Muons production and Neutrino Trapping in Binary Neutron Star mergers

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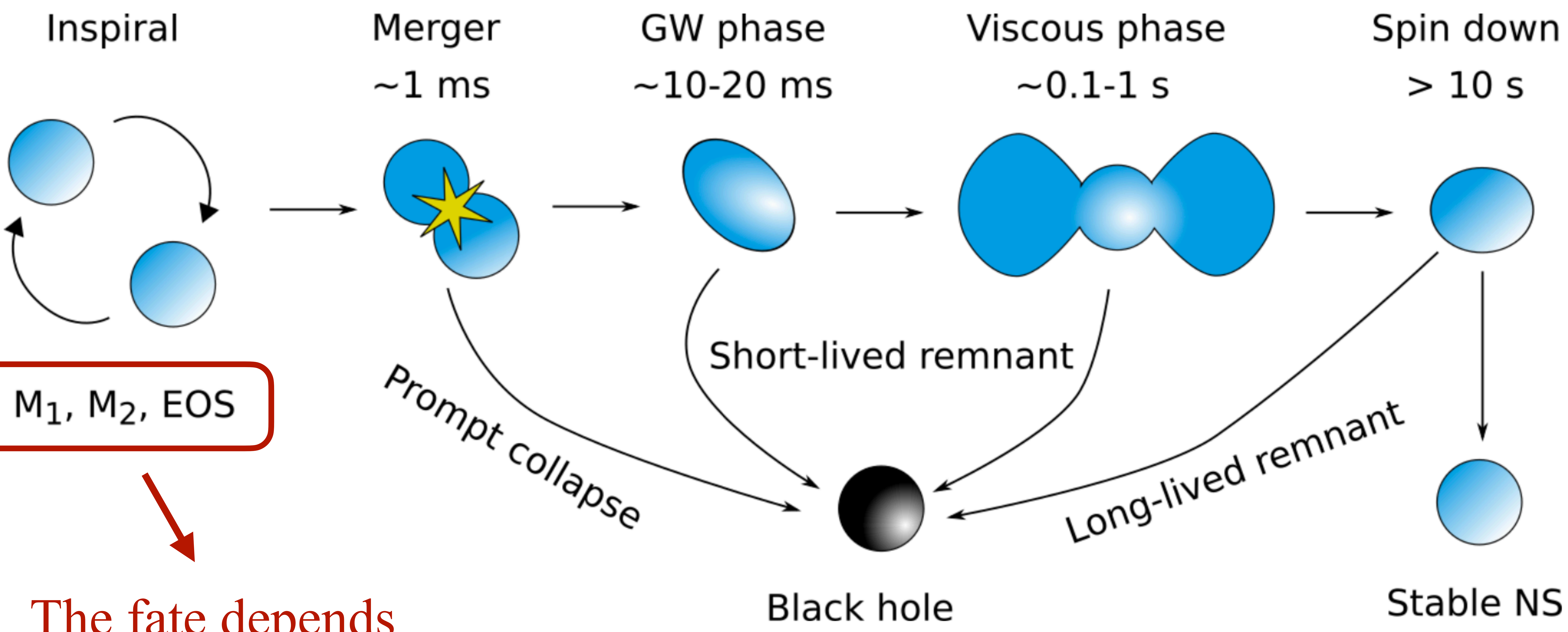
Which is the fate of a Binary Neutron Star merger?



