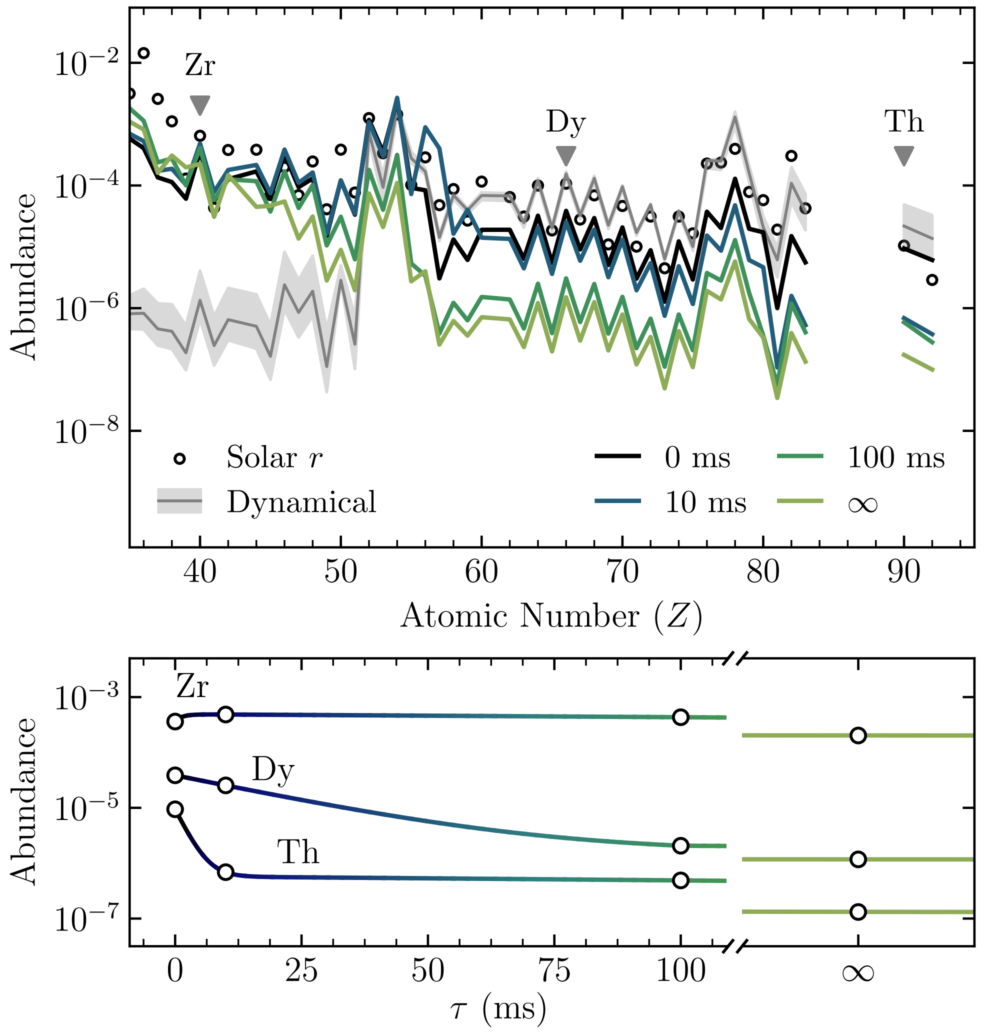
The disk wind composition depends on the remnant **lifetime**.
The longer-lived the remnant, the higher the $\langle Y_e \rangle$



Lippuner+ (2017)

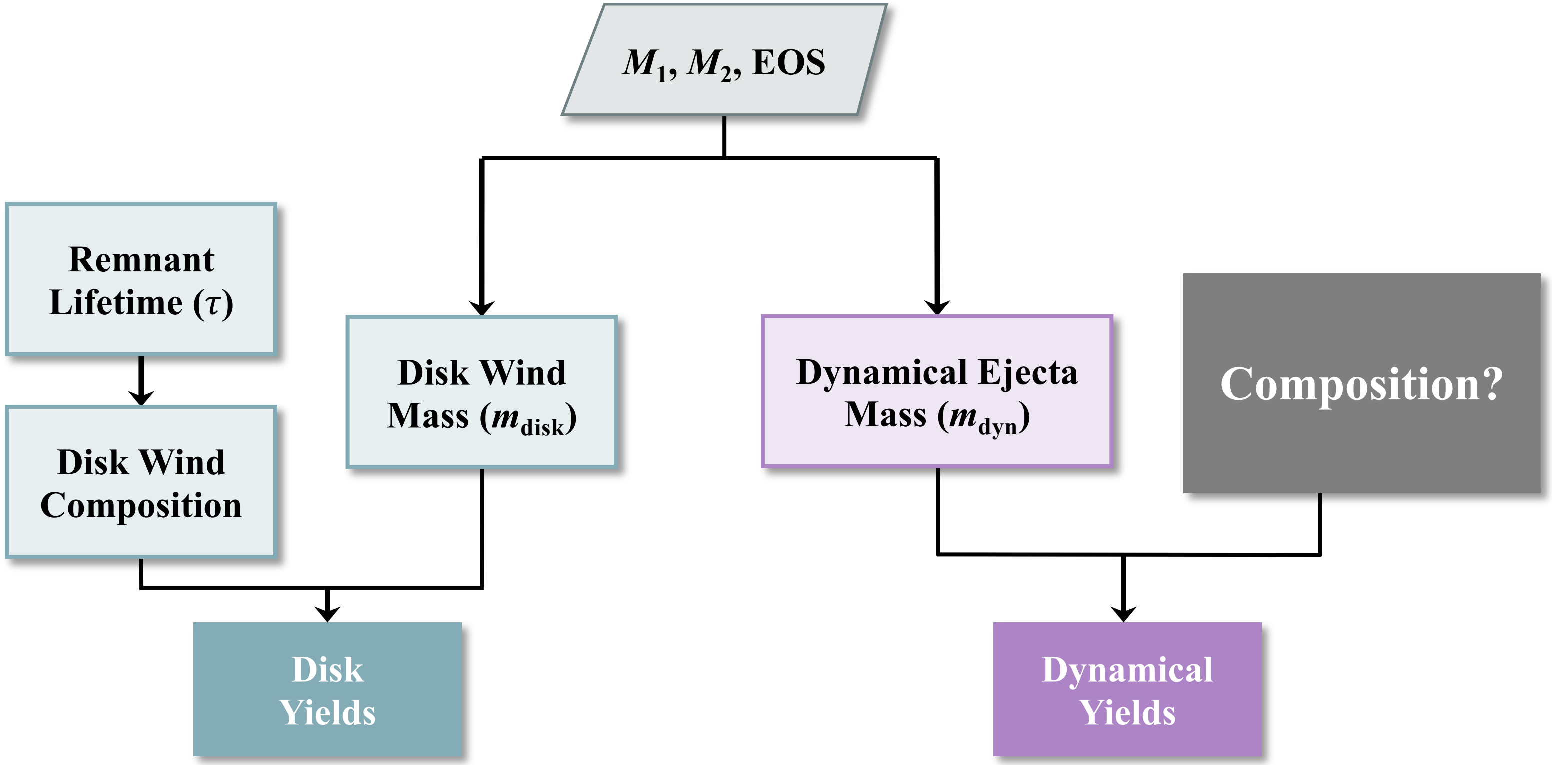
The remnant lifetime leaves a signature on the abundances of the ejected *r*-process elements





