

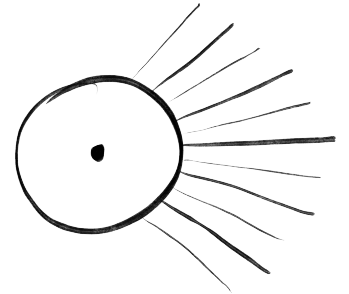


End-to-end modeling of NS mergers: Recent progress



Oliver Just
GSI Helmholtzzentrum Darmstadt

HeavyMetal Meeting Kinlochard June 8th, 2026

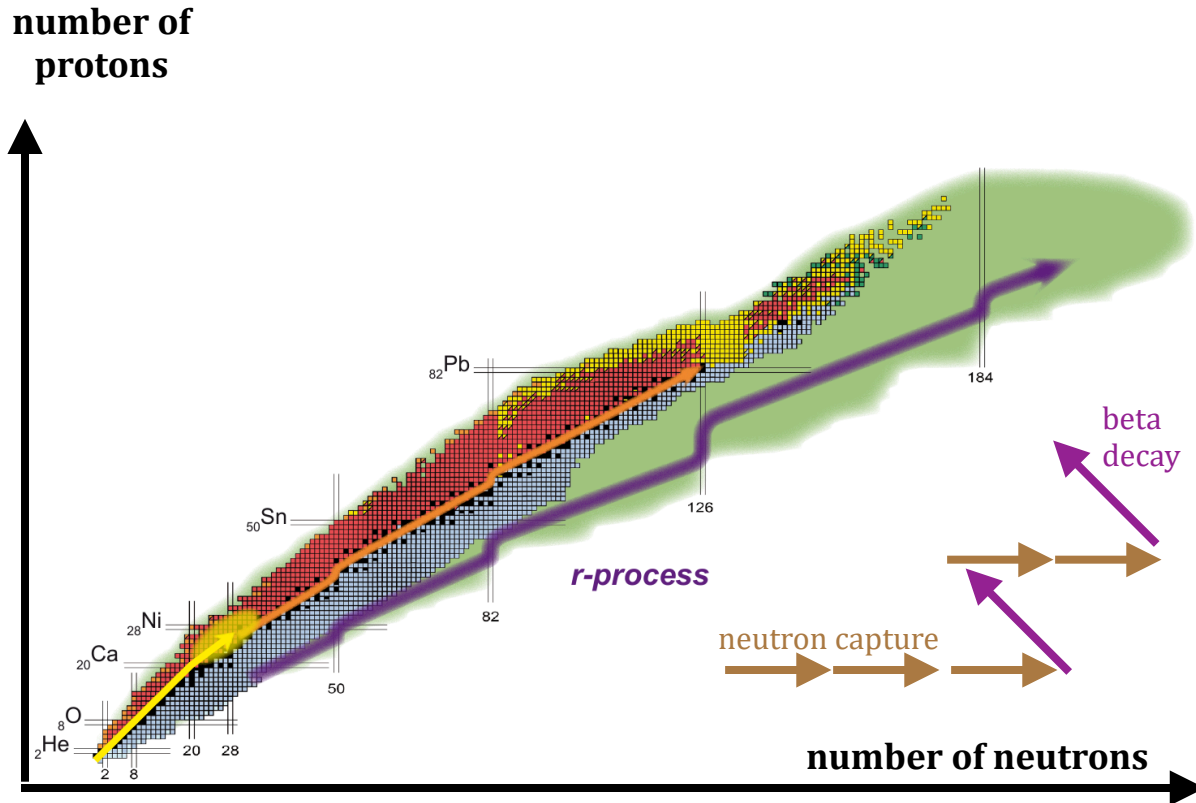


ERC synergy
HeavyMetal

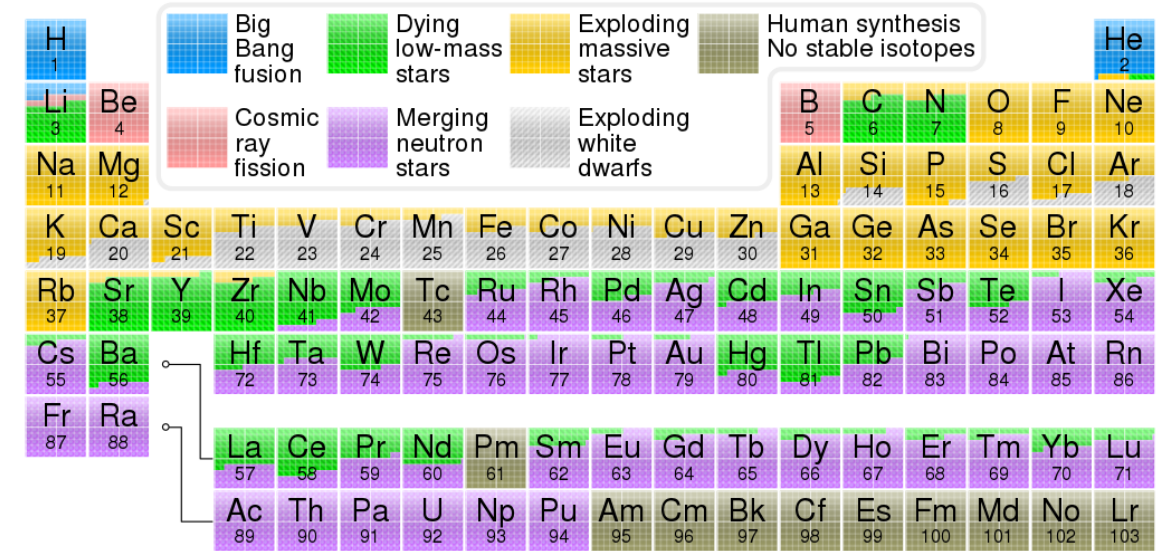


European Research Council
Established by the European Commission

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

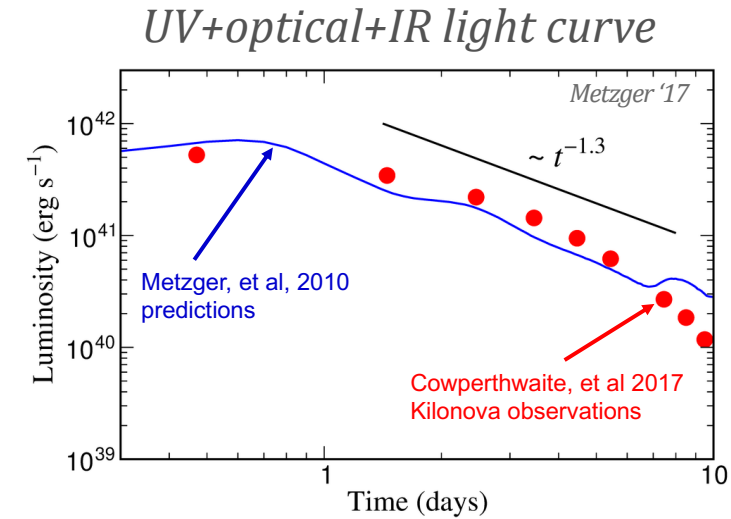
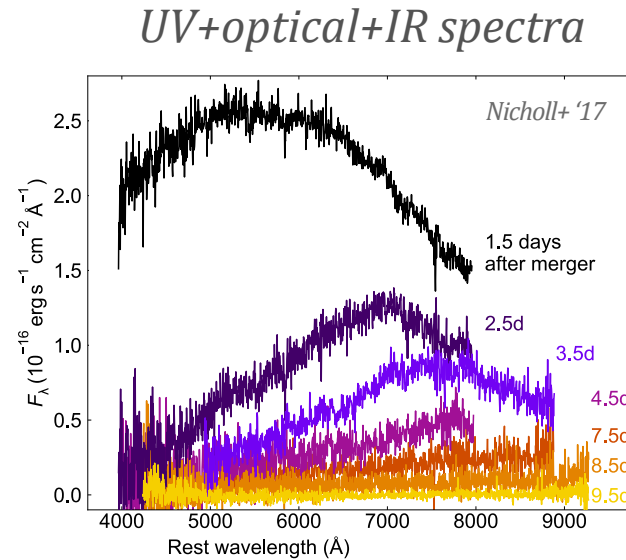
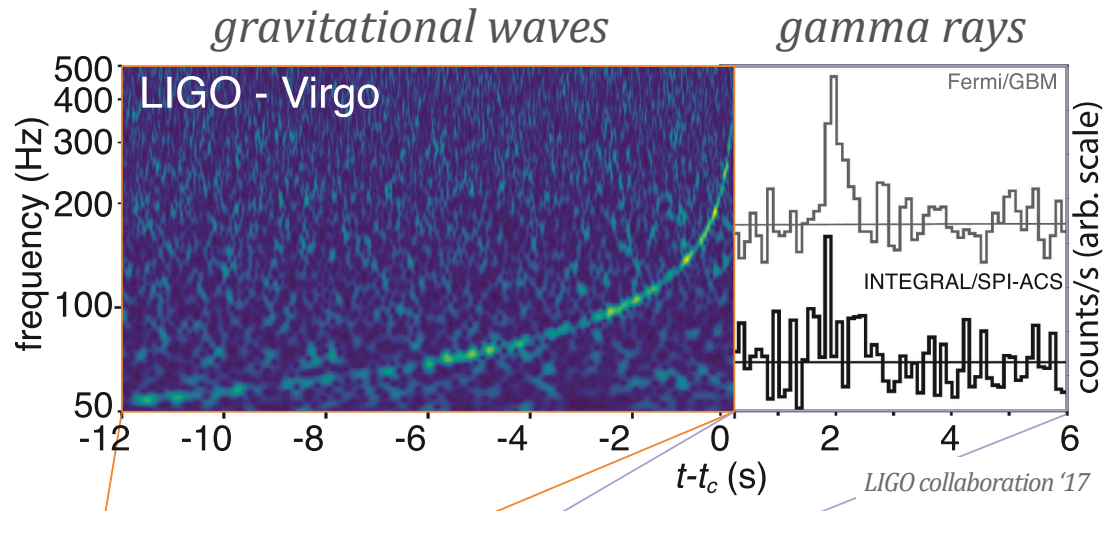
$$Y_e = \frac{n_{\text{proton}}}{n_{\text{neutron}} + n_{\text{proton}}} \stackrel{!}{<} 0.5$$

–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**

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?
- ▶ ...

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

Neutron-star mergers

inspiral

timescales:

~ 100 Myrs

merger

~ 10 ms

post-merger
evolution

prompt
collapse

delayed
collapse

~ 0.1 -100 s

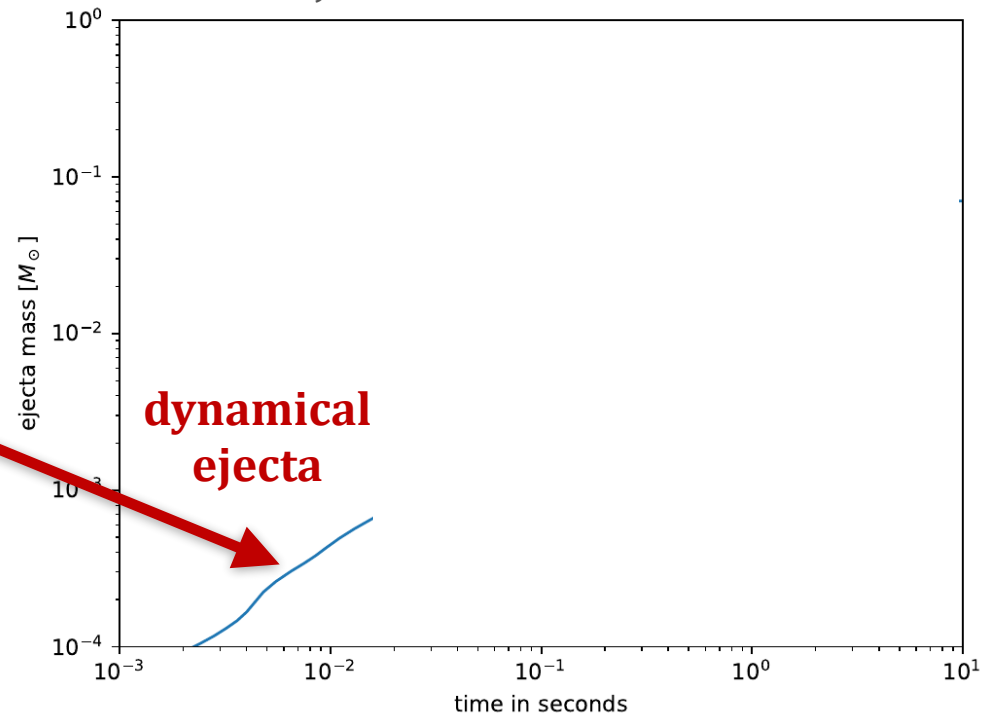
black hole –
torus system

(hyper-) massive
neutron star

ejecta
nucleosynthesis
& kilonova

$\sim$ secs - days

ejecta mass vs. time



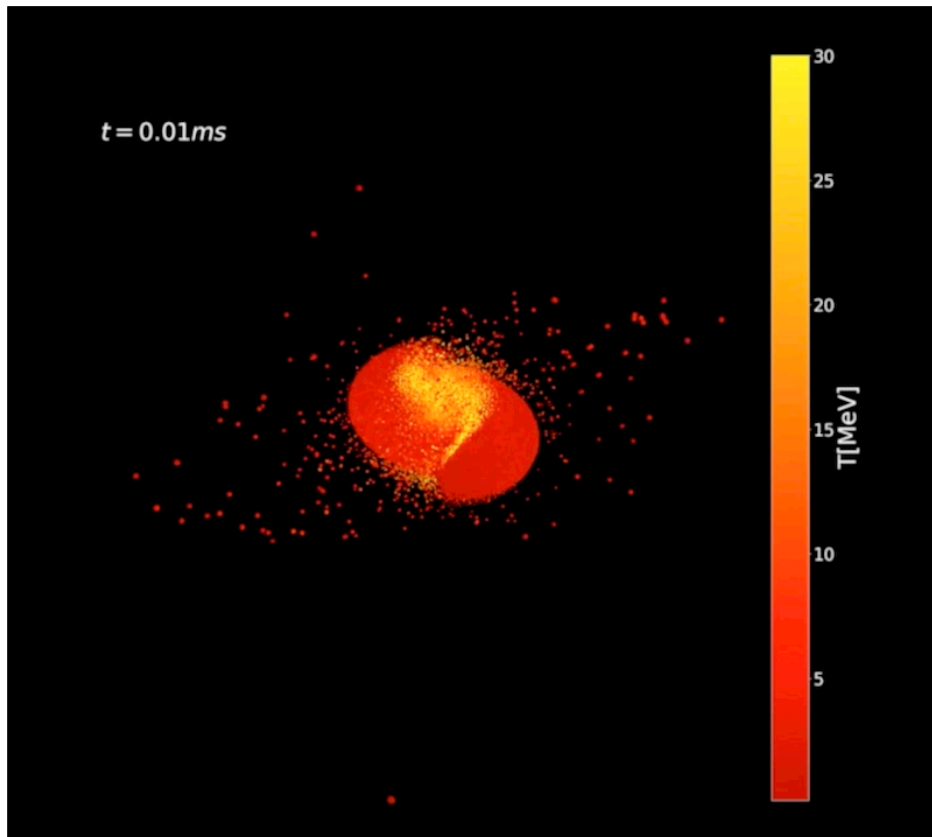
Neutron-star mergers

timescales:

