Accurate muonic interactions in neutron-star mergers and impact on heavy-element nucleosynthesis

Harry Ho-Yin Ng, Carlo Musolino, Samuel D. Tootle, and Luciano Rezzolla

hng@itp.uni-frankfurt.de, arXiv:2411.19178

GOETHE UNIVERSITÄT FRANKFURT AM MAIN

Introduction and motivation

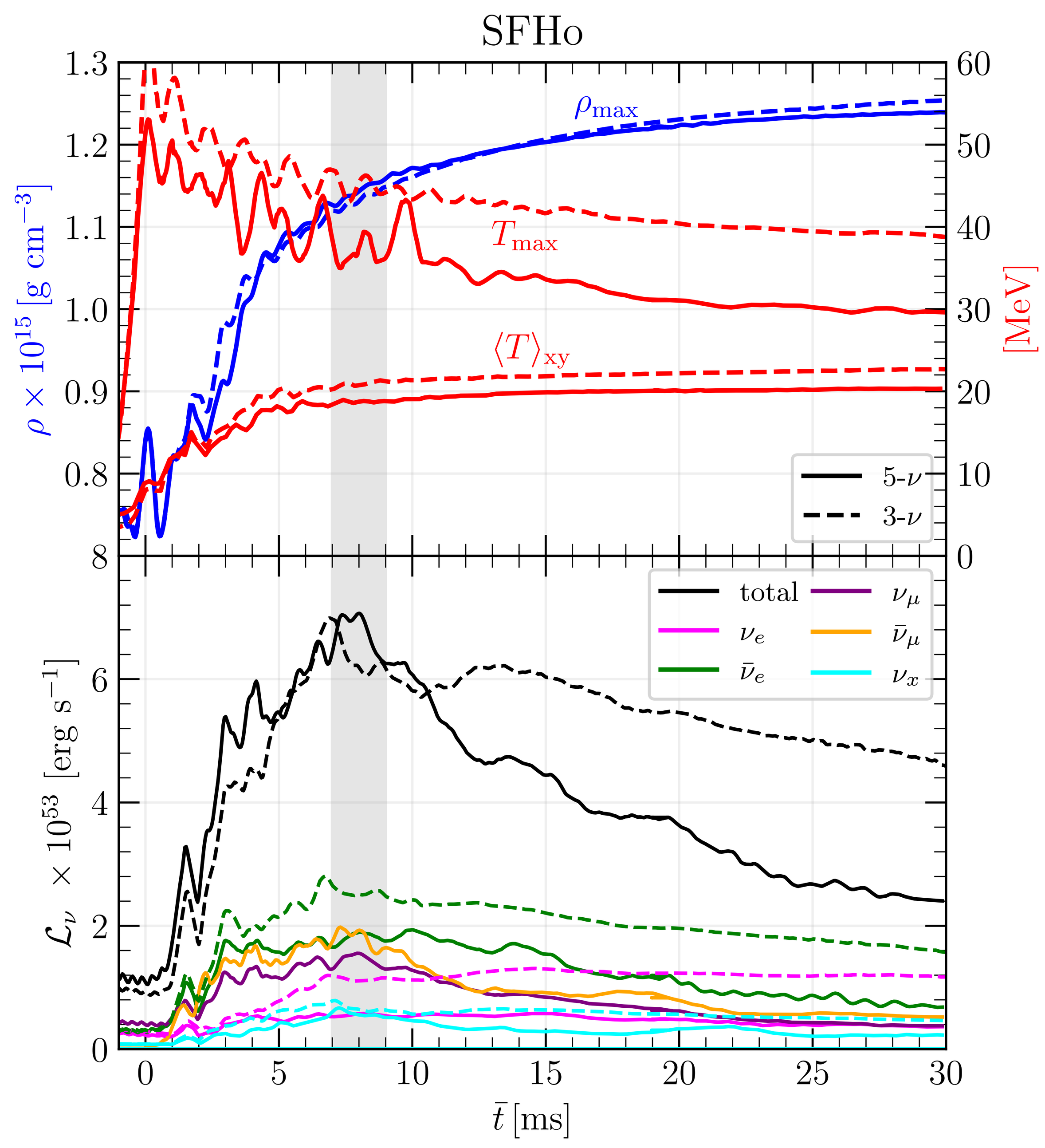
- Ejecta from binary neutron-star (BNS) mergers: Main source for heavy elements **r-process**.
- GW170817 + Ejecta → **r-process** → Kilonova → "blue": lanthanide-poor, low-opacity ejecta (with electron fraction $Y_e \gtrsim 0.25$); "red": lanthanide-rich, high-opacity ejecta (with $Y_e \lesssim 0.25$).
- **Problem**: Red component: too massive for dynamical ejecta only. blue component: too fast from the polar ejecta for a long-lived remnant [4].
- **Current explanations**: tidal ejecta in asymmetric binaries for red component and disk winds from prompt black hole collapse or short-lived remnants ($\therefore$ stop electronization for suppressing too much blue component).
- **Uncertainties**: Equation of state (EOS), remnant lifetime, neutrino microphysics and schemes.
- **Muons/antimuons (μ^-/μ^+) and muonic weak interactions, have been ignored for any BNS simulations. Alternative explanation for the problem?**