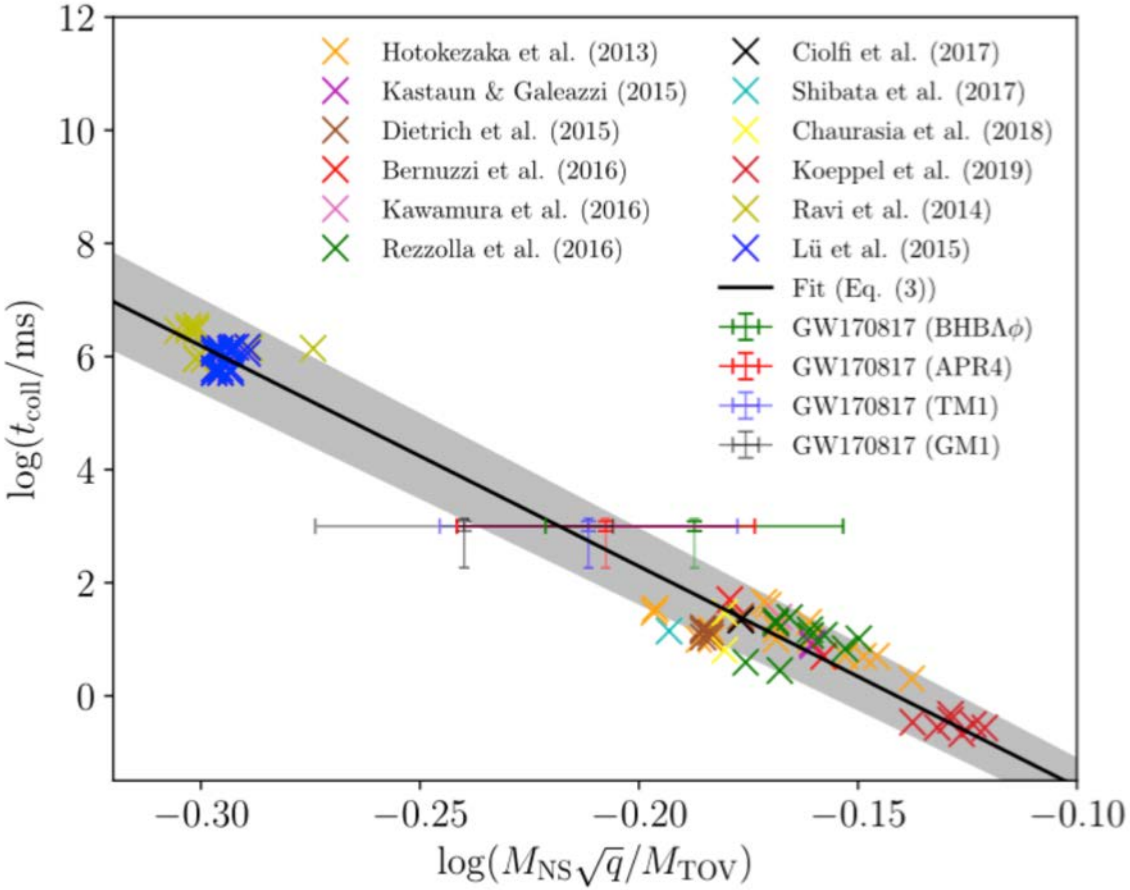
Lippuner+ (2017);
Holmbeck+ (*in prep.*)

The state so far: the disk wind composition depends on the remnant lifetime



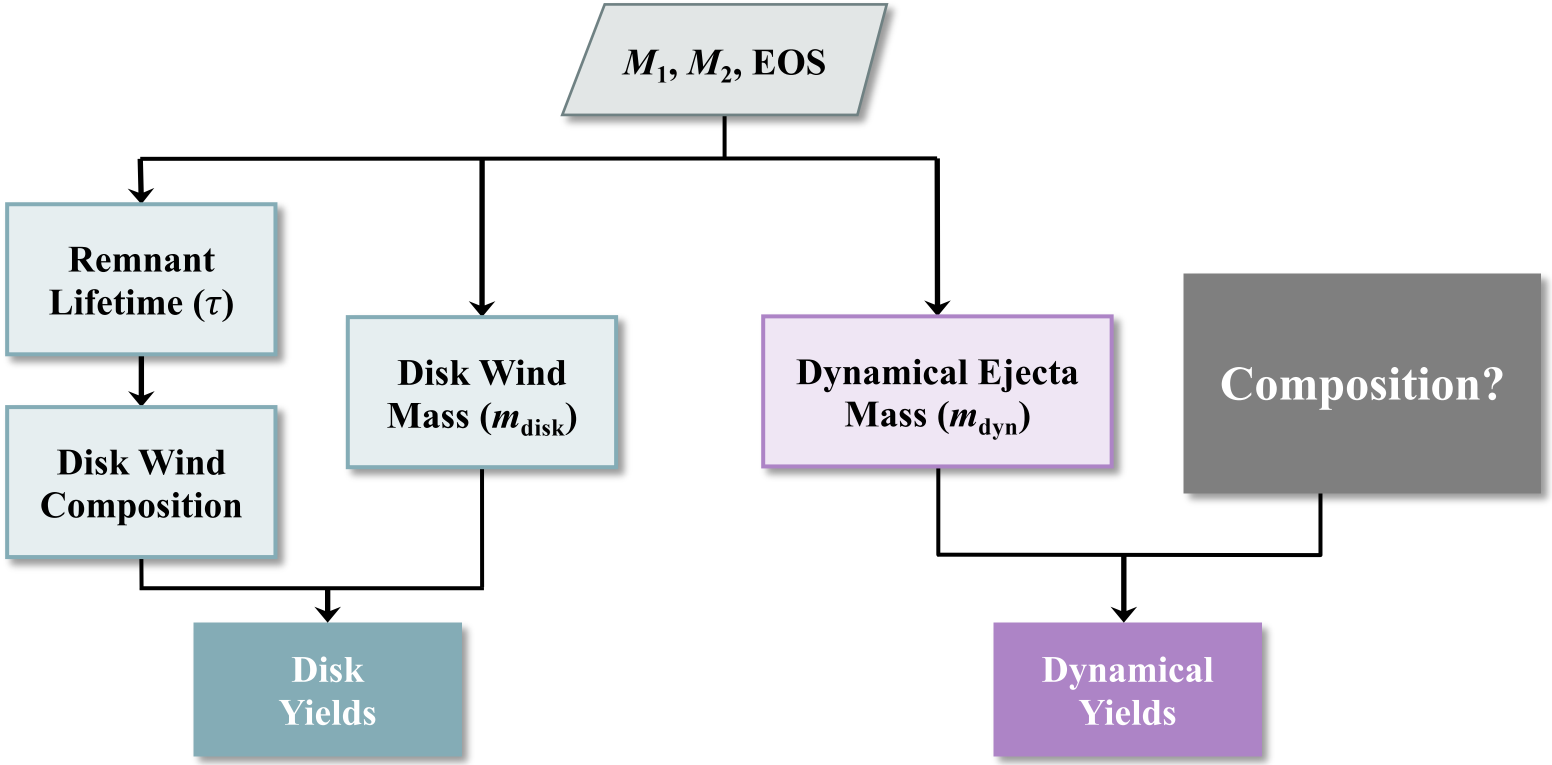
The remnant lifetime before collapse into a black hole (if at all) also depends on the NS masses

$$\log_{10}(\tau) = e_0 + e_1 \log_{10}\left(\frac{\sqrt{M_1 M_2}}{M_{\mathrm{TOV}}}\right)$$

