Muons production and Neutrino trapping in Binary Neutron Star Mergers

Eleonora Loffredo

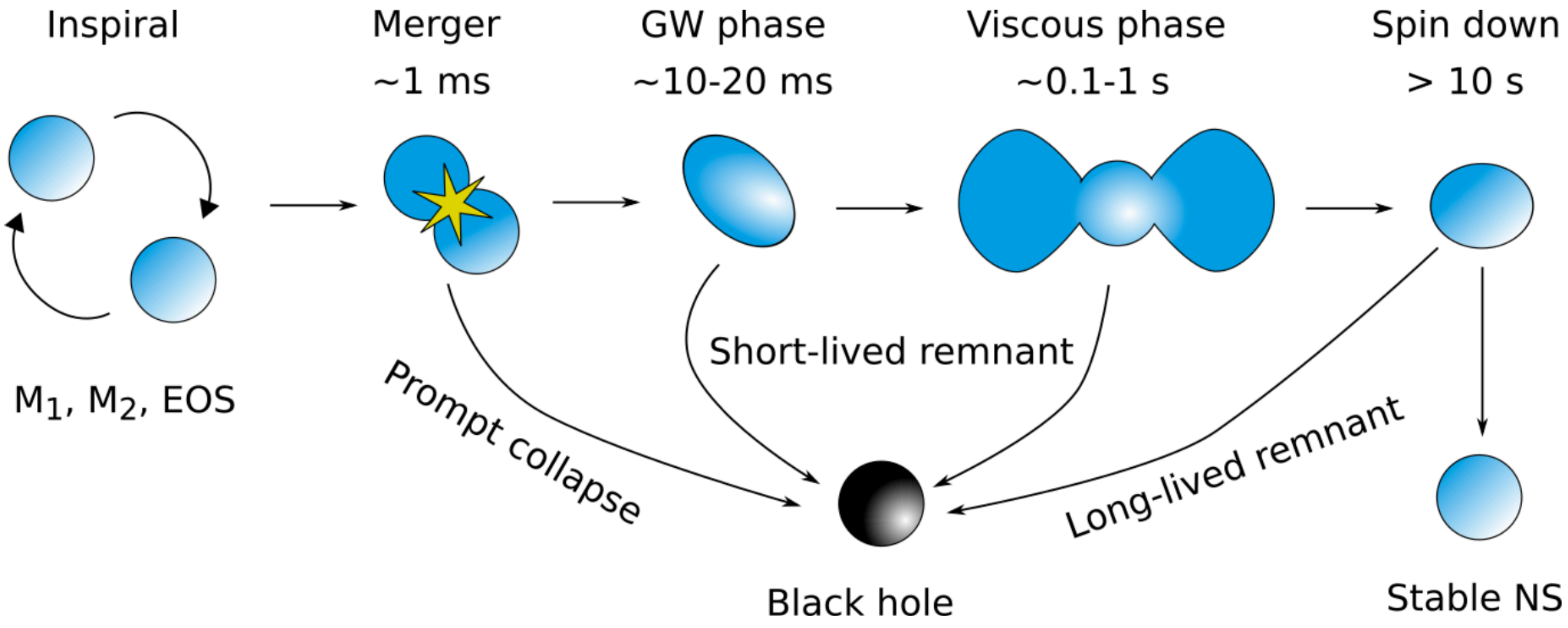
in collaboration with Albino Perego

GRAN SASSO SCIENCE INSTITUTE
SCHOOL OF ADVANCED STUDIES
Scuola Universitaria Superiore

INFN

Talk for the Ph.D. School “Neutrinos: Here, There & Everywhere” **05.07.2021**

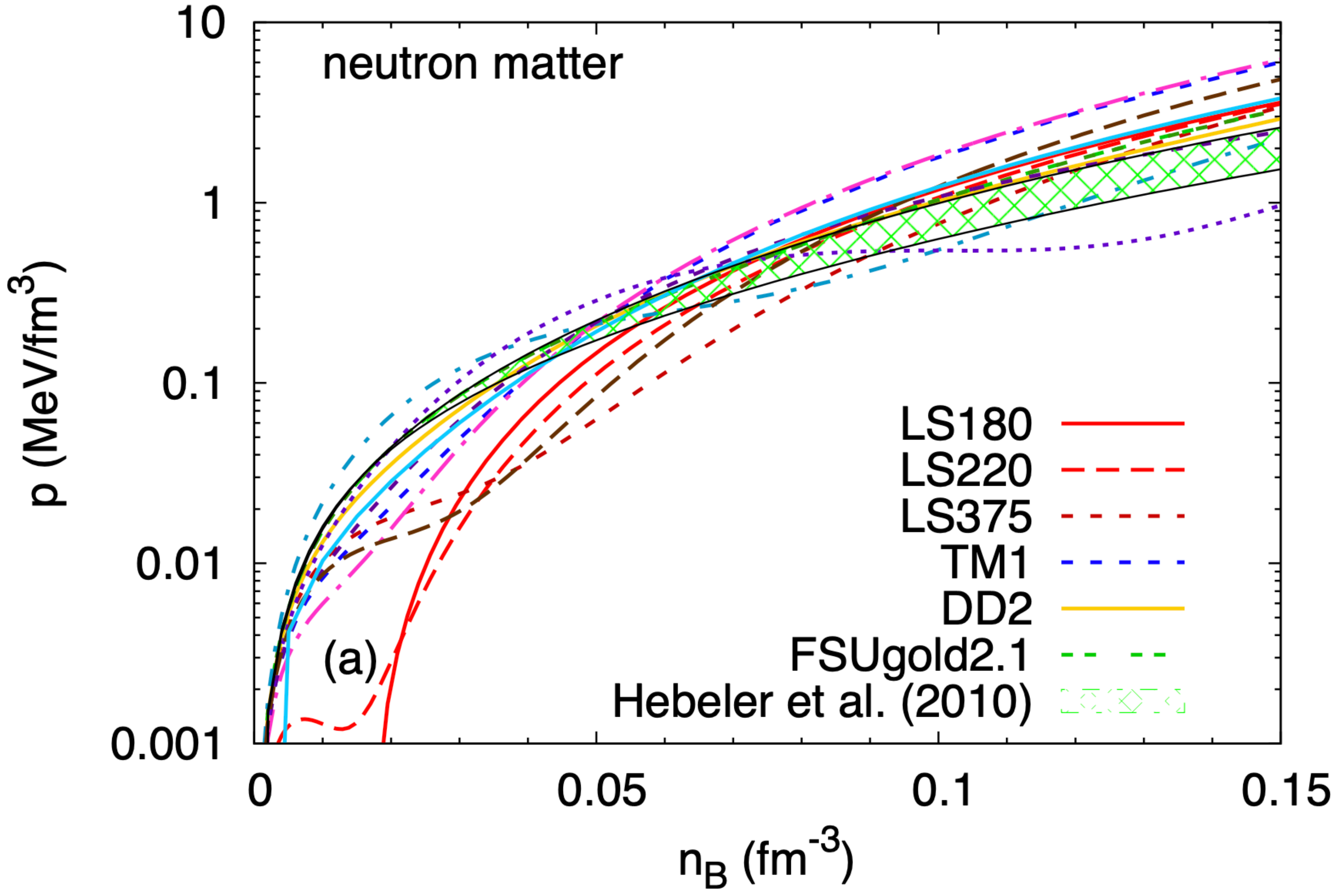
Which is the fate of a Binary Neutron Star (BNS) merger?

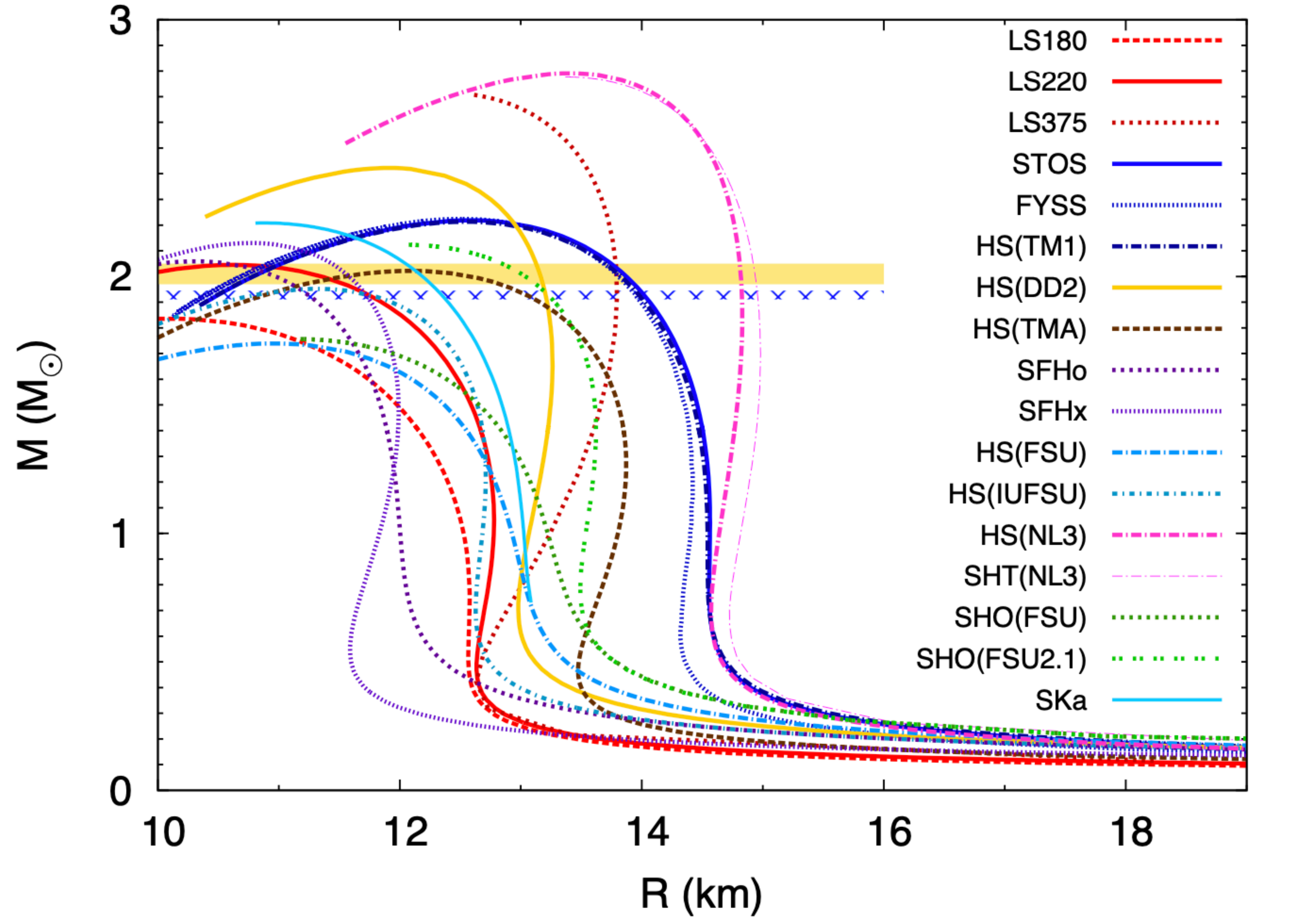


Credits: Radice, Bernuzzi, Perego 2020

The Equation of State of nuclear matter

- EOS: relation between matter density, temperature and thermodynamic variables
- The EOS of Neutron Stars is unknown
- Stiffer vs softer EOS
- Modelling of nuclear interaction and relevant degrees of freedom: neutrons, protons, pions, free quarks, muons, …
- The relevant degrees of freedom depend on the temperature other than the density

