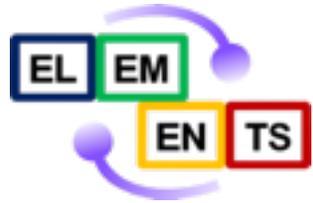




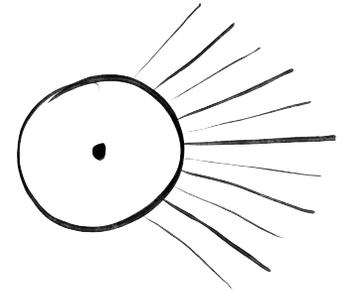
End-to-end modeling of NS mergers: Helium enrichment and r-process heating



Oliver Just

GSI Helmholtzzentrum Darmstadt

MM Astrophysics Workshop, Kyoto, Feb. 6th



ERC synergy
HeavyMetal

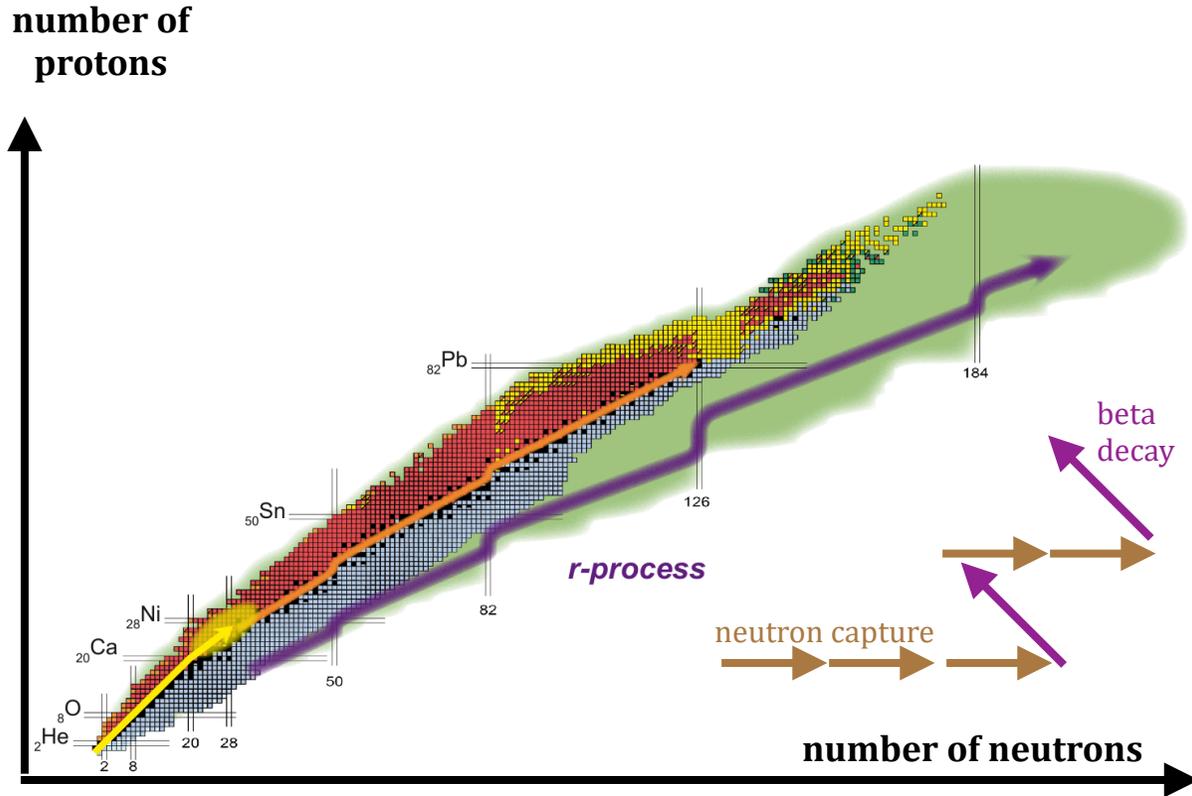


with: A. Bauswein, G. Martinez-Pinedo, S. Goriely, T. Janka, Z. Xiong, M. R. Wu, S. Abbar, I. Tamborra, V. Vijayan, C. Collins, L. Shingles, S. Sim, A. Snepken, D. Watson, R. Damgaard, M. McCann, S. Nagataki, H. Ito, M. Aloy, M. Obergaullinger, ... more

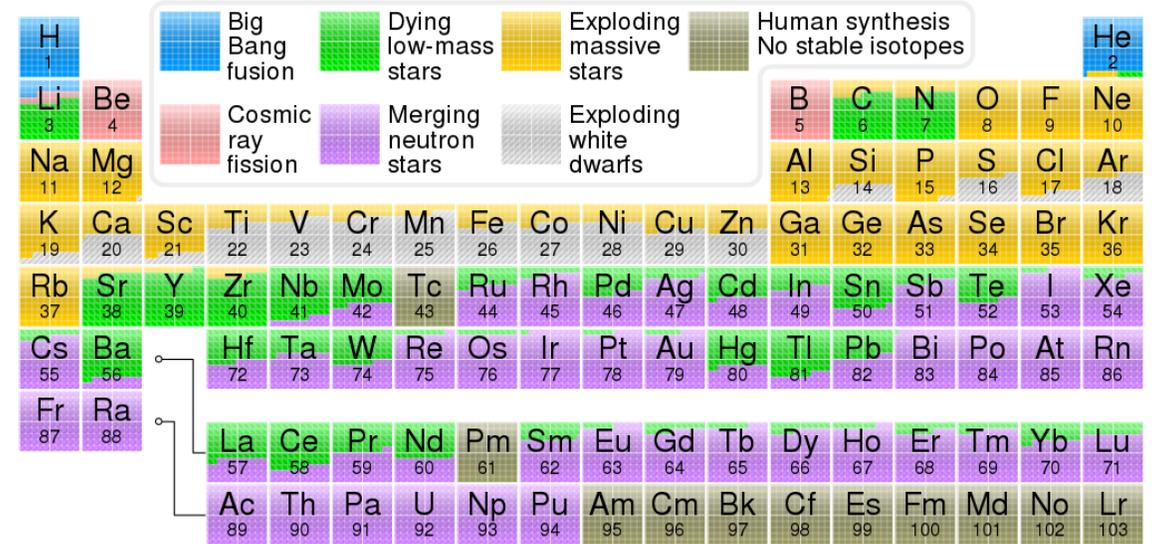


European Research Council
Established by the European Commission

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



suggested sites of origin



Main condition:

high neutron density = low electron fraction Y_e

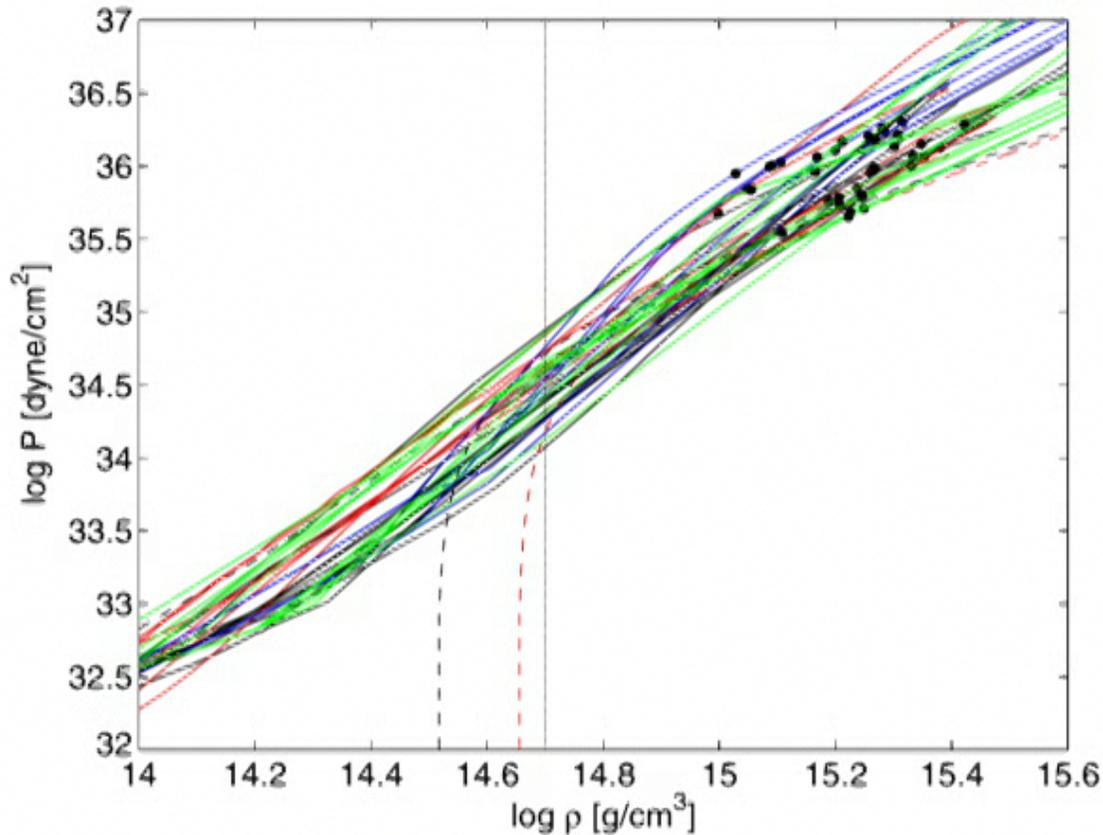
$$Y_e = \frac{n_{\text{proton}}}{n_{\text{neutron}} + n_{\text{proton}}} \lesssim 0.5$$

-NSMs are the **only confirmed site** so far, but are they main site?

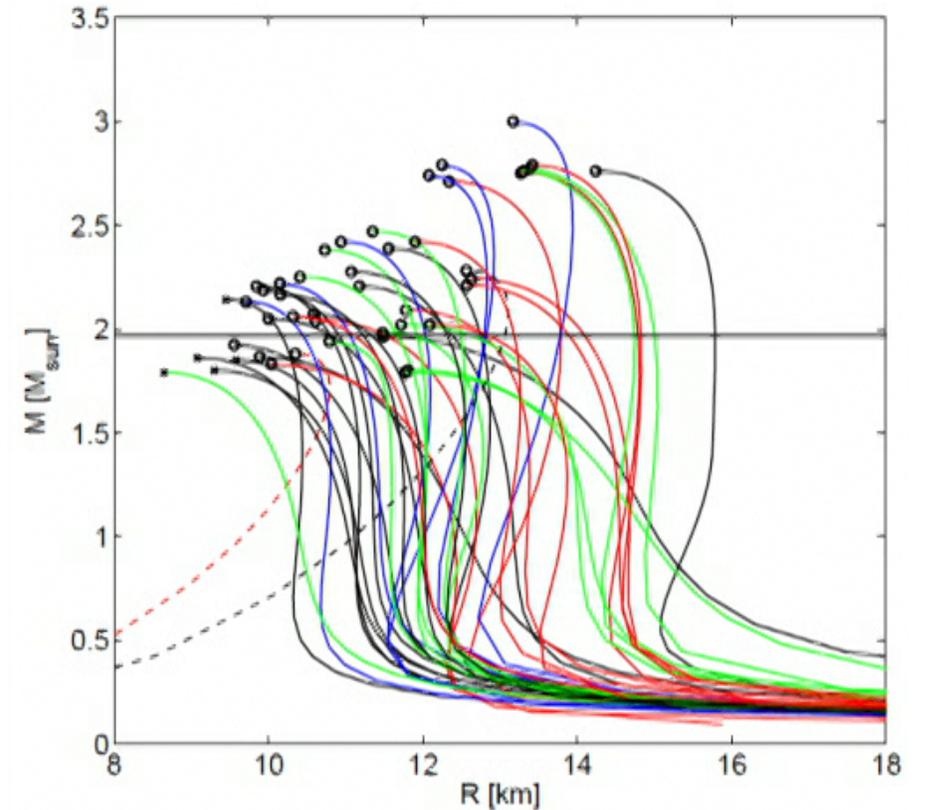
-other suggested sites: core-collapse supernovae, magneto-rotational SNe, collapsars, **magnetar giant flares**

What do NSMs tell us about the nuclear equation of state (EOS)?

possible nuclear equation of states



mass-radius relationships
of cold, non-rotating neutron stars

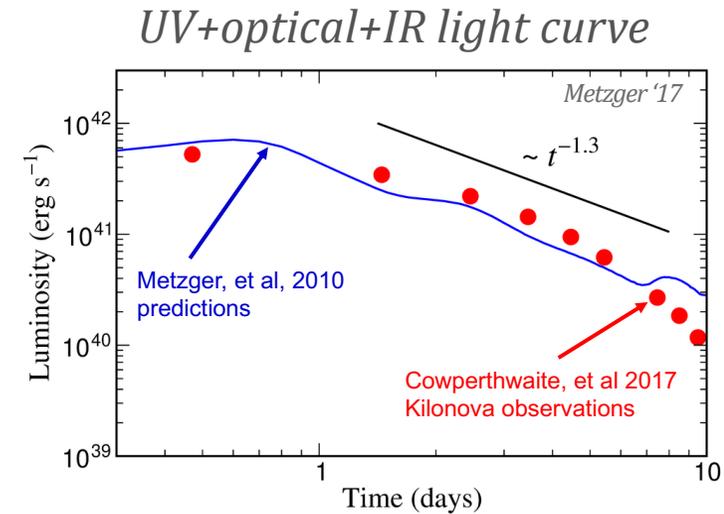
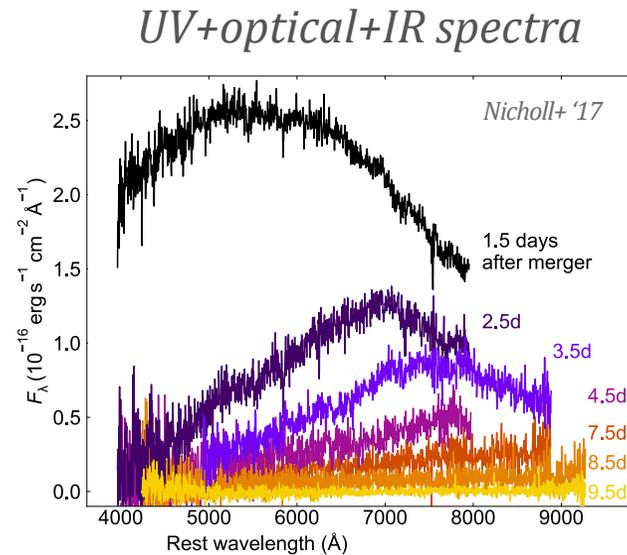
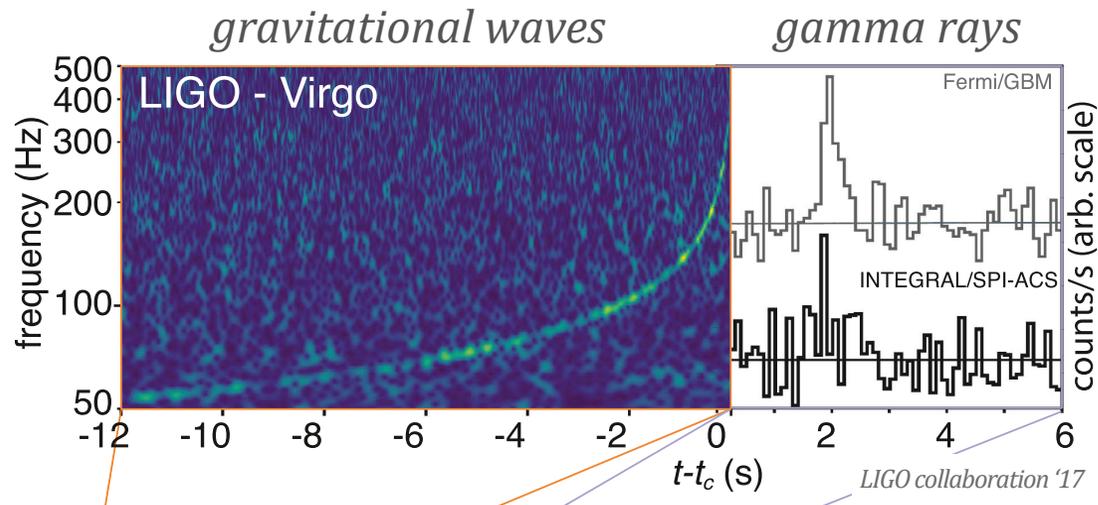


(plots by A. Bauswein)

- ▶ softer (stiffer) EOS \Leftrightarrow smaller (larger) neutron star
- ▶ softer (stiffer) EOS \Leftrightarrow shorter (longer) lifetime of HMNS merger remnant

GW170817 - the first direct observation of a NS merger

(on August 17th, 2017)



Many open questions remain:

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

Importance + challenges of post-merger modeling

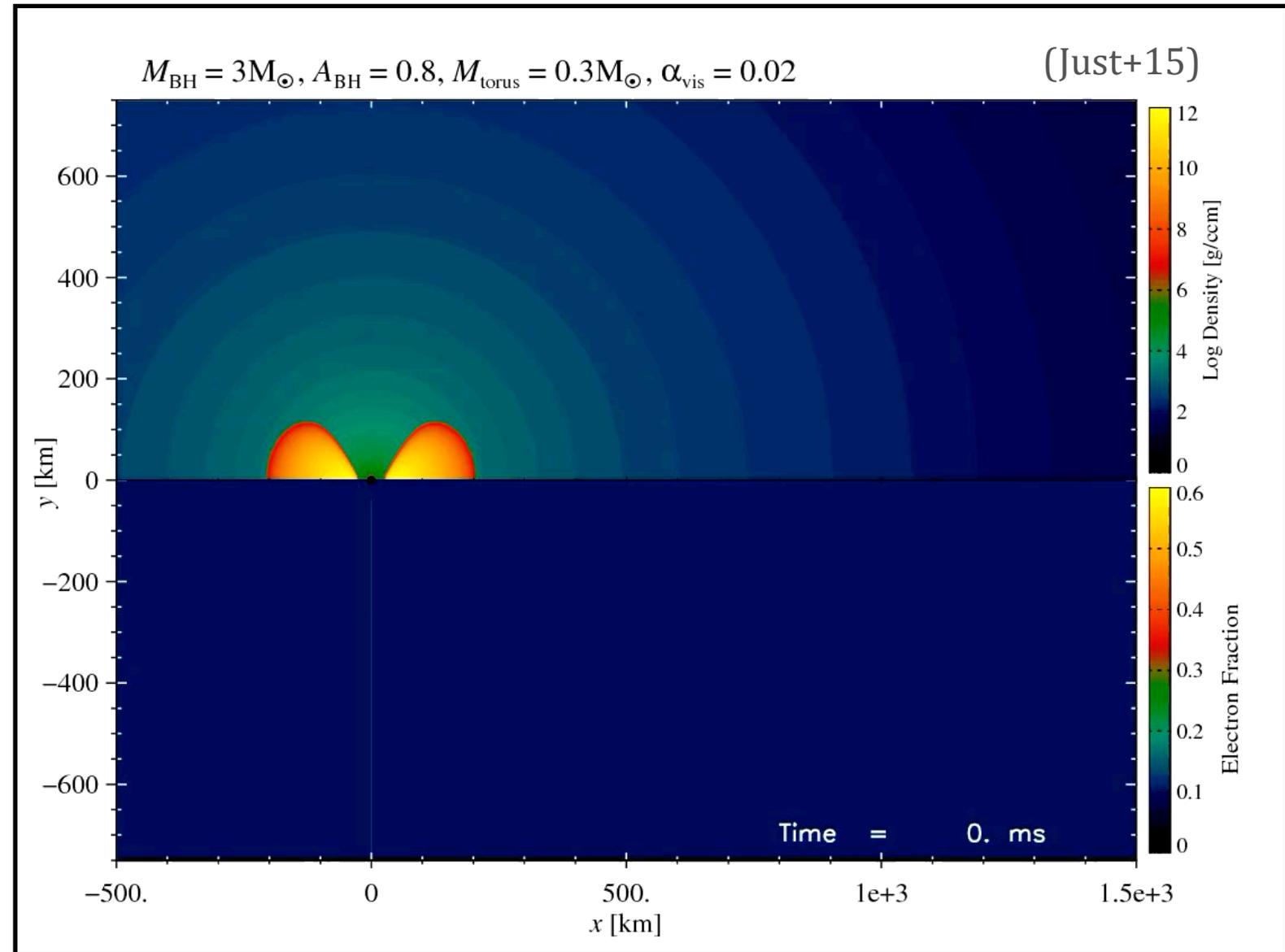
- ▶ 10-40% of disk can become (moderately) neutron-rich ejecta

- ▶ **Challenges:**

- ▶ combination of GR, neutrino transport, (MHD) turbulence
- ▶ large range of relevant scales

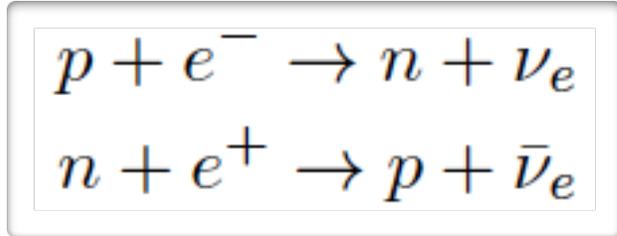
- ▶ **Common approximations:**

- ▶ M1 or leakage neutrino treatment
- ▶ simplified gravity
- ▶ Shakura-Sunyaev effective turbulent viscosity



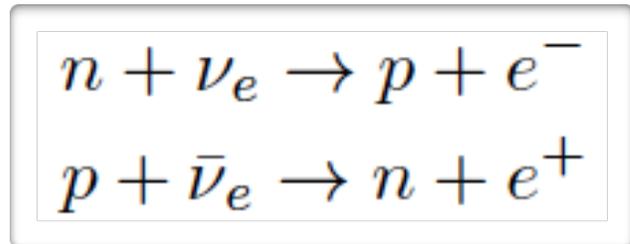
(see also Fernandez+13, Perego+14, Siegel+17, Fujibayashi+18, Miller+19, ...)

Ye equilibria of beta-processes



$$\lambda_{e^-} = K_\beta \int_0^\infty \epsilon^2 F_{e^-}(\epsilon_+) \epsilon_+^2 \sqrt{1 - \left(\frac{m_e c^2}{\epsilon_+}\right)^2} d\epsilon$$

$$\lambda_{e^+} = K_\beta \int_{\epsilon_0}^\infty \epsilon^2 F_{e^+}(\epsilon_-) \epsilon_-^2 \sqrt{1 - \left(\frac{m_e c^2}{\epsilon_-}\right)^2} d\epsilon$$



$$\lambda_{\nu_e} = K_\beta \int_0^\infty \epsilon^2 F_{\nu_e}(\epsilon) (1 - F_{e^-}(\epsilon_+)) \epsilon_+^2 \sqrt{1 - \left(\frac{m_e c^2}{\epsilon_+}\right)^2} d\epsilon$$

$$\lambda_{\bar{\nu}_e} = K_\beta \int_{\epsilon_0}^\infty \epsilon^2 F_{\bar{\nu}_e}(\epsilon) (1 - F_{e^+}(\epsilon_-)) \epsilon_-^2 \sqrt{1 - \left(\frac{m_e c^2}{\epsilon_-}\right)^2} d\epsilon$$

change of Y_e :

$$\frac{dY_e}{dt} = (\lambda_{e^+} + \lambda_{\nu_e}) Y_n - (\lambda_{e^-} + \lambda_{\bar{\nu}_e}) Y_p$$

emission equilibrium:

$$\lambda_{e^+} Y_n - \lambda_{e^-} Y_p \Big|_{\rho, T, Y_e^{\text{eq,em}}} = 0$$

(full) equilibrium:

$$(\lambda_{e^+} + \lambda_{\nu_e}) Y_n - (\lambda_{e^-} + \lambda_{\bar{\nu}_e}) Y_p \Big|_{\rho, T, Y_e^{\text{eq}}} = 0,$$

absorption equilibrium:

$$\lambda_{\nu_e} Y_n - \lambda_{\bar{\nu}_e} Y_p \Big|_{\rho, T, Y_e^{\text{eq,abs}}} = 0,$$

Neutrino absorption equilibrium: $Y_e^{eq,abs}$

$$Y_e^{eq,abs} \sim \left(1 + \frac{\langle \epsilon_{\bar{\nu}_e}^2 \rangle n_{\bar{\nu}_e}}{\langle \epsilon_{\nu_e}^2 \rangle n_{\nu_e}} \right)^{-1} \sim \left(1 + \frac{\langle \epsilon_{\bar{\nu}_e}^2 \rangle L_{N,\bar{\nu}_e}}{\langle \epsilon_{\nu_e}^2 \rangle L_{N,\nu_e}} \right)^{-1} \sim \mathbf{0.4 \dots 0.6 \text{ for typical conditions}}$$

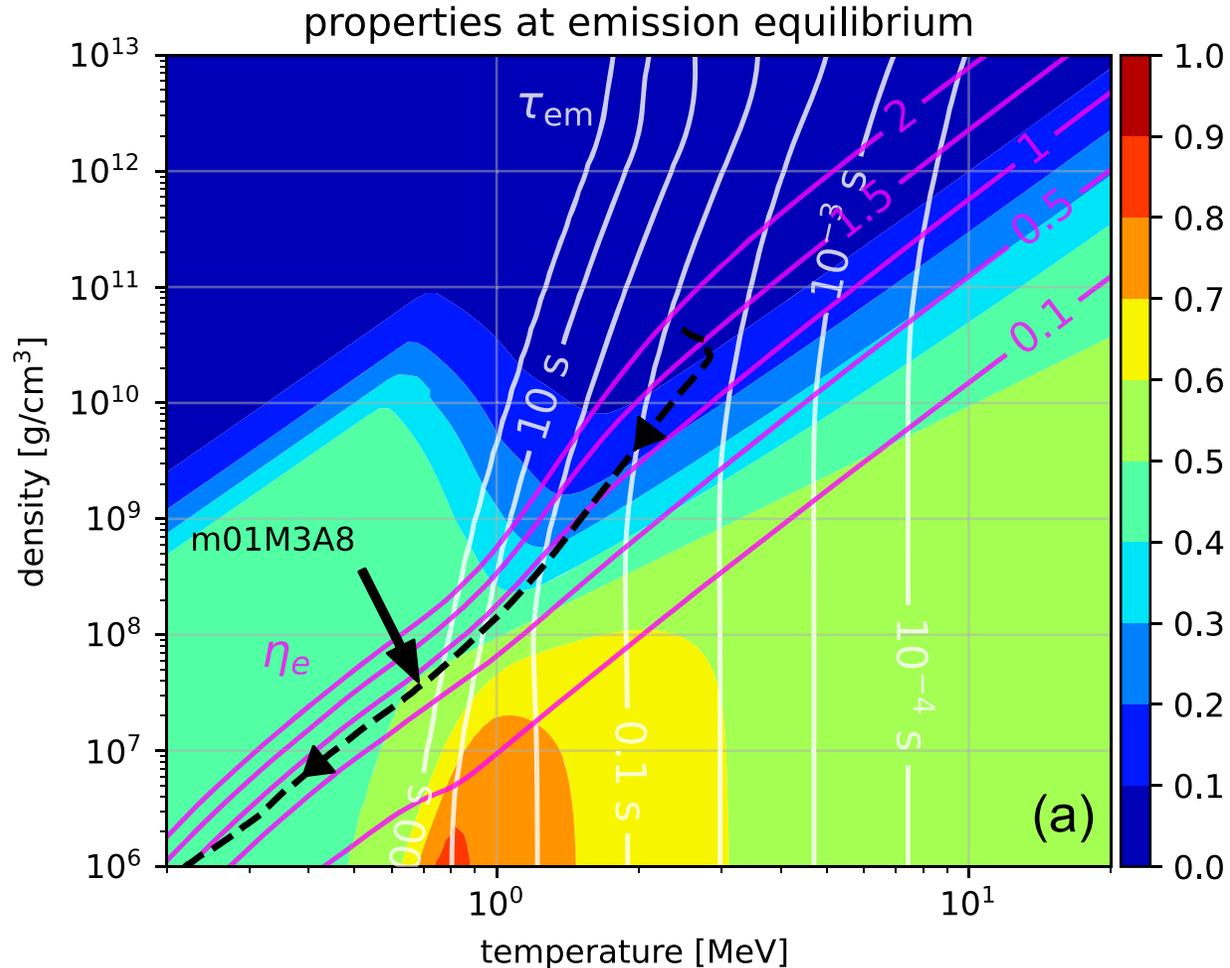
absorption equilibrium:

$$\lambda_{\nu_e} Y_n - \lambda_{\bar{\nu}_e} Y_p \Big|_{\rho, T, Y_e^{eq,abs}} = 0,$$

Neutrino emission equilibrium: $Y_e^{eq,em}$

emission equilibrium:

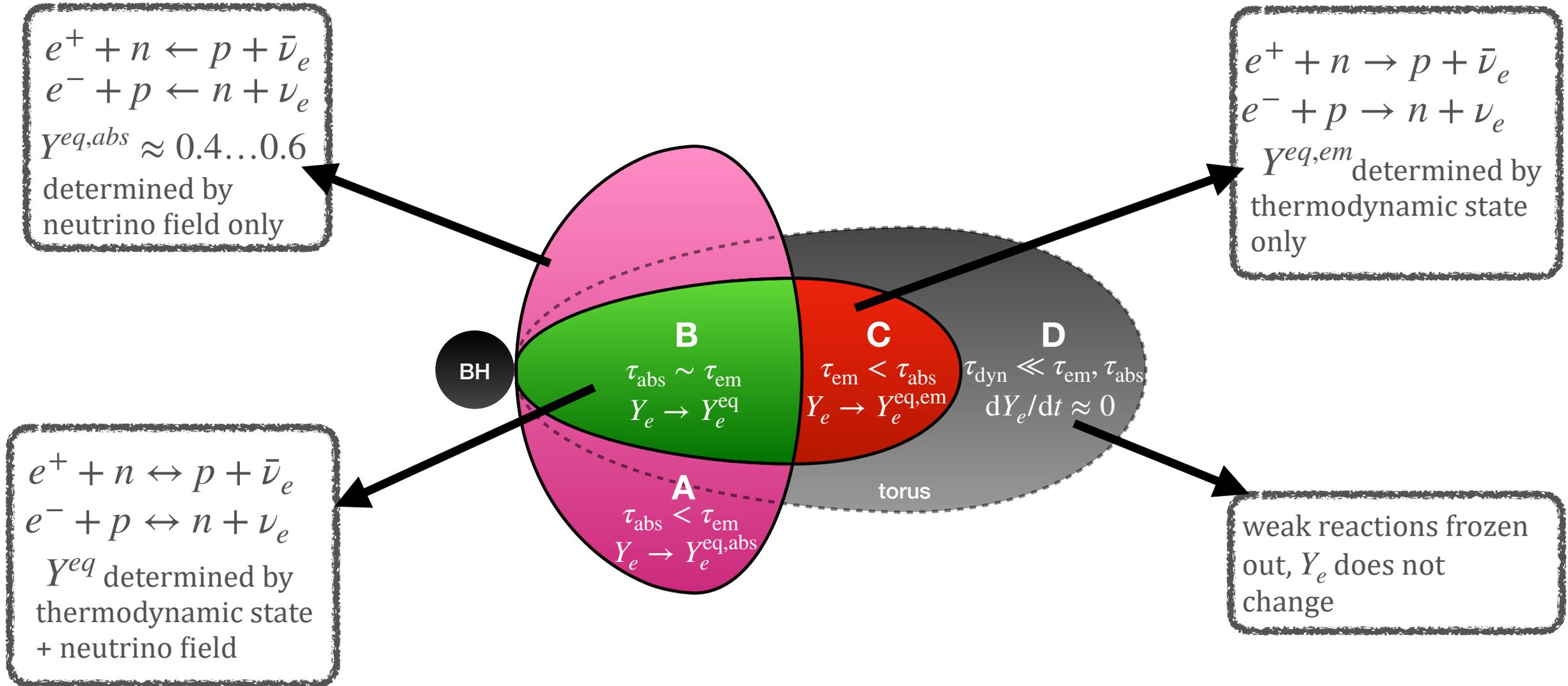
$$\lambda_{e+Y_n} - \lambda_{e-Y_p} \Big|_{\rho, T, Y_e^{eq,em}} = 0$$



- ▶ $Y_e^{eq,em}$ increases when disk expands (decreasing density and temperatures)
- ▶ freeze-out once weak timescales \gg dynamical timescales

