Neutron-star mergers hydrodynamic modeling: Ejecta components and their nucleosynthesis and kilonova signatures

Oliver Just

GSI Helmholtzzentrum Darmstadt

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ERC synergy
HeavyMetal

with: A. Bauswein, G. Martinez-Pinedo, S. Goriely, Z. Xiong, V. Vijayan, C. Collins, I. Kullmann, L. Shingles, S. Sim, A. Sneppen, D. Watson, H.-Th. Janka, M. R. Wu, I. Tamborra, S. Abbar, … many more

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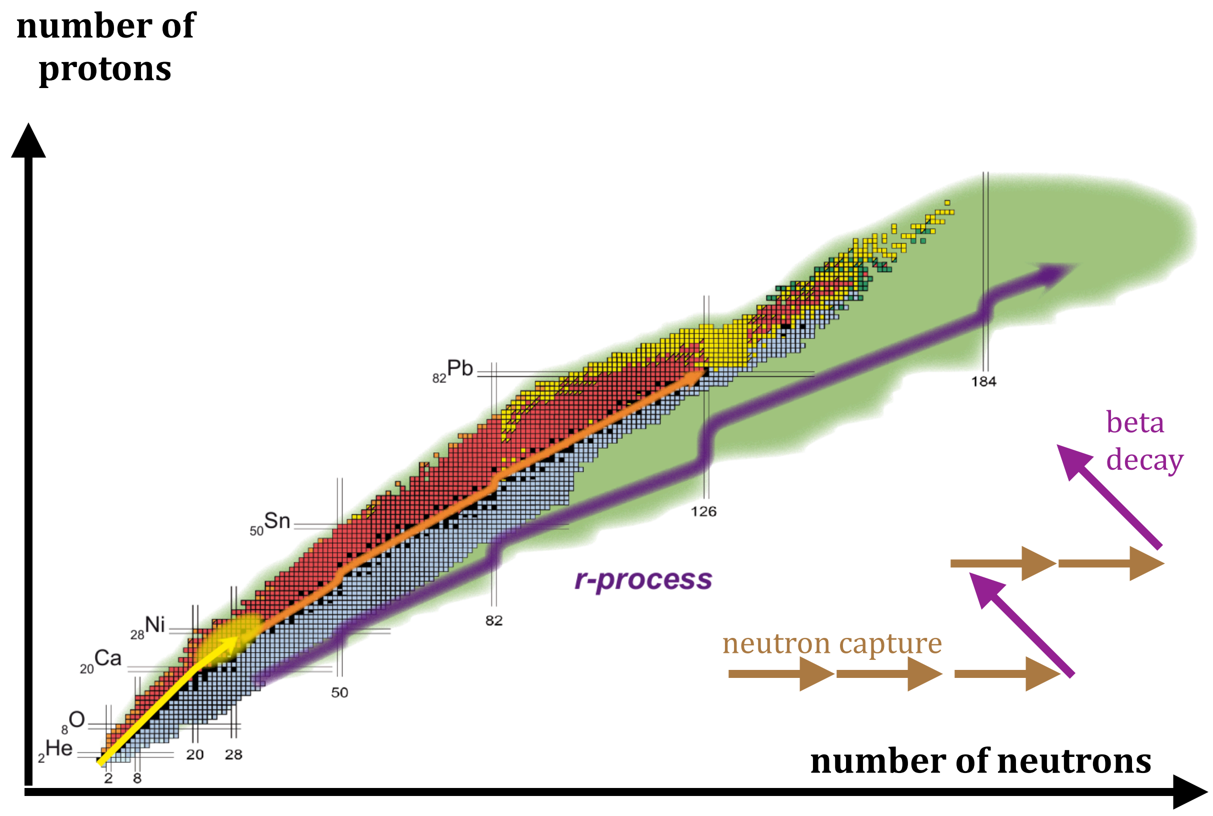
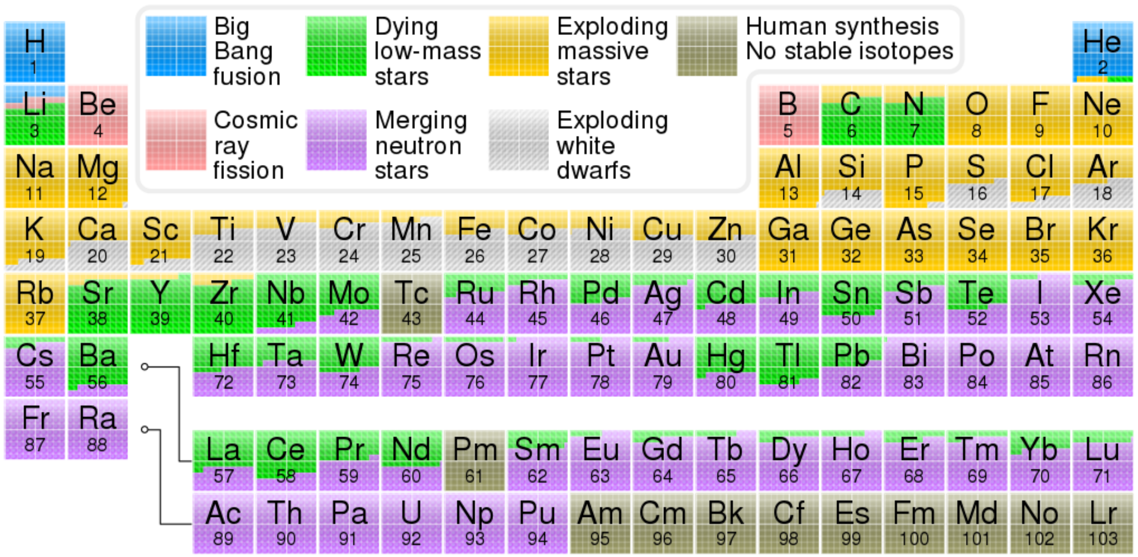
Are NSMs main sites of the "rapid neutron-capture" (r-) process?



suggested sites of origin



Main condition:

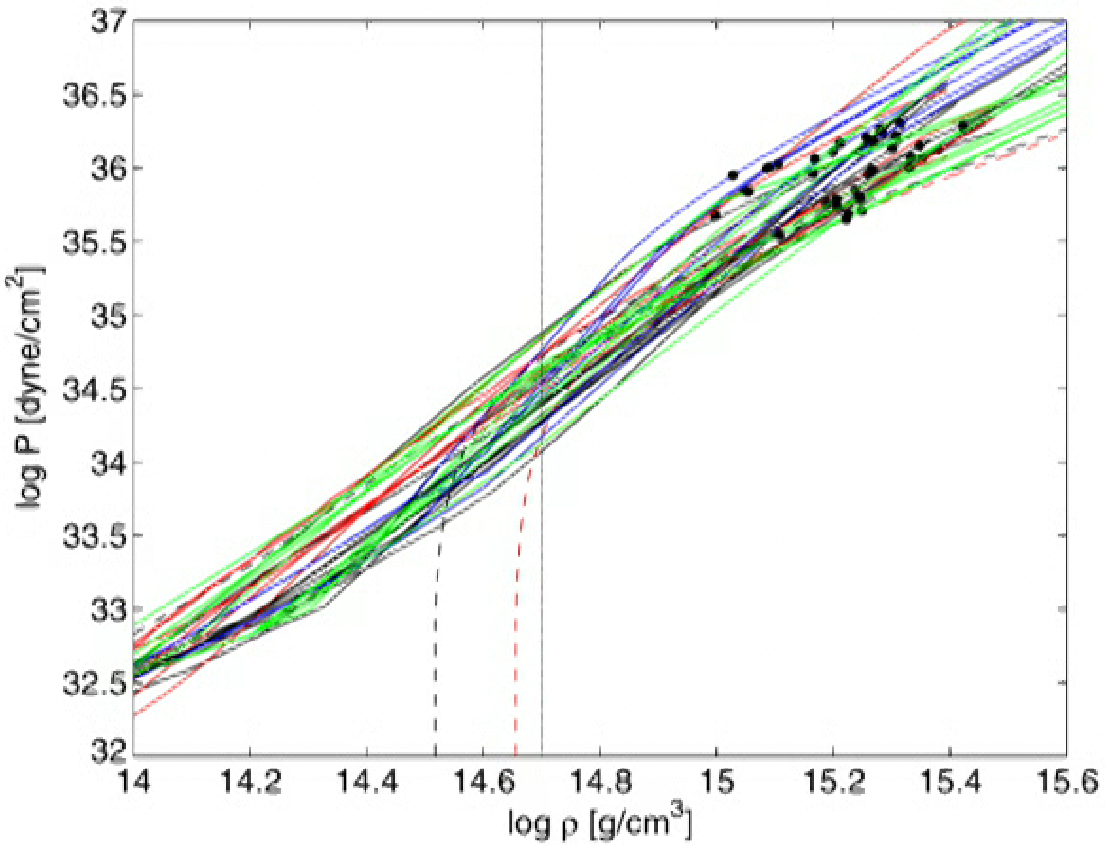
high neutron density = low electron fraction Y_e

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

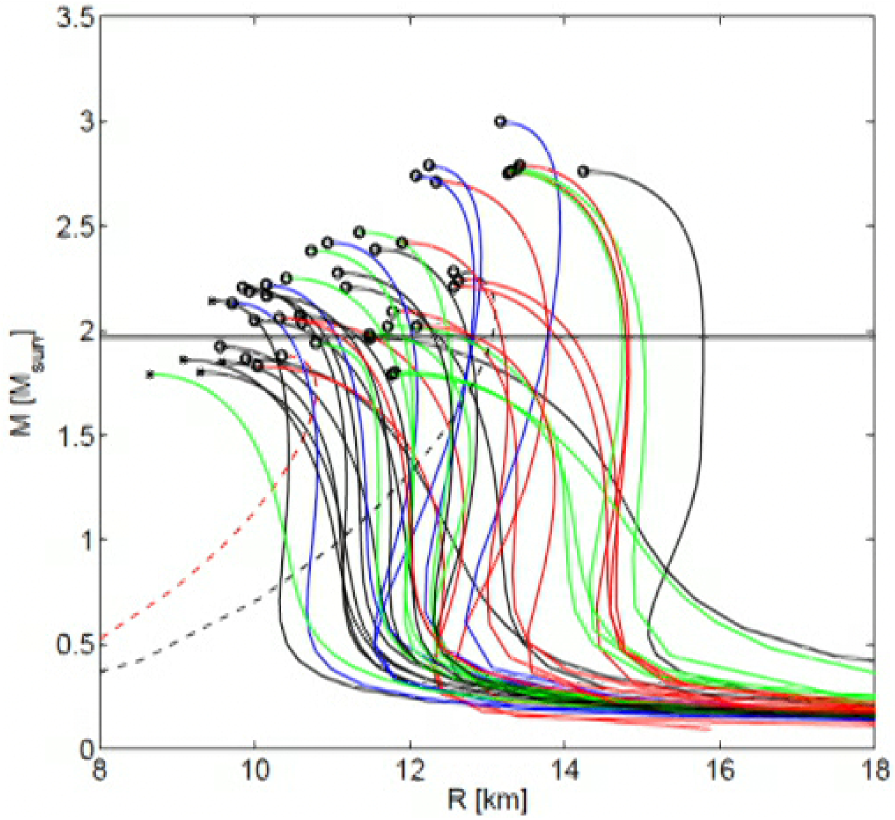
- NSMs are the **only confirmed site** so far, but are they main site?
- other suggested sites: core-collapse supernovae, magneto-rotational SNe, collapsars, magnetar giants flares

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

possible nuclear equation of states



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



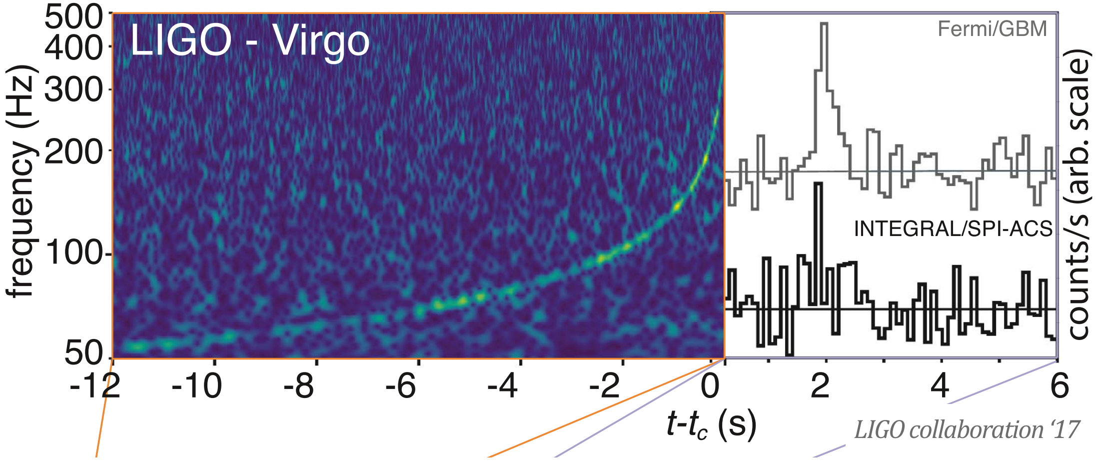
(plots by A. Bauswein)

- softer (stiffer) EOS <=> smaller (larger) neutron star
- softer (stiffer) EOS <=> shorter (longer) lifetime of HMNS merger remnant

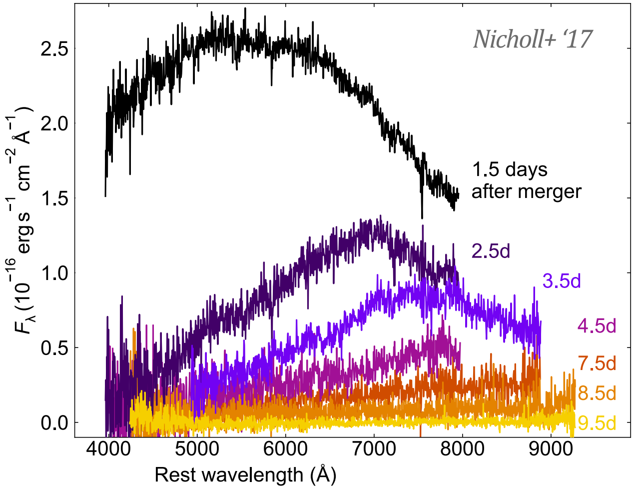
GW170817 - the first direct observation of a NS merger

(on August 17th, 2017)

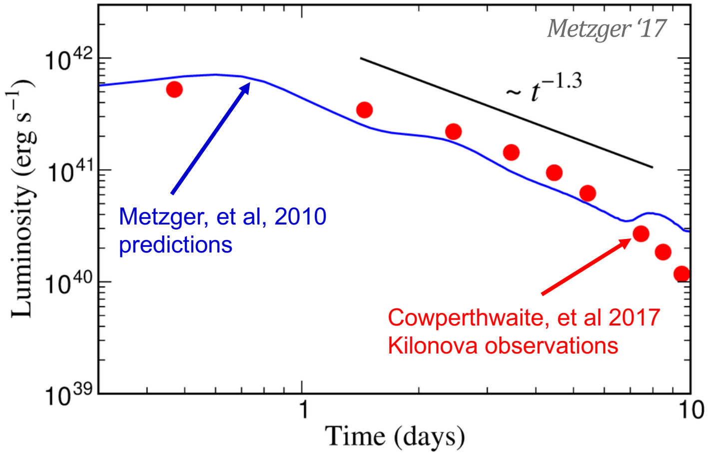
gravitational waves *gamma rays*



UV+optical+IR spectra



UV+optical+IR light curve

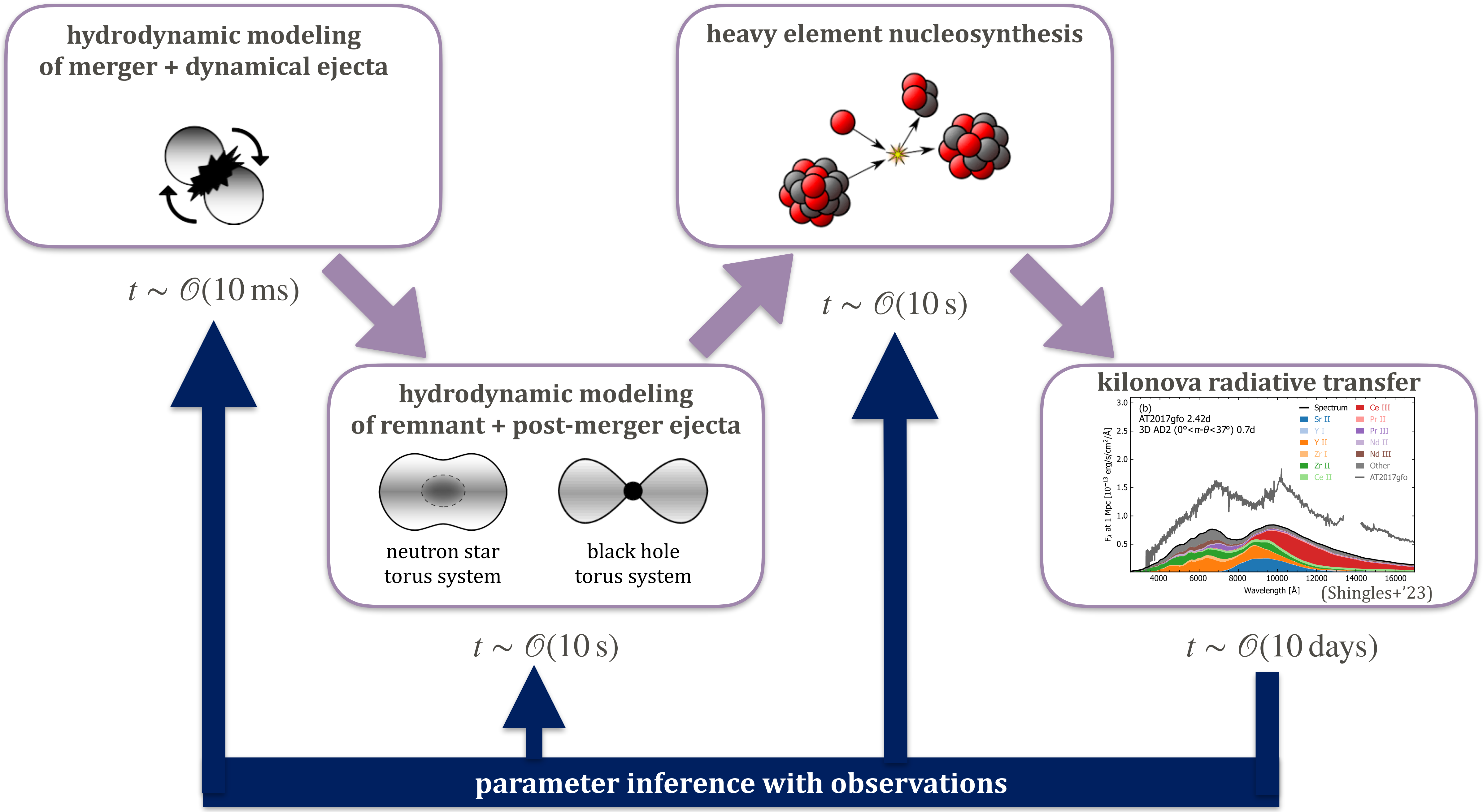


Many open questions remain:

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

Other groups working on hydro models, e.g.: Arcones, Bernuzzi, Dietrich, Foucart, Perego, Radice, Rezzolla, Rosswog, Shibata, … et al.

Kilonova modeling pipeline



Our "end-to-end" modeling pipeline

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

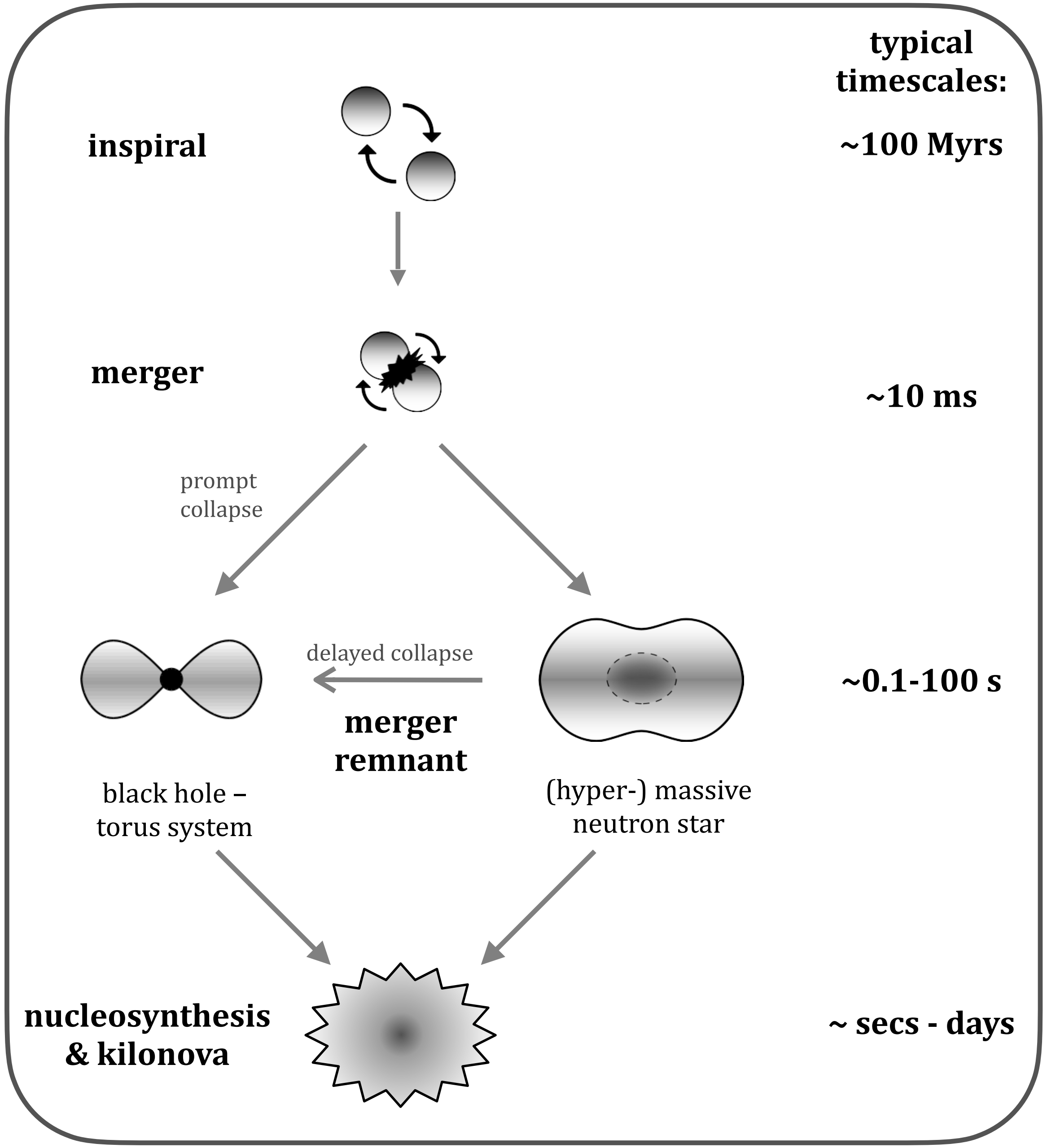
heavy element nucleosynthesis

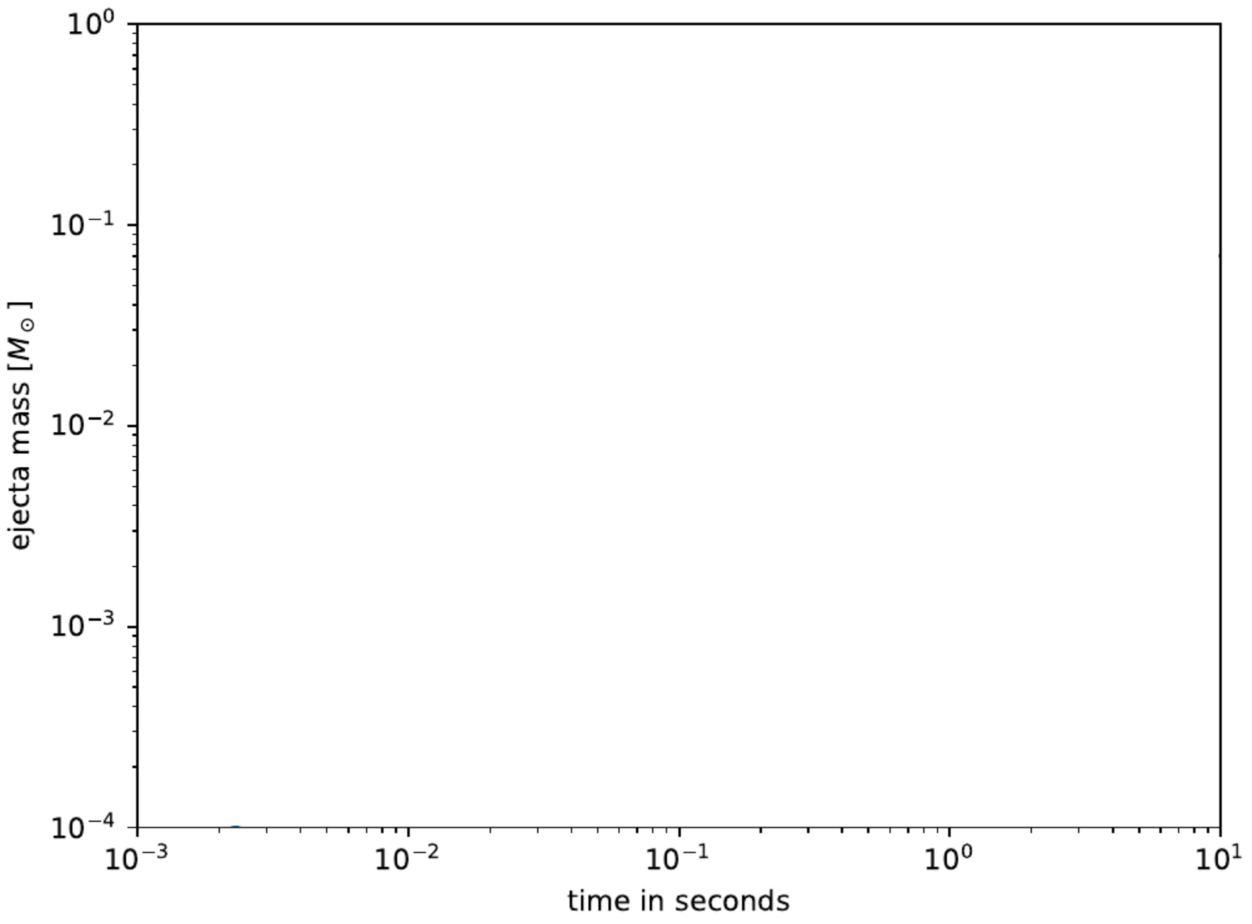
- extraction of ~5000 outflow tracers per model to sample local hydrodynamic history until 100 s
- post-processed by two nuclear networks (GSI & ULB)