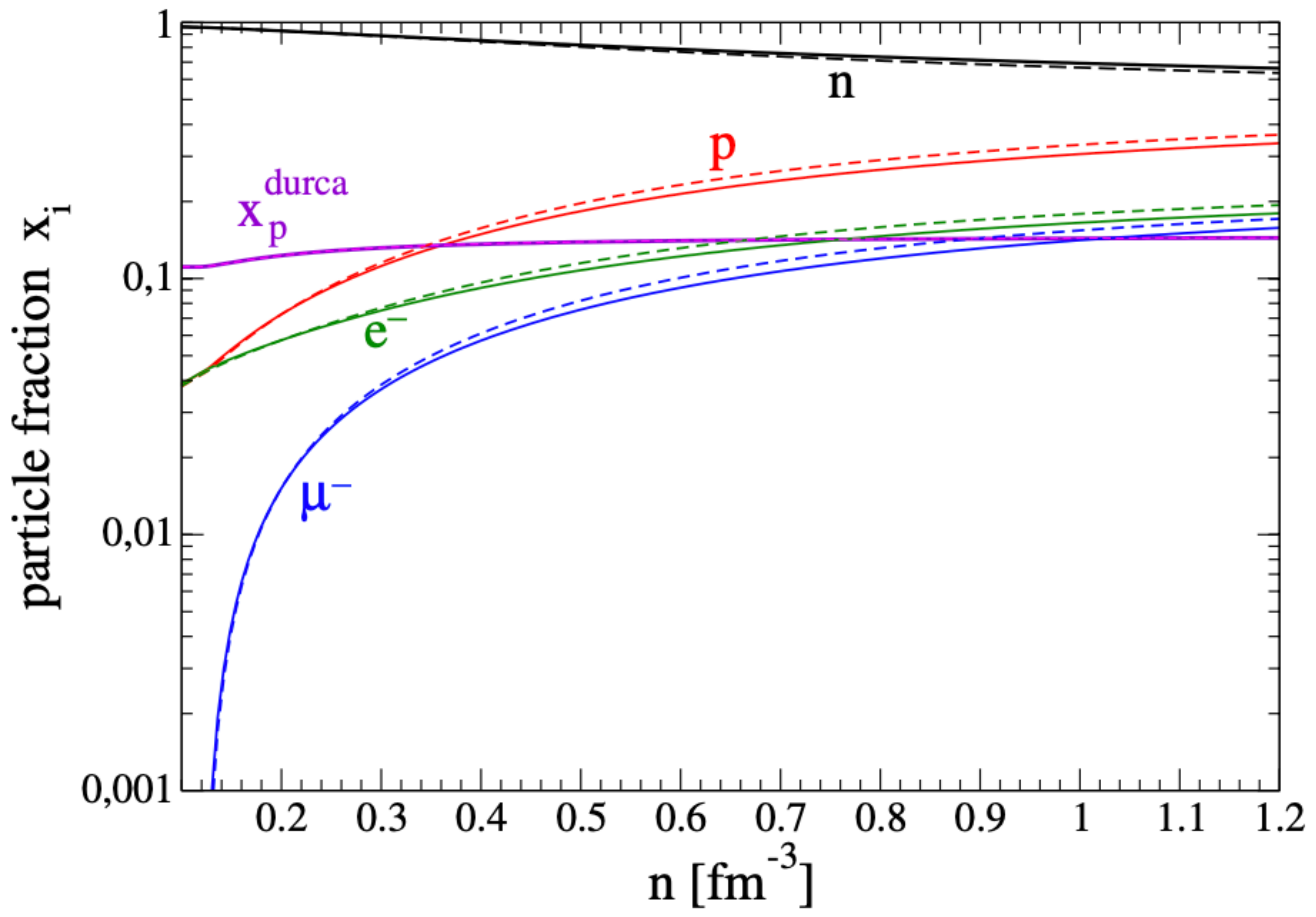




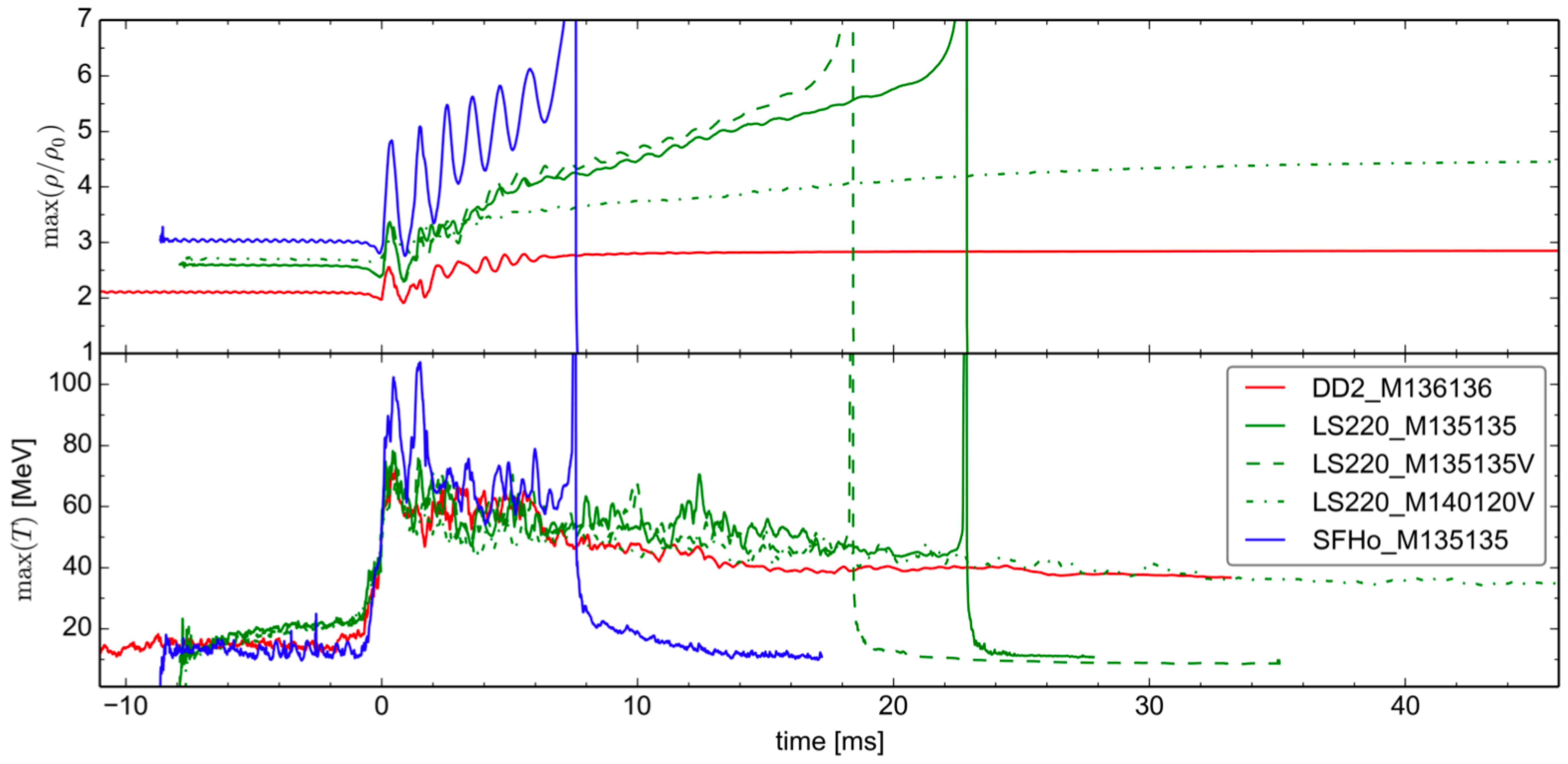
Credits: Oertel et al. 2016

The relevance of muons and trapped neutrinos

- Muons are included in cold Neutron Star EOS
- Thermodynamics conditions in BNS mergers favour muons and neutrinos production and neutrino trapping
- Trapped neutrinos can make the EOS softer



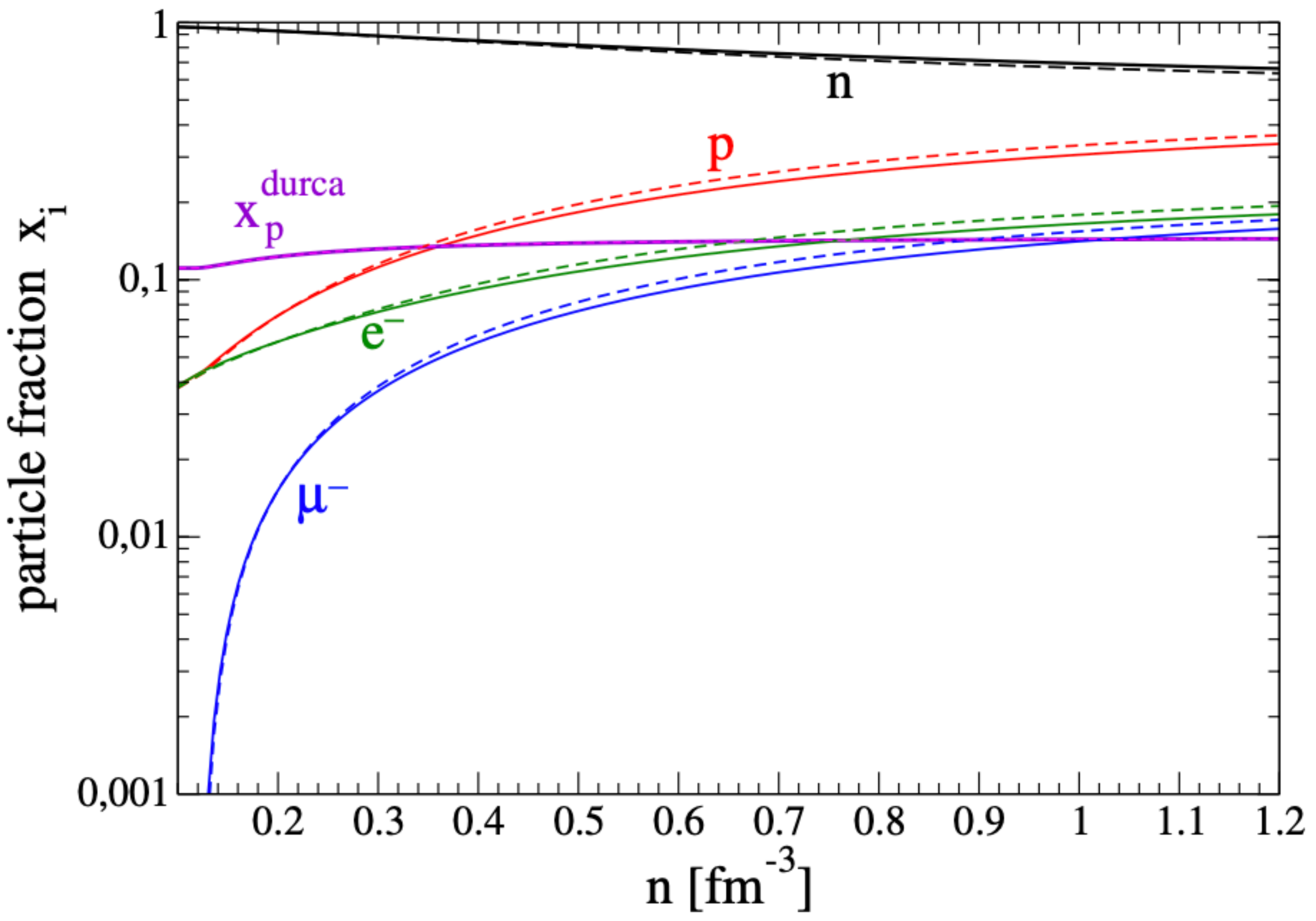
Credits: Bombaci, Logoteta 2018



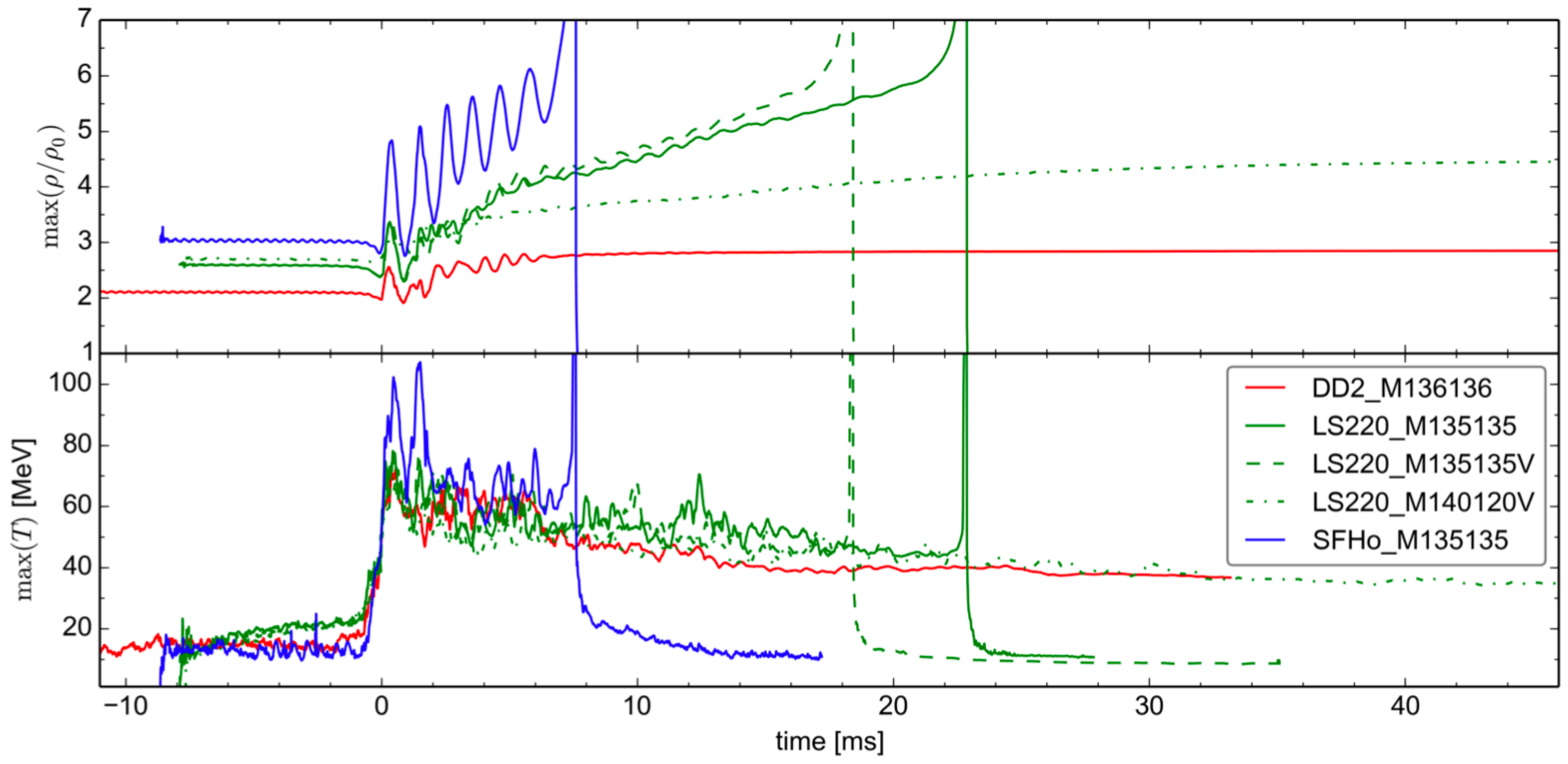
Perego et al. 2019

The relevance of muons and trapped neutrinos

State of the art simulations of BNS mergers **don't** include muons and trapped neutrinos. The **aim** of this work is to estimate their impact on the final outcome.



