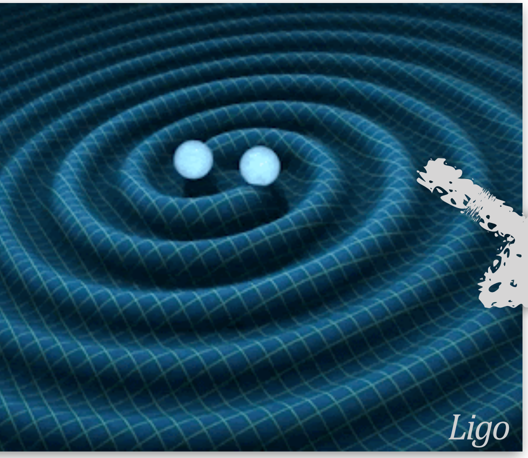
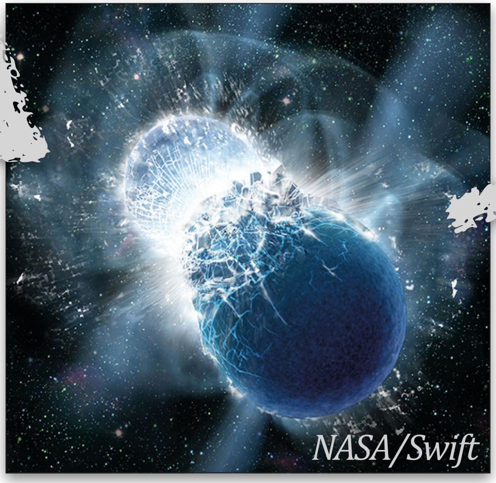
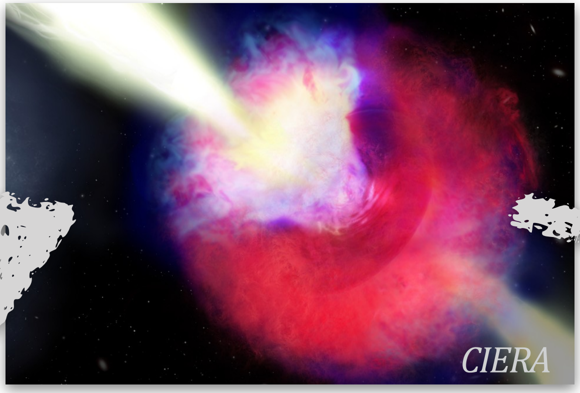
NPA Conference, Dresden, Sept. 9th 2024

Neutron-star merger models including all phases of matter ejection

(mainly from Just et al., ApJL 951, L12, 2023)


Ligo


NASA/Swift


CIERA


www.deraktionaer.de

Oliver Just

Relativistic Astrophysics Group, GSI

with: A. Bauswein, G. Martinez-Pinedo, Z. Xiong, V. Vijayan, S. Goriely, H.-Th. Janka, J. Guilet, T. Soultanis

SFB 1245

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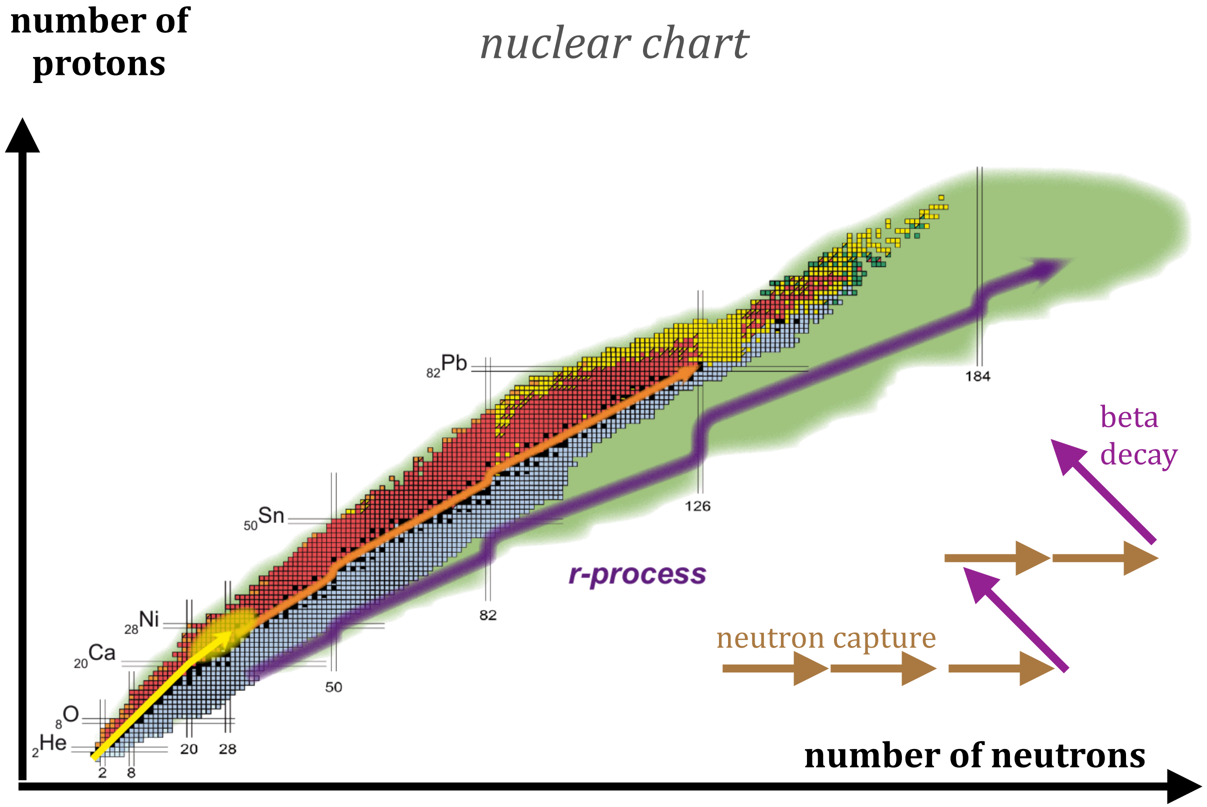
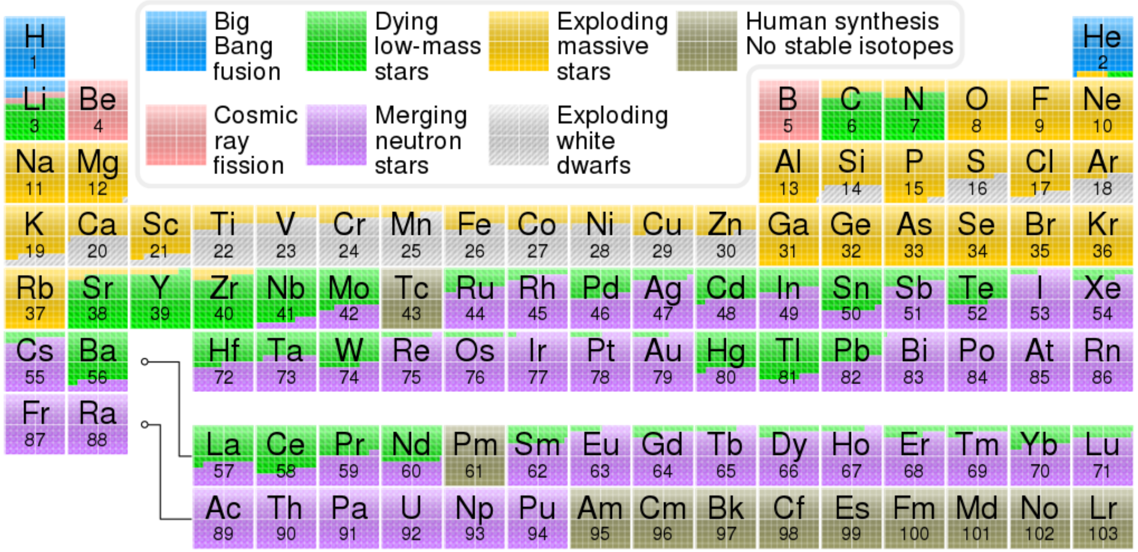
Are NSMs main sites of the “rapid neutron-capture” (r-) process?



*periodic system with **suggested** site of origin*



Main condition:

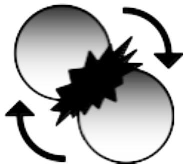
high neutron density = low electron fraction Y_e

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

- other suggested sites: core-collapse supernovae, magneto-rotational SNe, collapsars
- NSMs are **only confirmed site** so far
- NSMs probed with multi-messenger astronomy: **Kilonovae, gravitational waves, GRBs**

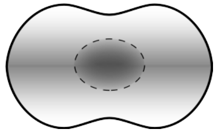
Kilonova modeling pipeline

hydrodynamic modeling of merger + dynamical ejecta

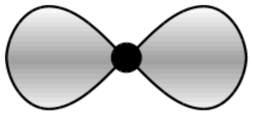


$t \sim \mathcal{O}(10\,\mathrm{ms})$

hydrodynamic modeling of remnant + post-merger ejecta



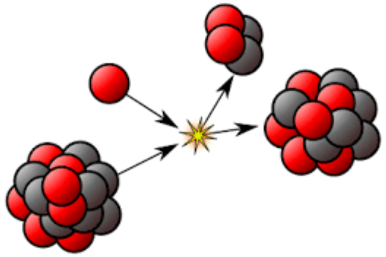
neutron star torus system



black hole torus system

$t \sim \mathcal{O}(10\,\mathrm{s})$

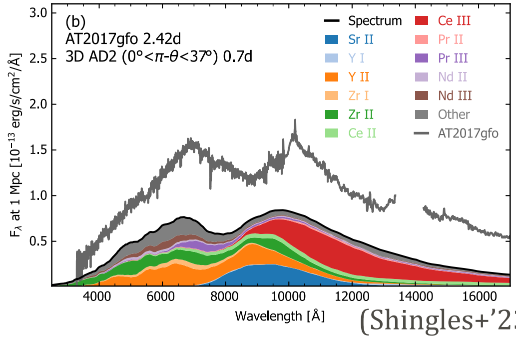
heavy element nucleosynthesis



$t \sim \mathcal{O}(10\,\mathrm{s})$

(see posters by G. Leck, A. Flörs + talk by C. Collins)

kilonova radiative transfer



(Shingles+'23)

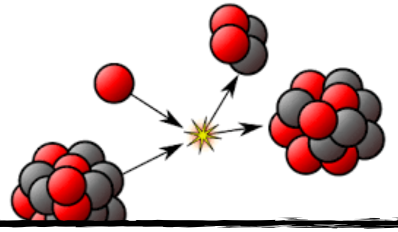
$t \sim \mathcal{O}(10\,\mathrm{days})$

parameter inference with observations

Kilonova modeling pipeline

hydrodynamic modeling of merger + dynamical ejecta

heavy element nucleosynthesis



Ideally:

- consistent merger + post-merger simulations until homologous expansion
- nucleosynthesis + kilonova based on all ejecta components

In practice, however, most existing studies:

- neglect post-merger ejecta or assume analytic estimates for nucleosynthesis + KN studies

ins)

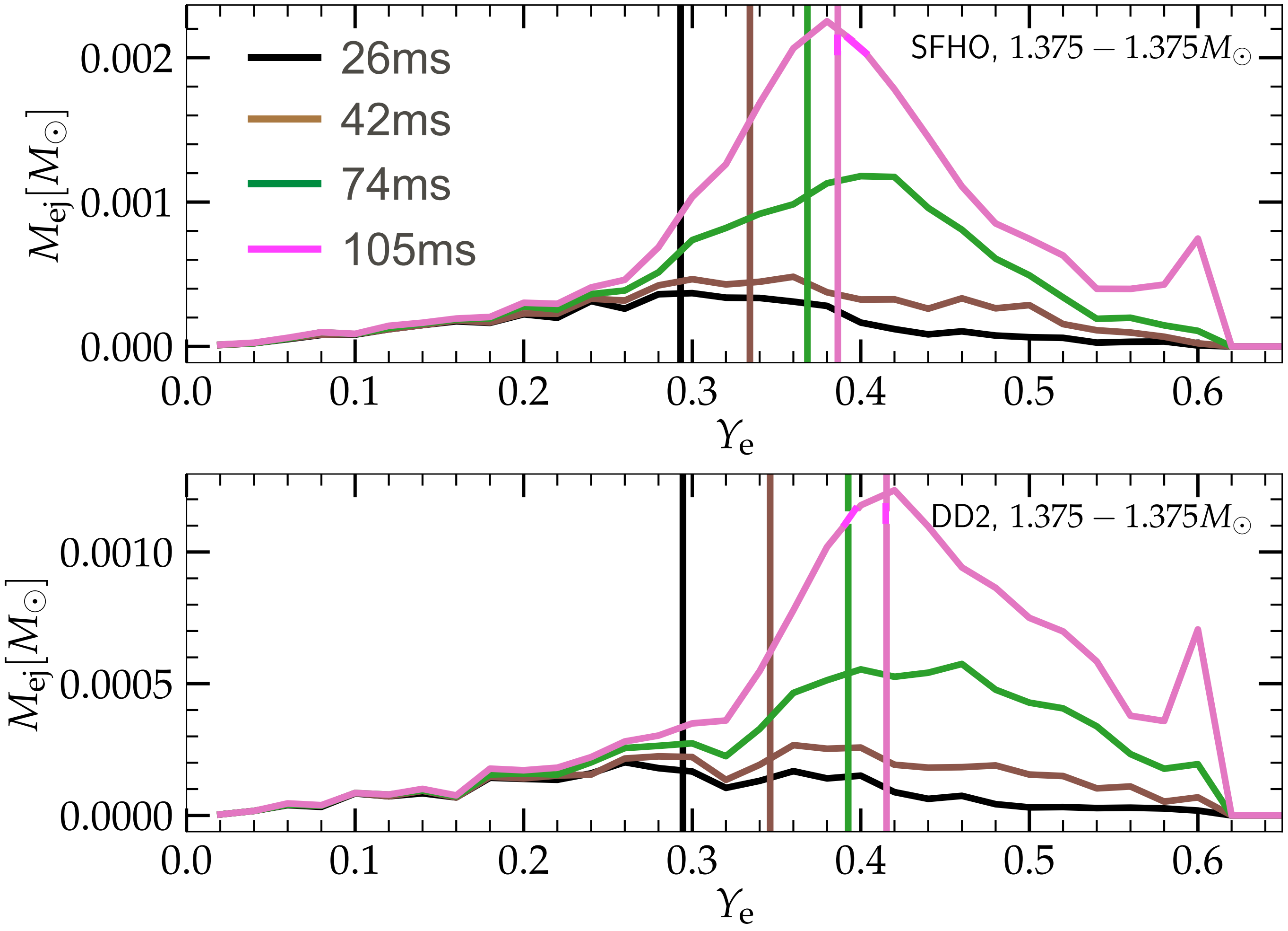
Wavelength [Å] (Shingles+'23)

