Fast flavor conversion in neutron-star merger models with phenomenological prescriptions (and some more)

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ERC synergy
HeavyMetal

Collective Oscillations Workshop, Taipei, Mar. 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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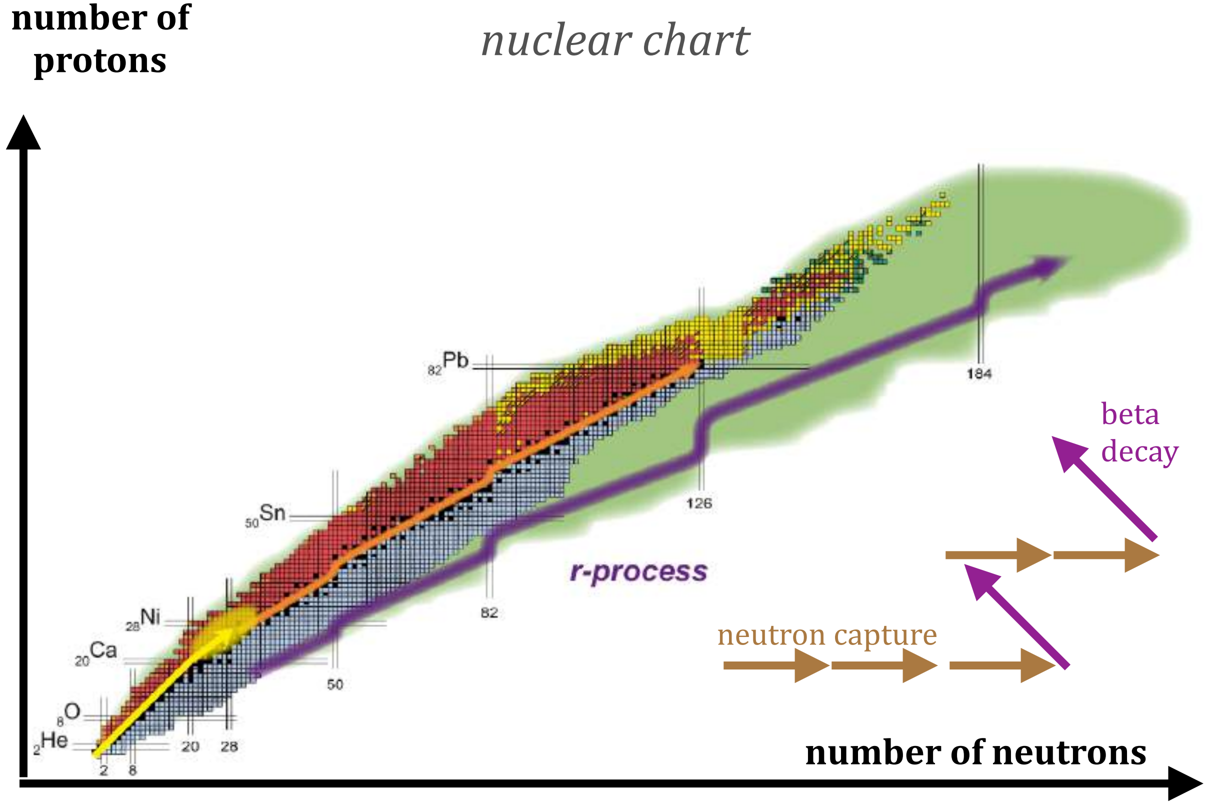
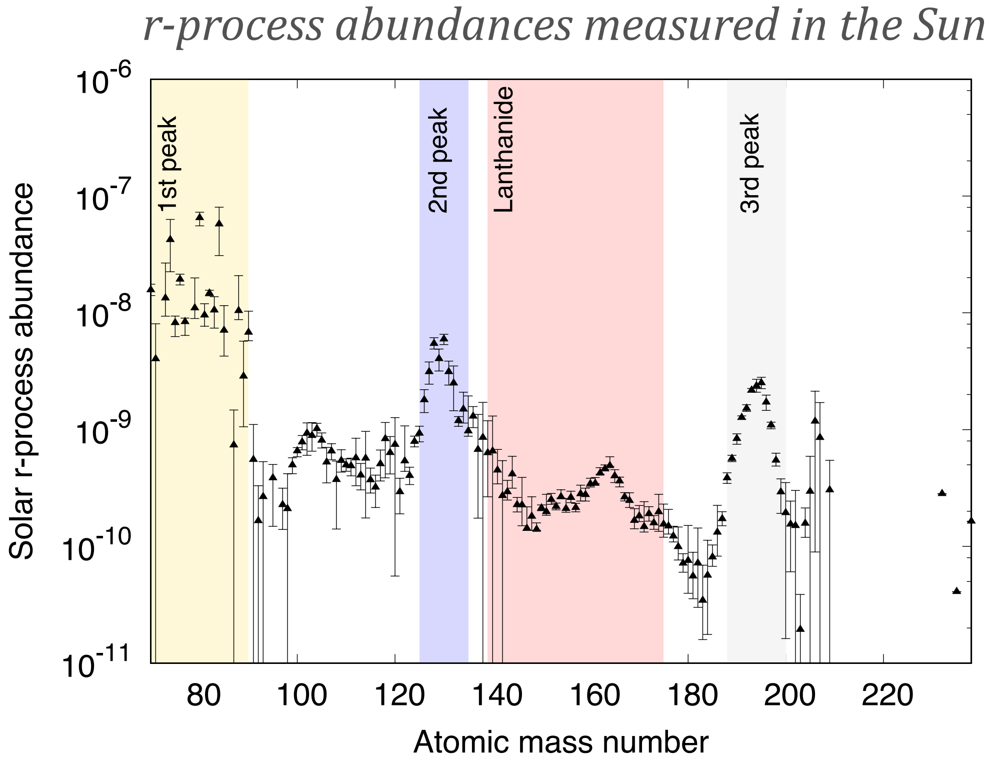
The rapid neutron-capture (or r-) process





Main condition:

high neutron density = low electron fraction Y_e

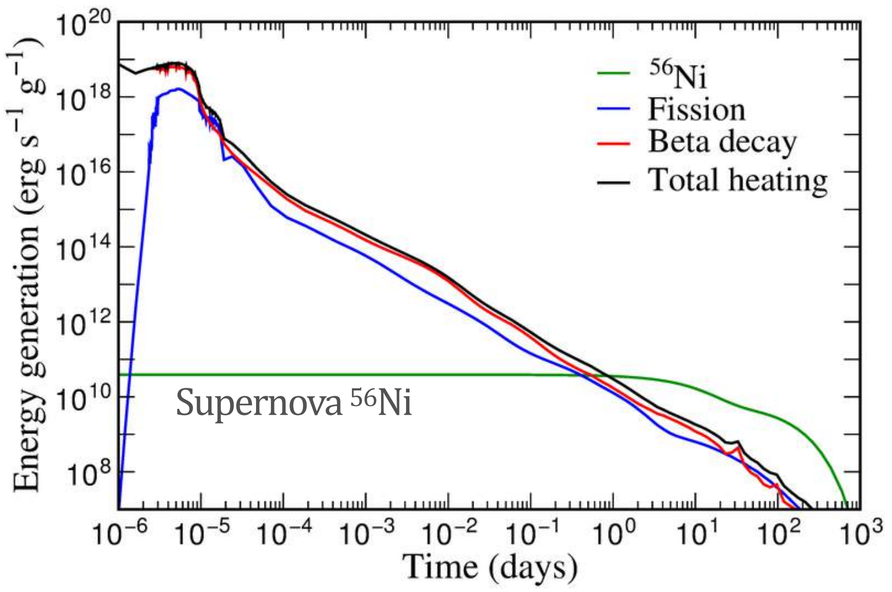
$$Y_e = \frac{n_{\text{proton}}}{n_{\text{neutron}} + n_{\text{proton}}} \overset{!}{<} 0.5$$

- other suggested sites: core-collapse supernovae, magneto-rotational supernovae, collapsars, accretion-induced collapse, magnetar giant flares
- NSMs **only observationally confirmed site** so far

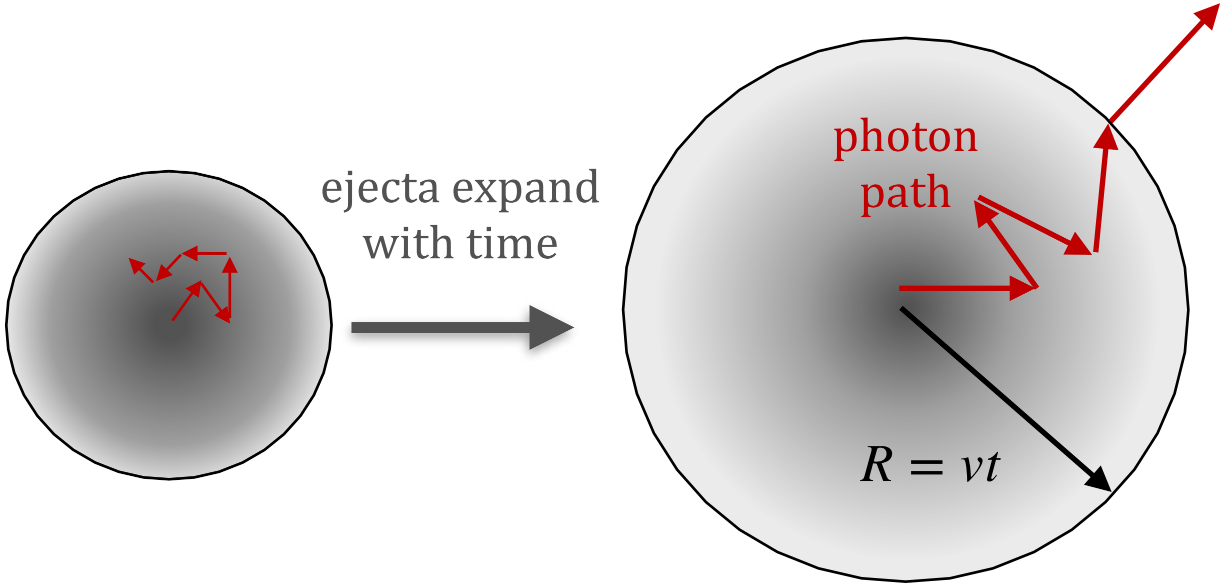
Kilonova: smoking gun for the r-process

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

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



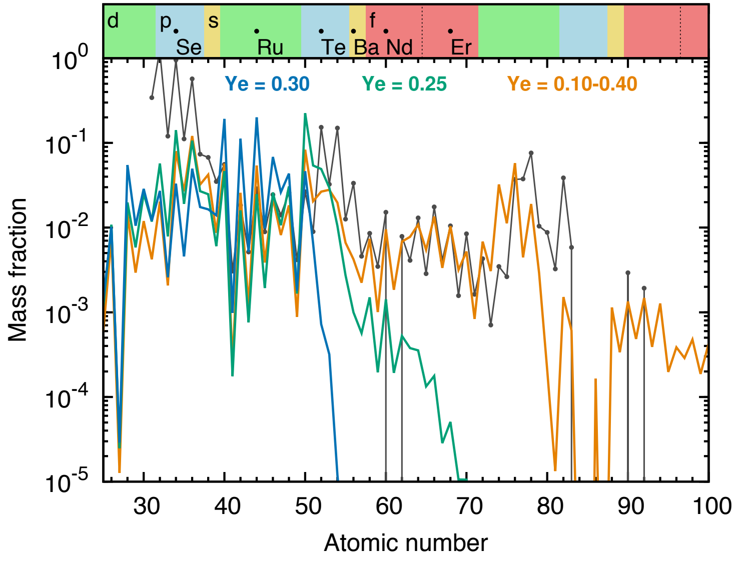
Metzger, Martinez-Pinedo et al. 2010



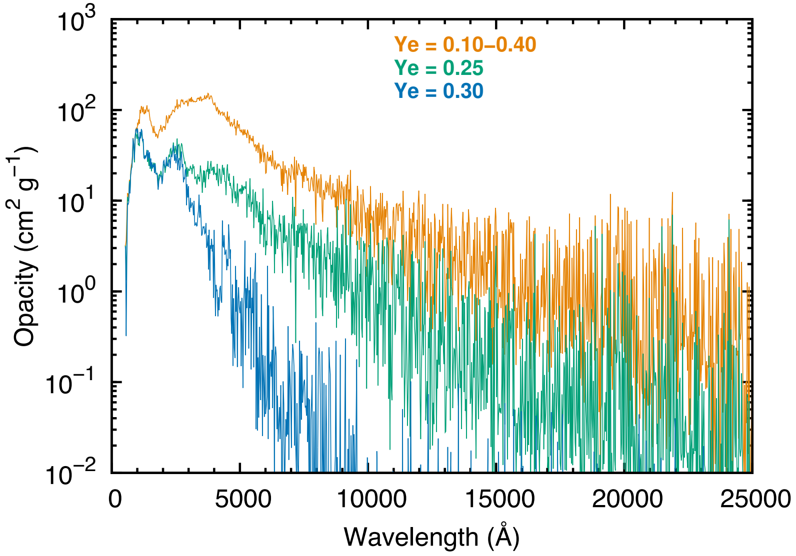
- allows in-situ observations of the r-process
- characteristic phases:
  - early photospheric phase (LTE ~ valid)
  - late nebular phase (need NLTE)

Kilonova opacities

composition (for different Y_e)



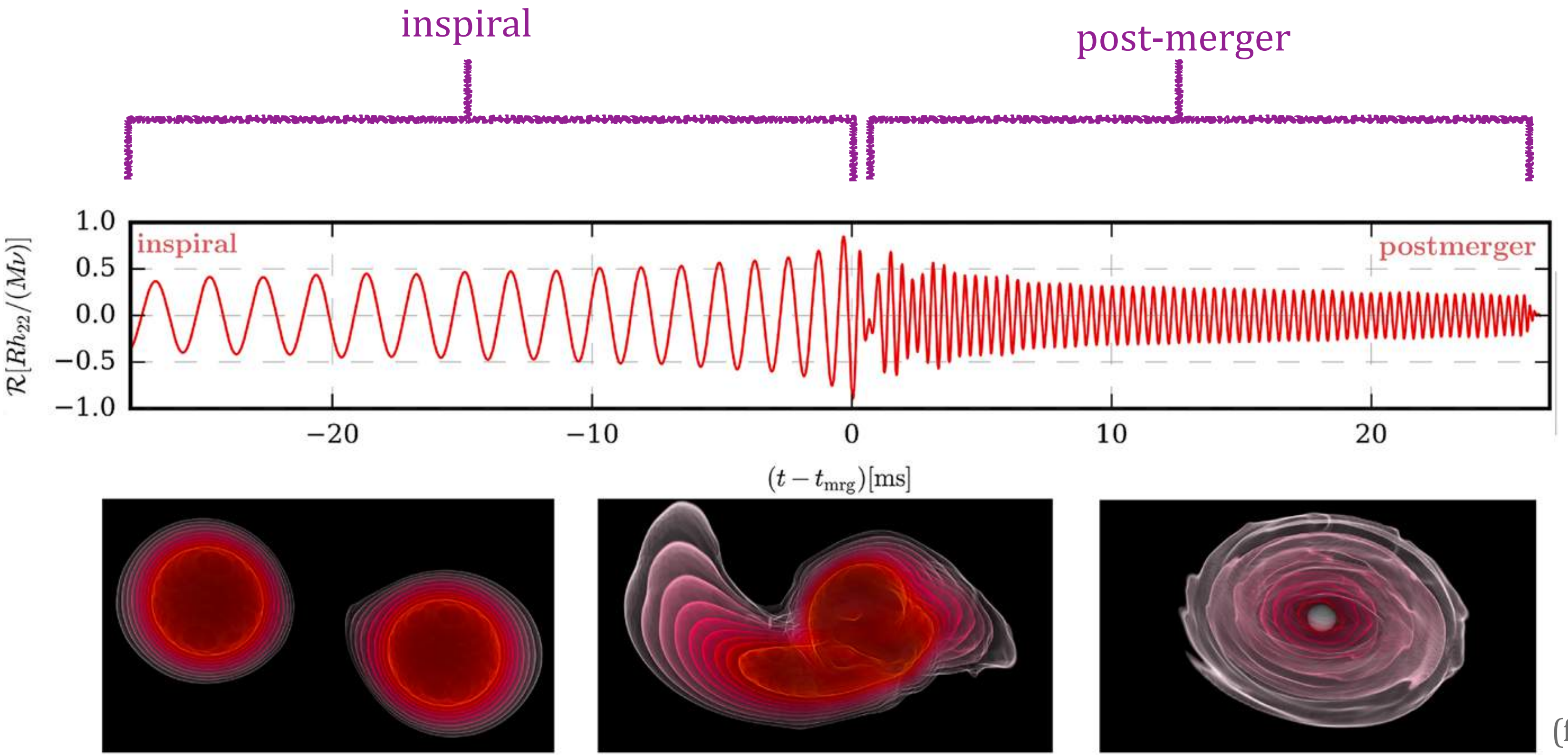
opacities



(plots from Tanaka ’18)

- strong dependence on Ye
- dominated by lanthanides (between 2nd and 3rd peak)
- recent compilation of calibrated opacities in A. Floers et al. (2025)

Other "messenger": Gravitational wave signal



(figure from Dietrich+21)

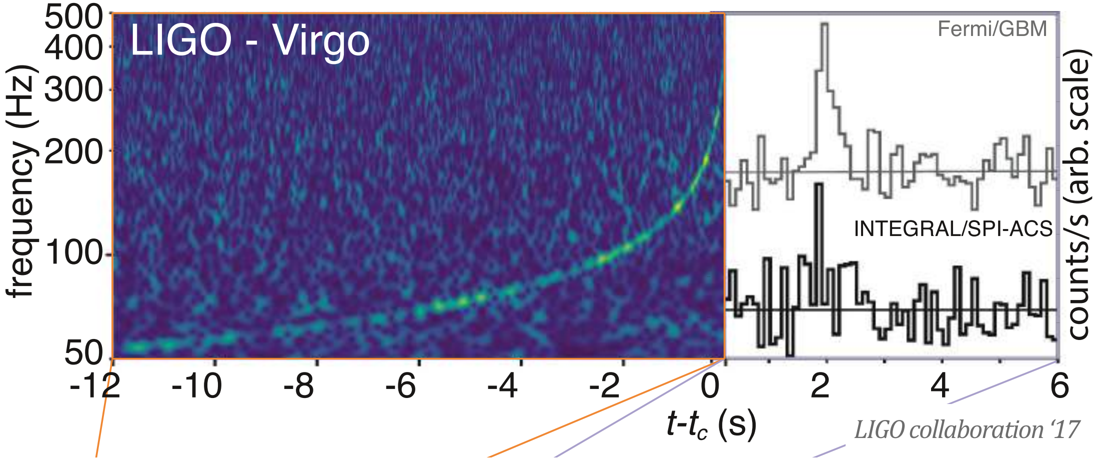
- easier to observe
- provides information about NS binary masses

- more difficult to observe (needs closer distance to event)
- could provide detailed information about nuclear EOS

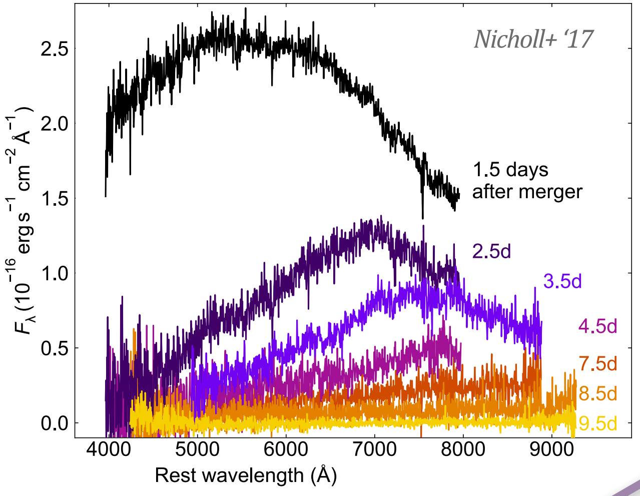
GW170817 - the first direct observation of a NS merger

(on August 17th, 2017)

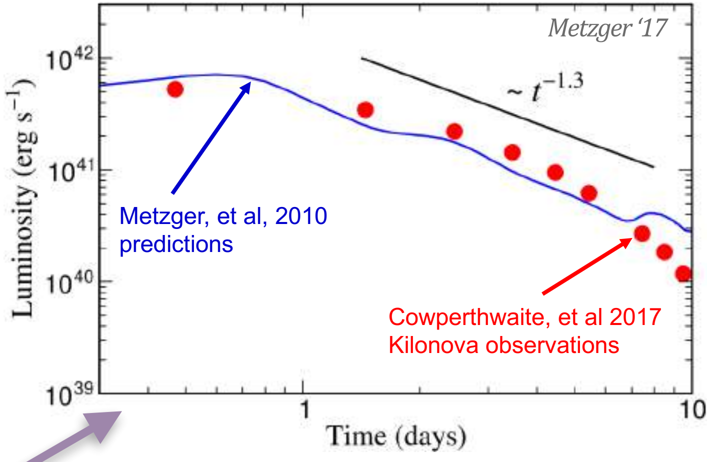
gravitational waves *gamma rays*



UV+optical+IR spectra



UV+optical+IR light curve



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

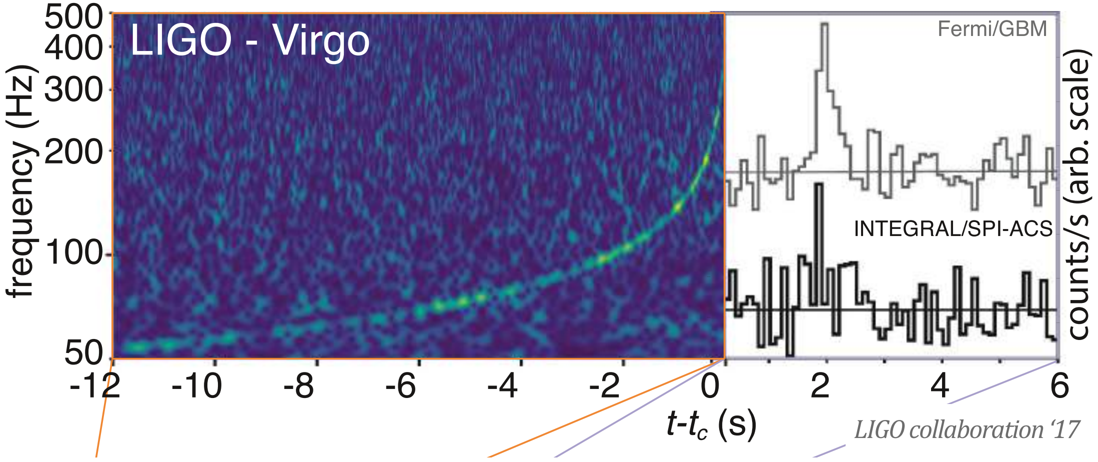
- light curve shows remarkable agreement with predicted $t^{-1.3}$ behavior
- strongly suggests that source of energy is radioactive decay of r-process elements

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

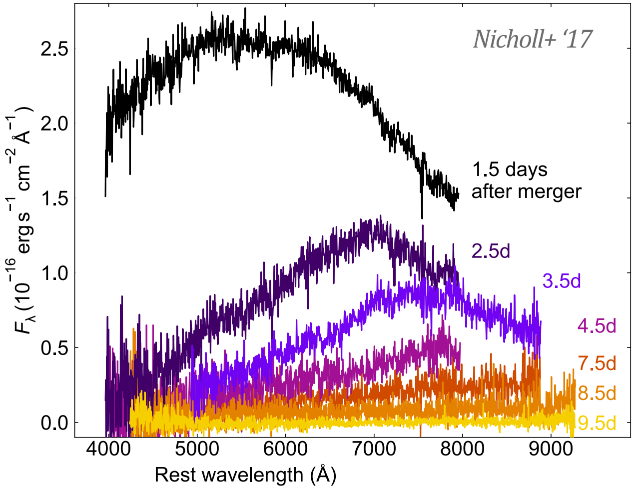
GW170817 - the first direct observation of a NS merger

(on August 17th, 2017)

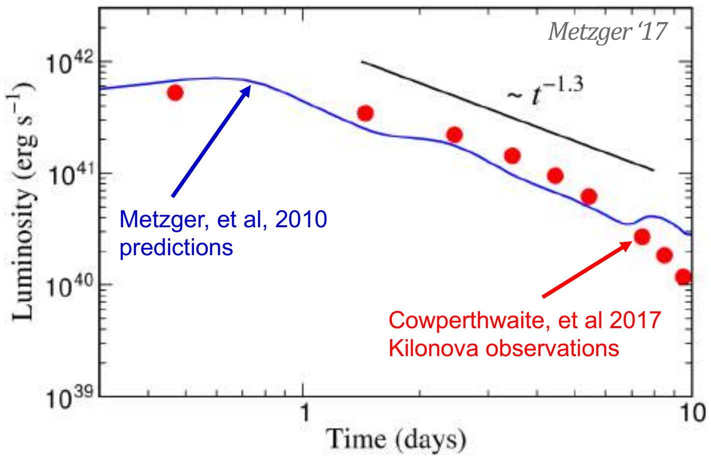
gravitational waves *gamma rays*



UV+optical+IR spectra



UV+optical+IR light curve

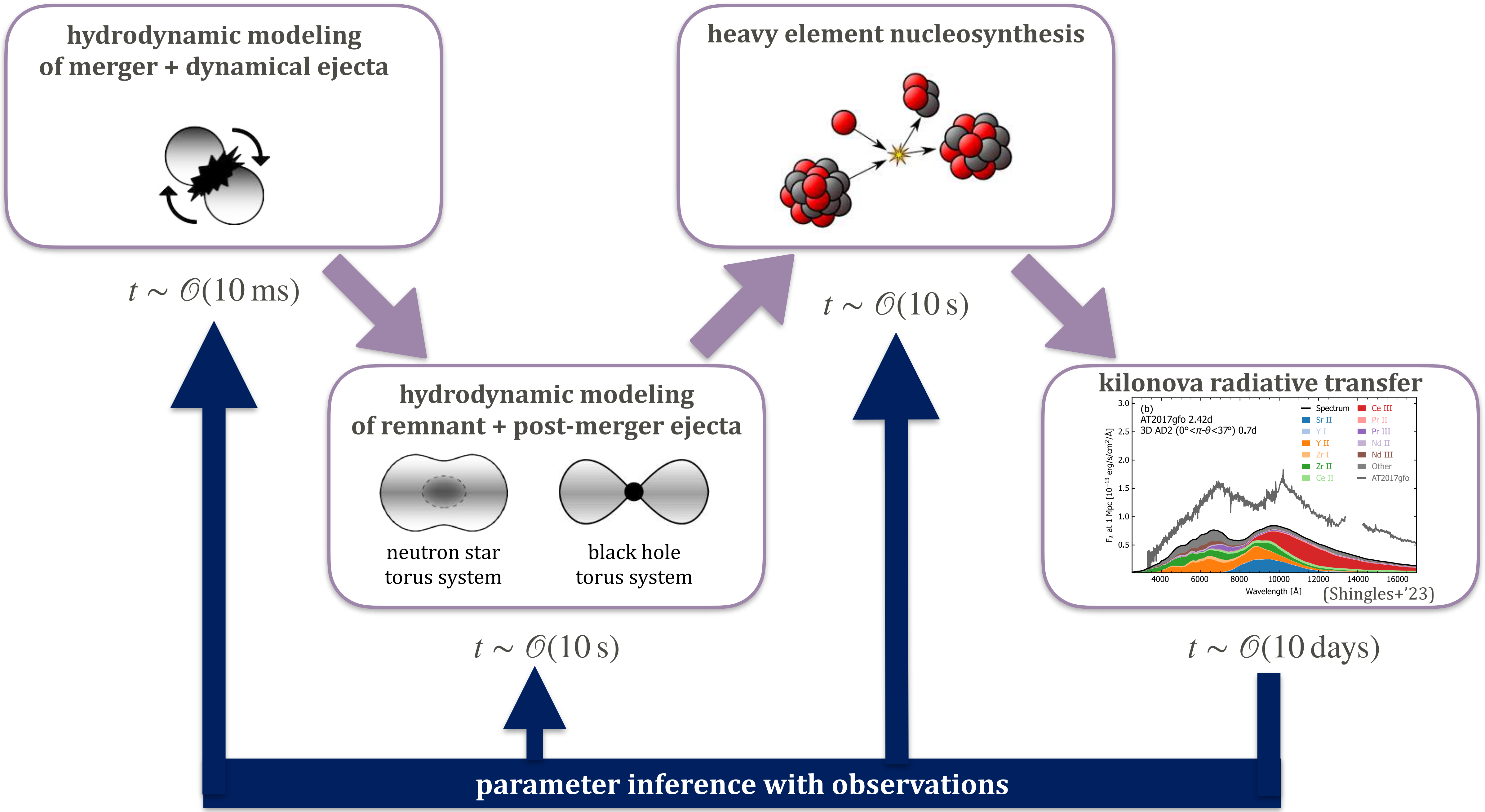


Many open questions remain:

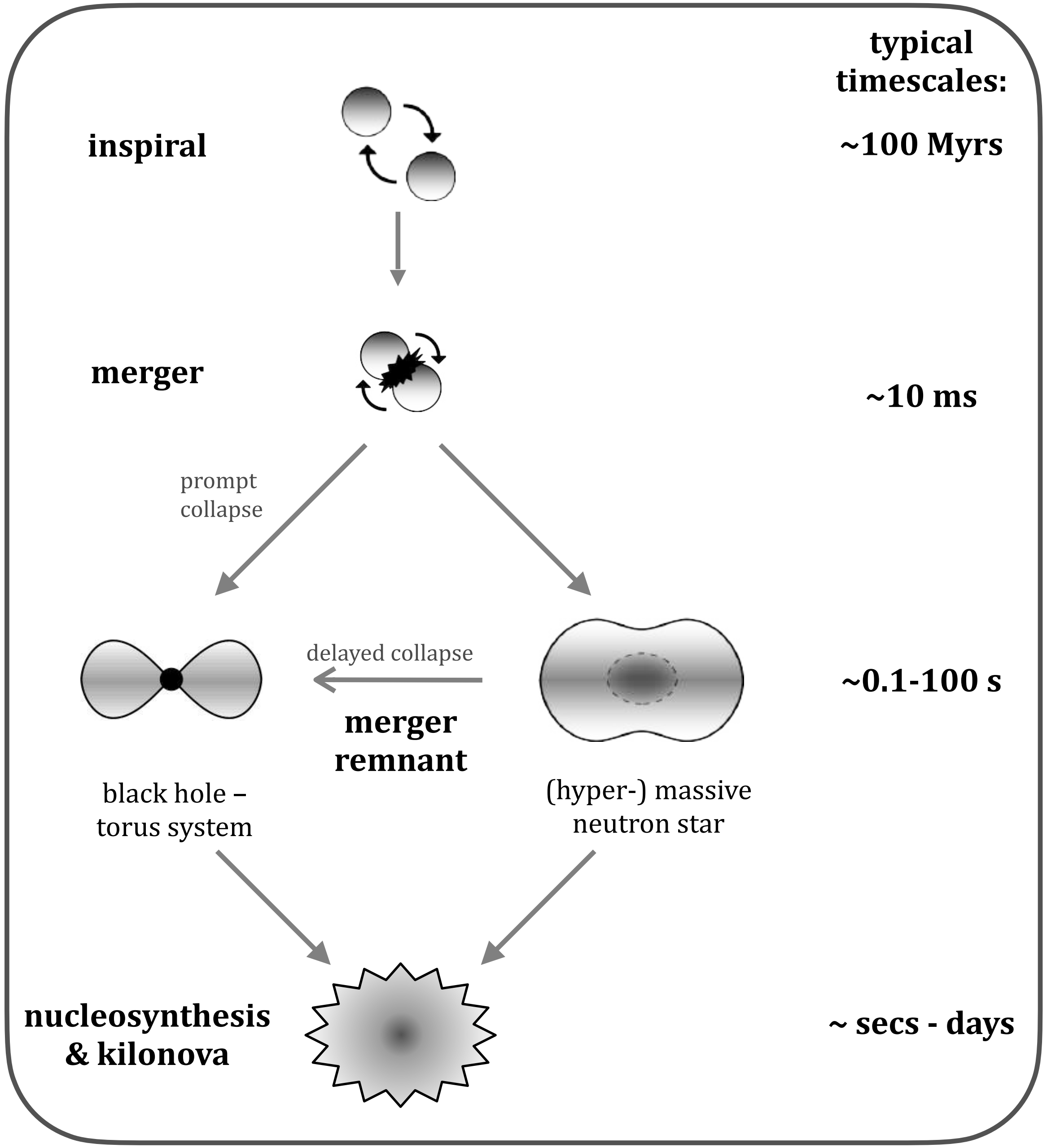
- Mass, composition and geometry of outflow material?
- When did BH form?
- How to infer properties of nuclear EOS?
- **Impact of flavor conversions?**
- …

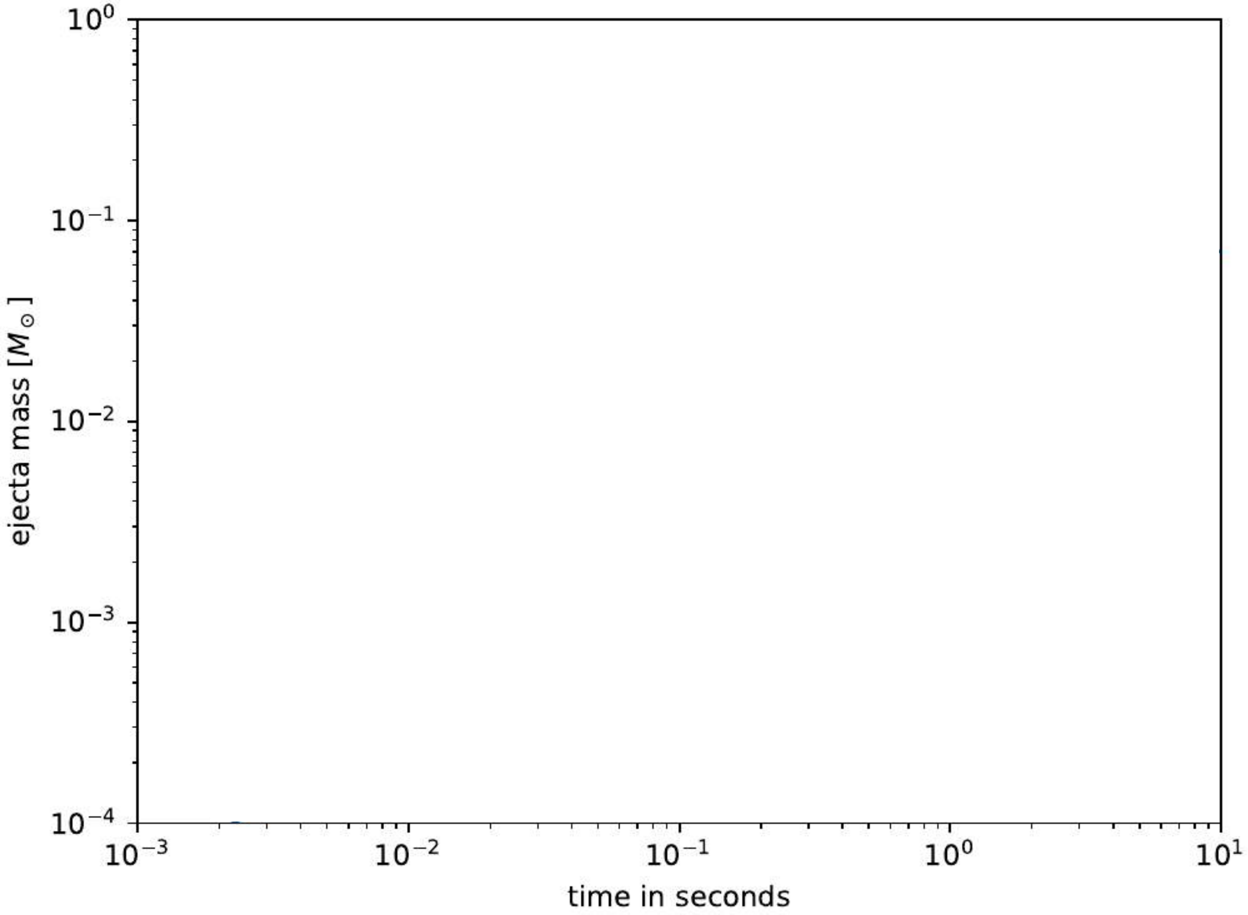
(also see David's talk)

