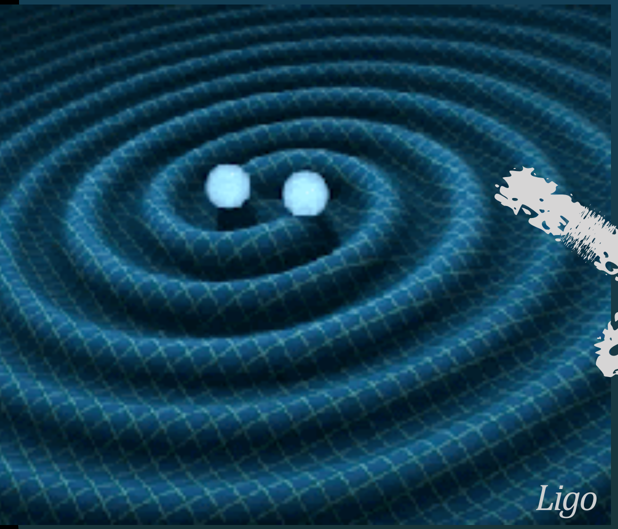
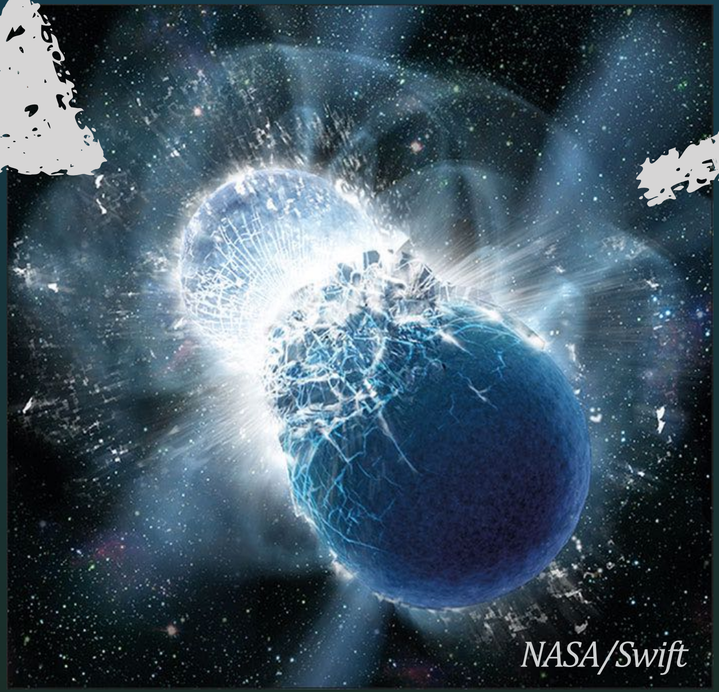
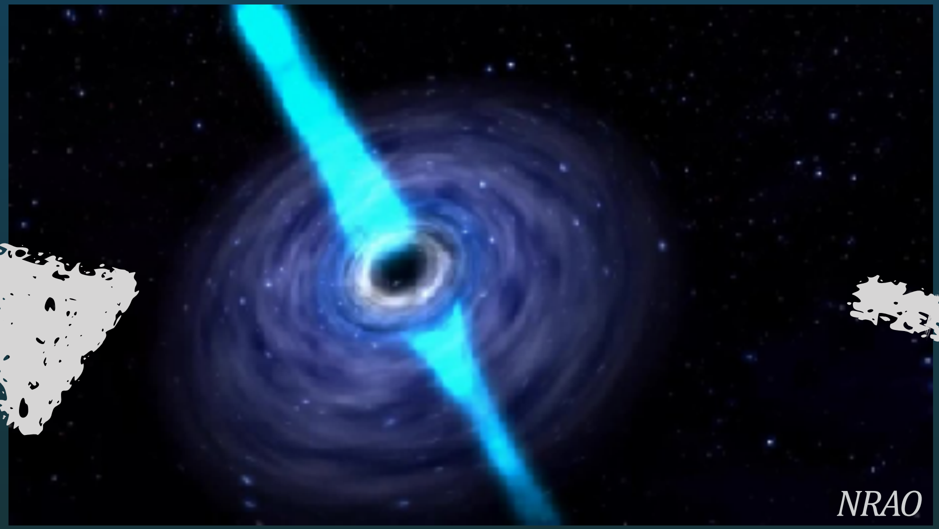
Weak-interactions, nucleosynthesis, and kilonovae


Ligo


NASA/Swift


NRAO


www.deraktionaer.de

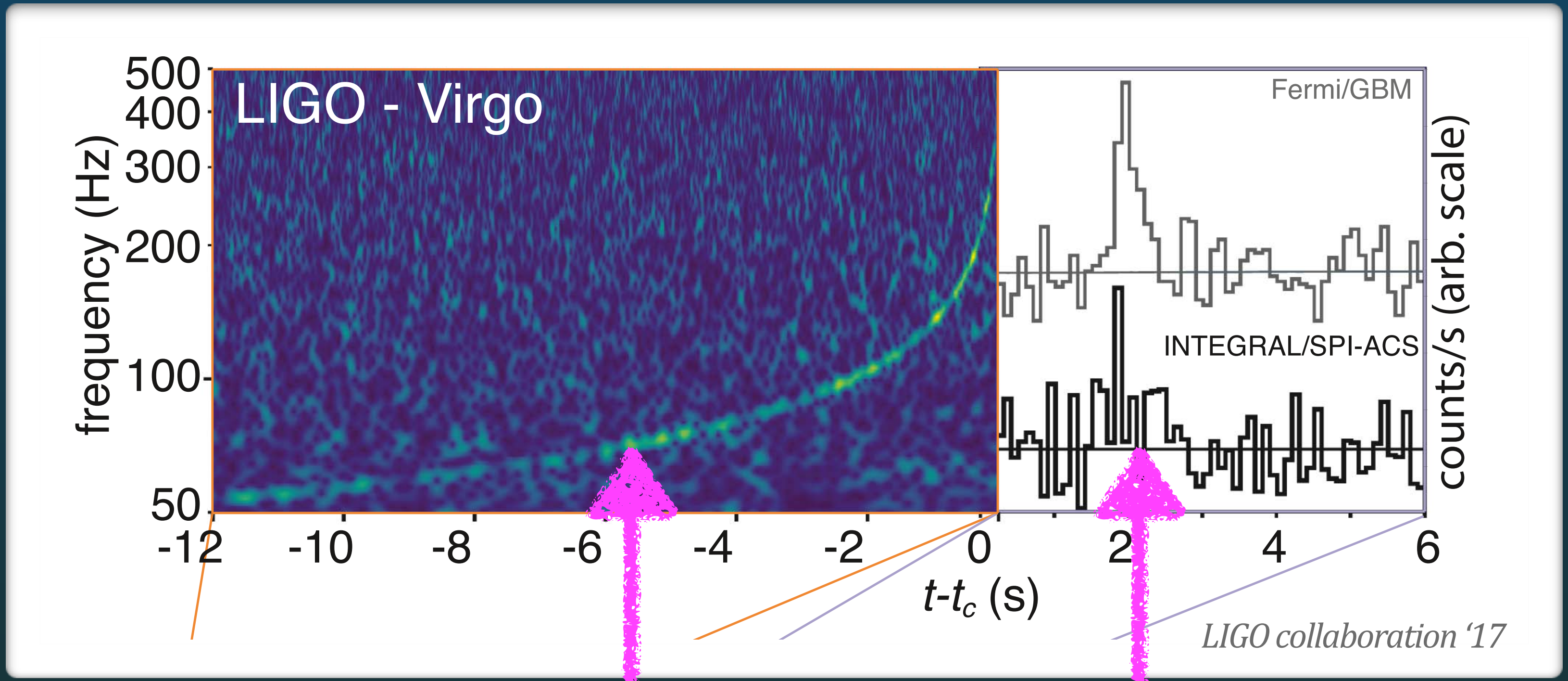
Oliver Just

GreatMoves Relativistic Astrophysics Group

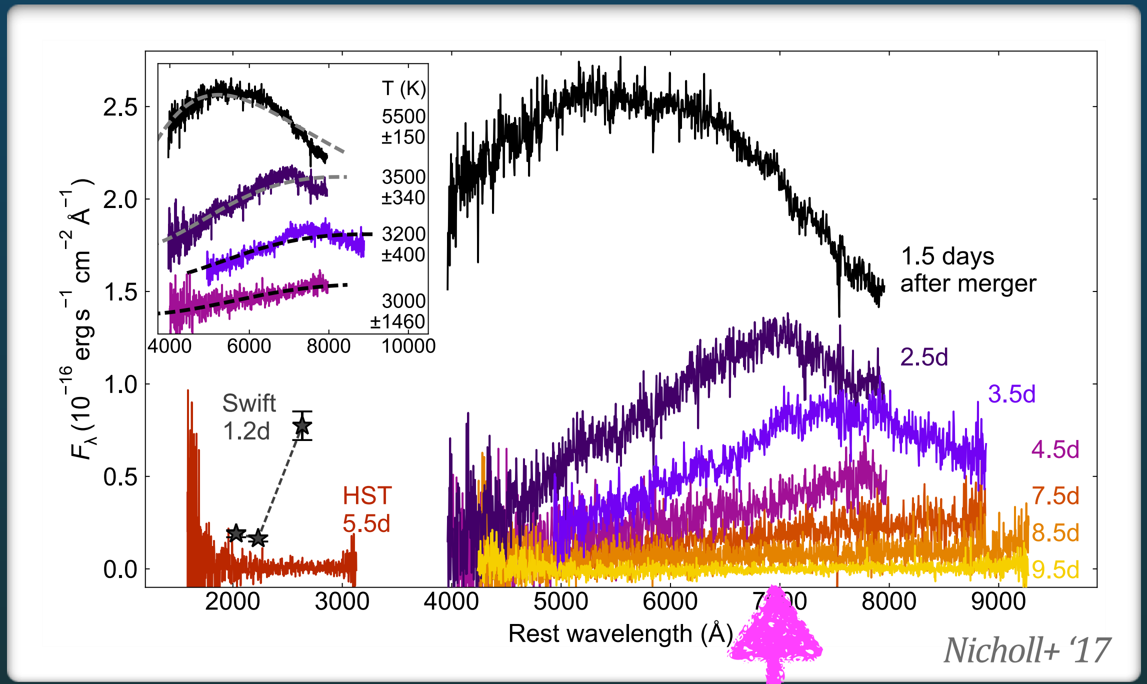
GSI Theory

- with: A. Bauswein, I. Kullmann, S. Goriely, H.T. Janka, C.E. Collins, H. Ito, S. Nagataki, R. Ardevol-Pulpillo, Y. Takei, M. Obergaulinger, M. Aloy, S. Abbar, M. R. Wu, I. Tamborra

GW170817 - the first multi-messenger observation of a binary neutron star merger



LIGO collaboration '17



Nicholl+ '17

Gravitational wave signal

short gamma-ray burst (sGRB)

