End-to-end merger models including all phases of matter ejection

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Oliver Just

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INT Workshop

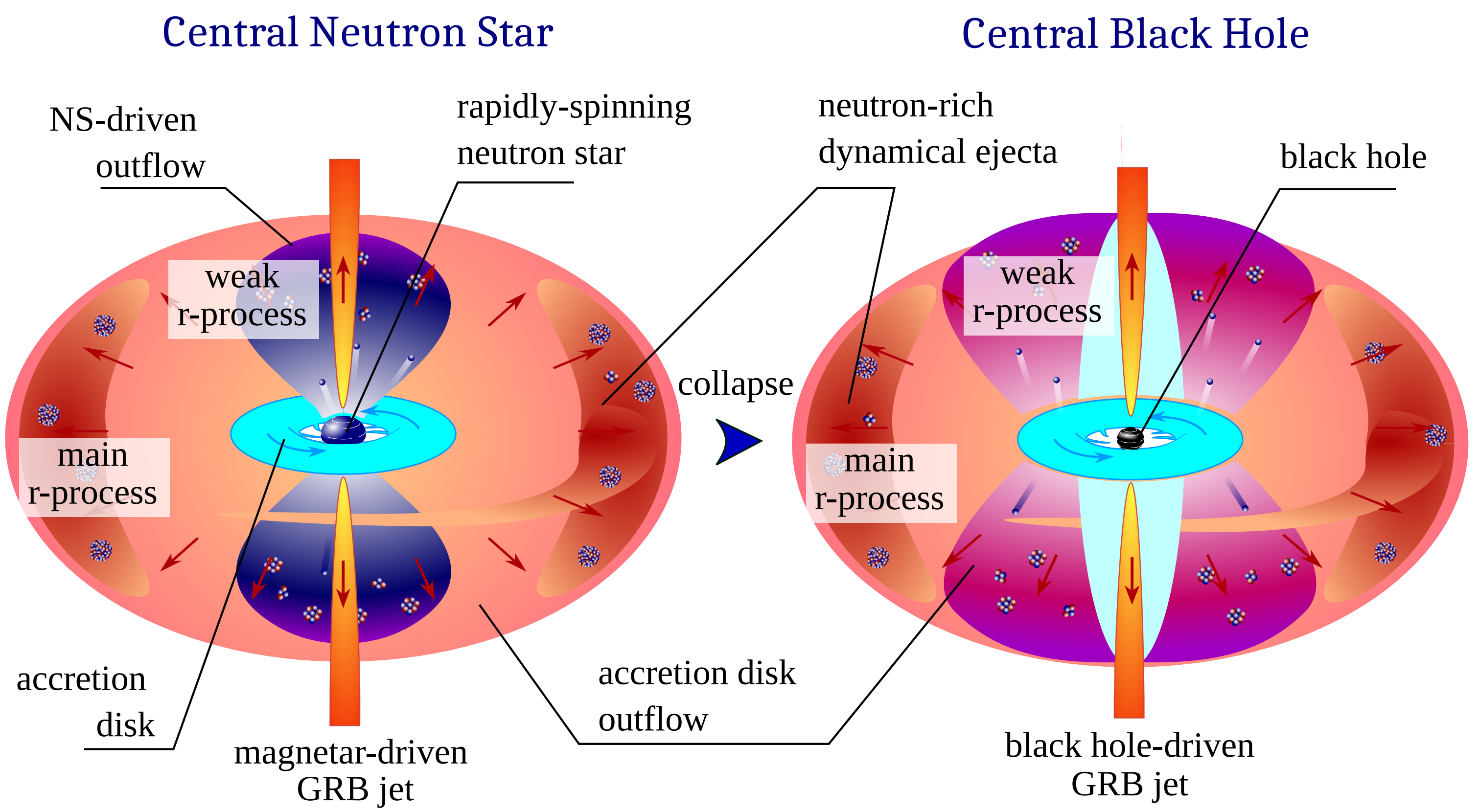
Astrophysical neutrinos and the origin of the elements

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

European Research Council

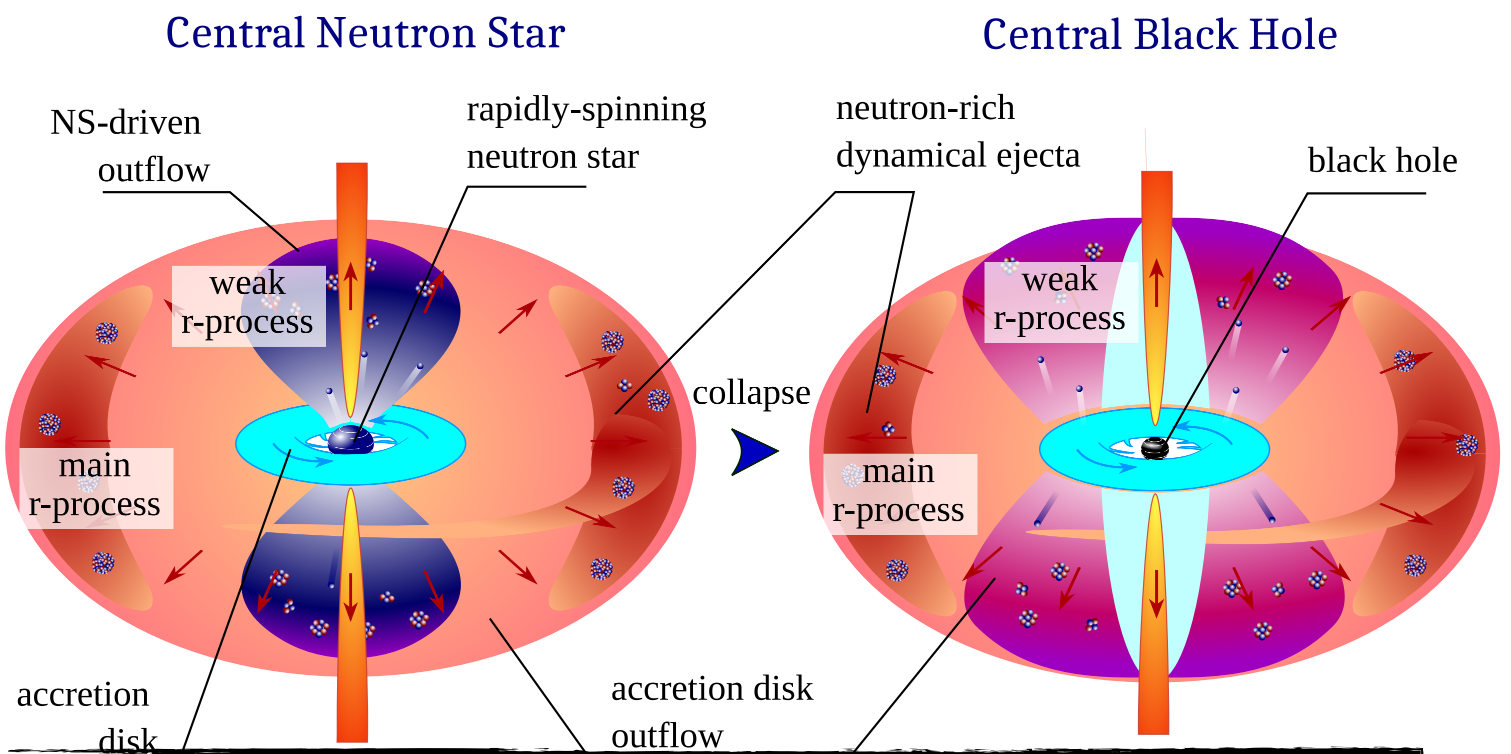
Established by the European Commission

Basic picture



(sketch by Rosswog & Korobkin 22)

Basic picture



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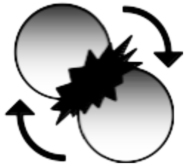
NO self-consistent hydro models yet of scenarios with collapse times > 20 ms ! (as was likely the case in GW170817)

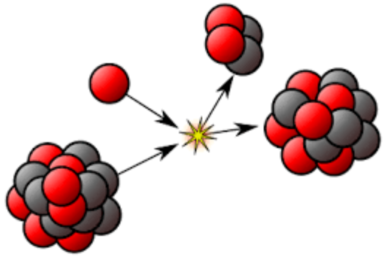
Ingredients of kilonova modeling pipeline

hydrodynamic modeling of merger + dynamical ejecta



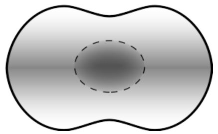
$t \sim \mathcal{O}(10\,\mathrm{ms})$

heavy element nucleosynthesis

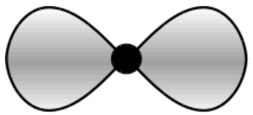


$t \sim \mathcal{O}(10\,\mathrm{s})$

hydrodynamic modeling of remnant + post-merger ejecta



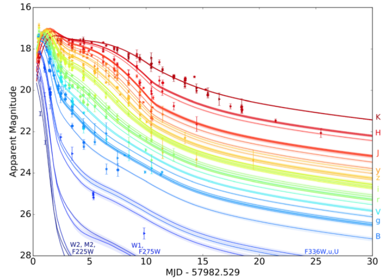
neutron star torus system



black hole torus system

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

kilonova radiative transfer



Villar 17

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

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Ingredients of kilonova modeling pipeline

hydrodynamic modeling
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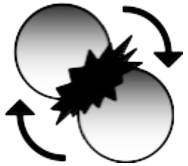

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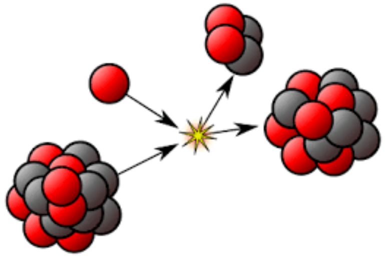
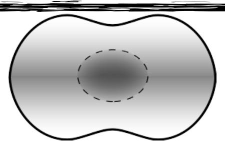
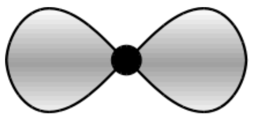


Ideally, all ingredients fully consistent, i.e.:

1. post-merger simulations adopting results from merger simulations
2. nucleosynthesis + kilonova calculations adopting local ejecta information



neutron star
torus system



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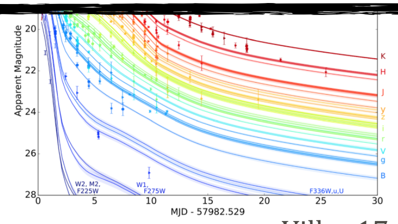

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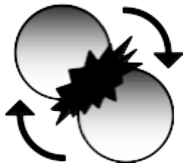
Often adopted simplifications

hydrodynamic modeling of merger + dynamical ejecta



heavy element nucleosynthesis

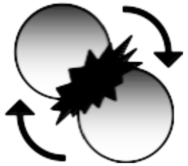
hydrodynamic modeling of remnant + post-merger ejecta

- often entirely ignored
- manually constructed initial models
- no or simple neutrino transport
- neglecting turbulent viscosity and angular momentum transport

kilonova radiative transfer

Often adopted simplifications

hydrodynamic modeling of merger + dynamical ejecta



heavy element nucleosynthesis

- parametrized outflow trajectories
- time extrapolation assuming self-similar expansion

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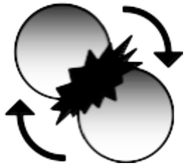

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kilonova radiative transfer

- spherical symmetry (i.e. 1D)
- analytic density structure
- using only **average** ejecta properties, not **local** properties

Open questions (that can only be addressed by delayed-collapse models)

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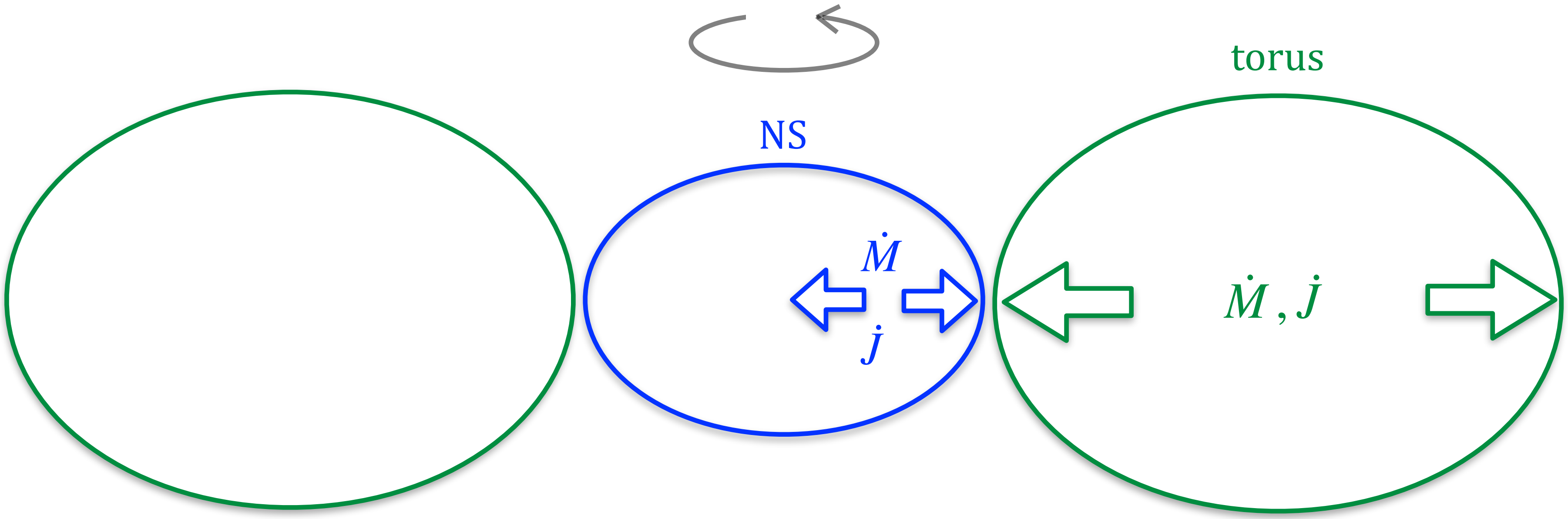
Challenge: Resolving all relevant processes in the NS remnant



What process (if any) transports angular momentum in the NS most effectively (MRI, Taylor Spruit dynamo, B-field winding, ...)???

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

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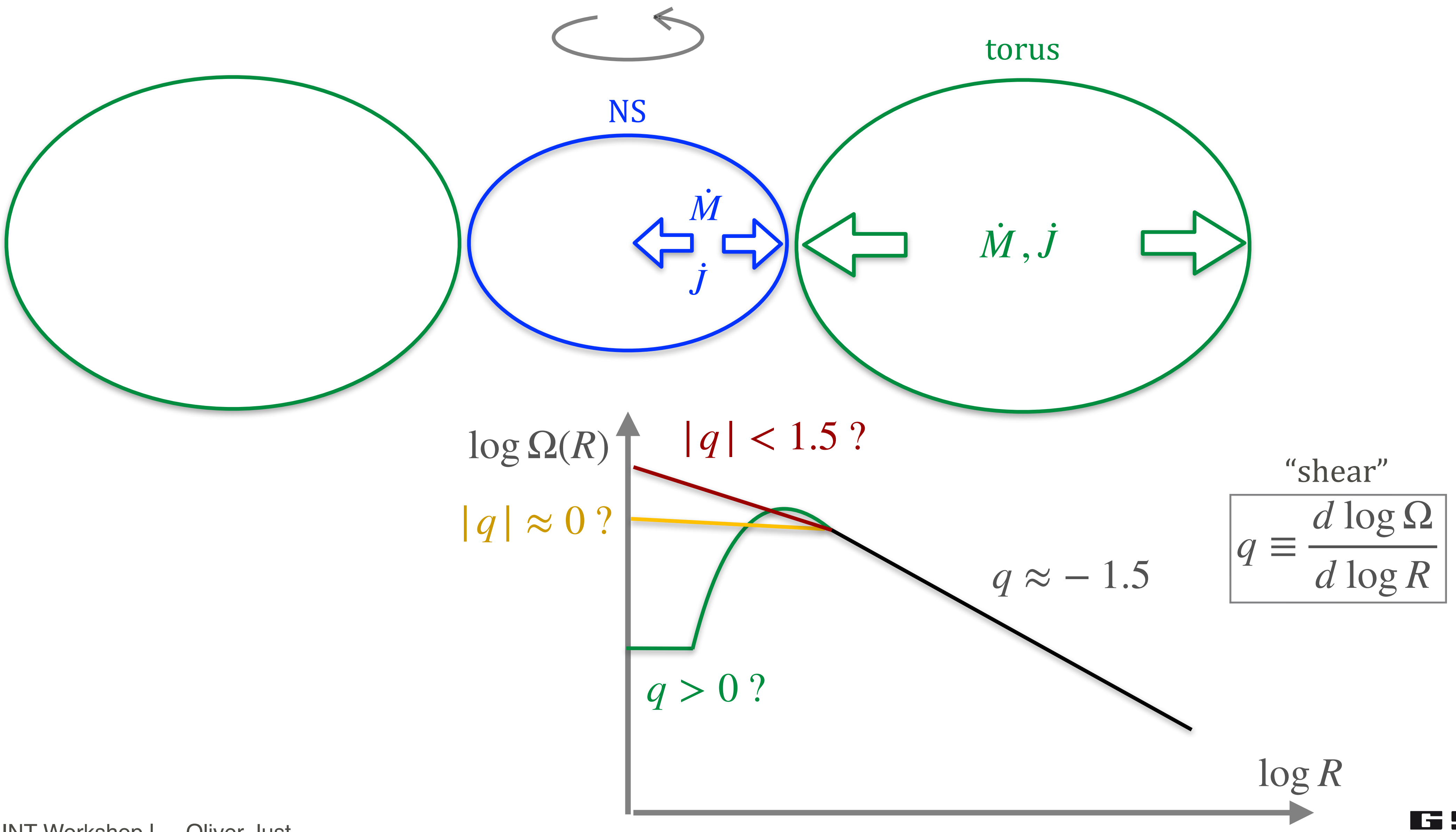

