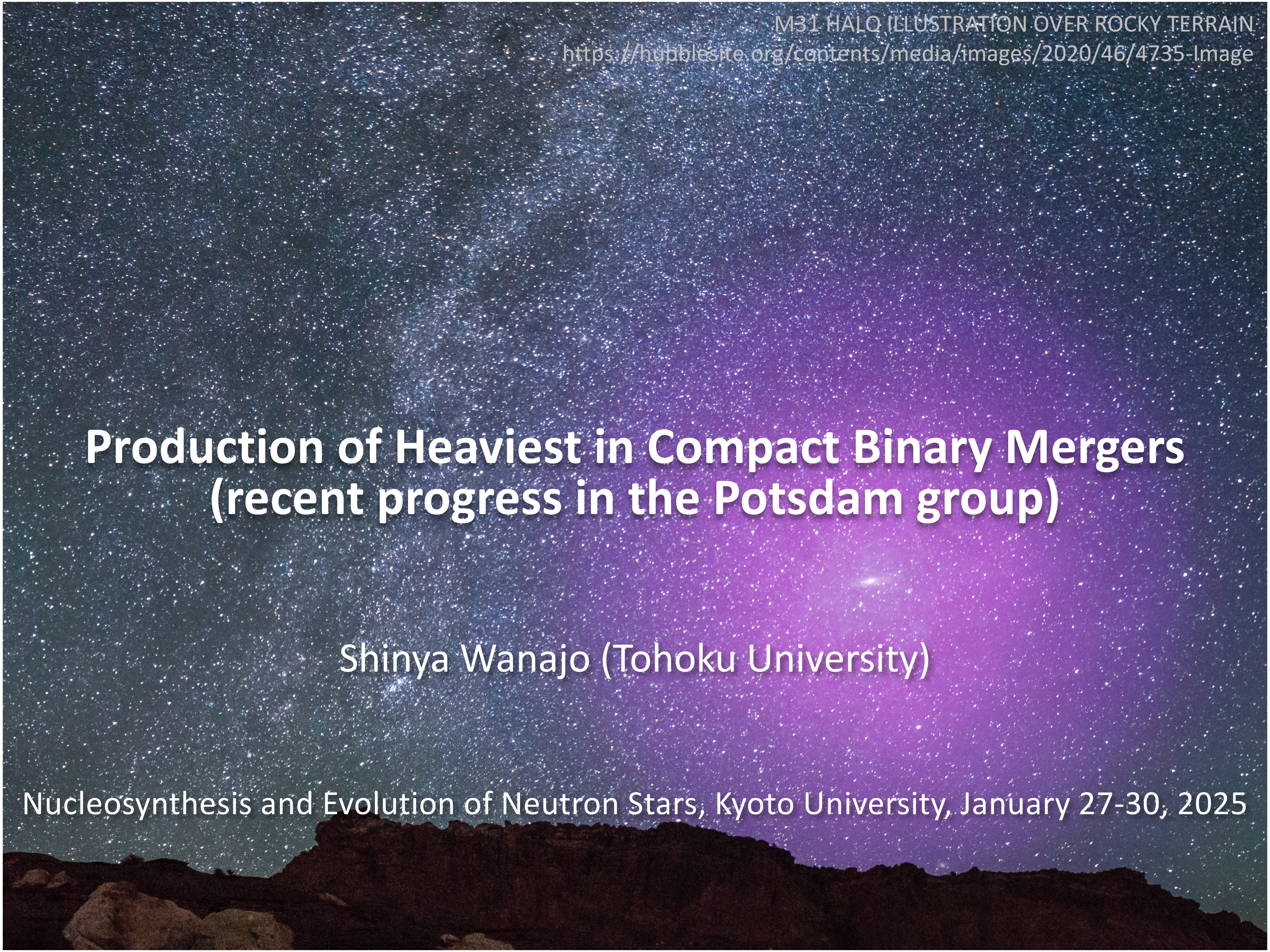


M31 HALO ILLUSTRATION OVER ROCKY TERRAIN
https://hubblesite.org/contents/media/images/2020/46/4735-Image

Production of Heaviest in Compact Binary Mergers (recent progress in the Potsdam group)

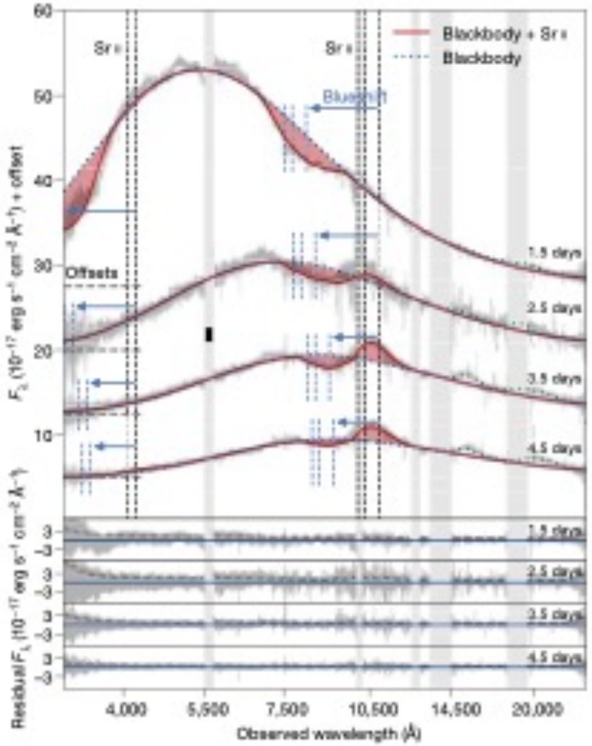
Shinya Wanajo (Tohoku University)

Nucleosynthesis and Evolution of Neutron Stars, Kyoto University, January 27-30, 2025

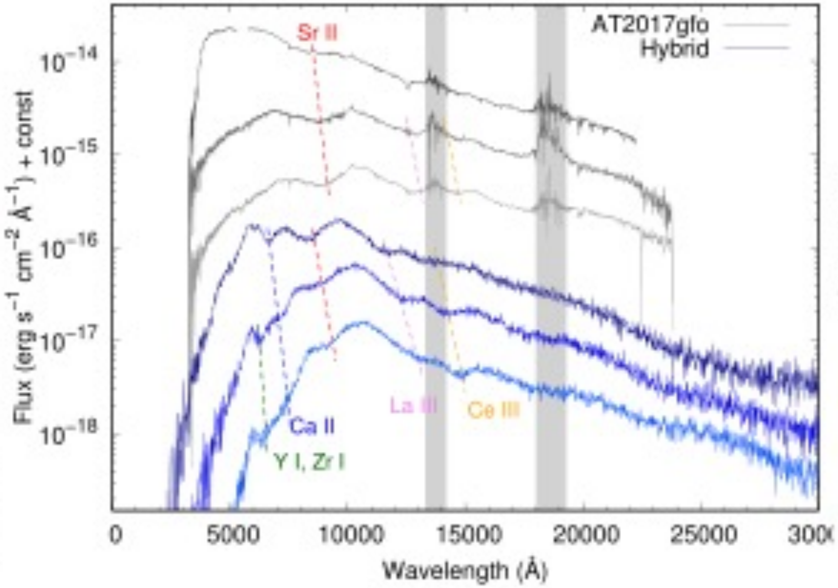
1. 2+1 mysteries from observations

did NS merger GW170817 make gold ?