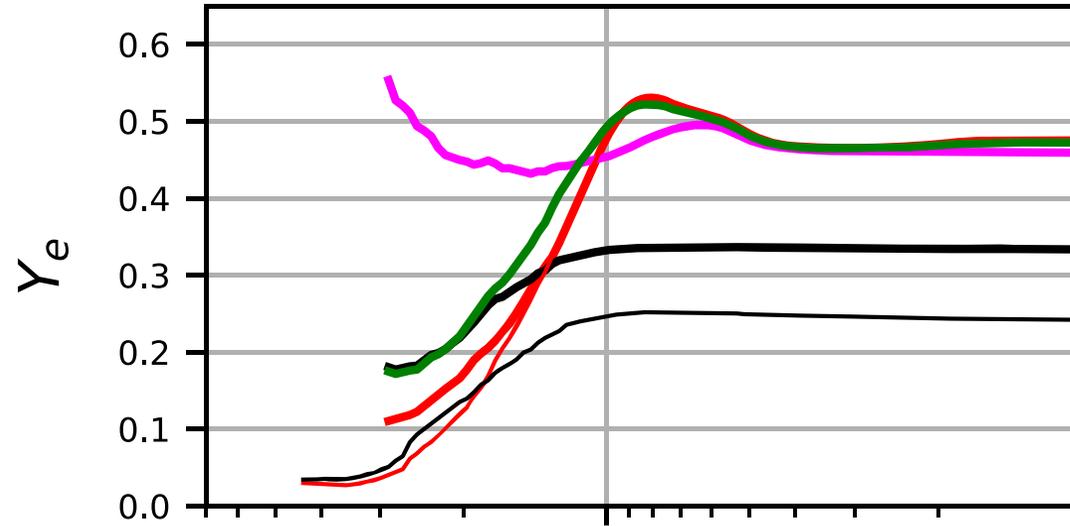
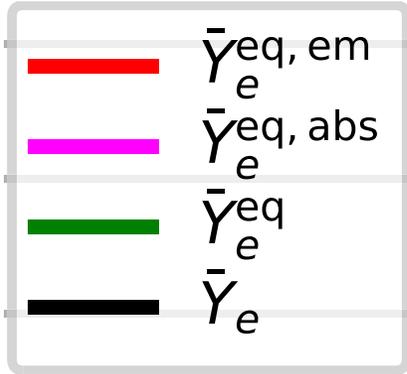
(Just, Goriely et al. 22,
see also Arcones+10,
Fujibayashi+18)

Characteristic regimes in post-merger disks



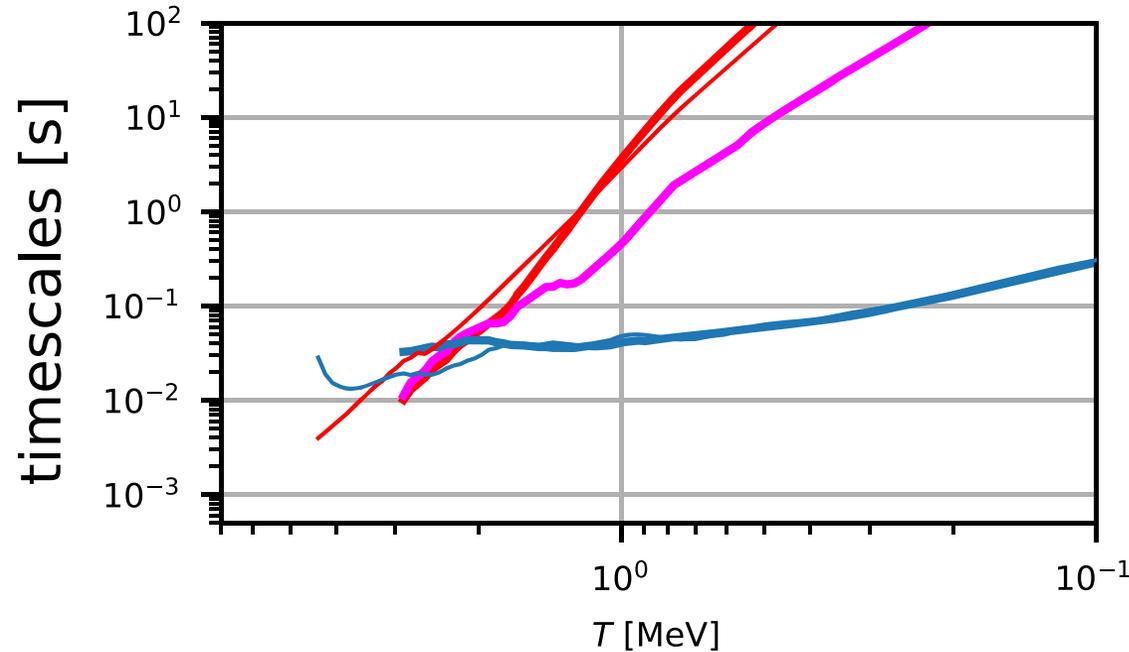
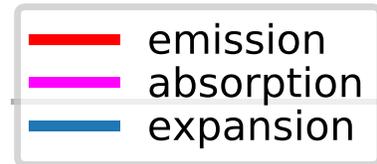
(Just, Goriely et al 22)

Ye evolution along Lagrangian outflow trajectories

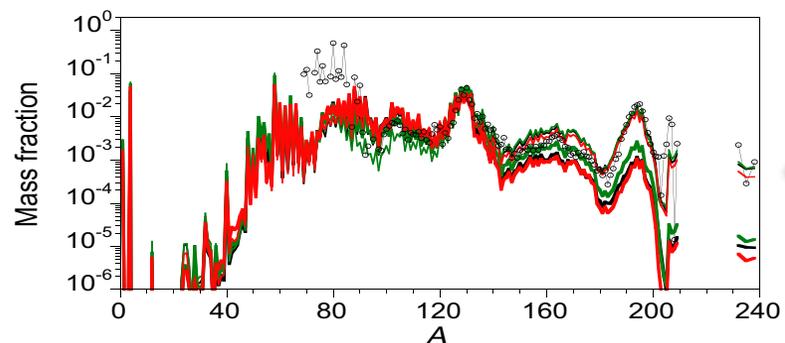
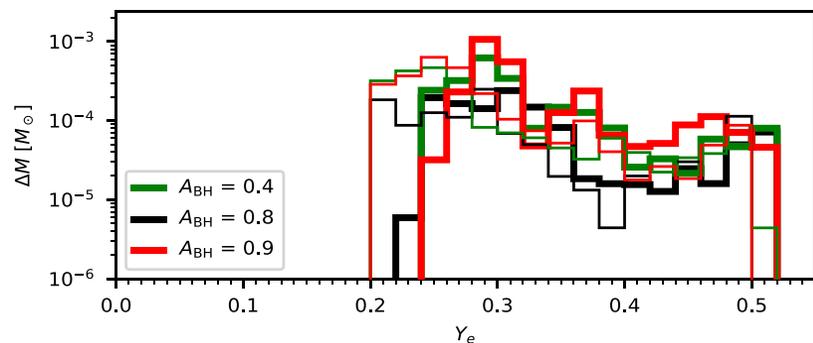
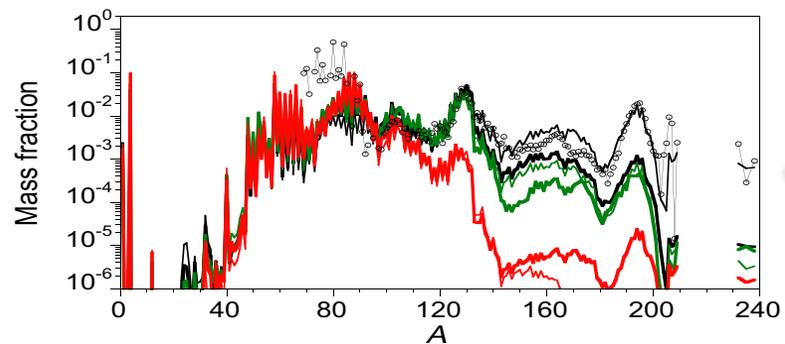
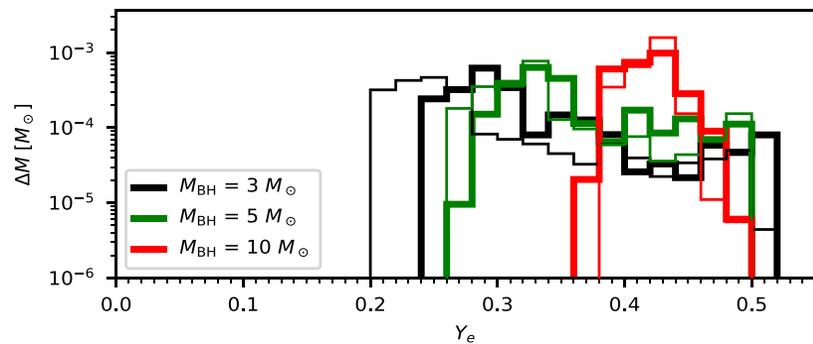
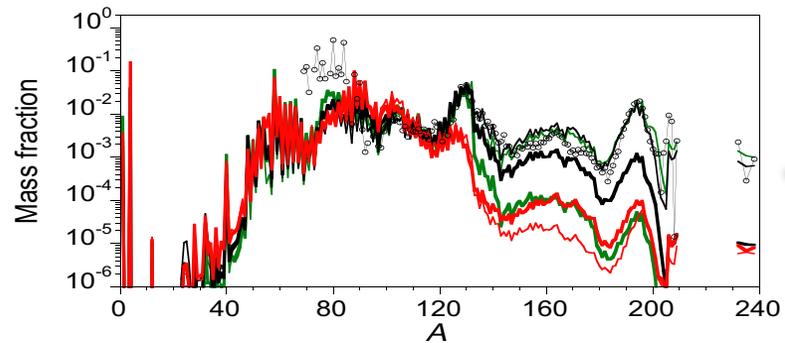
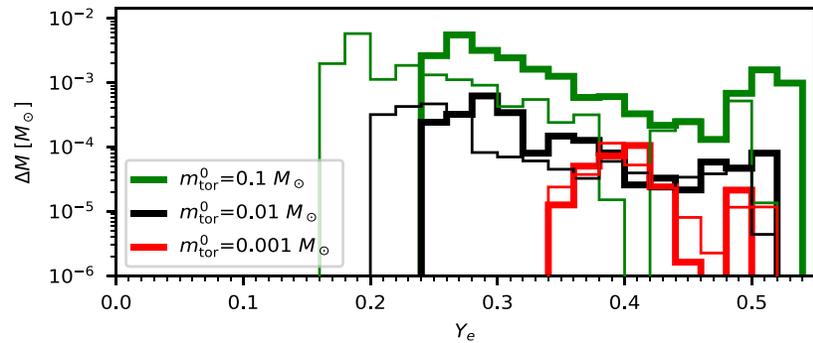


model with absorption

model without absorption



Ye distribution + nucl. yields



- ▶ relatively robust but depend on disk conditions
- ▶ overall higher Y_e + less agreement with solar pattern compared to dynamical ejecta

Impact of (effective) flavor mixing in neutrino-cooled disks

Just, Abbar, Wu, Tamborra,
Janka, Capozzi PRD 105 (2022)

effective flavor equipartition
e.g. like:

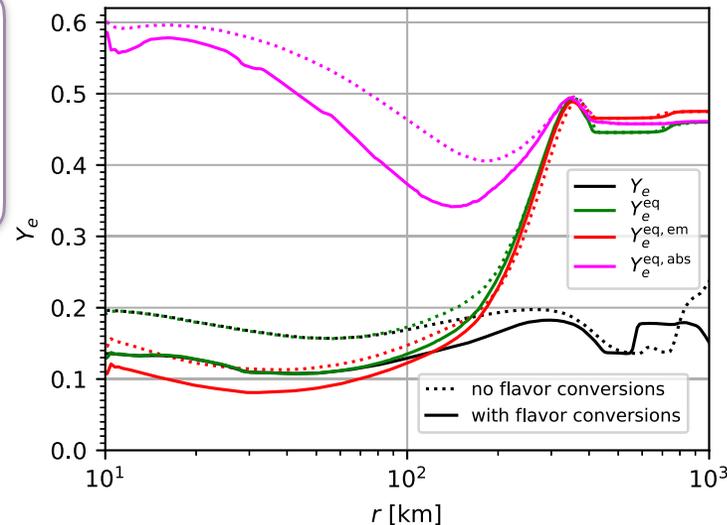
$$n_\nu = \frac{1}{6} (n_{\nu_{e,q}}^0 + n_{\bar{\nu}_{e,q}}^0 + 2n_{\nu_{x,q}}^0 + 2n_{\bar{\nu}_{x,q}}^0)$$

Two main effects:

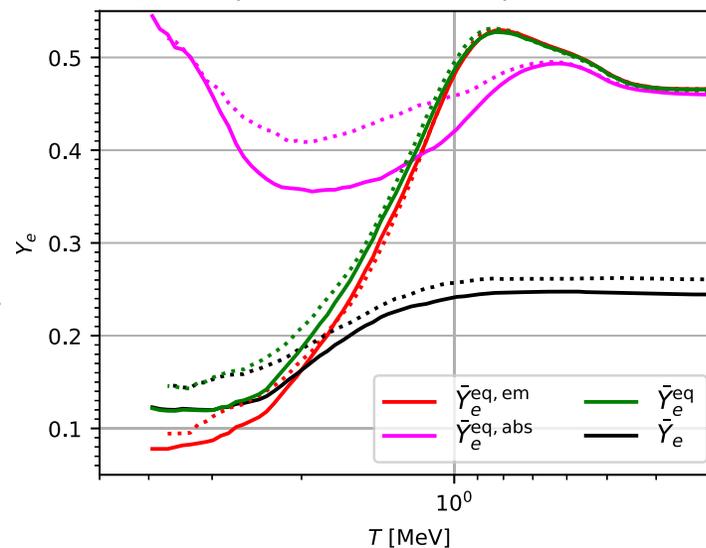
1) enhanced neutrino cooling rates lead to higher electron degeneracy → lower value of emission-equilibrium electron fraction $Y_e^{\text{eq,em}}$

$$(\lambda_{e^+} + \lambda_{\nu_e})Y_n - (\lambda_{e^-} + \lambda_{\bar{\nu}_e})Y_p \Big|_{\rho, T, Y_e^{\text{eq}}} = 0$$

radial profiles @ $t = 50$ ms

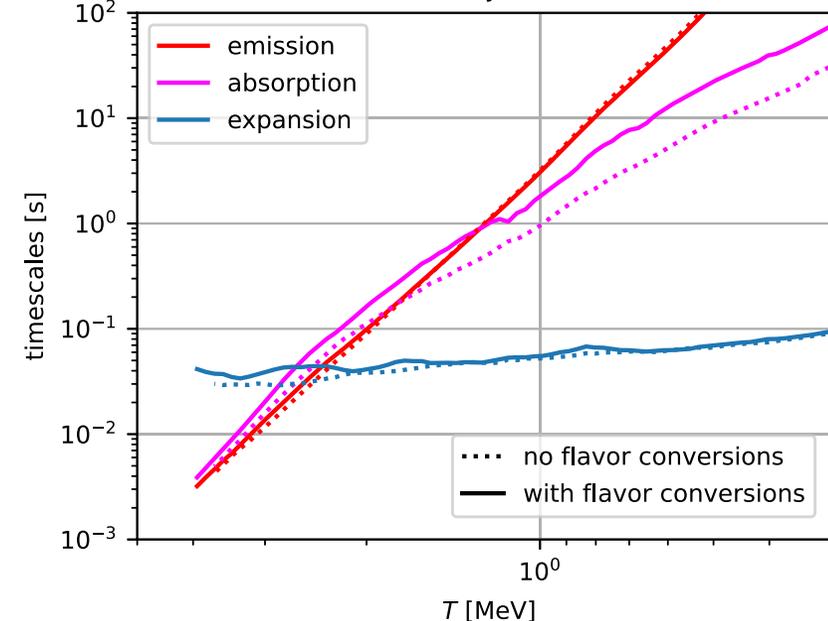


Y_e and equilibrium values in ejected material



2) smaller abundance of electron-type neutrinos → reduced absorption rates

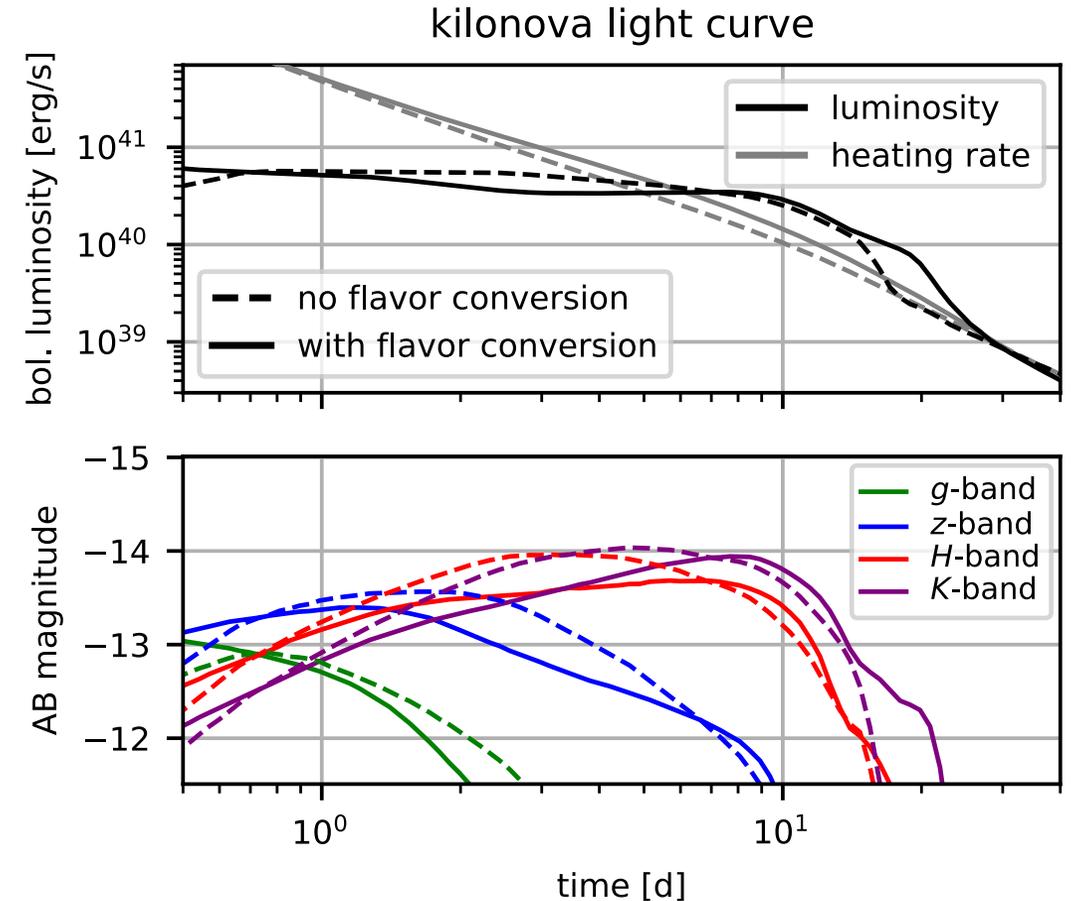
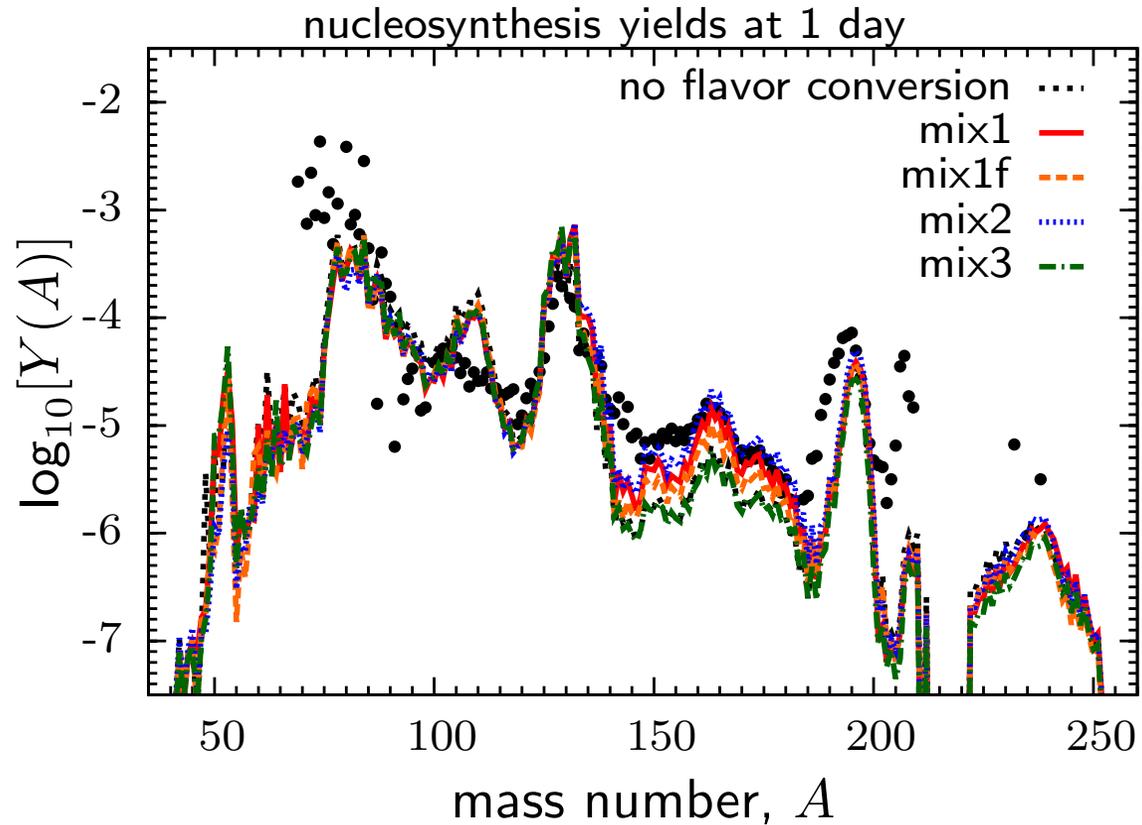
timescales in ejected material



$$\tau_\beta = \frac{1}{Y_p(\lambda_{e^-} + \lambda_{\bar{\nu}_e}) + Y_n(\lambda_{e^+} + \lambda_{\nu_e})}$$

Impact on nucleosynthesis and kilonova

Just, Abbar, Wu, Tamborra,
Janka, Capozzi PRD 105 (2022)

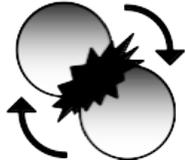


- ▶ moderate enhancement of r-process yields
- ▶ motivates development of more sophisticated flavor-mixing models

(see also Wu+17, Li+21, Fernandez+22, Ehring+23, Nagakura+25, Qiu+25, Kawaguchi+26, ...)

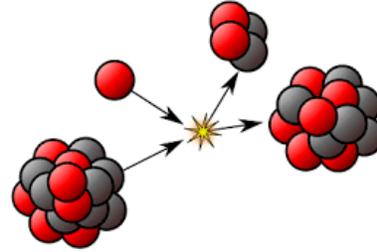
End-to-end Kilonova modeling pipeline

hydrodynamic modeling
of merger + dynamical ejecta



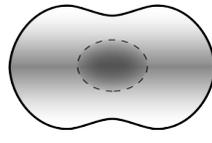
$t \sim \mathcal{O}(10 \text{ ms})$

heavy element nucleosynthesis

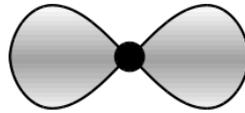


$t \sim \mathcal{O}(10 \text{ s})$

hydrodynamic modeling
of remnant + post-merger ejecta



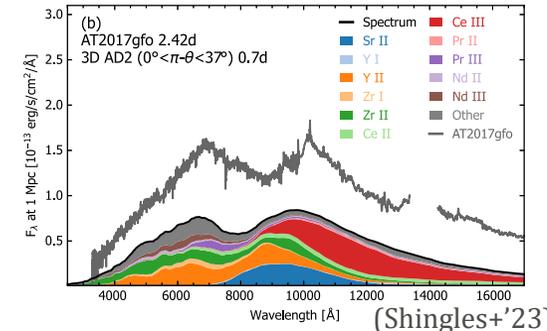
neutron star
torus system



black hole
torus system

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

kilonova radiative transfer



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

parameter inference with observations

Tools and methods

hydrodynamic modeling of merger + dynamical ejecta

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

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)

hydrodynamic modeling of remnant + post-merger ejecta

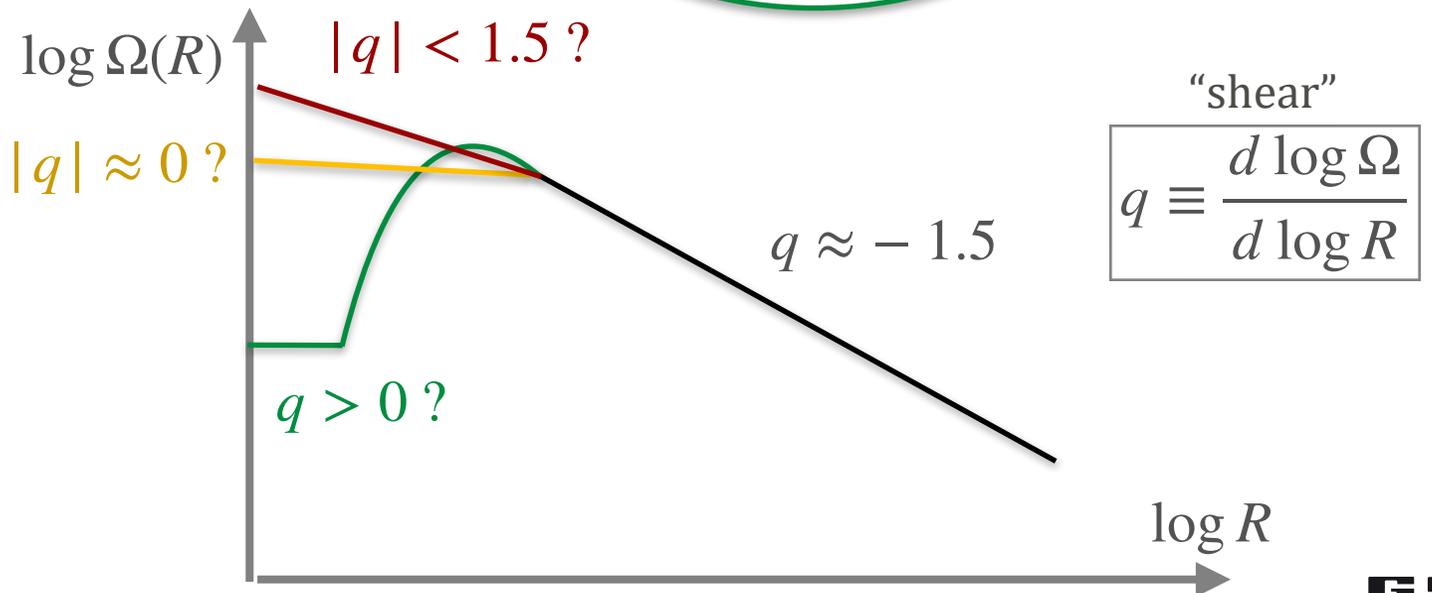
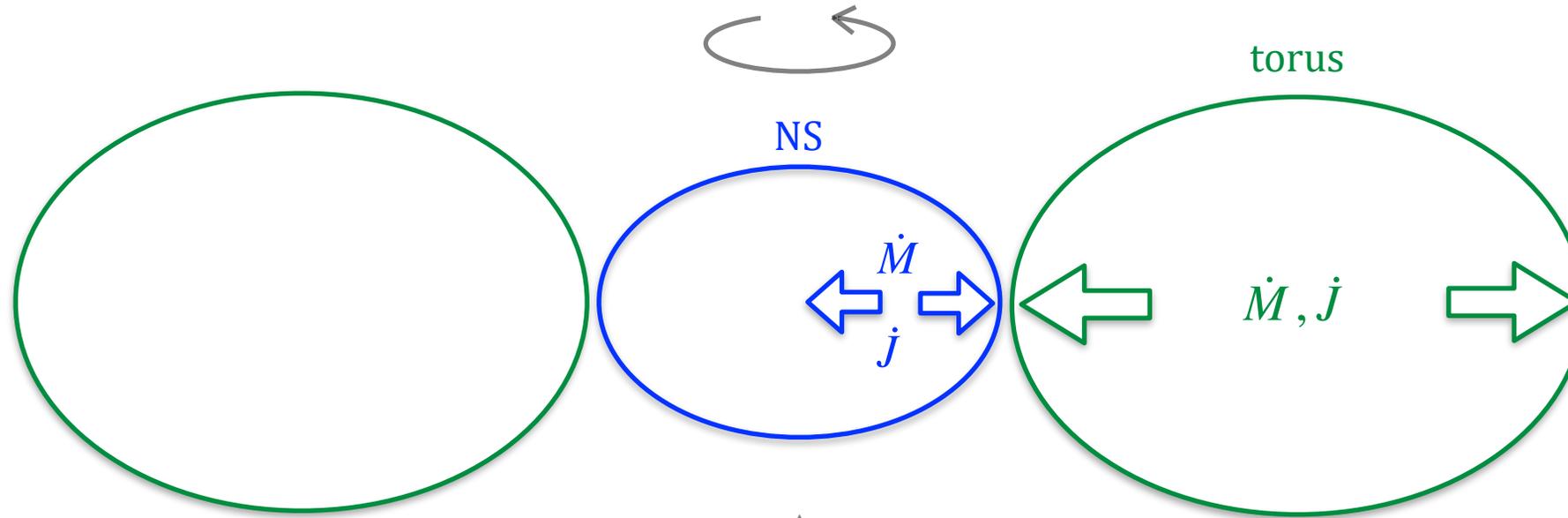
- initial conditions mapped from merger simulations
- 2D axisym. special relativistic with TOV potential
- energy-dependent M1 neutrino transport
- newly developed scheme to parametrize viscosity in the NS indep. of the surrounding disk

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

Challenge: Capture turbulent viscosity in the NS remnant

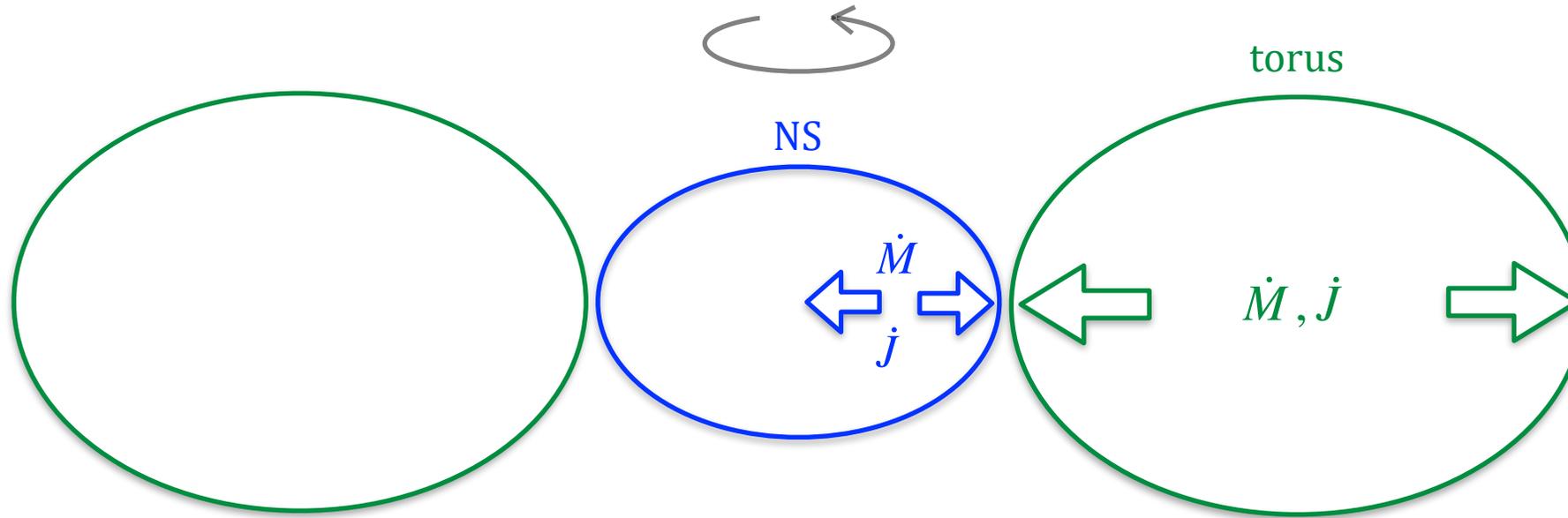
[O] et al., ApJL 951, L12, 2023)



(many works, e.g. by: Aguilera-Miret, Ciolfi, Duez, Fujibayashi, Fernandez, Guilet, Gutierrez, Kiuchi, Margalit, Metzger, Miravet-Tenes, Moesta, Palenzuela, Radice, Reboul-Salze, Rezzolla, Siegel, Shibata, ...)

