

Three-days of brainstorming workshop - Multimessenger astrophysics with core-collapse supernovae and binary neutron star mergers

Impact of Neutrino Fast Flavor Conversions in Neutron Star Mergers

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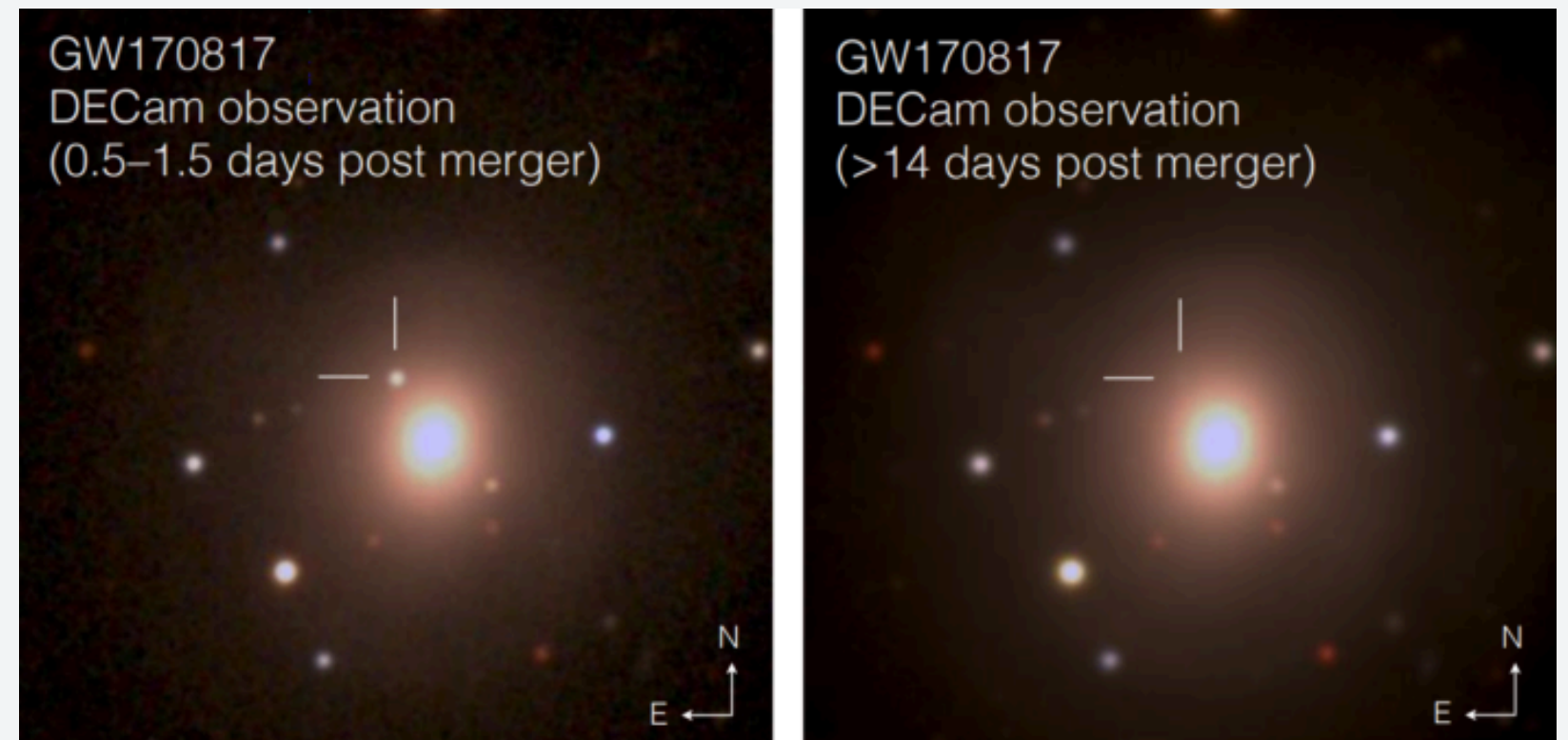
Background – Neutron Star Mergers

Neutron Star Mergers (NSMs)

- Two orbiting neutron stars lose energy to gravitational waves, spiral inward, and collide.
- The collision could end up with a short-lived, hypermassive neutron star (HMNS), which later collapses into a black hole, or the collapse can happen right away.
- Matter thrown out during and after the merger forms the **ejecta**.
- The ejecta is a heavy-element factory: a primary site of **rapid neutron-capture (r-process)** nucleosynthesis.
- **Radioactive decay** of the fresh r-process nuclei heats the ejecta and powers a transient: the **kilonova** (seen in AT2017gfo).

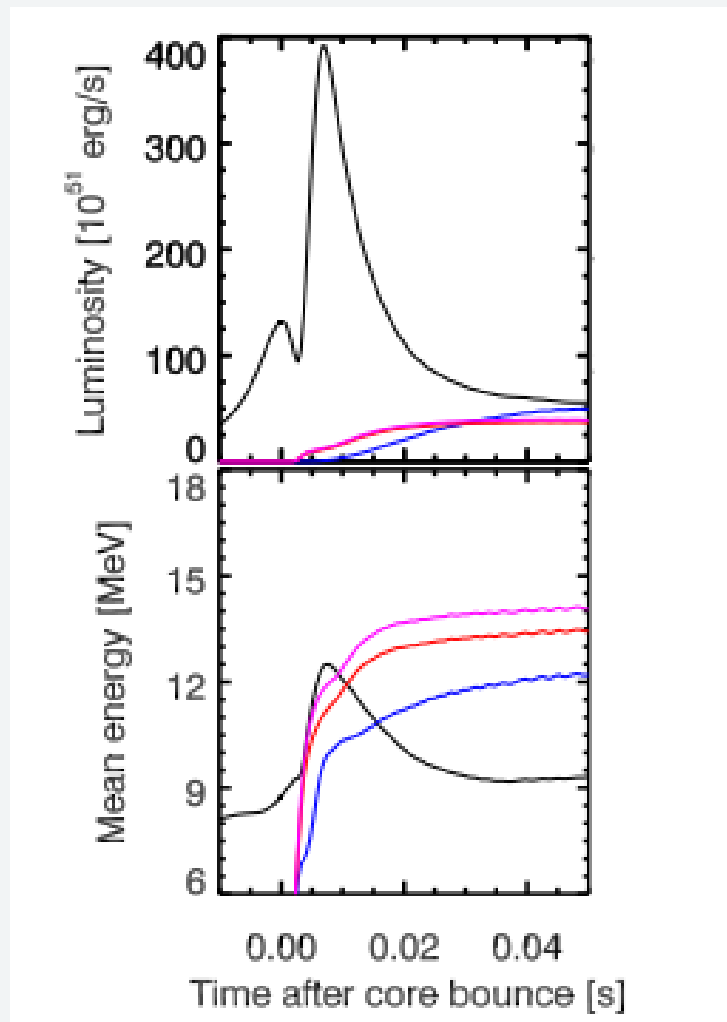


An illustration of NSM (ESO/University of Warwick/M. Kornmesser)



AT2017gfo, DECam observation (Soares-Santos et al. 2017)

Background – Fast Flavor Conversion



Neutrino signal of a core-collapse supernova (courtesy R. Bollig)

Dense Neutrino Gases in Core-collapse Supernovae and Neutron Star Mergers

- Around 10^{53} erg of gravitational binding energy is released in the form of neutrinos
- Around 10^{58} neutrinos with ~ 10 MeV mean escape energy
- Dense neutrino gases: Around 10^{33} neutrinos per cm^3

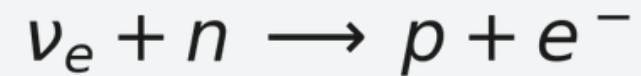
Fast Flavor Conversion (FFC)

- Neutrino–neutrino forward scattering makes the flavor content unstable
- Flavors can convert collectively on scales of nanoseconds and centimeters
- Change flavor composition in a blink

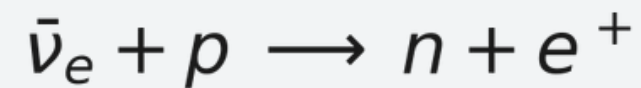
Will FFC Affect Neutron Star Mergers?