kilonova radiative transfer

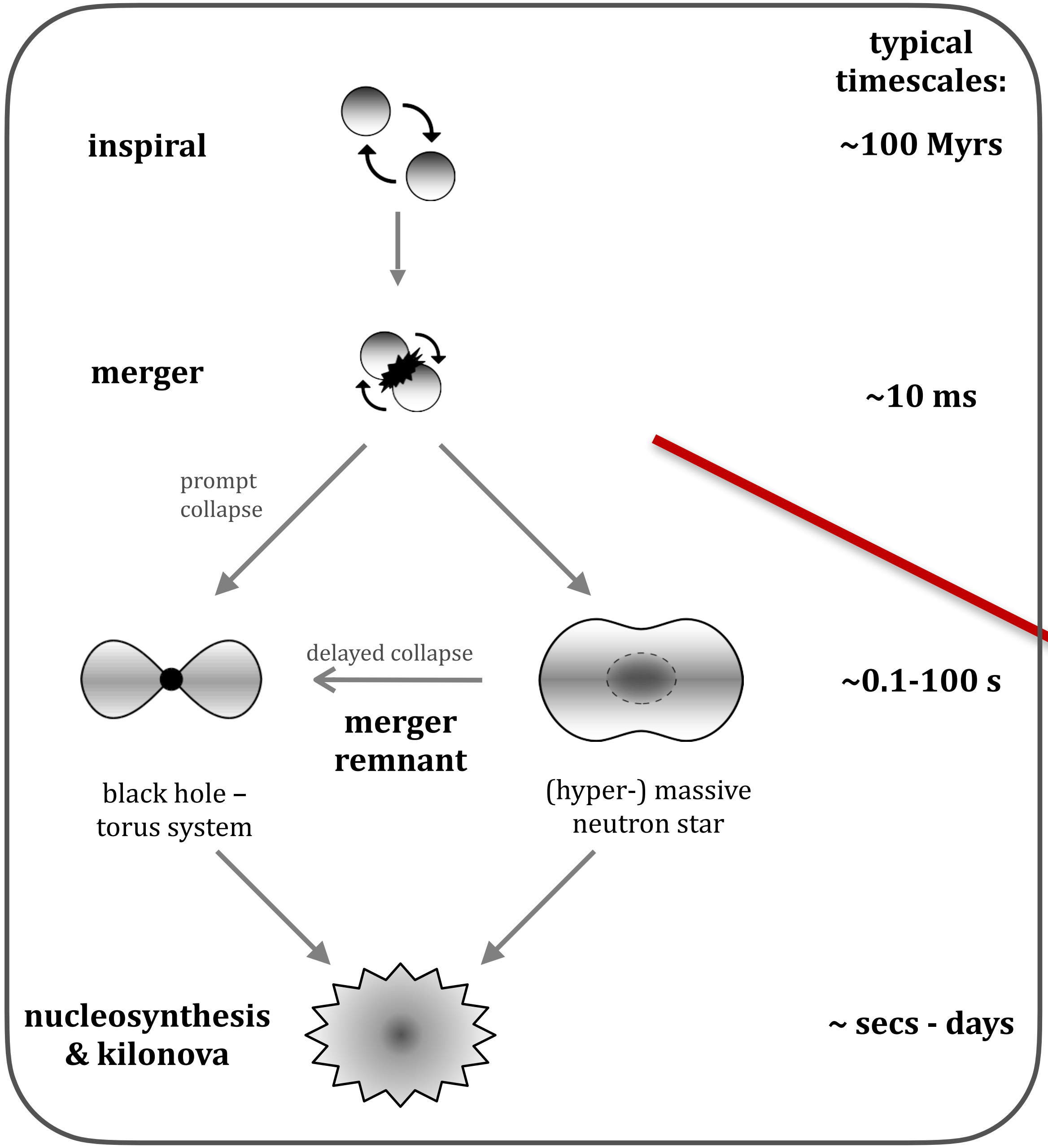
- 2D axisymmetric radiative transfer using approximate M1 scheme
- alternatively use ARTIS Monte-Carlo code (with Belfast)
- adopt local time-dependent results from nucleosynthesis calculations