Credits: Bombaci, Logoteta 2018



Perego et al. 2019

Method - 1

Modelling the microphysics

- Degrees of freedom: baryons, electrons, positrons, muons, anti-muons, photons and neutrinos

- The thermodynamic variables are determined by baryon number density n_b, temperature T and particle fractions $Y_i = n_i/n_B$ where $i = p, e^-, e^+, \mu^- \dots$

- Charge neutrality $Y_p = Y_e + Y_\mu$ where $Y_e = Y_{e^-} - Y_{e^+}$ and $Y_\mu = Y_{\mu^-} - Y_{\mu^+}$

- We assume thermal and weak equilibrium

- Under these assumptions the relevant variables are n_b, T, Y_e and Y_μ

Method - 1

Modelling the microphysics

$\gamma + \gamma \longleftrightarrow \mu^+ + \mu^-$	$e^+ + e^- \longleftrightarrow \mu^+ + \mu^-$
$\gamma + \gamma \longleftrightarrow e^+ + e^-$	$e^+ + e^- \longleftrightarrow \nu_x + \bar{\nu}_x$
$\gamma + \gamma \longleftrightarrow \nu_x + \bar{\nu}_x$	$\nu_x + \mu^\pm \longrightarrow \nu_x + \mu^\pm$
$\nu_\mu + e^- \longleftrightarrow \nu_e + \mu^-$	$\bar{\nu}_\mu + p \longleftrightarrow n + \mu^+$
$\nu_\mu + \bar{\nu}_e + e^- \longleftrightarrow \mu^-$	$\bar{\nu}_e + e^- \longleftrightarrow \bar{\nu}_\mu + \mu^-$
$\nu_\mu + n \longleftrightarrow p + \mu^-$	$\nu_e + n \longleftrightarrow p + e^-$
$\bar{\nu}_e + p \longleftrightarrow n + e^+$	$\bar{\nu}_\mu + e^+ \longleftrightarrow \bar{\nu}_e + \mu^+$
$\bar{\nu}_\mu + \nu_e + e^+ \longleftrightarrow \mu^+$	$\nu_e + e^+ \longleftrightarrow \nu_\mu + \mu^+$

- We assume thermal and weak equilibrium
- Under these assumptions the relevant variables are n_b, T, Y_e and Y_μ

Method - 2

The lepton fractions

- Consider a fluid element in thermal and weak equilibrium at high enough density

- Neutrinos are trapped, and electron lepton number $Y_{l,e}$ and muon lepton number $Y_{l,\mu}$ are conserved

$$\begin{cases} Y_{l,e} = Y_e + Y_{\nu_e}(n_b, T, Y_e, Y_\mu) - Y_{\bar{\nu}_e}(n_b, T, Y_e, Y_\mu) \\ Y_{l,\mu} = Y_\mu + Y_{\nu_\mu}(n_b, T, Y_e, Y_\mu) - Y_{\bar{\nu}_\mu}(n_b, T, Y_e, Y_\mu) \end{cases}$$

- Equivalent set of variables $(Y_e, Y_\mu) \longleftrightarrow (Y_{l,e}, Y_{l,\mu})$

Method - 3

The post-processing technique

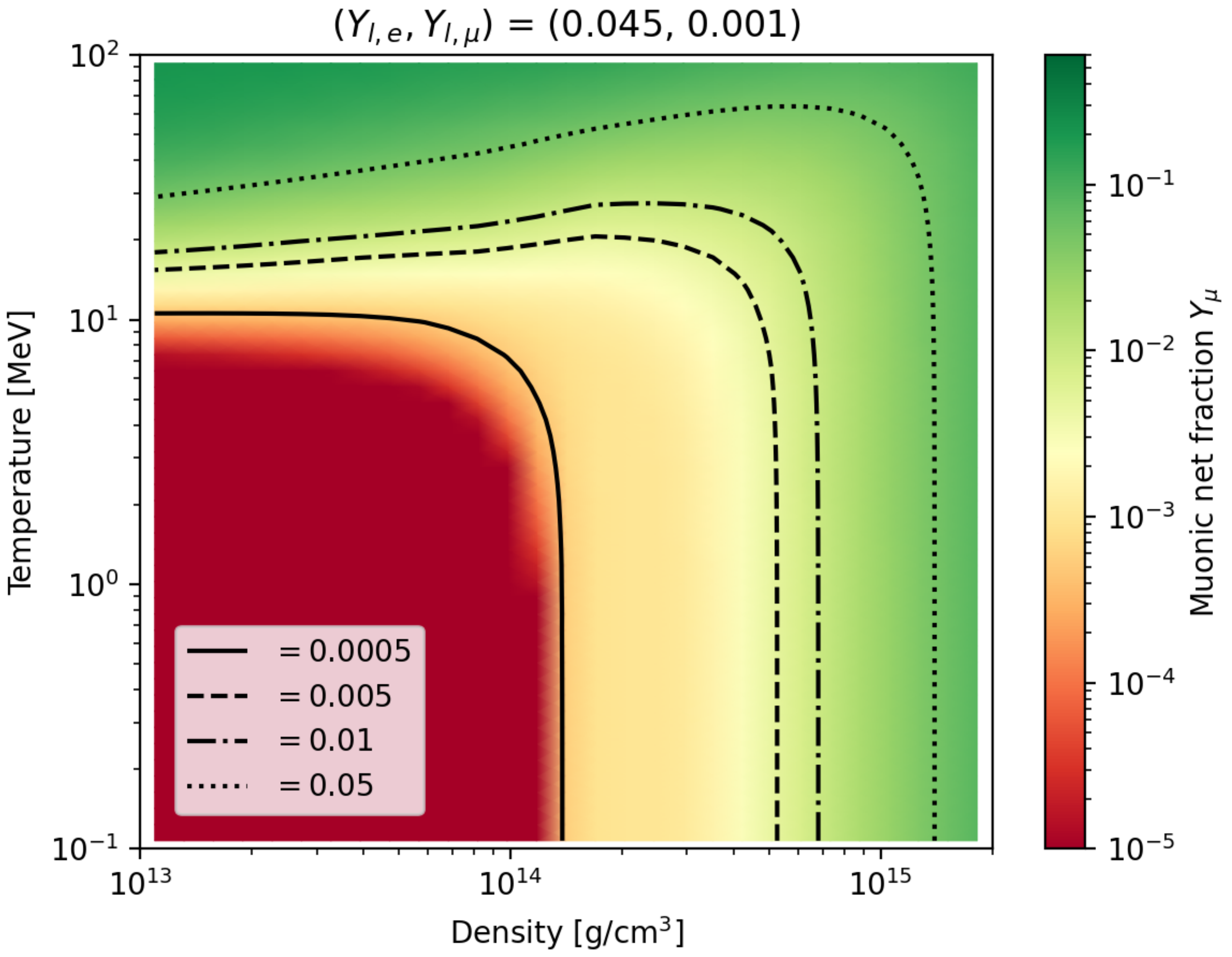
- During the merger the temperature of the fluid element increases → creation of muons and neutrinos
- At high enough density the neutrinos are trapped → $Y_{l,e}, Y_{l,\mu}$ conserved
- On a time-scale $t_{weak} \ll dt \ll t_{dyn}$ the internal energy u stays the same

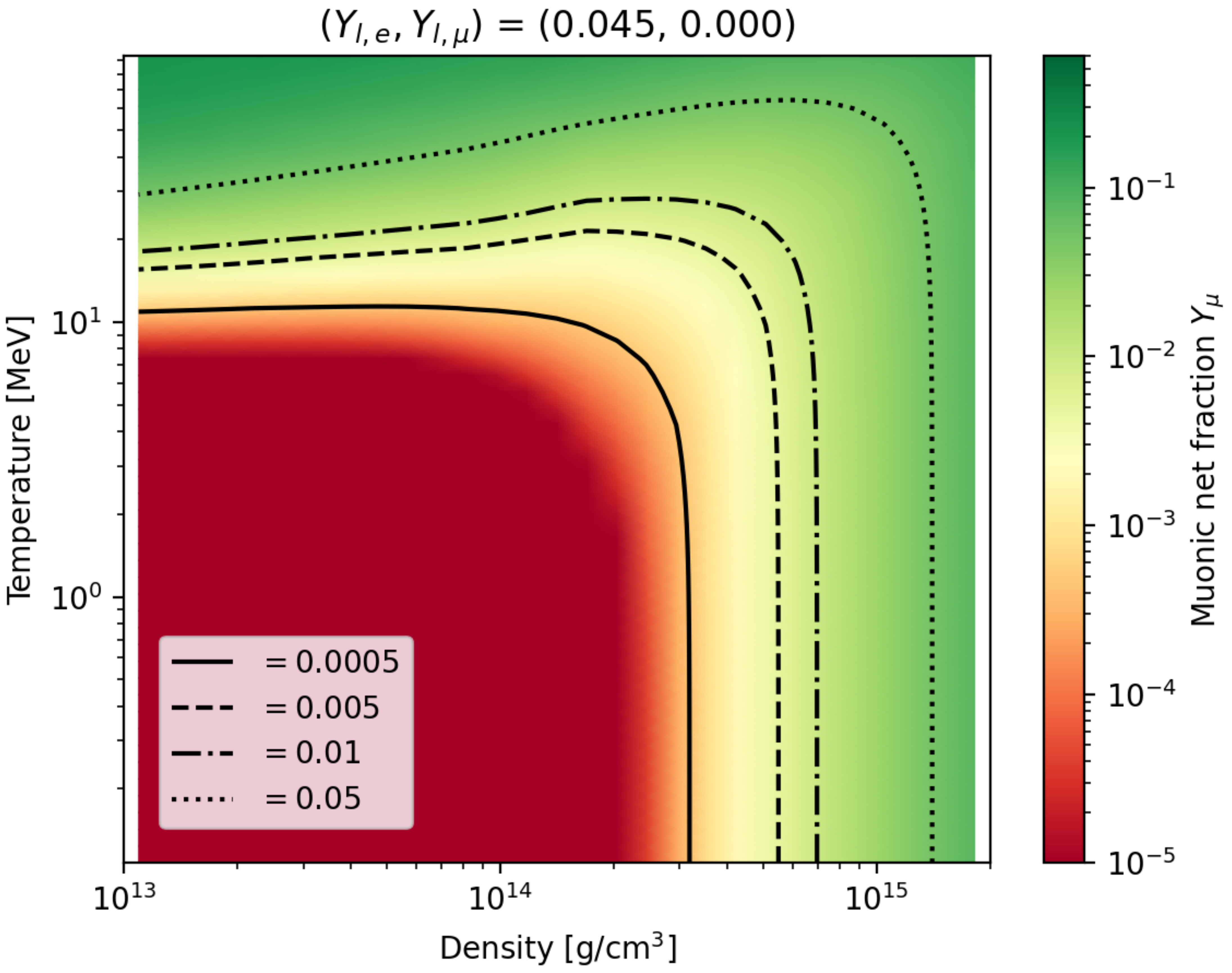
$$\begin{cases} Y_{l,e} = Y_e + Y_{\nu_e}(n_b, T, Y_e, Y_\mu) - Y_{\bar{\nu}_e}(n_b, T, Y_e, Y_\mu) \\ Y_{l,\mu} = Y_\mu + Y_{\nu_\mu}(n_b, T, Y_e, Y_\mu) - Y_{\bar{\nu}_\mu}(n_b, T, Y_e, Y_\mu) \\ u = \sum_i e_i(n_b, T, Y_e, Y_\mu) \quad i = b, e^{+/-}, \mu^{+/-}, \gamma, \nu, \bar{\nu} \end{cases}$$

- Numerical relativity simulations provide $(Y_{l,e}, Y_{l,\mu}, u)\ \forall (t, x, y, z)$ under the assumptions $Y_{l,e} = Y_e$ and $Y_{l,\mu} = Y_\mu = 0$ and no contributions from neutrino trapping
- By solving the system we get the *true* values of Y_e, Y_μ, T and all thermodynamic quantities