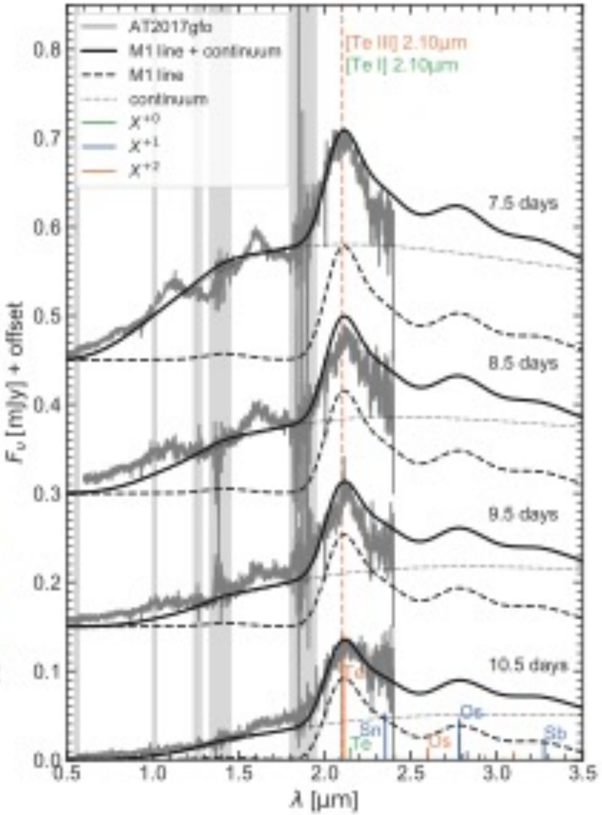
Sr; Watson+2019



La, Ce;
Domoto, Tanaka, Kato, Kawaguchi, Hotokezaka, Wanajo 2022



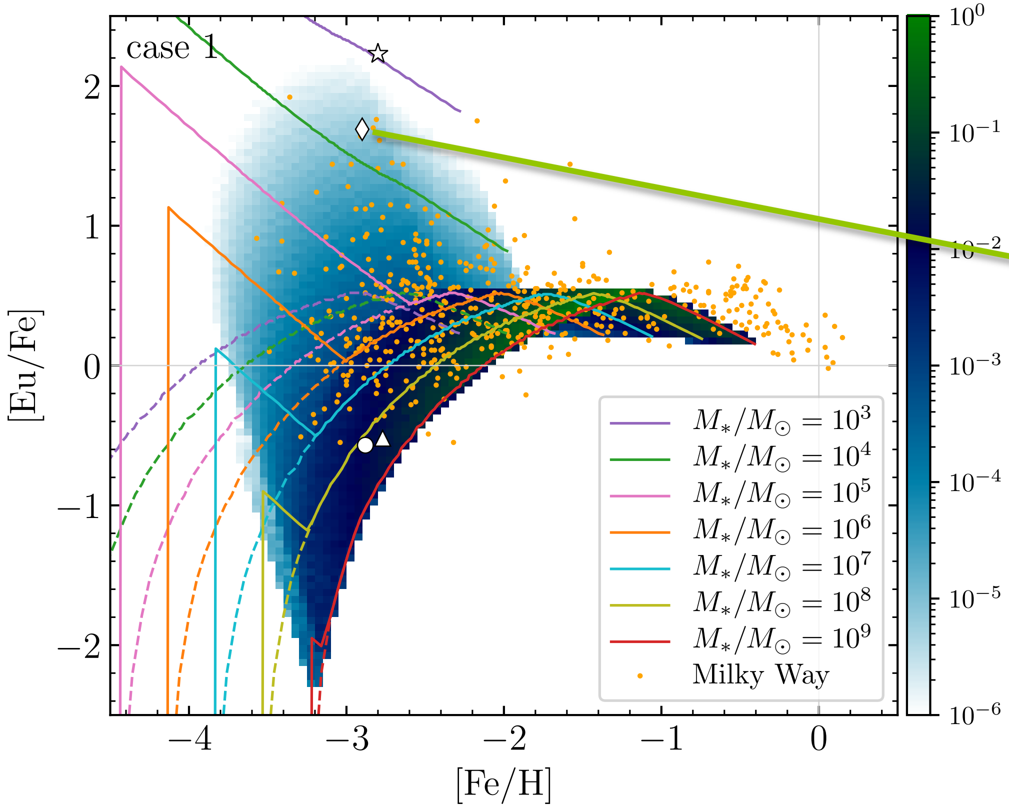
Te; Hotokezaka+2023

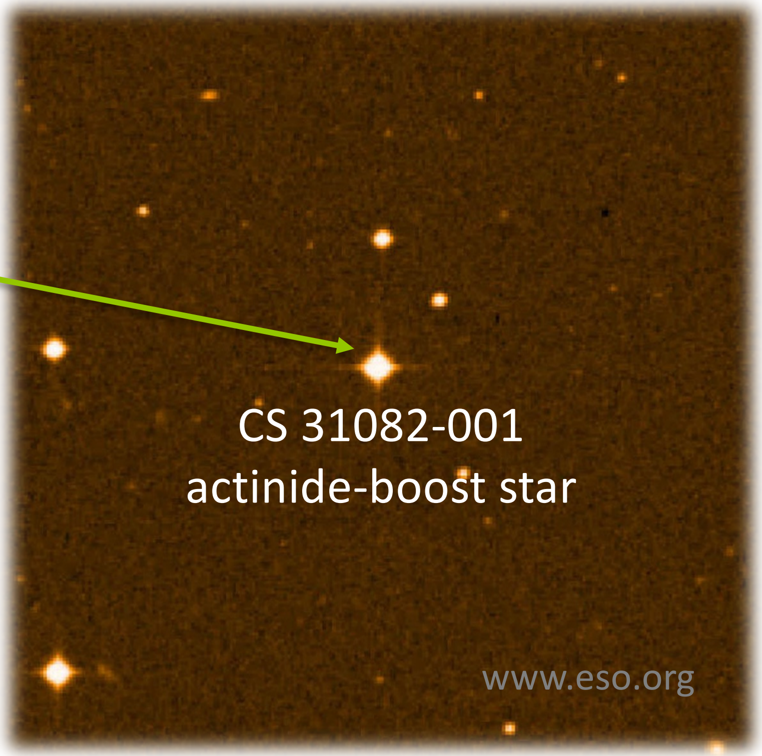


- ❖ heaviest measured element is Ce (Domoto+2022), a light lanthanide
- ❖ Th may be detectable by JWST in the future (Domoto, Wanajo+2024)

indication from galactic stars

Galactic chemical evolution model with neutron star mergers; Wanajo, Hirai, Prantzos 2021

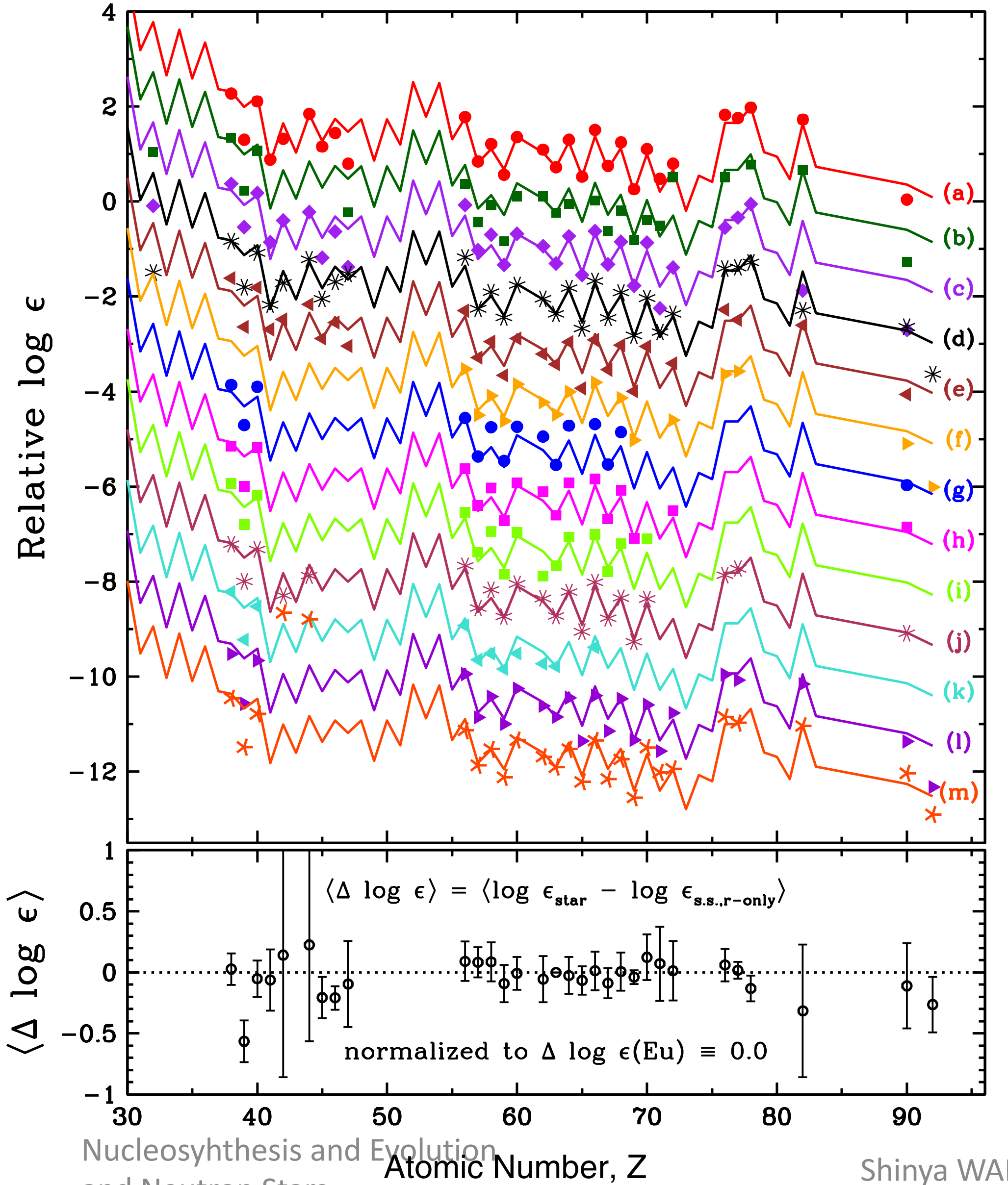




- r-process enhanced stars originate from low-mass building blocks ($M_*/M_\odot < 10^5$, Ishimaru+2015; Ojima+2018; Wanajo+2021; Hirai+2022)
- rare (~10 event per Myr) and prolific (0.01 $M_\odot$ r-elements) sources such as neutron star mergers (or a rare-class of SNe ?)

mystery 1: universality of r-process

r-enhanced stars with scaled solar r-pattern; Cowan+2021 Rev. Mod. Phys. ← good review !!

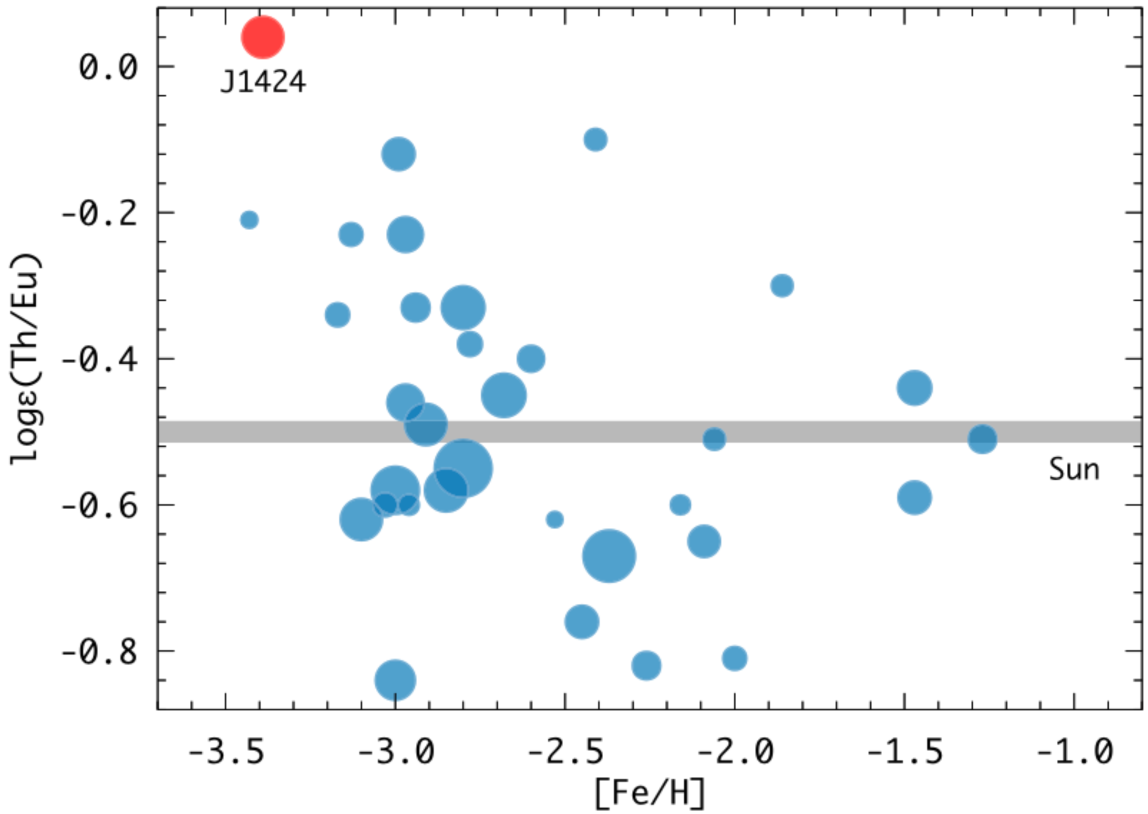


solar-like r-process abundance patterns in r-enhanced stars

❖ why the pattern is such robust ?