M_1, M_2, EOS

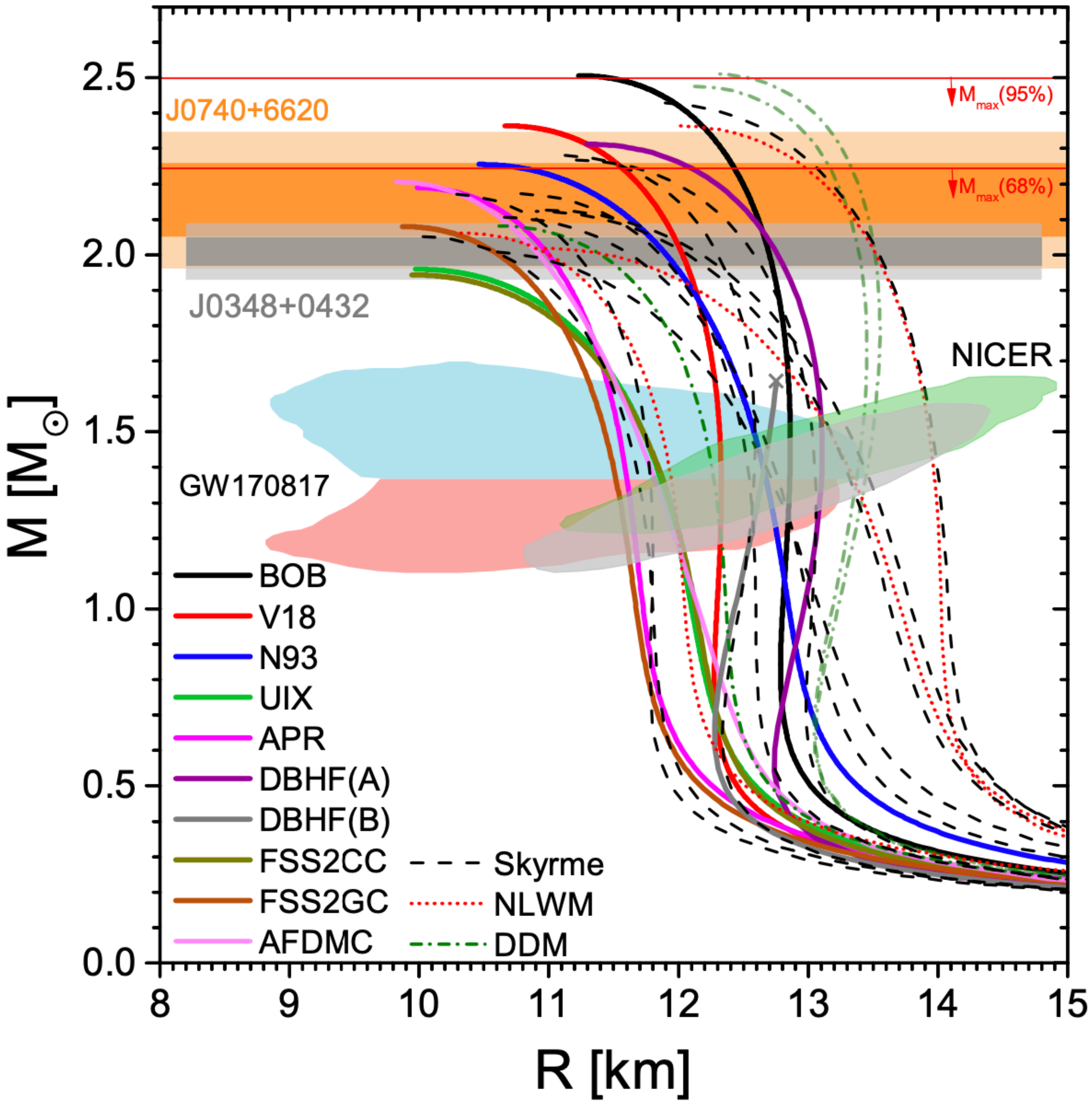
The fate depends on the masses and the Equation of State

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 uncertain
- Modelling of nuclear interaction and relevant degrees of freedom: neutrons, protons, pions, quarks, muons, …
- The relevant degrees of freedom depend on the temperature other than the density

Credits: Burgio et al. 2021



Numerical Relativity Simulations of BNS mergers

Why?

- Predict the merger outcome (GW signal, collapse time, ejecta, …)
- Necessary to interpret collected data and to constrain the nuclear EOS

How?