Methods

First self-consistent general-relativistic neutrino radiation hydrodynamics (GRRHD) simulations with moment-based neutrino scheme [2]:

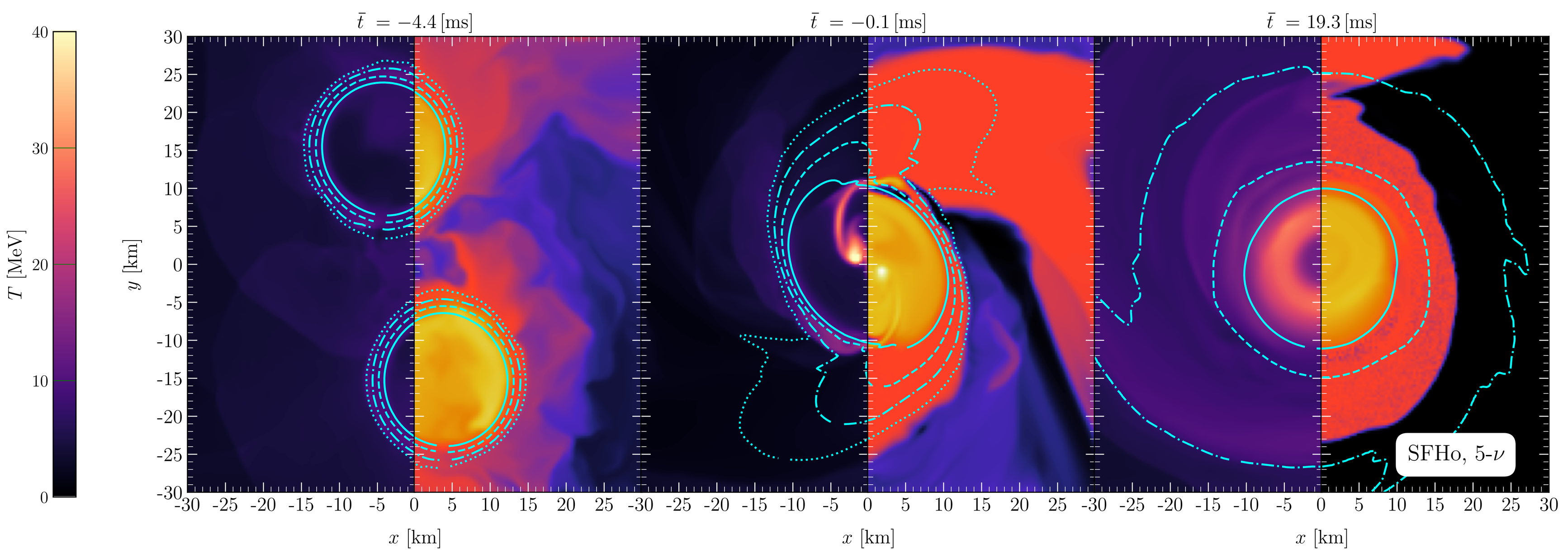
- $npe\mu$-matter (ρ, T, Y_e, Y_μ).
- Weak interactions: Electronic/Muonic β-processes (`Weakhub` [1]), e.g., $\mu^- + p \leftrightarrow \nu_\mu + n$; $\mu^+ + n \leftrightarrow \bar{\nu}_\mu + p$
- **SFHo (soft) and DD2 (stiff) EOSs**
- Equal-mass, a low total mass of 2.5 $M_\odot$
- 5-ν case: $\nu_e, \bar{\nu}_e, \nu_\mu, \bar{\nu}_\mu, \nu_x \in [\nu_\tau, \bar{\nu}_\tau]$,
  3-ν case: $\nu_e, \bar{\nu}_e, \nu_x \in [\nu_\mu, \bar{\nu}_\mu, \nu_\tau, \bar{\nu}_\tau]$