inspiral

merger

post-merger
evolution



simulation by V. Vijayan

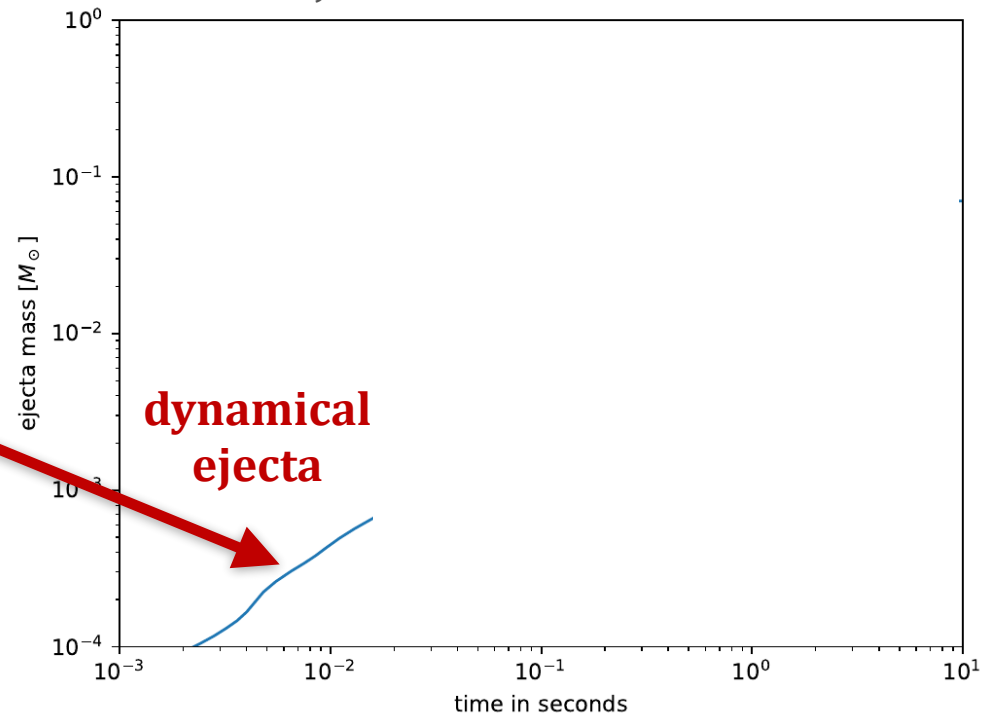
0 Myrs

0 ms

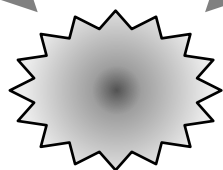
1-100 s

~ secs - days

ejecta mass vs. time



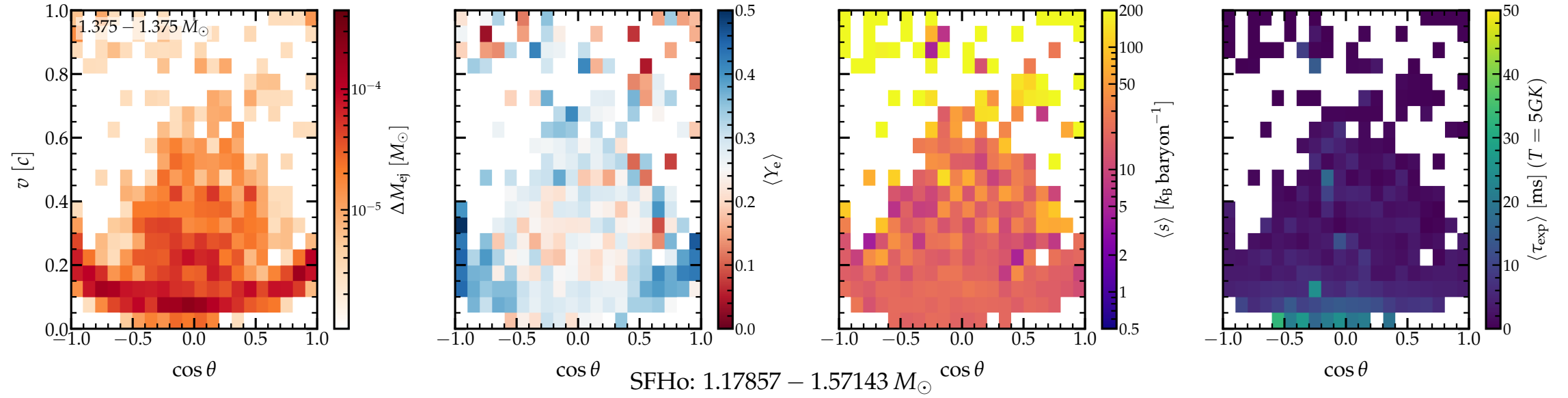
ejecta
nucleosynthesis
& kilonova



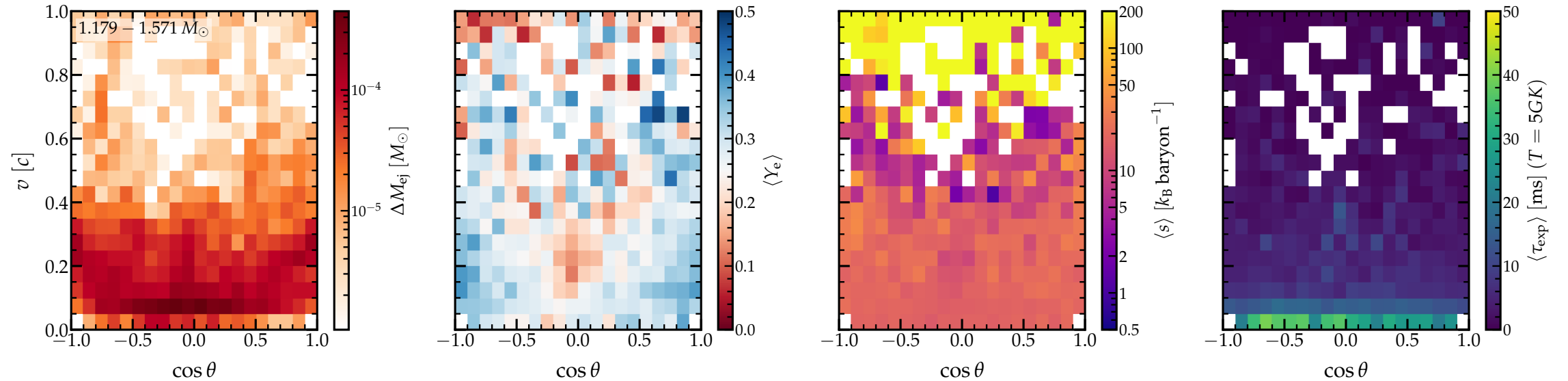
Dynamical ejecta

(Kullmann+22, Vijayan+26 in prep.)

SFHo: $1.375 - 1.375 M_{\odot}$

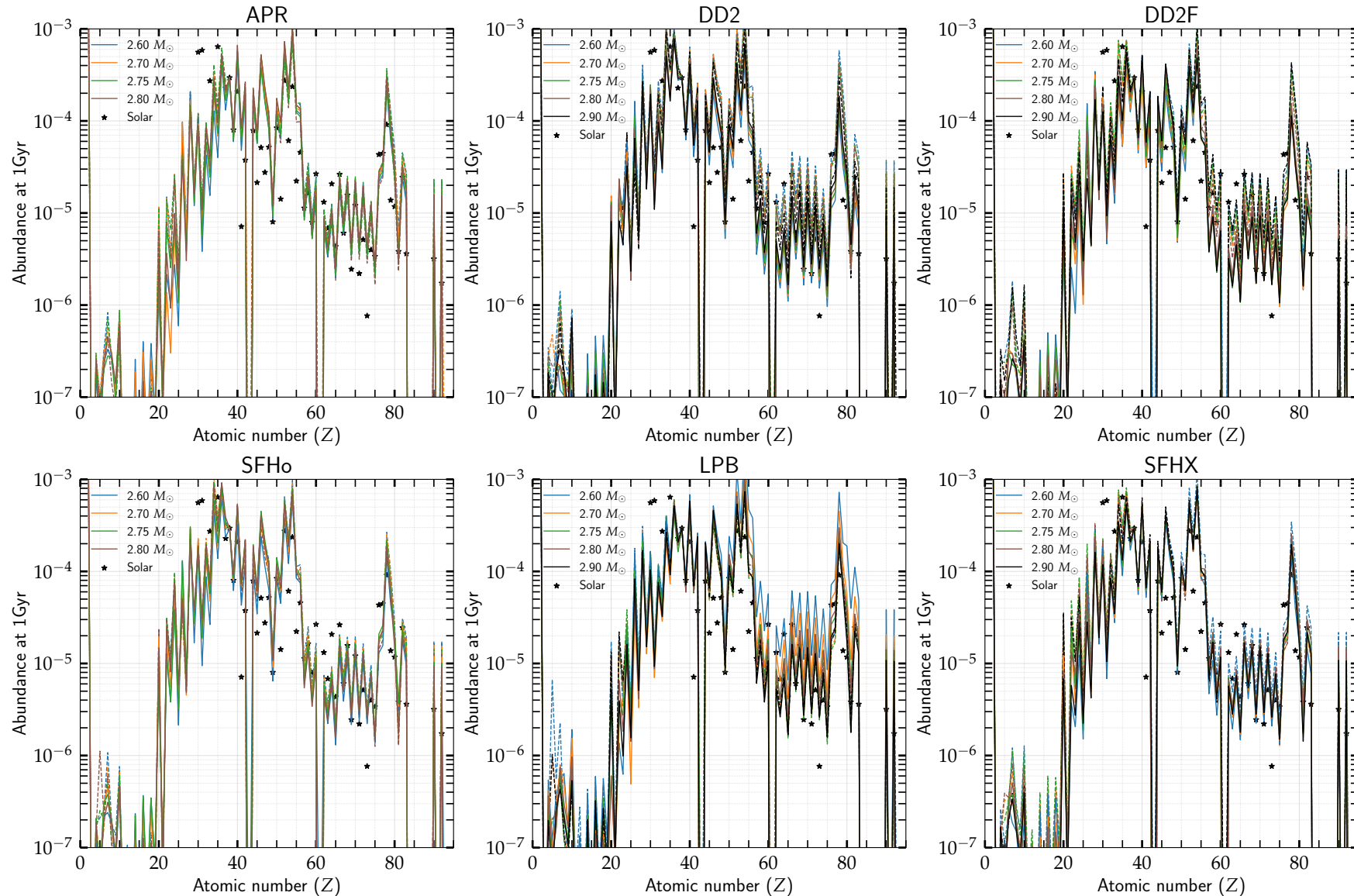


SFHo: $1.17857 - 1.57143 M_{\odot}$



Dynamical ejecta

(Vijayan et al., in prep)



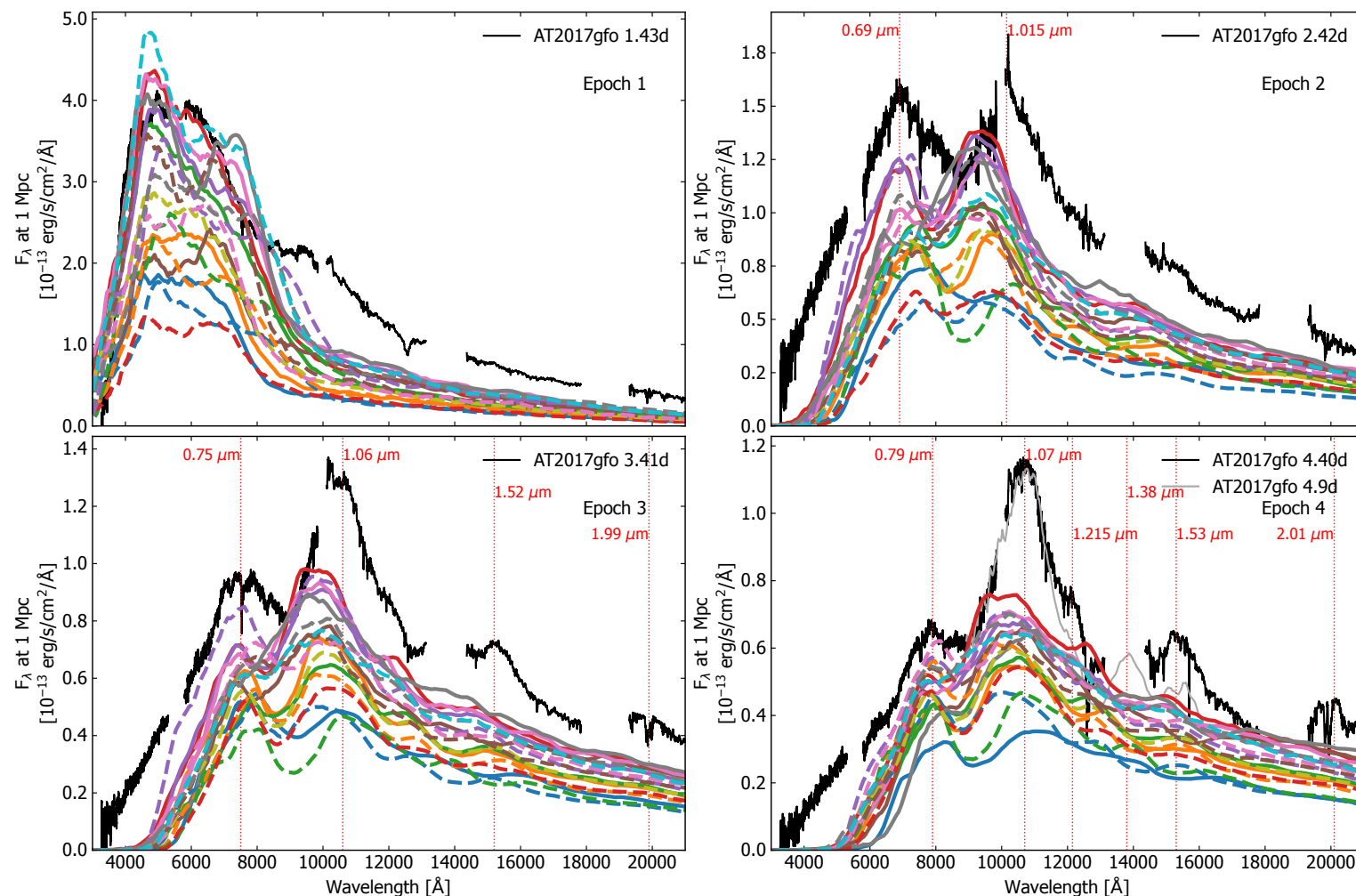
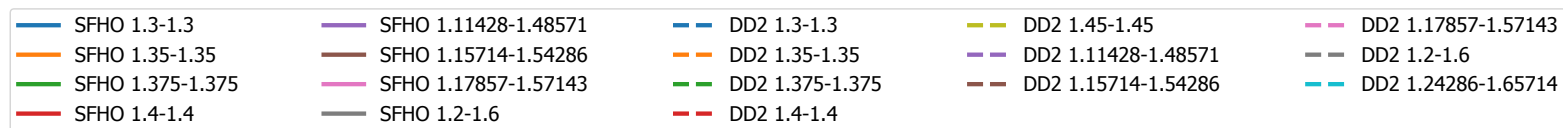
► relatively small sensitivity to EOS and binary masses

see Vimal's talk

Kilonova spectrum of dynamical ejecta

(Collins+2026)

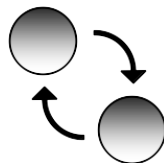
see Stuart's talk (?)



- ▶ main spectral features reproduced in most models
- ▶ however, only dynamical ejecta so far...i.e. models are incomplete
- ▶ how to reproduce BOTH spectrum and light curve of GW170817?

Neutron-star mergers

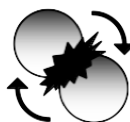
inspiral



timescales:

~100 Myrs

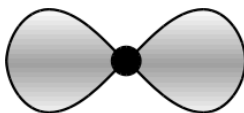
merger



~10 ms

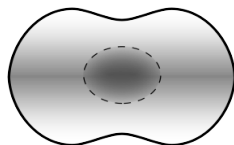
post-merger
evolution

prompt
collapse



black hole -
torus system

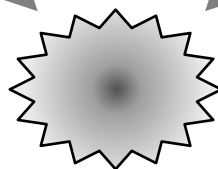
delayed
collapse



(hyper-) massive
neutron star

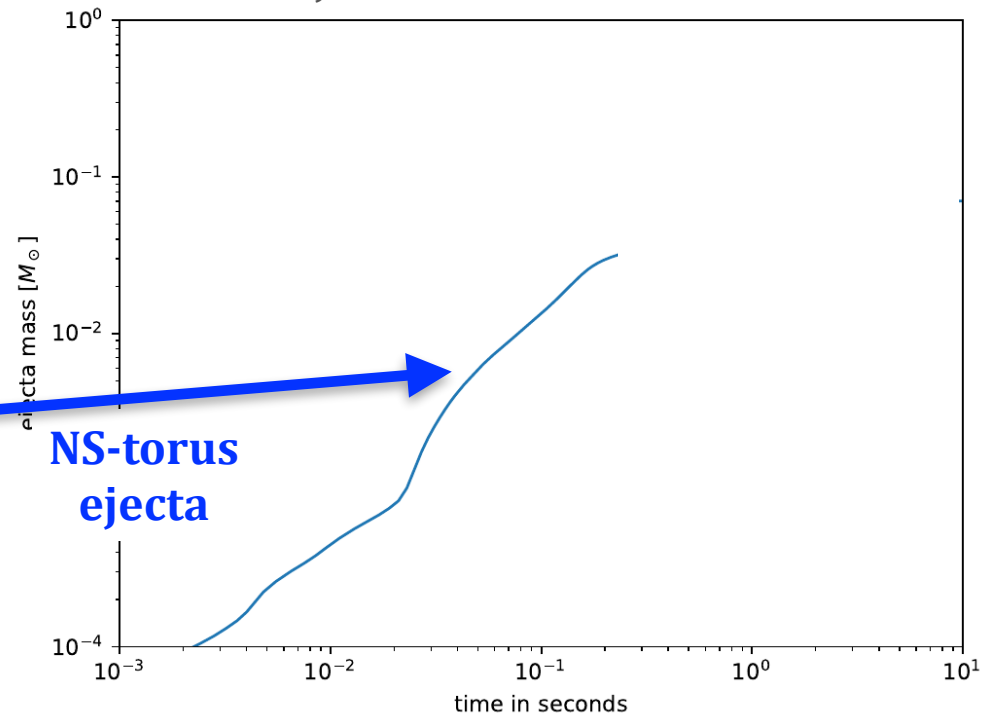
~0.1-100 s

ejecta
nucleosynthesis
& kilonova



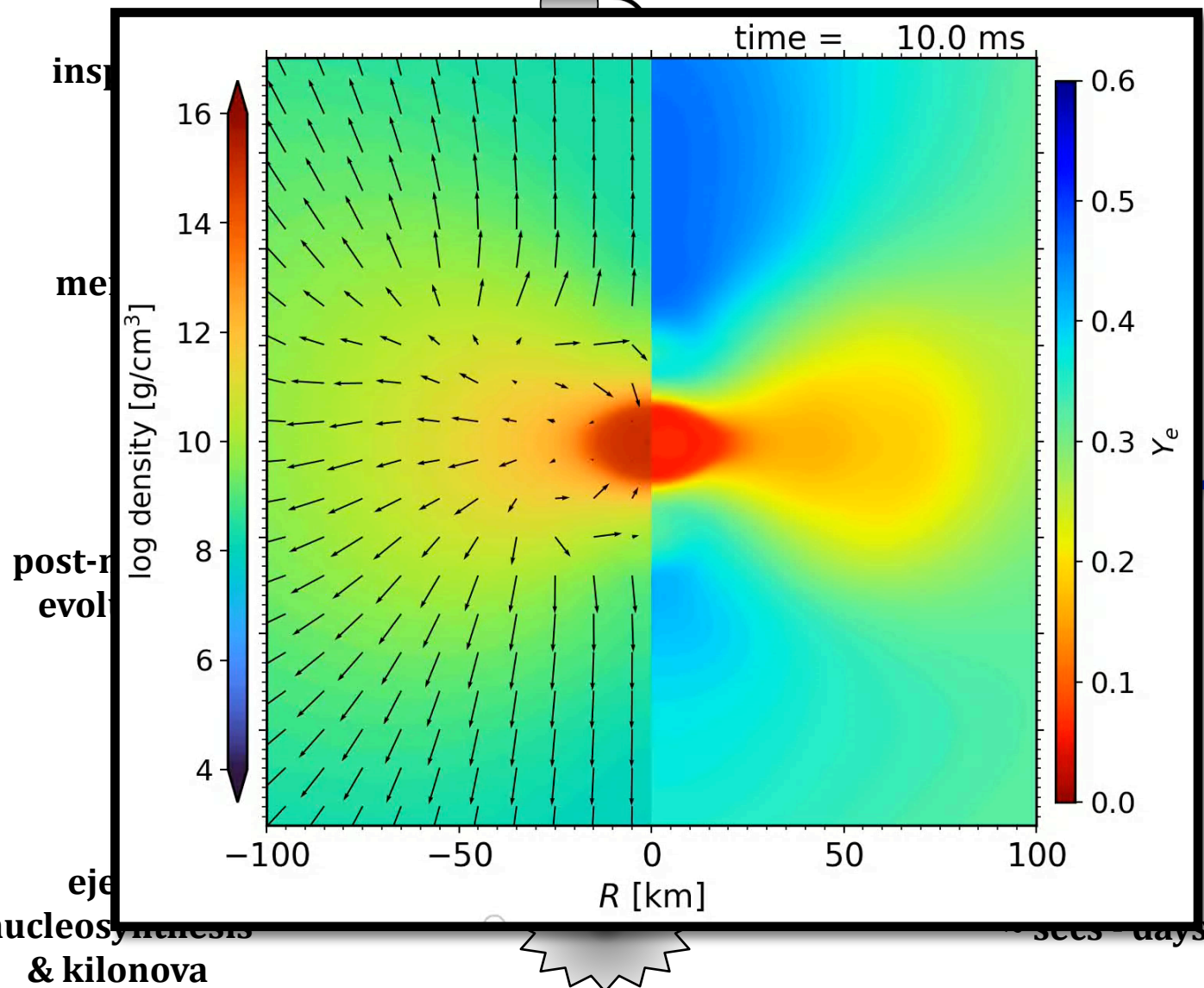
~ secs - days

ejecta mass vs. time

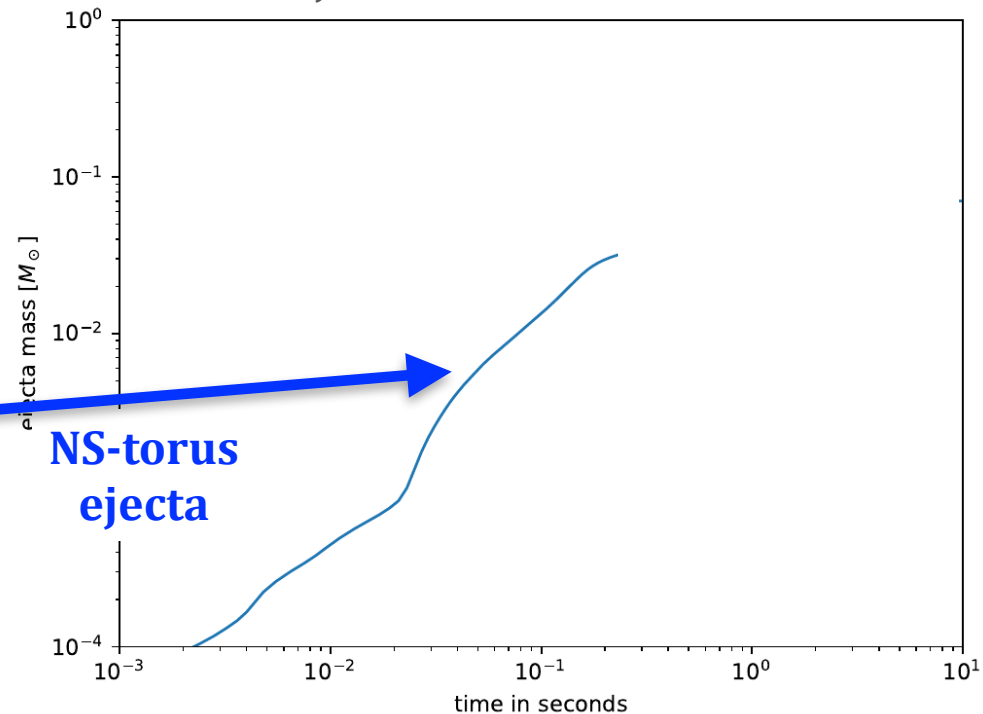


Neutron-star mergers

timescales:



ejecta mass vs. time



Neutron-star mergers

inspiral

timescales:

~100 Myrs

merger

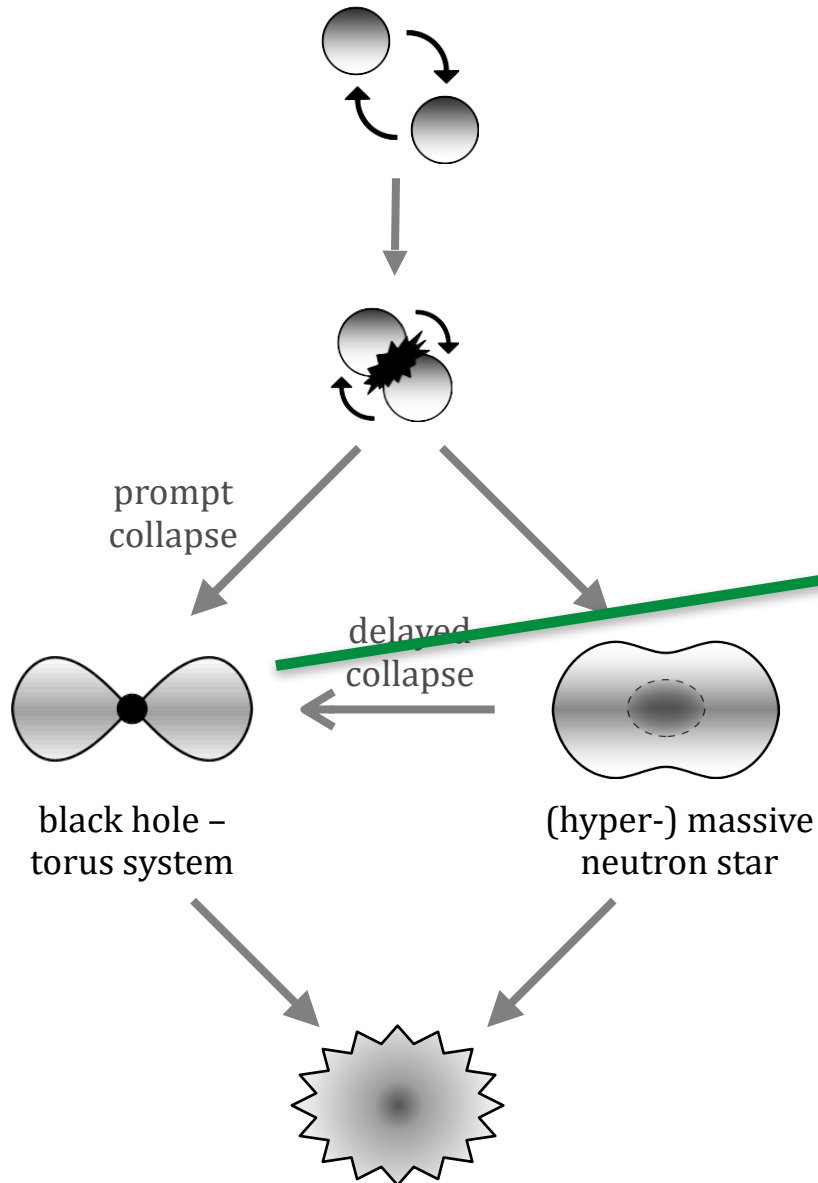
~10 ms

post-merger
evolution

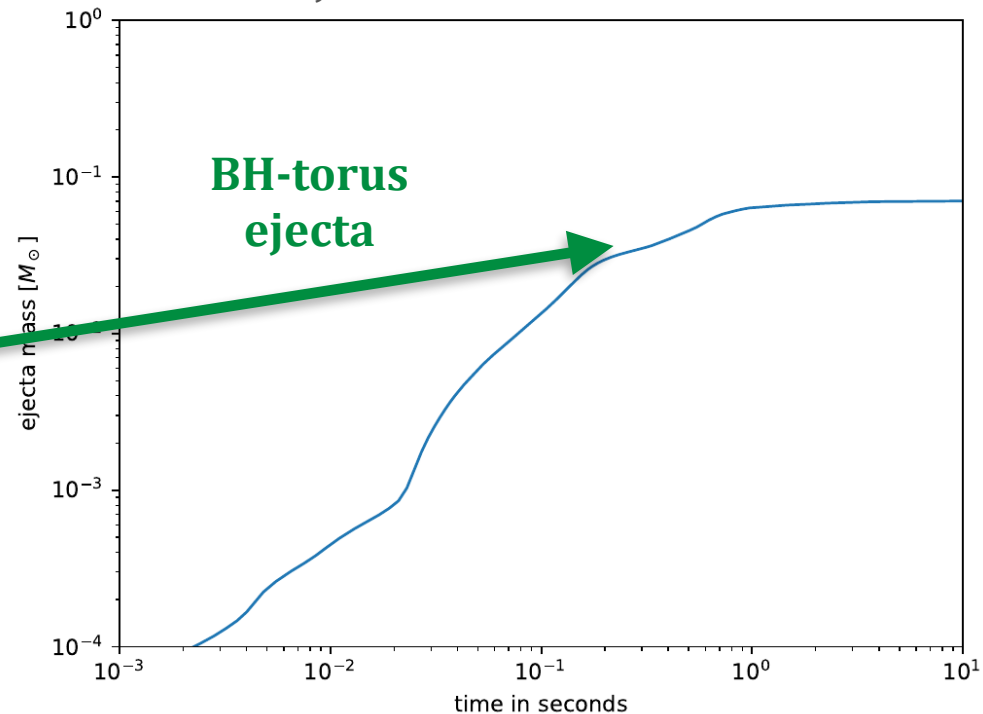
~0.1-100 s

ejecta
nucleosynthesis
& kilonova

~ secs - days

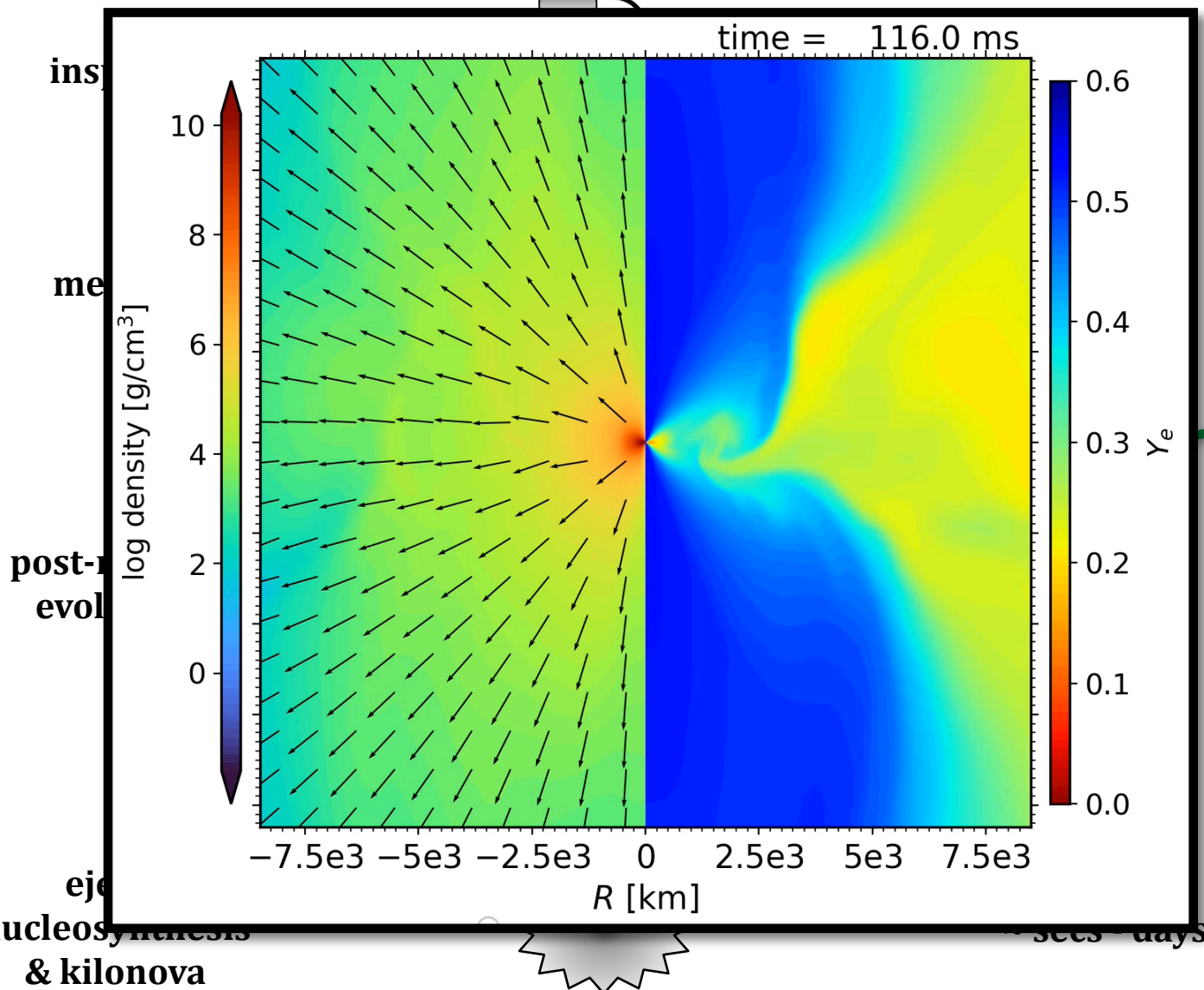


ejecta mass vs. time

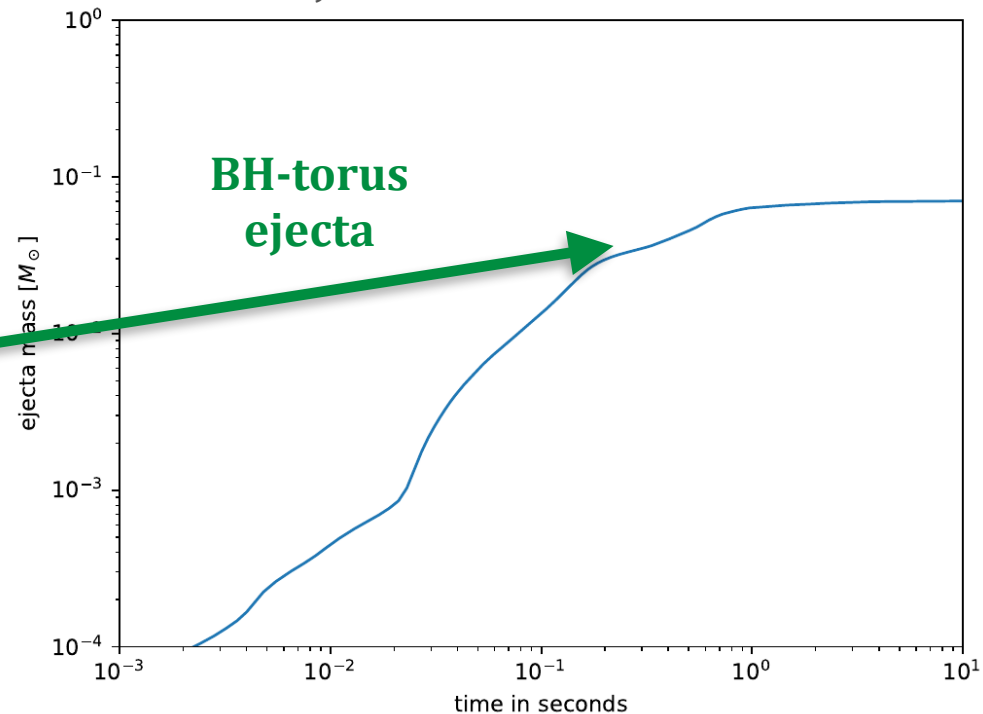


Neutron-star mergers

timescales:

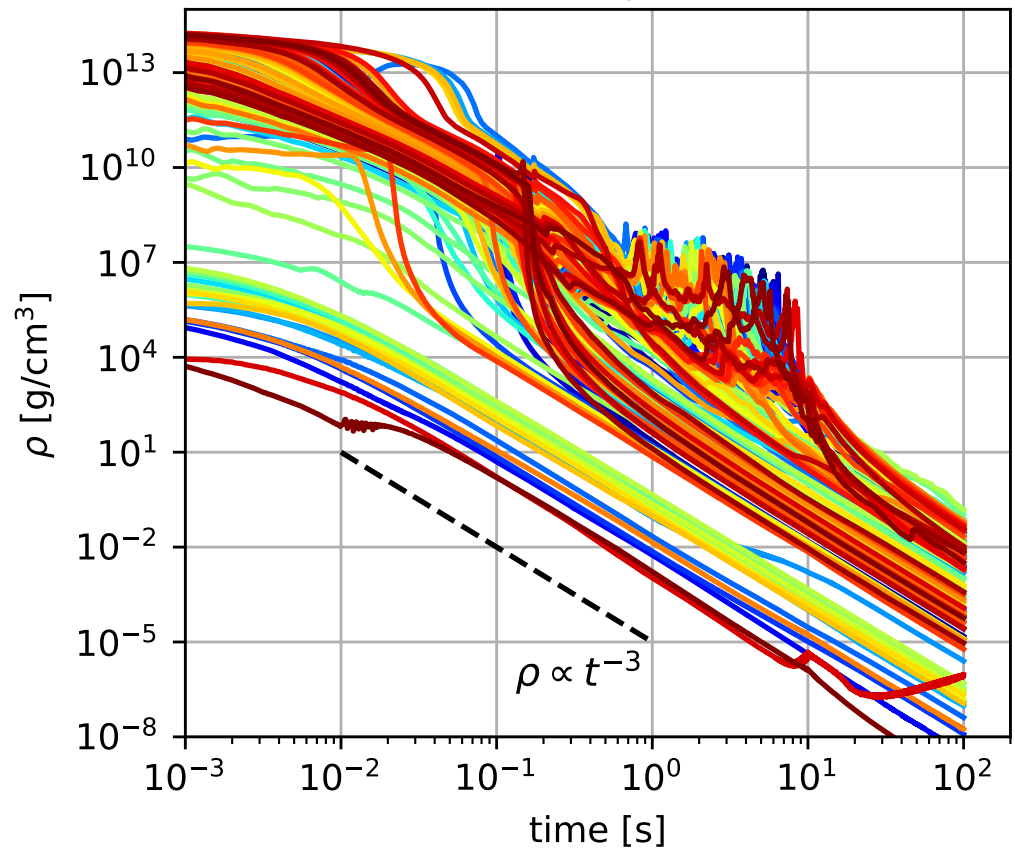


ejecta mass vs. time

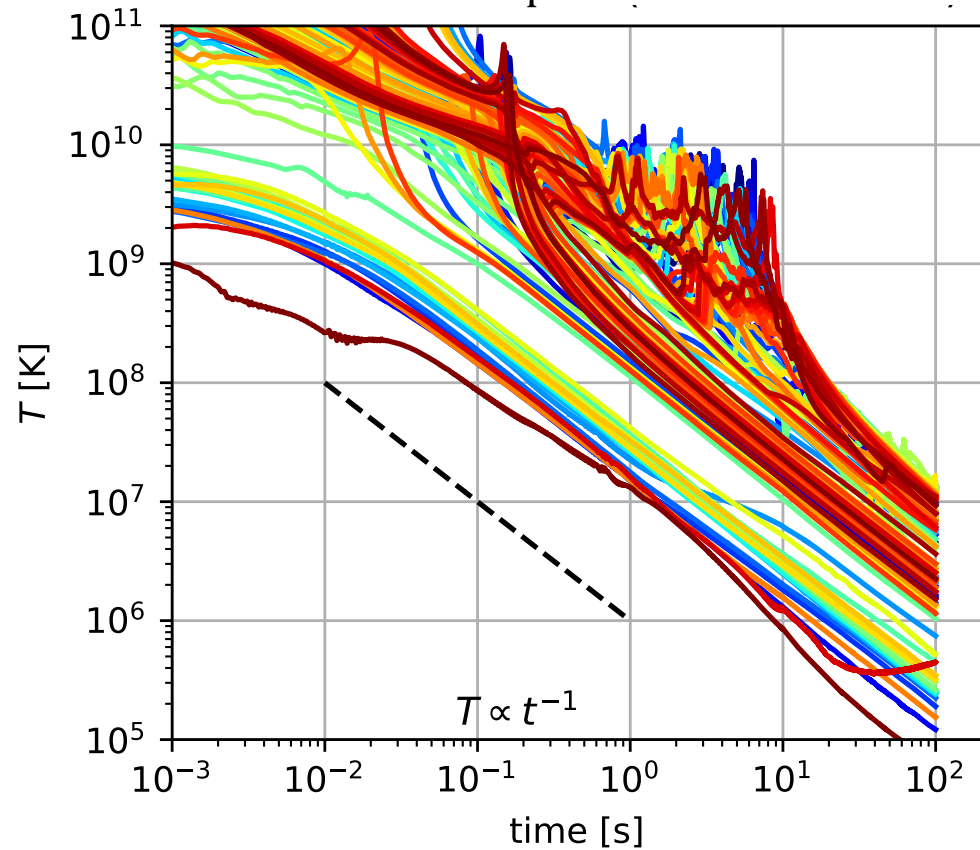


Long-term evolution until homologous expansion

density



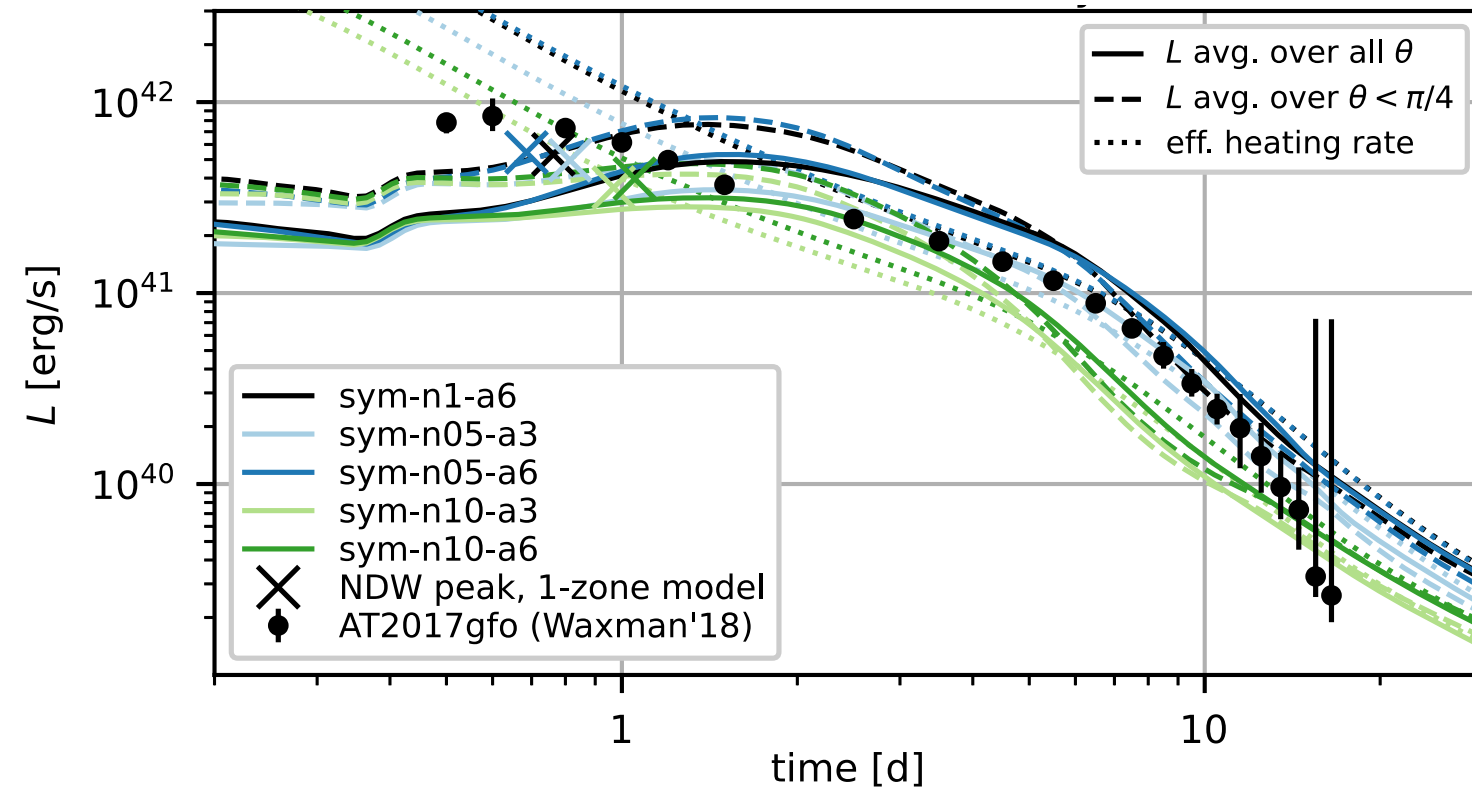
temperature



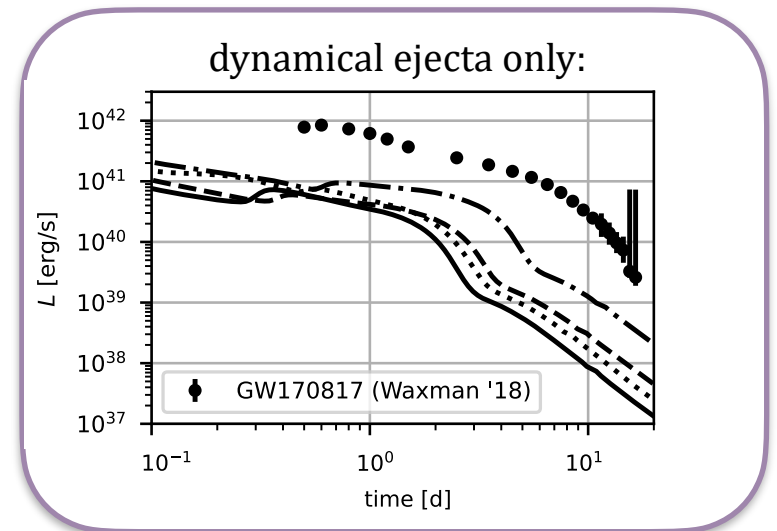
► almost all outflow homologous after ~ 10 -100s

Kilonova bolometric light curve

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

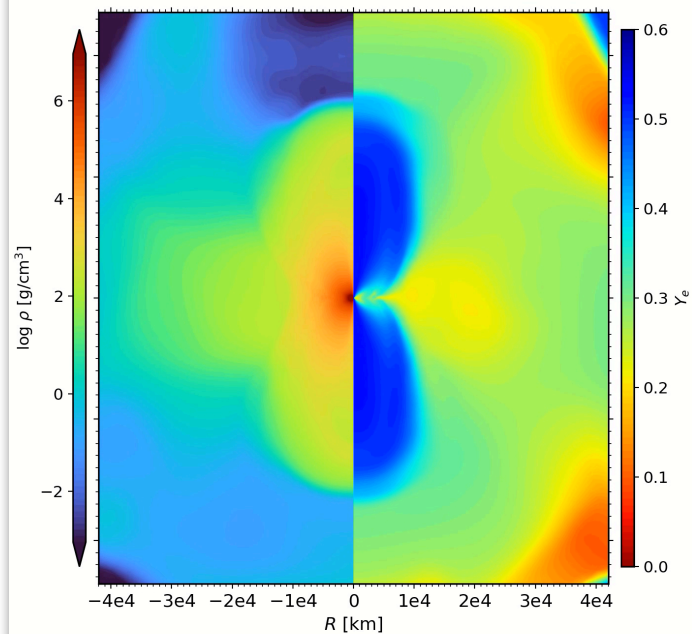
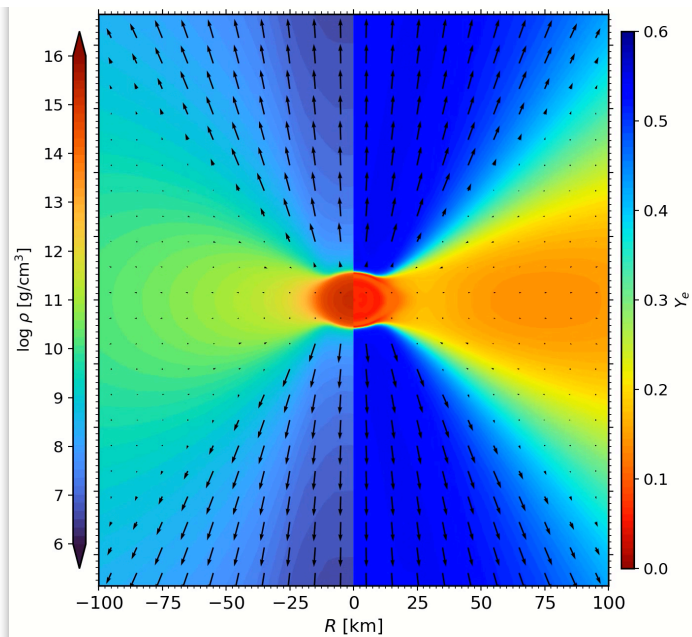


- ▶ approximate M1 photon transfer
- ▶ good agreement with GW170817
- ▶ supports idea that GW170817 was a delayed-collapse scenario with massive post-merger ejecta



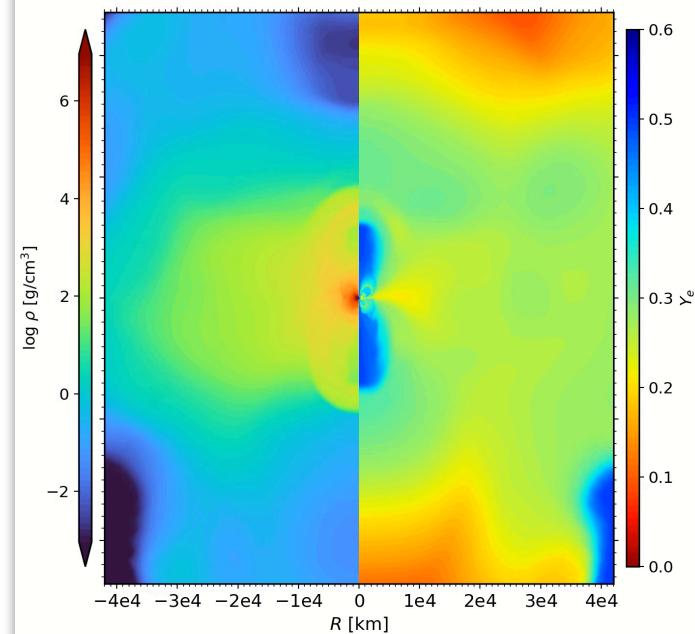
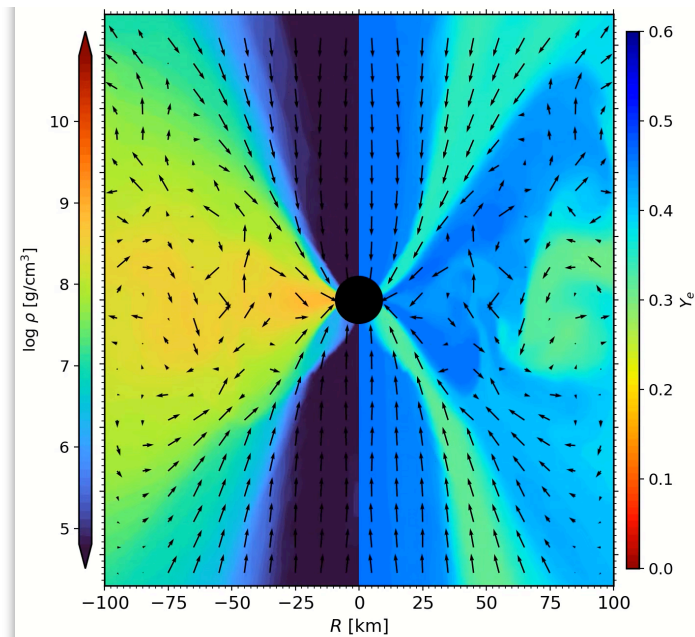
(see also Kawaguchi+21,22, Bernuzzi+24, Sippens-Groenewegen+25, ...)

