Hydrodynamical models of neutron-star mergers and other r-process sites

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ERC synergy HeavyMetal

NUSTAR Annual Meeting, February 26th

with: A. Bauswein, G. Martinez-Pinedo, S. Goriely, T. Janka, Z. Xiong, M. R. Wu, S. Abbar, I. Tamborra, V. Vijayan, C. Collins, L. Shingles, S. Sim, A. Sneppen, D. Watson, R. Damgaard, M. McCann, S. Nagataki, H. Ito, M. Aloy, M. Obergaulinger, ... more

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GSI

ELEMENTS

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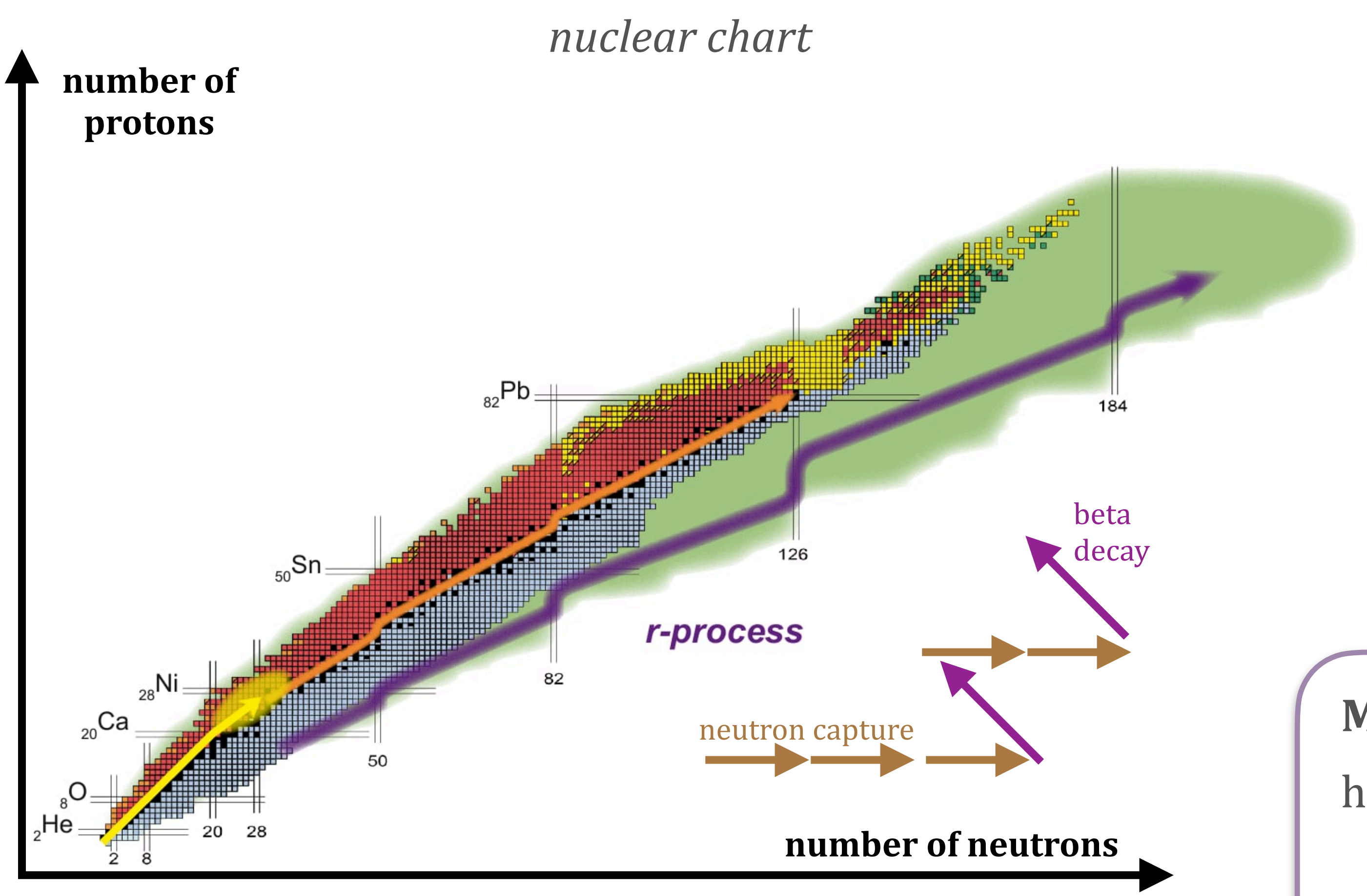
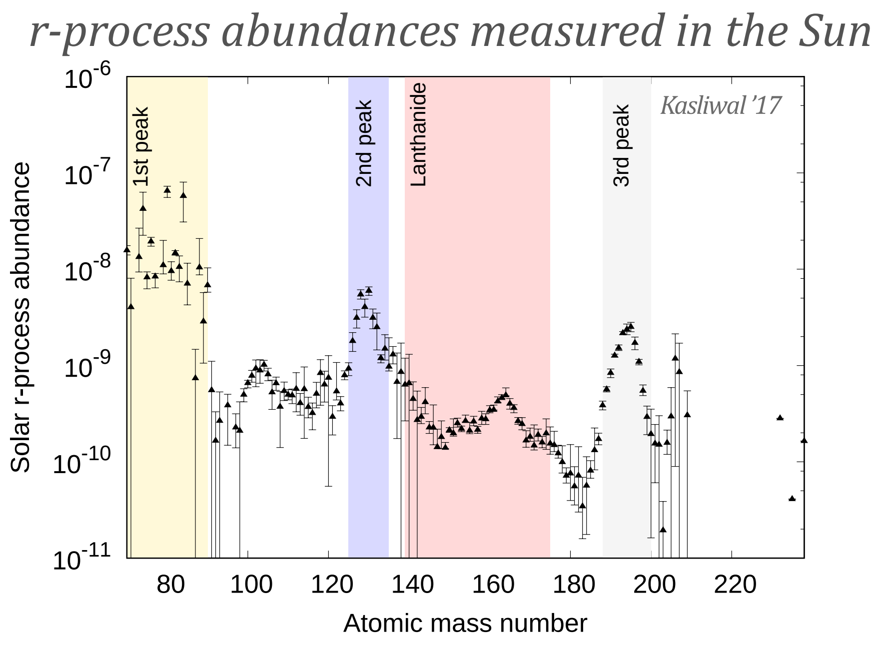
The rapid neutron-capture (or r-) process



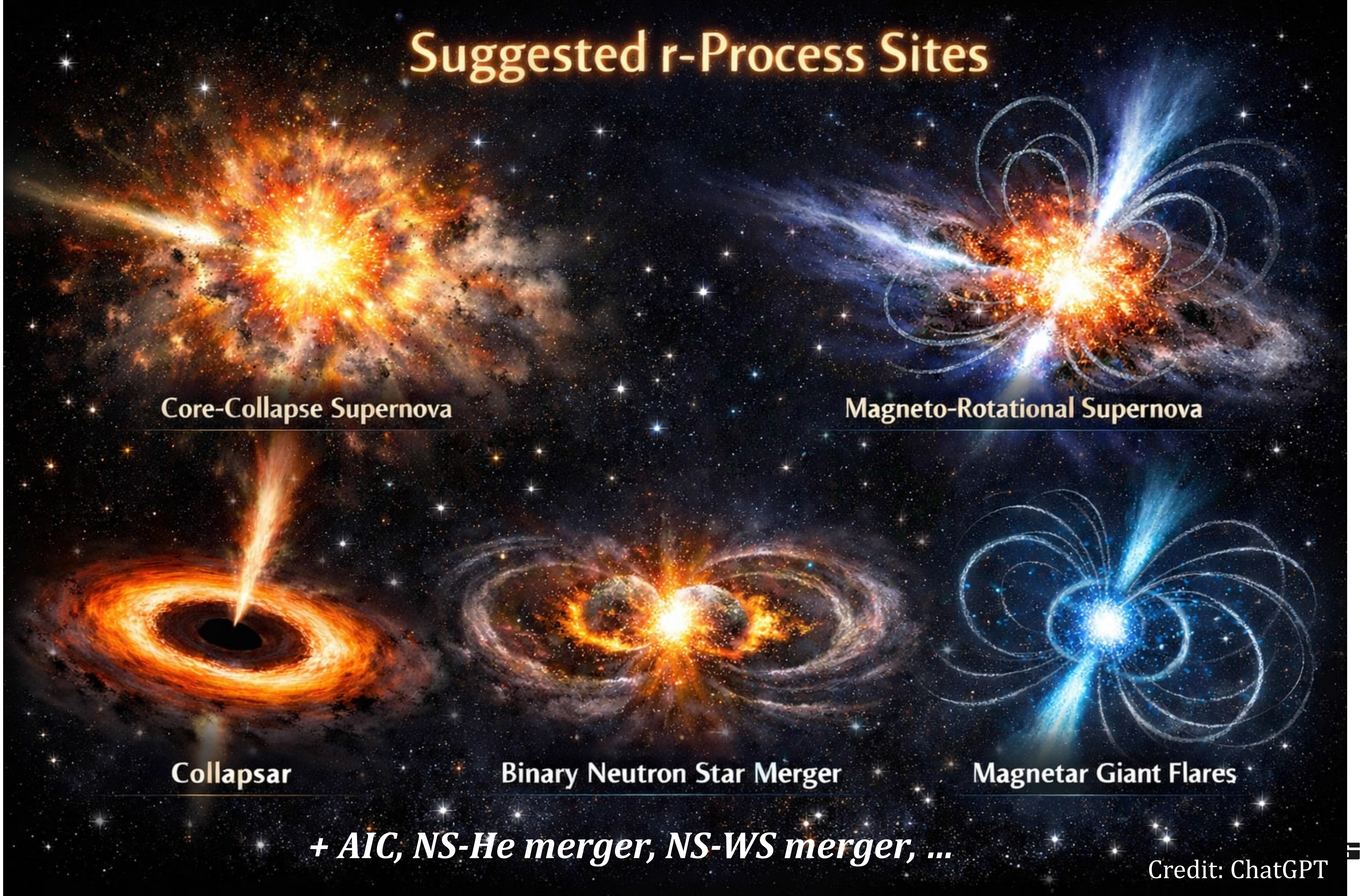


Main condition:

high neutron density = low electron fraction Y_e

$$Y_e = \frac{n_{\text{proton}}}{n_{\text{neutron}} + n_{\text{proton}}} \overset{!}{<} 0.5$$

Where does the r-process take place??? 🧐



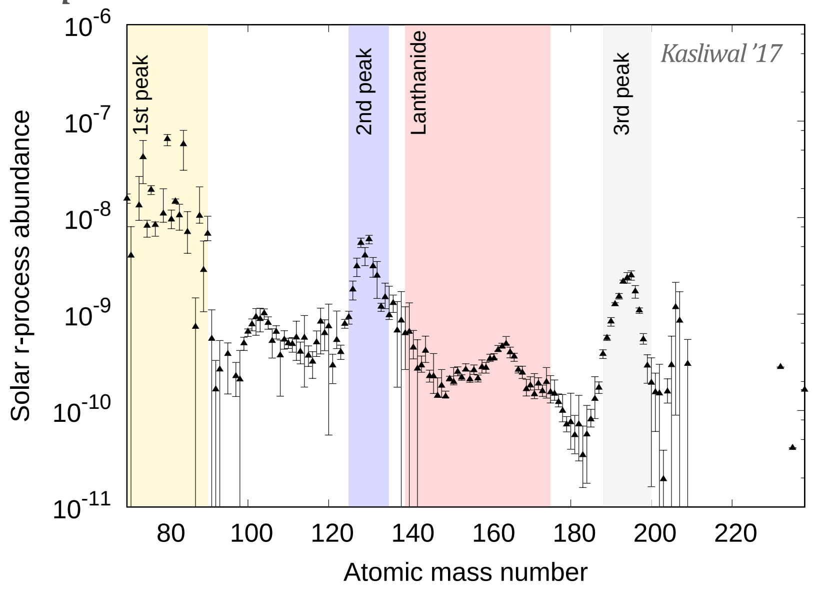
+ AIC, NS-He merger, NS-WS merger, …

Credit: ChatGPT

Motivation + challenges of hydro modeling

- hydro-models needed for predicting mass and thermodynamic properties of material ejected in each event
- analytic models often too simple and unreliable —> expensive numerical simulations necessary
- challenges:
  - neutrino transport
  - general relativistic effects
  - turbulence
- after hydro-simulation: nucleosynthesis yields from nuclear-network calculations (using nuclear data from experiments and theory)

r-process abundances measured in the Sun



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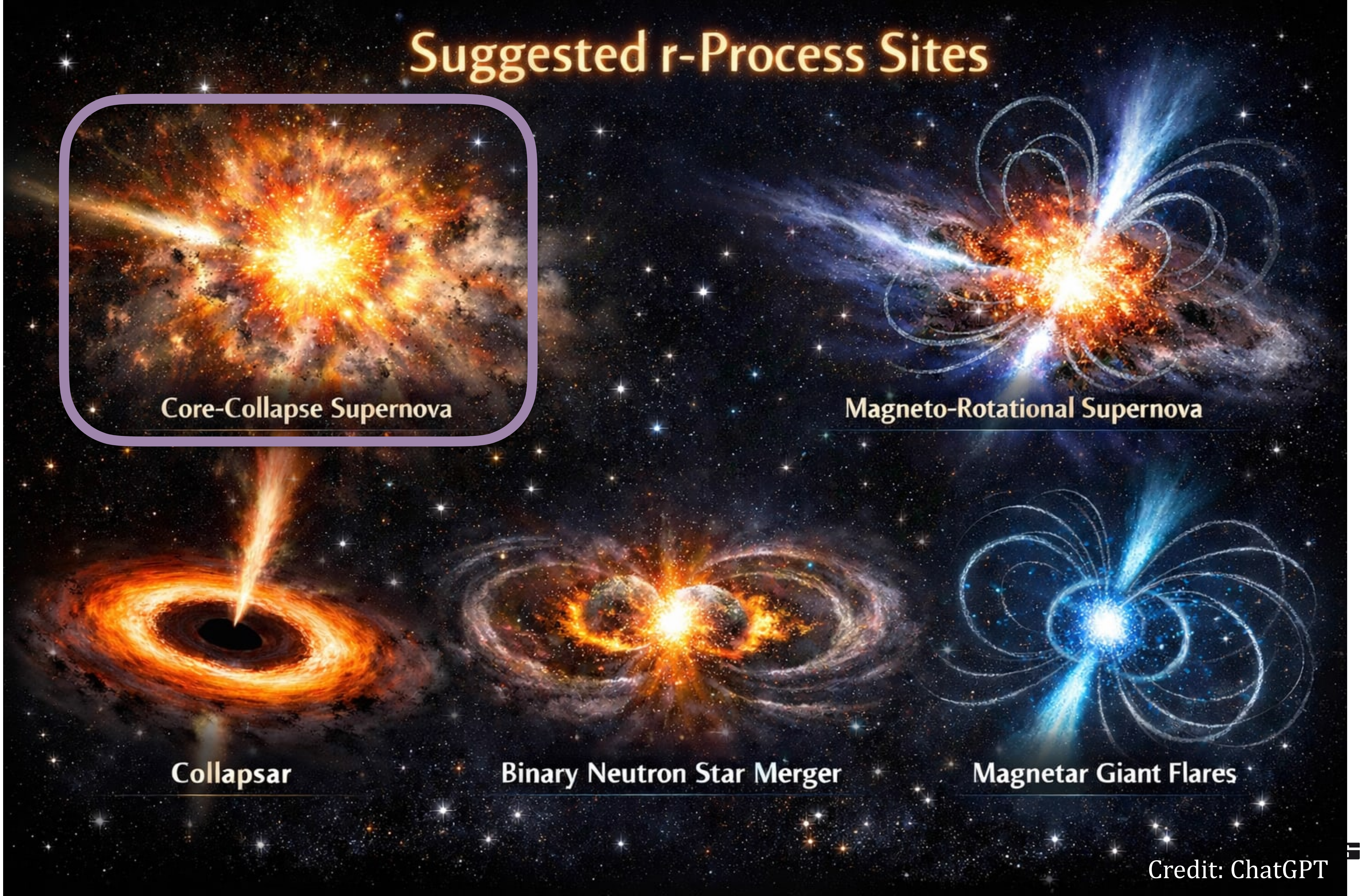
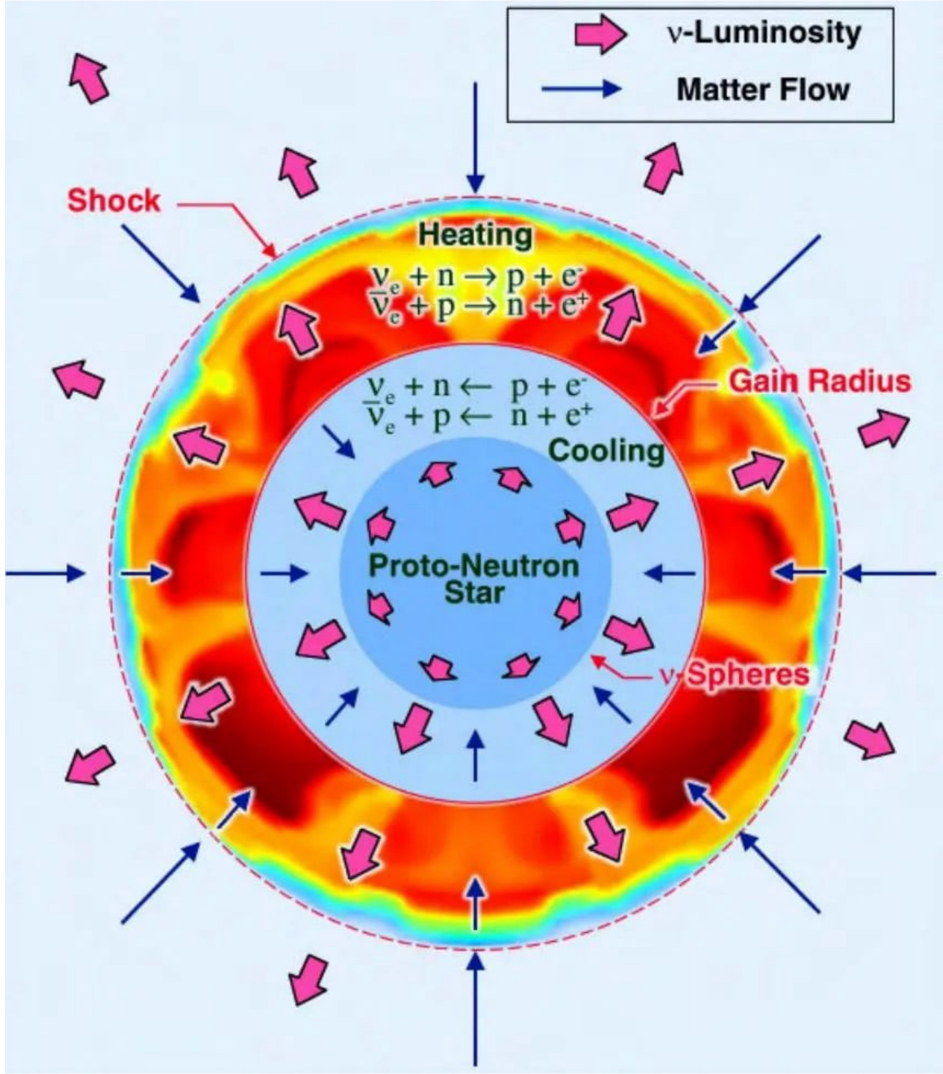


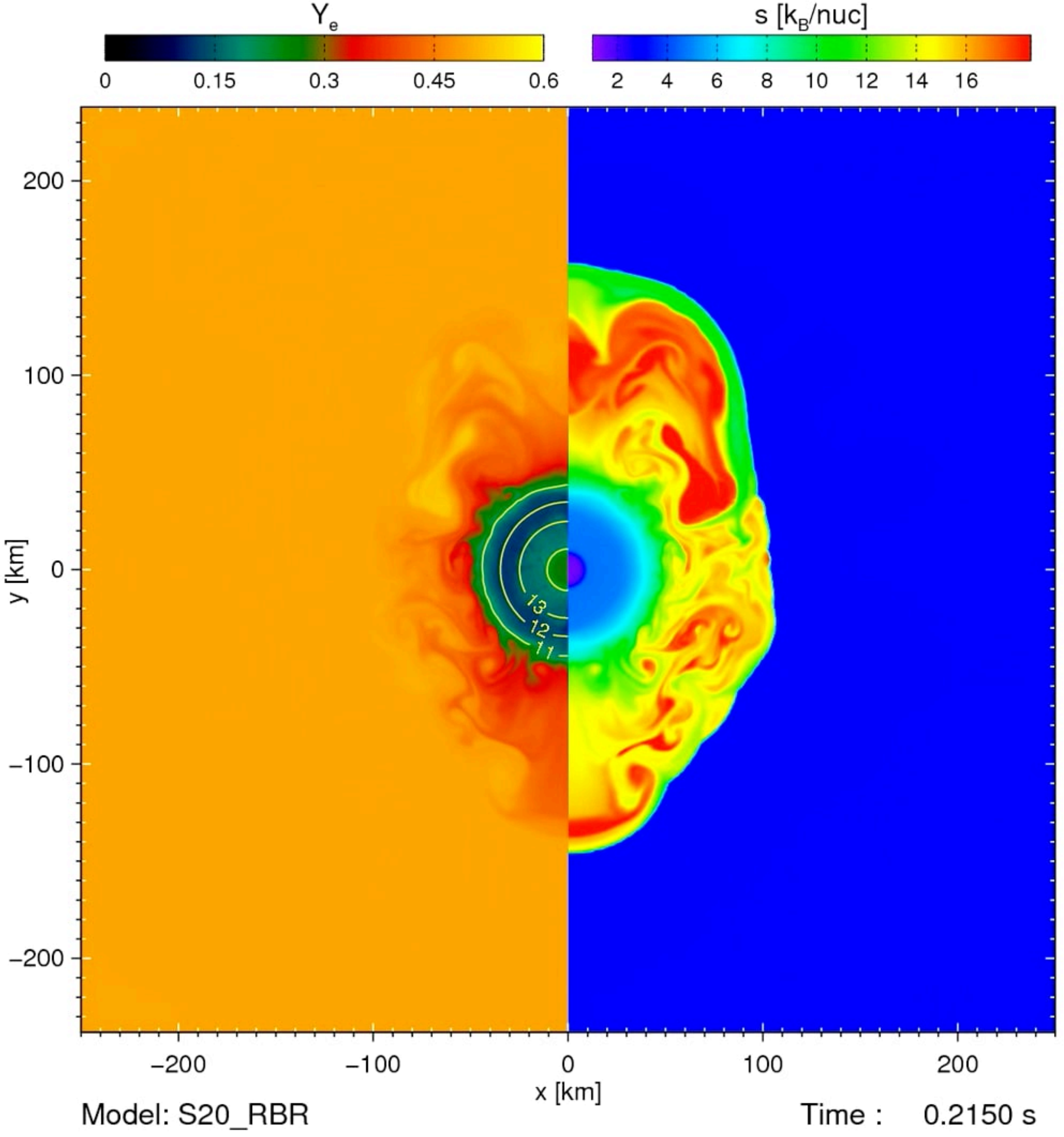
Credit: ChatGPT

(Ordinary) core-collapse supernova



(Credit: Mezzacappa+2001)

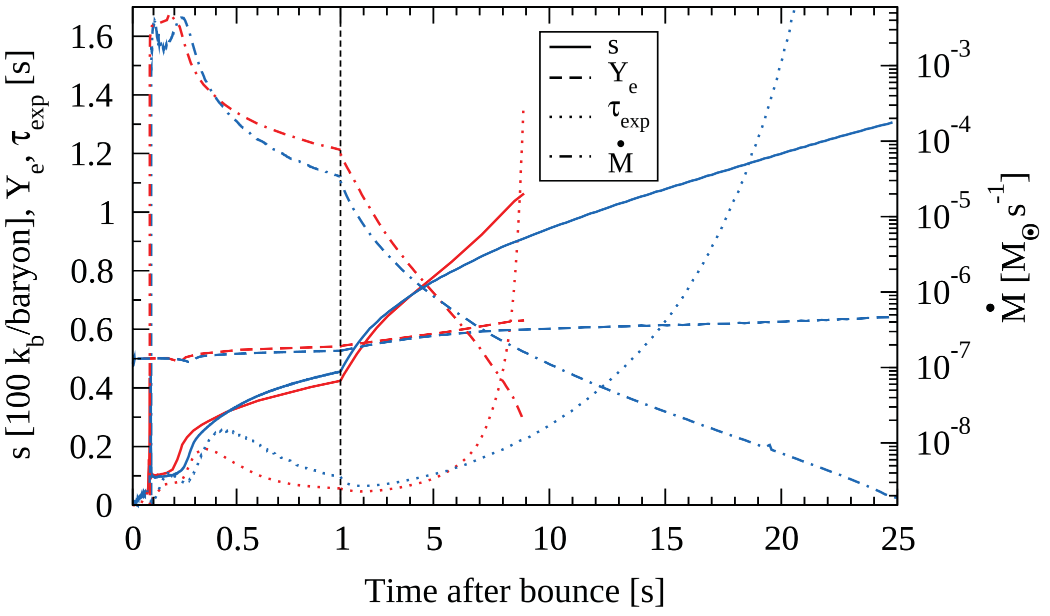
Simulation movie



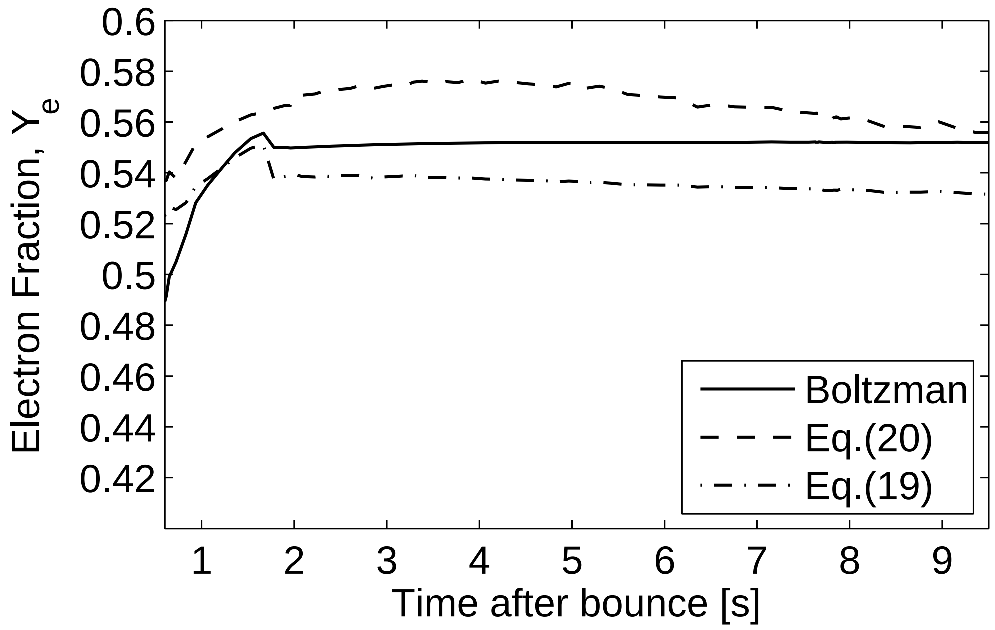
(Just, Bollig, Janka et al. 2018, MNRAS 481)

Is neutrino-driven wind actually neutron rich?