Two competing reactions modify the electron fraction (Y_e):

$$Y_e = \frac{n_p}{n_n + n_p}$$



destroys neutrons,
raises Y_e



creates neutrons,
lowers Y_e

Why the net effect of FFC might lower Y_e :

- The ejecta starts far more **neutron-rich** than proton-rich.
- FFC converts part of ν_e and $\bar{\nu}_e$ into heavy-lepton flavors, suppressing both absorption rates.
- Dominant channel: Fewer ν_e captures save way more neutrons than are lost by reducing $\bar{\nu}_e$.
- **More free neutrons survive $\rightarrow Y_e$ drops.**

Numerical challenge

- FFC occurs on nanosecond scales, far below typical merger simulation timesteps (millisecond scales).
- **Resolving FFC directly is computationally expensive in a global simulation $\rightarrow$ we adopt a subgrid model.**

Implementation – When Do We Apply FFC?

FFC requires a “crossing”

FFC is triggered when the angular distributions of ν_e and $\bar{\nu}_e$ cross: one flavor dominates in one direction, and the other in another.

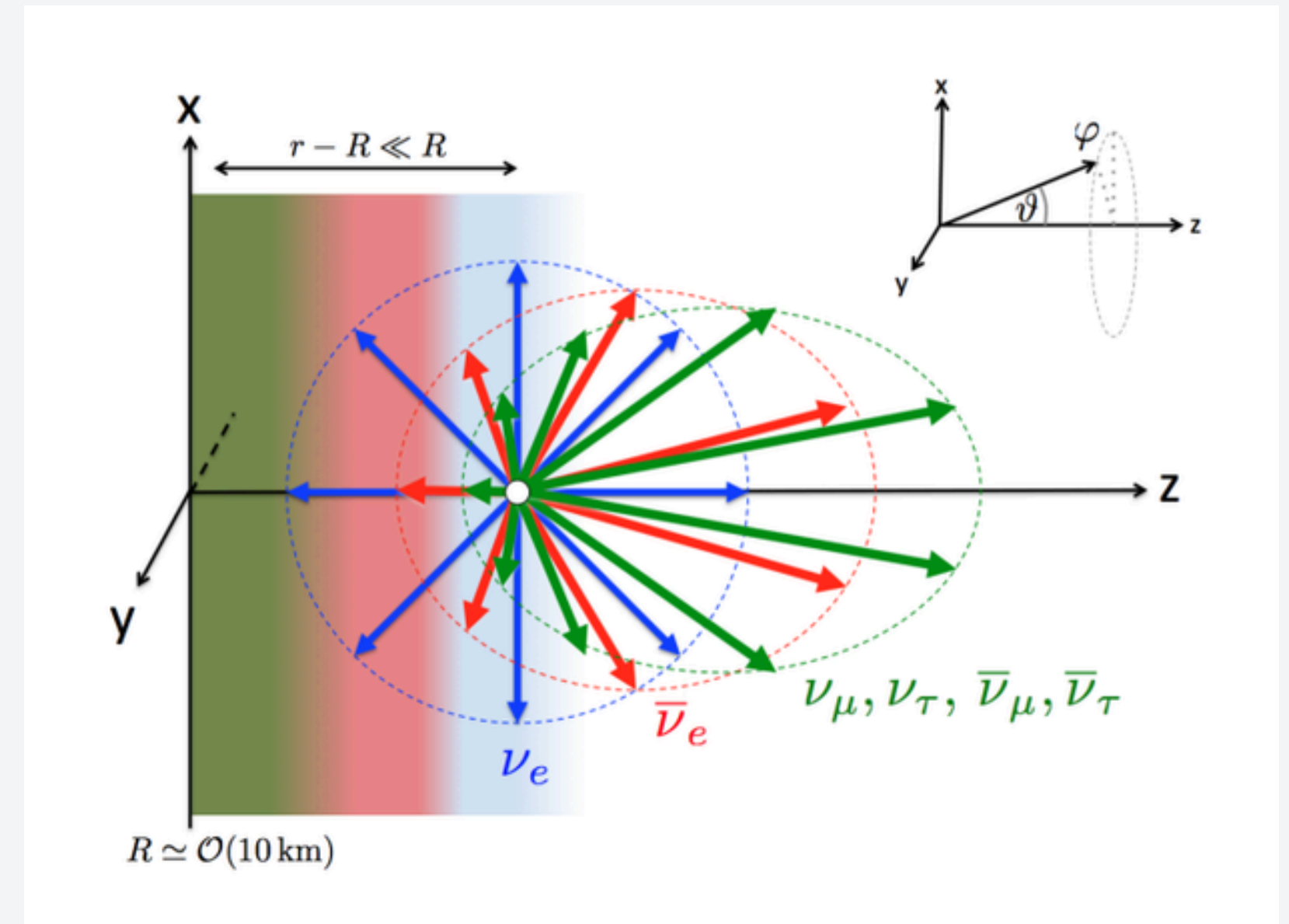
Our transport does not evolve full angular distributions, so we use two practical indicators as the condition for FFC:

1. Density is high enough: $\rho > 10^6 \text{ g/cm}^3$

At lower baryon density, FFC no longer plays a large role

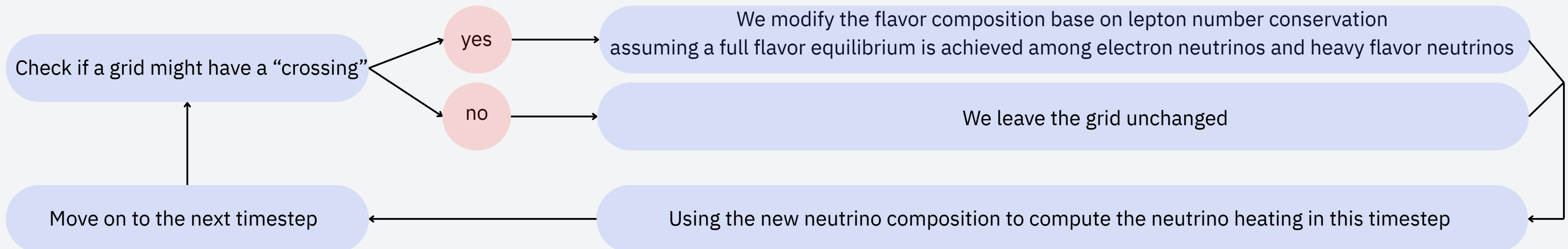
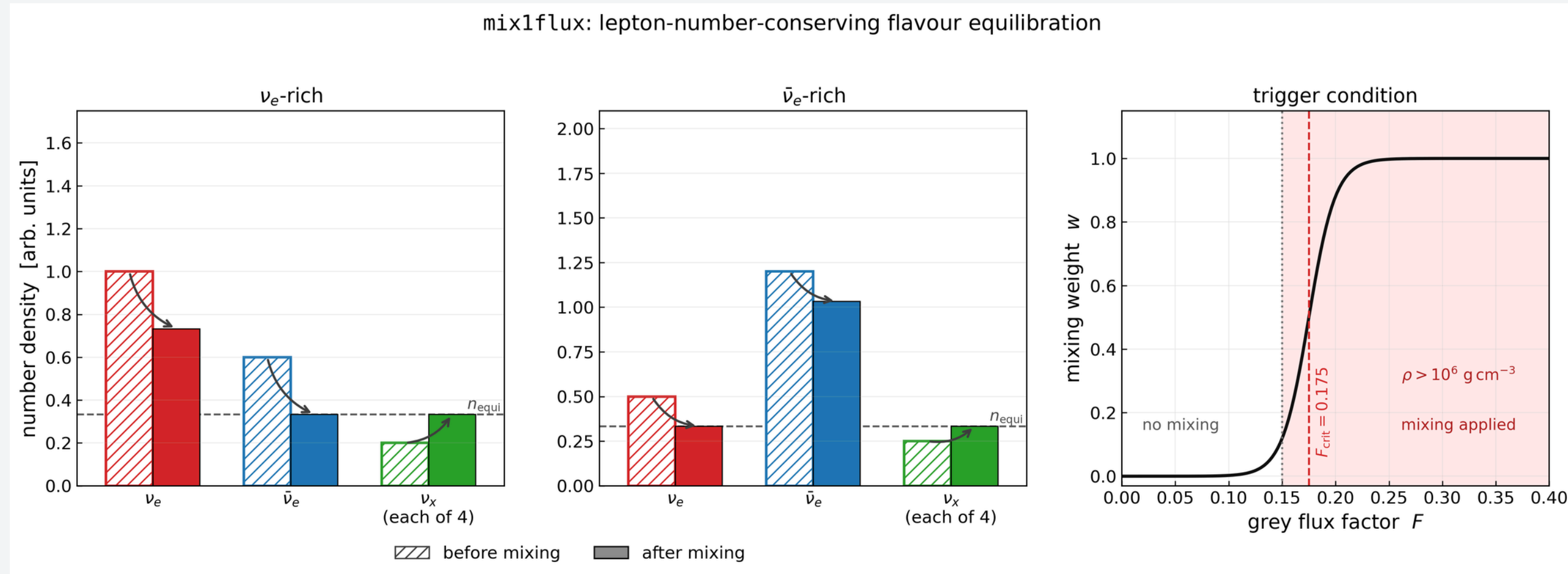
2. Electron antineutrinos flux factor $F \gtrsim 0.175$