long-lived HMNS



time = 206.0 ms

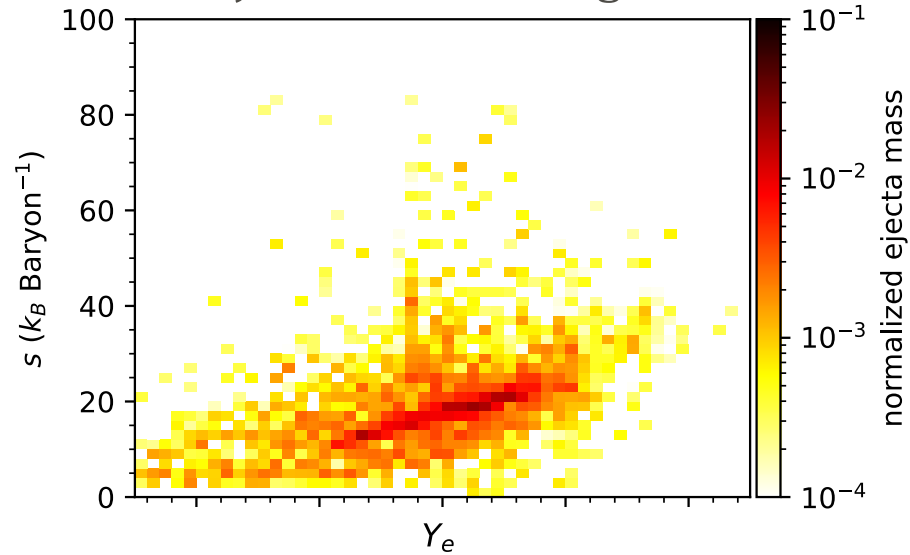
short-lived HMNS



time = 206.0 ms

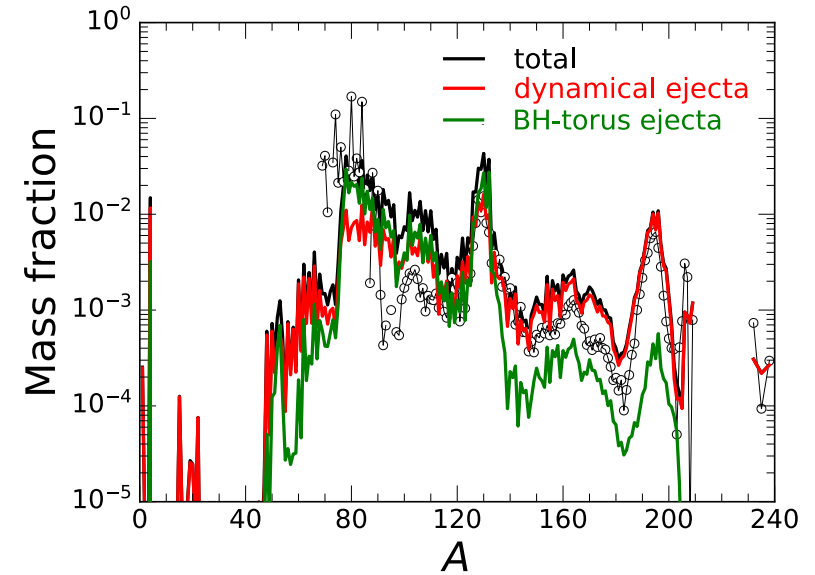
Short- vs. long-lived NS remnant

ejecta mass histogram



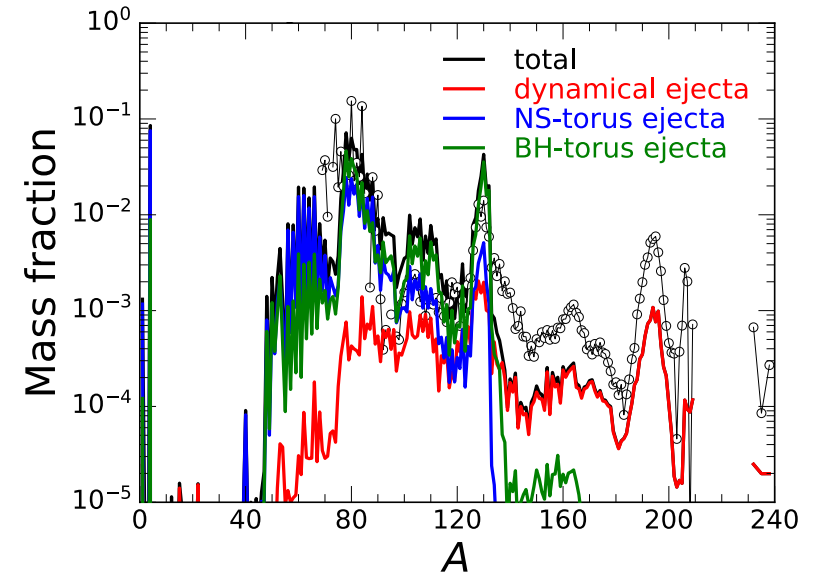
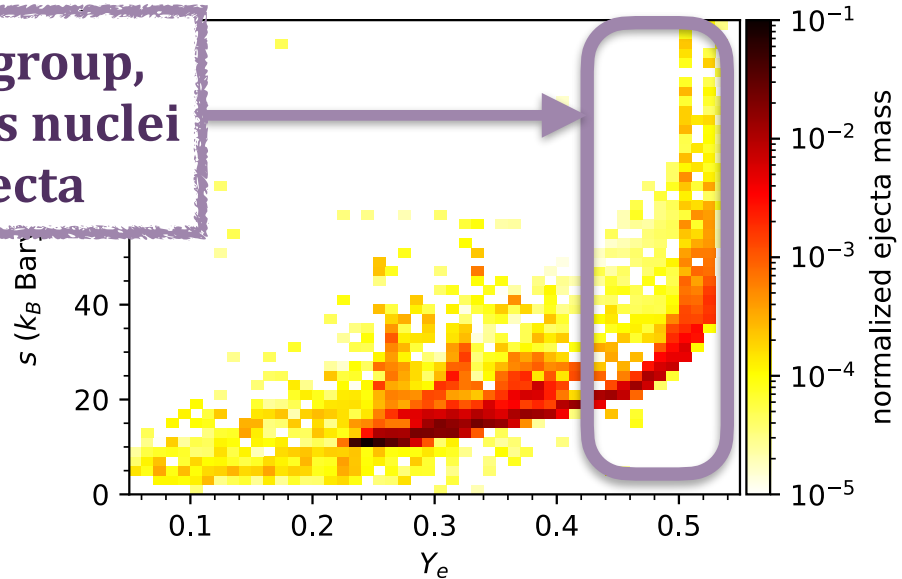
short-lived
(10ms)

ejecta nucleosynthesis yields



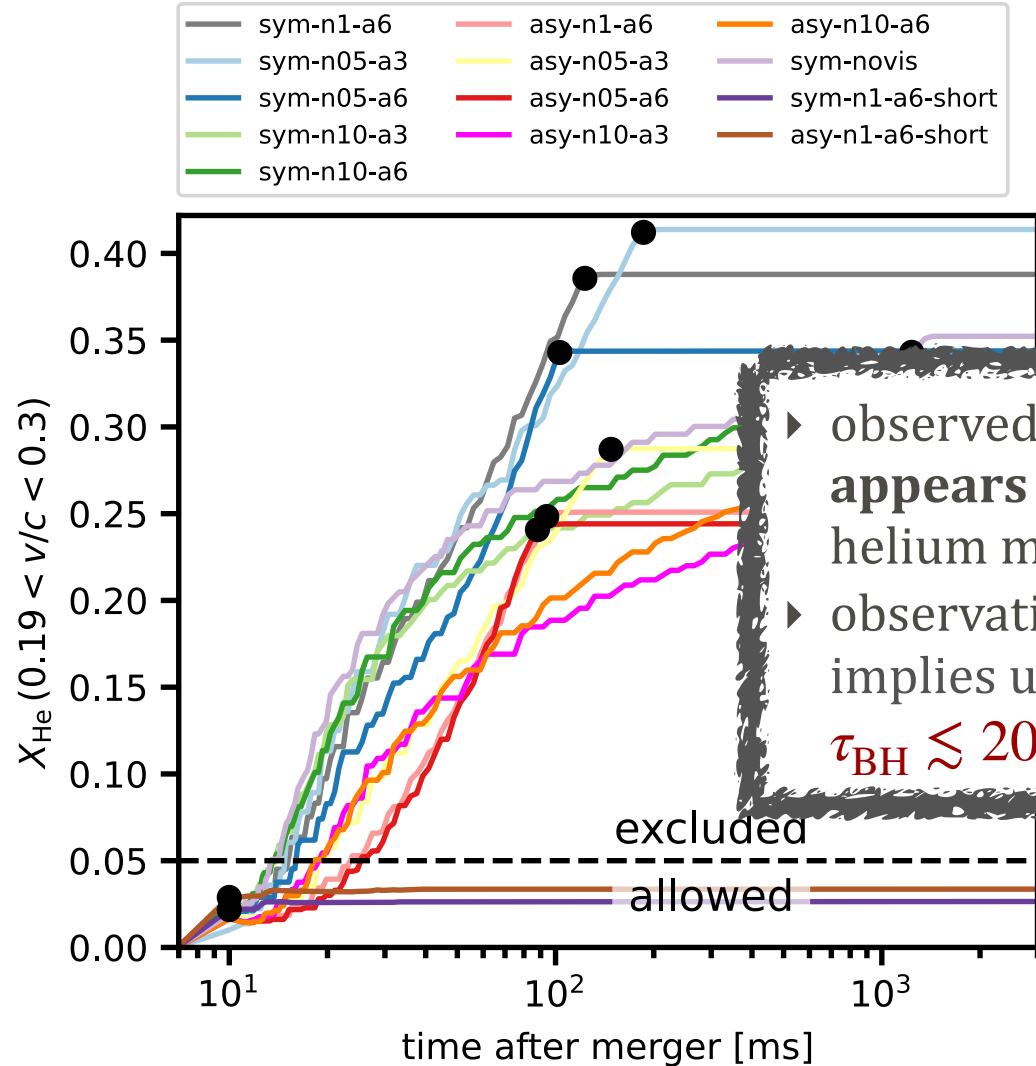
mainly He, iron-group,
and light r-process nuclei
in NS-torus ejecta

long-lived
(120ms)

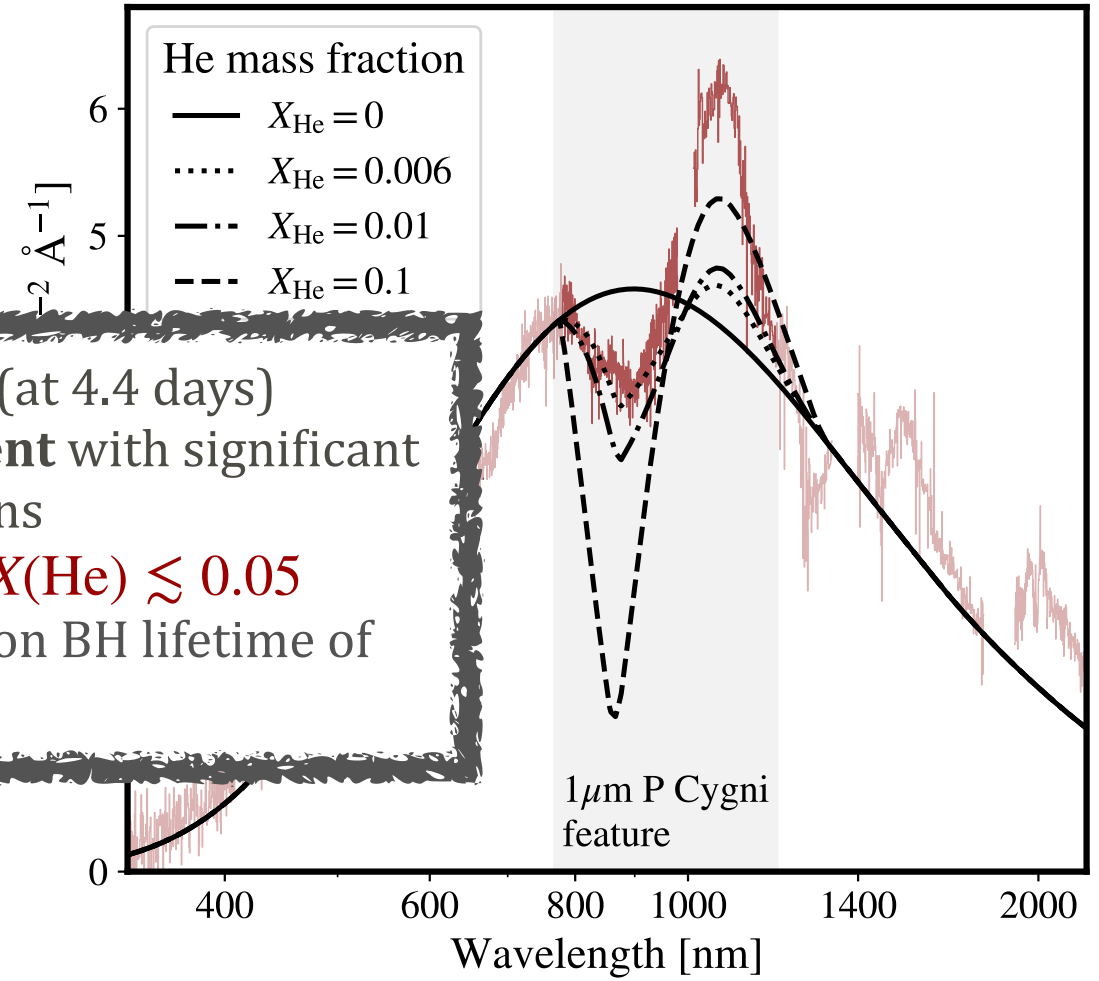


Helium production in NS merger models (Sneppen, OJ, et al., 2026)

hydro models



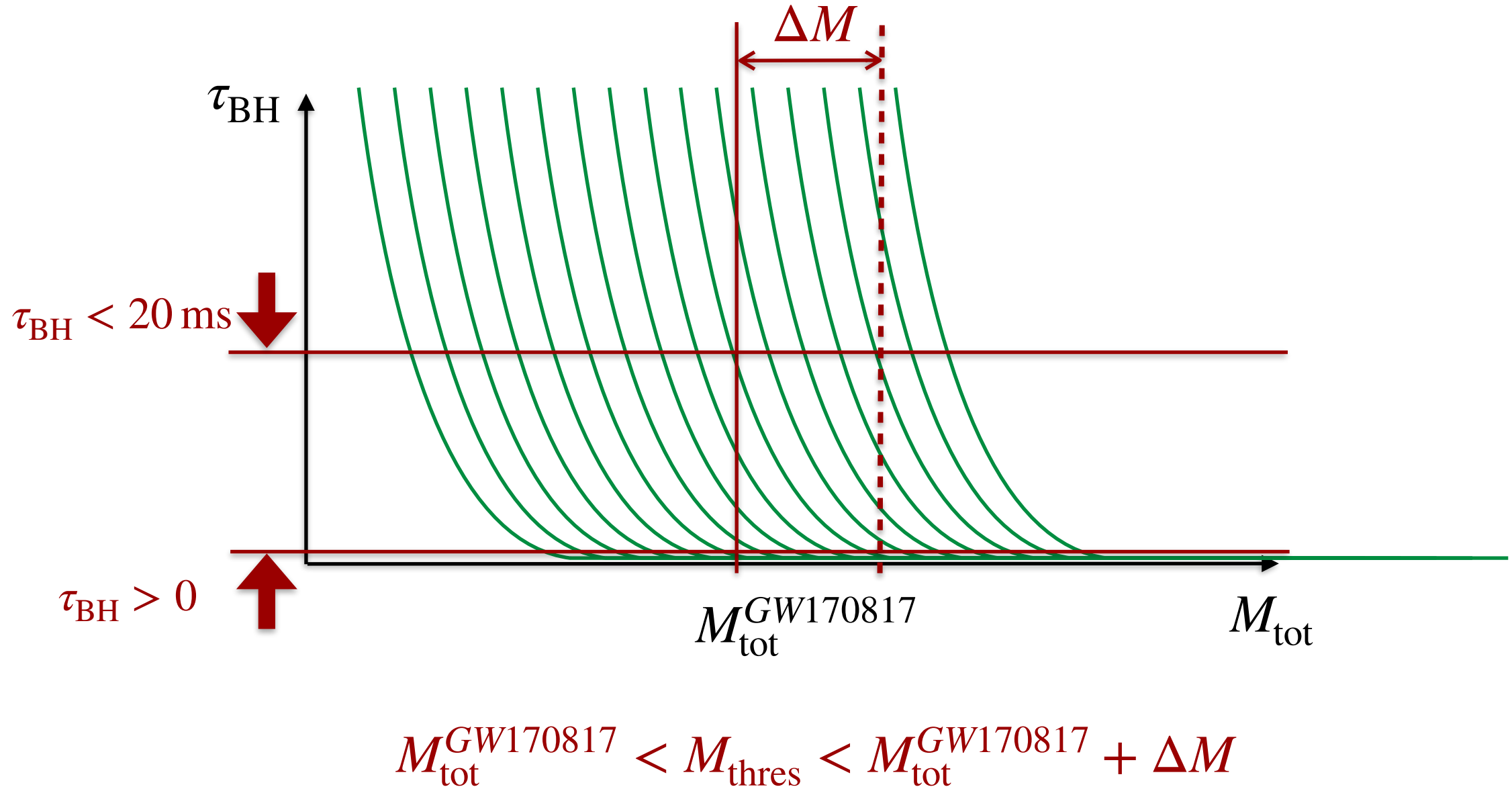
*observed spectrum of AT2017gfo at 4.4 days
+ estimated hypothetic contribution of helium*