Kilonova modeling pipeline

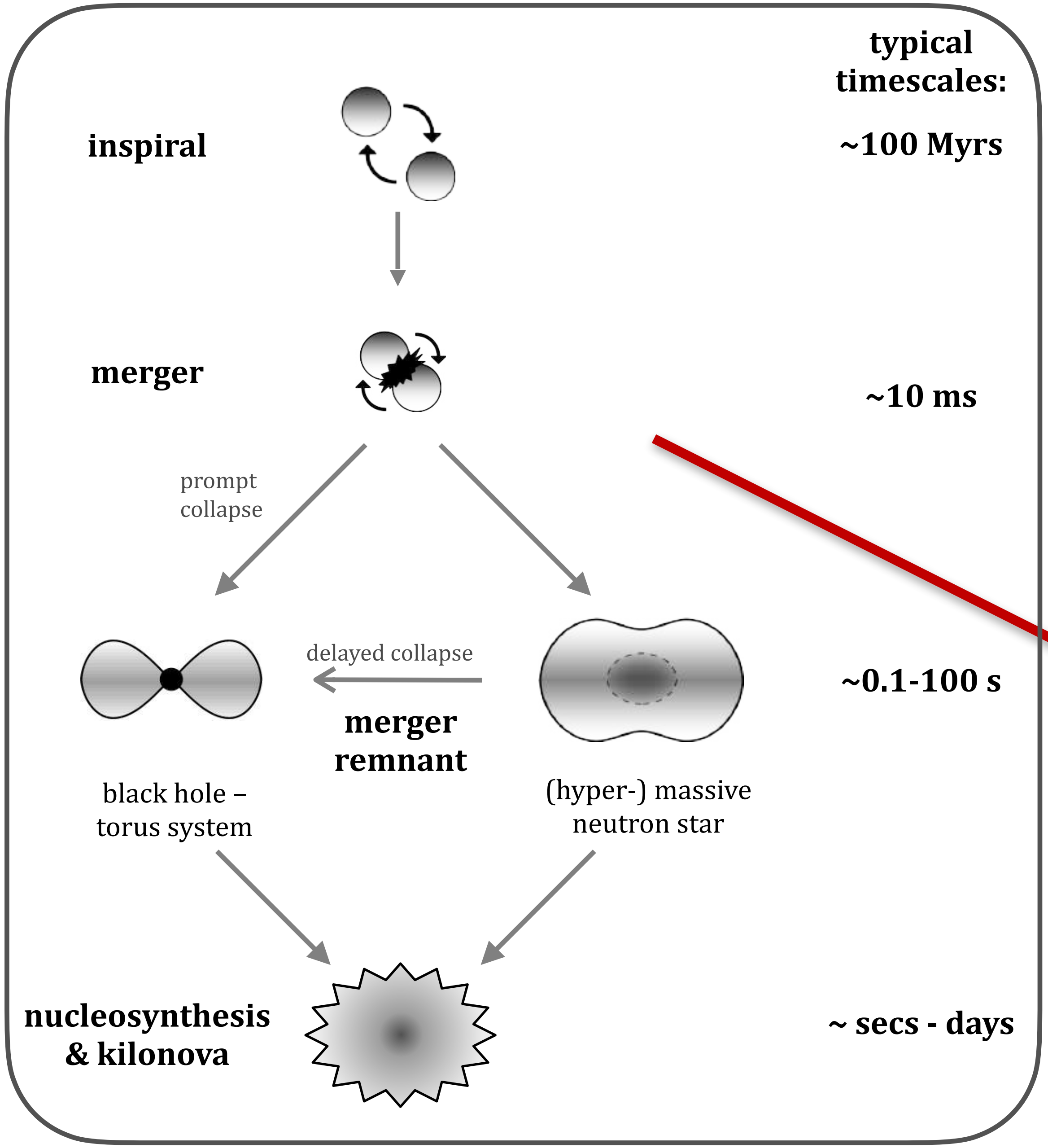


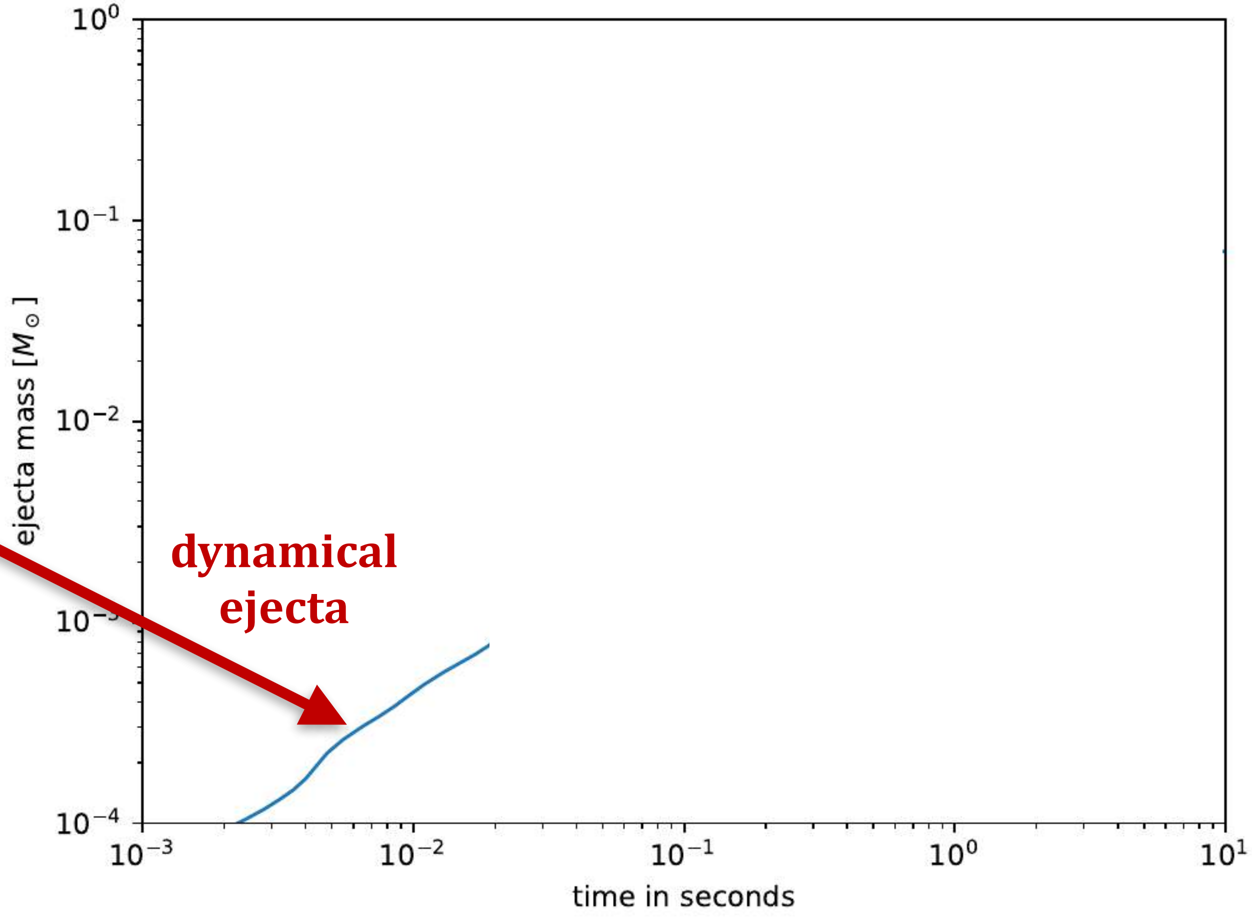
Phases of matter ejection



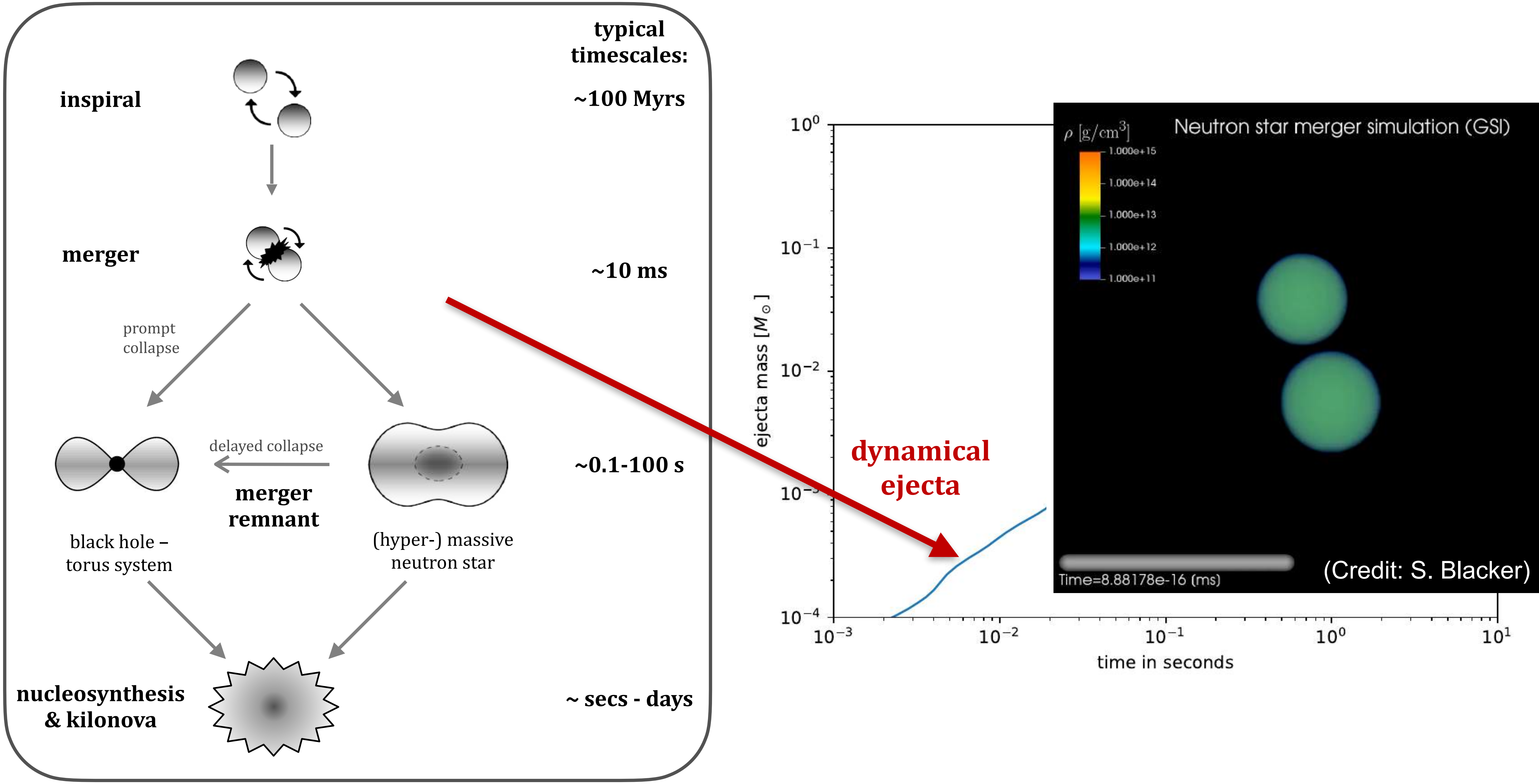


Phases of matter ejection

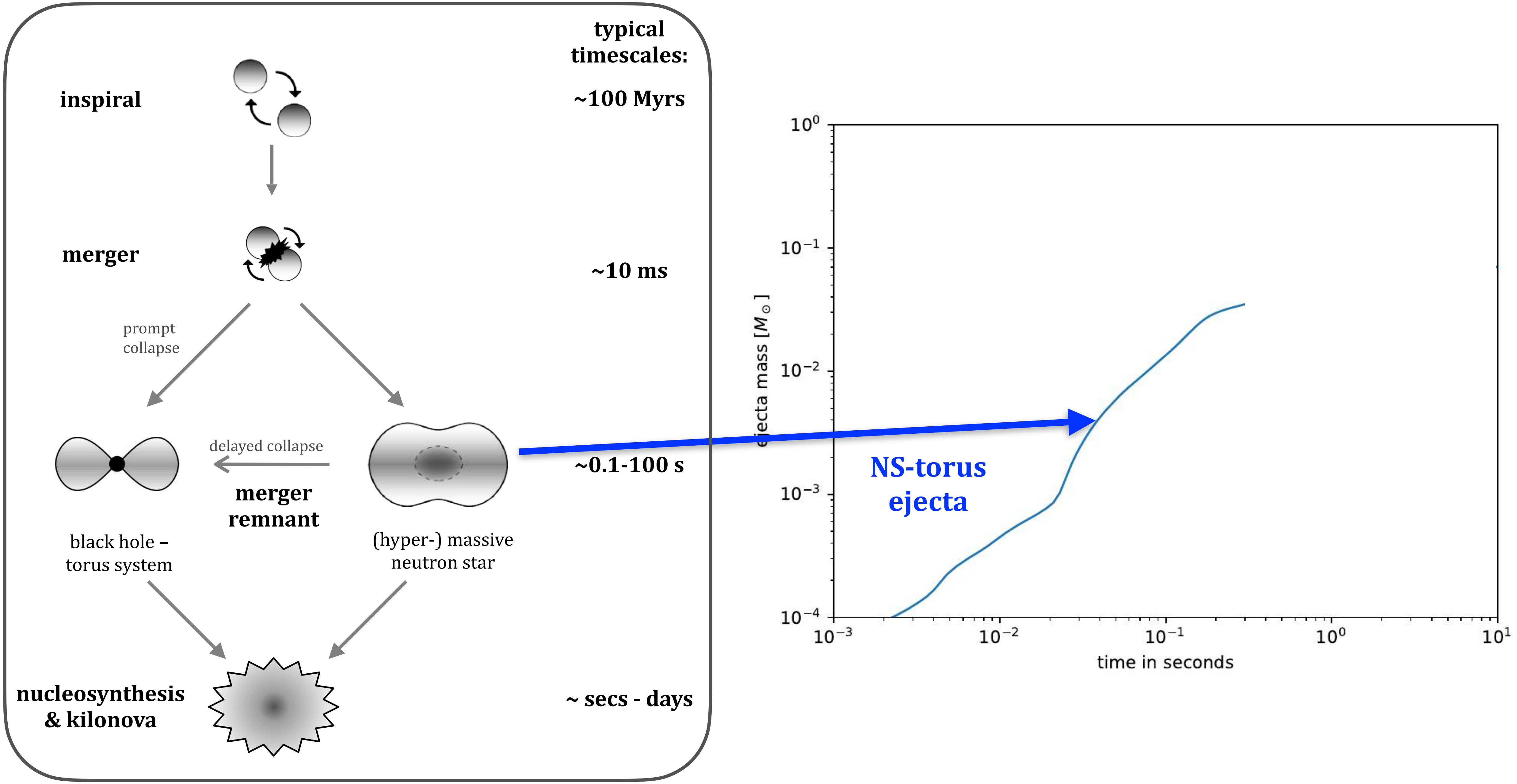




Phases of matter ejection

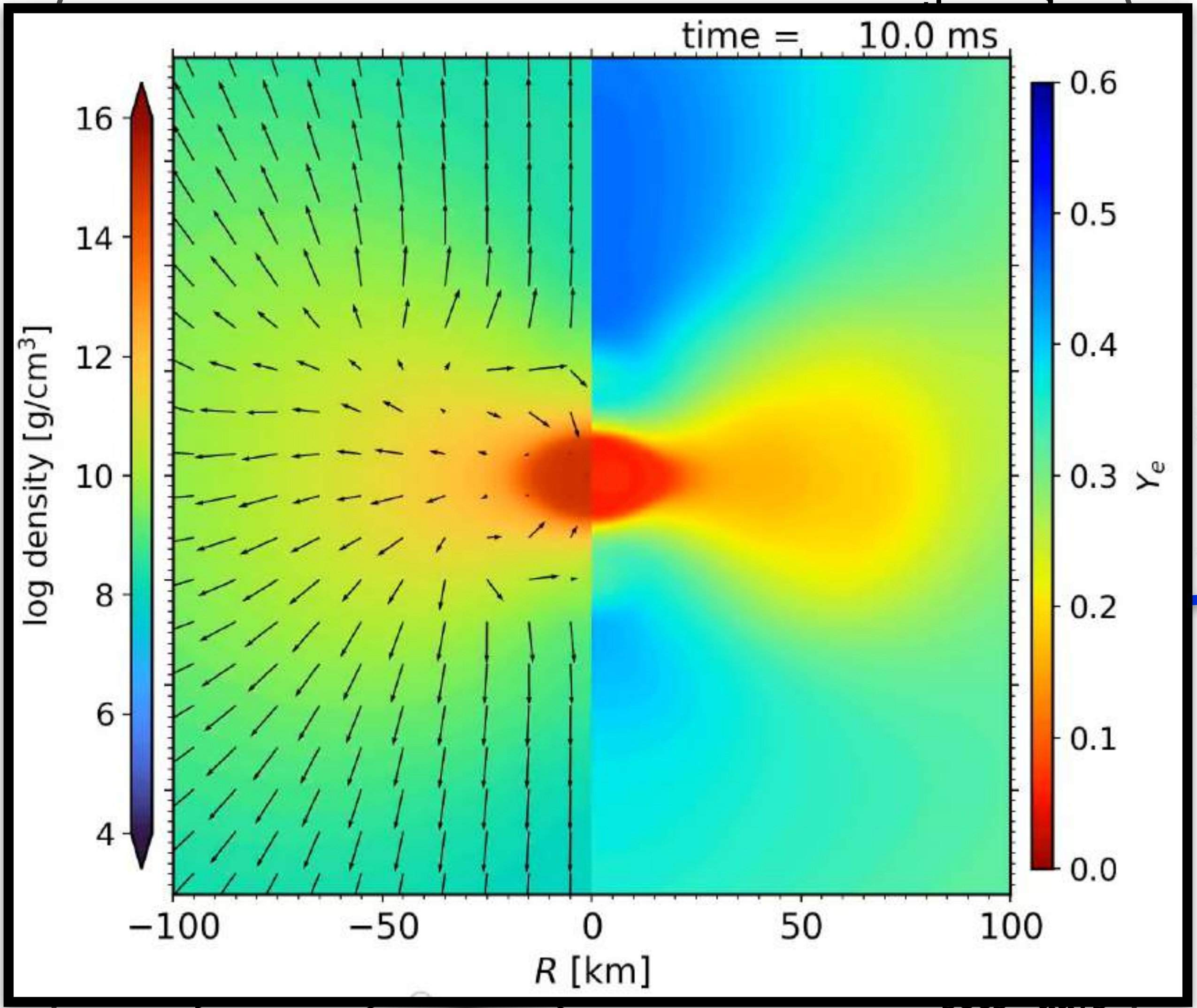


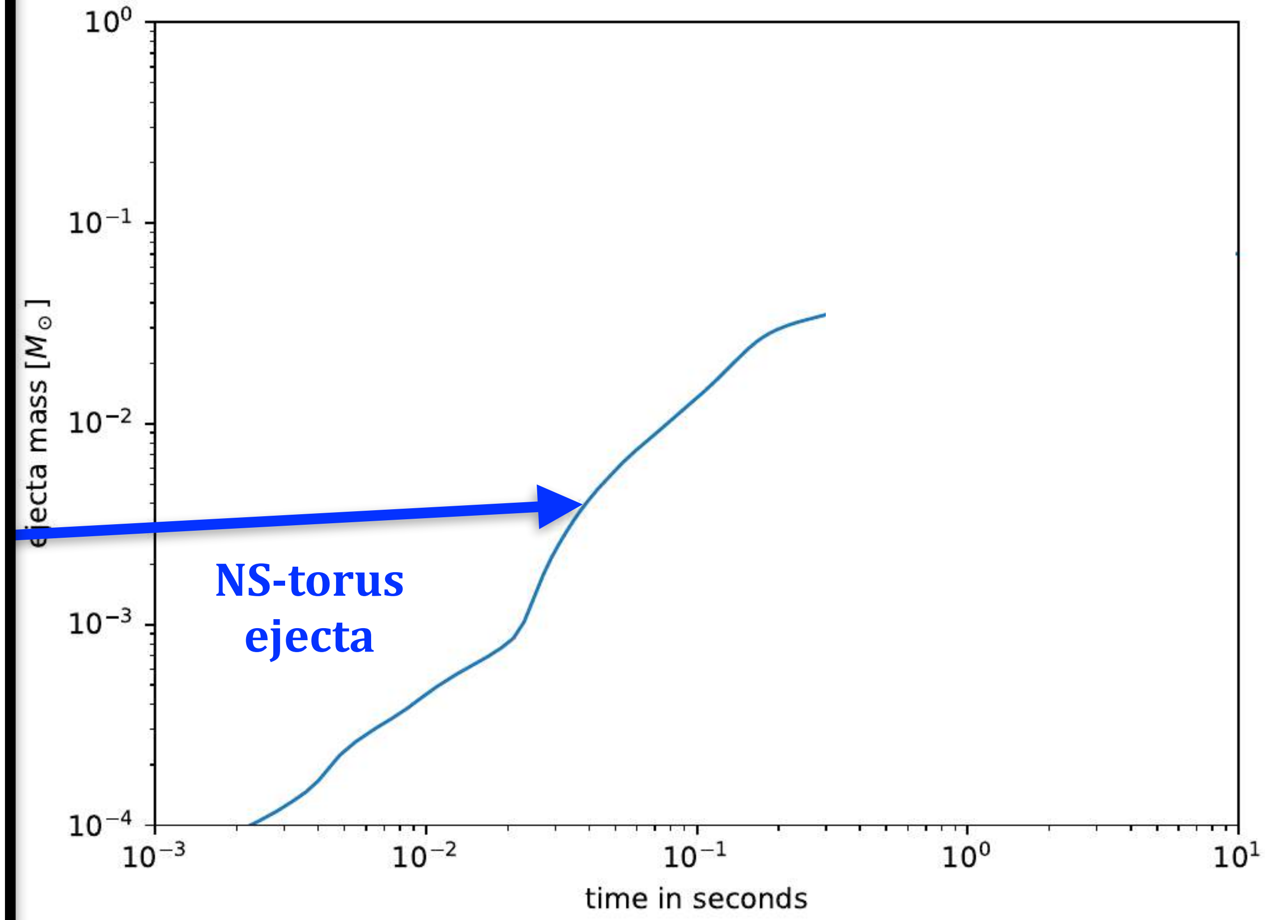
Phases of matter ejection



Phases of matter ejection

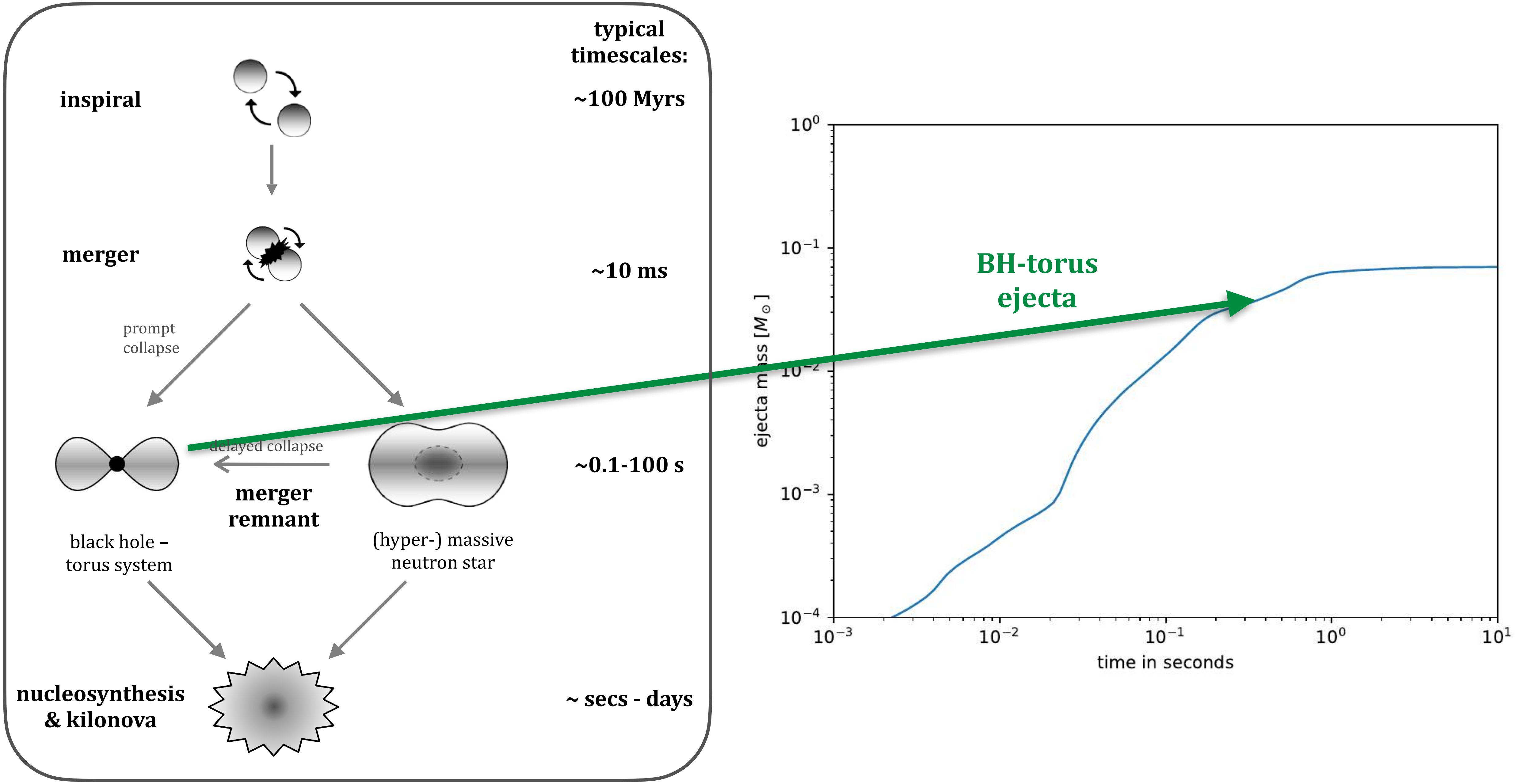
typical





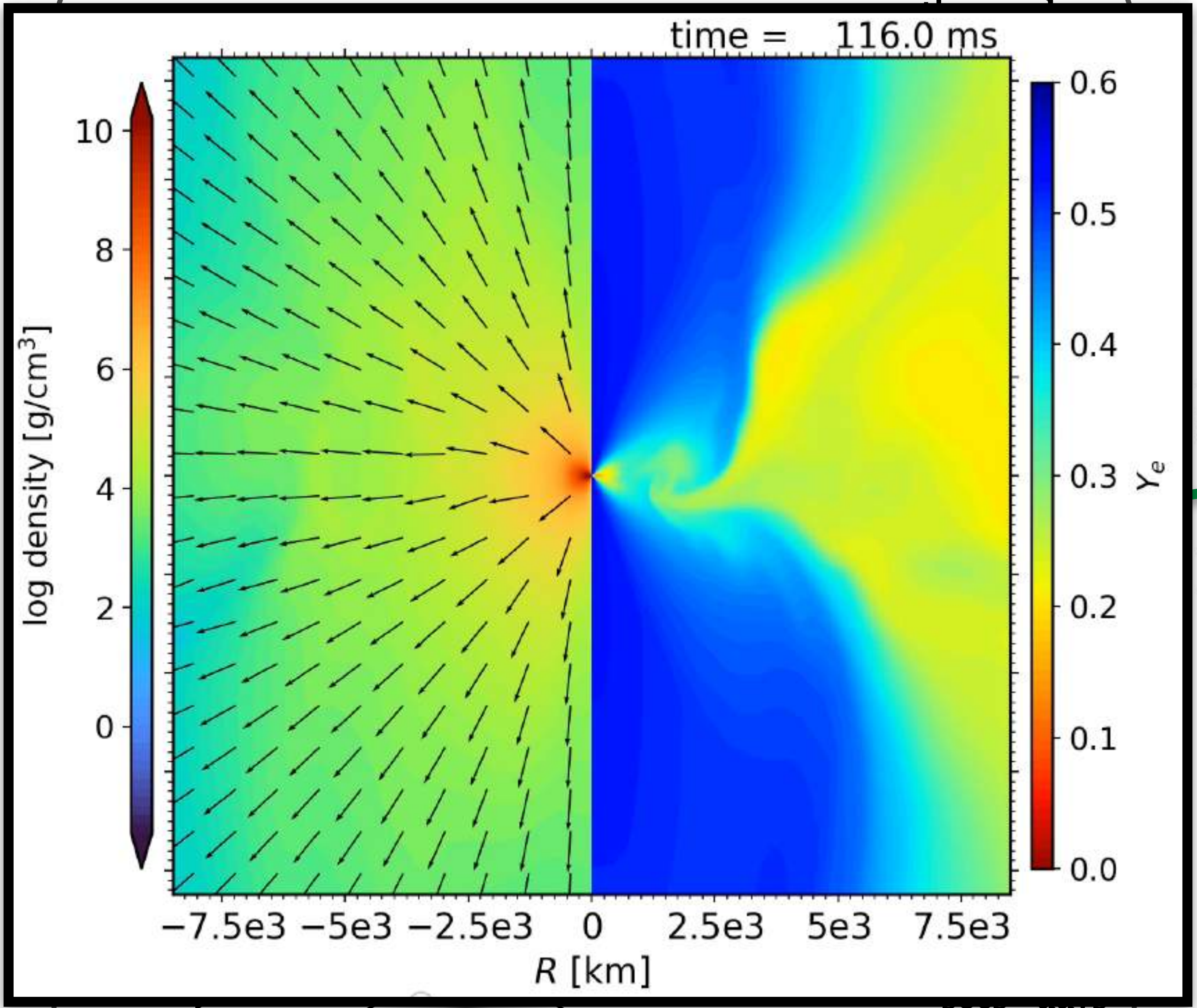
& kilonova

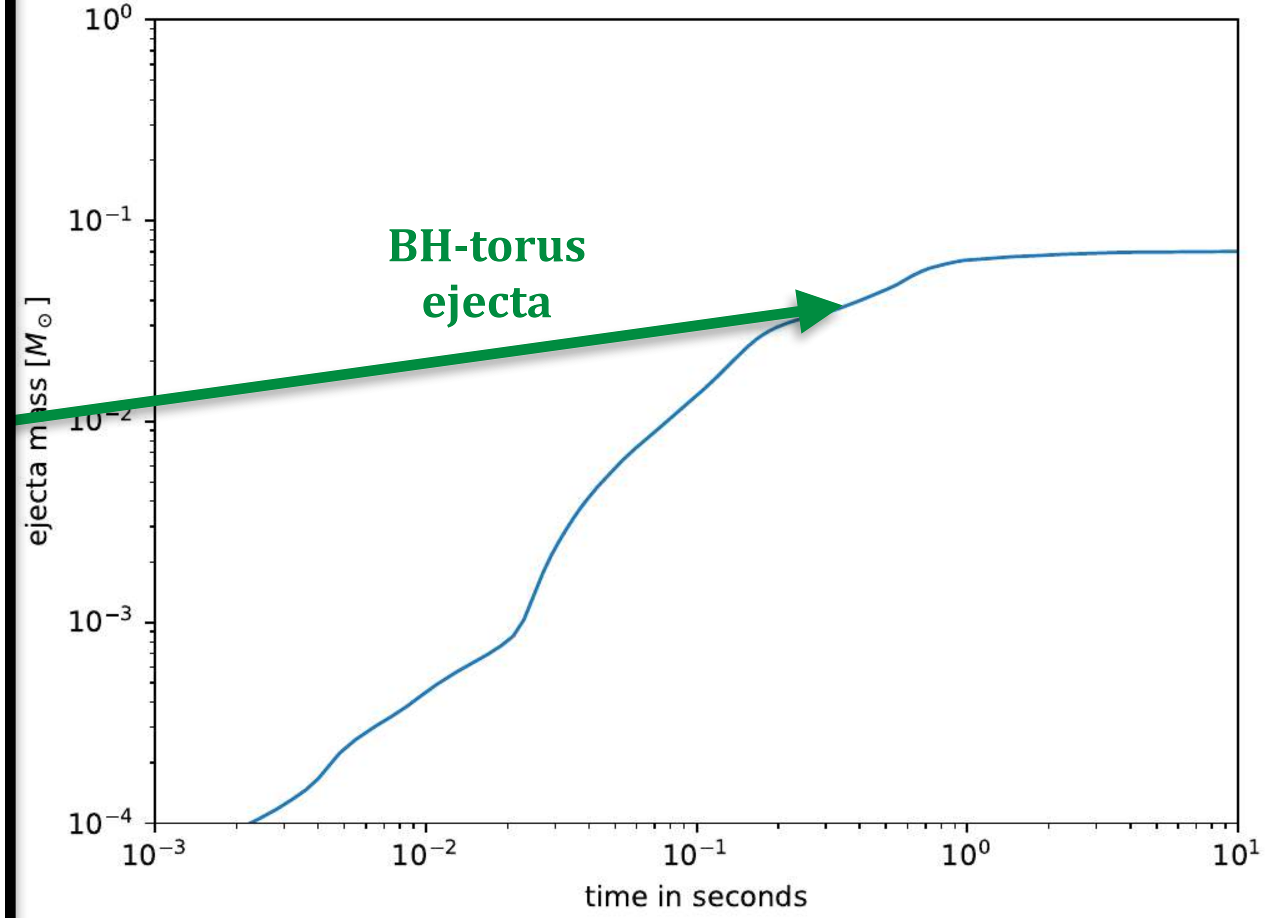
Phases of matter ejection



Phases of matter ejection

typical

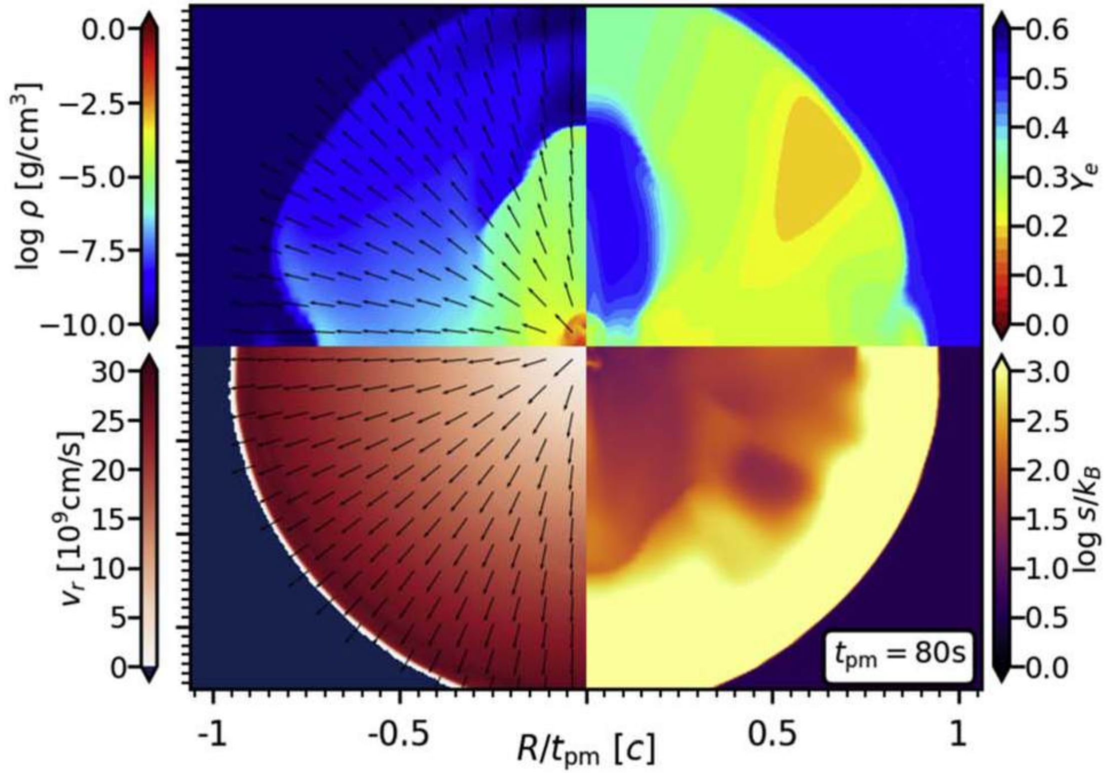


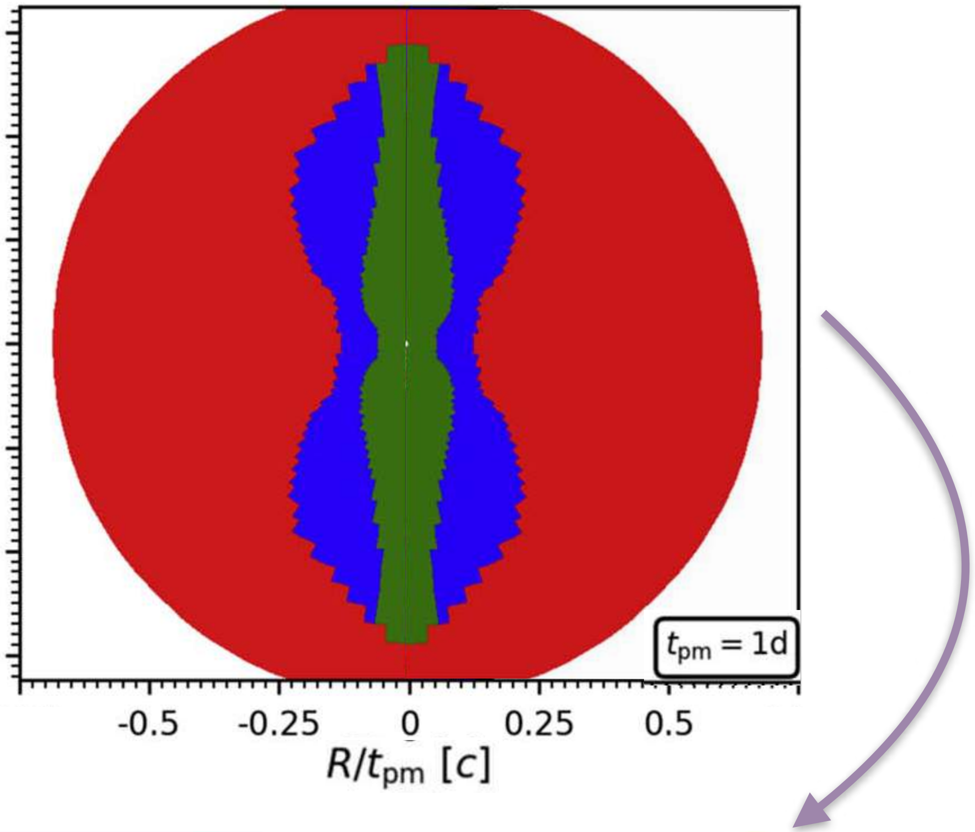


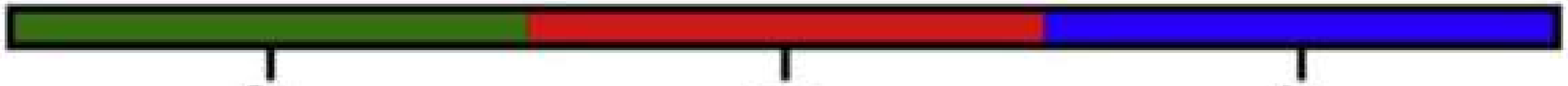
& kilonova

Typical final ejecta distribution (delayed collapse)

(OJ et al., 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:

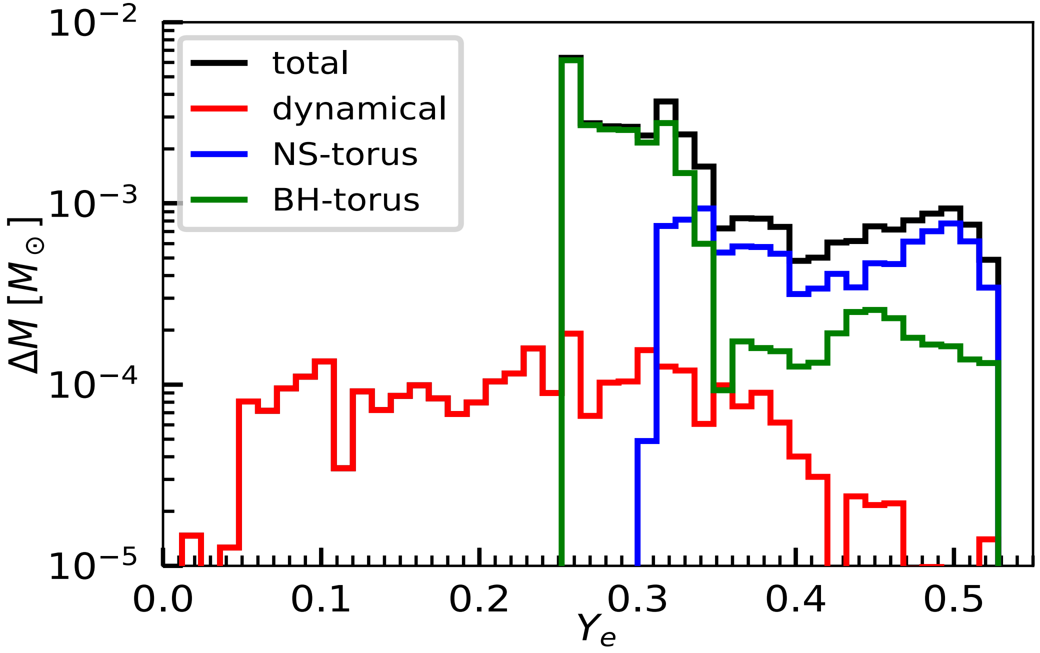
m ~ 0.01–0.04 $M_\odot$

<v> ~ 0.1–0.2 c

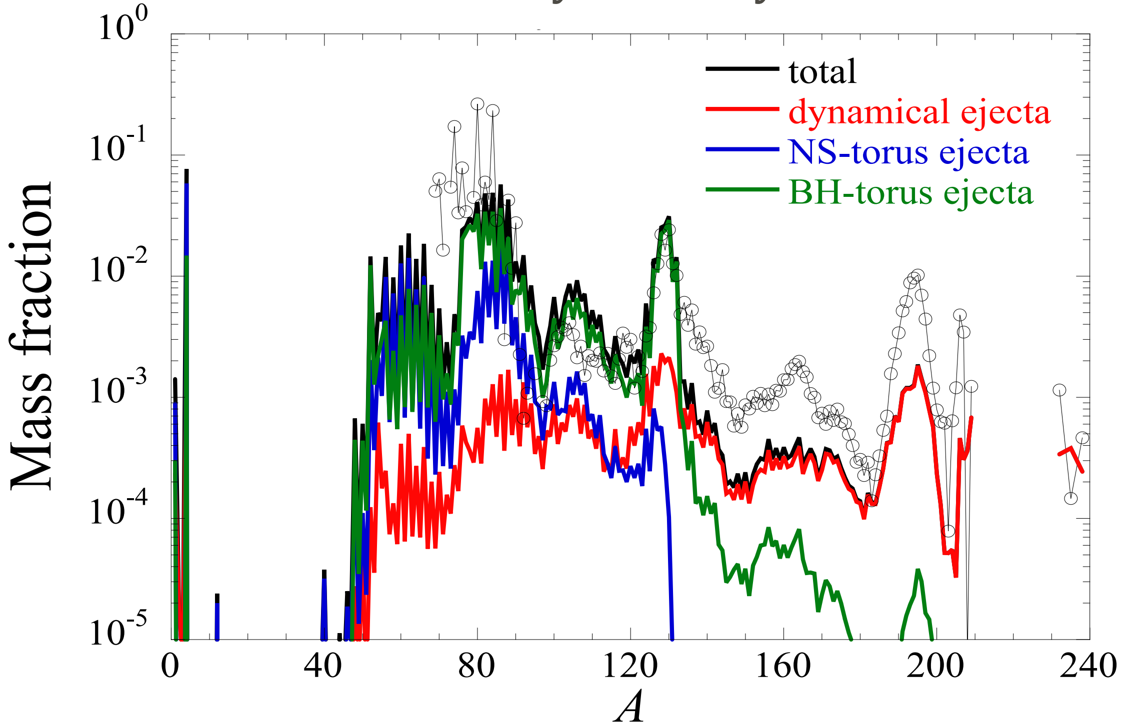
Typical ejecta composition (delayed collapse)

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

Y_e histogram



nucleosynthesis yields



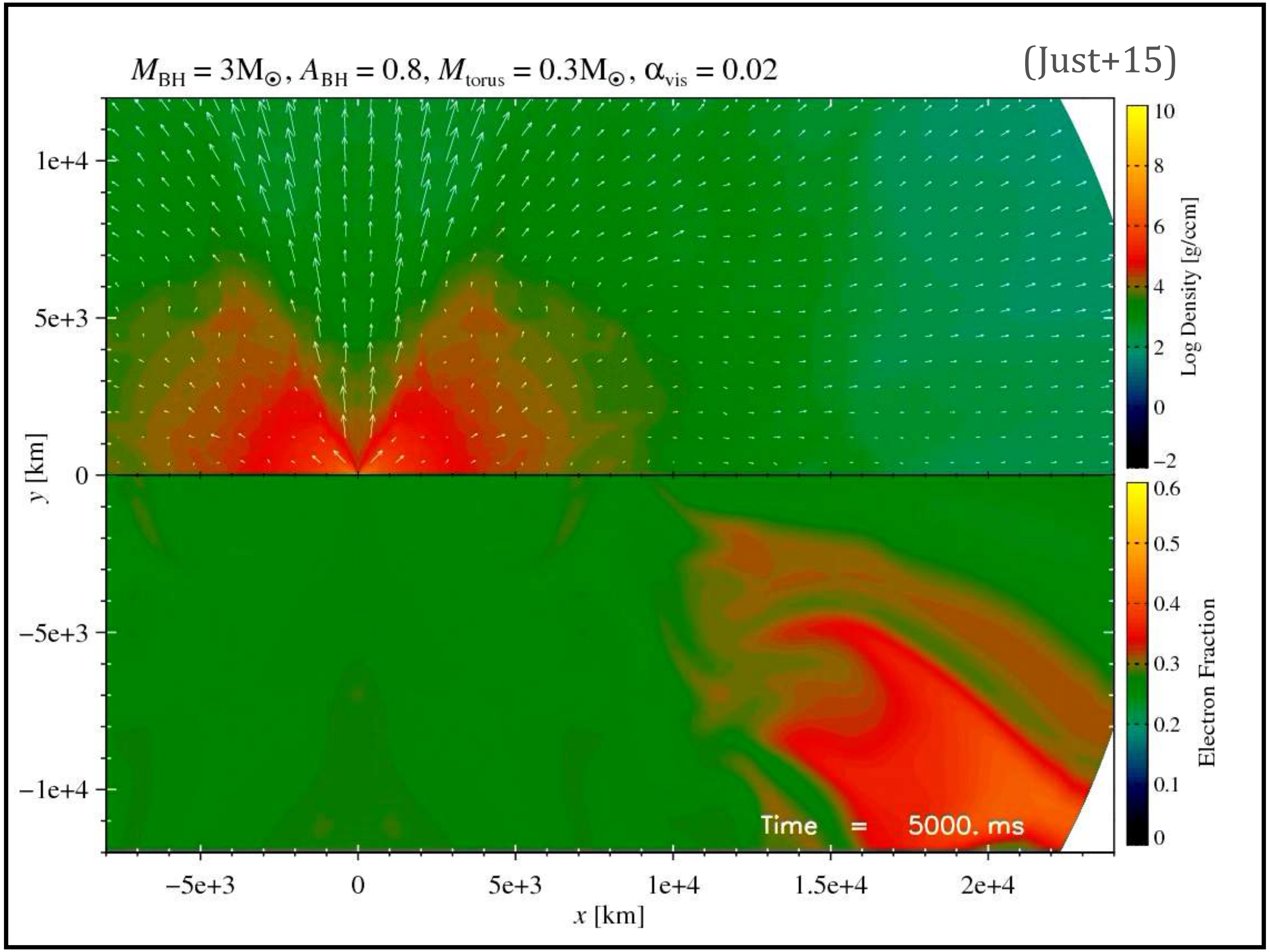
- early dynamical ejecta predominantly A>130 elements
- post-merger ejecta predominantly A<130 elements

(qualitative agreement with other groups: Radice, Shibata, Dietrich, …)