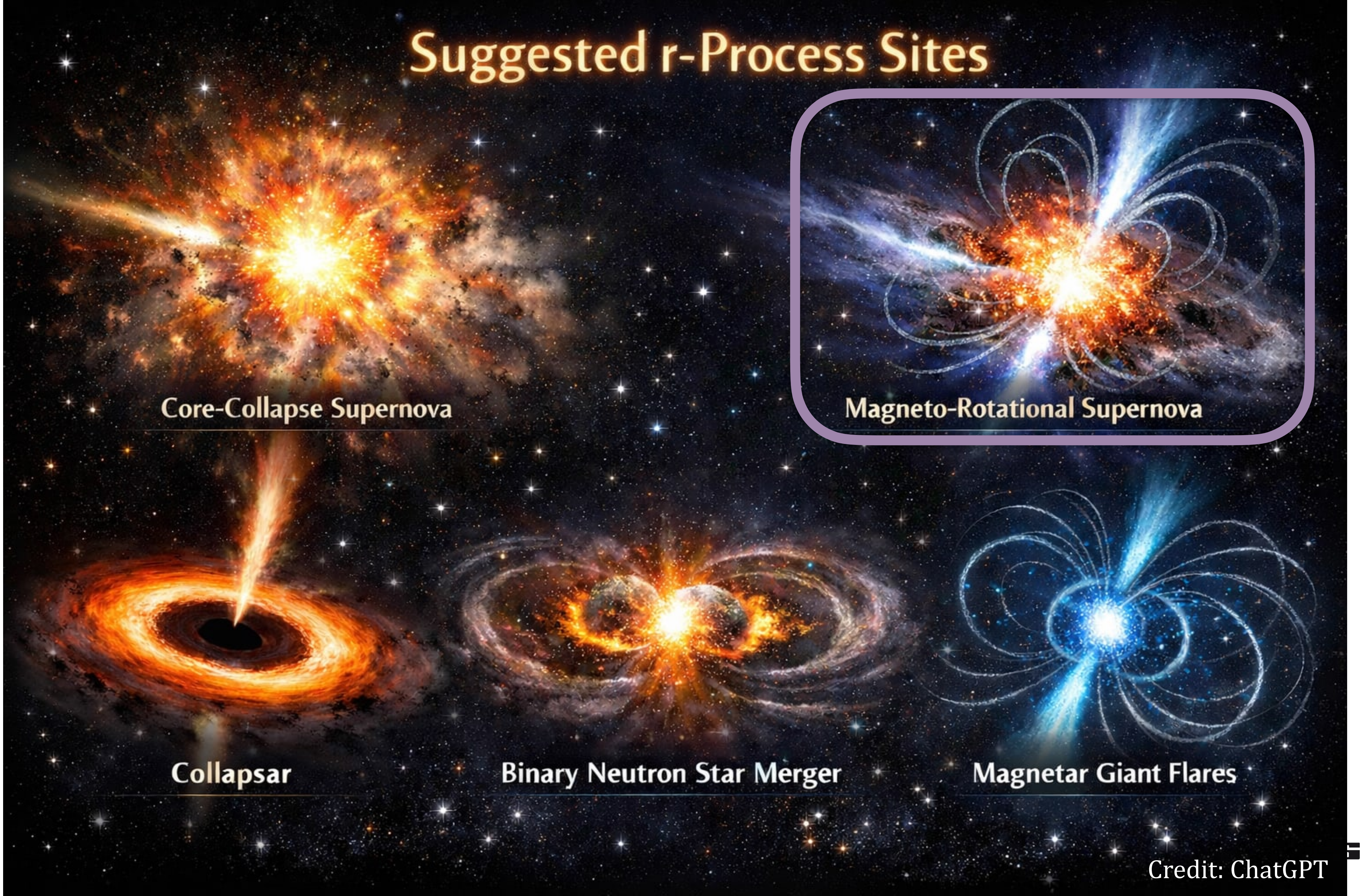
(Hüdepohl et al. 2010, PRL 104)



(Fischer et al. 2010, A&A 517)



- No… simulations rather predict proton-rich wind
- in some cases mildly neutron-rich at most
- **ordinary CCSNe no promising candidate for r-process nucleosynthesis**

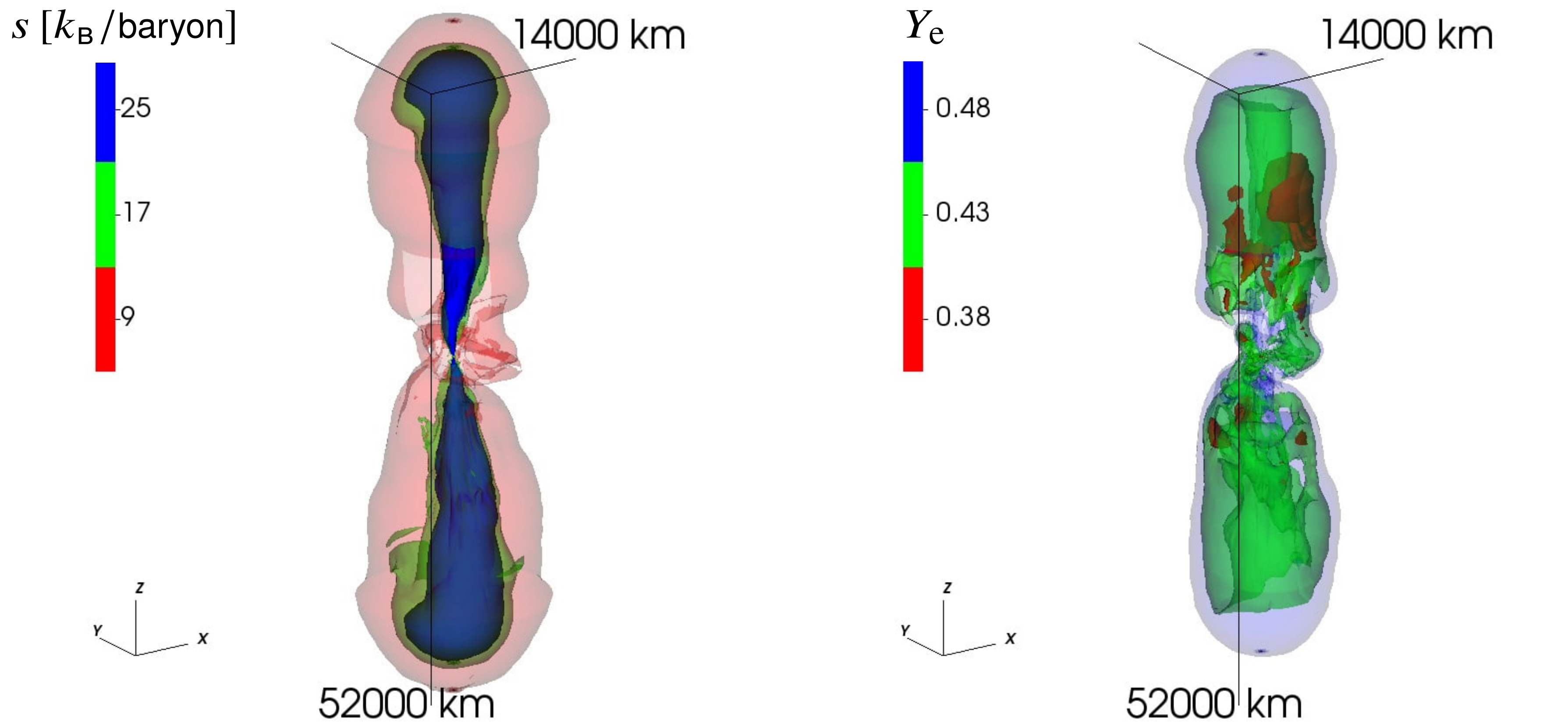


Credit: ChatGPT

Magnetorotational CCSN

(= CCSN of star with strong B-fields + fast rotation)

(Obergaulinger et al. 2021, MNRAS 503)

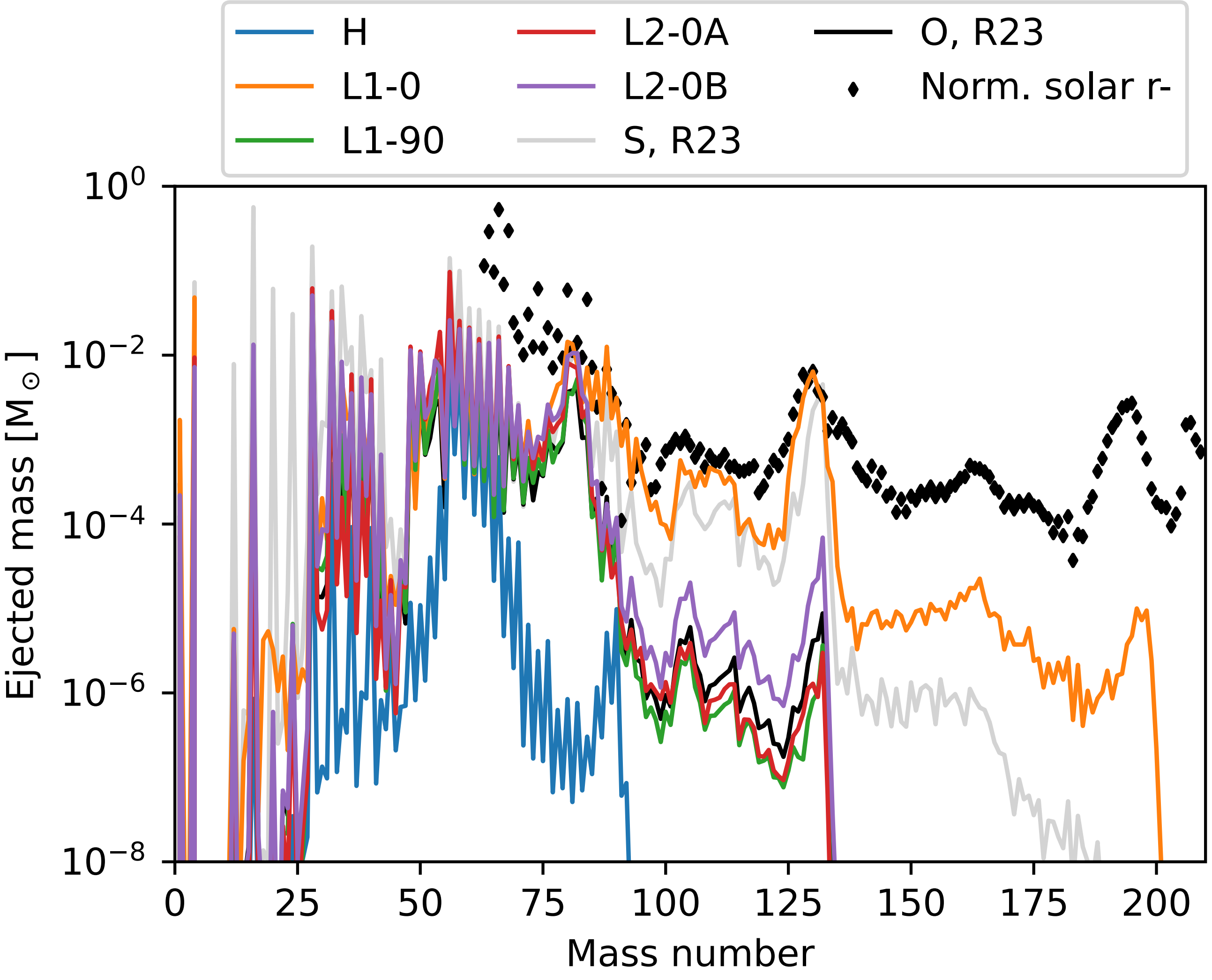


- magnetic field amplification through compression and helical winding around rotation axis
- fast jet-like outflows along the rotation axis
- outflow contains neutron-rich “pockets”

Magnetorotational supernova

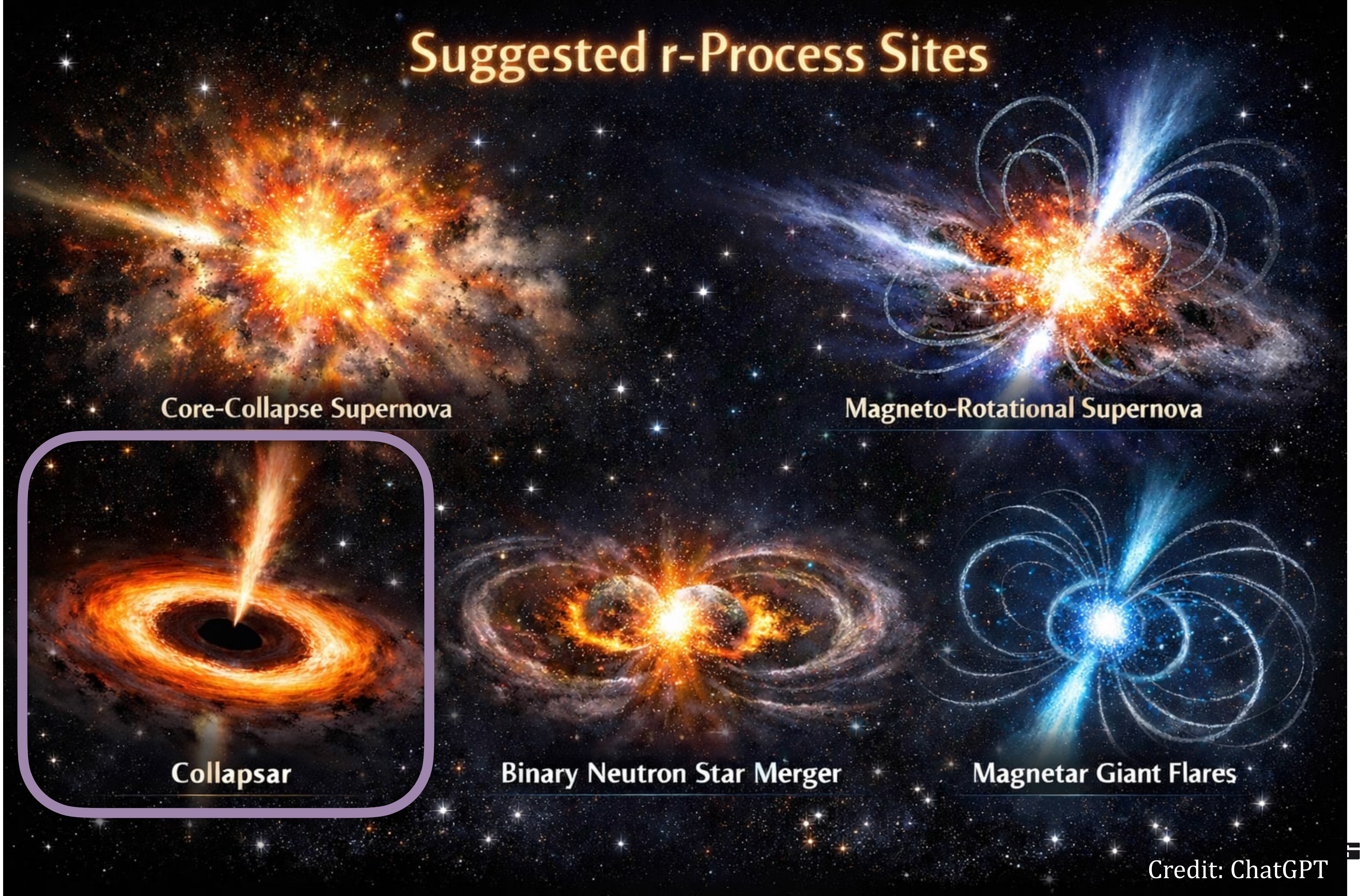
(= CCSN of star with strong B-fields + fast rotation)

- nucleosynthesis pattern strongly sensitive to the B-field and rotation rate of progenitor star
- stronger B-field + faster rotation => more heavy elements
- unfortunately: “realistic” B-field configuration and rotation rate only poorly known from stellar evolution theory and observations
- **maybe some MR-SNe are promising r-process sites, but possibly only for lighter r-process elements**



(Reichert et al. 2024, MNRAS 529)

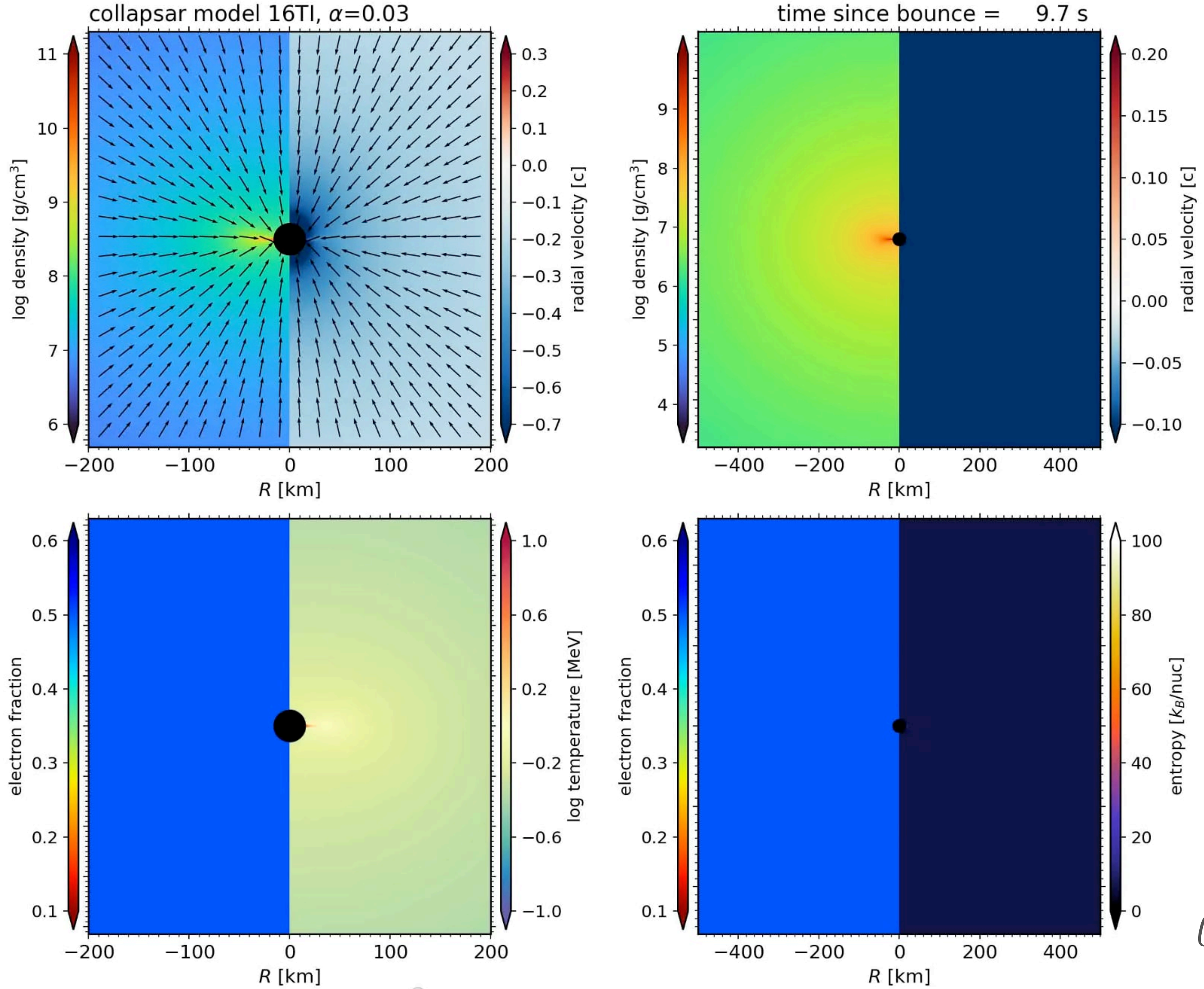
GSI



Credit: ChatGPT

Collapsars

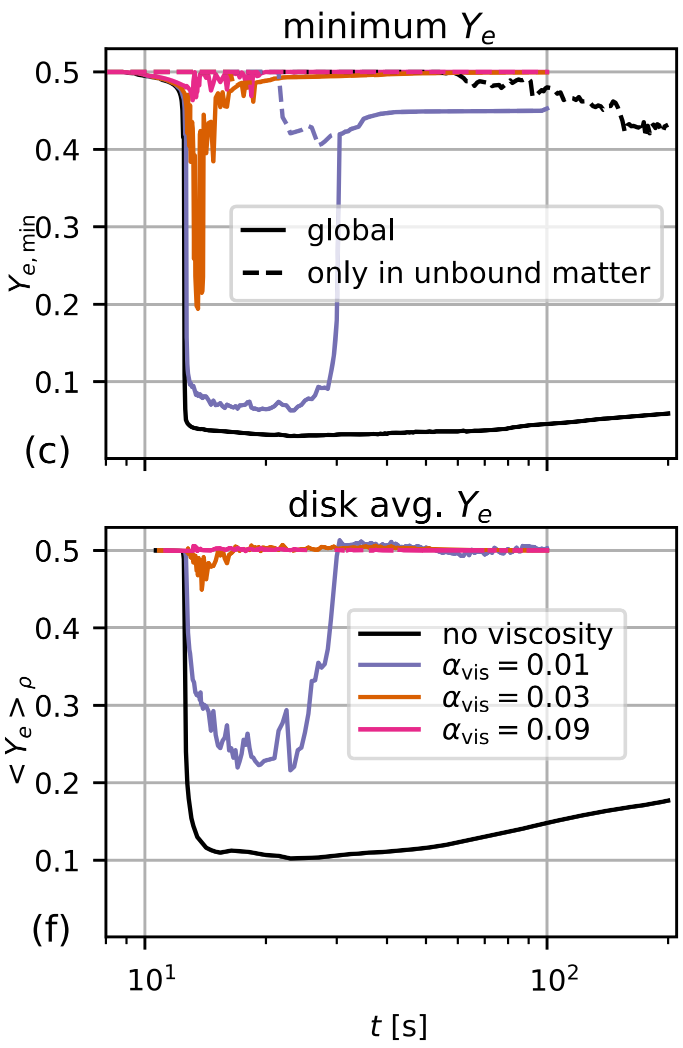
(= MR-SNe with black-hole formation)



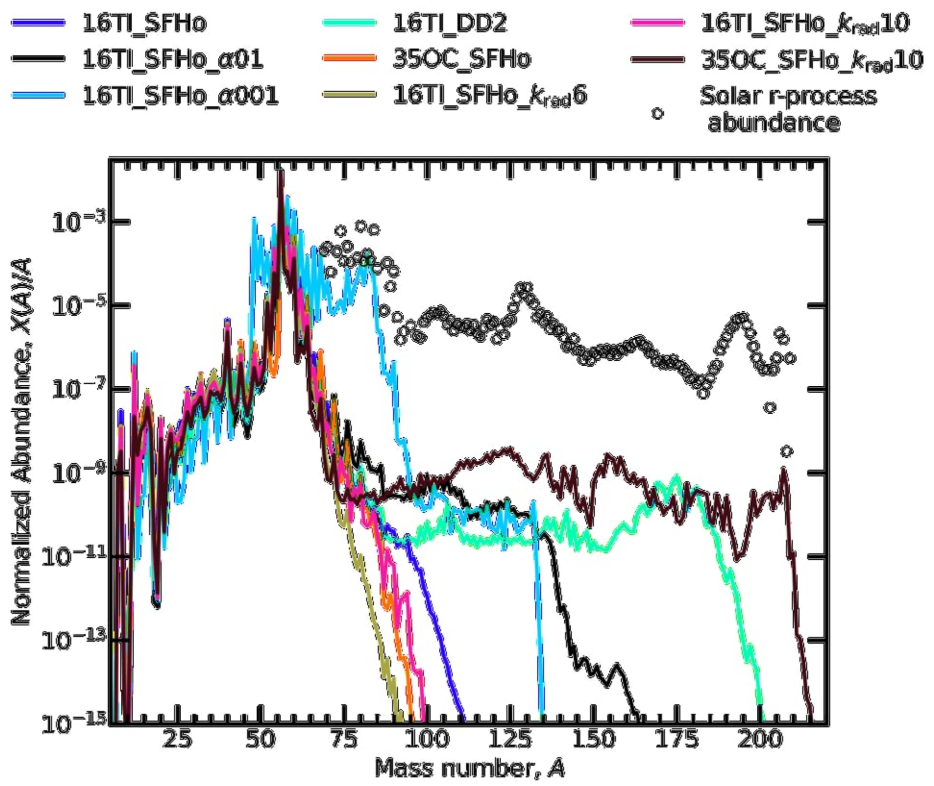
(Just et al. 2022, ApJL 934)

Collapsars as r-process sites?

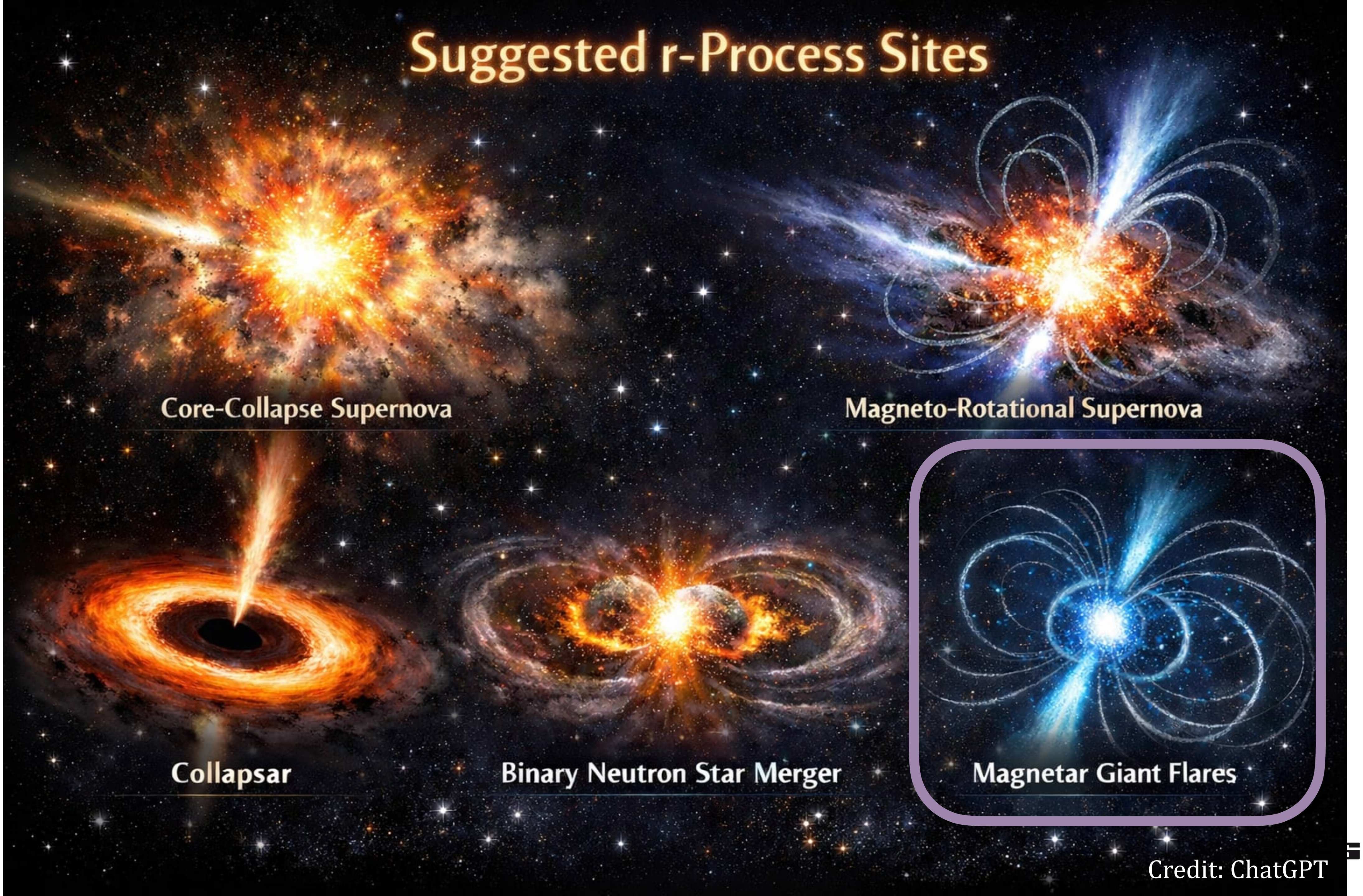
- sensitive progenitor dependence (same problem as for MR-SNe)
- strong B-fields needed to produce neutron-rich outflows
- most current models "emulate" B-field effects through mean-field viscosity
- **maybe some collapsars are promising r-process sites, but possibly only for lighter r-process elements**



(Just et al. 2022, ApJL 934)



(Dean et al. 2024, PRD 110)