A large flux factor means $\bar{v}_e$ are strongly forward-peaked, which is more likely to form a crossing with the more isotropic v_e .



Angular crossing between νe (blue) and $\bar{\nu} e$ (red) near the decoupling region

Implementation – What Does the Mixing Do? (mix1flux)



Simulation Setup

- The NSM simulations are conducted with the finite-volume neutrino-hydrodynamics code **Aenus-ALCAR** ^[1] ^[2]

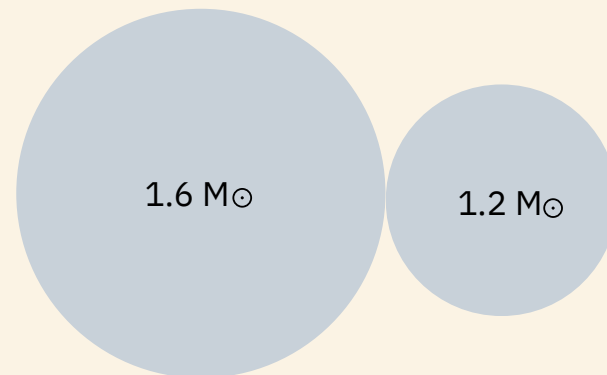
Two merger systems (SFHo EOS)

- **SFHO1375** – symmetric



collapse at around 200ms

- **SFHO1216** – asymmetric



collapse at the very beginning of the simulation

Two neutrino schemes

- **noosc**
no flavor conversion
- **mix1flux**
FFC subgrid mixing as described

[1] O. Just, M. Obergaulinger, and H.-T. Janka, MNRAS 453, 3386 (2015), arXiv:1501.02999

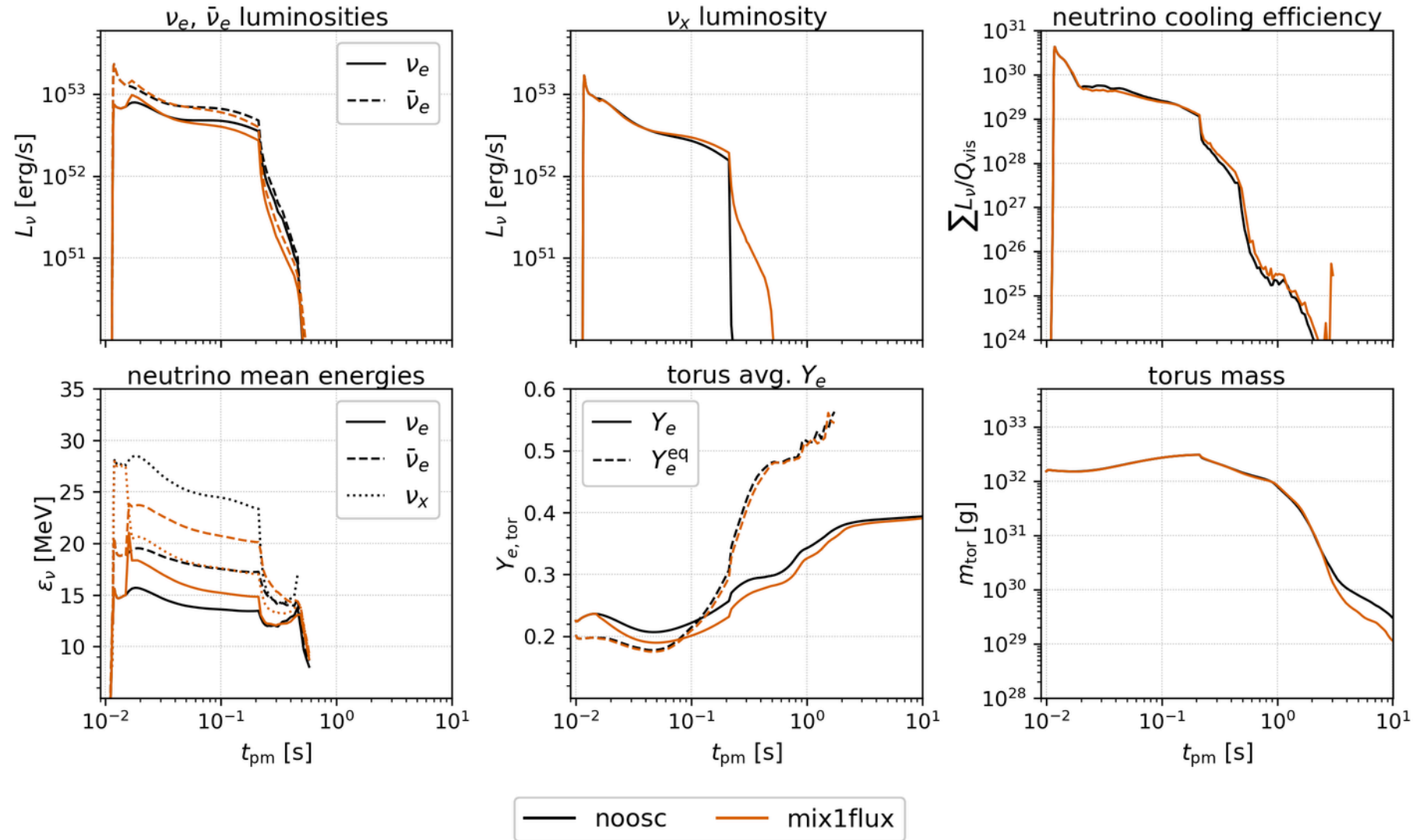
[2] O. Just, Z. Xiong, and G. Martínez-Pinedo, Phys. Rev. D 113 (2026), arXiv:2507.09040