optical emission

+ various other signals in X-ray, radio, near-infrared, …

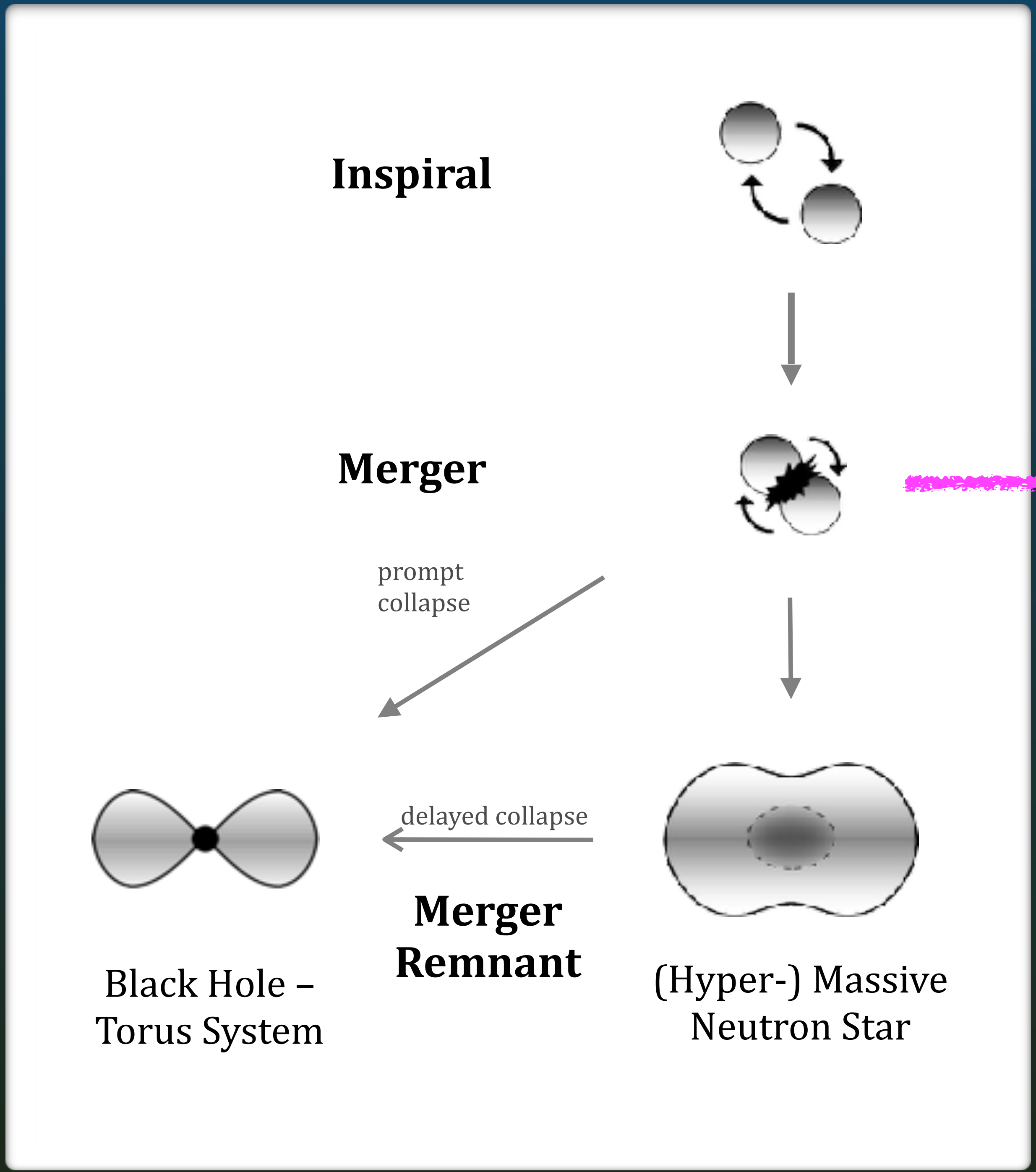
Interpretation of these signals needs sophisticated theoretical models!

- *Which EM signal corresponds to what ejecta component?*
- *Mass, velocity, composition of each component?*
- *Lifetime of the (hyper-)massive neutron star (HMNS)?*
- *Are NS mergers main r-process sites?*

Dynamical ejecta: Composition and Kilonova

Kullmann, Goriely, OJ, Ardevol-Pulpillo, Bauswein, Janka ’22
OJ, Kullmann, Goriely, Bauswein, Janka ‘22

Evolutionary phases of a NS merger



Inspiral

Merger

prompt collapse

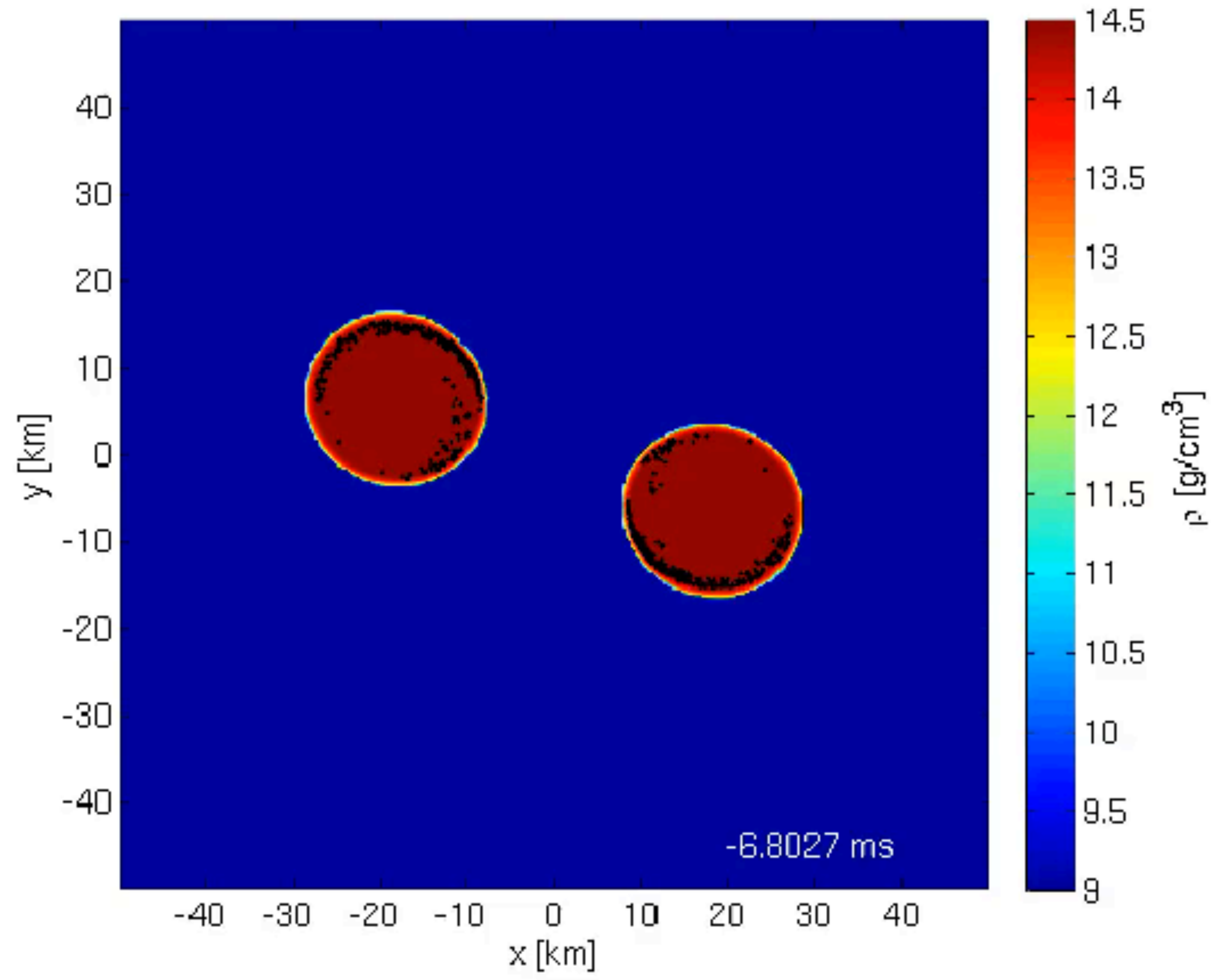
delayed collapse

Merger Remnant

Black Hole – Torus System

(Hyper-) Massive Neutron Star

merger phase

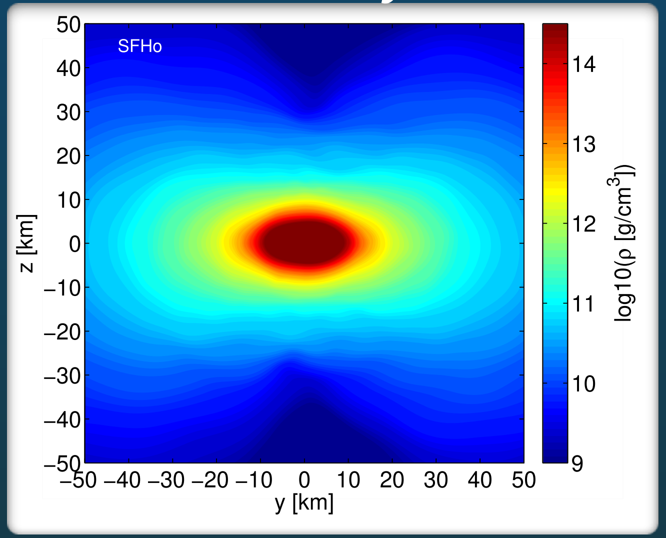


Movie: A. Bauswein

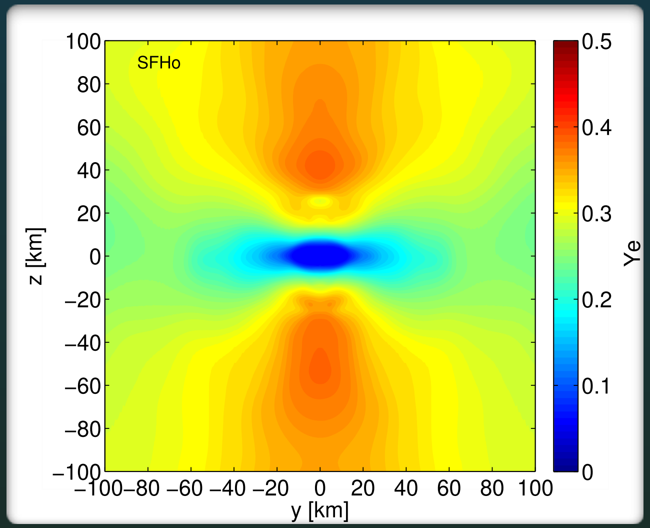
Merger simulations

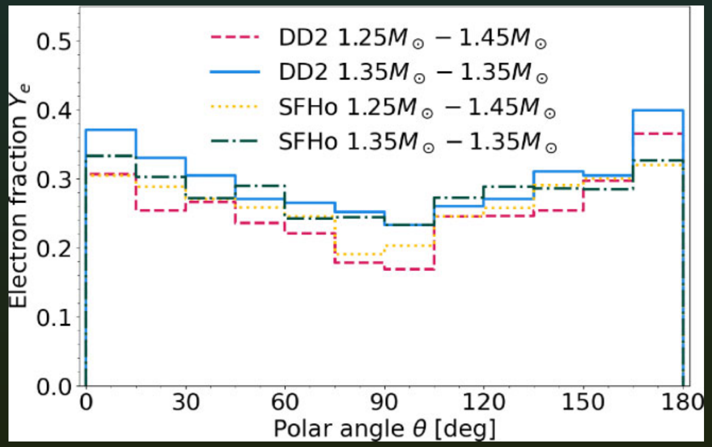
- ✓ CFC general relativistic SPH code
- ✓ neutrinos module “ILEAS” features:
  - ➡ *neutrino trapping and equilibration*
  - ➡ *neutrino absorption via simplified ray-tracing*
  - ➡ *reproduction of the diffusion law at high optical depth*
- ✓ DD2 and SFHO EOS
- ✓ symmetric and asymmetric binary configurations
- ✓ includes ejecta up to ~ 10ms post merger
- ✓ generic pole-to-equator variation of Ye (consistent with, e.g., Sekiguchi ’16, Foucart ’16, Radice ’18)