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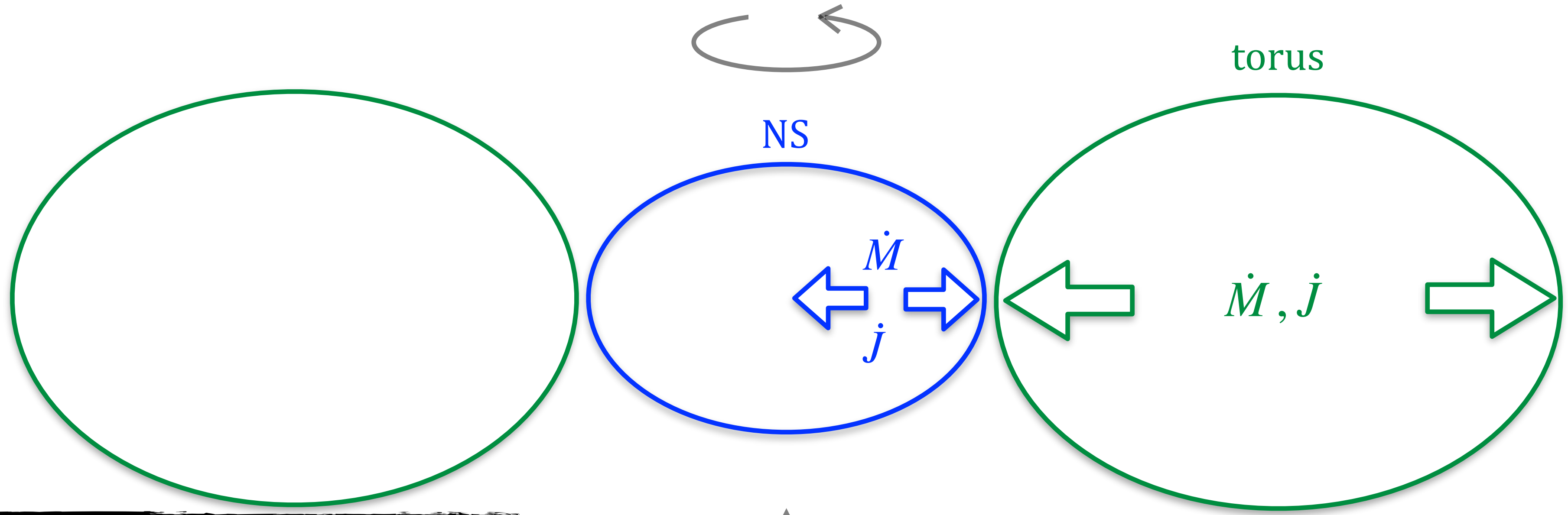
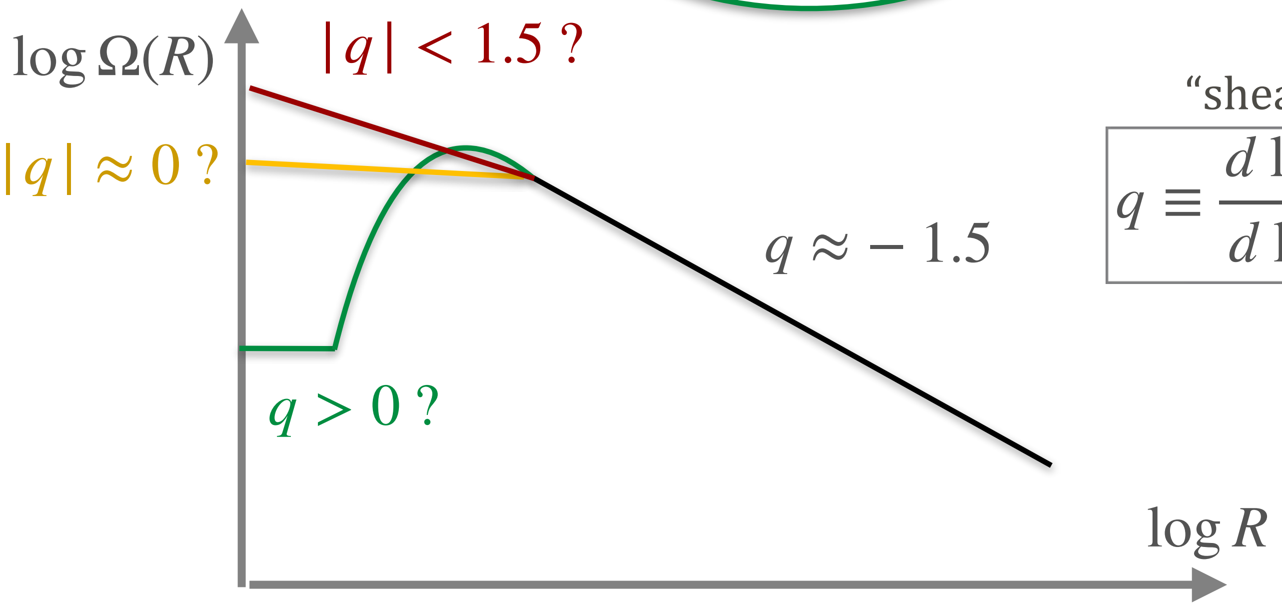


Our approach:

- parametrize turbulent viscosity depending on the **shear *q***
- **in the torus** (q~-1.5): "usual" alpha-viscosity scheme
- **in the NS** (|q|<1.5): reduced viscosity
- allows to regulate viscosity in the NS **independently** of visc. in the torus!



"shear"

$$q \equiv \frac{d \log \Omega}{d \log R}$$

Setup of our models

hydrodynamic modeling of merger + dynamical ejecta

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

hydrodynamic modeling of remnant + post-merger ejecta

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

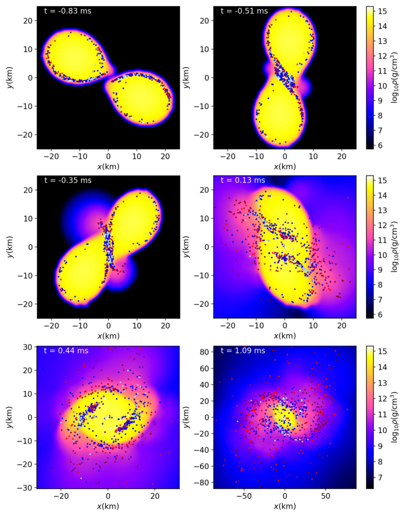
heavy element nucleosynthesis

- extraction of ~5000 outflow tracers per model to sample local hydrodynamic history until 100 s
- post-processed by two high-end nuclear networks

kilonova radiative transfer

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

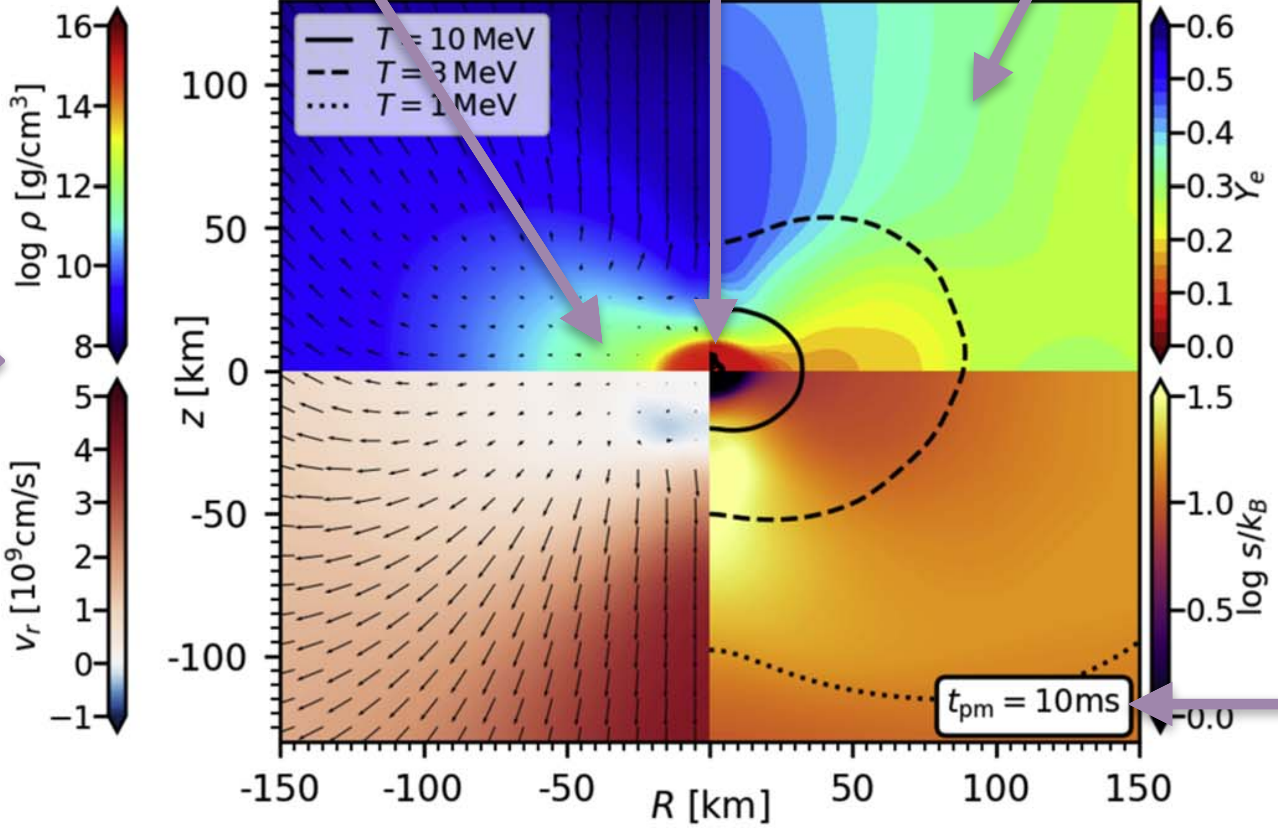
Evolutionary phases 1: merger



accretion disk

(hypermassive)
neutron star
remnant

dynamical
ejecta



"post-merger time"
(since first
touch of NSs)

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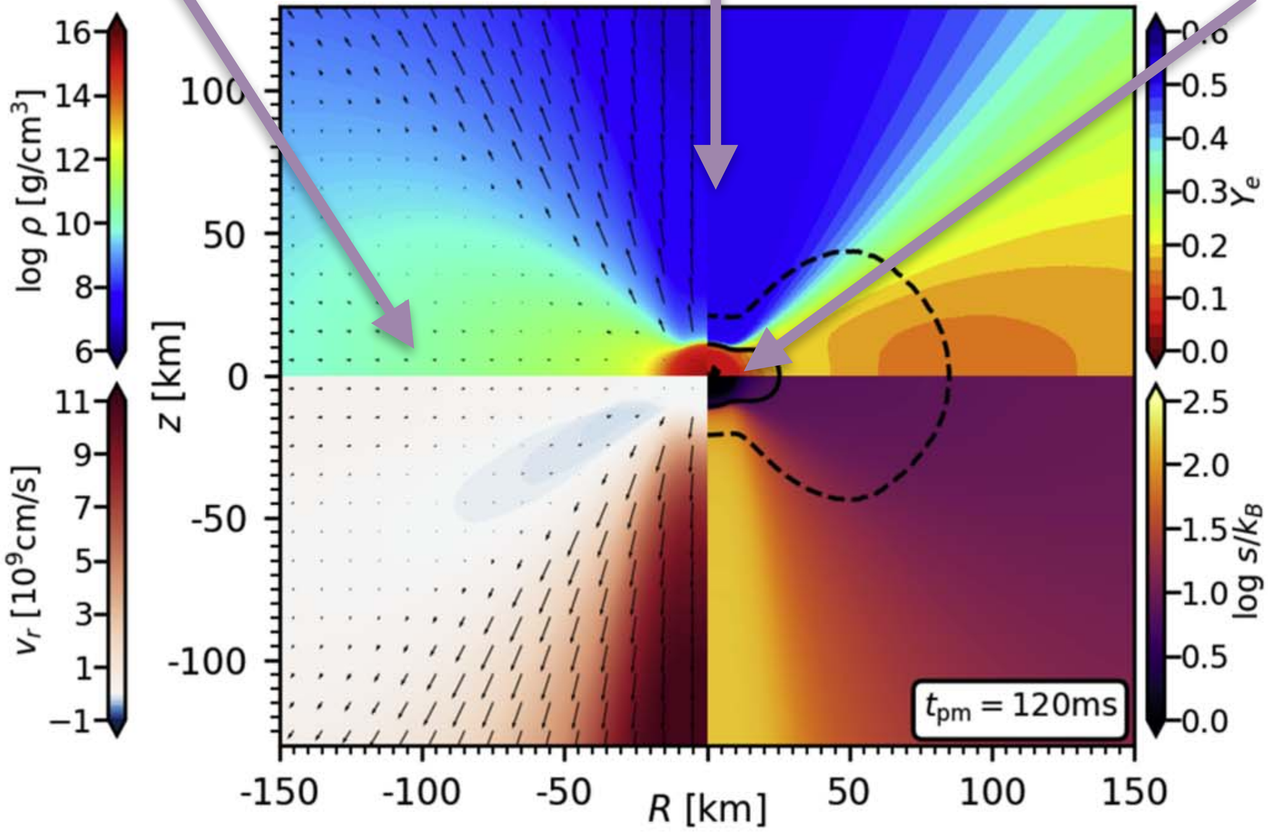
Evolutionary phases 2: NS-torus evolution

accretion disk expands
due to turbulent viscosity

polar wind powered by
absorption of neutrinos from NS
("neutrino-driven wind")

NS cools by neutrino emission and looses angular momentum by viscosity

- causes rise of central density
- eventually: gravitational instability + BH formation



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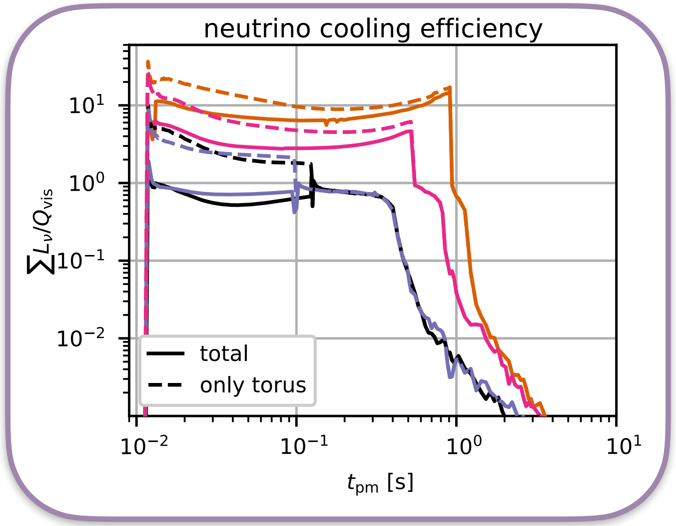
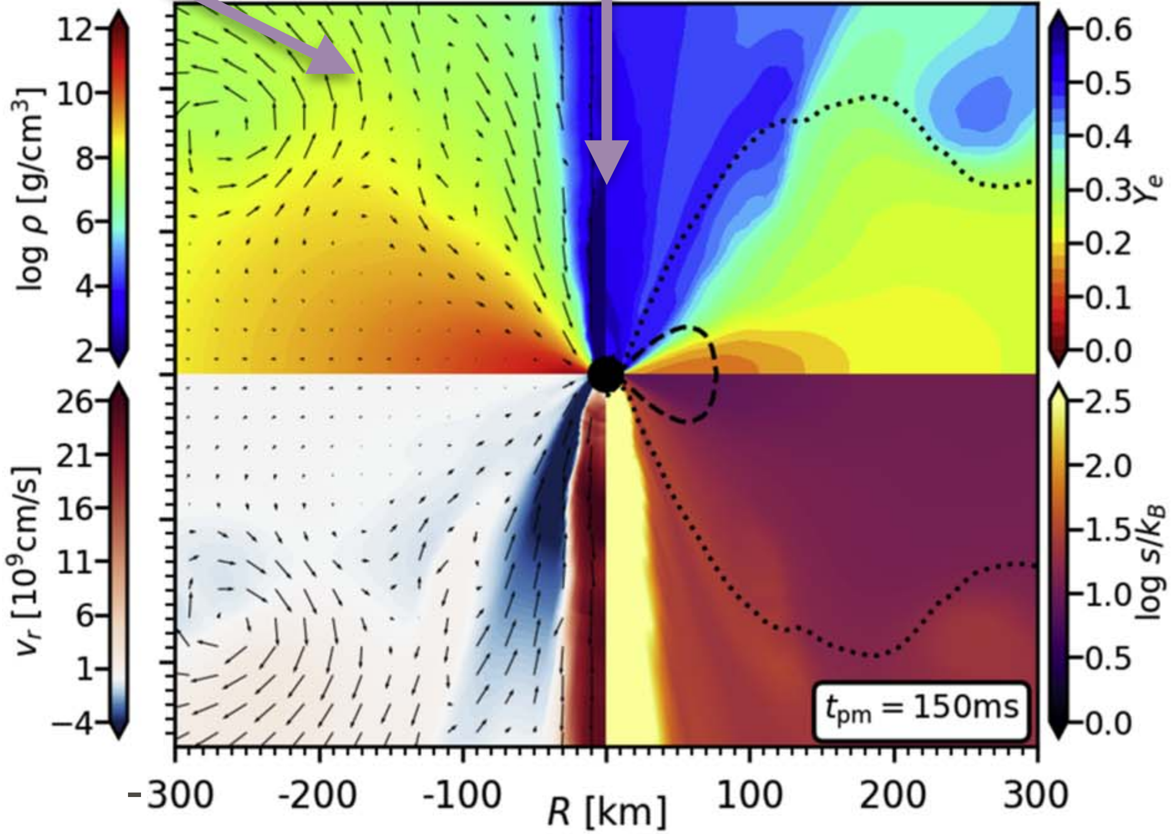
Evolutionary phases 3: BH-torus evolution