GSI

Neutrino-cooled post-merger remnant disks

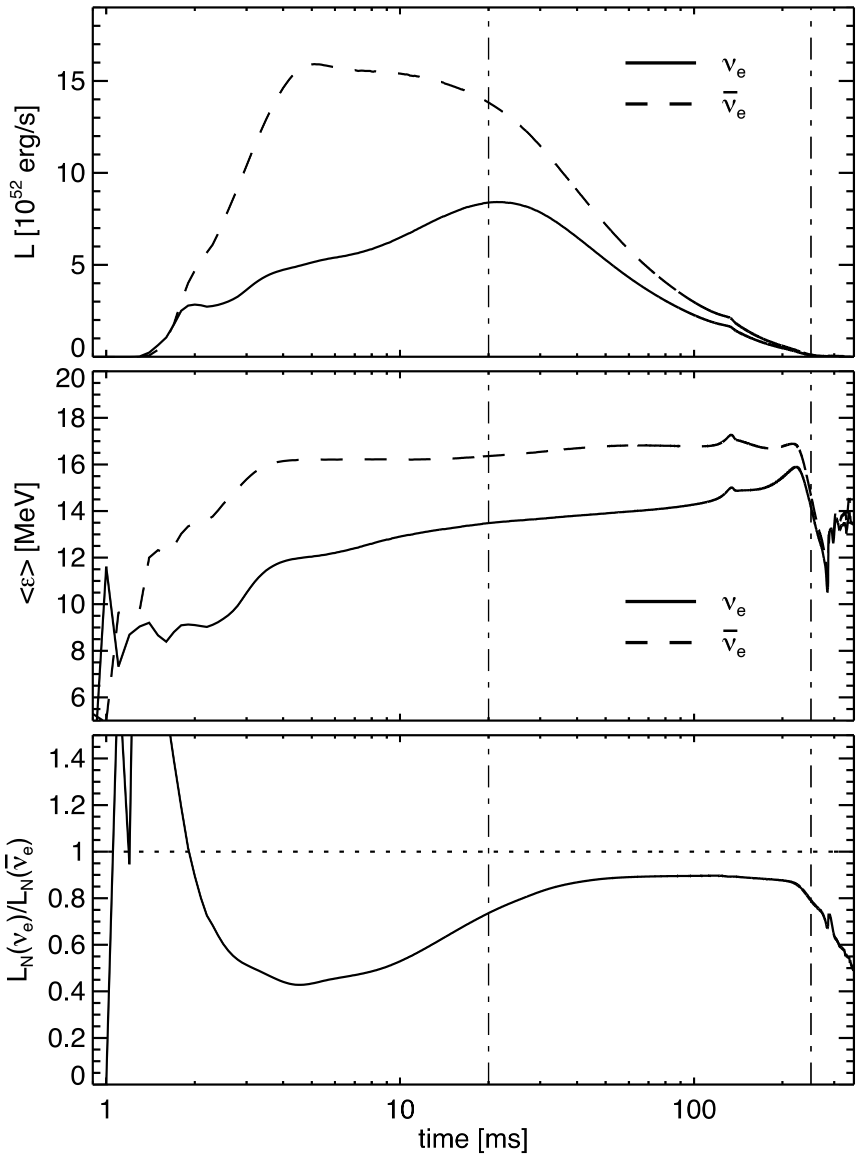
- 10-40% of disk can become (moderately) neutron-rich ejecta
- **Challenges:**
  - combination of GR, neutrino transport, (MHD) turbulence
  - large range of relevant scales
- **Common approximations:**
  - M1 or leakage neutrino treatment
  - simplified gravity
  - Shakura-Sunyaev effective turbulent viscosity

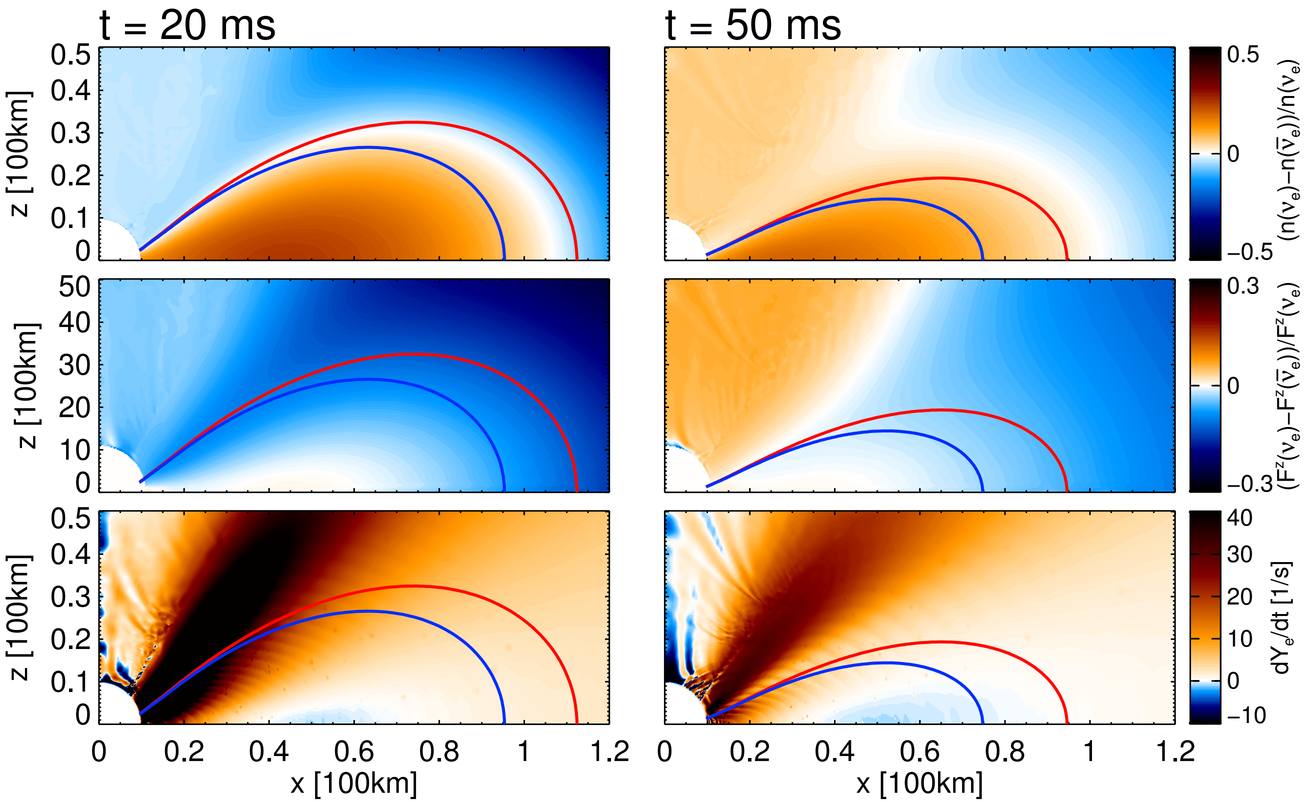


Imprints of neutrino-pair flavor conversions on nucleosynthesis in ejecta from neutron-star merger remnants

(M. R. Wu, I. Tamborra, OJ, H.-Th. Janka, PRD 96, 2017)

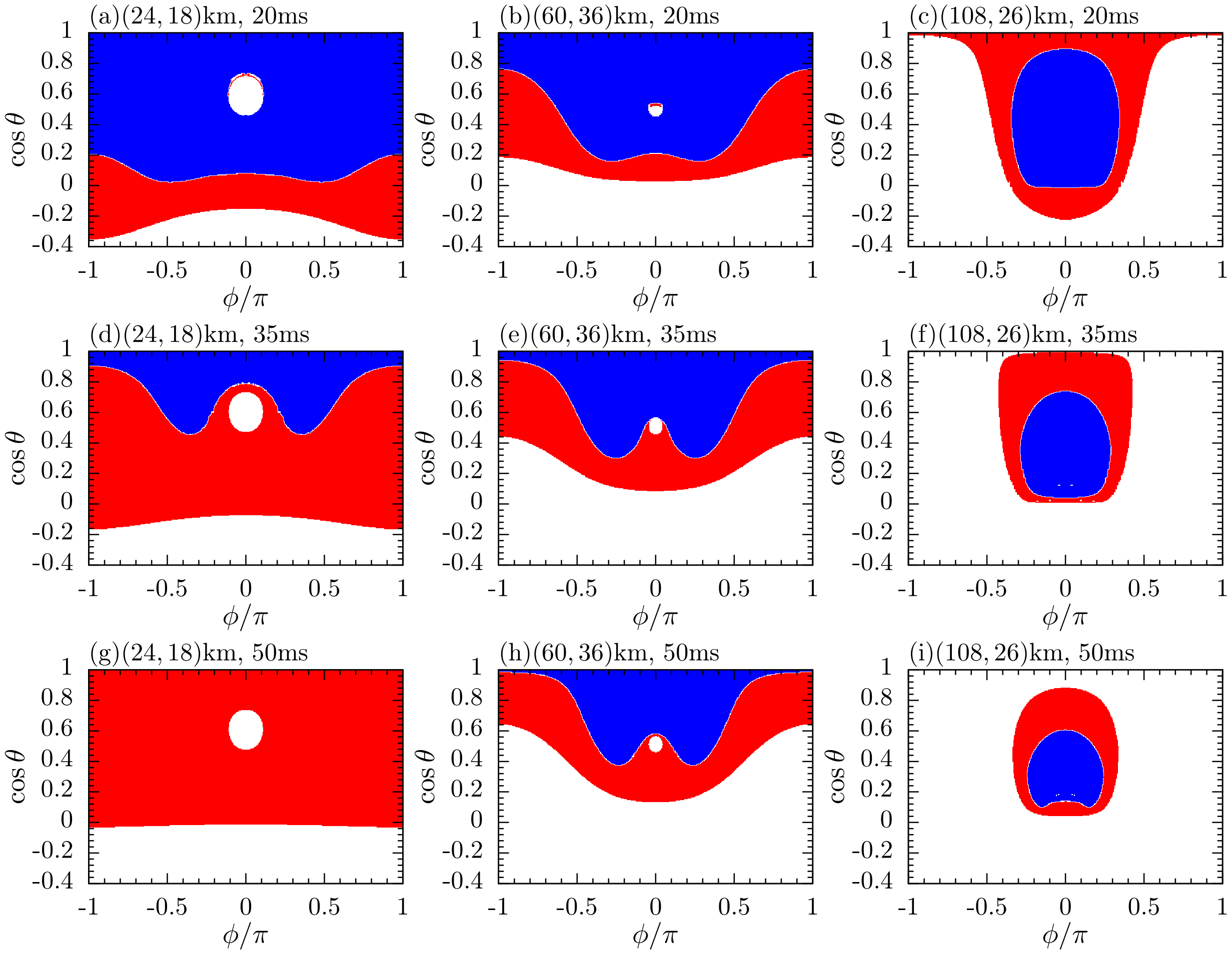
Neutrino field around the disk

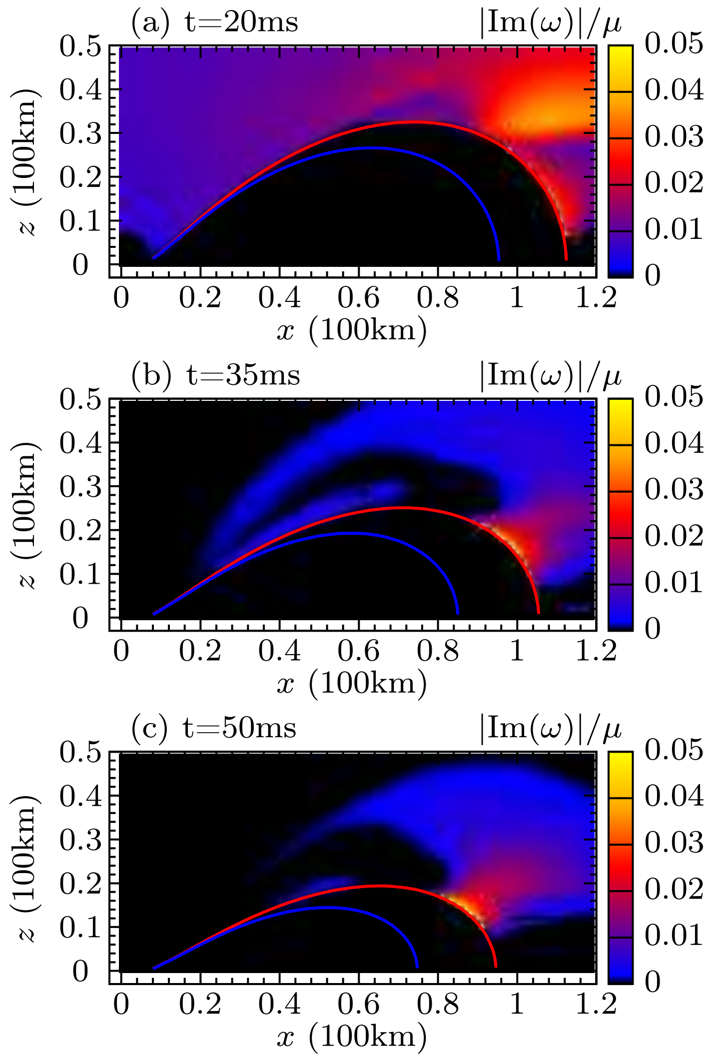




- post-process simulations conducted with M1 neutrino transport without FC

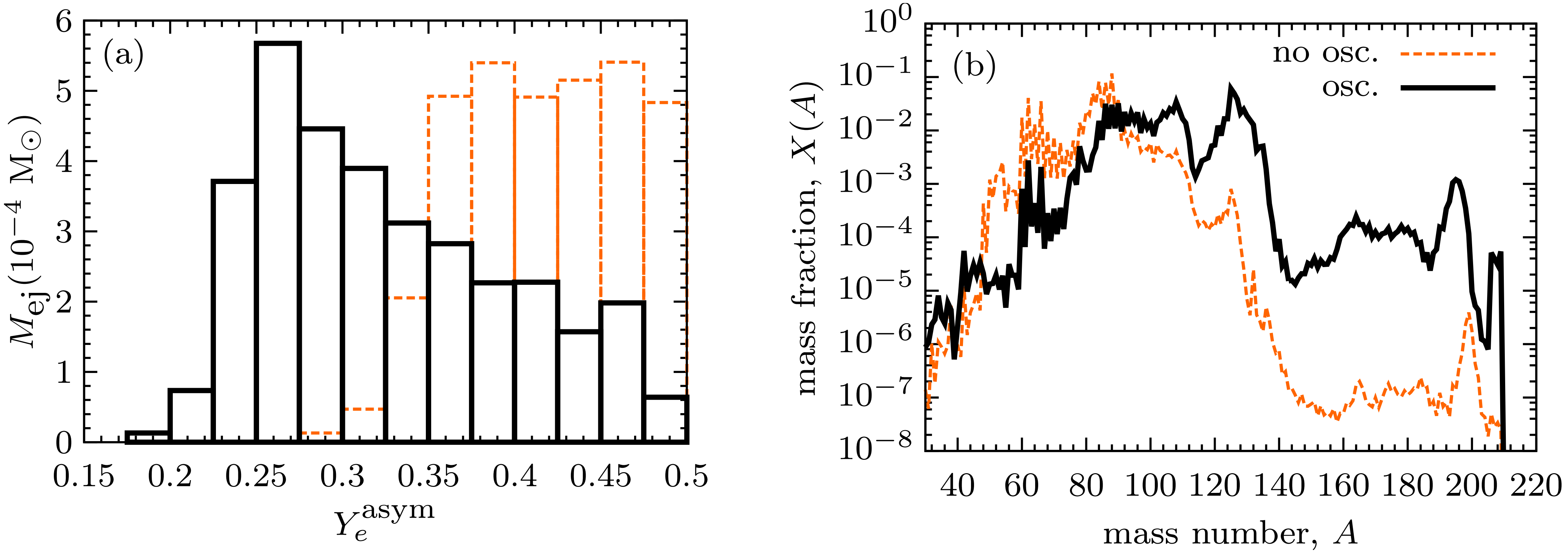
ELN crossings and FFI growth rates





- ELN crossings appear to be generic

Estimated impact on Ye and nucleosynthesis yields



- extreme assumption: neutrino absorption completely shut off
- large impact, but maybe too optimistic?

What determines Ye?

Ye equilibria of beta-processes

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

$$\lambda_{e^-} = K_\beta \int_0^\infty \epsilon^2 F_{e^-}(\epsilon_+)\epsilon_+^2 \sqrt{1-\left(\frac{m_e c^2}{\epsilon_+}\right)^2}\, d\epsilon$$
$$\lambda_{e^+} = K_\beta \int_{\epsilon_0}^\infty \epsilon^2 F_{e^+}(\epsilon_-)\epsilon_-^2 \sqrt{1-\left(\frac{m_e c^2}{\epsilon_-}\right)^2}\, d\epsilon$$

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

$$\lambda_{\nu_e} = K_\beta \int_0^\infty \epsilon^2 F_{\nu_e}(\epsilon)(1 - F_{e^-}(\epsilon_+))\epsilon_+^2 \sqrt{1-\left(\frac{m_e c^2}{\epsilon_+}\right)^2}\, d\epsilon$$
$$\lambda_{\bar{\nu}_e} = K_\beta \int_{\epsilon_0}^\infty \epsilon^2 F_{\bar{\nu}_e}(\epsilon)(1 - F_{e^+}(\epsilon_-))\epsilon_-^2 \sqrt{1-\left(\frac{m_e c^2}{\epsilon_-}\right)^2}\, d\epsilon$$

change of Ye:

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

emission equilibrium:

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

(full) equilibrium:

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

absorption equilibrium:

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

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

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

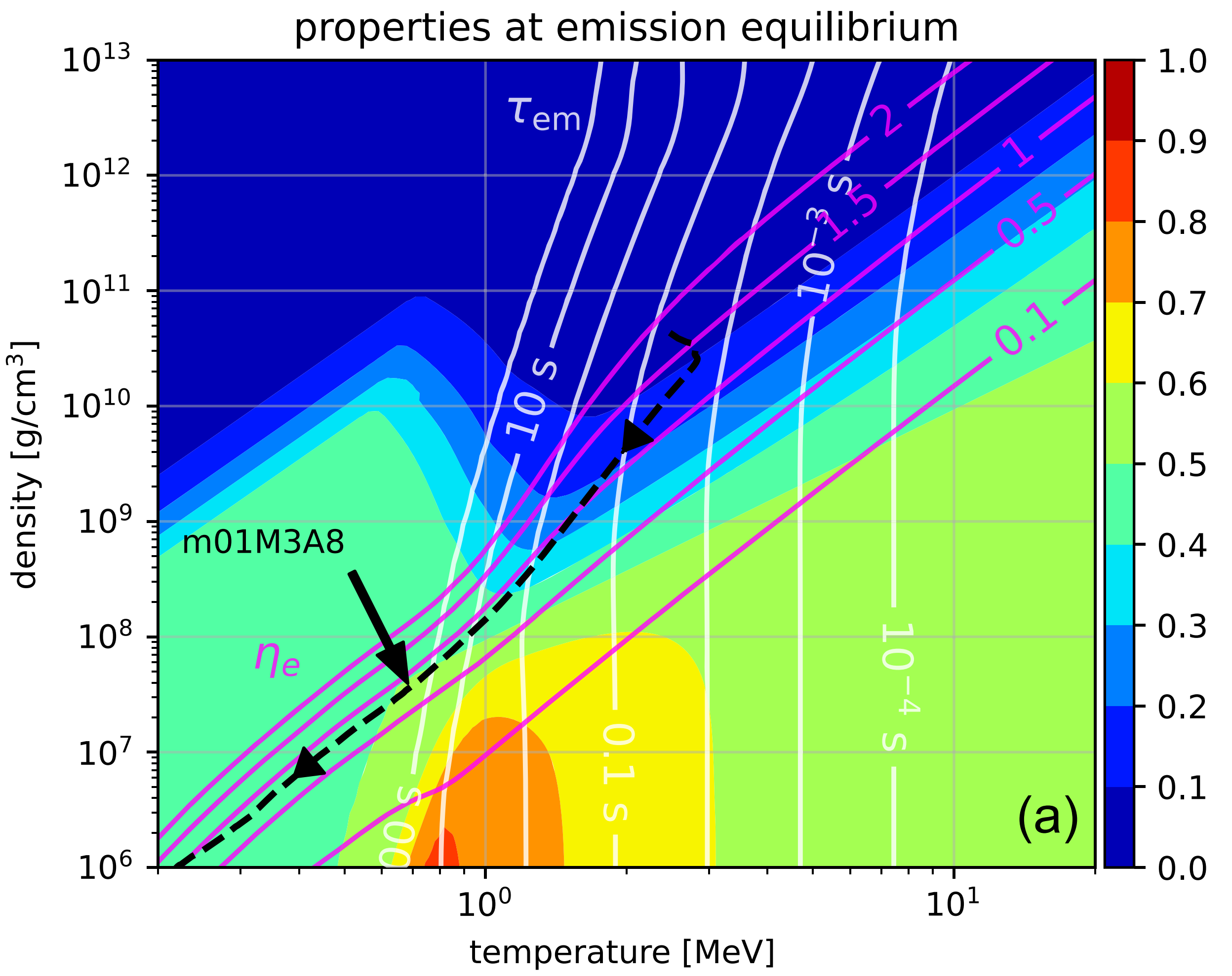
absorption equilibrium:

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

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

emission equilibrium:

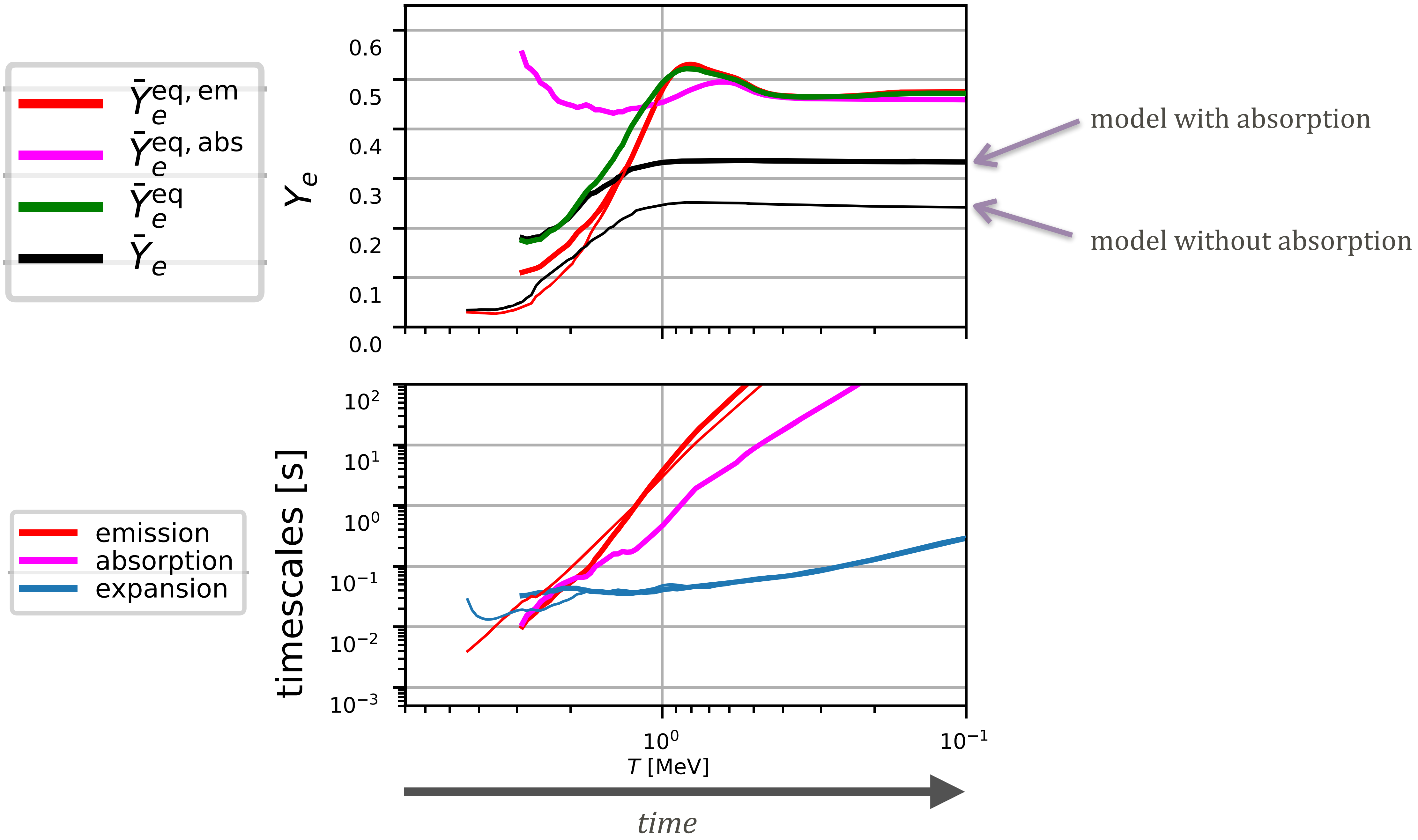
$$\left.\lambda_{e^+}Y_n - \lambda_{e^-}Y_p\right|_{\rho,T,Y_e^{\mathrm{eq,em}}} = 0$$



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

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

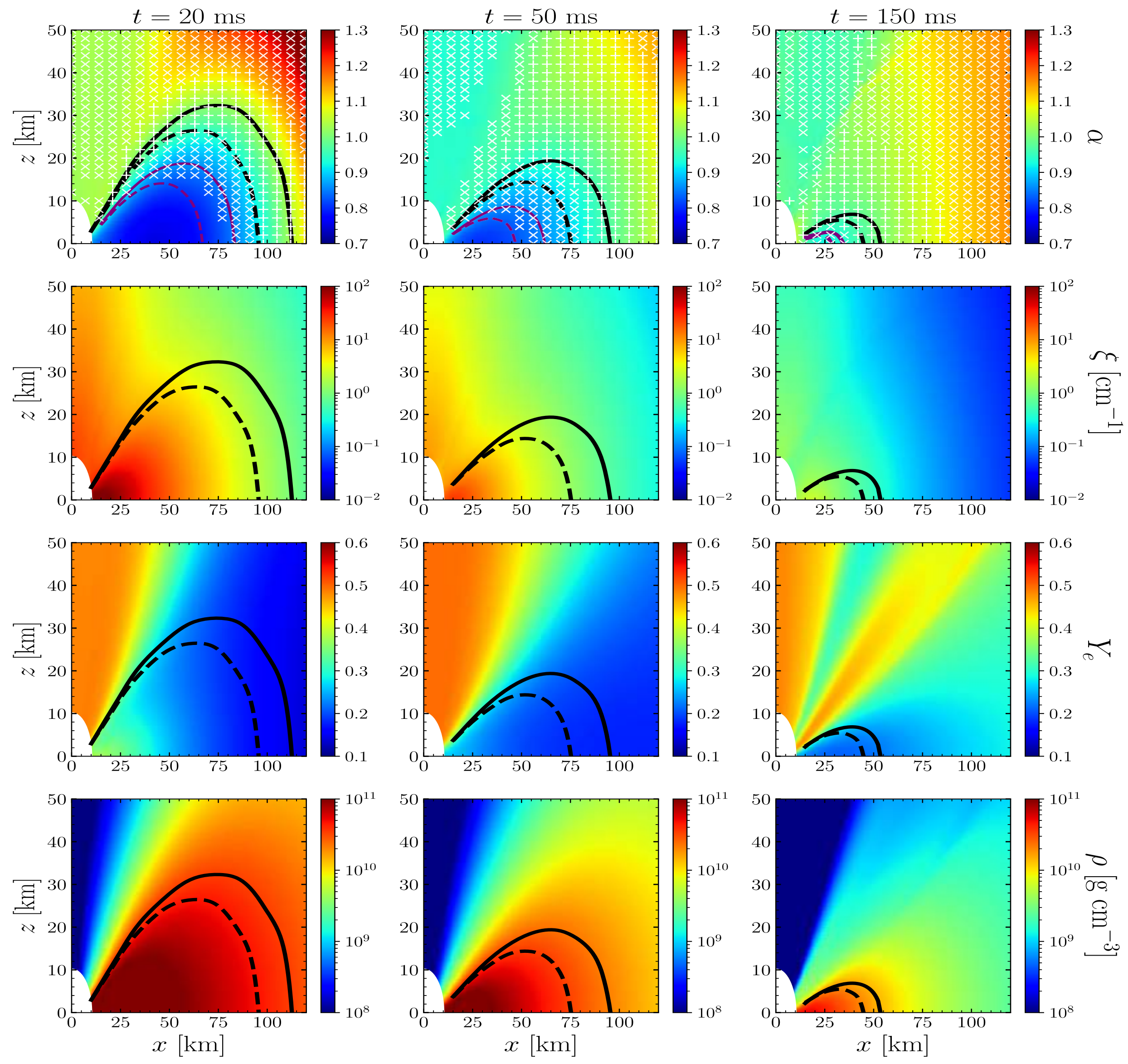
Ye evolution along Lagrangian outflow trajectories



Fast neutrino conversion in hydrodynamic simulations of neutrino-cooled accretion disks

(OJ, S. Abbar, M. R. Wu, I. Tamborra, H.-Th. Janka, F. Capozzi, PRD 105, 2022)