Challenge: Capture turbulent viscosity in the NS remnant

(O) et al., ApJL 951, L12, 2023)



Our approximate approach:

- parametrize turbulent viscosity depending on the **shear q**
- **in the torus** ($q \sim -1.5$): usual disk alpha-viscosity scheme
- **in the NS** ($|q| < 1.5$): reduced viscosity
- allows to regulate viscosity in HMNS and torus **independently**

$$\nu_{\text{vis}} = \alpha_{\text{vis}} H_{\text{vis}}^2 |\Omega| \tilde{q}^{n_{\text{vis}}}$$

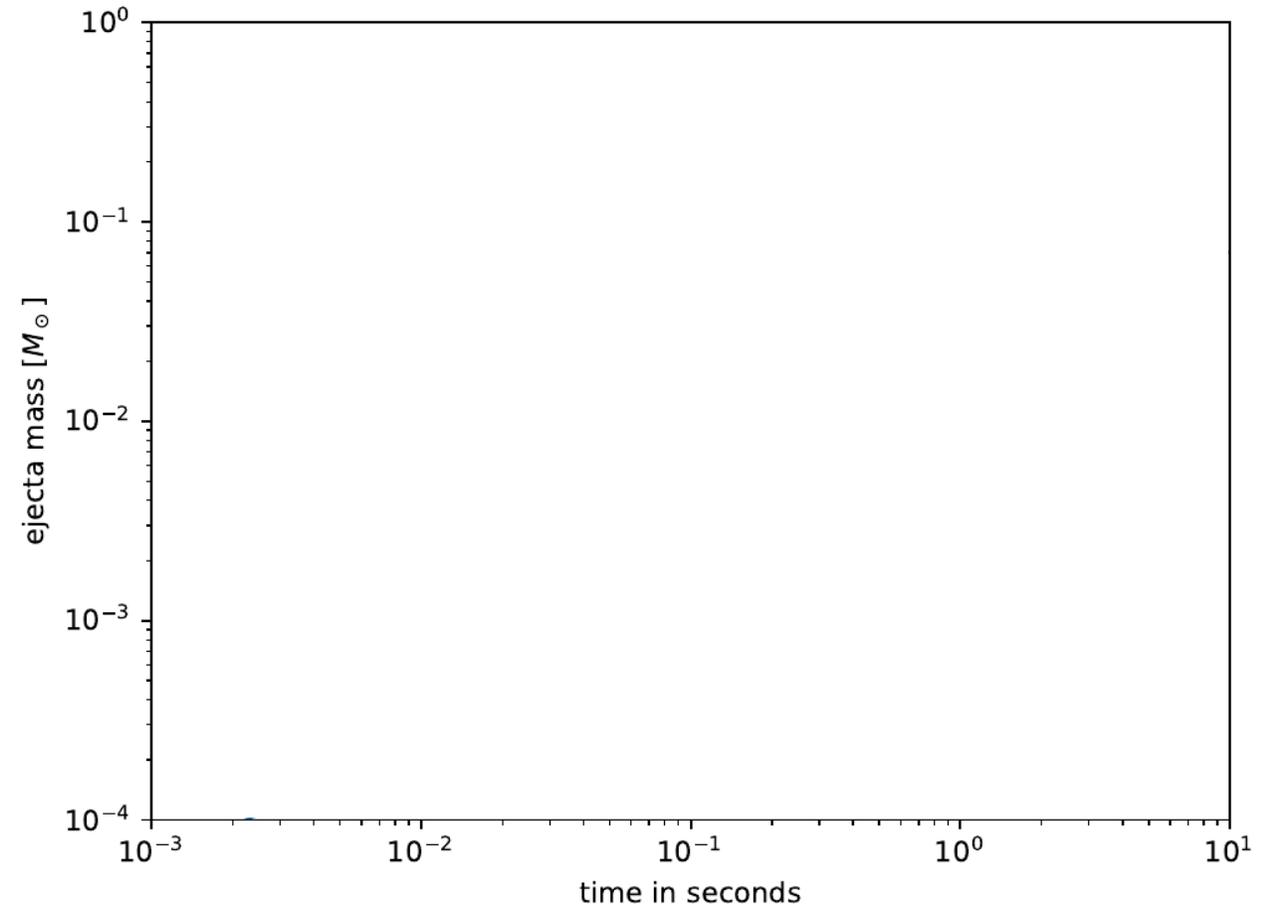
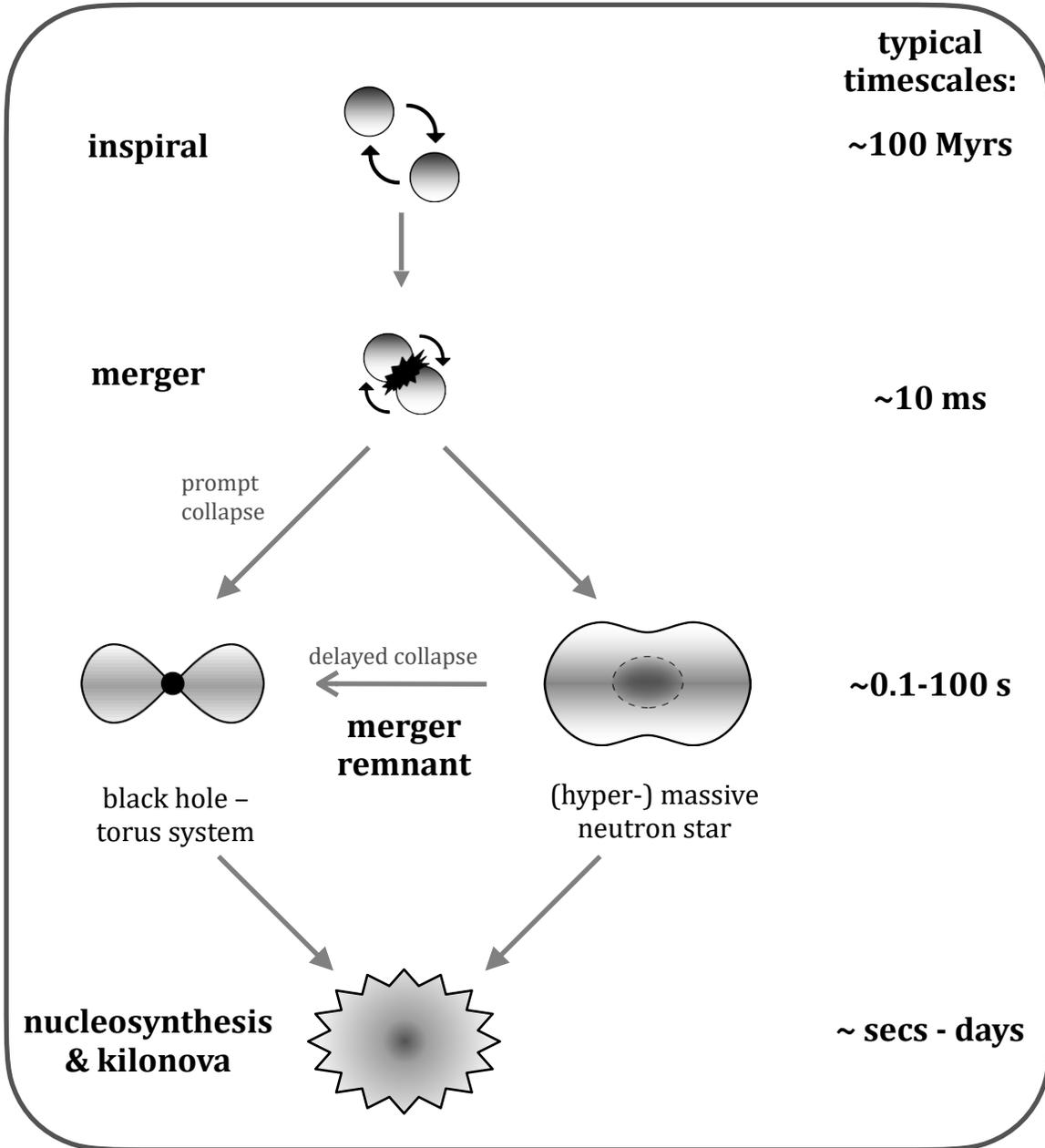
with

$$\tilde{q}^{n_{\text{vis}}} = \begin{cases} 0, & \text{if } d\Omega/dR > 0, \\ 1, & \text{else if } |d \ln \Omega / d \ln R| > q_0, \\ \left(\frac{1}{q_0} \left| \frac{d \ln \Omega}{d \ln R} \right| \right)^{n_{\text{vis}}}, & \text{else} \end{cases}$$

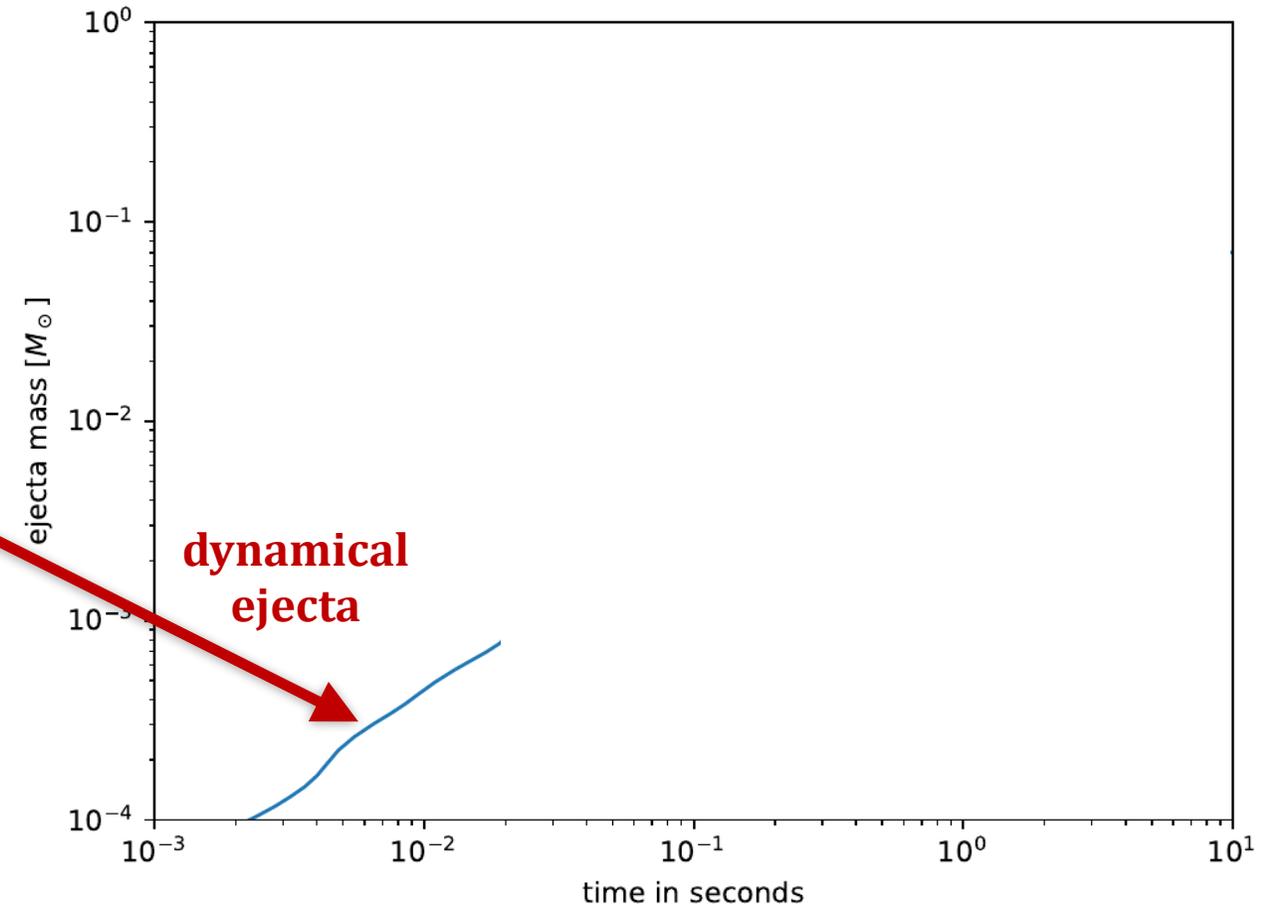
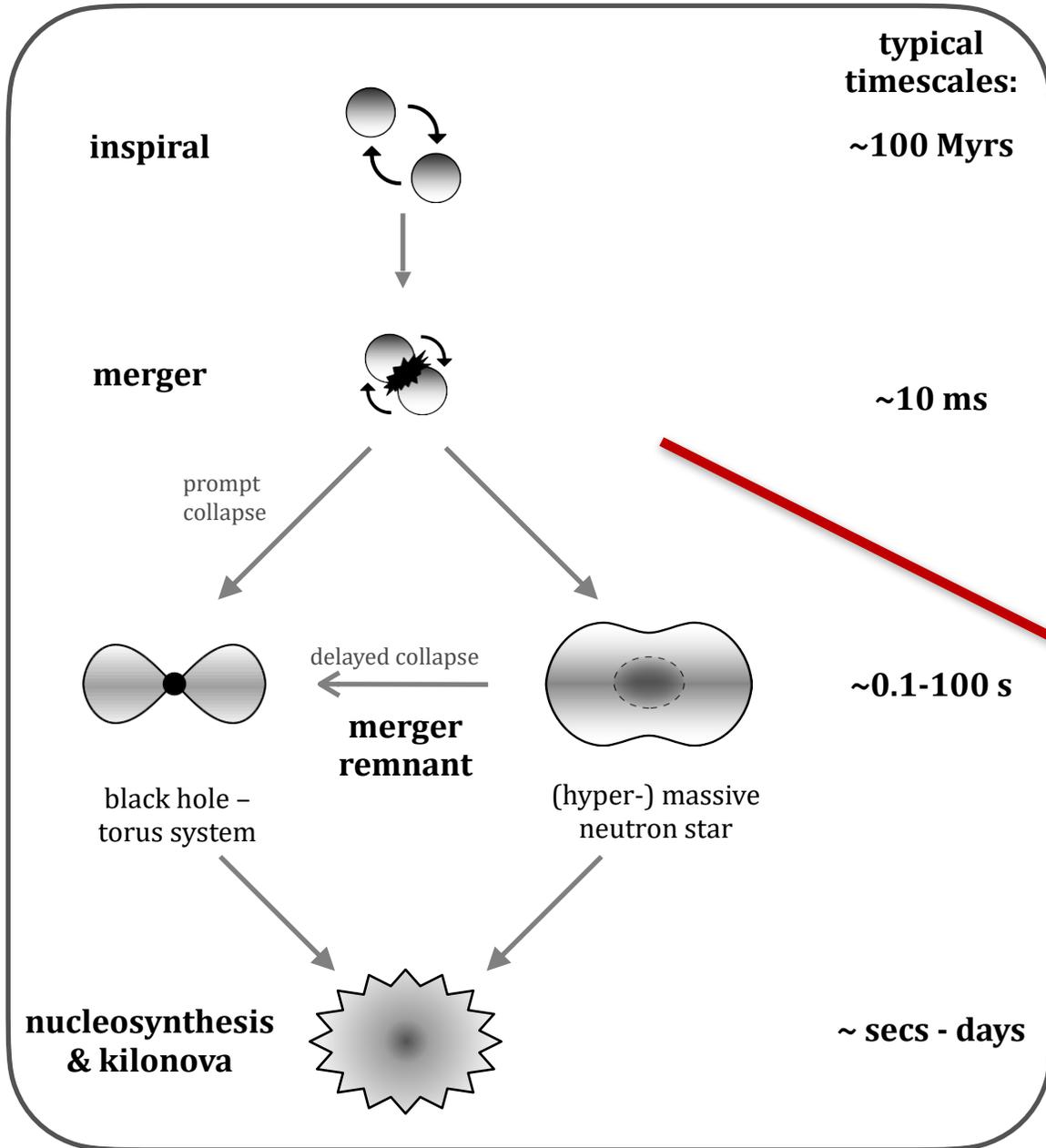
$$H_{\text{vis}} = \min \{ |\rho / \nabla \rho|, r, c_i / \Omega_K \}$$

(see also Fujibayashi+18 for related scheme)

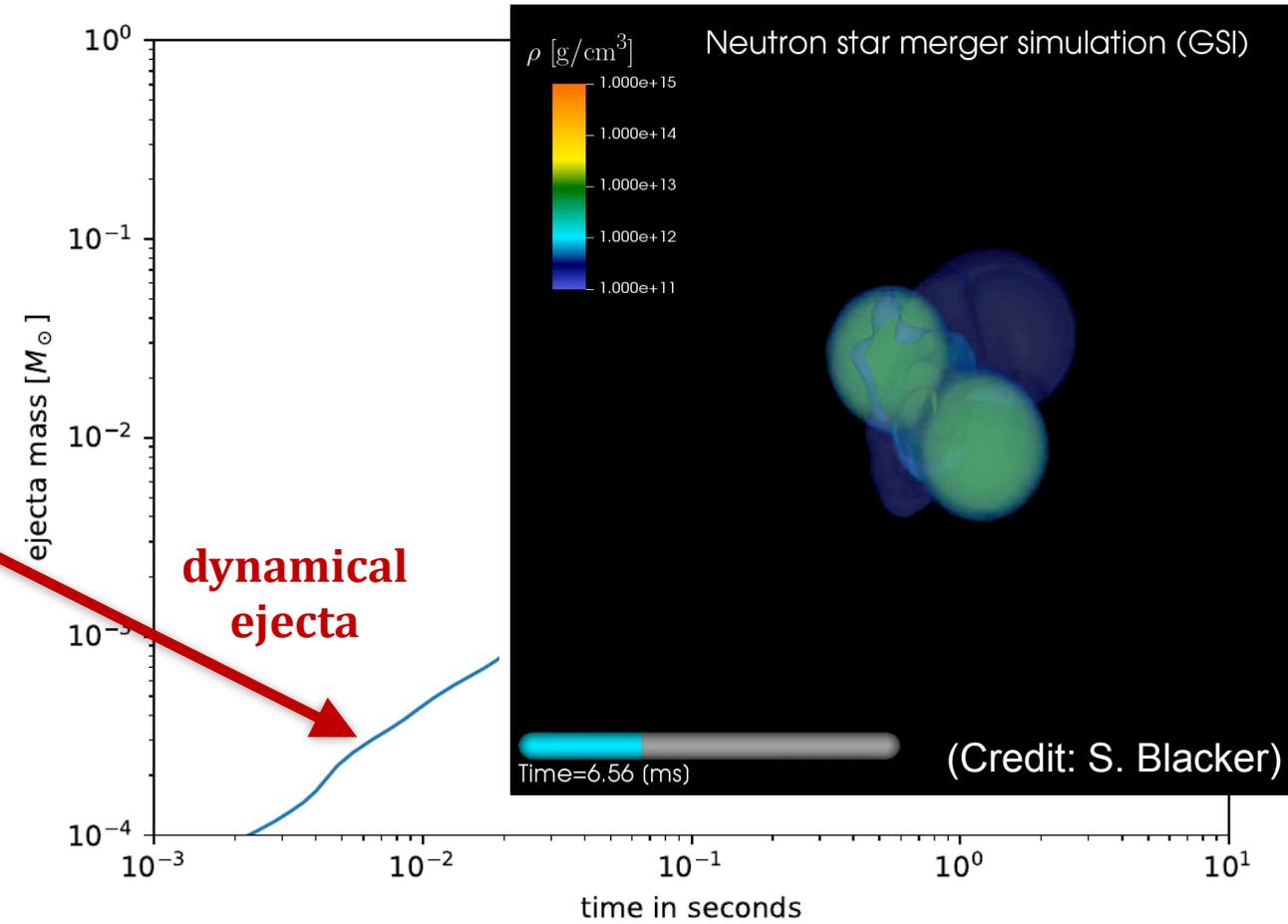
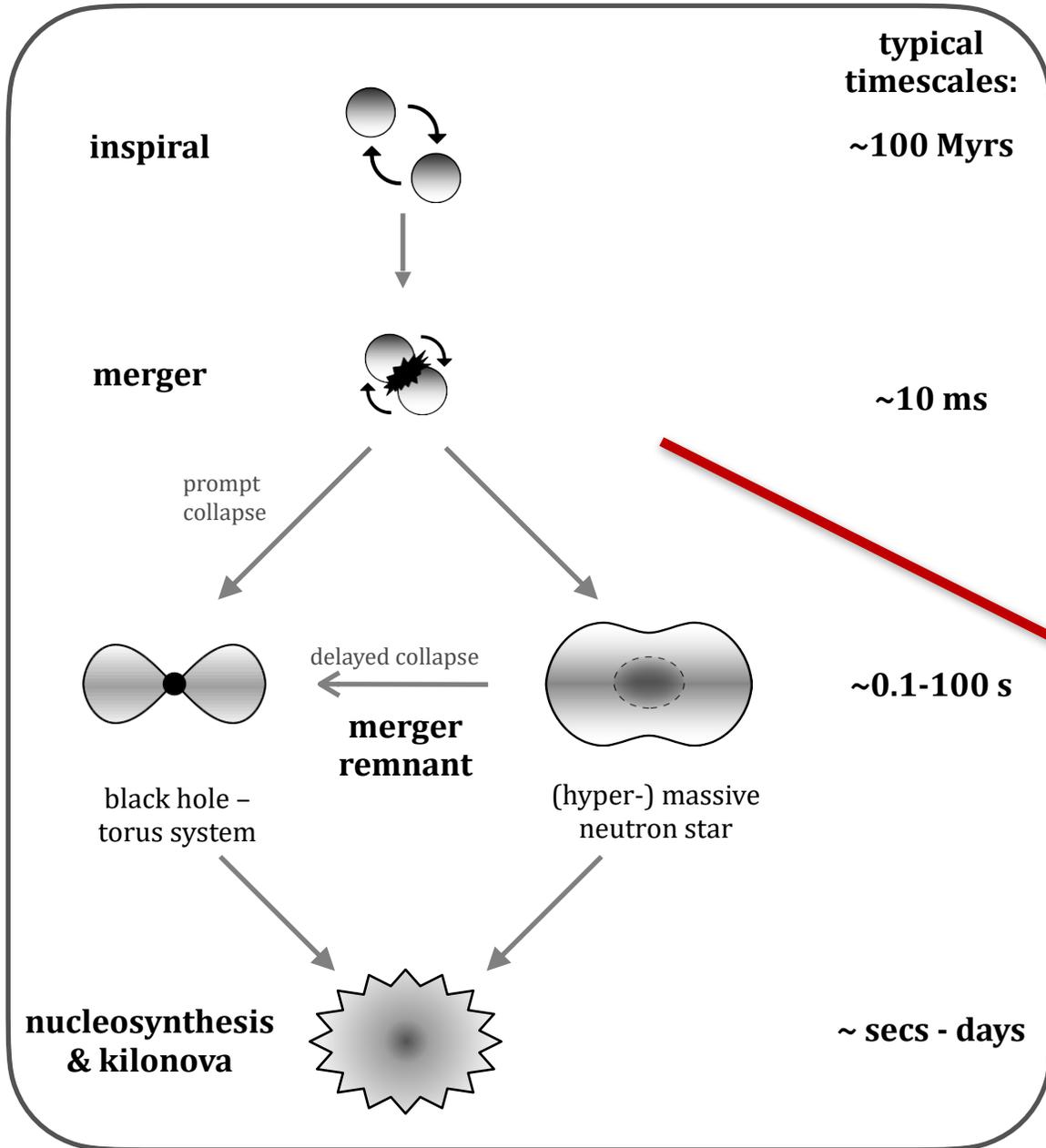
Phases of matter ejection



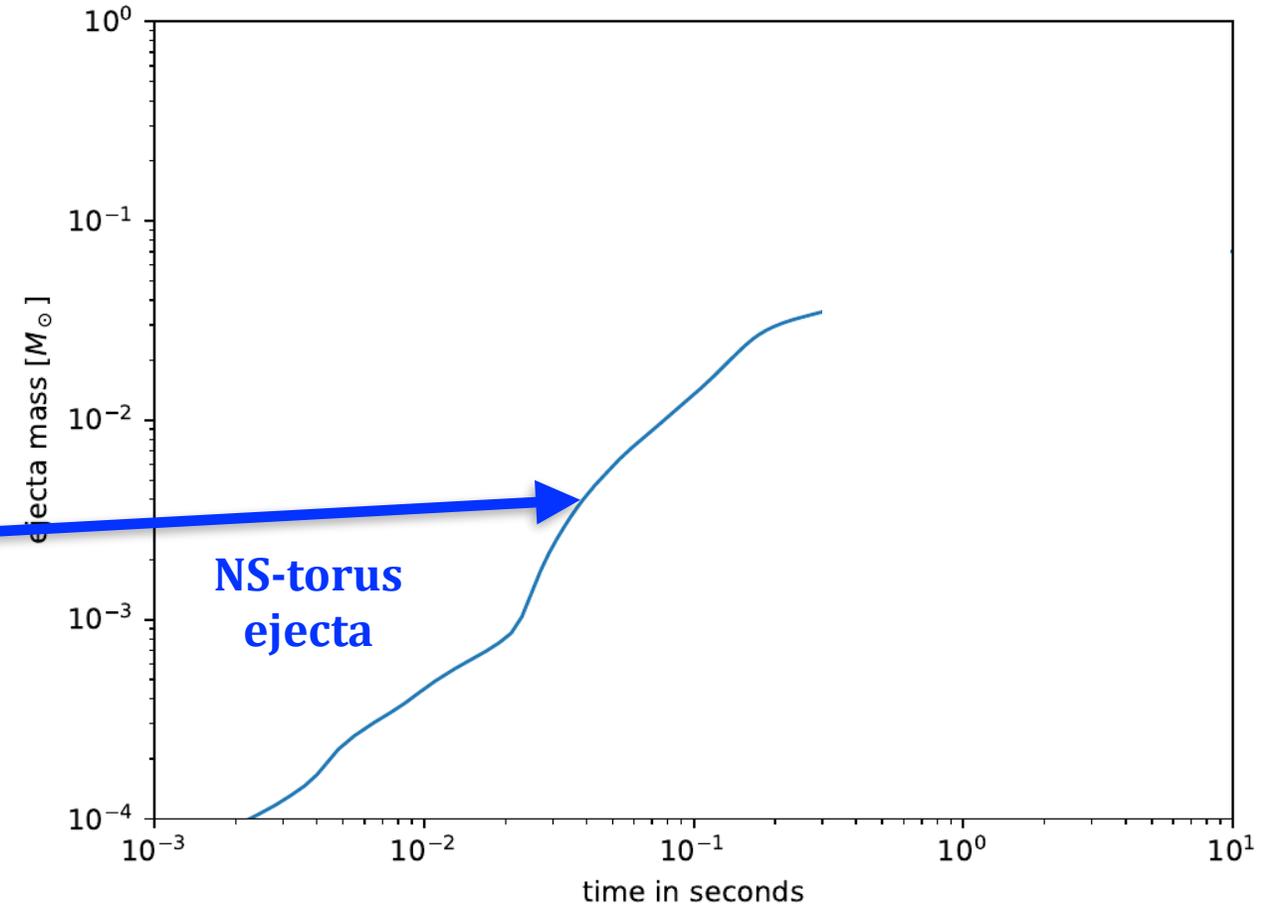
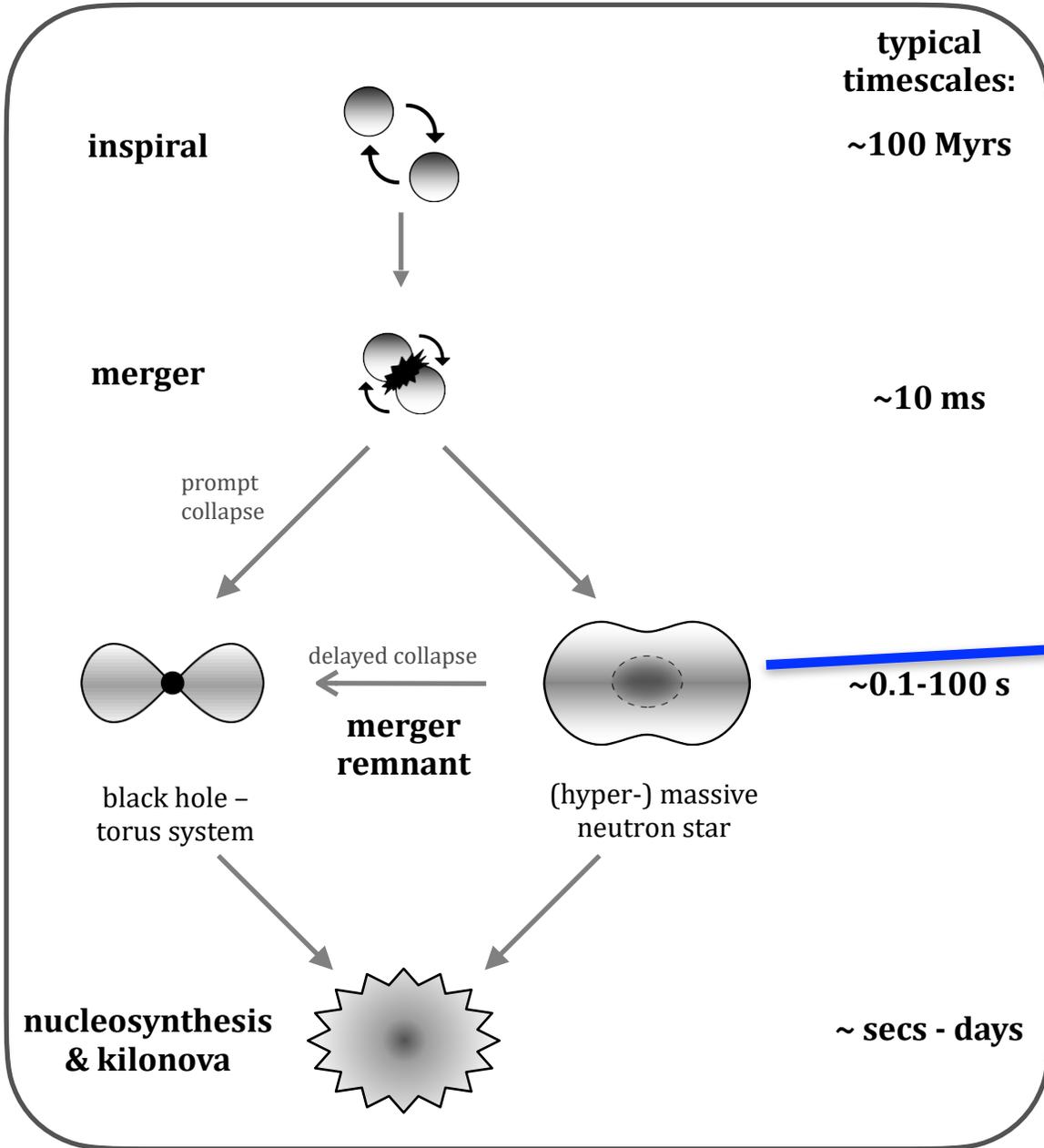
Phases of matter ejection