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

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

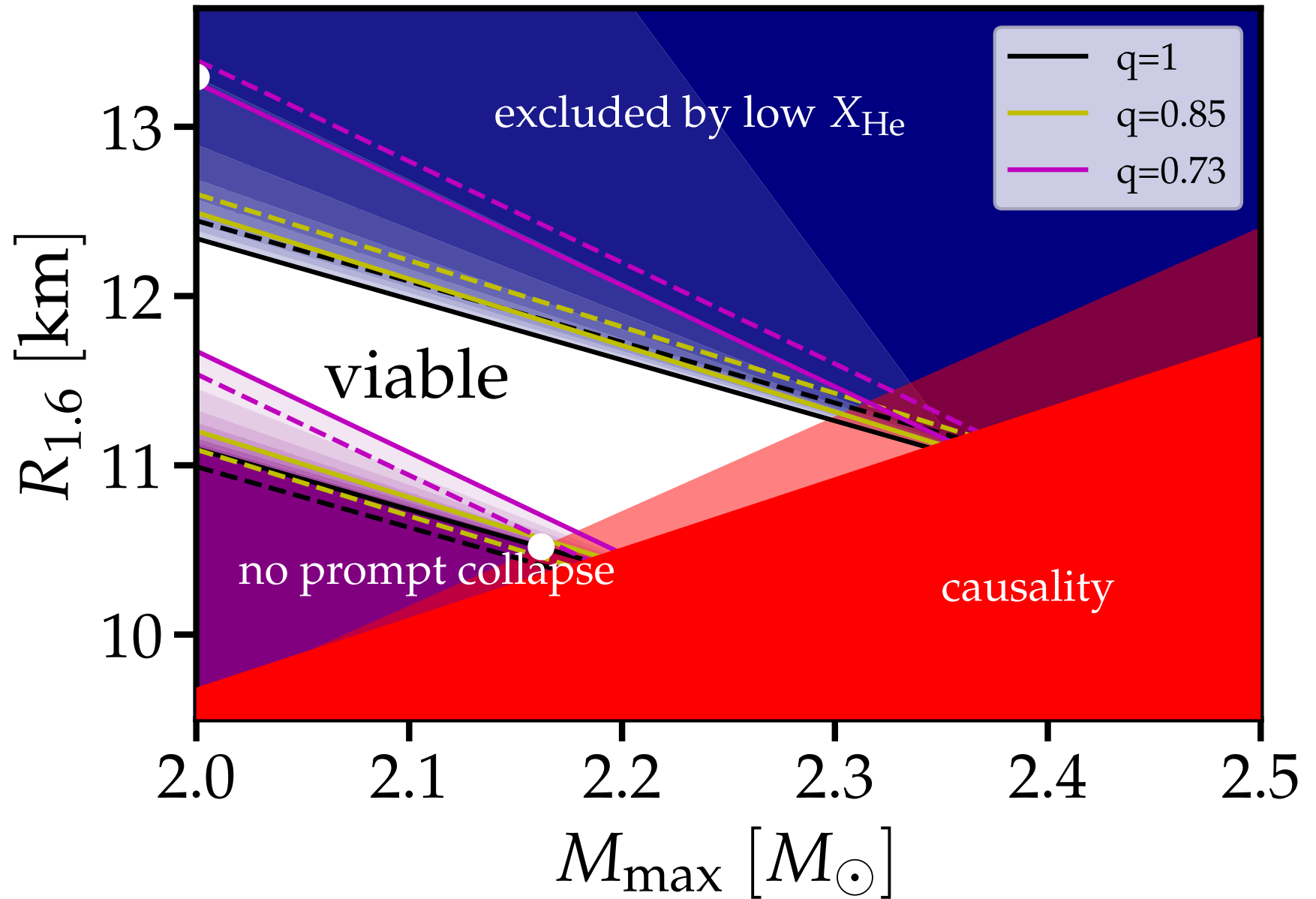
Implications of $\tau_{\text{BH}} > 0$ and $\tau_{\text{BH}} < 20 \text{ ms}$



Implications for NS properties

(Sneppen, OJ, et al., 2026)

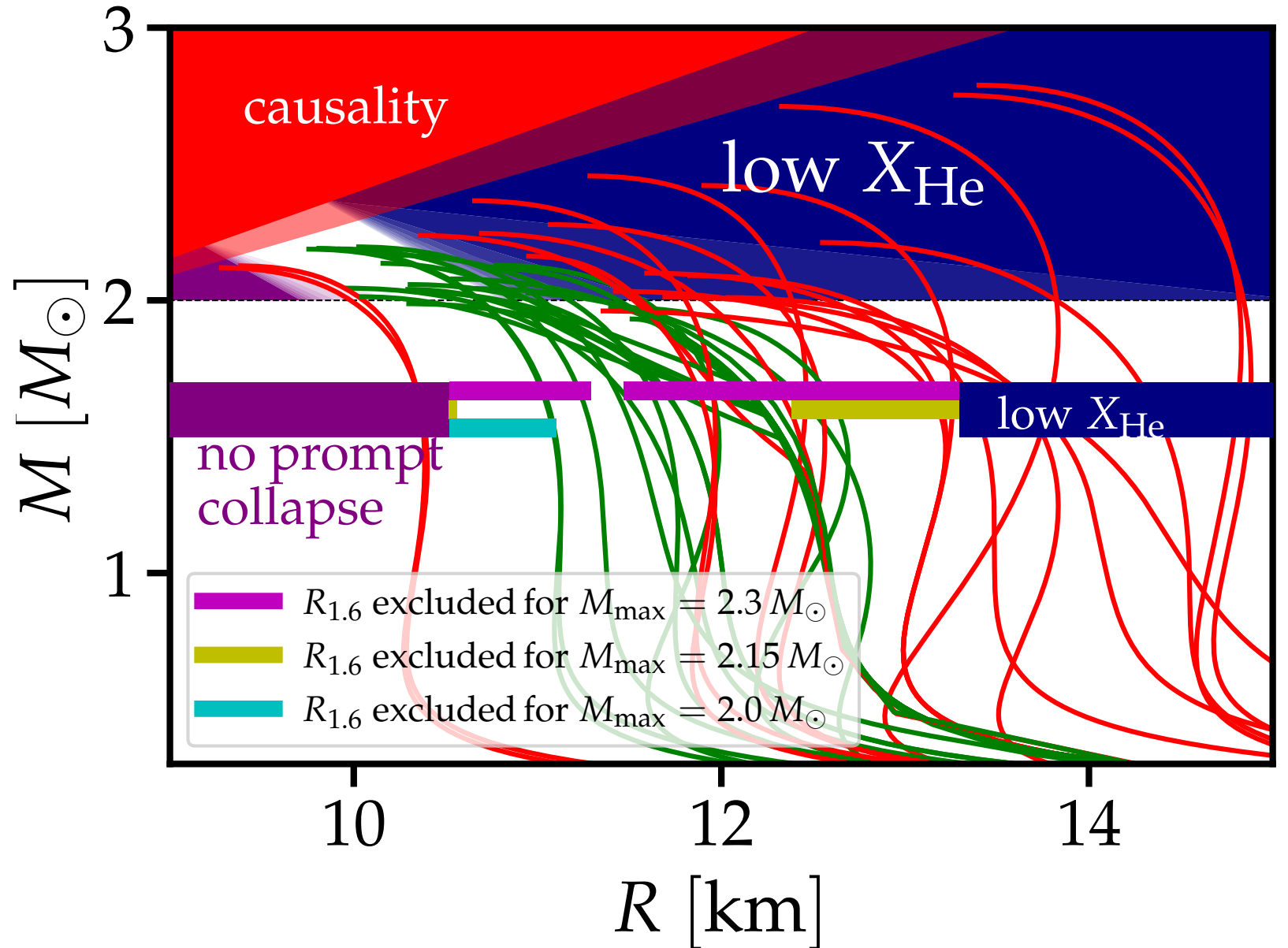
- ▶ narrow window of allowed values
- ▶ potentially powerful new EOS constraint, but with remaining modeling uncertainties



Implications for NS properties

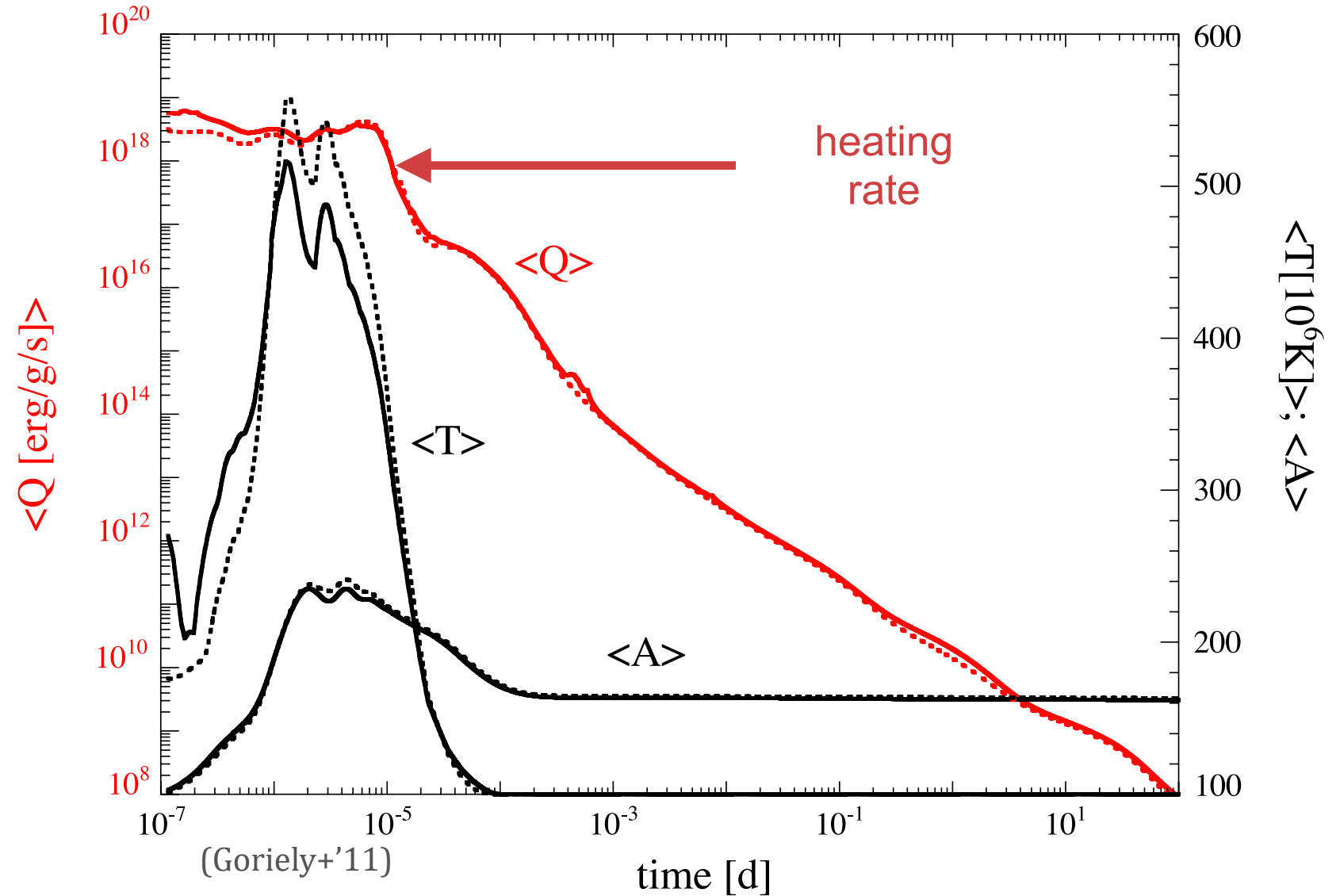
(Sneppen, OJ, et al., 2026)

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



Energy release from r-process

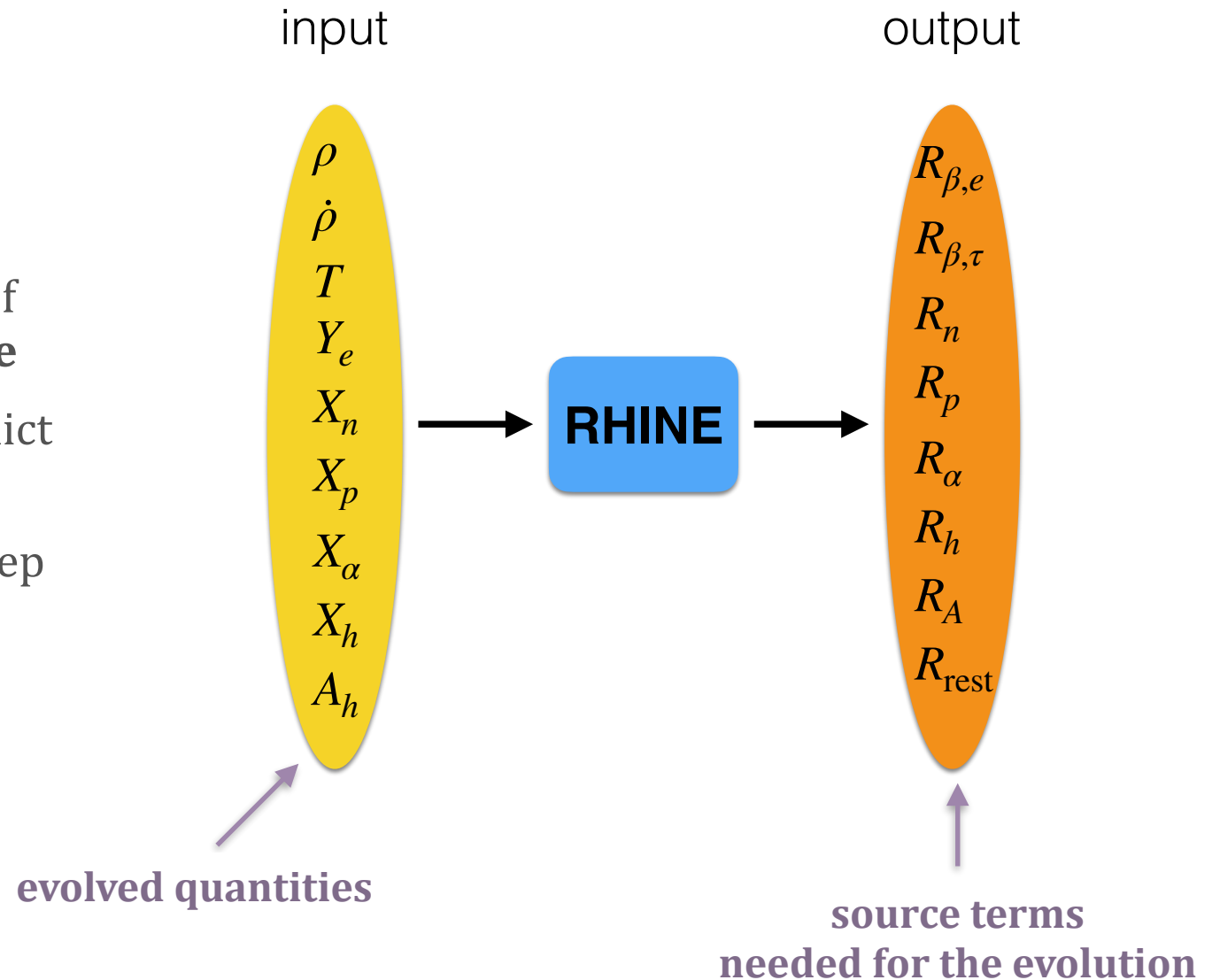
- ▶ radioactive decay of freshly synthesized r-process elements releases heat
- ▶ **ignored in almost all existing hydro-simulations**



(also see Kawaguchi+22, Magistrelli+24, Ma+25)

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

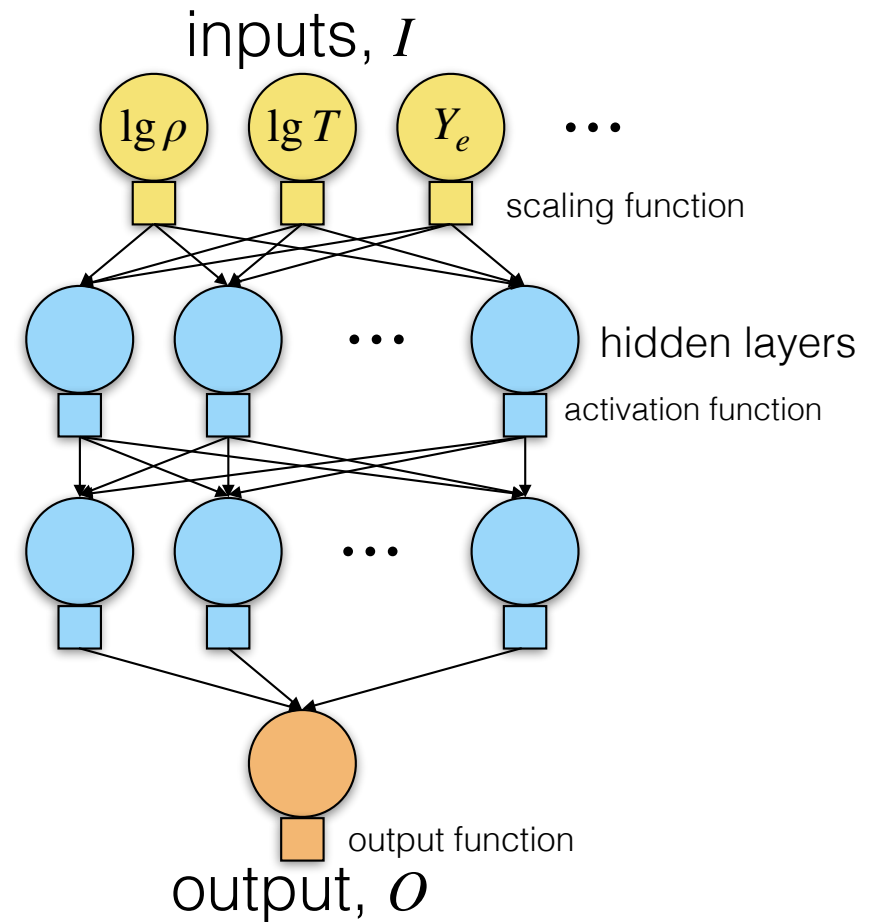
- ▶ output of a perceptron:

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

- ▶ with non-linear activation function:

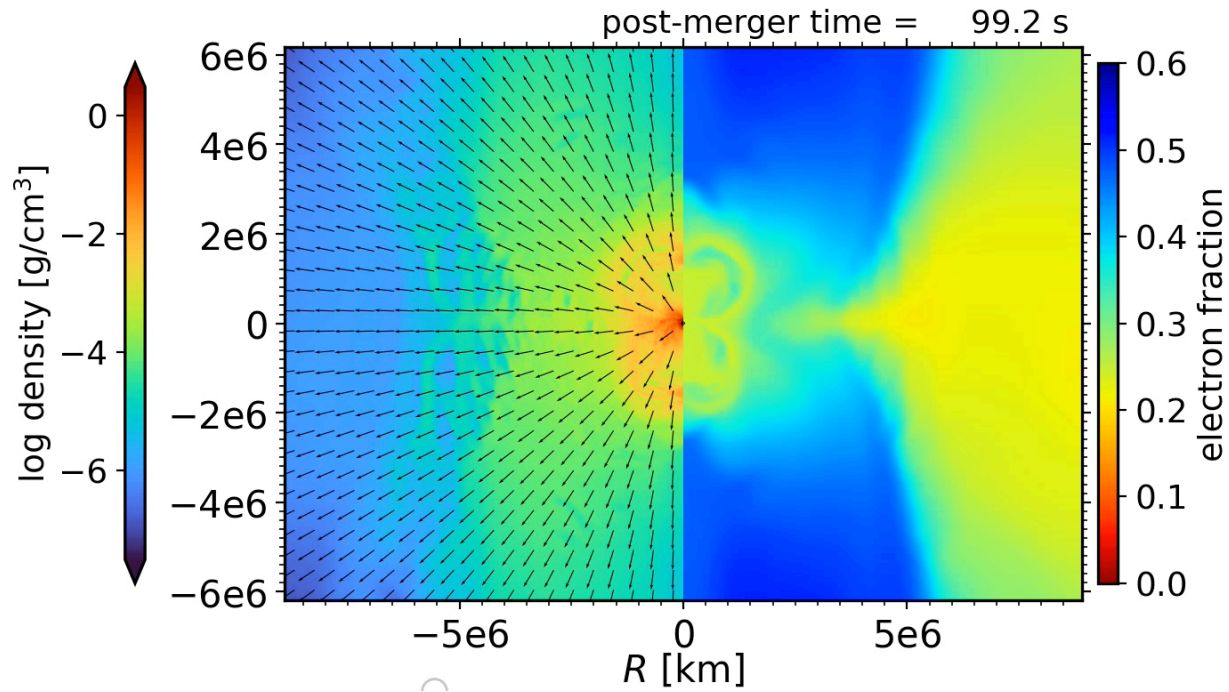
$$f_{\text{act}}(x) = \begin{cases} x, & \text{if } x \geq 0 \\ e^x - 1, & \text{if } x < 0 \end{cases}$$

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

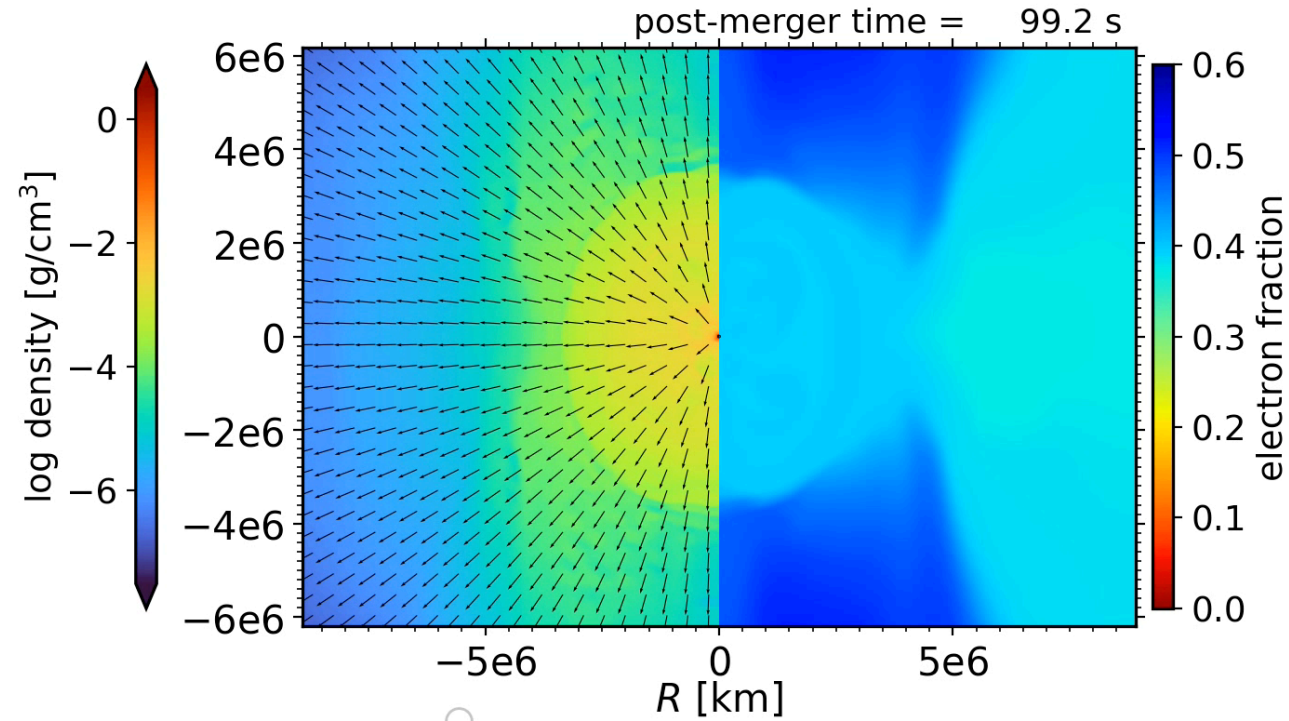


NS merger models + RHINE

without RHINE:

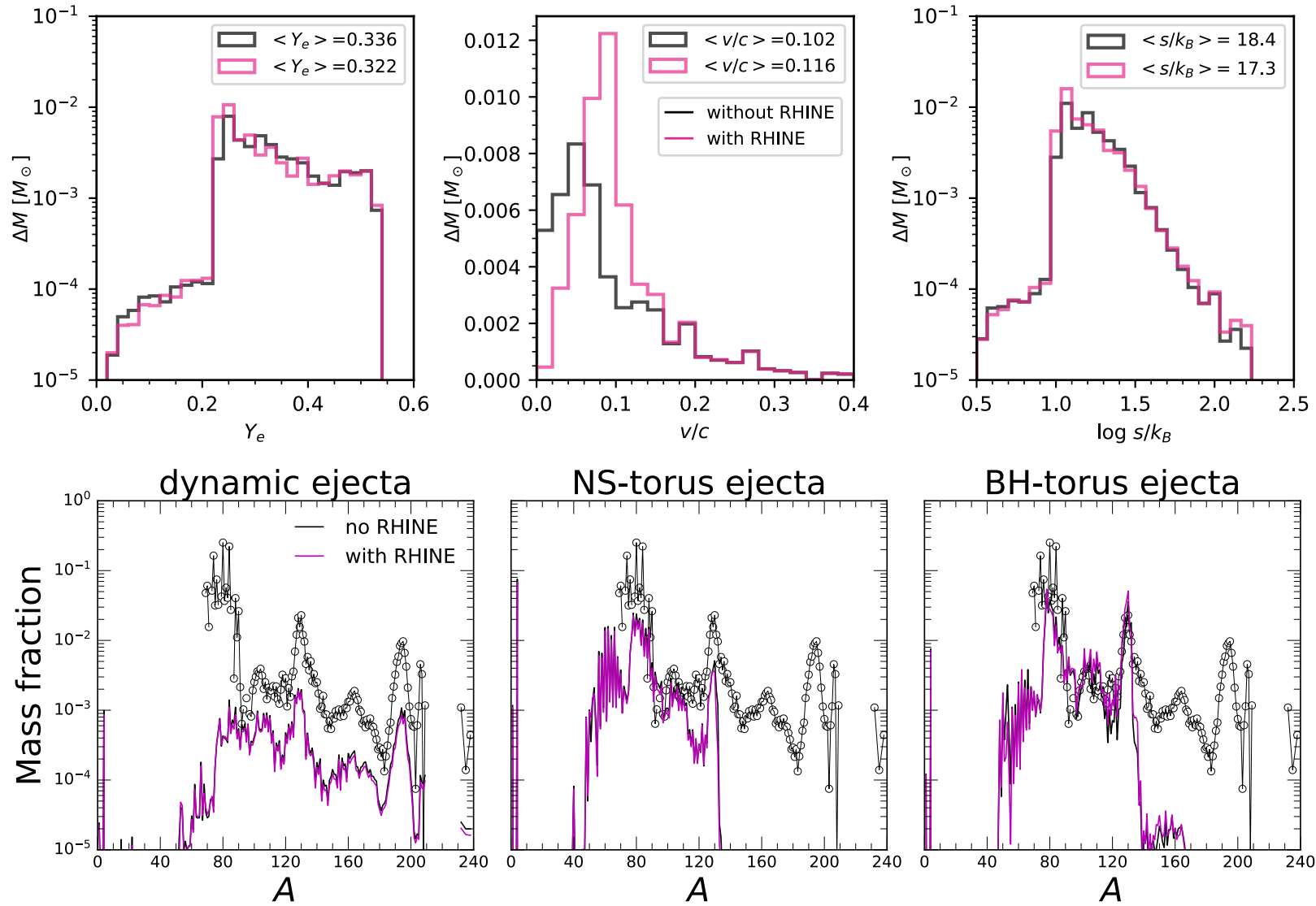


with RHINE:



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

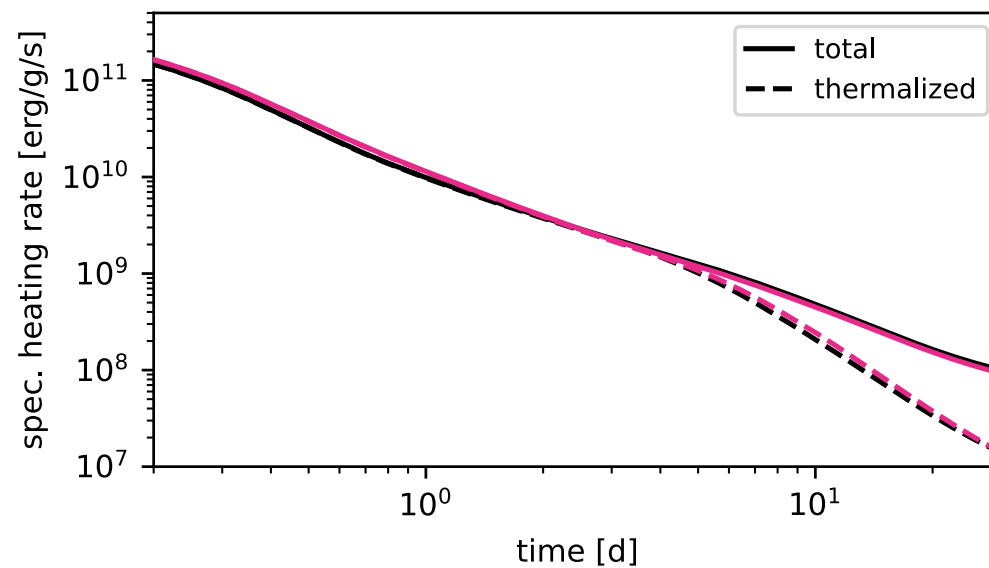
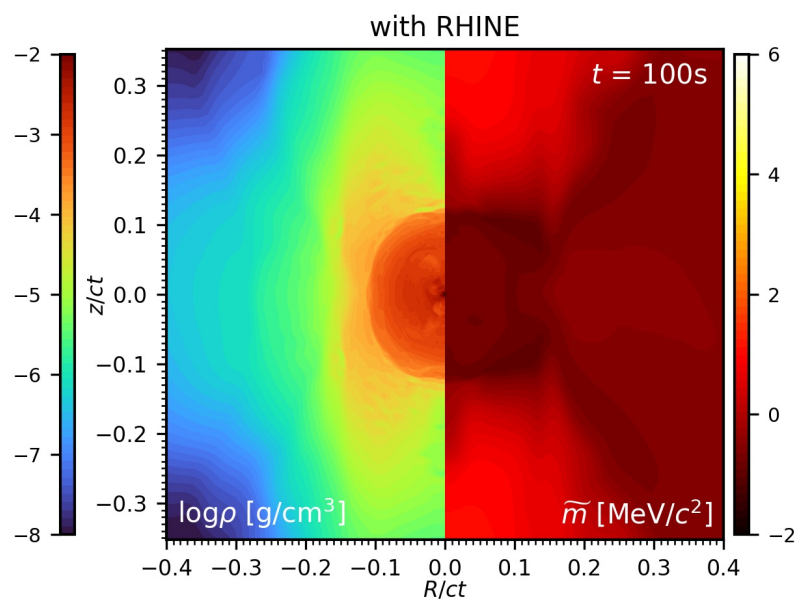
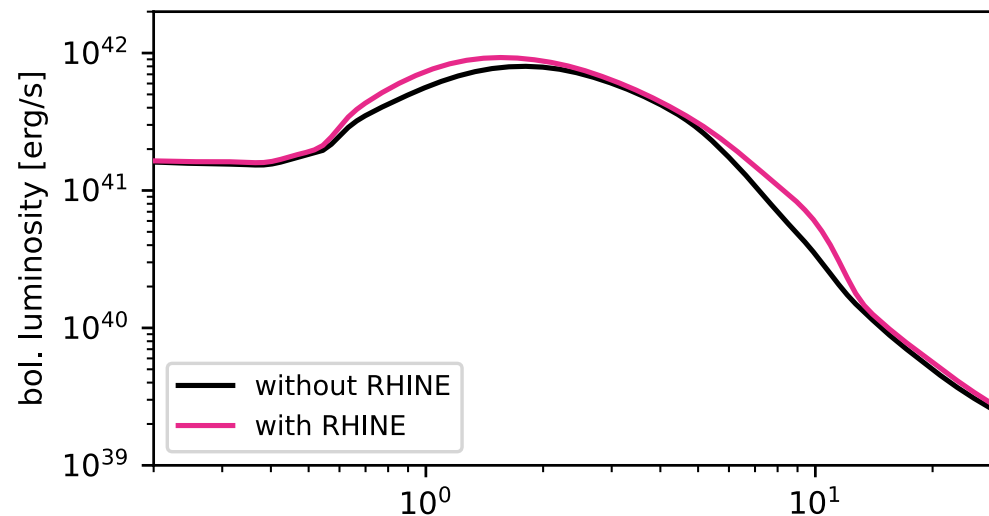
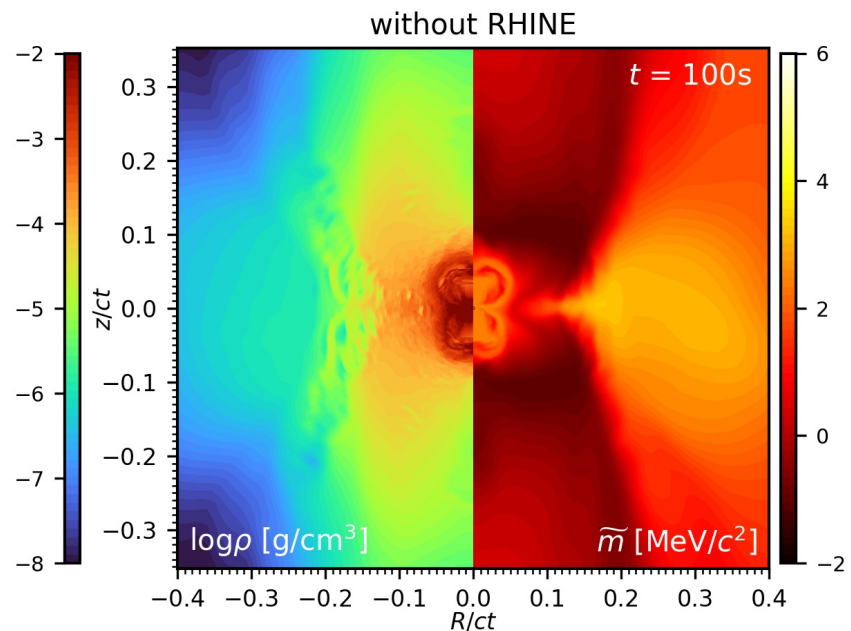
NS merger models + RHINE (O), Xiong, Martinez-Pinedo, PRD 2026)



- relatively small impact on nucleosynthesis yields
- significant impact on velocity distribution