mystery 2: actinide boost

Placco+2023



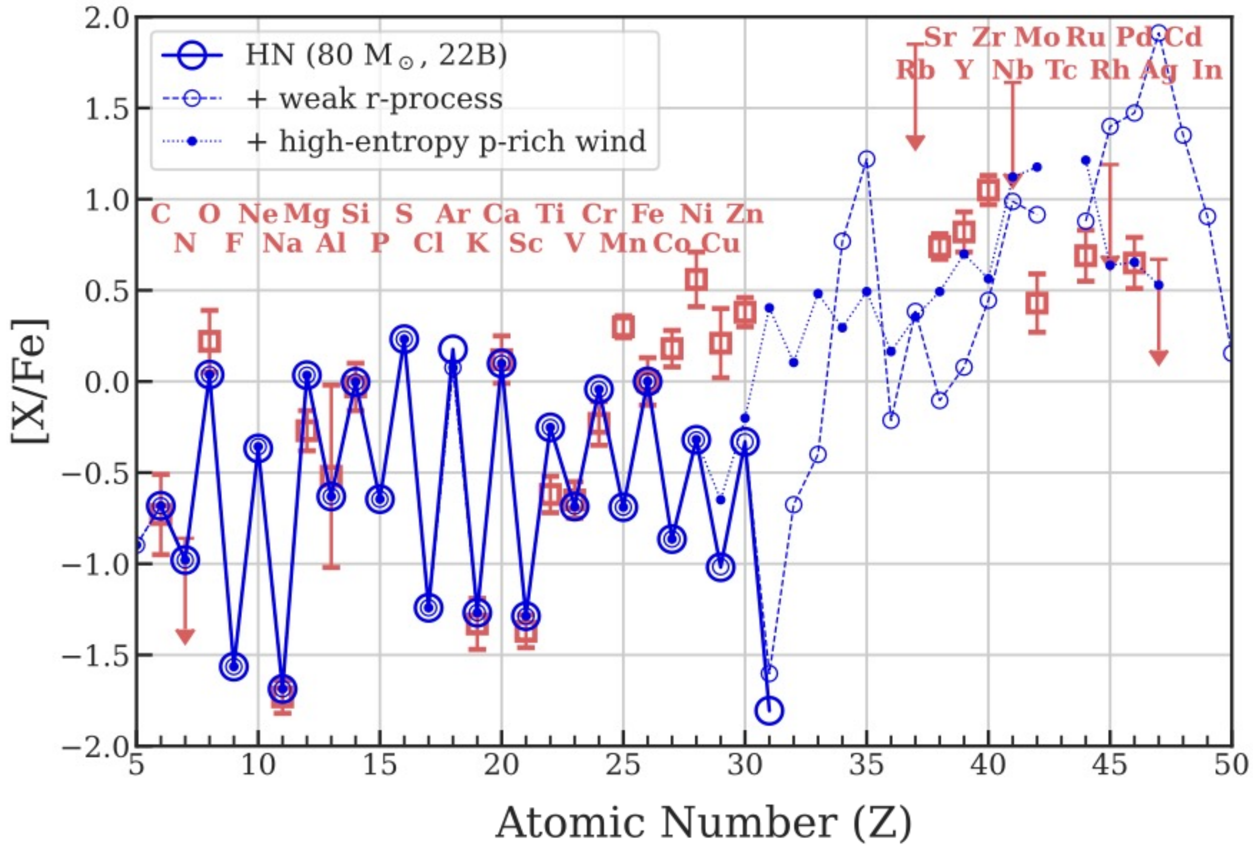
factor of 8 variation in Th/Eu

- above Th/Eu = 0.5 (Th/Eu ~ 0.9 when the stars were born) are defined as "actinide-boost" stars (1/3 of all r-rich stars)

what gives rise to the actinide boost ?

mystery +1: unknown nucleosynthesis

“Spectacular Nucleosynthesis”; Ji+2024



strong odd-even effect in alpha elements and light r-process elements

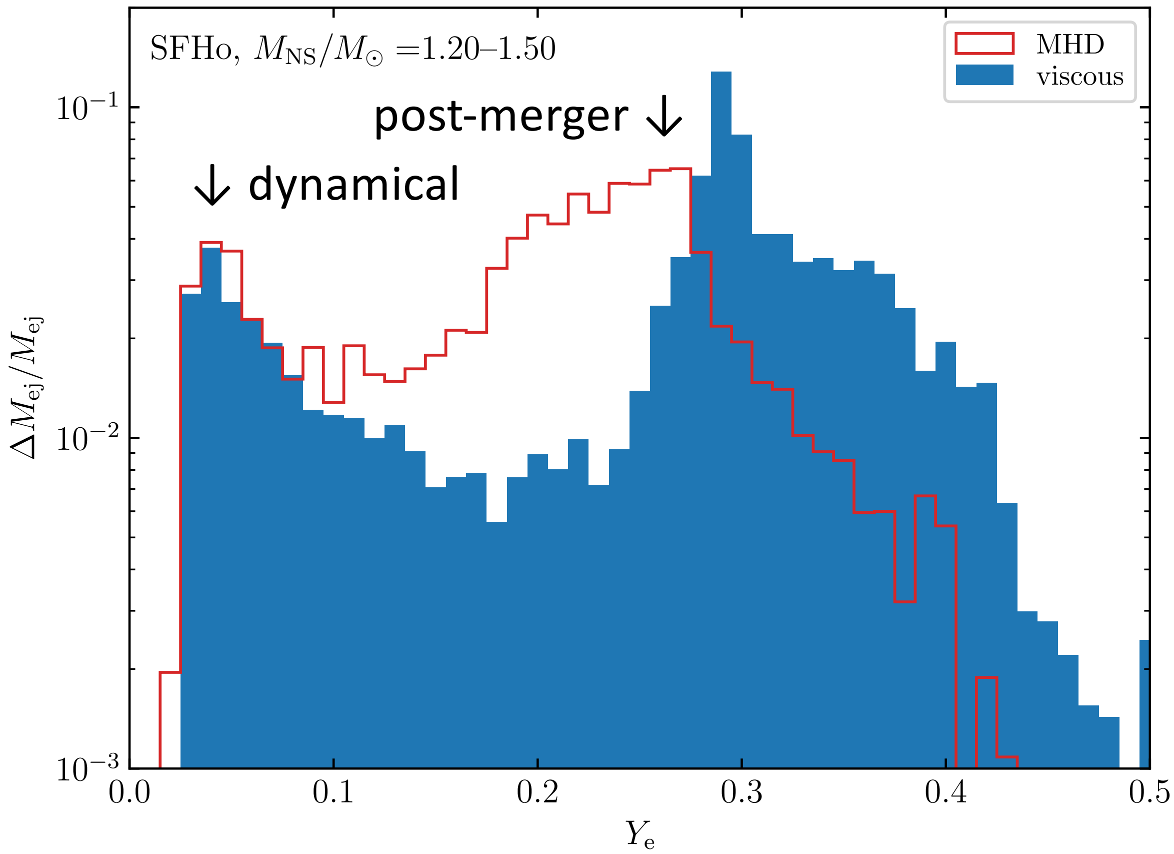
❖ nucleosynthesis from stars of > 50 $M_\odot$?: hypernovae or pair-instability supernovae ?

what gives rise to the weak r-process ?

2. neutron star mergers in MHD

Y_e distribution in MHD model

MHD vs viscous models; Wanajo+ in prep.