$t \sim \mathcal{O}(10\,\mathrm{s})$

$t \sim \mathcal{O}(10\,\mathrm{days})$

parameter inference with observations

Challenge of post-merger evolution



(simulation by V. Vijayan, SPH,CFC-GR,ILEAS)

- required ingredients:
  - *neutrino transport*
  - *MHD and turbulent viscosity*
  - *general relativity*
- extremely expensive to resolve all relevant length-scales in 3D
- approximations necessary for efficient long-term evolution

Setup of our models

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

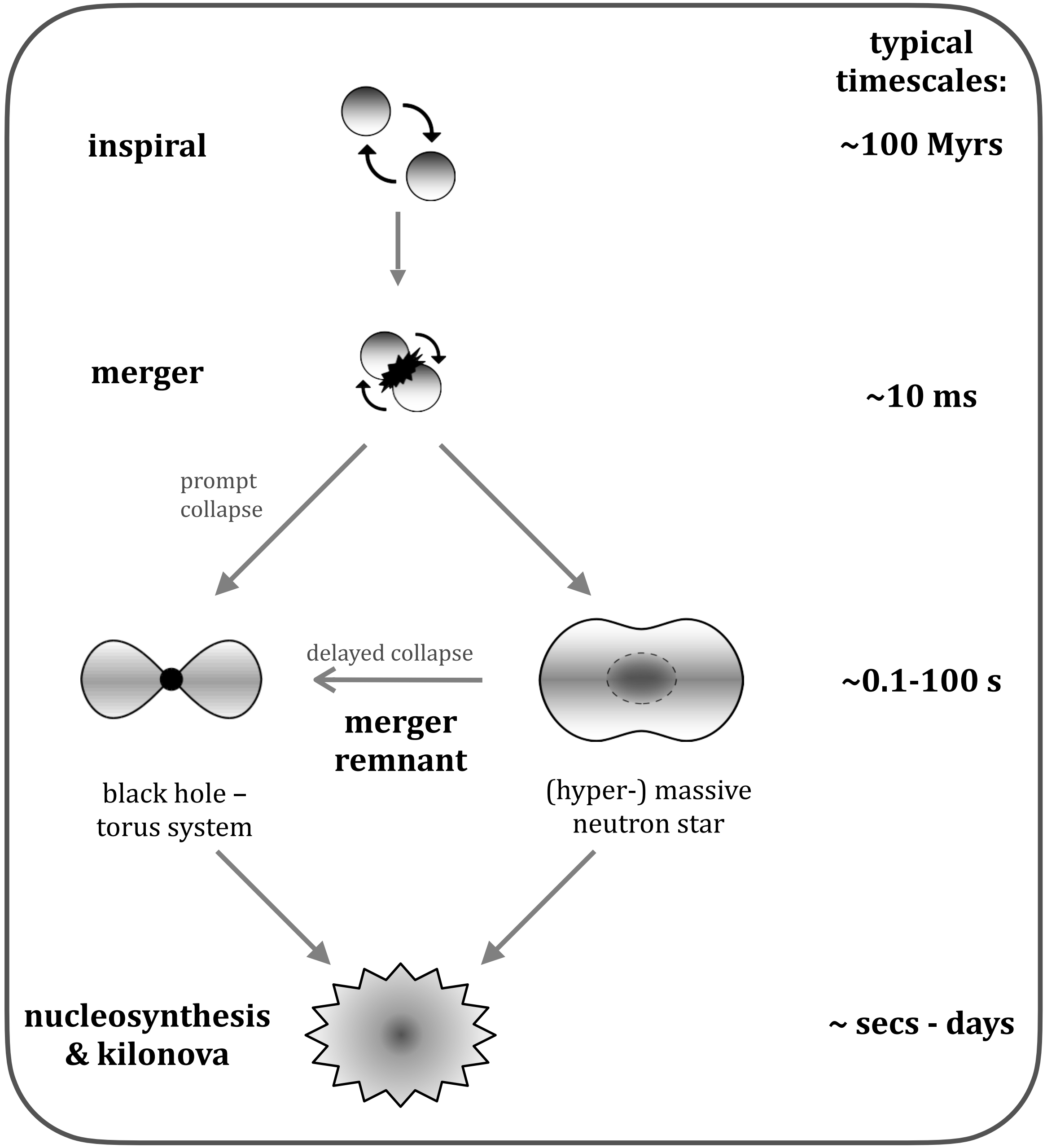
heavy element nucleosynthesis

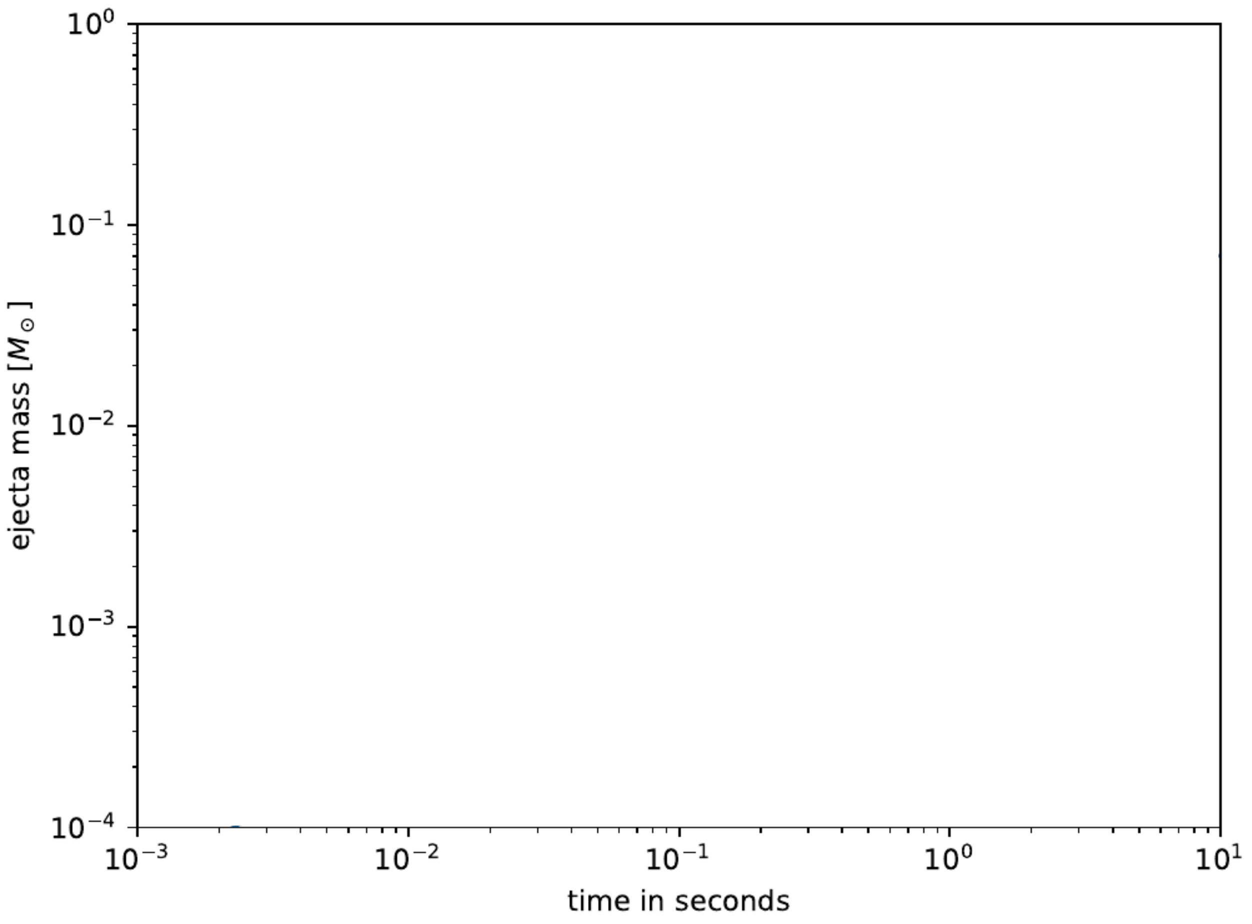
- extraction of ~5000 outflow tracers per model to sample local hydrodynamic history until 100 s
- post-processed by two nuclear networks (GSI & ULB)

kilonova radiative transfer

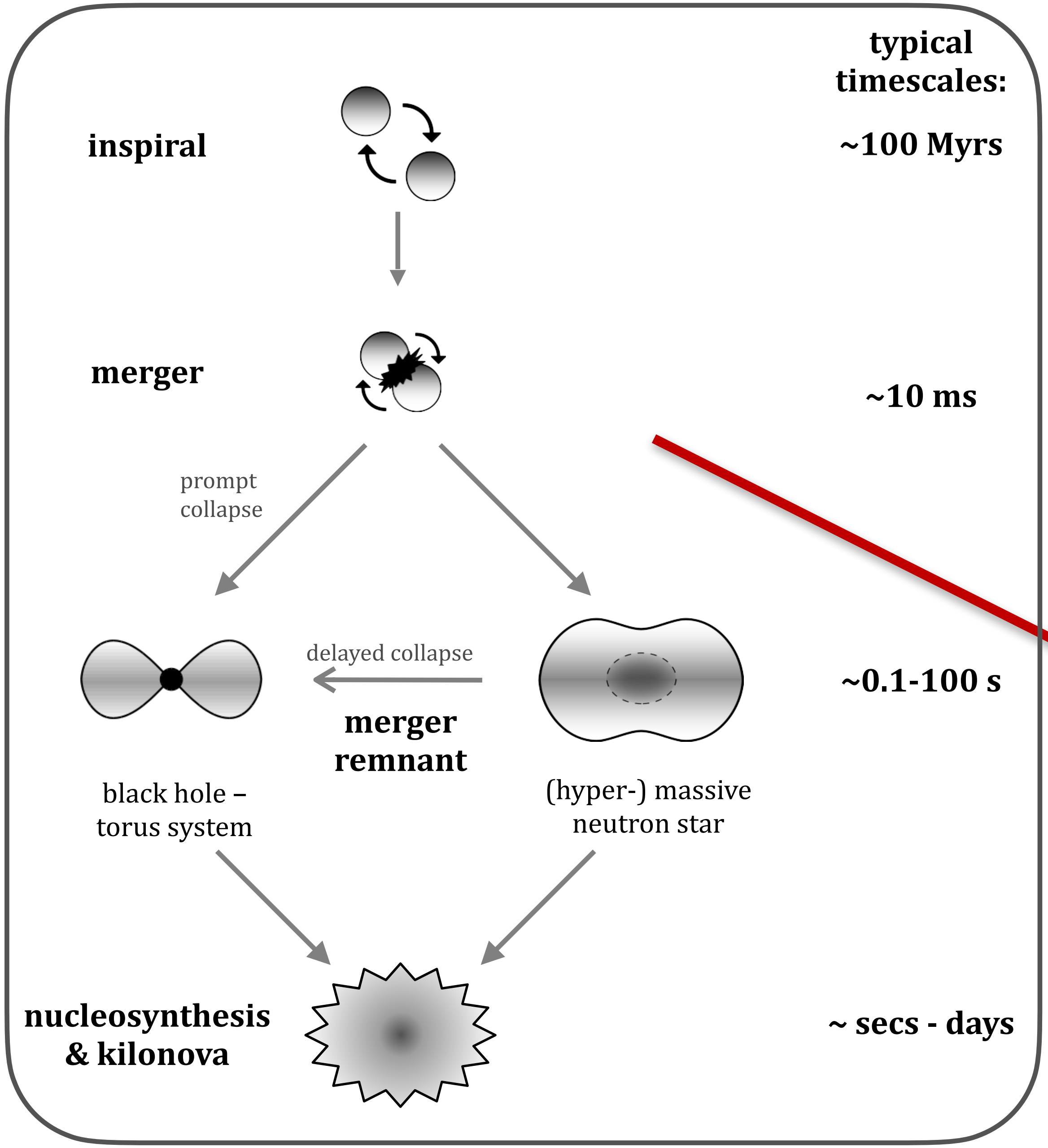
- 2D axisymmetric radiative transfer using approximate M1 scheme
- using local time-dependent results from nucleosynthesis calculations