Results

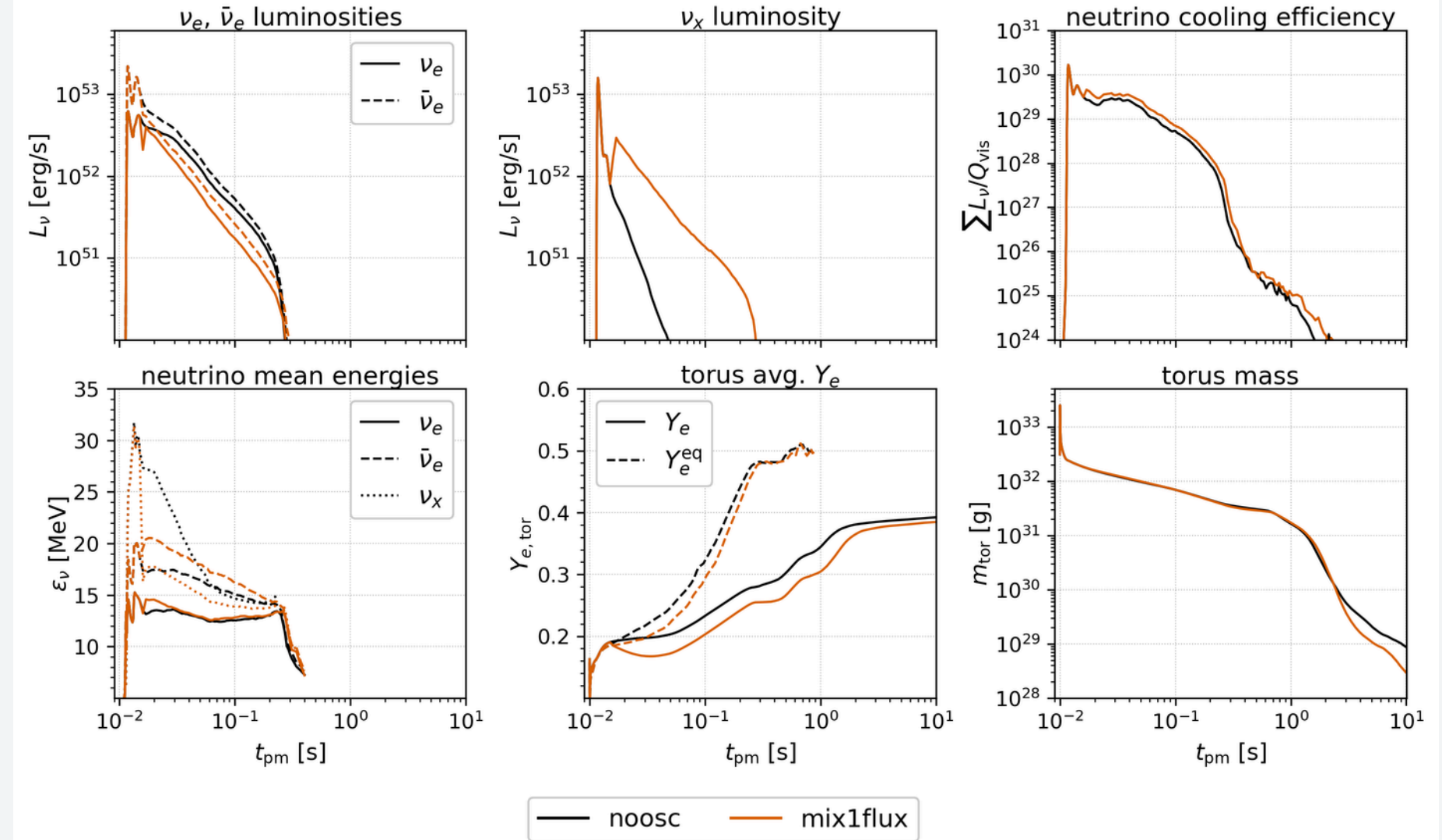
global evolution → ejecta neutron-richness → r-process yields → kilonova

Global Evolution

SFHO1375: noosc vs mix1flux



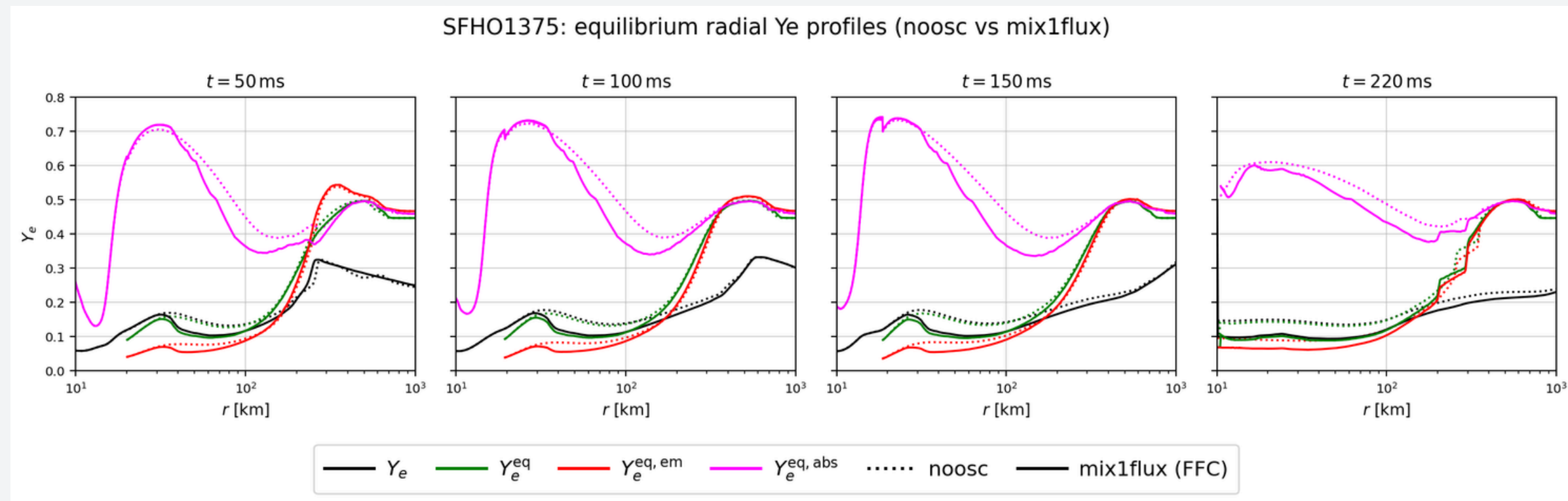
SFHO1216: noosc vs mix1flux



What changes:

- ν_e and $\bar{\nu}_e$ luminosities drop, while the ν_x luminosity rises.
- The mean energy of ν_e and $\bar{\nu}_e$ rises, while the mean energy of ν_x drops.
- There is no huge difference in outflow masses, but the neutron-richness has been modified by FFC.

Why Does Y_e Drop? – Absorption vs. Emission Equilibrium



Equilibrium Y_e^{em} (red):

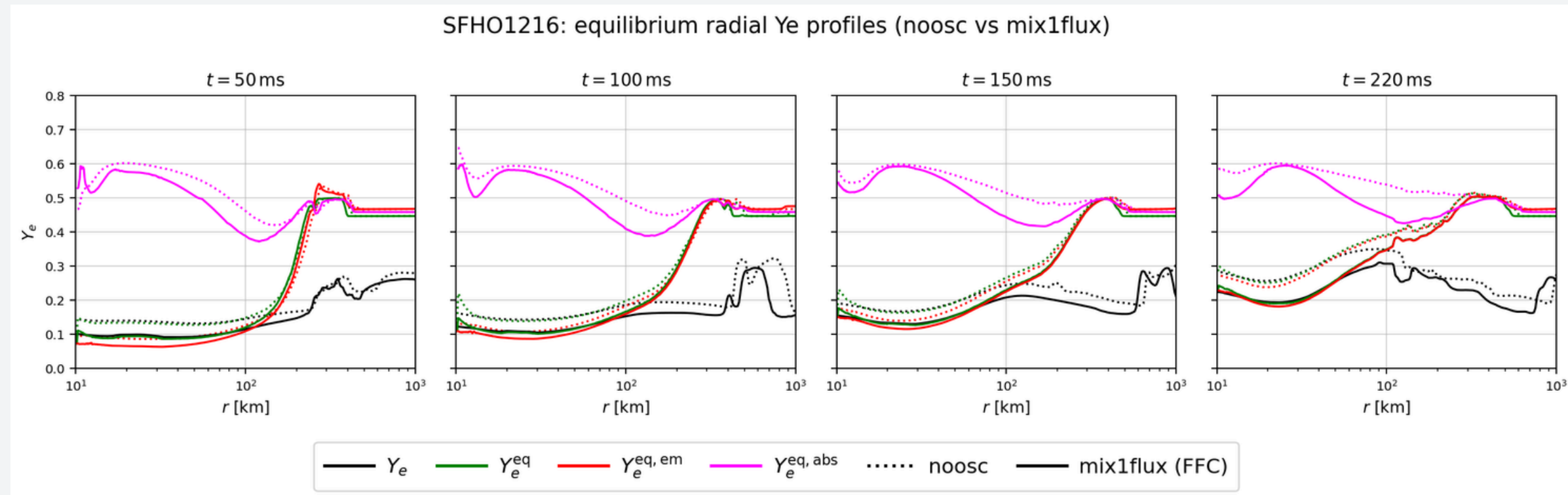
- Set by electron captures

Equilibrium Y_e^{abs} (magenta):