Polynomial angular-moment method for identifying for ELN crossings



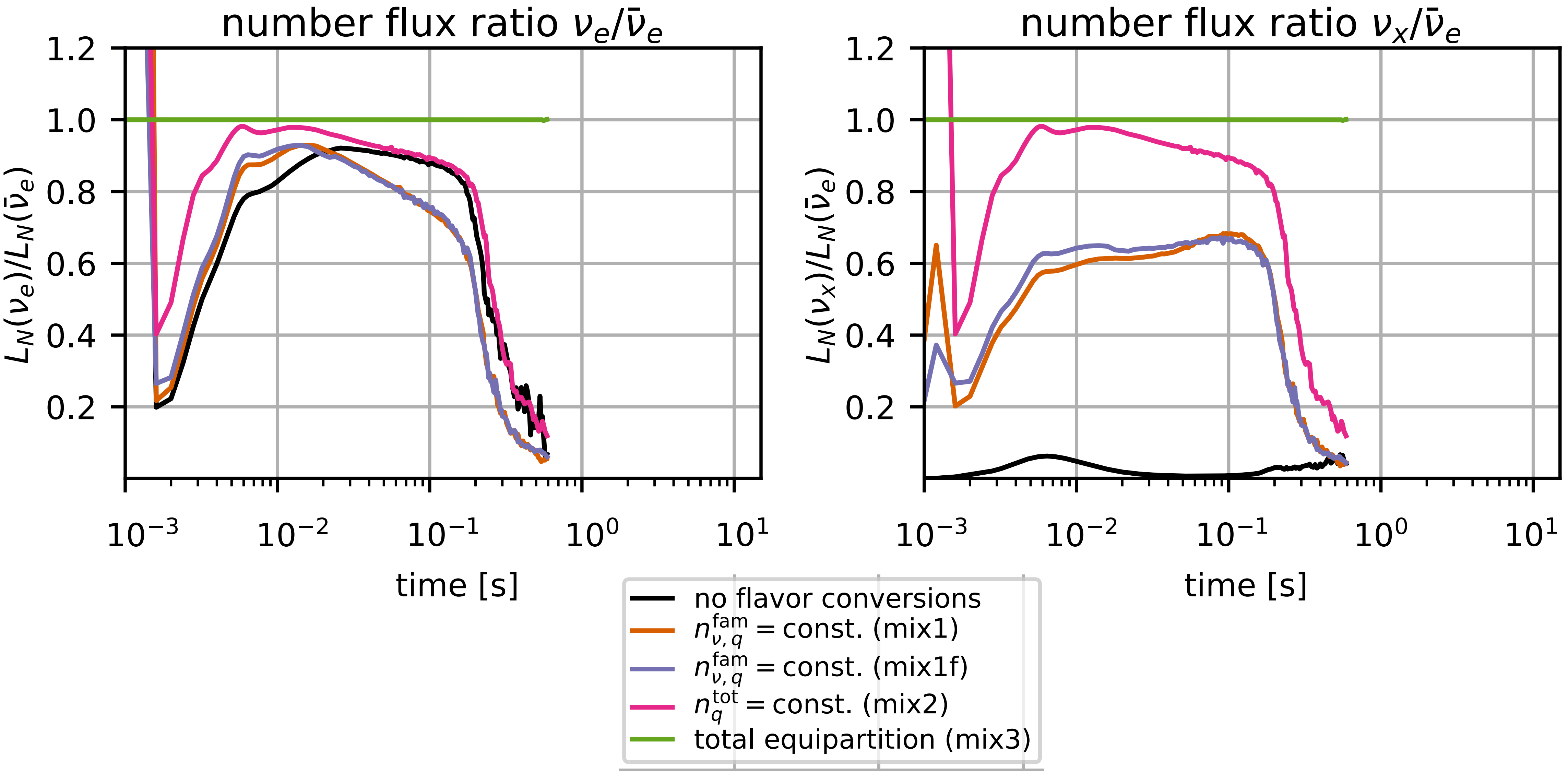
$$I_n = \int_{-1}^{1} \mathrm{d}\mu \mu^n G(\mu),$$

$$I_{\mathcal{F}} = \int_{-1}^{1} \mathrm{d}\mu \mathcal{F}(\mu) G(\mu). \quad I_{\mathcal{F}} = a_0 I_0 + a_1 I_1 + \cdots + a_N I_N.$$

$$I_{\mathcal{F}} I_0 < 0$$

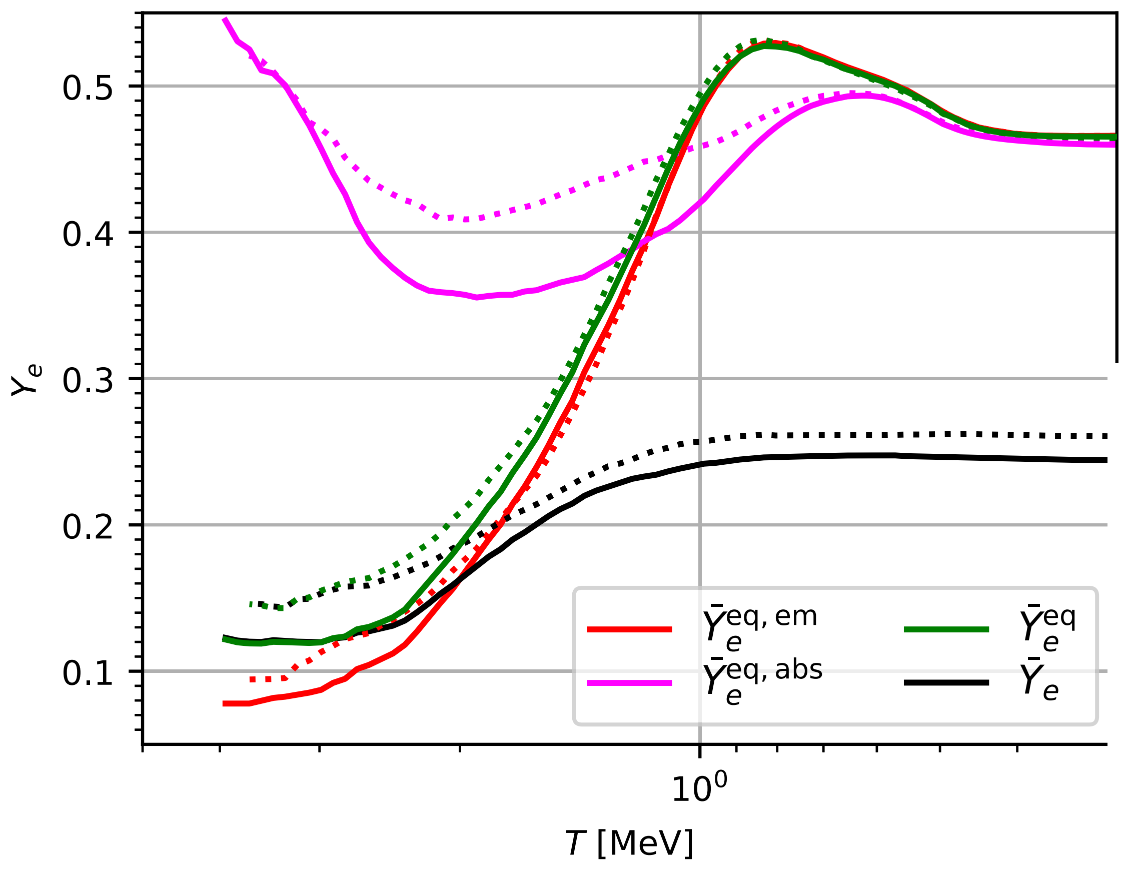
- take moments from M1 transport scheme
- supports presence of ELN crossings
- motivates simple prescription to be used in dynamical simulations

Impact of FFI in dynamical simulations: neutrino emission

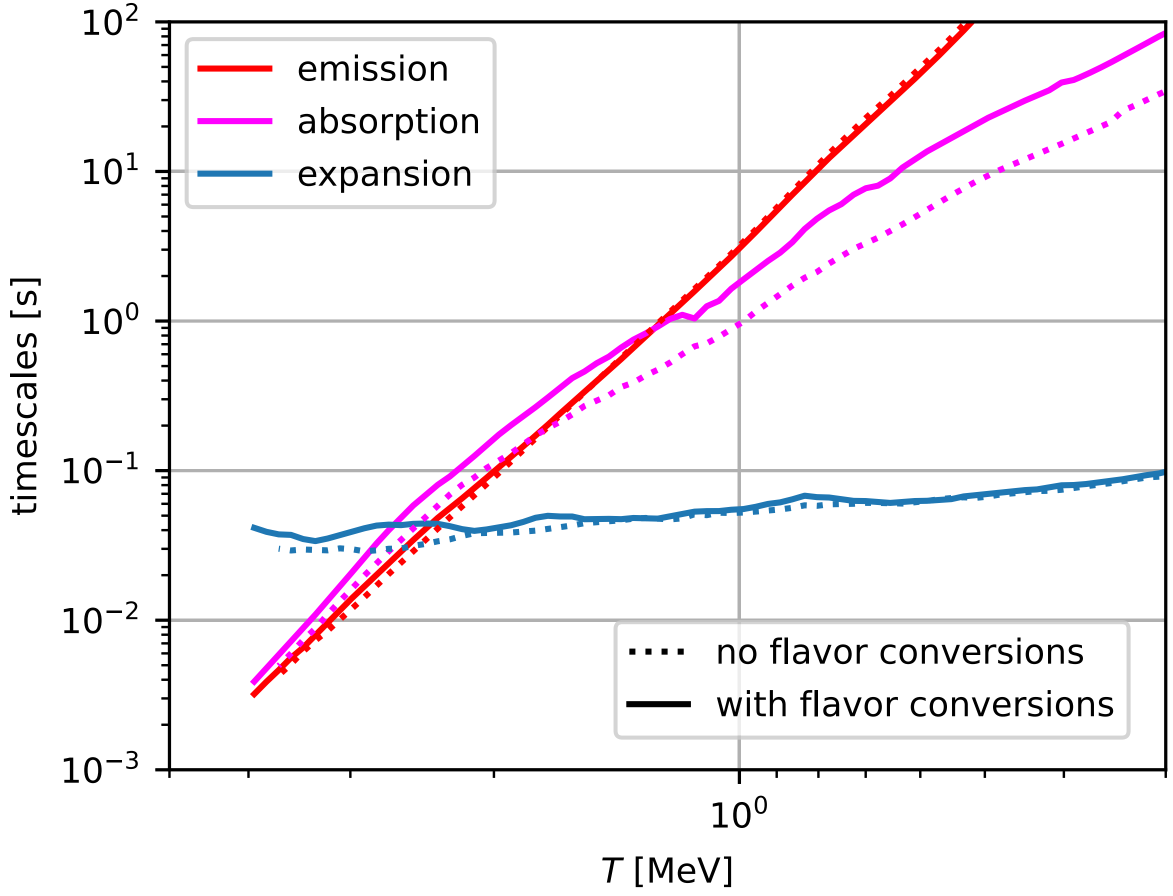


Impact of FFI in dynamical simulations: Ye

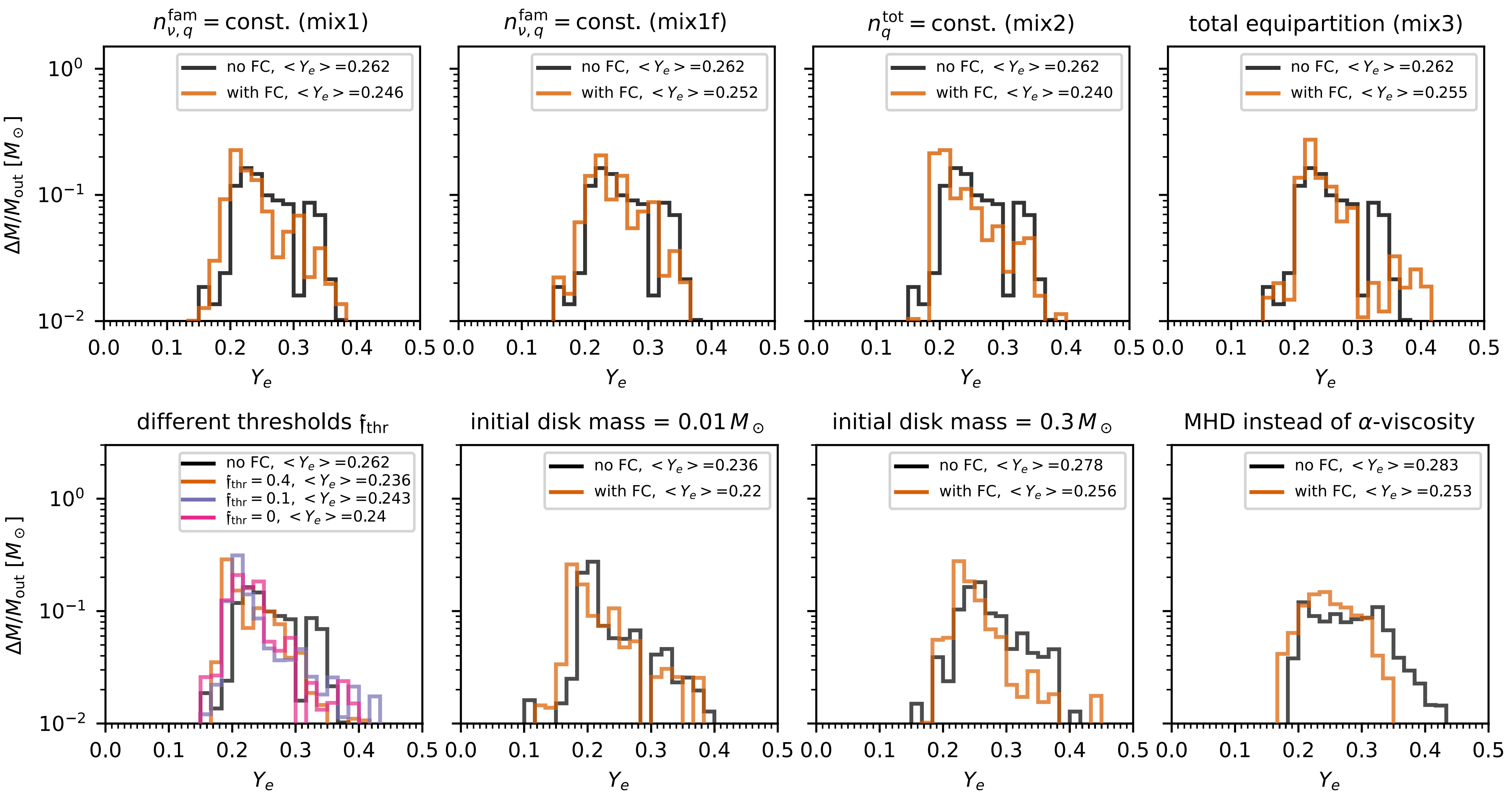
1) enhanced neutrino cooling rates
—> higher electron degeneracy
—> lower emission-equilibrium $Y_e^{\mathrm{eq,em}}$



2) smaller abundance of electron-type neutrinos
—> reduced absorption rates
(= longer absorption timescales)

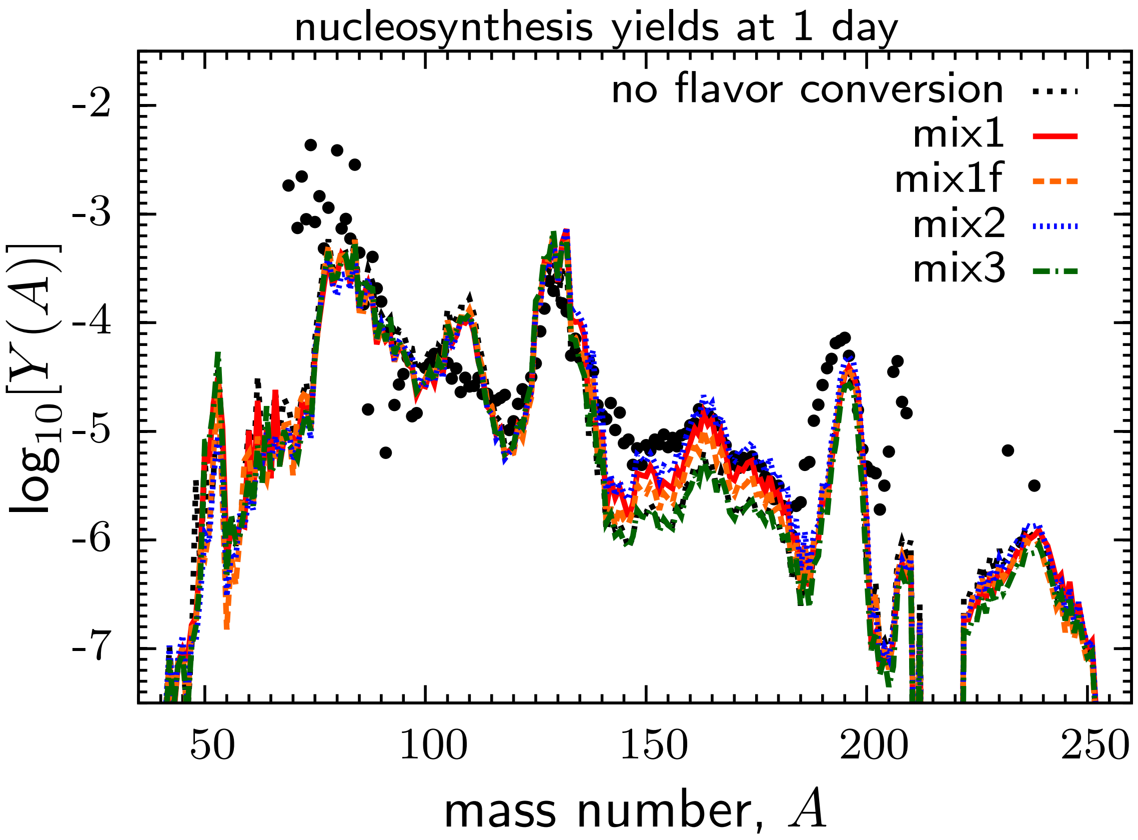


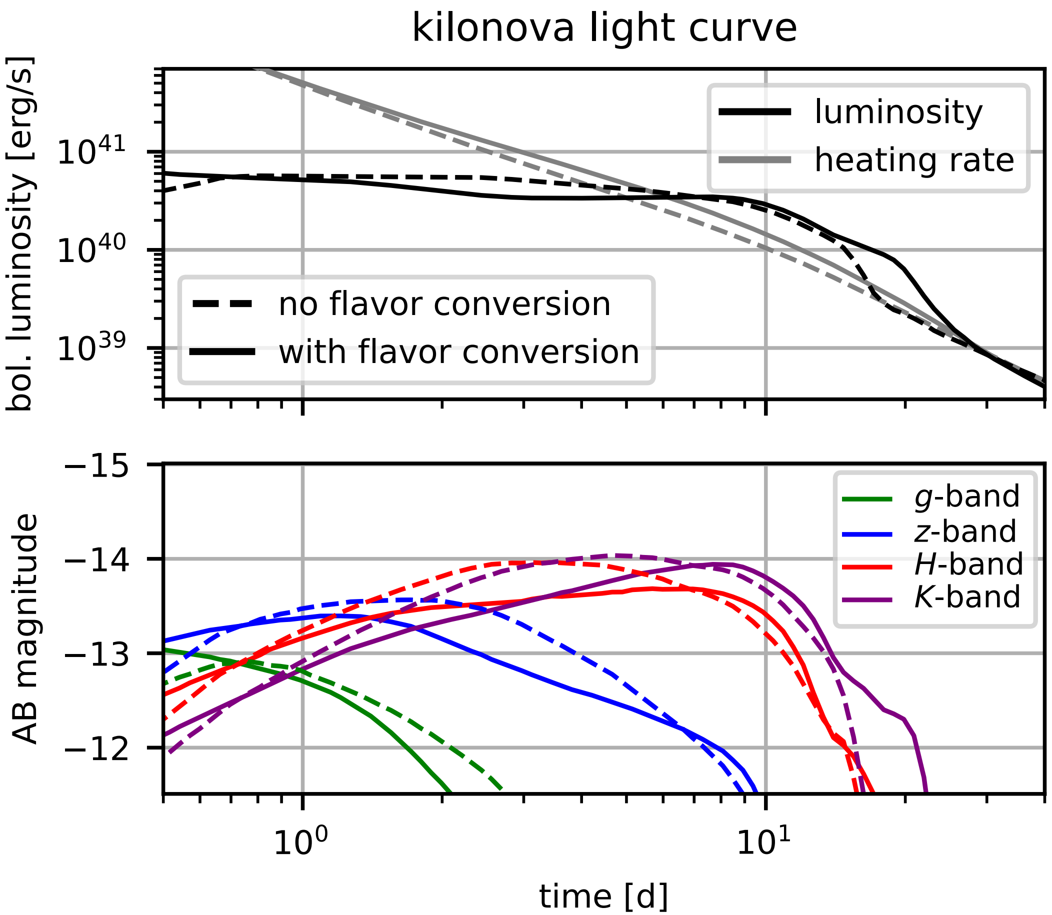
Impact on Ye



- systematic, mild reduction of Ye

Impact on nucleosynthesis and kilonova





- moderate enhancement of r-process yields
- longer, redder kilonova signal

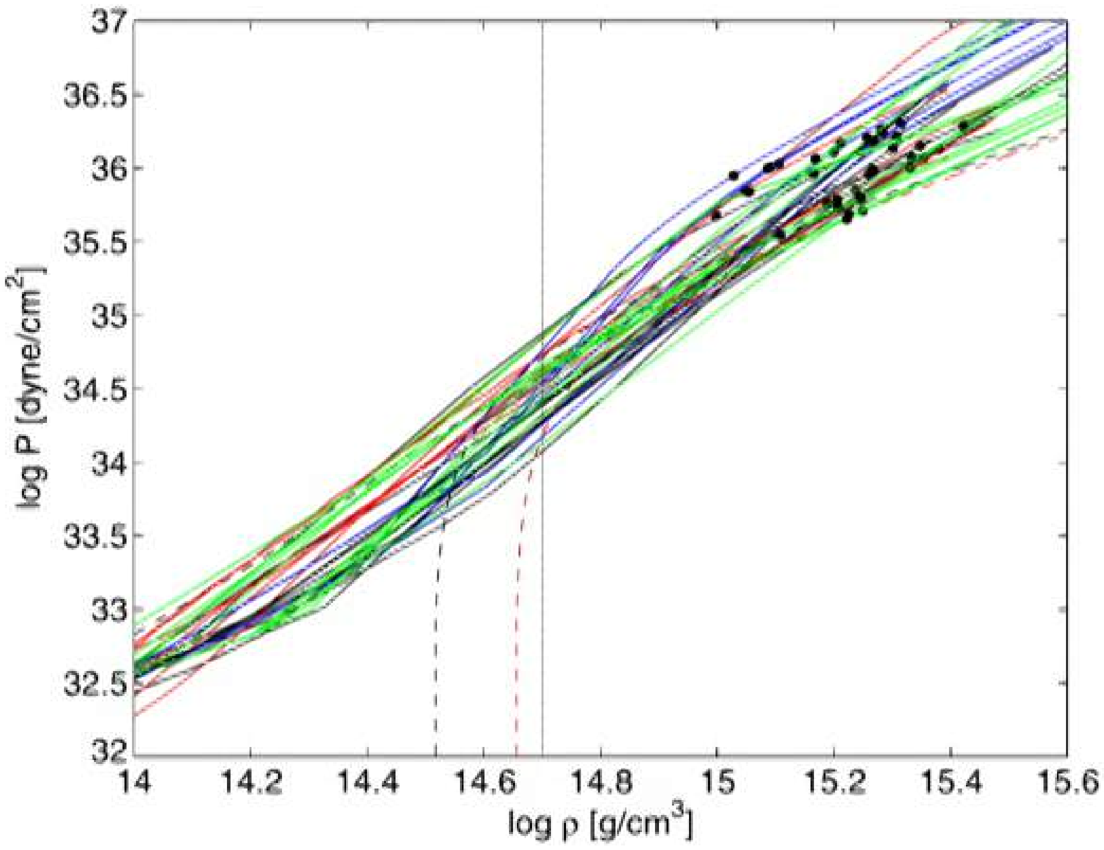
(see also Li+21, Fernandez+22, Qiu+25, Kawaguchi+26, ...)

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

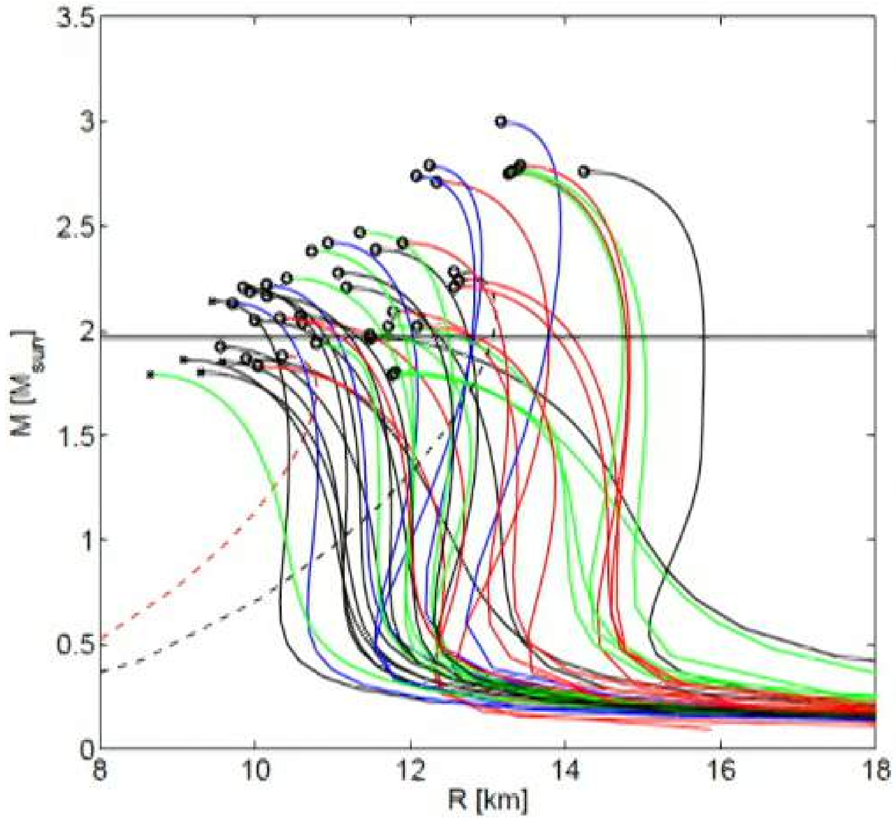
(A. Sneppen, OJ, A. Bauswein, R. Damgaard, D. Watson, L. J. Shingles, C. E. Collins, S. A. Sim, Z. Xiong, G. Martinez-Pinedo, T. Soultanis, and V. Vijayan, PRD accepted)

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

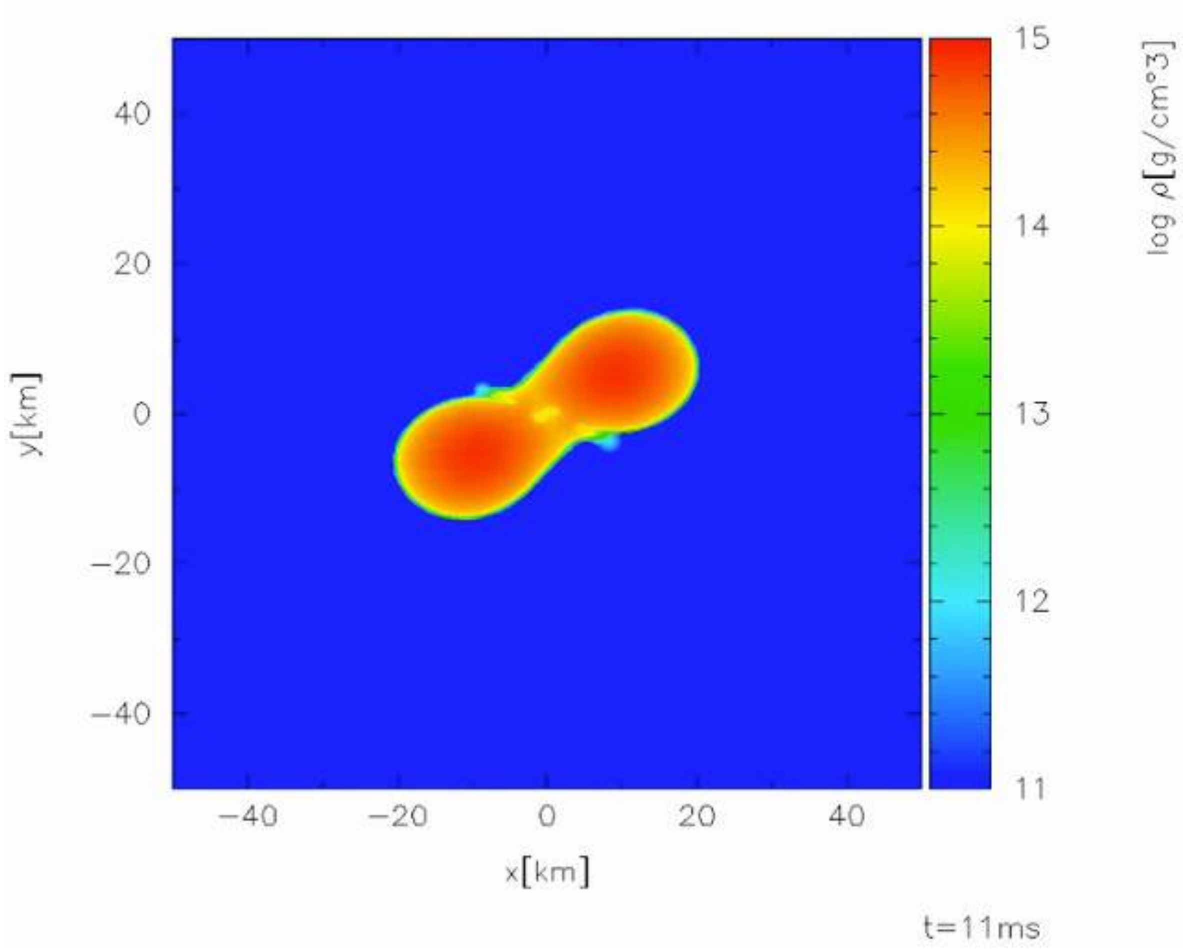


(plots by A. Bauswein)

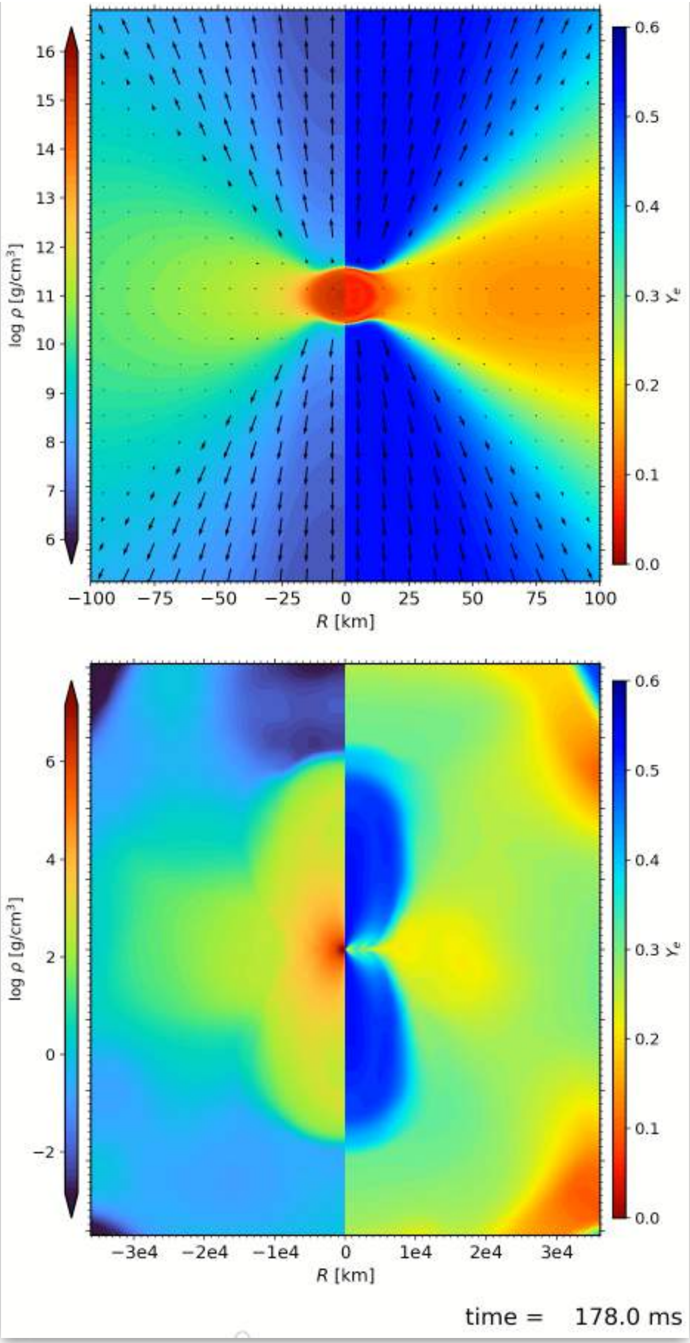
- softer (stiffer) EOS <=> smaller (larger) neutron star
- softer (stiffer) EOS <=> shorter (longer) lifetime of HMNS merger remnant

What was the lifetime $\tau_{\rm BH}$ of the NS remnant in GW170817?