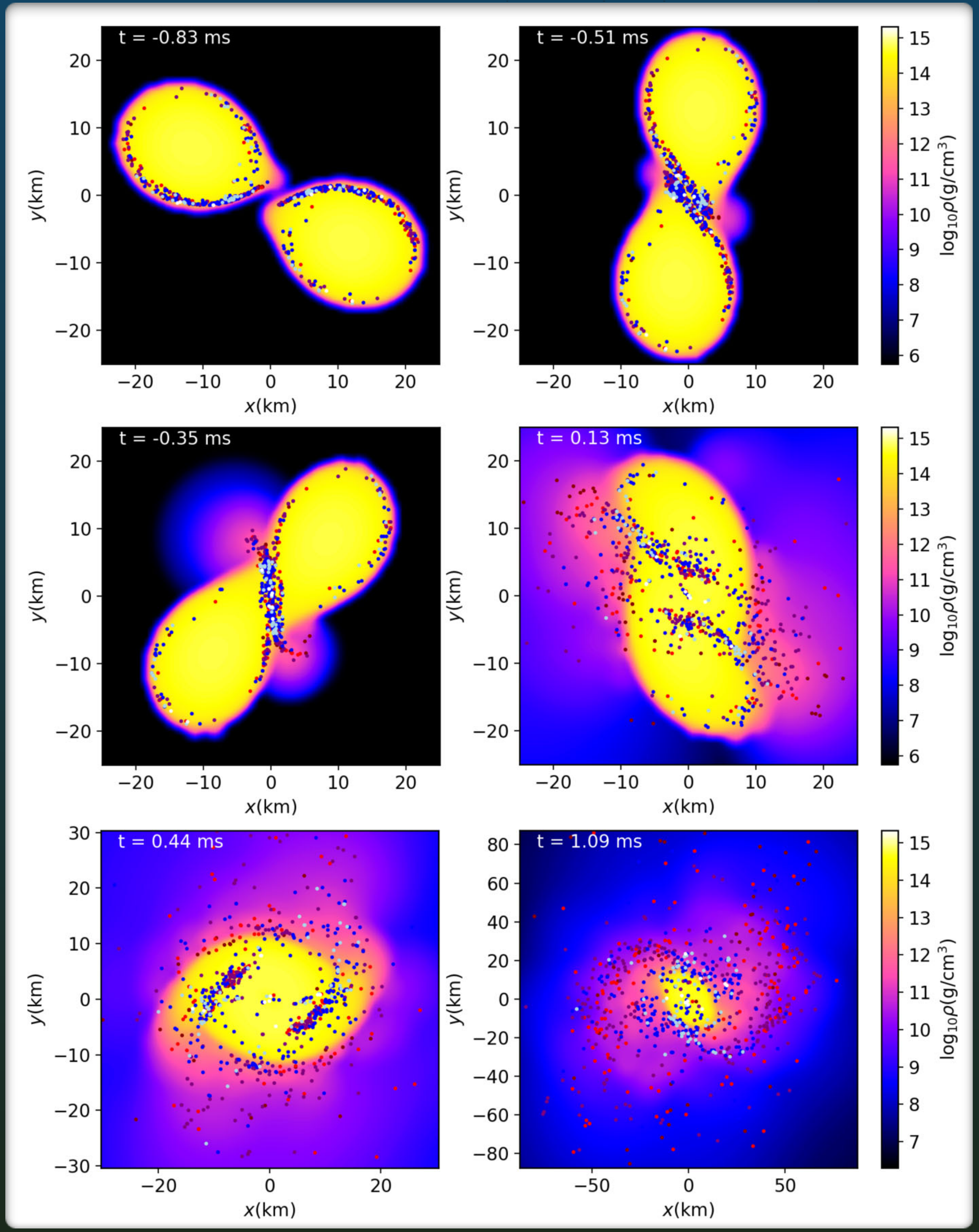
density



electron fraction Y_e

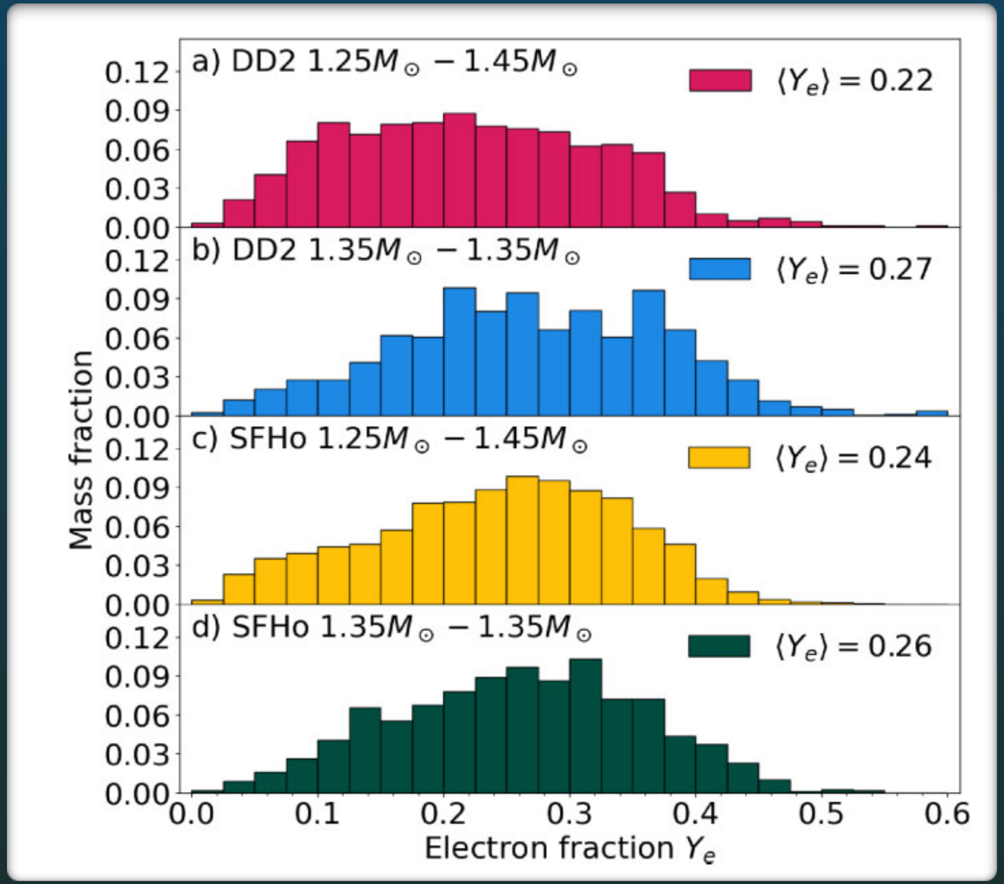






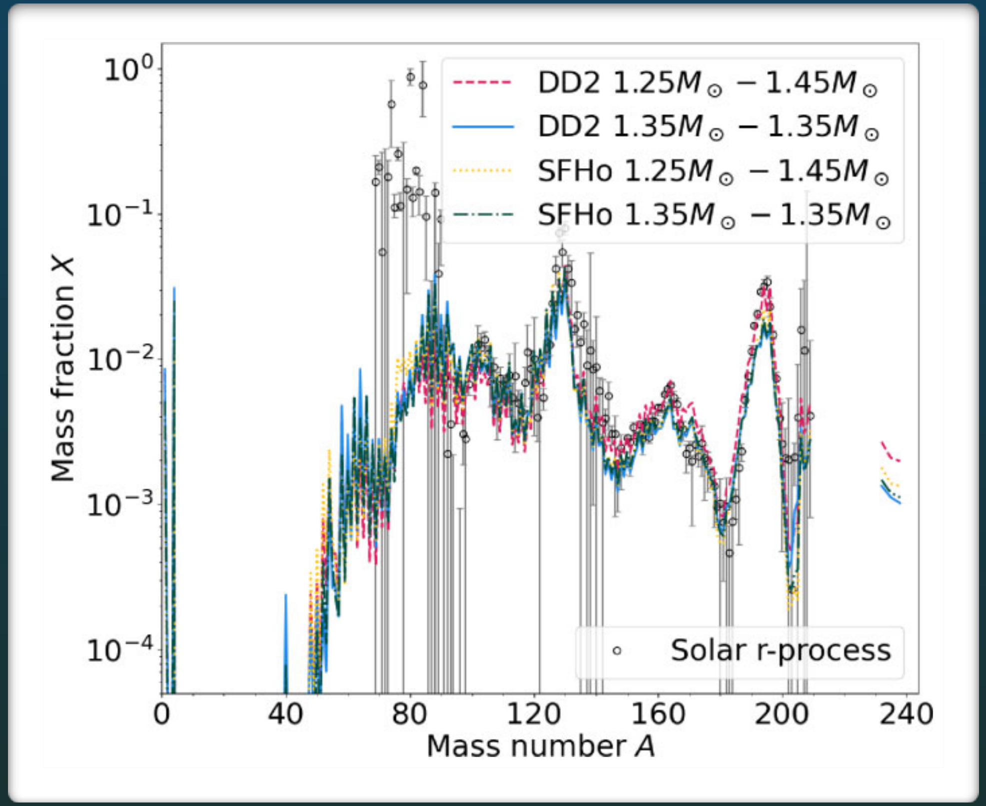
Nucleosynthesis yields and radioactive heating rates

Ye distribution



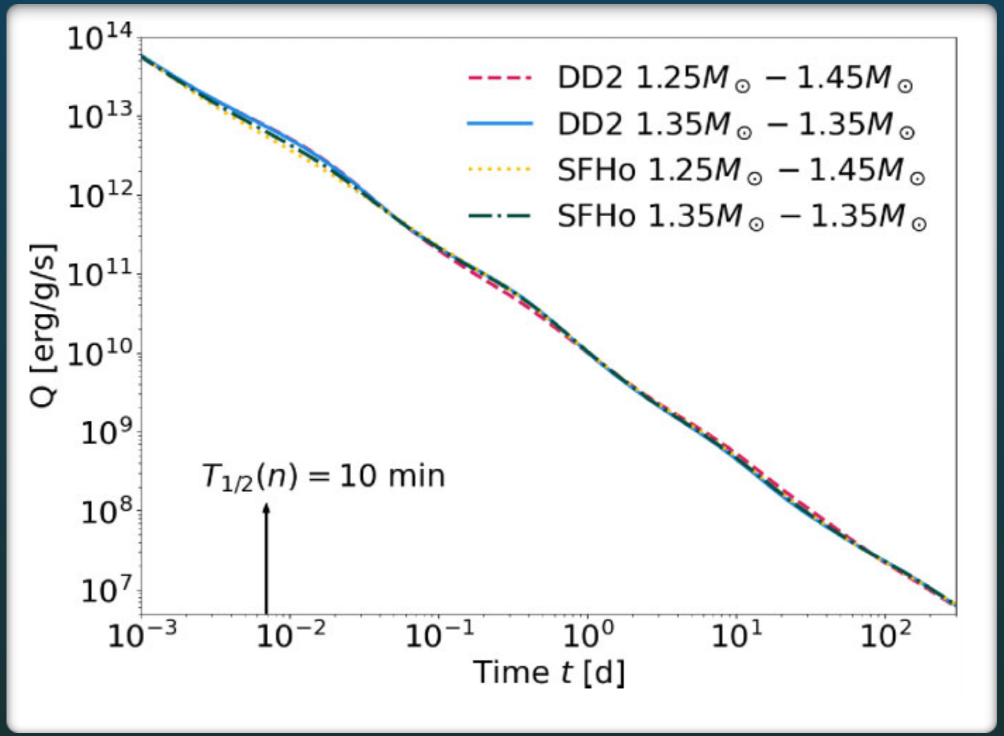
→

abundance pattern



→

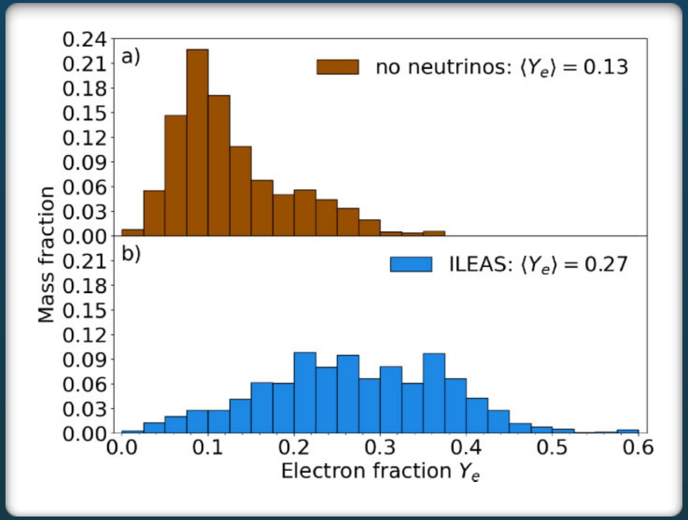
heating rate (before thermalization)

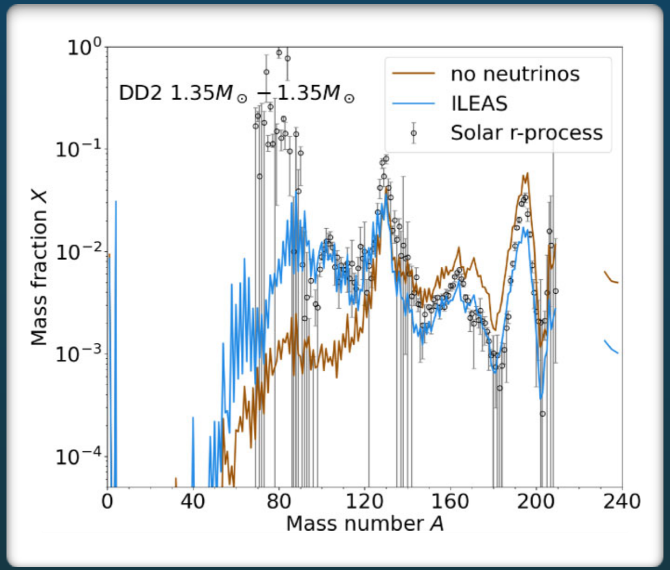


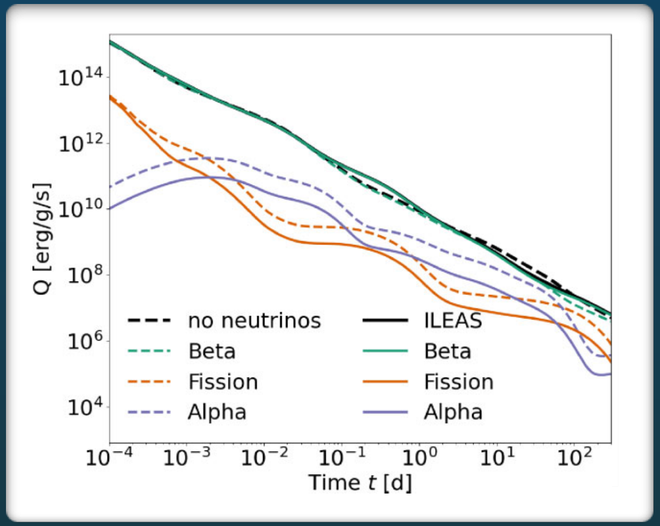
- ✓ solar-like for A>90
- ✓ only mild sensitivity of abundances and heating rate to nuclear EOS and mass ratio