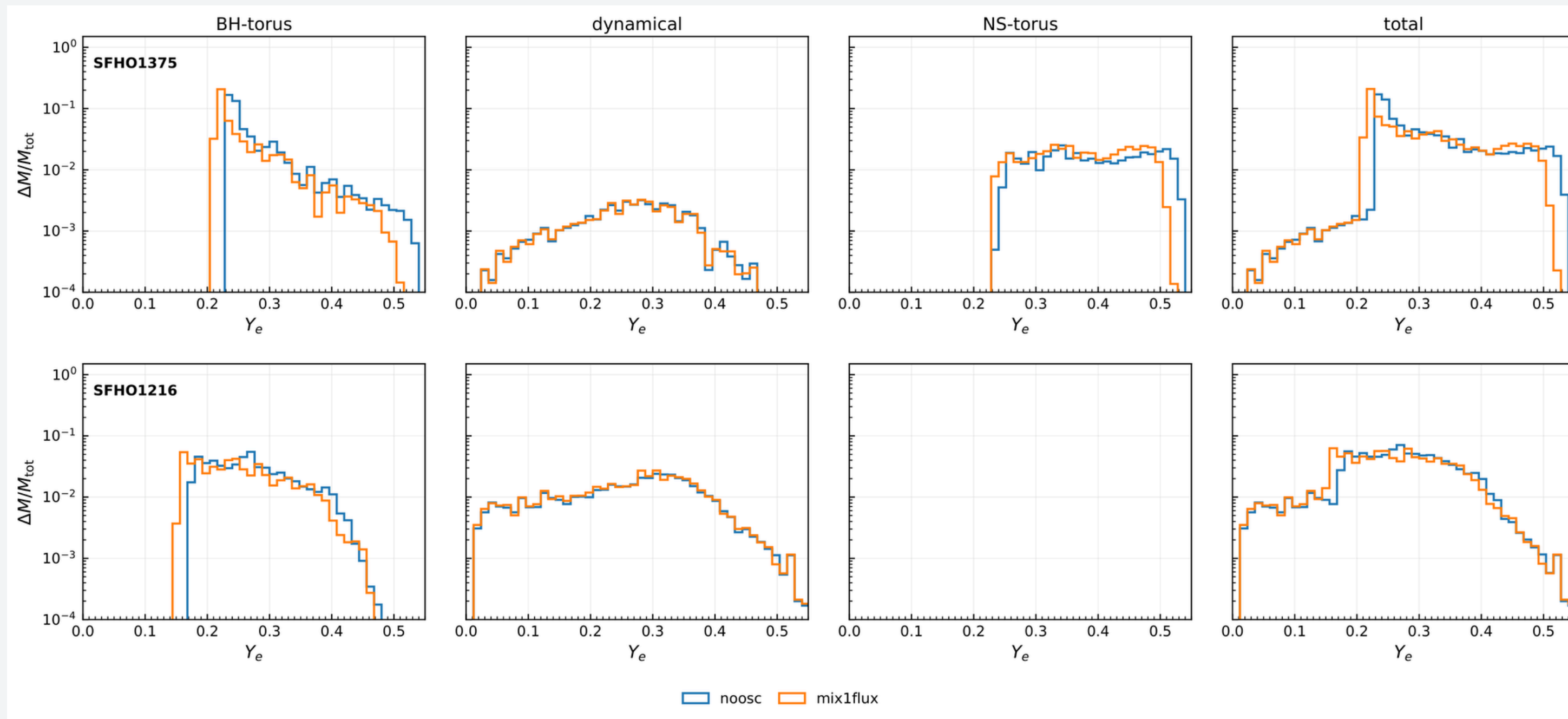
- Set by neutrino absorption

The actual Y_e (black):

- the outflow freezes out more neutron-rich.



Ejecta Ye Distributions – FFC Shifts Ejecta to Lower Ye



dynamical

Unbound during the merger

NS-torus

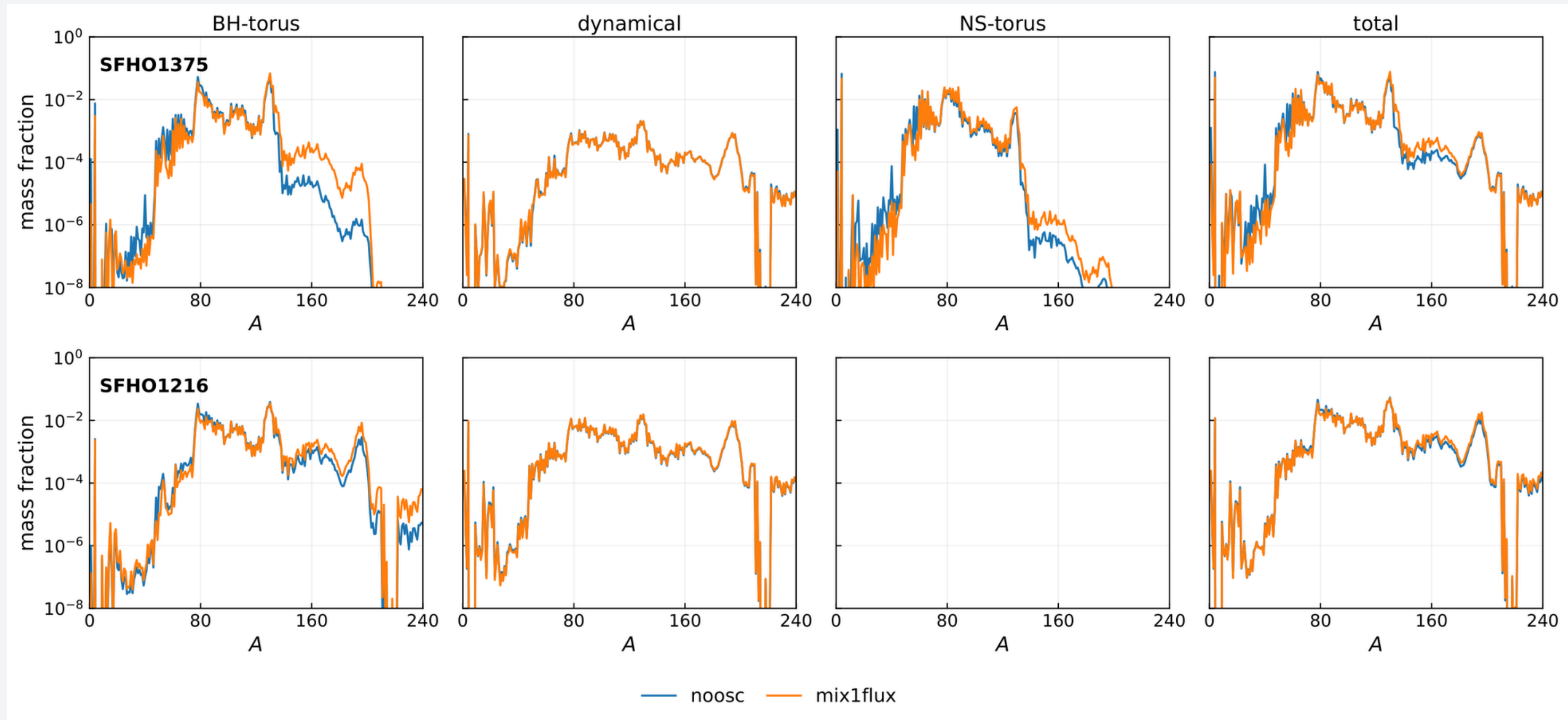
Leaves during the HMNS phase, before collapse