Results

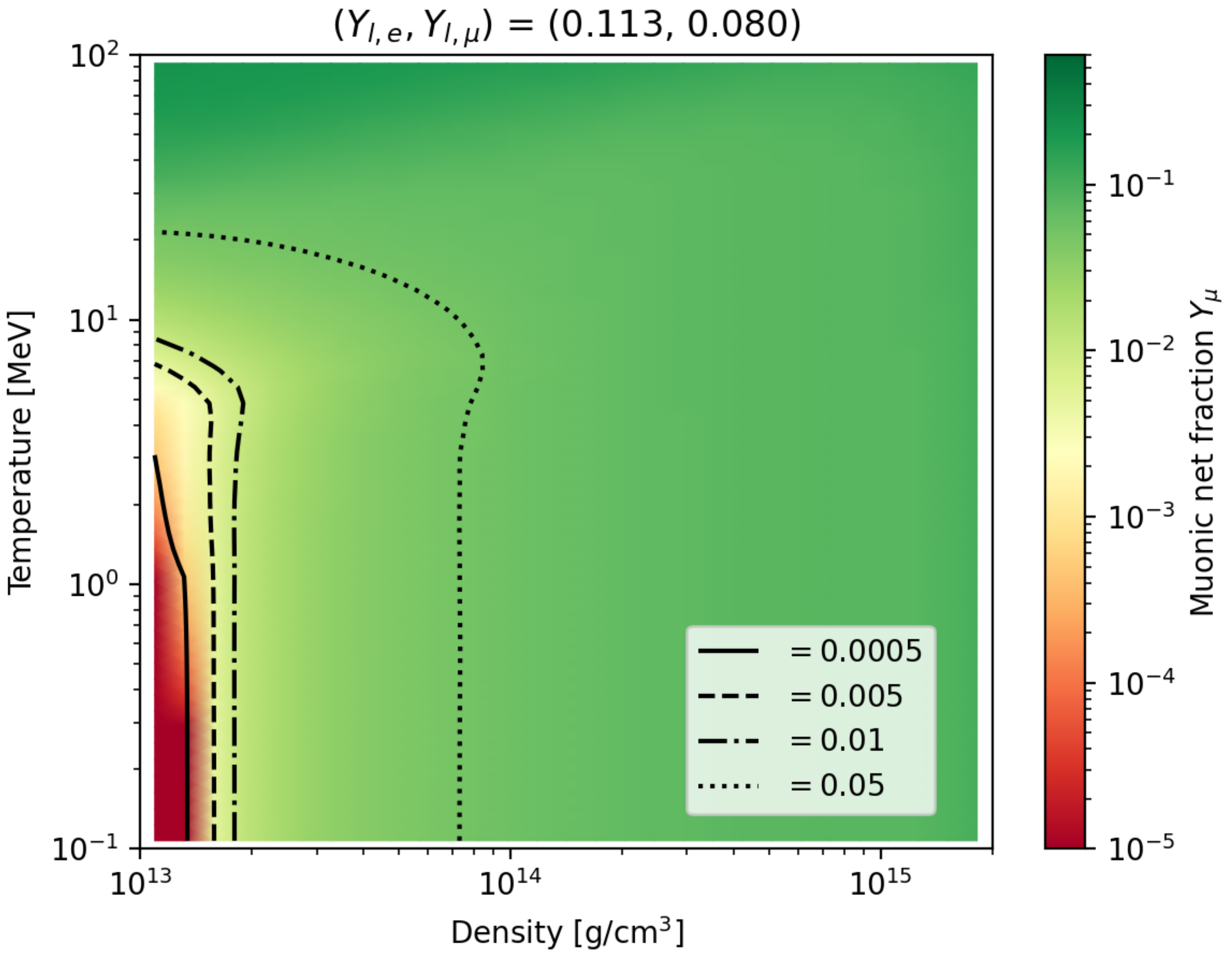
The density-temperature plane - Muons

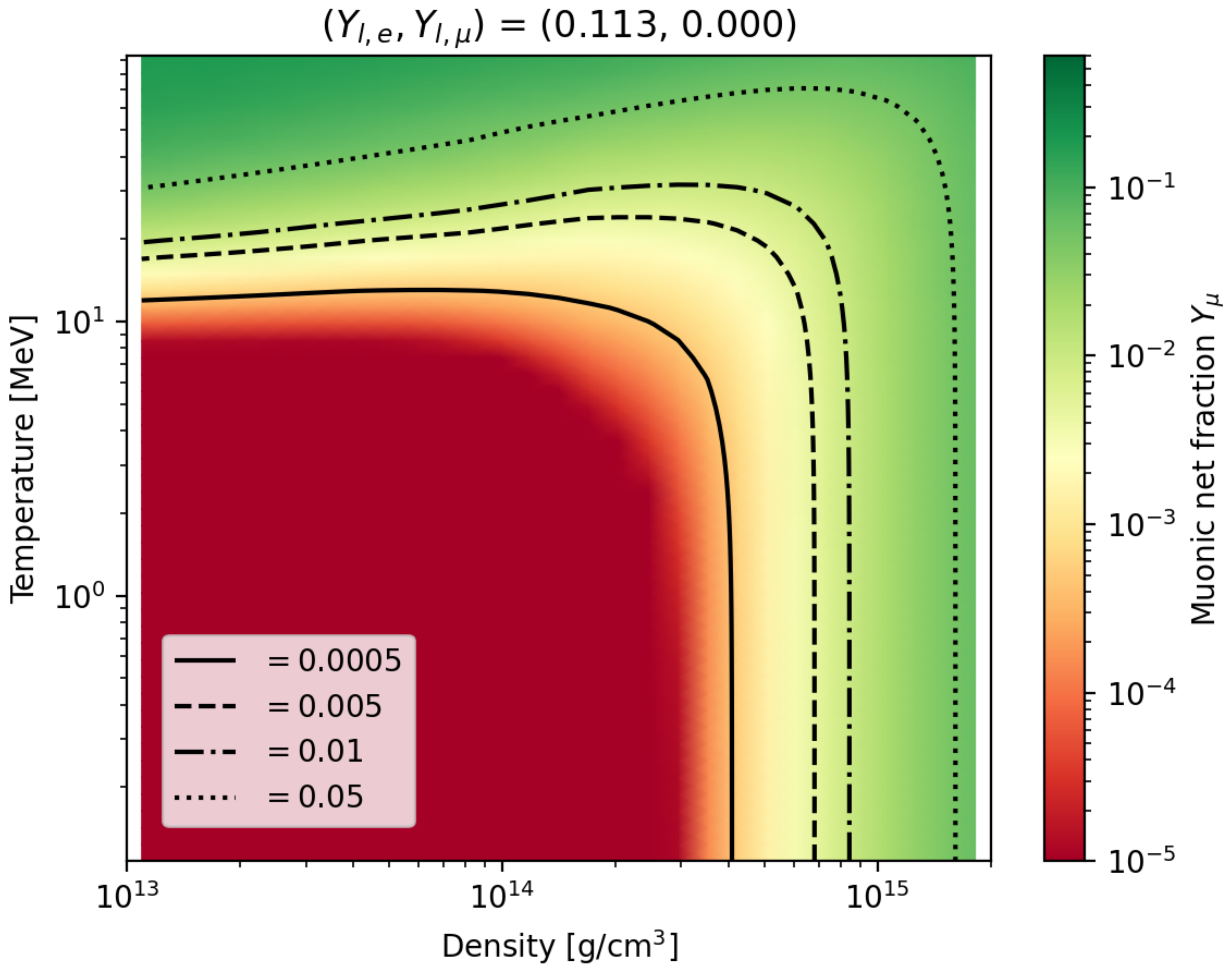




Results

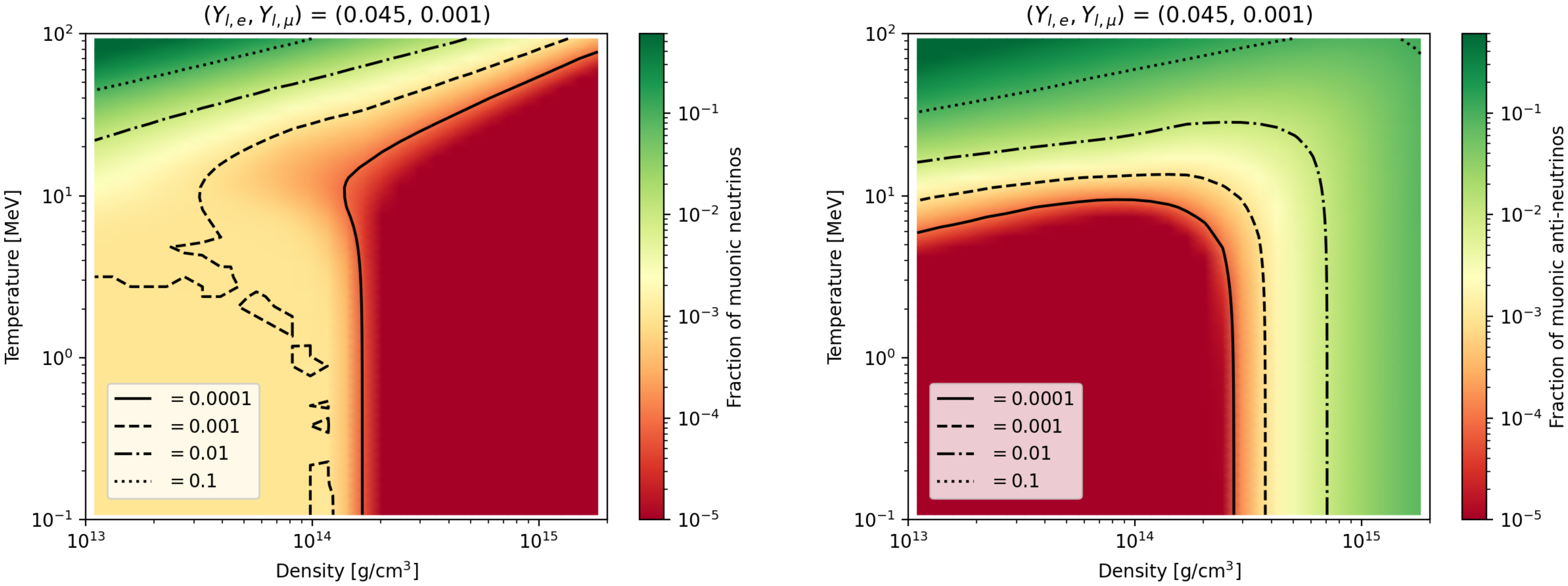