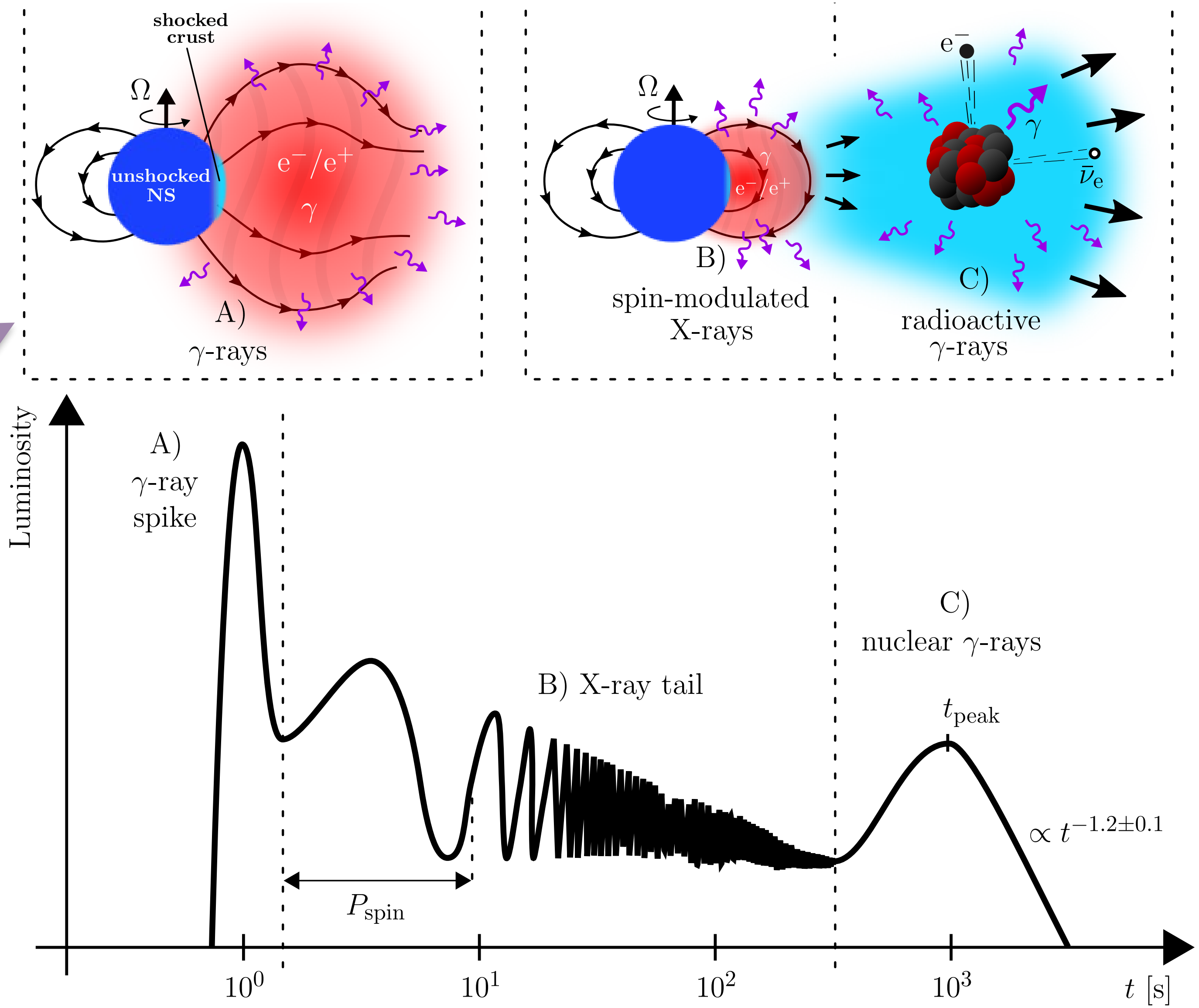


Credit: ChatGPT

Magnetar giant flares

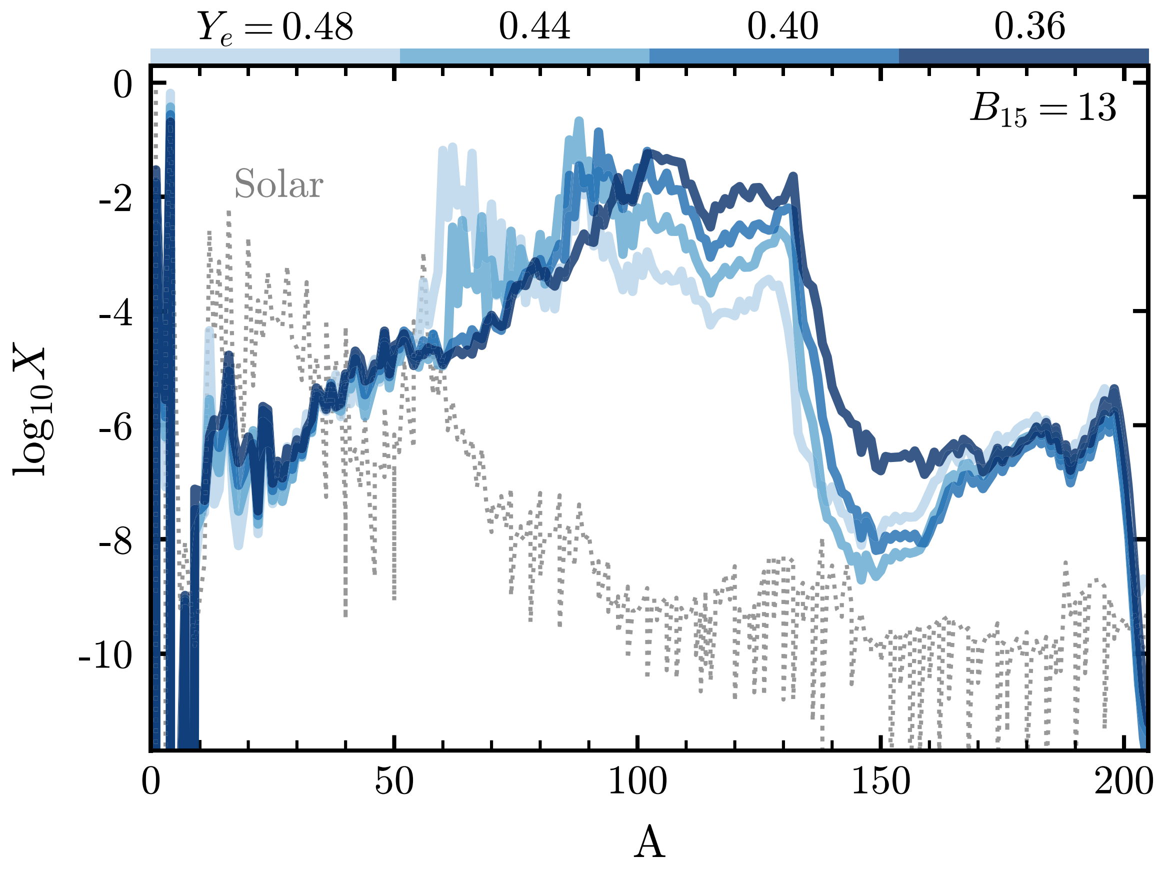
(magnetars = compact remnants of MR-SNe not forming black holes)

- several MGFs have been observed but unclear if r-process takes place
- promising scenario recently suggested by Patel et al. 2024, ApJL 984
- B-field reconnection event shocks NS crust
  —> dissociation into free neutrons
  —> thermal expansion

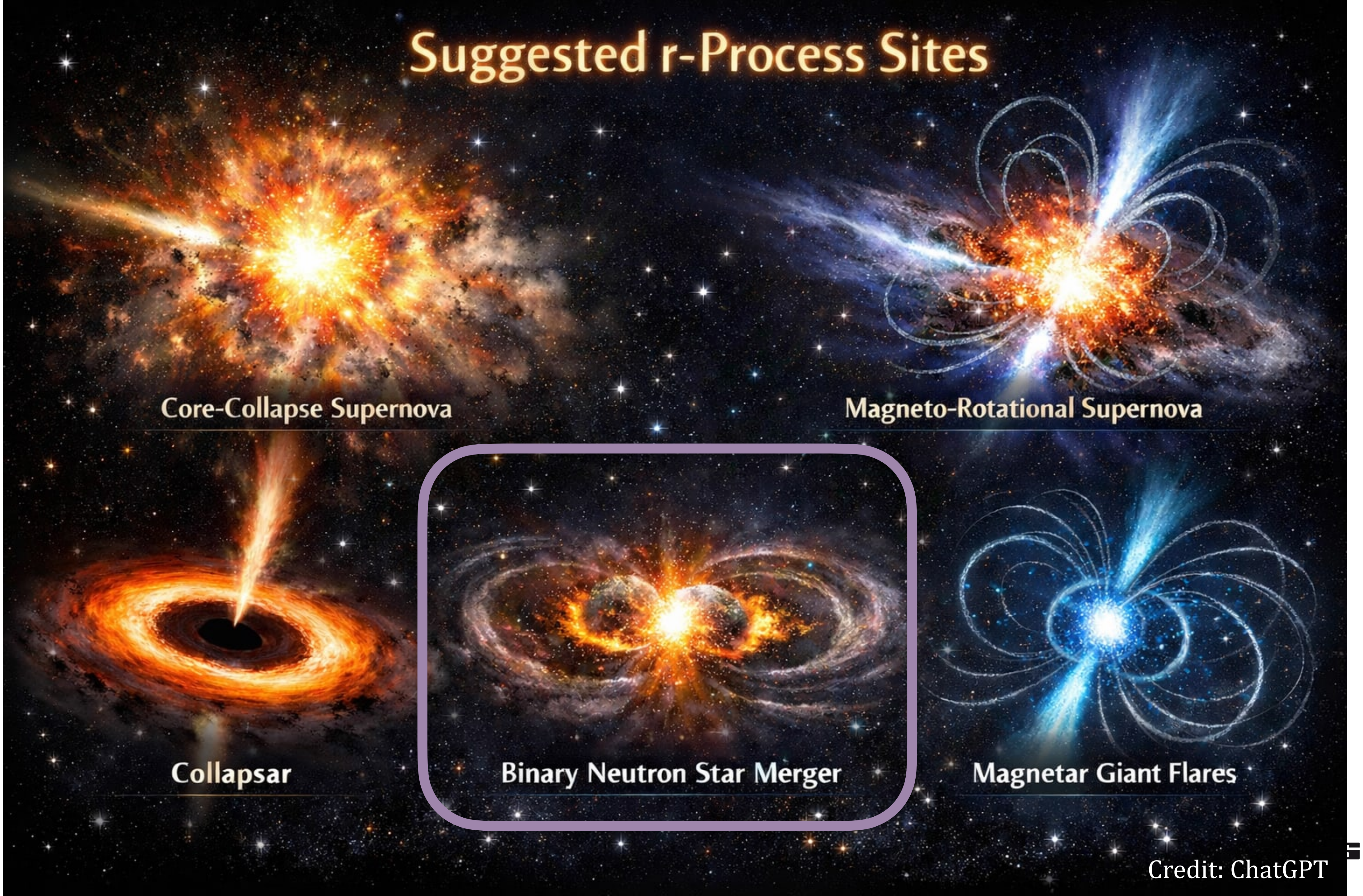


MGFs as r-process sites?

- currently only rather simplistic 1D hydro-models available
- heavy elements produced but no solar-like abundance pattern
- event rate and ejecta mass may be too low for significant contribution to galactic chemical enrichment
- **promising site, but still many questions open**

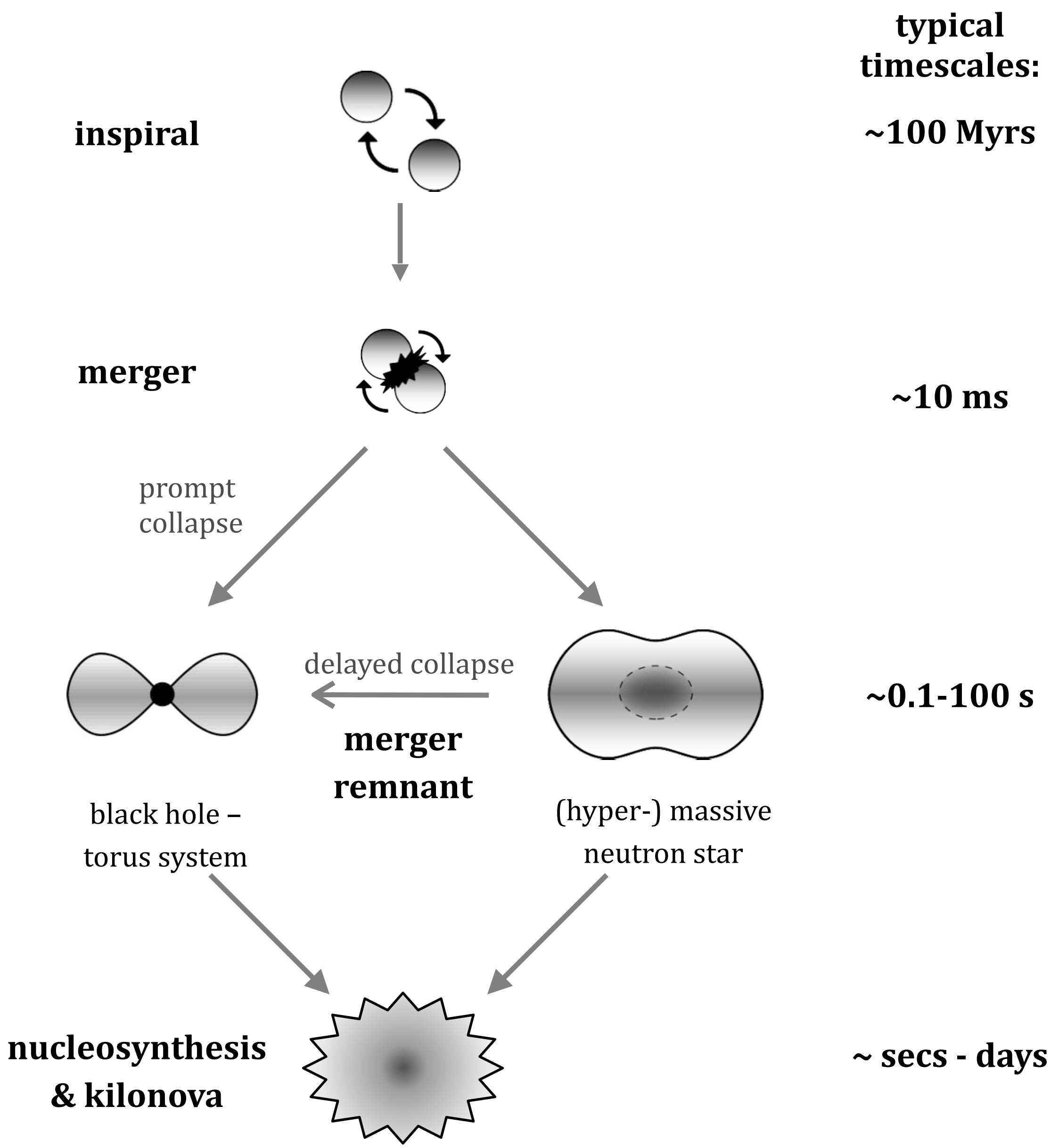


(Patel et al. 2024, ApJL 984)



Credit: ChatGPT

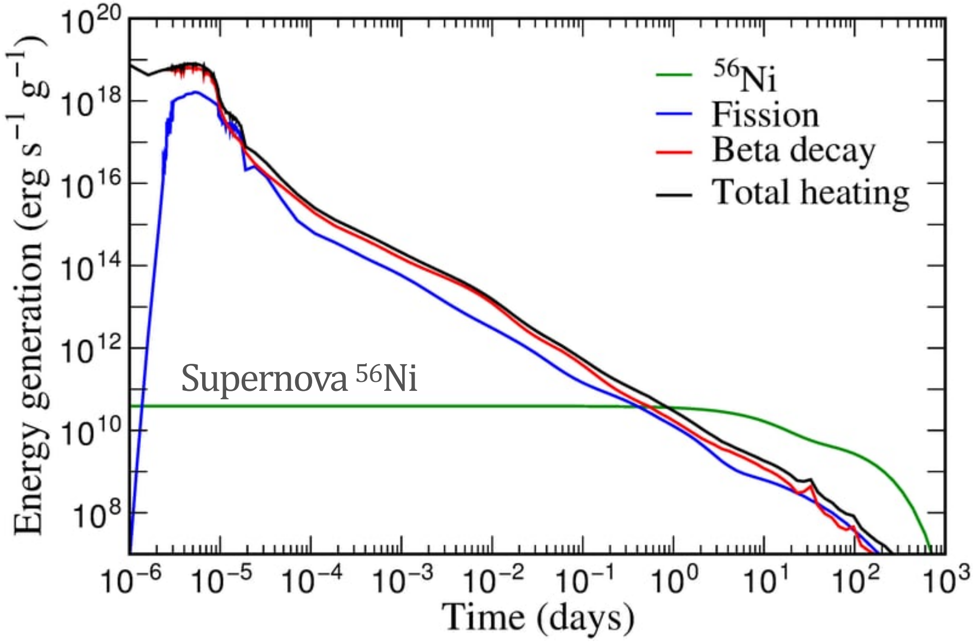
Evolutionary pathways of NS mergers



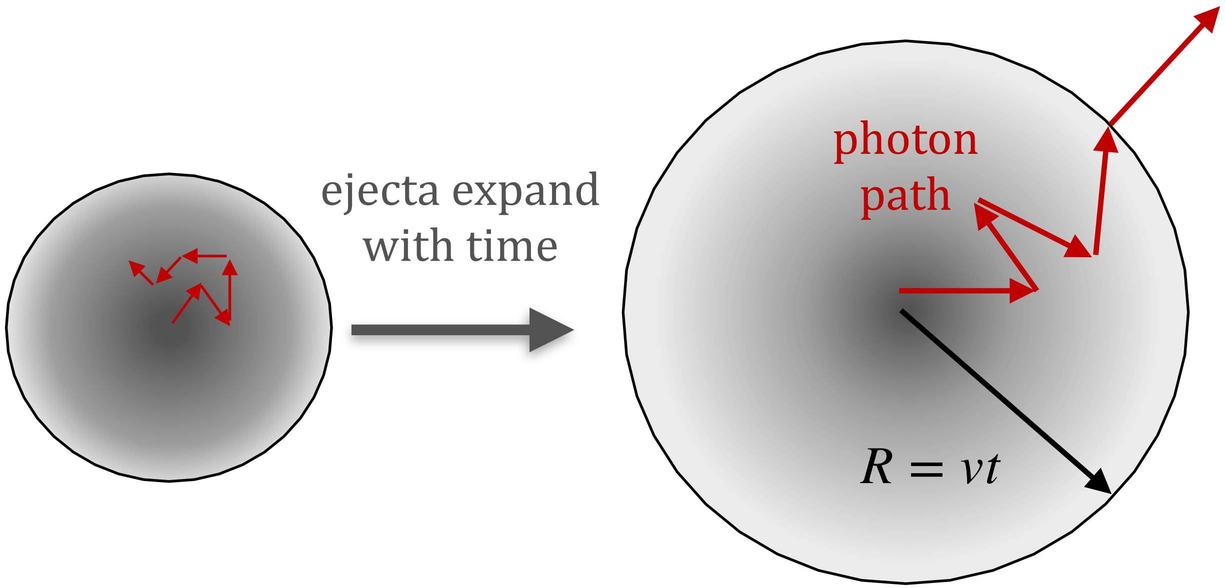
Kilonova: smoking gun for the r-process

("Kilo" because 1000 times brighter than a nova)

- radioactive decay of freshly synthesized material produces energy (= heat)
- heating rate typically declines as $t^{-1.3}$



(Metzger, Martinez-Pinedo et al. 2010, MNRAS 406)

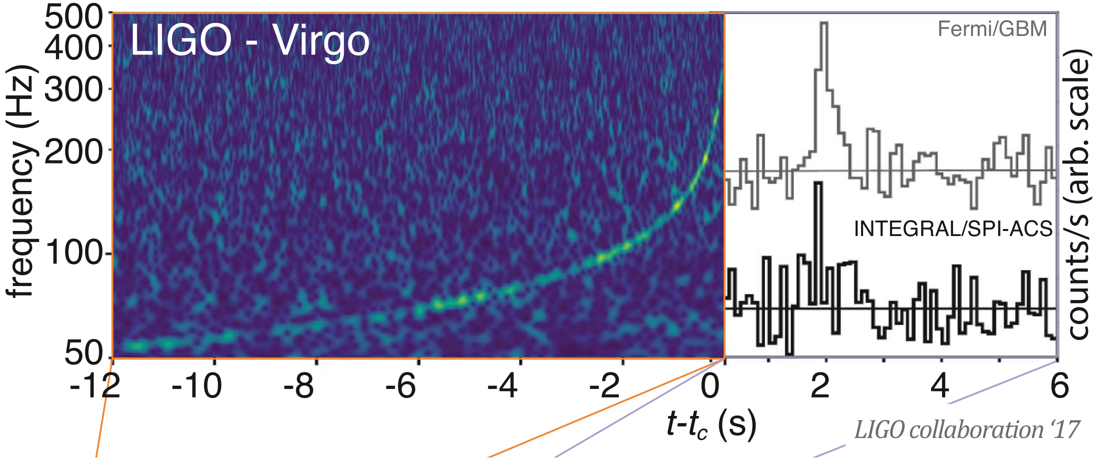


- random walk diffusion through expanding ejecta while density decreases
- **allows in-situ observations of the r-process**

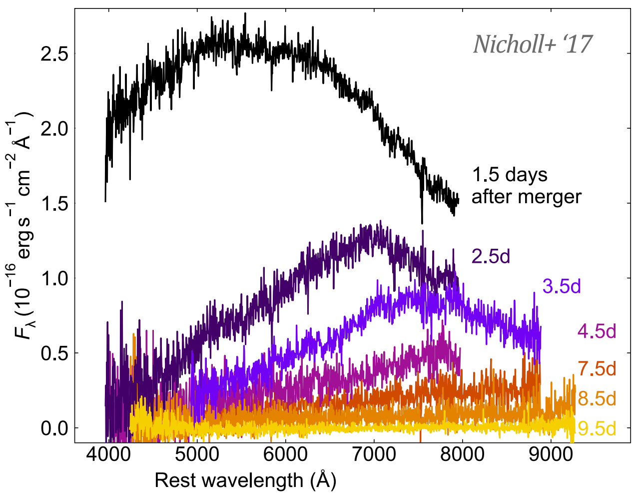
GW170817 - the first direct observation of a NS merger

(on August 17th, 2017)

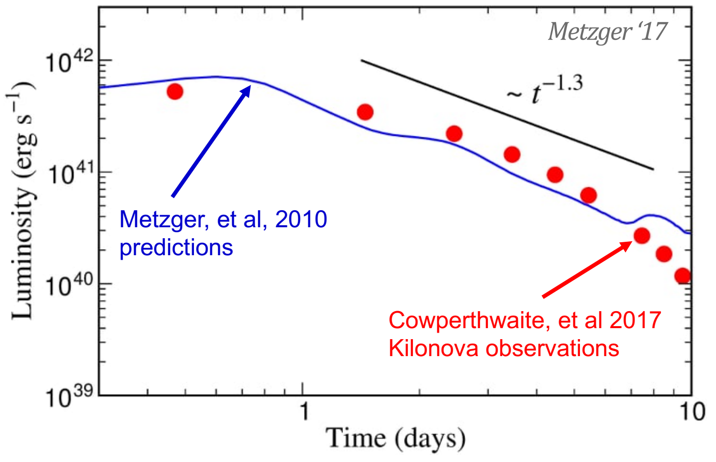
gravitational waves *gamma rays*



UV+optical+IR spectra



UV+optical+IR light curve



- dawn of new era of **multi-messenger** astronomy:
  - gravitational wave signal of binary inspiral
  - gamma-ray burst ~1.7 sec after GW signal
  - Kilonova ~1-10 days later
  - radio, optical, X-ray afterglow ~100-1000 days later

➡ ***confirmed idea that NS mergers are sites of heavy element nucleosynthesis***

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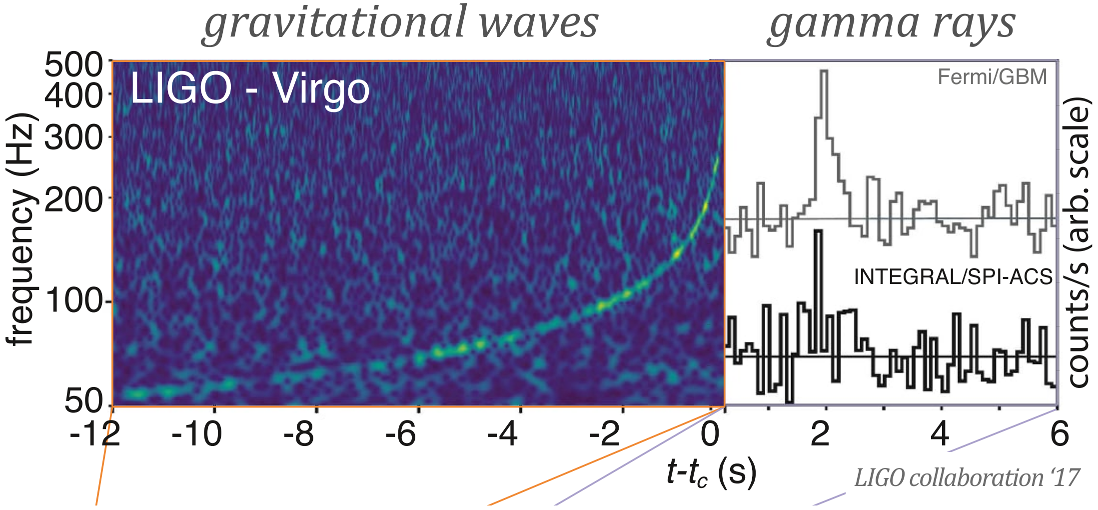
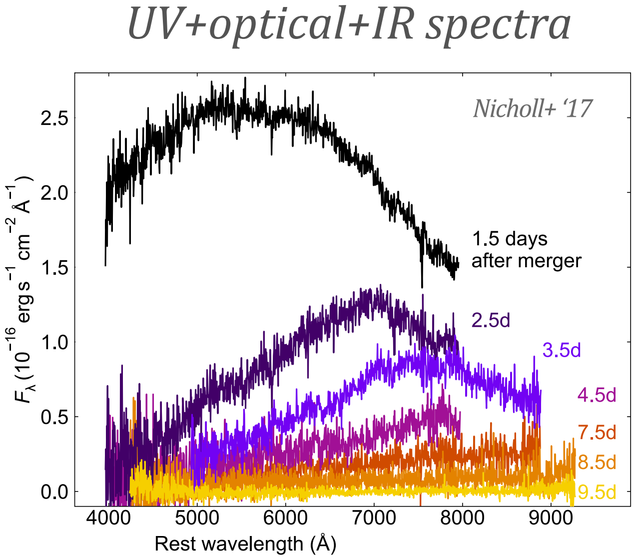
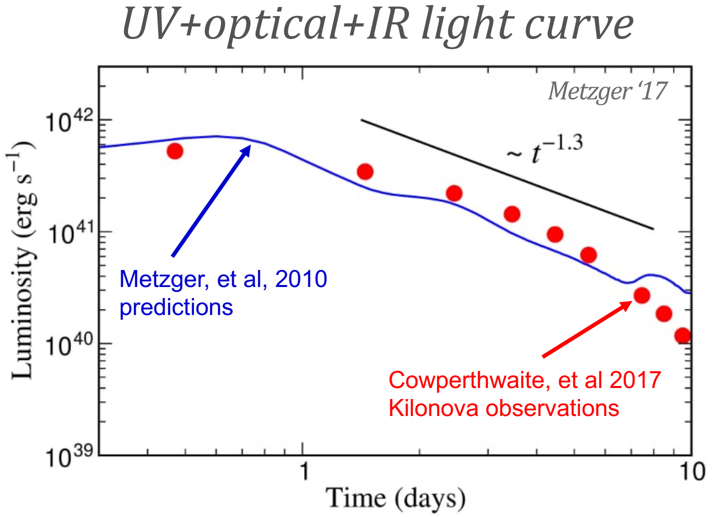