Sensitivity to weak interactions (Ye)

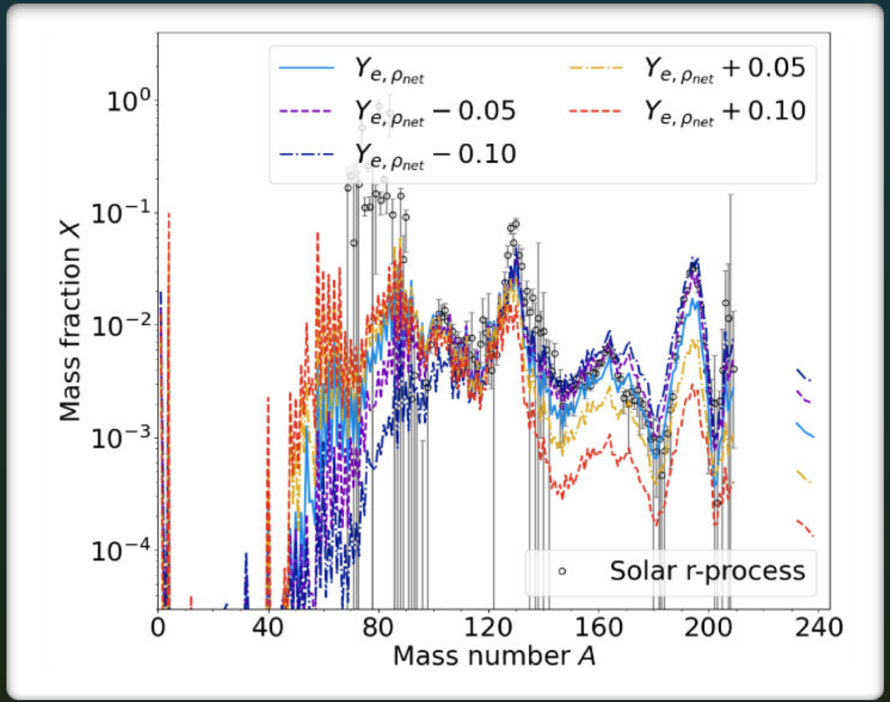
- ✓ ignoring neutrino effects reduces A<130 component, but small impact on heating rate

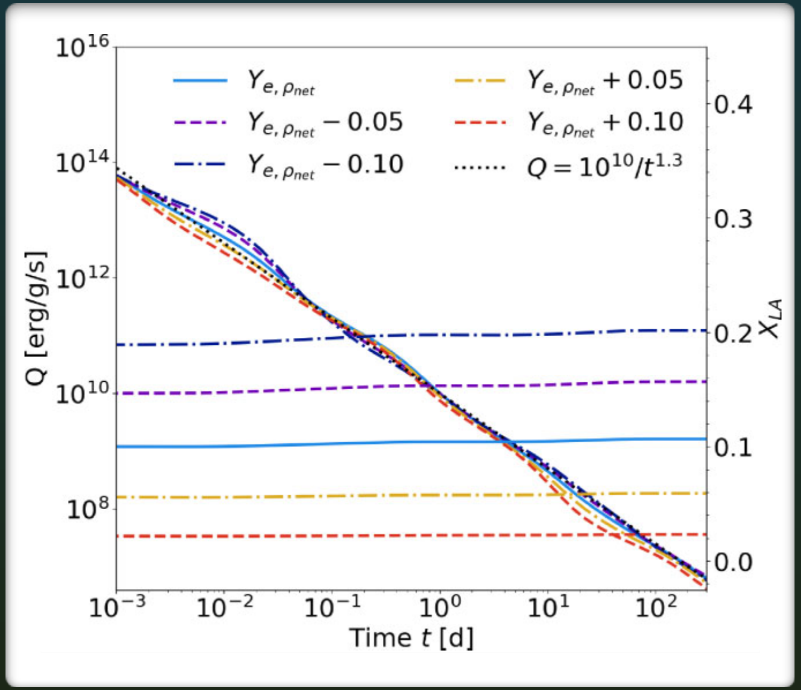






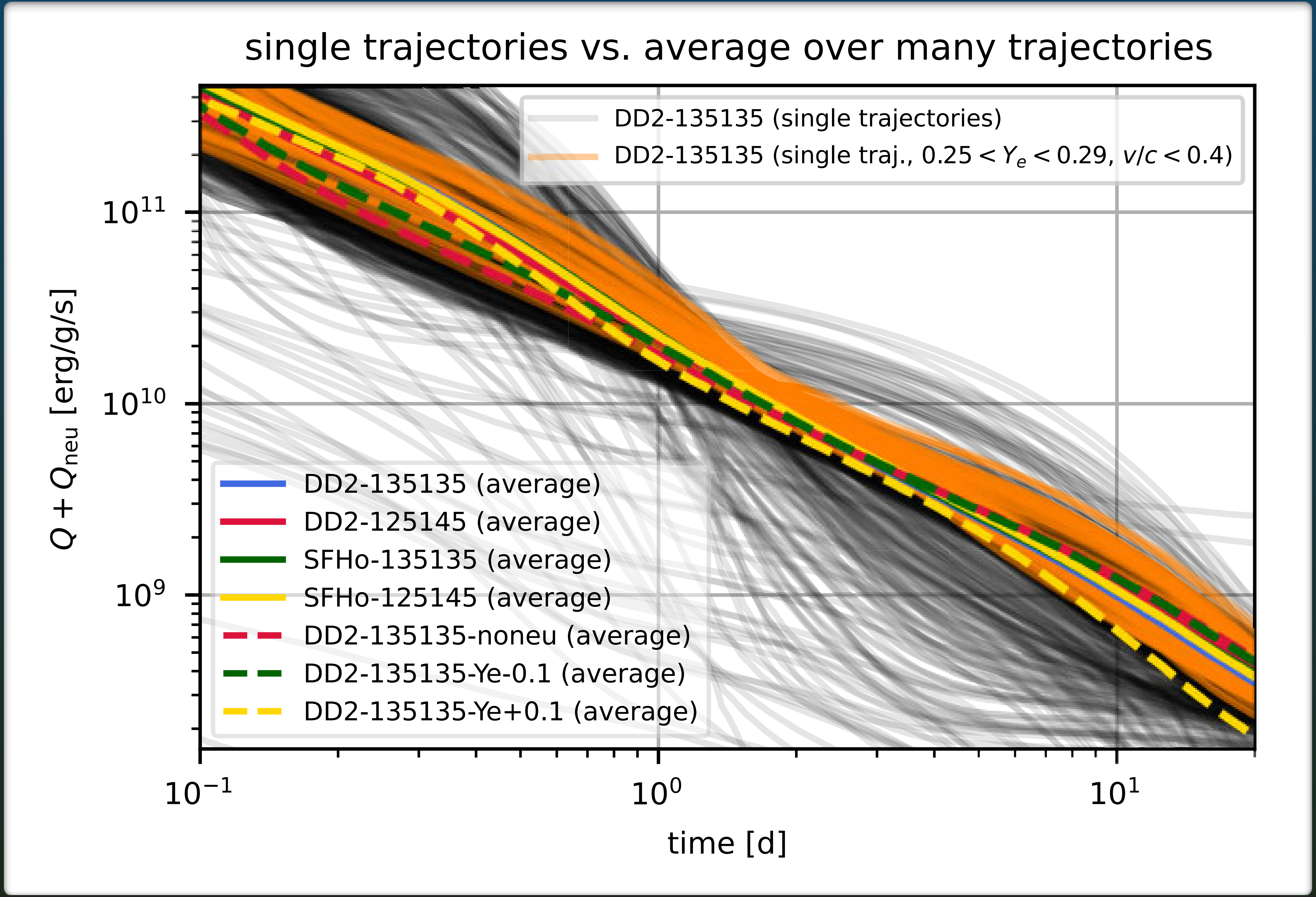
- ✓ manually increasing/ decreasing Ye by 0.1 has dramatic impact on A>130 abundance, but small impact on heating rate





Importance of using ensembles of outflow trajectories

- ➡ heating rates of single trajectories **subject to much stronger variations** than those of ensembles of trajectories
- ➡ suggests that nuclear-physics sensitivity studies should not use individual representative trajectories



New approximate kilonova calculation scheme

- ✓ evolve E and F using two-moment M1 scheme assuming homologous expansion
- ✓ uses as input only the results of nucleosynthesis trajectories
- ✓ computationally much less expensive than full-fledged Monte-Carlo radiative transfer
- ✓ more accurate and consistent than (quasi-)one-zone, Arnett-type models (used by e.g. Villar ’18)

photon energy density

$$\frac{\mathrm{d}E_\nu}{\mathrm{d}t} + \frac{1}{ct}\nabla_{\mathbf{x}}\cdot\mathbf{F}_\nu + \frac{4E_\nu}{t} - \frac{1}{t}\frac{\partial}{\partial\nu}(\nu E_\nu) = c\rho\kappa(E_\nu^{\mathrm{eq}} - E_\nu)\,,$$

photon flux density

$$\frac{\mathrm{d}\mathbf{F}_\nu}{\mathrm{d}t} + \frac{c}{t}\nabla_{\mathbf{x}}\cdot\mathbf{P}_\nu + \frac{4\mathbf{F}_\nu}{t} - \frac{1}{t}\frac{\partial}{\partial\nu}(\nu \mathbf{F}_\nu) = -c\rho\kappa\mathbf{F}_\nu$$

gas energy density

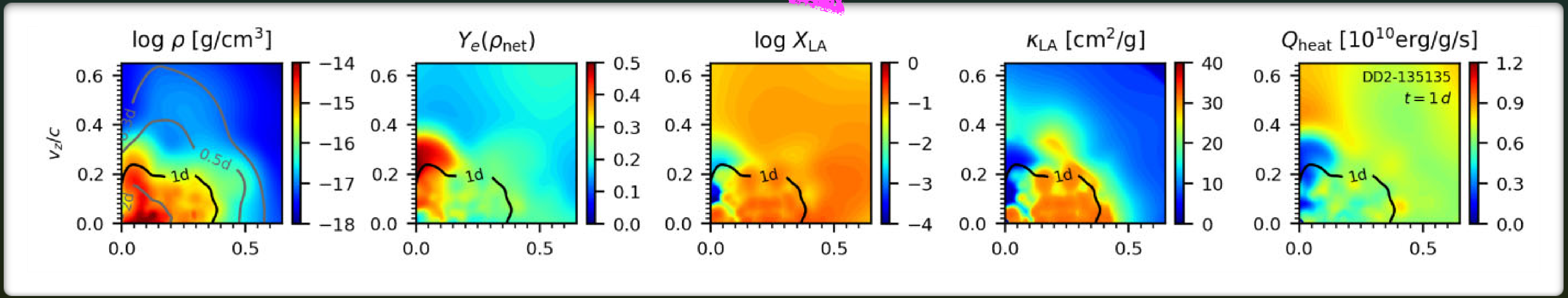
$$\frac{\mathrm{d}e}{\mathrm{d}t} + \frac{5e}{t} = \rho Q_{\mathrm{heat}} - \int_0^\infty c\rho\kappa(E_\nu^{\mathrm{eq}} - E_\nu)\mathrm{d}\nu$$

opacity as simple function of lanthanide fraction and temperature

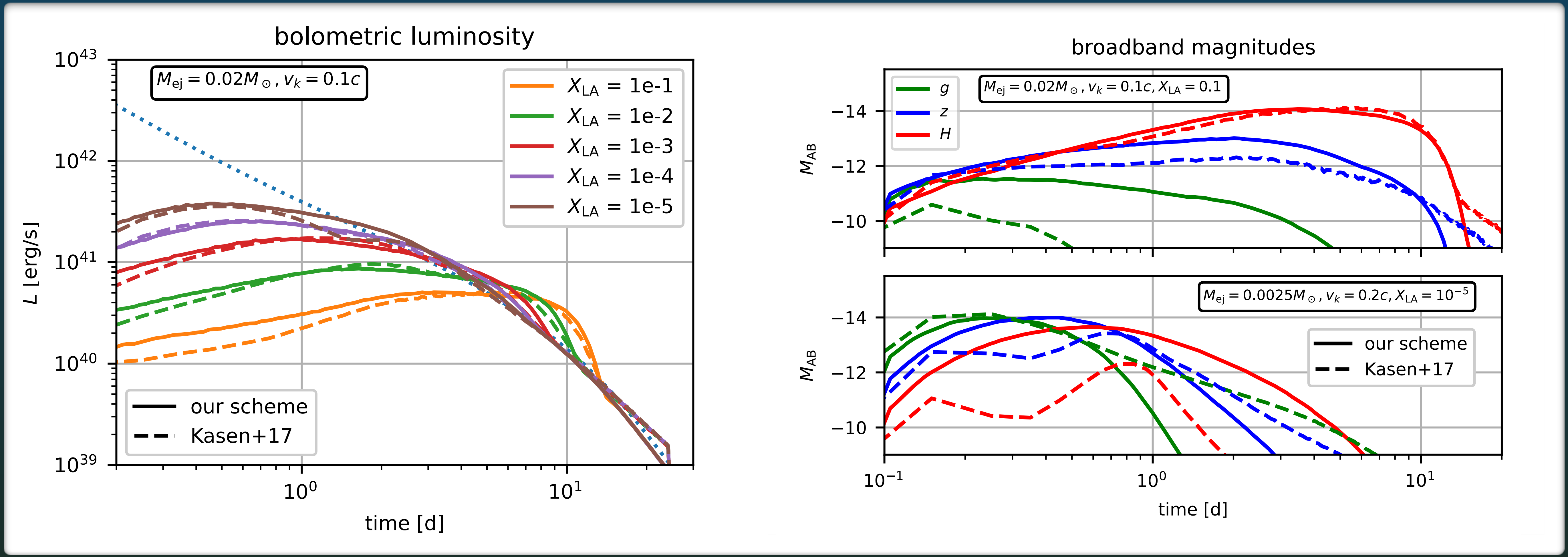
$$\kappa(X_{\mathrm{LA}}, T) = \kappa_{\mathrm{LA}} \times \kappa_T$$

spatial interpolation of mass, composition and heating rate using nucleosynthesis trajectories