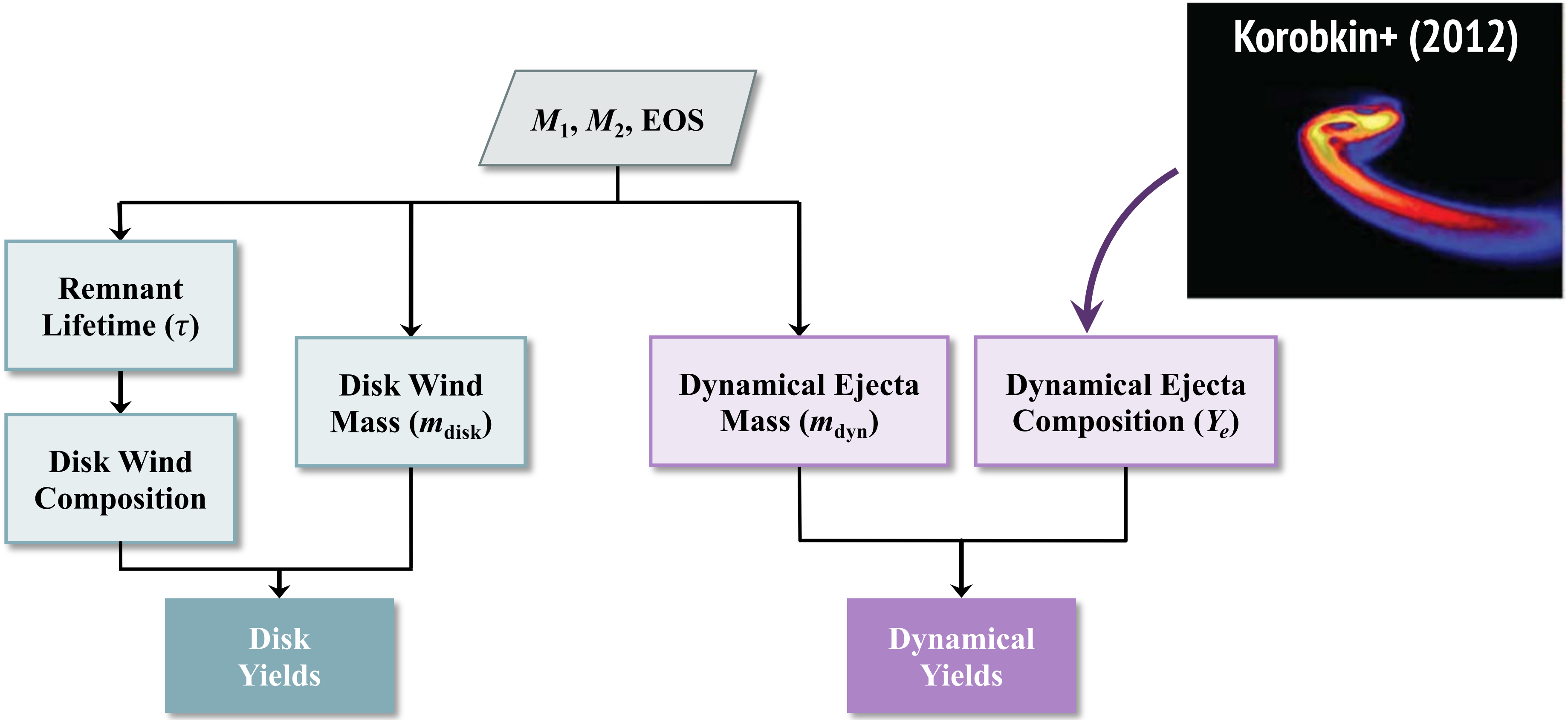


Lucca & Sagunski (2020)

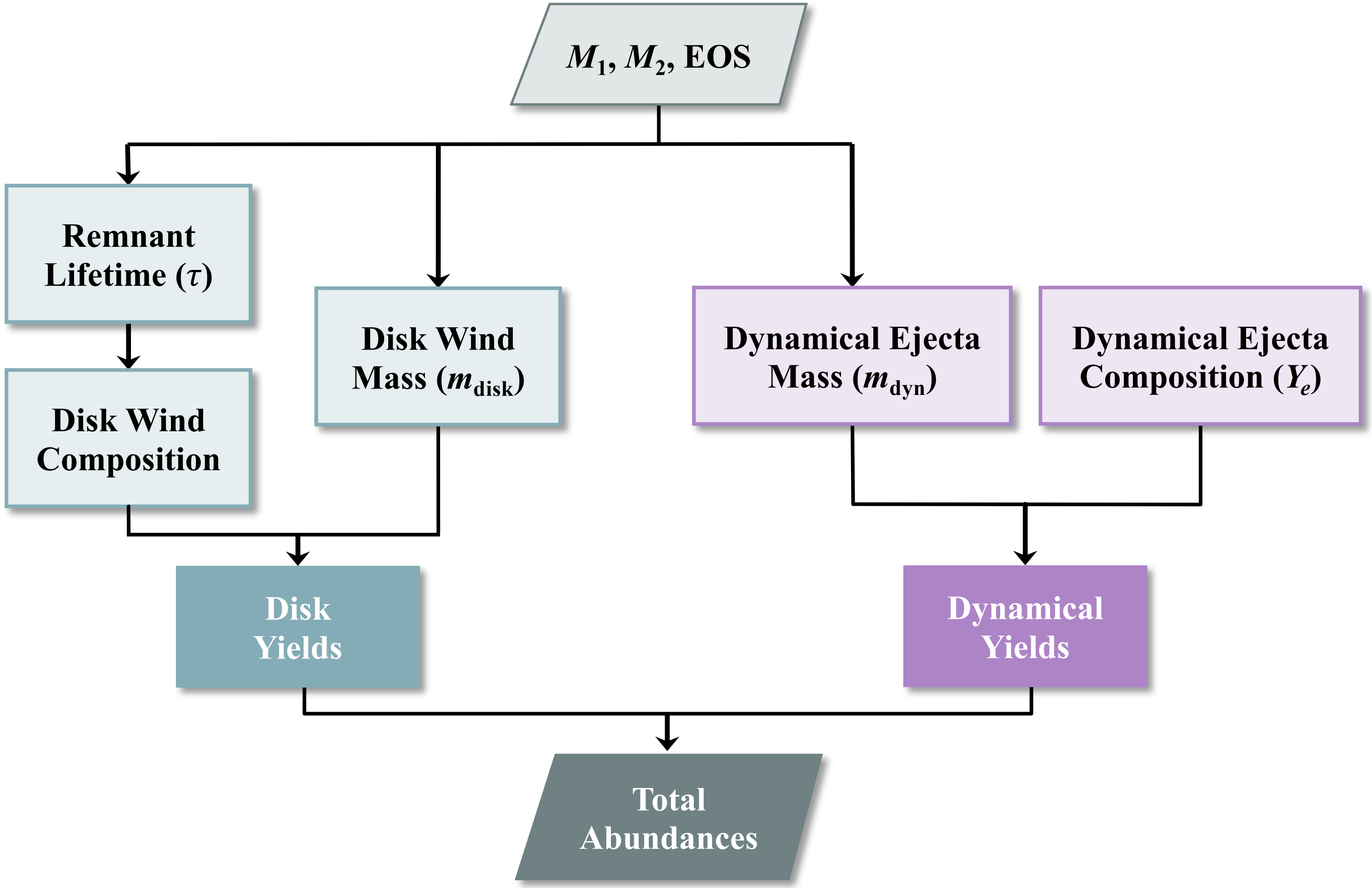
The state so far: the disk wind composition can also be related to the binary parameters and an EOS