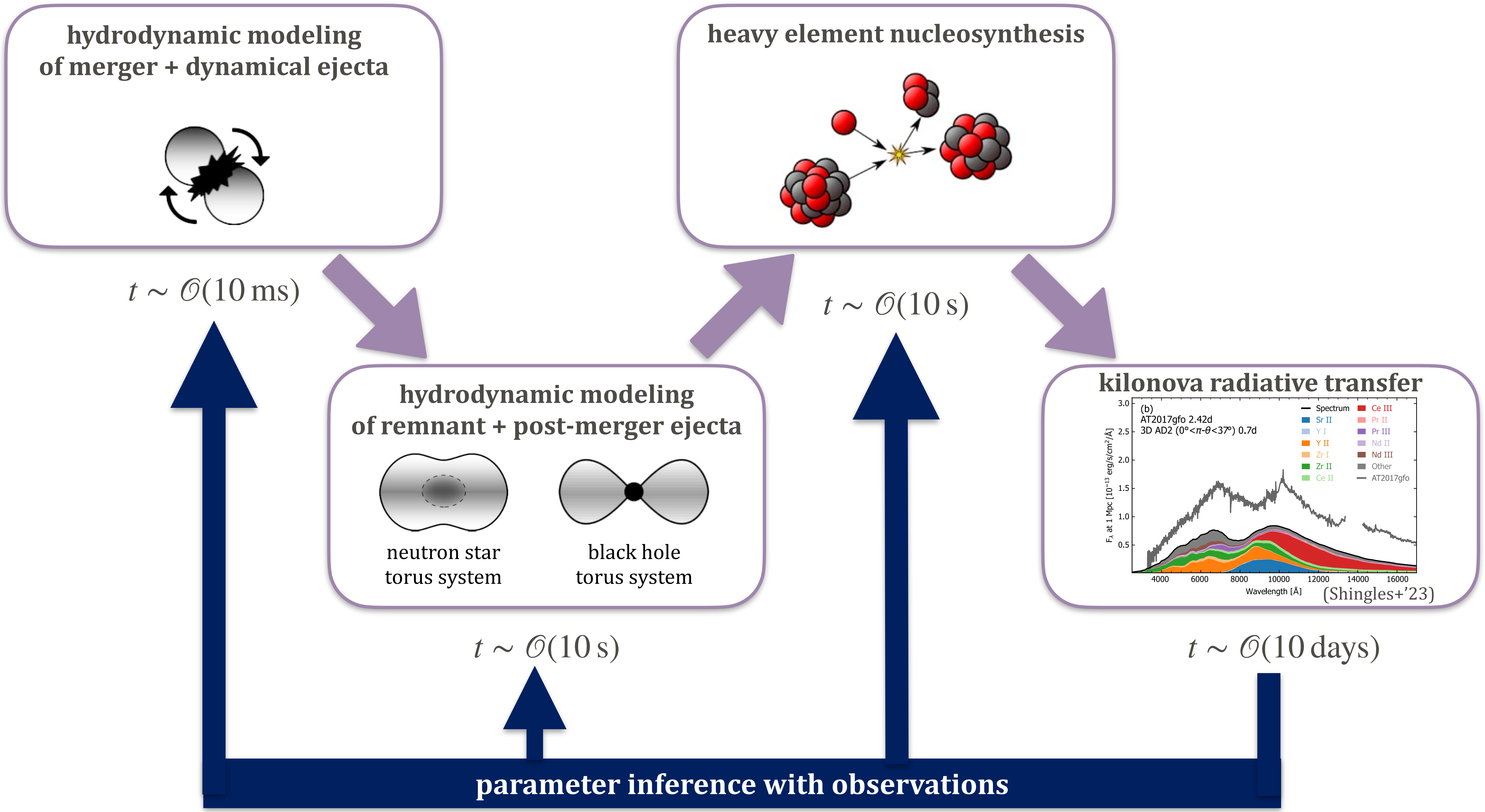




Many open questions remain:

- Mass, composition and geometry of outflow material?
- What are the relevant nuclear reactions and rates?
- When did BH form?
- How to infer properties of nuclear EOS?
- …

End-to-end Kilonova modeling pipeline



Tools and methods used by GSI and collaborators

hydrodynamic modeling of merger + dynamical ejecta

- 3D smoothed-particle hydro with conformal flatness condition
- ILEAS neutrino scheme

hydrodynamic modeling of remnant + post-merger ejecta

- initial conditions mapped from merger simulations
- 2D axisym. special relativistic with TOV potential
- energy-dependent M1 neutrino transport
- newly developed scheme to parametrize viscosity in the NS indep. of the surrounding disk

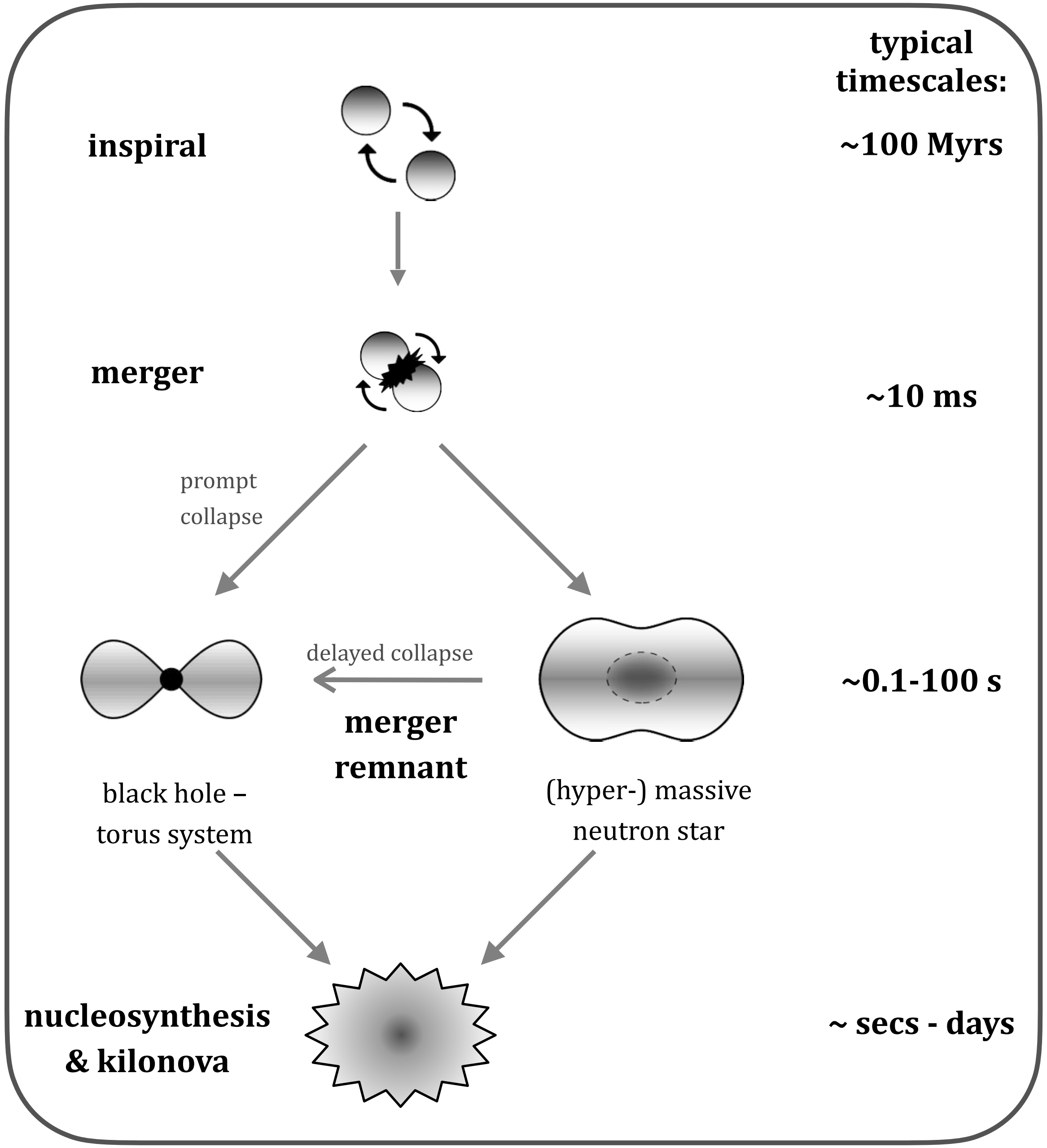
heavy element nucleosynthesis

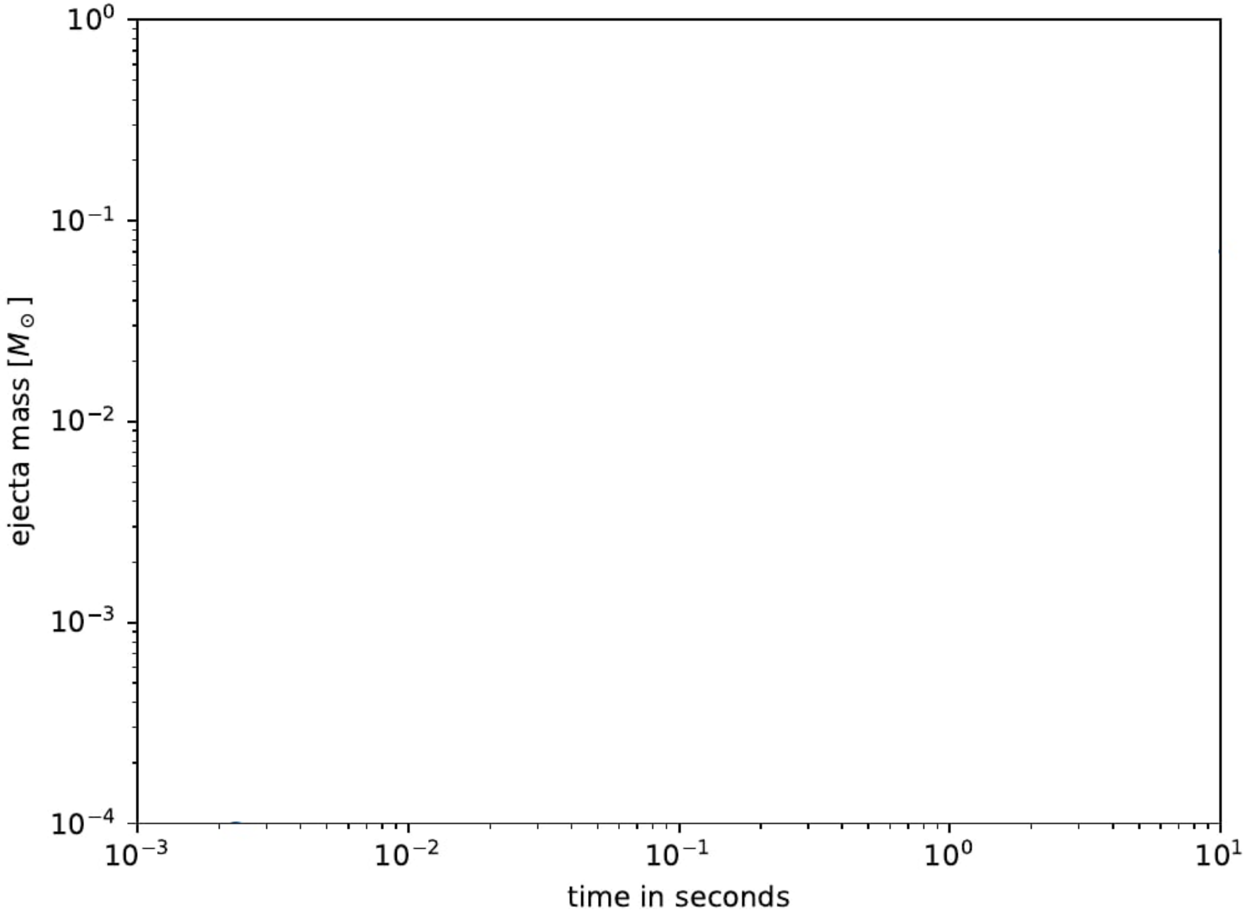
- extraction of ~5000 outflow tracers per model to sample local hydrodynamic history until 100 s
- post-processed by two nuclear networks (GSI & ULB)

kilonova radiative transfer

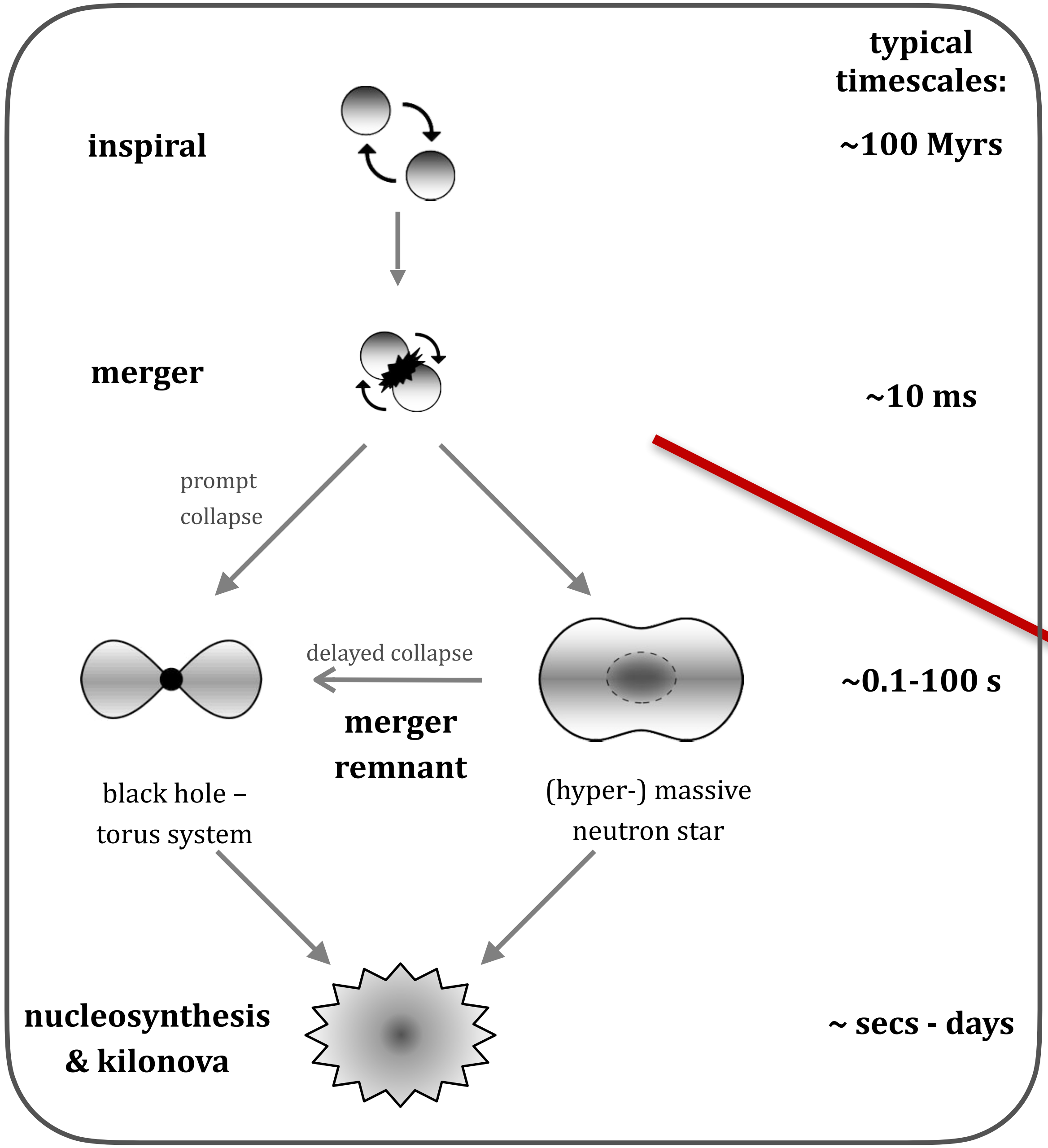
- 2D axisymmetric radiative transfer using approximate M1 scheme
- alternatively use ARTIS Monte-Carlo code (with Belfast)
- adopt local time-dependent results from nucleosynthesis calculations