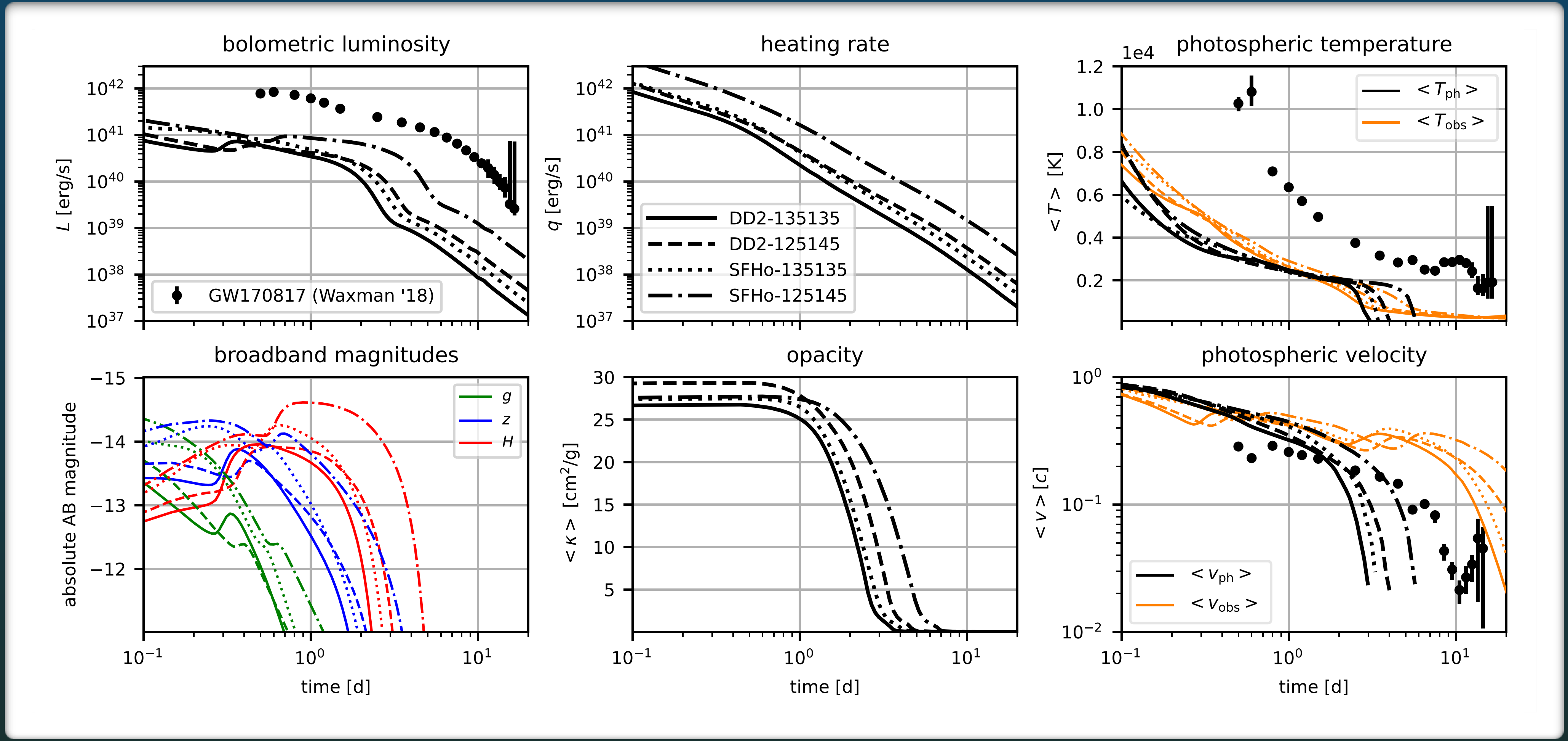
$$A(\mathbf{x}) = \frac{\sum_j^N \frac{m_j}{\rho_{\mathrm{2D},j}} A_j W_{\mathrm{2D}}(\mathbf{x}-\mathbf{x}_j, h_j)}{\sum_j^N \frac{m_j}{\rho_{\mathrm{2D},j}} W_{\mathrm{2D}}(\mathbf{x}-\mathbf{x}_j, h_j)}$$



Opacities benchmarked by detailed Monte Carlo results by Kasen+17



Resulting kilonova lightcurves



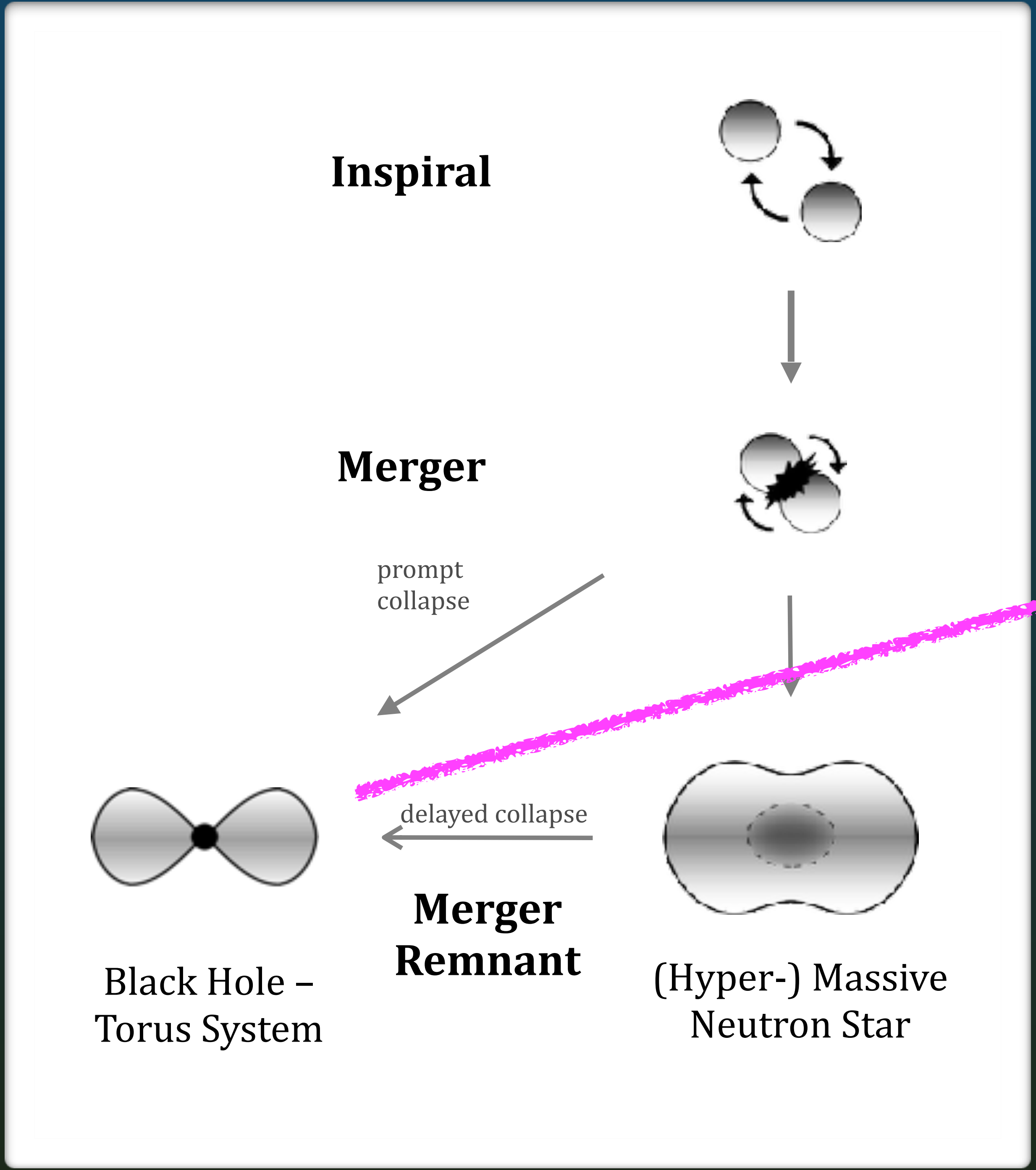
- too faint compared to KN of GW170817
- challenging to explain kilonova of GW170817 with typical dynamical ejecta alone
- need either more extreme EOS/mass ratio or additional outflow components
- consistent with previous works