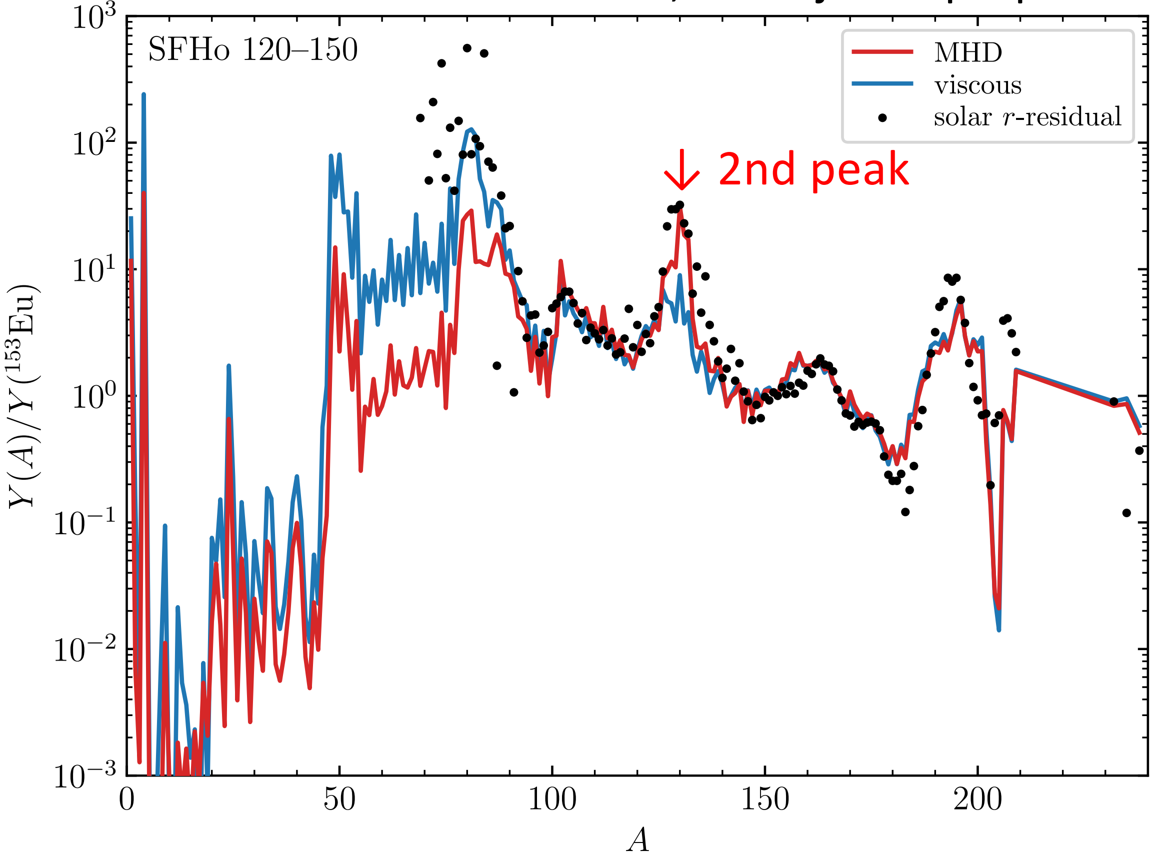
Y_e = N(proton)/N(proton+neutron)

1st self-consistent 3D simulation of a neutron star merger over 1s (including both dynamical and post-merger ejecta; Kiuchi+2023)

- MHD model results in Y_e = 0.2-0.26 (and ~0.01 $M_\odot$) instead of ~ 0.3 in viscous model (Fujibayashi+2023)

nucleosynthesis in MHD model

MHD vs viscous models; Wanajo+ in prep.

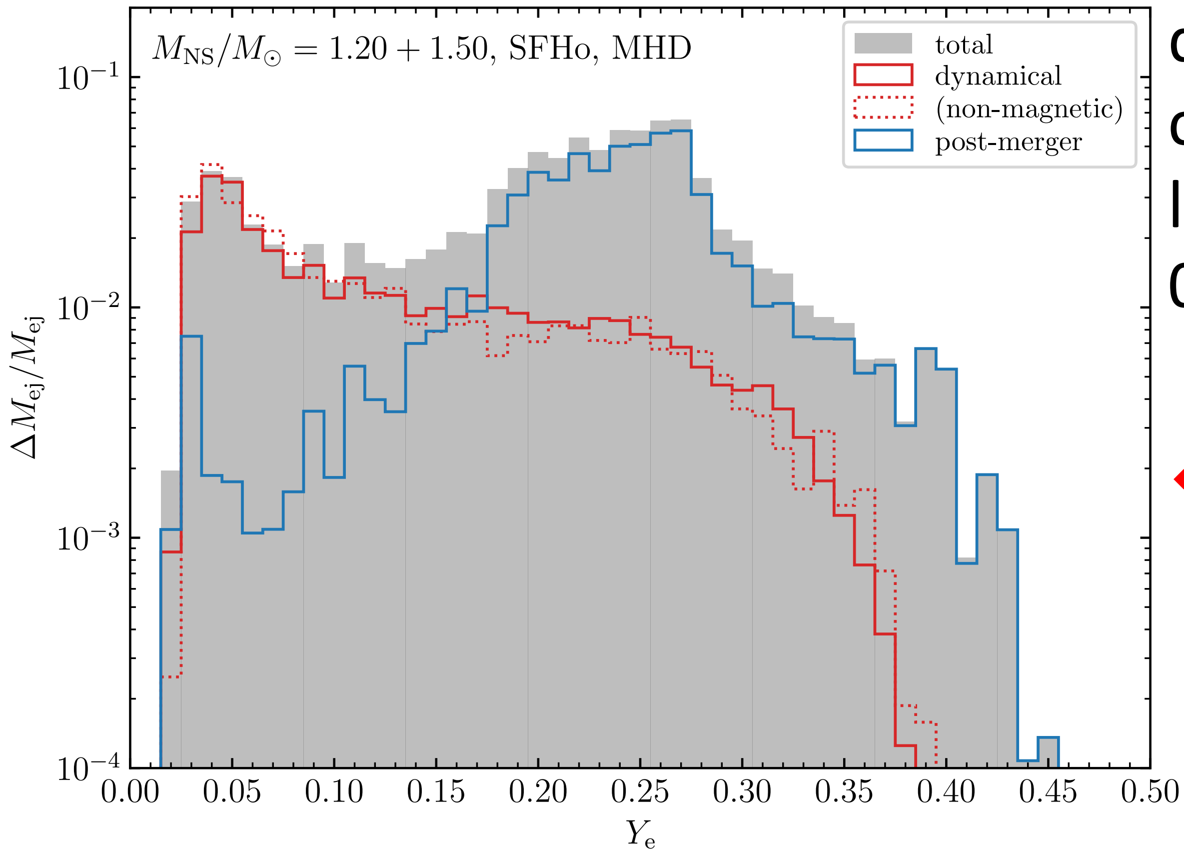


~16000 tracer particles are used for nucleosynthesis calculations

- MHD model results in very good agreement with solar r-process pattern including 2nd peak (A~ 130)

dynamical vs post-merger

MHD vs viscous models; Wanajo+ in prep.



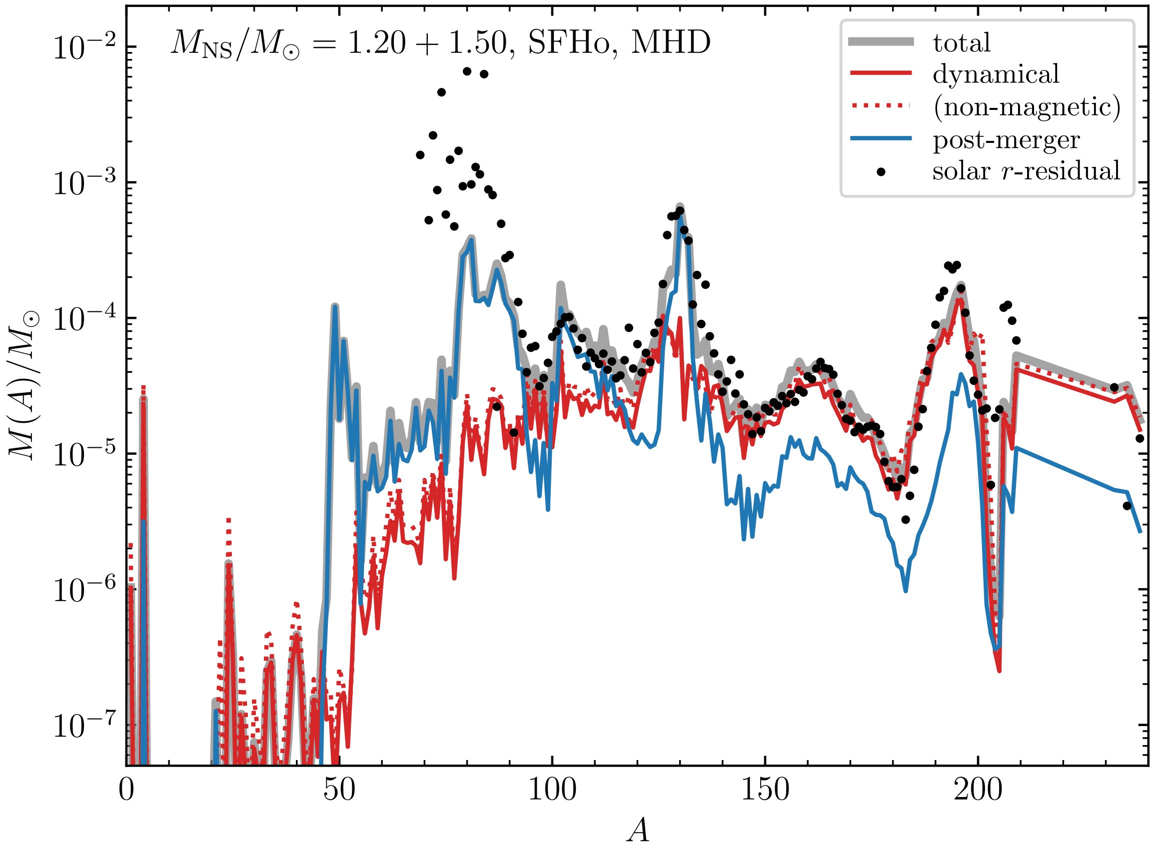
Y_e = N(proton)/N(proton+neutron)

dynamical and post-merger components are dominated by low (Y_e < 0.2) and high (Y_e > 0.2) ejecta, respectively

- ensemble of both components exhibit a wide range of Y_e ~ 0.05-0.45 (also in viscous models; Fujibayashi+2023)

dynamical vs post-merger

MHD vs viscous models; Wanajo+ in prep.