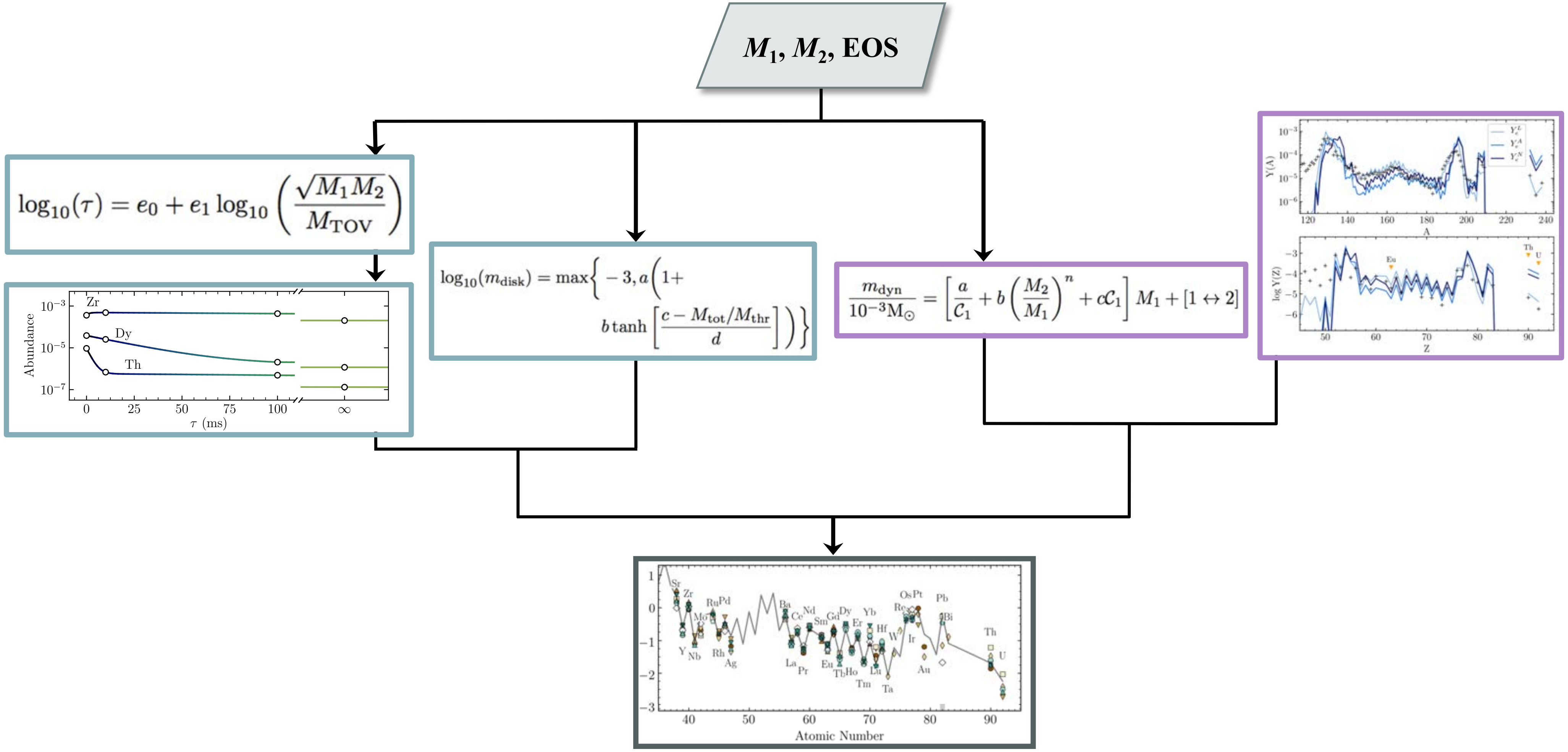
The state so far: the disk wind composition can also be related to the binary parameters and an EOS

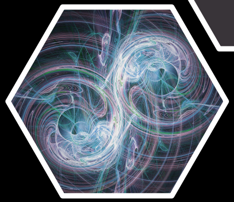


From a selection of M_1, M_2, and EOS, we can find the total *r*-process yields from an NSM event



From a selection of M_1, M_2, and EOS, we can find the total *r*-process yields from an NSM event