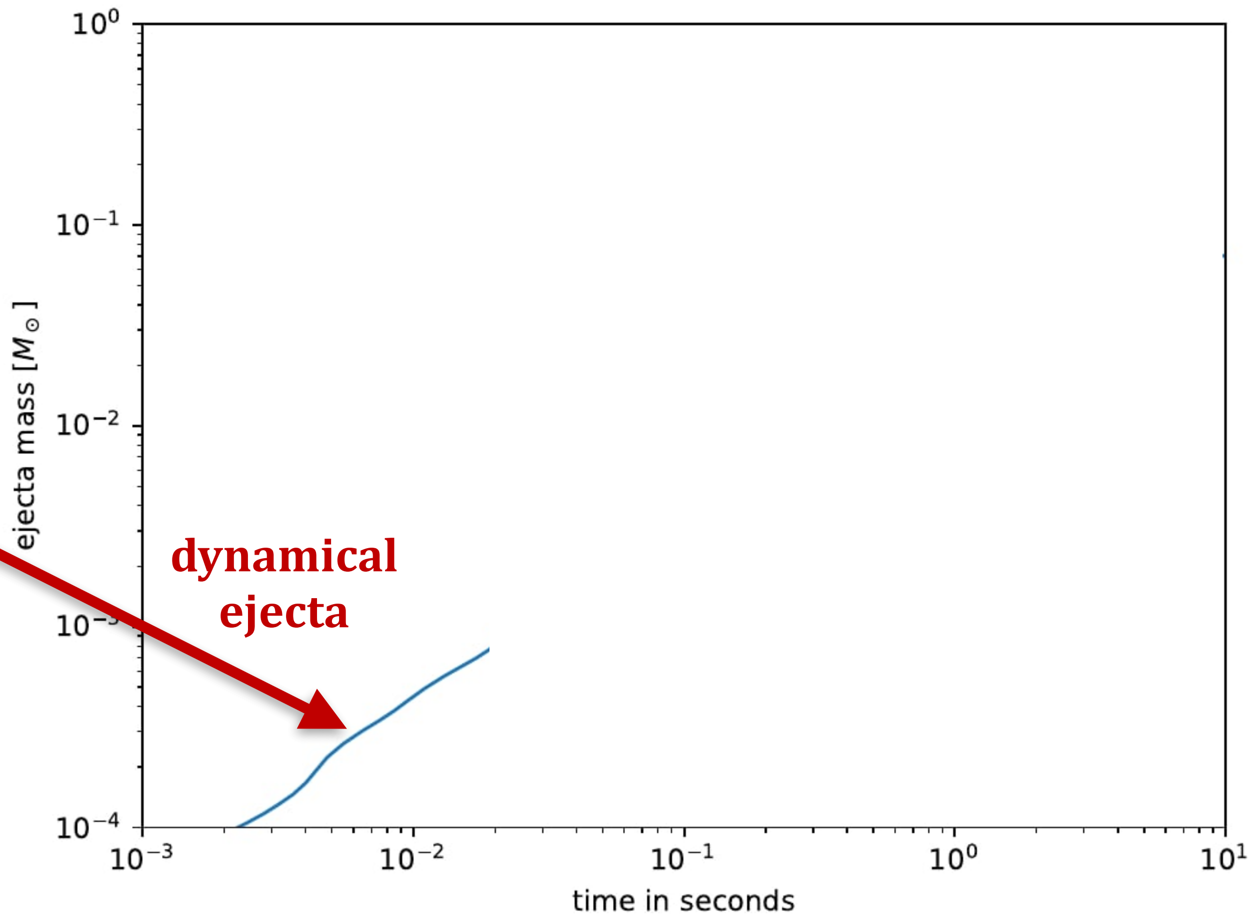
Phases of matter ejection



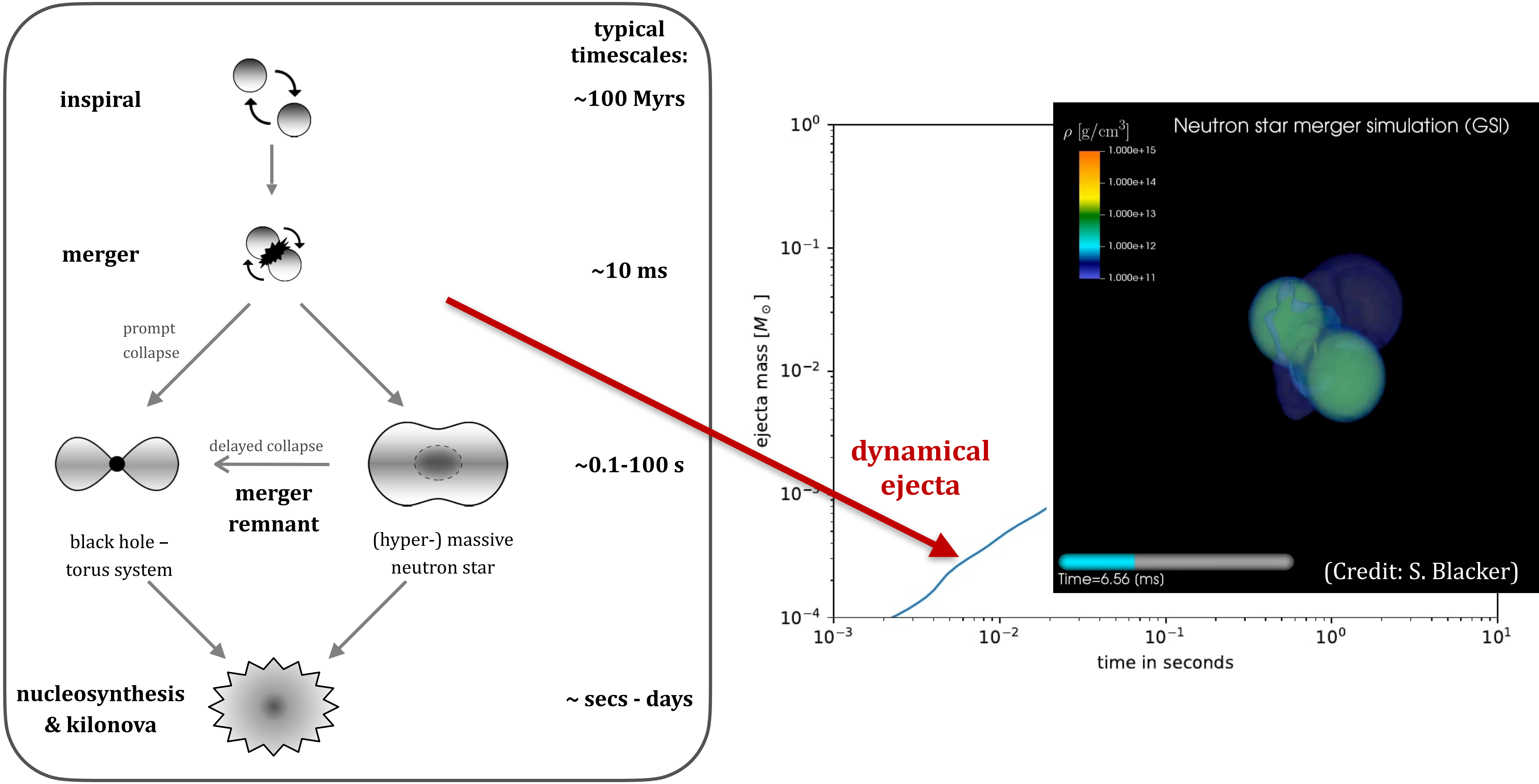


Phases of matter ejection

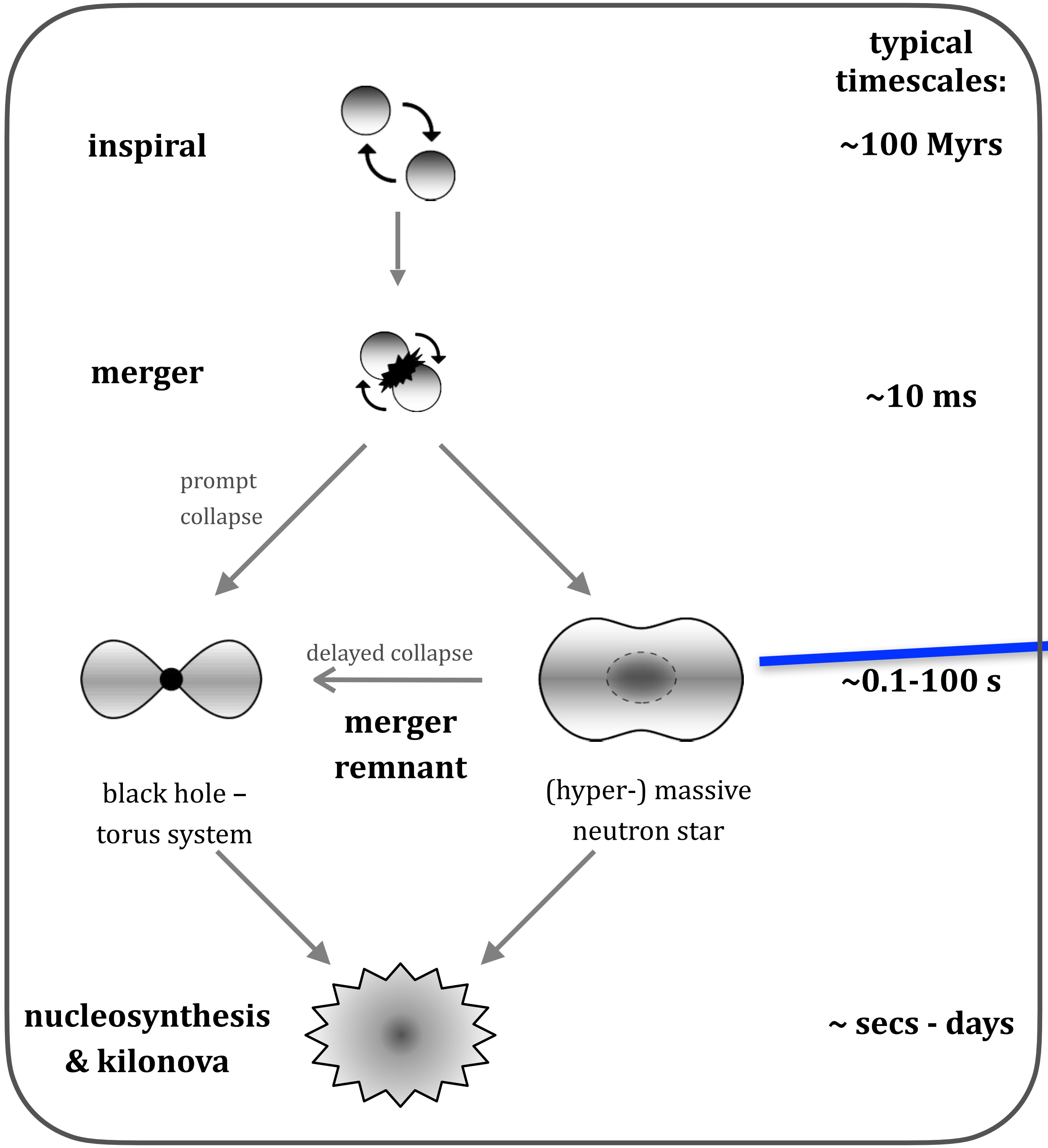


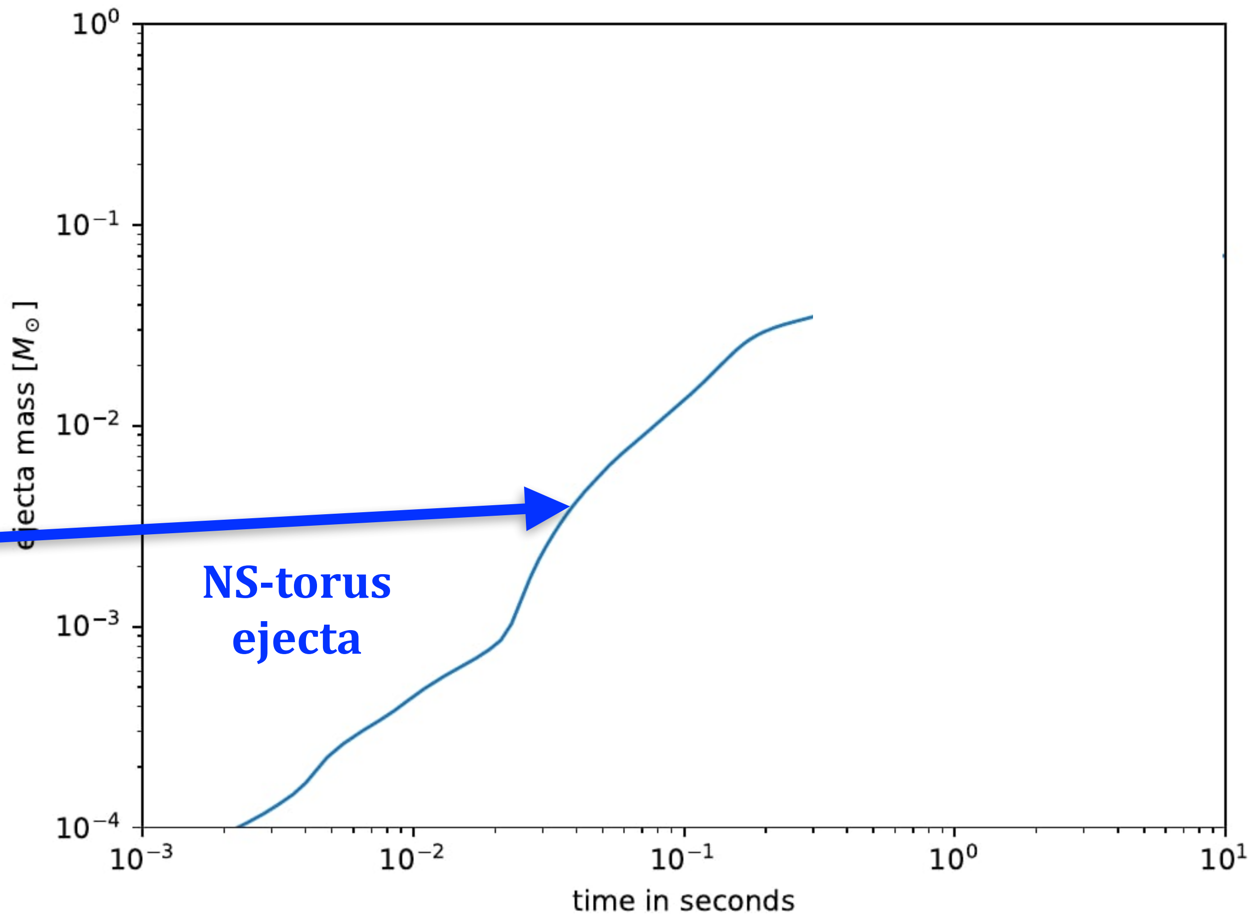


Phases of matter ejection

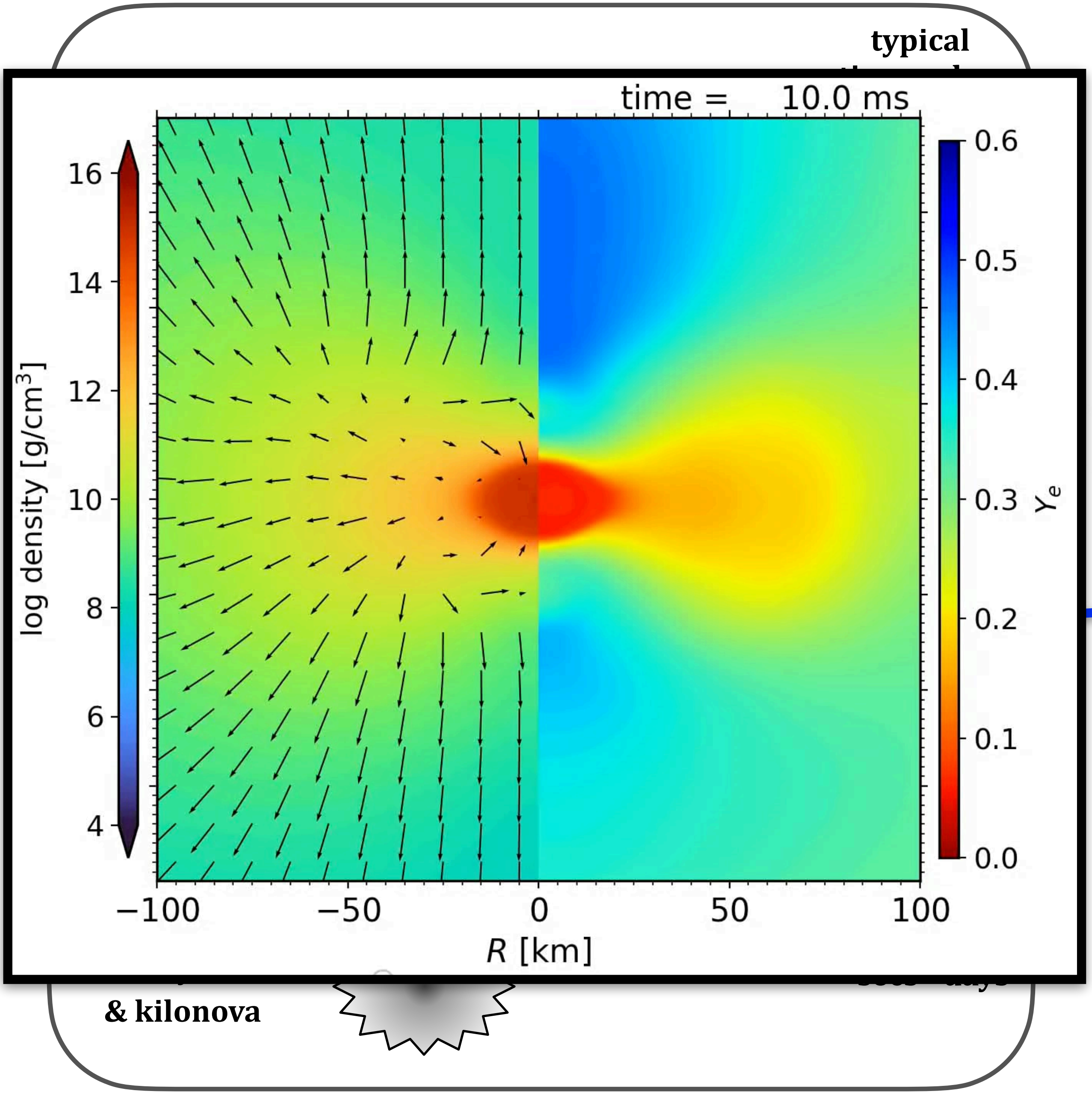


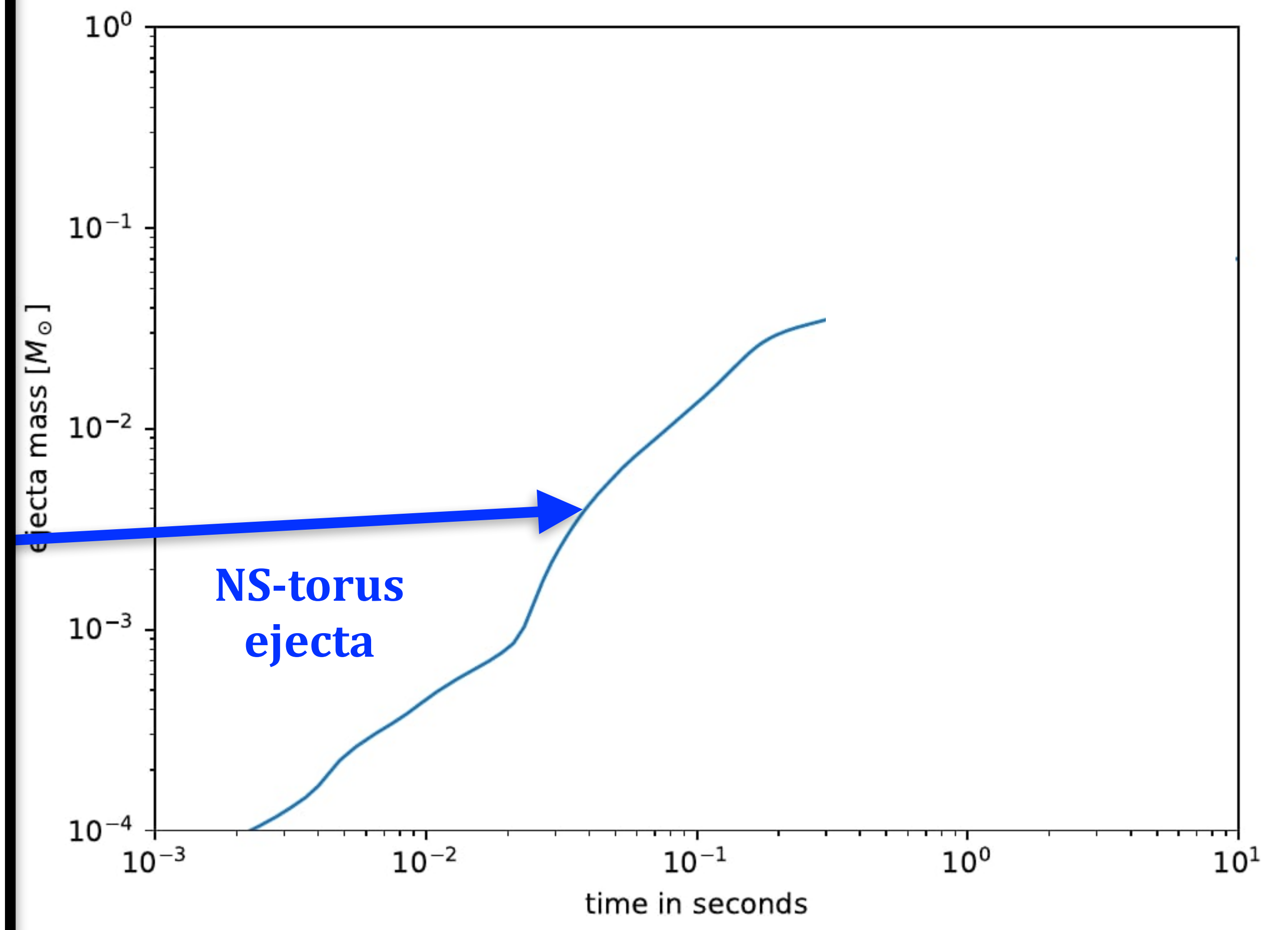
Phases of matter ejection



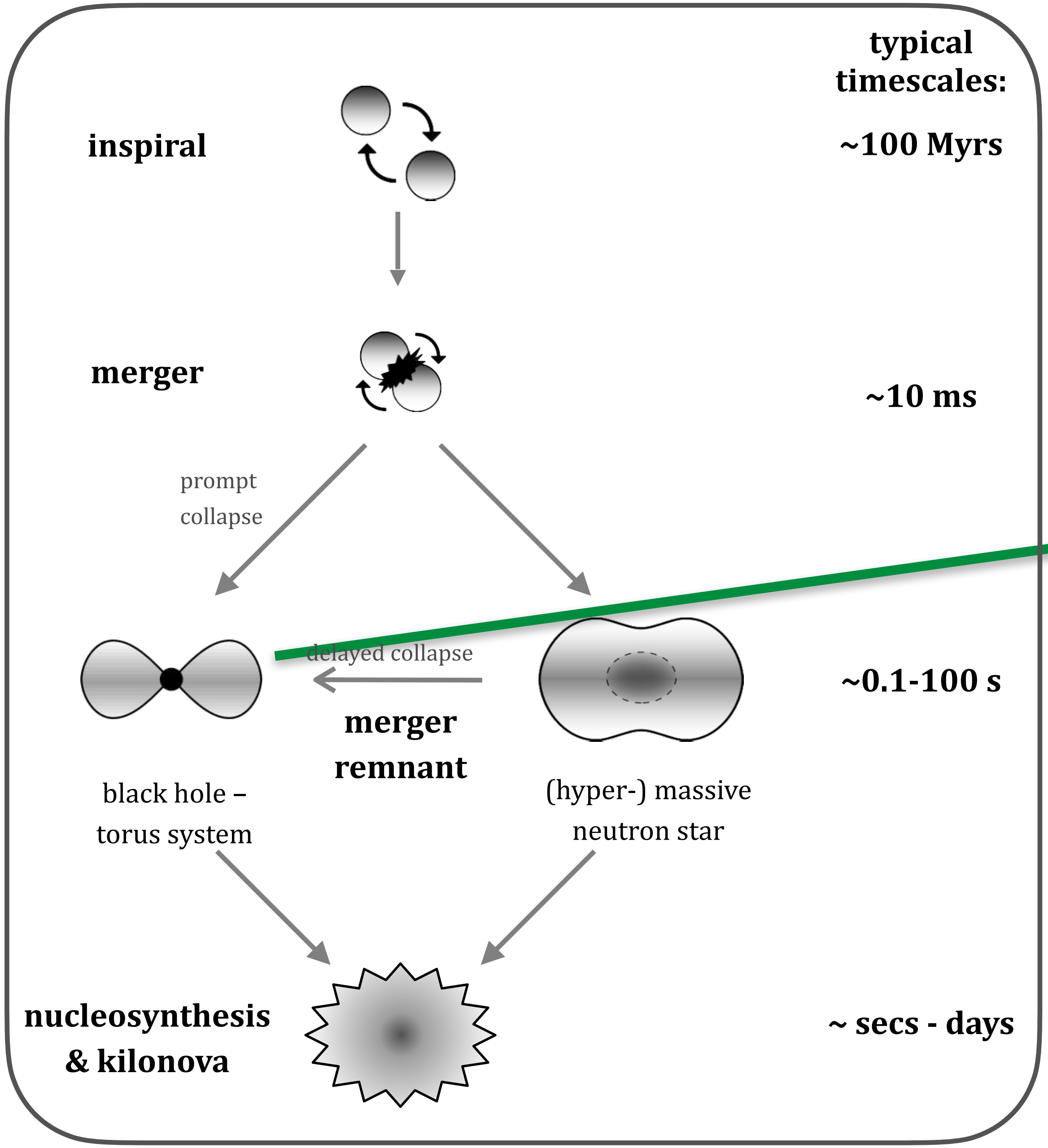


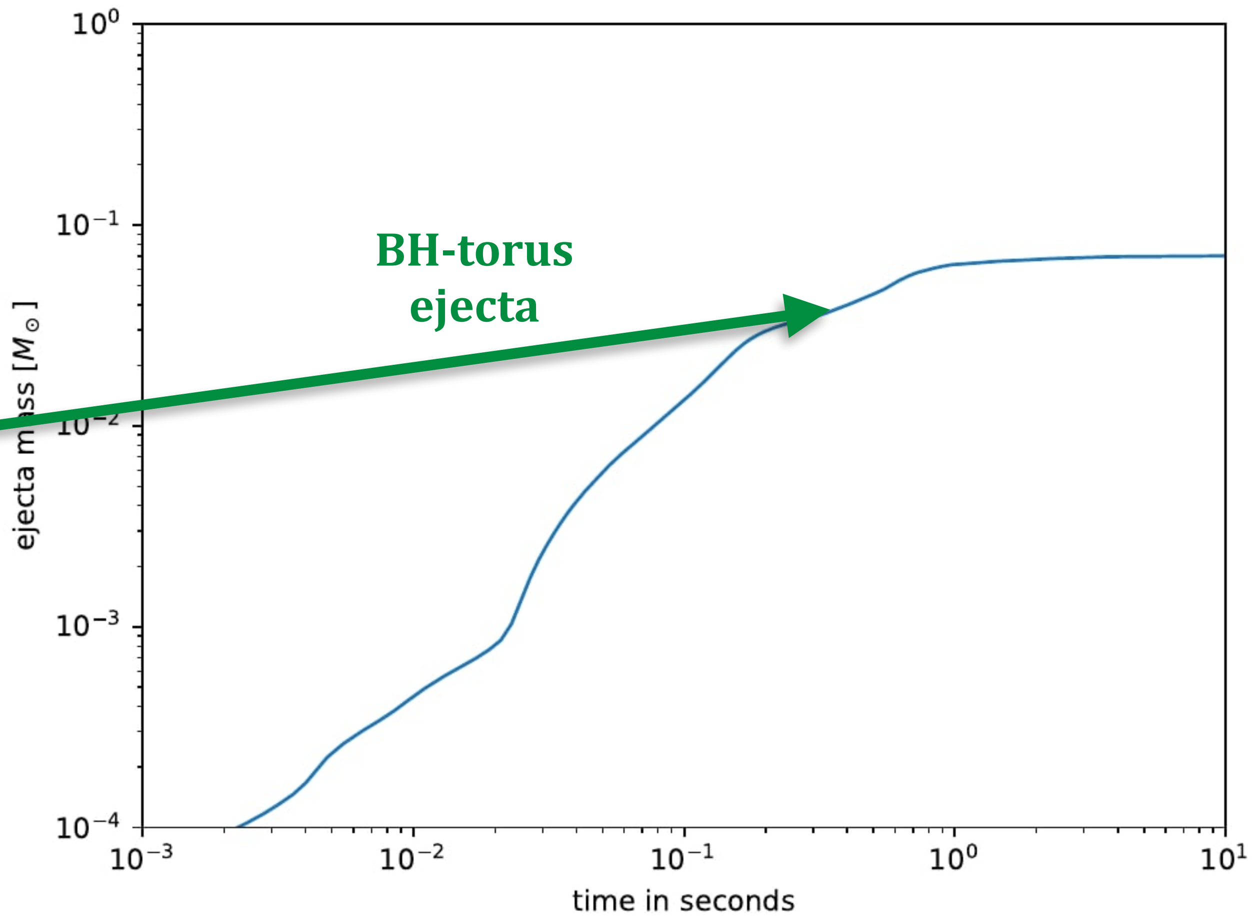
Phases of matter ejection





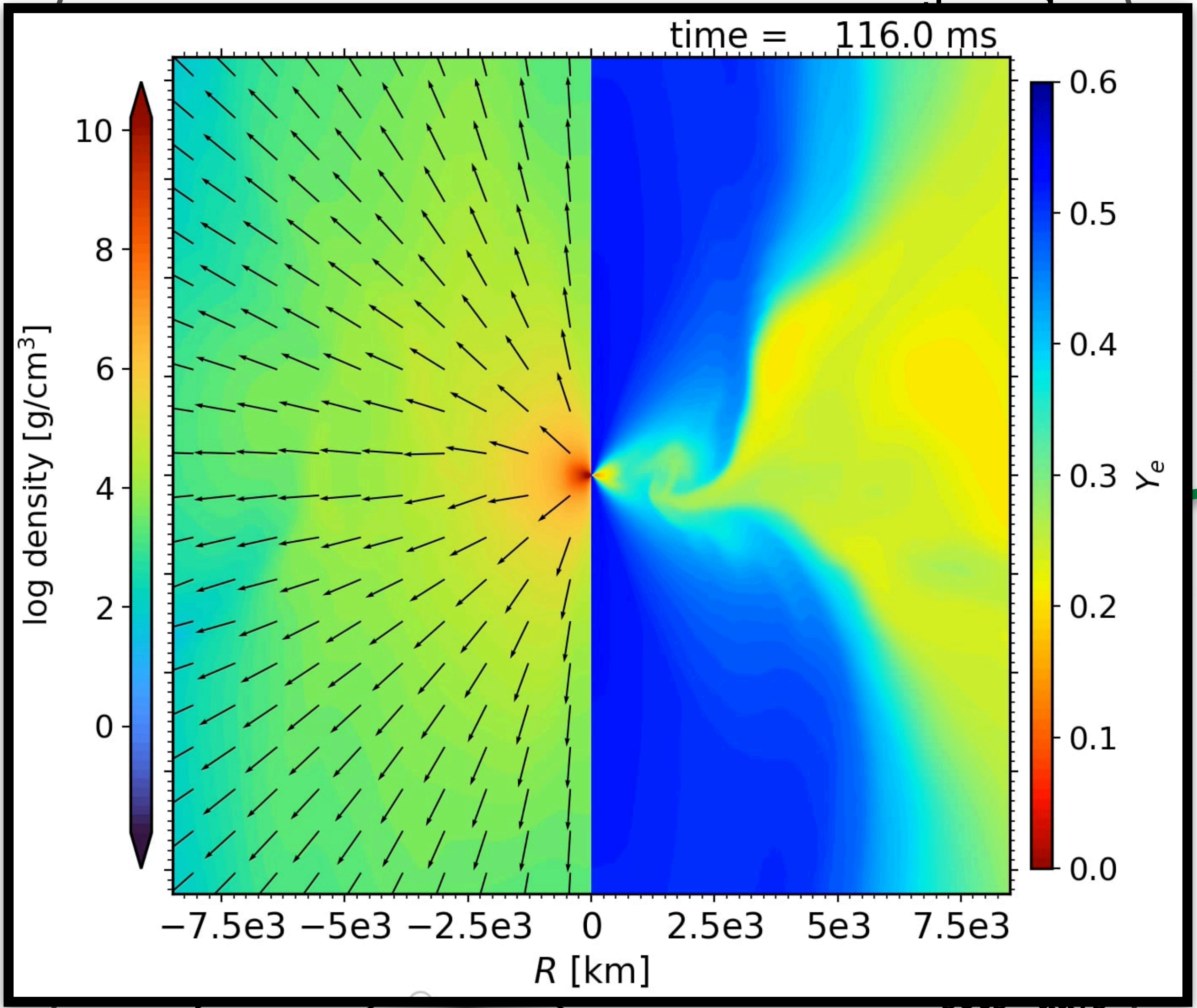
Phases of matter ejection

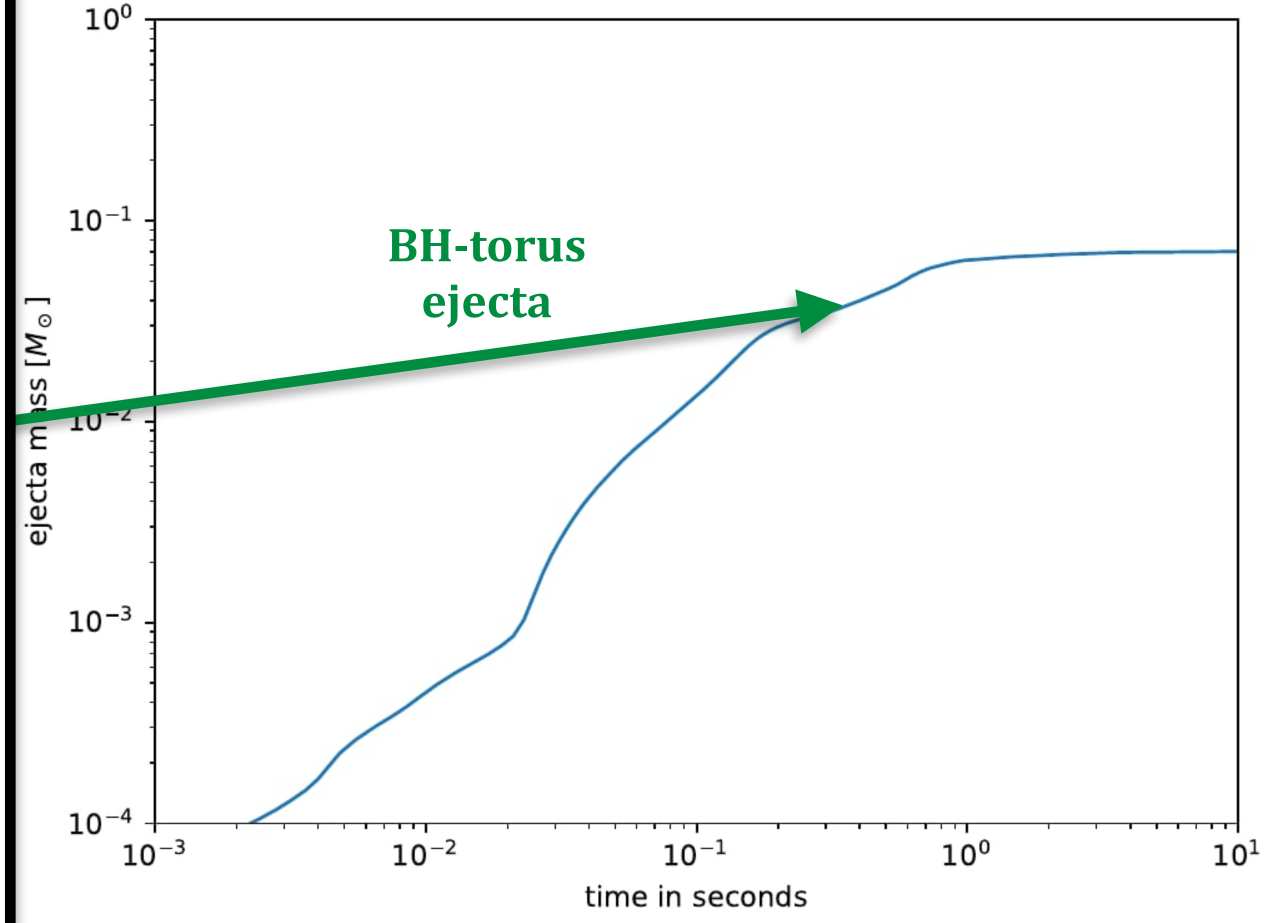




Phases of matter ejection

typical

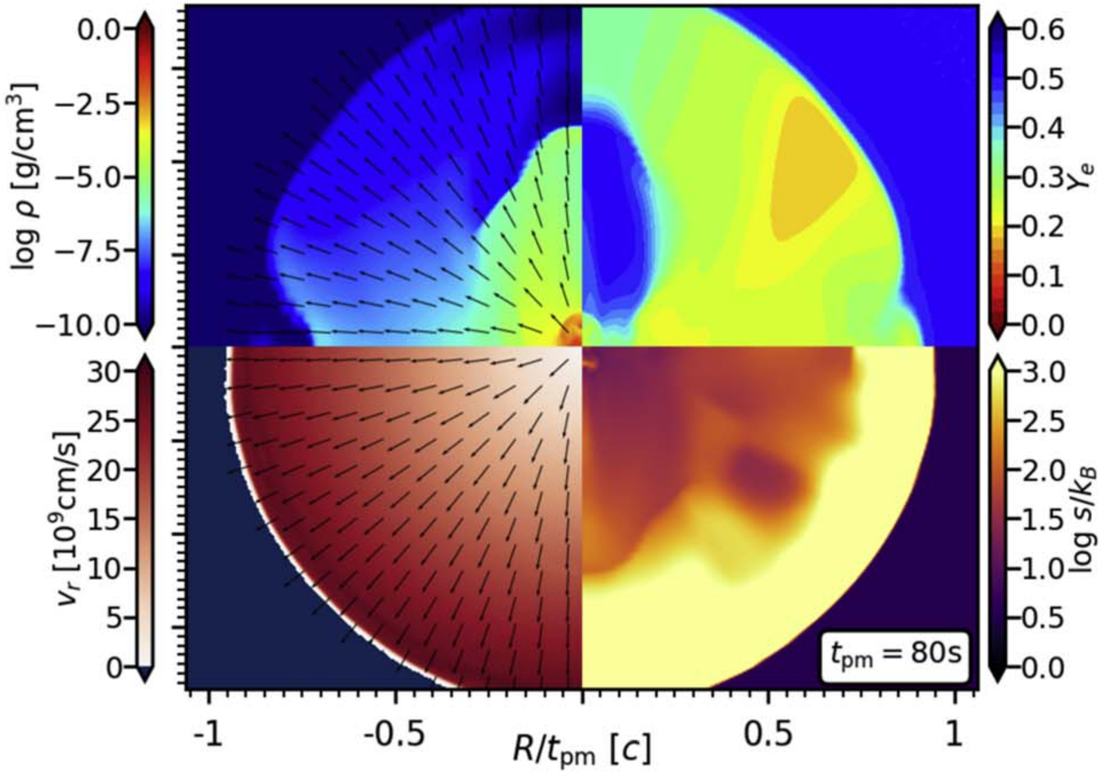


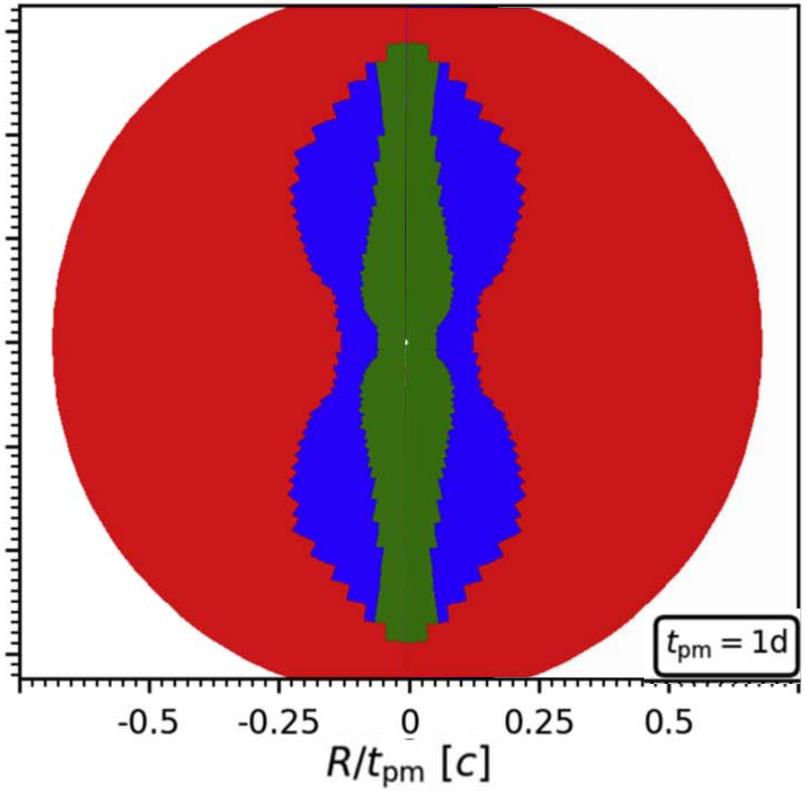


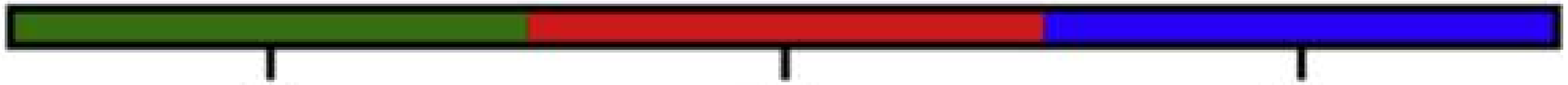
& kilonova

Final ejecta distribution (τ_{BH} ~ 120ms model)