Results

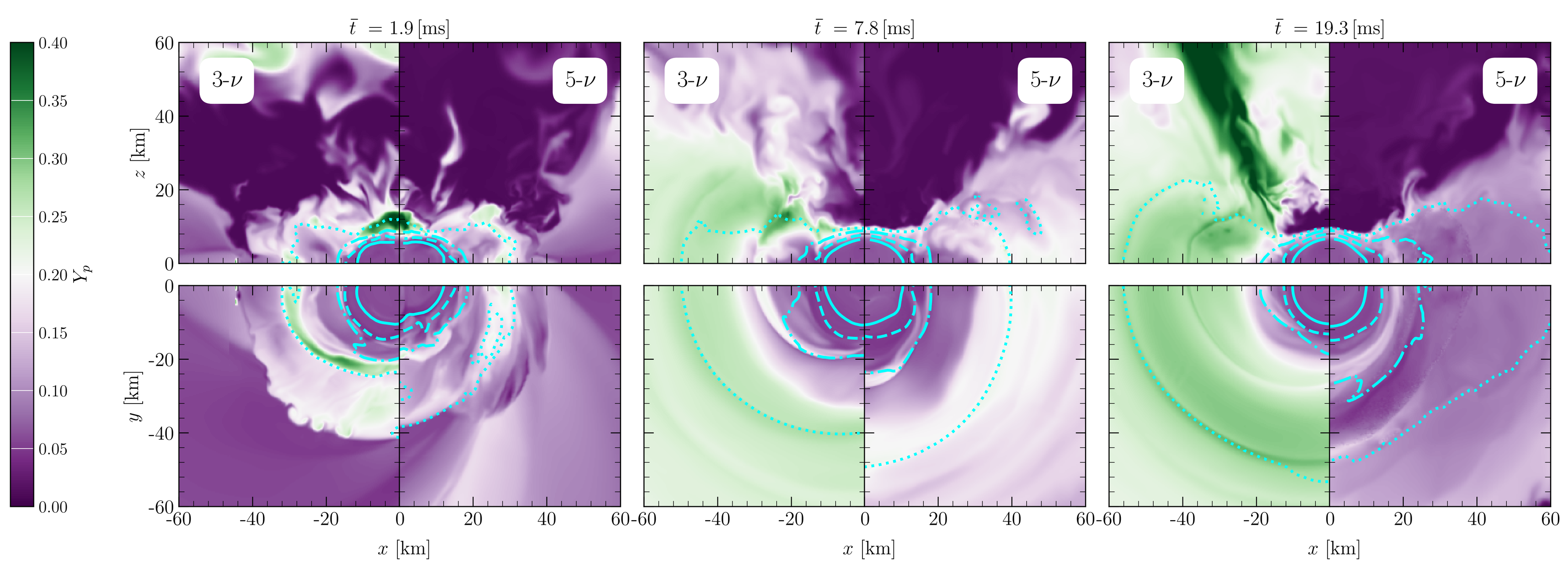


Top: evolution of the maximum rest-mass density ρ_{max} and temperature T_{max}. ***Bottom:*** neutrino luminosities $\mathcal{L}_\nu$; In both panels, the shaded region denotes the time when trapped neutrino equilibrium is attained.

- Muonic processes redirect energy reserved for protonization by electronic processes.
- Cold β-equilibrium: Muons already exist inside cold NSs $Y_\mu^{max} \sim 0.02$.
- μ^- tend to stay/be produced in high-ρ and high-T environment.
- Muonic β-processes ⇒ **Muonization** at merger ⇒ Y_μ^{max} increases to 0.05
  ⇒ stronger emission for ν_x (e.g. $\bar{\nu}_\mu$ and ν_μ) & weaker for $\bar{\nu}_e$ and ν_e
  ⇒ colder remnant (5-10 MeV lower at high-density regions)
- Reached trapped neutrino β equilibrium $\sim$ 6-7 ms after merger.
- Trapped ν hierarchy: $\mu_{\bar{\nu}_e} > \mu_{\nu_x} > \mu_{\nu_e}$ (3-ν) **VS** $\mu_{\bar{\nu}_\mu} > \mu_{\bar{\nu}_e} > \mu_{\nu_x} > \mu_{\nu_e} > \mu_{\nu_\mu}$ (5-ν).
- Muonization (**merger**), de-muonization in disk (**postmerger**):