Impact on kilonova light curve

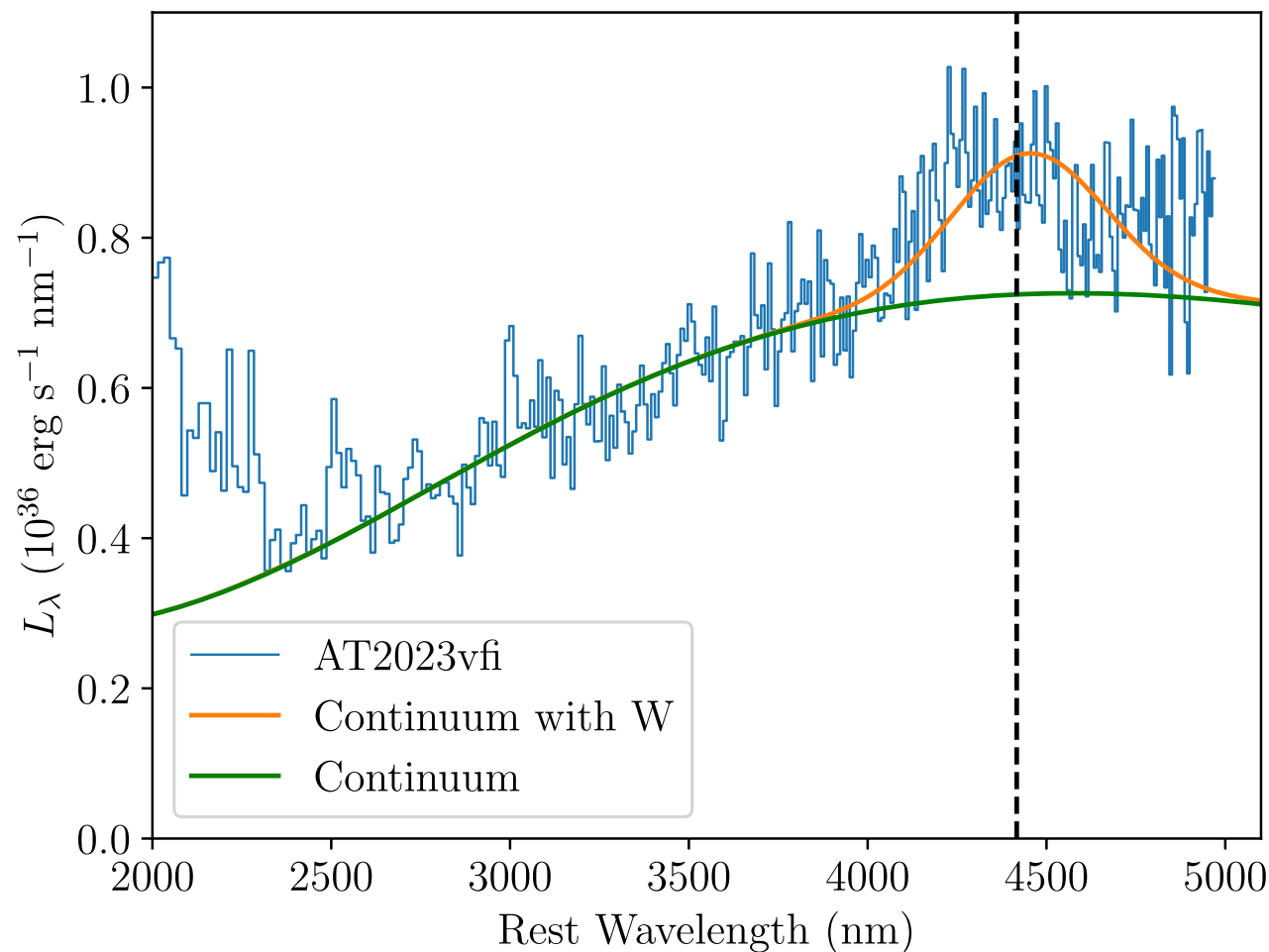
[O], Xiong, Martinez-Pinedo, PRD 2026)



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

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

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

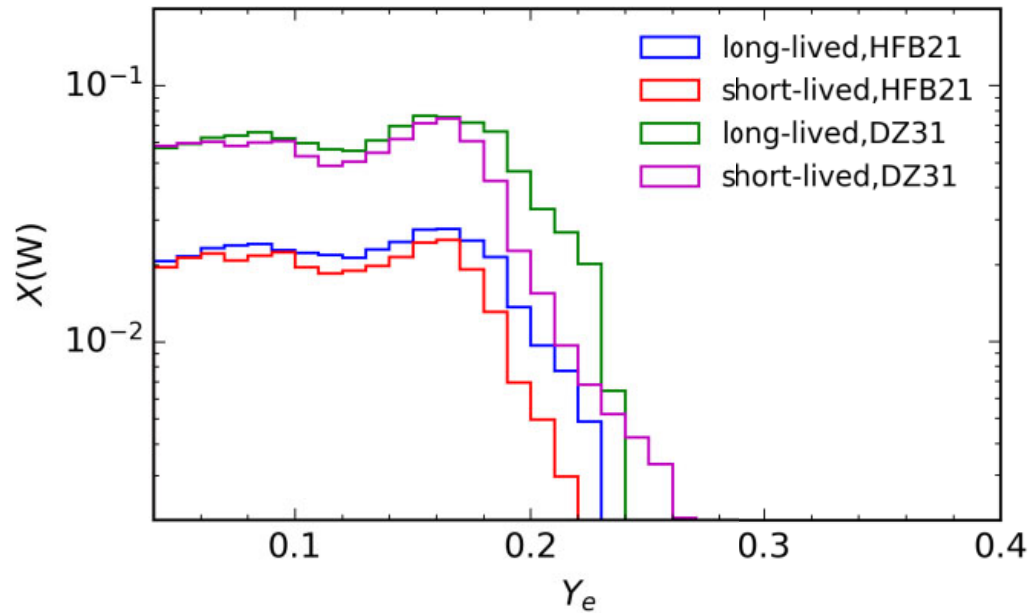


see talks by Michael, Leo

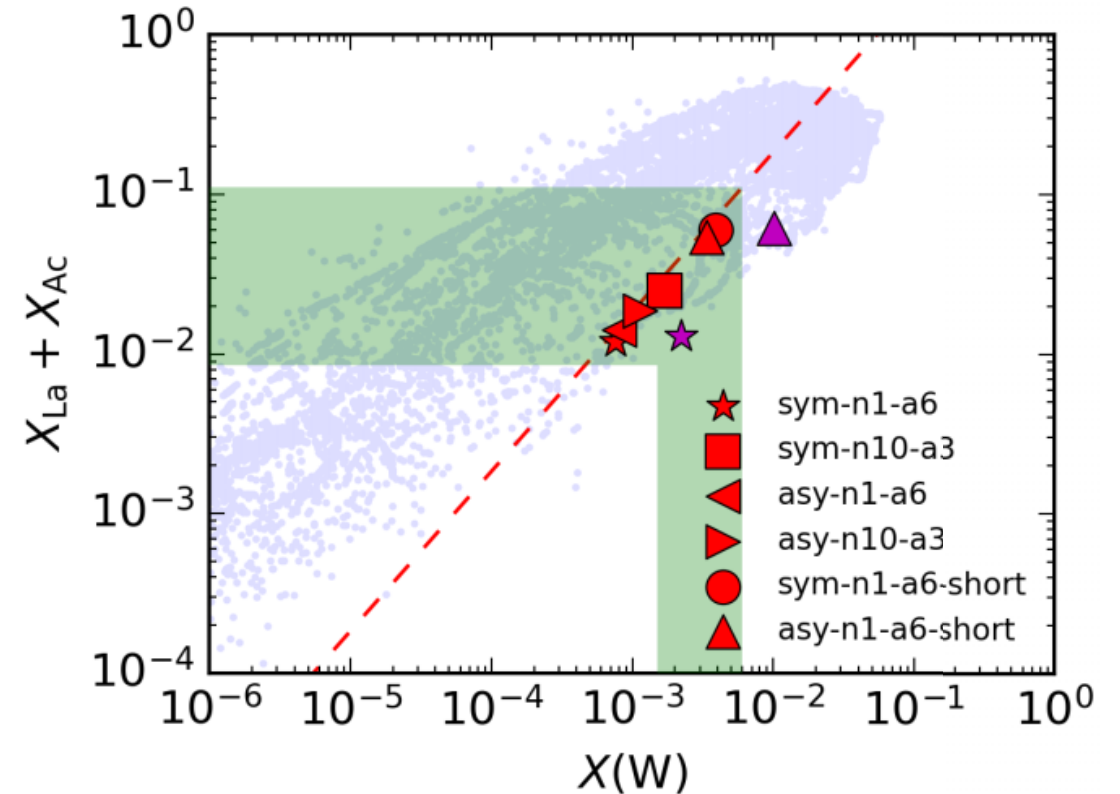
(also see Hotokezaka+22, Pognan+25)

Implications from end-to-end models

(*IF* feature was produced by W)



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



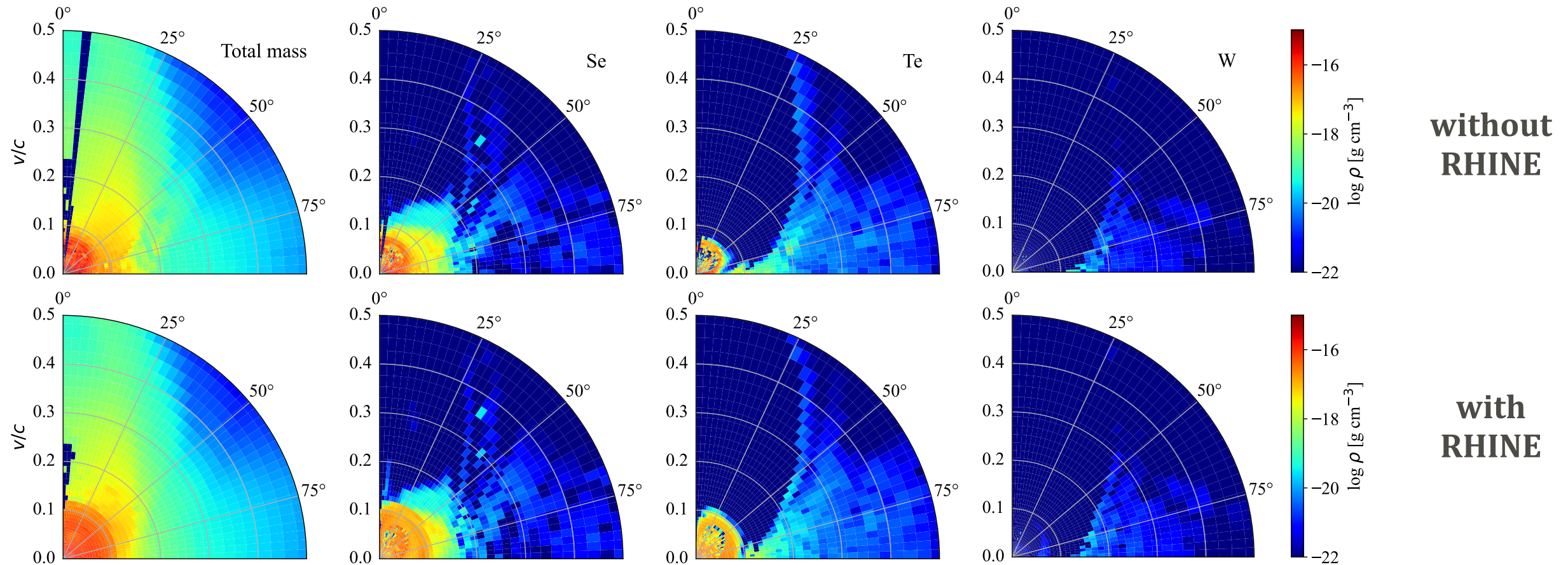
- ▶ symbols denote different merger simulations
- ▶ correlation between W and lanthanides allows estimate on lanthanide fraction

Late-time emission-line profiles from kilonova models

(submitted to MNRAS)

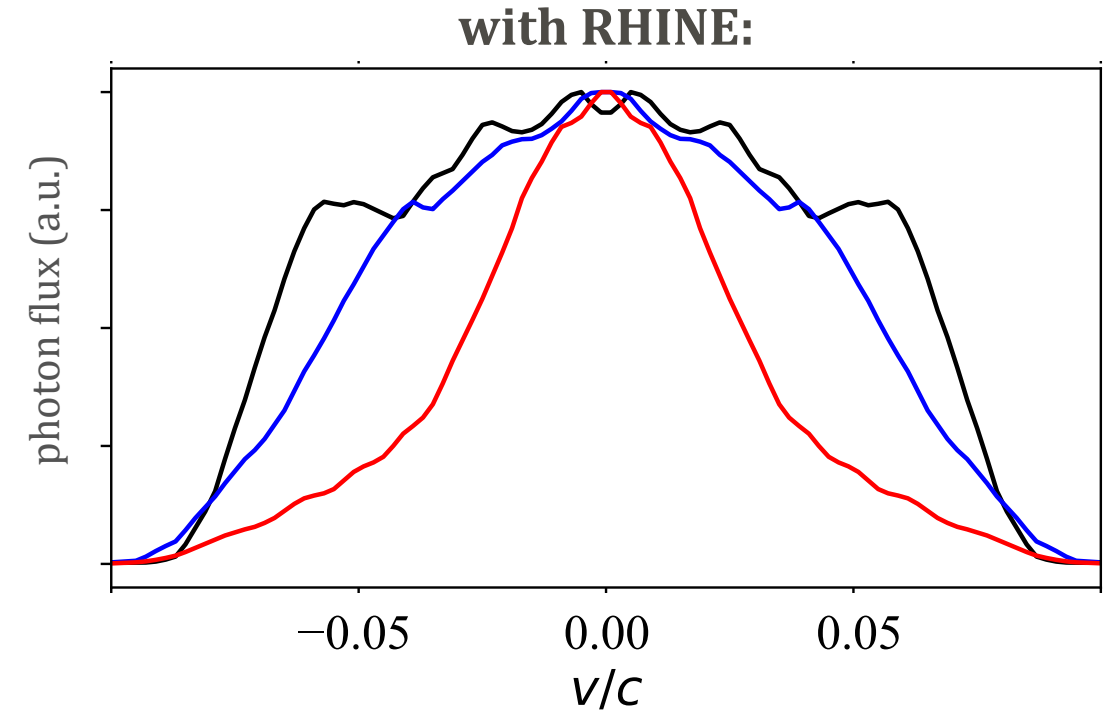
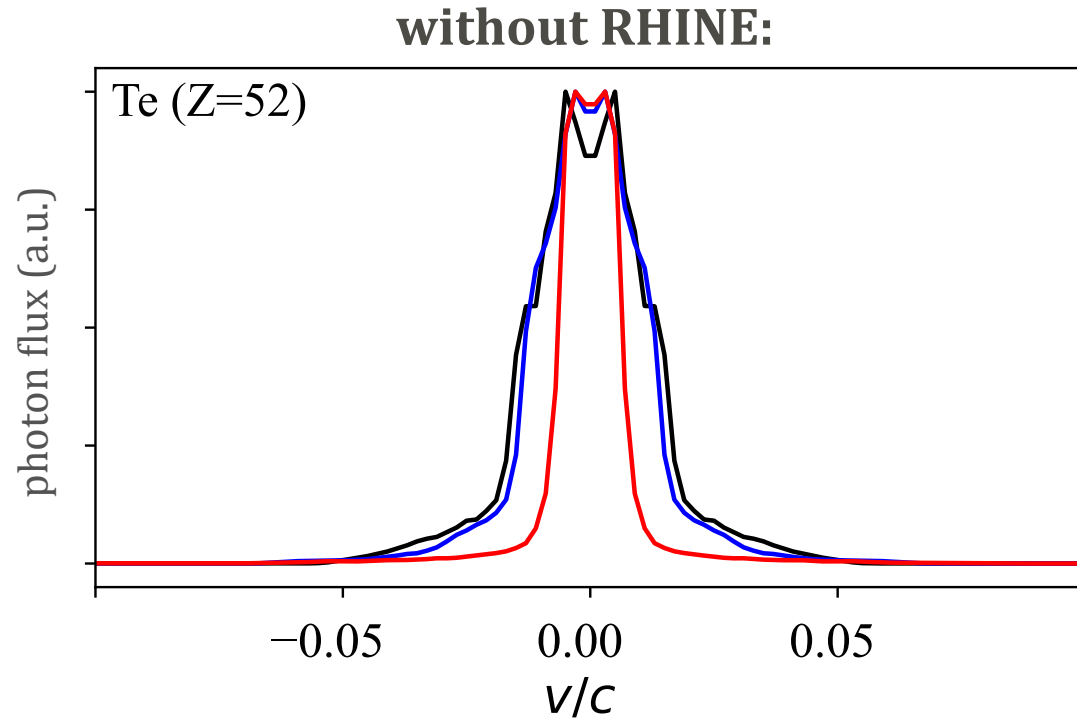
S. A. Sim¹★, O. Just^{2,3}, Z. Xiong², A. Bauswein^{2,4}, L. P. Mulholland¹, G. Leck^{2,5},
G. Martínez-Pinedo^{2,5,4}, L. J. Shingles^{1,2}, C. E. Collins⁶, F. McNeill¹, M. McCann¹,
C. P. Ballance¹, C. A. Ramsbottom^{7,1}

1.375-1.375 Msun end-to-end model



Impact of r-process heating on late-time line shape

(Sim+, 2026, submitted to MNRAS)



- ▶ RHINE: significant line broadening and extended wings
- ▶ long-term modeling + nuclear heating **important for interpretation of nebular phase**

see Stuart's talk!

Summary

- ▶ **Early dynamical ejecta robust production site of heaviest r-elements**
 - ▶ small dependence of nucleosynthesis + KN spectra on EOS and NS masses
- ▶ **Long-term modeling crucial for ejecta mass, yields 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 ~ 20 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**
 - ▶ long-term modeling + r-process heating important for predicting line shape