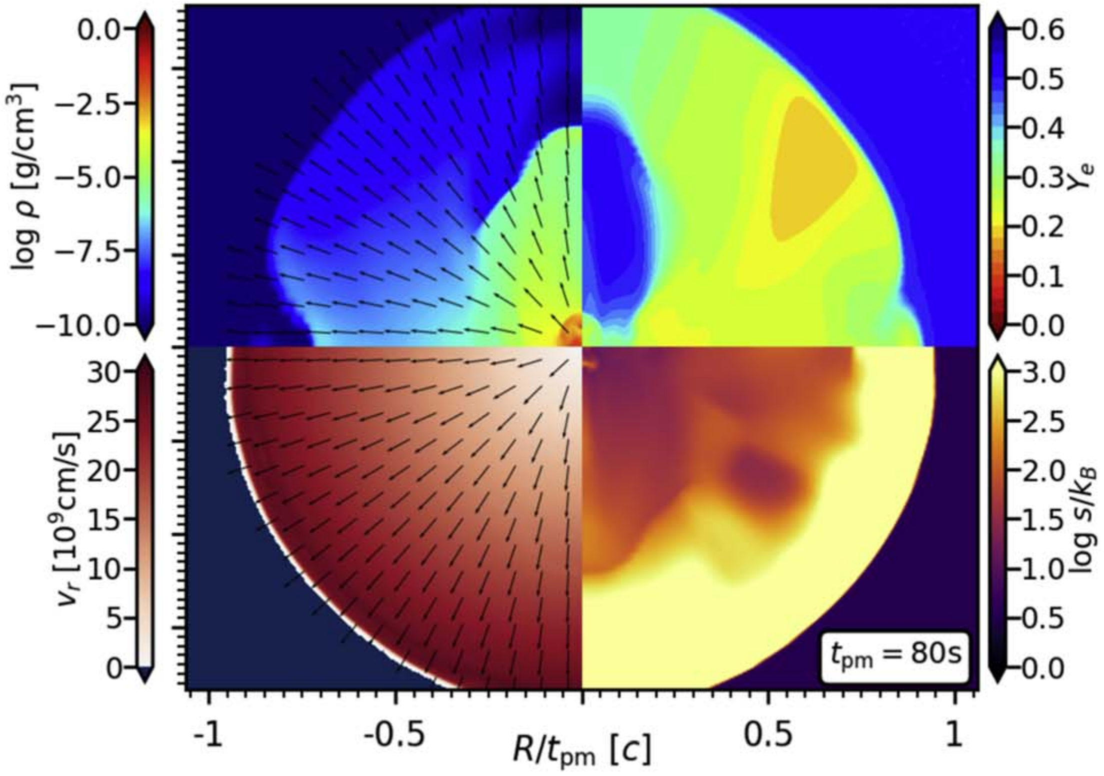
viscous disk winds
(once neutrino cooling
becomes inefficient)

polar jet outflow powered by
neutrino annihilation
(or magnetic-field effects
not included here)





Evolutionary phases 4: expansion until homology



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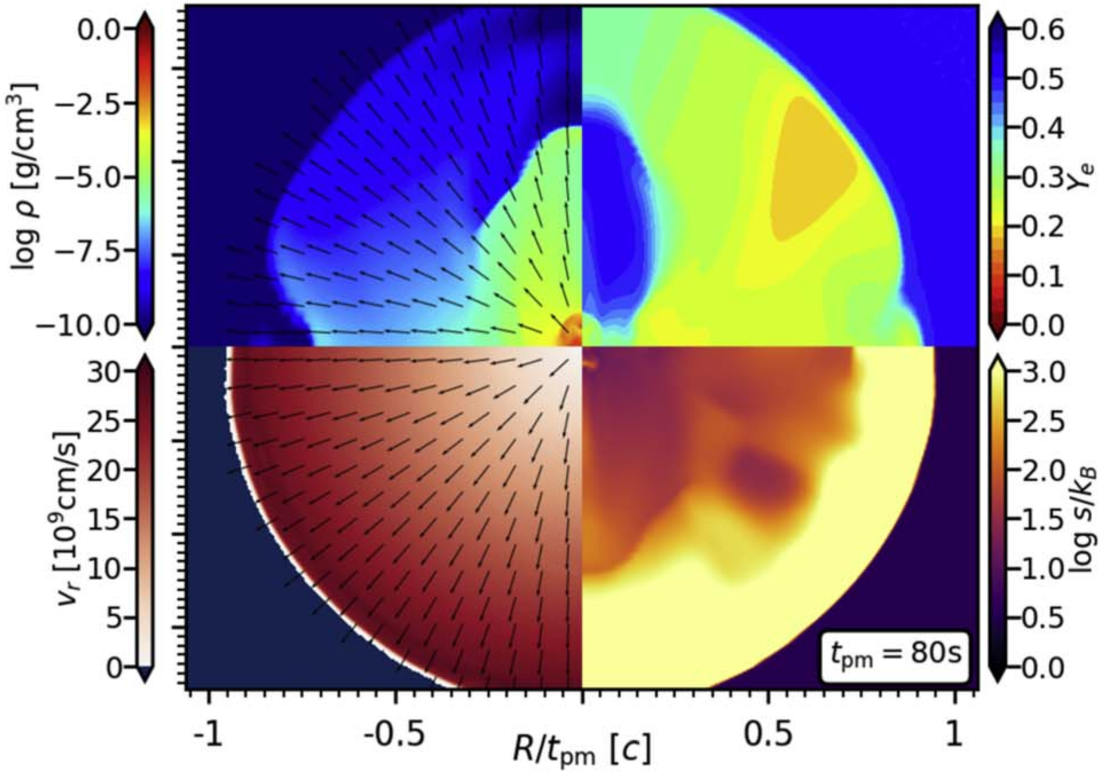
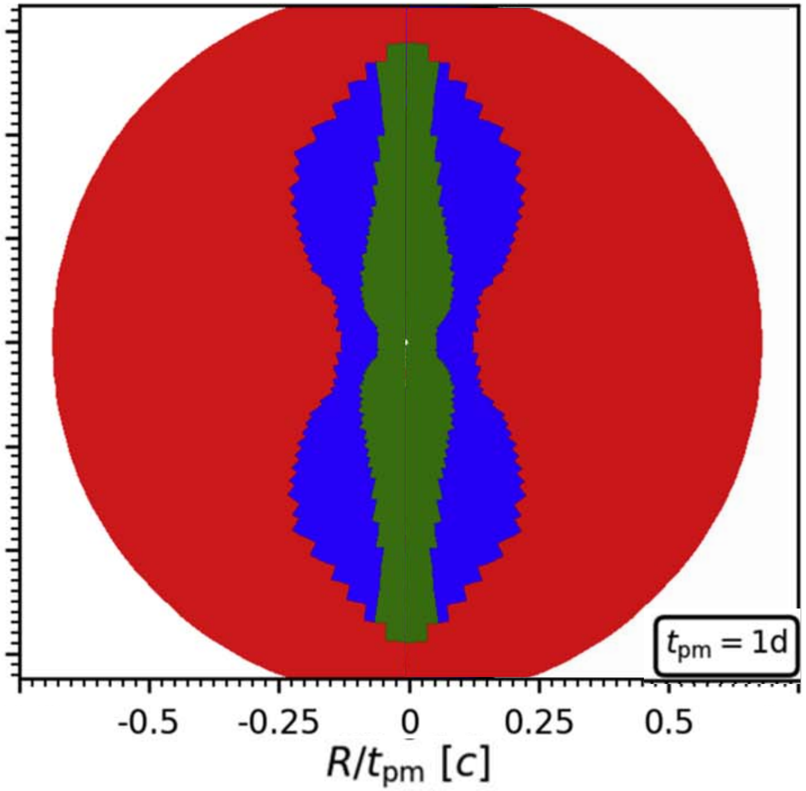
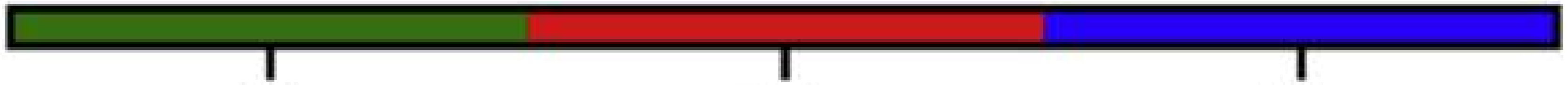






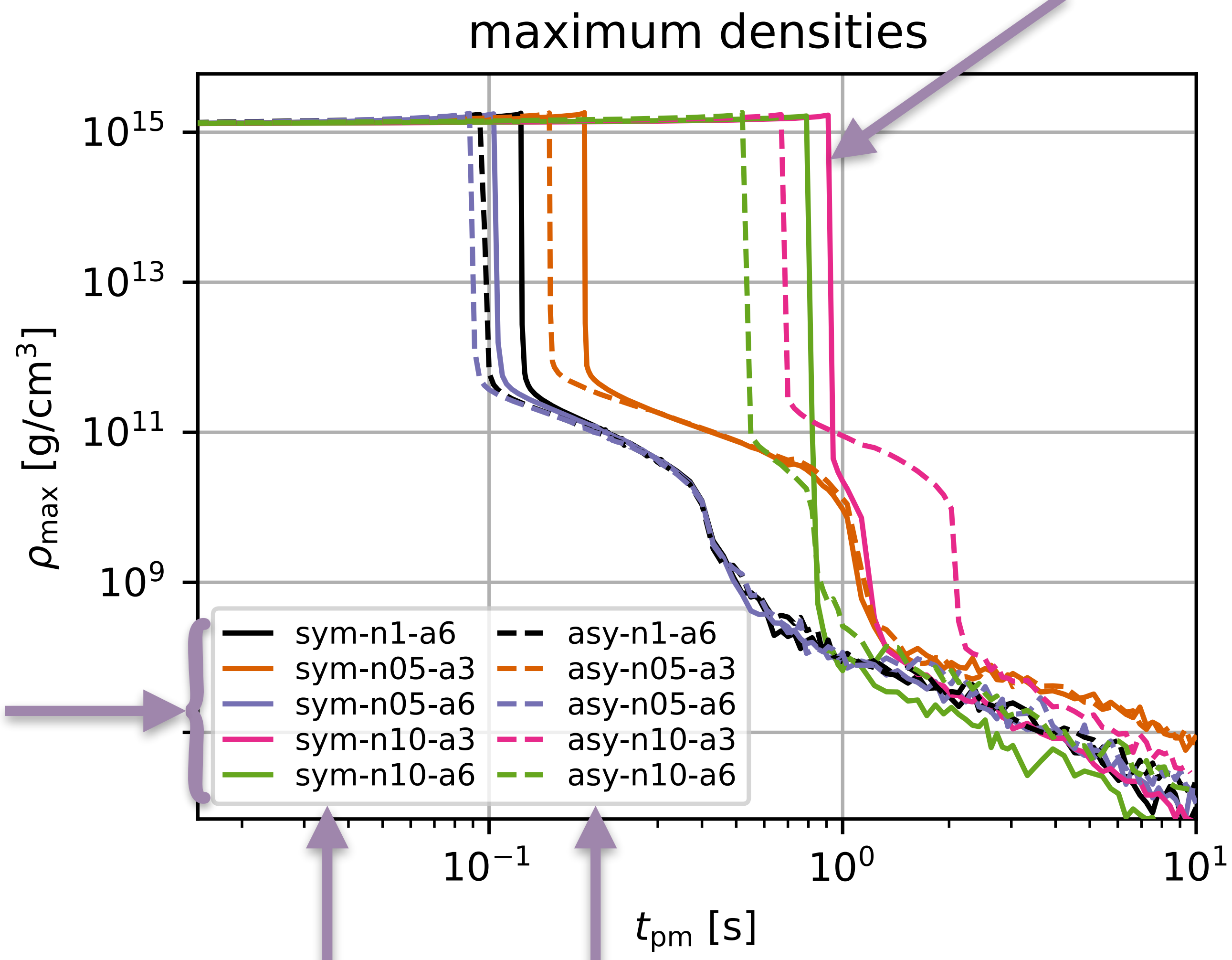
BH-torus ejecta:
m ~ 0.01–0.04 $M_\odot$
<v> ~ 0.03–0.1 c