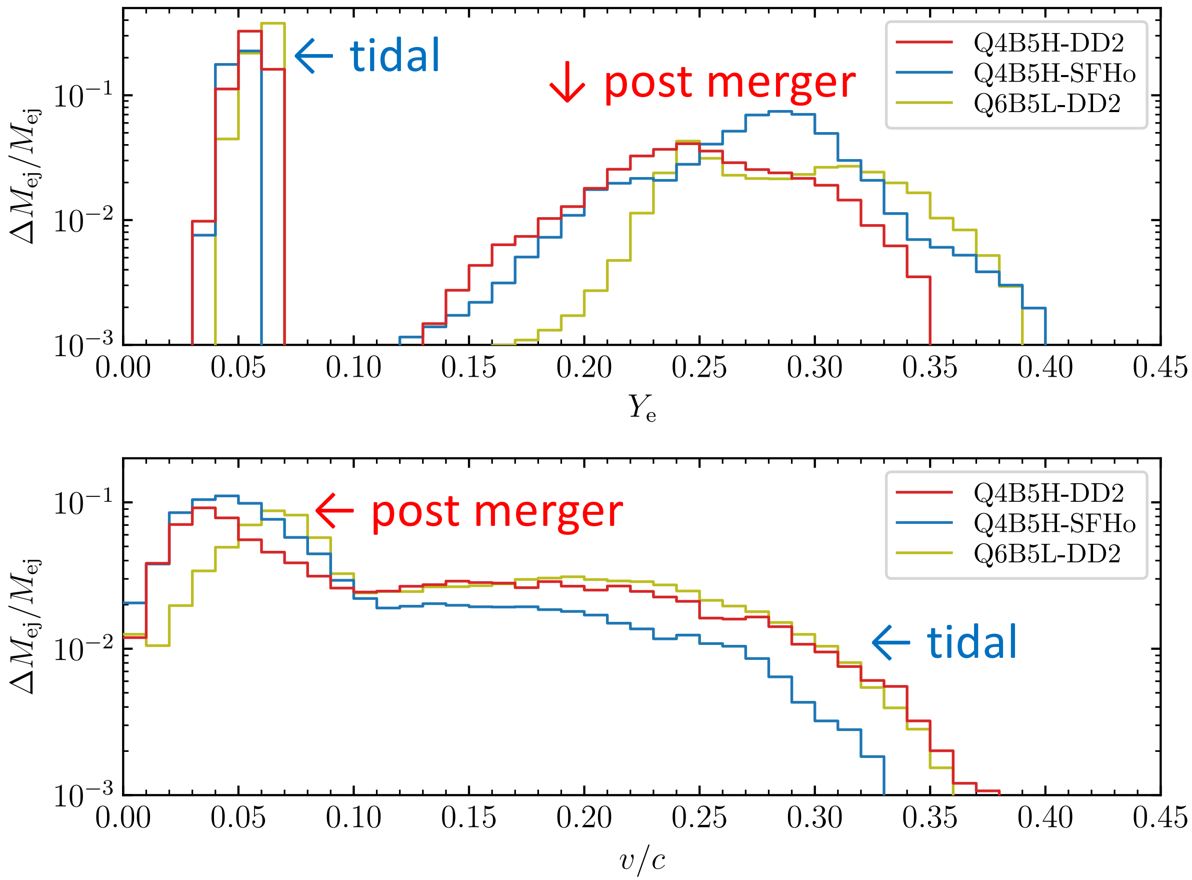
dynamical and post-merger components are responsible for heavier (A > 140) and lighter (A < 140) nuclei, respectively

- ensemble of both components results in very good agreement with solar r-process pattern (also in viscous models; Fujibayashi+2023)

3. black hole-neutron star mergers in MHD

ejecta compositions of BH-NS mergers

Wanajo+2024; adopted from Hayashi+2022

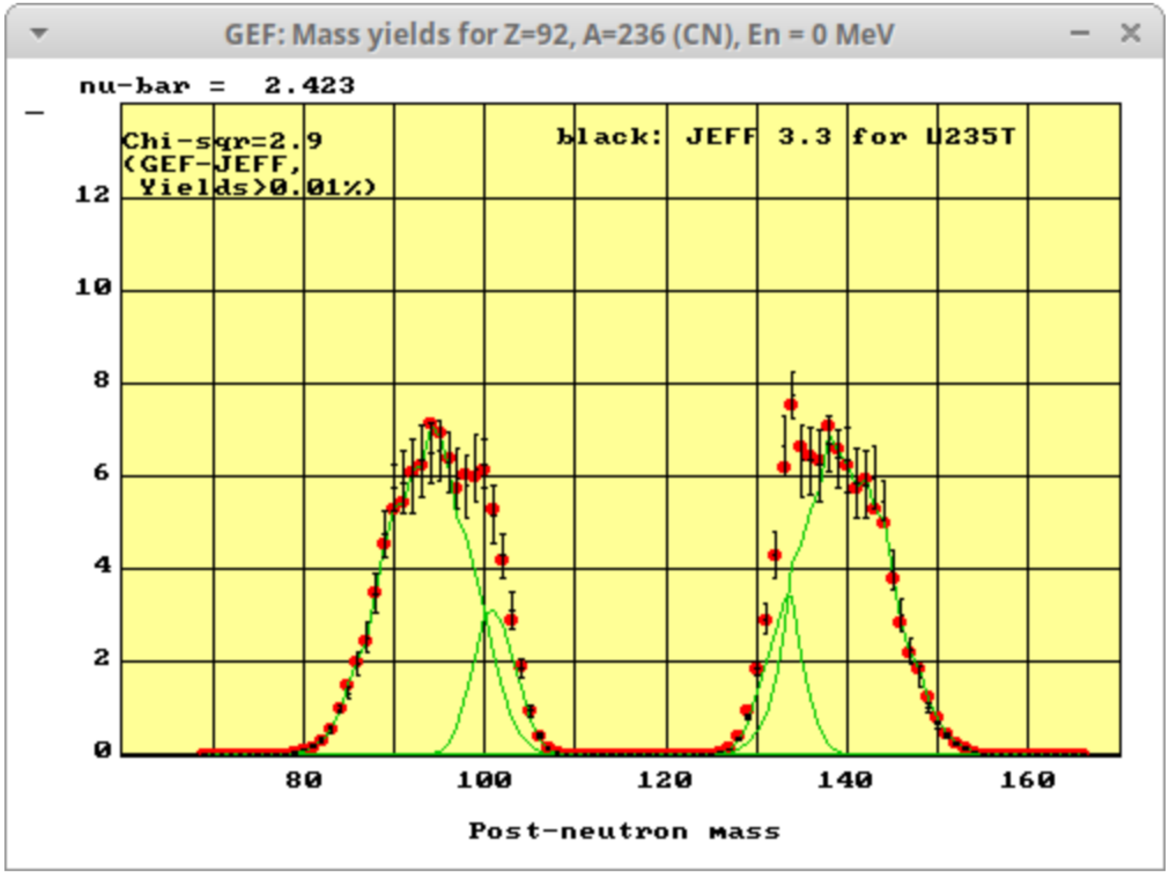


self-consistent, 3D GRMHD BH-NS simulations over 1 s (with DD2 or SFHo EOSs)

- tidal (cold) component: Y_e ~ 0.05-0.06 (pure NS material without weak interaction)
- post-merger (hot) component: Y_e ~ 0.2-0.3 (weak-processed material)

fission fragment distribution

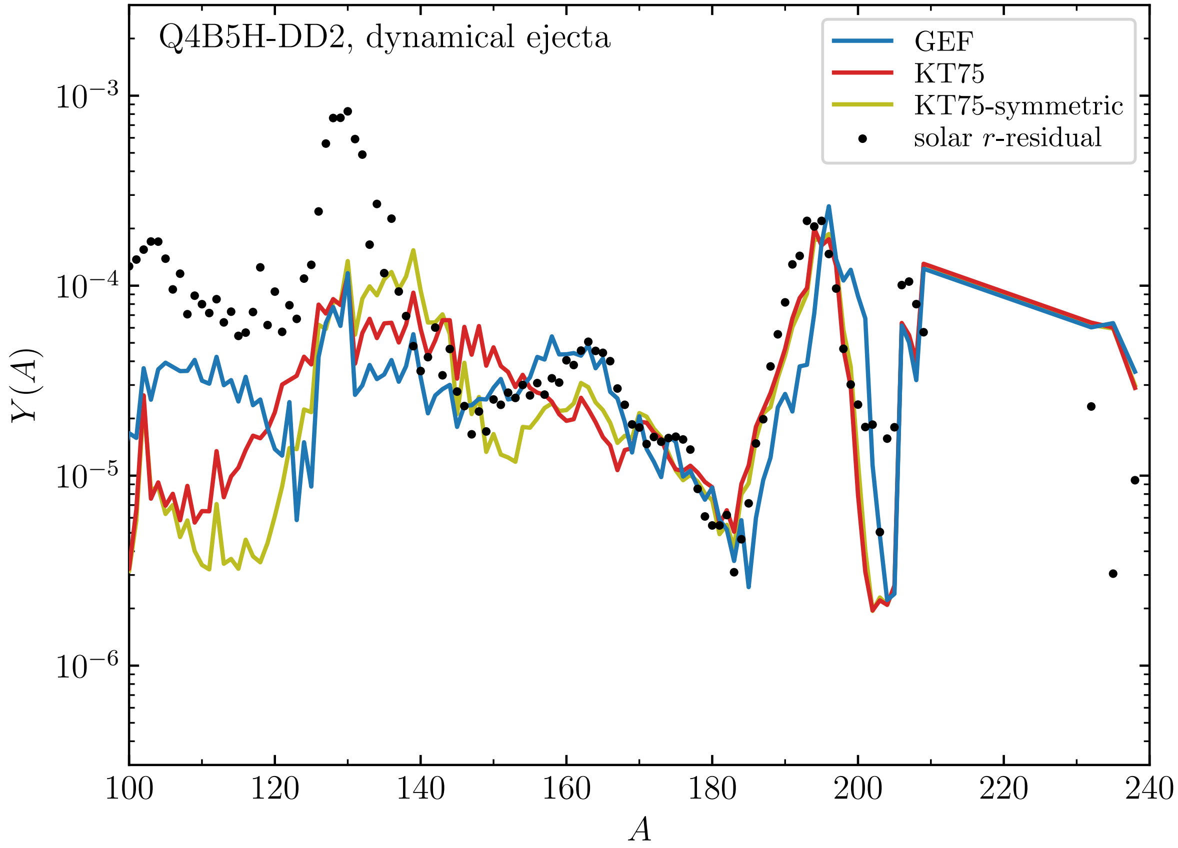
GEF 2021/1.1; Schmidt et al.