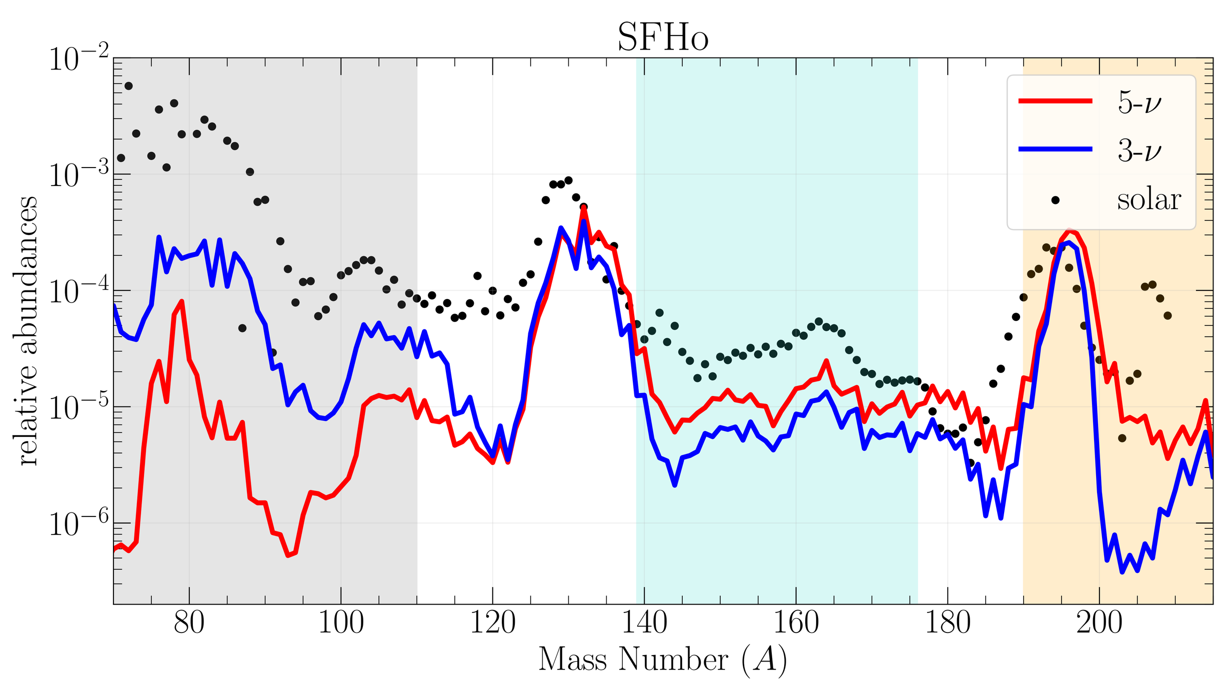
T and muon fraction Y_μ in **Inspiral, Merger, Postmerger** phases. The dotted, dash-dotted, dashed, and solid lines show rest-mass density contours at 10^{11}, 10^{12}, 10^{13}, and 10^{14} g cm^{-3}.



Proton fraction $Y_p = Y_e + Y_\mu$. The top (bottom) rows are polar (equatorial) views.

- Much lower Y_p for polar wind and disk ($Y_\mu \ll Y_e$ in different regions).
- Absence of strong electronization at pole.
- 1. Colder remnant ⇒ weaker ν_e-reabsorption in disk and weaker e^+-capture in hot ring/pole.
  2. Changed trapped ν hierarchy: $\mu_{\bar{\nu}_e} \downarrow$
  3. Disk: Muonic interactions (de-muonization) compete with electronic interactions
- ***Another possible explanation for kilonova with a long-lived remnant!***

R-process nucleosysthesis



Abundance yields vs the mass number A of nuclei. Black filled circles are solar abundance and All abundances are rescaled by A = 132 of the solar abundance.

- Total ejecta mass of 5-ν is 2 times lower; more neutron-rich from disk-wind.
- Ejecta is processed by `Skynet` [3].
- 5-ν: 100% **increase** in the yields of lanthanides (blue-shaded); an order of magnitude larger yields for elements shaded orange; 18% better match in the actinides.

References

[1] Ng, Harry Ho-Yin, et al. "General-relativistic Radiation Transport Scheme in Gmunu. II. Implementation of Novel Microphysical Library for Neutrino Radiation—Weakhub." The Astrophysical Journal Supplement Series 272.1 (2024): 9.

[2] Musolino, Carlo, and Luciano Rezzolla. "A practical guide to a moment approach for neutrino transport in numerical relativity." Monthly Notices of the Royal Astronomical Society 528.4 (2024): 5952-5971.

[3] Lippuner, Jonas, and Luke F. Roberts. "SkyNet: A modular nuclear reaction network library." The Astrophysical Journal Supplement Series 233.2 (2017): 18.

[4] Kawaguchi, Kyohei, et al. "Kilonovae of binary neutron star mergers leading to short-lived remnant neutron star formation." Monthly Notices of the Royal Astronomical Society 525.3 (2023): 3384-3398.