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

NS lifetime until BH formation

steep drop marks
BH formation



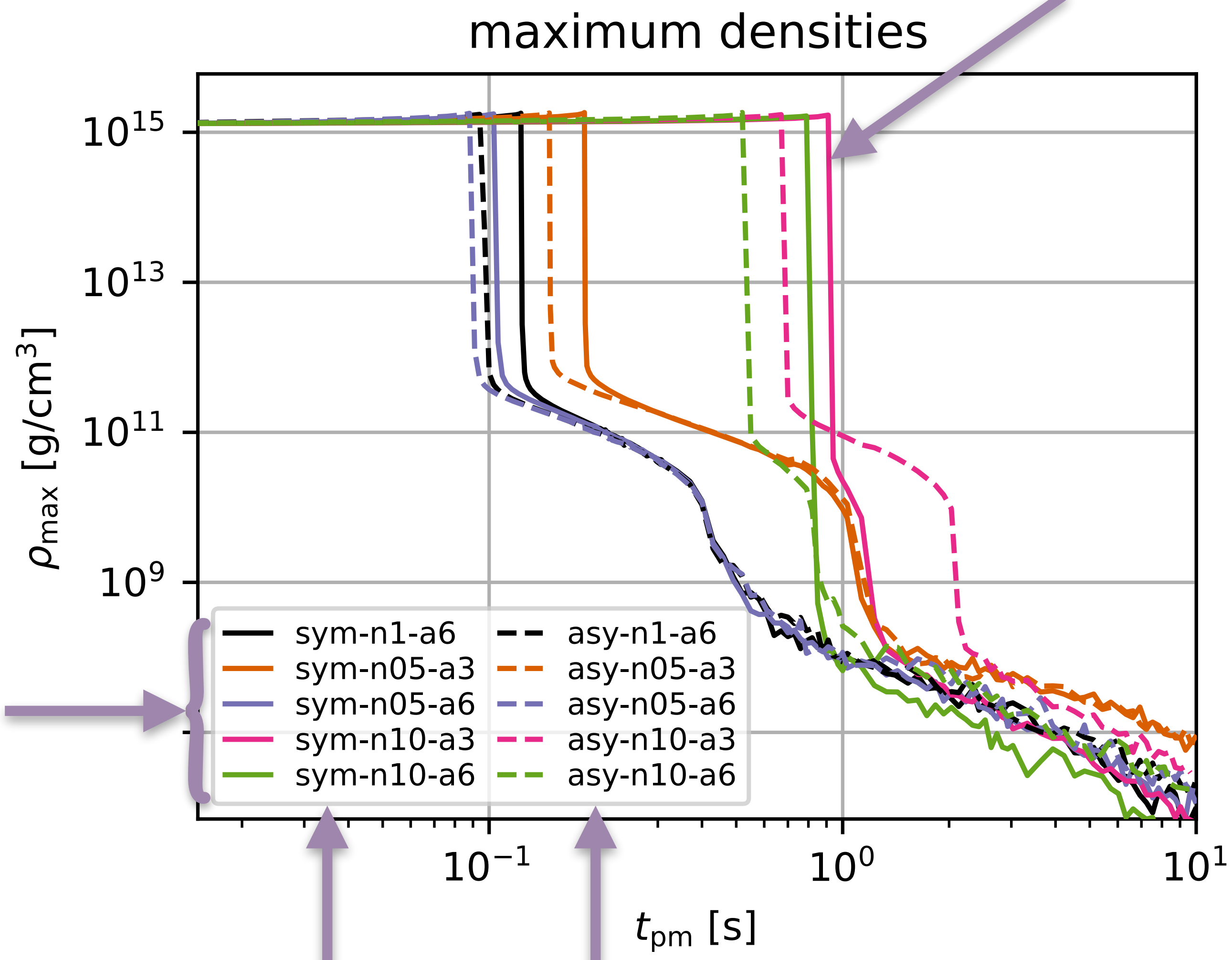
variation of
viscosity

symmetric
models

asymmetric
models

NS lifetime until BH formation

steep drop marks BH formation



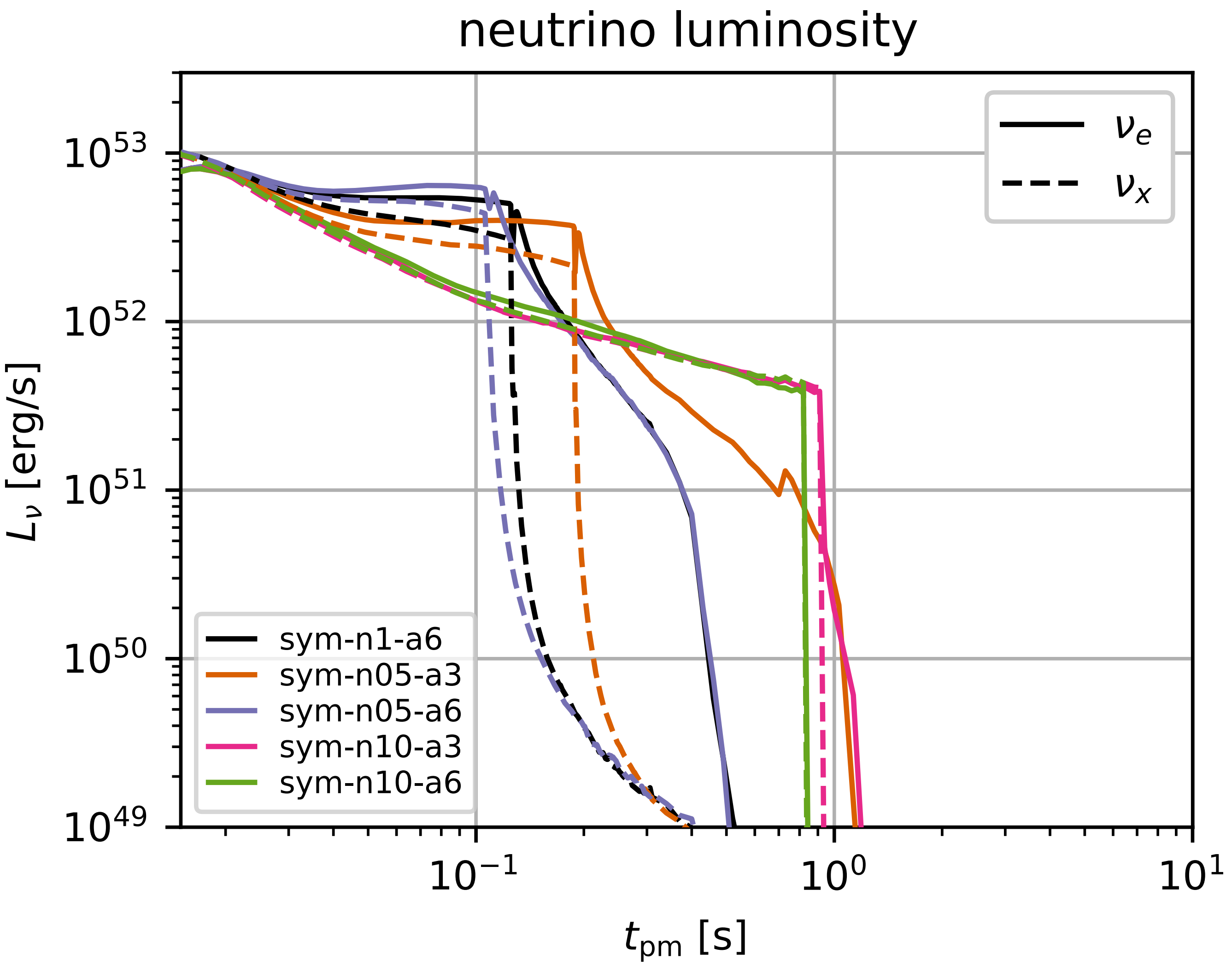
variation of viscosity

symmetric models

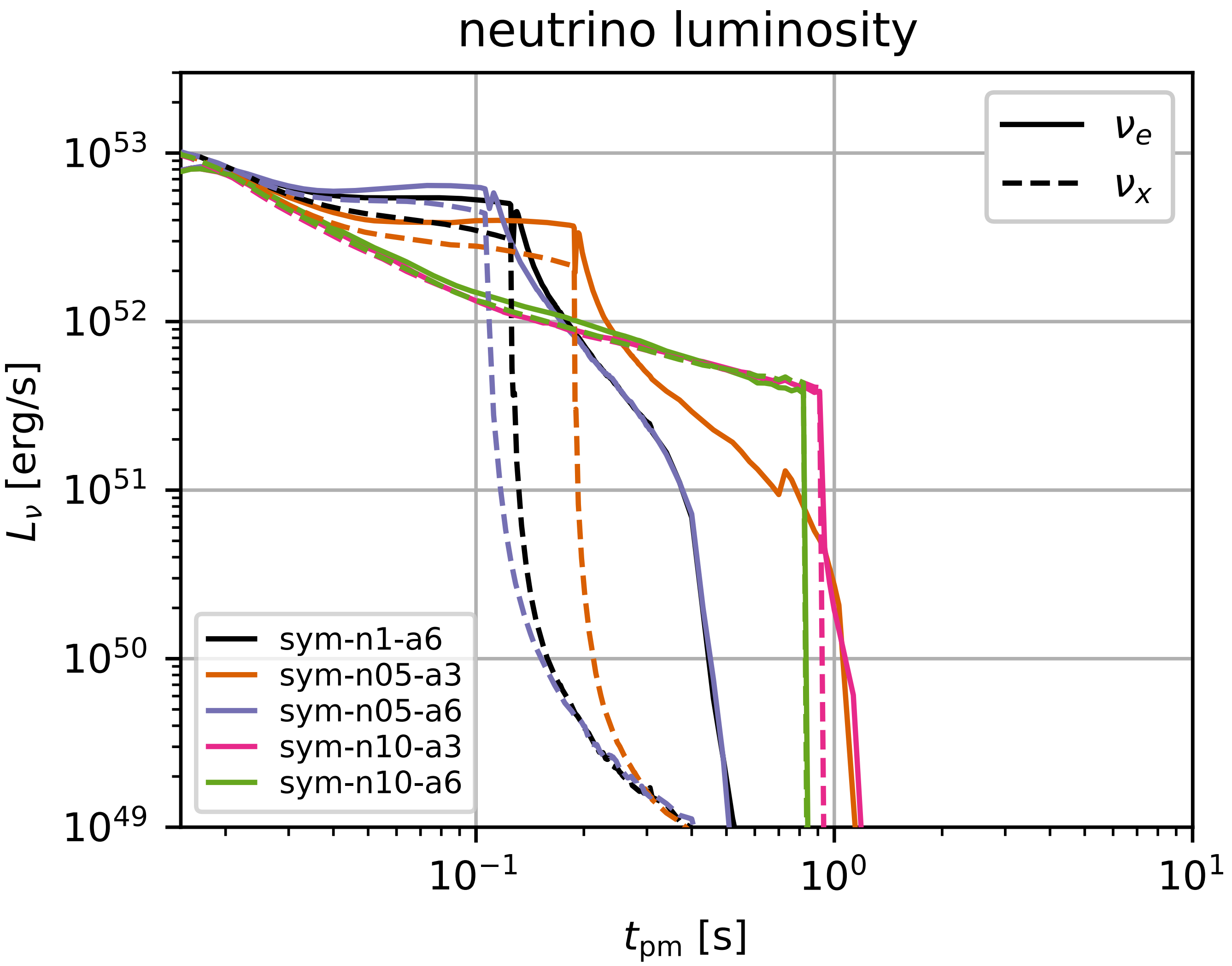
asymmetric models

- asymmetric mergers tend to lead to more slowly rotating NS remnants
  —> asymmetric models collapse systematically earlier than symmetric models (for same viscosity)
- strong sensitivity to viscosity
  —> solid understanding of viscosity required to predict NS lifetime for given progenitor

Neutrino emission

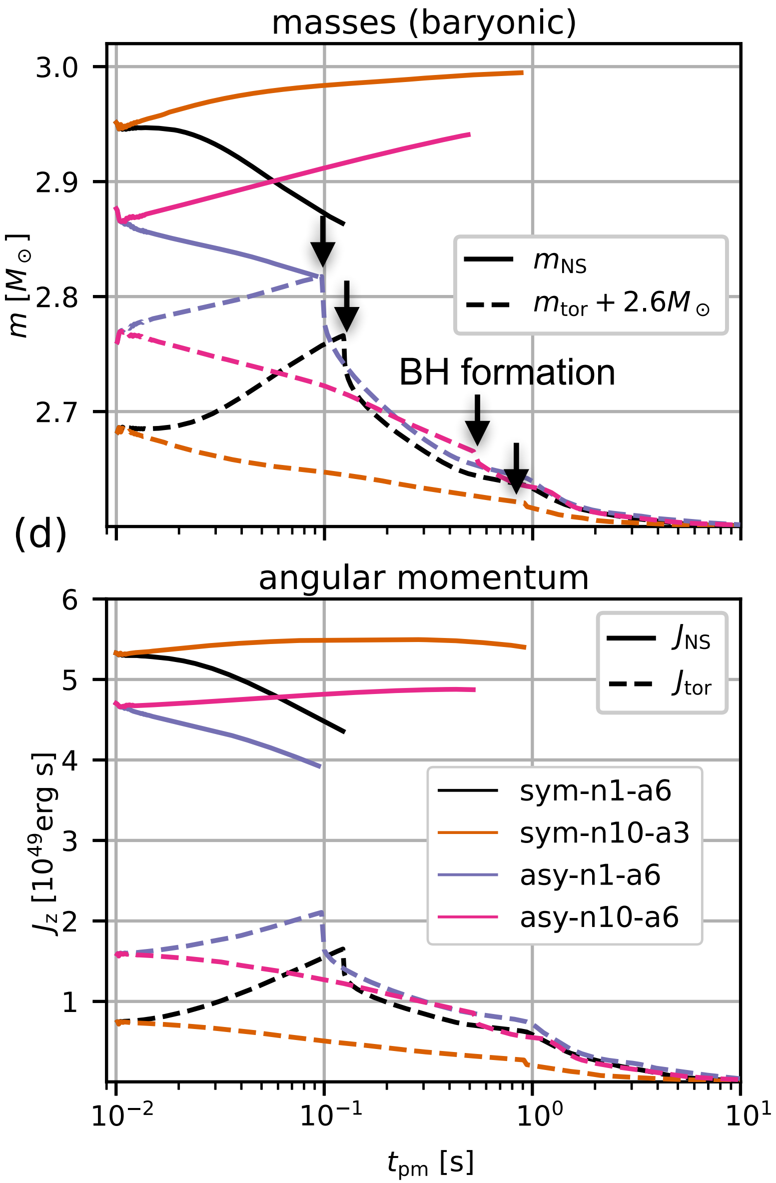


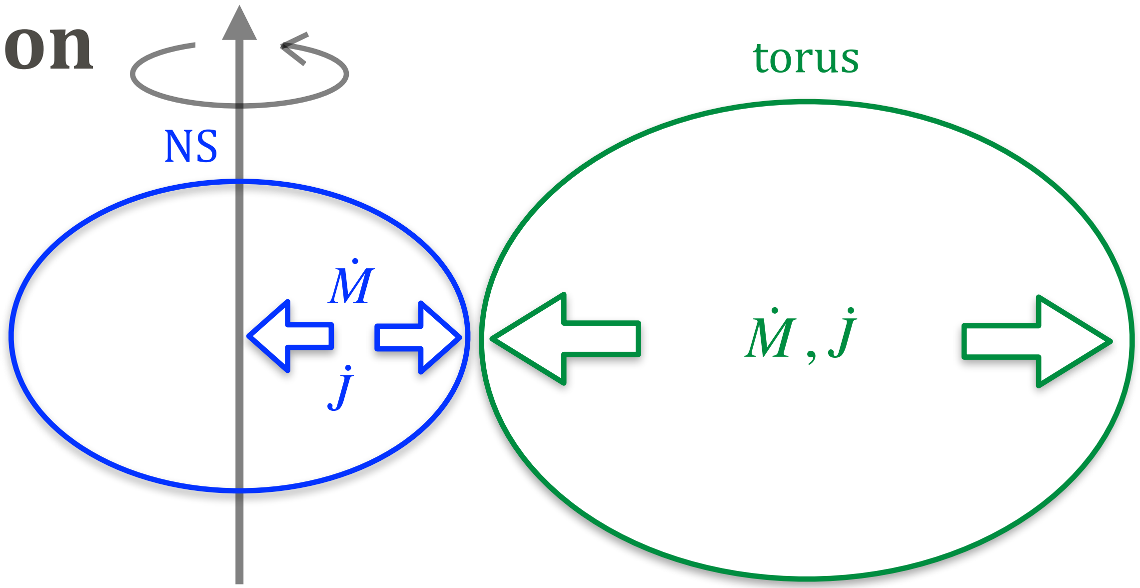
Neutrino emission



- stronger viscosity causes higher luminosities —> stronger neutrino-driven wind
- however, total wind mass comparable between all models, because cases of stronger viscosity have shorter NS lifetimes

Torus mass @ BH formation





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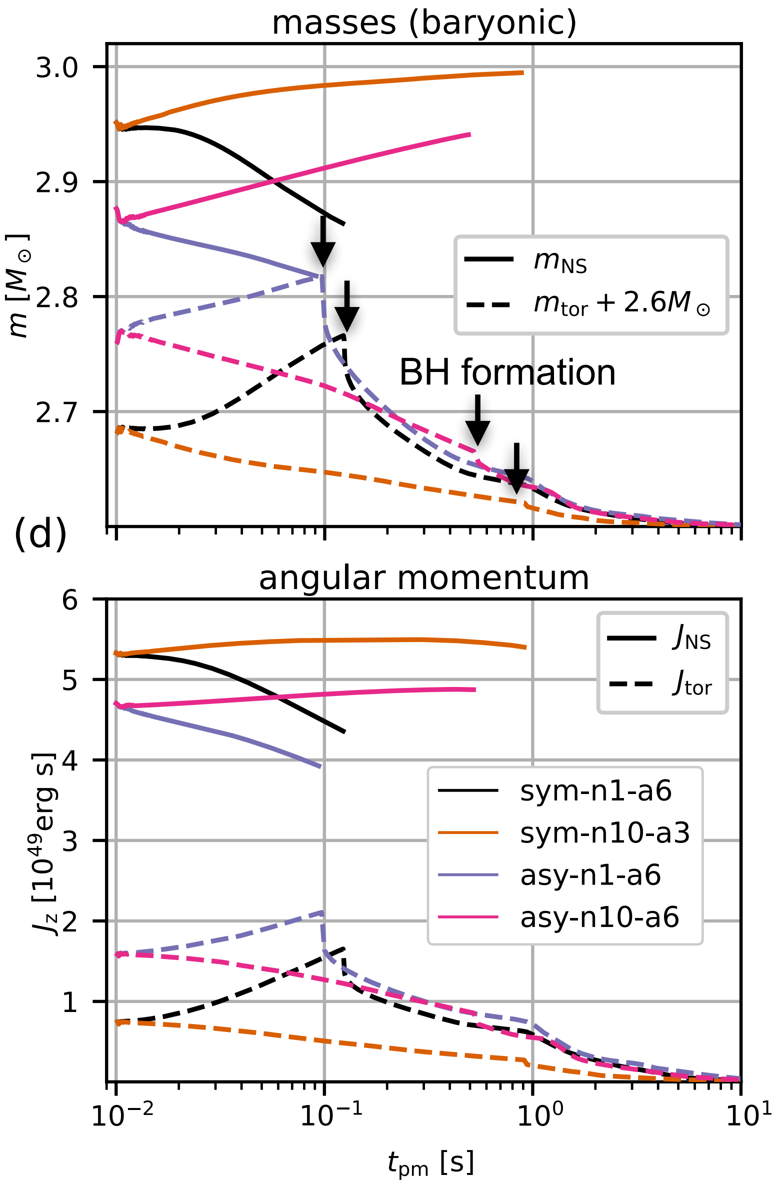
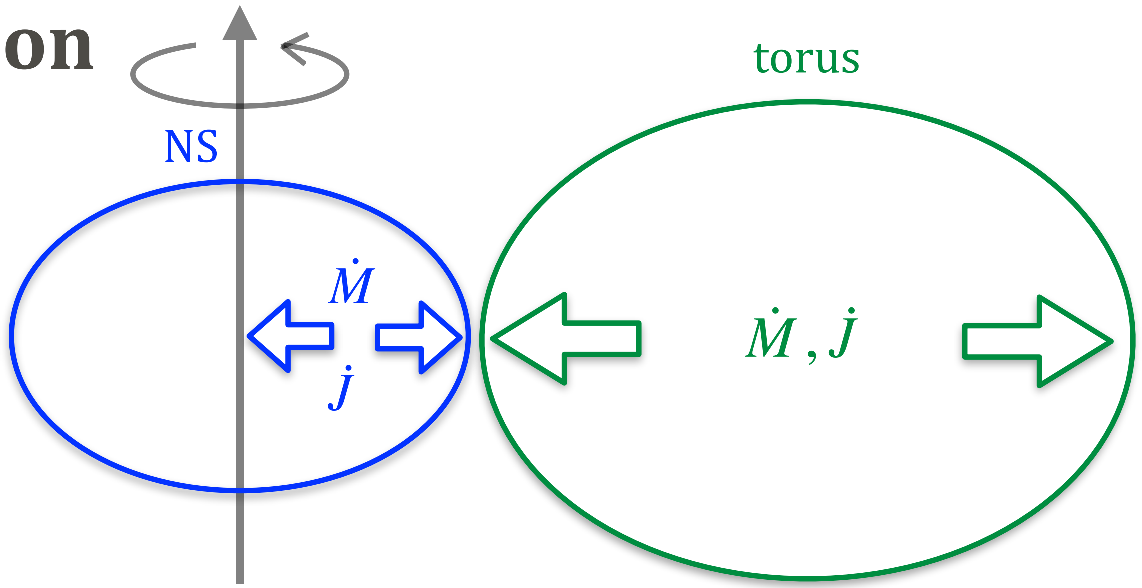
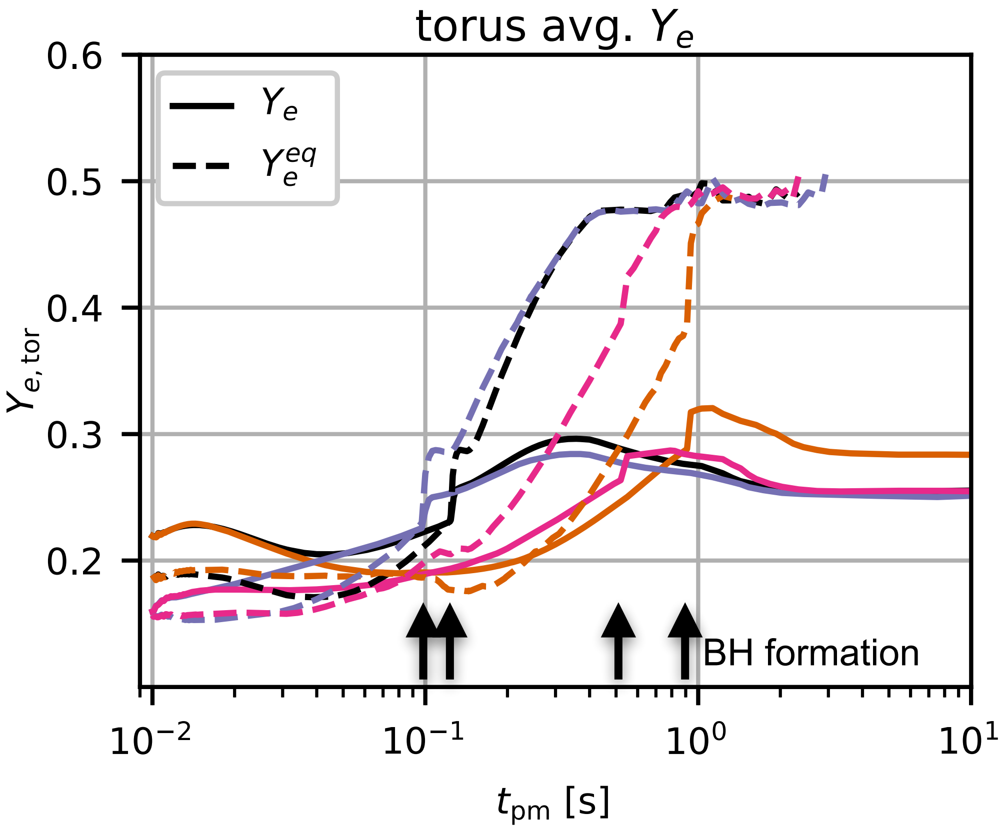