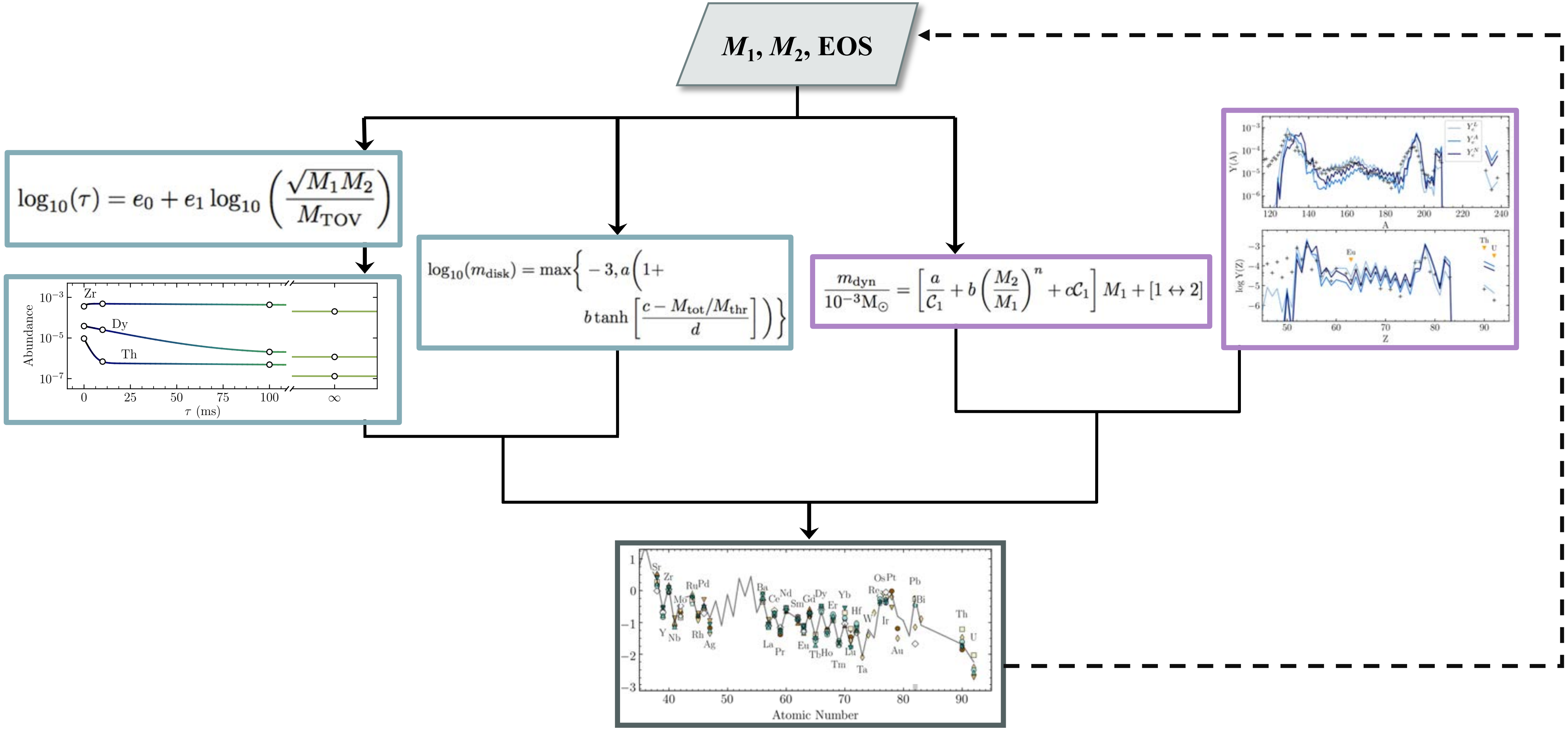




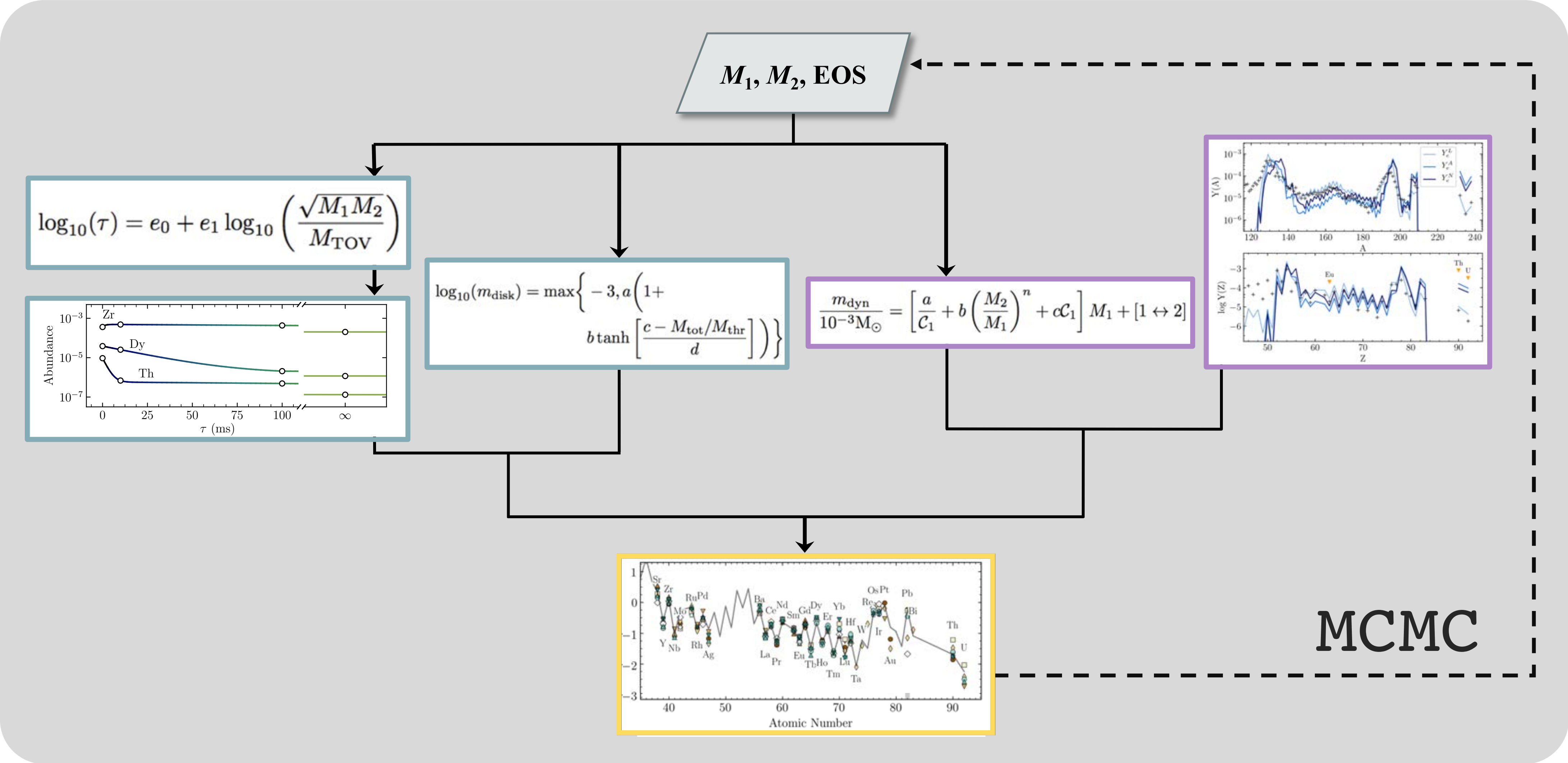
Project Goal

Reconstruct the **masses of the NSs** that merged to produce the elements in metal-poor stars **from their *r*-process abundance patterns**

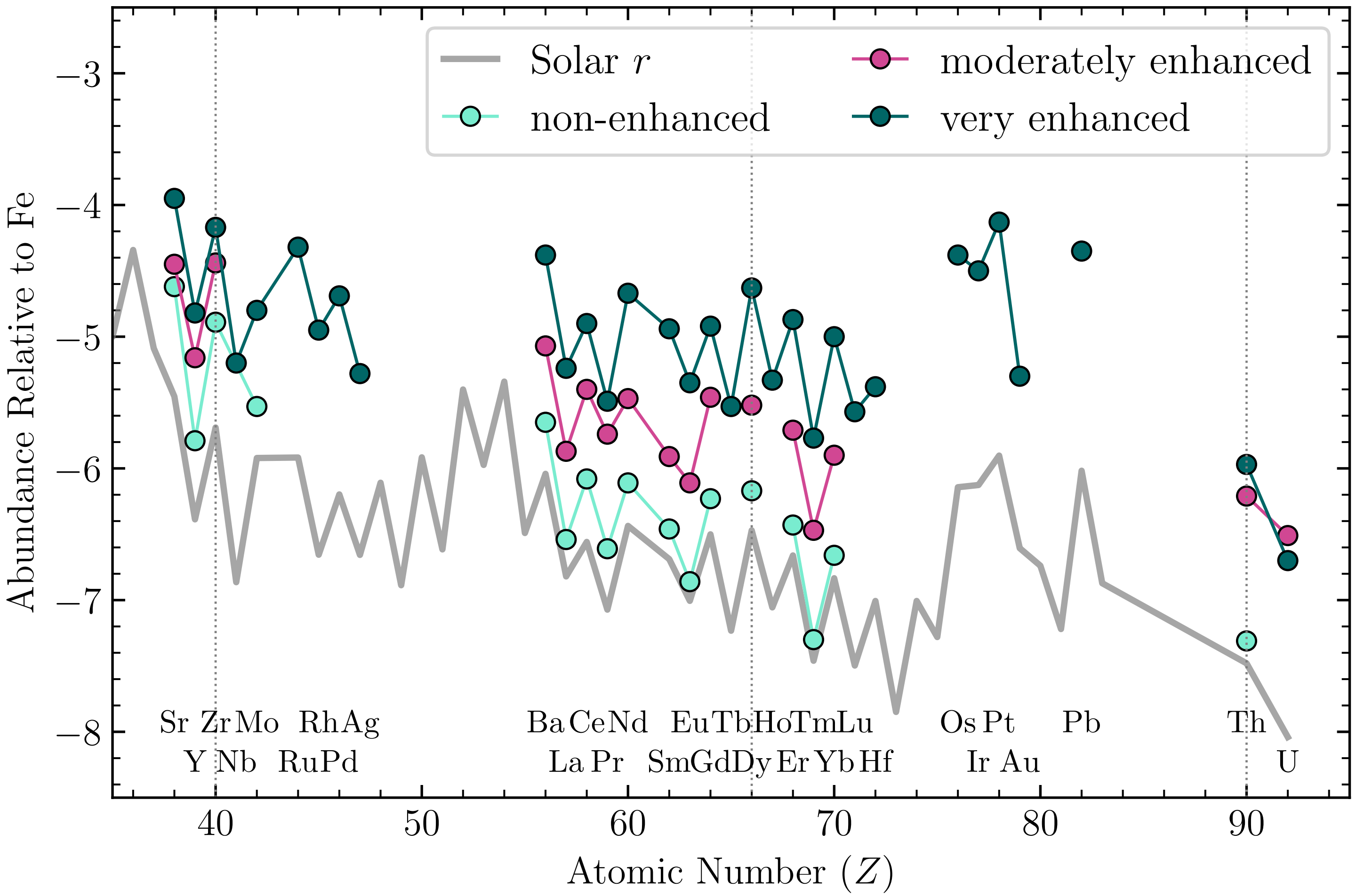
How do we **solve** for M_1 and M_2 from observed abundances?