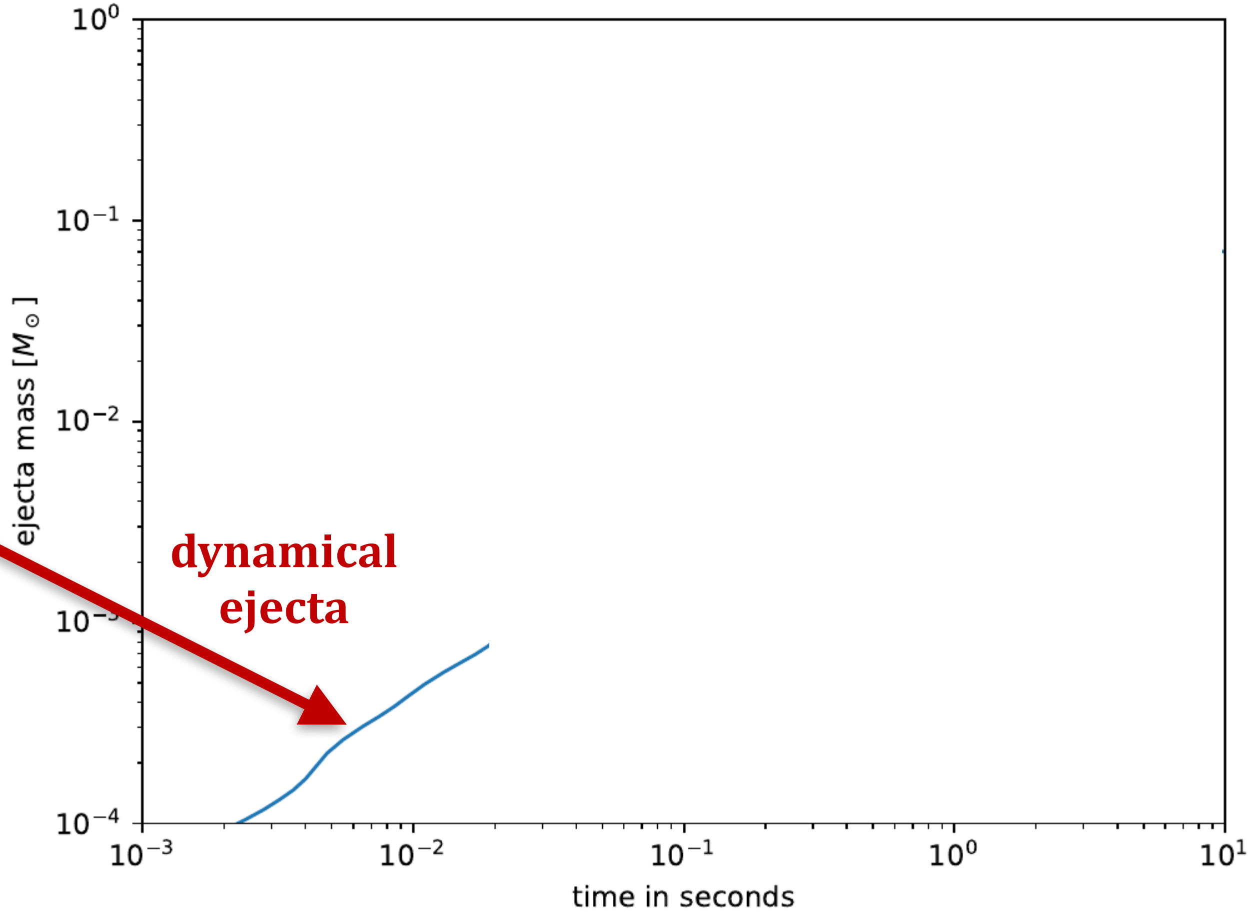
Phases of matter ejection



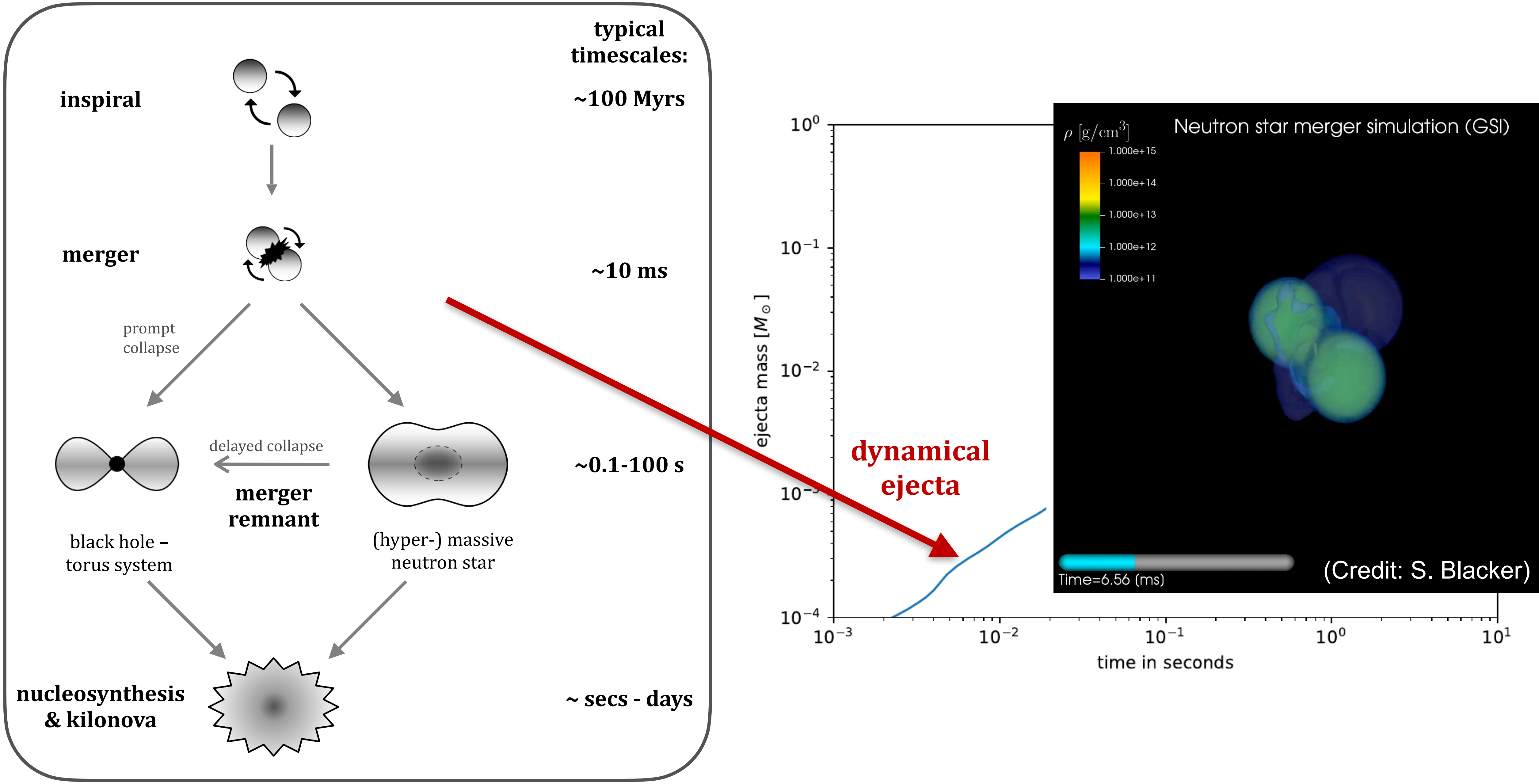


Phases of matter ejection

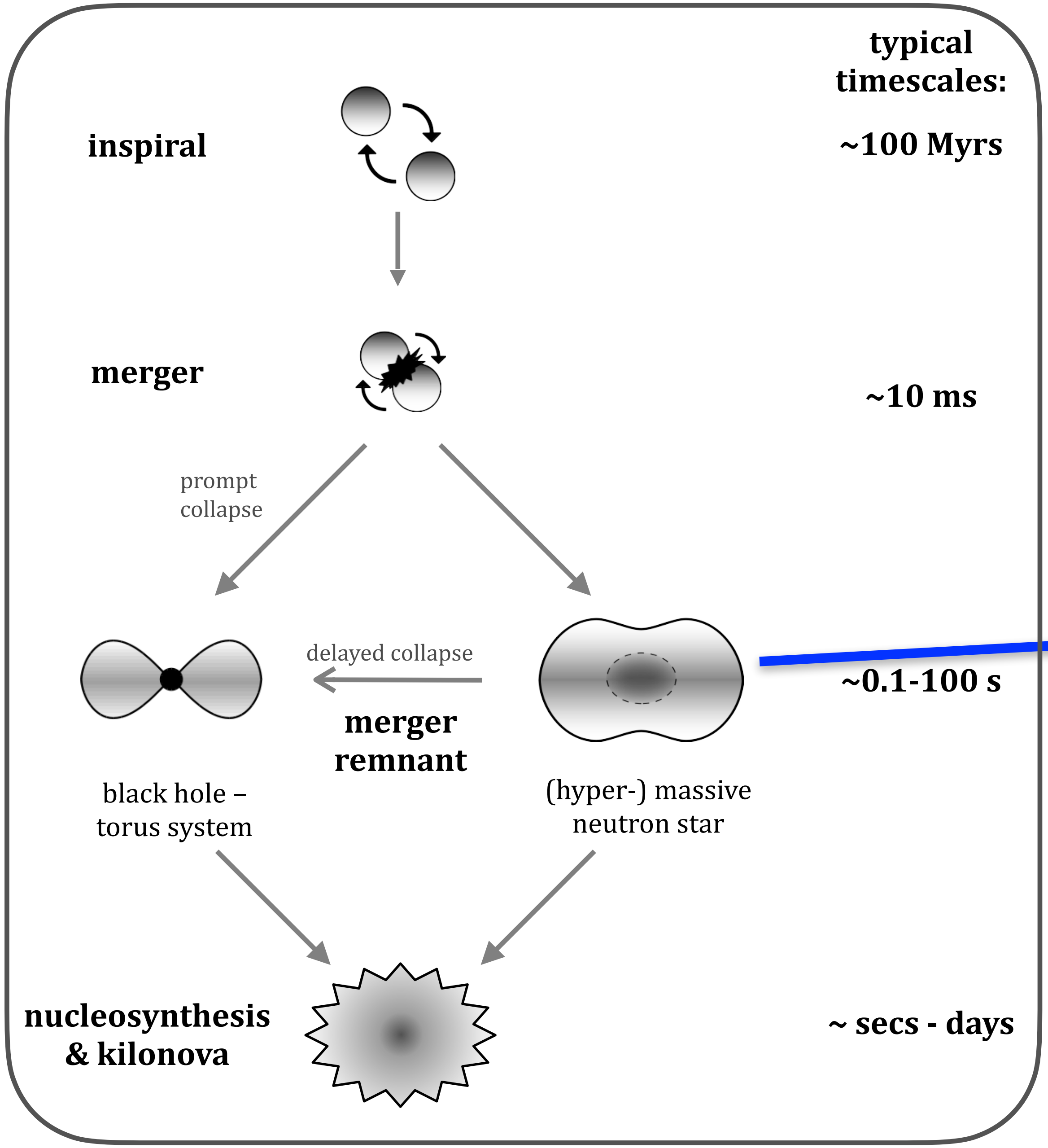


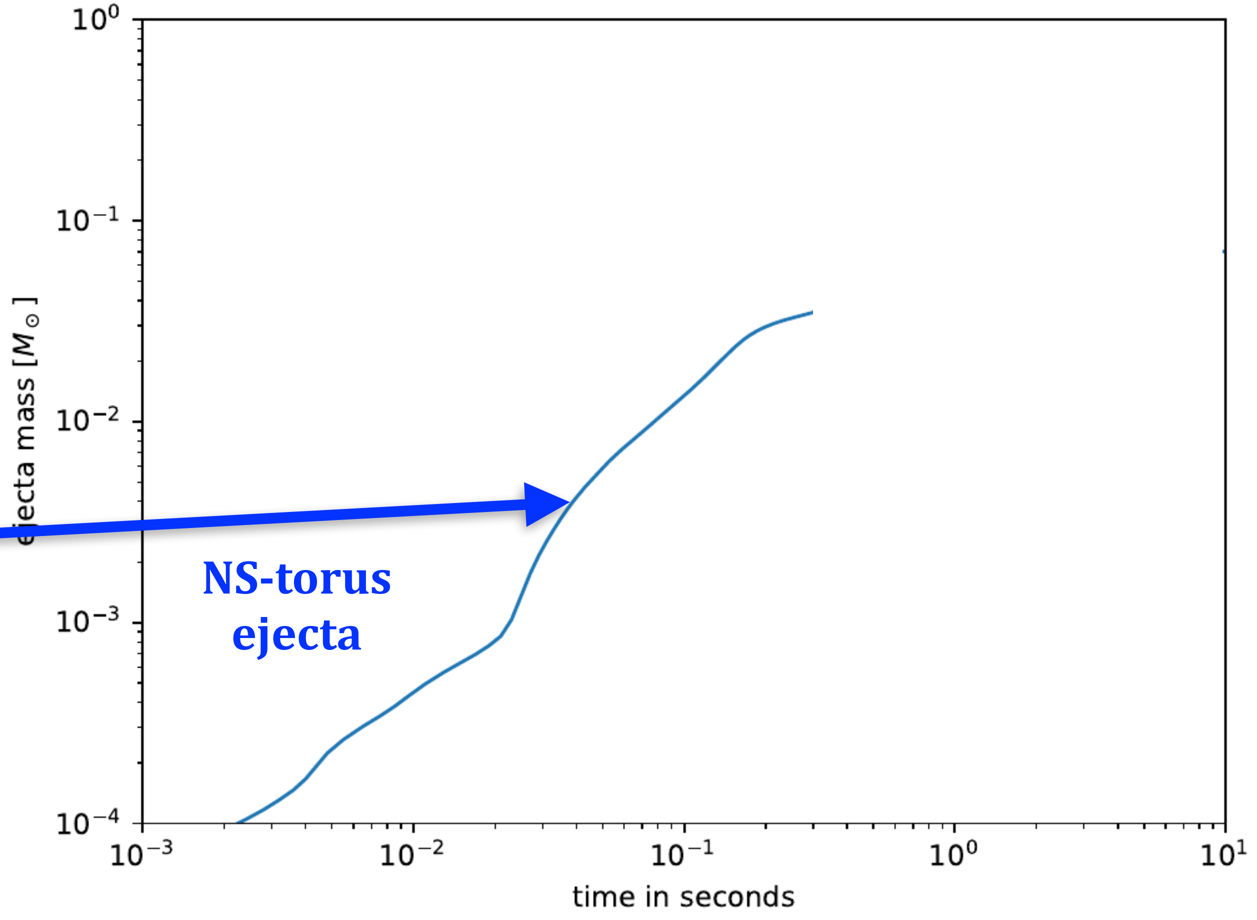


Phases of matter ejection



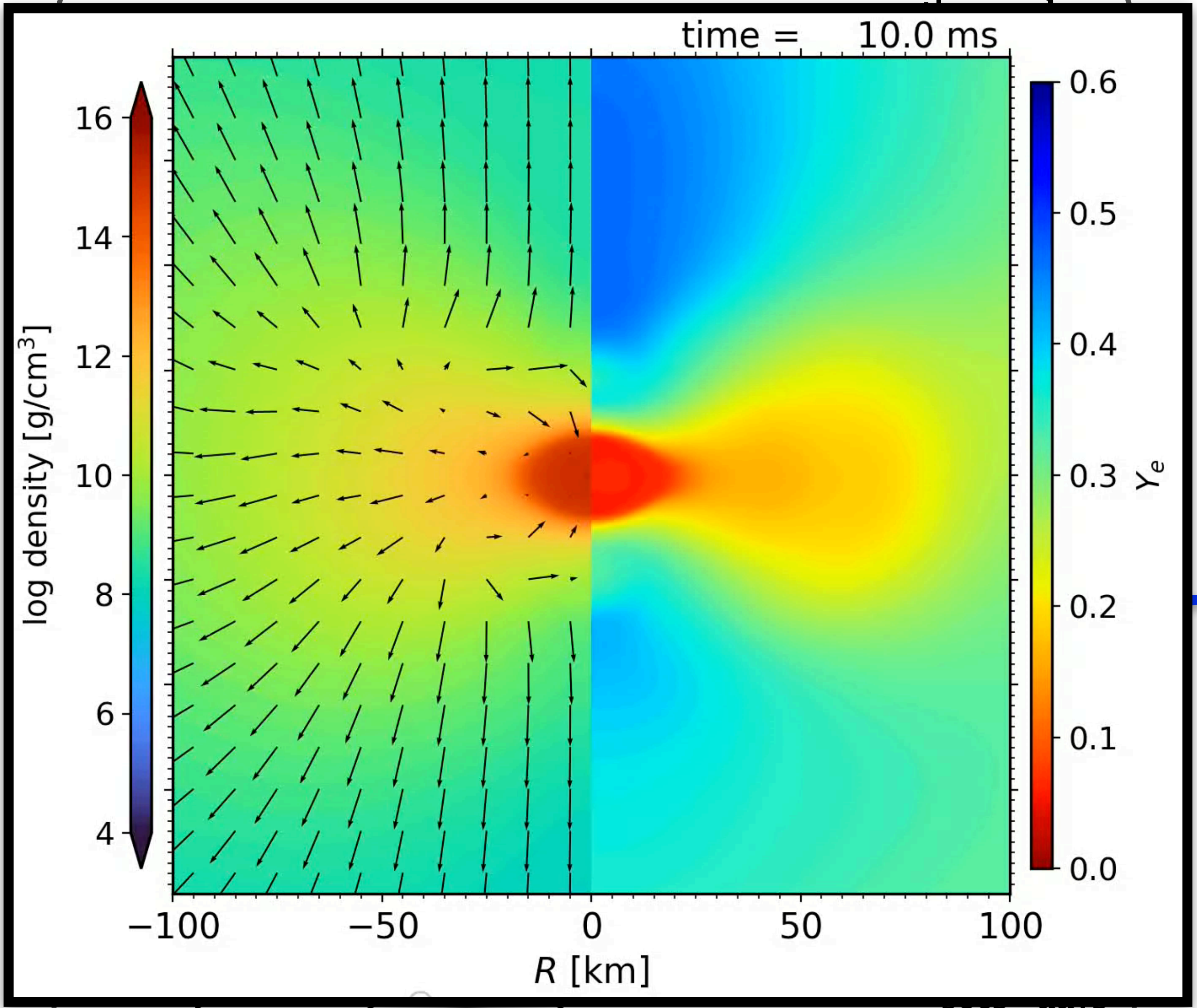
Phases of matter ejection

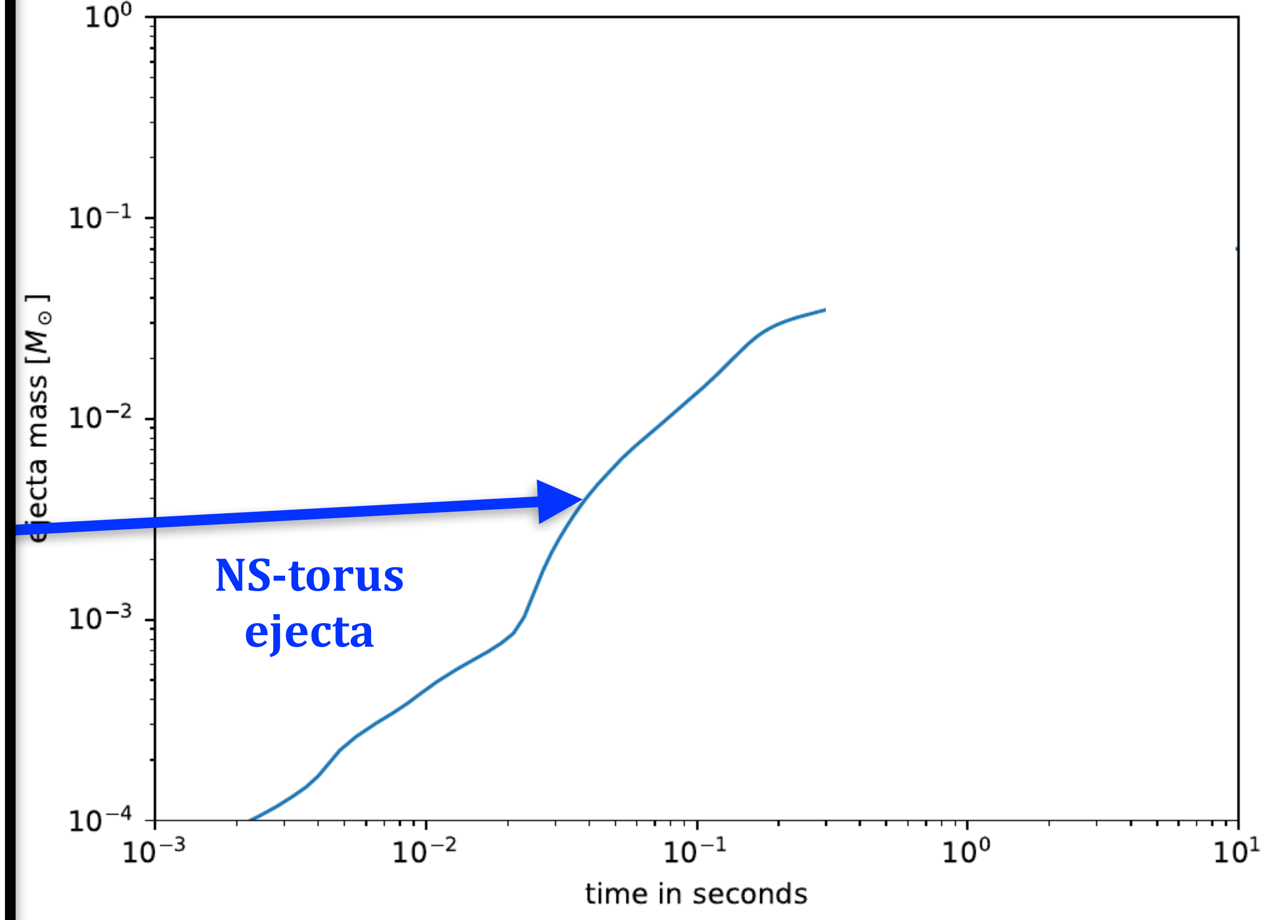