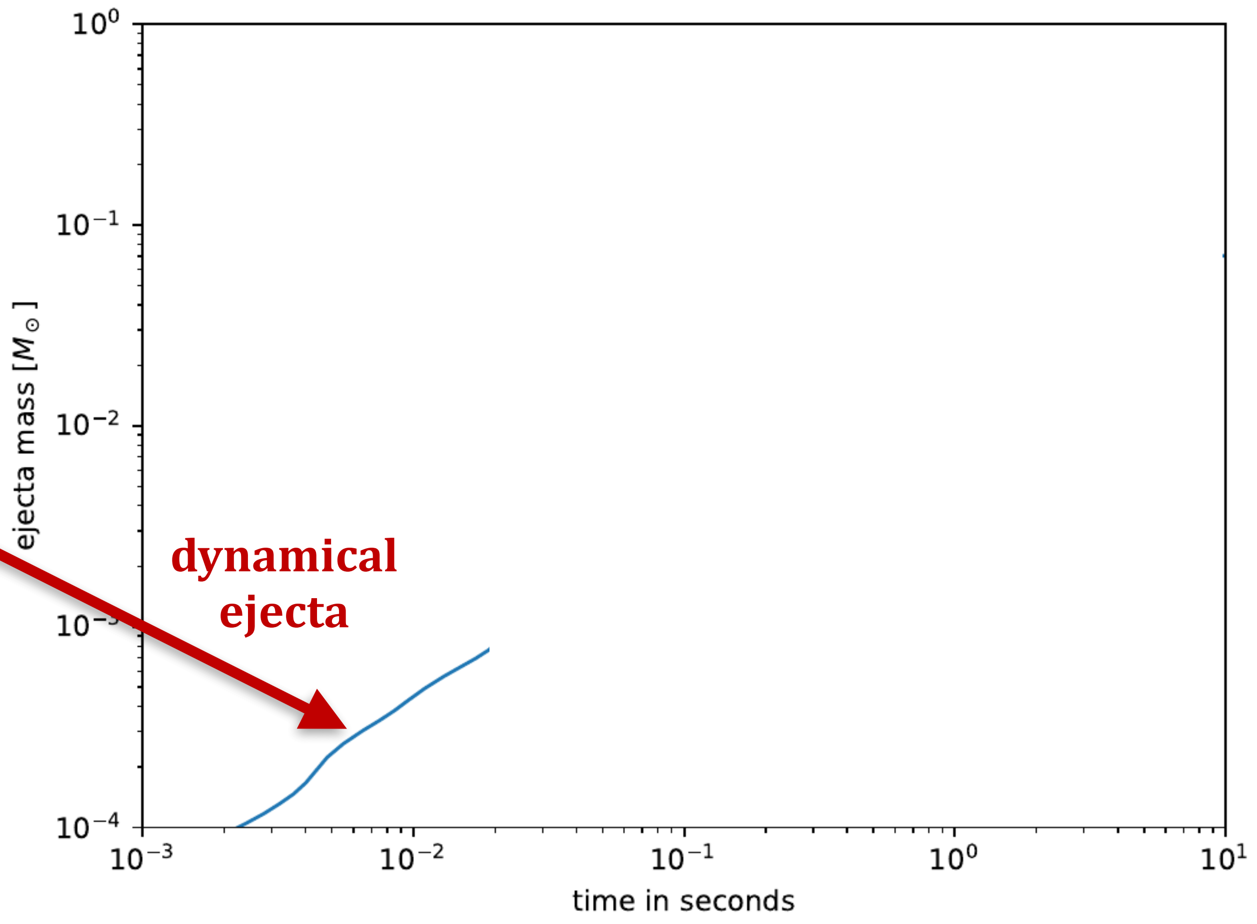
Phases of matter ejection



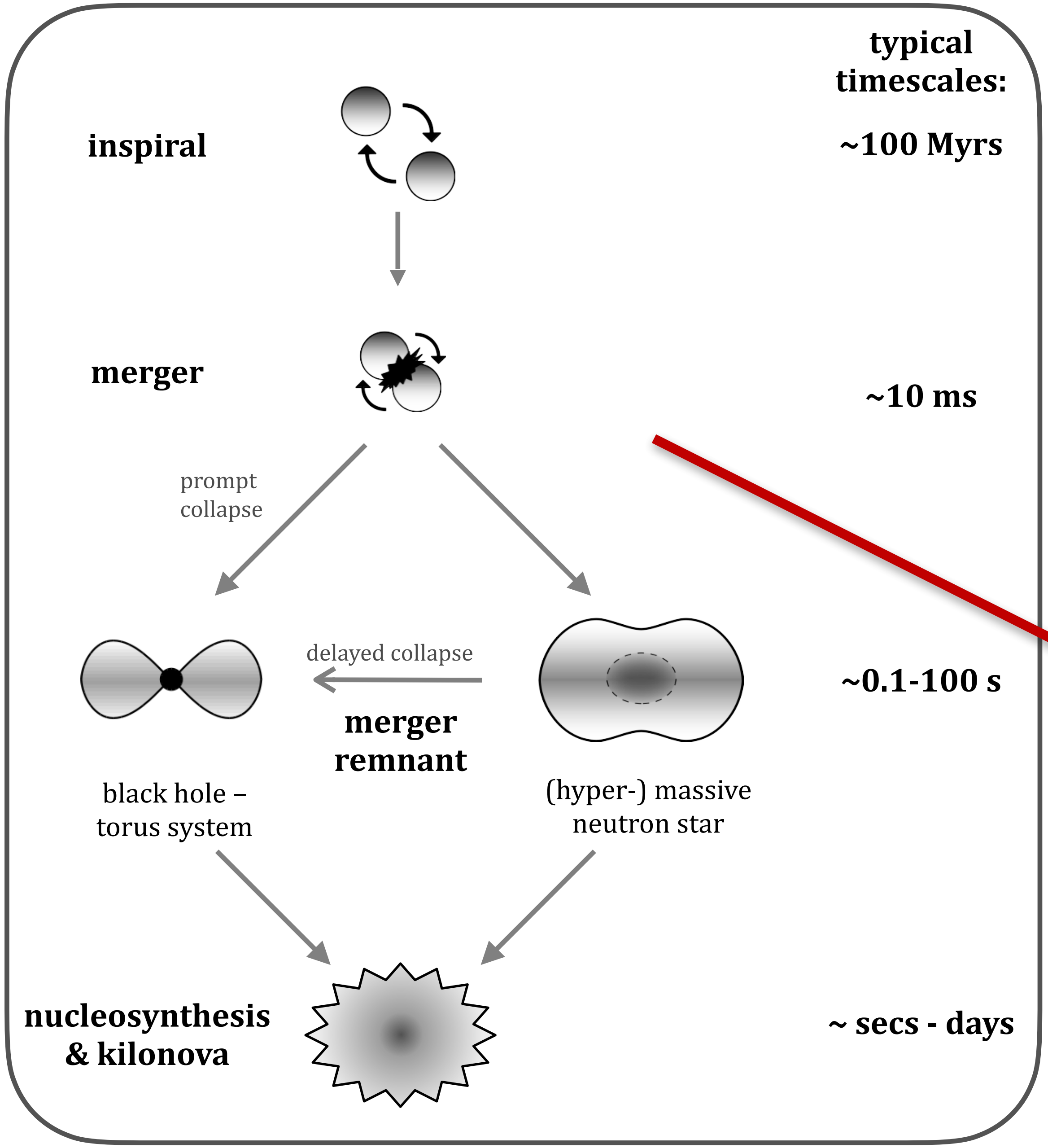


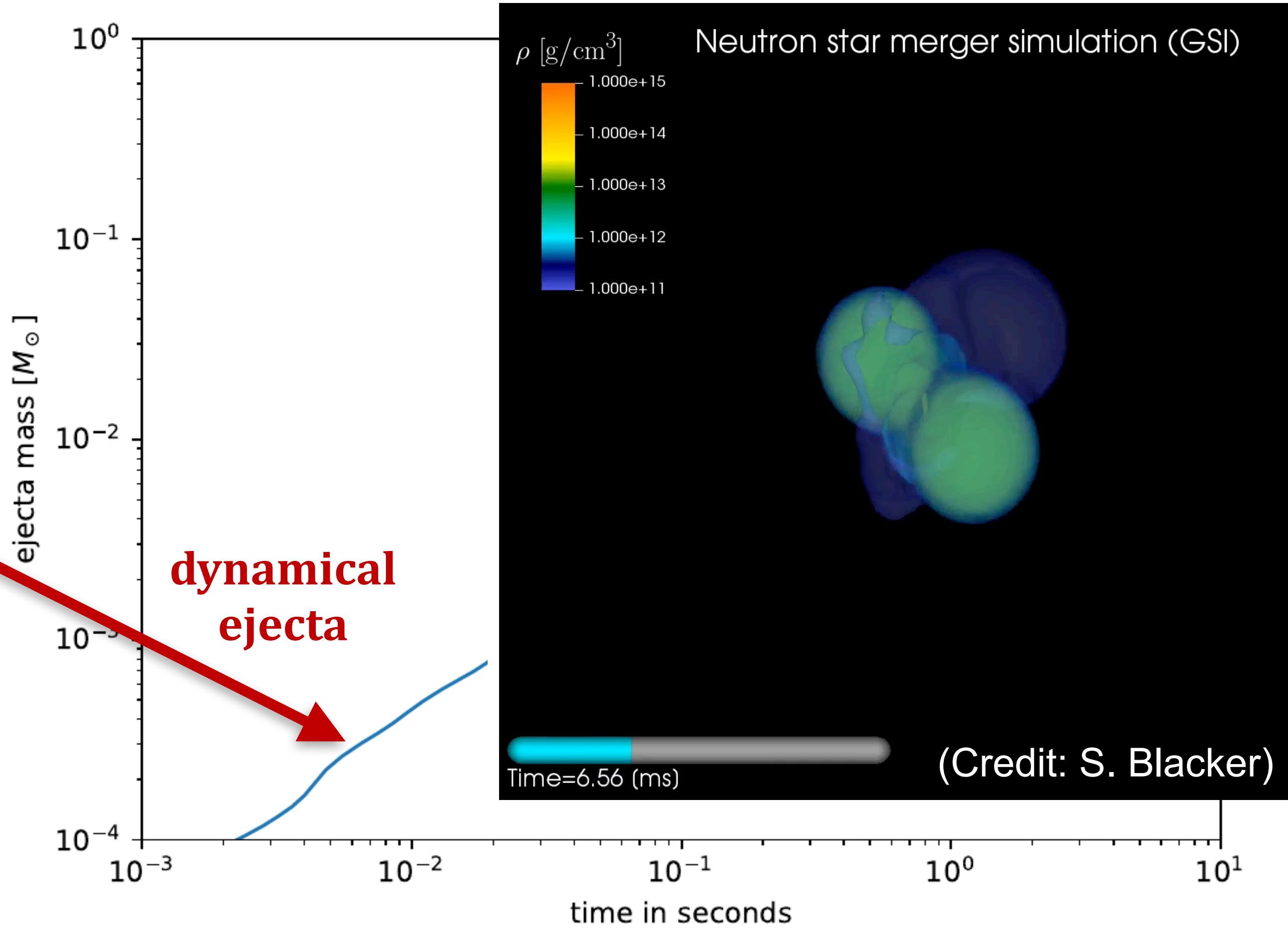
Phases of matter ejection



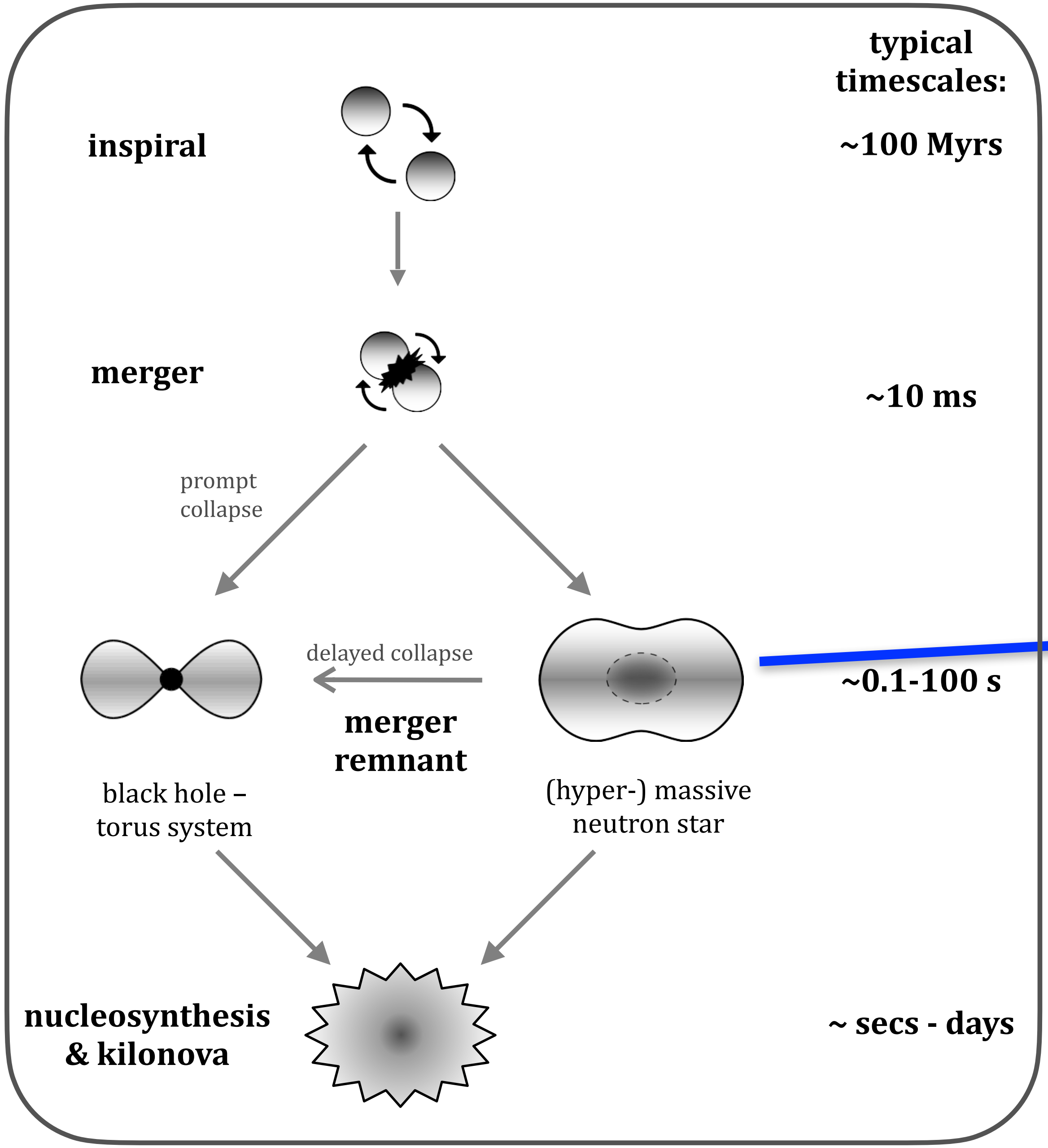


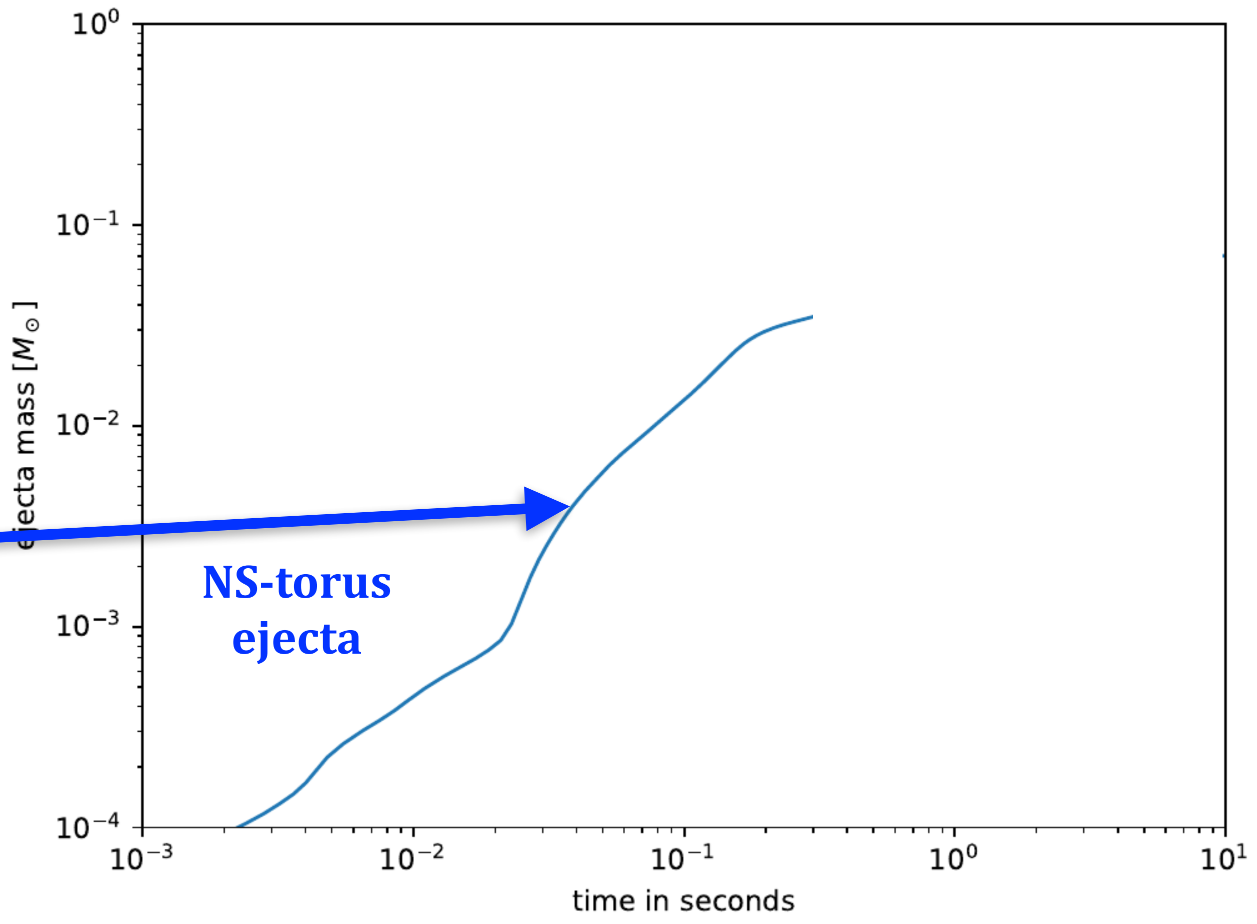
Phases of matter ejection



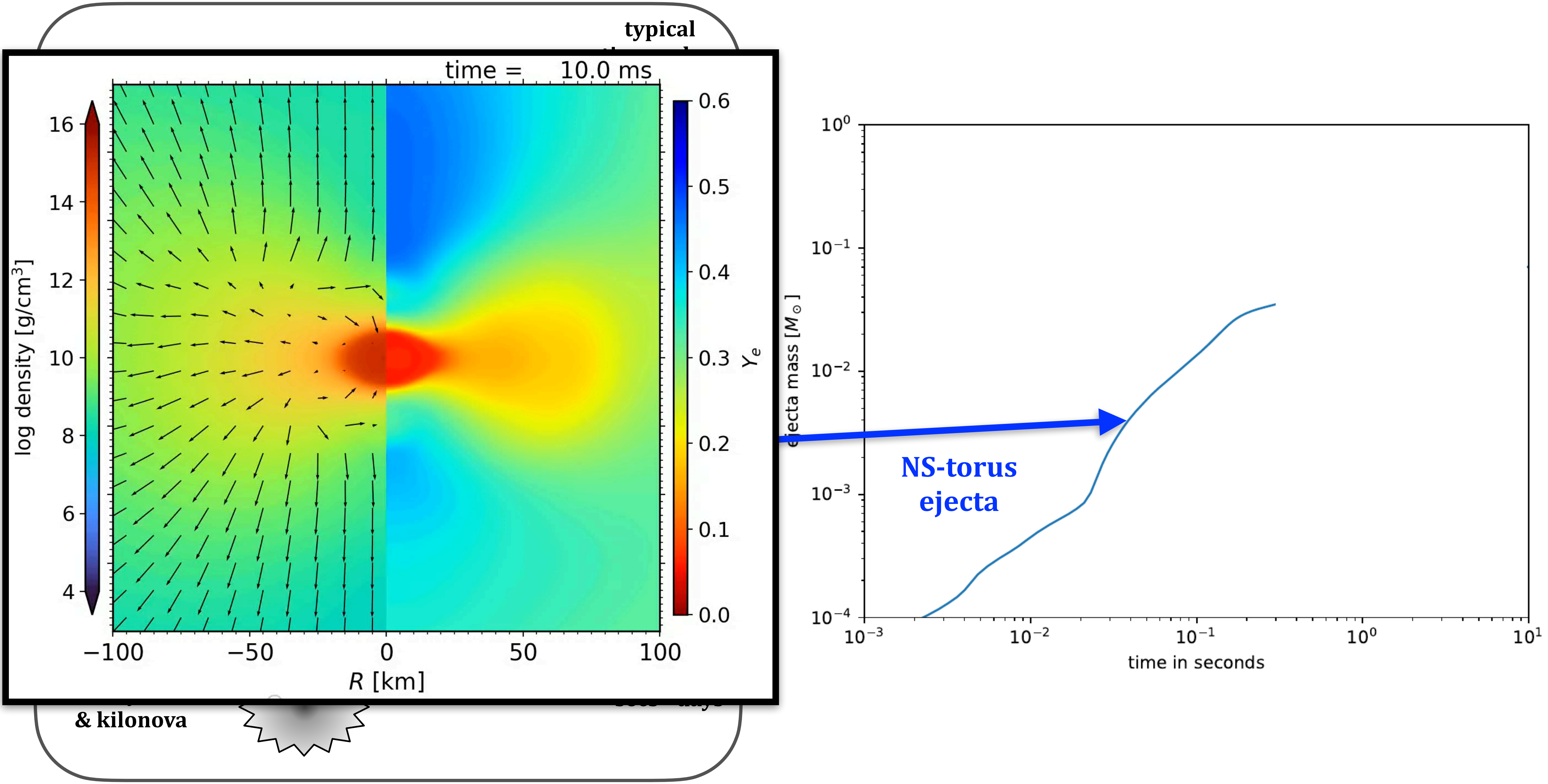


Phases of matter ejection

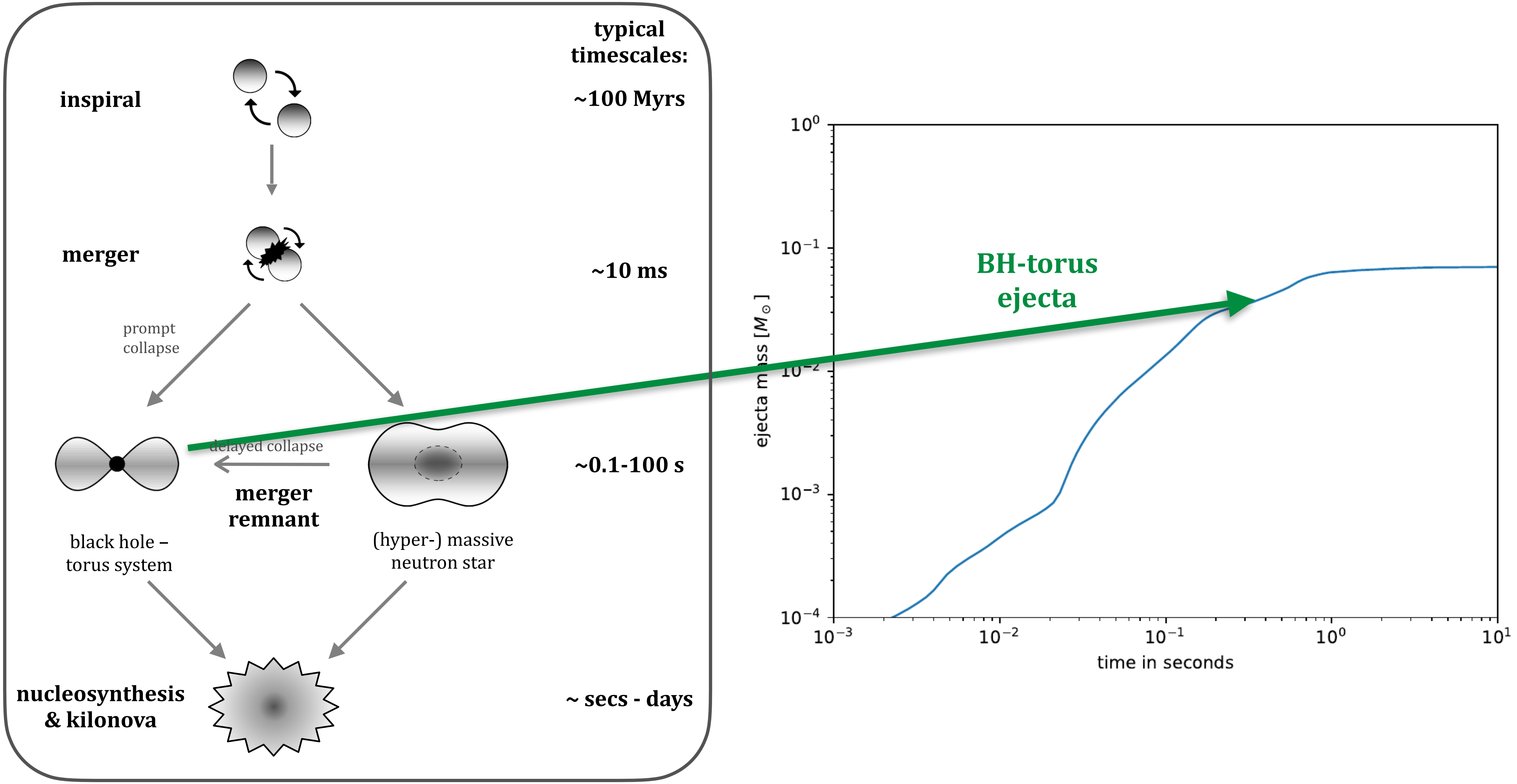




Phases of matter ejection

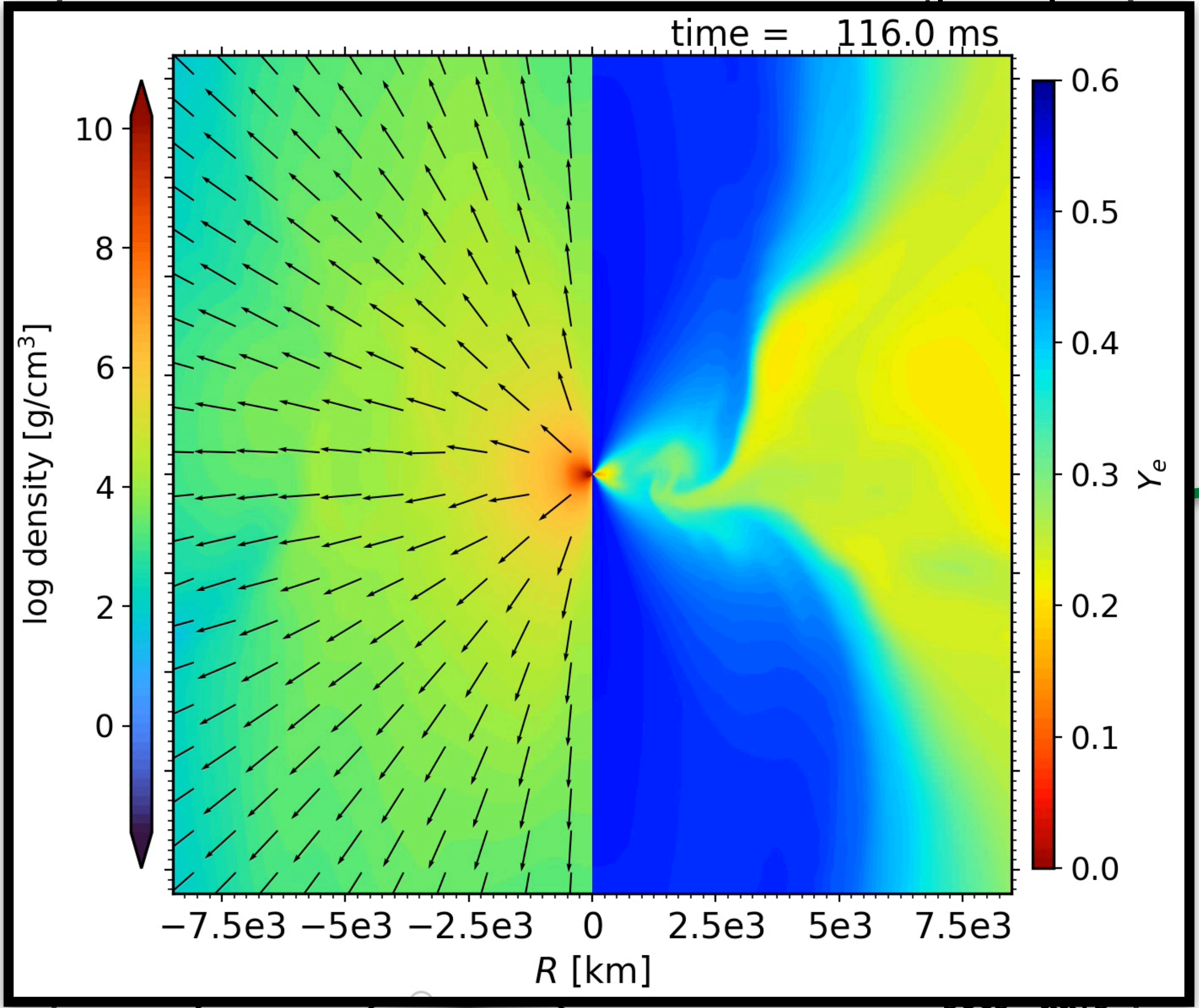


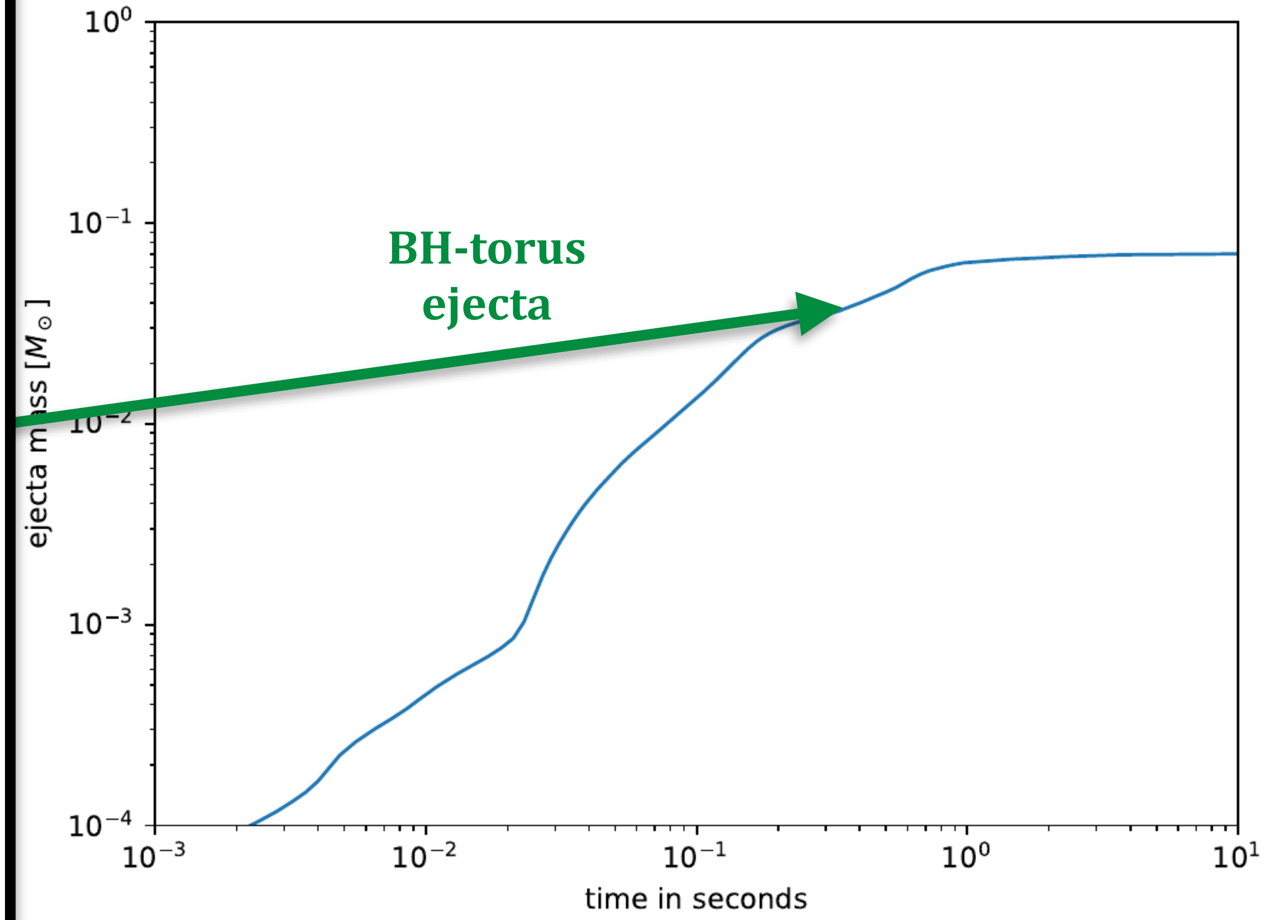
Phases of matter ejection



Phases of matter ejection

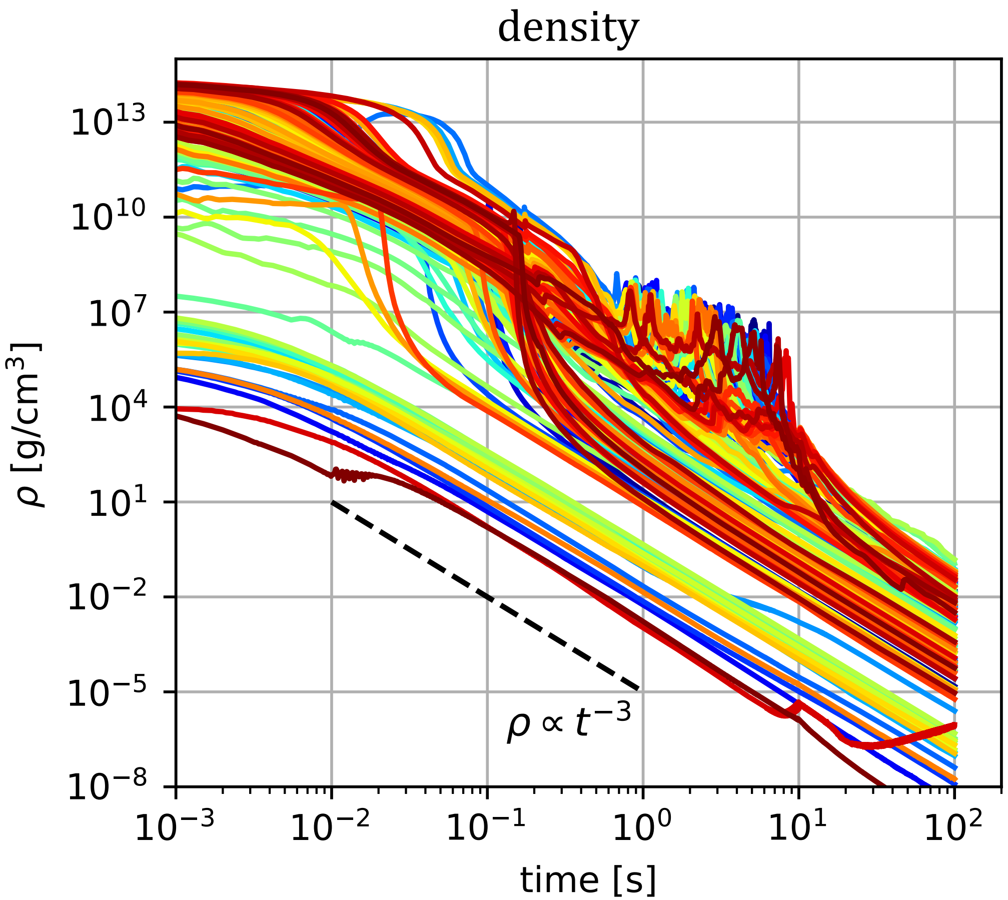
typical

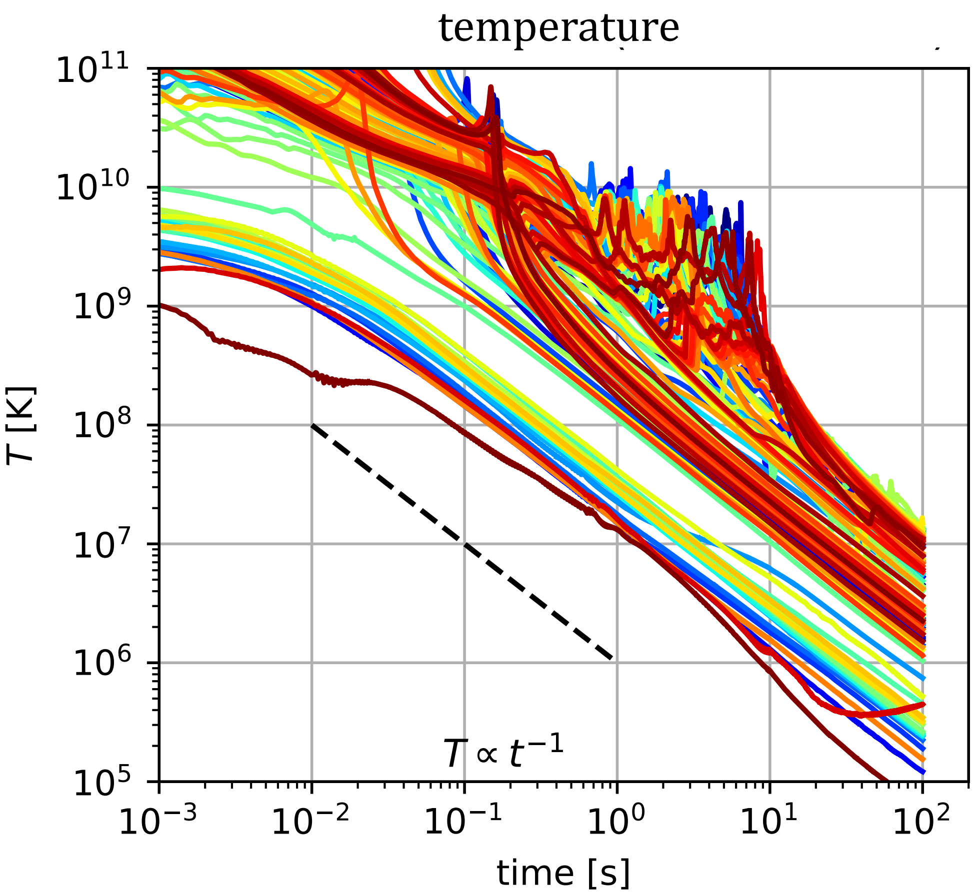




& kilonova

Long-term evolution until homologous expansion

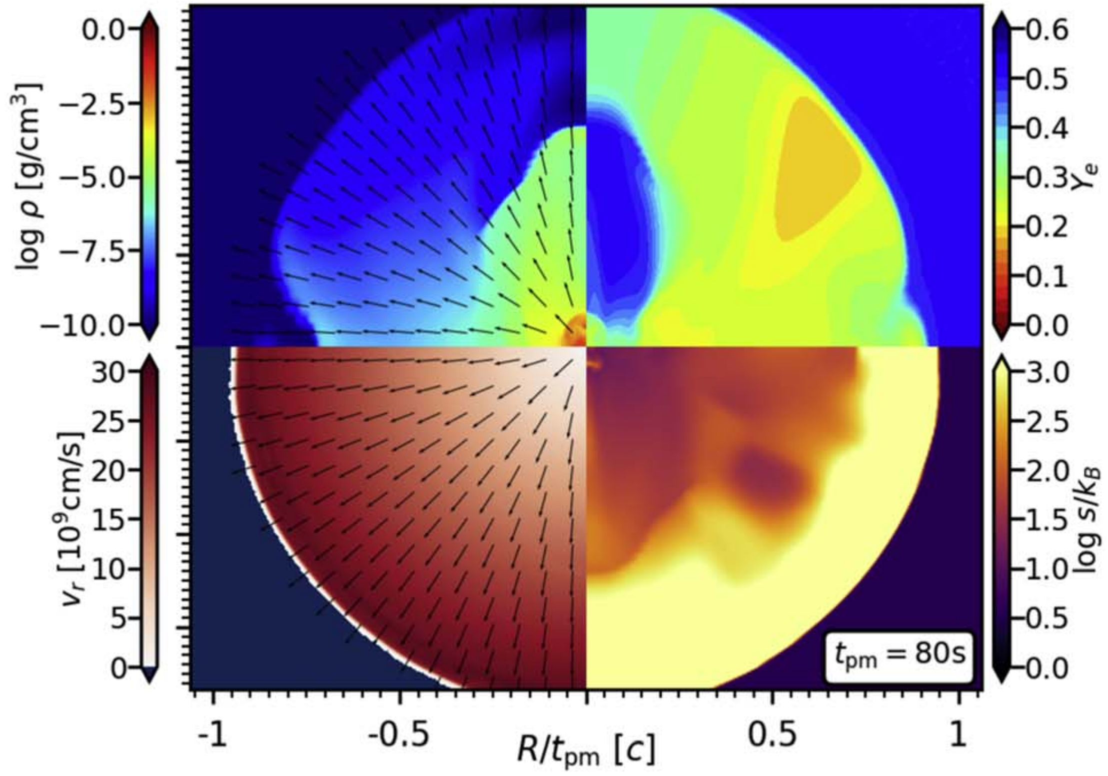


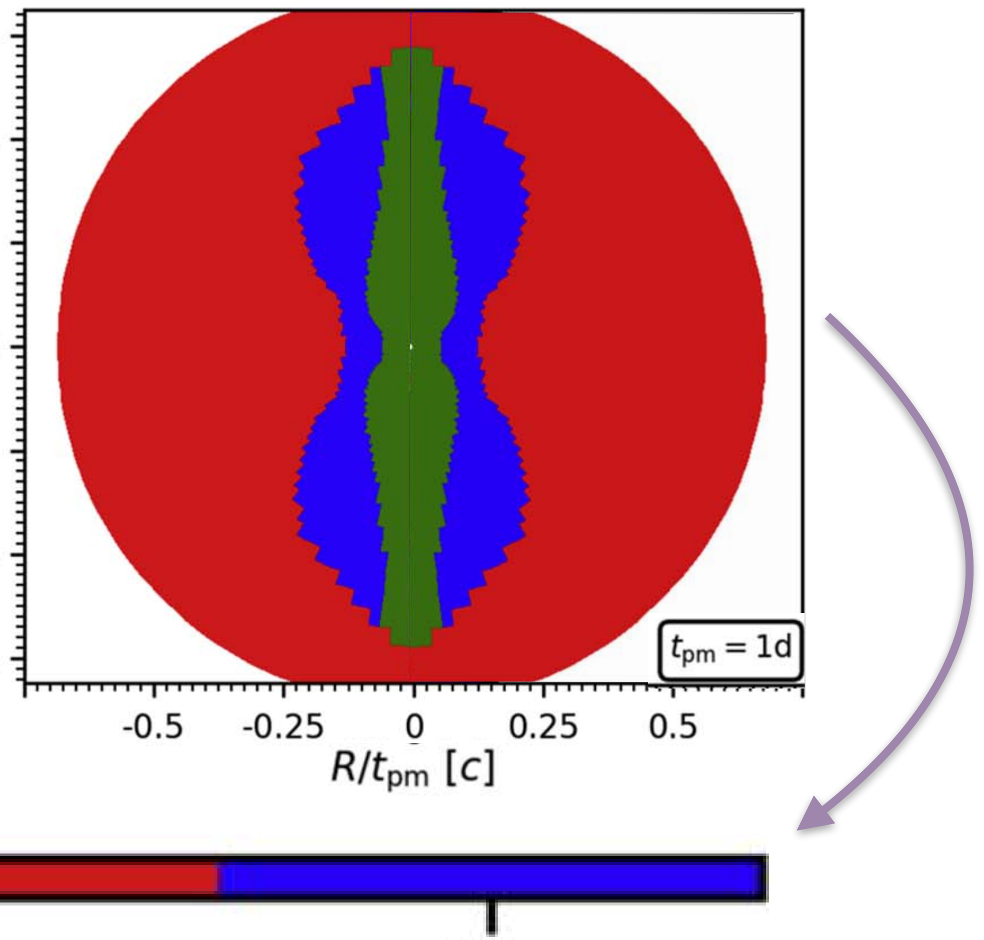


- almost all outflow homologous after ~O(100s)

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

(Just+ ApJL 951, L12, 2023)





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

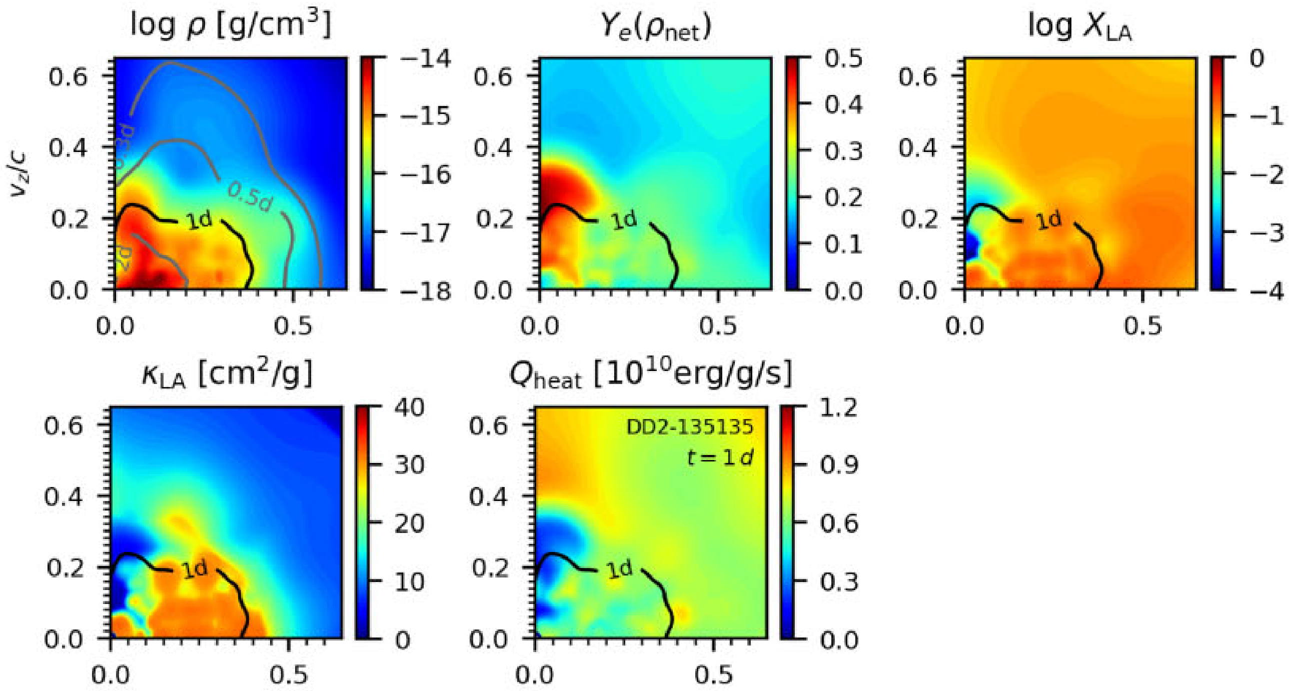
dynamical ejecta:
m ~ 0.001–0.01 $M_\odot$
<v> ~ 0.2–0.4 c