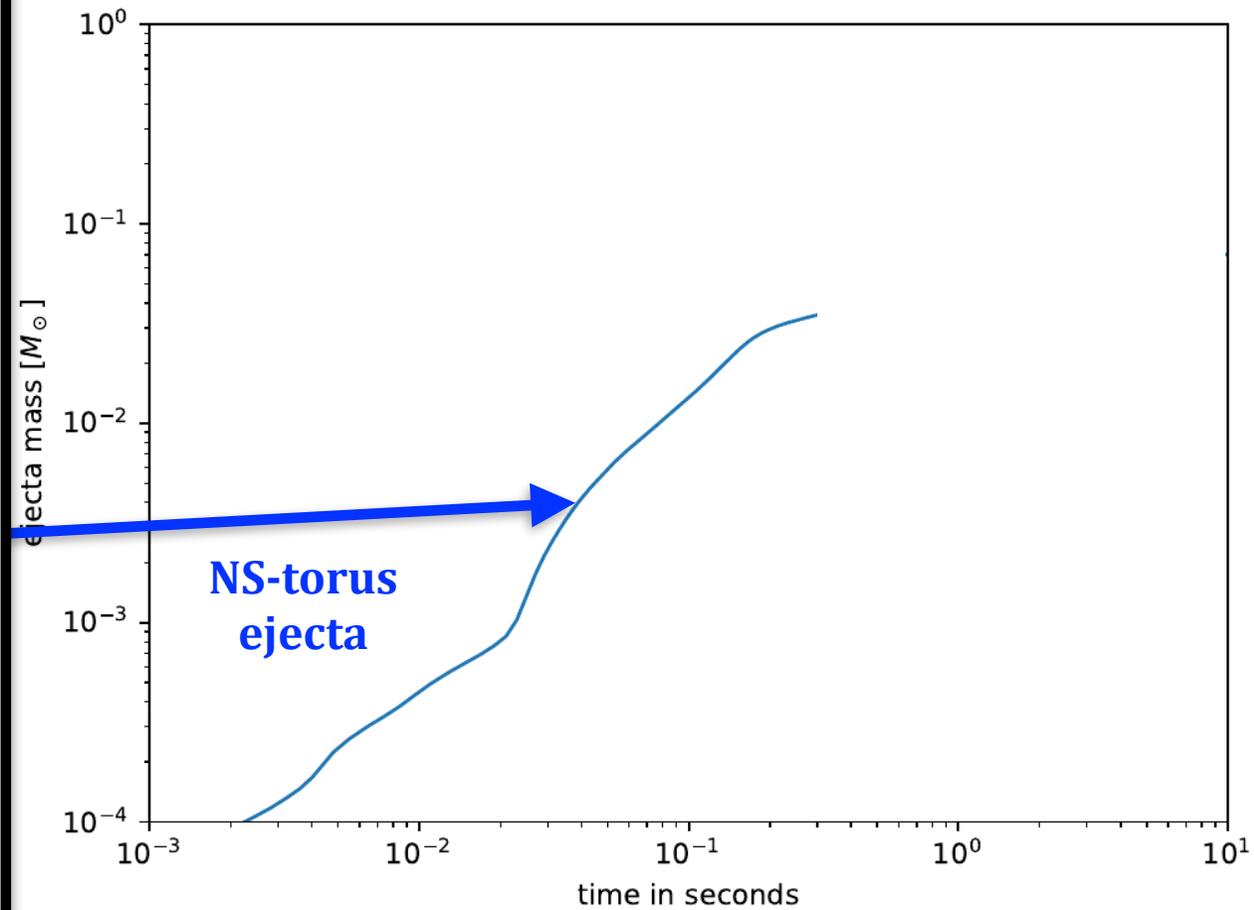
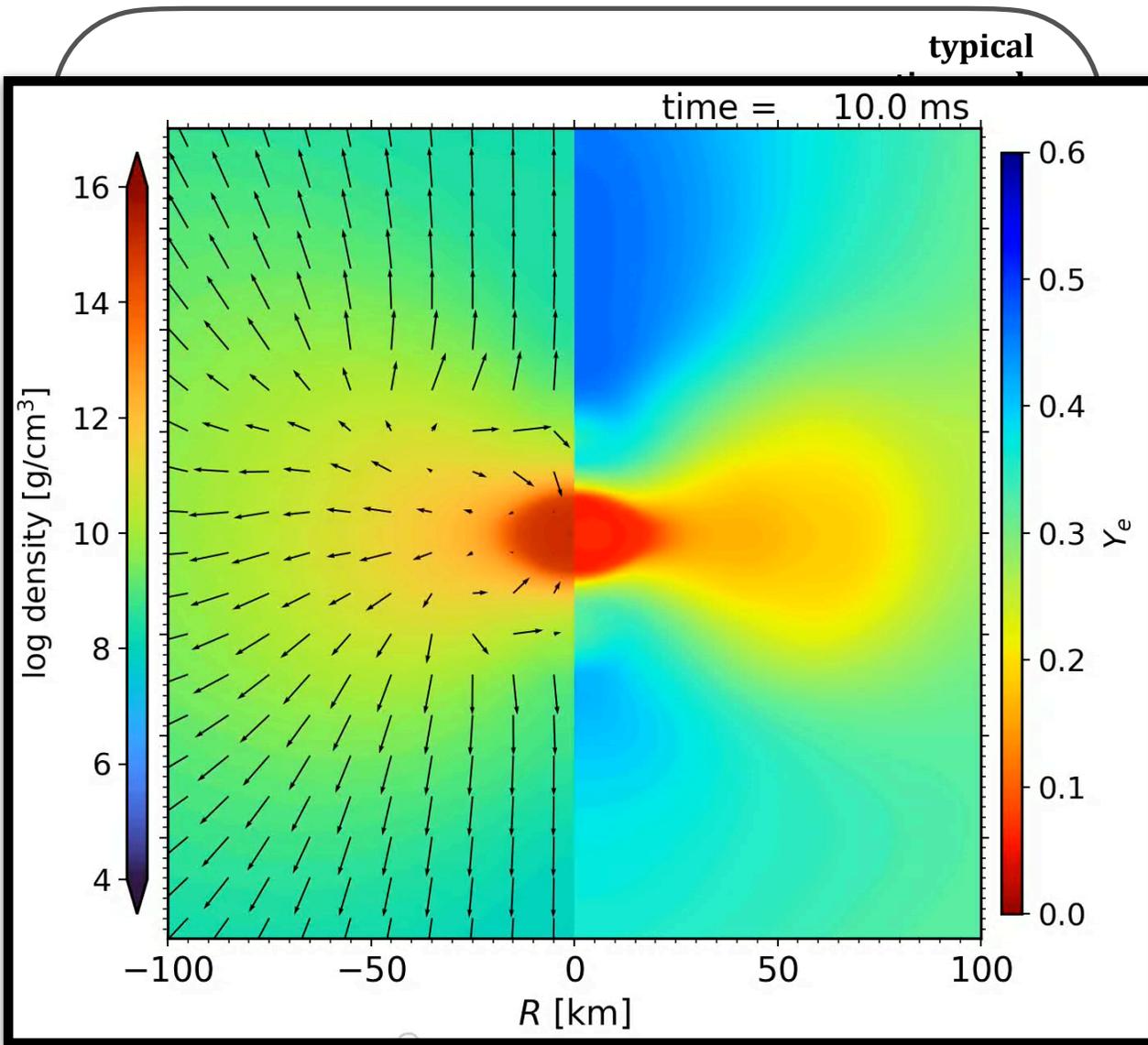
Phases of matter ejection



Phases of matter ejection



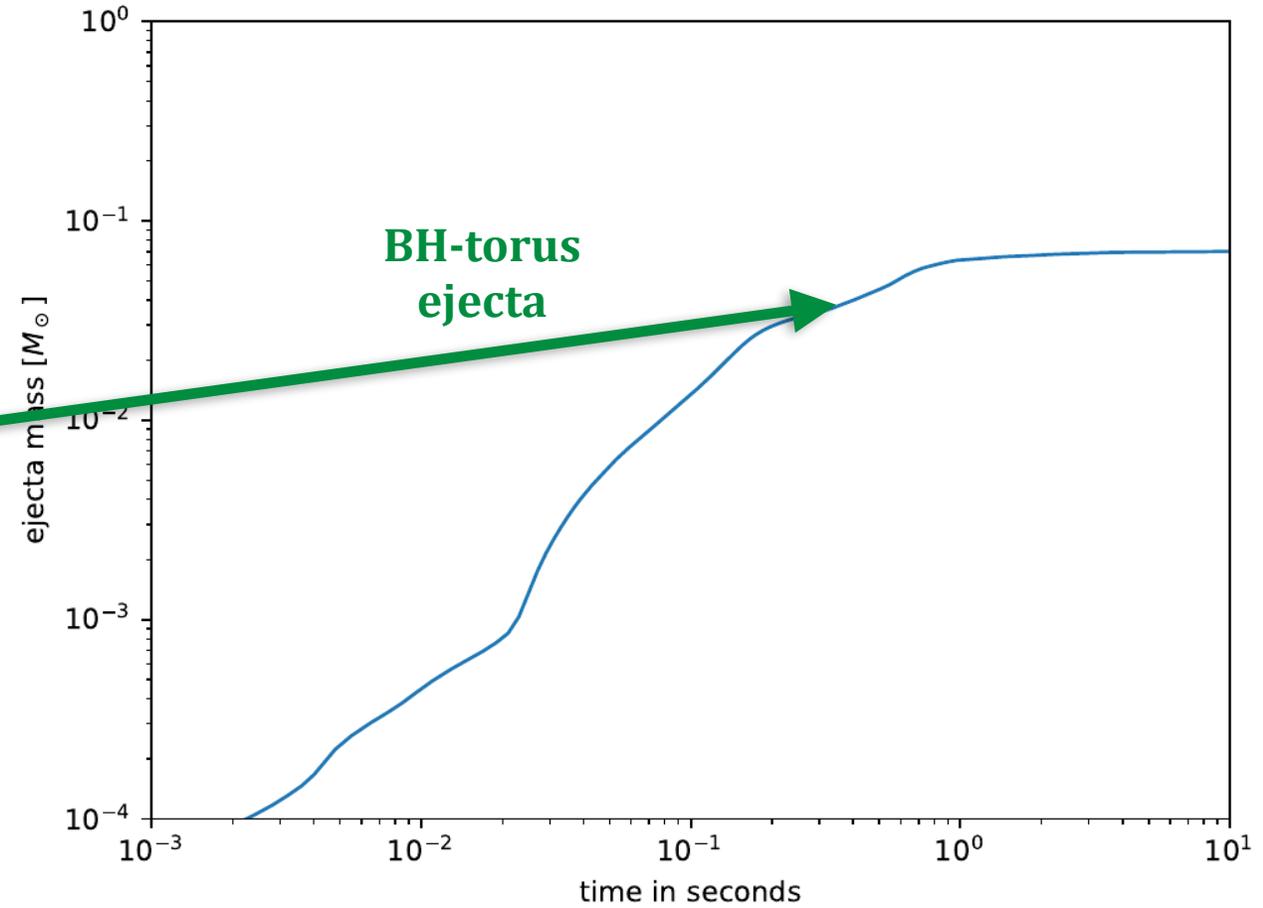
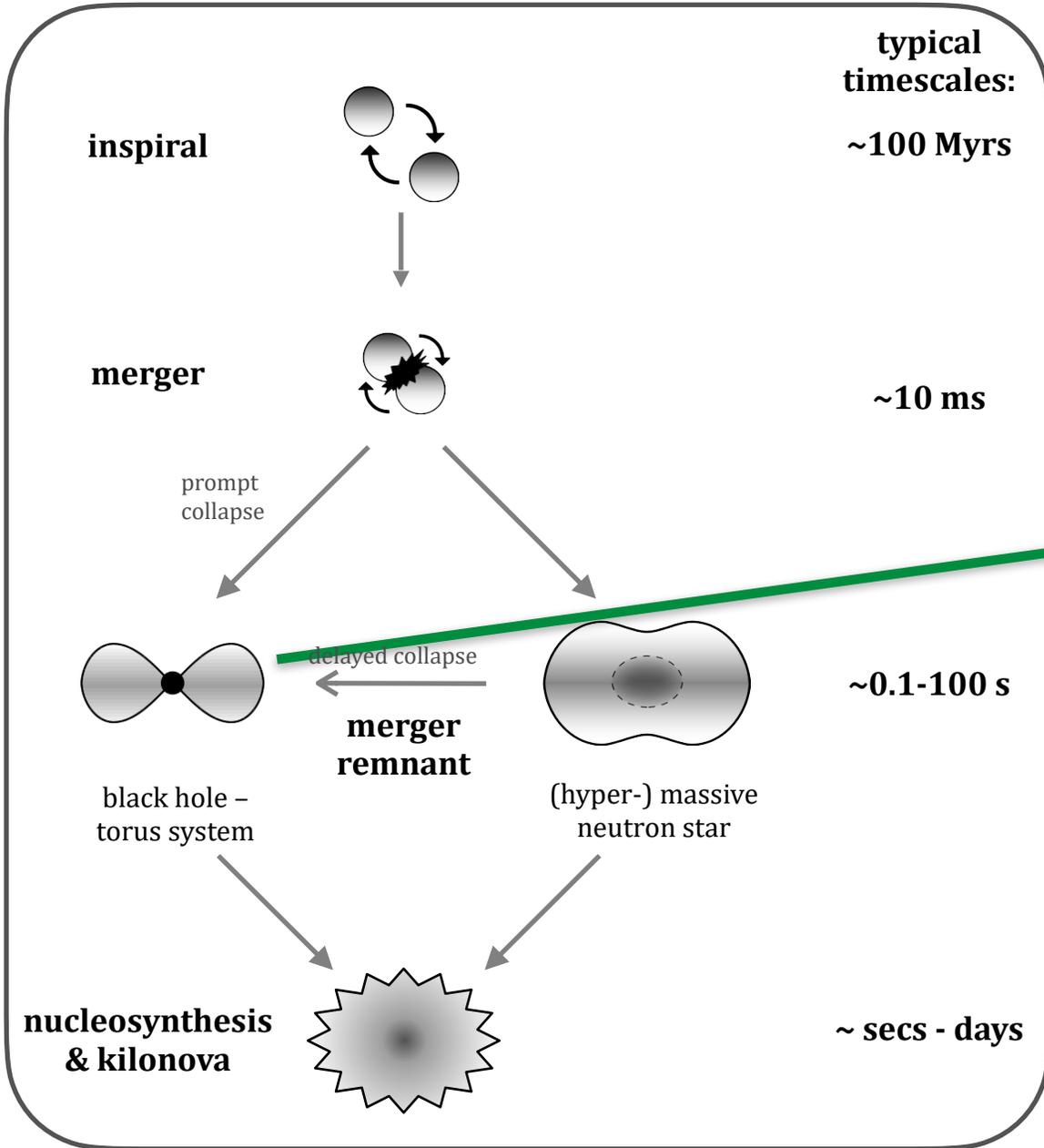
Phases of matter ejection



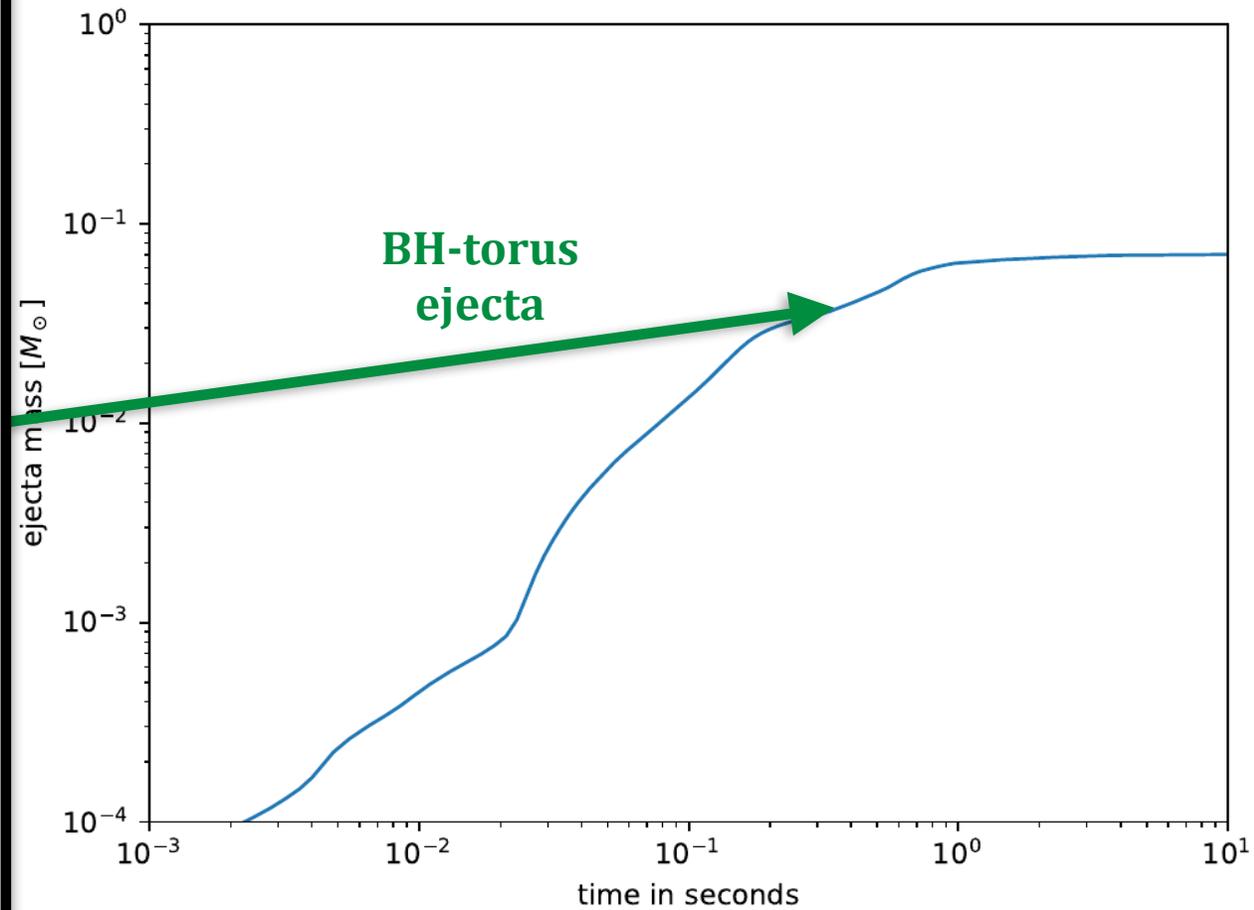
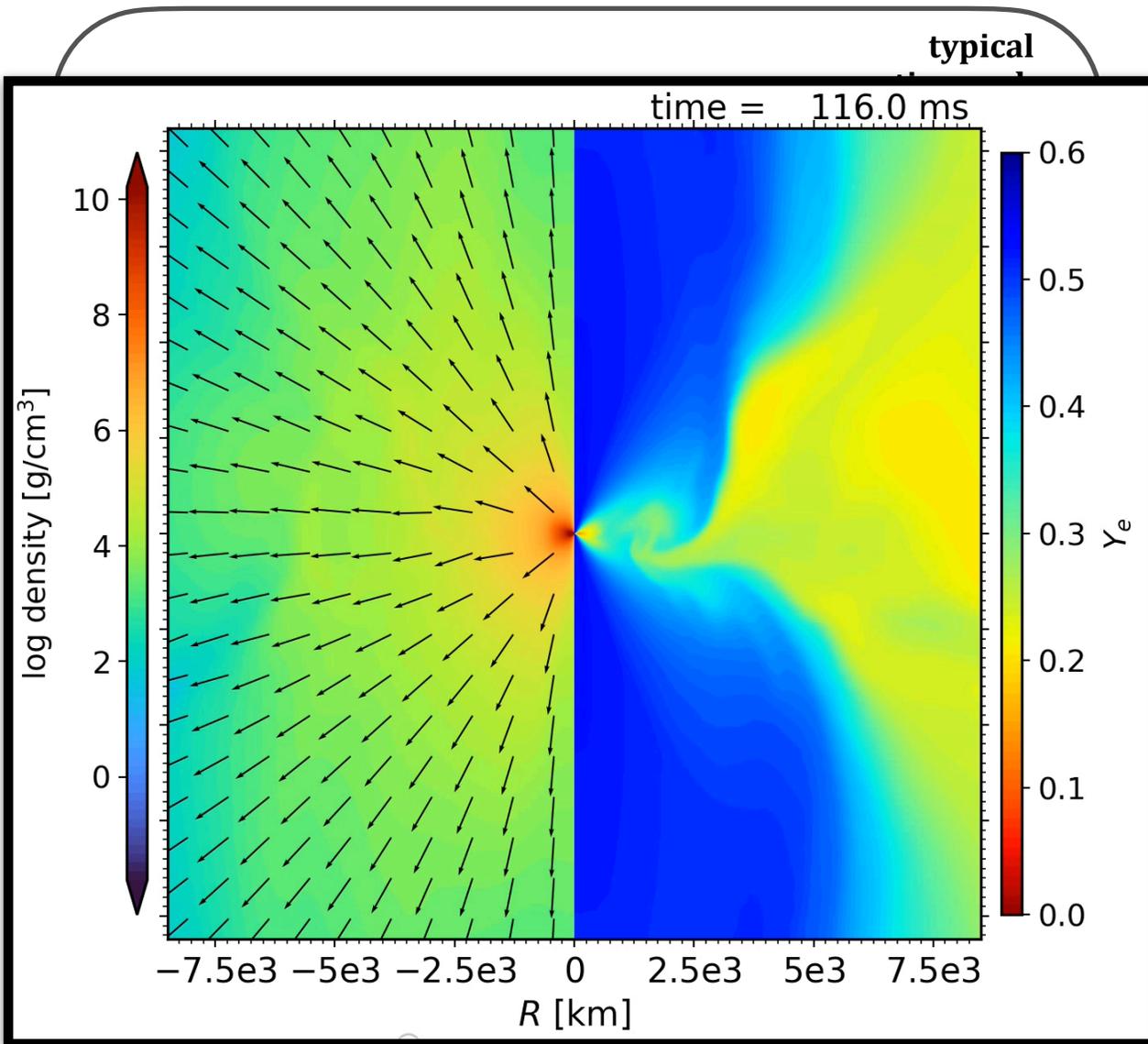
& kilonova



Phases of matter ejection

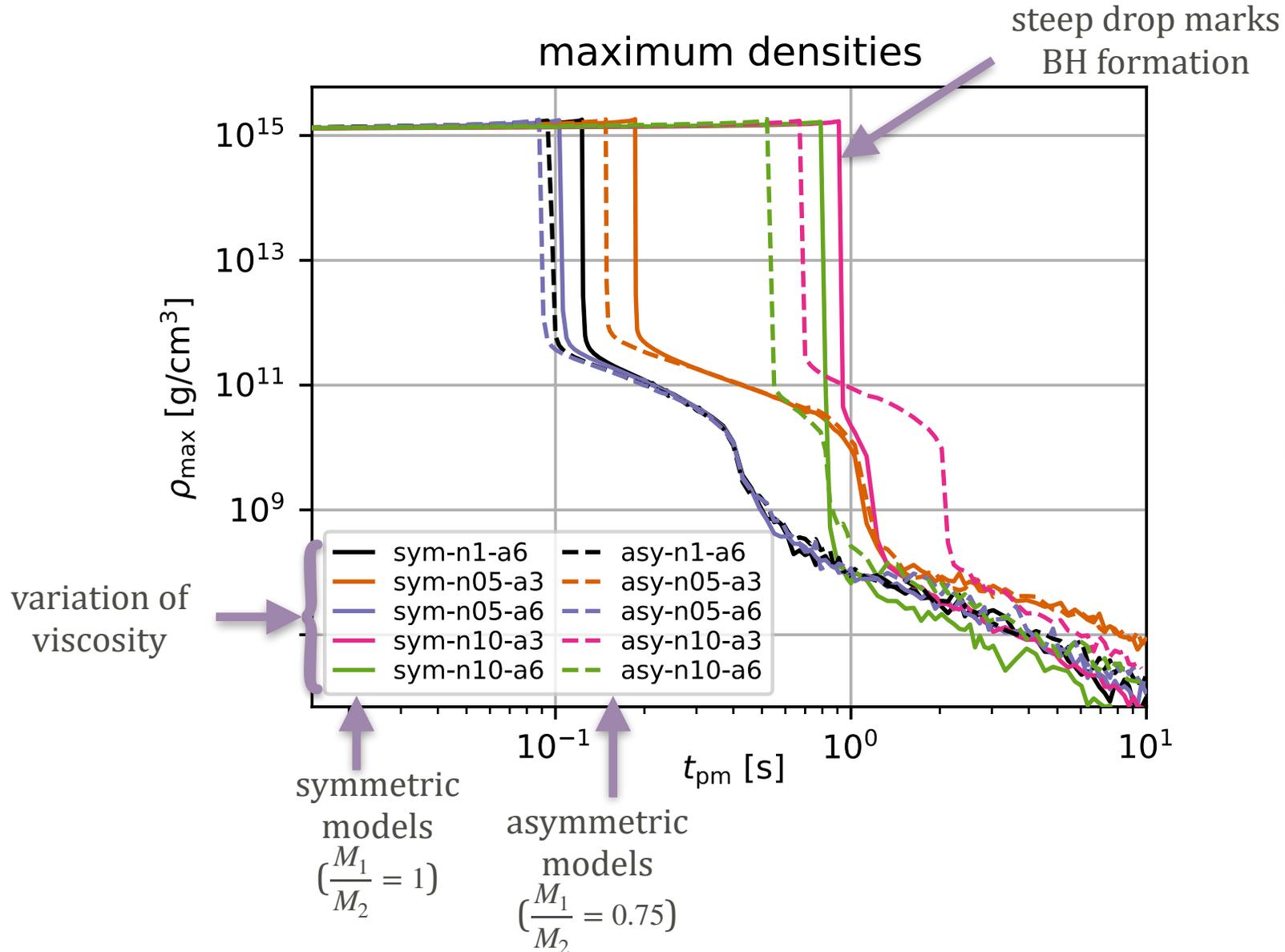


Phases of matter ejection



& kilonova

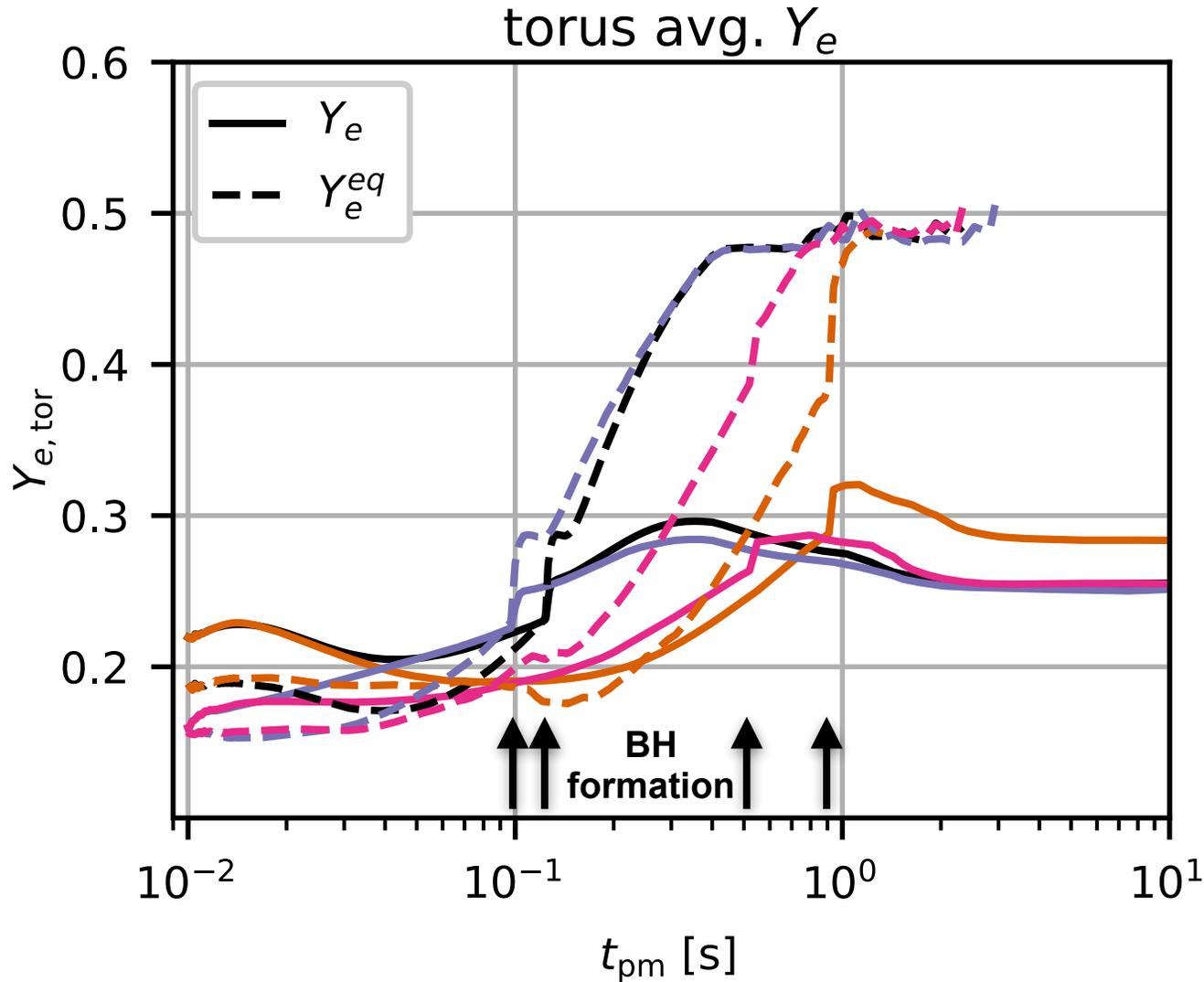
NS remnant lifetime until BH formation (O) et al., ApJL 951, L12, 2023)



- ▶ asymmetric models **collapse earlier** than symmetric models (for same viscosity)
- ▶ strong lifetime sensitivity to viscosity —> calls for solid understanding of viscosity to predict NS lifetime

Torus Y_e @ BH formation

[O] et al., ApJL 951, L12, 2023)

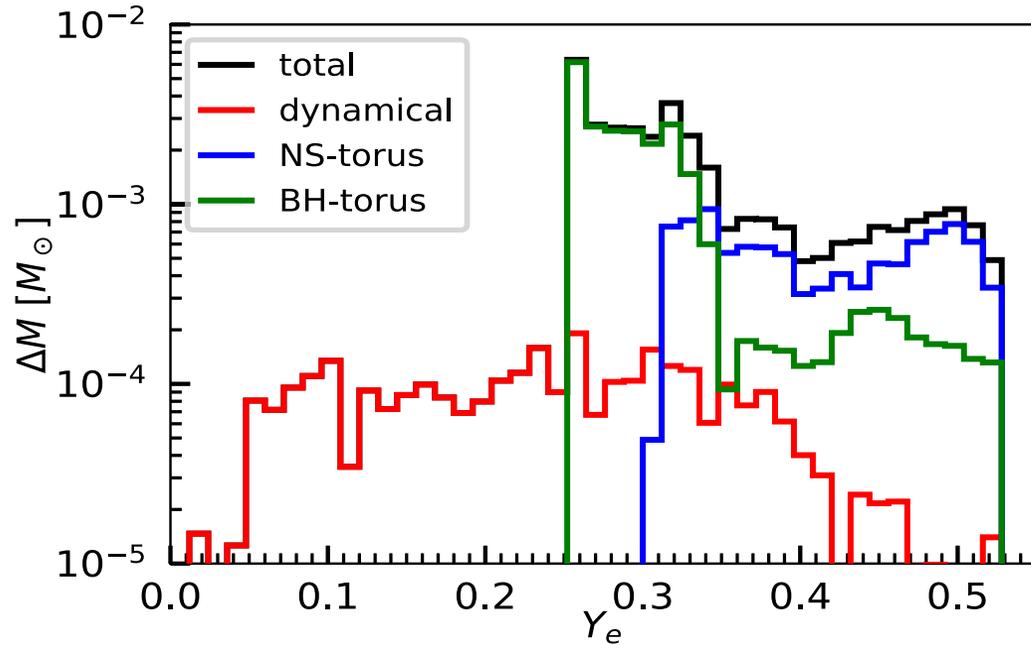


- ▶ $Y_e \sim 0.25\text{--}0.3$ at birth of BH torus because of expansion before BH formation
- ▶ higher than the “canonical” $Y_e=0.1$ assumed in previous studies
- ▶ less efficient r-process in BH-torus ejecta than previously assumed

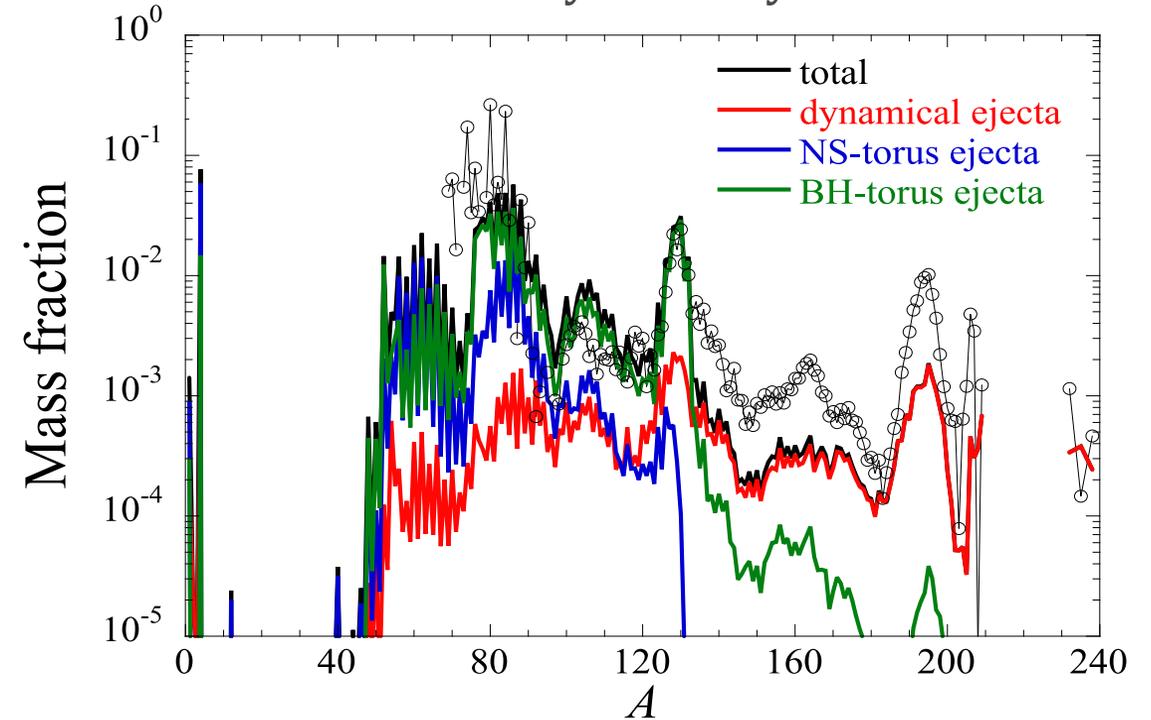
Ejecta composition — model with $t_{\text{BH}} \sim 120\text{ms}$