(Just et al. 2023, ApJL 951)







BH-torus ejecta:
m ~ 0.01–0.04 $M_\odot$
<v> ~ 0.03–0.1 c

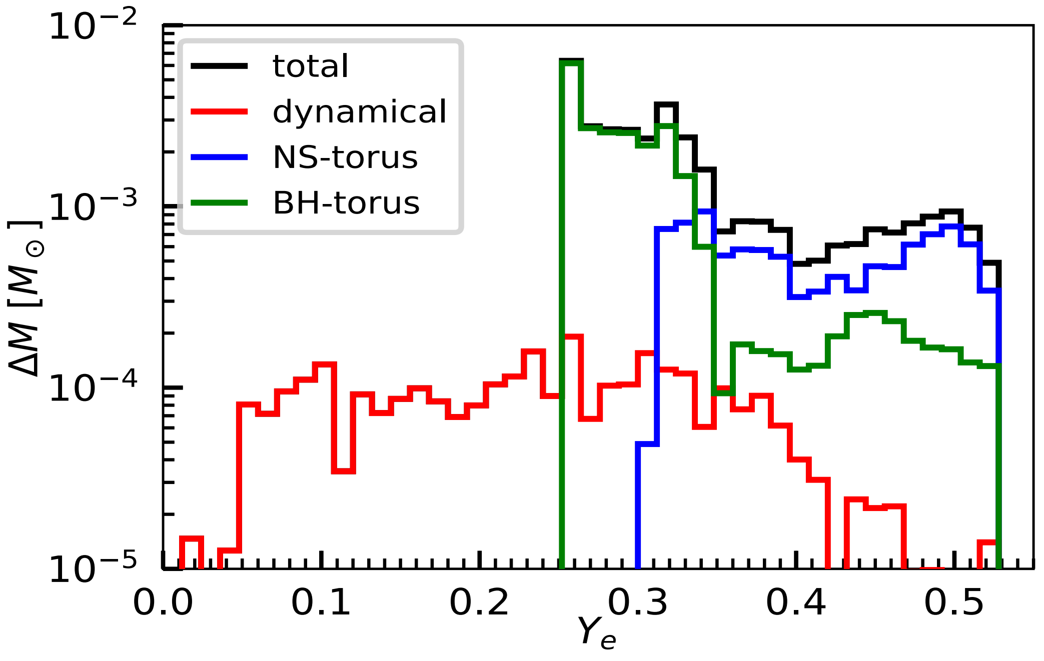
dynamical ejecta:
m ~ 0.001–0.01 $M_\odot$
<v> ~ 0.2–0.4 c

NS-torus ejecta:
m ~ 0.01–0.04 $M_\odot$
<v> ~ 0.1–0.2 c

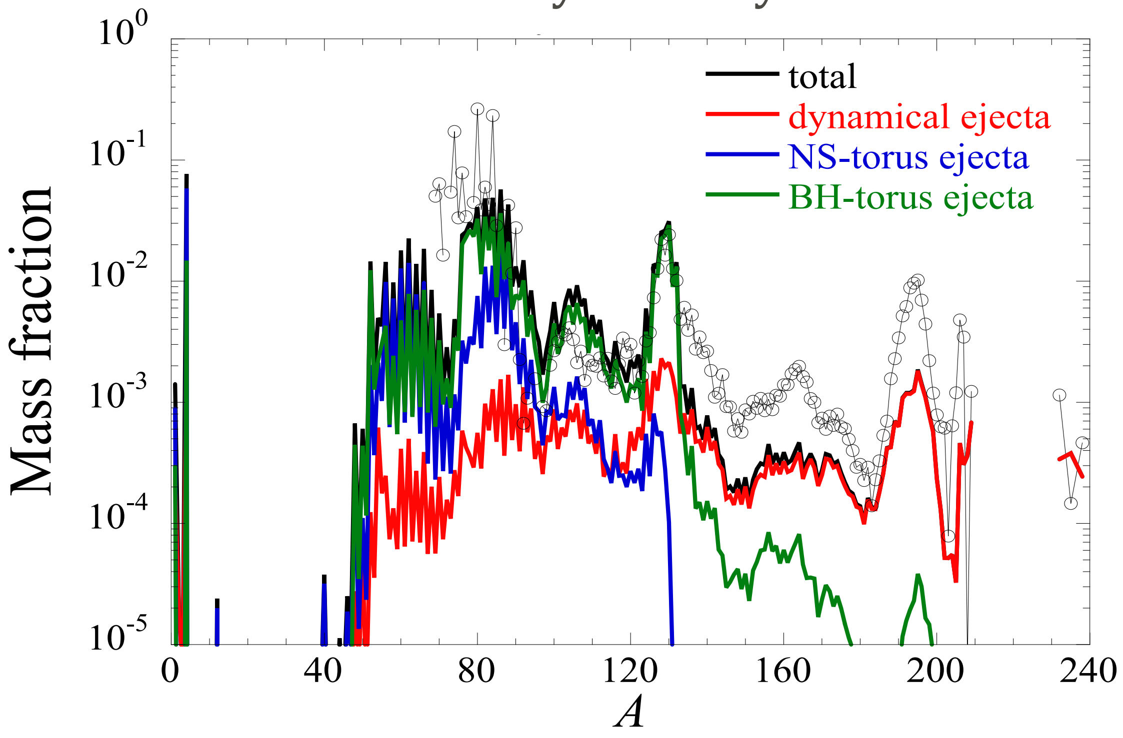
Ejecta composition — model with t_{BH}~120ms

(Just et al. 2023, ApJL 951)

Y_e histogram



nucleosynthesis yields

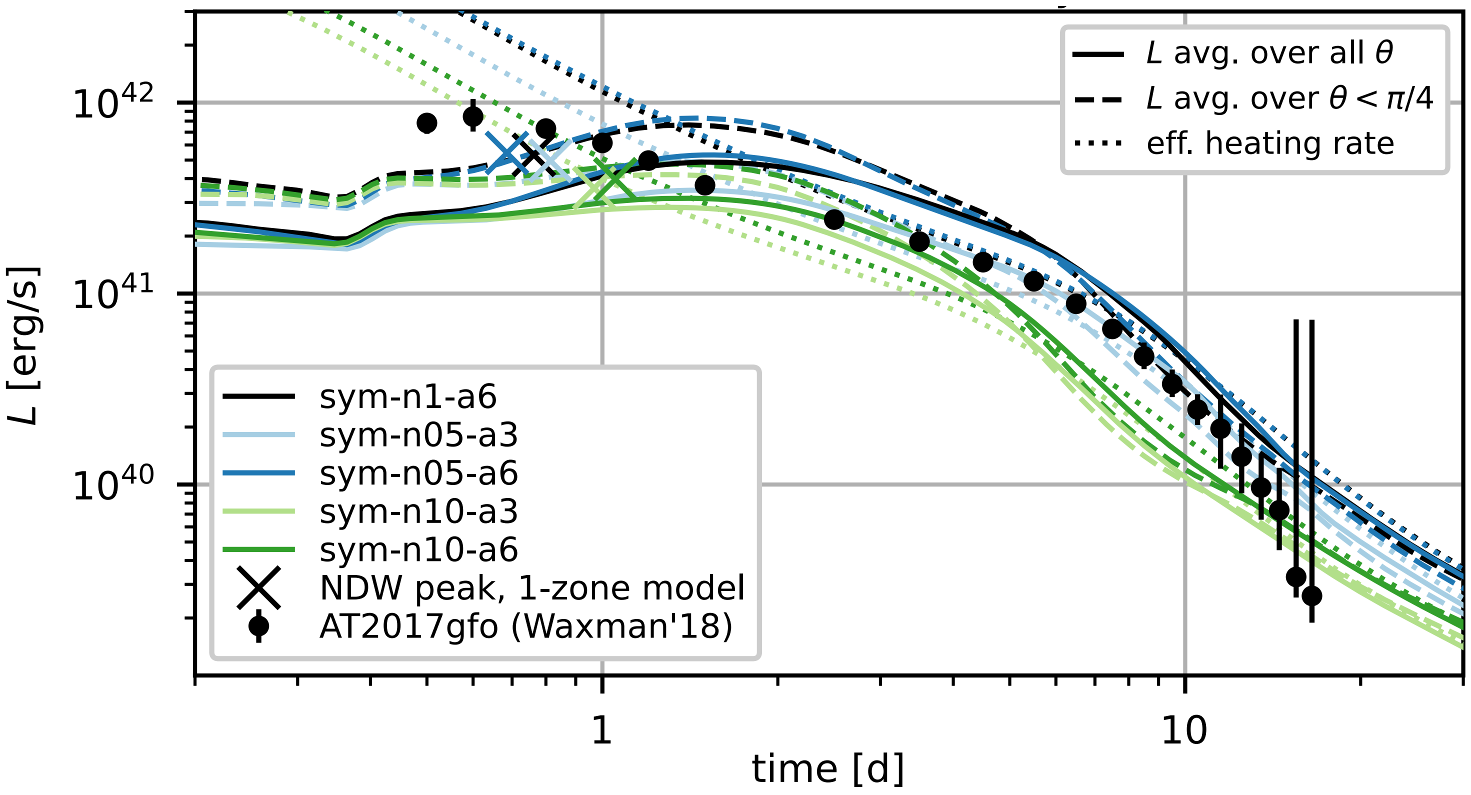


(nucleosynthesis calculation by Z. Xiong & G. Martinez-Pinedo)

- early dynamical ejecta predominantly A>130 elements
- post-merger ejecta predominantly A<130 elements

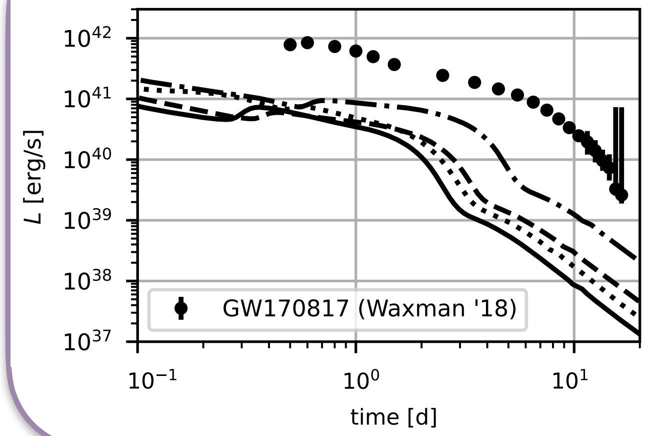
Kilonova bolometric light curve

(Just et al. 2023, ApJL 951)



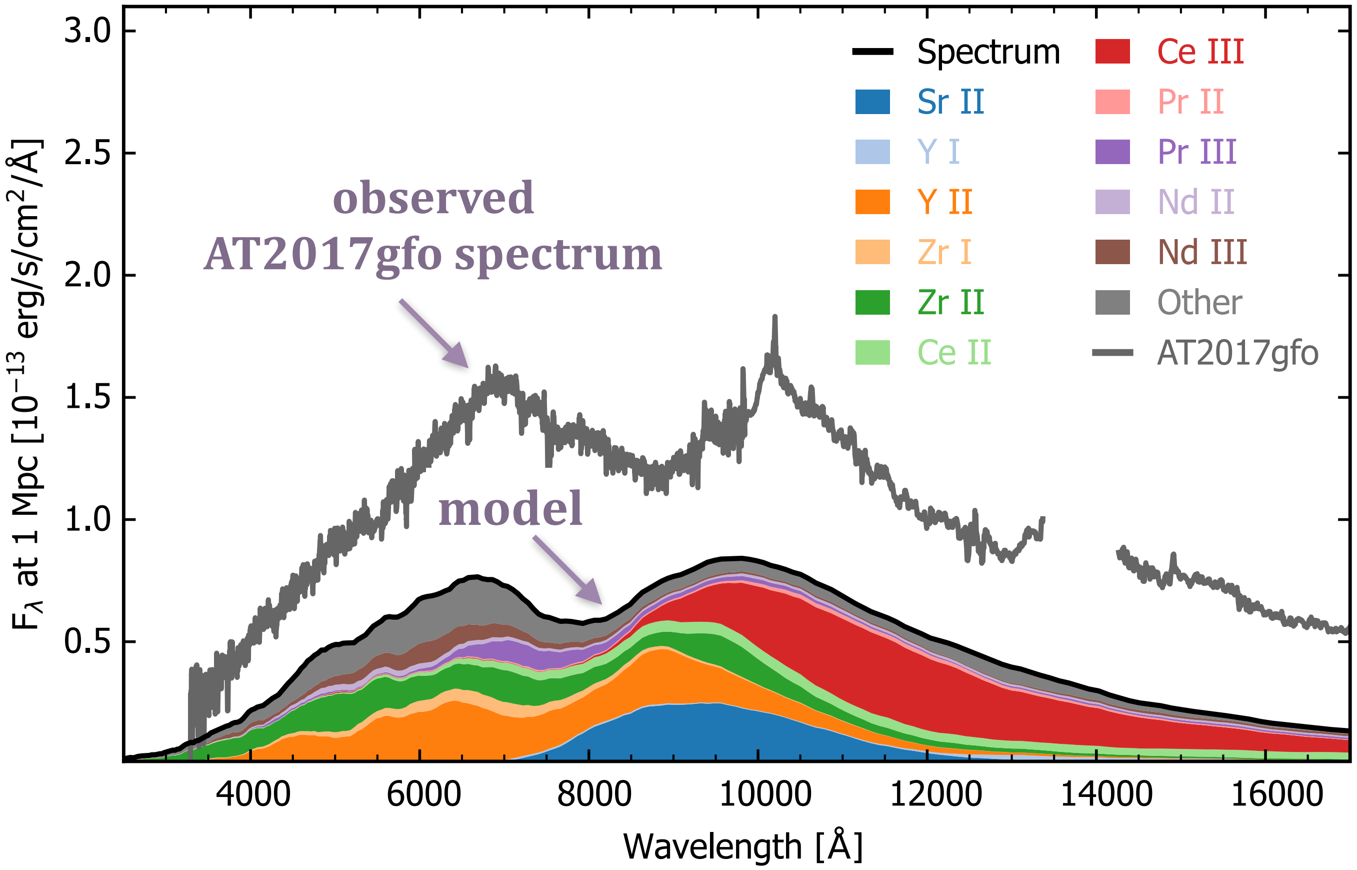
- good agreement with GW170817
- supports idea that GW170817 was a delayed-collapse scenario with massive post-merger ejecta

dynamical ejecta only:



Step towards more accurate kilonova radiative transfer modeling

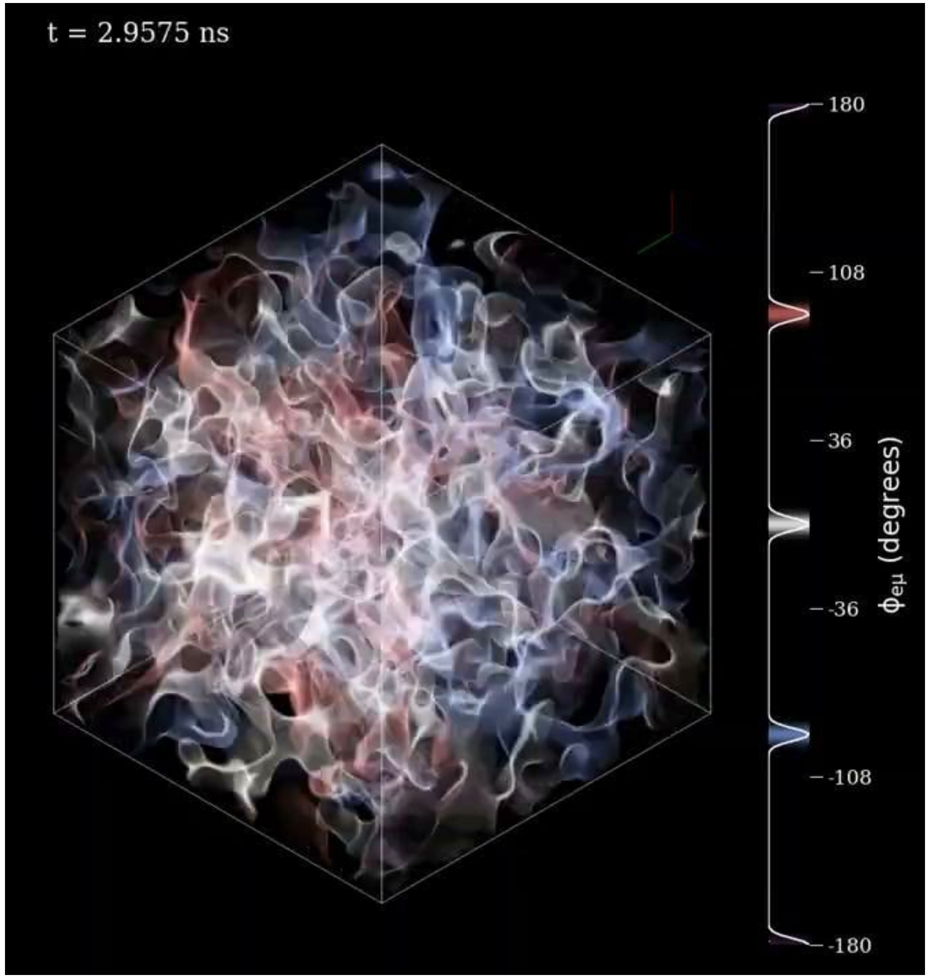
(Shingles et al. 2023, ApJL 954)



- 3D Monte-Carlo radiative transfer code ARTIS
- uses detailed atomic opacity data
- spectra **remarkably similar** to AT2017gfo
- so far only dynamical ejecta, but end-to-end models underway (Leck+2026, in prep.)
- new calibrated opacities computed recently (Floers et al. 2025, arXiv:2507.0778)

Fast neutrino flavor instability

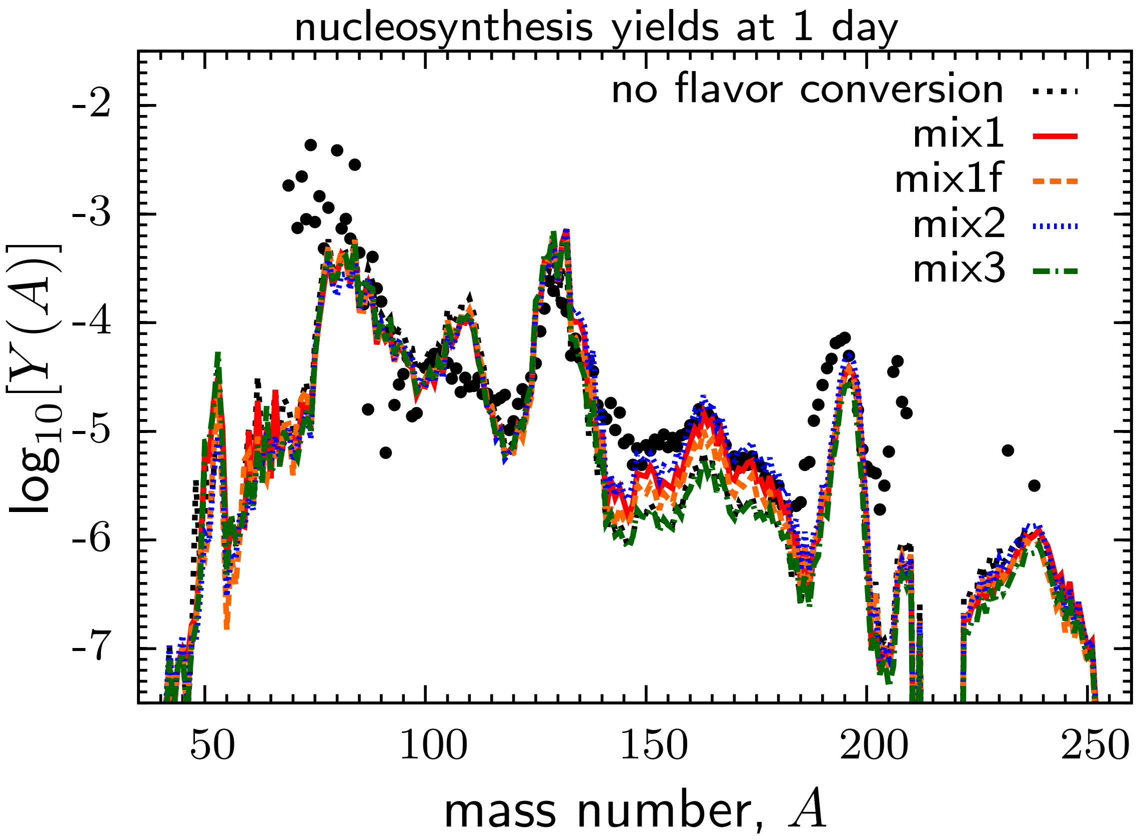
- takes place on extremely short time and length scales (~nanoseconds, centimeters)
- outcome: “turbulent” state in flavor space
- very difficult to tackle computationally
- ERC starting grant by Z. Xiong at GSI

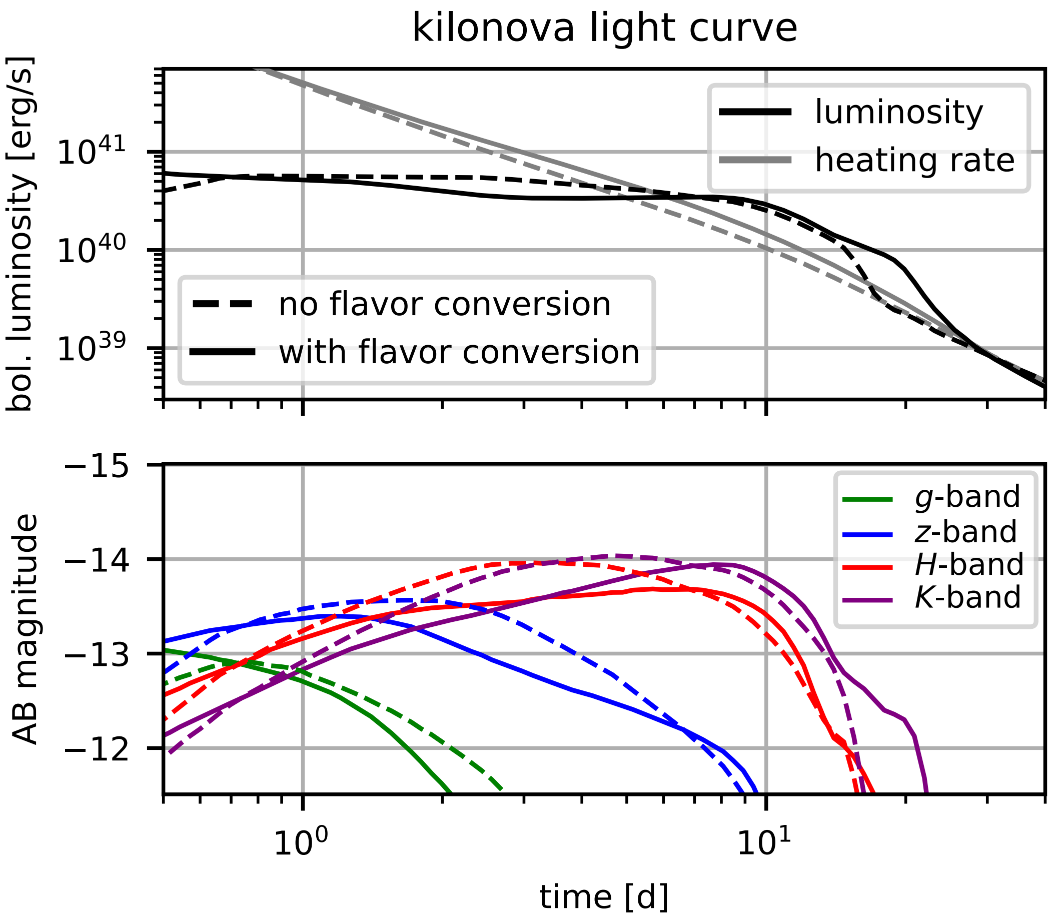


(local quantum kinetics simulation by S. Richers ’22)

Estimated impact on nucleosynthesis and kilonova

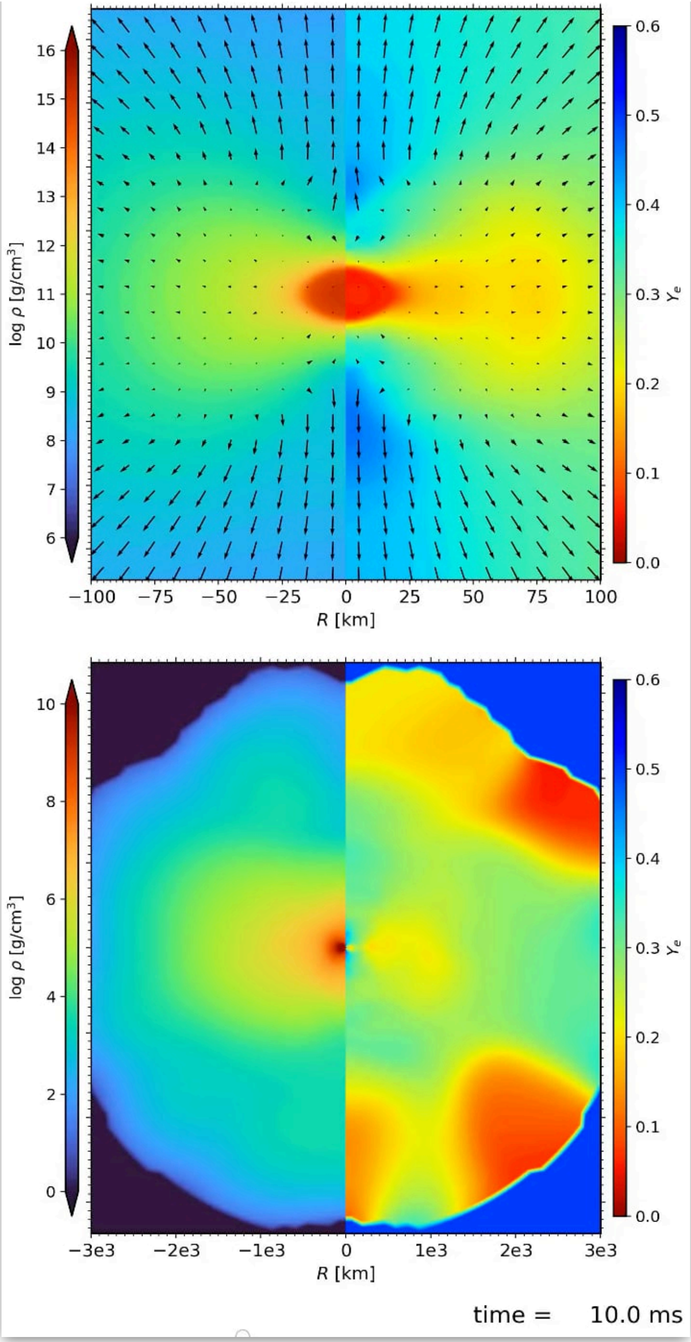
(Just et al. 2022, PRD 105)