BH-torus

Still near the torus at collapse, ejected afterward

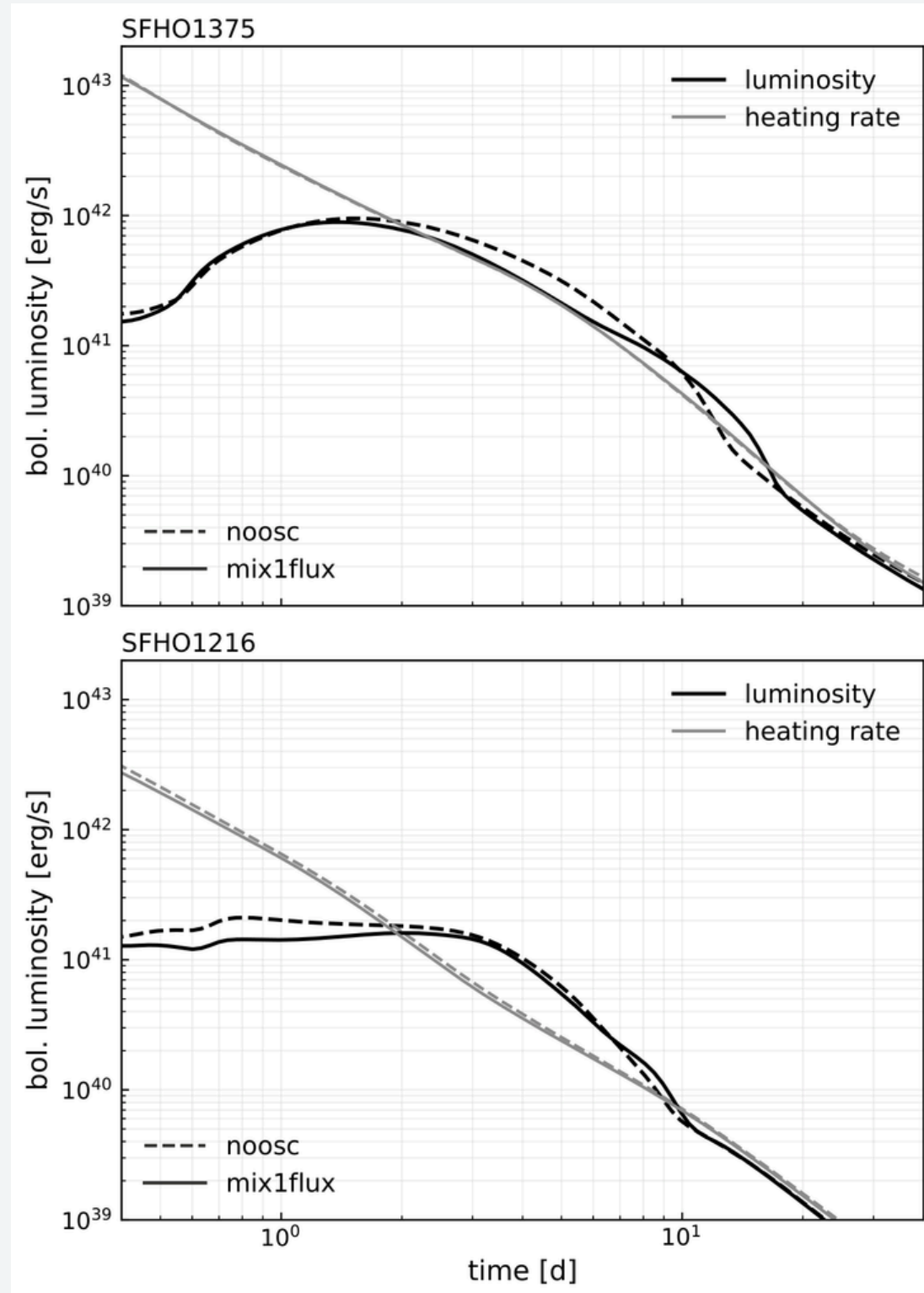
Largest shift in the BH-torus: the lowest Y_e moves from 0.22 to 0.20 for SFHO1375 and from 0.17 to 0.15 for SFHO1216. Dynamical ejecta stays nearly the same.

Abundance – r-Process Elements Yields boosted by FFC



The abundance of r-process elements is enhanced (ex., lanthanides).

Kilonova Light curves



SFHO1375:

- peak luminosity nearly unchanged ($\sim 10^{42}$ erg/s at ~ 1 d)
- after the peak, the FFC curve declines faster (higher lanthanide opacity), then stays slightly brighter at ~ 10 – 20 d.

SFHO1216:

- light curves nearly overlap, which is consistent with the milder composition change.

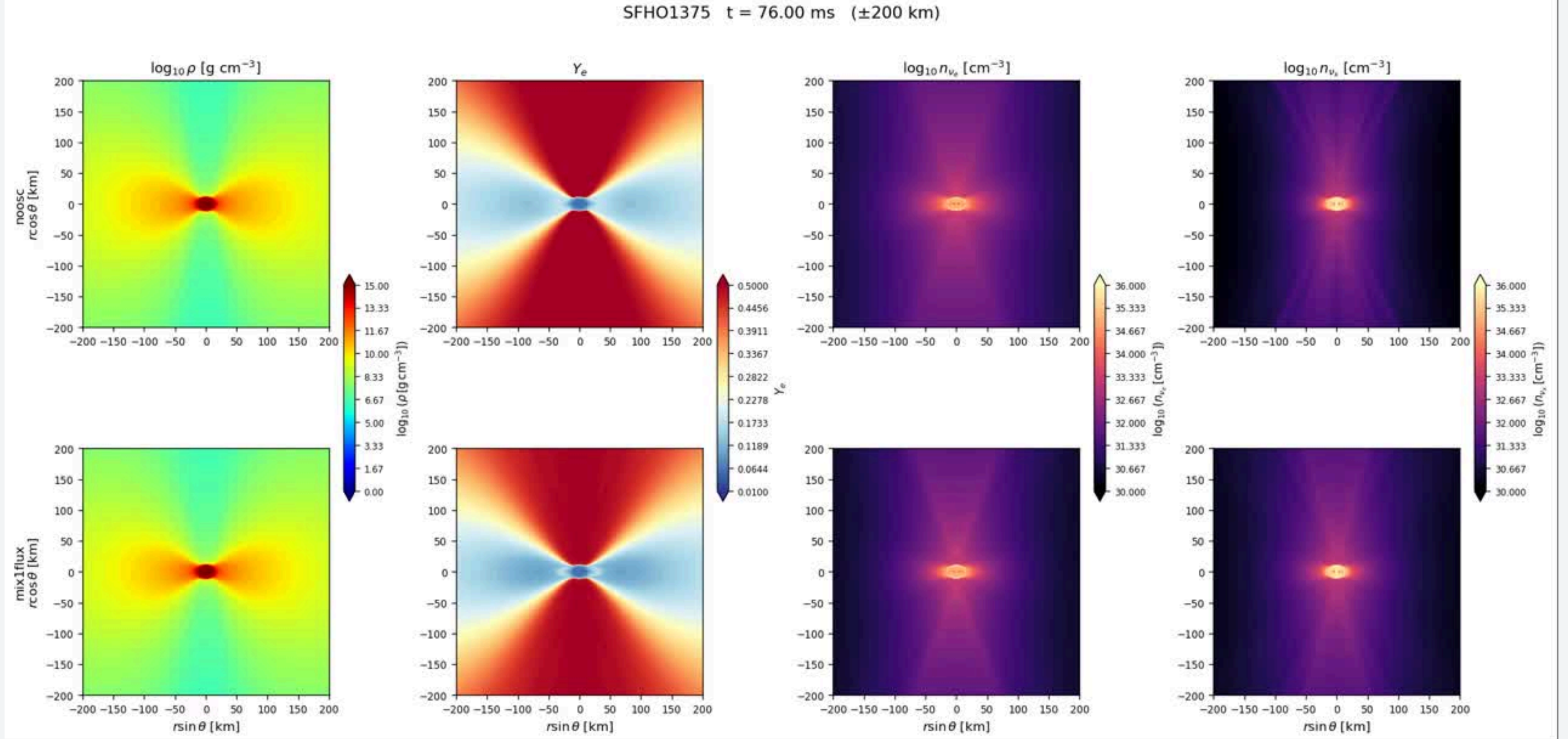
Conclusions

- FFC systematically lowers the ejecta Y_e , most strongly in the BH-torus component.
- The resulting neutron-rich outflow strengthens the r-process. The second abundance peak becomes more pronounced, and the lanthanide mass fraction is substantially enhanced, most strongly in Model SFHO1375, while the effect in Model SFHO1216 is relatively mild.
- FFC makes the kilonova of SFHO1375 fade faster after the peak and stay slightly brighter later, but has only a mild effect on SFHO1216.