(O) et al., ApJL 951, L12, 2023)

Y_e histogram



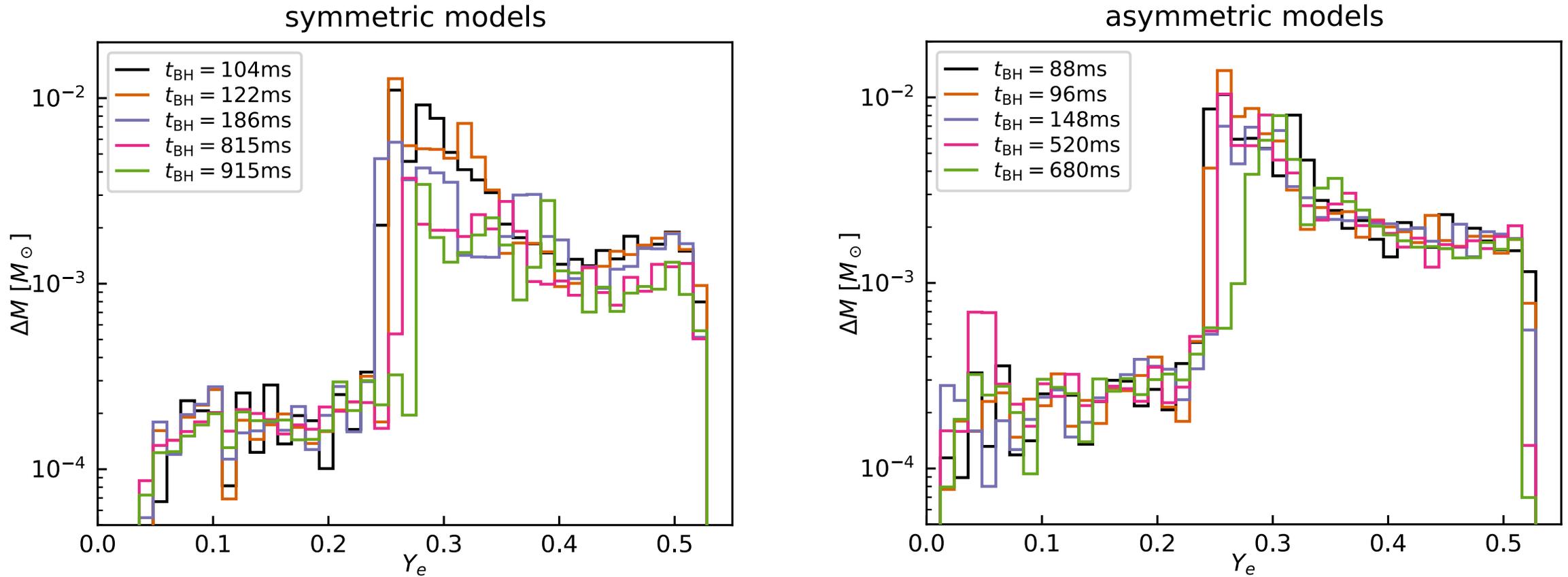
nucleosynthesis yields



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

Ejecta composition — all models

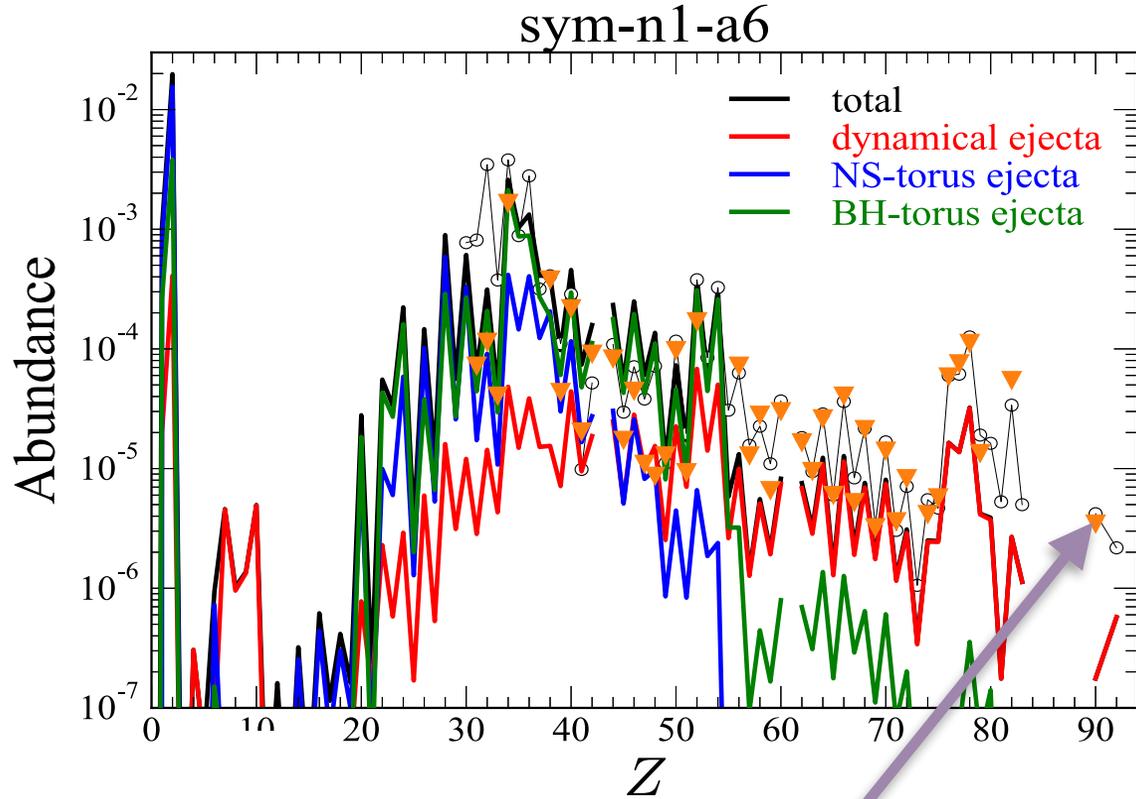
[O] et al., ApJL 951, L12, 2023)



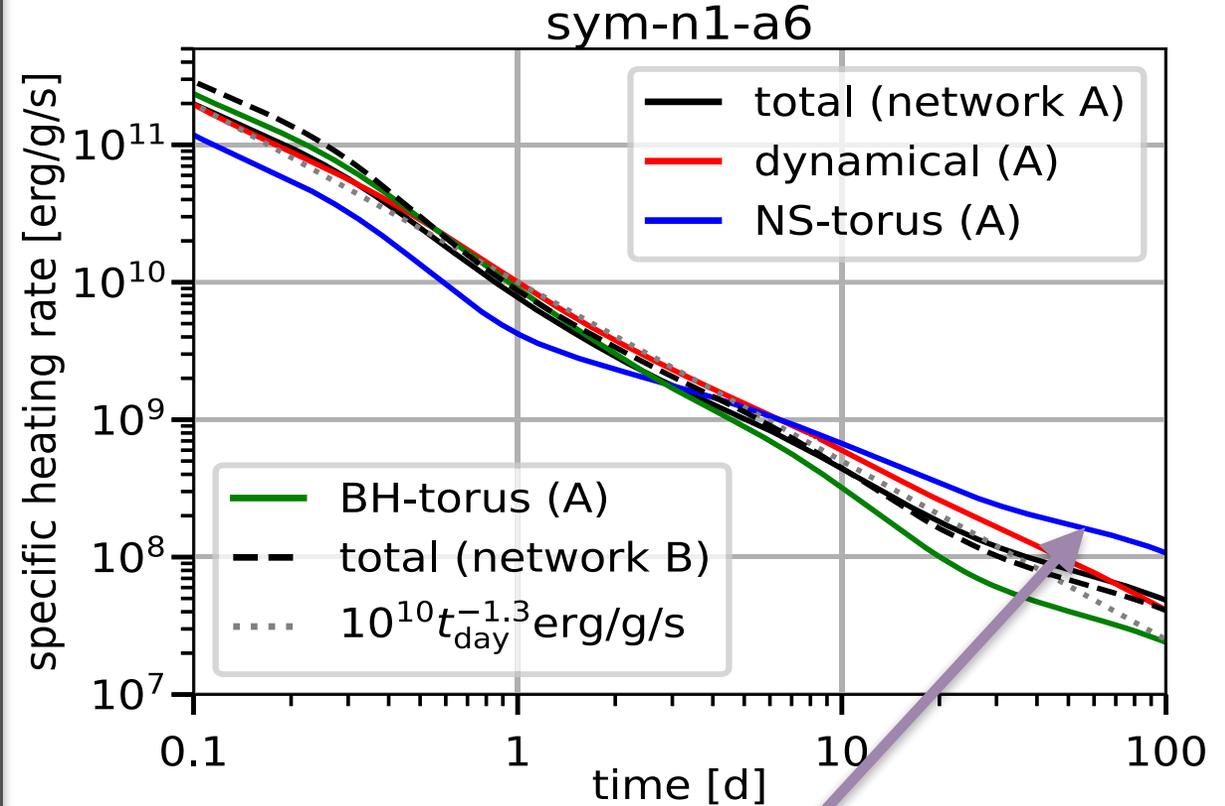
- ▶ only mild sensitivity to viscosity and mass ratio
- ▶ trend of less neutron-rich matter for longer NS lifetime

Elemental yields & nuc. heating rate ($t_{\text{BH}} \sim 120\text{ms}$ model)

(O) et al., ApJL 951, L12, 2023)



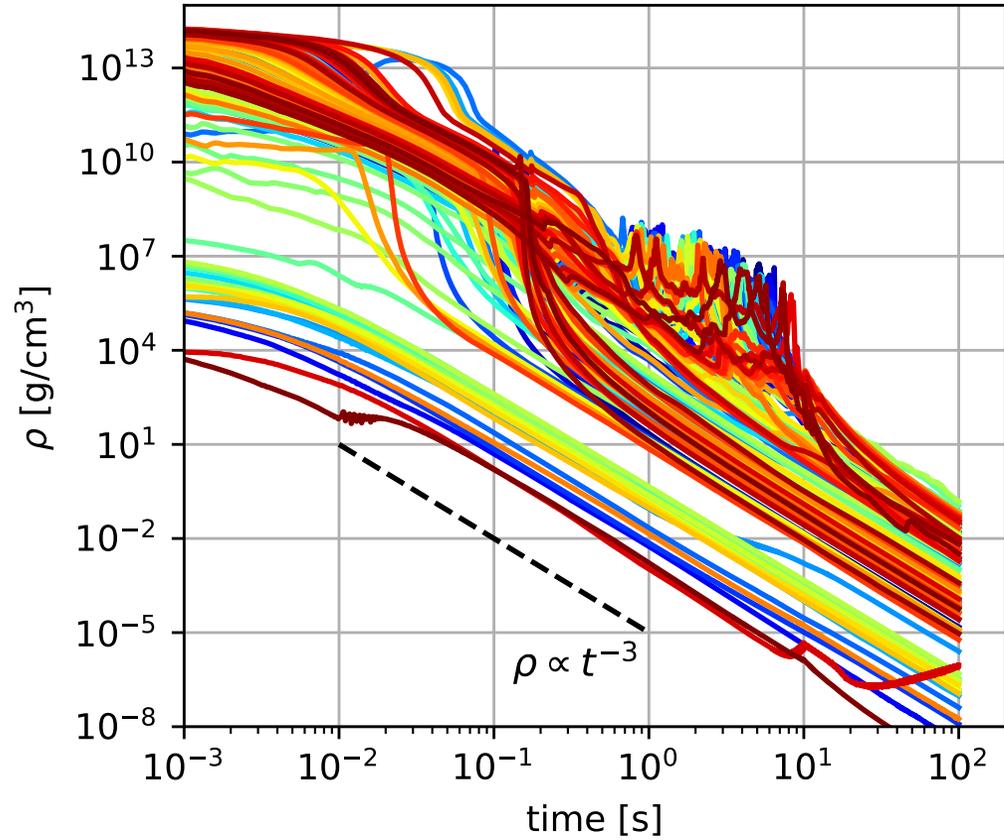
- ▶ observed metal-poor star HD 222925 (Roederer '22)



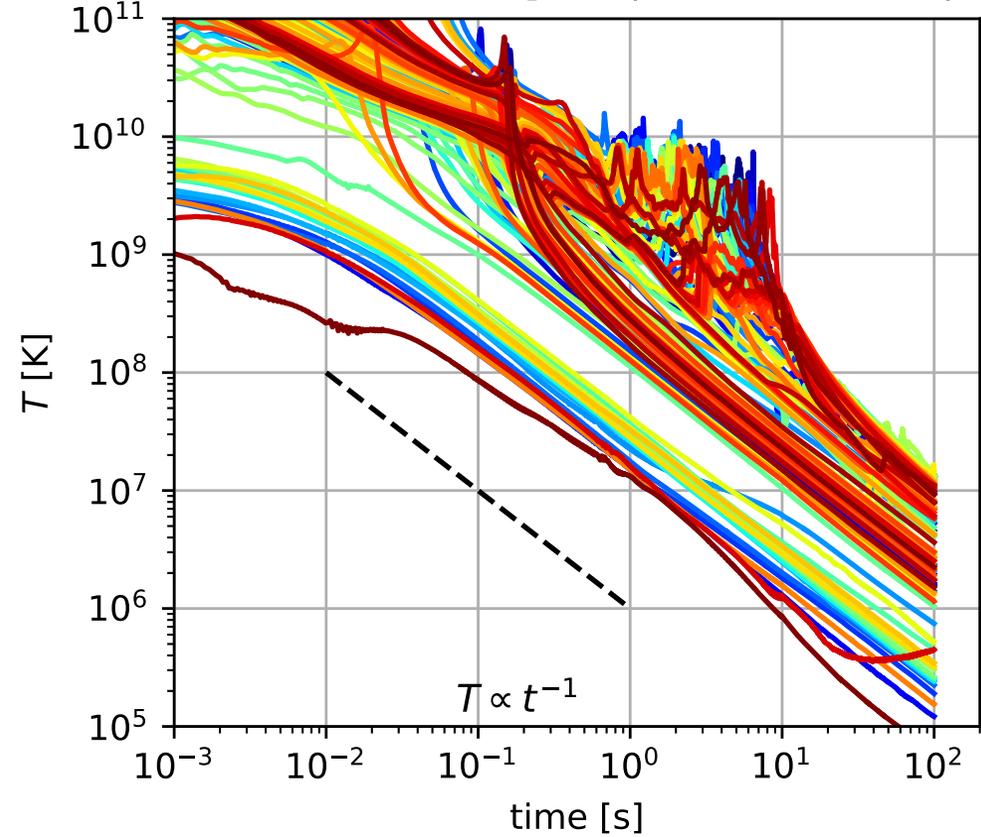
- ▶ late-time increase in NS-torus winds from Ni56 and Co56 decay
- ▶ may be hard to see in KN due to inefficient thermalization (see Jacobi+25)

Long-term evolution until homologous expansion

density



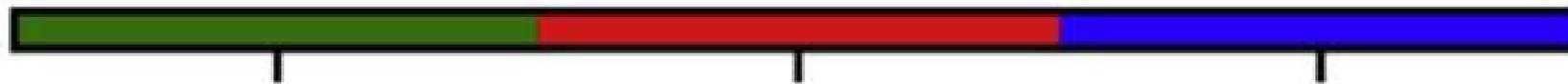
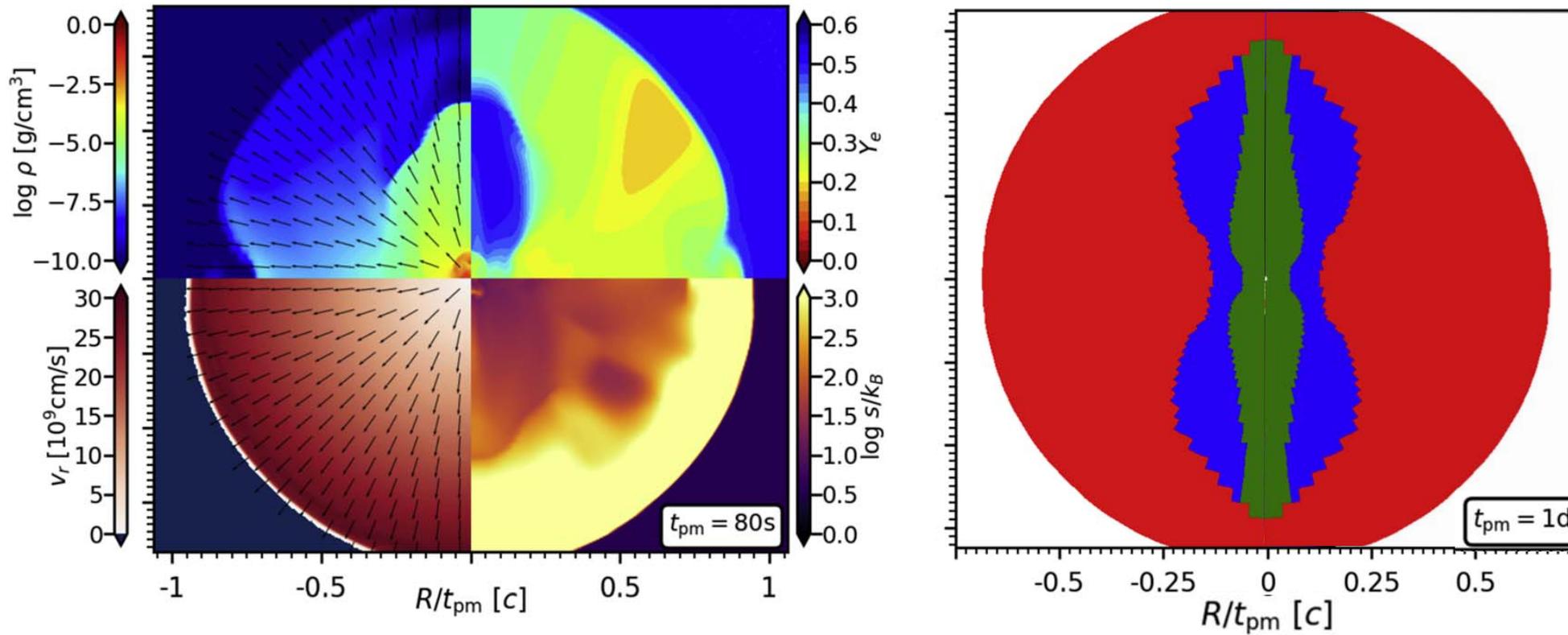
temperature



► almost all outflow homologous after ~ 10 - 100 s

Final ejecta distribution ($\tau_{\text{BH}} \sim 120\text{ms}$ model)

(O) et al., ApJL 951, L12, 2023)



BH-torus ejecta:

$m \sim 0.01-0.04 M_{\odot}$

$\langle v \rangle \sim 0.03-0.1 c$

dynamical ejecta:

$m \sim 0.001-0.01 M_{\odot}$

$\langle v \rangle \sim 0.2-0.4 c$

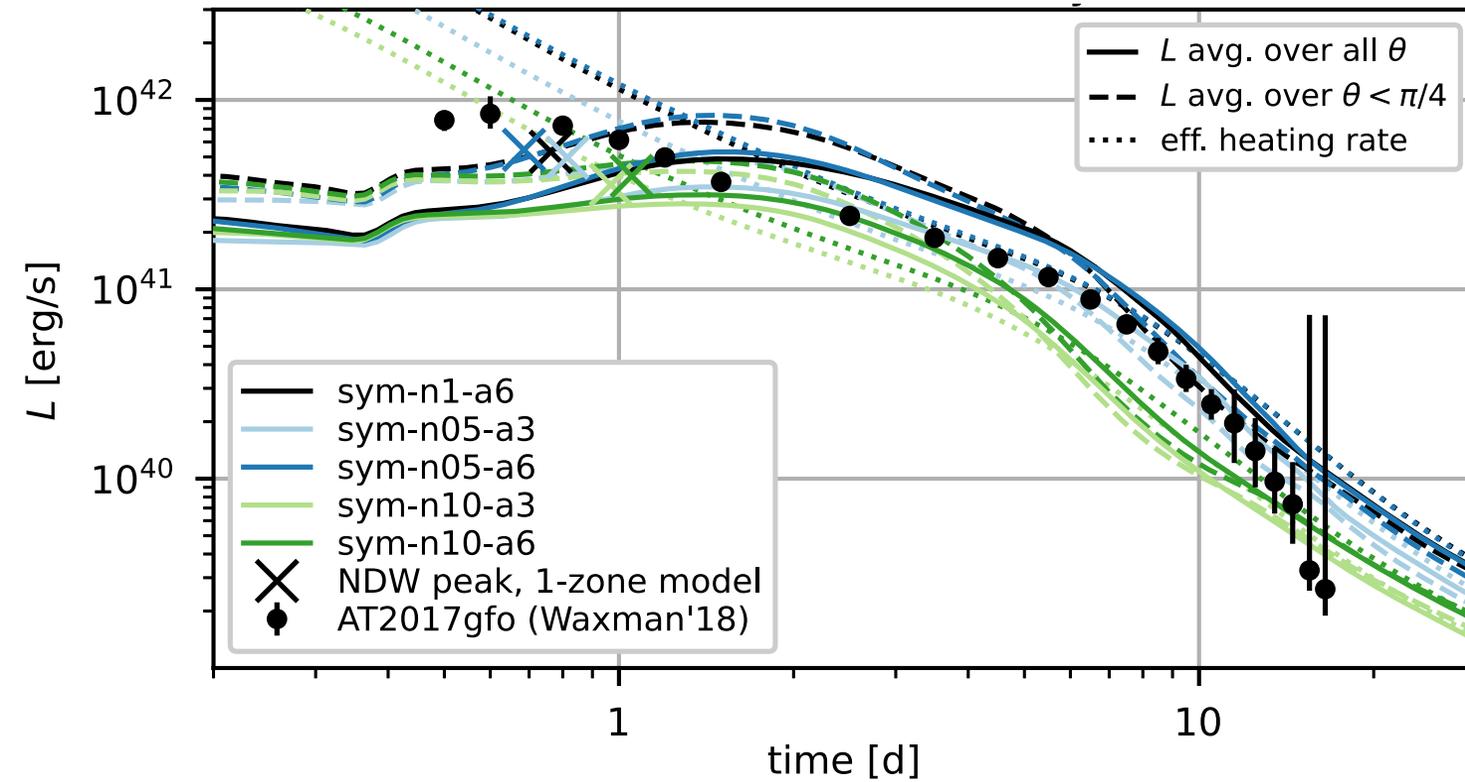
NS-torus ejecta:

$m \sim 0.01-0.04 M_{\odot}$

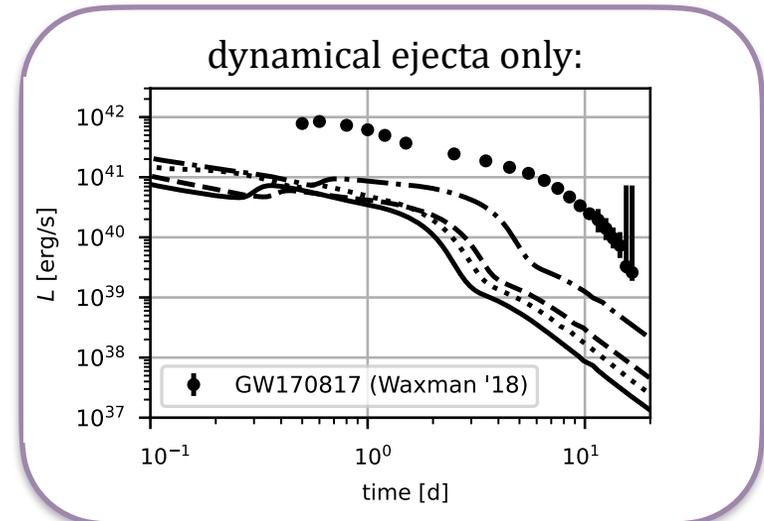
$\langle v \rangle \sim 0.1-0.2 c$

Kilonova bolometric light curve

(O) et al., ApJL 951, L12, 2023)



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



(see also Kawaguchi+21,22, Combi+23, Bernuzzi+24)

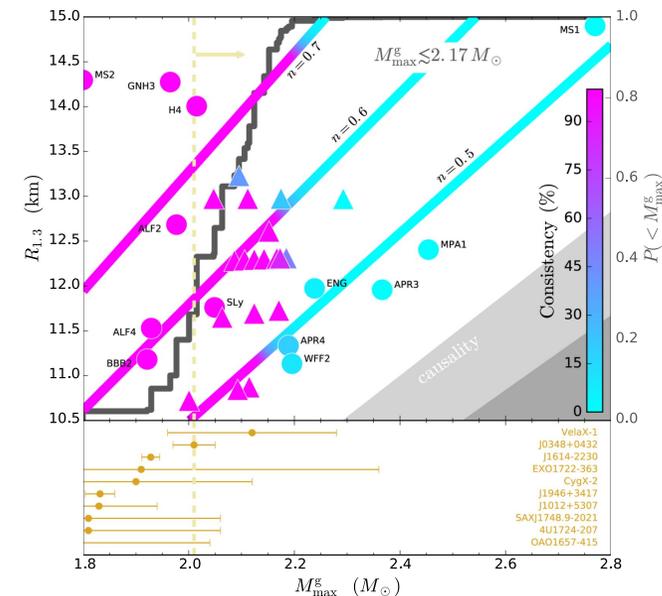
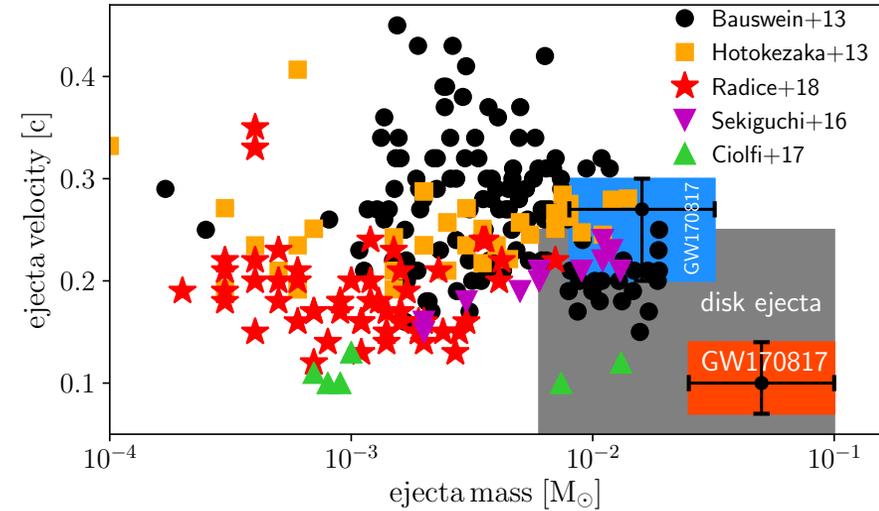
Helium as an indicator of the neutron-star merger remnant lifetime and its potential for equation of state constraints

(A. Sneppen, OJ, A. Bauswein, R. Damgaard, D. Watson, L. J. Shingles, C. E. Collins, S. A. Sim, Z. Xiong, G. Martinez-Pinedo, T. Saultanis, and V. Vijayan, *submitted, arxiv:2411.03427*)

What was the lifetime τ_{BH} of the NS remnant in GW170817?

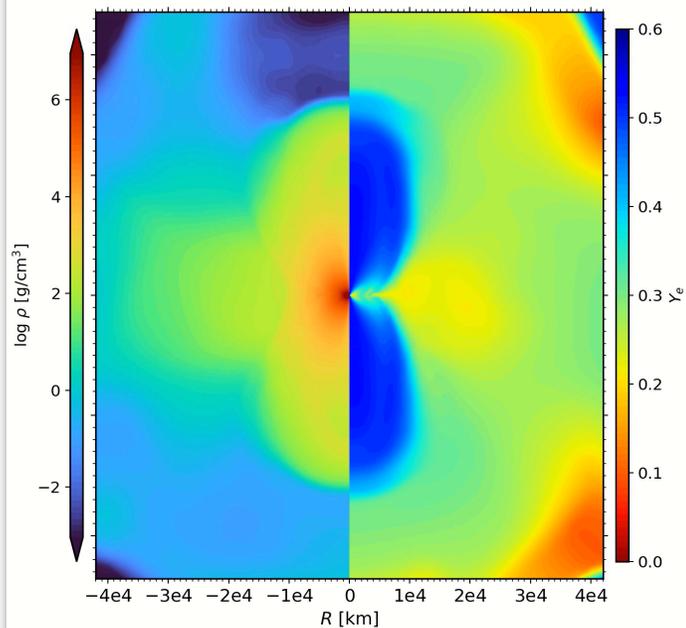
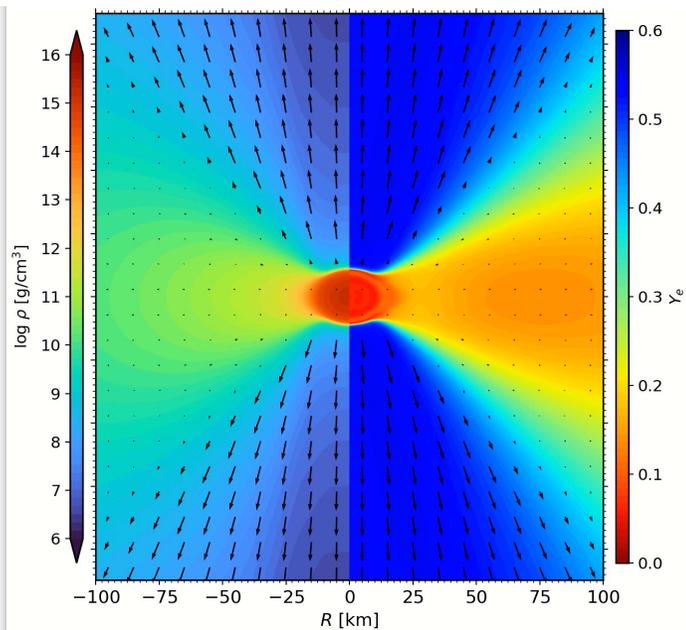
(compilation by Siegel '19)

- ▶ prompt collapse scenario ($\tau_{\text{BH}} = 0$) almost certainly excluded because of bright KN \Leftrightarrow high ejecta masses (Bauswein+17, Radice+18, ...)
- ▶ absence of spindown emission + observed sGRB signal (Margalit+17, Shibata+18, Rezzolla+18, ...) $\Rightarrow \tau_{\text{BH}} \lesssim 1.7$ sec
- ▶ lifetime of NS remnant still largely unconstrained within $10 \text{ ms} \lesssim \tau_{\text{BH}} \lesssim 1.7 \text{ s}$