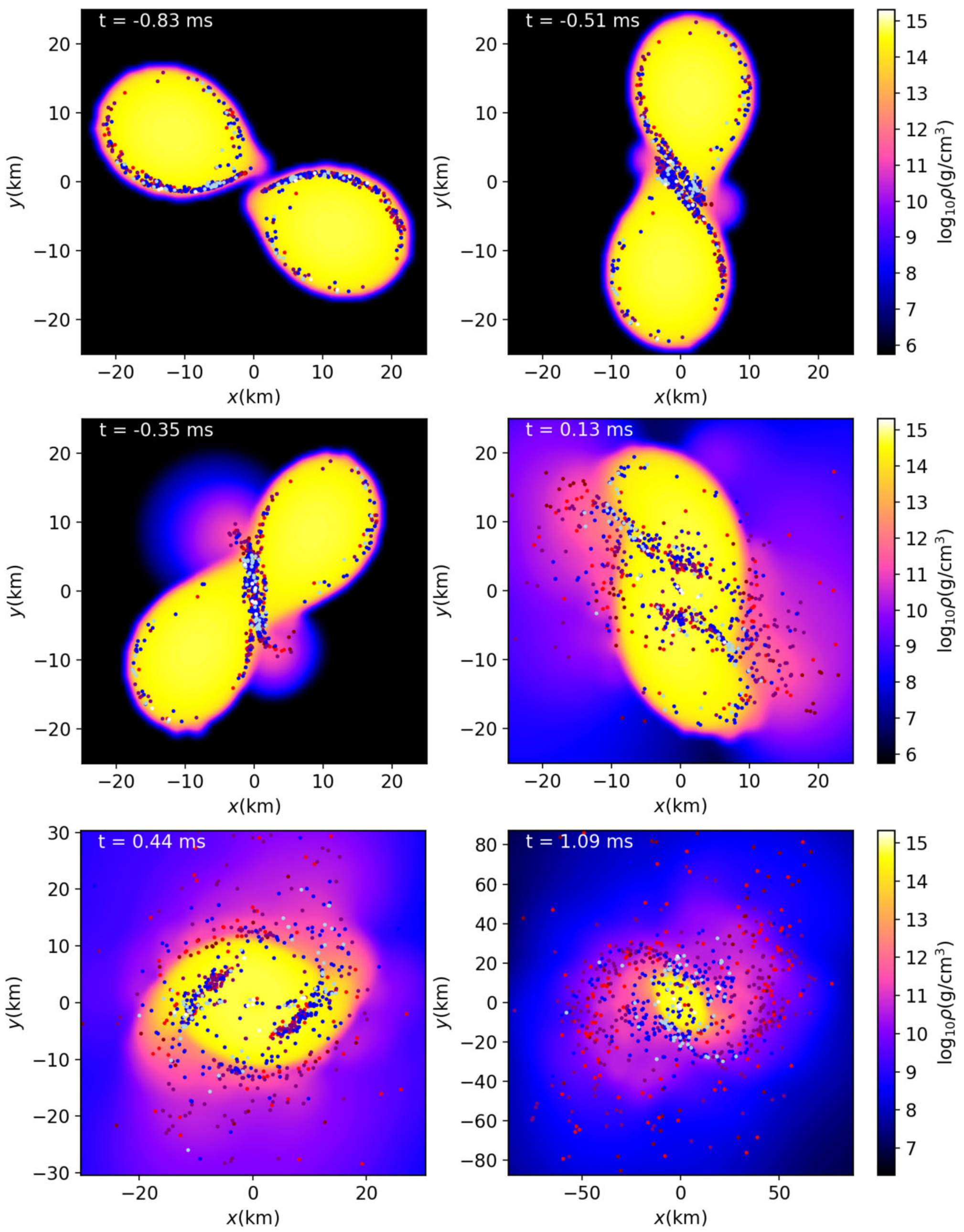
NS-torus ejecta:
m ~ 0.01–0.04 $M_\odot$
<v> ~ 0.1–0.2 c

Dynamical ejecta

(Kullmann+22, Just+22)

- Two main components:
  - **from tidal tails**:
    - mostly equatorial direction
    - cold, low Y_e , lanthanide rich, high opacity
  - **from collision shock**:
    - mostly polar direction
    - hot, high Y_e , less lanthanide rich, low opacity

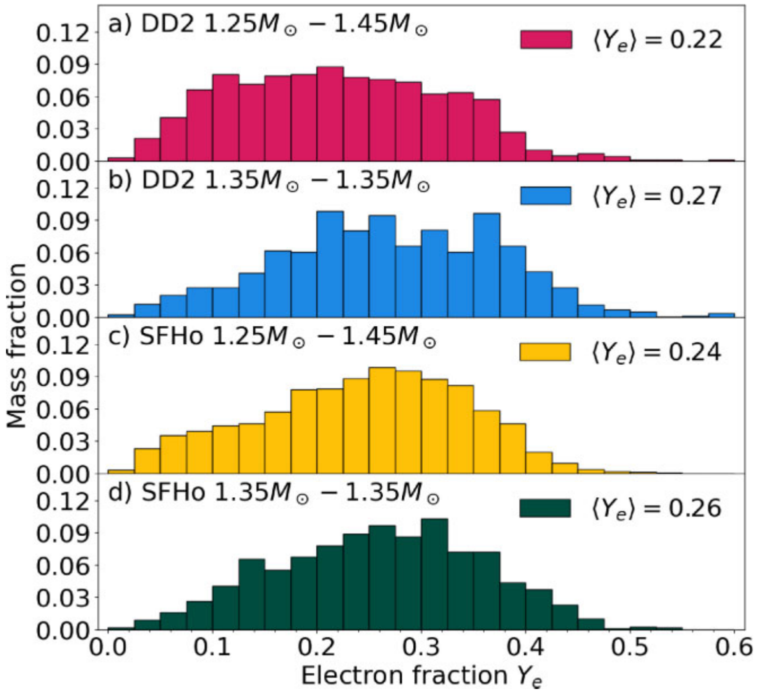




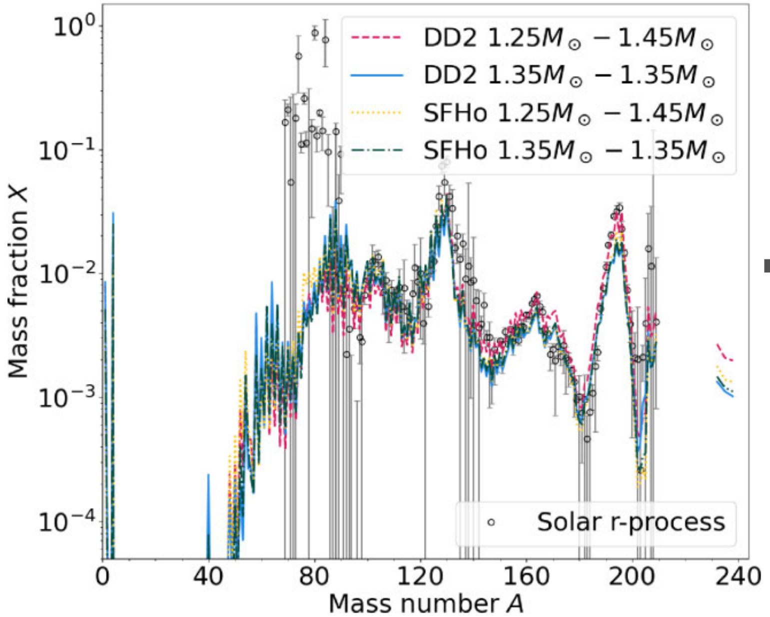
Nucleosynthesis yields and radioactive heating rates

(Kullmann+22)

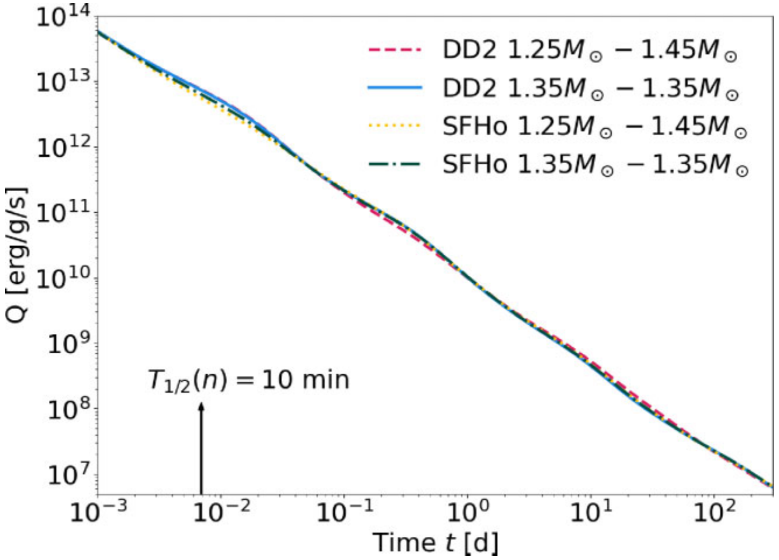
Ye distribution



abundance pattern



heating rate (before thermalization)

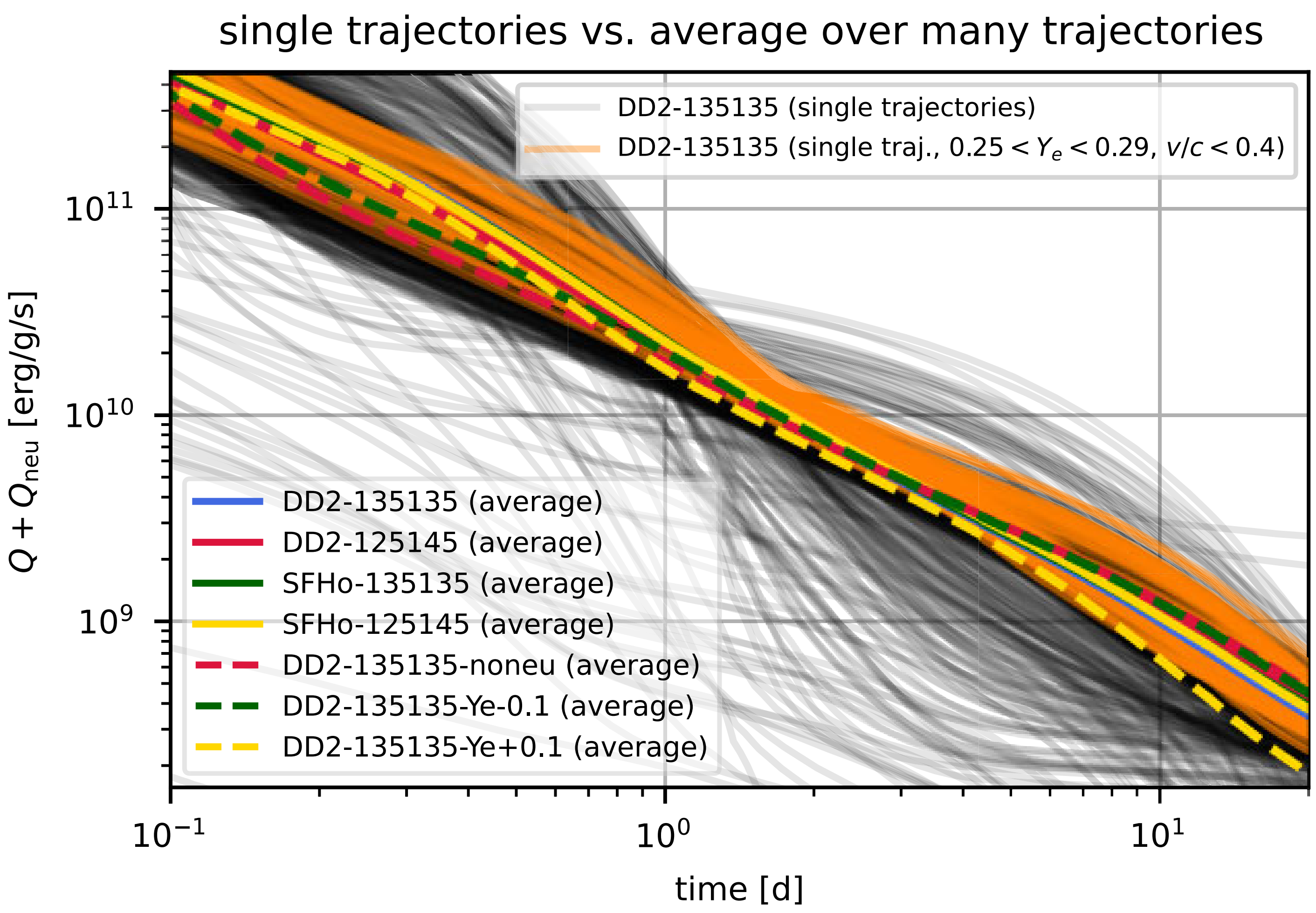


- nearly solar abundance for A>80
- only mild sensitivity to nuclear EOS and mass ratio

Importance of using ensembles of outflow trajectories

(Just+22)

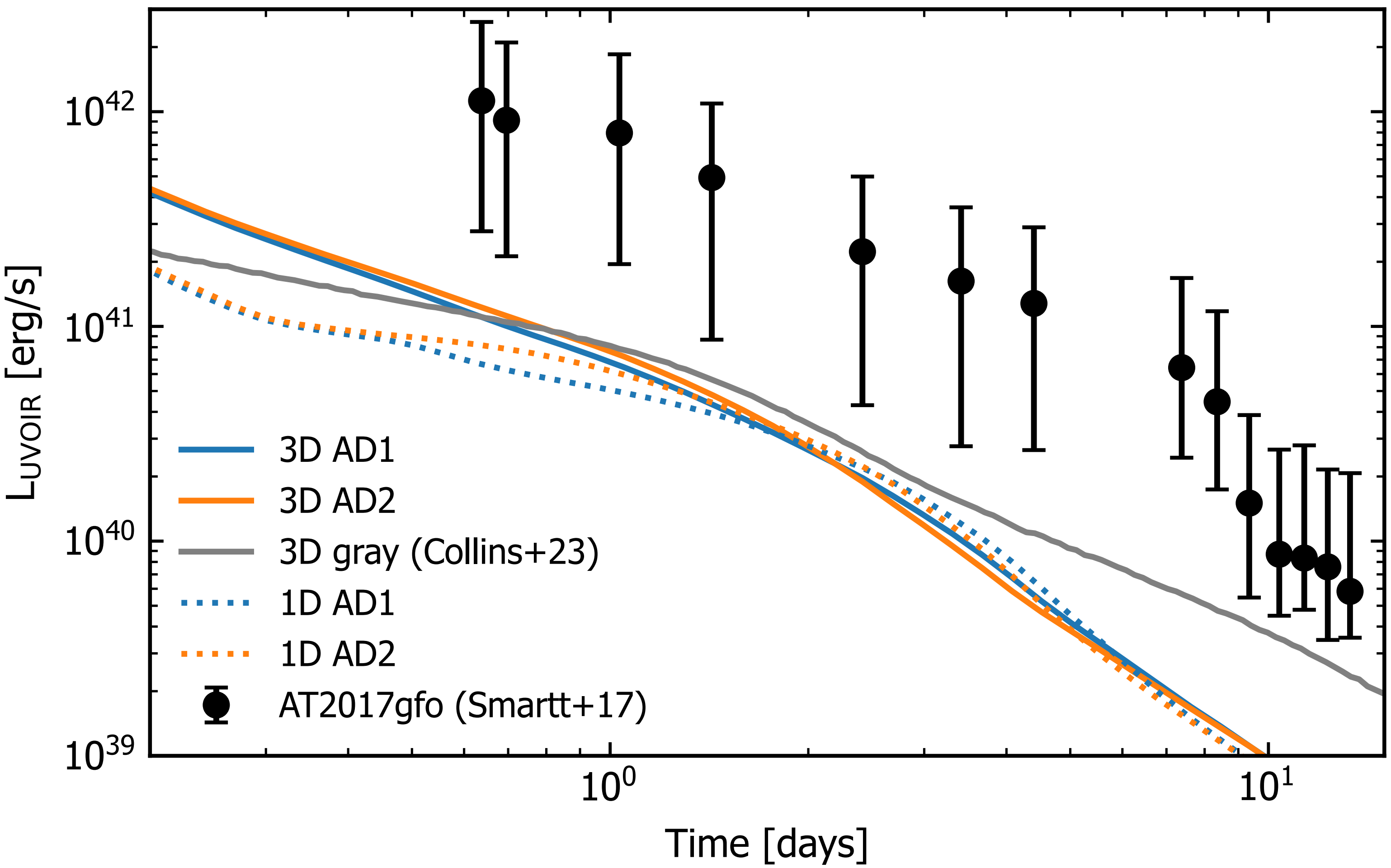
- heating rates of single trajectories subject to **much stronger variations** than ensemble-averages for different hydro models
- suggests that studies should **be careful when using individual “representative”** trajectories



Kilonova light curve from dynamical ejecta only

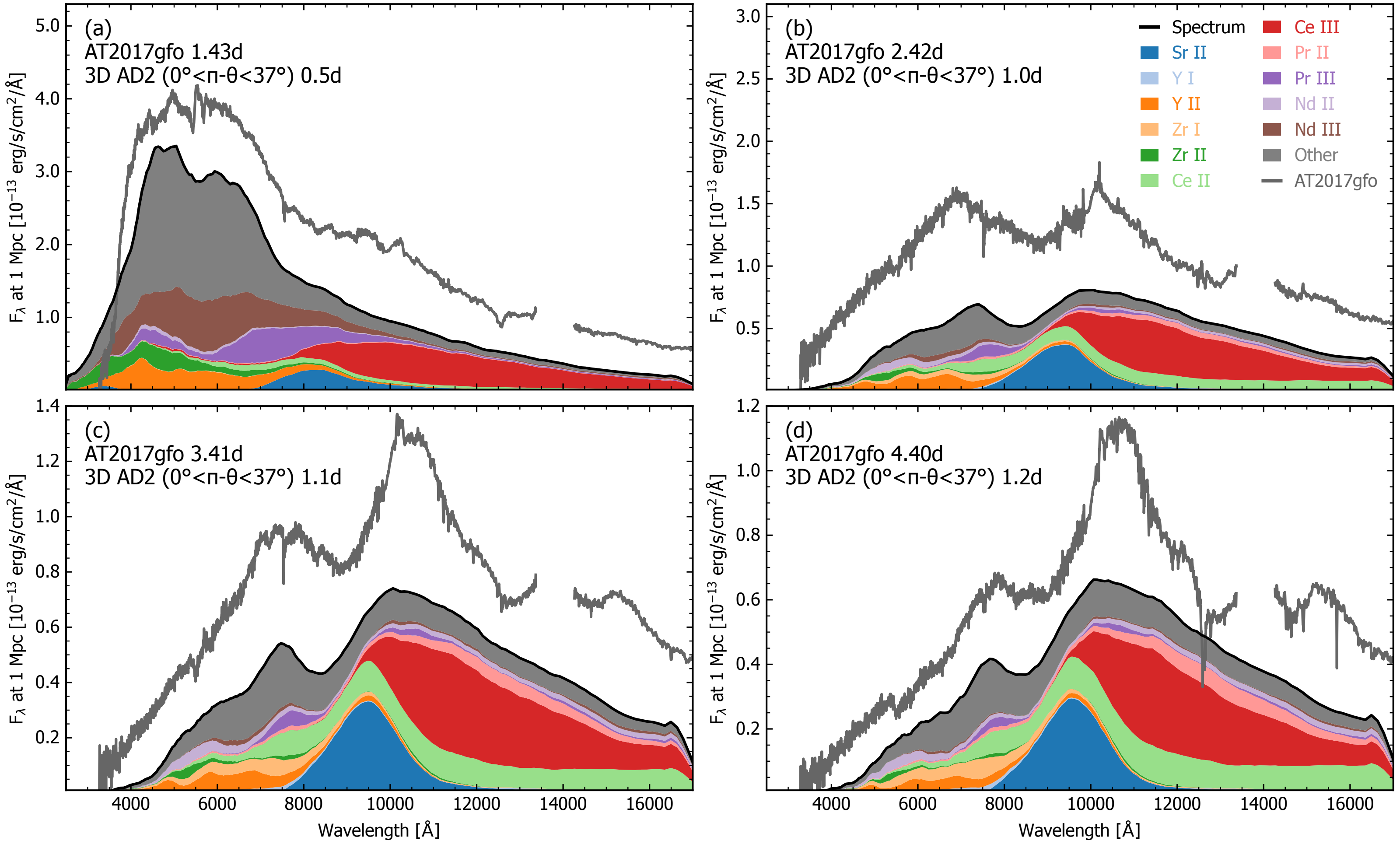
(Shingles+23, Collins+24)

- detailed KN model using ARTIS Monte-Carlo code
- includes millions of atomic line transitions
- too faint to explain AT2017gfo
- main reason: insufficient ejecta mass
  -> calls for contribution from post-merger ejecta



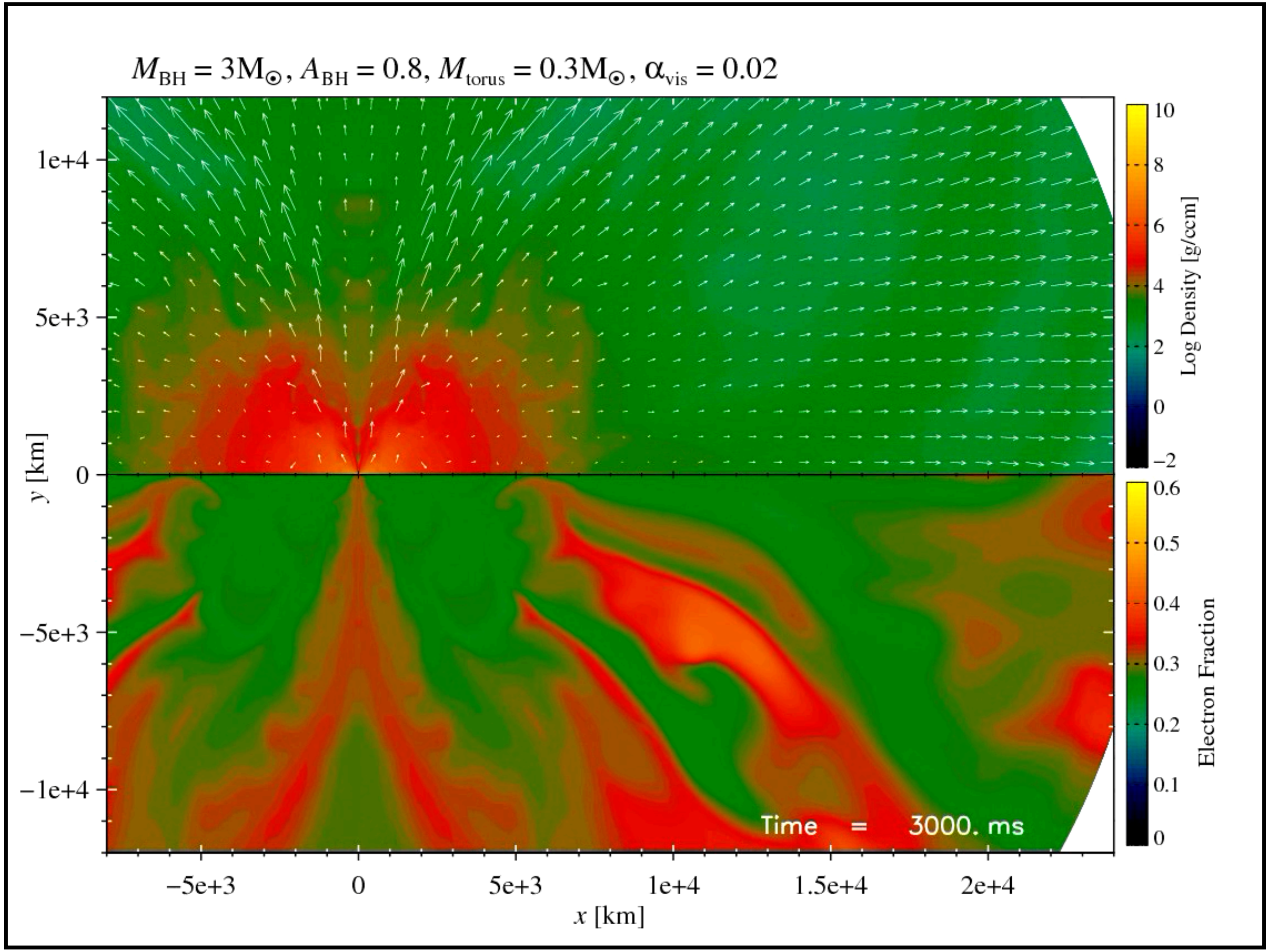
Kilonova spectra from dynamical ejecta only

(Shingles+23, Collins+24)



- feature around 8000-10000 Angstrom reproduced remarkably well
- strong indication that strontium was synthesized in AT2017gfo

BH-torus ejecta



(Movie: Just+15)

Weak interaction equilibria

beta-process rates:

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

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

$$p + e^- \to n + \nu_e$$
$$n + e^+ \to p + \bar{\nu}_e$$

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

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

$$n + \nu_e \to p + e^-$$
$$p + \bar{\nu}_e \to n + e^+$$

change of Y_e:

$$\frac{\mathrm{d}Y_e}{\mathrm{d}t} = (\lambda_{e^+} + \lambda_{\nu_e})Y_n - (\lambda_{e^-} + \lambda_{\bar{\nu}_e})Y_p$$

emission equilibrium:

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

absorption equilibrium:

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

(full) equilibrium:

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

Neutrino absorption equilibrium

$$Y_e^{\mathrm{eq,abs}} \sim \left(1 + \frac{\langle \epsilon_{\bar{\nu}_e}^2 \rangle n_{\bar{\nu}_e}}{\langle \epsilon_{\nu_e}^2 \rangle n_{\nu_e}}\right)^{-1} ,$$

$$\sim \left(1 + \frac{\langle \epsilon_{\bar{\nu}_e}^2 \rangle L_{N,\bar{\nu}_e}}{\langle \epsilon_{\nu_e}^2 \rangle L_{N,\nu_e}}\right)^{-1}$$