Wrap entire framework in an MCMC method to find a posterior **distribution** of M_1 and M_2 solutions



Use stars with measured **Zr**, **Dy**, and **Th** as input with a range of enhancement levels

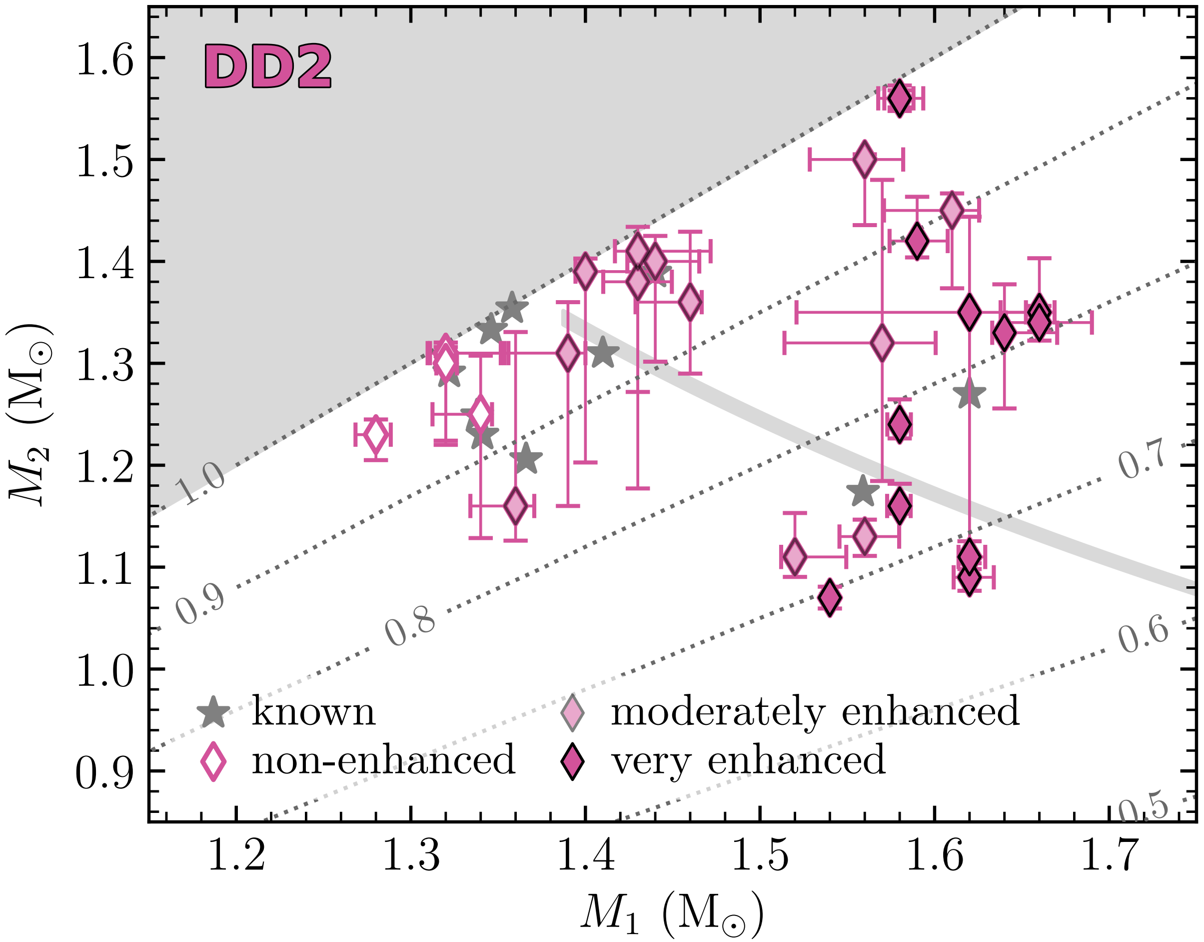


Results

Reconstructed the **masses of the NSs** that merged to produce **all *r*-process elements** (Zr→Th) in these stars

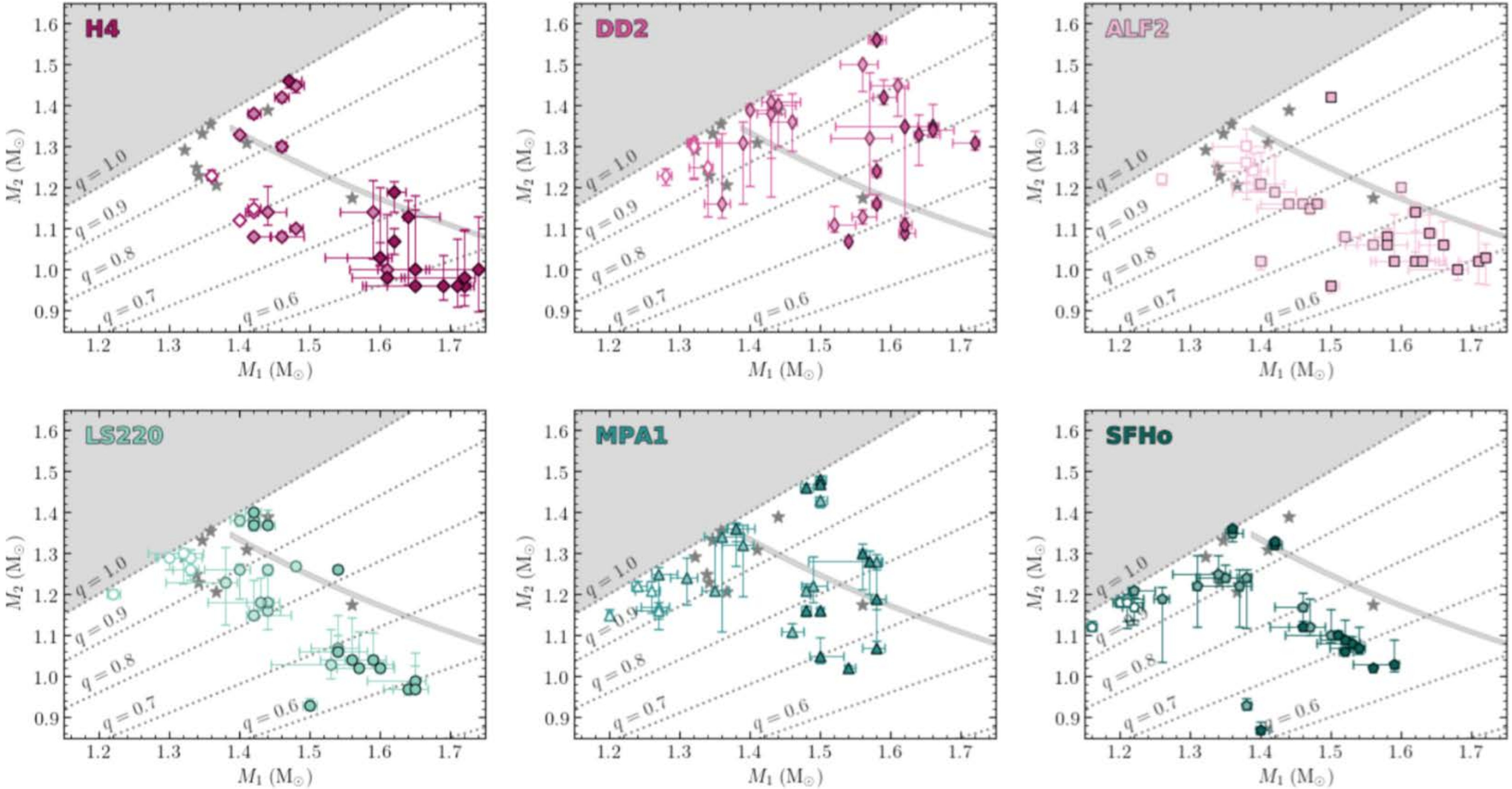
How do these masses **compare to present-day** NS-NS systems?