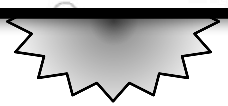
Phases of matter ejection

typical

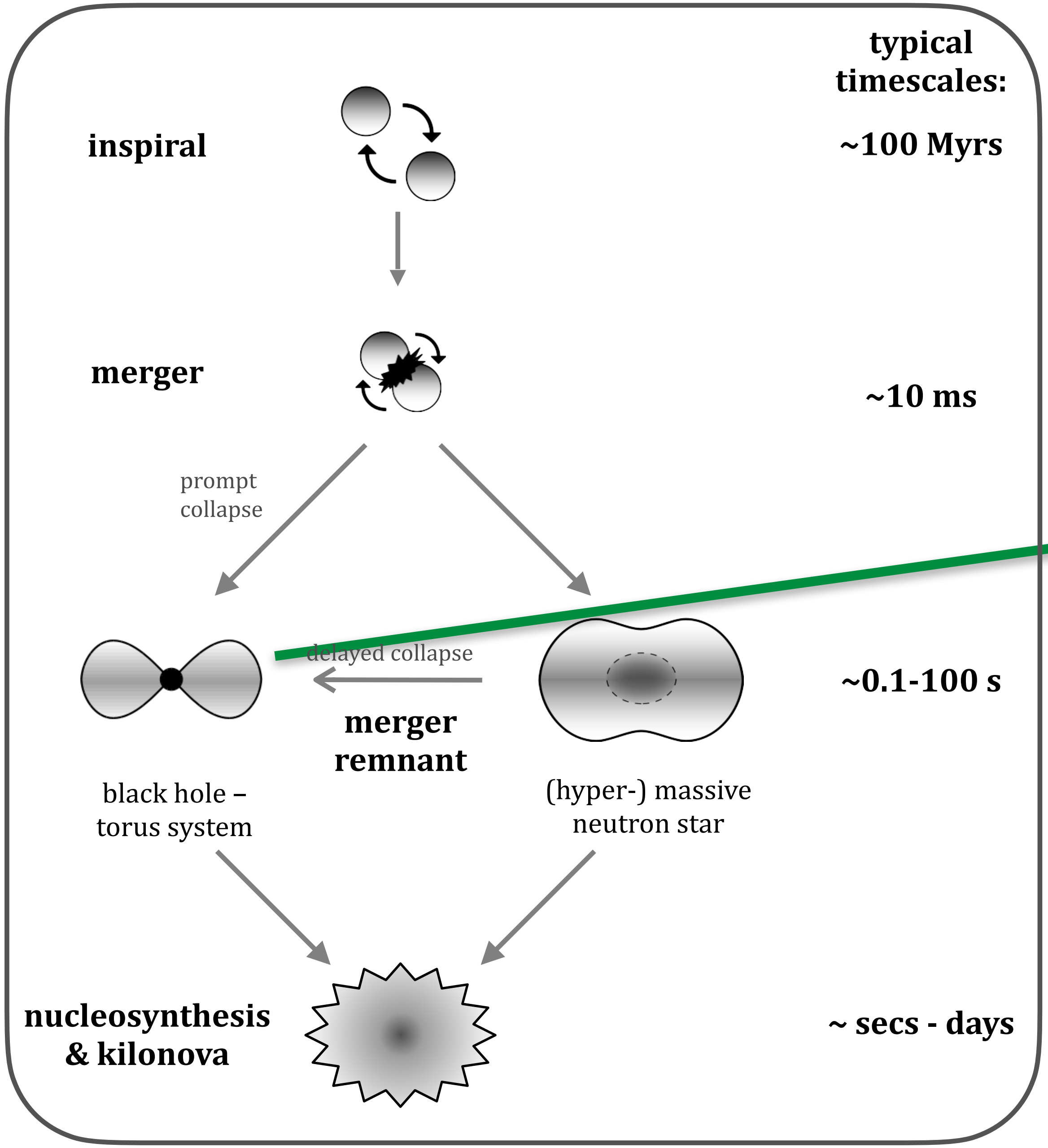


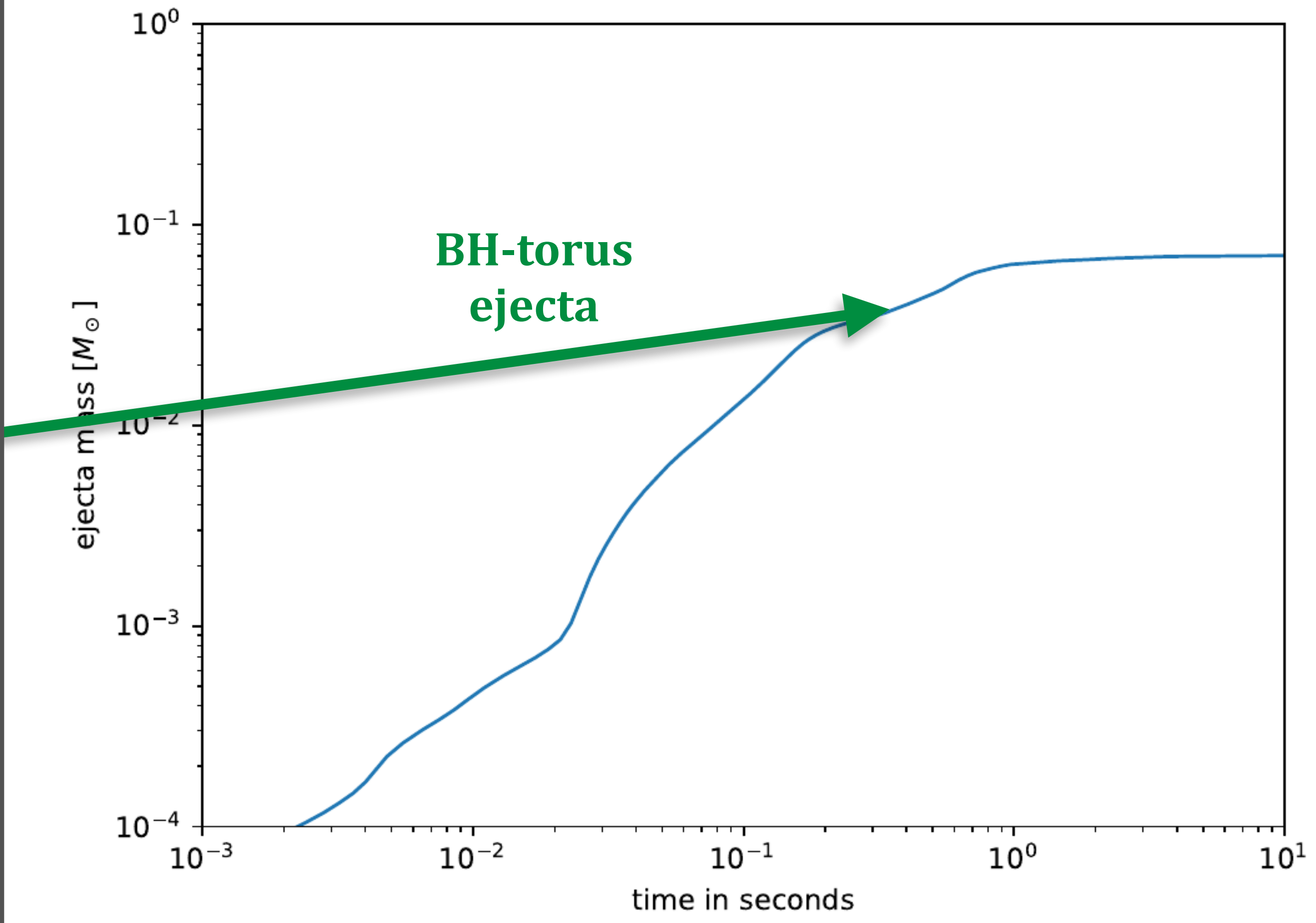


& kilonova



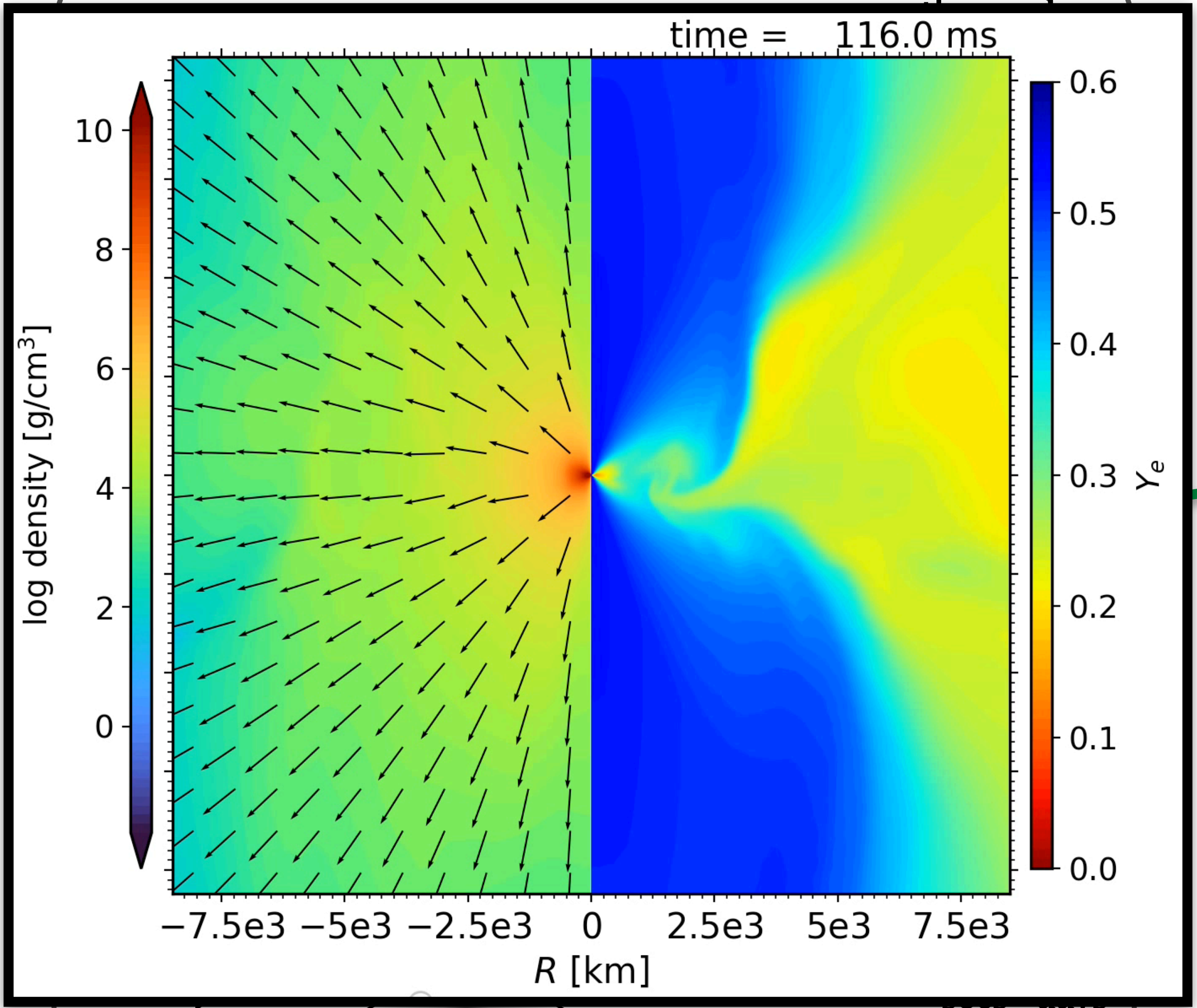
Phases of matter ejection

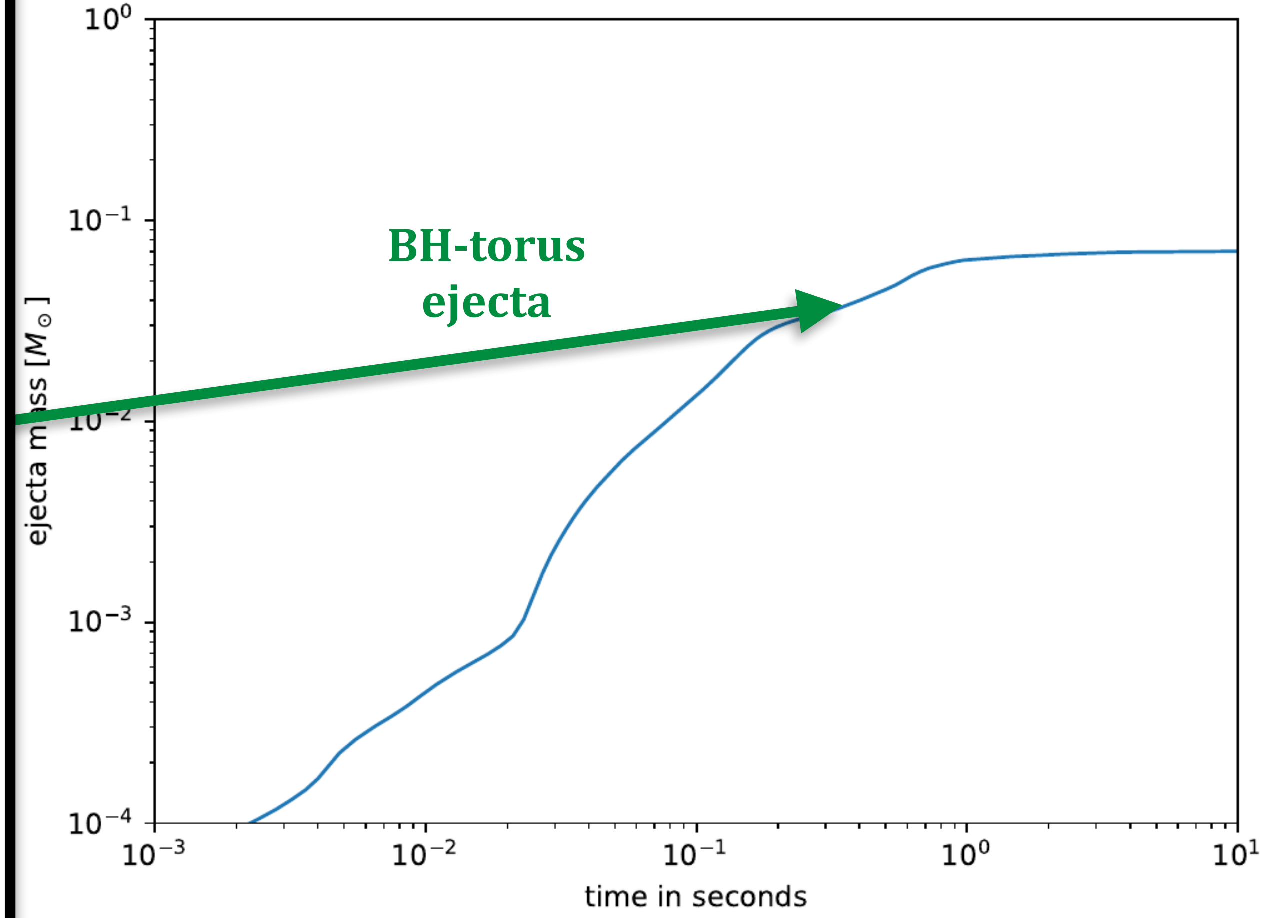




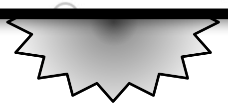
Phases of matter ejection