~ 0.5 for typical conditions

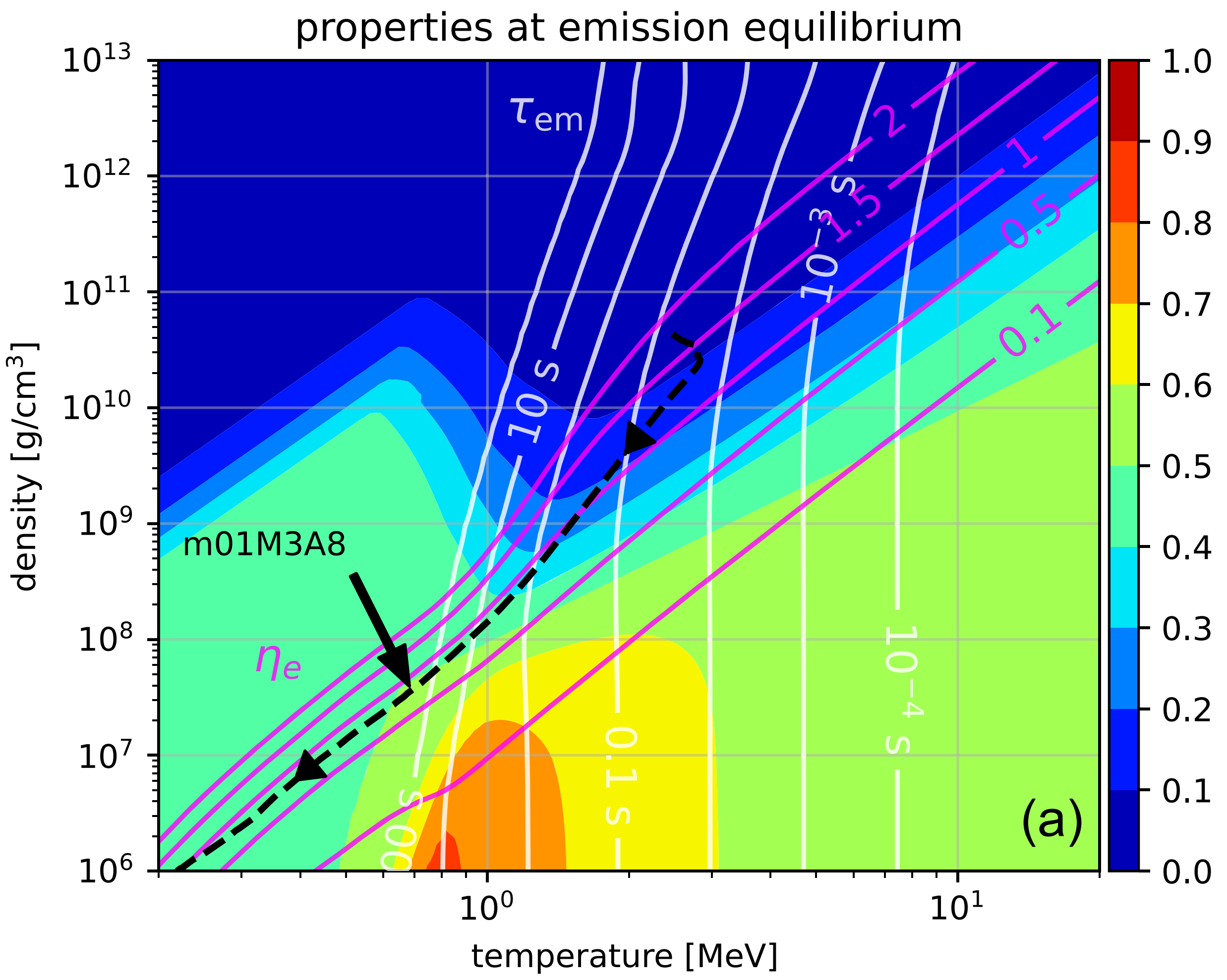
absorption equilibrium:

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

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

emission equilibrium:

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



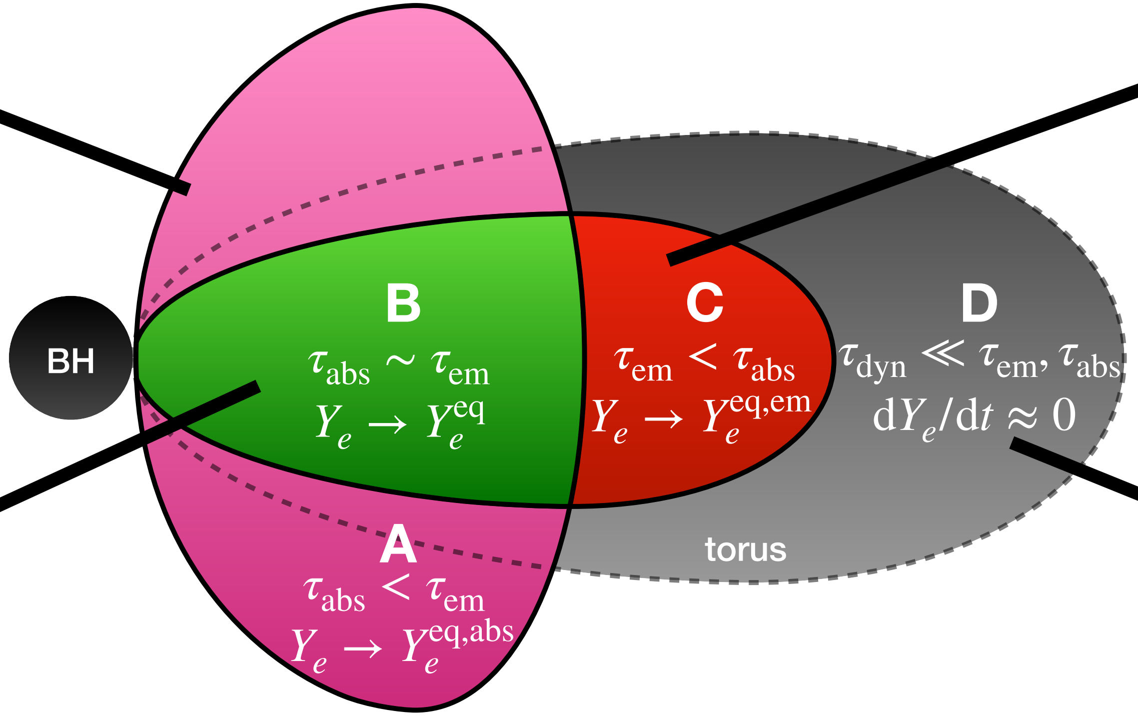
- $Y_e^{eq,em}$ increases when disk expands (decreasing density and temperatures)
- freeze-out once weak timescales >> dynamical timescales

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

Characteristic weak equilibria in BH disks

$e^+ + n \leftarrow p + \bar{\nu}_e$
$e^- + p \leftarrow n + \nu_e$
$Y^{eq,abs} \approx 0.5$

$e^+ + n \rightarrow p + \bar{\nu}_e$
$e^- + p \rightarrow n + \nu_e$
$Y^{eq,em}$ determined by thermodynamic state only

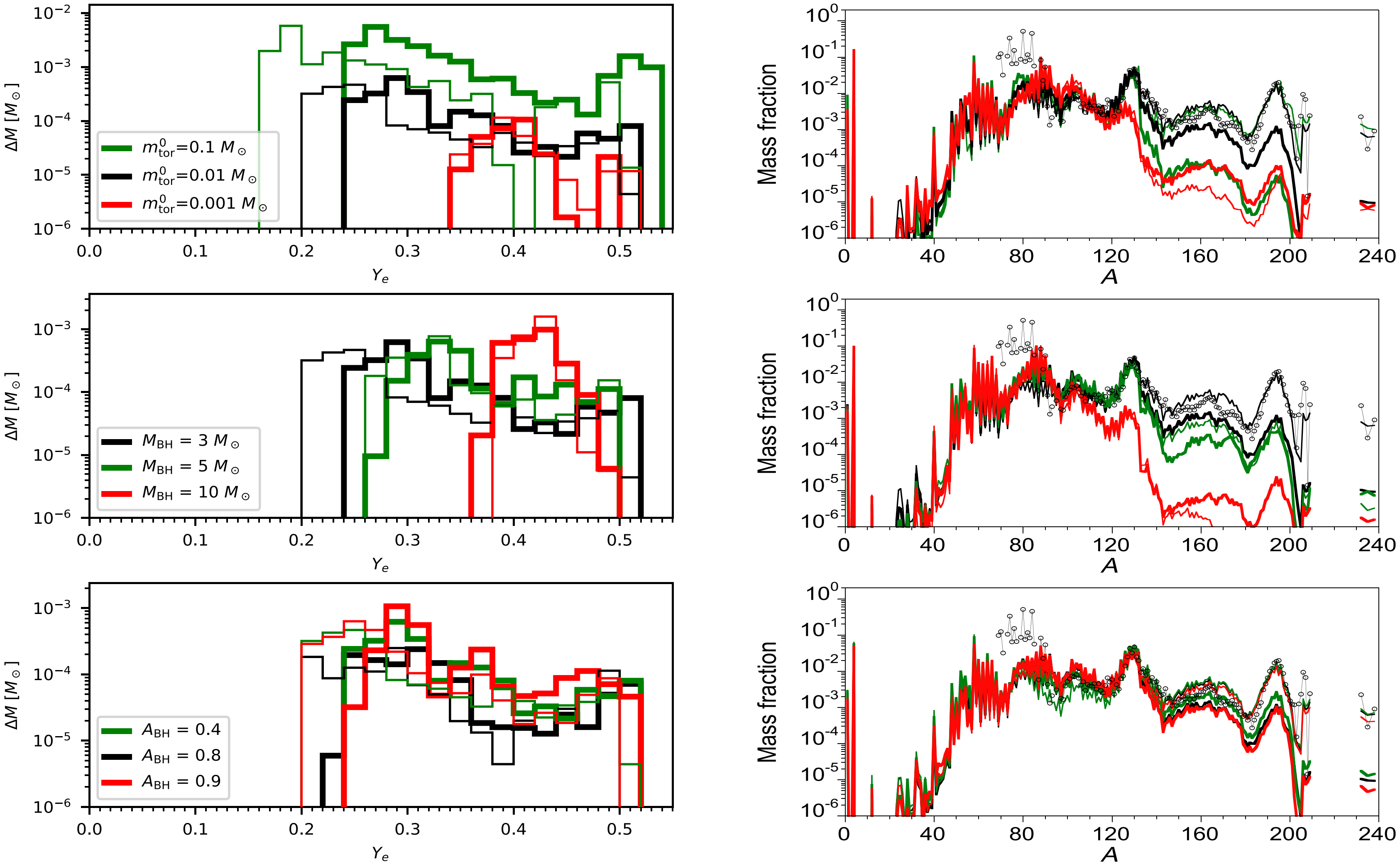


$e^+ + n \leftrightarrow p + \bar{\nu}_e$
$e^- + p \leftrightarrow n + \nu_e$
Y^{eq} determined by thermodynamic state + neutrino field

weak reactions frozen out, Y_e does not change

(Just, Goriely et al 22)

Nucleosynthesis yields of BH disk outflows



(Just, Goriely et al 22)

- can vary strongly depending on the disk conditions
- **overall higher Ye and less robust nucleosynthesis pattern compared to dynamical ejecta**

Impact of neutrino flavor mixing (“fast pairwise oscillations”)

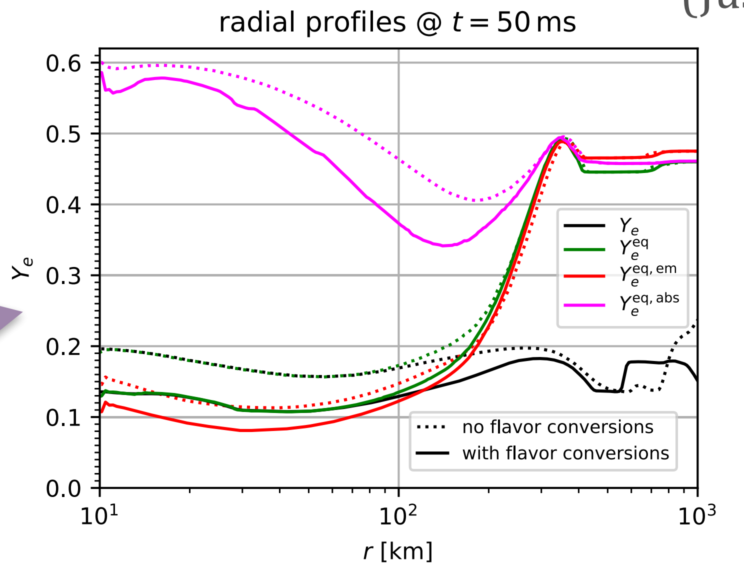
(Just, Abbar et al ’22)

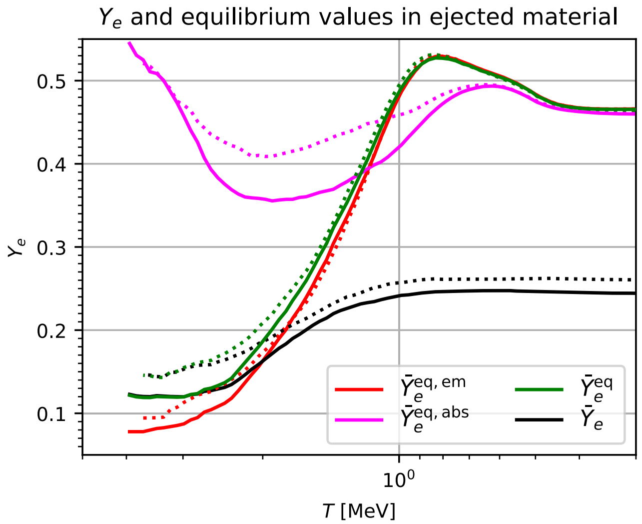
flavor equipartition, e.g. like:

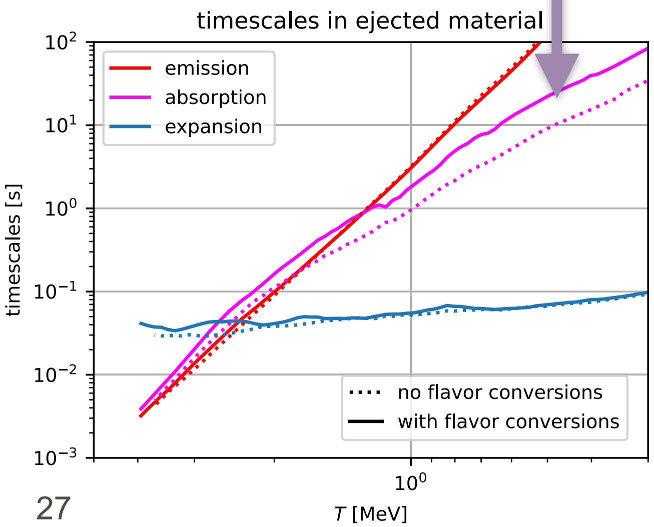
$$n_\nu = \frac{1}{6}\left(n^0_{\nu_e,q} + n^0_{\bar{\nu}_e,q} + 2n^0_{\nu_x,q} + 2n^0_{\bar{\nu}_x,q}\right)$$

two main effects:

- enhanced neutrino cooling rates lead to high electron degeneracy and lower value of $Y_e^{\mathrm{eq,em}}$
- reduced abundances of electron-type neutrinos reduce impact of absorption and lead to additional reduction of Y_e^{eq}

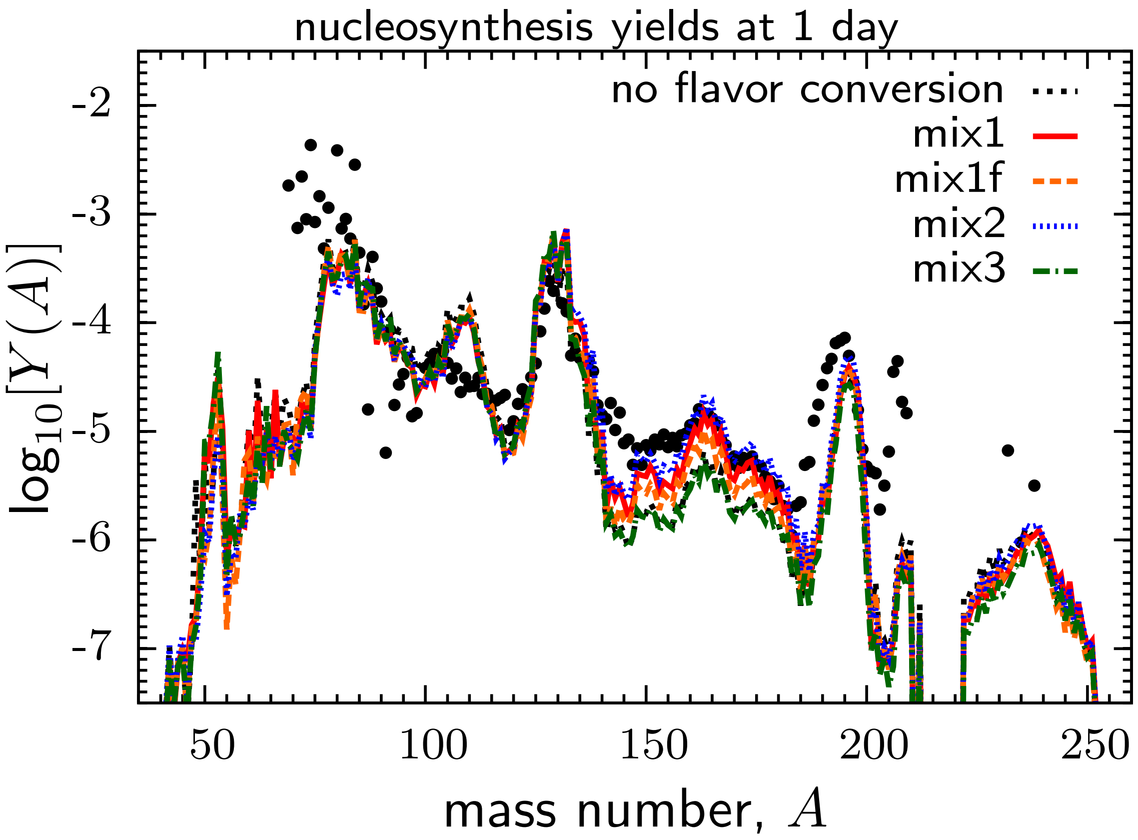


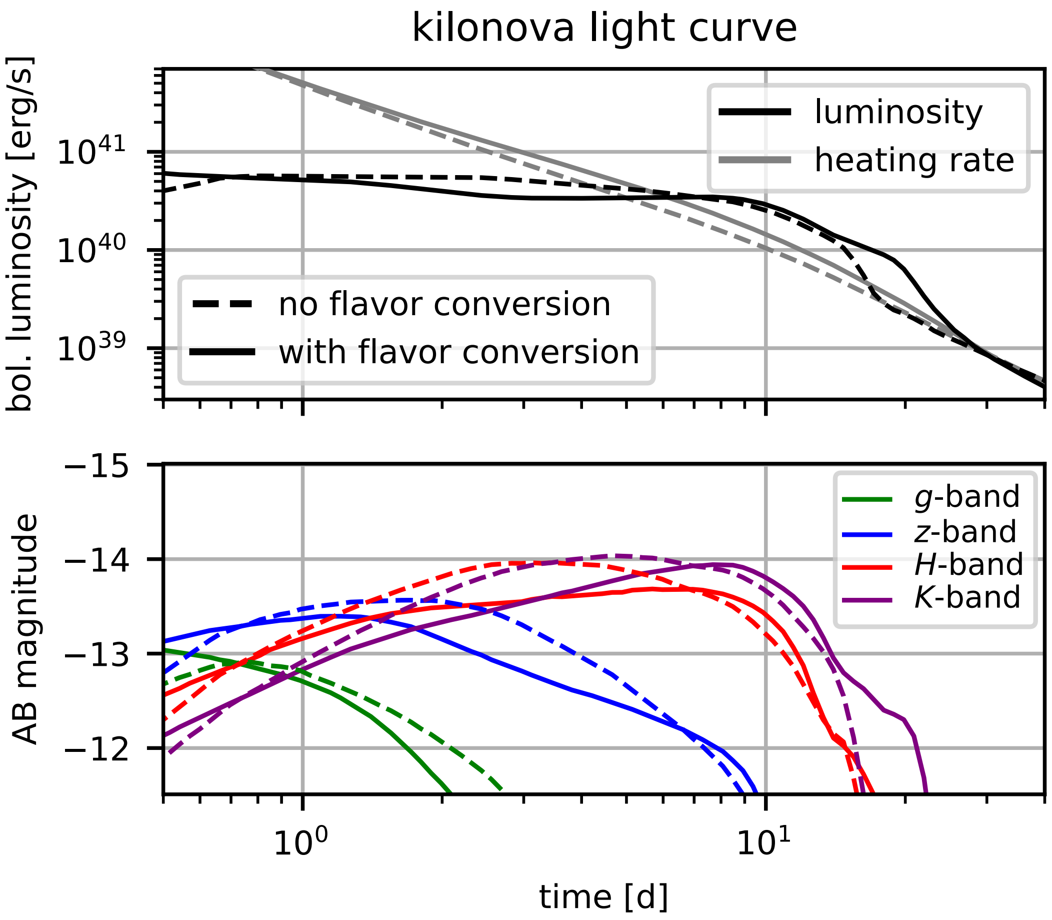




Impact on nucleosynthesis and kilonova

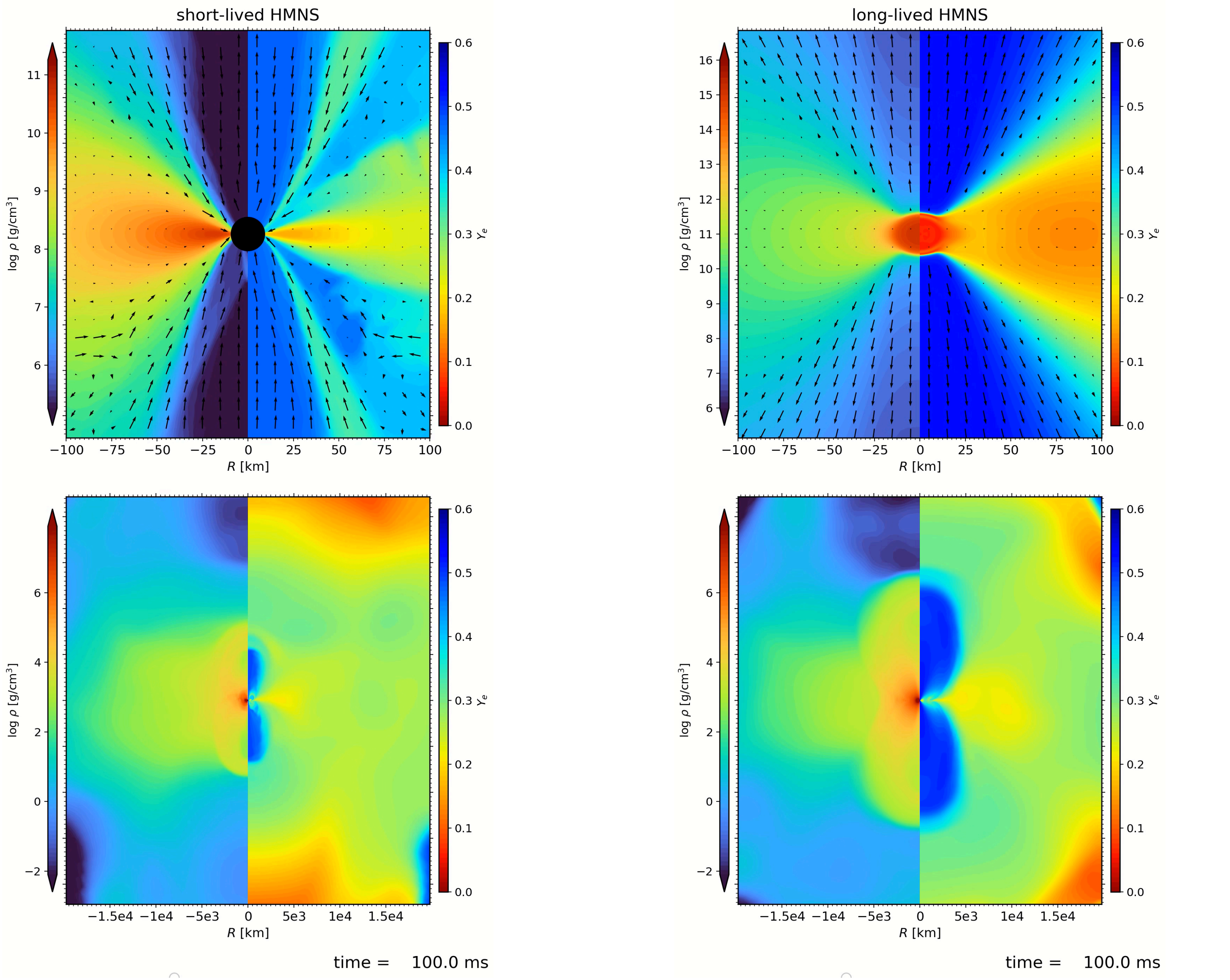
(Just, Abbar et al ’22)