MCMC run for each stellar input to produce the possible combinations of NS masses that could produce the abundances in their NSM ejecta

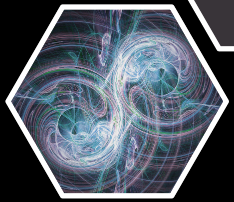


Results for different EOSs generally agree that **more *r*-process enhancement → more mass-asymmetric NSMs**

stiffest EOS

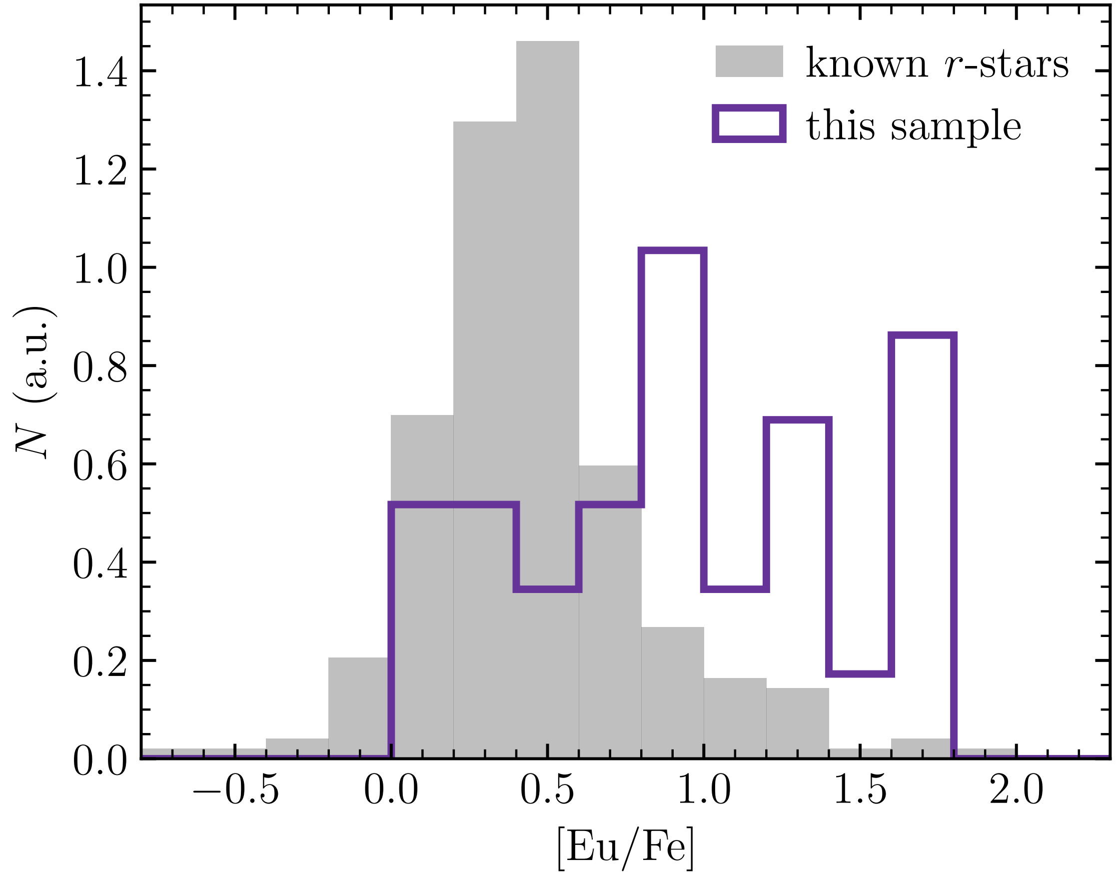


softest EOS



Are NSMs the **dominant** source of *r*-process material in **all** metal-poor *r*-stars?

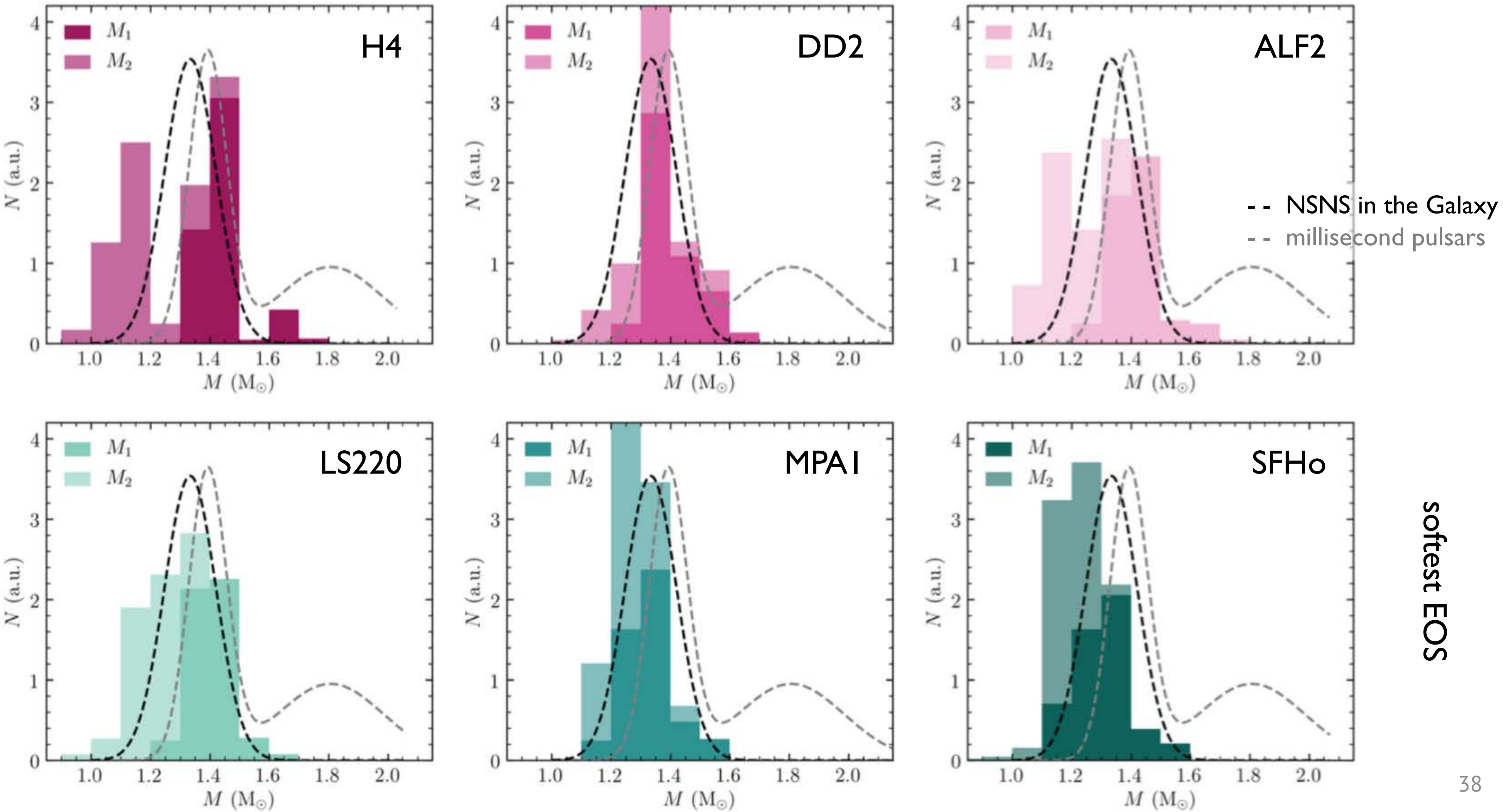
Need to weigh our results to determine in NSMs could be a **dominant** *r*-process source for metal-poor *r*-stars