typical



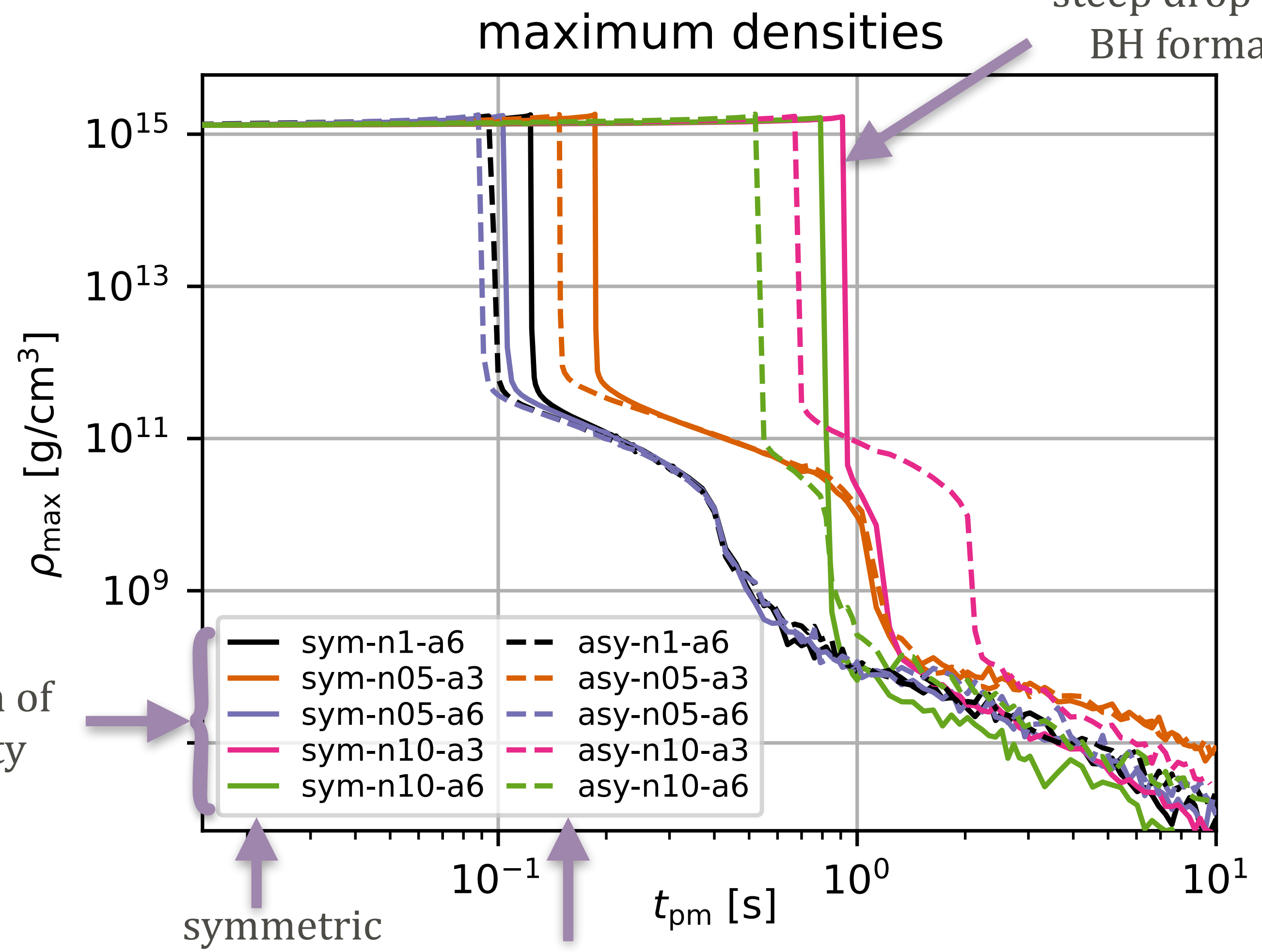


& kilonova



Results 1: NS remnant lifetime until BH formation

steep drop marks BH formation



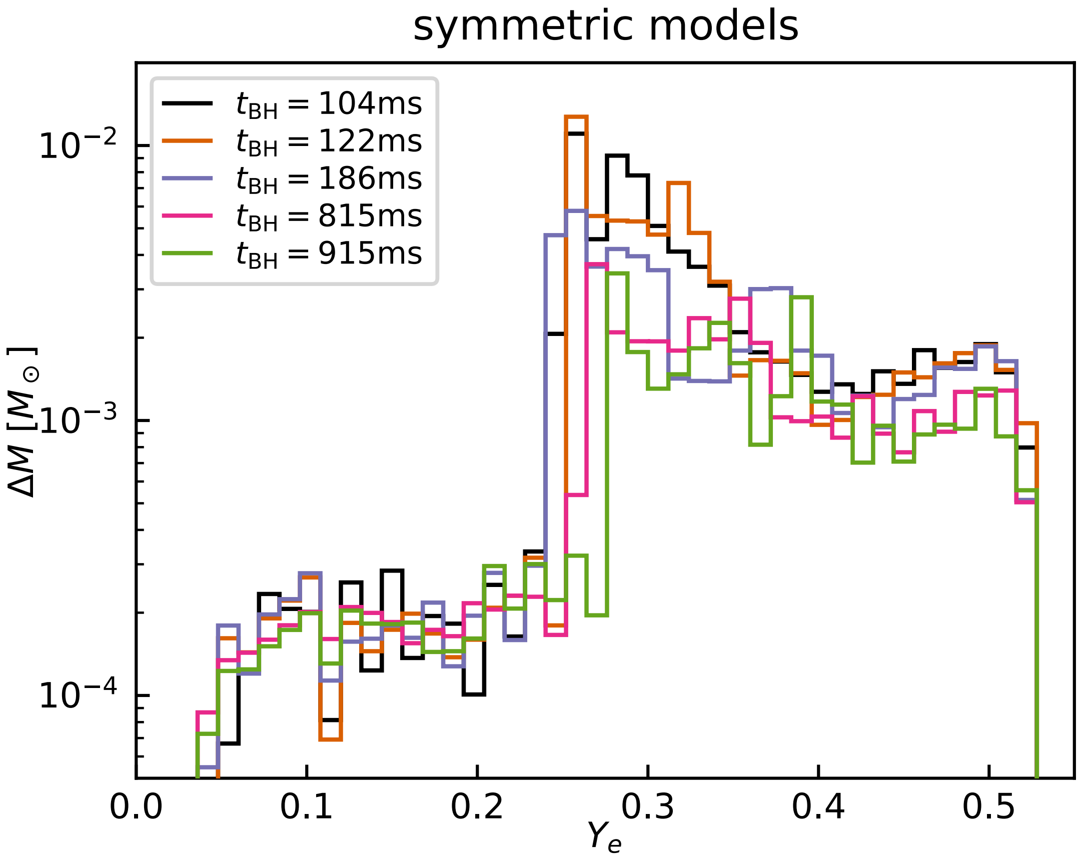
variation of viscosity

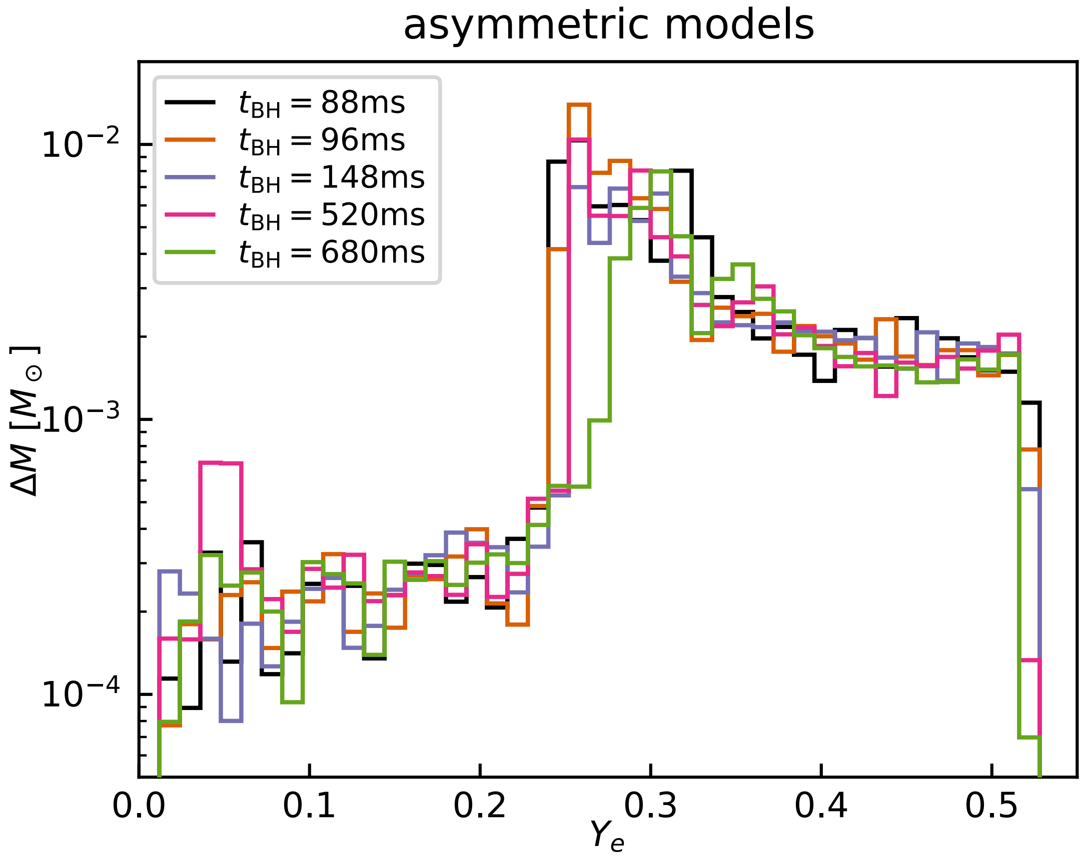
symmetric models ($\frac{M_1}{M_2} = 1$)

asymmetric models ($\frac{M_1}{M_2} = 0.75$)