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

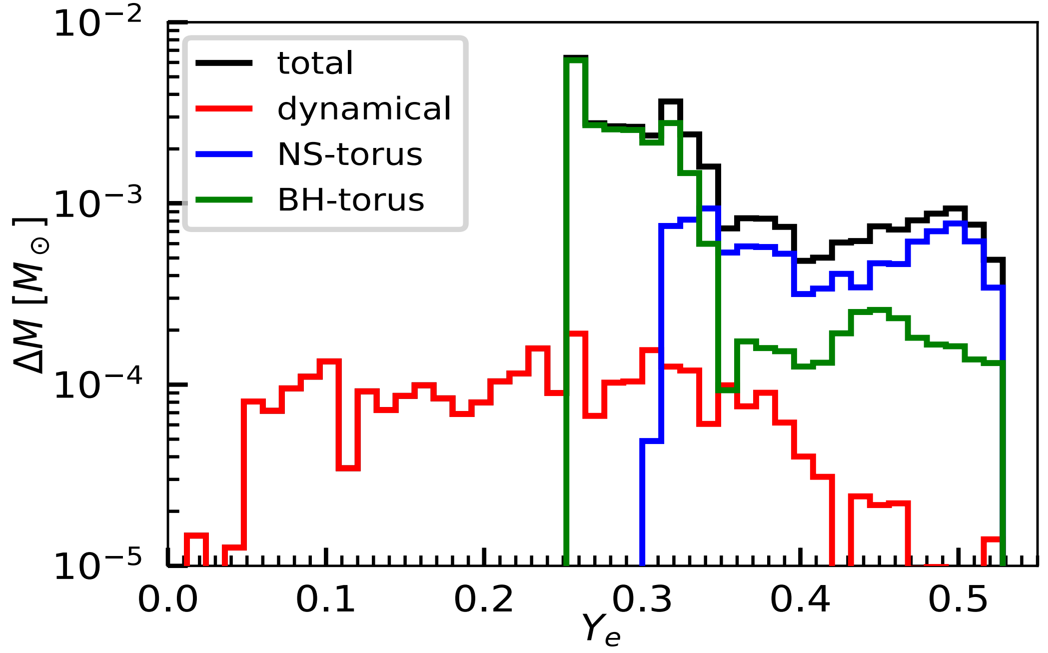
NS-torus ejecta



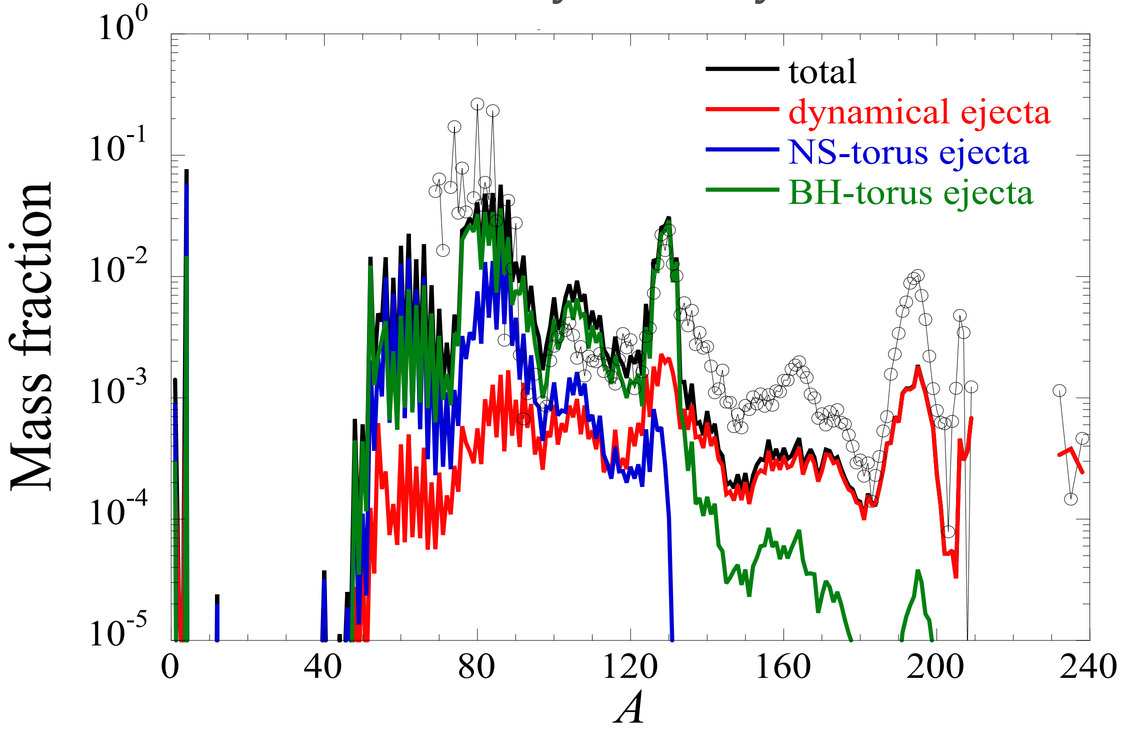
Composition
(model with $\tau_{\rm BH}$ ~ 120 ms)

(Just+ ApJL 951, L12, 2023)

Y_e histogram



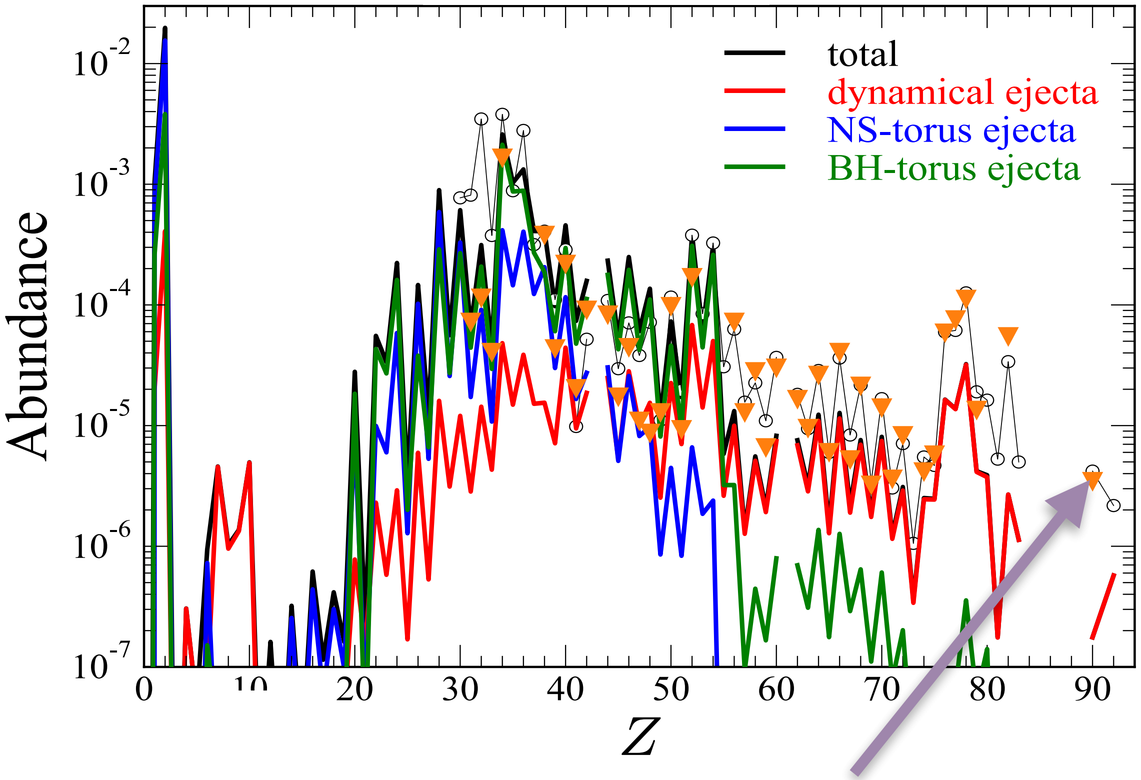
nucleosynthesis yields



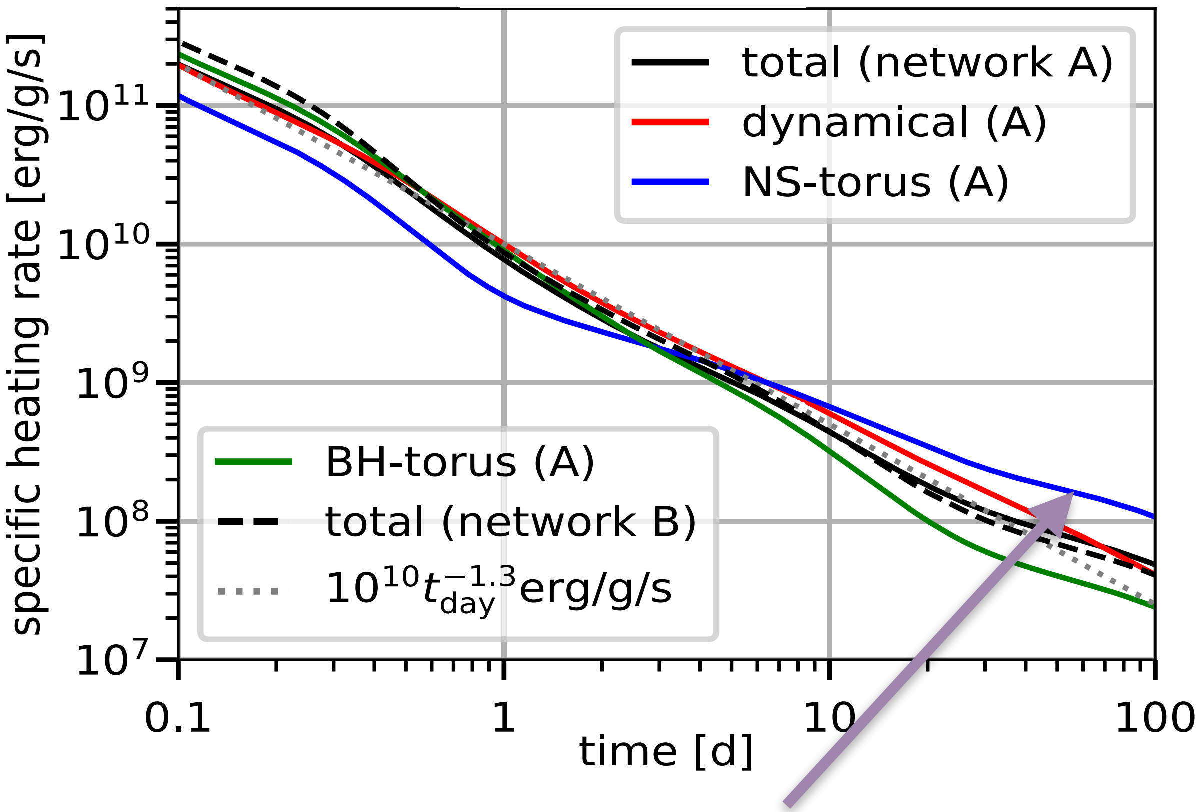
- different, characteristic Y_e and yields for each ejecta component
- requires long-term modeling of the merger remnant

Elemental yields & heating rate

(Just+ ApJL 951, L12, 2023)



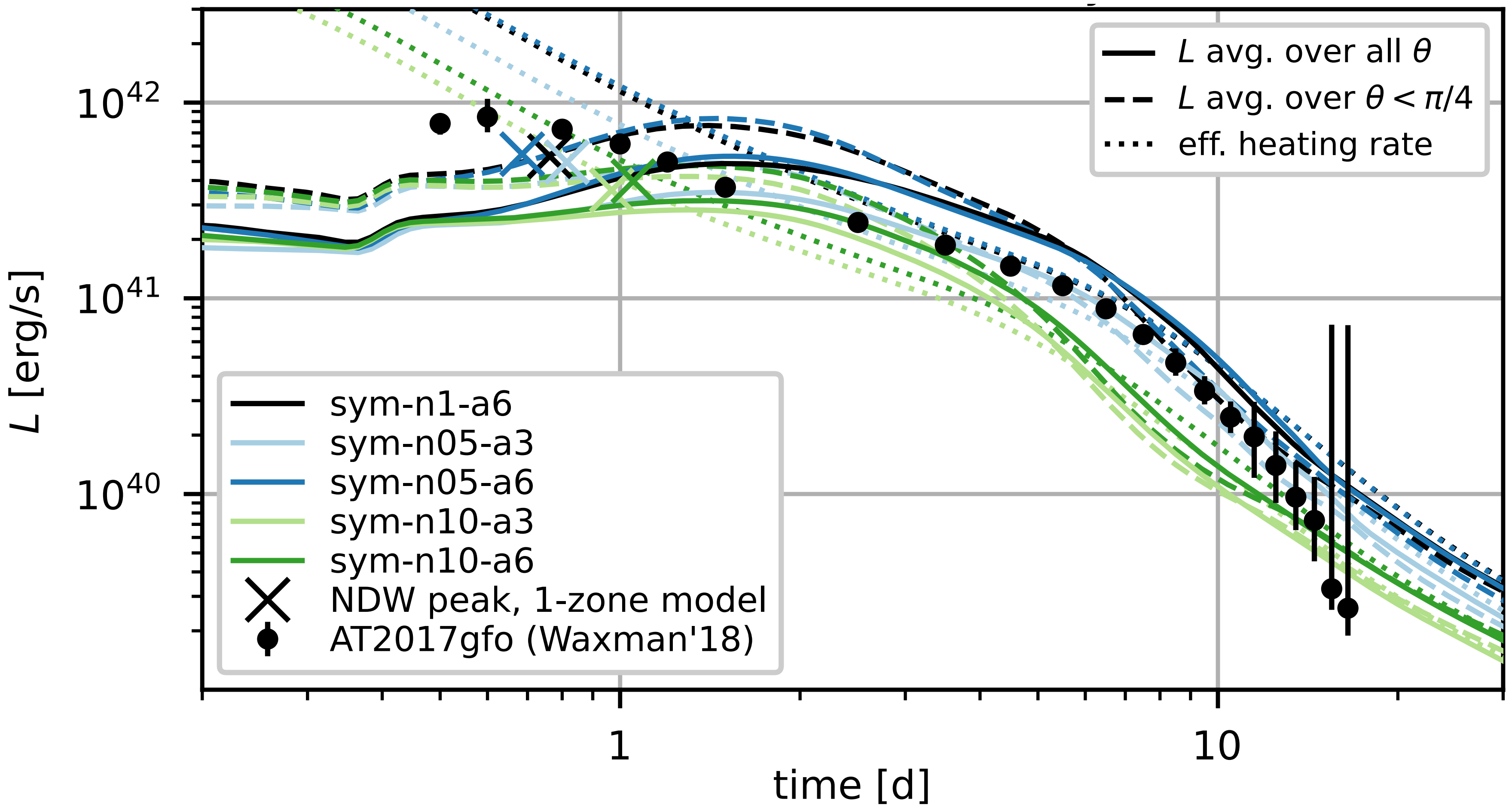
- observed metal-poor star HD 222925 (Roederer '22)
- deficient in Z>55, but reproduce drop at Z<33



- late-time increase in NS-torus winds from Ni56 and Co56 decay
- may not be visible in KN due to inefficient thermalization (but see Jacobi+2025)

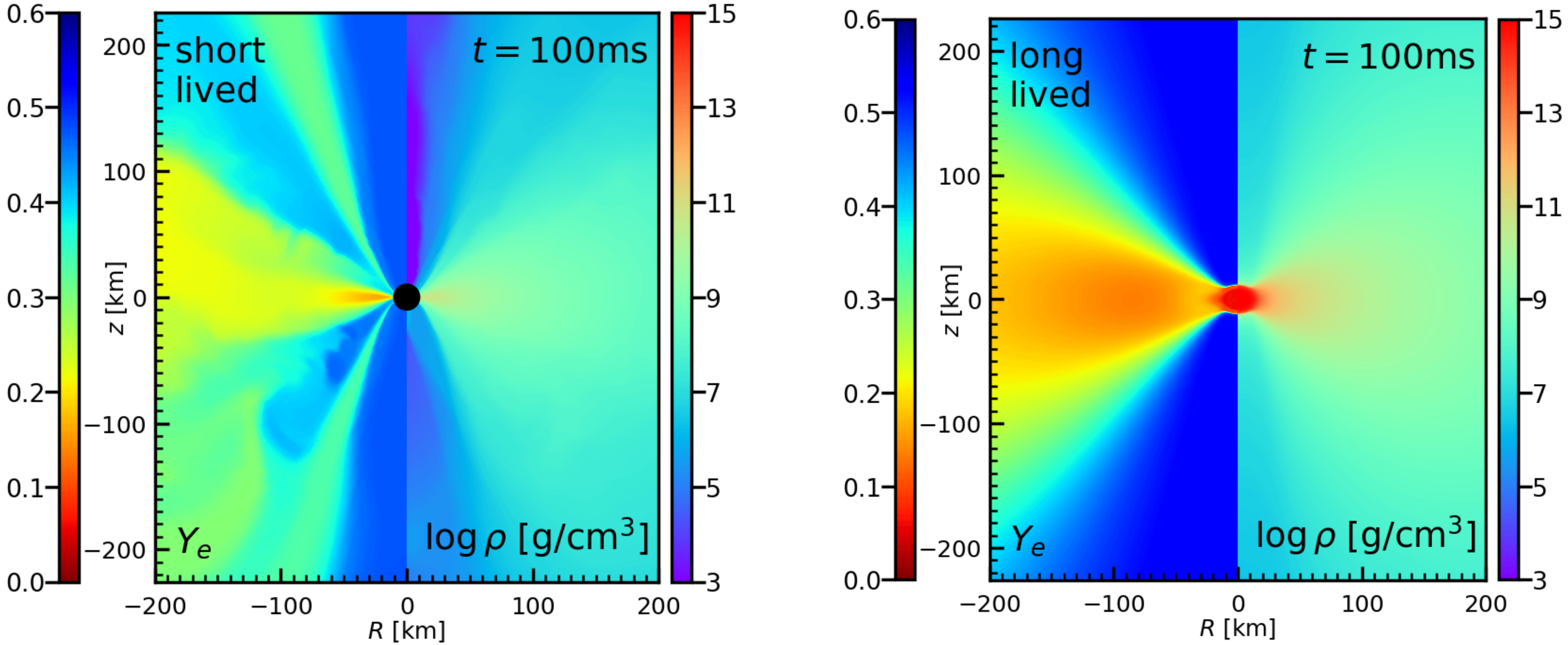
Comparison with AT2017gfo

(Just+ ApJL 951, L12, 2023)



- estimated of light curve using simplified radiative transfer scheme
- relatively good agreement with GW170817 (though not perfect)
- **next step:** more sophisticated kilonova calculations using ARTIS

Short- vs. long-lived NS remnant



- high-Ye polar wind powered by absorption of neutrinos on free nucleons
- estimate of Y_e:

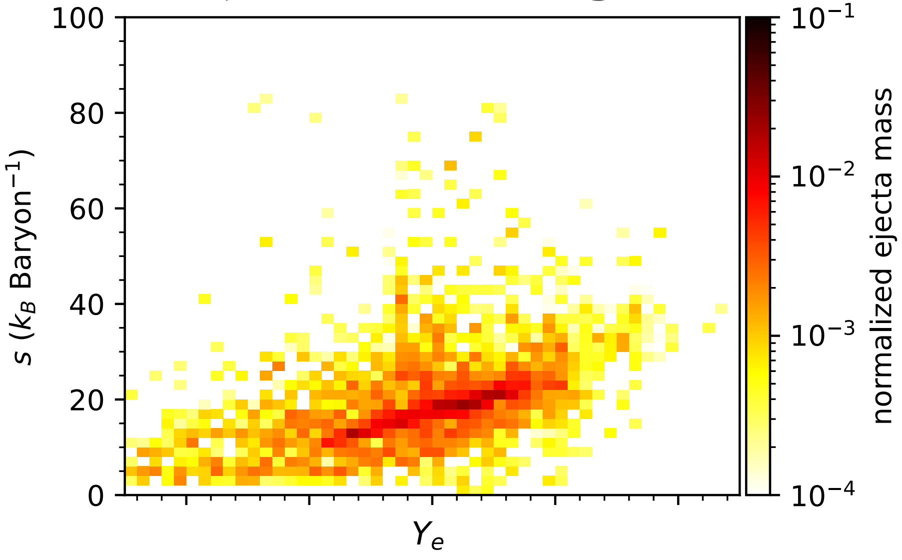
$$Y_e^{\text{eq,abs}} \simeq \frac{1}{1 + \frac{\langle \epsilon^2_{\bar{\nu}_e} \rangle L_{N,\bar{\nu}_e}}{\langle \epsilon^2_{\nu_e} \rangle L_{N,\nu_e}}} \simeq 0.5$$

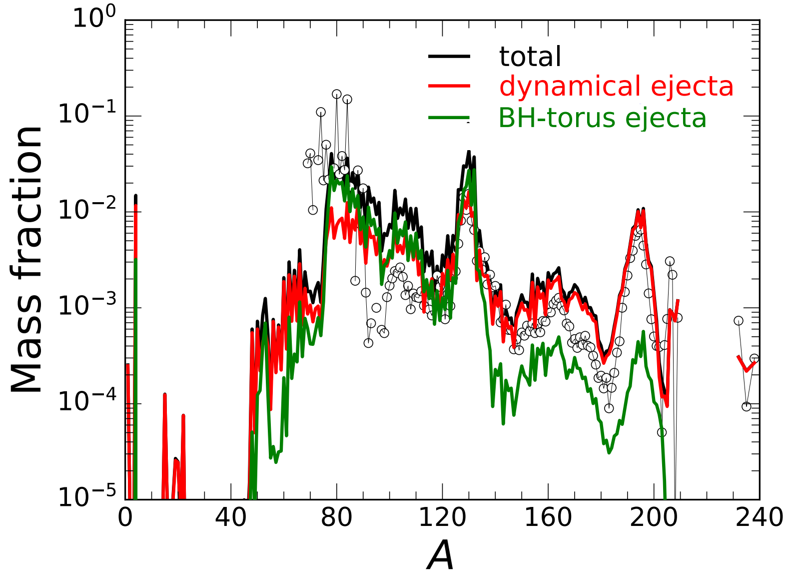
Short- vs. long-lived NS remnant

ejecta mass histogram

ejecta nucleosynthesis yields

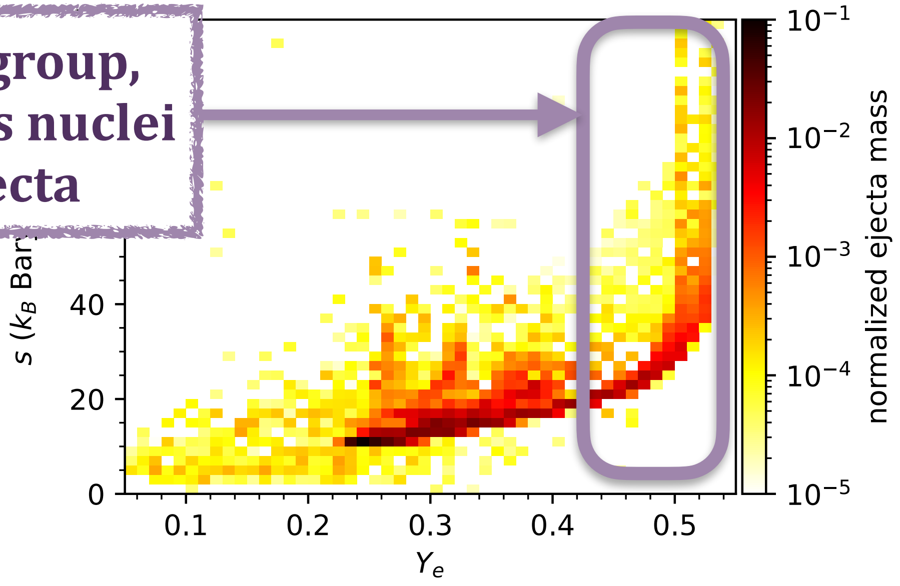
short-lived
(10ms)

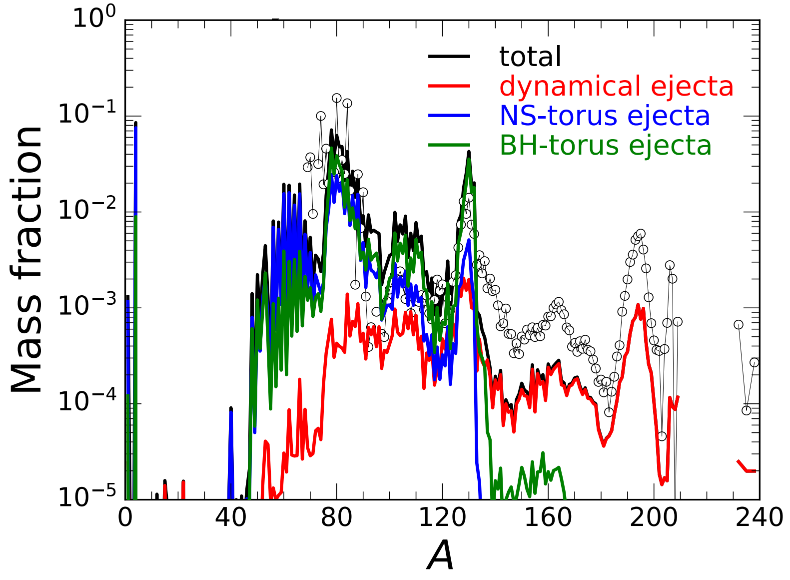




mainly He, iron-group, and light r-process nuclei in NS-torus ejecta

long-lived
(120ms)