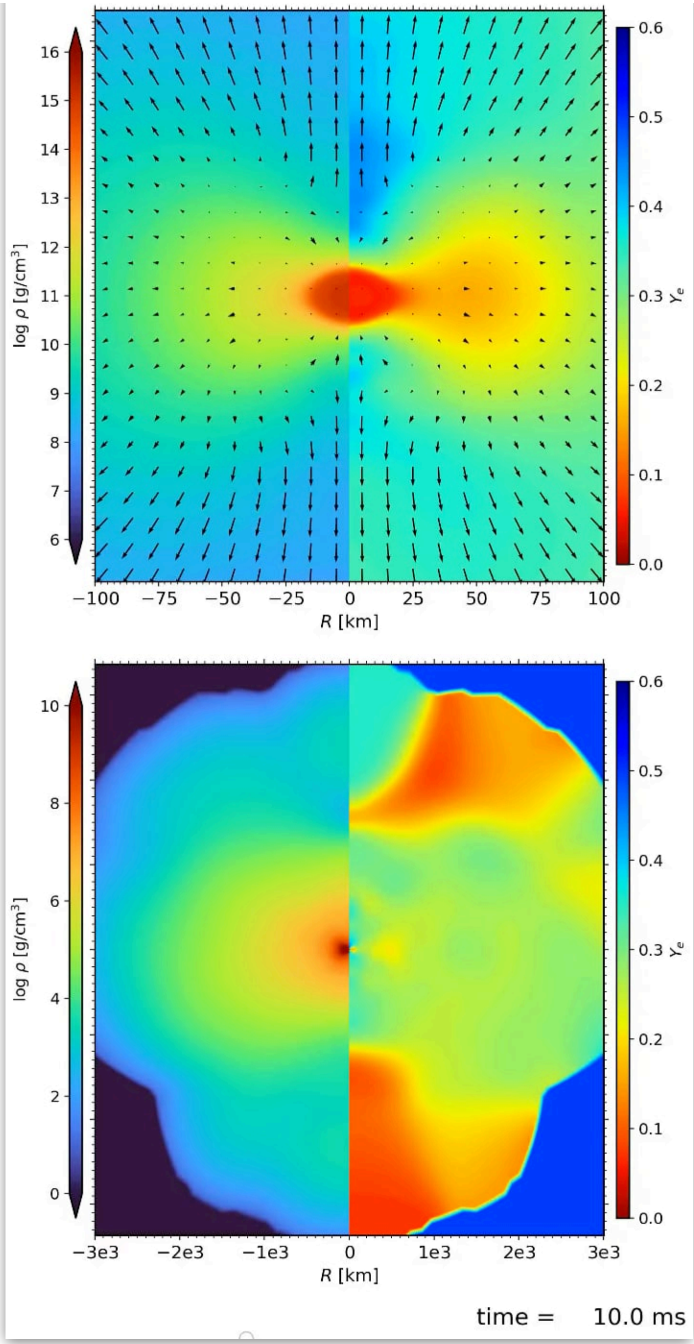


- significant impact on r-process yields and kilonova signal
- motivates development of more sophisticated flavor-mixing models

long-lived HMNS



short-lived HMNS



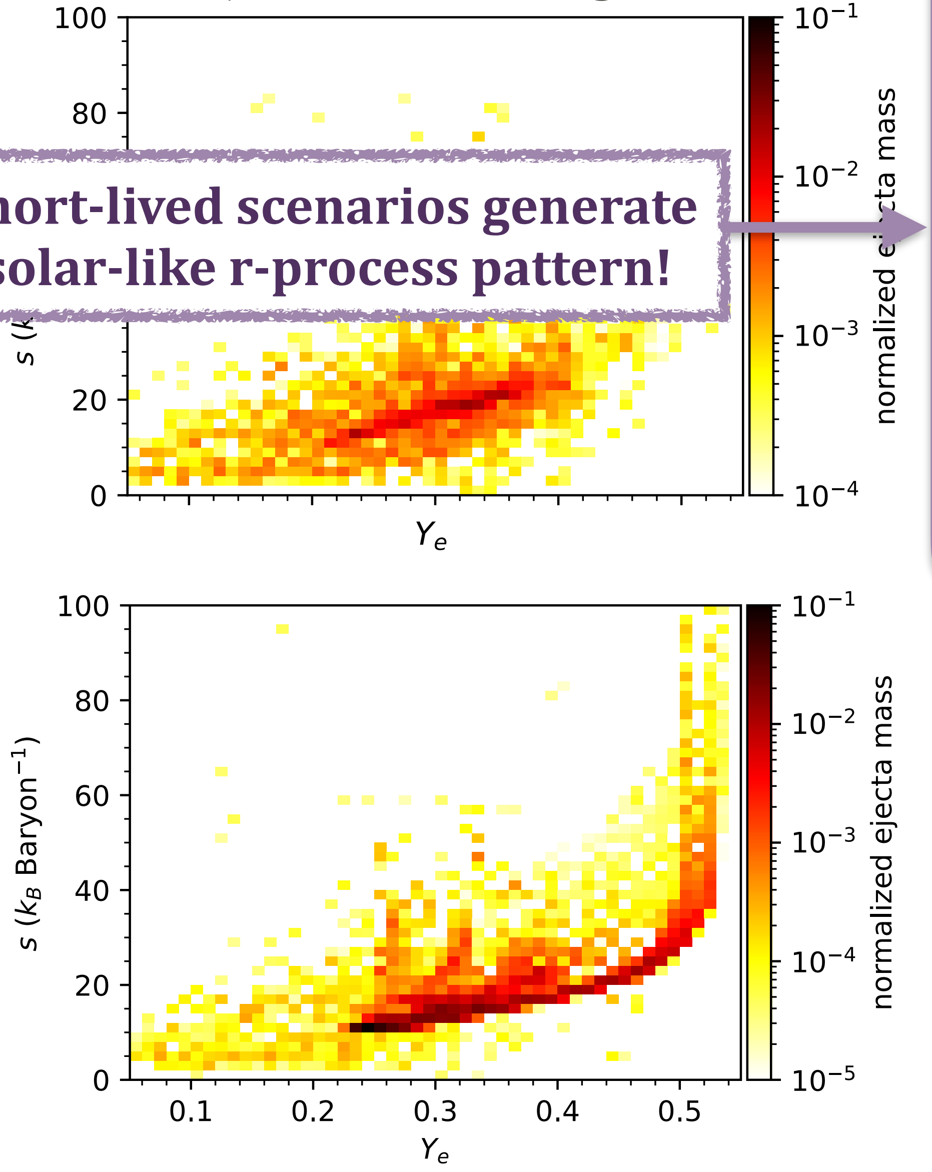
Short- vs. long-lived NS remnant

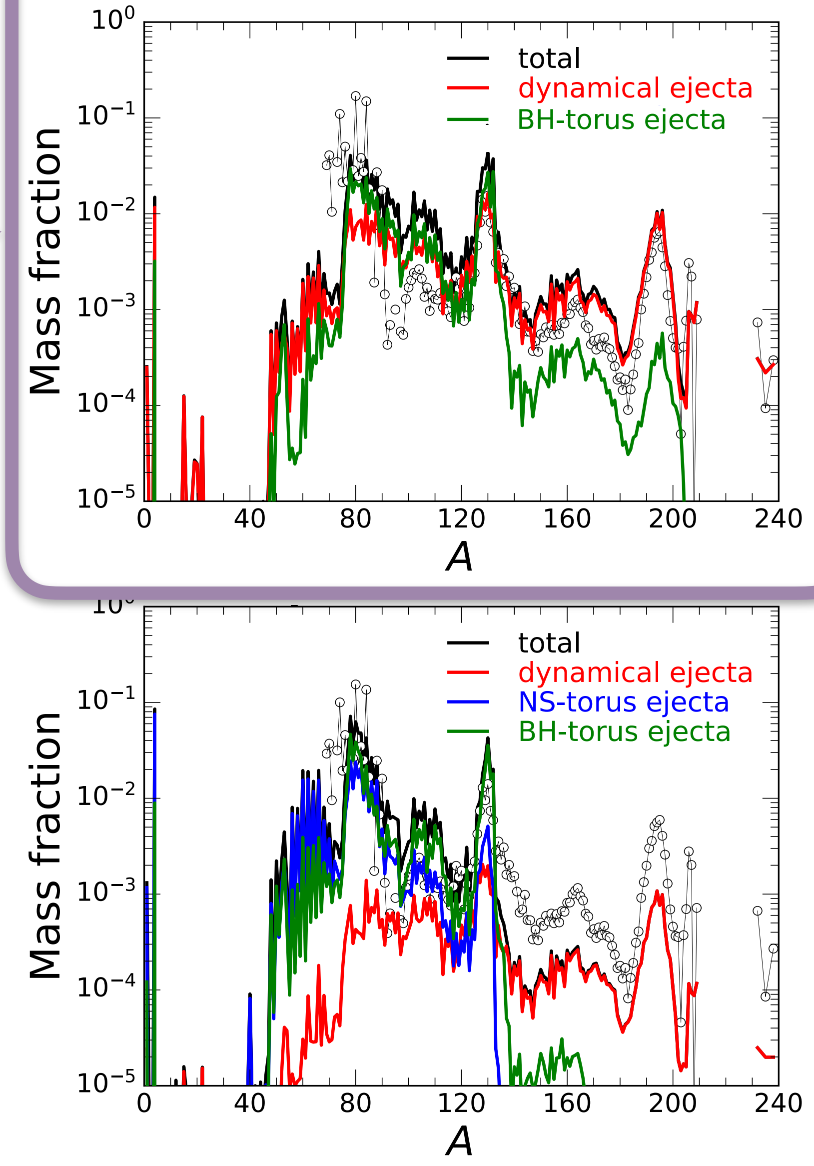
ejecta mass histogram

ejecta nucleosynthesis yields

short-lived
(10ms)

short-lived scenarios generate solar-like r-process pattern!





long-lived
(120ms)

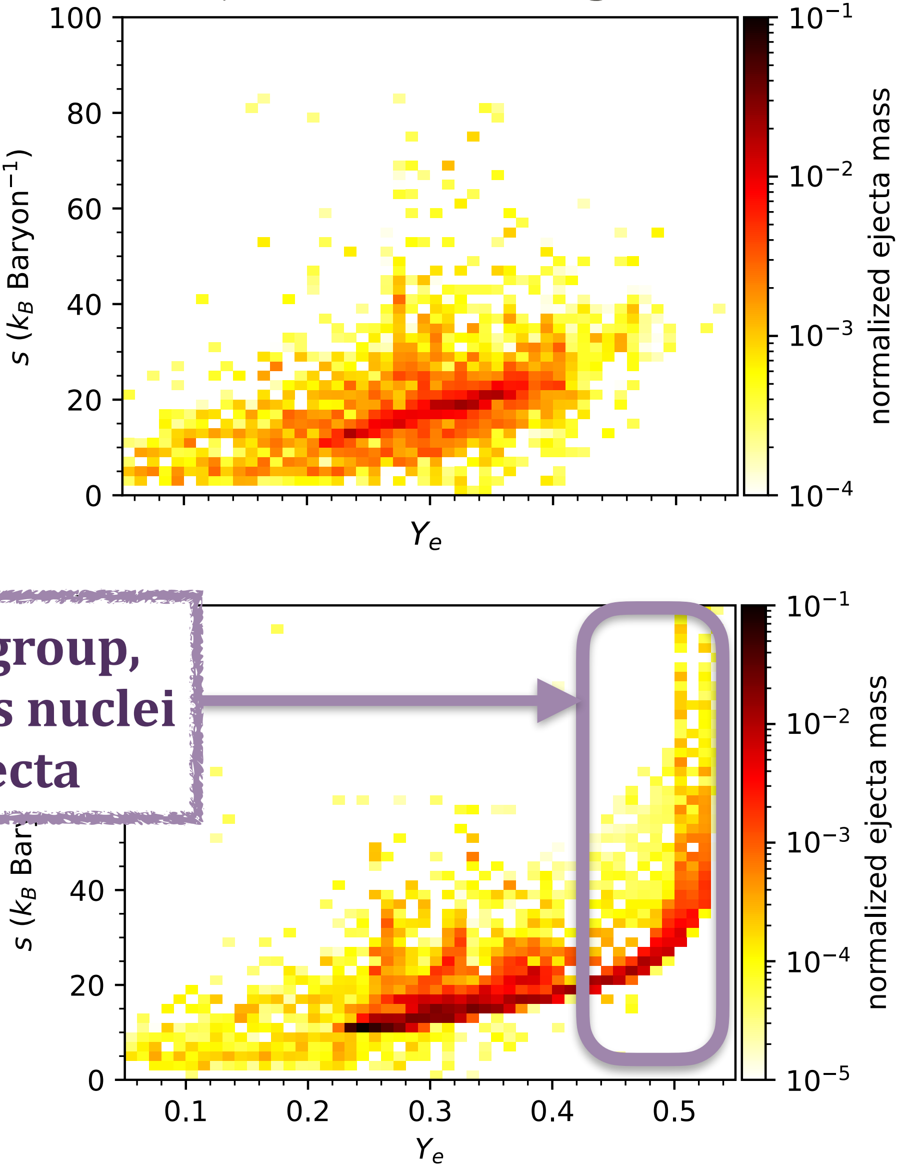
Short- vs. long-lived NS remnant

ejecta mass histogram

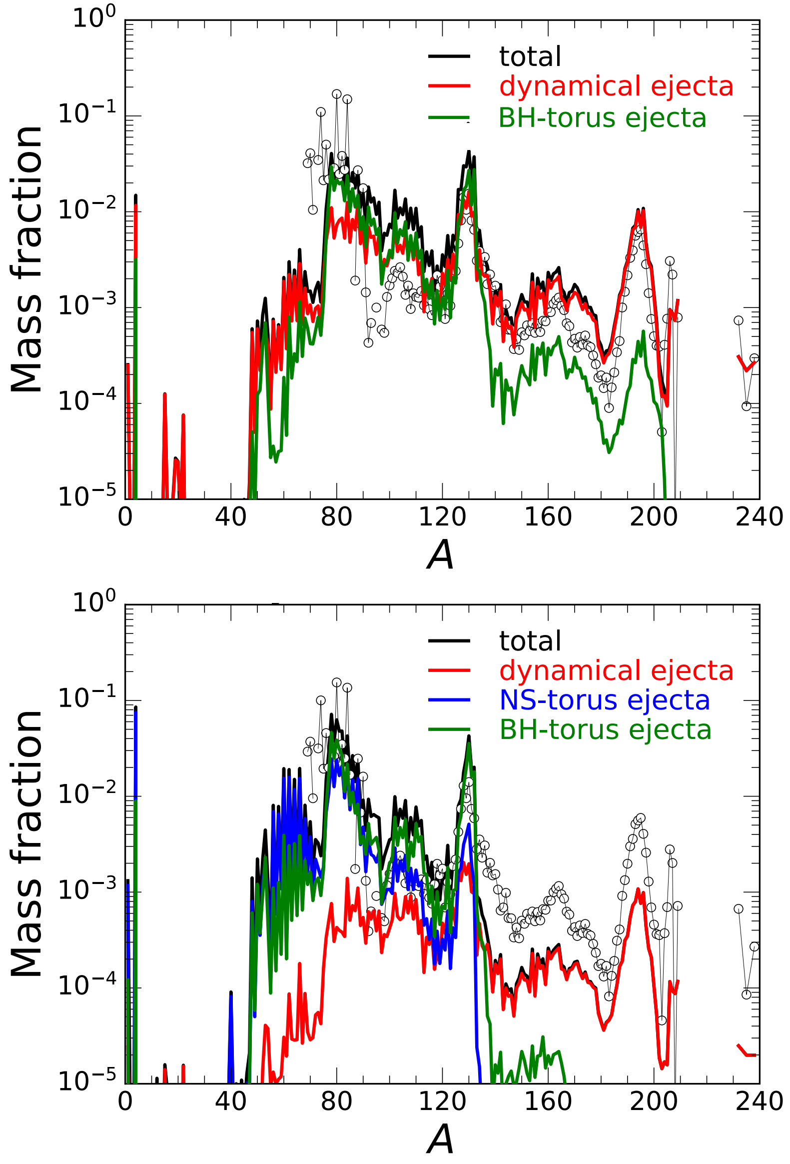
ejecta nucleosynthesis yields

short-lived
(10ms)

long-lived
(120ms)



mainly He, iron-group, and light r-process nuclei in NS-torus ejecta

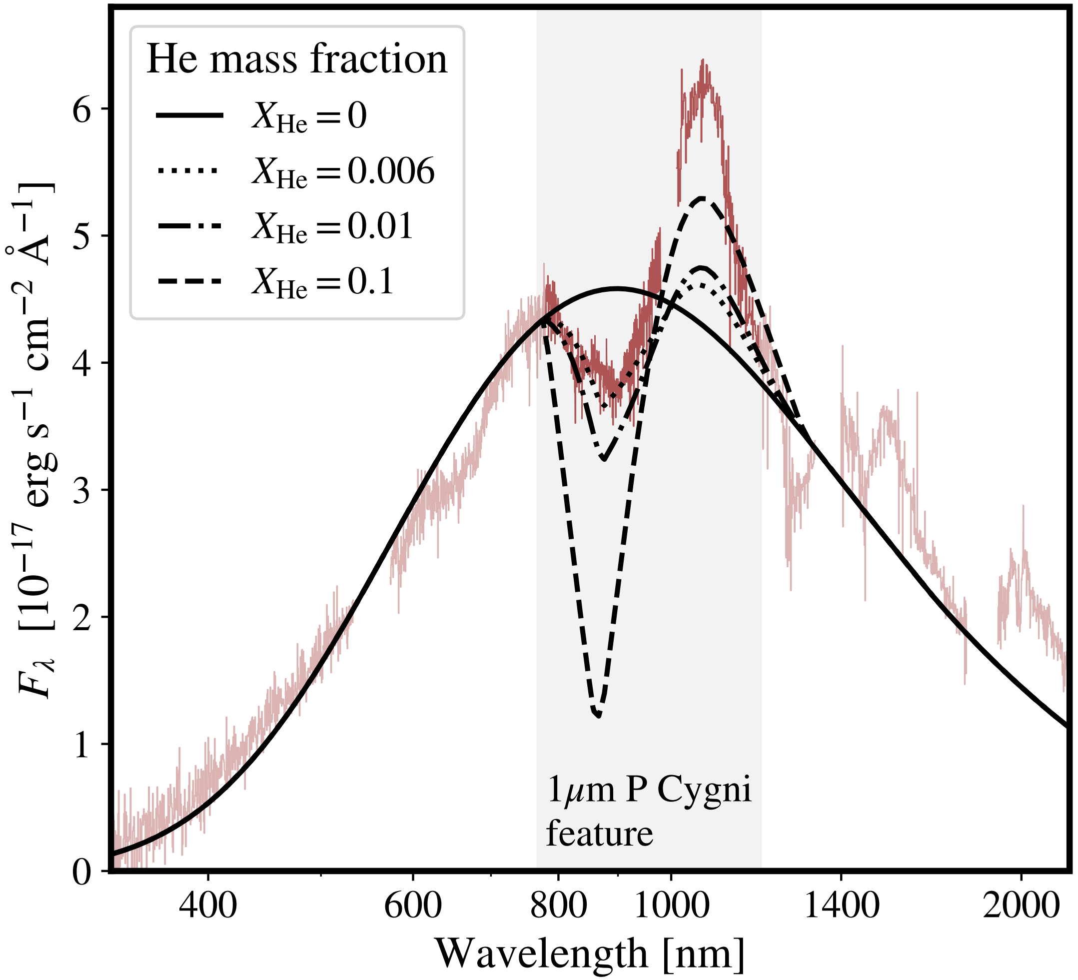


Observational limit on helium abundance

(Sneppen, OJ, Bauswein et al. 2024, PRD)

- observed spectrum (at 4.4 days) **appears inconsistent** with significant helium mass fractions
- observational limit $X(\mathrm{He}) \lesssim 0.05$ implies upper limit on HMNS lifetime of $\tau_{\mathrm{BH}} \lesssim 20 - 30\,\mathrm{ms}$ in AT2017gfo

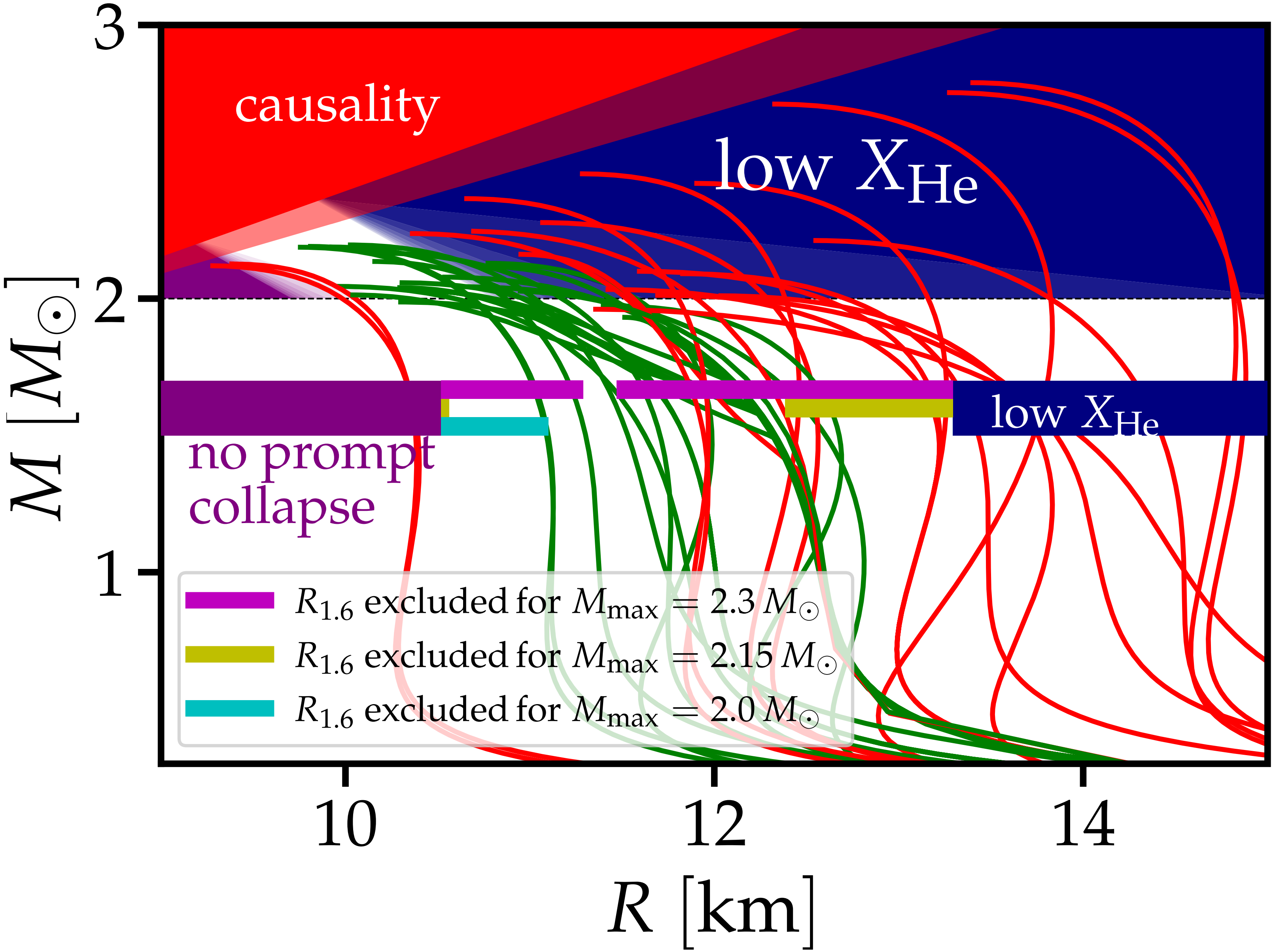
observed spectrum of AT2017gfo at 4.4 days
+ estimated hypothetic contribution of helium



Implications for NS equation-of-state models

(Sneppen, OJ, Bauswein et al. 2024, PRD)

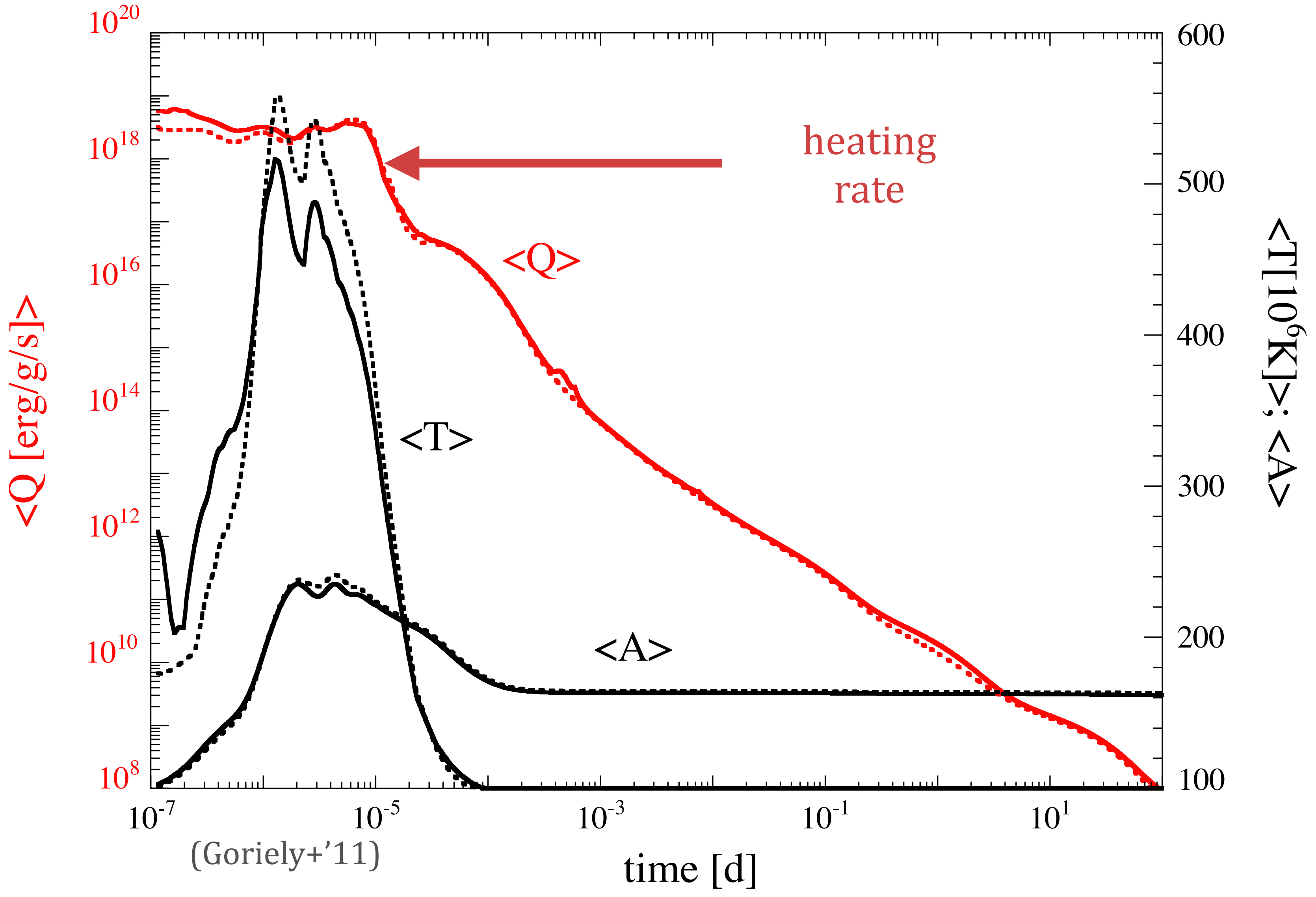
- large number of EOSs excluded (red lines)
- in particular EOSs with simultaneously large $R_{1.6}$ and M_{max}



R-process heating

(Just, Xiong, Martinez-Pinedo 2025, PRD)

- radioactive decay of freshly synthesized r-process elements releases heat
- **ignored in almost all existing hydro-simulations**

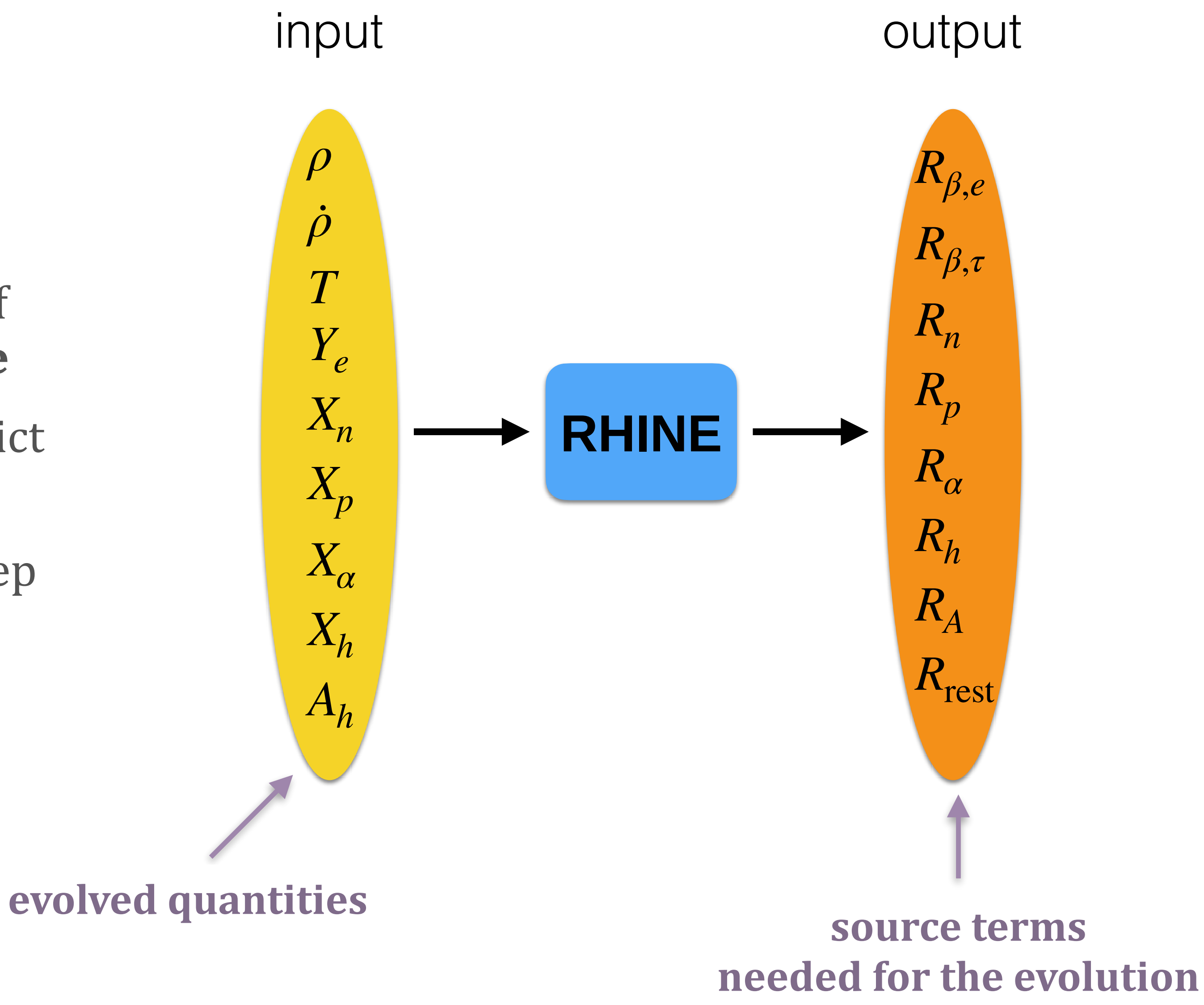


(Goriely+'11)