The density-temperature plane - Muons



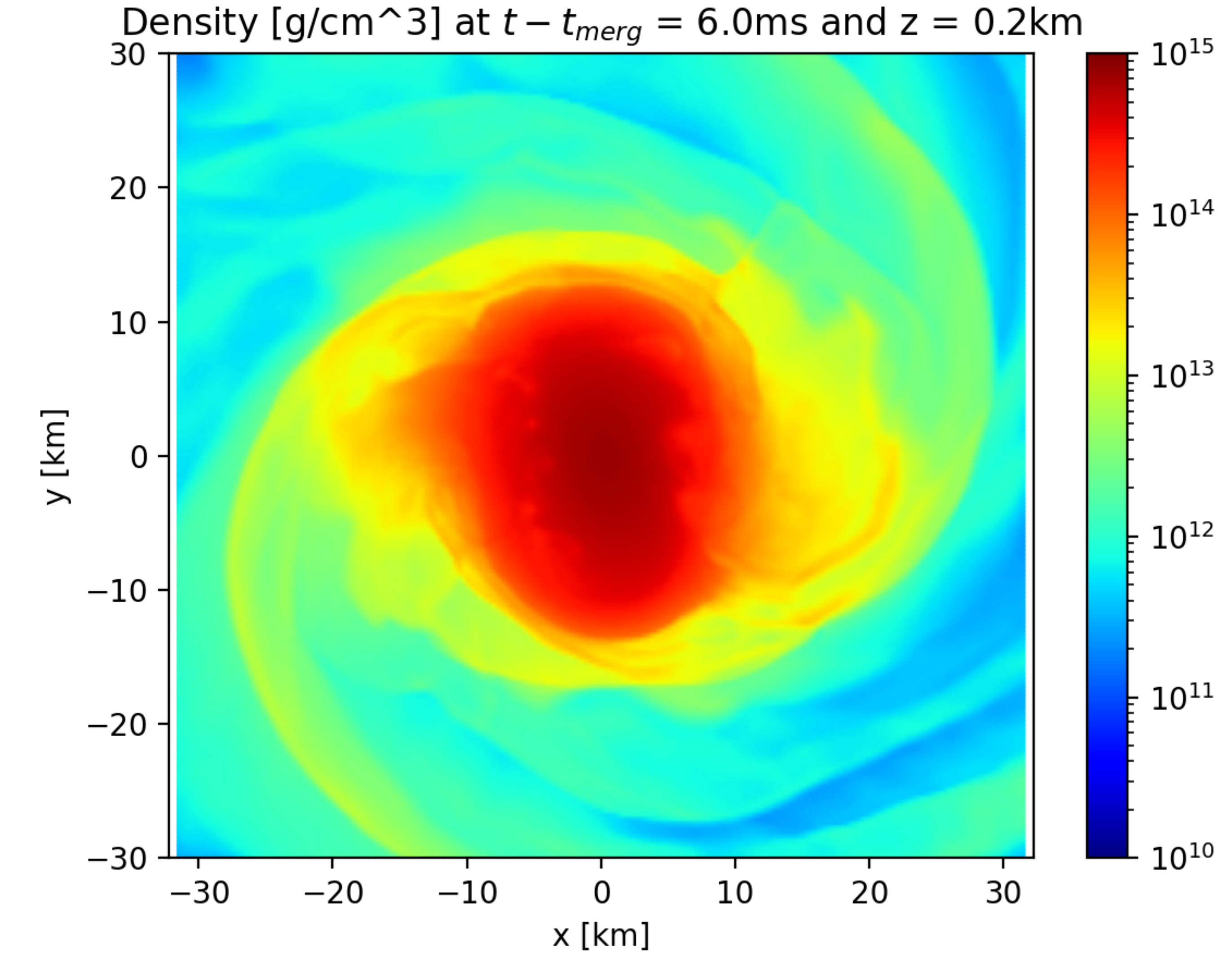


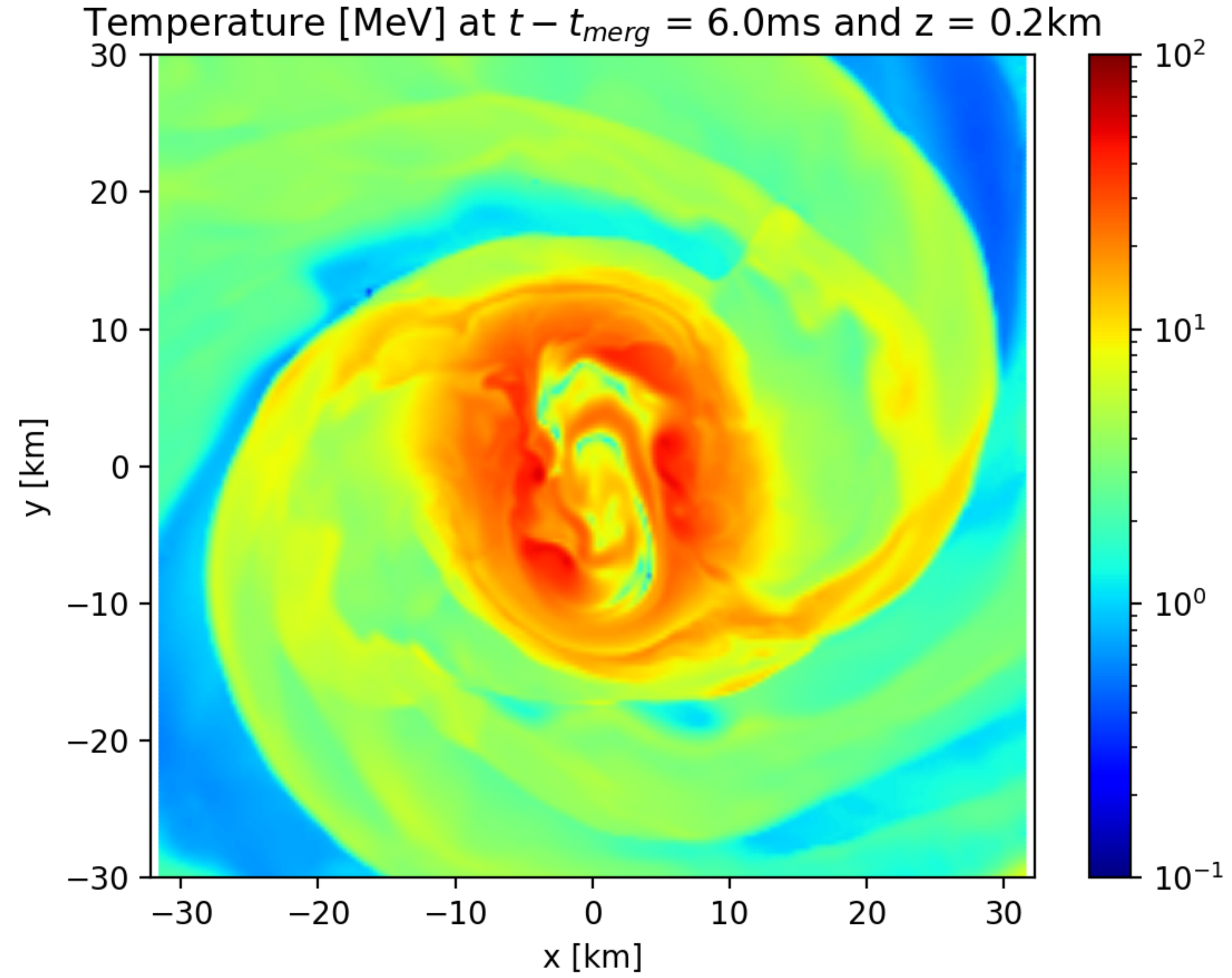
Results

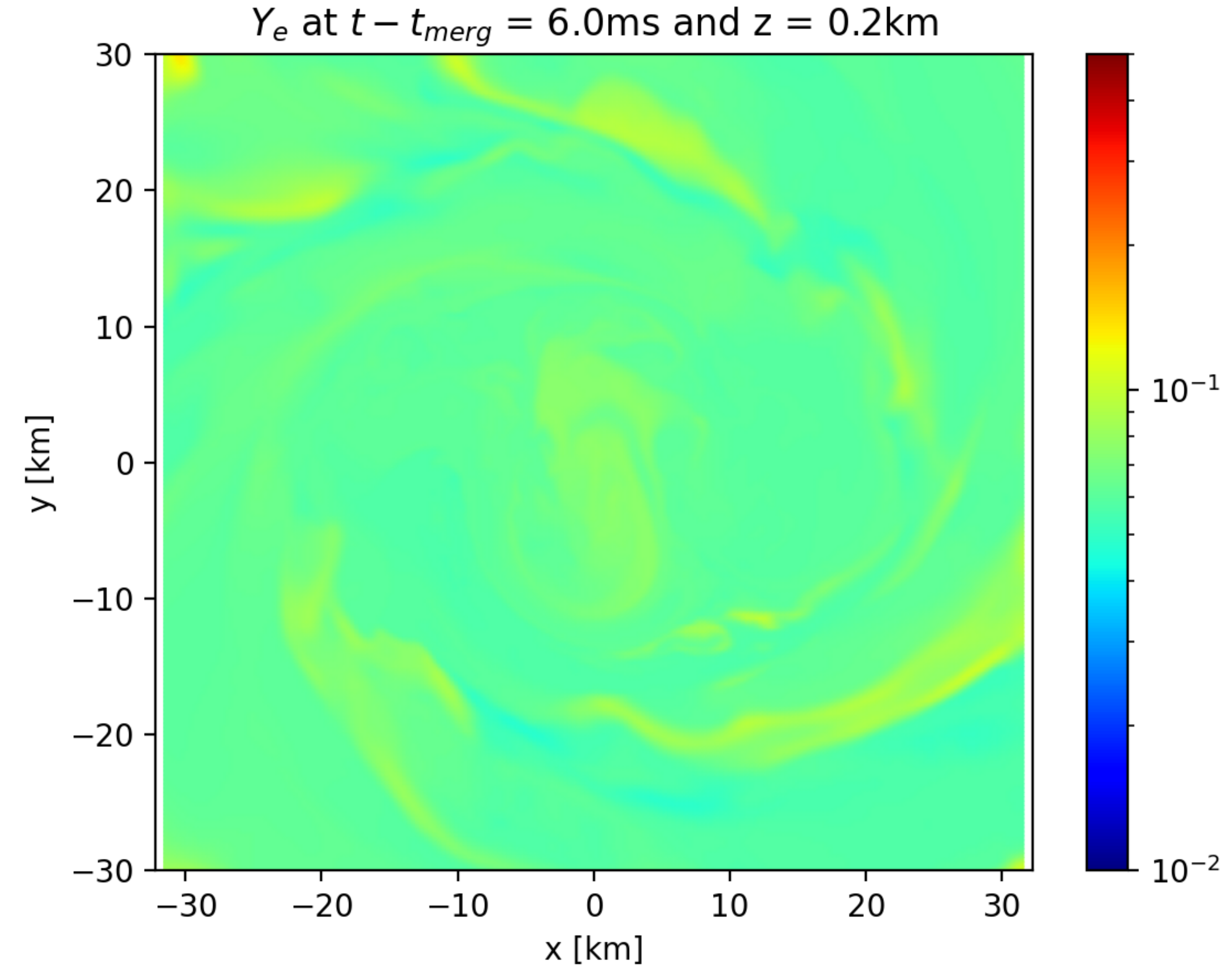
The density-temperature plane - Neutrinos