Weak interactions in neutrino-cooled BH disks

OJ, Goriely, Janka, Nagataki, Bauswein ‘21

Evolutionary phases of a NS merger

post-merger black-hole torus system



Inspiral

Merger

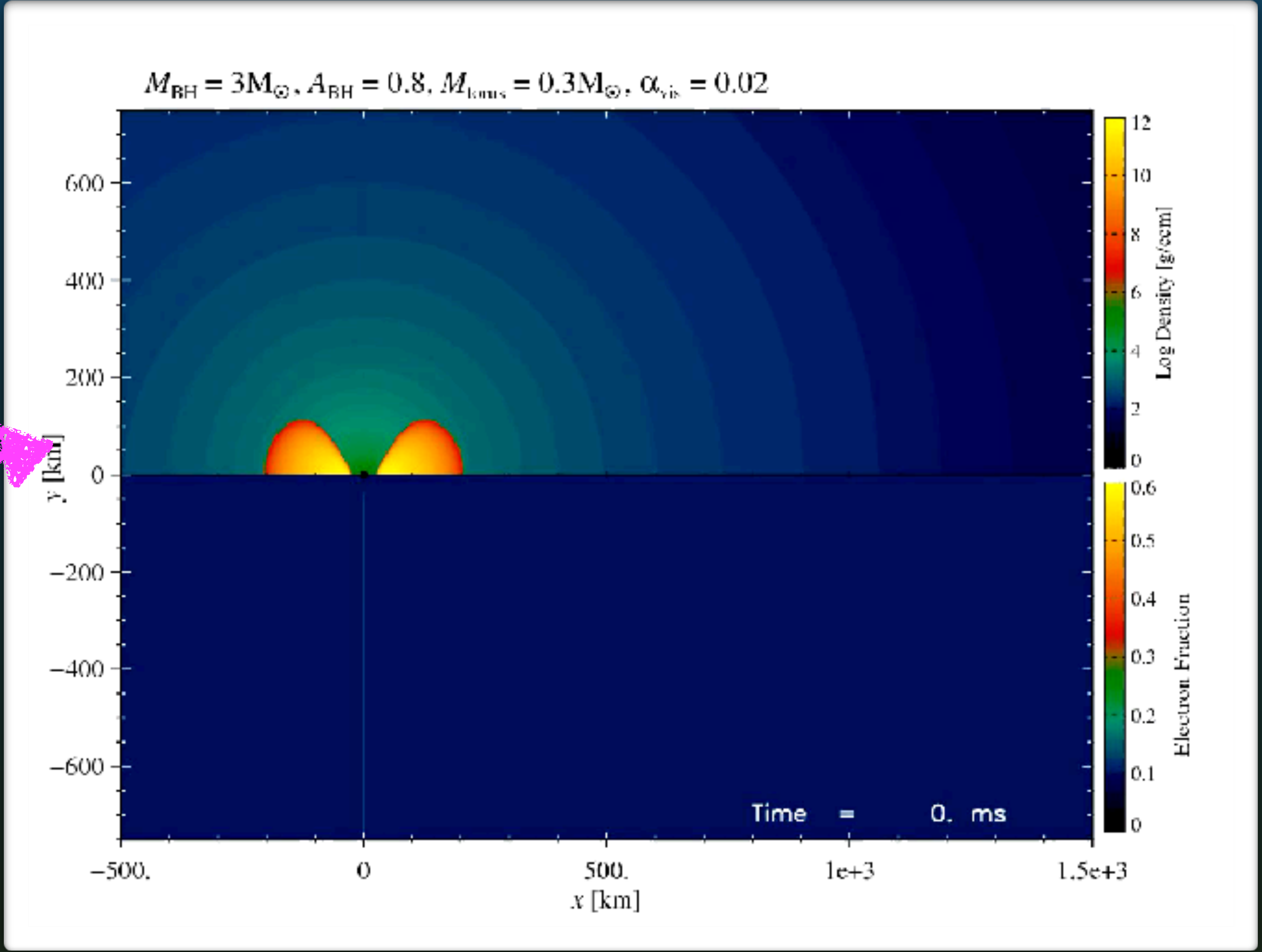
prompt collapse

delayed collapse

Black Hole –
Torus System

Merger Remnant

(Hyper-) Massive
Neutron Star



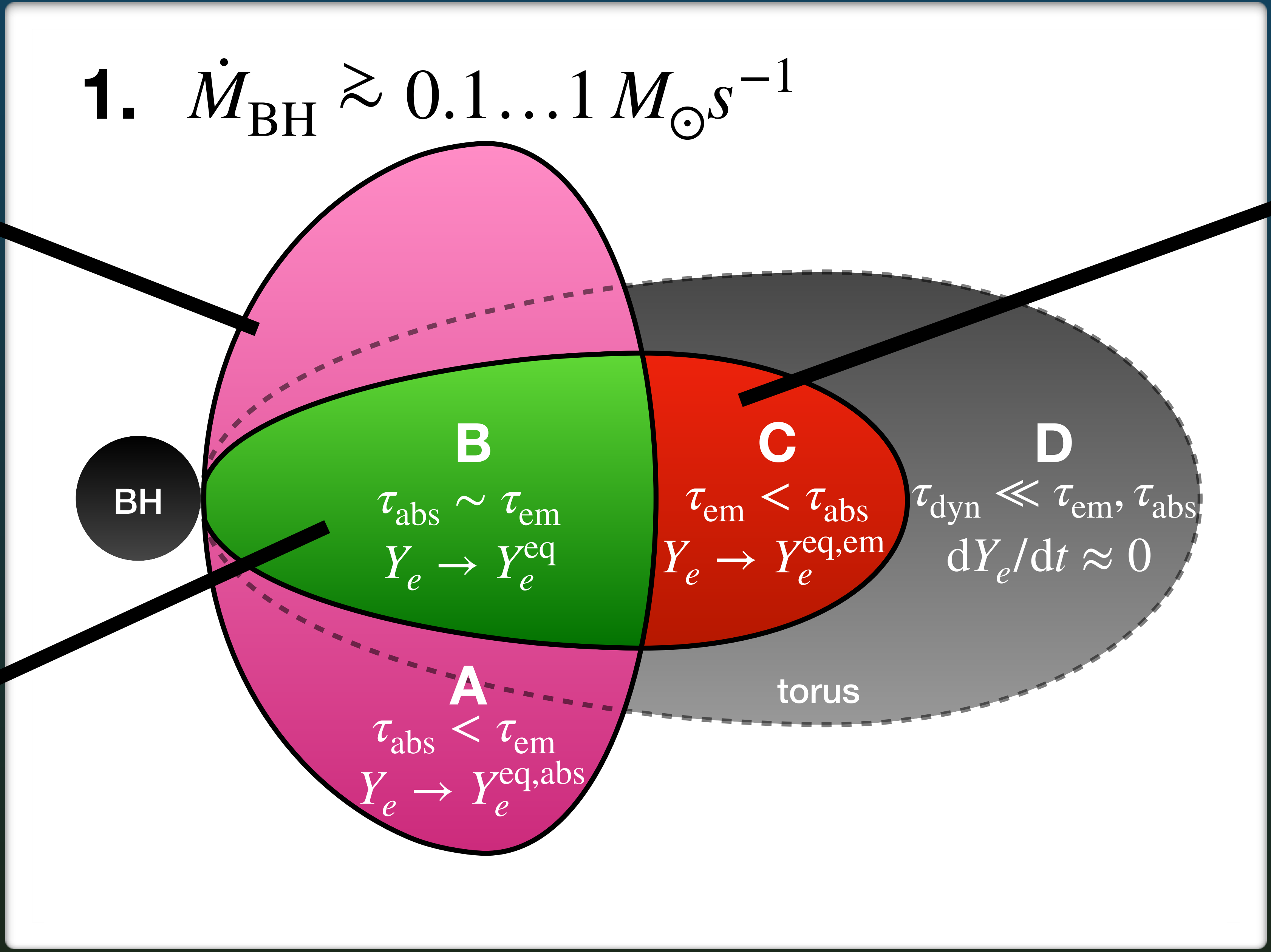
Characteristic regimes of Ye equilibria in BH disks

$e^+ + n \leftarrow p + \bar{\nu}_e$

$e^- + p \leftarrow n + \nu_e$

$Y^{eq,abs} \approx 0.5$

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



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

$e^- + p \rightarrow n + \nu_e$

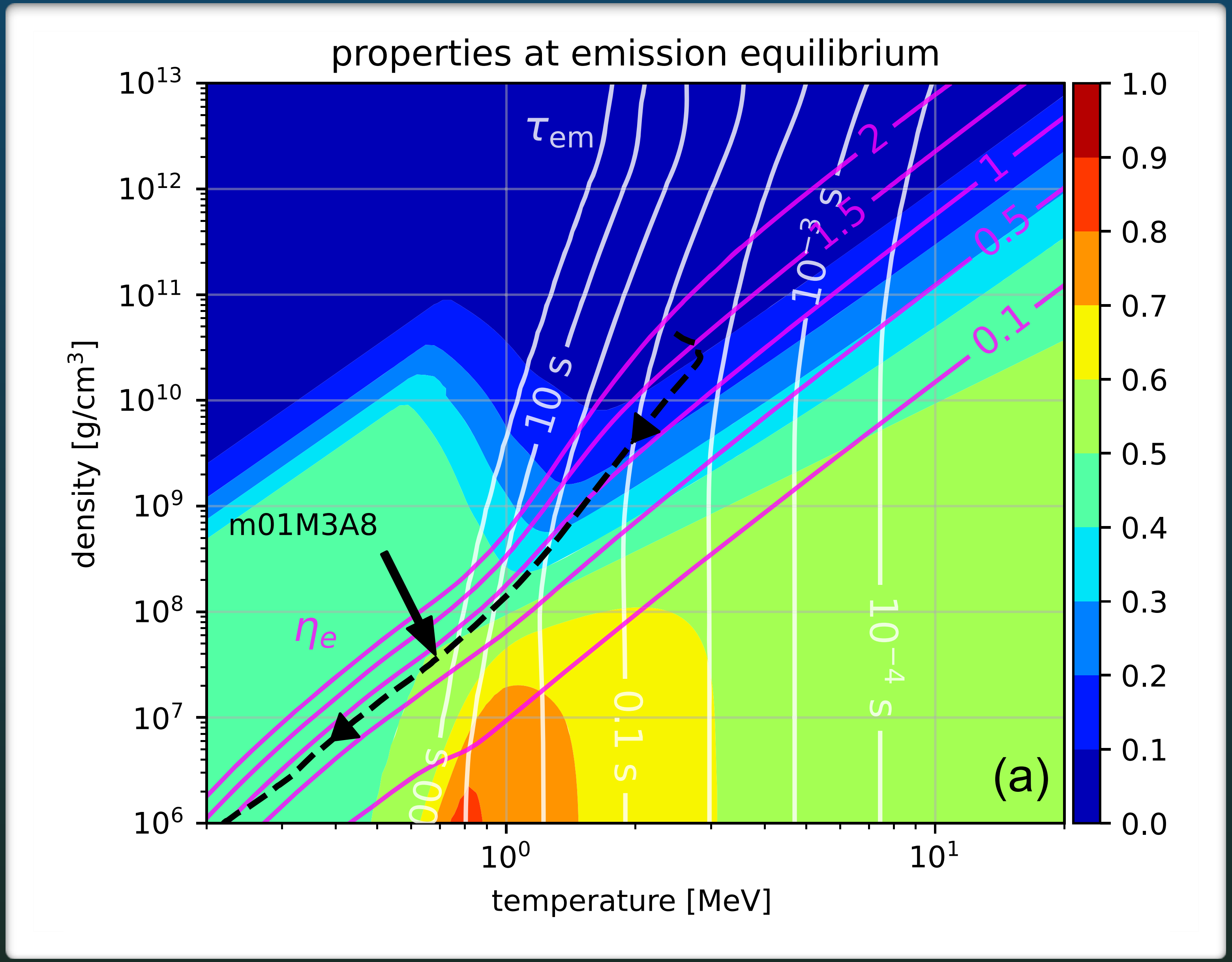
$Y^{eq,em}$ determined by thermodynamic state only

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

$e^- + p \leftrightarrow n + \nu_e$

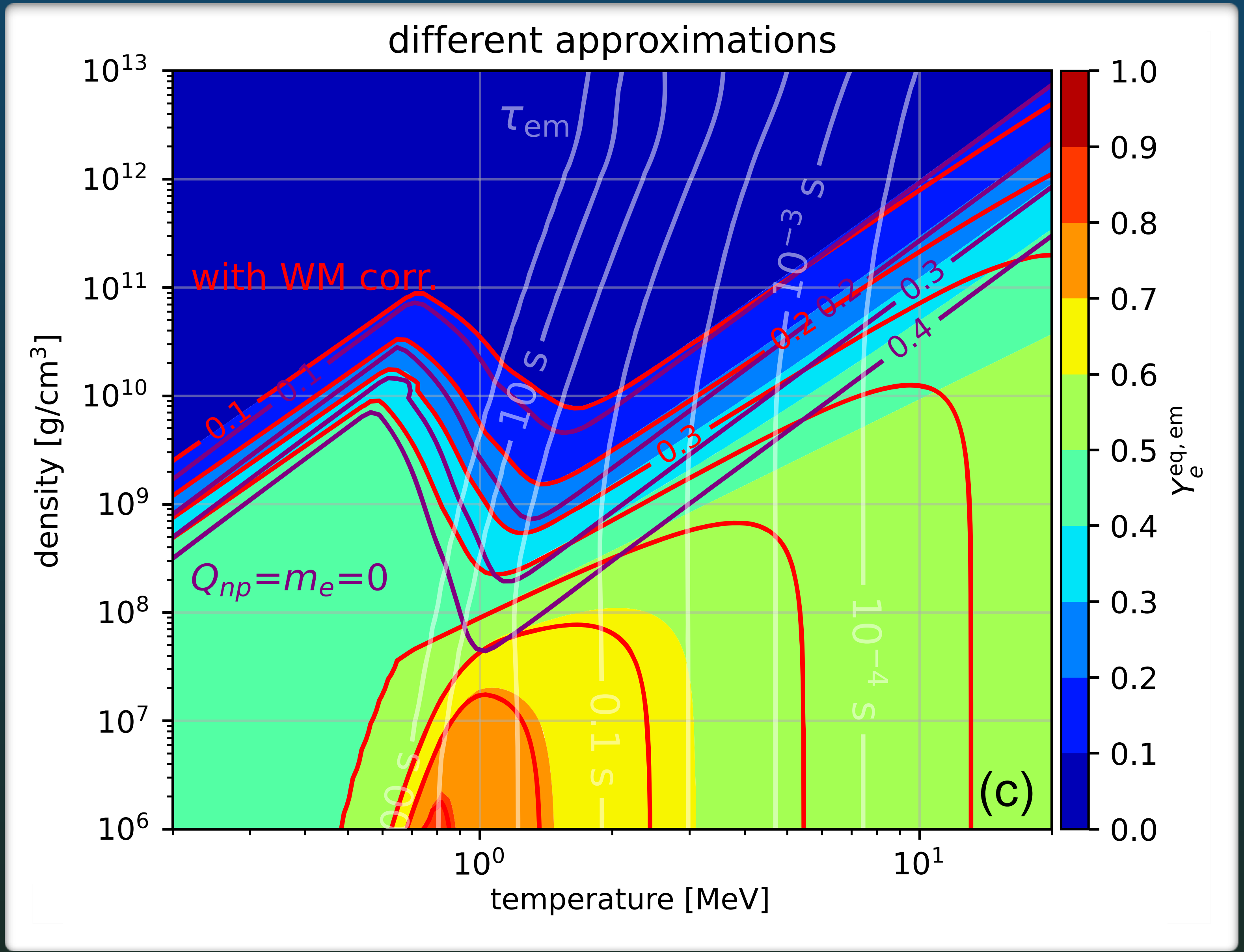
Y^{eq} determined by thermodynamic state + neutrino field