- initial BH torus mass m_{tor} (t_{BH}) relevant property for models of BH-torus remnants
- m_{tor} result of competition between angular momentum transport in NS and torus
- for strong (weak) NS viscosity —> m_{tor} grows (declines) with time until t_{BH}

Torus neutron-richness @ BH formation

$$Y_e = \frac{N_{\text{proton}}}{N_{\text{proton}} + N_{\text{neuton}}}$$



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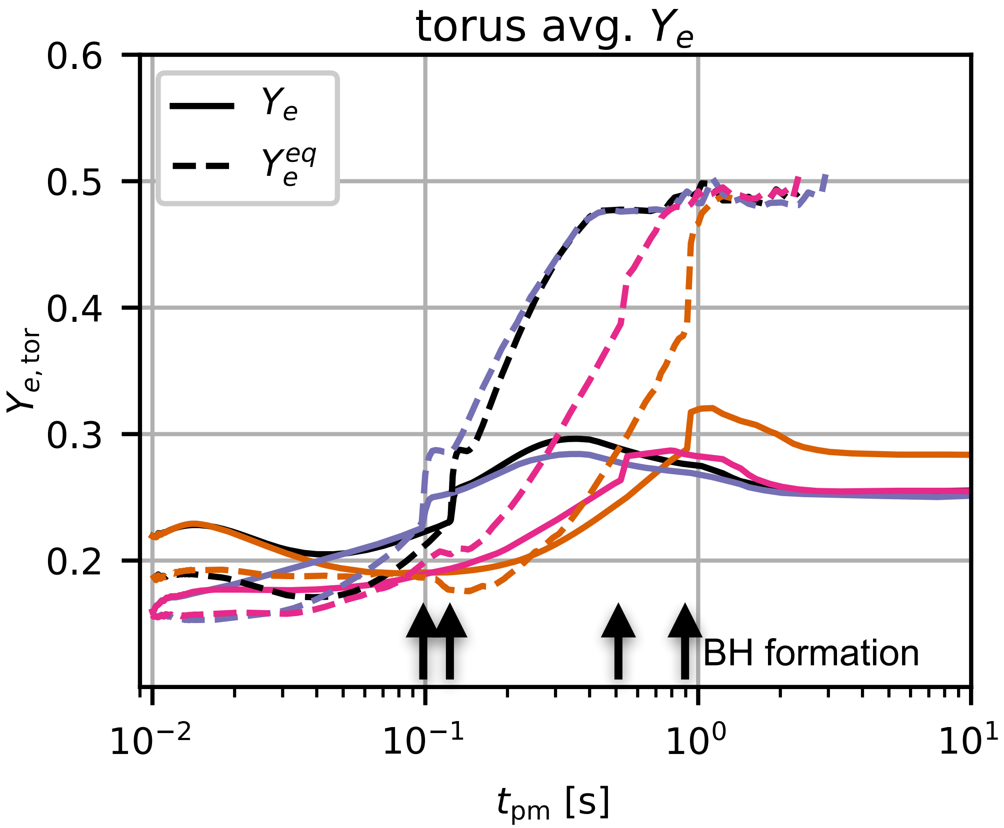
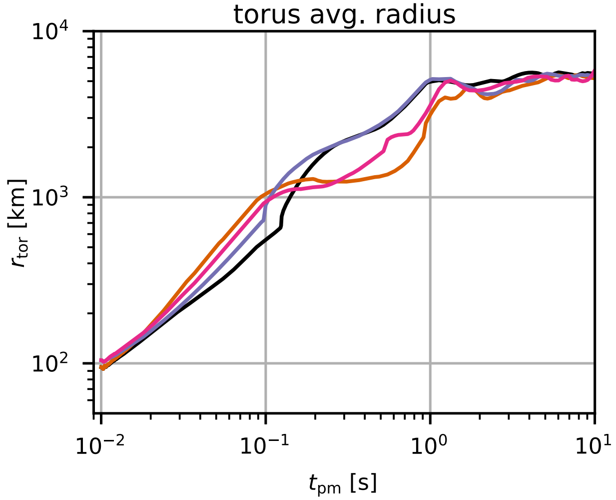
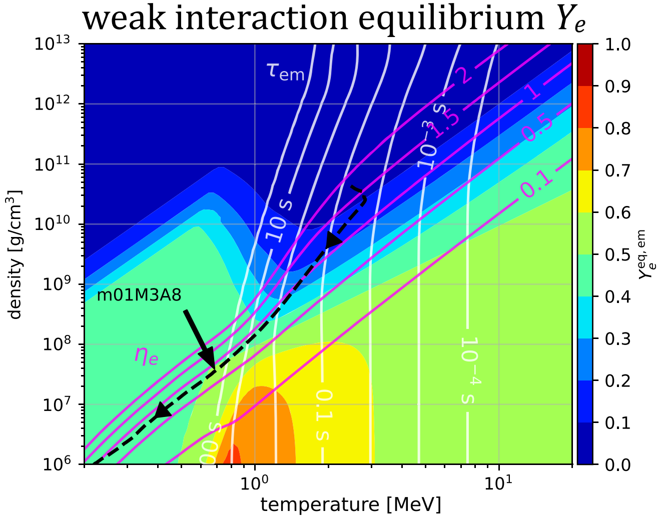
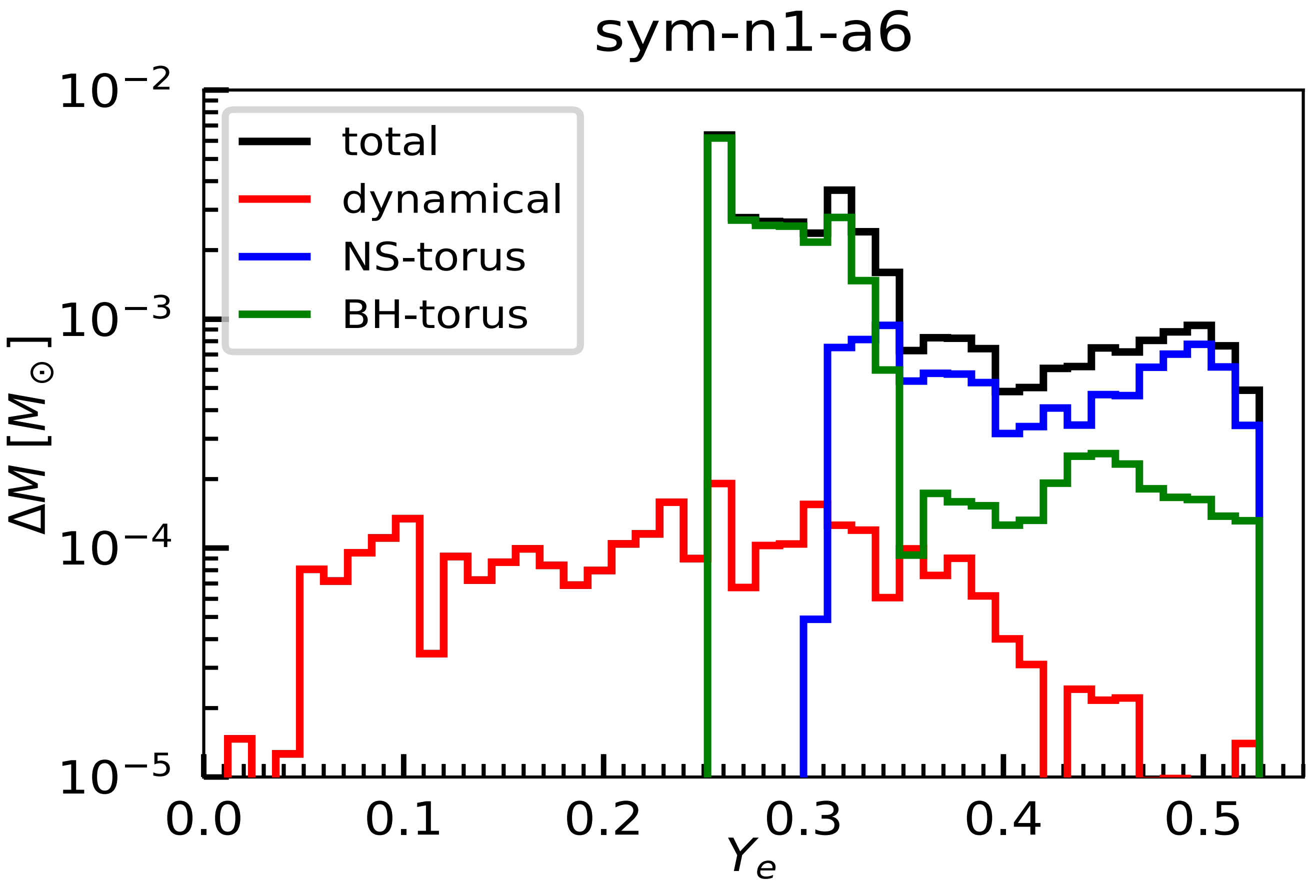






- $Y_e \sim 0.25$–0.3 at birth of BH torus
- Y_e higher than assumed by many previous BH torus studies based on manually constructed initial conds.
- **reason:** disk expansion during NS phase —> low densities = high weak equilibrium Y_e

Neutron richness by ejecta component



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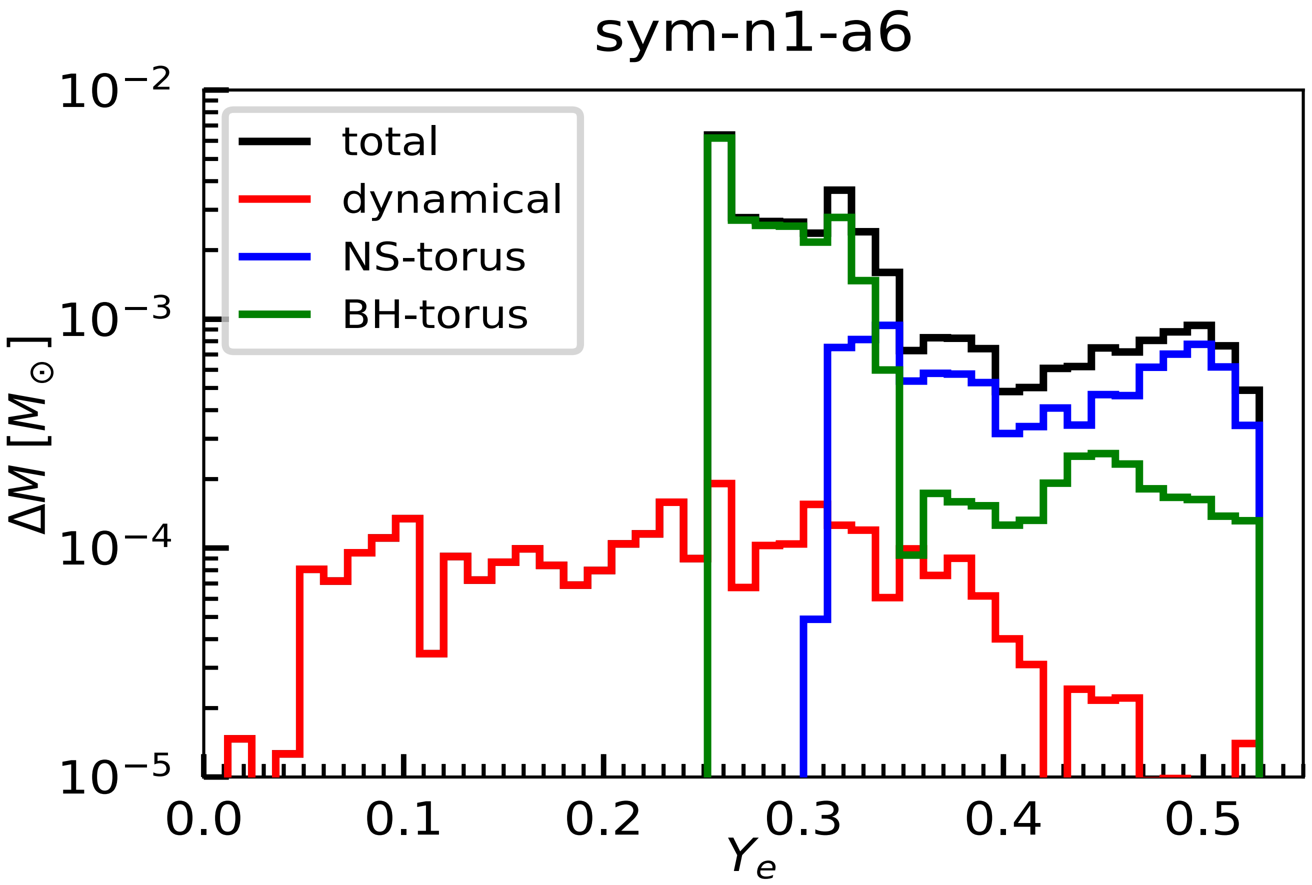
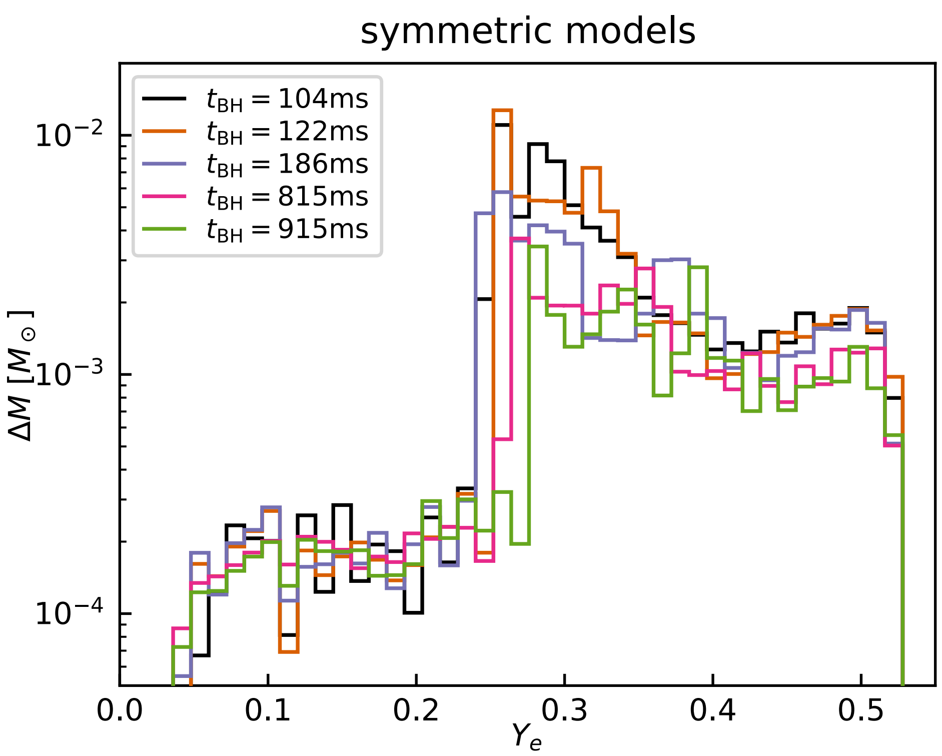
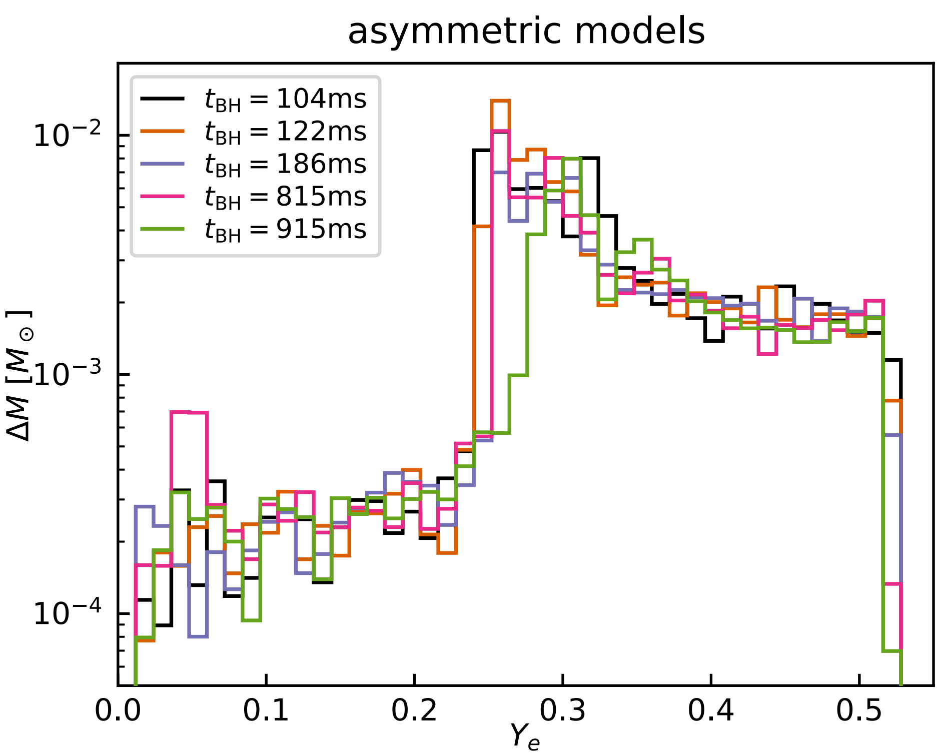