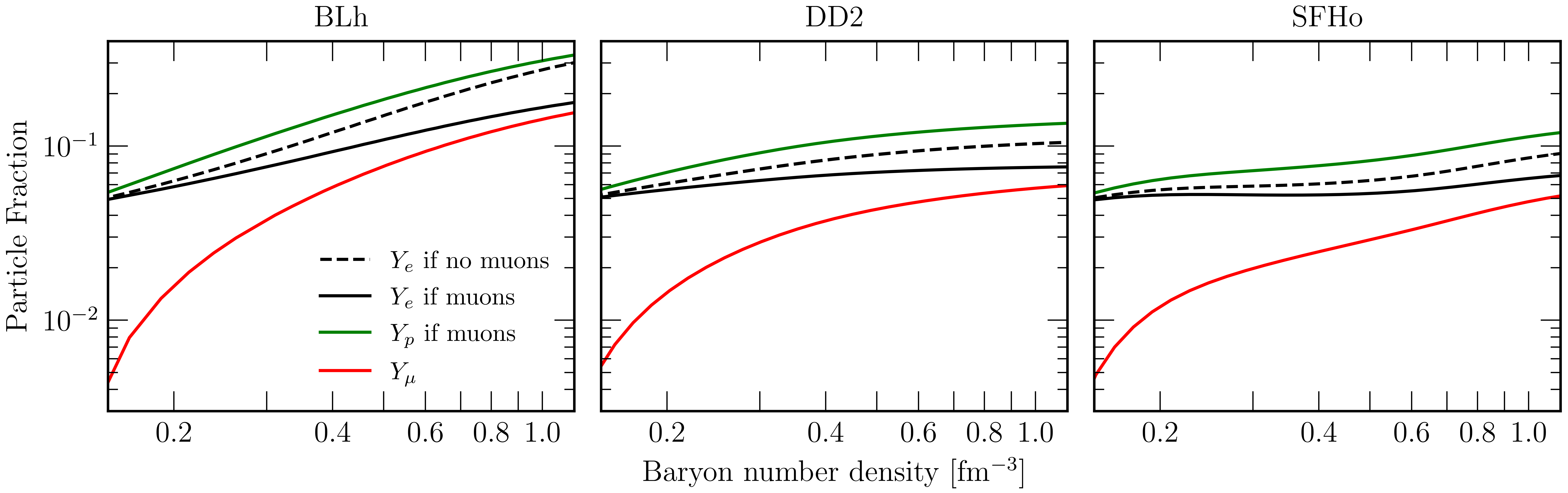
- GR Equations + relativistic hydrodynamics
- Microphysics → nuclear EOS, weak reactions with neutrinos, …
- Magnetic fields

State of the art simulations don't include muons and often trapped neutrinos!

But see *Fore & Reddy 2020*, *Foucart et al. 2016*, *Bollig et al. 2017* for CCSN, *Radice et al. 2022*

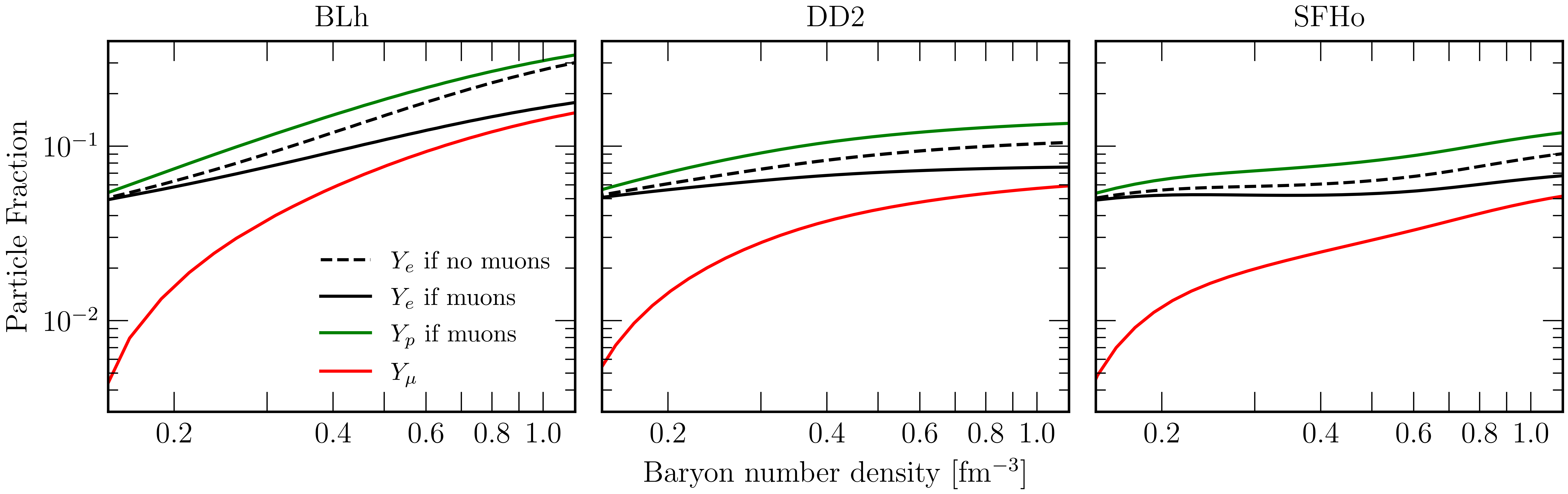
The relevance of muons and trapped neutrinos

- Muons are included in cold Neutron Star EOS
- Thermodynamics conditions in BNS mergers favour muons and neutrinos production and neutrino trapping
- Muons and trapped neutrinos can change the EOS stiffness and affect the collapse time



The relevance of muons and trapped neutrinos

The aim of this work is to estimate the impact of muons and trapped neutrinos on the merger remnant in post-processing.