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



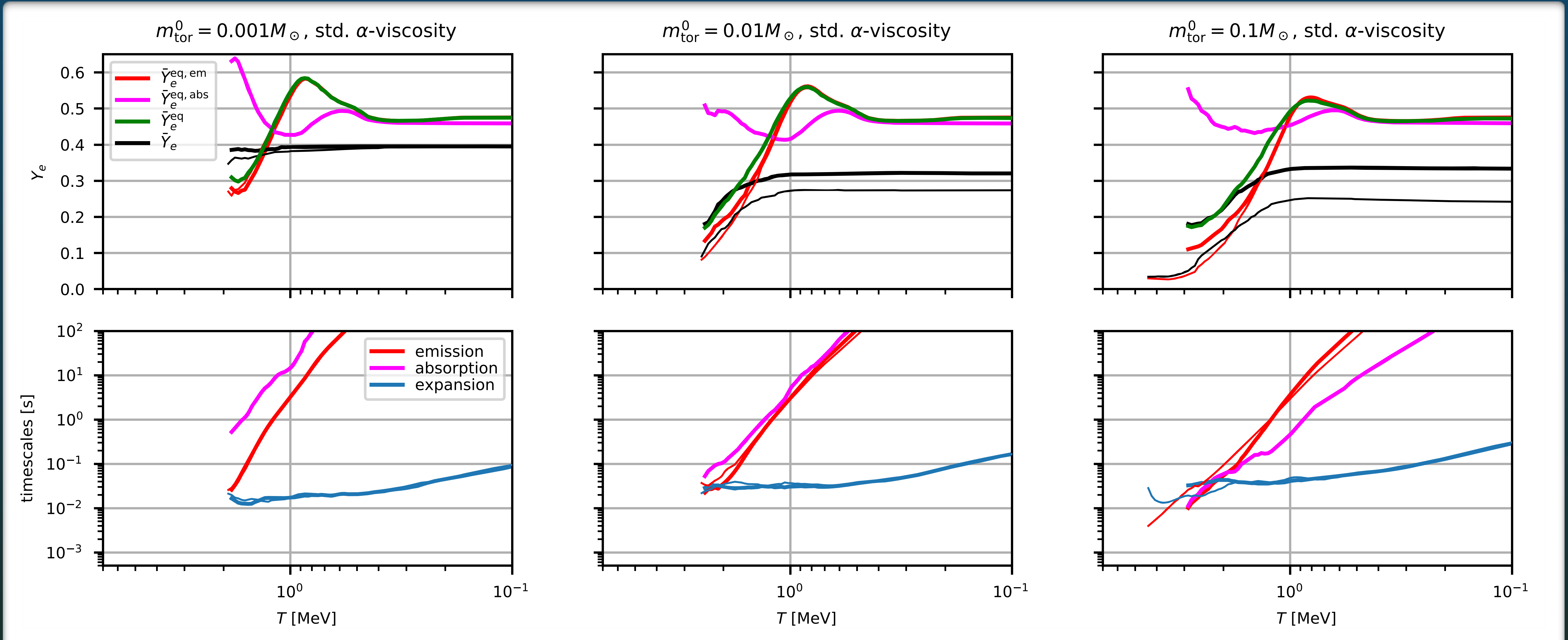
- generically low Ye for neutrino-cooled disks because of moderate electron degeneracy eta~1
- freeze-out at relatively low Ye roughly when weak timescales tau_{em} > 1-10 seconds

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



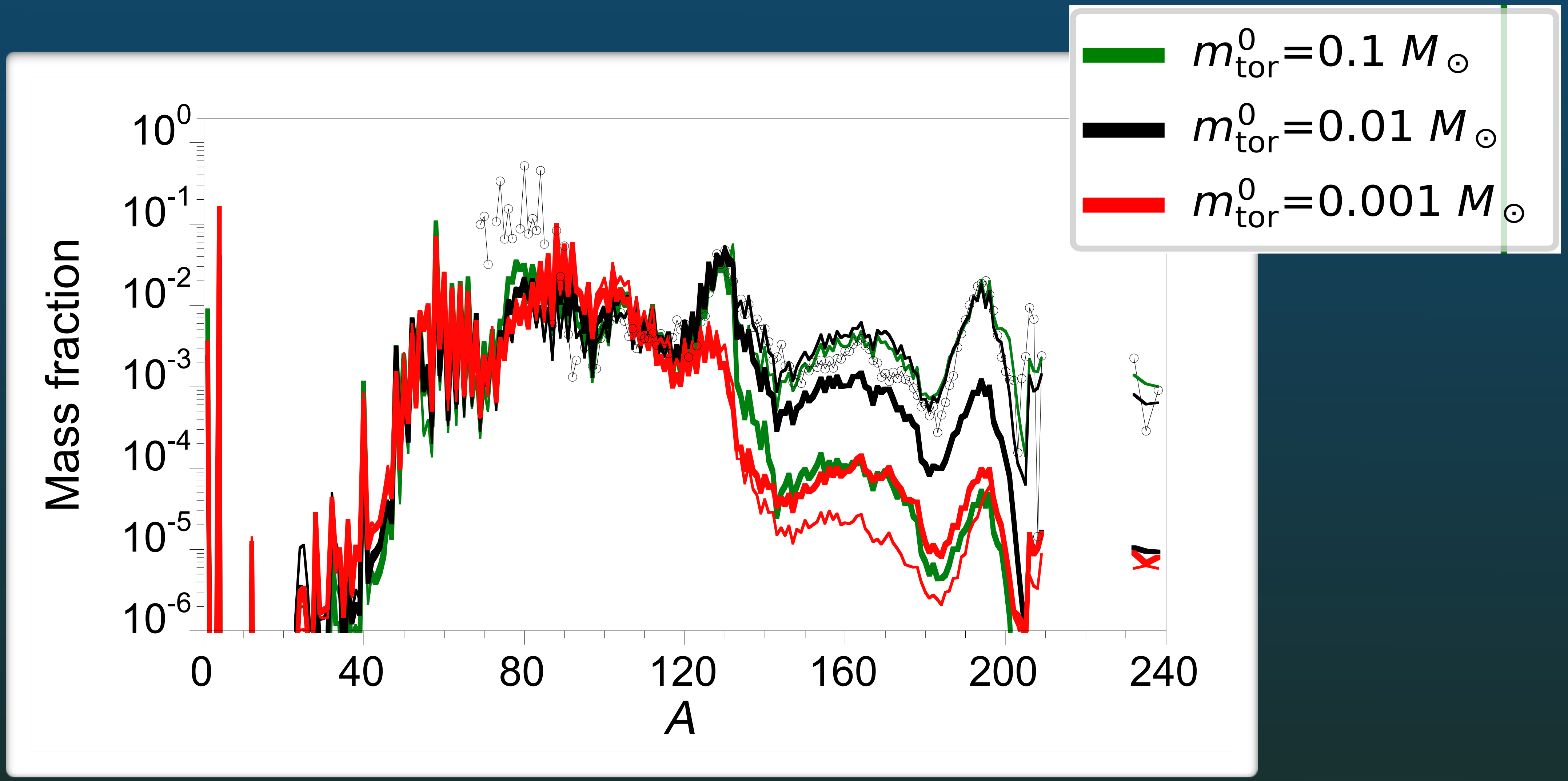
- small impact of weak magnetism corrections
- significant impact when neglecting electron mass and n-p mass difference
- the 2nd assumption is made in most conventional leakage schemes (e.g. Ruffert+1996)

Equilibrium values in BH disk outflows



- ➡ neutrino absorption increases equilibrium Ye by ~0.05-0.1 in the disk
- ➡ during expansion, Ye increases due to emission and absorption
- ➡ relative impact of absorption increases with disk mass

Nucleosynthesis yields



- optimal conditions for r-process for disk mass of ~ 0.01 Msun
- at lower disk mass -> high Ye^{eq, em}
- at higher disk mass -> strong impact of absorption

Impact of fast flavor conversions in BH disks

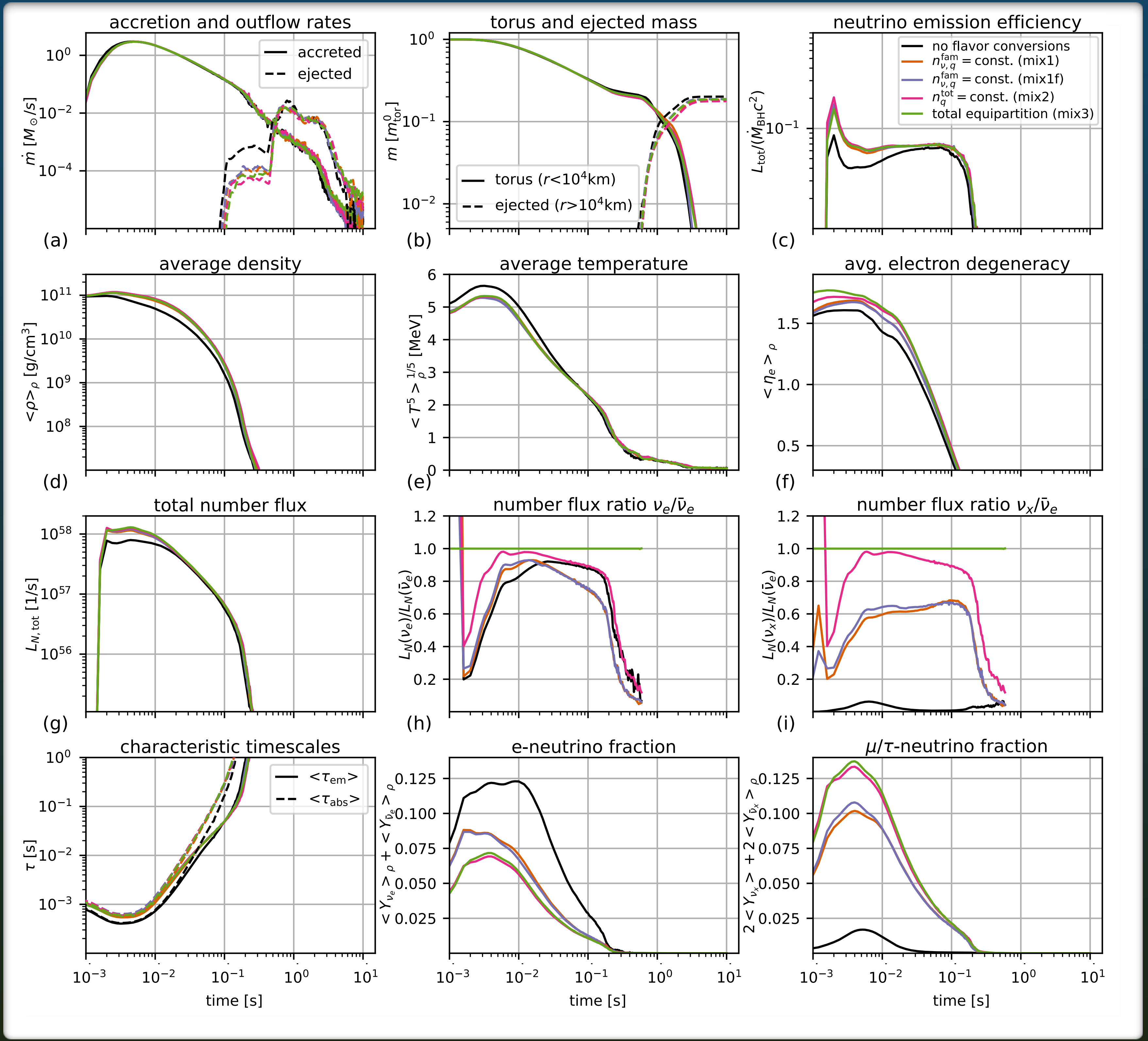
OJ, Abbar, Wu, Tamborra, Janka, Capozzi ‘22

Impact on the disk

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 Ye^{eq, em}
  - ➡ reduced abundances of electron-type neutrinos reduce impact of absorption and lead to additional reduction of Ye^{eq}
- ✓ overall only moderate impact, because the two electron neutrinos already have relatively similar abundances
- ✓ see talks by Meng Ru Wu for impact on nucleosynthesis, and Xinyu Li for a similar, independent study



BH disk in the core of a collapsar

OJ, Obergaulinger, Aloy, Nagataki, to be submitted

Collapsars as r-process sites?