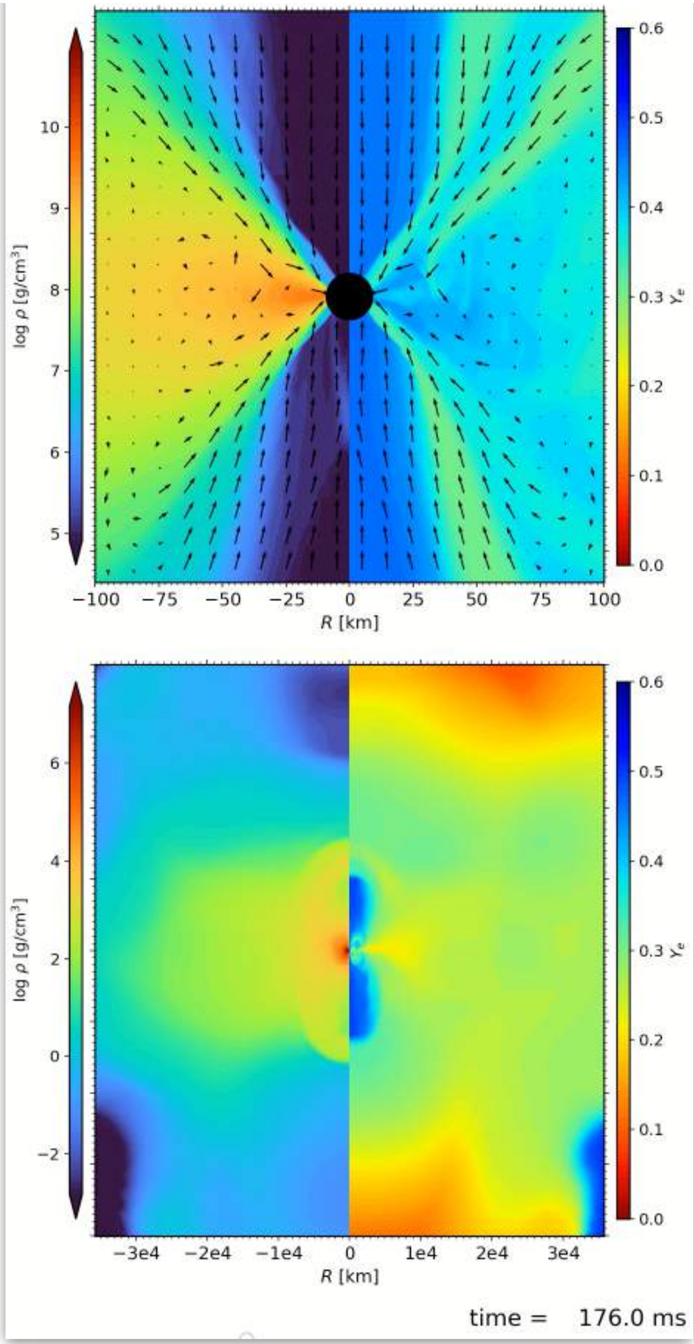
- prompt collapse scenario ($\tau_{\rm BH} = 0$) almost certainly excluded because of bright KN <=> high ejecta masses (Bauswein+17, Radice+18, …)
- absence of spindown emission + observed sGRB signal (Margalit+17, Shibata+18, Rezzolla+18, …)
  => $\tau_{\rm BH} \lesssim 1.7$ sec
- **lifetime of NS remnant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



long-lived HMNS



short-lived HMNS

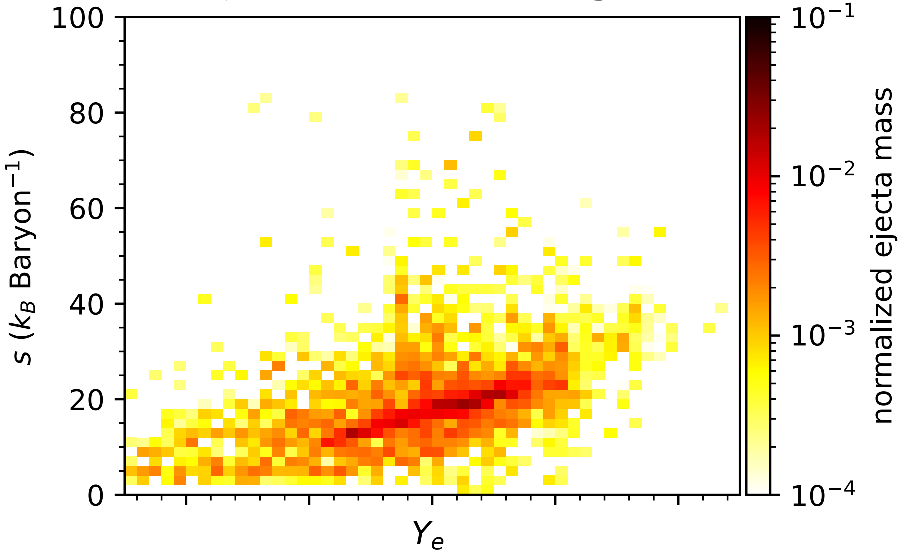


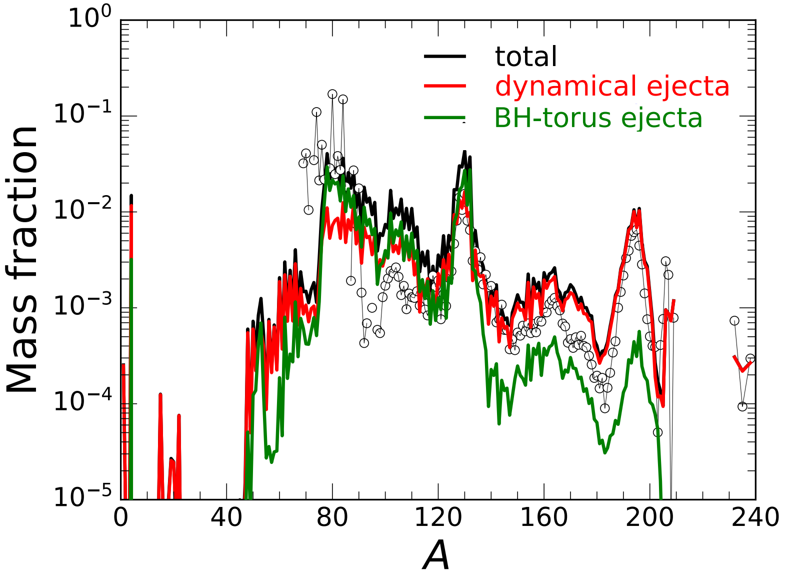
Short- vs. long-lived NS remnant

ejecta mass histogram

ejecta nucleosynthesis yields

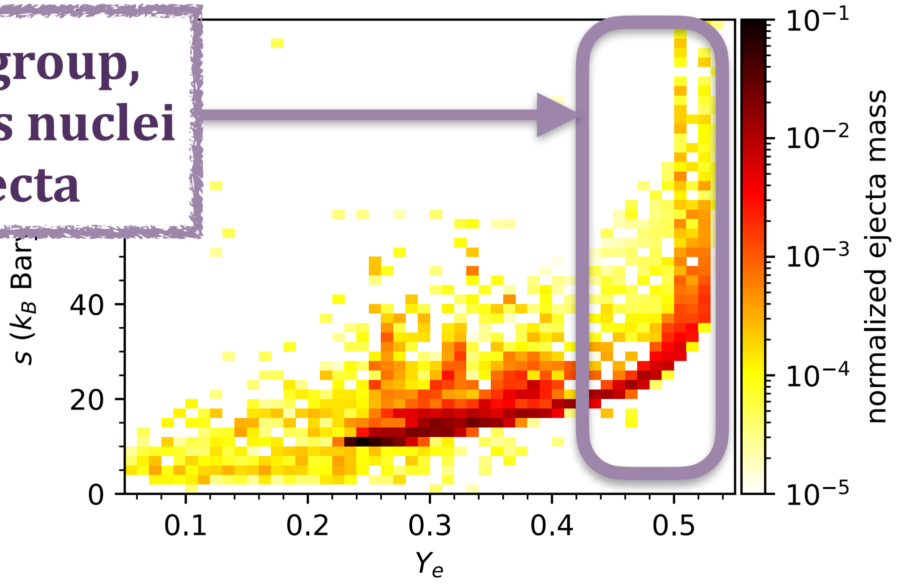
short-lived
(10ms)

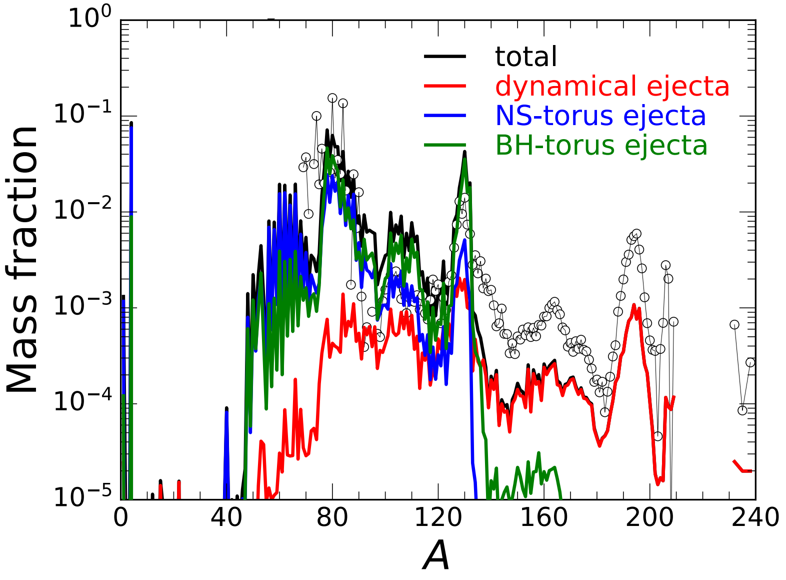




mainly He, iron-group, and light r-process nuclei in NS-torus ejecta

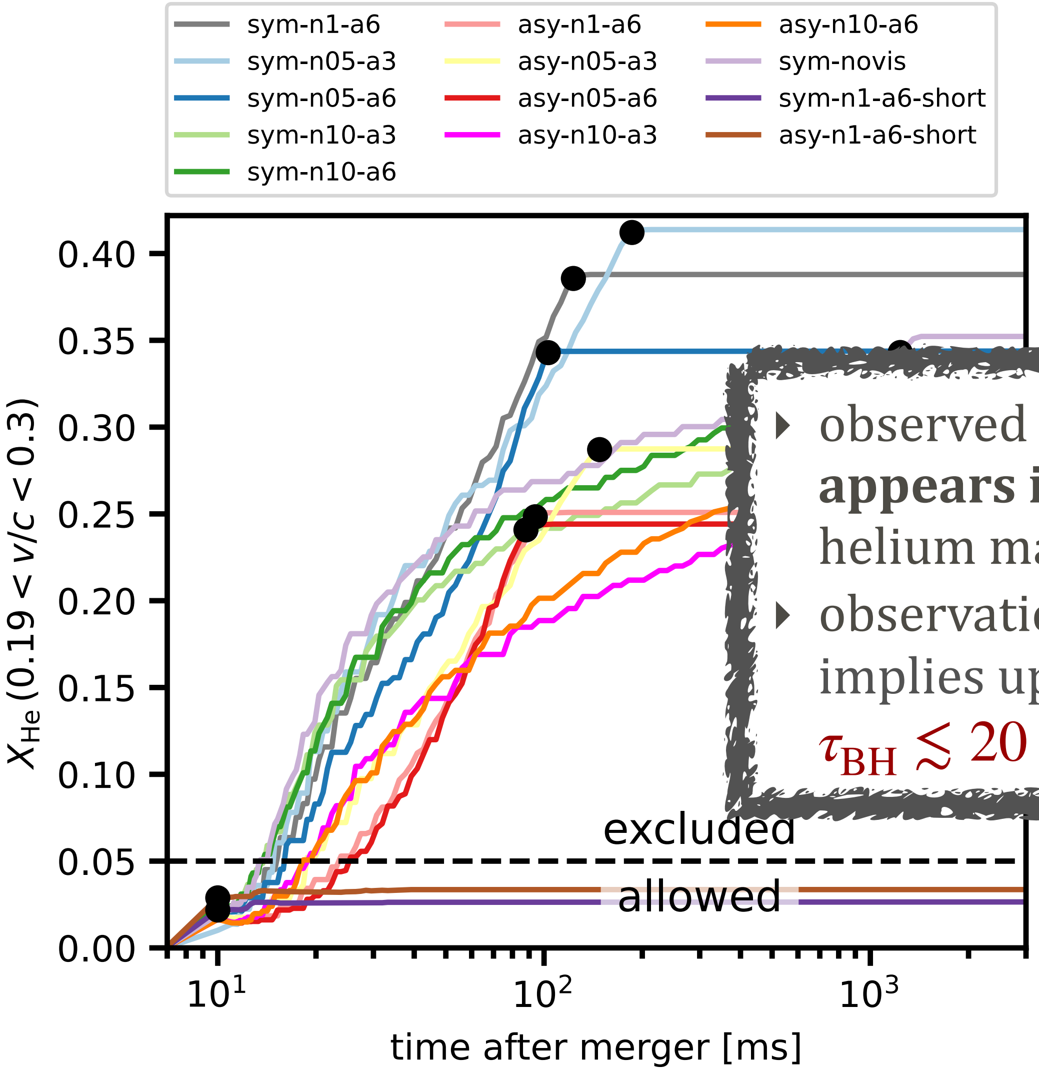
long-lived
(120ms)



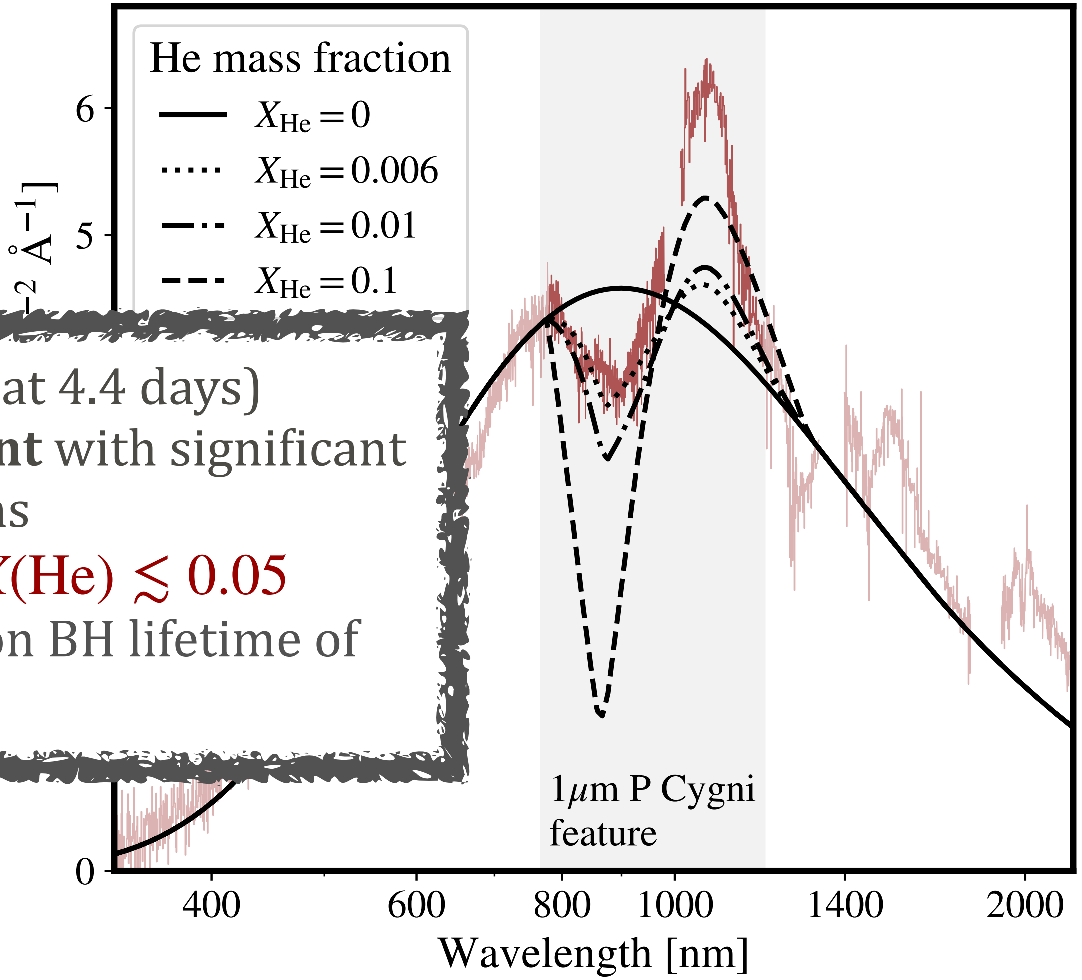


Helium production in NS merger models

hydro models



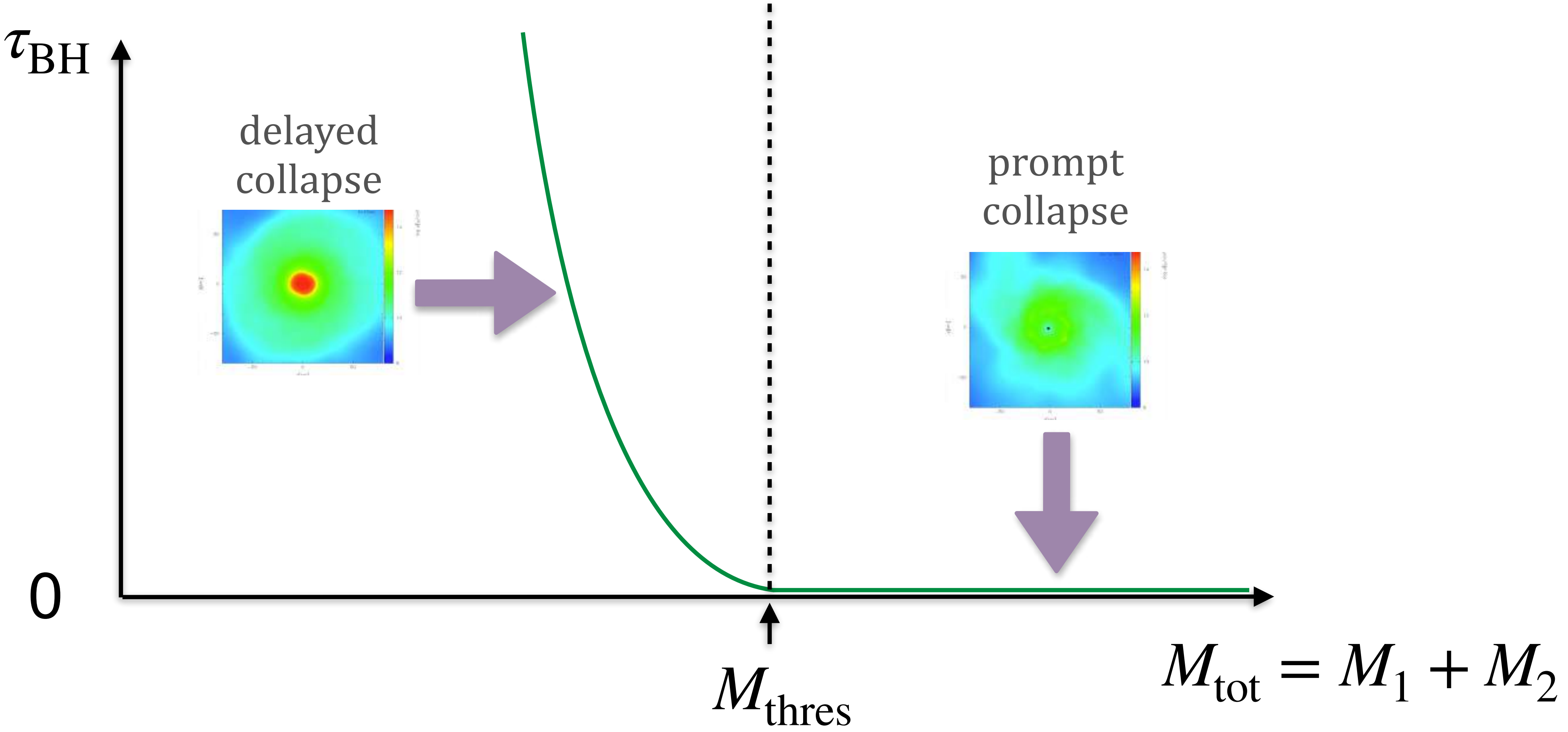
observed spectrum of AT2017gfo at 4.4 days
+ estimated hypothetic contribution of helium



- 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 $\tau_{BH} \lesssim 20 - 30\,\mathrm{ms}$

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

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

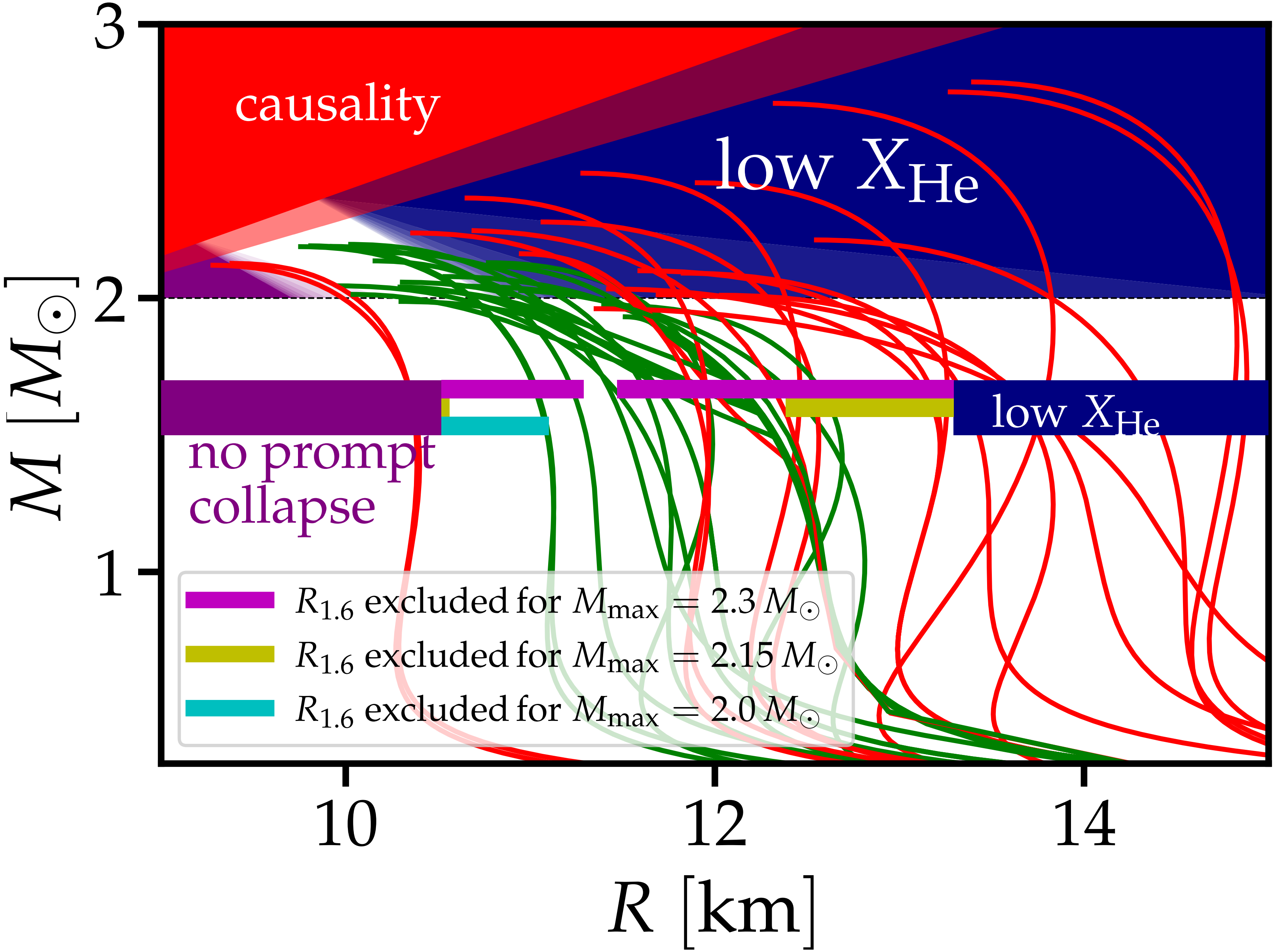


- threshold mass $M_{\rm thres}$ separates prompt-collapse from delayed-collapse cases
- exploit empirical relations (e.g. Bauswein+19, Kölsch+23):