- asymmetric models collapse earlier than symmetric models (for same viscosity)
- strong sensitivity to viscosity —> good understanding of viscosity required to predict NS lifetime for given progenitor

Results 2: Ejecta composition — all models

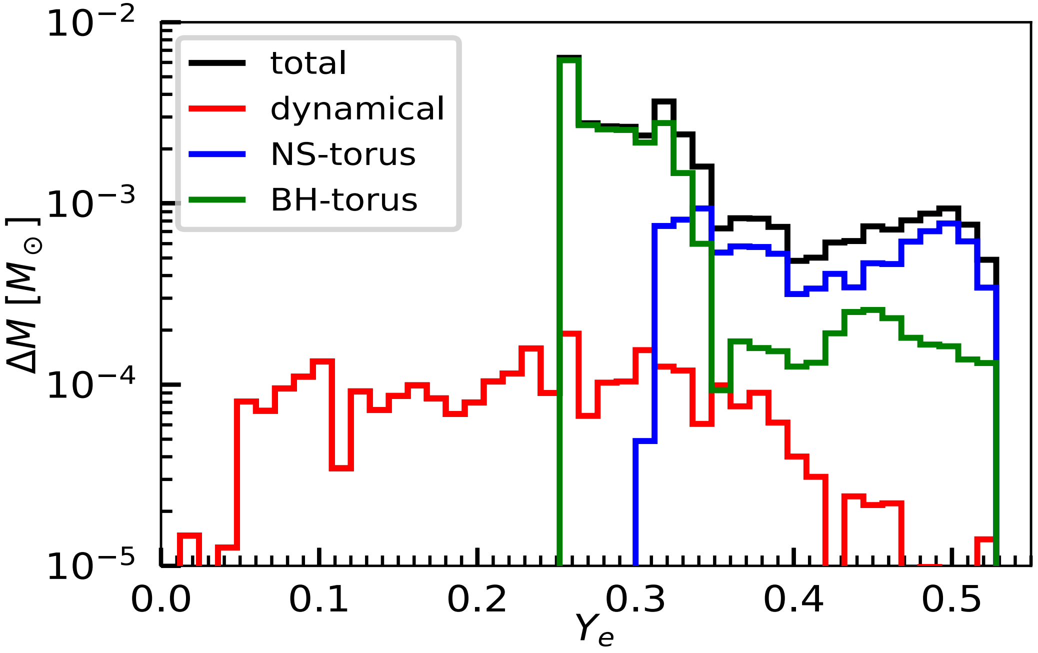




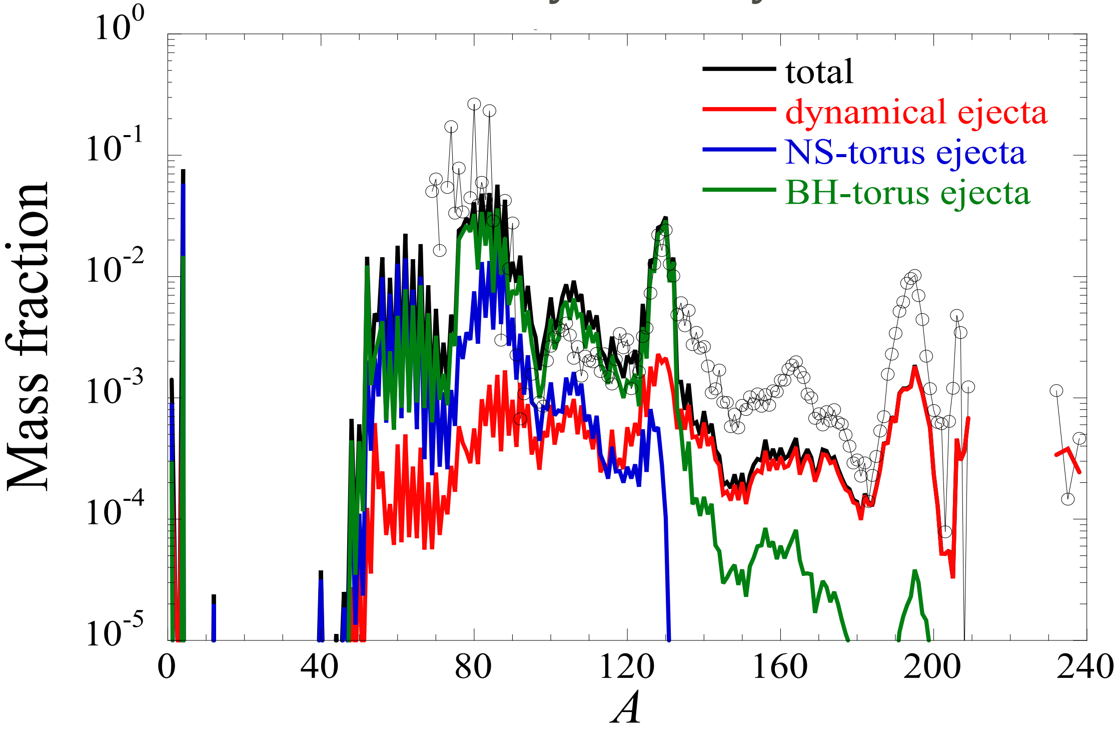
- only mild sensitivity to viscosity and mass ratio
- trend of less neutron-rich matter for longer NS lifetime

Results 2: Ejecta composition — model with t_{BH}~120ms

Y_e histogram

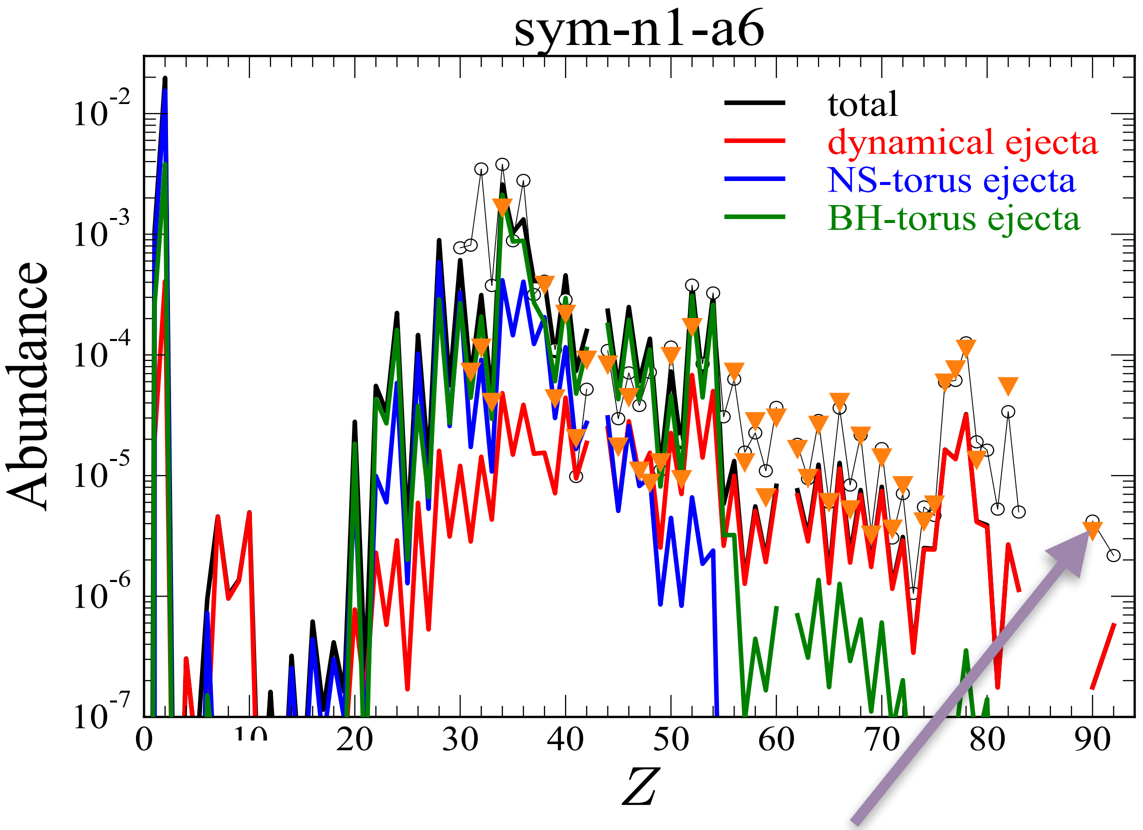


nucleosynthesis yields

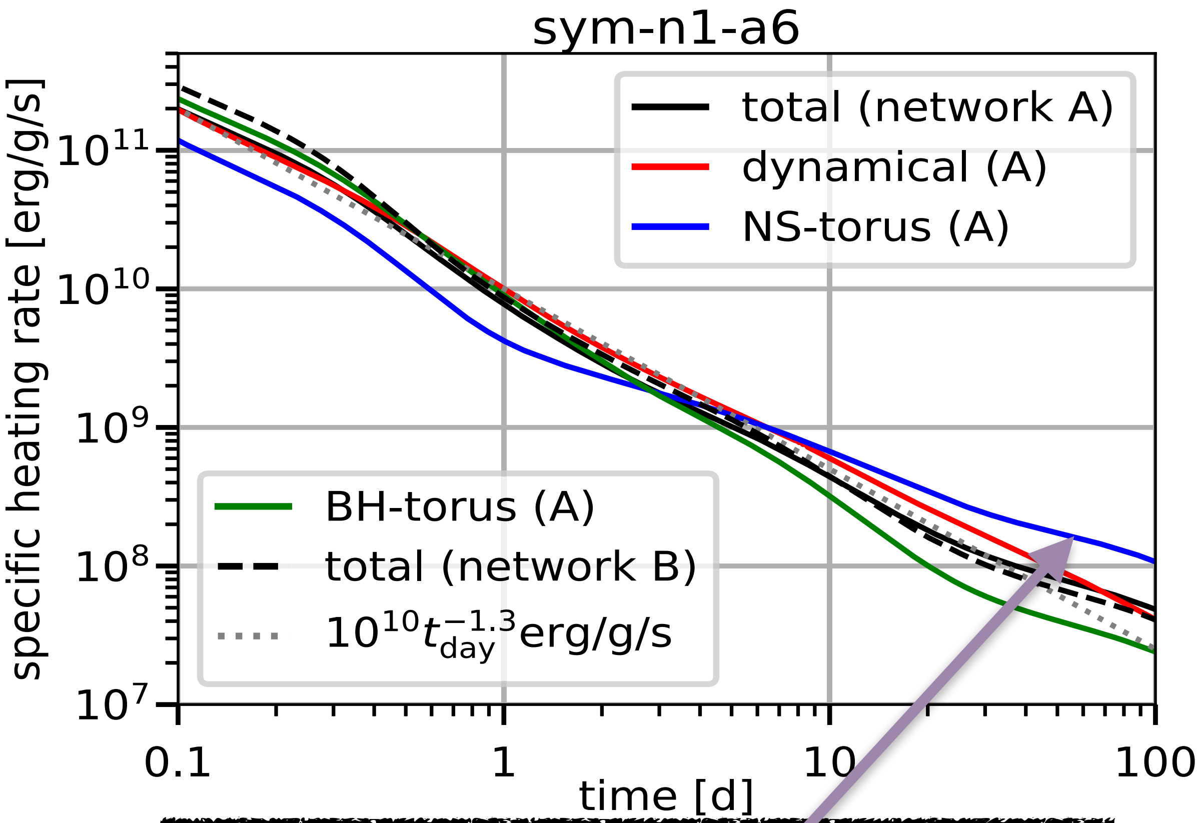


- different Y_e and yields for each ejecta component
- relative contribution of each component only accessible through end-to-end modeling

Results 3: Elemental yields & nuc. heating rate (t_{BH}~120ms model)