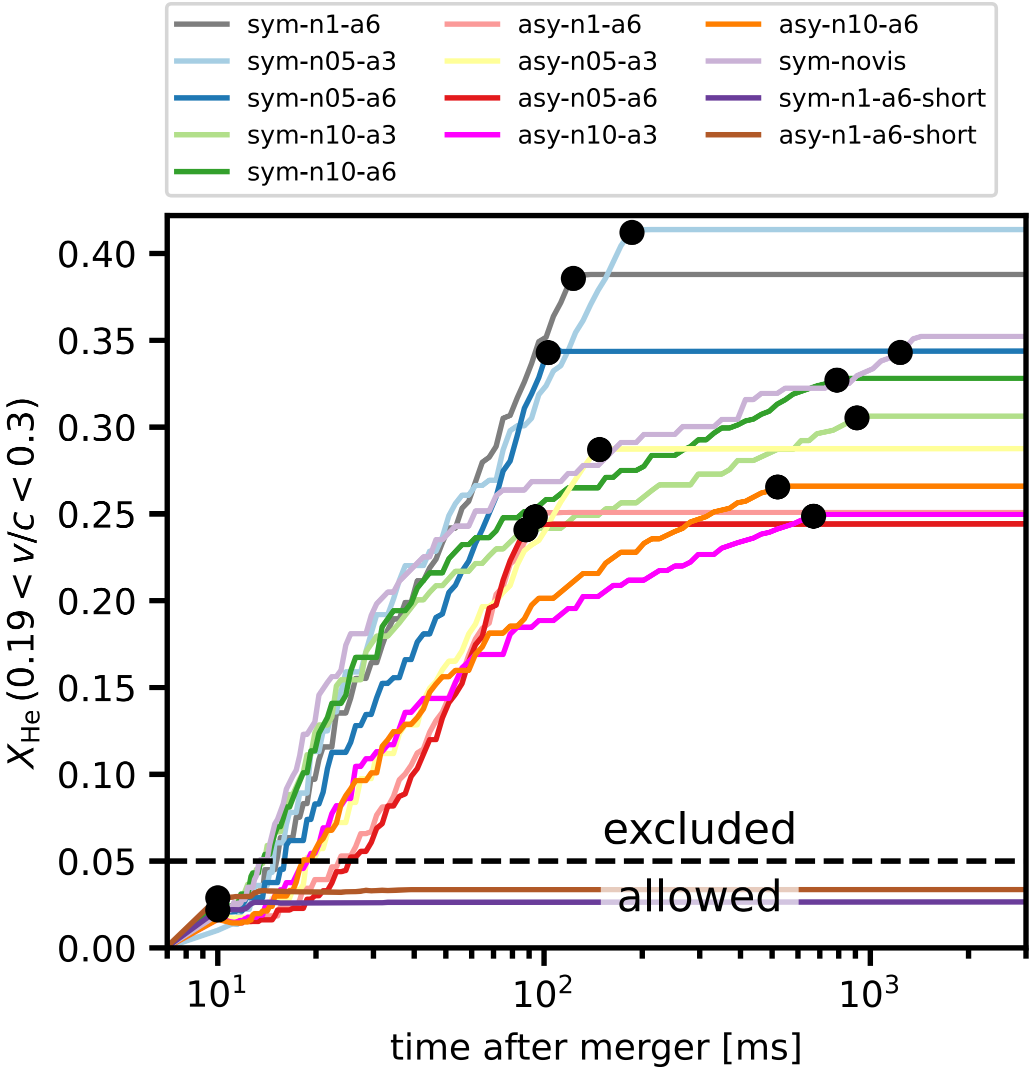




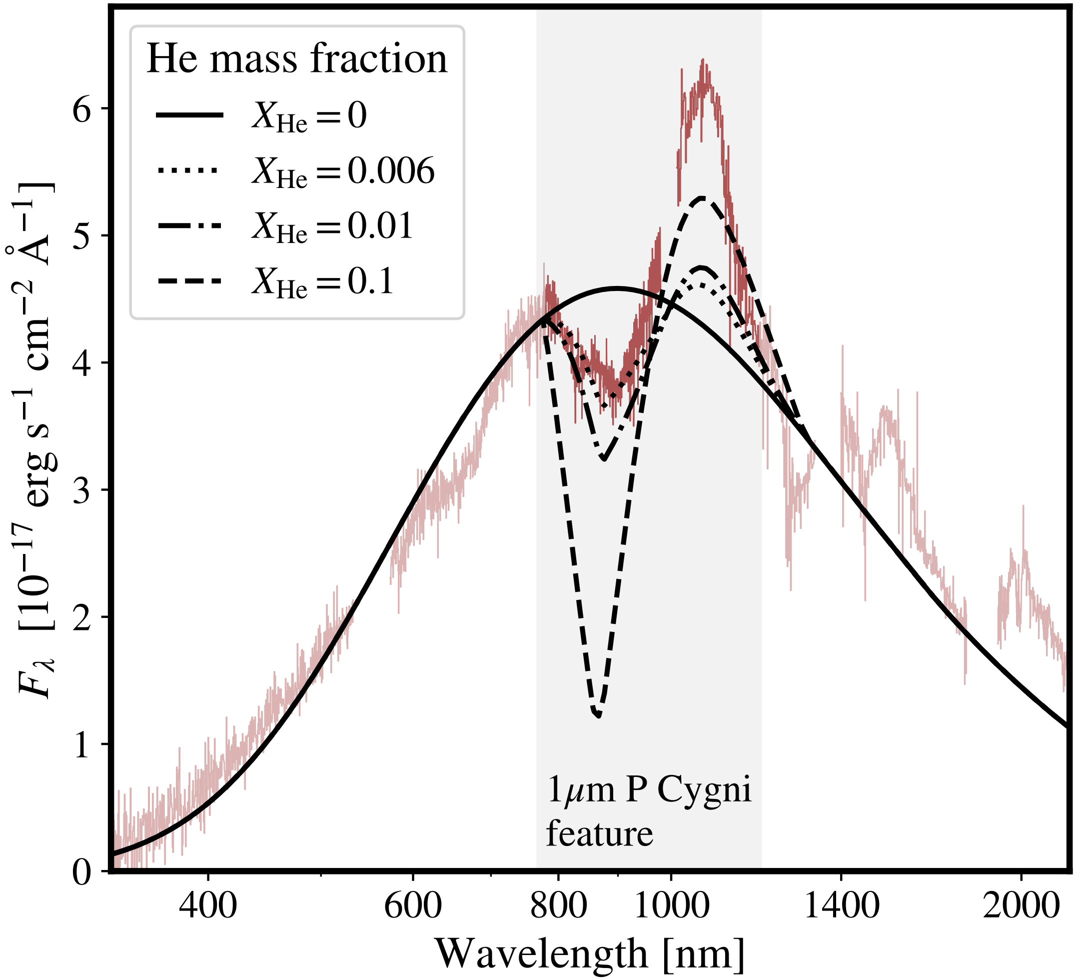
Helium production in NS merger models

(Sneppen+25, submitted)

hydro models



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



Helium production in NS merger models

(Sneppen+25, submitted)

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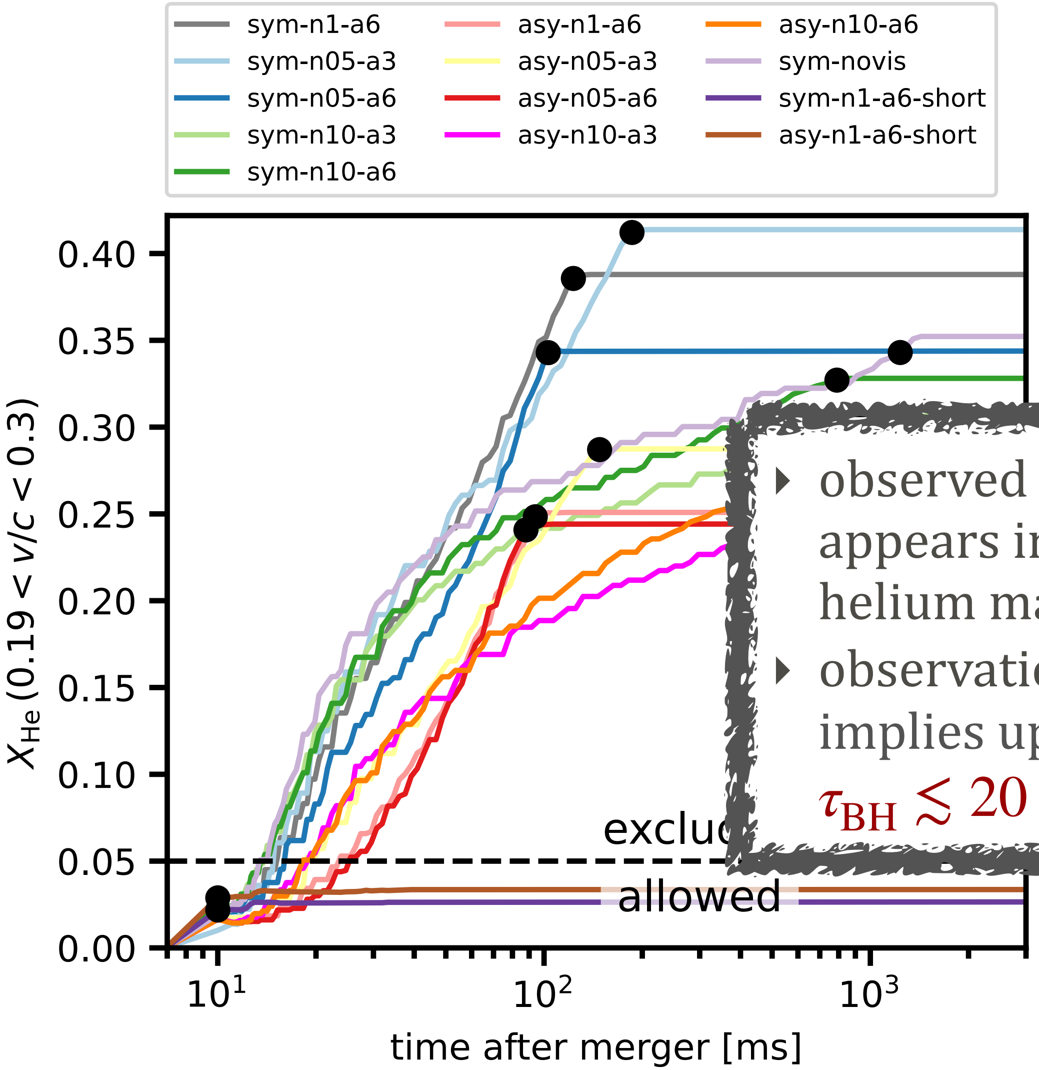
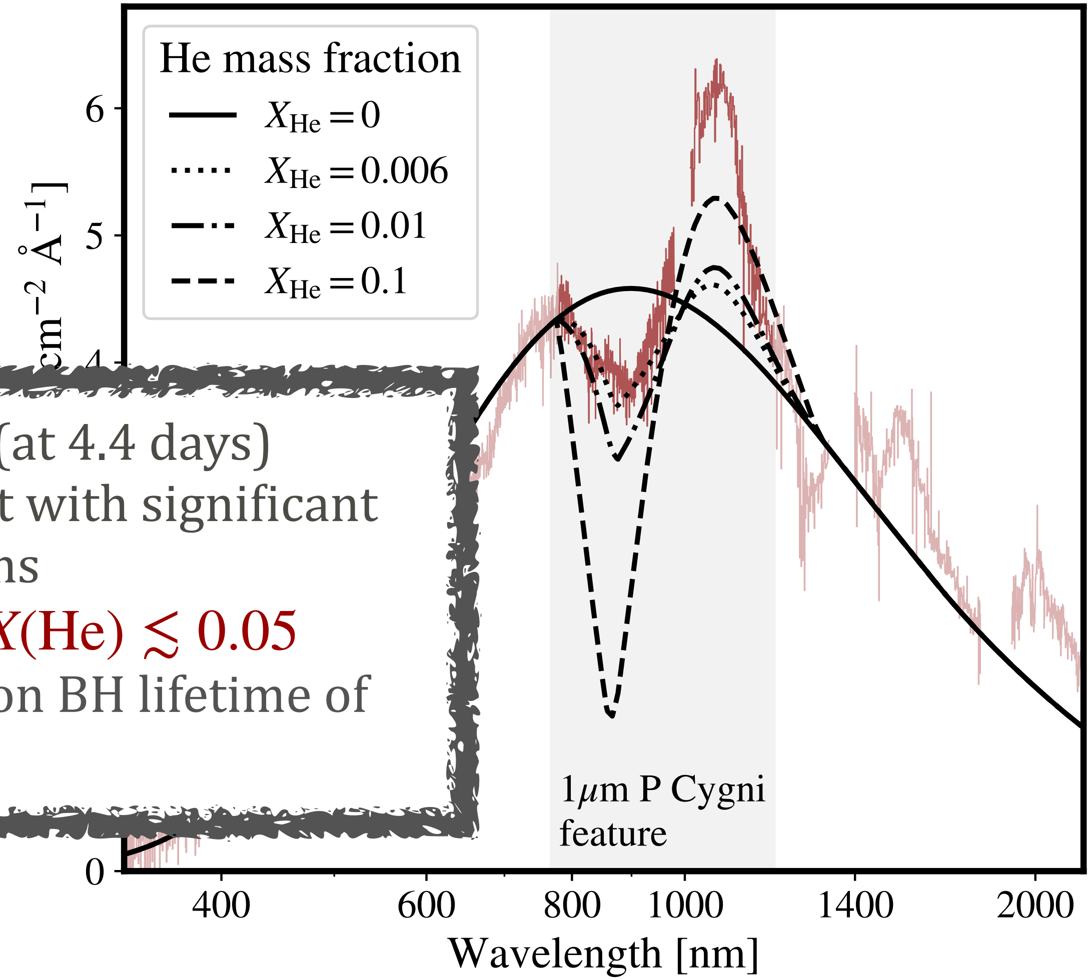
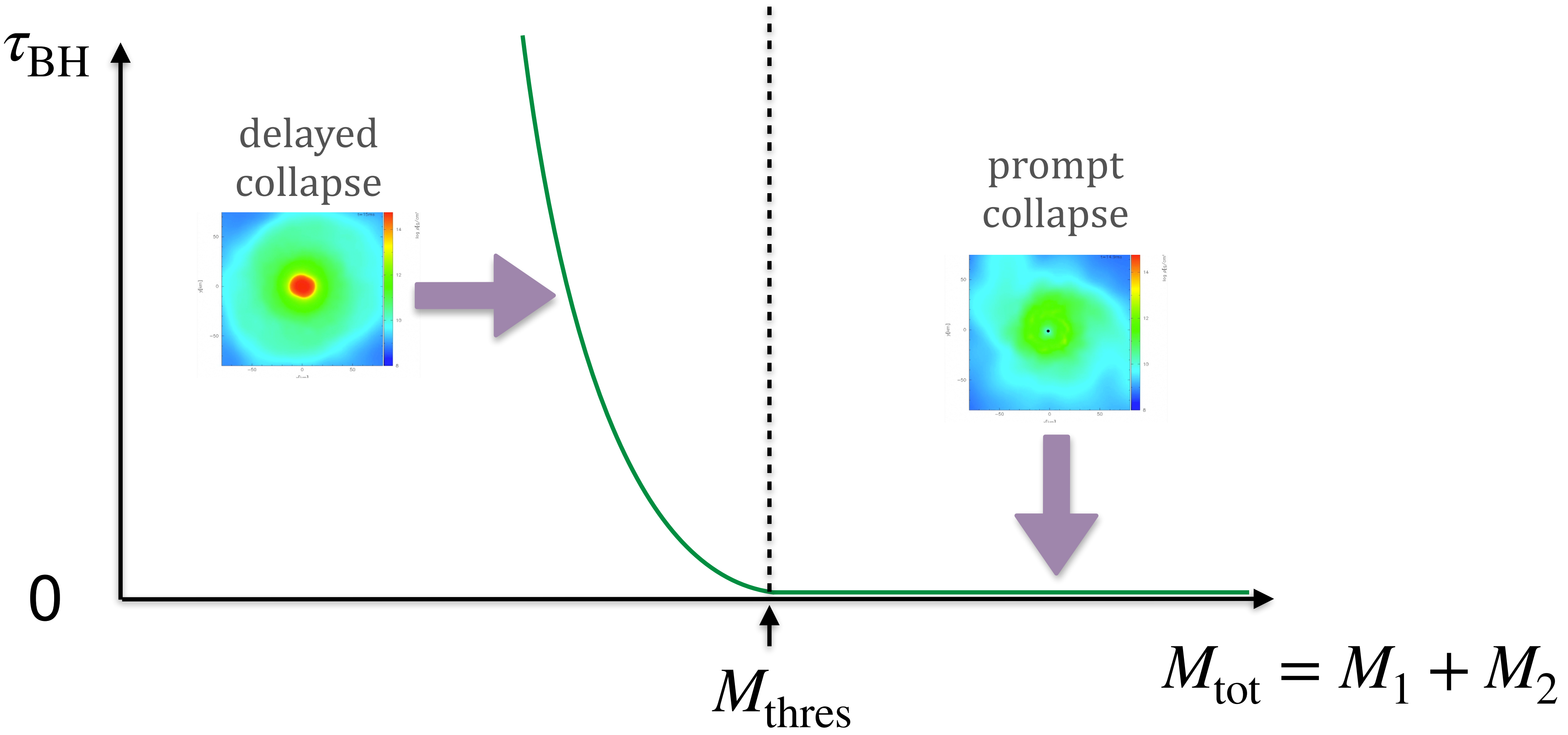


observed spectrum of AT2017gfo at 4.4 days + estimated hypothetic contribution of helium



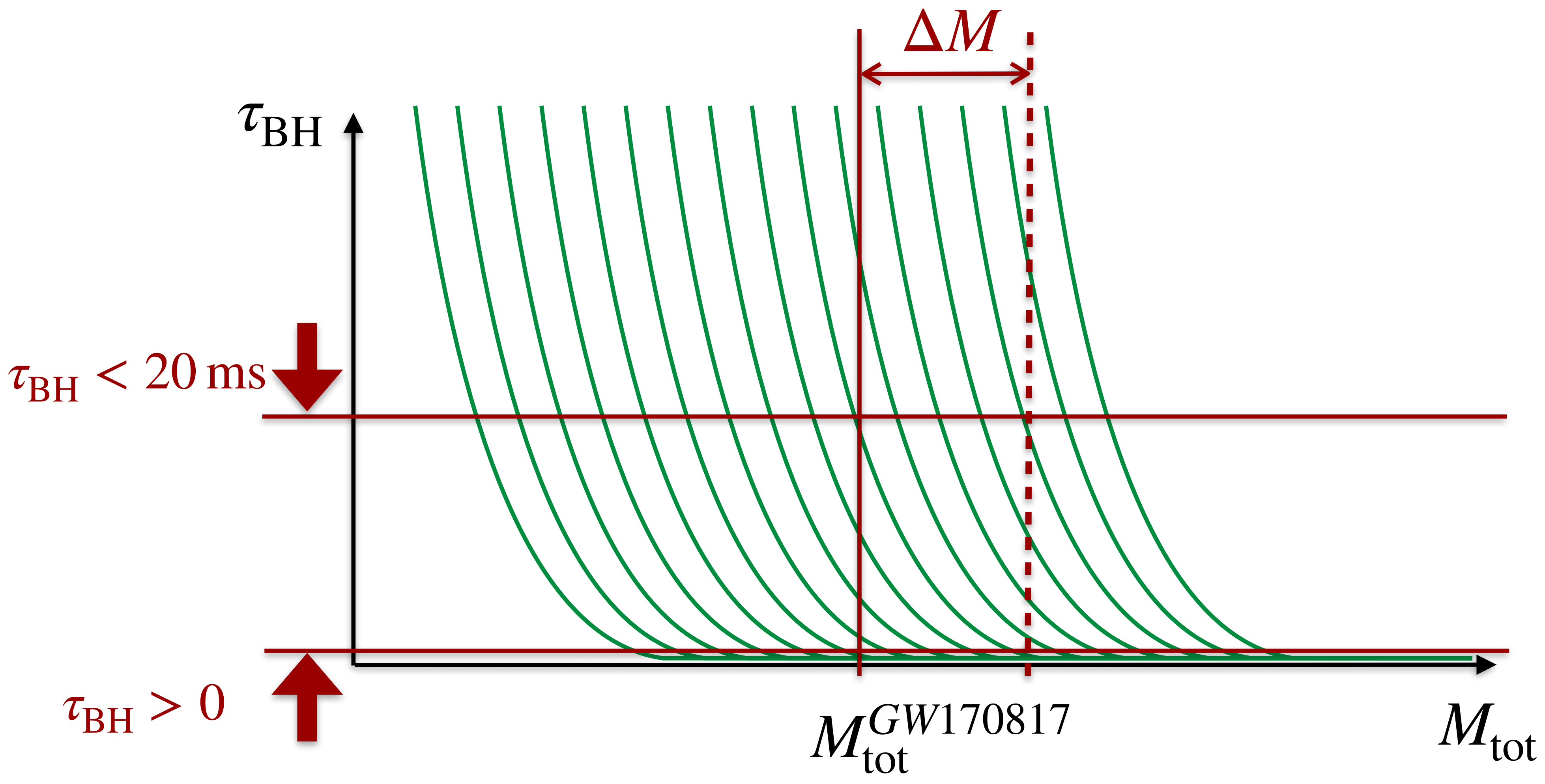
- observed spectrum (at 4.4 days) appears inconsistent with significant helium mass fractions
- observational limit $X(\mathrm{He}) \lesssim 0.05$ implies upper limit on BH lifetime of $\tau_{\mathrm{BH}} \lesssim 20 - 30\,\mathrm{ms}$

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



- threshold mass $M_{\rm thres}$ separates prompt-collapse from delayed-collapse cases

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

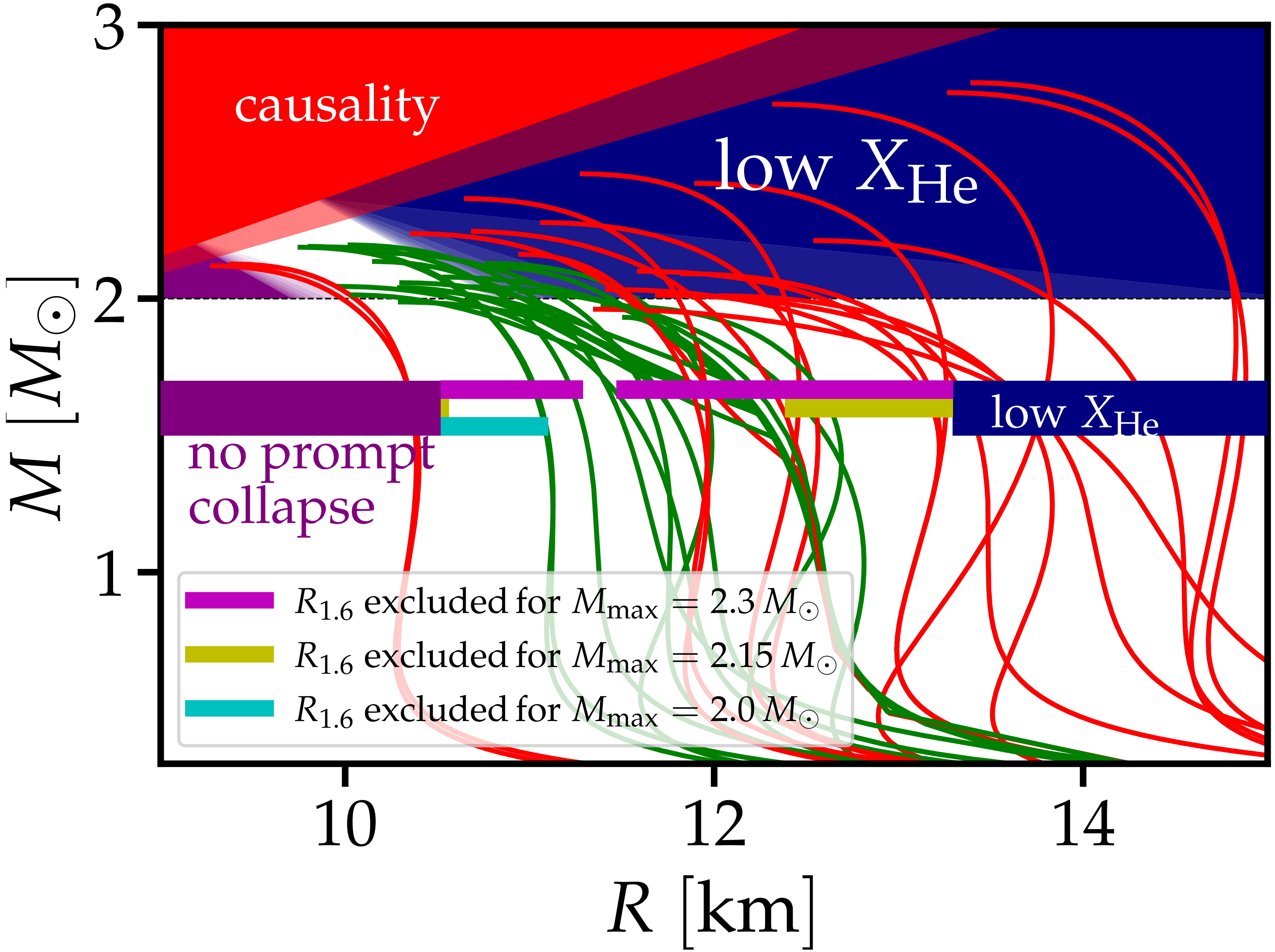


$$M_{\mathrm{thres}} - \Delta M < M_{\mathrm{tot}}^{GW170817} < M_{\mathrm{thres}}$$

Implications for NS properties

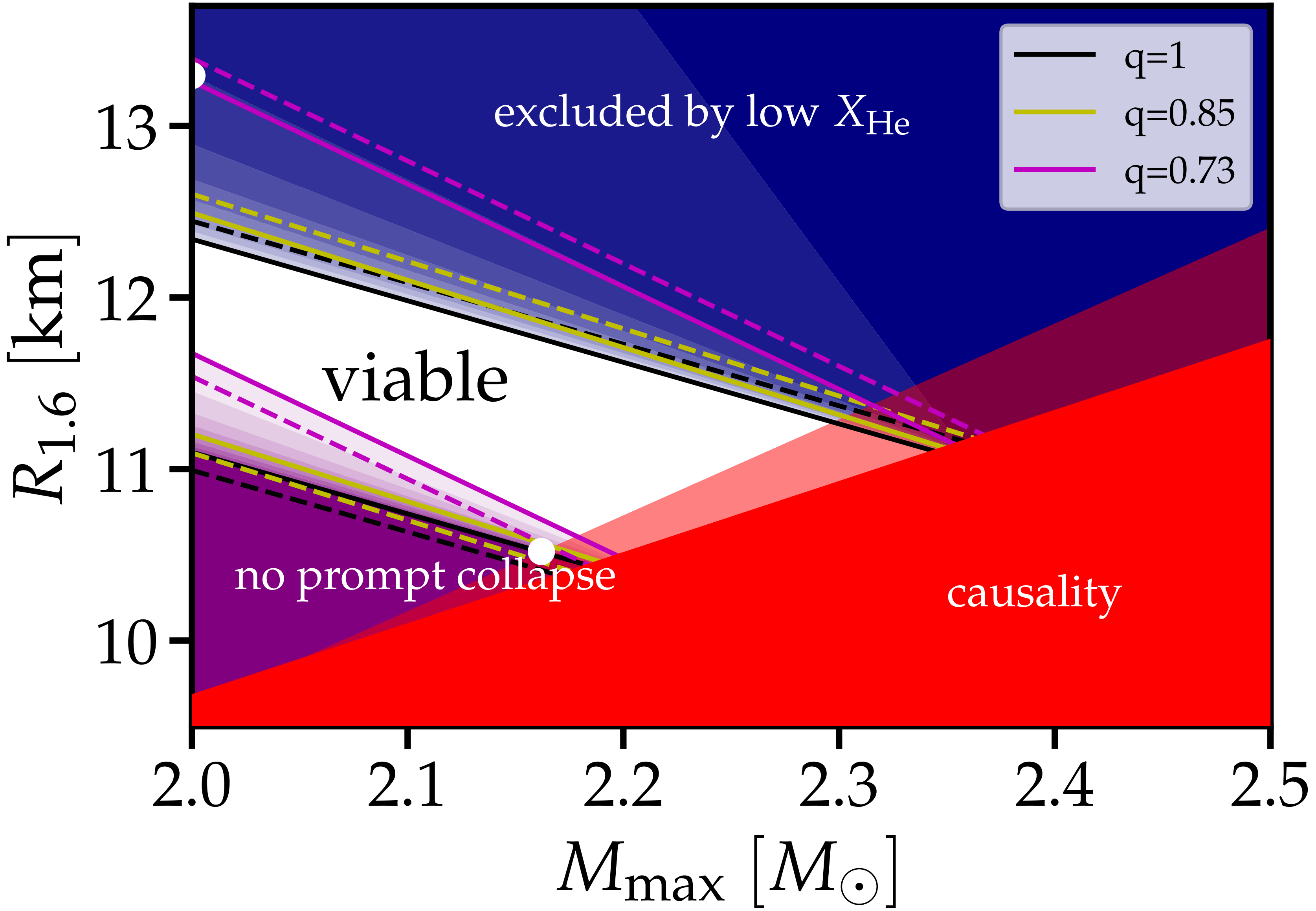
(Sneppen+25, submitted)