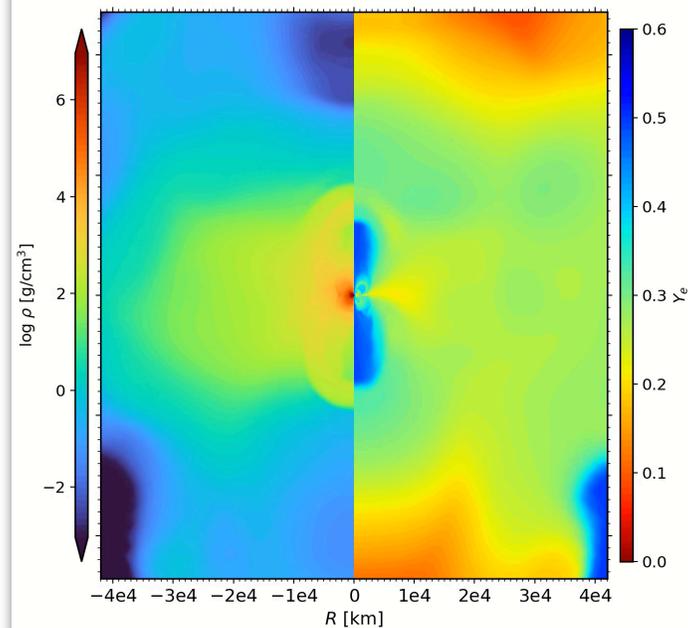
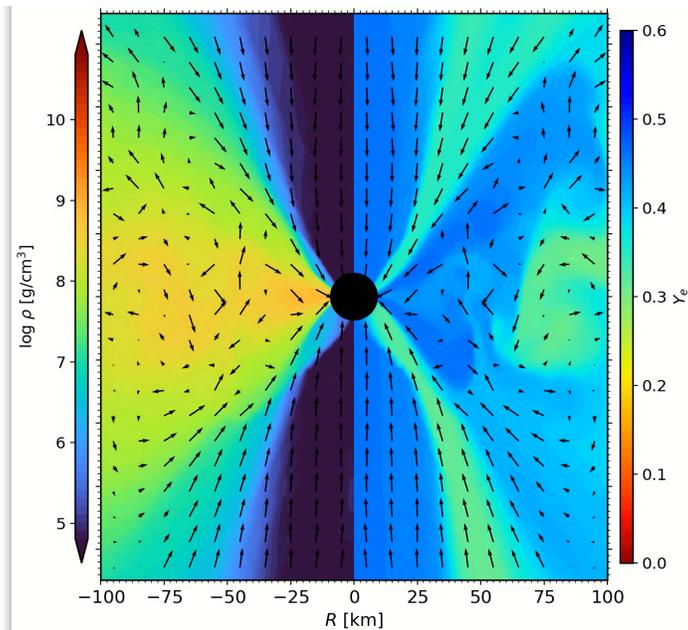
(Margalit+17)

long-lived HMNS



time = 206.0 ms

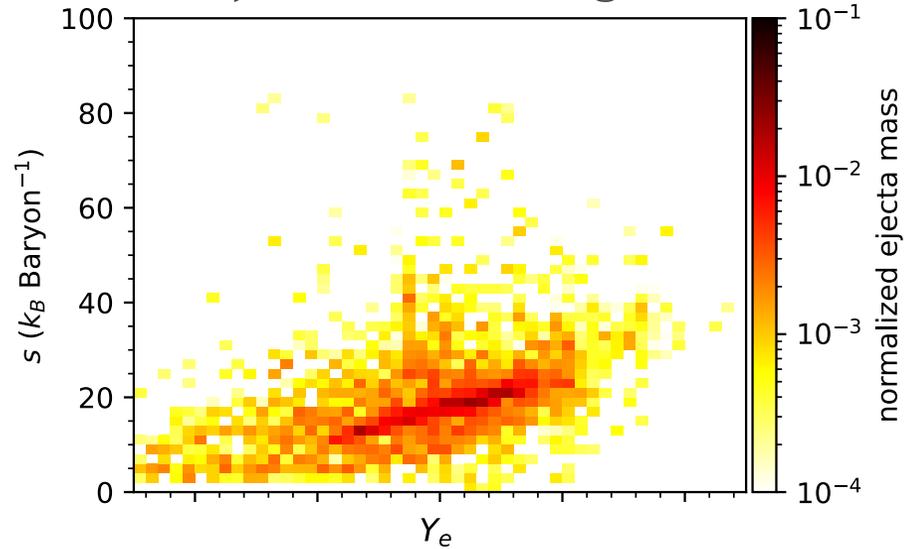
short-lived HMNS



time = 206.0 ms

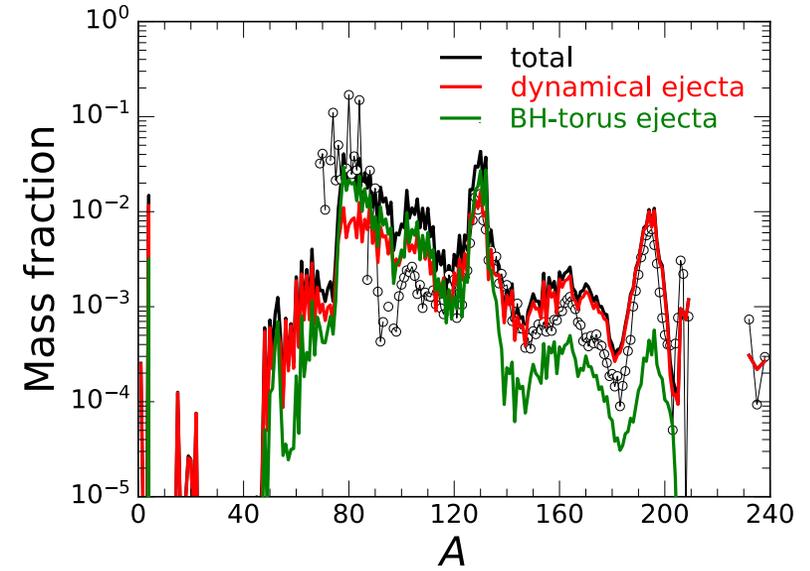
Short- vs. long-lived NS remnant

ejecta mass histogram



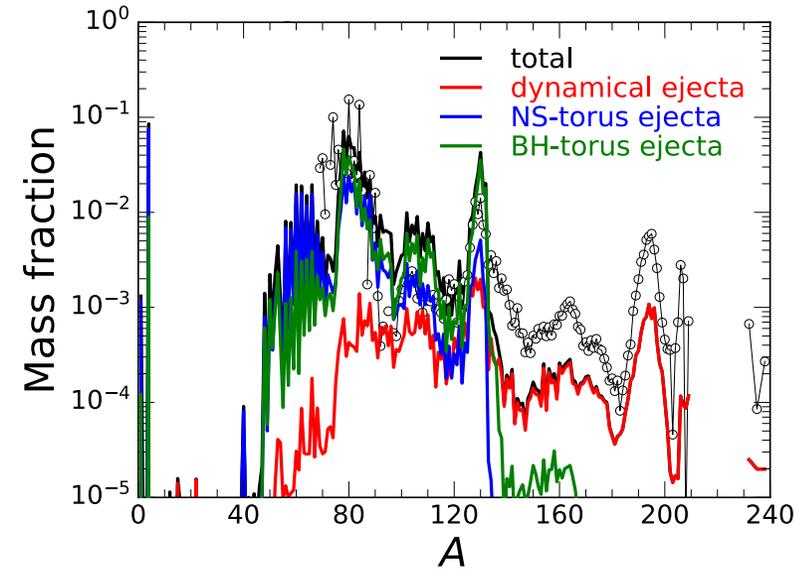
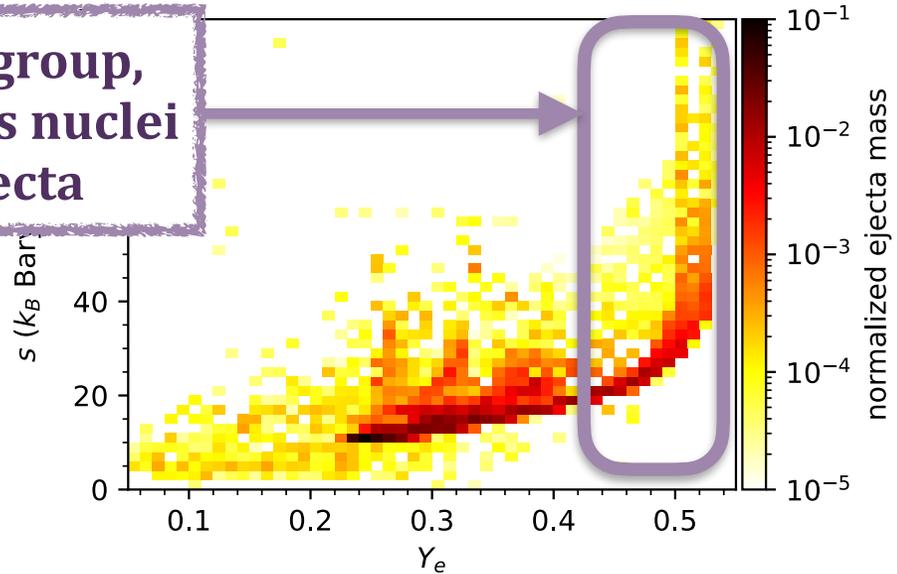
short-lived
(10ms)

ejecta nucleosynthesis yields



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

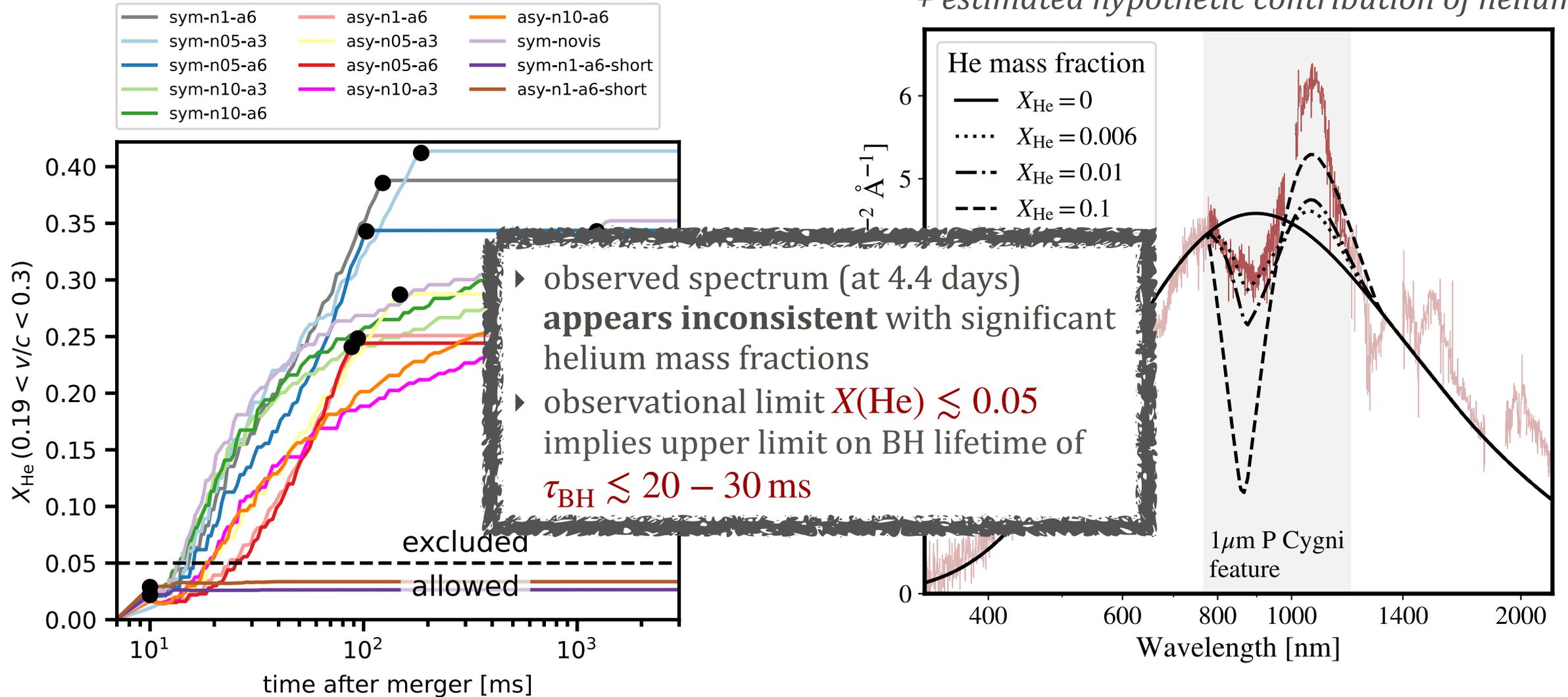
long-lived
(120ms)



Helium production in NS merger models

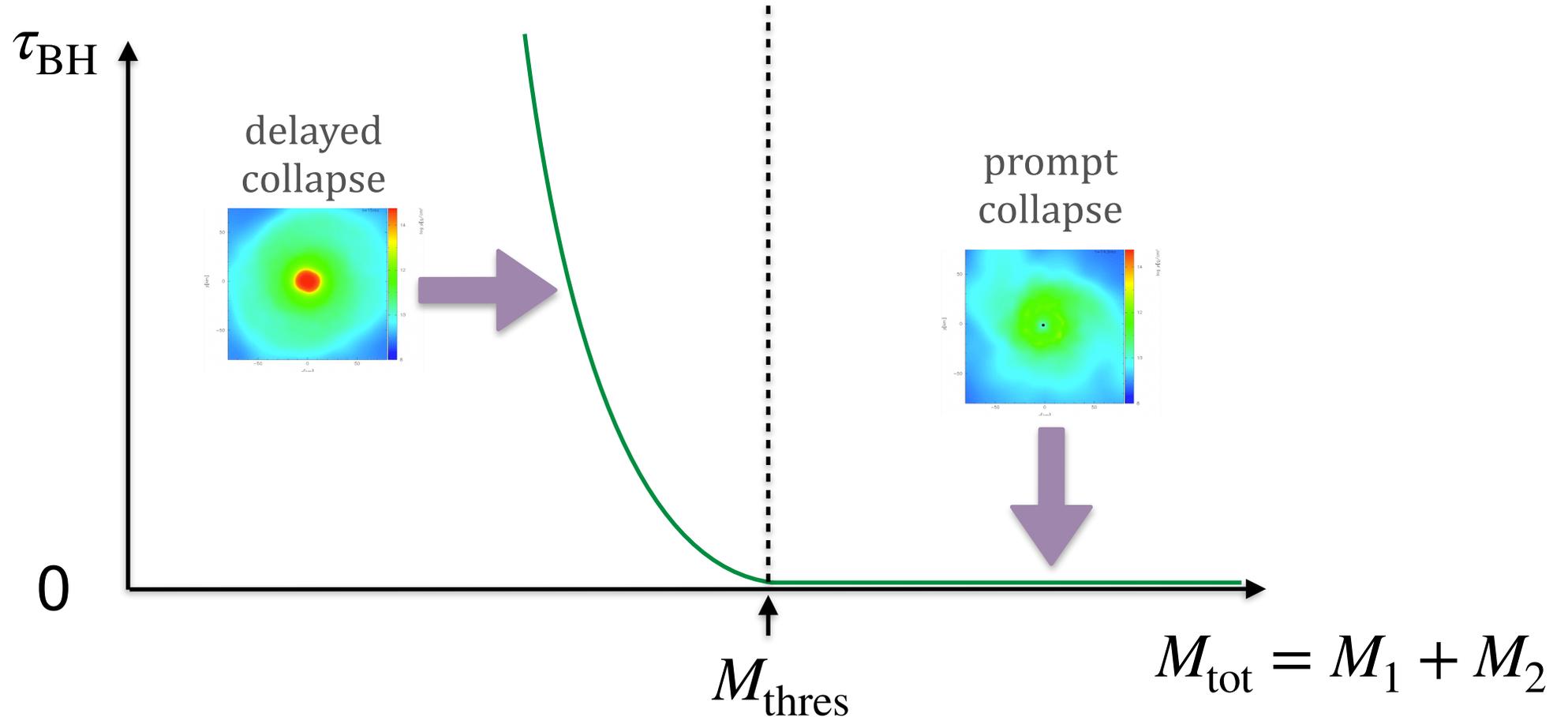
hydro models

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



(for helium interpretation also see Perego+22,
Tarumi+23, Sneppen+24)

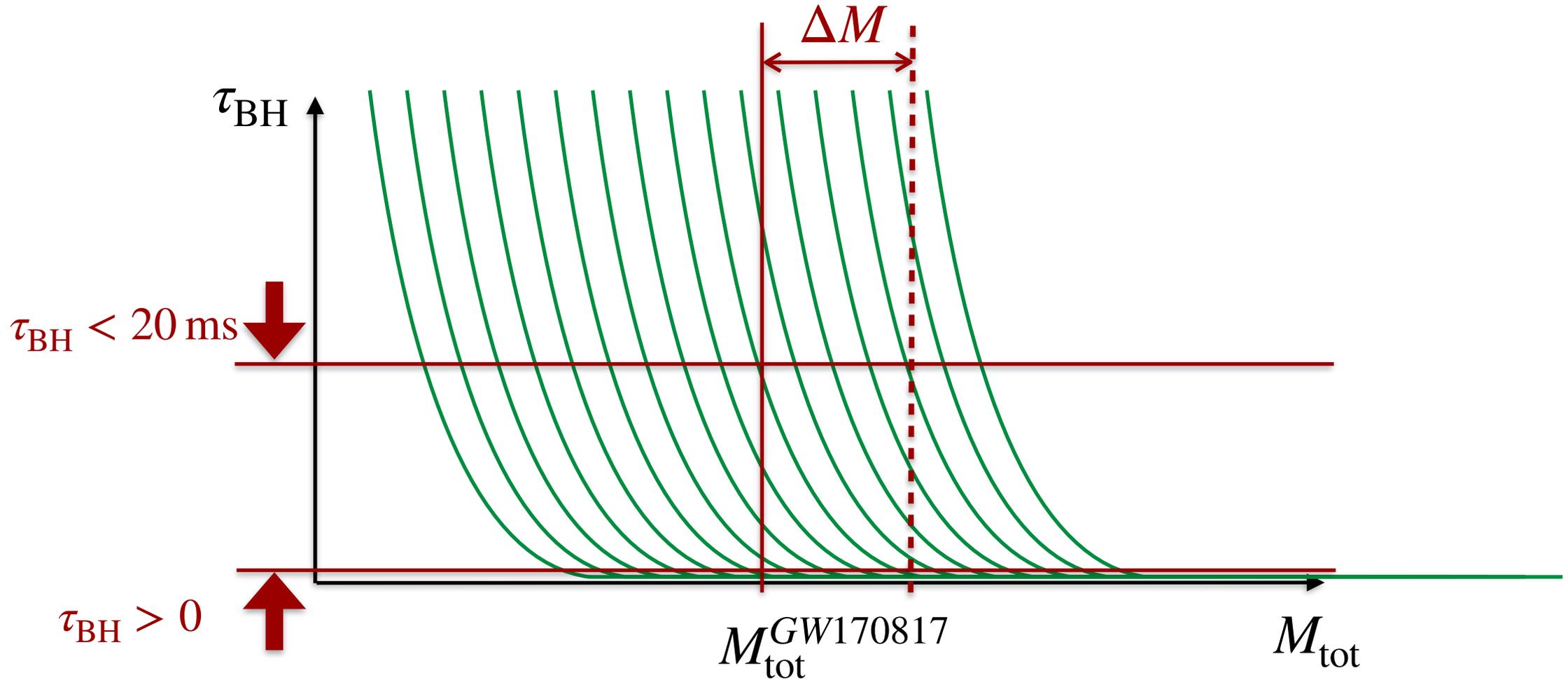
Connecting remnant lifetime with the EOS: The $\tau_{\text{BH}} - M_{\text{tot}}$ relationship



- ▶ threshold mass M_{thres} separates prompt-collapse from delayed-collapse cases

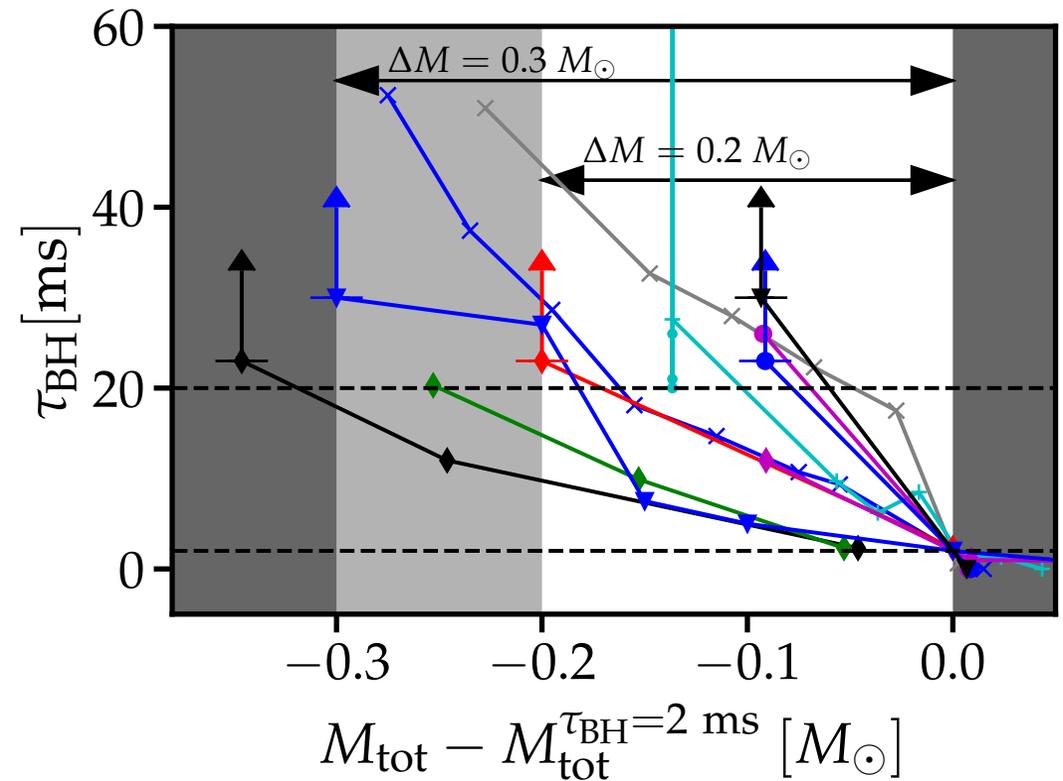
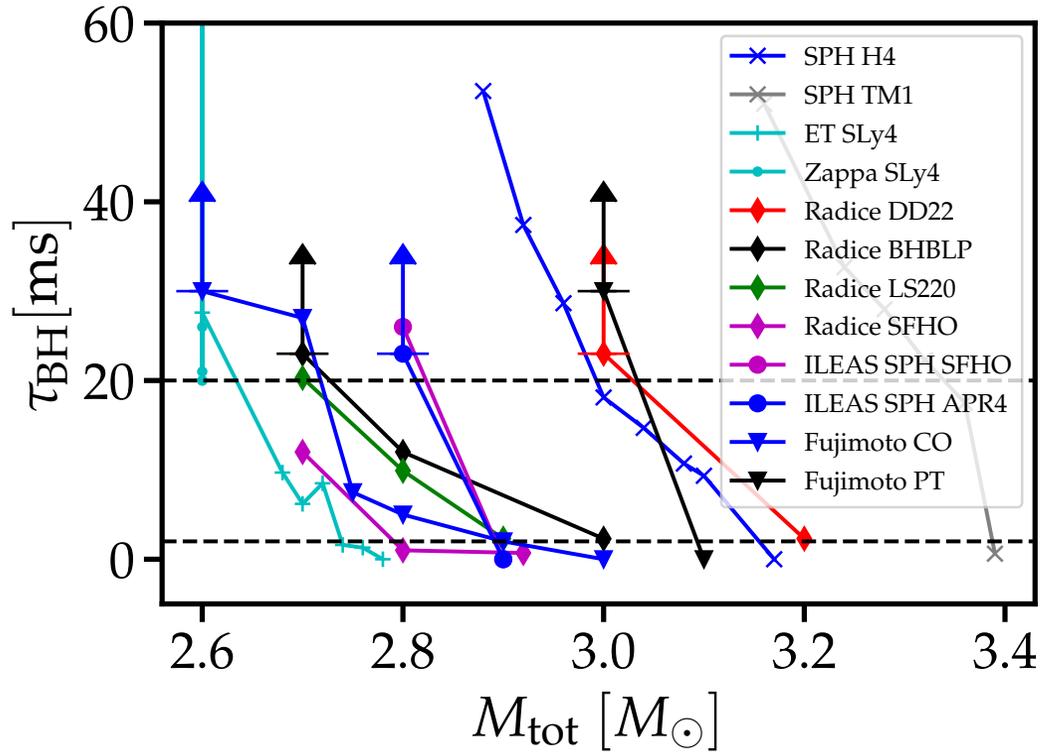
(e.g. talks by Radice, Dietrich)

Implications of $\tau_{\text{BH}} > 0$ and $\tau_{\text{BH}} < 20$ ms



$$M_{\text{tot}}^{\text{GW170817}} < M_{\text{thres}} < M_{\text{tot}}^{\text{GW170817}} + \Delta M$$

Reasonable choice for ΔM ?

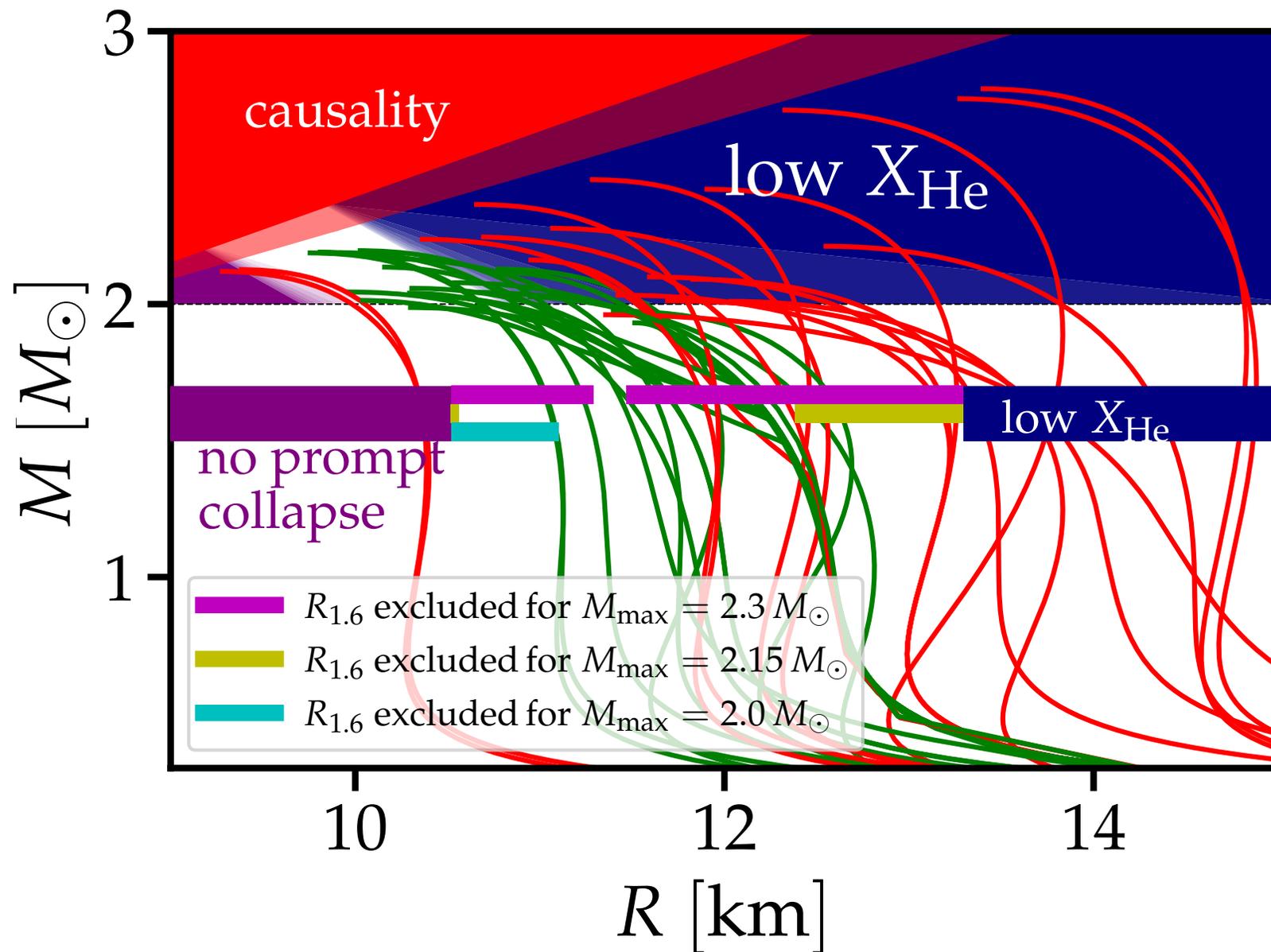


- ▶ challenging: numerical errors, missing physical ingredients, sparsity of published simulations, ...
- ▶ $\tau_{\text{BH}} < 20$ ms suggests $\Delta M \approx 0.2 M_{\odot}$
- ▶ exploit empirical relations (e.g. Bauswein+19, Kölsch+23):

$$M_{\text{thres}}(q, M_{\text{max}}, R) = c_1 M_{\text{max}} + c_2 R + c_3 + c_4 \delta q^3 M_{\text{max}} + c_5 \delta q^3 R$$

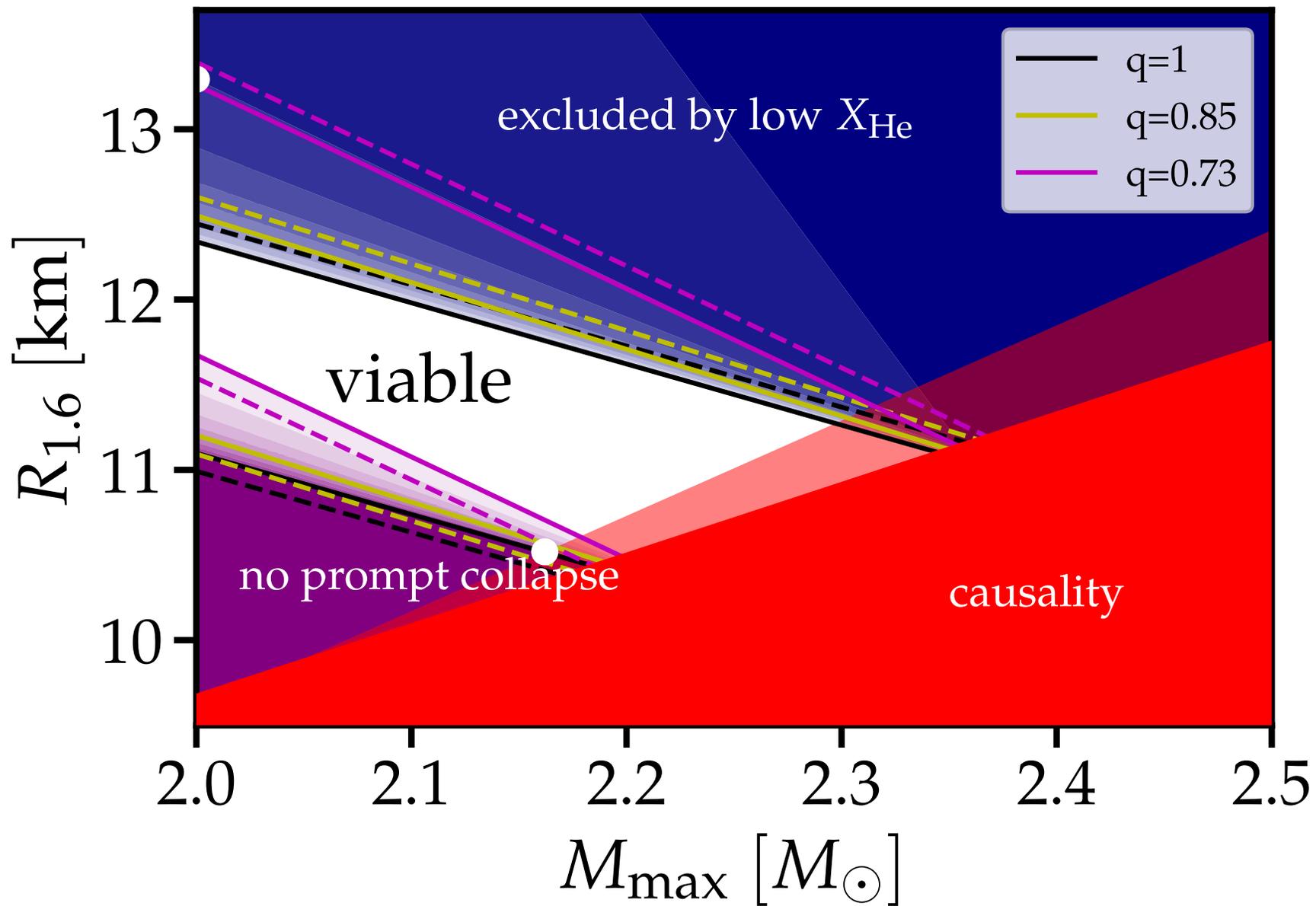
Implications for NS properties

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



Implications for NS properties

- ▶ narrow window of allowed values
- ▶ potentially powerful new EOS constraint, but with remaining modeling uncertainties