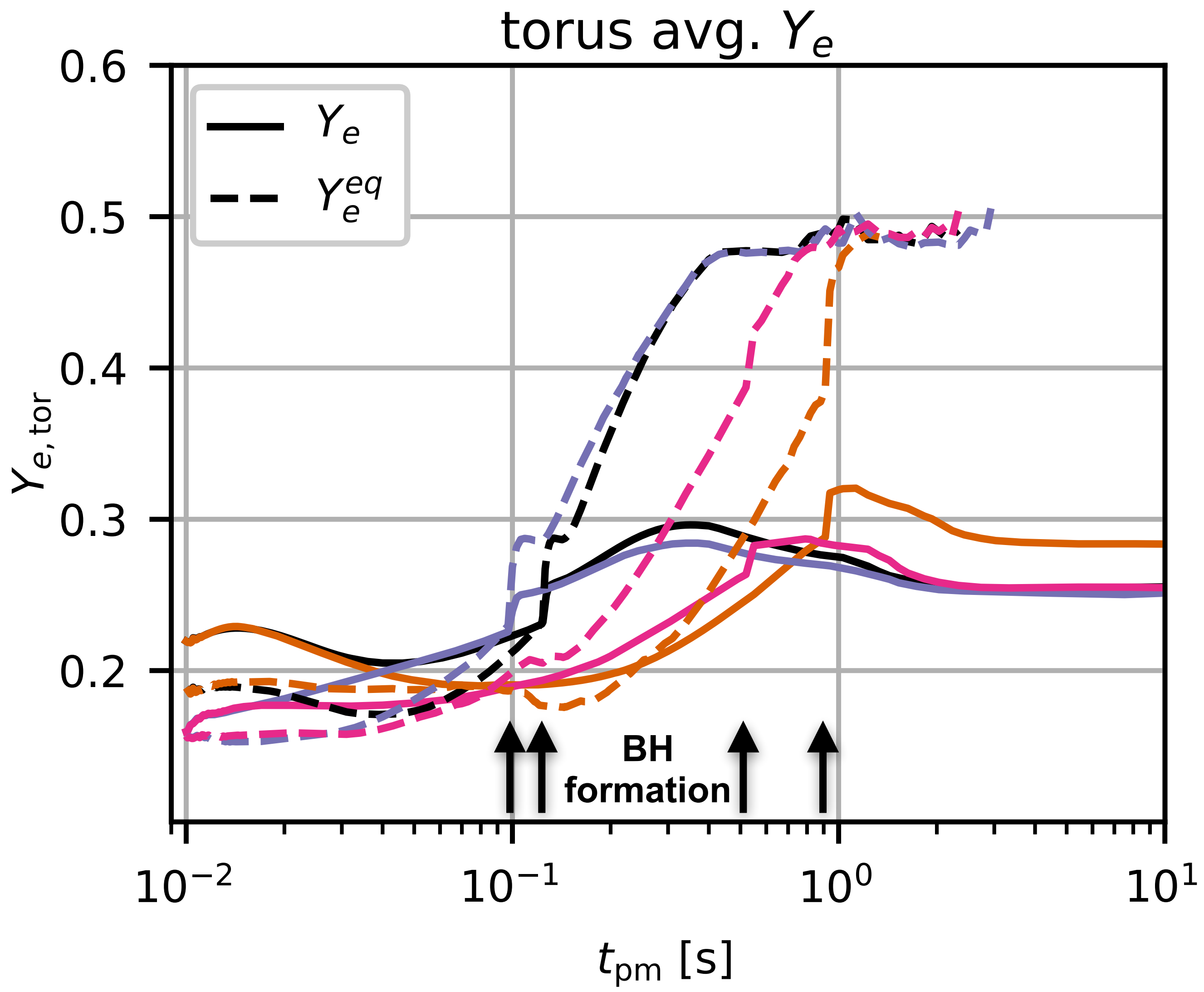


- observed metal-poor star HD 222925 (Roederer '22, *talk by A. Frebel*)
- deficient in Z>55, but reproduce drop at Z<33



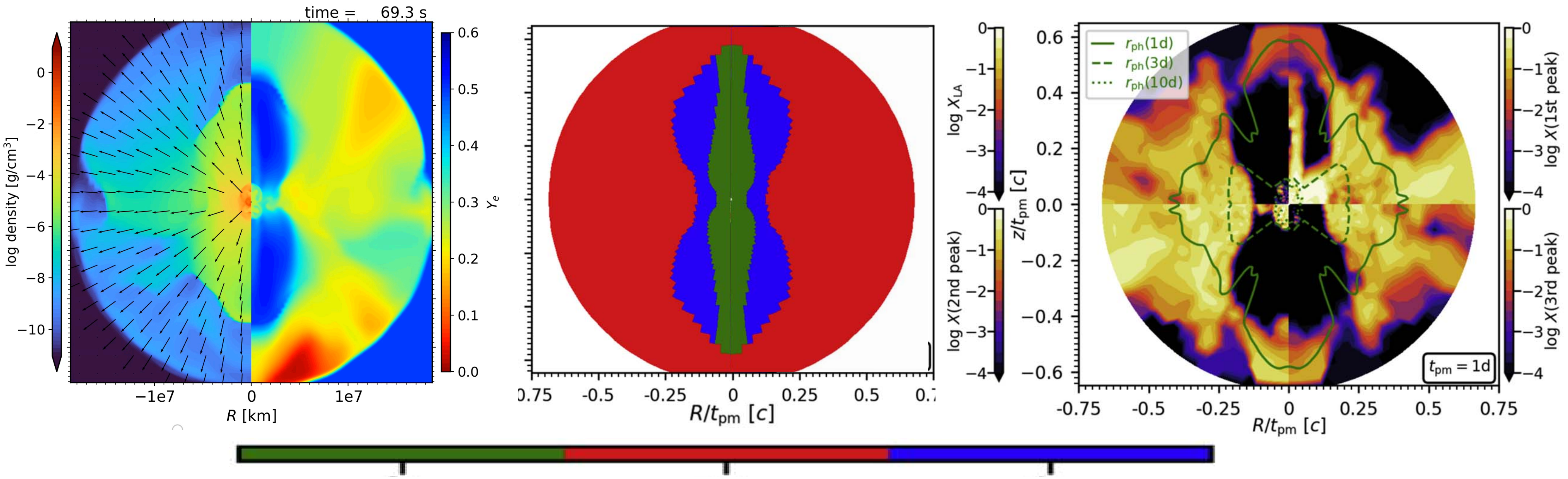
- late-time increase in NS-torus winds from Ni56 and Co56 decay
- **But:** not visible in KN due to inefficient thermalization *(see, however, poster by Max Jacobi)*

Results 4: Torus Y_e @ BH formation



- $Y_e \sim 0.25$–0.3 at birth of BH torus because of expansion before BH formation
- higher than the "canonical" Y_e=0.1 assumed in previous studies
- less efficient r-process in BH-torus ejecta than previously assumed

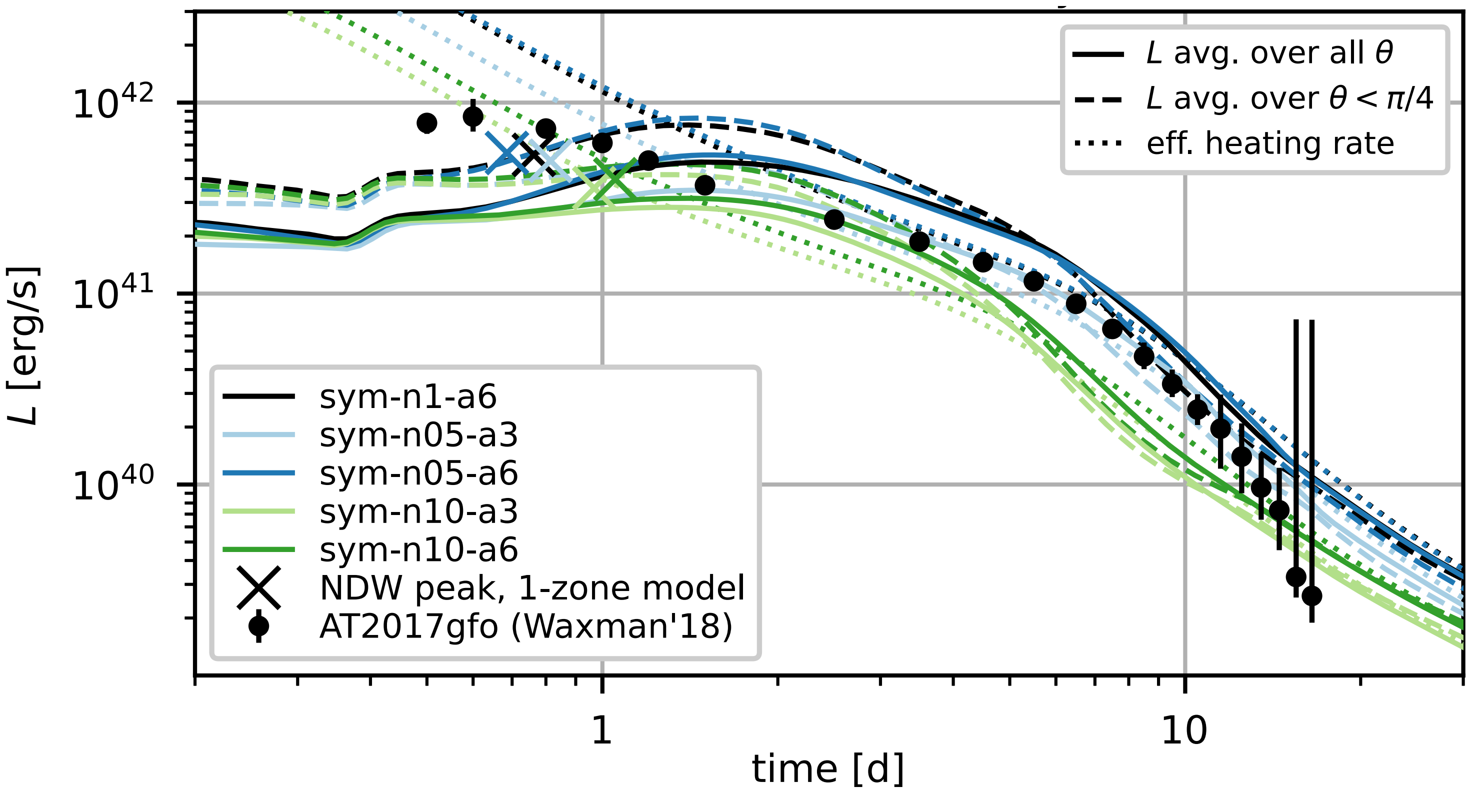
Results 5: Ejecta spatial distribution (t_{BH}~120ms model)



BH-torus ejecta dynamical ejecta NS-torus ejecta

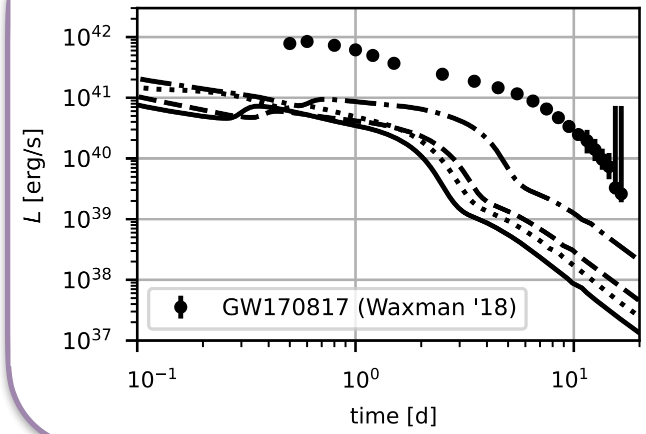
- polar high-Y_e neutrino-driven wind "bubble" surrounded by dynamical ejecta
- slow viscous ejecta
- strongly anisotropic yield distribution

Results 6: KN bolometric light curve



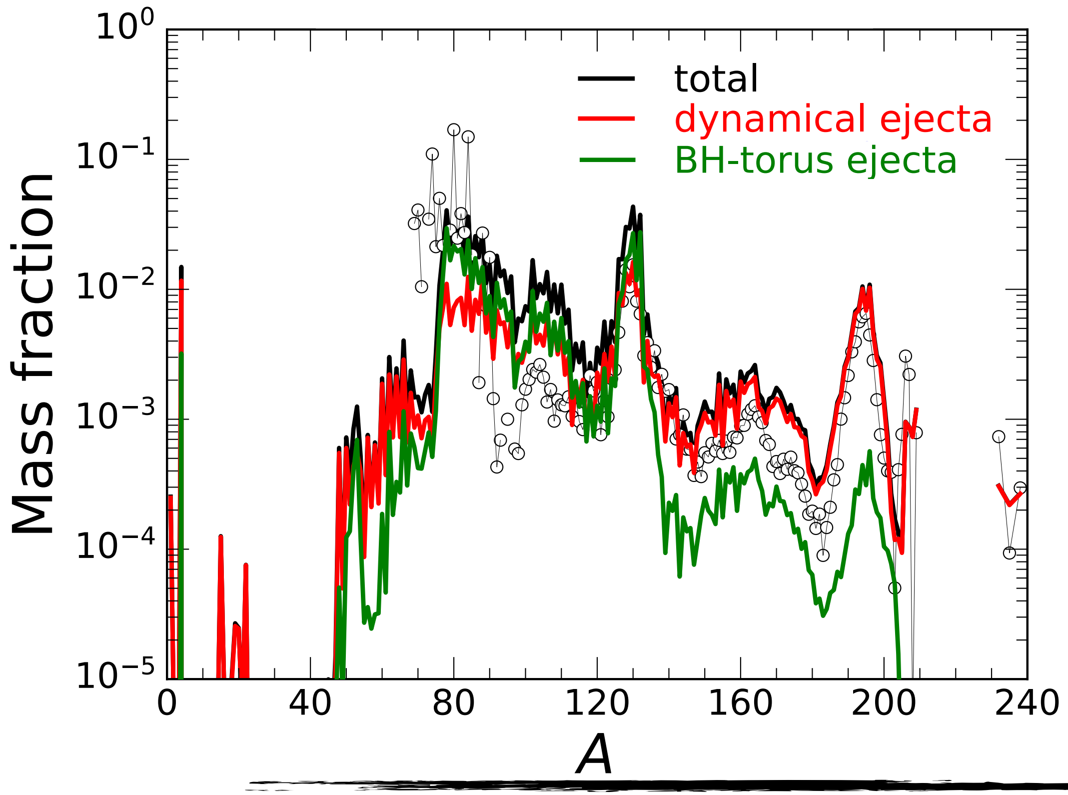
- good agreement with GW170817, except at early times
- may support the idea that GW170817 was a delayed-collapse scenario with massive post-merger ejecta

dynamical ejecta only:

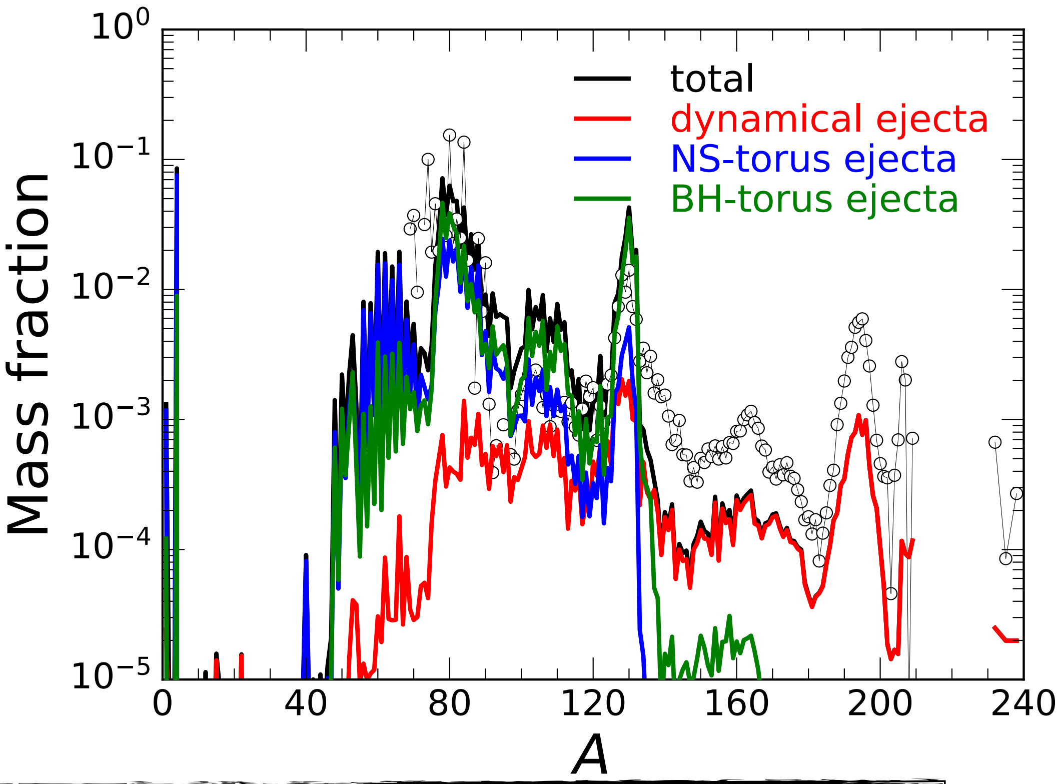


How to get solar-like pattern?

short-lived remnant (10ms):



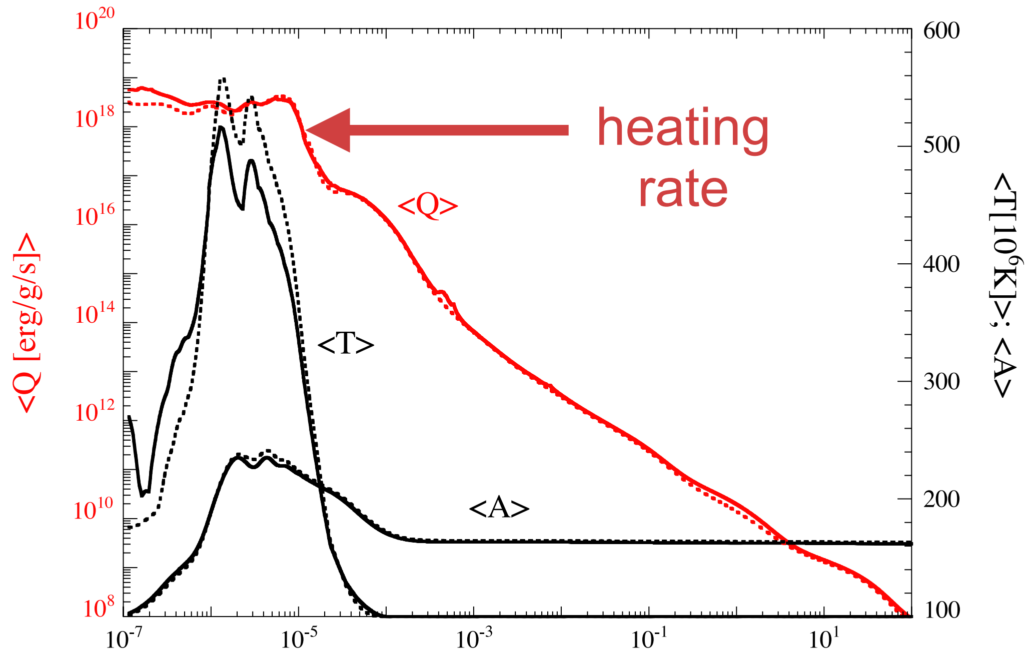
long-lived remnant (~120ms):



- … for short NS remnant lifetime!
- suggests that **short-lived dominate over long-lived** events for GCE
- *similar conclusion as Fujibayashi et al. '22*

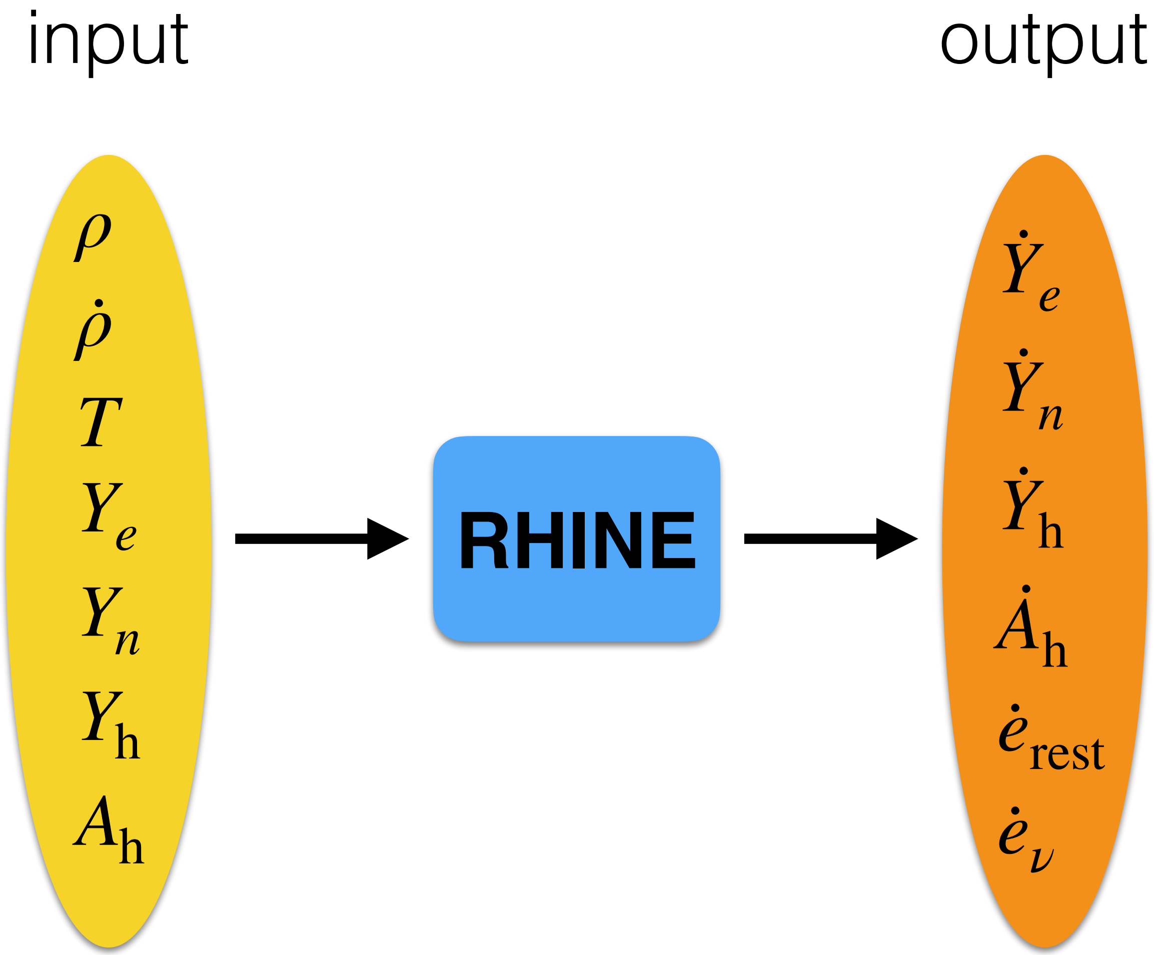
RHINE: R-process Heating Implementation with NEural networks

(Z. Xiong, OJ, G. Martinez-Pinedo, in prep.)



(Goriely+'11)

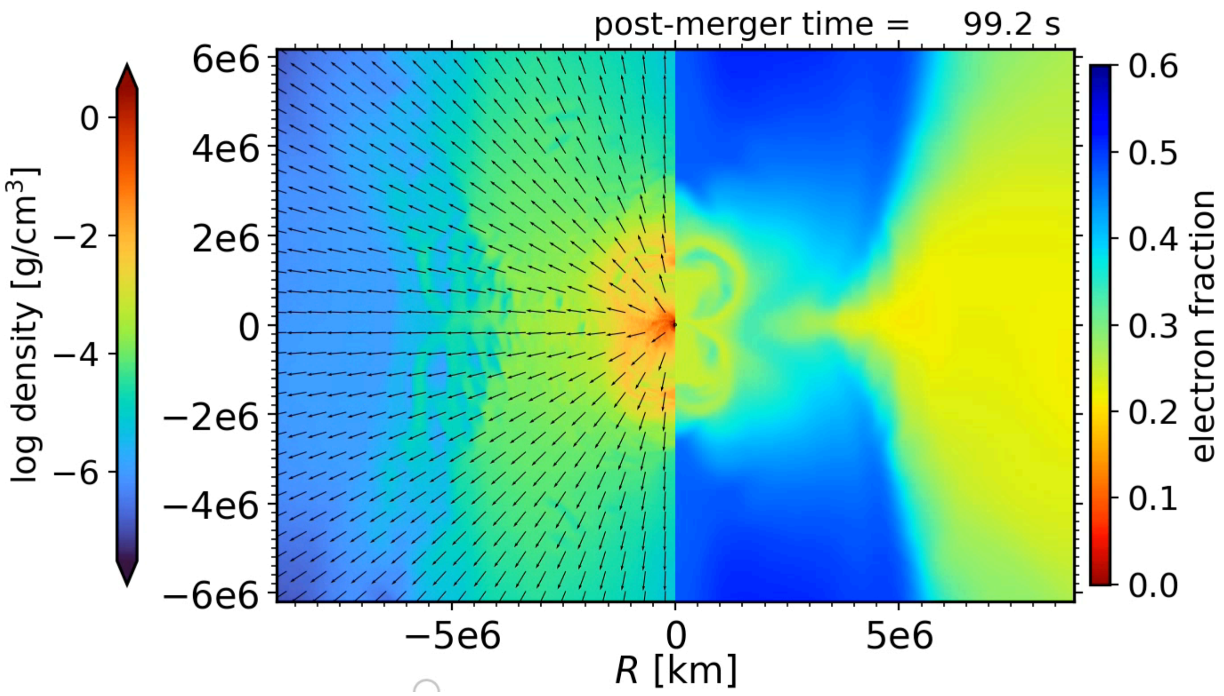
- efficient & accurate scheme to capture r-process heating in hydrodynamic simulations
- use machine learning to predict hydro source terms on-the-fly



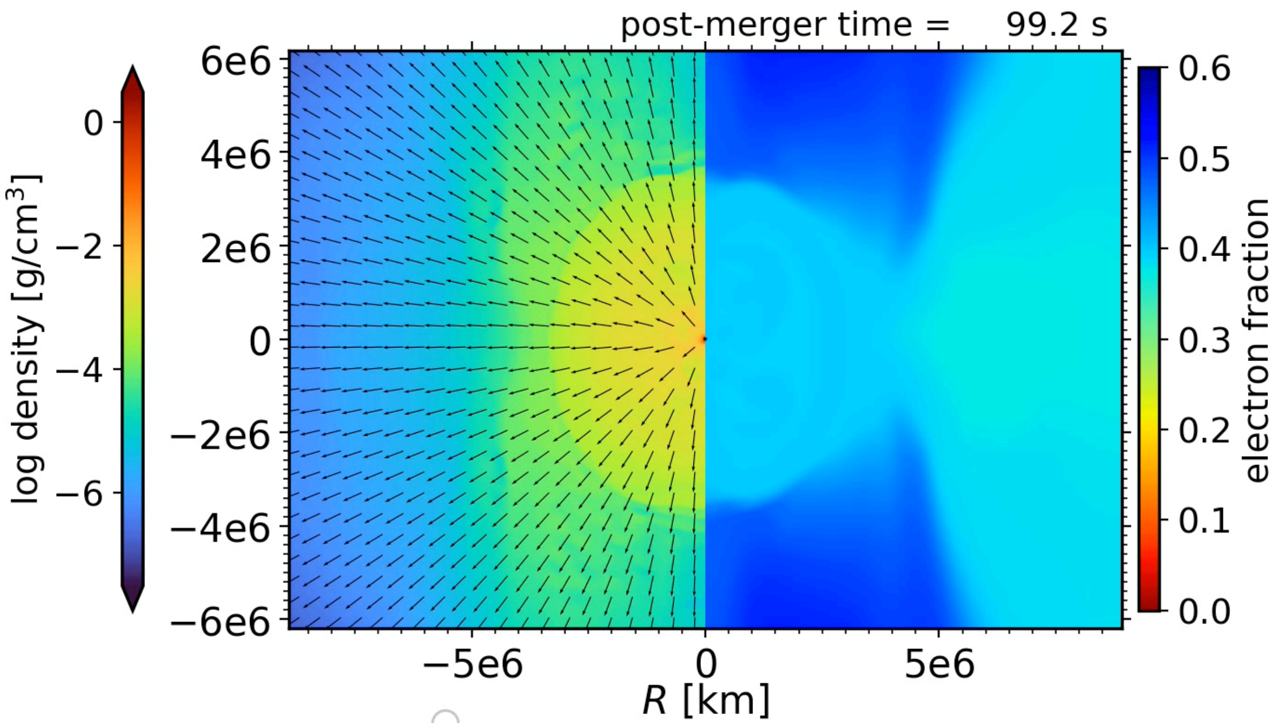
see poster by Z. Xiong!

End-to-end models + RHINE

without RHINE:



with RHINE:



- accelerates BH-torus ejecta from ~0.04c to ~0.08 c
- makes ejecta more spherical (*consistent with Grossman+Rosswog '14*)

Summary

- new end-to-end models capturing all phases of matter ejection
- main results:
  - asymmetric collapse earlier than symmetric merger models
  - reproduce abundance pattern of Sun and of HD222925 reasonably well
  - long-lived events deficient in A>140 —> short-lived events may dominate GCE
  - good, though not perfect, agreement with AT2017gfo supports delayed-collapse scenario in GW170817

- new scheme RHINE to capture r-process heating in hydrodynamic models
  - boosts slow BH-torus ejecta from ~0.04c to ~0.08c