computed by using the GEF code (free BASIC) for isotopes with Z = 90-110

dependence on fission models

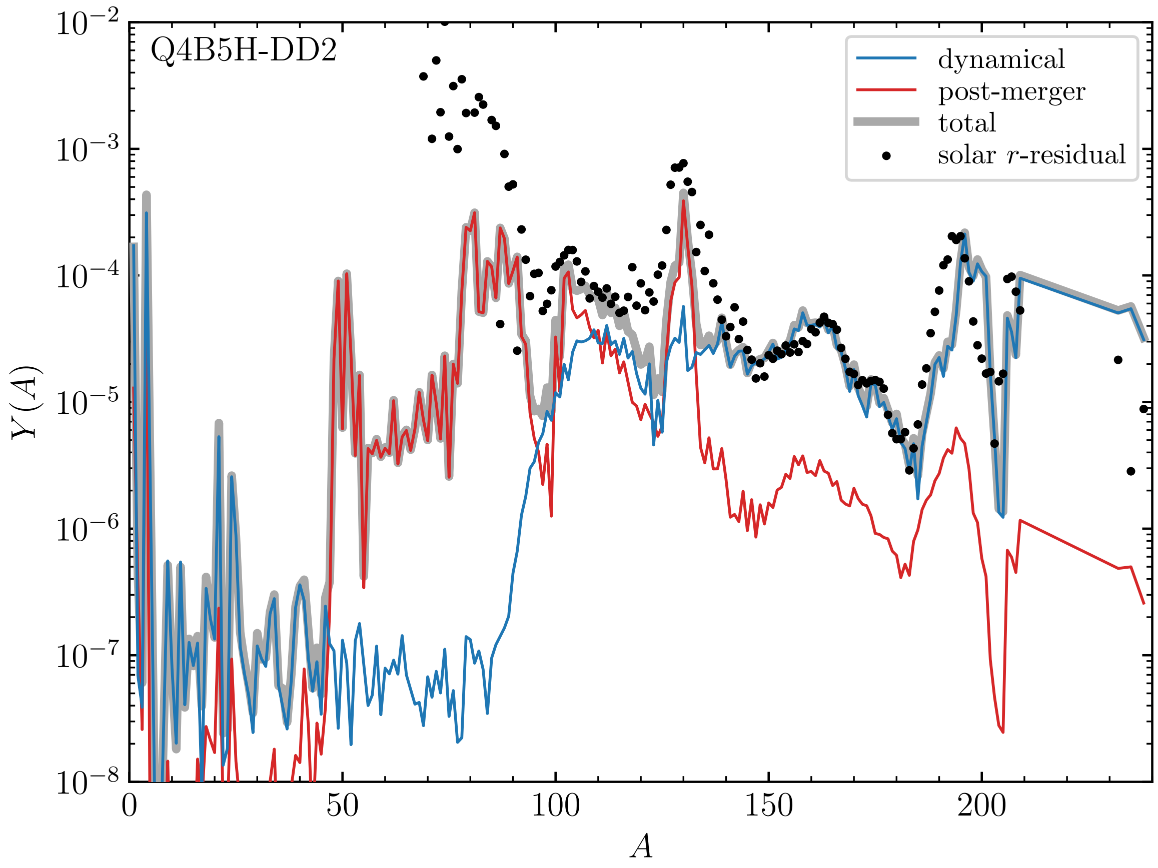
Wanajo+2024



- GEF well reproduces the solar r-pattern for $A > 140$
- Kodama & Takahashi 1975 (phenomenological double gaussian distribution) cannot reproduce the solar r-pattern

comparison with solar r-abundance

Wanajo+2024

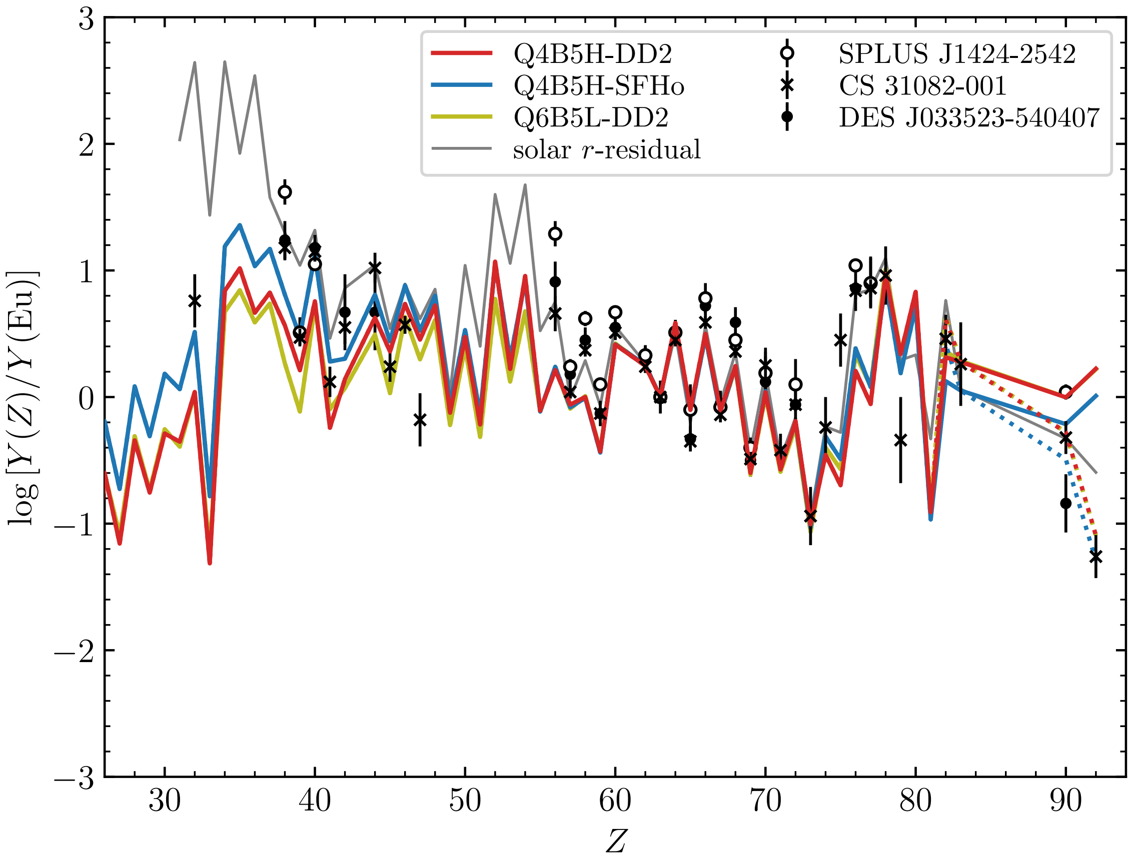


good agreement with the solar r-process abundance

- tidal (cold) component: responsible for A > 140
- post-merger (hot) component: responsible for A = 90-140

comparison with actinide-boosted stars

Wanajo+2024

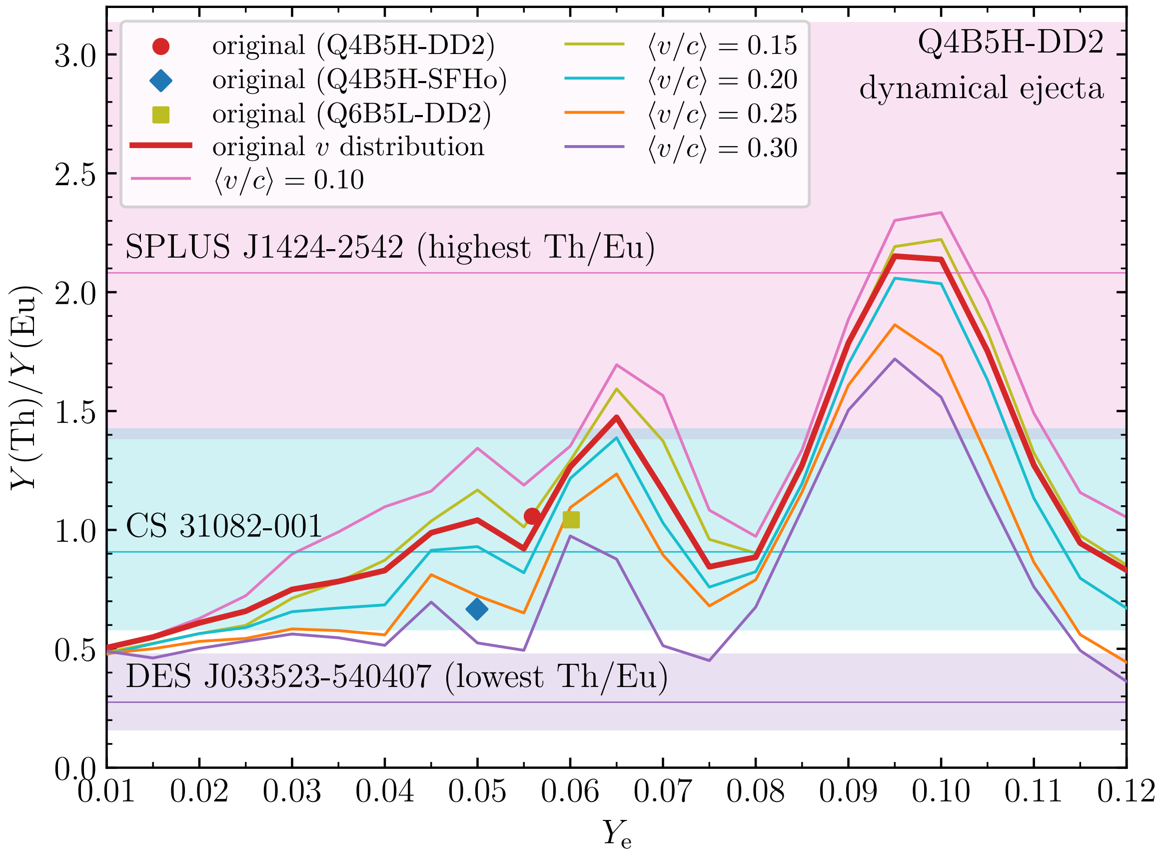


actinides (Th and U) after 13 Gyr (~ ages of these stars) with respect to lanthanides (Eu)