- Mass-radius relationship for various EOS models
- large number of EOS models excluded (red lines)
- in particular EOS models with simultaneously large $R_{1.6}$ and M_{max}



Implications for NS properties

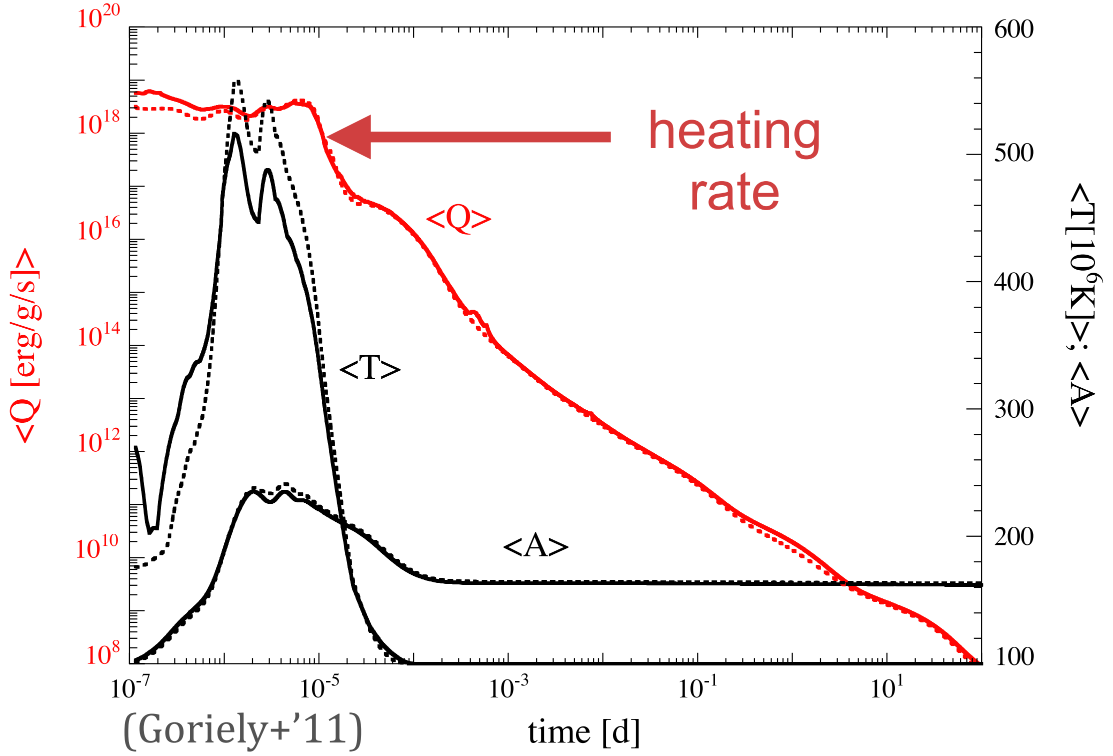
(Sneppen+25, submitted)



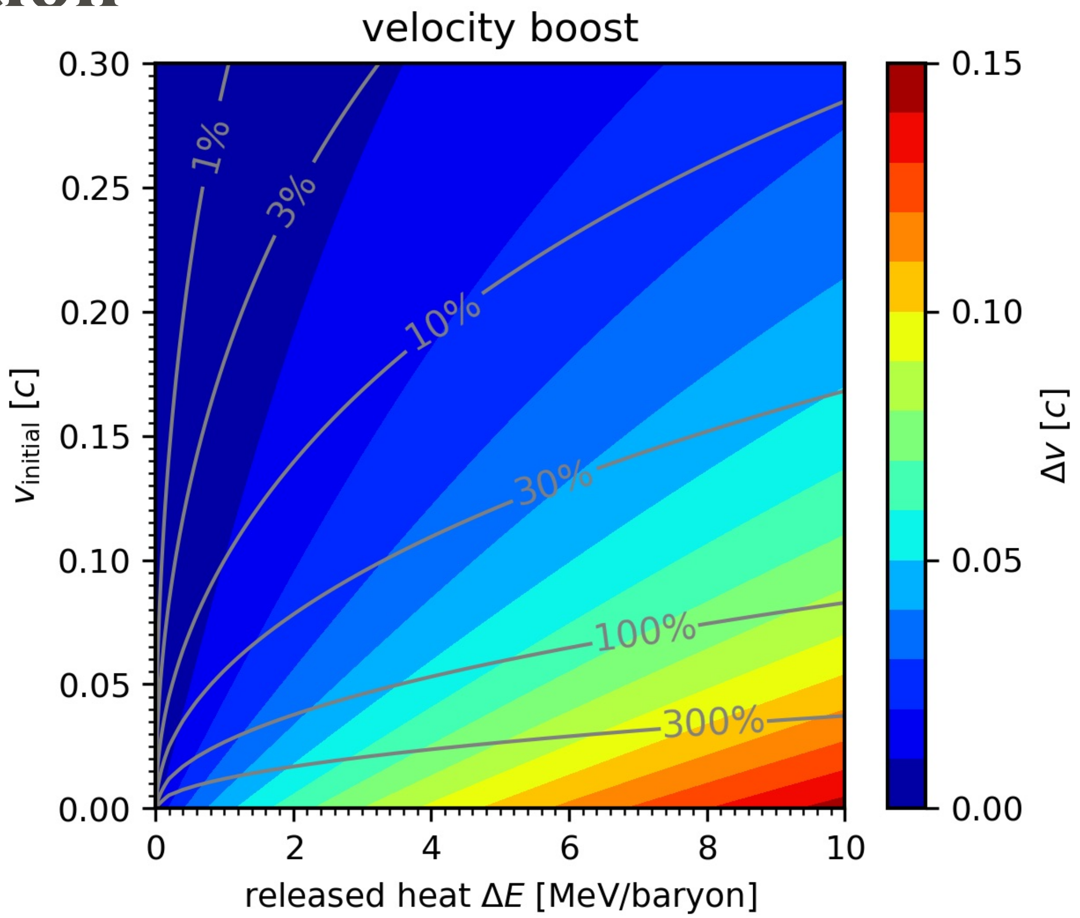
RHINE: R-process Heating Implementation in hydrodynamic simulations with NEural networks

(OJ, Z. Xiong, G. Martinez-Pinedo, submitted)

Motivation



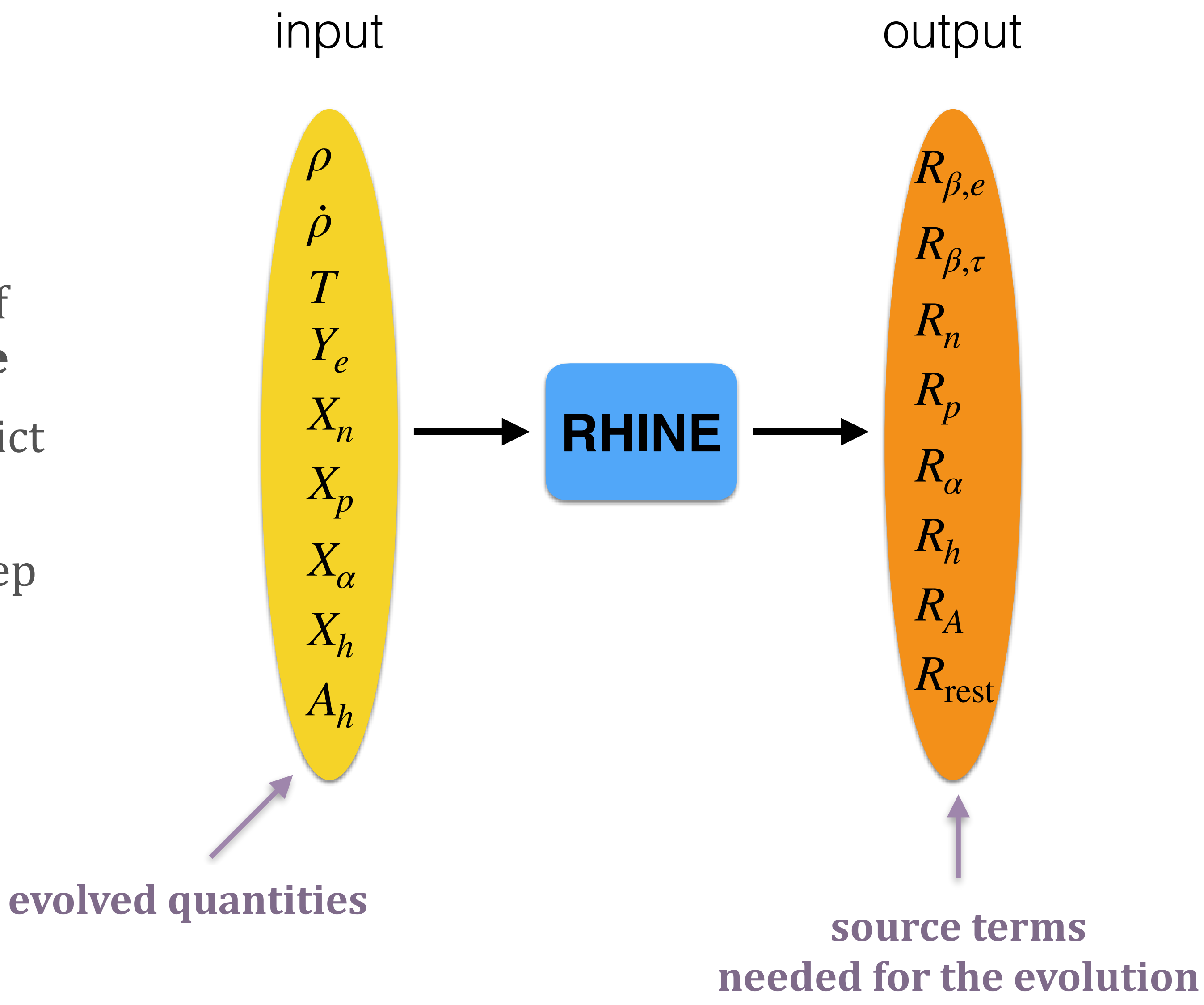
- radioactive decay of freshly synthesized r-process elements releases heat
- **ignored in almost all existing hydro-simulations**



- 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

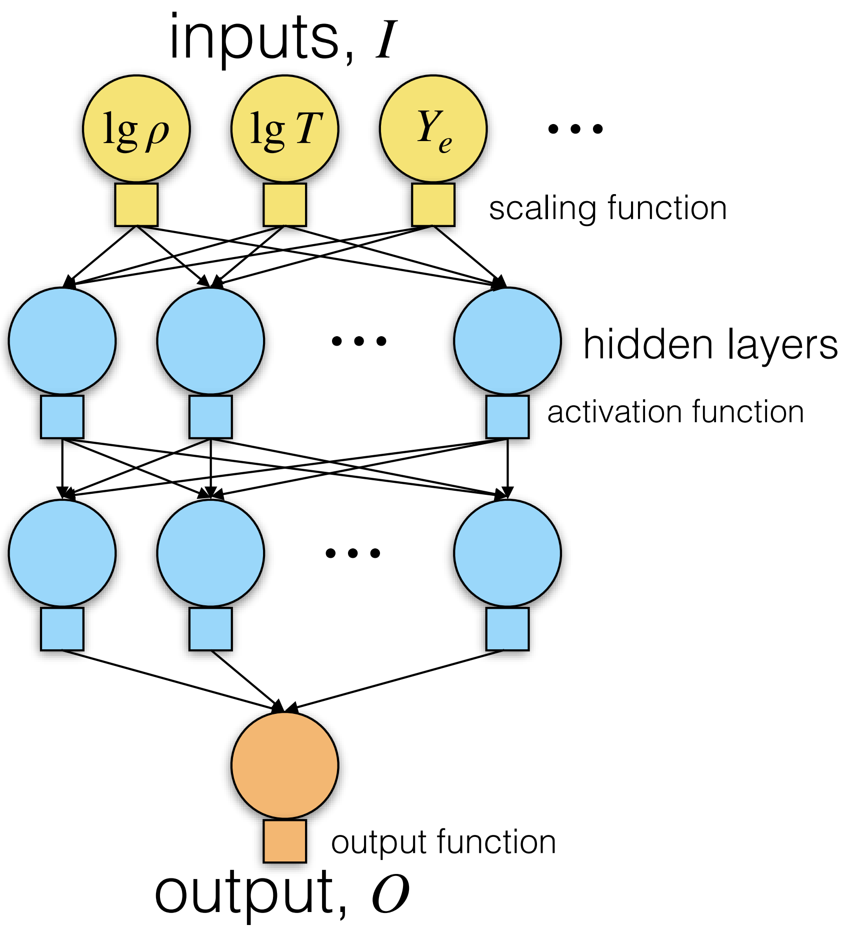
- each circle represents a "perceptron" or "neuron"
- information passes through sequence of hidden layers
- output of a perceptron:

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

- with non-linear activation function:

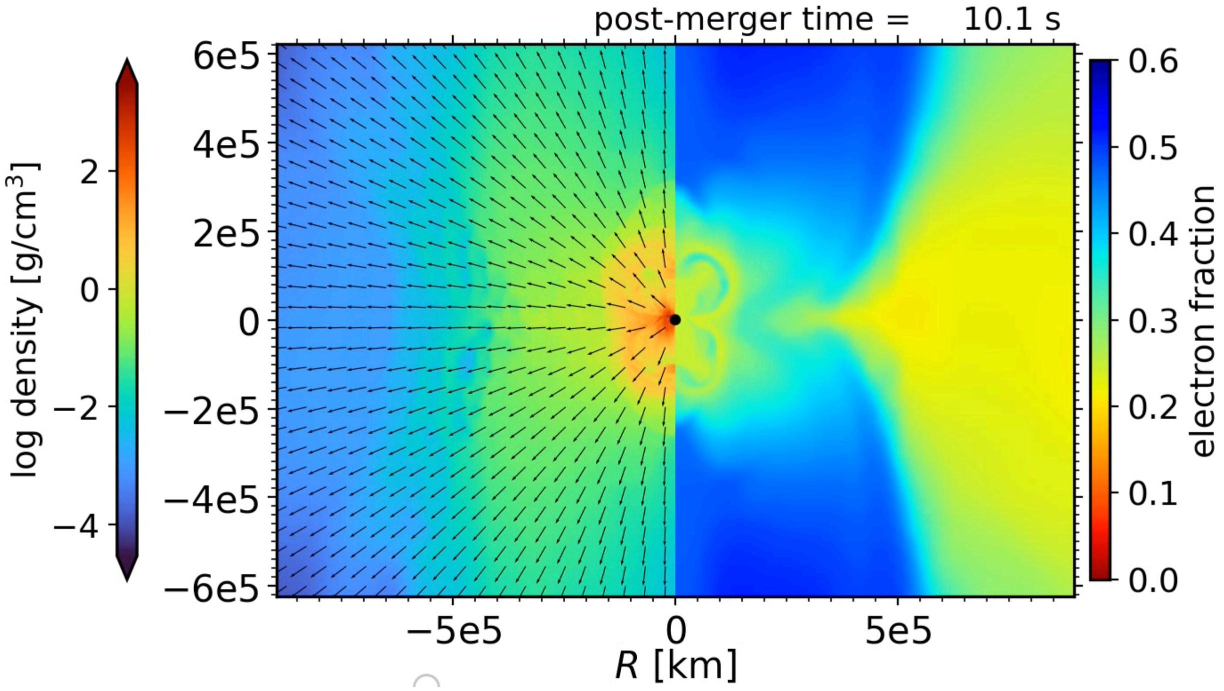
$$f_{\rm act}(x) = \begin{cases} x, & \text{if } x \geq 0 \\ e^x - 1, & \text{if } x < 0 \end{cases}$$

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

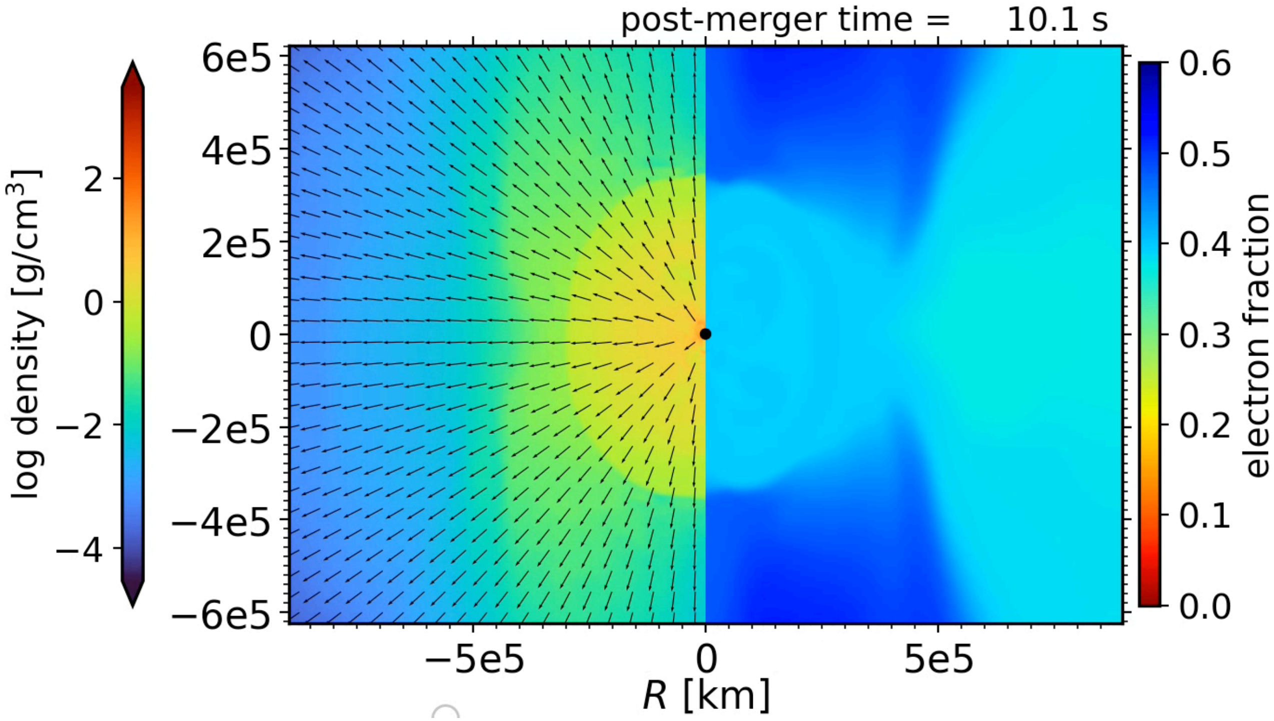


NS merger models + RHINE

without RHINE:

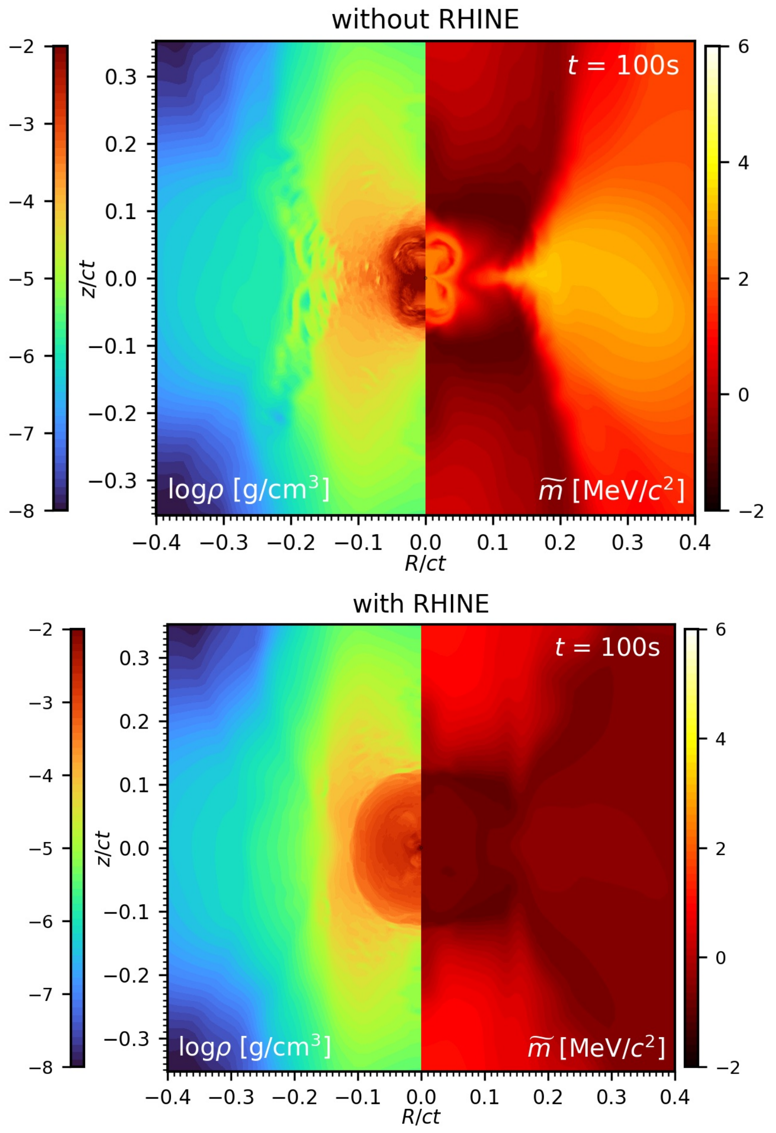


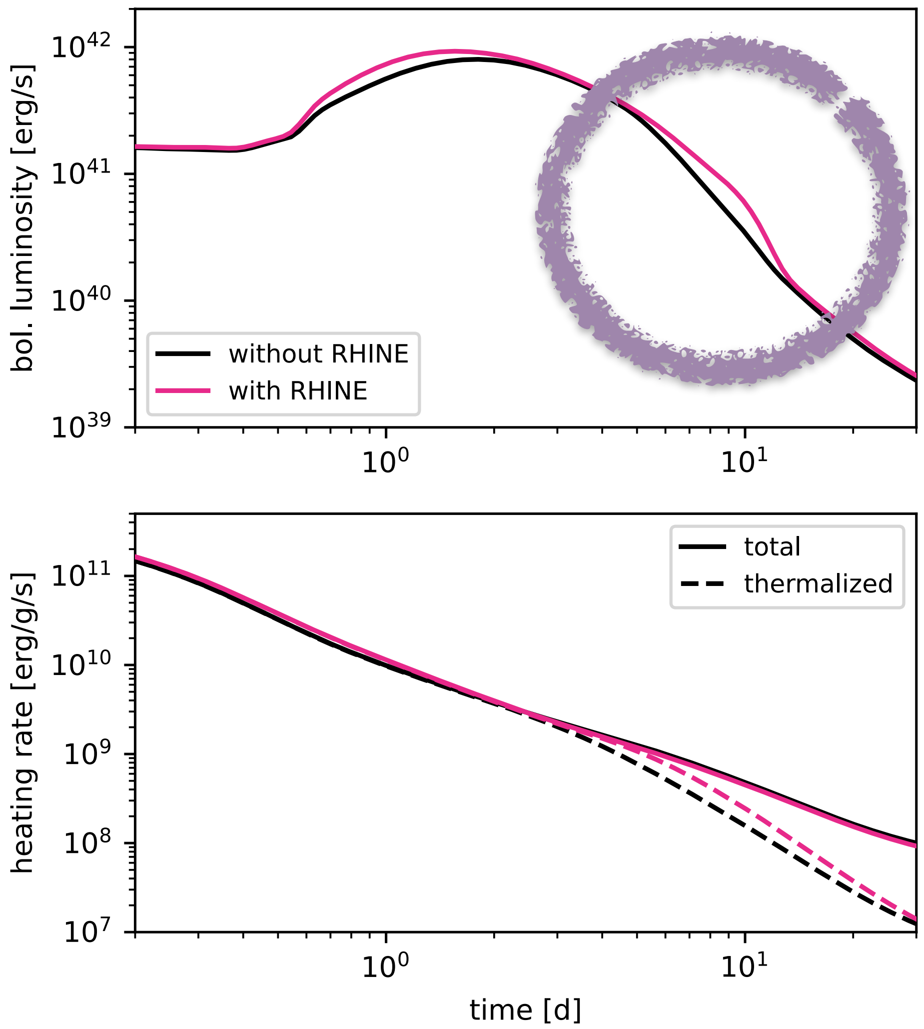
with RHINE:



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

Impact on kilonova





- increases luminosity at late times when BH-torus ejecta become visible

Summary

- **NS mergers exhibit three (main) ejecta components:**
  - dynamical ejecta: fairly robustly solar for A>~90 because of low Ye from tidal component
  - BH-torus ejecta: can be solar up to 3rd peak, but more sensitive to detailed conditions
  - NS-torus ejecta: likely only 1st and 2nd peak + helium + iron group
- **HMNS lifetime in AT2017gfo still unknown**
  - may be constrained by observational limit on $X(\mathrm{He})$ in late-time spectrum
  - promising new possibility to constrain nuclear EOS
- **Hydro + r-process nucleosynthesis extremely expensive**
  - however, r-process heating can be “emulated” by using ML models as source-term predictors
  - r-process heating boosts BH-torus ejecta and corresp. KN luminosity

Still many open questions…

- **after 8 years of AT2017gfo only very few elements confirmed or suggested**
  - Which spectral feature from which element in which ionization state? (millions of atomic lines…)
  - Why was AT2017gfo nearly perfect black body?
- **uncertainties and challenges (apart from nuclear physics):**
  - physics approximations (neutrino transport, GR, MHD)
  - numerics (2D, resolution, convergence, grid effects, limited simulation time, …)
  - lack of atomic data and computational cost of NLTE radiative transfer
  - impact of neutrino flavor oscillations
  - …
- **further need to improve hydro + nucleosynthesis + radiative transfer modeling!!! (and of course need more observations…)**