- NS-torus ejecta $Y_e > 0.3$, dominated by neutrino-driven wind
- BH-torus ejecta $Y_e > 0.25$, mainly viscous winds with high equilibrium Y_e at freeze-out
- $Y_e < 0.25$ only reached by dynamical ejecta

Total neutron richness by model

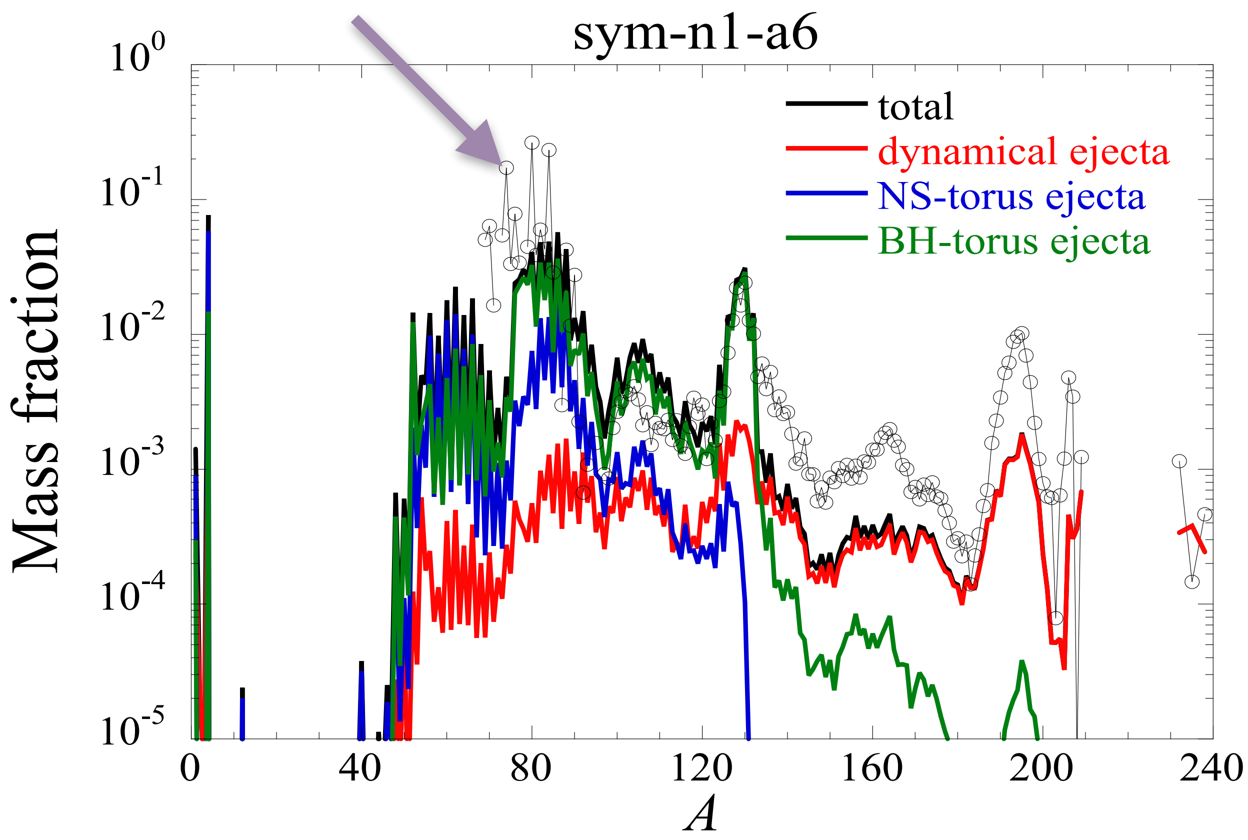




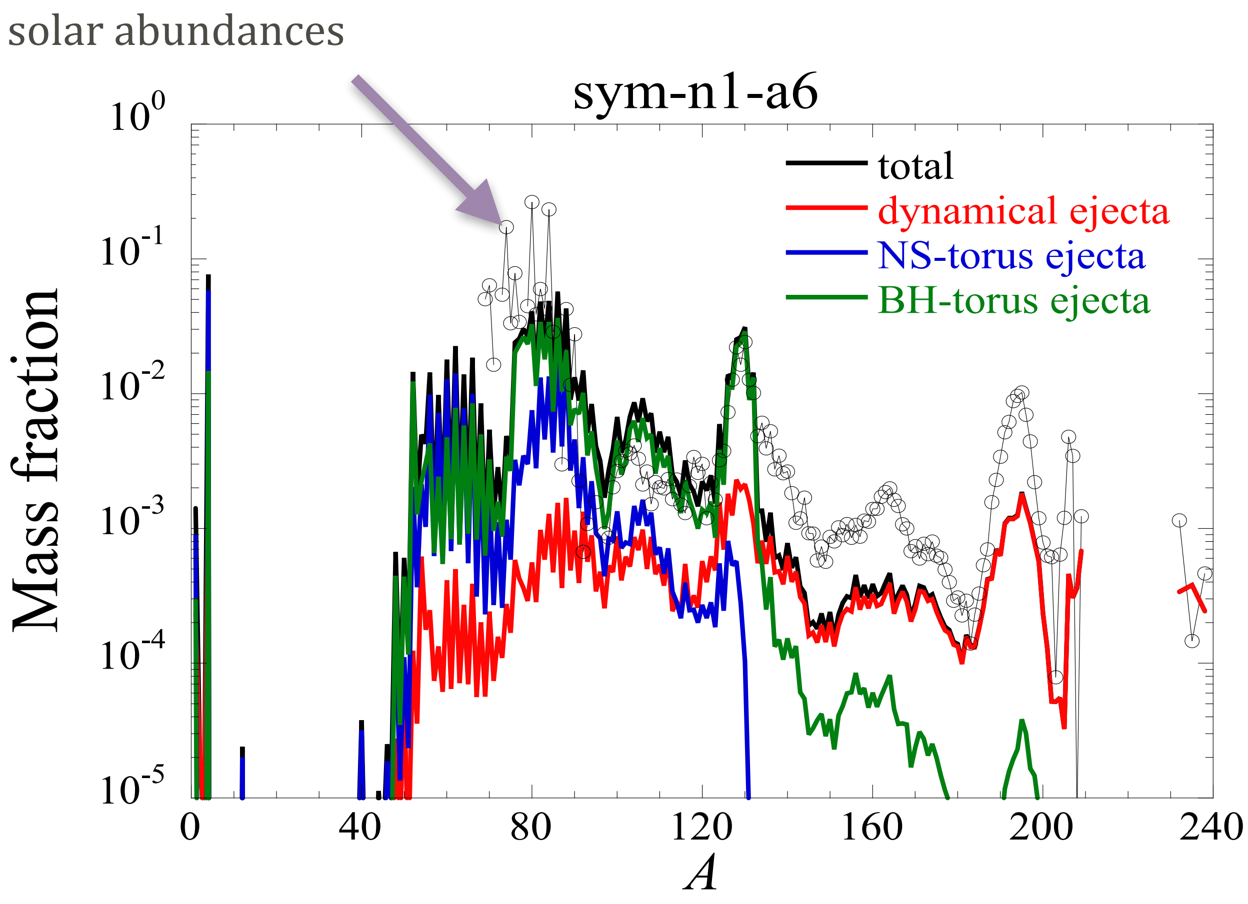
- Y_e pattern relatively robust w.r.t. different viscosities and mass ratio
- trend towards less neutron-rich matter for longer NS lifetime

Ejecta nucleosynthesis yields

solar abundances

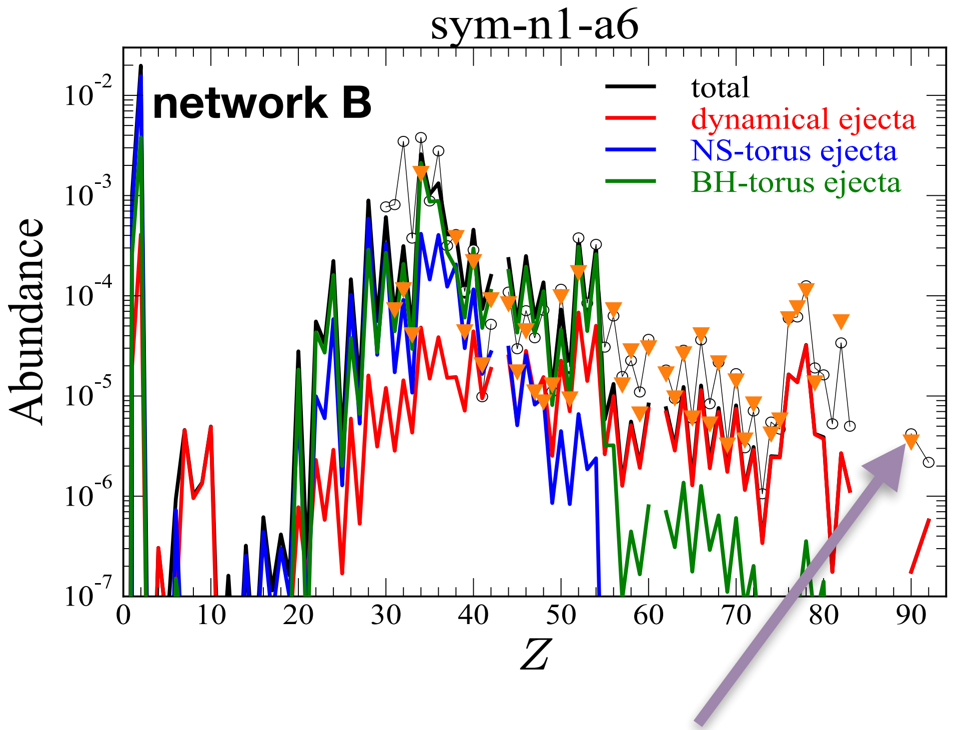


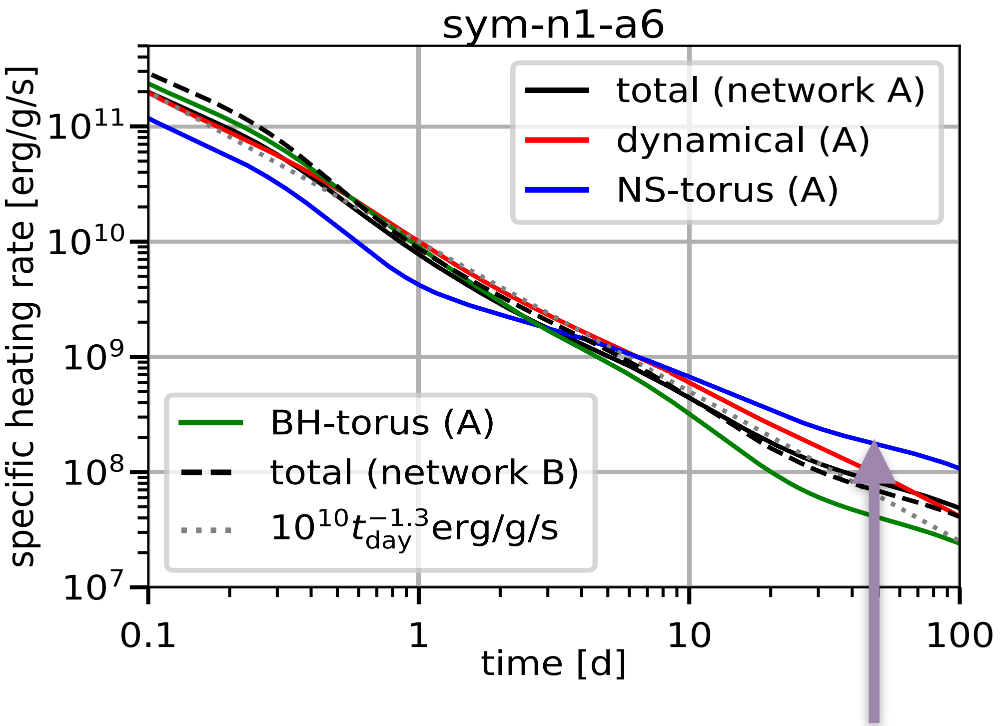
Ejecta nucleosynthesis yields



- dominance of high Y_e material causes underproduction of A>130 elements cp. to solar abundance pattern
- suggests that delayed collapse mergers are sub-dominant r-process sites and that most mergers have short delay times (<~0.1seconds)
- results consistent with models of short and very long delay times by Fujibayashi et al.