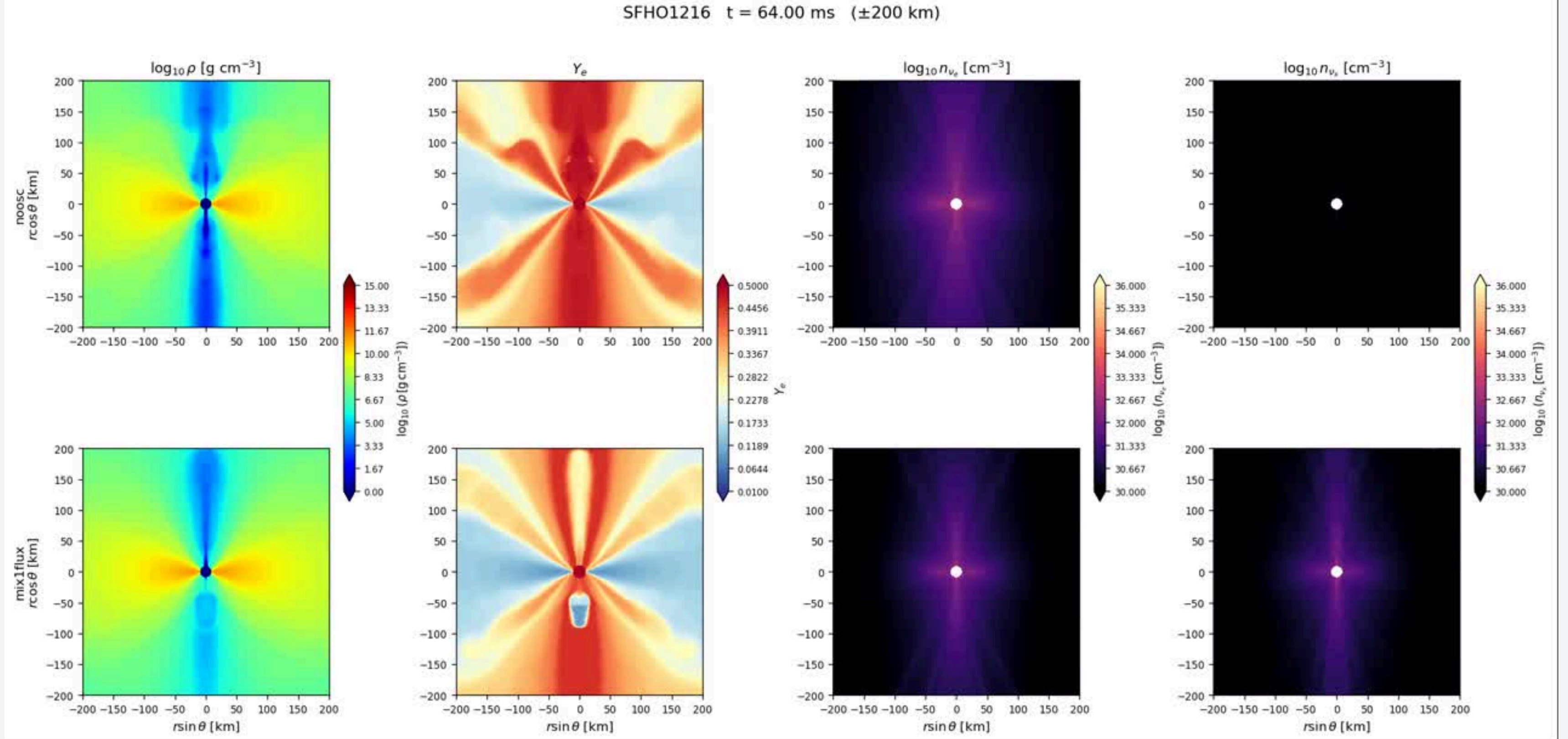
⇒ Including FFC is a necessary step toward reliable predictions of element yields and kilonova signals from neutron star mergers.