Loffredo et al., in preparation

Method - The microphysics modelling

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

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

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

- Assume thermal and weak equilibrium

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

Method - The simulation sample

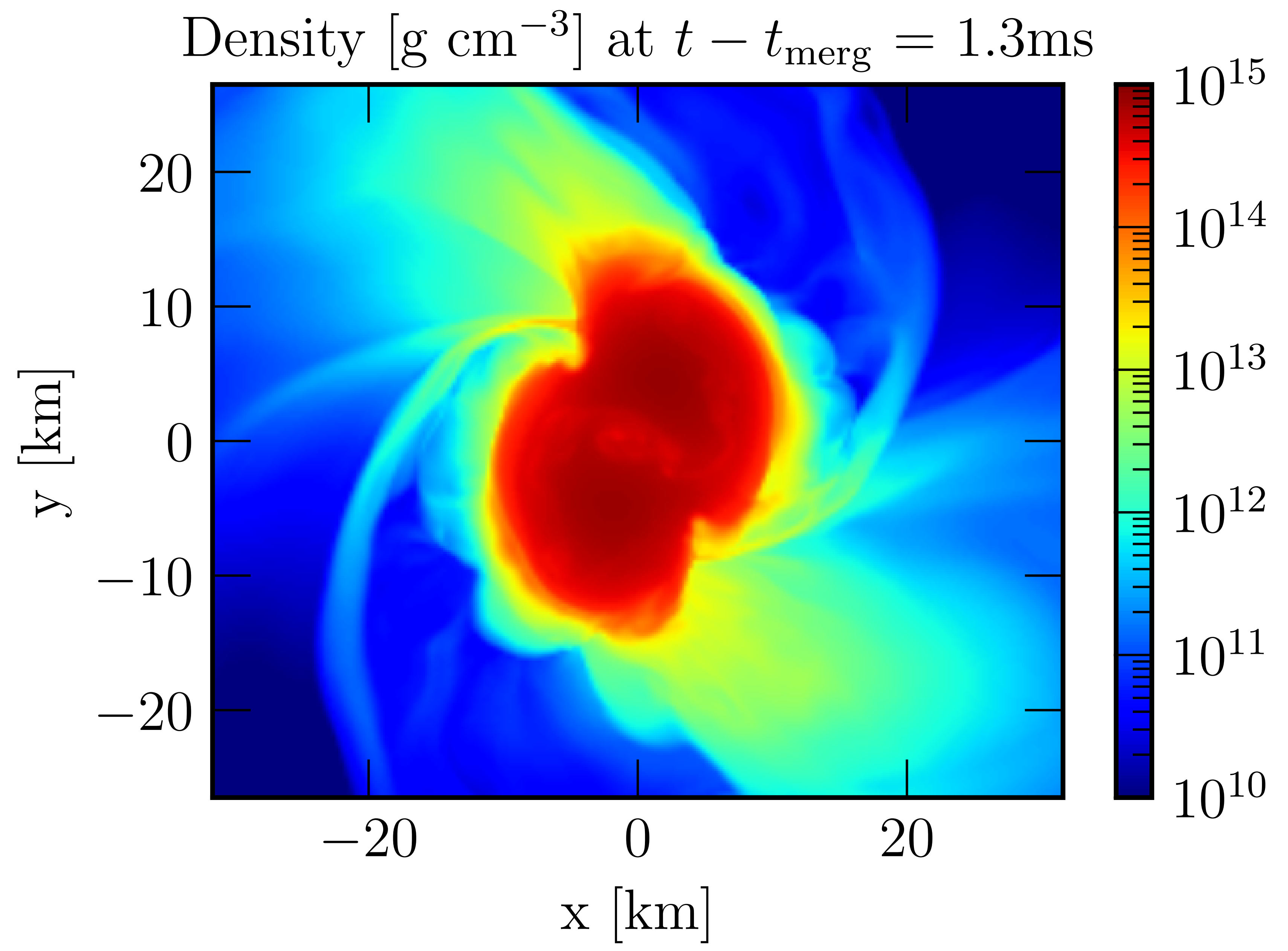
- We consider GW170817 targeted simulations
  Nedora et al. 19, Bernuzzi et al. 20, Nedora et al. 21