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

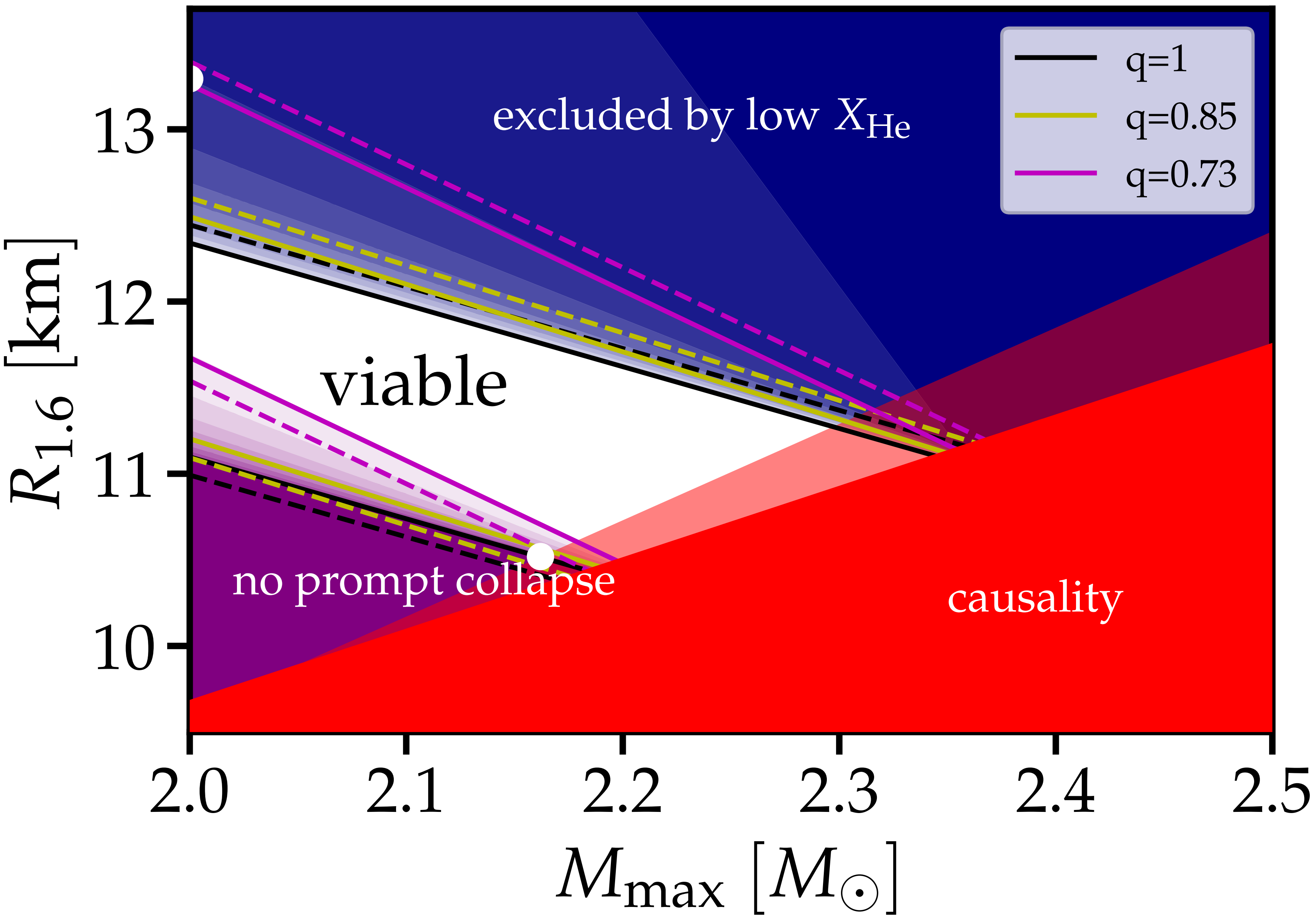
Implications for NS properties

- large number of EOSs excluded (red lines)



Implications for NS properties

- narrow window of allowed values
- **potentially powerful new EOS constraint, but with remaining modeling uncertainties**
- **impact of flavor conversions on polar outflows???**

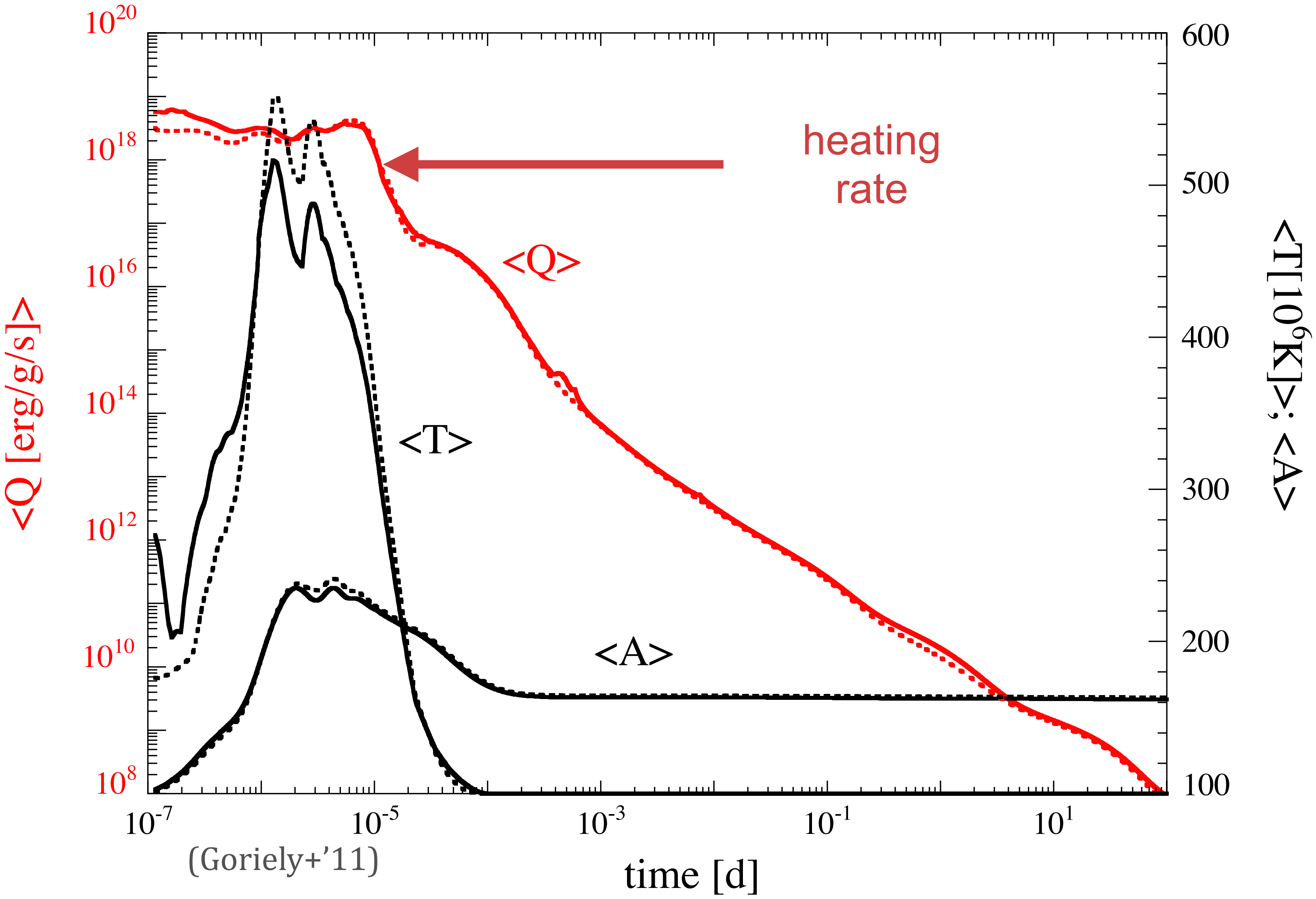


RHINE: R-process Heating Implementation in hydrodynamic simulations with NEural networks

(OJ, Z. Xiong, G. Martinez-Pinedo, PRD, accepted)

Motivation

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



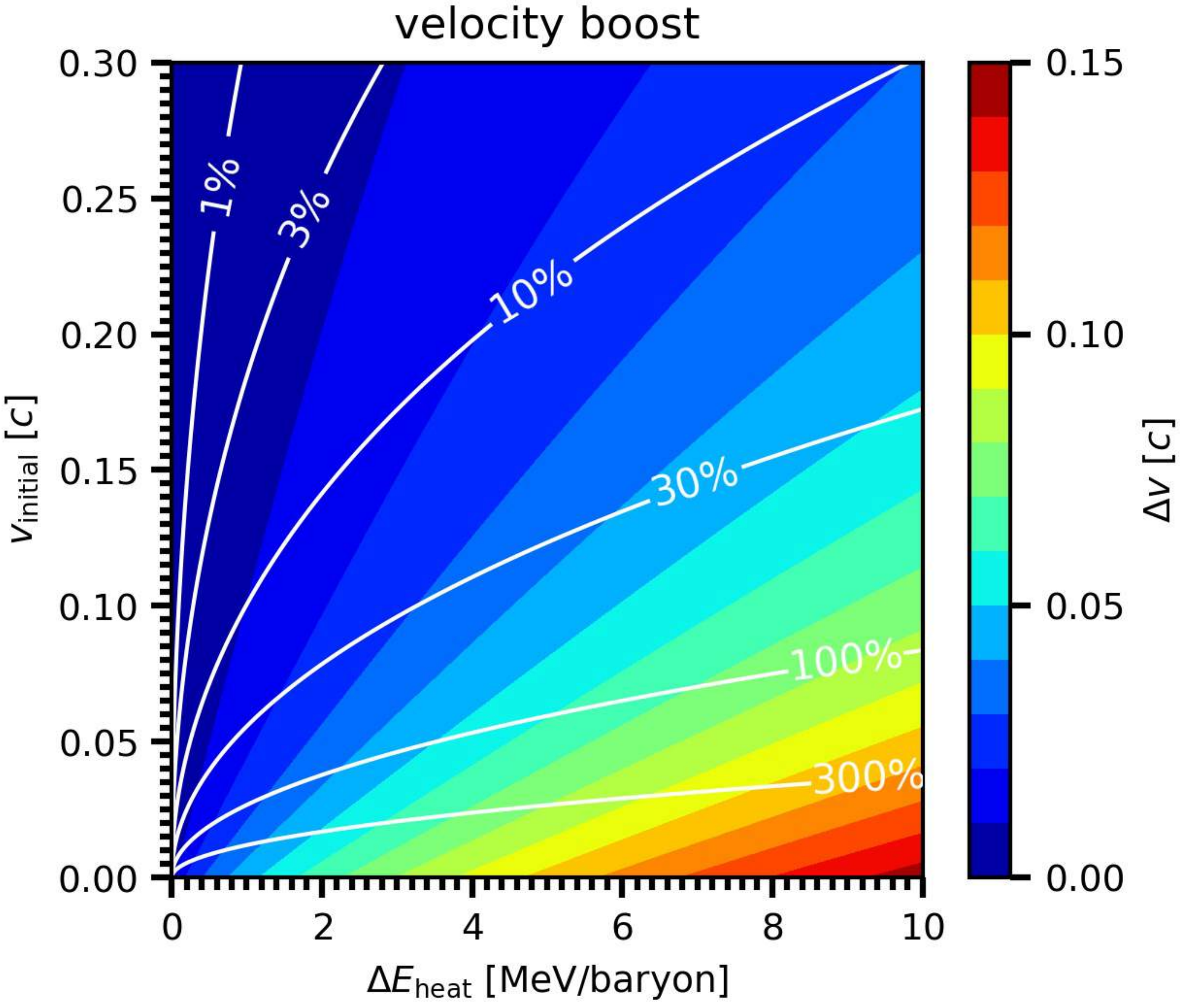
(Goriely+'11)

Expected impact on velocity

- energy conservation:

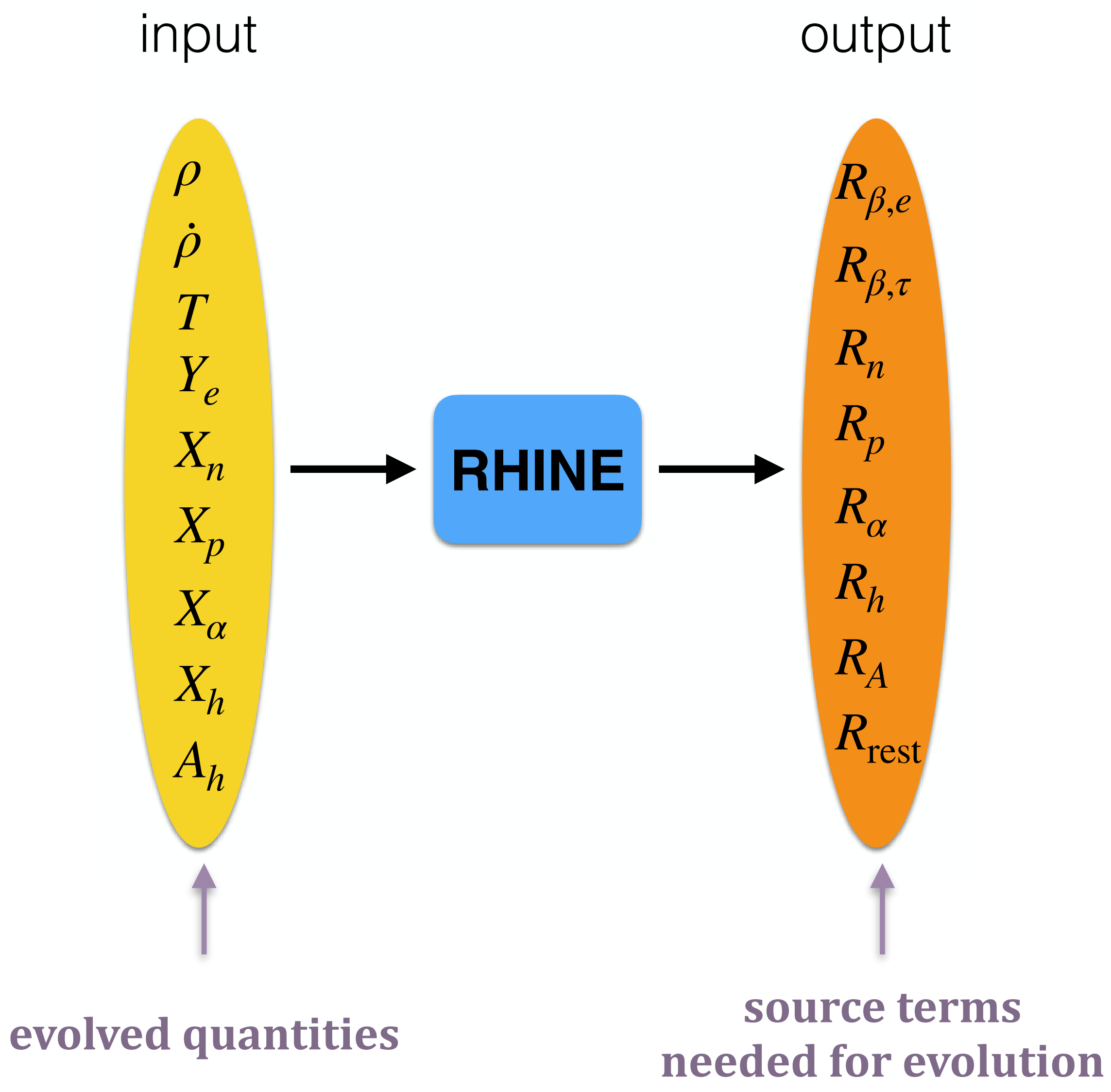
$$W_{\mathrm{final}} mc^2 = W_{\mathrm{initial}} (mc^2 + \Delta E_{\mathrm{heat}})$$

- 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



Multilayer perceptron neural networks

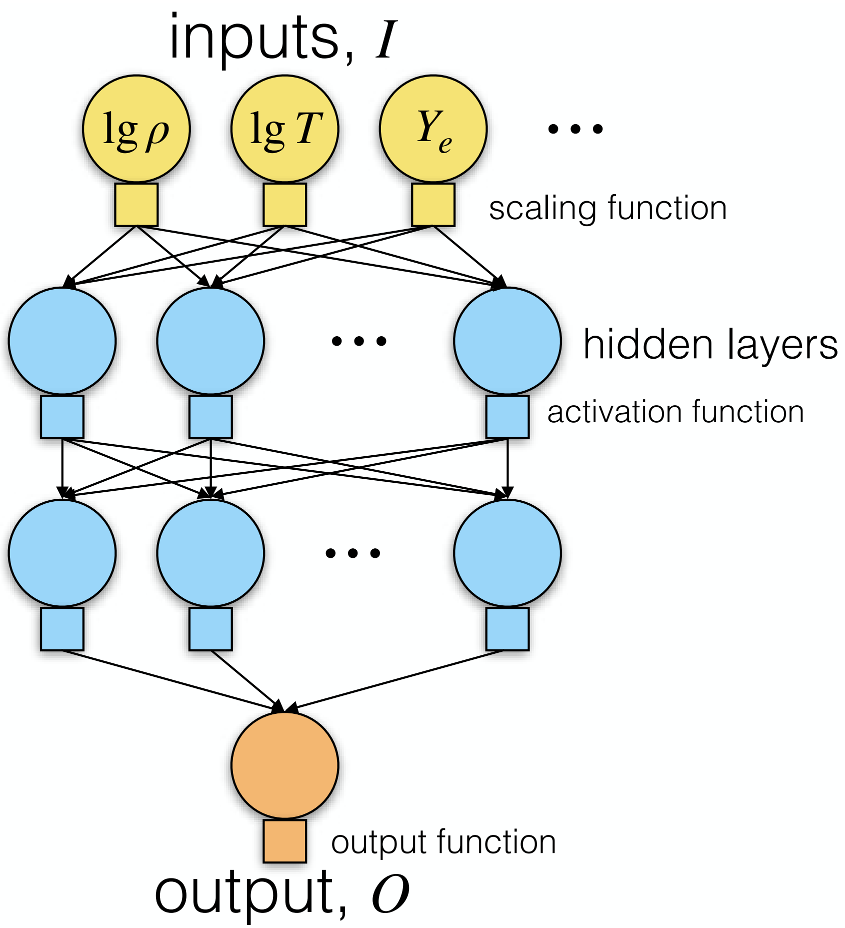
- each circle represents a "perceptron" or "neuron"
- information passes through sequence of hidden layers
- output of a perceptron:

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

- with non-linear activation function:

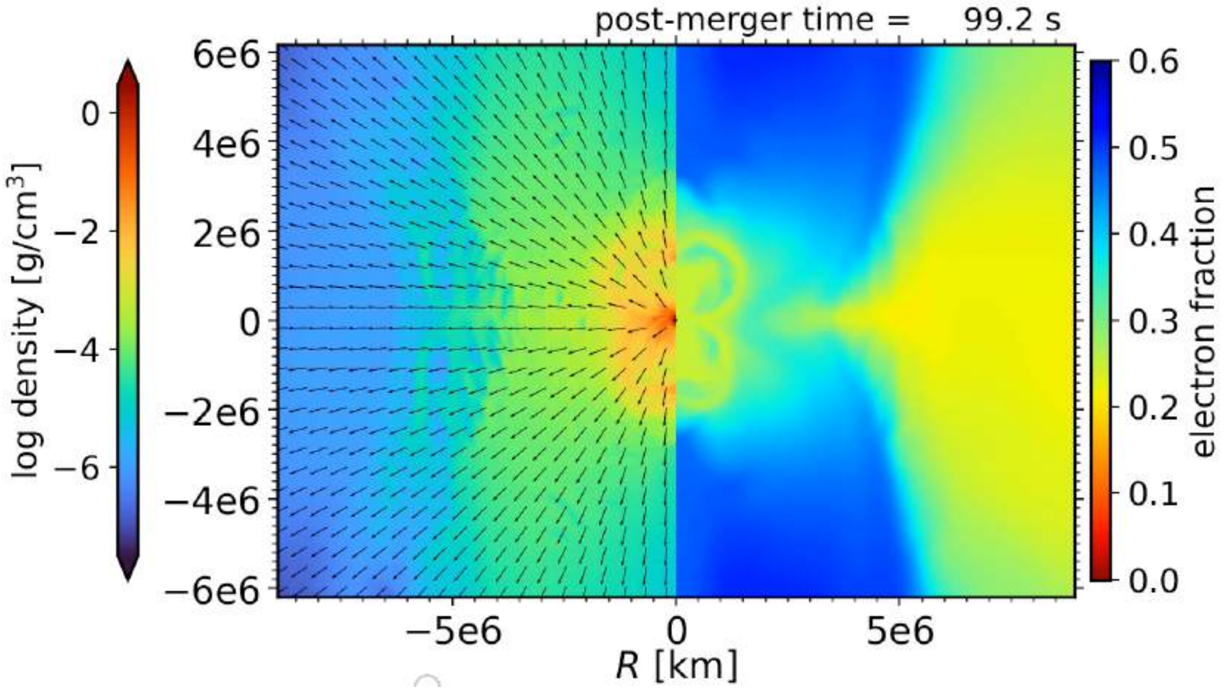
$$f_{\mathrm{act}}(x) = \begin{cases} x, & \text{if } x \geq 0 \\ e^x - 1, & \text{if } x < 0 \end{cases}$$

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

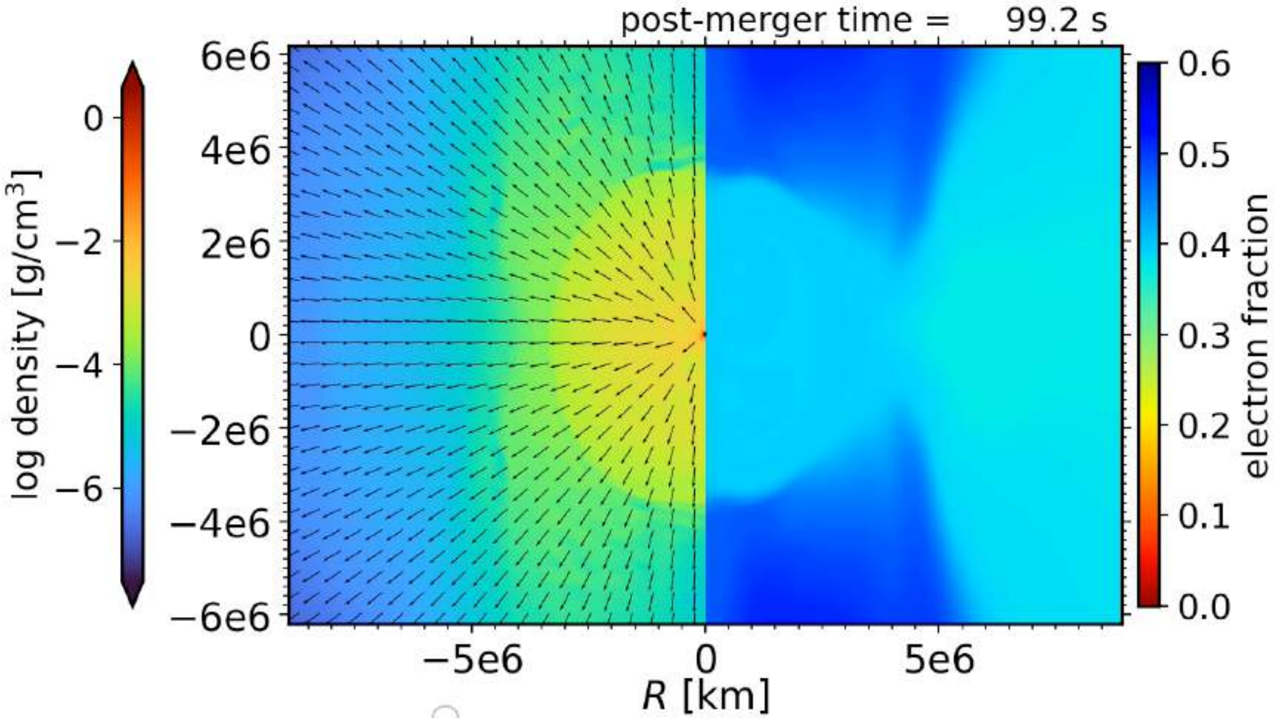


NS merger models + RHINE

without RHINE:

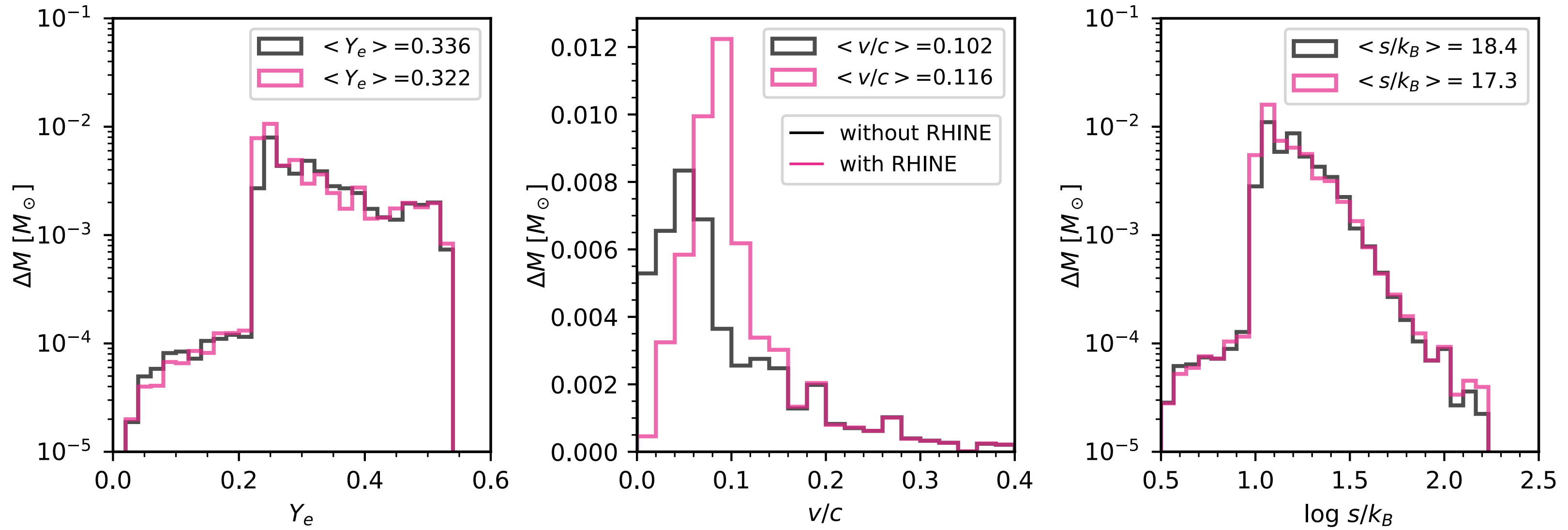


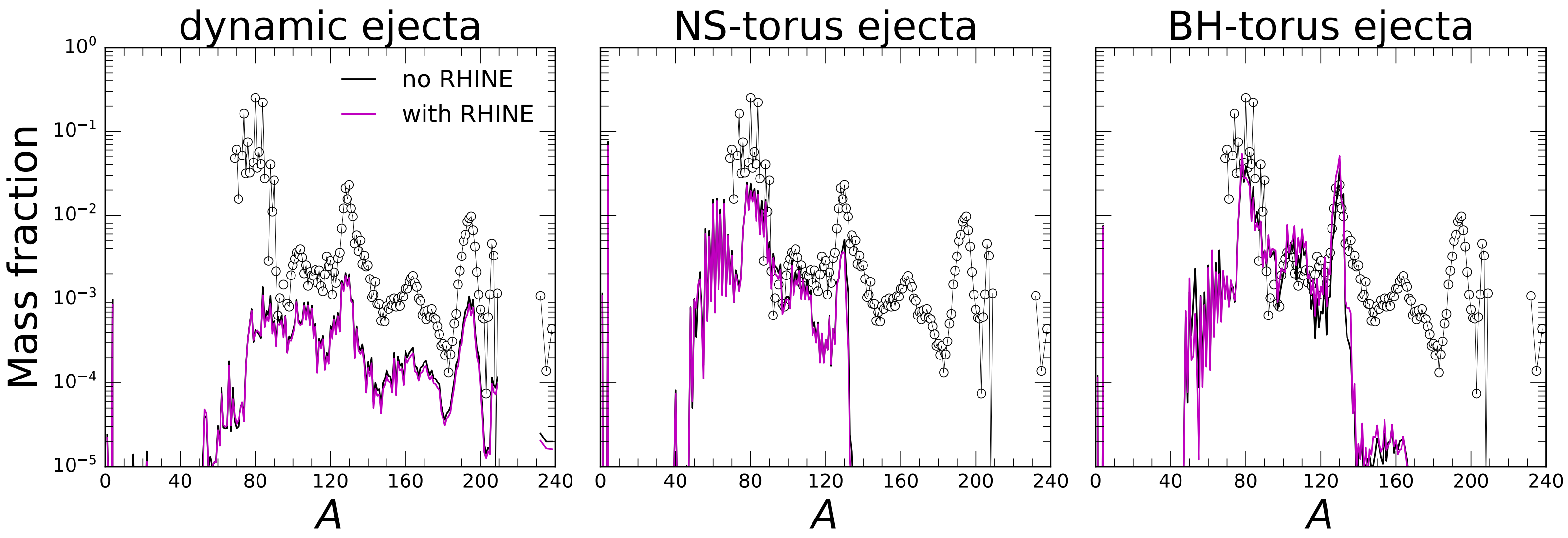
with RHINE:



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

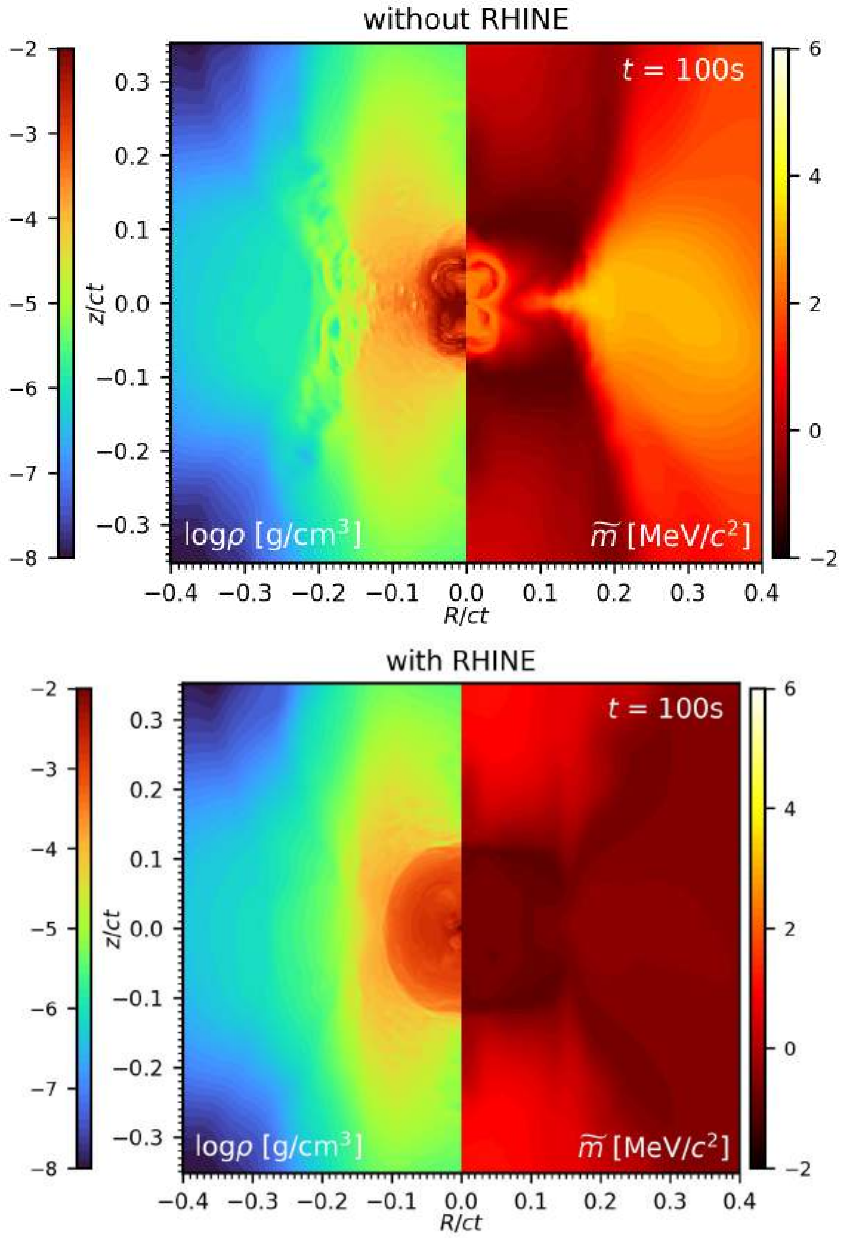
NS merger models + RHINE

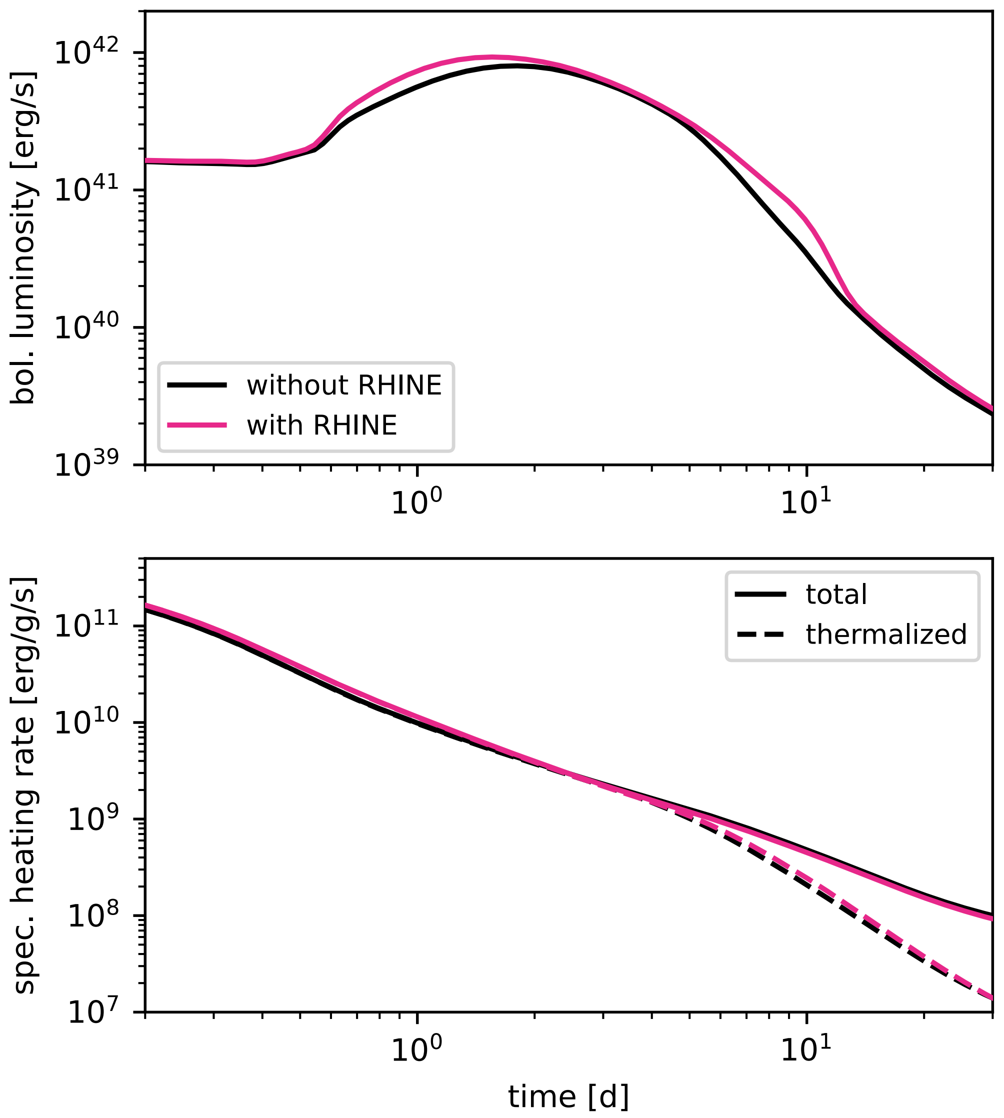




- relatively small impact on nucleosynthesis yields

Impact on kilonova light curve



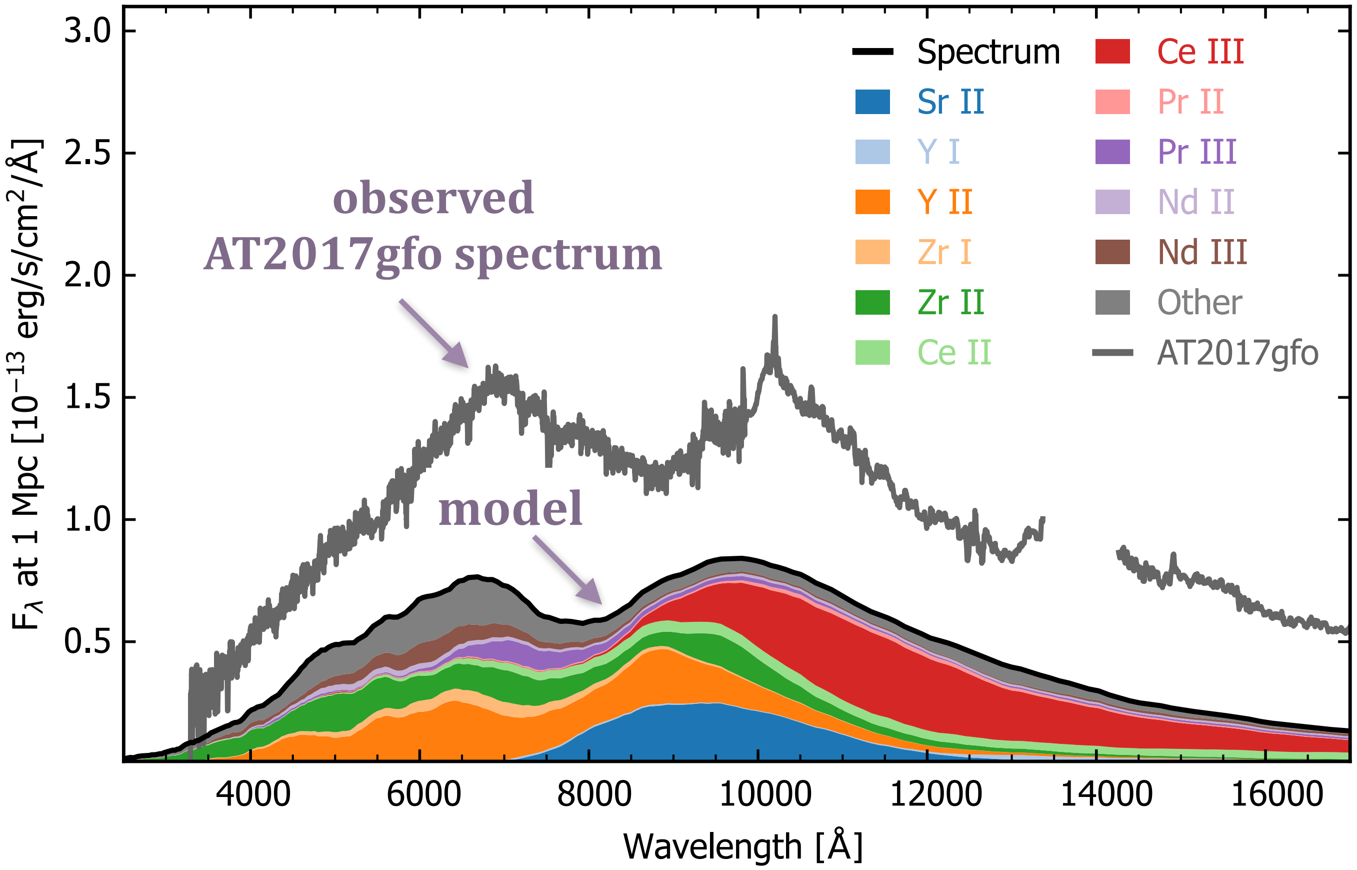


The Astrophysical Journal Letters, 954:L41 (11pp), 2023 September 10 https://doi.org/10.3847/2041-8213/acf29a

Self-consistent 3D Radiative Transfer for Kilonovae: Directional Spectra from Merger Simulations

Luke J. Shingles[1], Christine E. Collins[1], Vimal Vijayan[1,2], Andreas Flörs[1], Oliver Just[1,3], Gerrit Leck[1,4], Zewei Xiong[1], Andreas Bauswein[1], Gabriel Martínez-Pinedo[1,4], and Stuart A. Sim[5]

Step towards more accurate kilonova radiative transfer modeling



- 3D Monte-Carlo radiative transfer code ARTIS
- early photospheric epoch (~few days)
- main spectral feature from Sr (Z=38)
- spectra remarkably similar to AT2017gfo

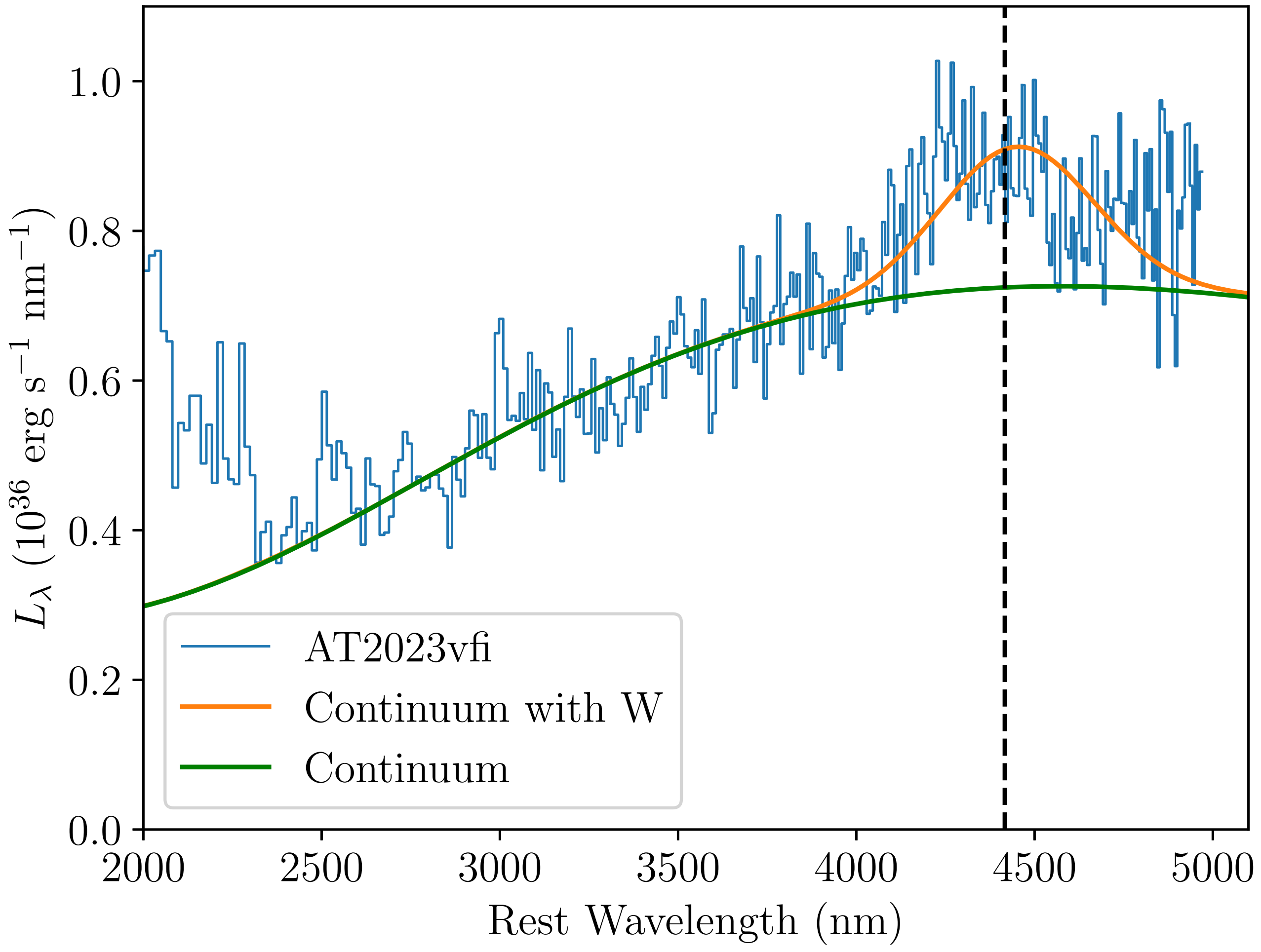
MNRAS **538,** 537–552 (2025)
Advance Access publication 2025 February 14
https://doi.org/10.1093/mnras/staf283

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

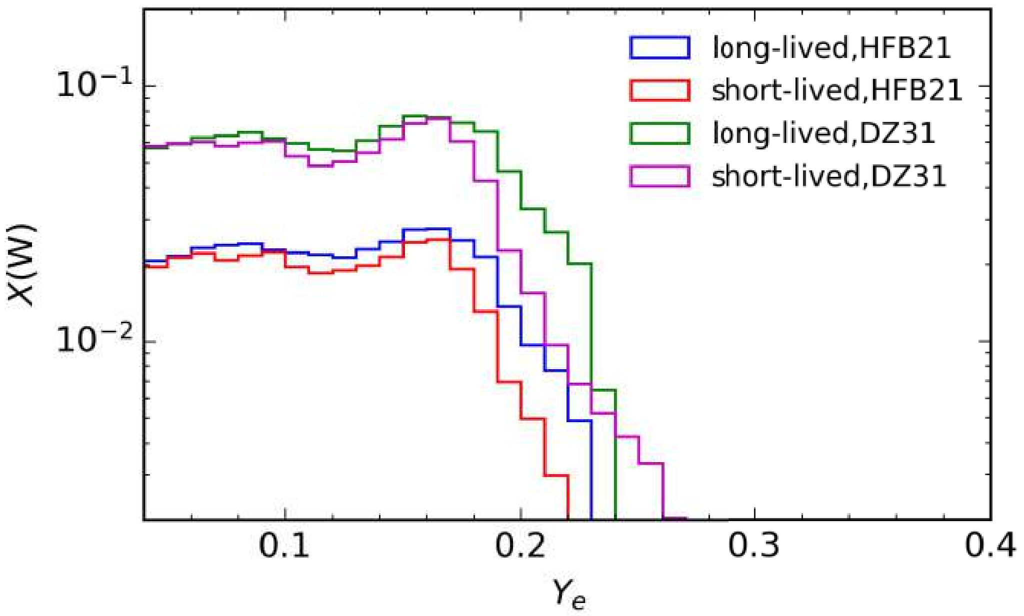
M. McCann ,[1★] L. P. Mulholland ,[1] Z. Xiong ,[2] C. A. Ramsbottom ,[1] C. P. Ballance ,[1] O. Just ,[2,3] A. Bauswein ,[2,4] G. Martínez-Pinedo ,[2,5,4] F. McNeill [1] and S. A. Sim [1]

Motivation

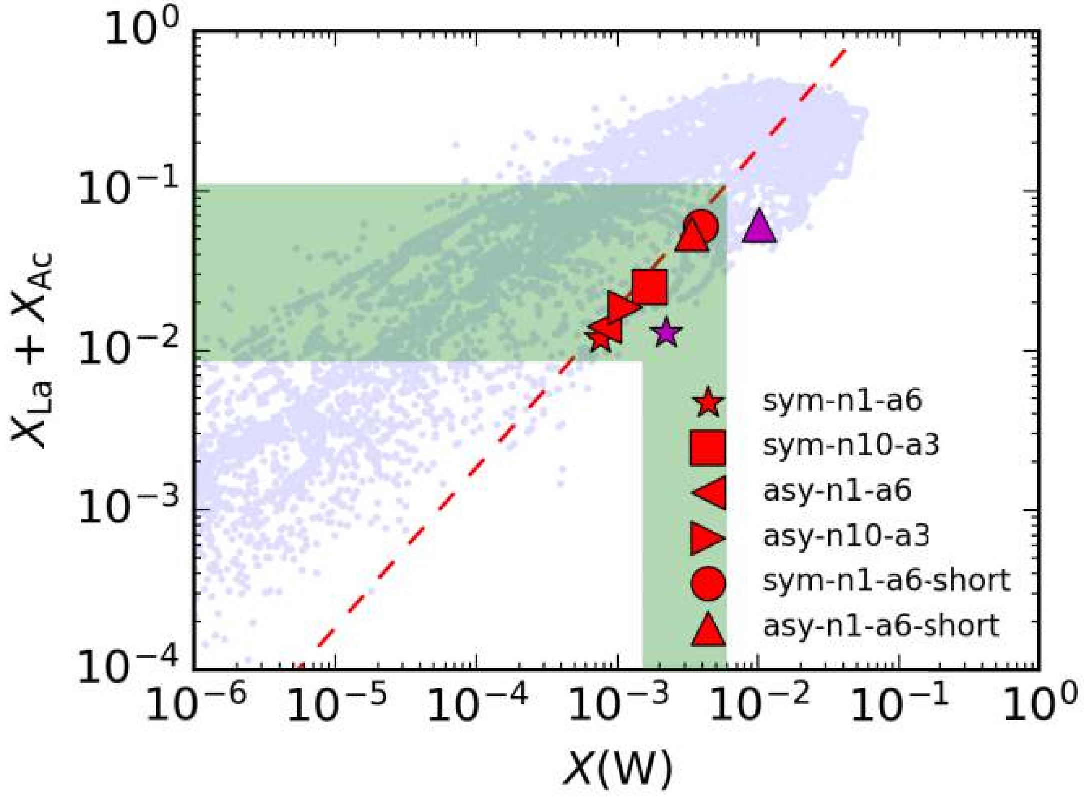
- late, nebular epoch: LTE -> NLTE
- sensitive to poorly known detailed atomic properties (excitation, recombination, ...)
- new atomic data for W (tungsten, Z=74)
- **tentative candidate** to explain 4.5 micron bump in late spectrum of long-GRB kilonova AT2023vfi
- estimated mass: 9.4 x 10^-4 Msun



Implications
(if feature produced by W)



- W only produced for neutron-rich conditions -> proxy for low-Ye material

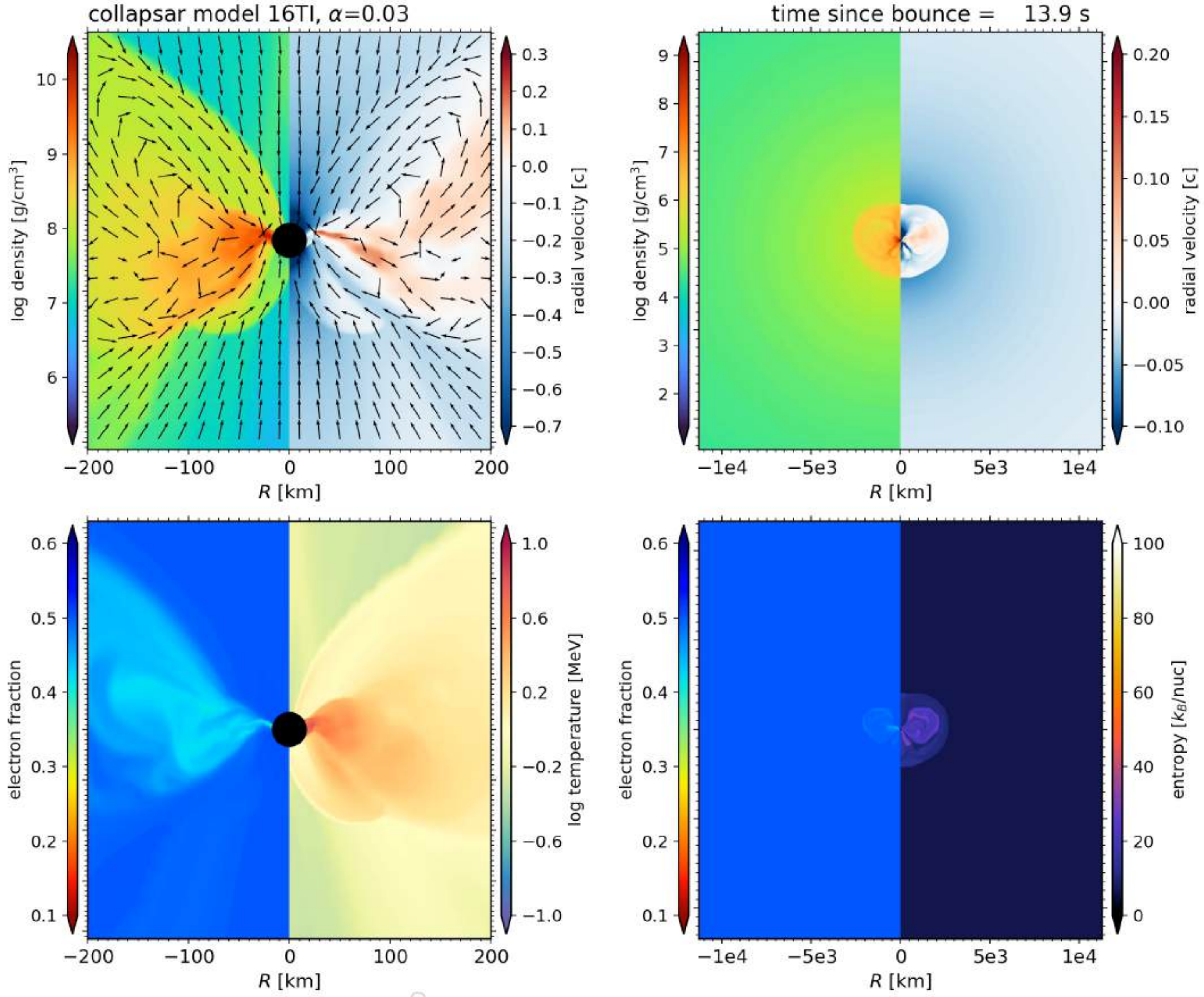


- symbols denote different merger simulations
- correlation between W and lanthanides allows estimate on lanthanide fraction

R-process viable outflows are suppressed in global alpha-viscosity models of collapsar disks

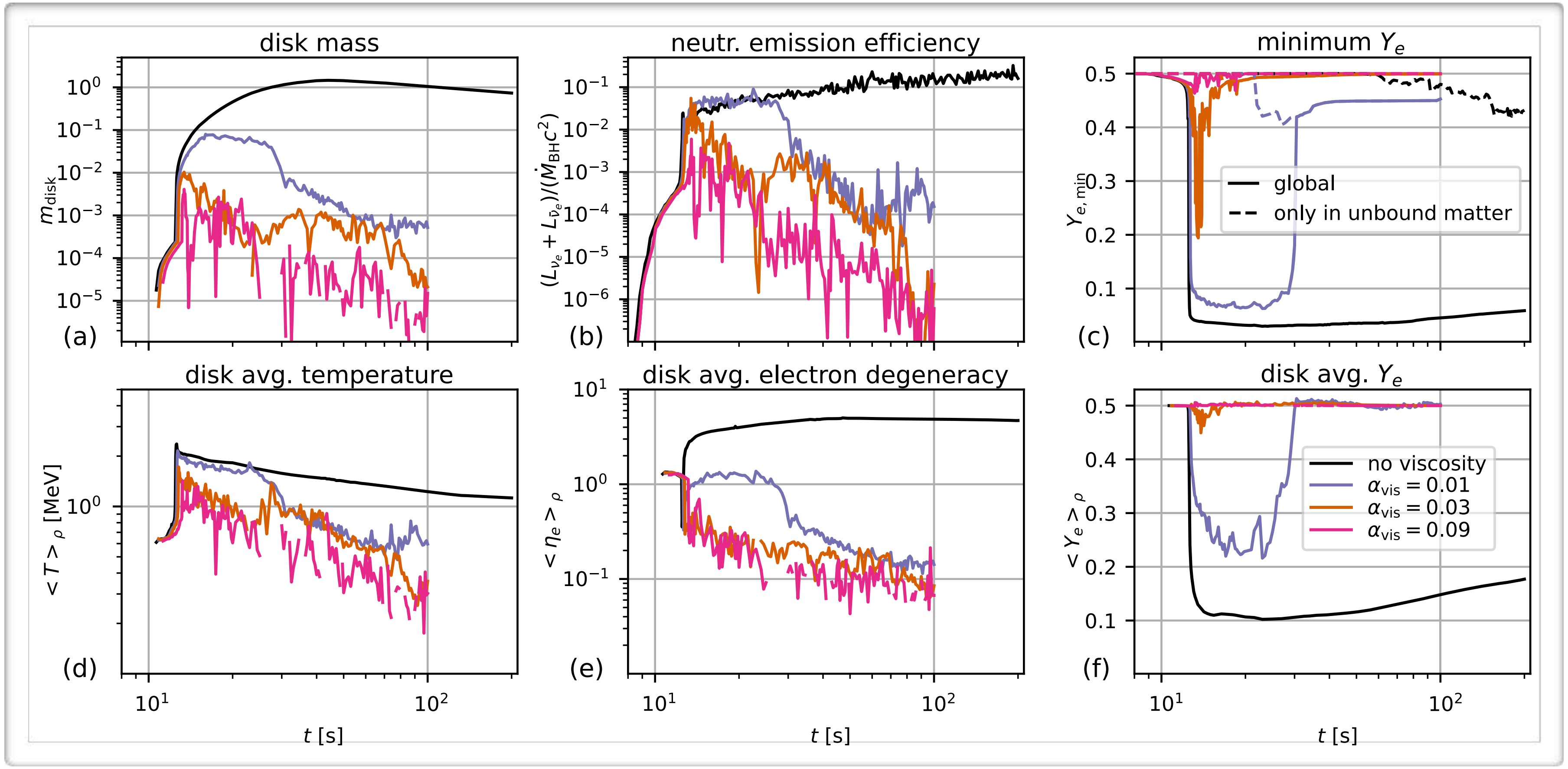
(OJ, M. Aloy, M. Obergaulinger, S. Nagataki, ApJL 934, 2022)

Collapsars as r-process sites?



Collapsars as r-process sites?

- 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:
  - approximate GR, MHD
  - **no flavor oscillations**



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

Summary

- Long-term modeling crucial for ejecta nucleosynthesis and kilonova signal
- FFC tends to make disks and outflow more neutron-rich and closer to solar distribution
- New potential EOS constraint from helium signature in kilonova spectrum
- Hydro-Implementation of r-process heating by direct coupling of hydro with machine learning models
- Late-time KN emission features may provide mass of r-process elements
- Still significant modeling uncertainties…