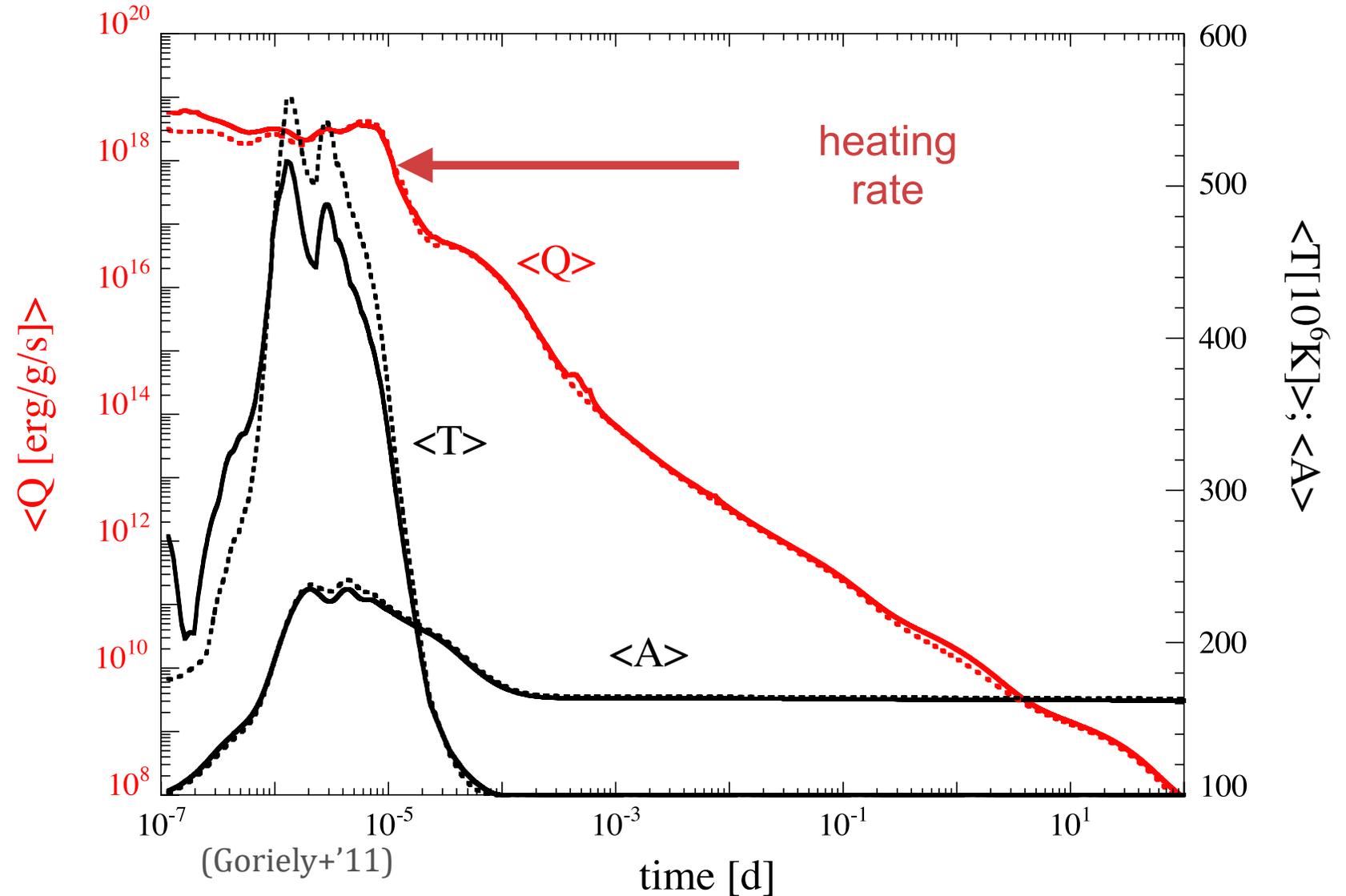


RHINE: R-process Heating Implementation in hydrodynamic simulations with NEural networks

(O), Z. Xiong, G. Martinez-Pinedo, arxiv:2507.09040)

Motivation

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



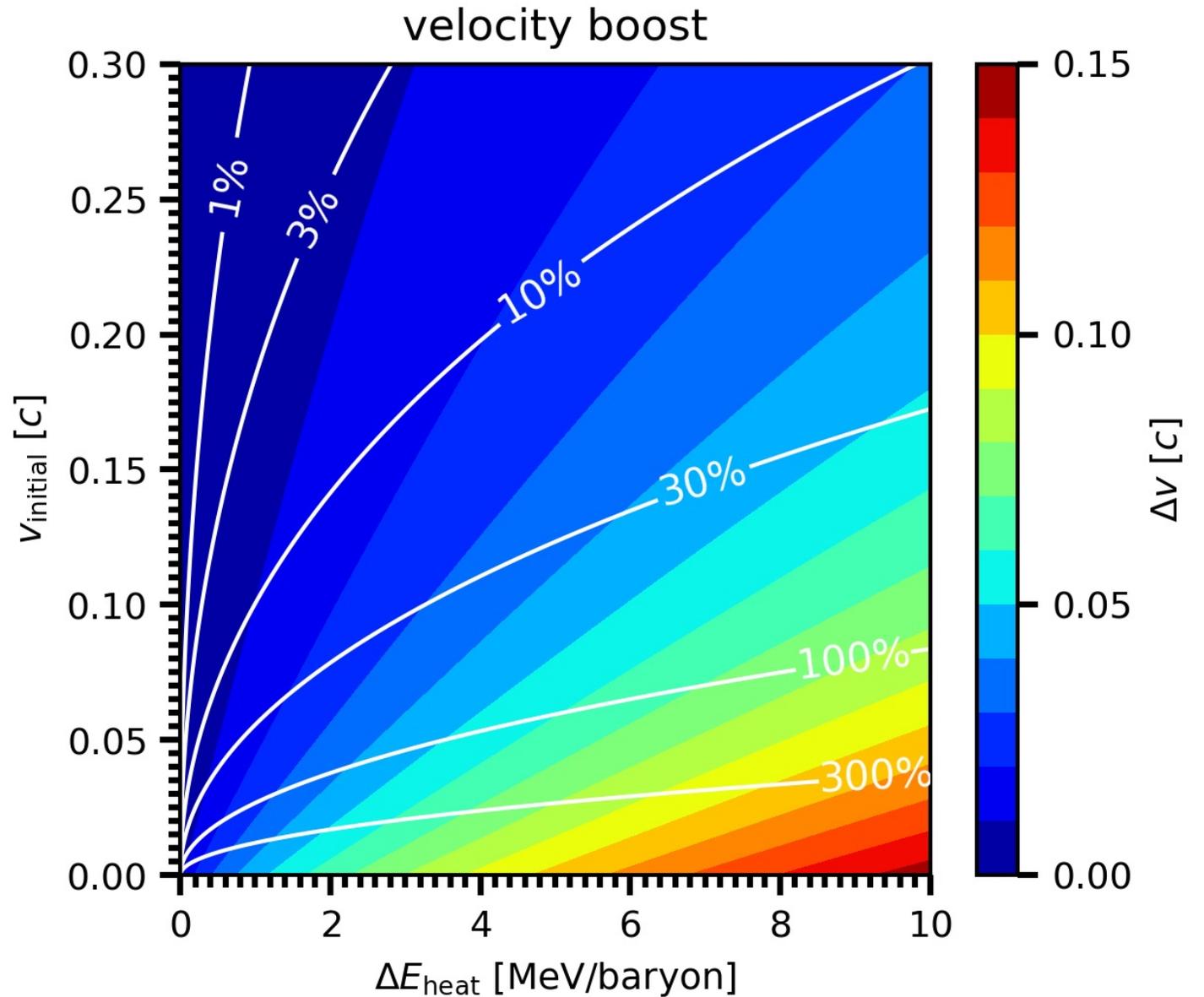
(also see Kawaguchi+22, Magistrelli+24, Ma+25 and talks by Wu, Longo-Michi)

Expected impact on velocity

- ▶ energy conservation:

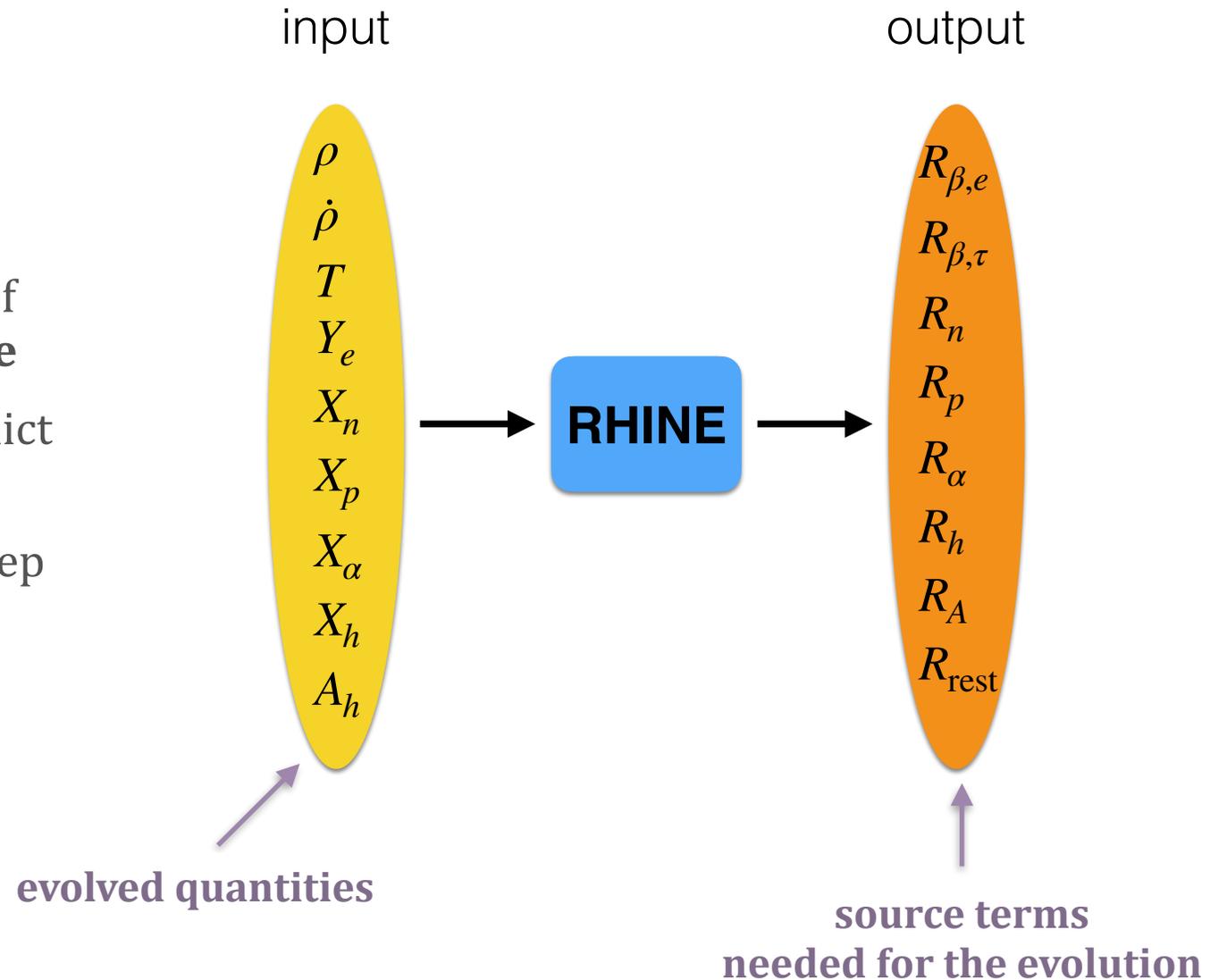
$$W_{\text{final}}mc^2 = W_{\text{initial}}(mc^2 + \Delta E_{\text{heat}})$$

- ▶ stronger velocity boost for initially slow ejecta



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



Multilayer perceptron neural networks

- ▶ each circle represents a “perceptron” or “neuron”
- ▶ information passes through sequence of hidden layers

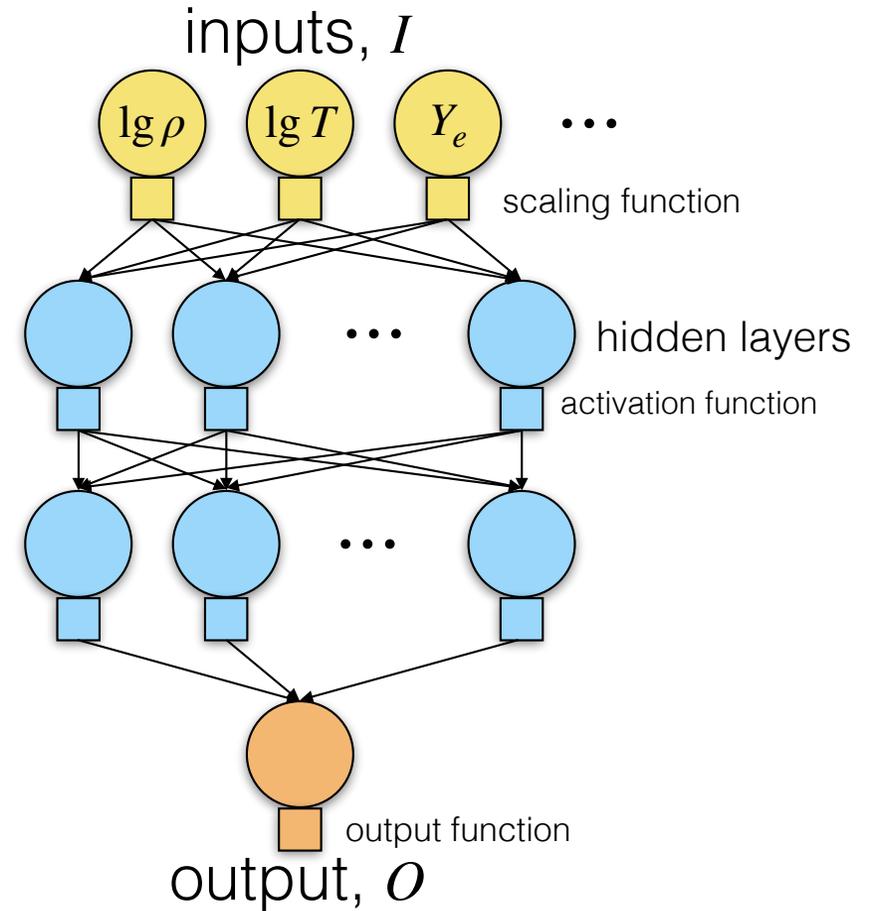
- ▶ output of a perceptron:

$$x^{\text{out}} = f_{\text{act}} \left(\sum_n w_n x_n^{\text{in}} + b \right)$$

- ▶ with non-linear activation function:

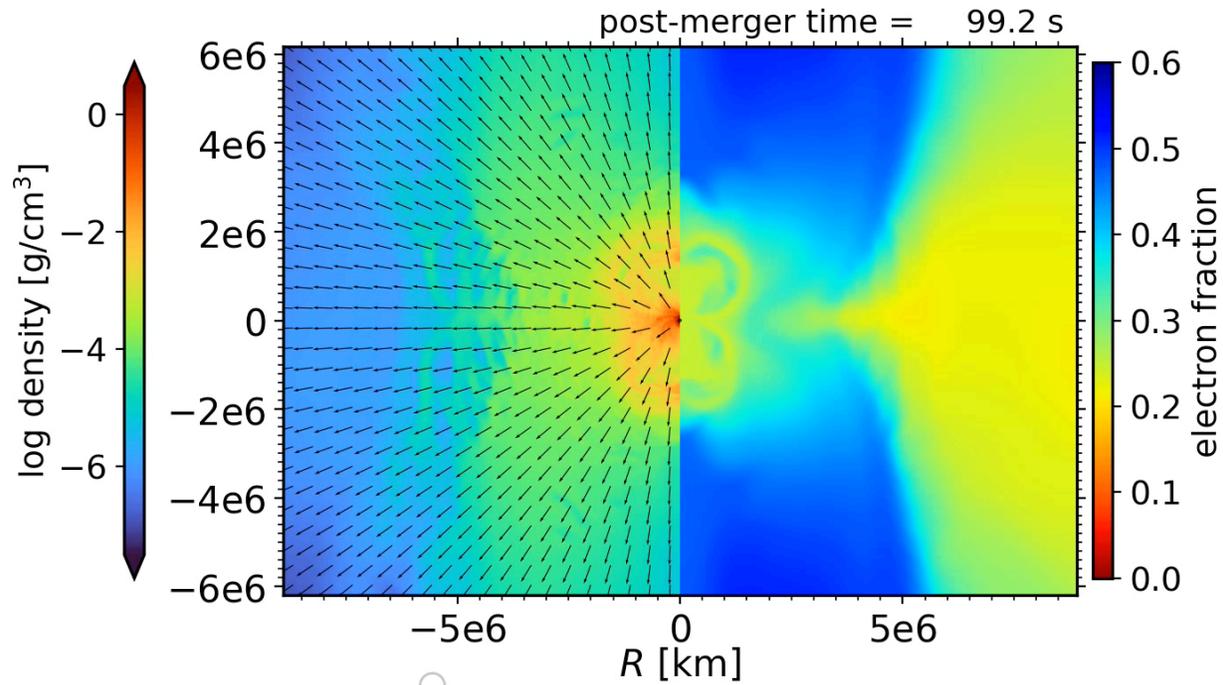
$$f_{\text{act}}(x) = \begin{cases} x, & \text{if } x \geq 0 \\ e^x - 1, & \text{if } x < 0 \end{cases}$$

- ▶ we use 2 hidden layers with 60 perceptrons each
- ▶ altogether ~2500 parameters per neural network

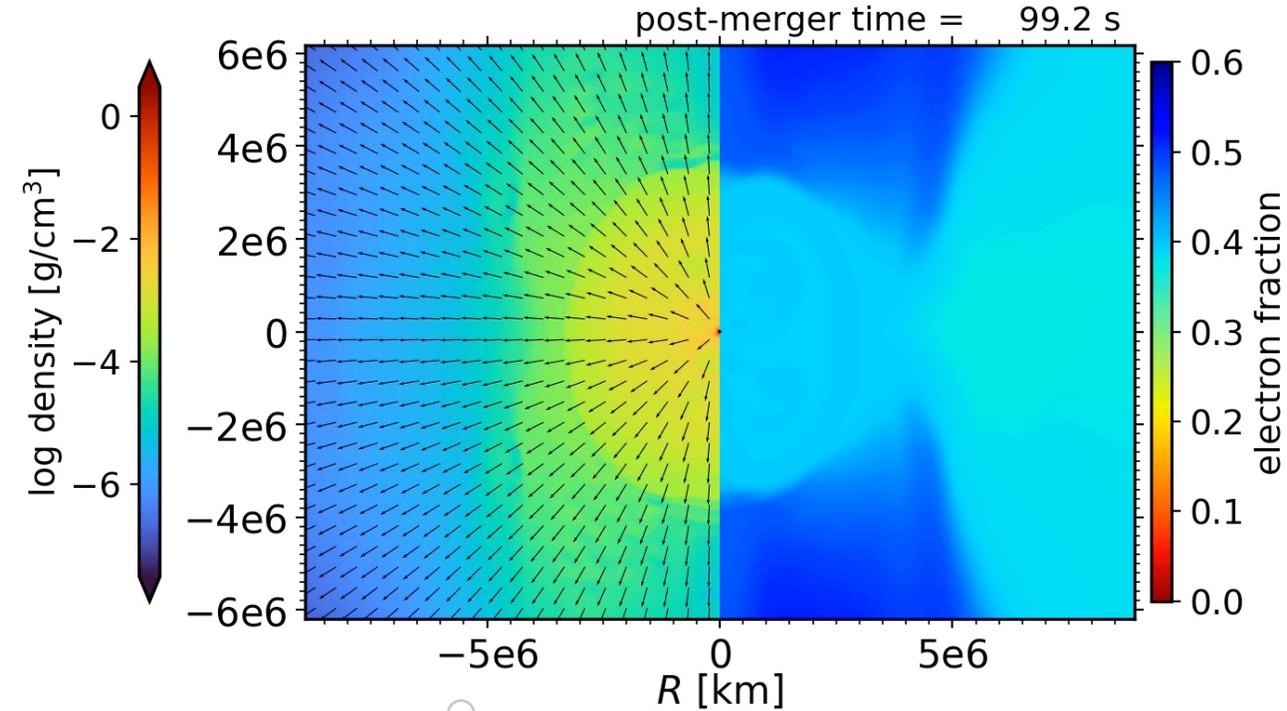


NS merger models + RHINE

without RHINE:

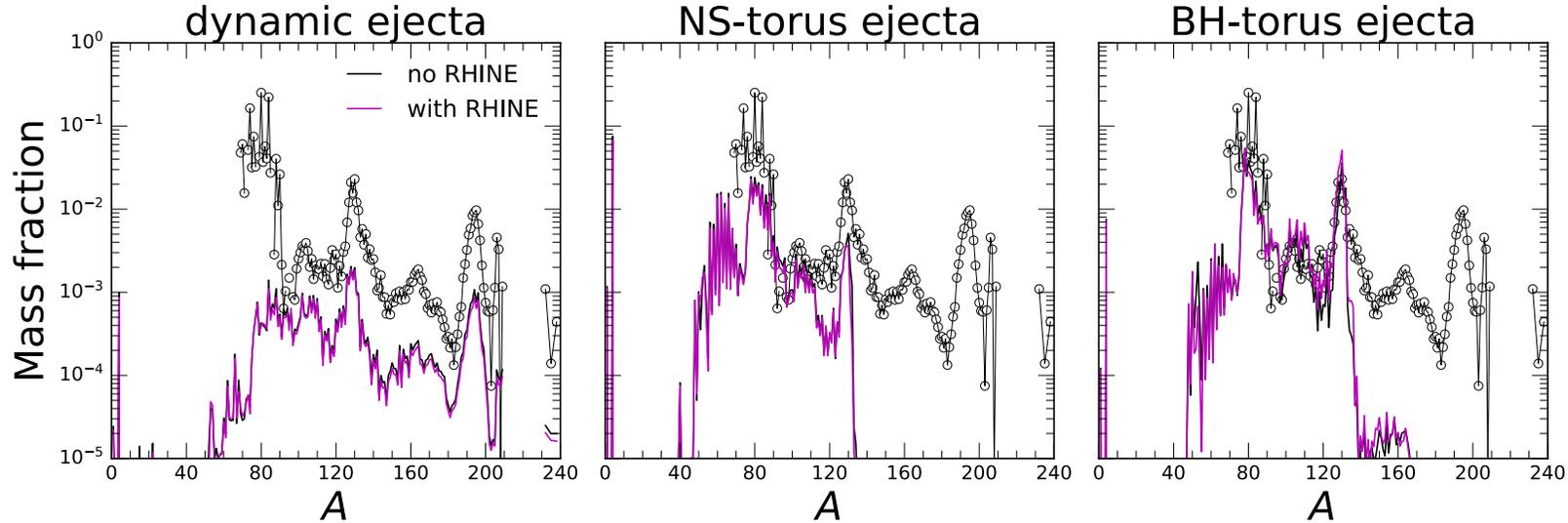
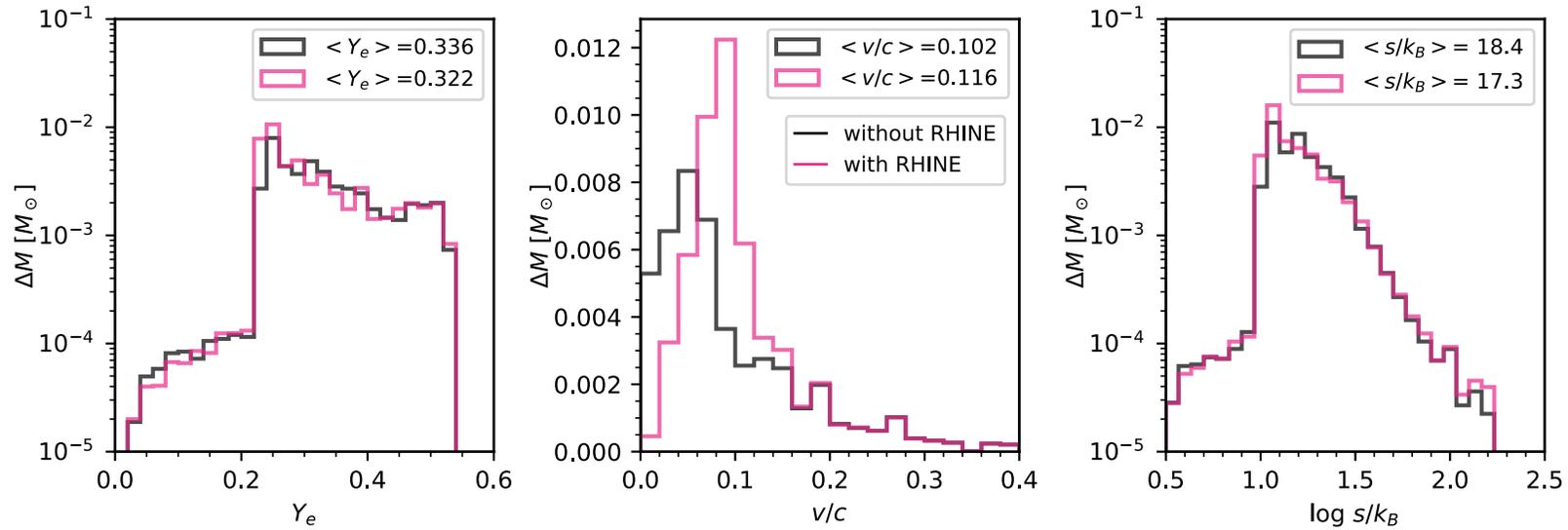


with RHINE:



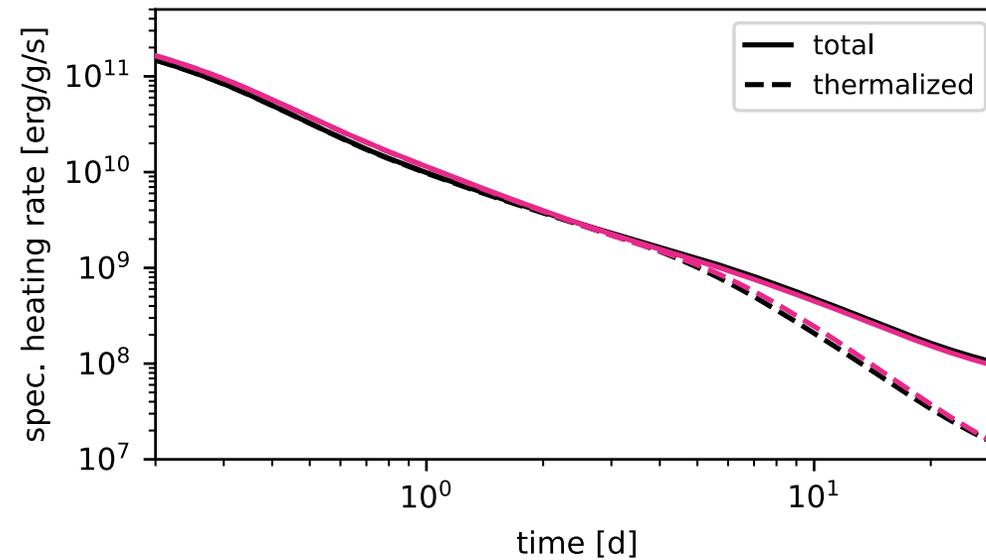
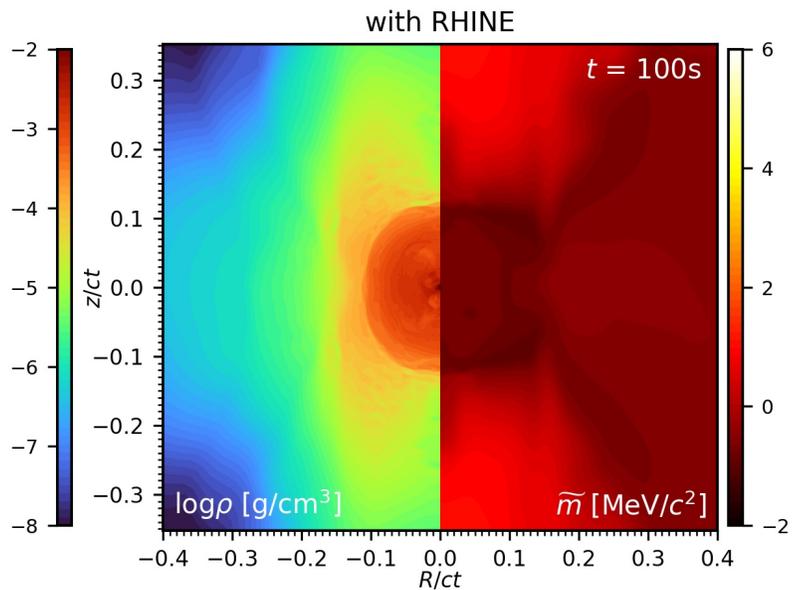
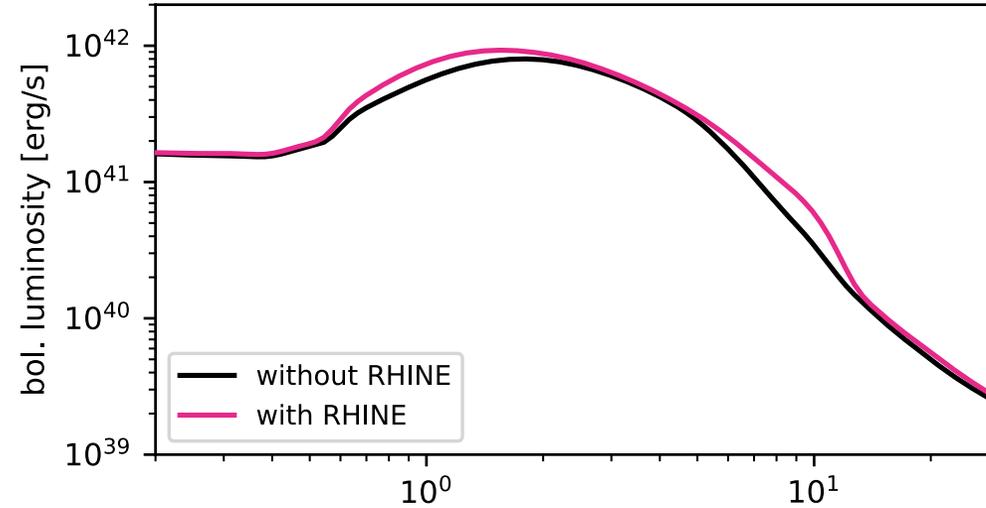
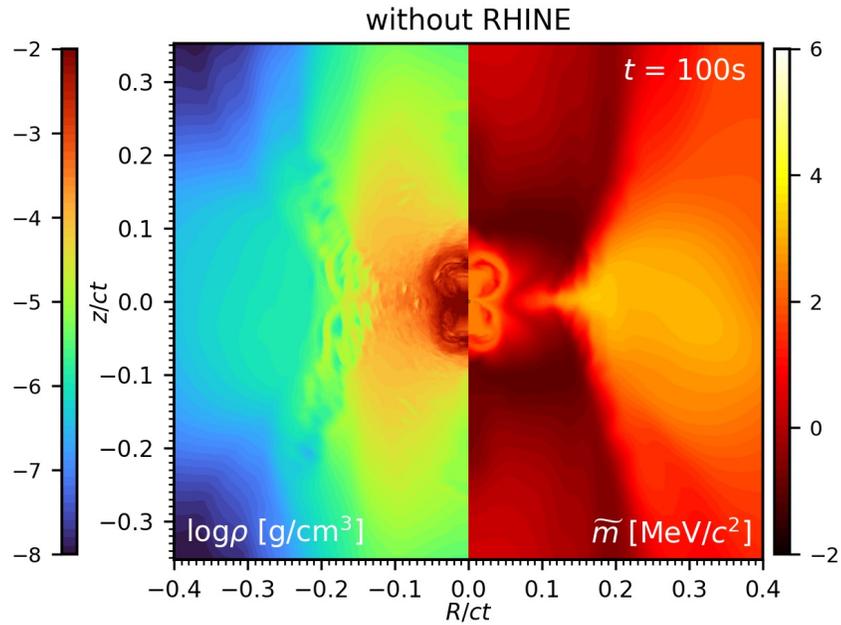
- ▶ accelerates BH-torus ejecta from $\sim 0.04c$ to $\sim 0.08c$
- ▶ makes ejecta more spherical
- ▶ increases ejecta mass