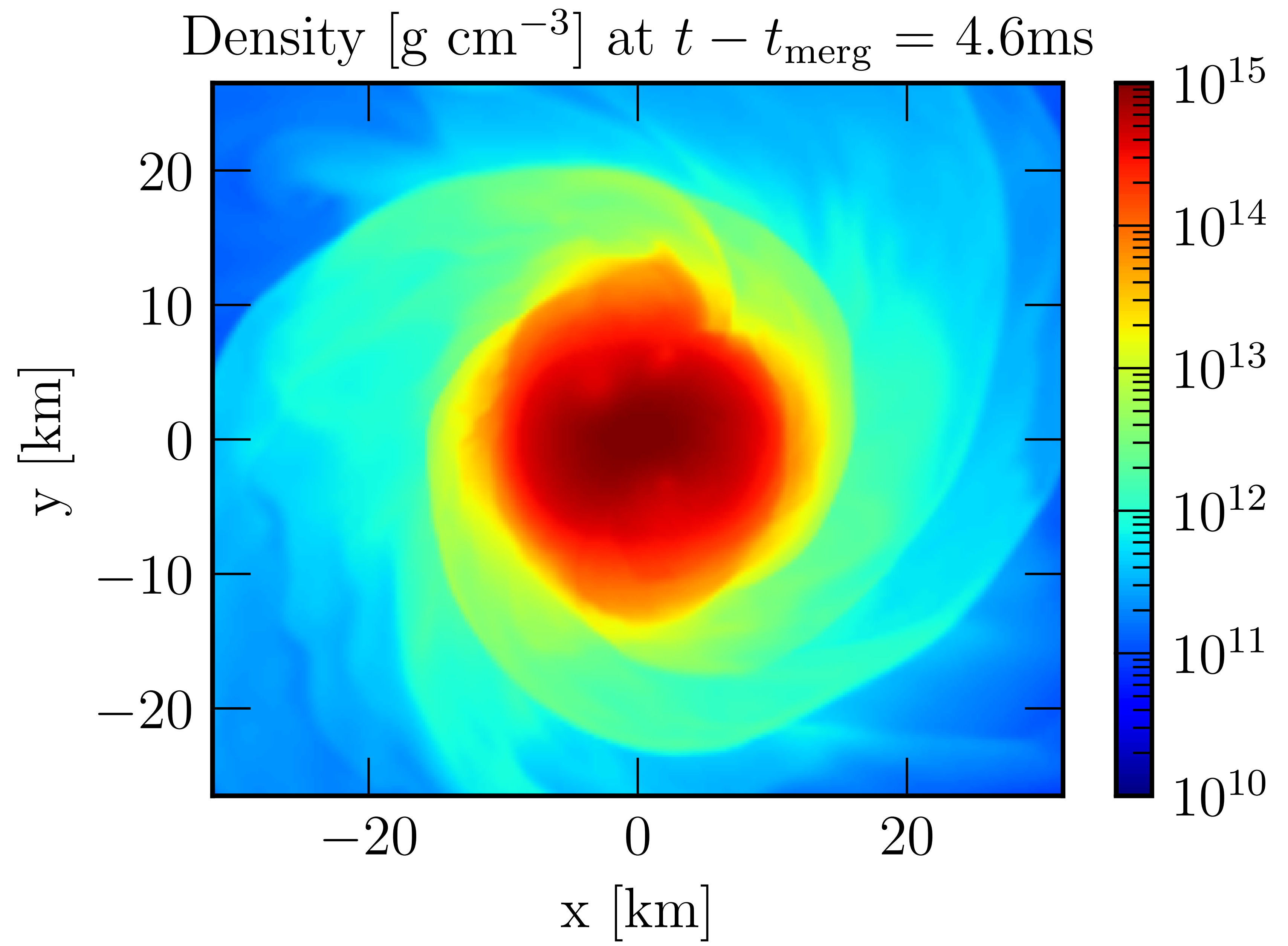
- NR simulations performed with WhiskyTHC code
  Radice et al. 12, Radice et al. 14

- 3 different nuclear EOS at finite temperature: BLh, DD2, SFHo
  Logoteta et al. 21, Hempel et al. 10