- good agreement with the present-day Th and U for CS31082-001 (actinide-boost star)

Y_e constraint from actinide production

Wanajo+2024

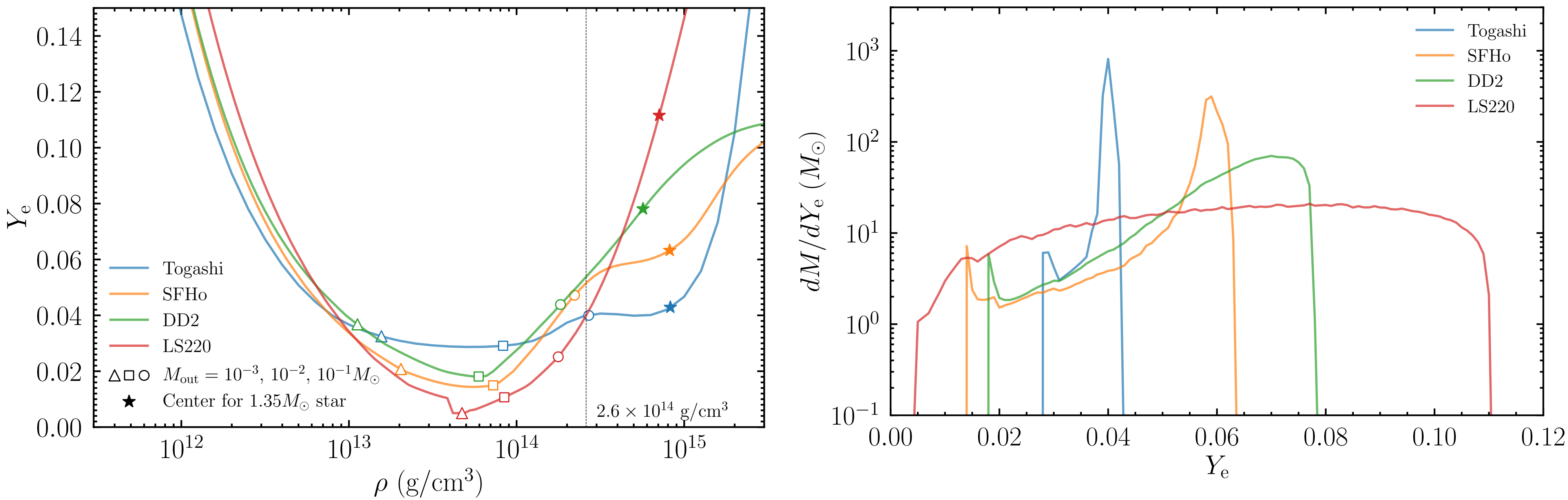


tests with Y_e = 0.01, ..., 0.1 are consistent with Th/Eu in metal-poor stars (13 Gyr ago)

- presence of actinide-boost stars (Th/Eu > 0.9) implies Y_e ~ 0.05-0.1 in the dynamical ejecta

constraint on nuclear equations of state

Wanajo+2024



- ❖ range of Y_e ~ 0.05-0.1 excludes some nuclear equations of state (e.g., Togashi EOS)

4. hypernovae in MHD

GR-MHD collapsar models

Shibata, Fujibayashi, Wanajo+2024, in prep.

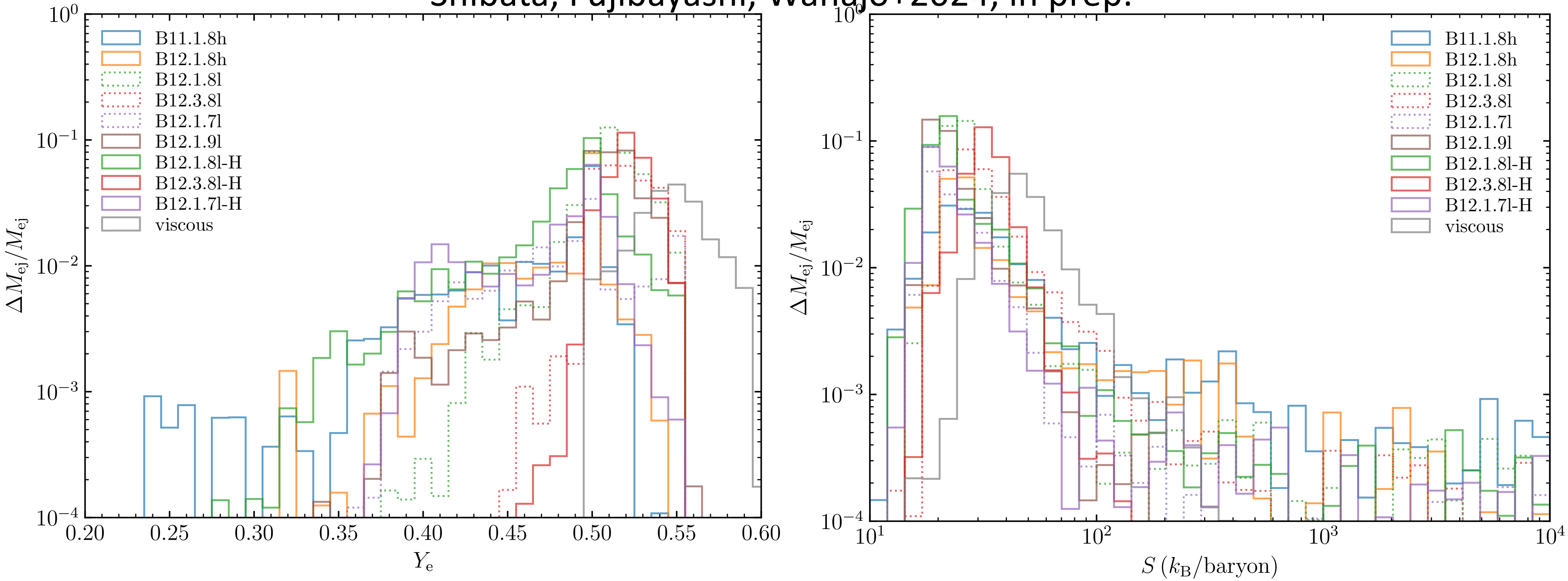
Model	$B_{\rm max}$ (G)	$\alpha_{\rm d}$	$\sigma_{\rm c}$ ($\rm s^{-1}$)	$\rho_{\rm cut}$ ($\rm g/cm^3$)	Δx (m)	Explosion	Jet
B11.1.8h	10^{11}	10^{-4}	10^8	10^8	360	Yes	Yes
B12.1.8h	10^{12}	10^{-4}	10^8	10^8	360	Yes	Yes
B12.1.8l	10^{12}	10^{-4}	10^8	10^6	360	Yes	Yes
B12.3.8l	10^{12}	3×10^{-4}	10^8	10^6	360	Yes	Yes
B12.1.7l	10^{12}	10^{-4}	10^7	10^6	360	Yes	Weak
B12.1.9l	10^{12}	10^{-4}	10^9	10^6	360	Yes	Yes
B12.1.8l-H	10^{12}	10^{-4}	10^8	10^6	300	Yes	Yes
B12.3.8l-H	10^{12}	3×10^{-4}	10^8	10^6	300	Yes	No
B12.1.7l-H	10^{12}	10^{-4}	10^7	10^6	300	Yes	Weak
viscous	—	—	—	—	360	Yes	No

long-term (> 10 s) 2D neutrino-radiated, GR-MHD simulations of BH-forming SNe (collapsars) from a 35 $M_\odot$ star (Aguilera-Dena+2020) with phenomenological dynamo parameters (Shibata+2021)

- all models explode with or without jets (depending on the stochastic nature of magnetic field evolution)

nucleosynthesis-relevant conditions

Shibata, Fujibayashi, Wanajo+2024, in prep.