Backup Slides

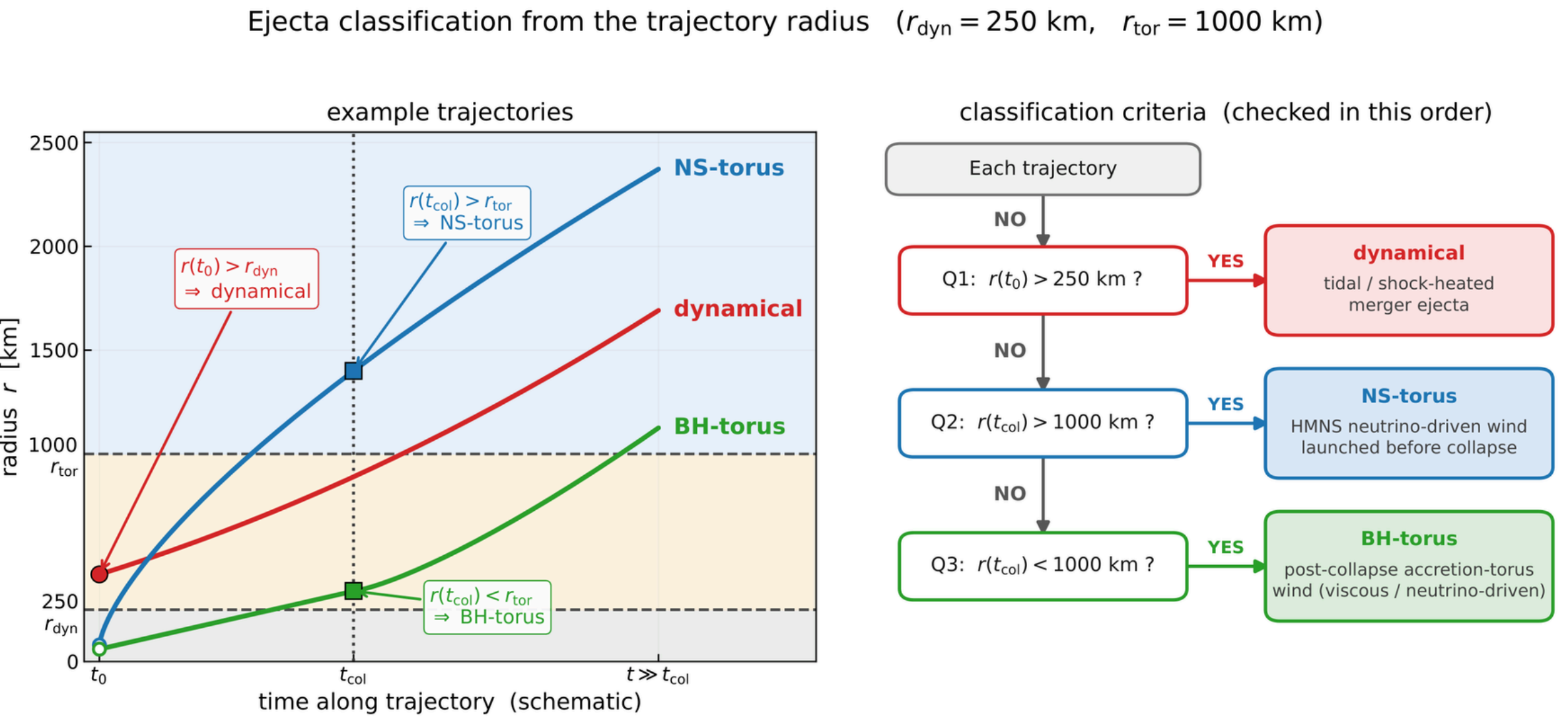
2D Animation – SFHO1375



2D Animation – SFHO1216



From Simulation to Ejecta – Three Components



dynamical

tidal / shock-heated matter expelled during the merger itself

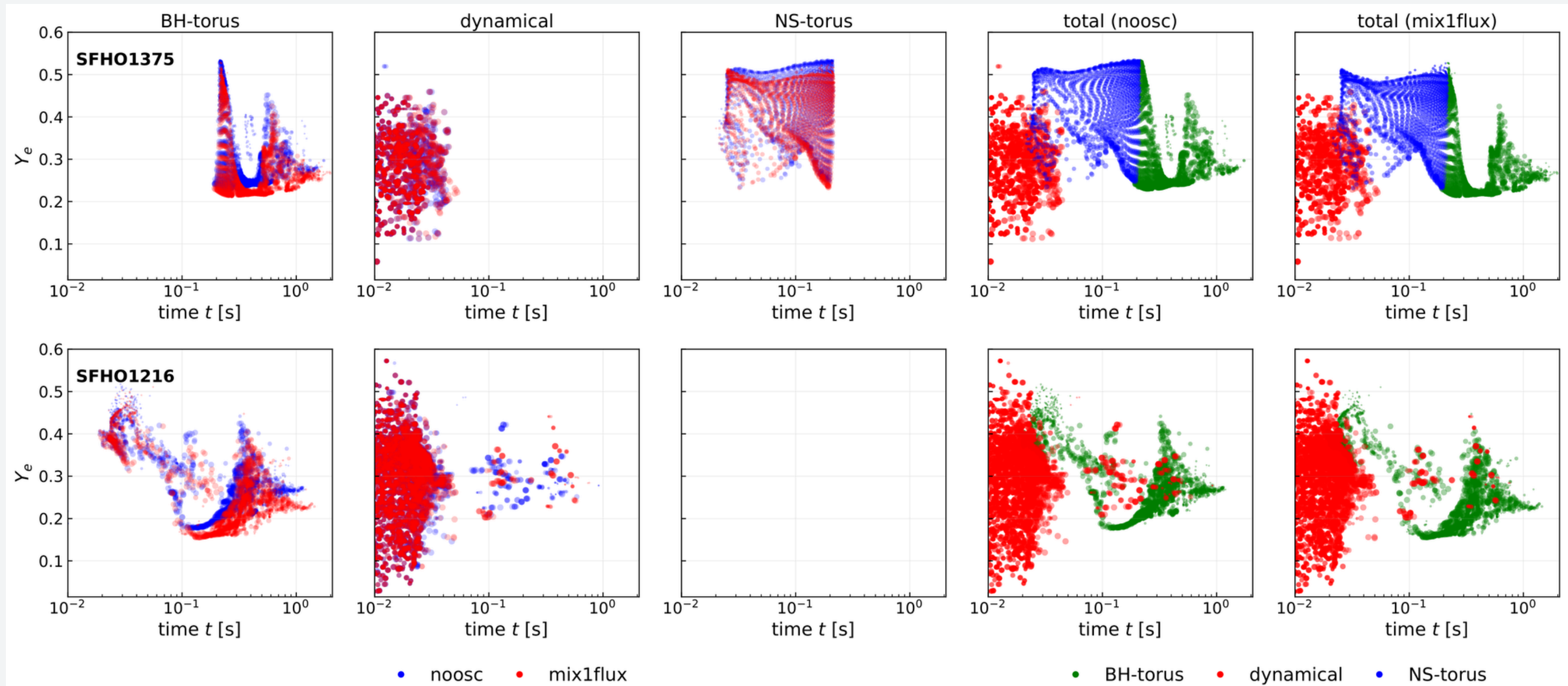
NS-torus

neutrino-driven wind launched while the HMNS is still alive (only in SFHO1375)

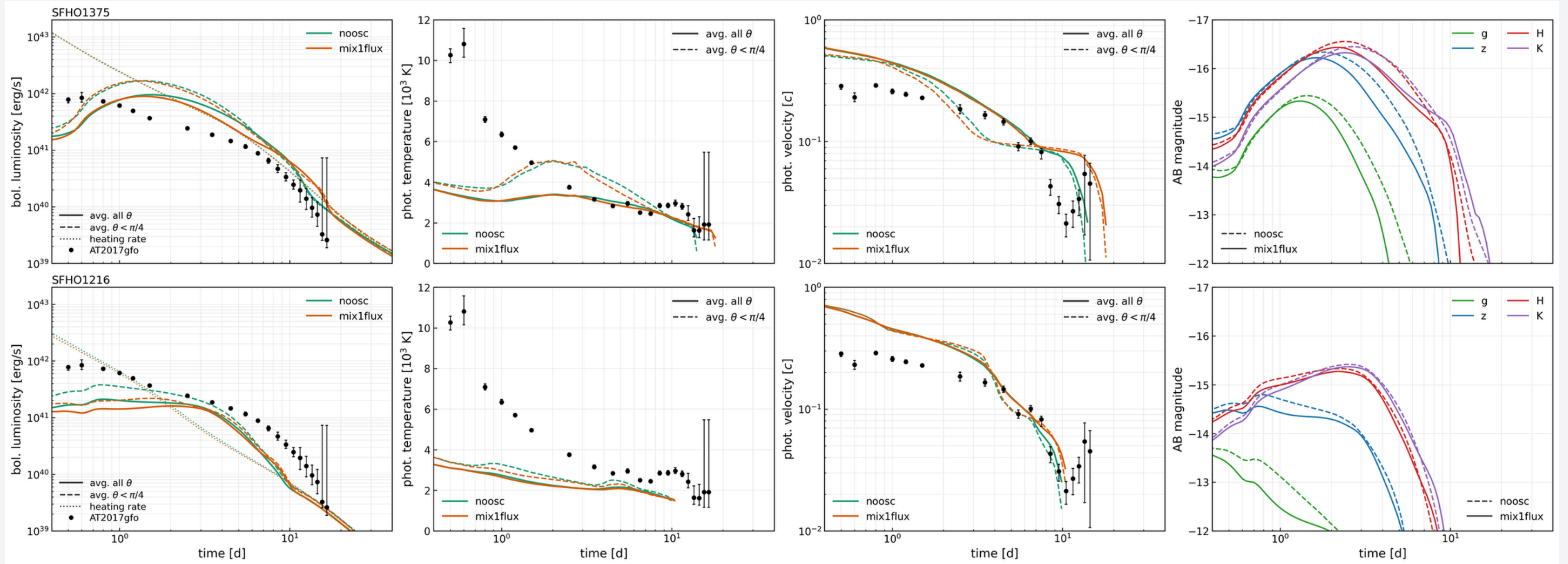
BH-torus

wind unbound from the accretion torus after collapse – the dominant component

Ye of Ejected Matter vs. Time



Backup – Full Kilonova Panels incl. AT2017gfo



Bolometric luminosity, photospheric temperature & velocity, and AB magnitudes vs. AT2017gfo data.

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

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

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

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

$$\lambda_{\mathrm{e}^{+}}Y_{\mathrm{n}}-\lambda_{\mathrm{e}^{-}}Y_{\mathrm{p}}\Big|_{\rho,T,Y_{\mathrm{e}}^{\mathrm{eq,em}}} = 0$$

$$Y_{\mathrm{e}}^{\mathrm{eq,abs}}=\frac{\lambda_{\nu_{\mathrm{e}}}}{\lambda_{\nu_{\mathrm{e}}}+\lambda_{\bar{\nu}_{\mathrm{e}}}},$$