Elemental yields + spec. heating rate

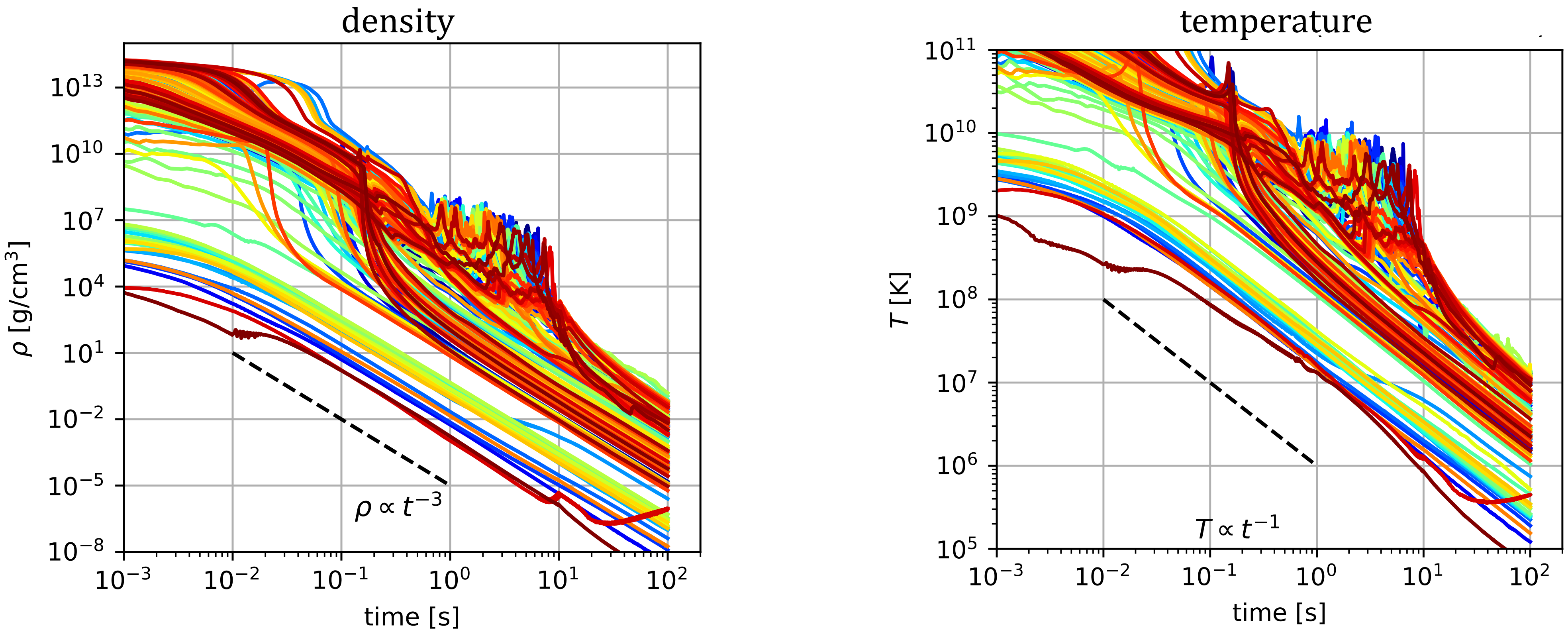




observed metal-poor star
HD 222925 (Roederer '22)

late-time increase in NS-torus ejecta
from Ni56 and Co56 decay

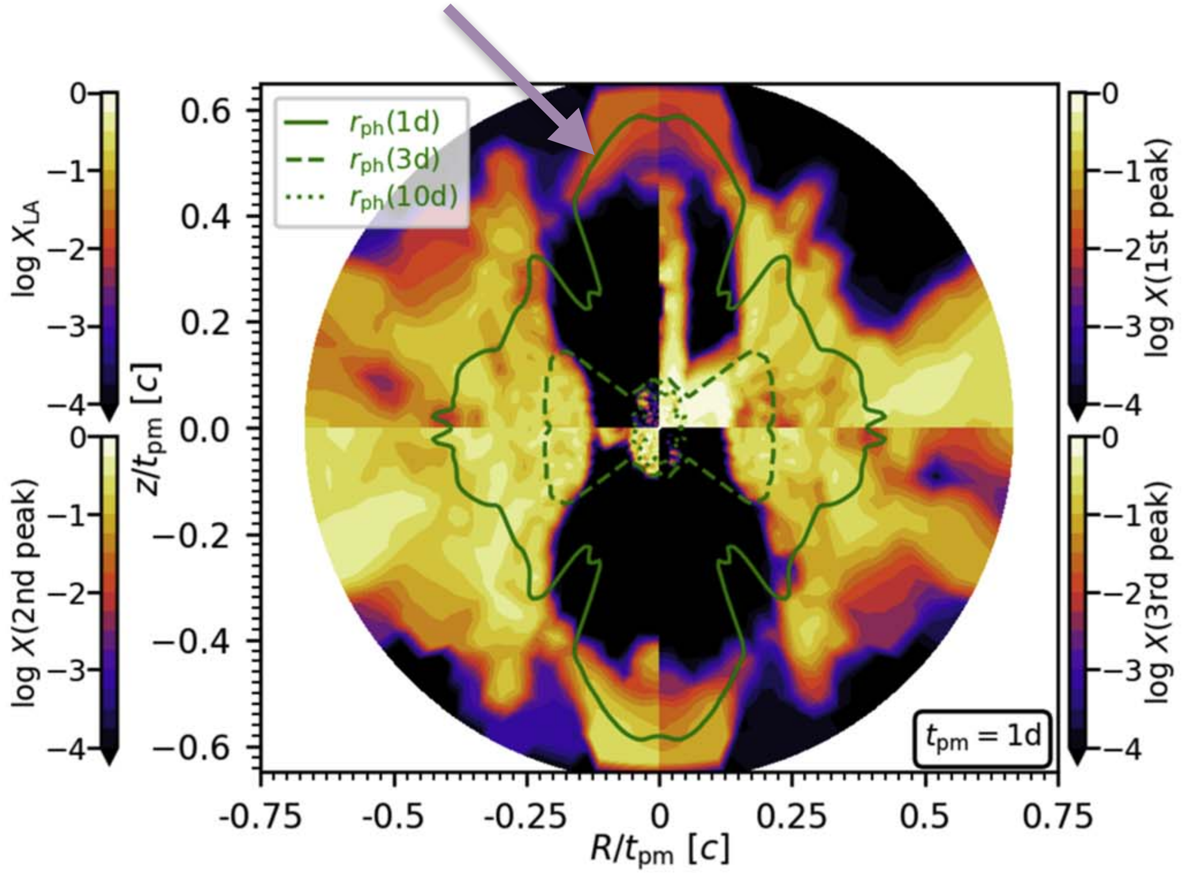
Ejecta expansion towards homology



- each line represents a finite-mass outflow trajectory
- r-process heating ignored
- almost all outflow homologous after 100s

Ejecta geometry and composition

time dependent
location of photosphere



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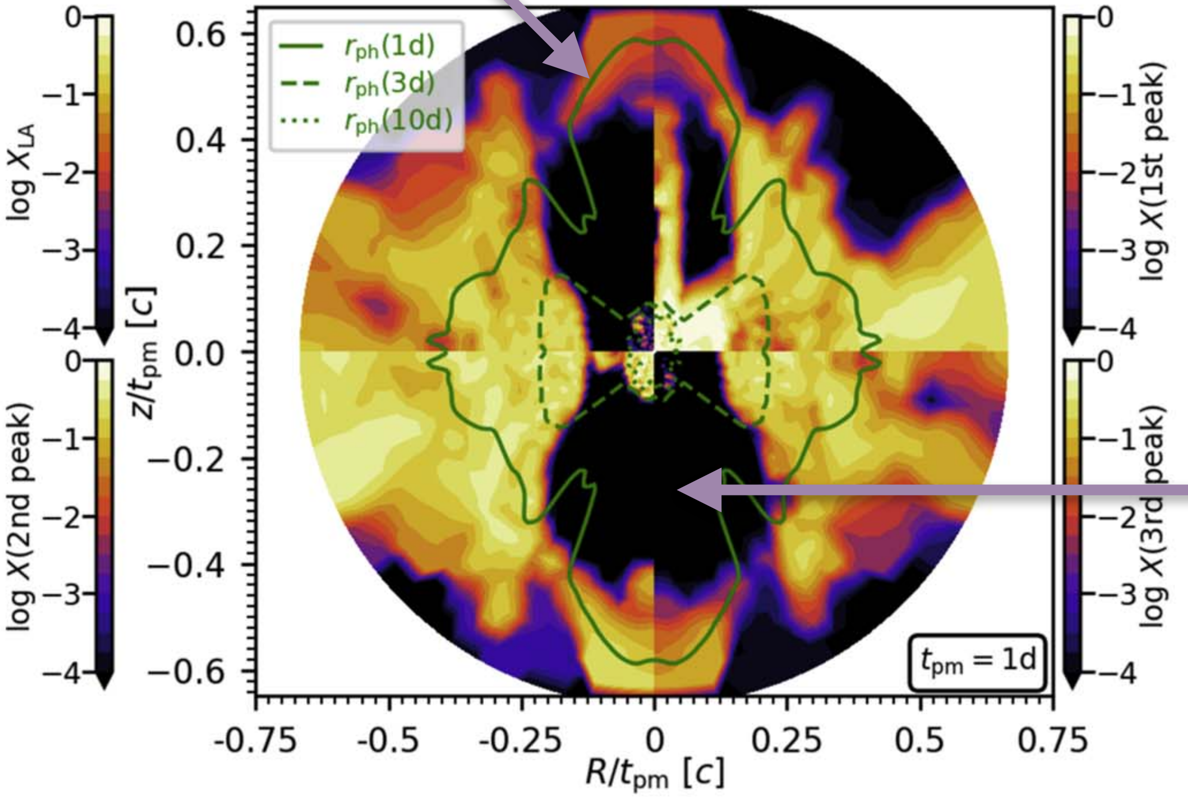
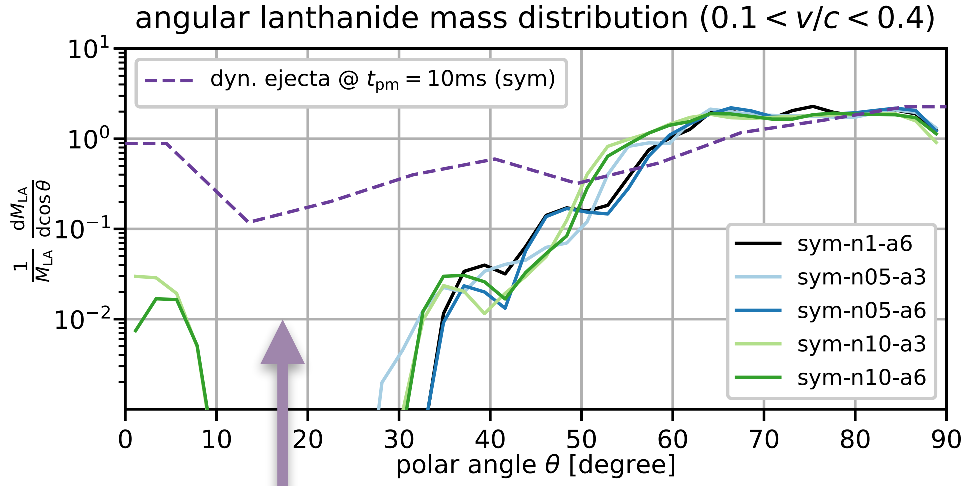
location of photosphere



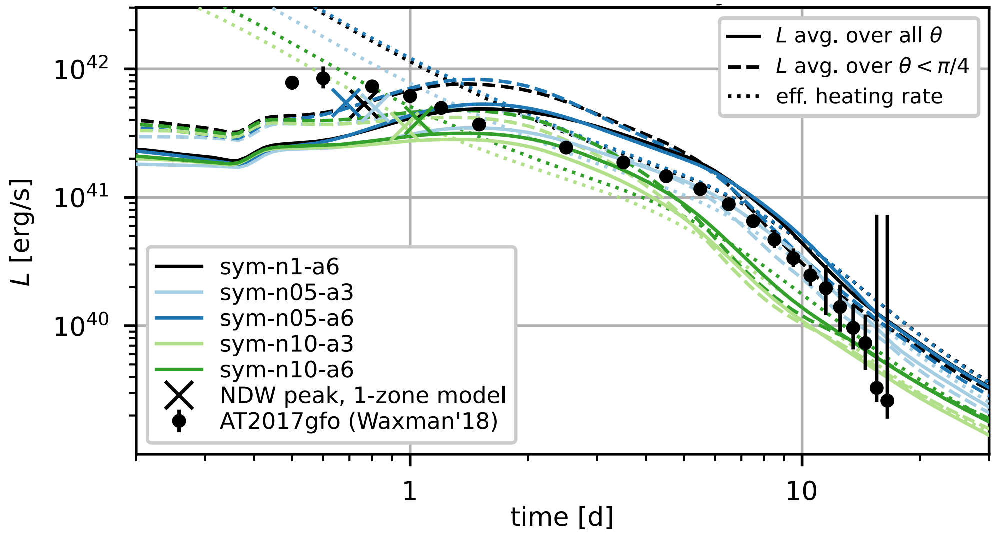


polar neutrino-driven wind pushes aside dynamical ejecta and creates a polar “hole” for abundances of A>100 elements

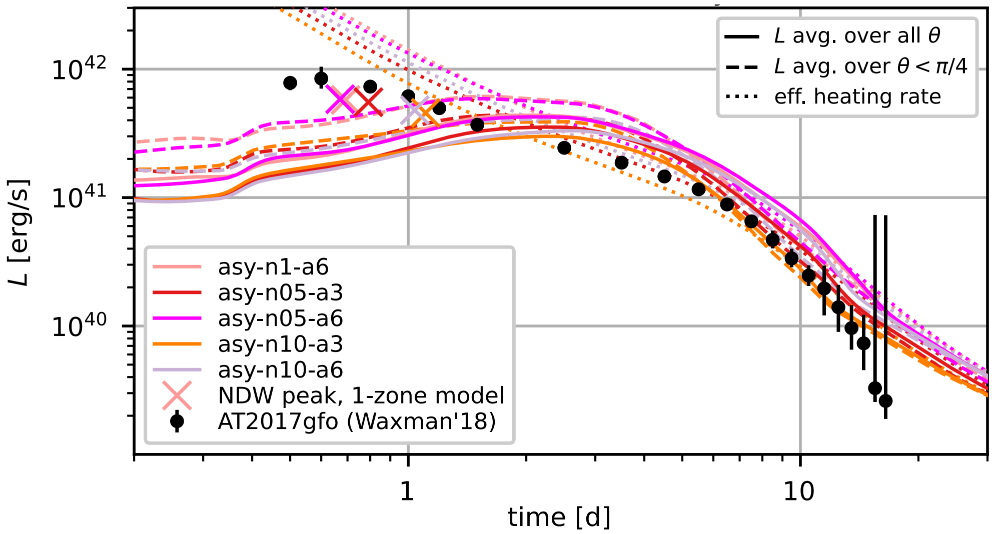
—> impact of anisotropy on the kilonova may be used to distinguish prompt from delayed collapse events (cf. Sneppen ’23)

Kilonova: comparison with GW170817/AT2017gfo

symmetric models



asymmetric models



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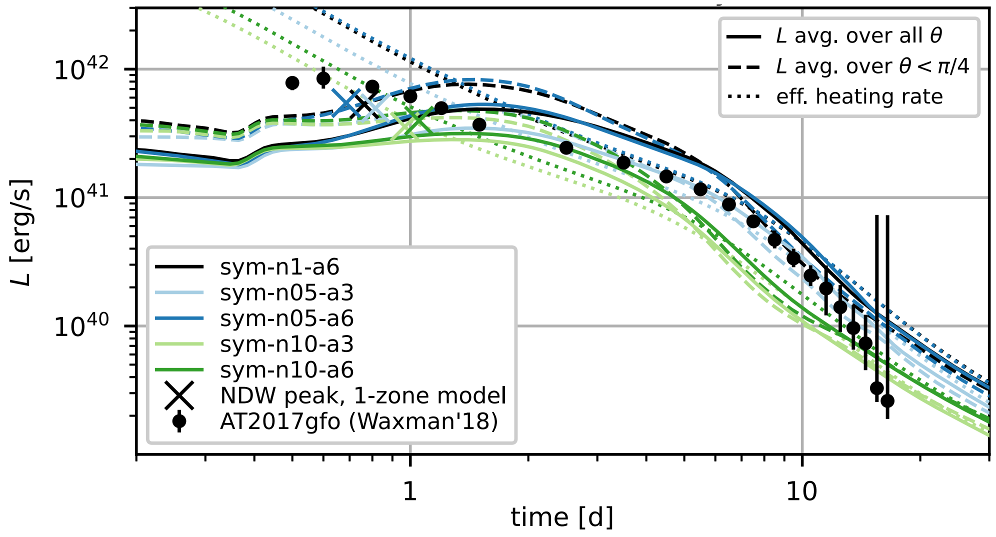
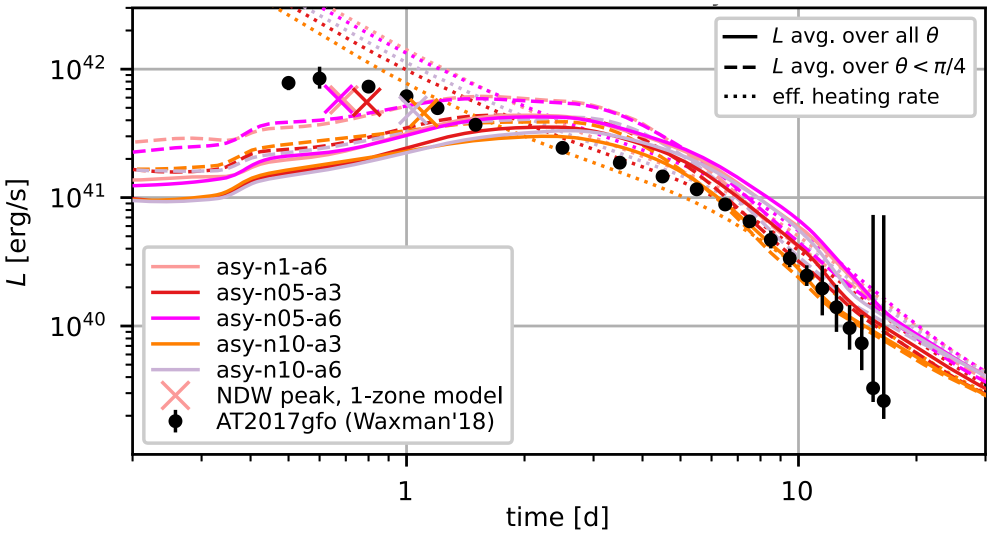
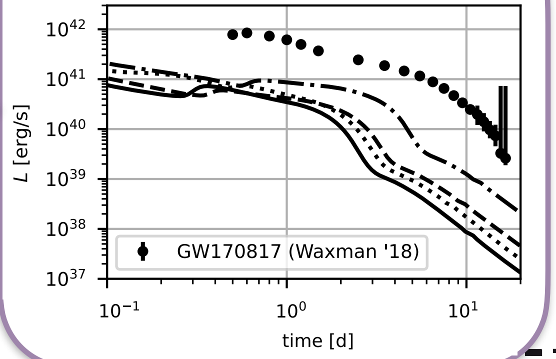


asymmetric models



- overall good agreement with AT2017gfo
- post-merger ejecta make the KN signal brighter and longer than for just the dynamical ejecta
- slightly too faint at early times $t < 1$day
- MHD effects **may** not be necessary to explain blue component of GW170817 (e.g. Metzger ’18, Siegel ’22, Kiuchi ’22, Curtis ’23)

dynamical ejecta only:



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5. How does the NS lifetime affect the kilonova?
   - long NS lifetime —> more anisotropic ejecta composition (polar neutrino wind, equatorial dynamical ejecta)
   - MHD effects maybe not required to explain blue component of GW170817

Impact of fast flavor conversions in BH disks

OJ, Abbar, Wu, Tamborra, Janka, Capozzi ‘22

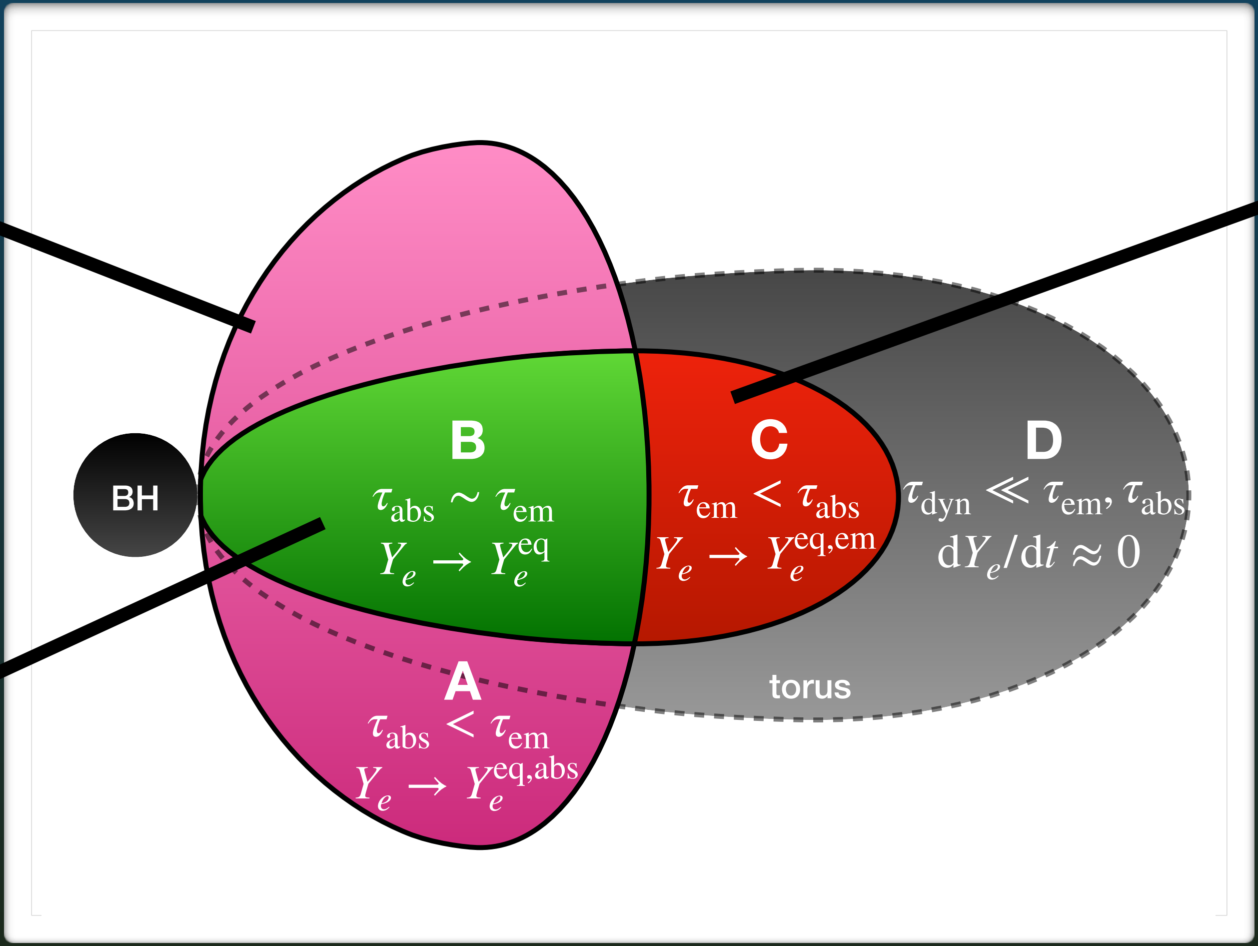
Characteristic regimes of Y_e equilibria in BH disks

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

because n(nue)~n(nuebar) during the quasi-stationary secular evolution

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

$Y^{eq,em}$ determined by thermodynamic state only

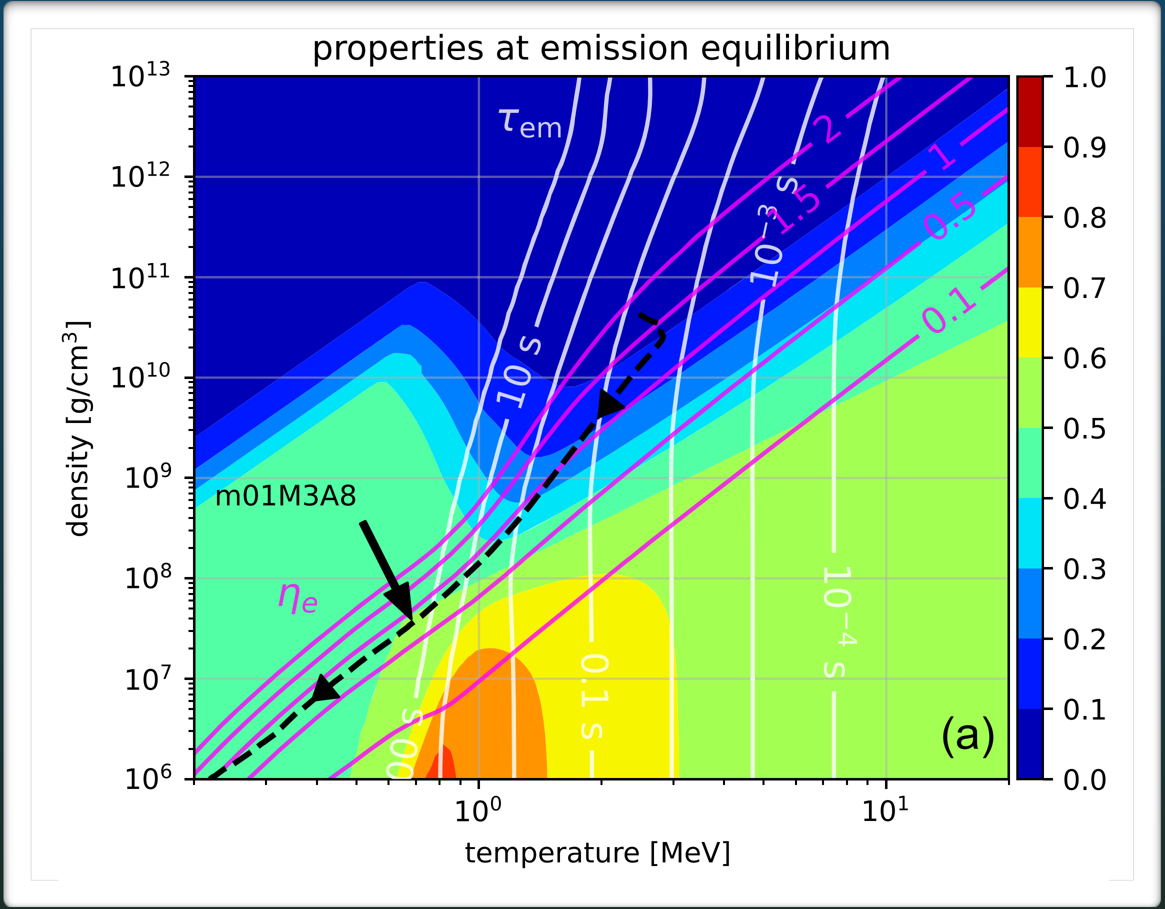


(from OJ, Goriely, Janka, Nagataki, Bauswein '22)

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

Y^{eq} determined by thermodynamic state + neutrino field

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



- generically low Y_e for neutrino-cooled disks because of moderate electron degeneracy eta~1
- freeze-out at relatively low Ye roughly when weak timescales tau_{em} > 1-10 seconds

Impact of instantaneous flavor mixing

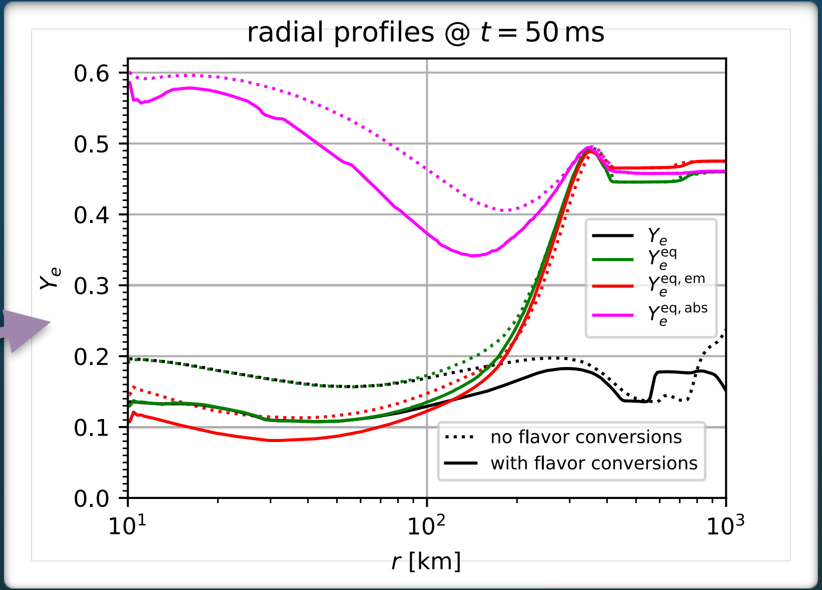
flavor equipartition, e.g. like:

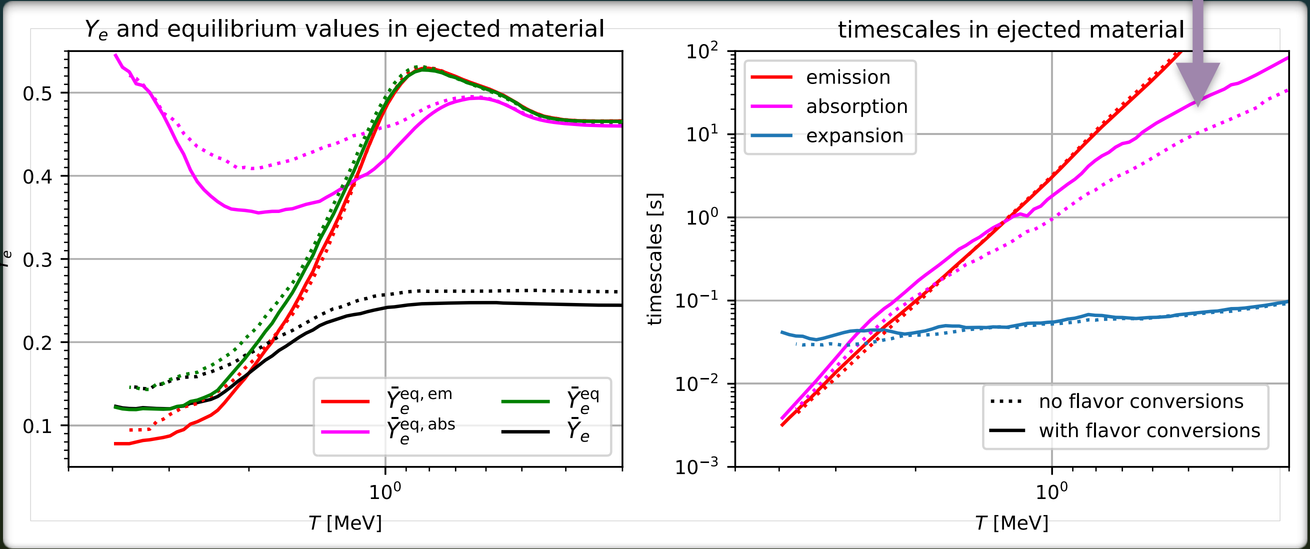
$$n_\nu = \frac{1}{6}\left(n^0_{\nu_e,q} + n^0_{\bar{\nu}_e,q} + 2n^0_{\nu_x,q} + 2n^0_{\bar{\nu}_x,q}\right)$$

✓ two main effects due to the effective creation of mu/tau neutrinos:

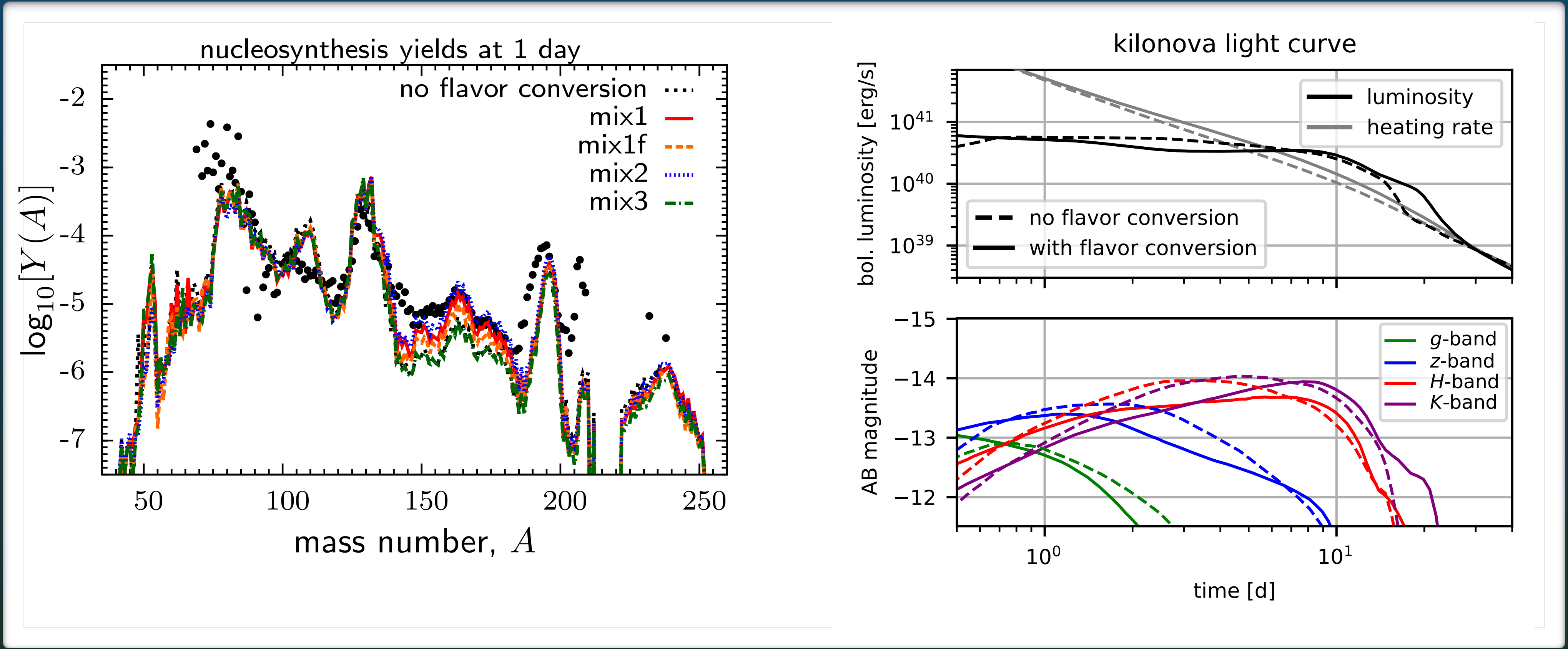
➡ enhanced neutrino cooling rates lead to high electron degeneracy and lower value of $Y_e^{\mathrm{eq,em}}$

➡ reduced abundances of electron-type neutrinos reduce impact of absorption and lead to additional reduction of Y_e^{eq}





Impact on nucleosynthesis and kilonova



- moderate enhancement of r-process yields
- mildly prolonged kilonova signal due to enhanced lanthanide abundance
- possibly larger effect for more realistic mixing/QKT treatment (???)