- Neutrino radiation treated through leakage+M0 scheme
  Radice et al. 16

- Muons and trapped neutrinos **not** included





Method - The post-processing technique

- During the merger the temperature of fluid elements 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 $t_{\text{weak}} \ll dt \ll t_{\text{dyn}}$ the internal energy u stays the same

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

- From numerical relativity simulations output we infer $(Y_{l,e}, Y_{l,\mu}, u)$ $\forall (t, x, y, z)$

- By solving the system we get the values of Y_e, Y_μ, T and all thermodynamic quantities

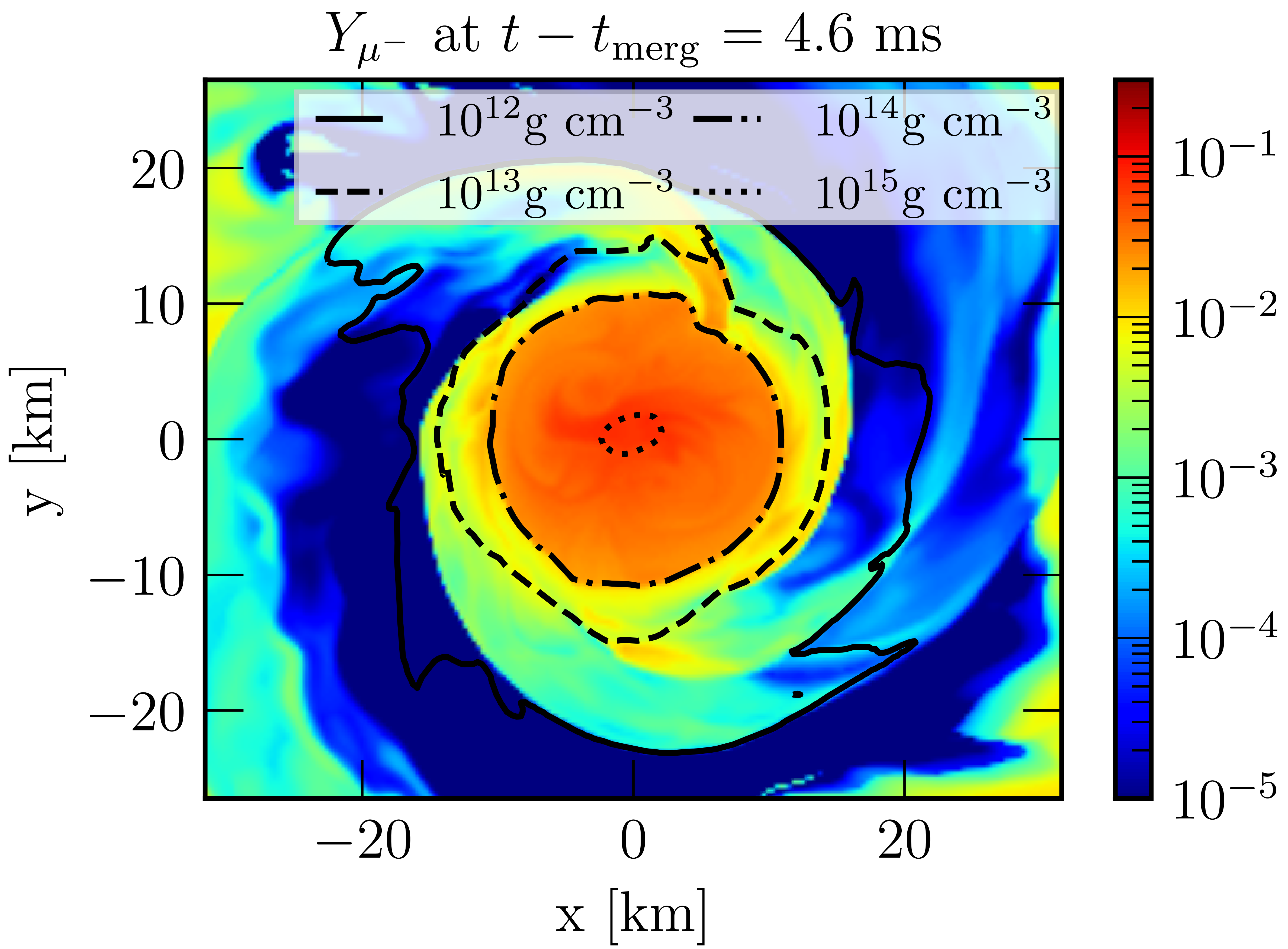
The appearance of muons

The fraction of muons Y_{μ^-}

- Muons present at density $> 10^{13}$g cm^{-3}
- Bulk of muons from the two cold Neutron Stars
- Muons created during merger via thermal processes and Urca processes, e.g.