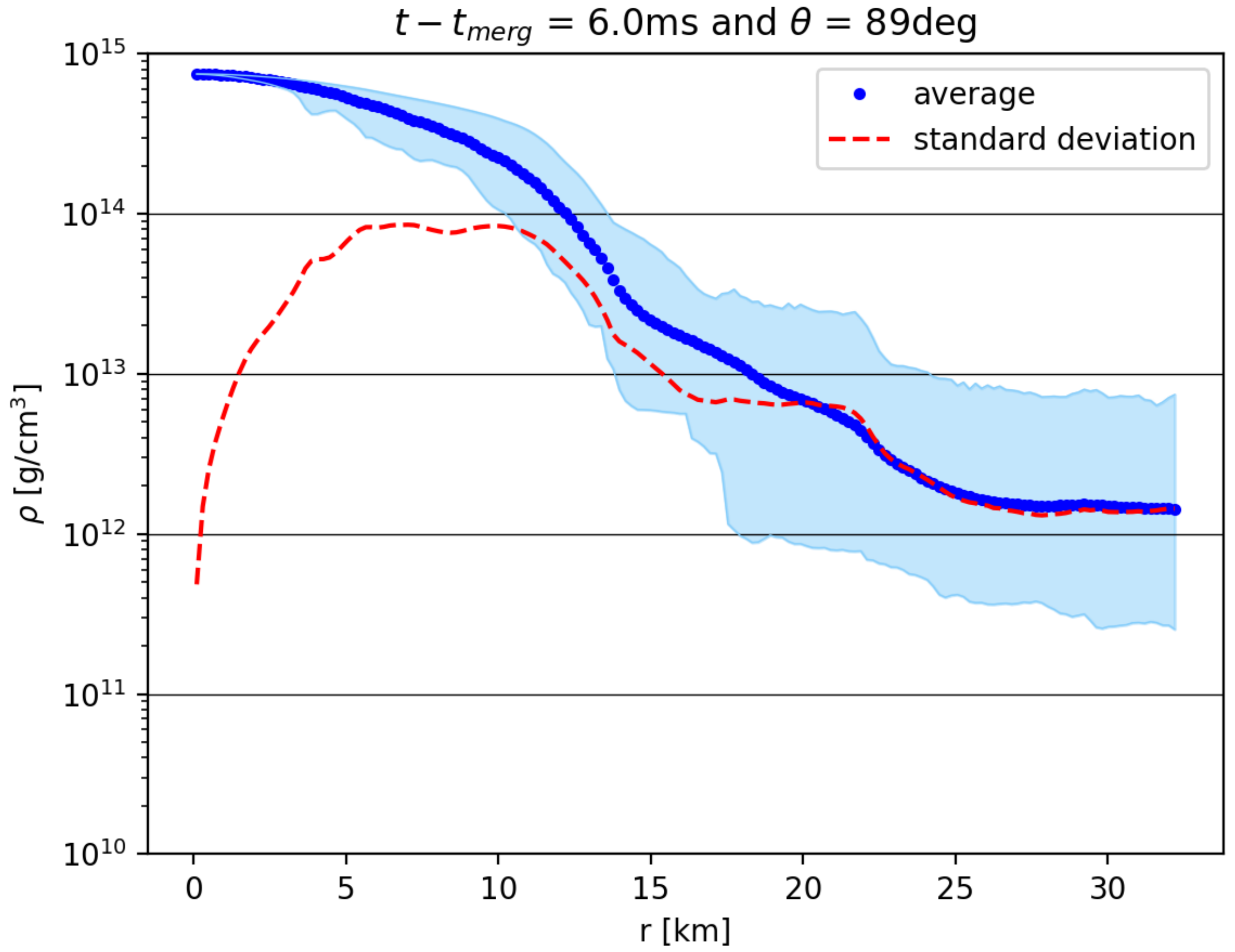


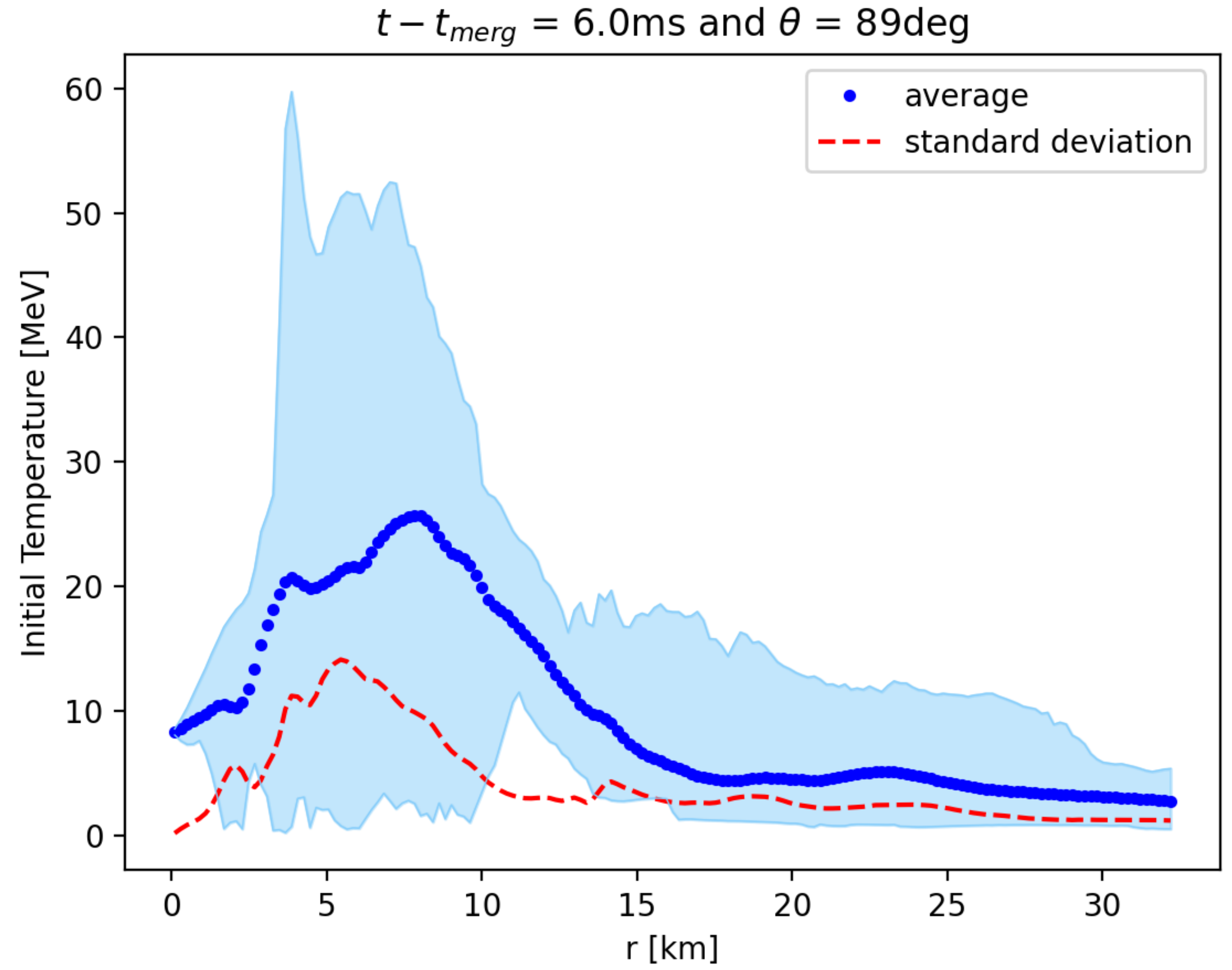
The outcome of the simulation

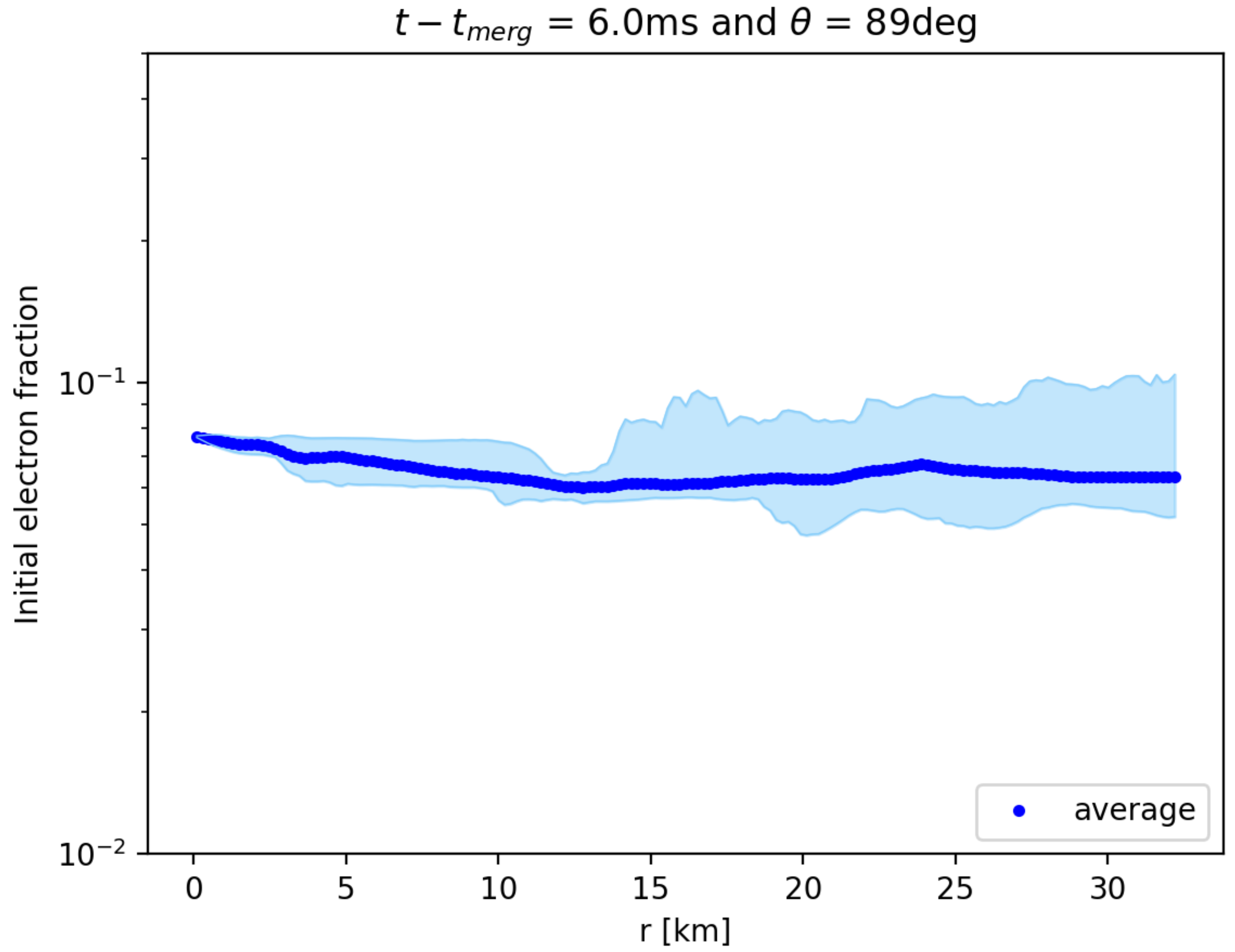






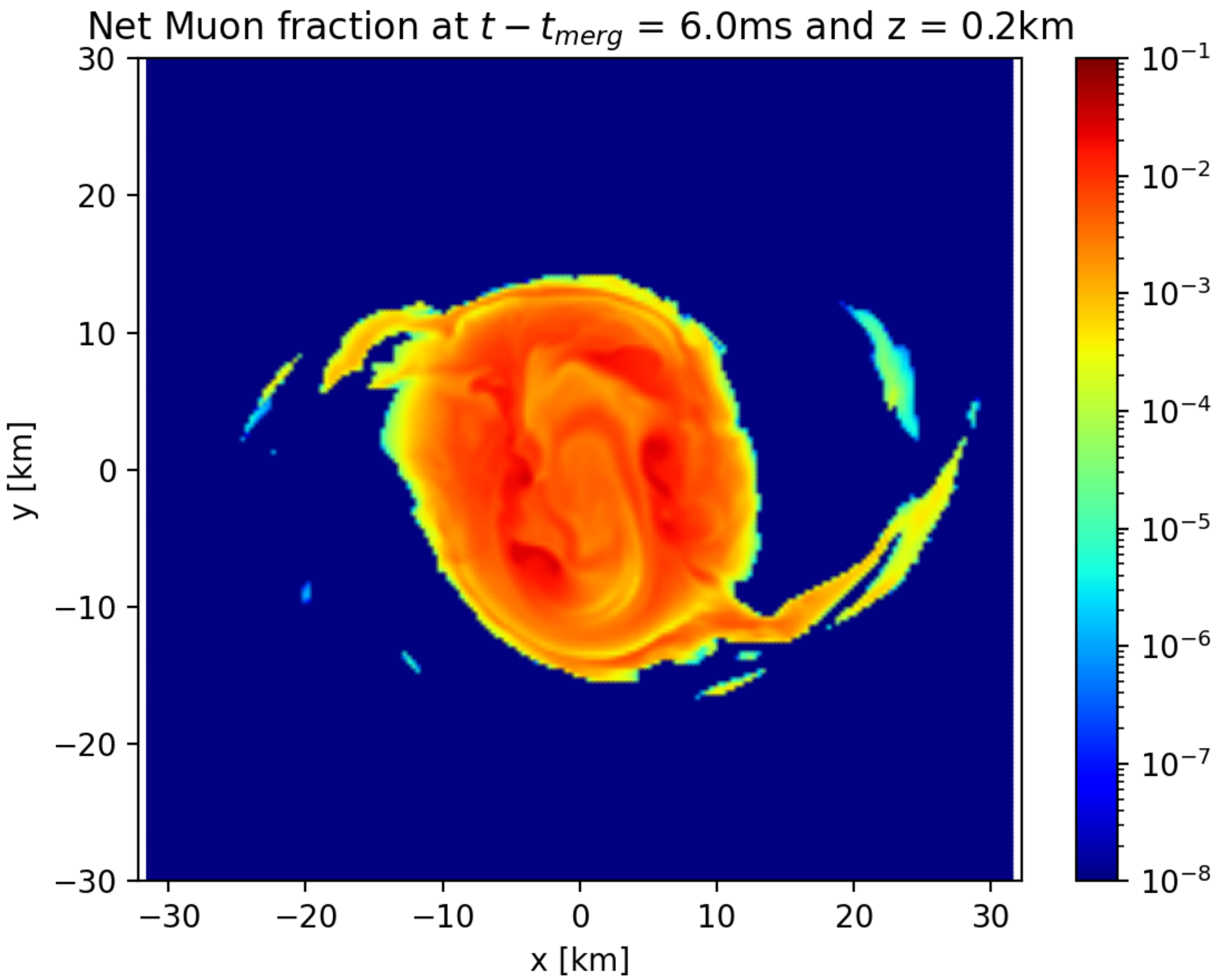


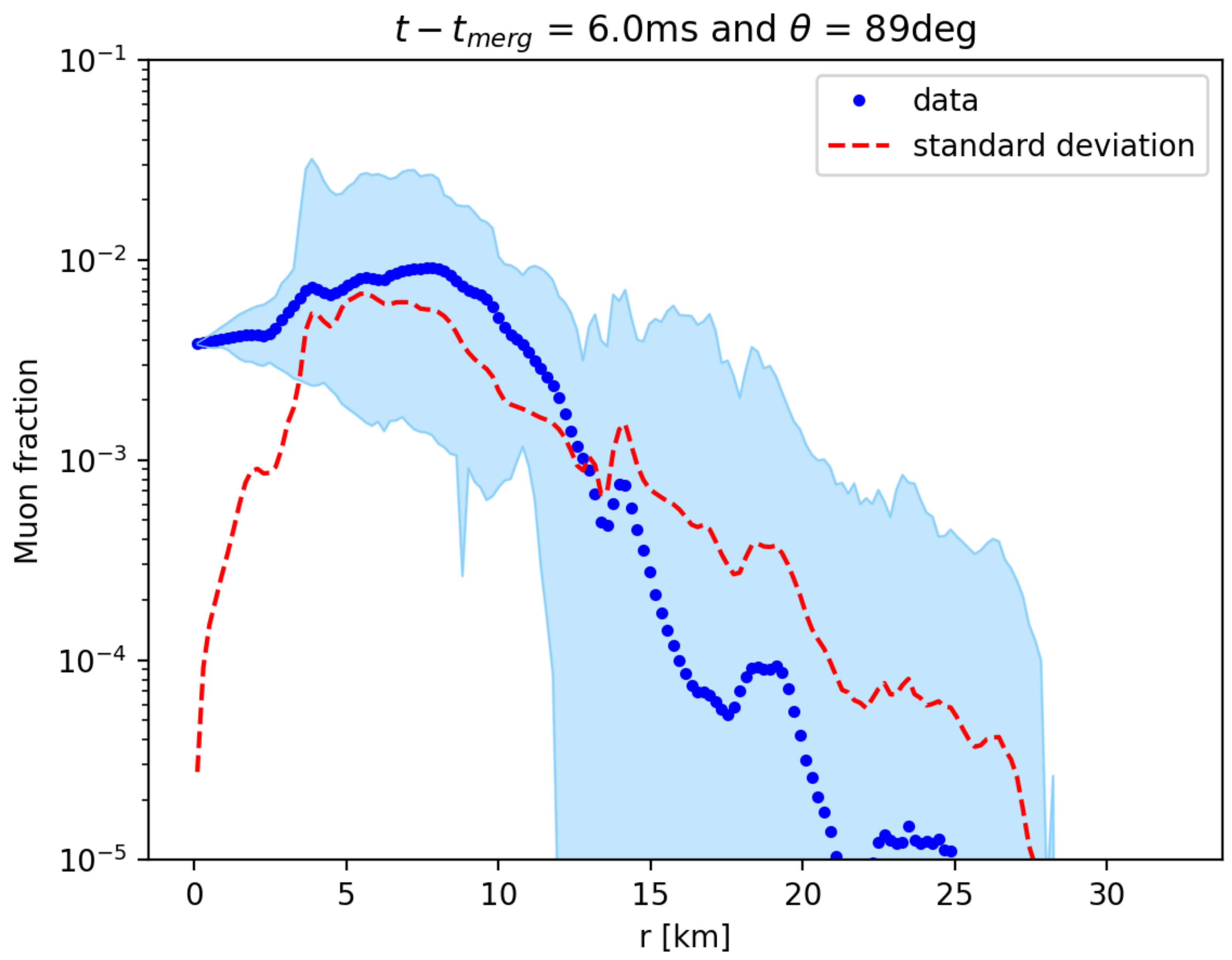


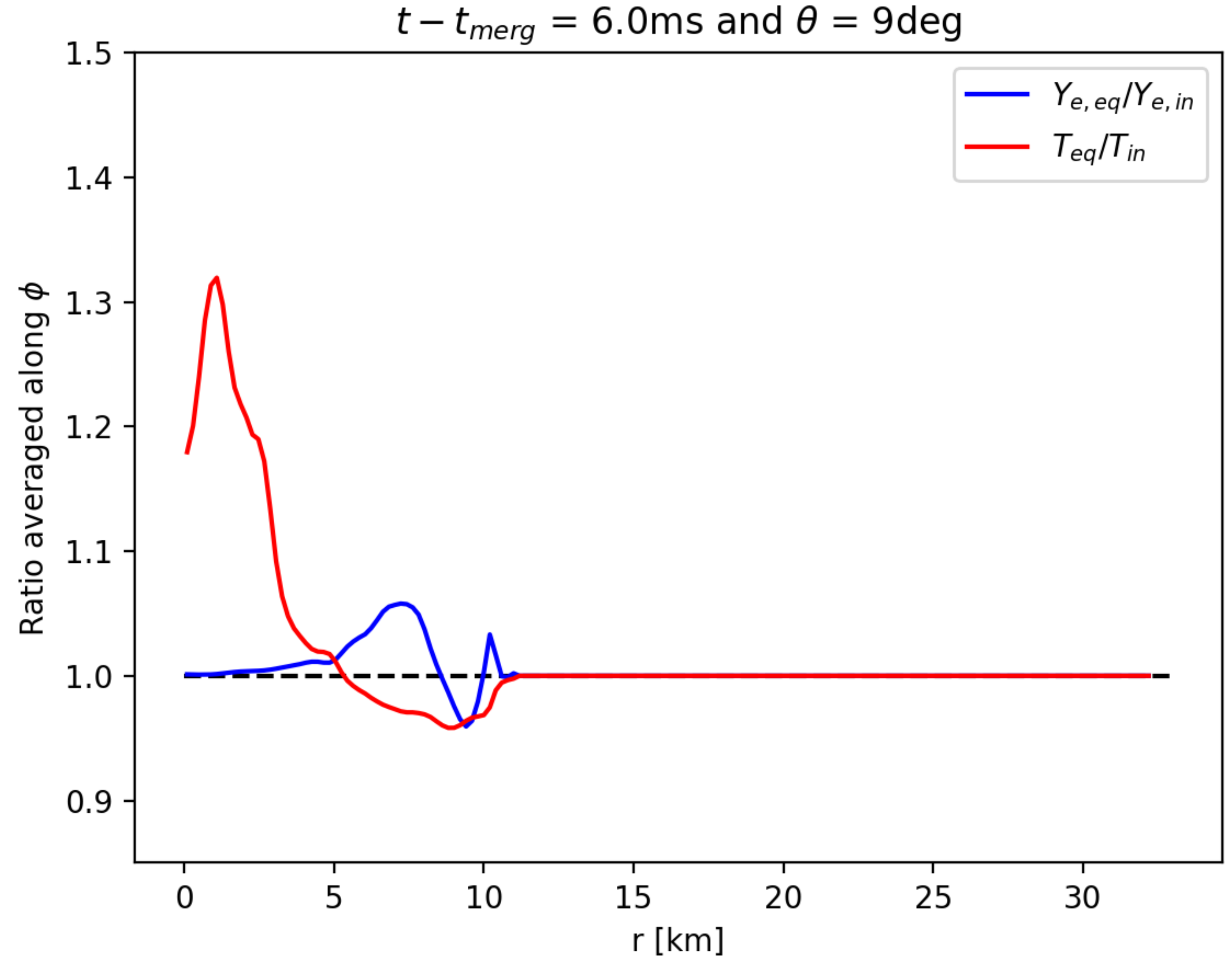


Results

Post-processing: the appearance of muons

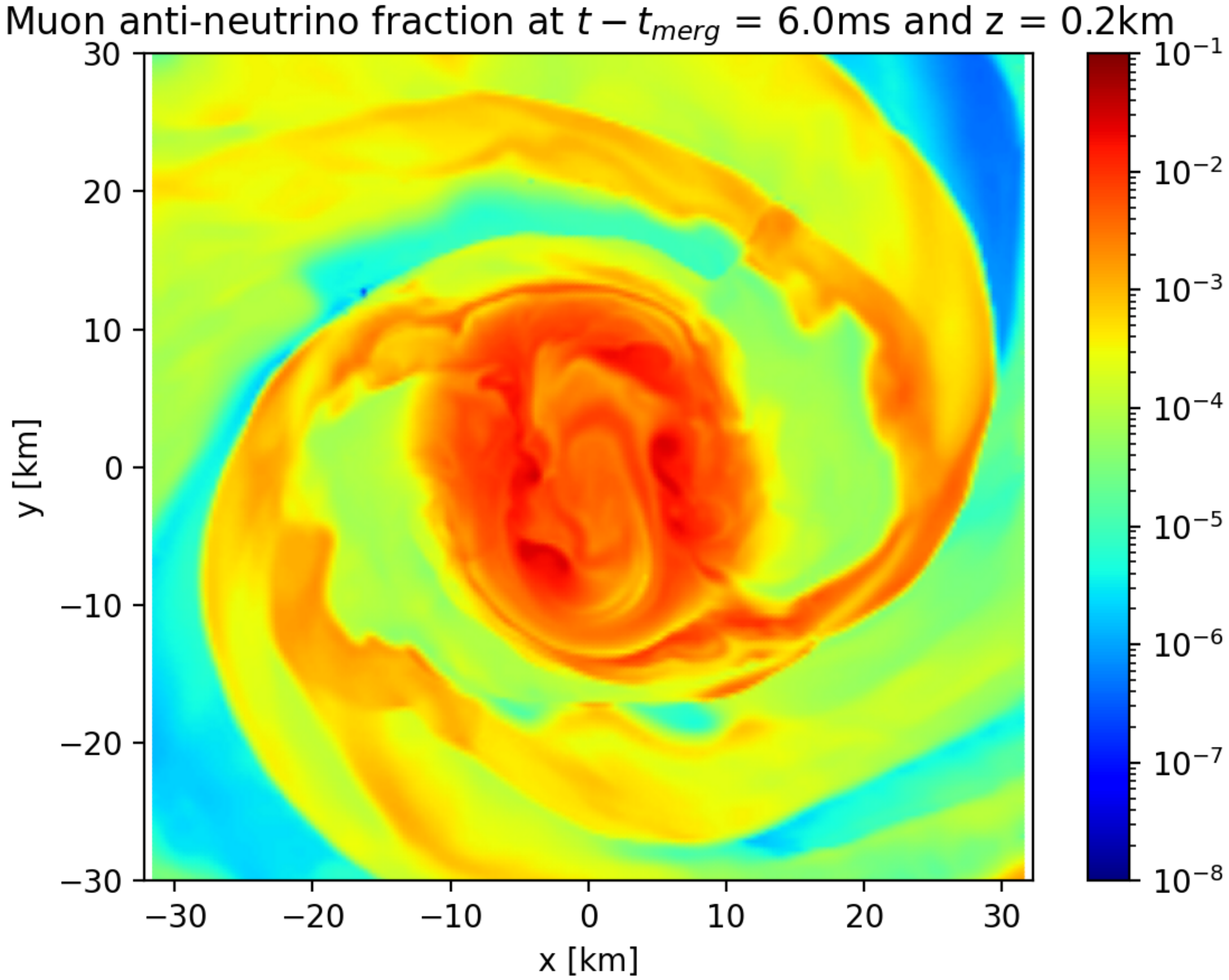