NS merger models + RHINE



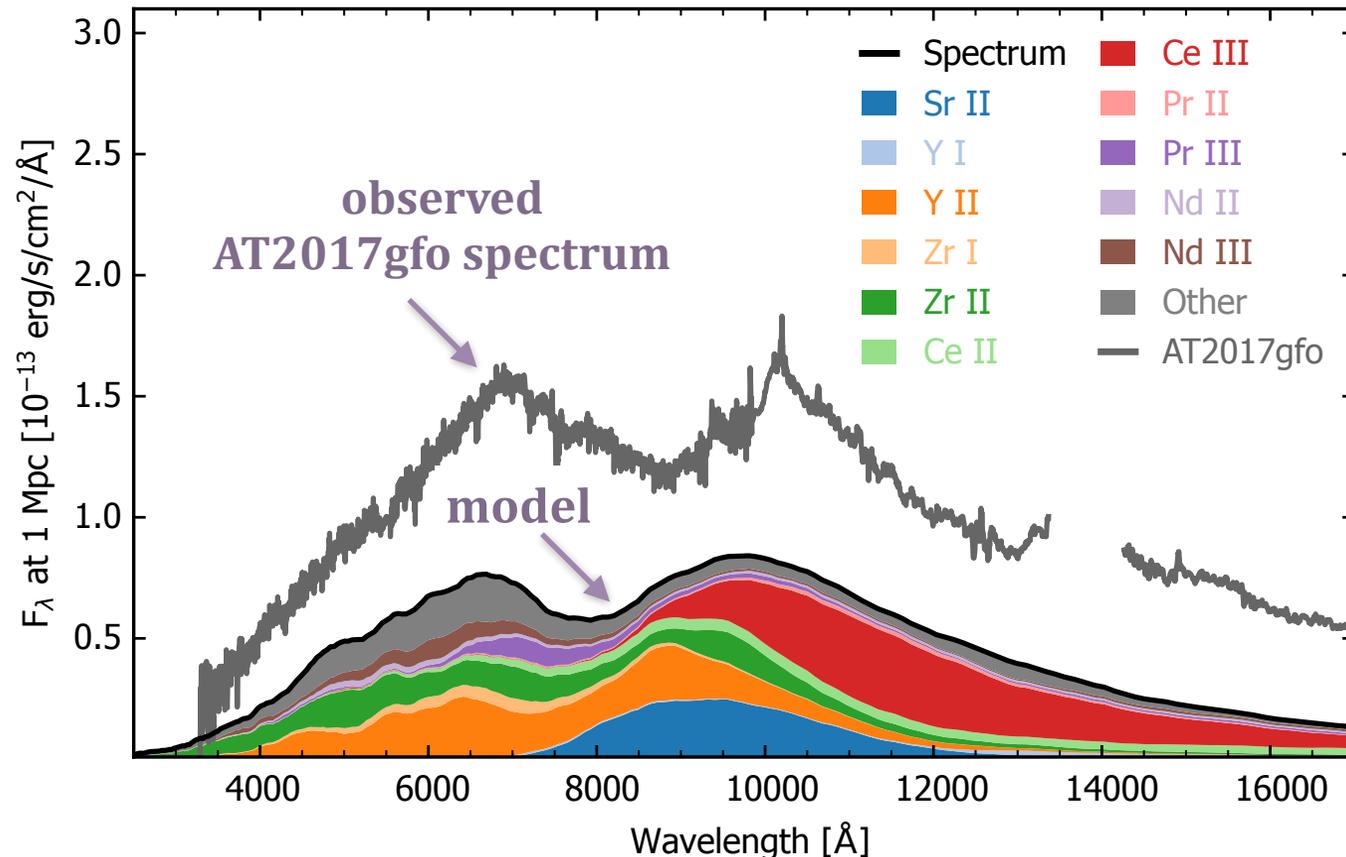
► relatively small impact on nucleosynthesis yields

Impact on kilonova light curve



Step towards more accurate kilonova radiative transfer modeling

(Shingles et al. '23, ApJL 954, L41)



- 3D Monte-Carlo radiative transfer code ARTIS
- line-by-line opacities including detailed atomic data
- so far only dynamical ejecta component (total luminosity lower than AT2017gfo)
- spectra **remarkably similar** to AT2017gfo
- new calibrated opacities by Floers+25

(see Floers+25 for new calibrated opacities)
(for other KN RT works see Tanaka+, Kasen+, Kawaguchi+, Wollaeger+)

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

M. McCann ¹★ L. P. Mulholland ¹ Z. Xiong ² C. A. Ramsbottom ¹ C. P. Ballance ¹ O. Just ^{2,3}
A. Bauswein ^{2,4} G. Martínez-Pinedo ^{2,5,4} F. McNeill ¹ and S. A. Sim ¹

¹*Astrophysics Research Centre, School of Mathematics & Physics, Queen's University Belfast, Belfast BT7 1NN, UK*

²*GSI Helmholtzzentrum für Schwerionenforschung, Planckstraße 1, D-64291 Darmstadt, Germany*

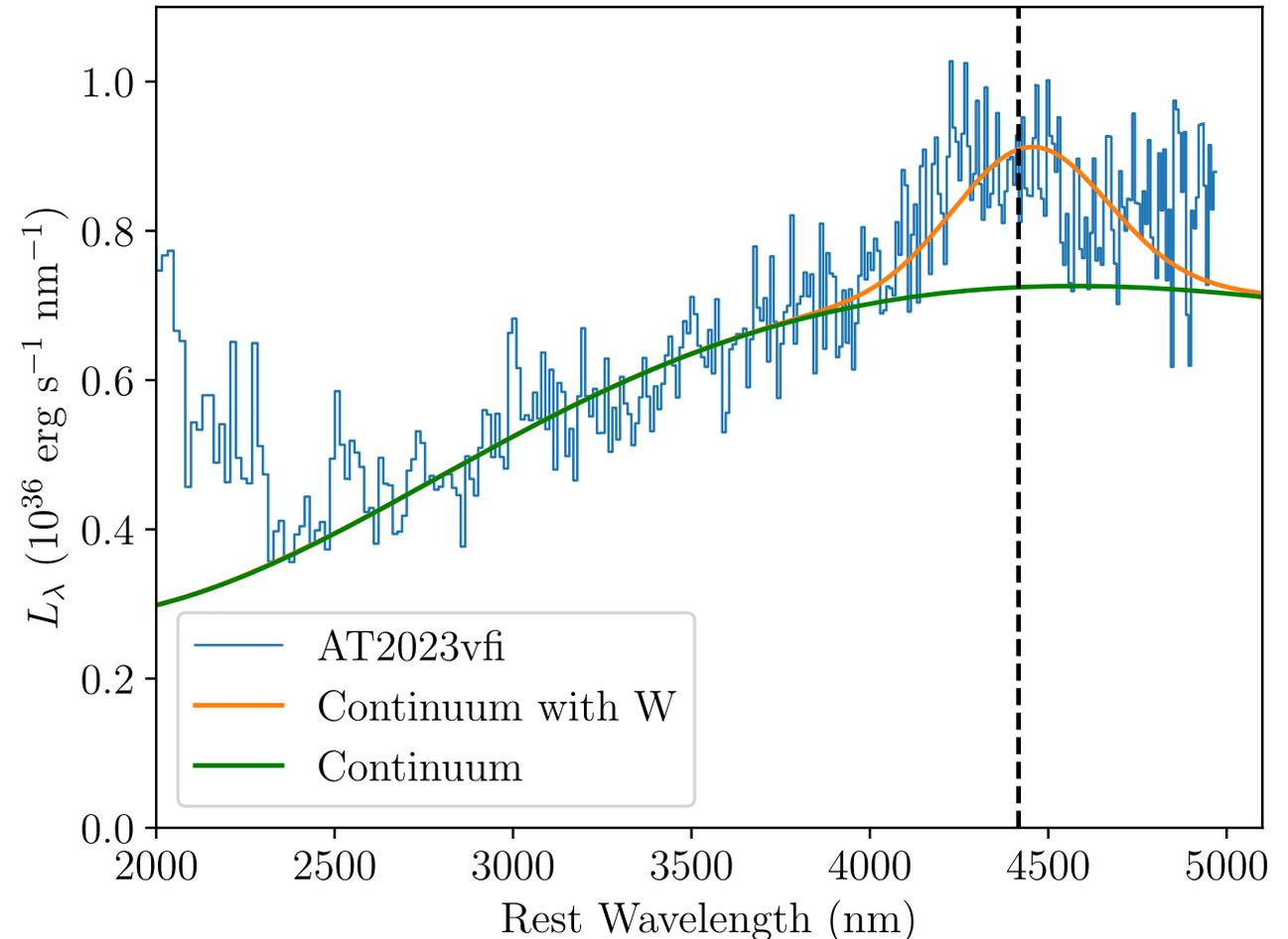
³*Astrophysical Big Bang Laboratory, RIKEN Cluster for Pioneering Research, 2-1 Hirosawa, Wako, Saitama 351-0198, Japan*

⁴*Helmholtz Forschungsakademie Hessen für FAIR, GSI Helmholtzzentrum für Schwerionenforschung, Planckstraße 1, D-64291 Darmstadt, Germany*

⁵*Institut für Kernphysik (Theoriezentrum), Fachbereich Physik, Technische Universität Darmstadt, Schlossgartenstraße 2, D-64289 Darmstadt, Germany*

Motivation

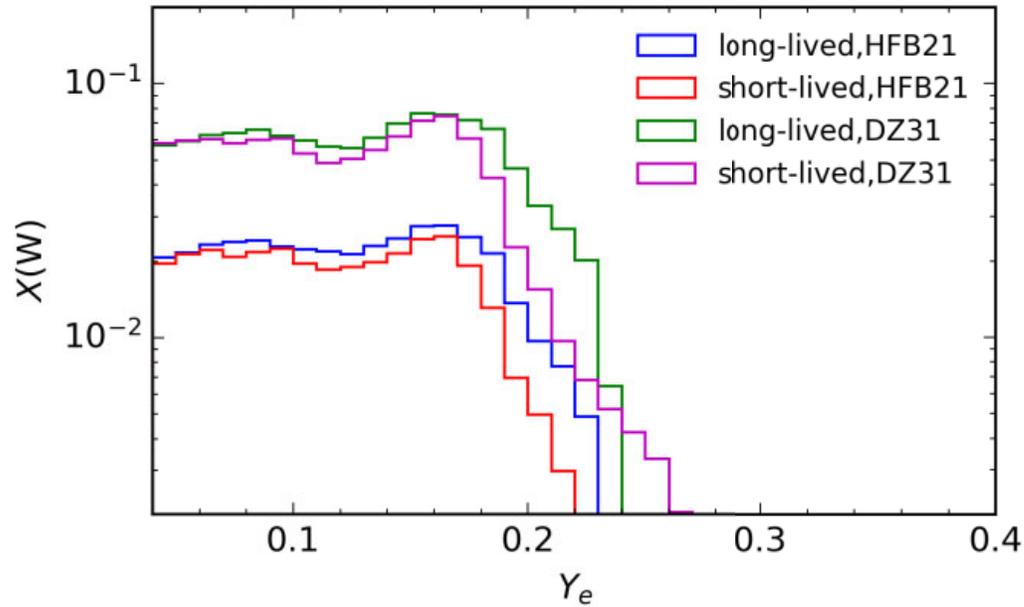
- ▶ new atomic data for W (tungsten, $Z=74$)
- ▶ may explain 4.5 micron bump in late spectrum of long-GRB kilonova AT2023vfi
- ▶ estimated mass: $9.4 \times 10^{-4} M_{\text{sun}}$



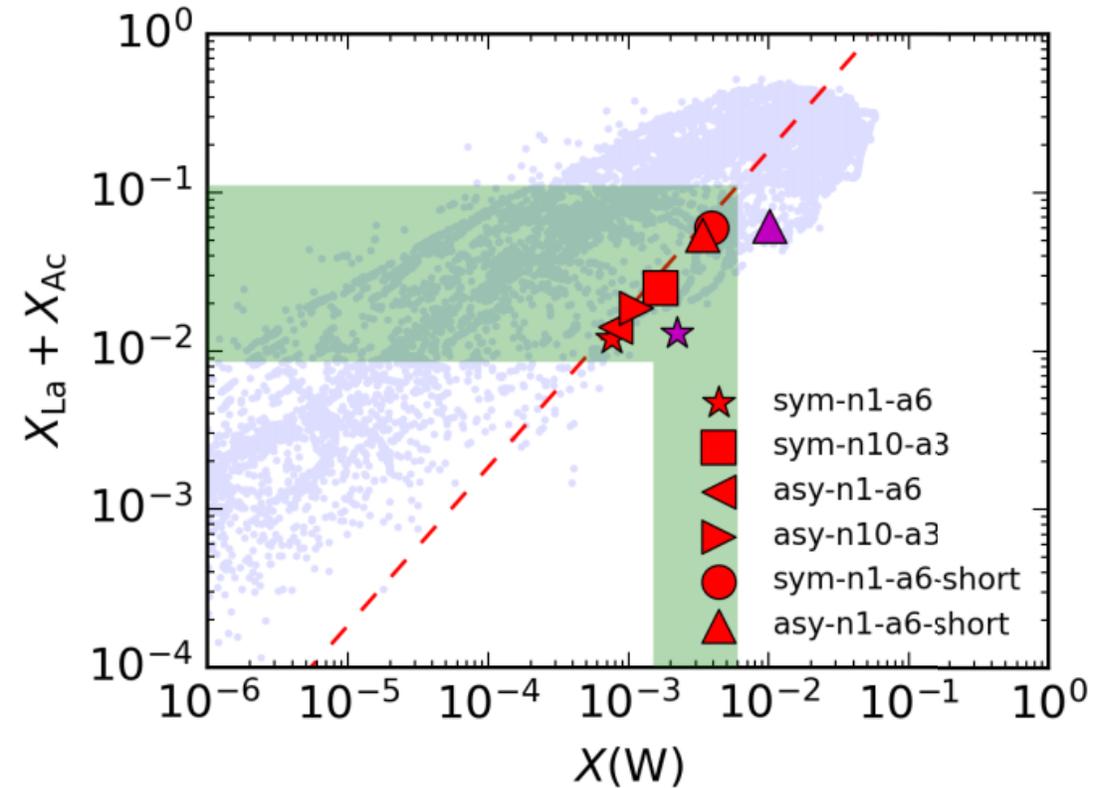
(also see Hotokezaka+22, Pognan+25)

Implications

(if feature produced by W)



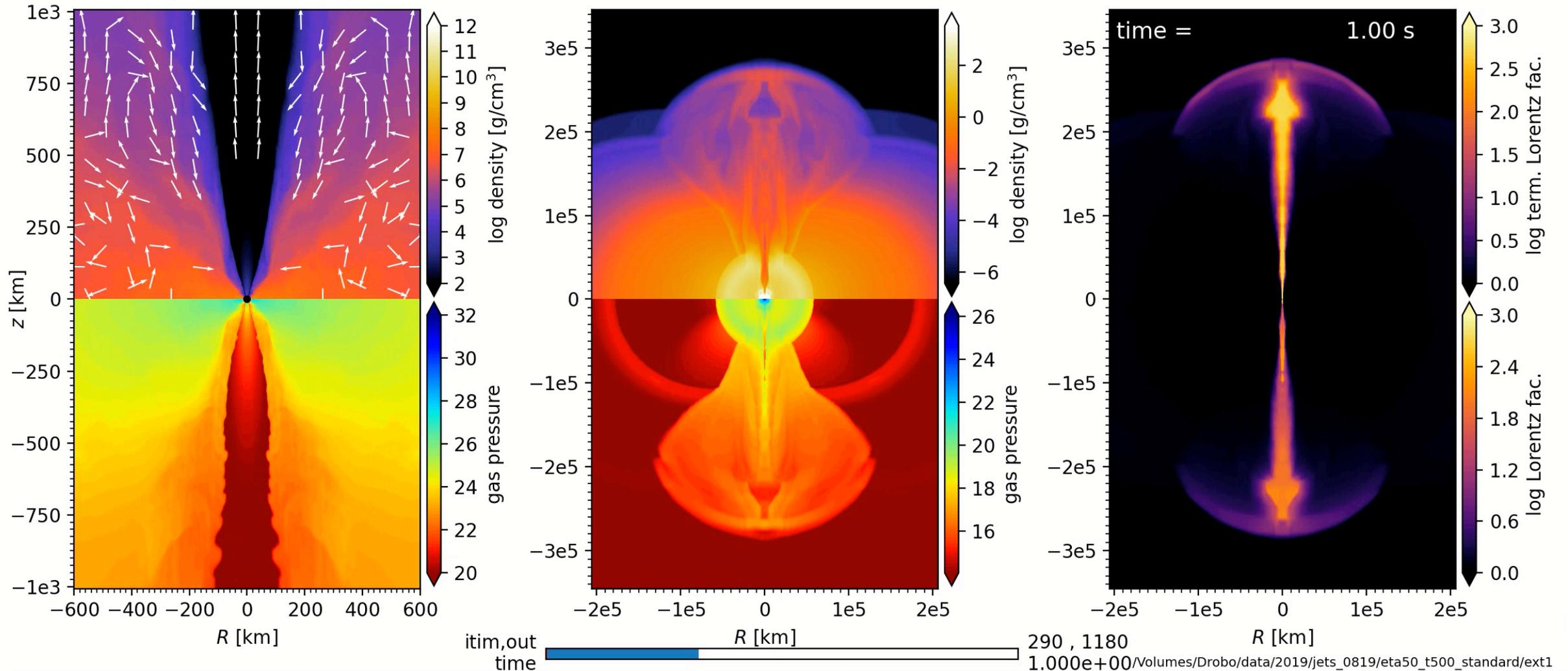
- ▶ W only produced for neutron-rich conditions \rightarrow proxy for low- Y_e material



- ▶ symbols denote different merger simulations
- ▶ correlation between W and lanthanides allows estimate on lanthanide fraction

Short-GRB jet from post-merger BH-disk

(Ito, O), Takei, Nagataki ApJ 918, 59, 2021)

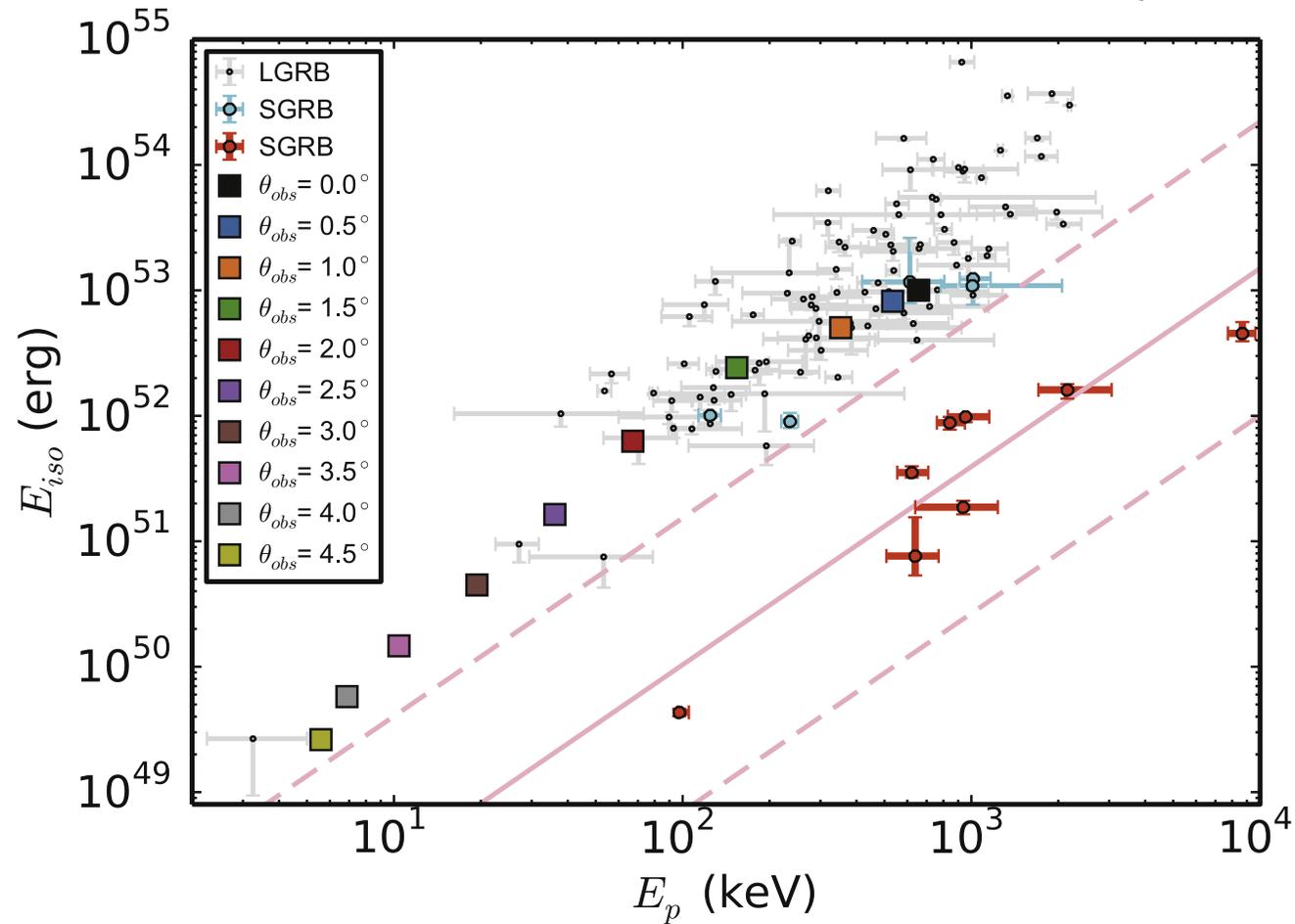


- ▶ full-scale modeling of merger remnant + injected jet at BH horizon + photospheric sGRB emission (\backslash w Monte-Carlo gamma-ray transport)

(also see works by Gottlieb+, Hamidani+, Hayashi+ Mizuta+,...)

Short-GRB jet from post-merger BH-disk

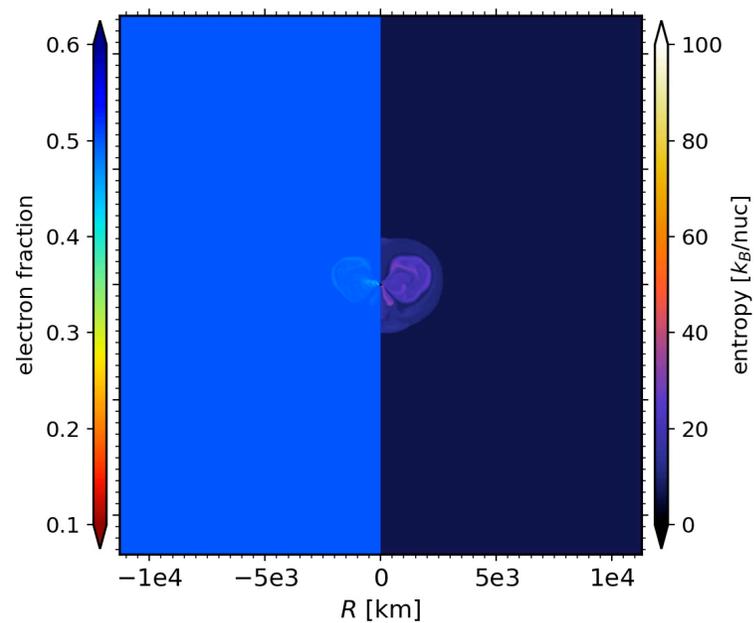
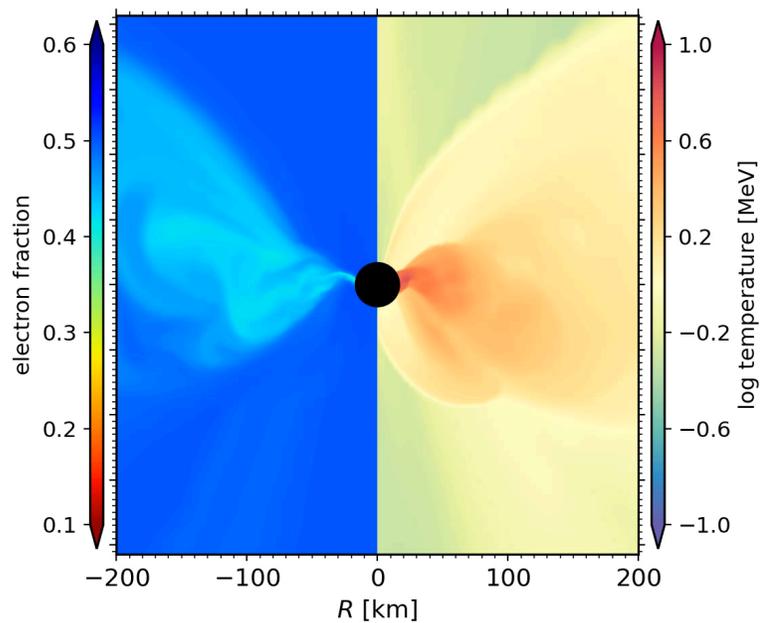
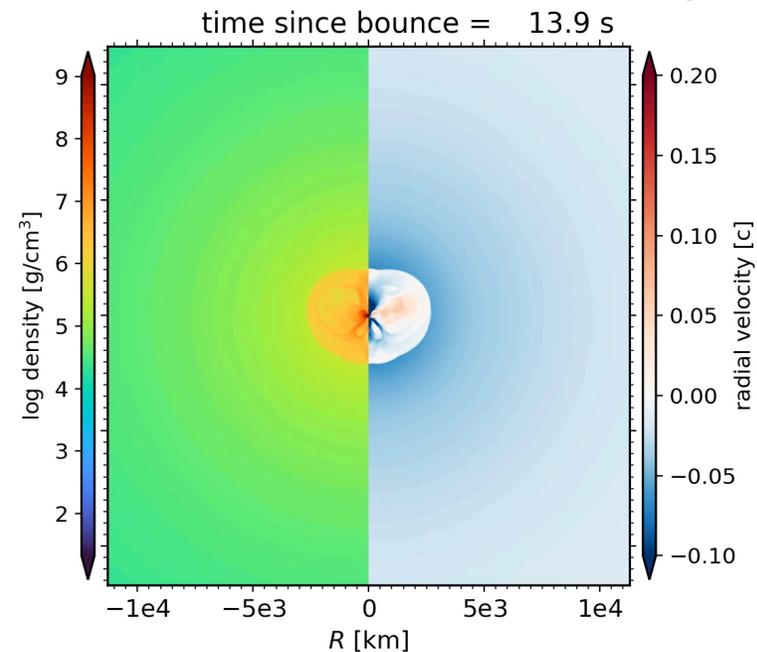
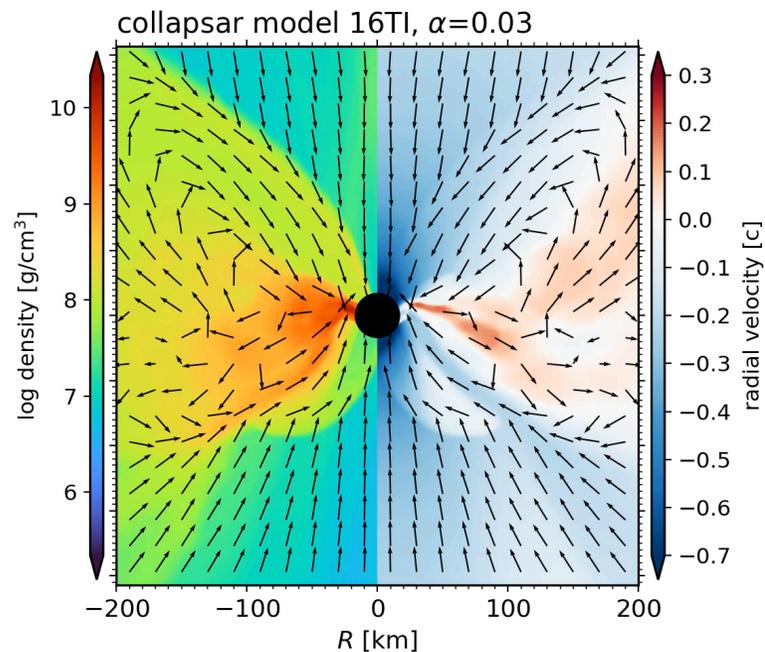
(Ito, O), Takei, Nagataki ApJ 918, 59, 2021)



- ▶ qualitatively agree with Amati relation but with offset
- ▶ unable to explain sGRB of GW170817 ($E_{iso} \sim 10^{47}$ erg, $E_p \sim 100$ keV)
- ▶ results support shock-breakout scenario for prompt emission (see Nakar, Gottlieb, et al 2017,18)

Collapsars as r-process sites?

(O), Aloy, Obergaulinger,
Nagataki ApJL 2022)

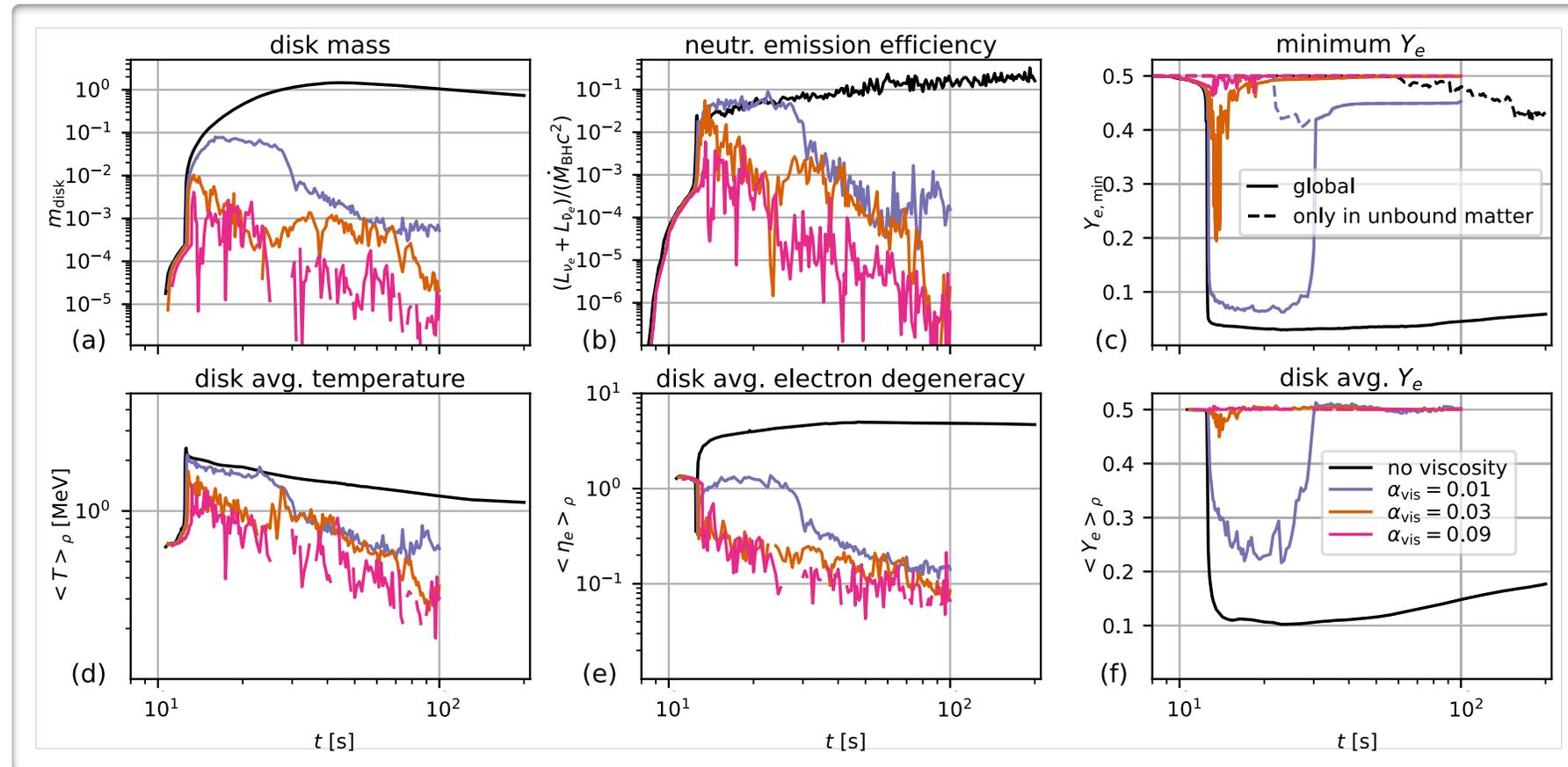


Collapsars as r-process sites?

(O), Aloy, Obergaulinger,
Nagataki ApJL 2022)

- ▶ neutron-rich disk (NDAF) formed at $t \sim 13$ s
- ▶ however, viscosity leads to rapid disintegration
- ▶ transition to advective disk (ADAF) after short time ($t \sim 14$ s)
- ▶ minimum outflow $Y_e \sim 0.4$ too high for efficient r-process
- ▶ **r-process less readily activated in collapsar disks than in merger disks**

- ▶ Caveats:
 - no GR
 - no MHD
 - no jet included



(also see Siegel+19, Miller+23, Fujibayashi+23, Shibata+24)

Summary

- ▶ **Long-term modeling crucial for ejecta nucleosynthesis and kilonova signal**
 - ▶ established end-to-end modeling pipeline including merger models with approximate treatment of GR and turbulent viscosity
- ▶ **New potential EOS constraint from helium signature in kilonova spectrum**
 - ▶ suggests upper limit on NS remnant lifetime of about 30 ms in AT2017gfo
 - ▶ warrant further exploration of modeling uncertainties
- ▶ **Hydro-Implementation of r-process heating using machine learning**
 - ▶ O(10%) effect on ejecta mass, velocities, kilonova luminosity
- ▶ **Late-time KN emission features may provide mass of r-process elements**
 - ▶ assuming 4.5micron feature in two observed events from W (Z=74)
 - ▶ imposes lower limits on synthesized lanthanides + 3rd peak elements