r-process enhancement level →

How do the (weighted) mass distributions compare to existing NS binaries?

stiffest EOS

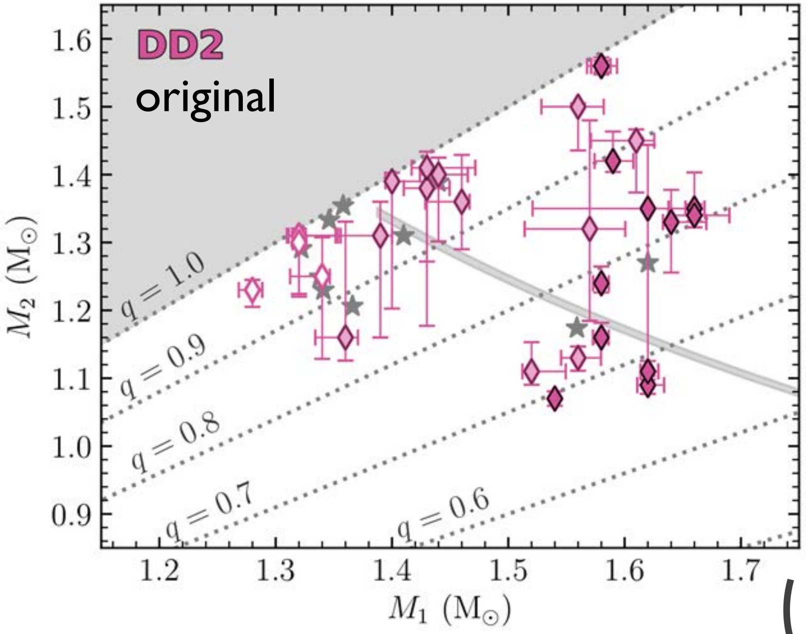


softest EOS

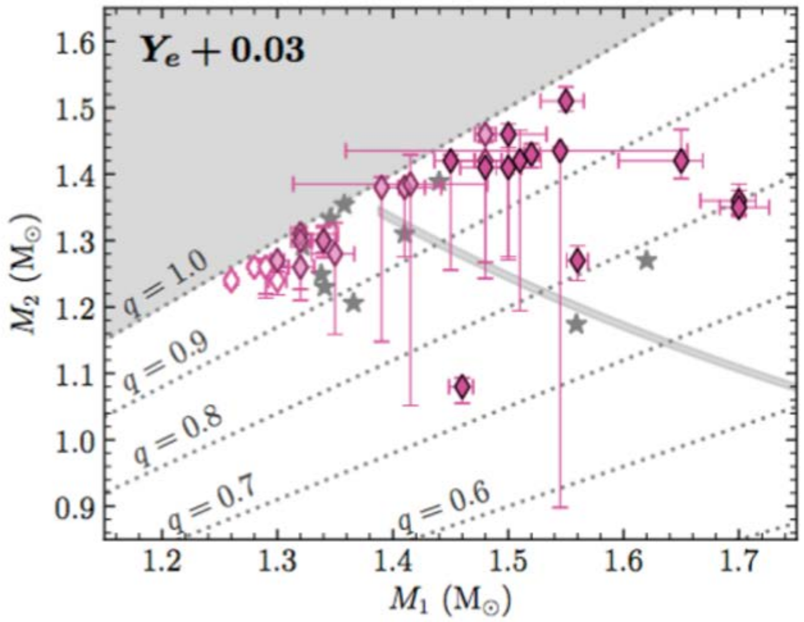
This method is **model-dependent**

How does it hold up to variations?

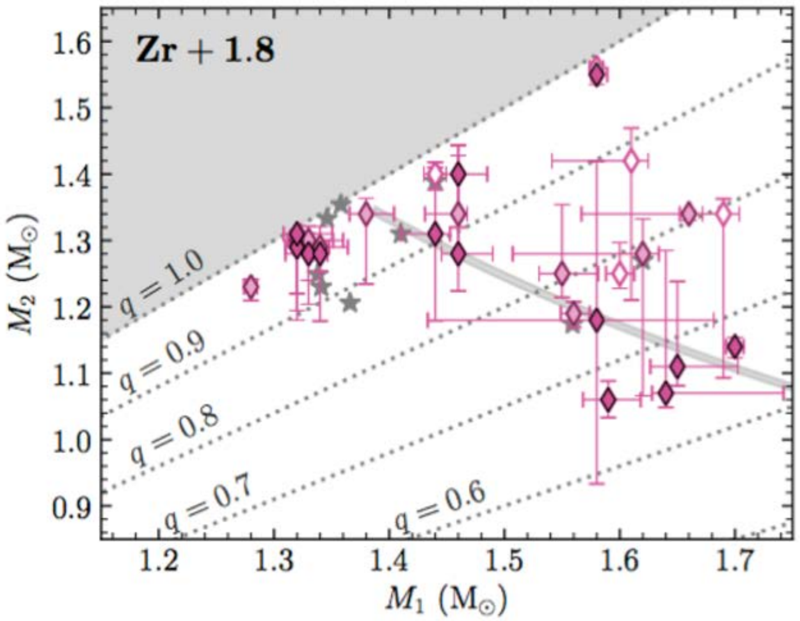
Compositional variations: very sensitive to disk wind Y_e



variation to disk wind



variation to dynamical ejecta



arXiv:2010.01621

Summary

NS binary masses have important effects on *r*-process nucleosynthesis in NSMs

Elemental abundance patterns of metal-poor stars could be sensitive to the binary properties

A majority of the *r*-process elements from Zr to Th **can be reproduced with NSMs similar to existing NS-NS** in the Galaxy

Outflow **composition** is essential

Future **EOS** constraints...?

Special Thanks

Rebecca Surman (ND)

Gail McLaughlin (NC State)

Anna Frebel (MIT)

Rodrigo Fernandez (U. Alberta)

Brian Metzger (Columbia)

Matthew Mumpower (LANL)

Trevor Sprouse (LANL)

NSF

N3AS

UNIVERSITY OF NOTRE DAME

R-Process Alliance

JINA-CEE