(Just, Xiong, Martinez-Pinedo 2025, PRD)

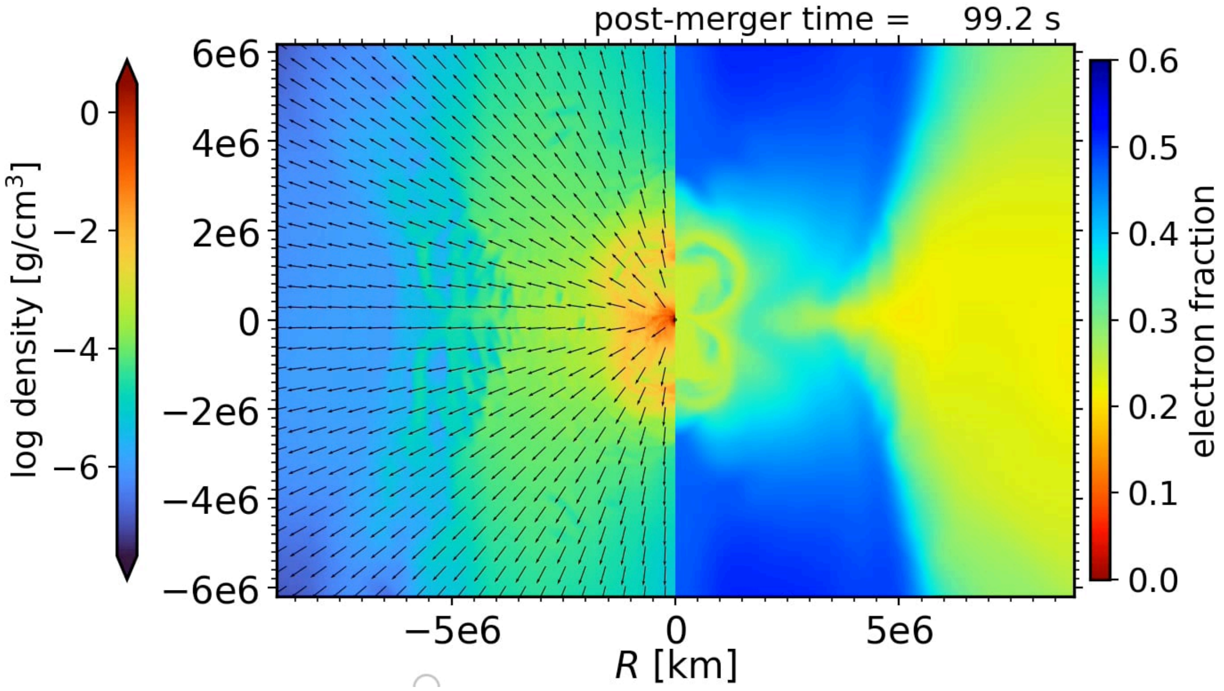
RHINE: R-process Heating Implementation with NEural networks

- evolving full nuclear network with 1000’s of isotopes together with hydro **too expensive**
- RHINE: only advect key quantities and predict source terms using neural networks
- source terms inferred at each hydro time step using current values of evolved quantities

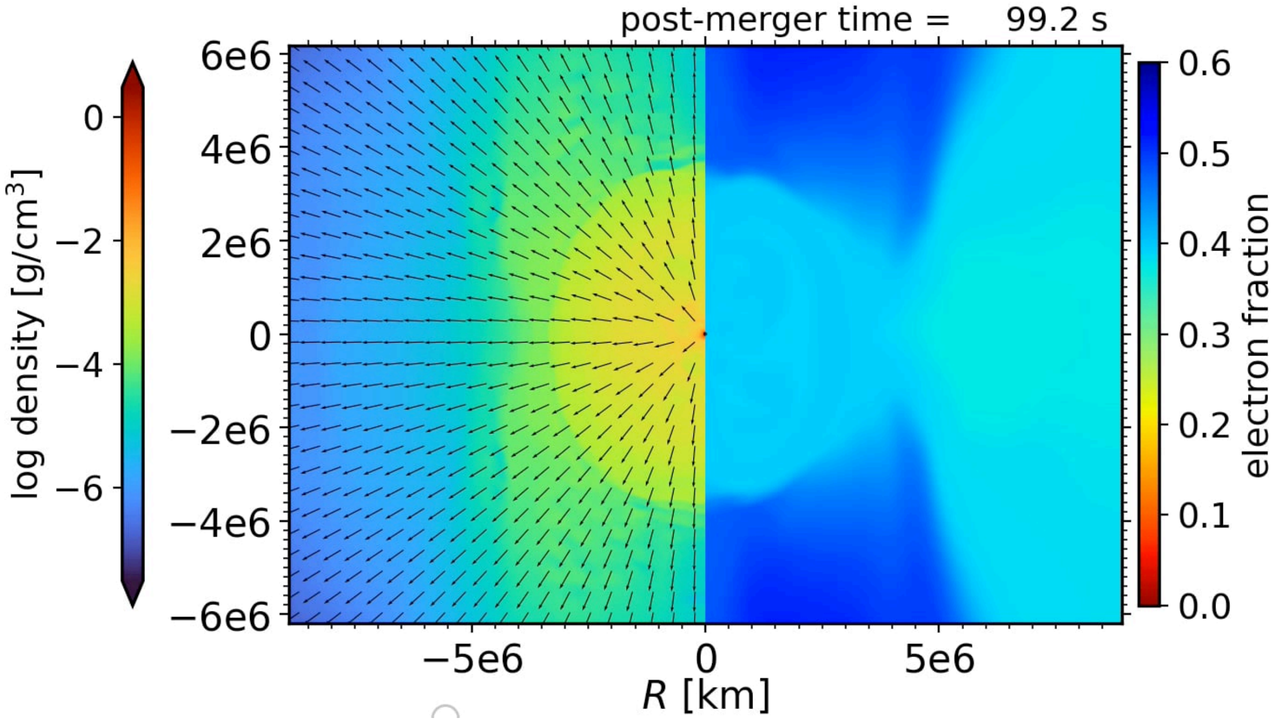


NS merger models + RHINE

without RHINE:



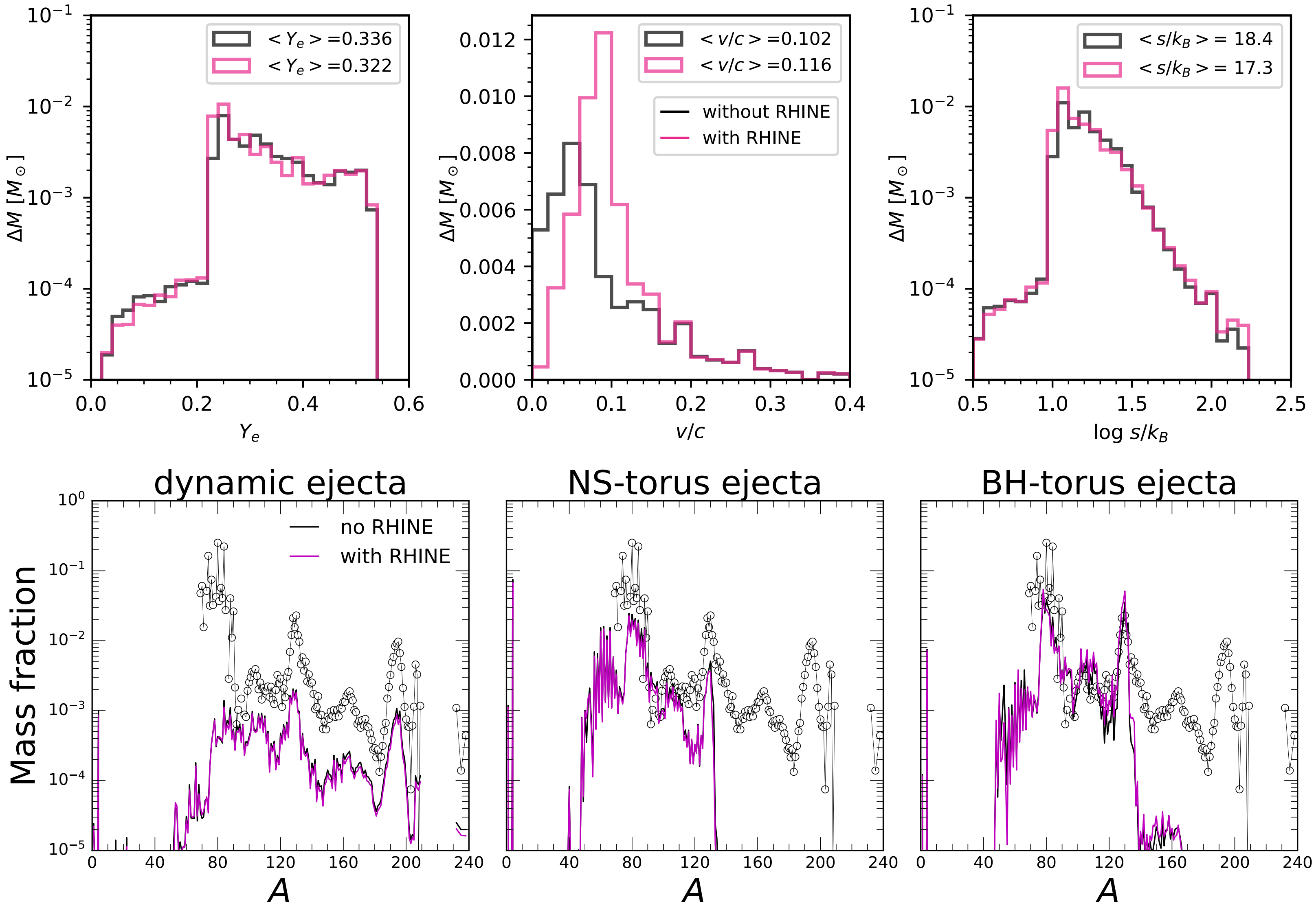
with RHINE:



- accelerates BH-torus ejecta from ~0.04c to ~0.08 c
- makes ejecta more spherical
- increases ejecta mass

NS merger models + RHINE

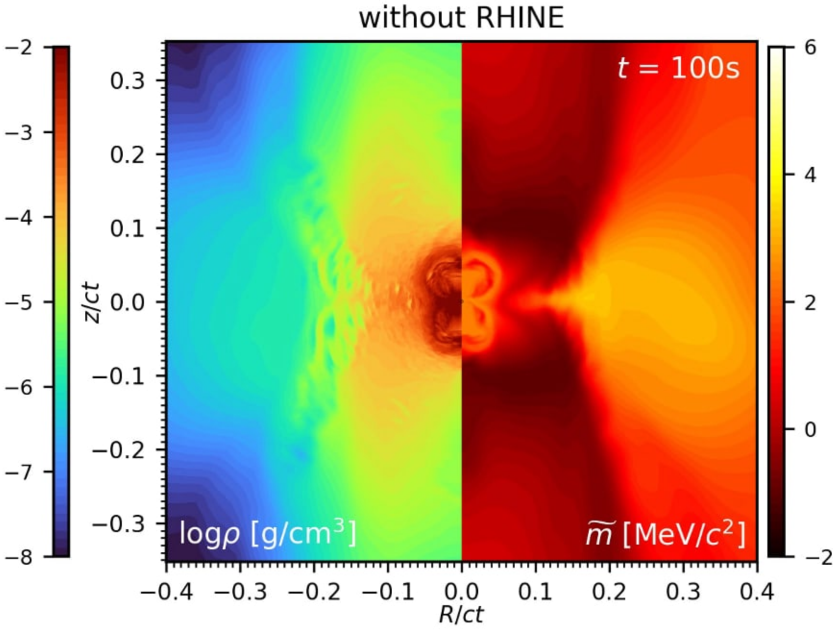
(Just, Xiong, Martinez-Pinedo 2025, PRD)

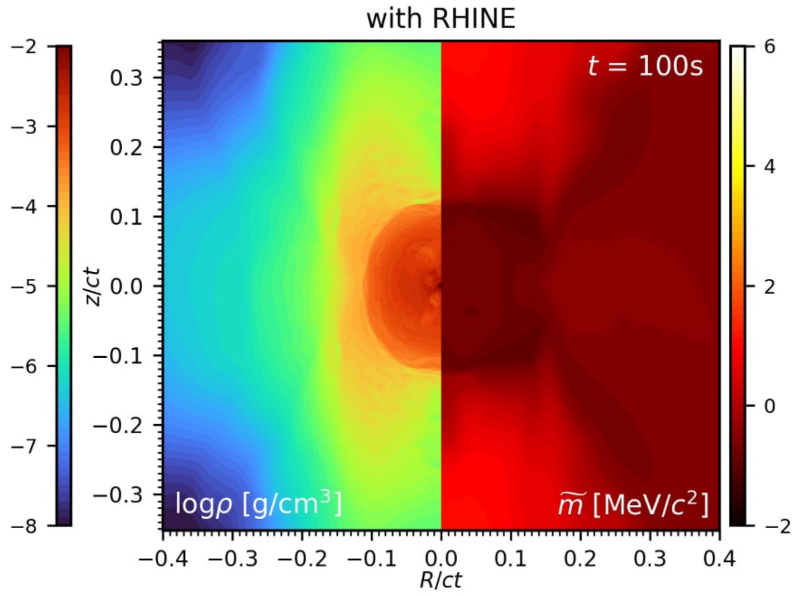


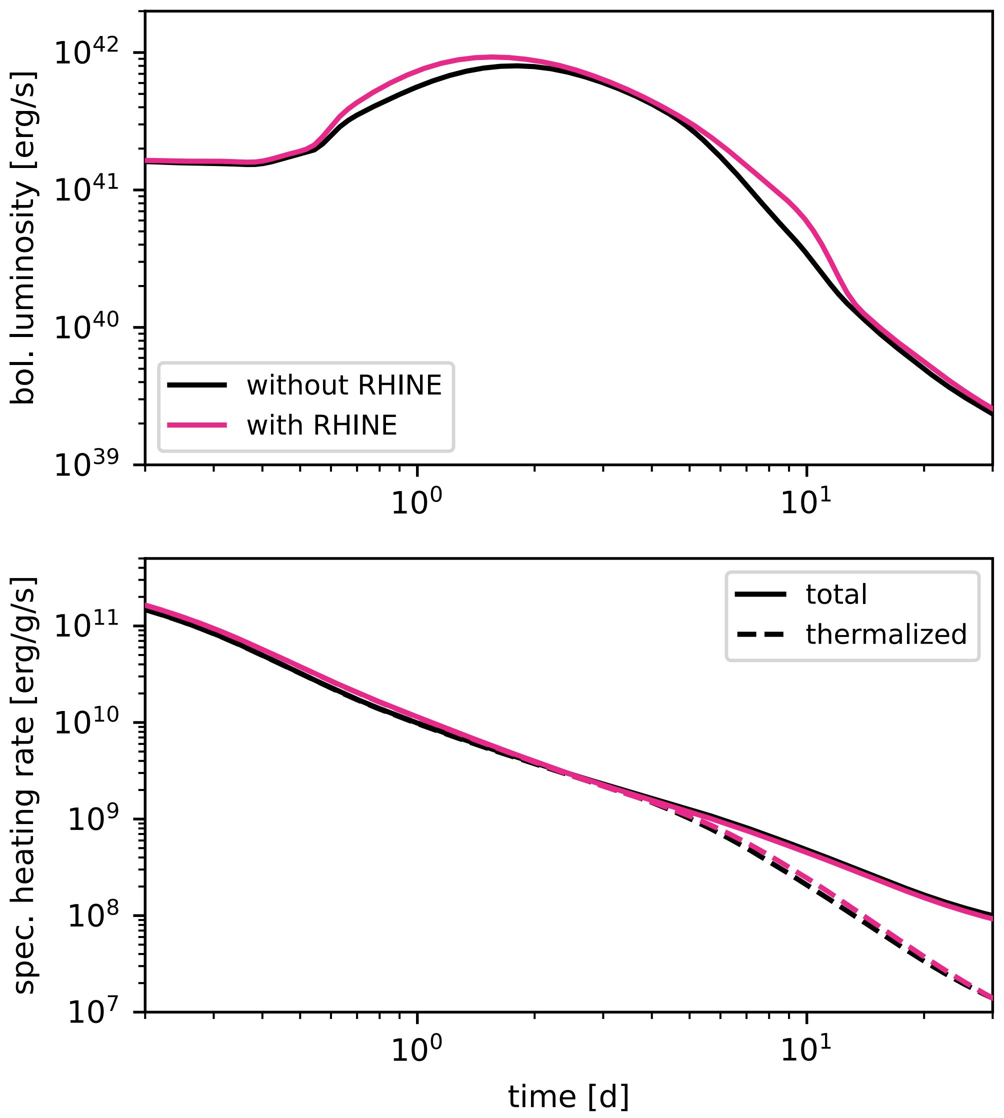
- relatively small impact on nucleosynthesis yields

Impact on kilonova light curve

(Just, Xiong, Martinez-Pinedo 2025, PRD)







Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY

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Luminosity predictions for the first three ionization stages of W, Pt, and Au to probe potential sources of emission in kilonova

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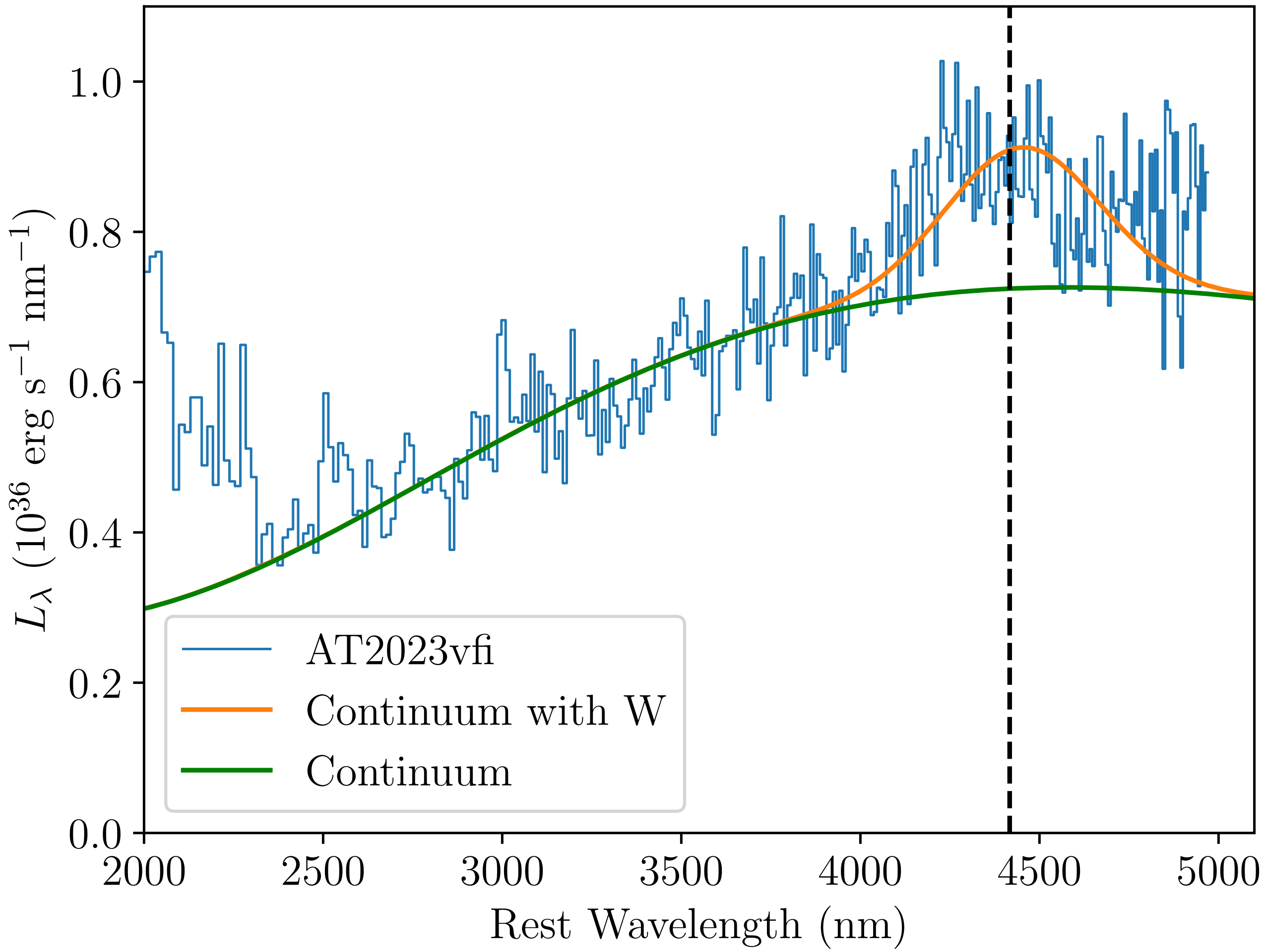
Spectrum in “nebular” phase of AT2023vfi

(McCann et al., 2025, MNRAS 538)

- AT2023vfi accompanied a long gamma-ray burst and was presumably a kilonova
- new atomic data developed for W (tungsten, Z=74)
- may explain 4.5 micron bump in late spectrum of long-GRB kilonova AT2023vfi
- estimated mass: 9.4 x 10^-4 Msun

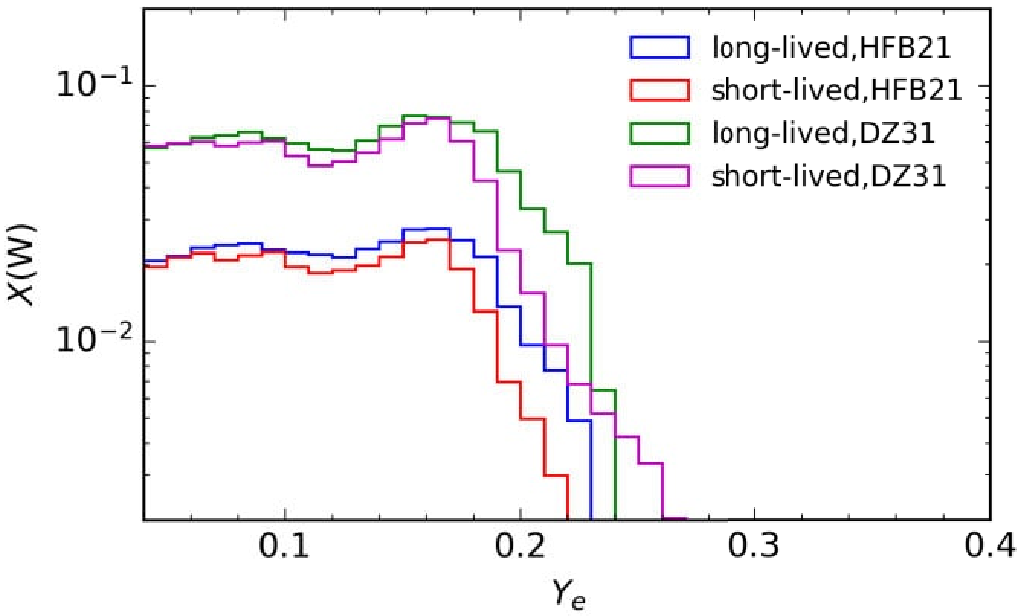
spectrum at 29 days

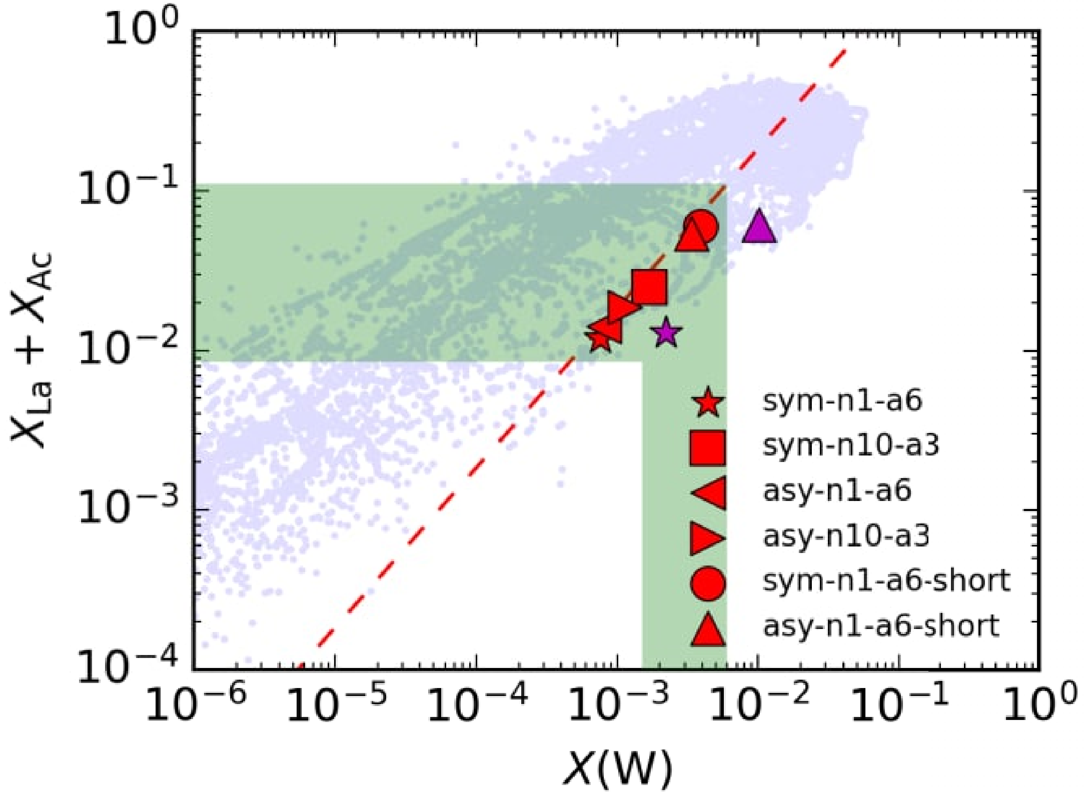


Implications

(if feature produced by W)

(McCann et al., 2025, MNRAS 538)





- W only produced for neutron-rich conditions -> proxy for low-Ye material
- correlation between W and lanthanides allows estimate on lanthanide fraction
- **abundance of single element can provide information on entire group of elements**

Summary

- **Suggested r-process sites: CCSNe, MR-SNe, collapsars, MGFs, NSMs**
  - ordinary CCSNe: so far no model with successful r-process beyond 1st peak
  - MR-SNe and collapsar models may produce (lighter?) r-elements, but suffer from uncertainties in stellar evolution (stellar B-field + rotation rate)
  - MGFs only simplistic 1D models available so far
  - only NSMs observationally confirmed r-process site so far
  - only NSM models predict solar-like abundance pattern from 1st- to 3rd peak (so far)
- **however, significant modeling uncertainties in each model**
- **better modeling + nuclear data (from NUSTAR) + more observations needed!**

Thank you for your attention !!!