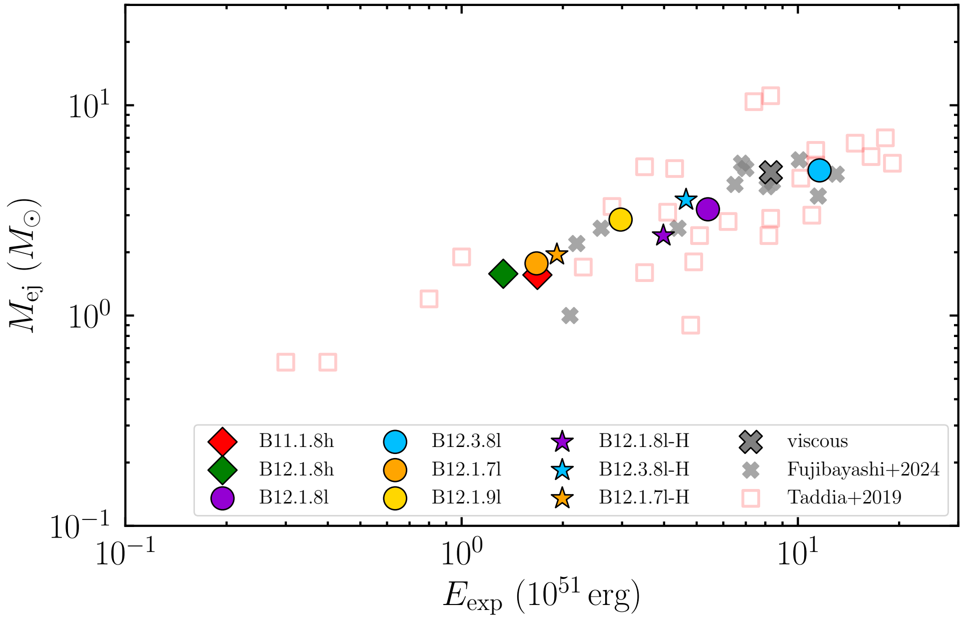


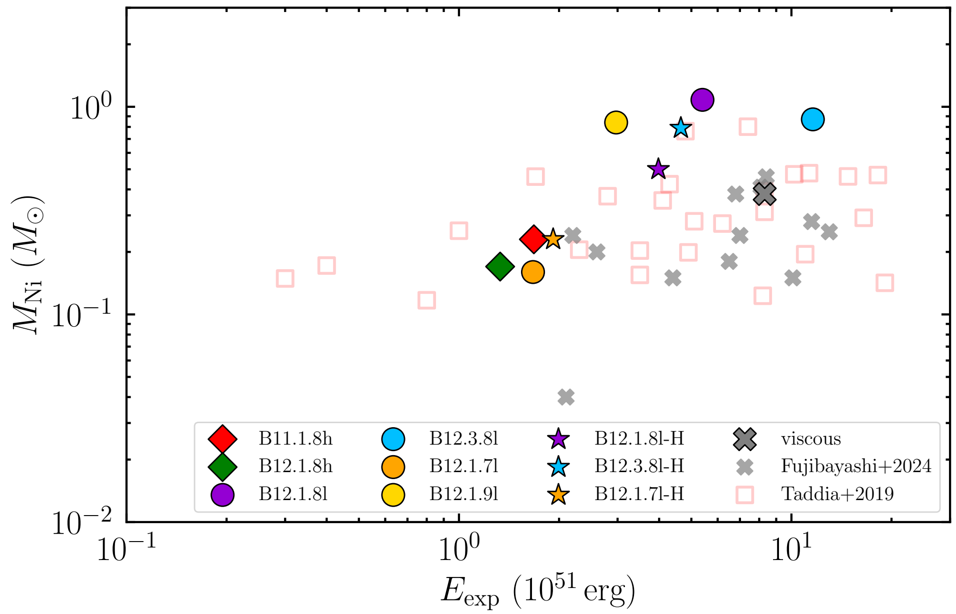
matter is modestly neutron rich but with high entropy for jet models

❖ ejecta near the jet achieve the conditions for successful r-process (and νp-process ?)

explosion energy and Ni production

Shibata, Fujibayashi, Wanajo+2024, in prep.



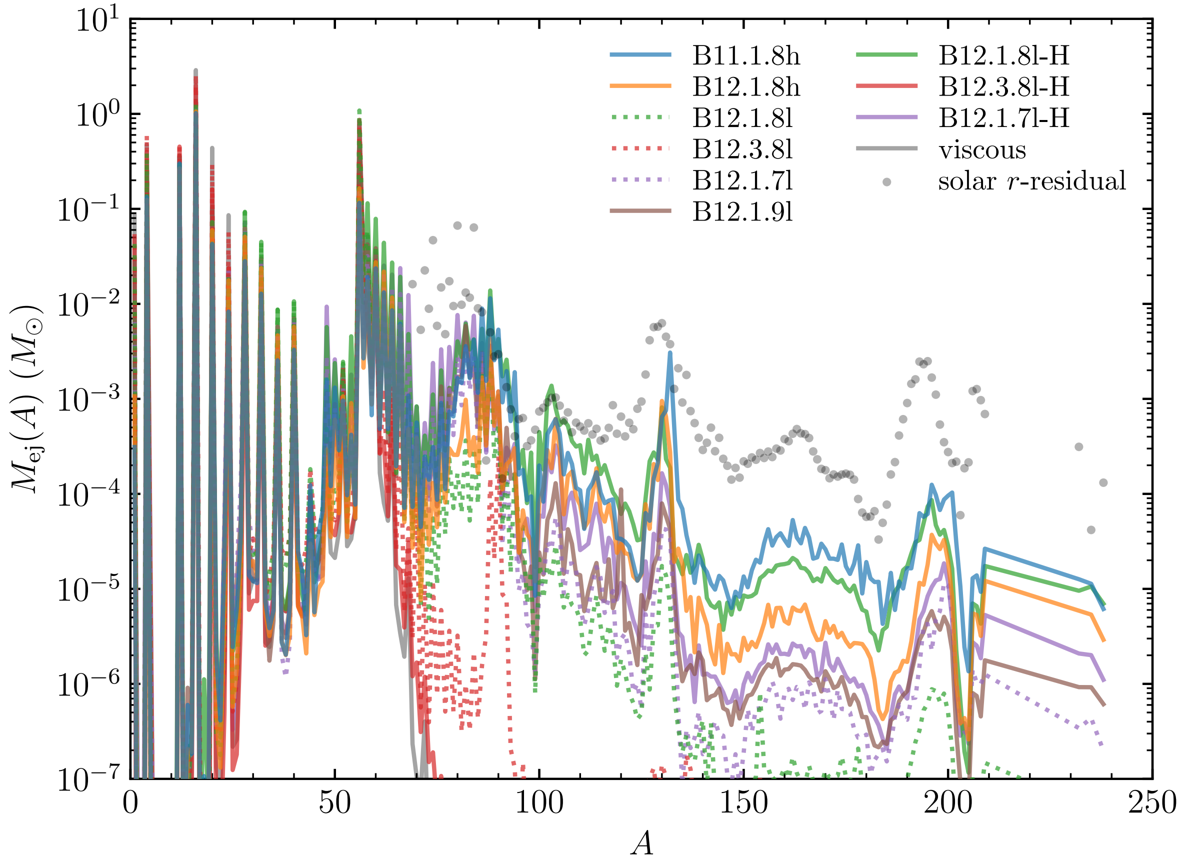


observed SNe Ic-BL (hypernovae) exhibit large explosion energies and large ^{56}Ni masses (Taddia+2019)

- models well reproduce the observational trends for explosion energy, ejecta mass, and ^{56}Ni mass

unknown nucleosynthesis ?

Shibata, Fujibayashi, Wanajo+2024, in prep.

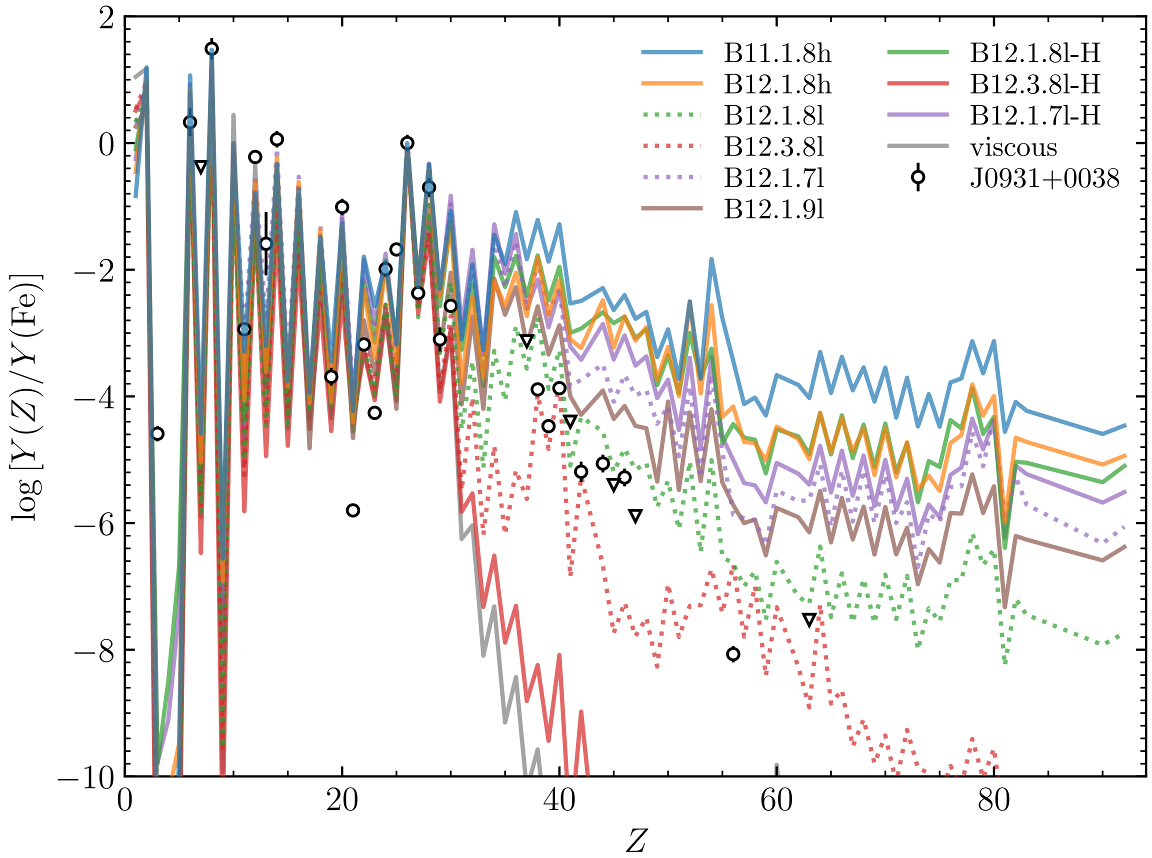


high entropy and mild neutron-richness in ejecta for models with jets

- no r-process in non-GRB SNe
- weak r-process in GRB-SNe
- no kilonova-like transients because of low lanthanides (consistent with observation of SNe Ic-BL; Rastinejad+2024)

unknown nucleosynthesis ?

Shibata, Fujibayashi, Wanajo+2024, in prep.



comparison with the star of Ji+2024 (J0931+0038) normalized at Fe

- different dynamo parameters lead to variation in weak r-process patterns
- more observation of stars with such rare abundance patterns constrain models

summary

❖ universality of r-process abundance patterns
→ ensemble of dynamical (heavy) and post-merger (light) ejecta
→ both NS-NS and BH-NS mergers can be the sites

❖ actinide boost
→ highly neutron-rich dynamical ejecta leading to fission recycling
→ BH-NS mergers are favored than NS-NS mergers

❖ peculiar nucleosynthesis (the star of Ji+2024)
→ large ^{56}Ni production with weak r-process in hypernovae with jets
→ MHD-driven BH-forming SNe (collapsars) may be possible sites

M31 HALO ILLUSTRATION OVER ROCKY TERRAIN