✓ different possibly channels:

➡ neutron-rich magneto-rotationally launched jet from a highly magnetized porto-neutron star

➡ ejecta from BH disk formed after collapse of porto-neutron star

✓ the second scenario has been investigated, e.g., by Pruet ’03, Surman ’05, Nagataki ’06 who found Ni-rich ejecta for typical mass accretion rates **(no self-consistent hydro)**

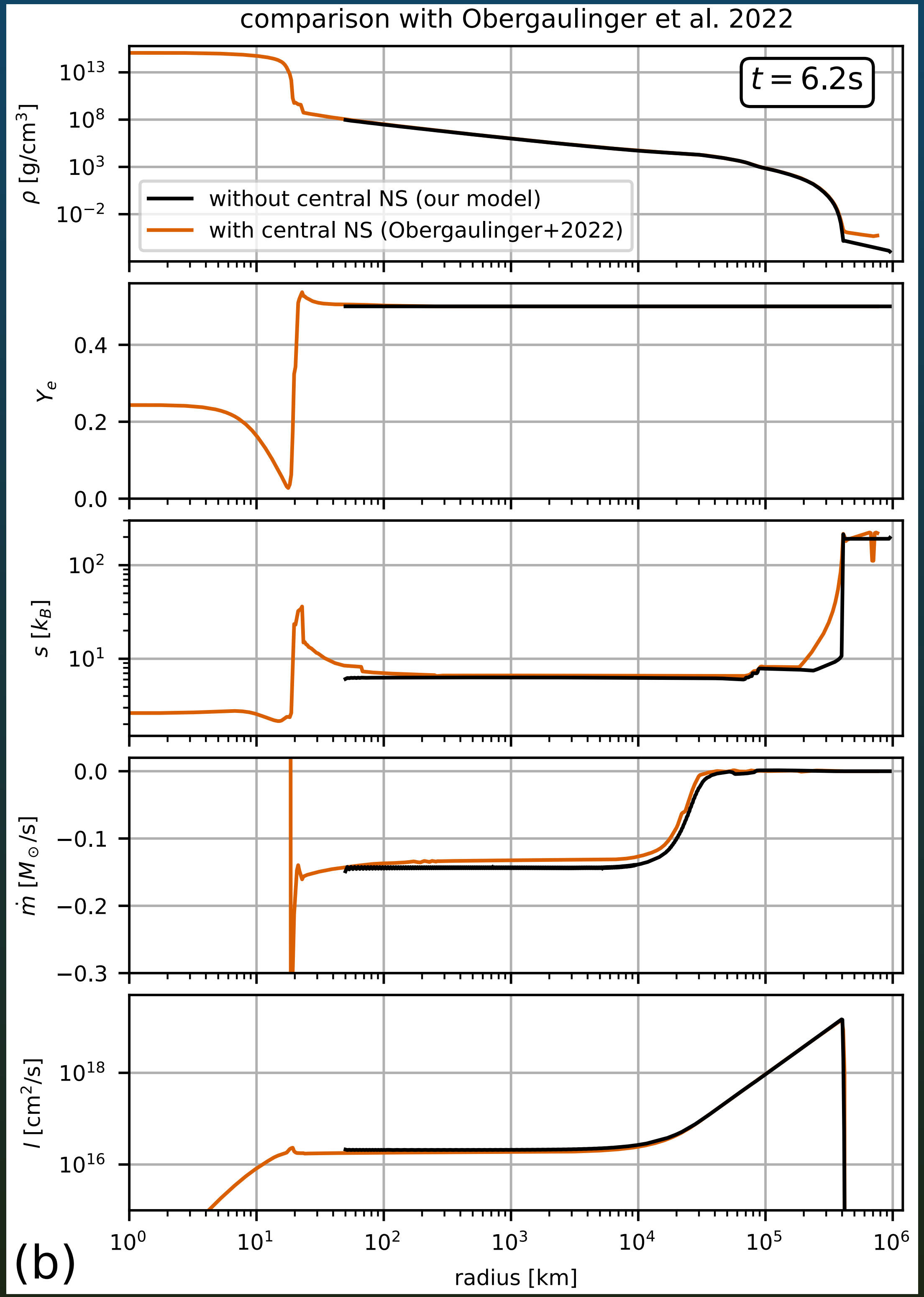
✓ Siegel ’19 found very neutron-rich ejecta using self-consistent 3D GRMHD models **but neglecting the stellar progenitor**

✓ our model: 2D viscosity + M1 neutrino transport **including the stellar progenitor (16TI by Woosley 2006) and neglecting the proto-NS**

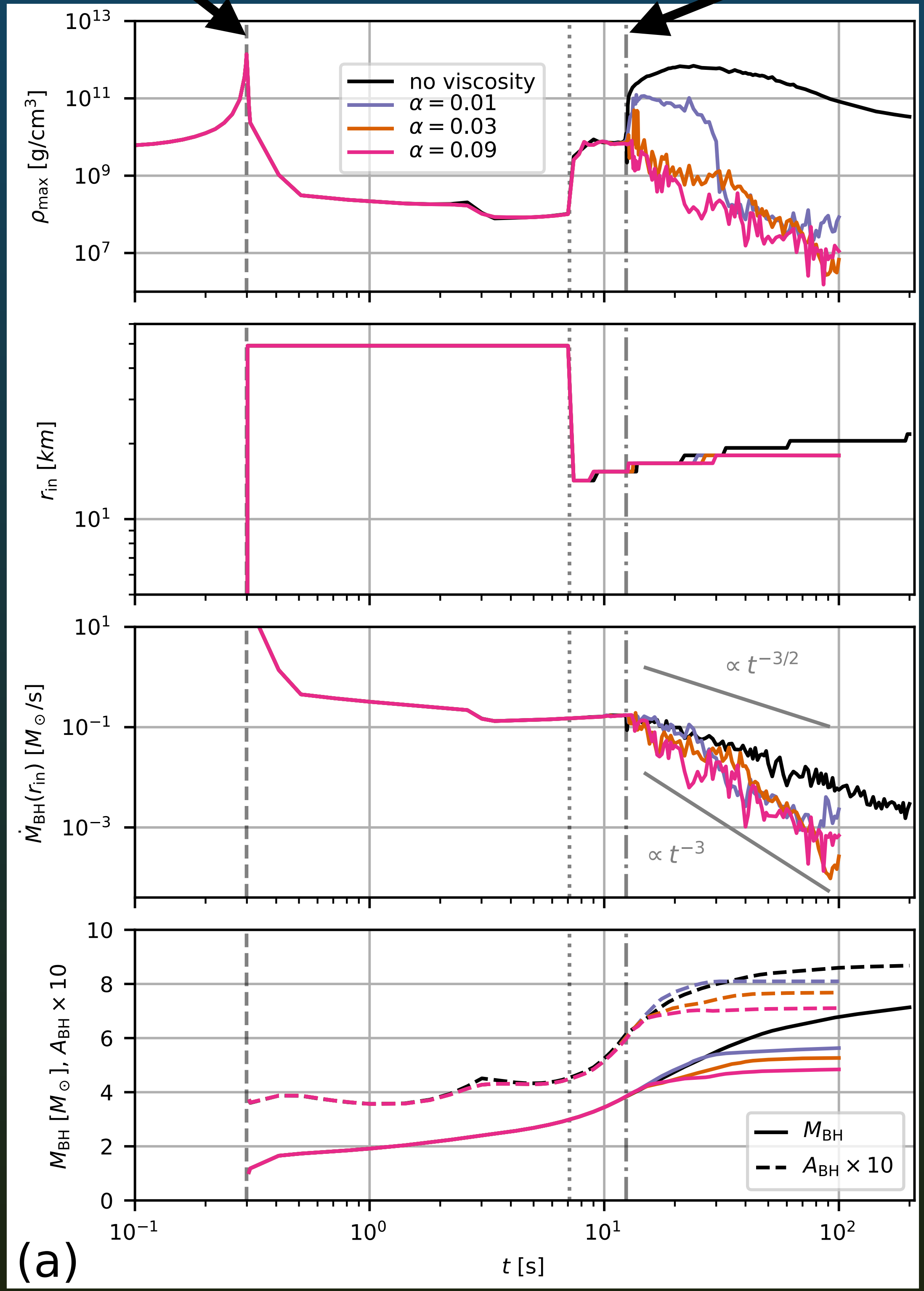
What happens when using self-consistent progenitor models? Does a neutron-rich, neutrino-cooled disk form? How long until it becomes advective (Ye=0.5)?

Comparison with simulation including the proto-NS

- ✓ neglecting the proto-NS does not significantly alter the evolution


comparison with Obergaulinger et al. 2022

Global evolution

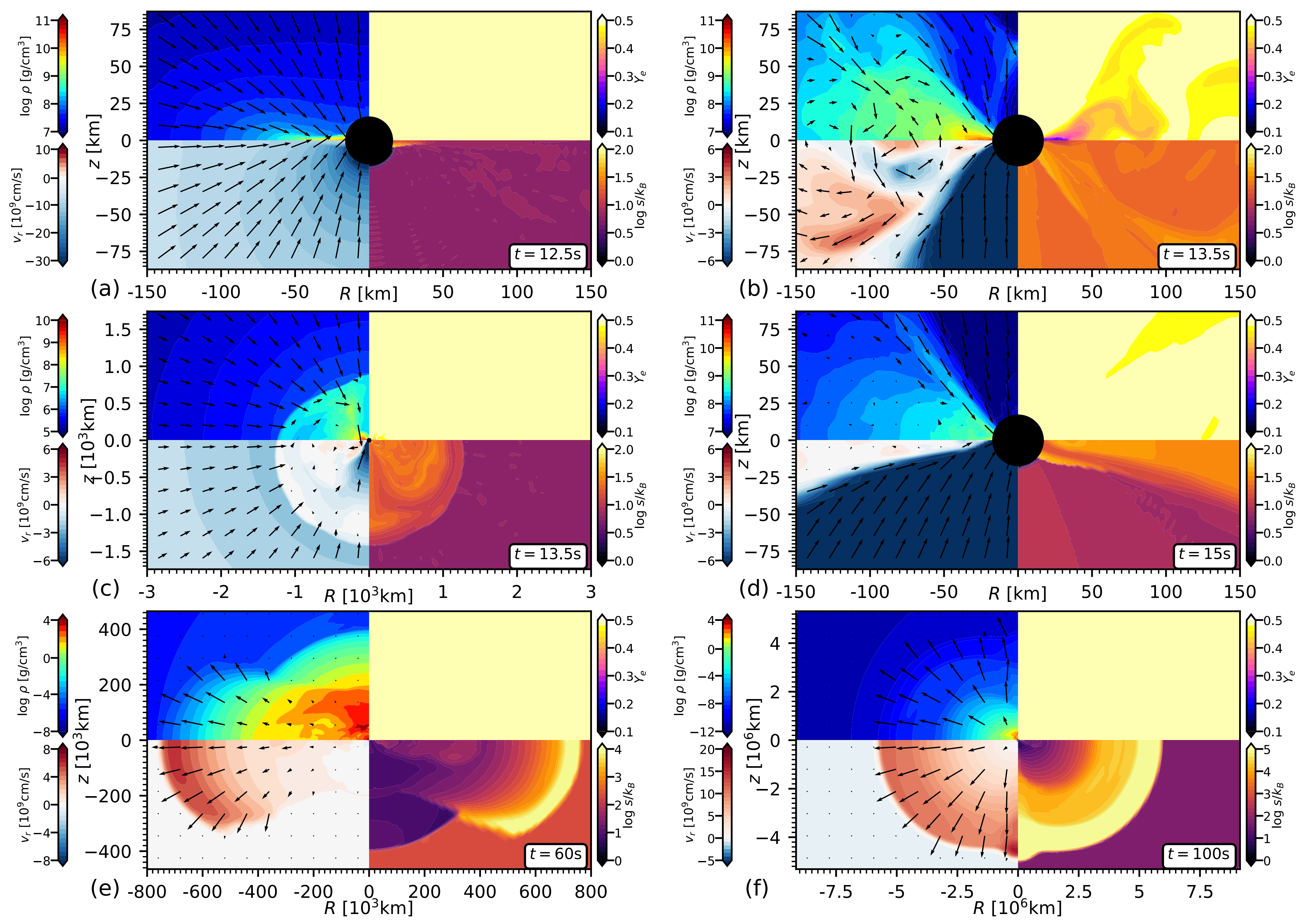


core bounce

time of disk formation

Global evolution

- ✓ neutrino-cooled, neutron-rich disk (NDAF) formed at t~13 s
- ✓ however, viscosity leads to disintegration and reduces disk temperature
- ✓ neutrino emission rates insufficient for sustained NDAF
- ✓ transition to advective disk (ADAF) after short time (t~14s)
- ✓ minimum outflow Ye>~ 0.4
- ✓ CAVEATS:
  - ➡ no GR
  - ➡ no MHD
  - ➡ no jet included



viscous model

Summary

- ✓ consistent hydro+nucleosynthesis+kilonova study suggests that (typical) dynamical ejecta unlikely to explain KN of GW170817
- ✓ new kilonova scheme based on M1 for fast KN computation, needs only the nucleosynthesis trajectories as input
- ✓ detailed investigation of Ye equilibria in neutrino-cooled BH disks
- ✓ disk mass close to 0.01 Msun optimal for prolific r-process
- ✓ fast pairwise neutrino conversions mildly reduce Ye in BH disks
- ✓ viscous models of collapsar disks may not be generically neutron-rich

Thank you for your attention!