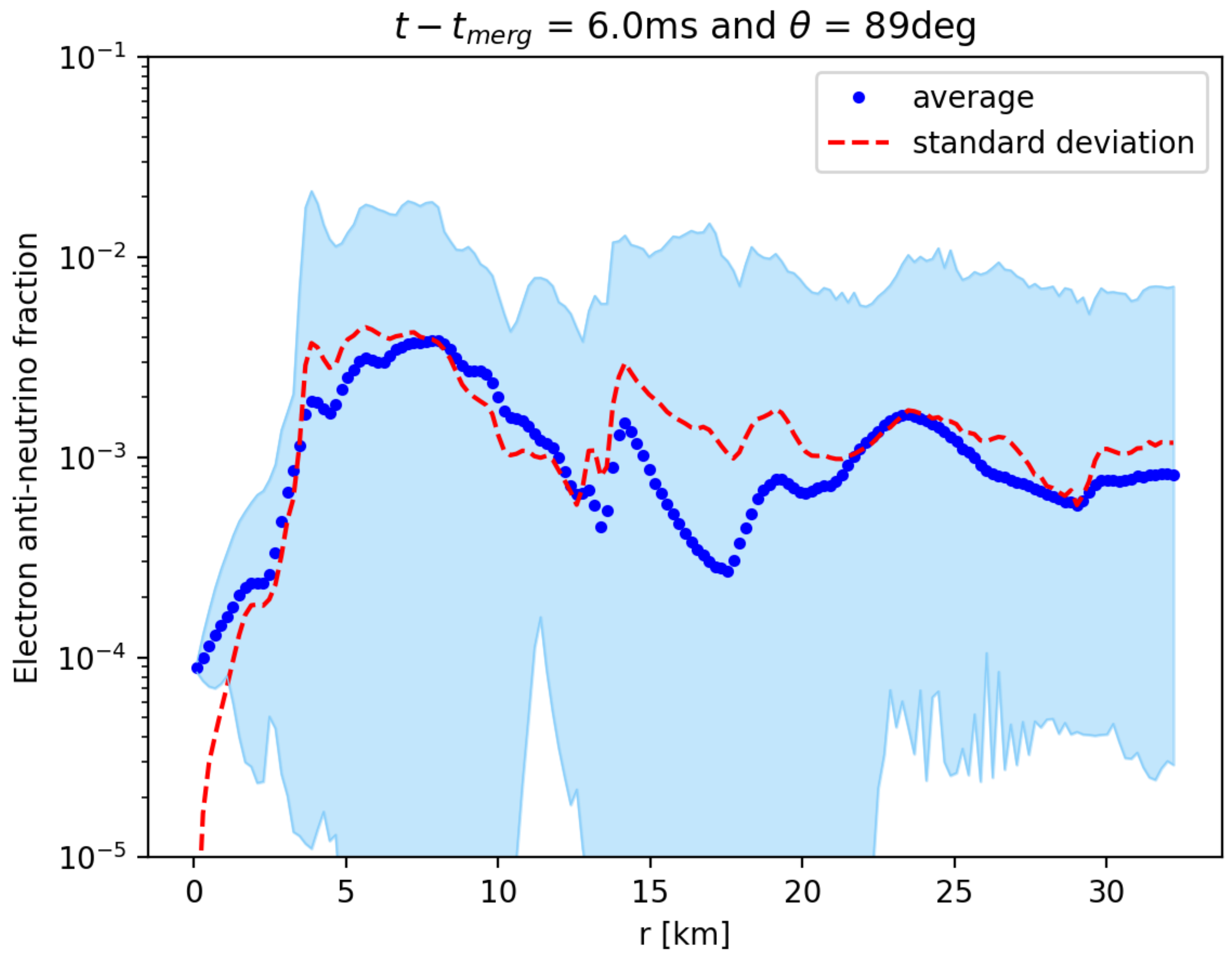


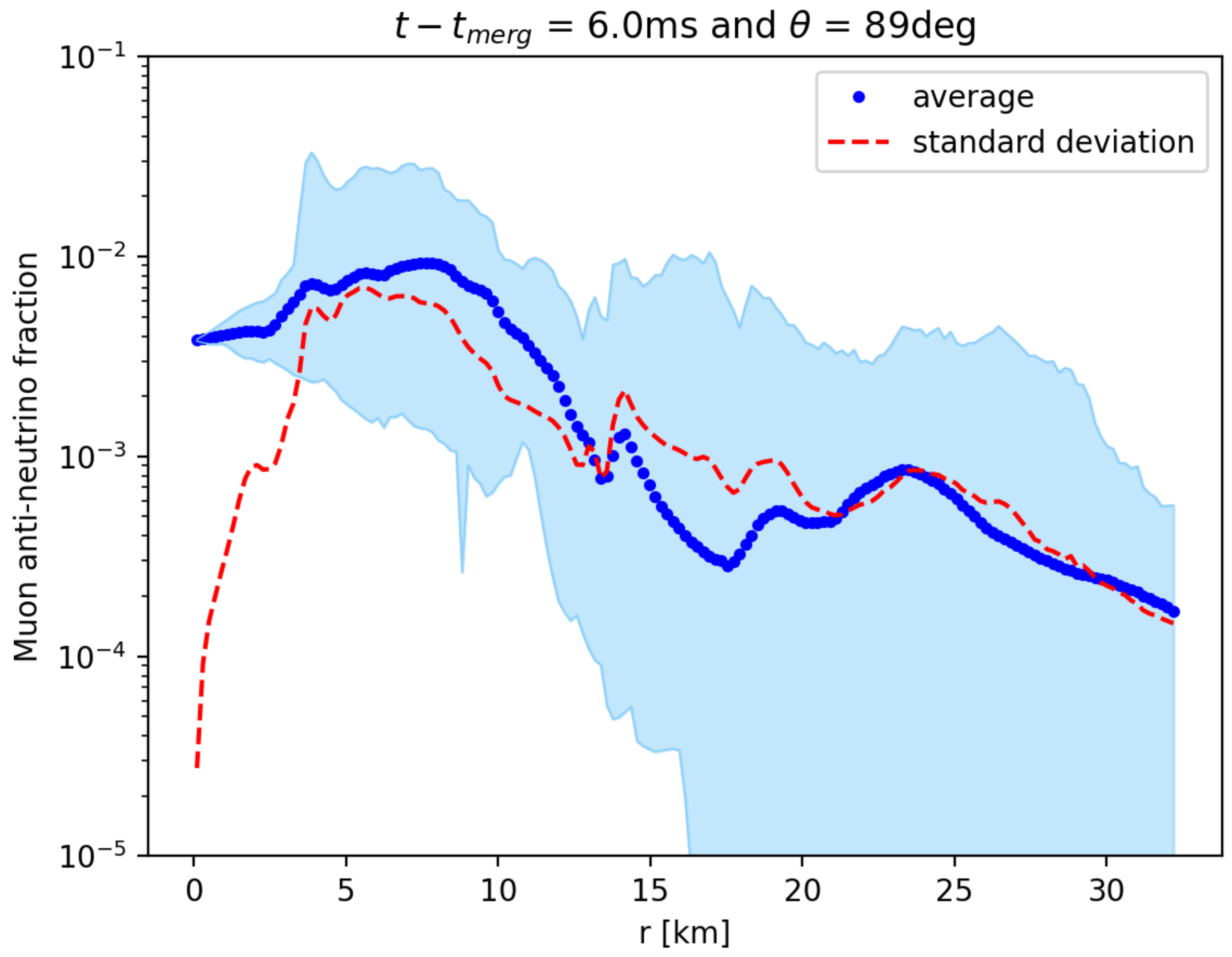


Results

Post-processing: the trapping of neutrinos

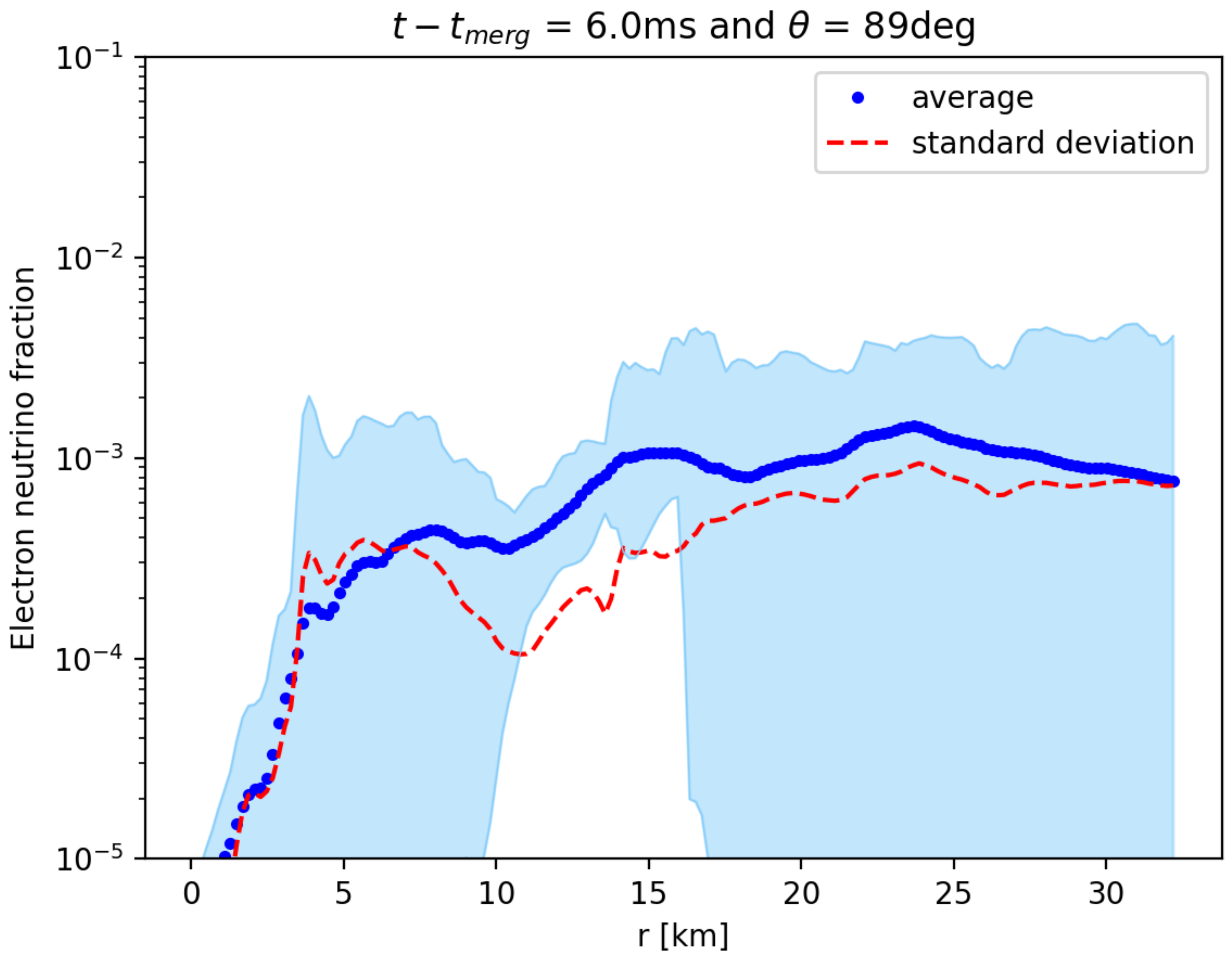


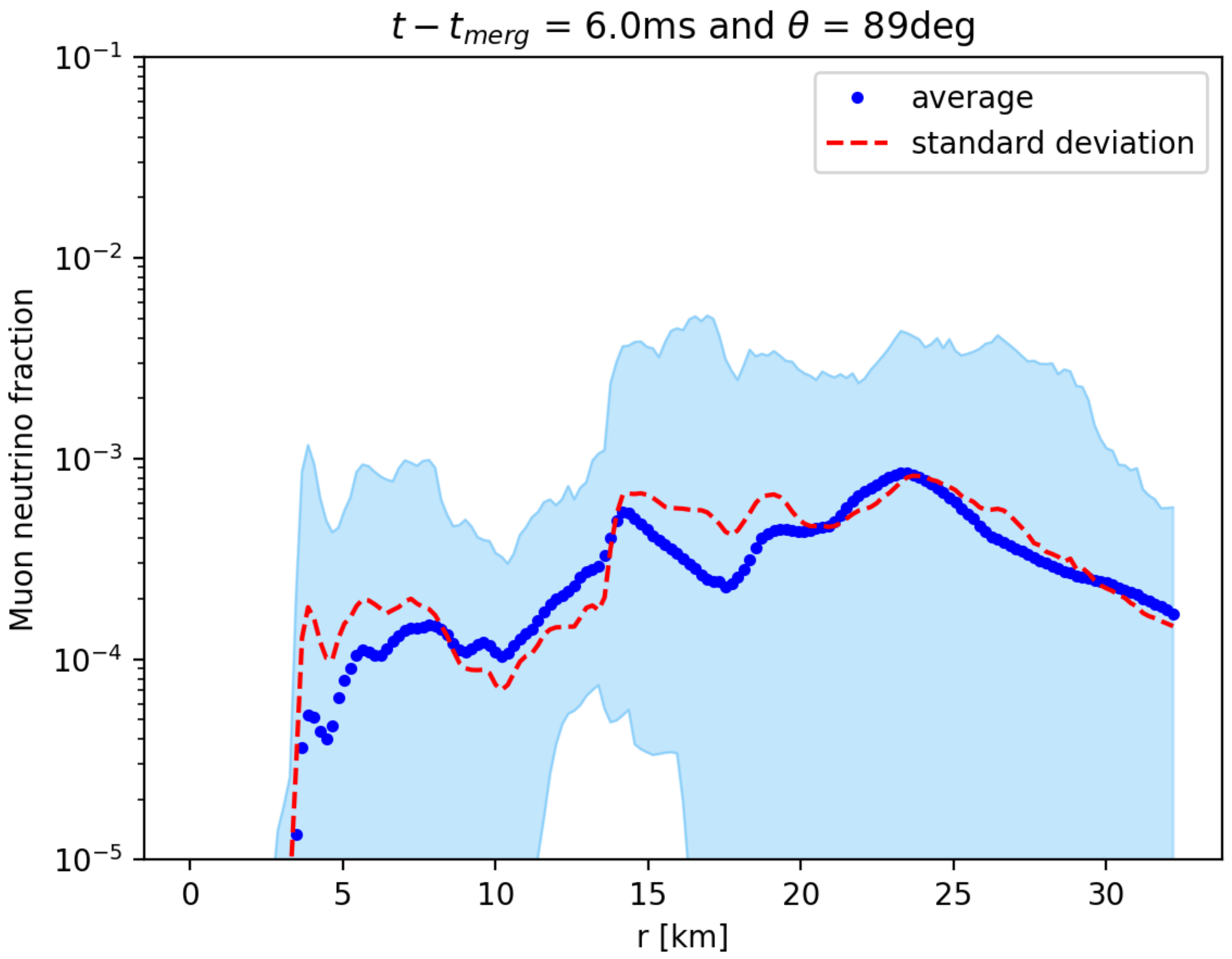


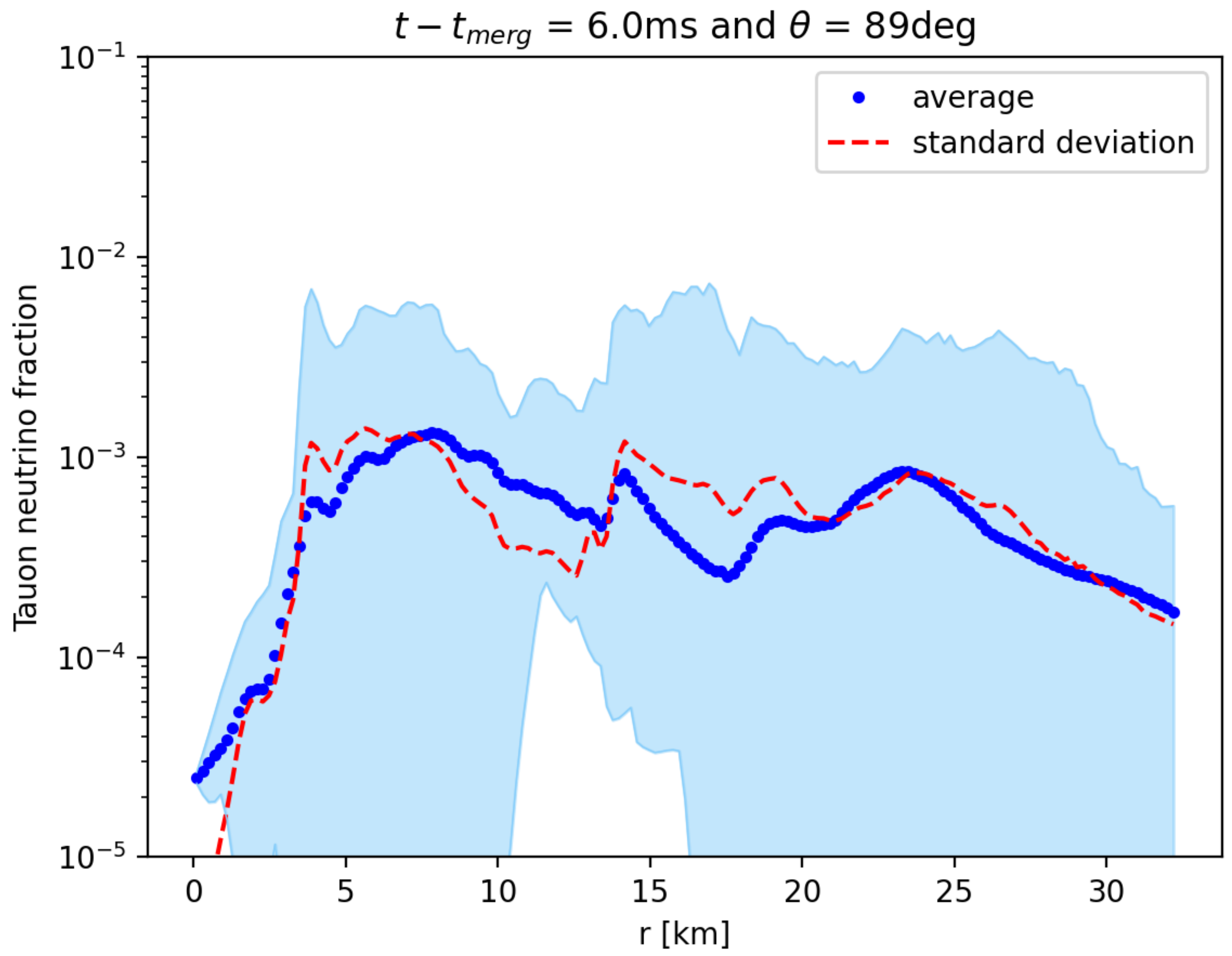


Results

Post-processing: the trapping of neutrinos







Conclusions

- The fraction of muons and/or trapped neutrinos is $\simeq 10\,\%$ of Y_e. The inclusion of muons and trapped neutrinos will improve state of the art simulations.
- Trapped neutrinos tend to increase Y_e and to soften the EOS → possibly faster collapse of the remnant

Outlook

- Check the pressure variation…
- What if we consider $Y_{l,\mu} \neq 0$ in simulation post-processing?
- What if we change the baryonic EOS?
- What if we change the binary mass ratio?