$$\gamma + \gamma \rightarrow \mu^- + \mu^+$$

$$n \rightarrow p + \mu^- + \bar{\nu}_\mu$$

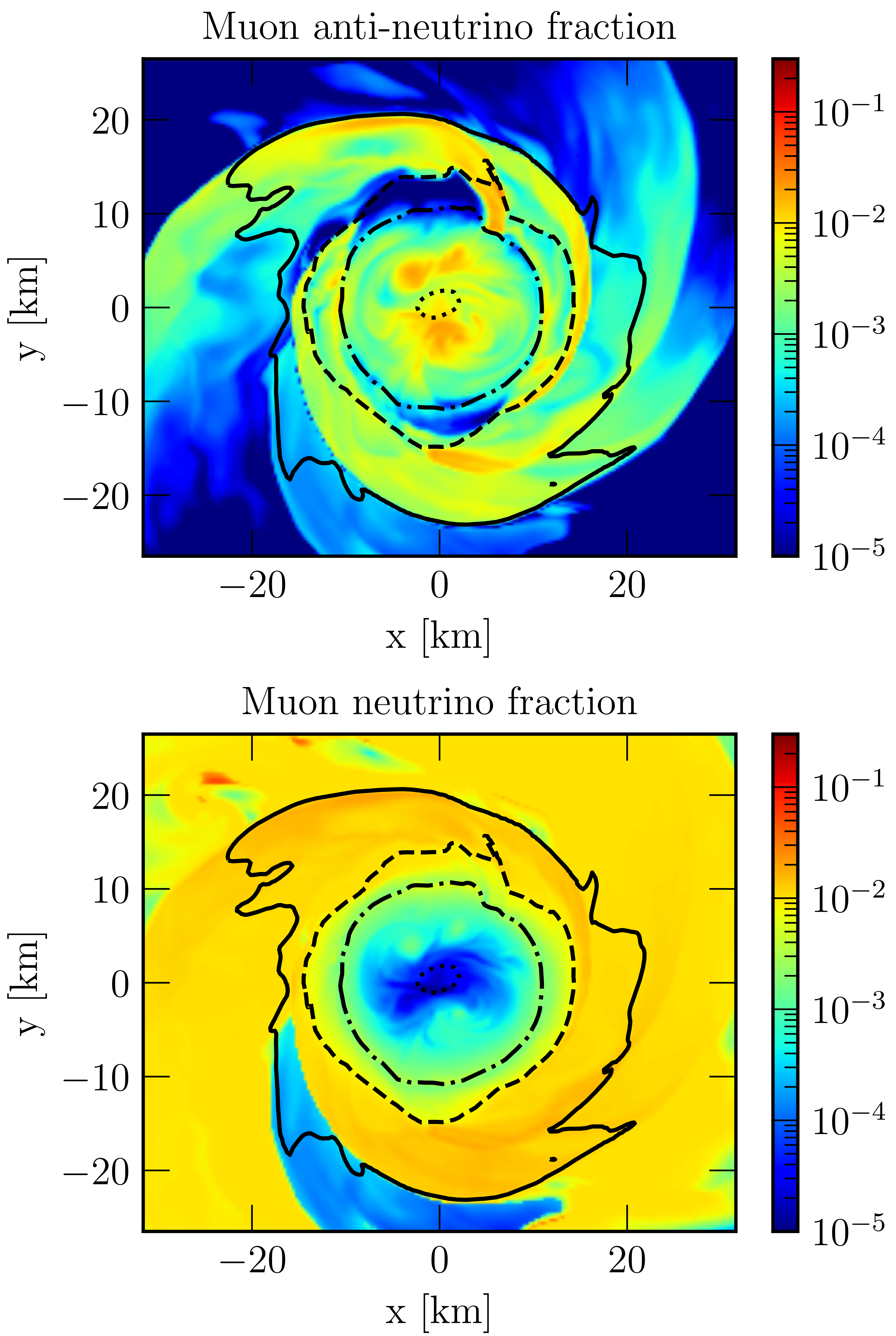


The trapping of neutrinos

The hierarchy

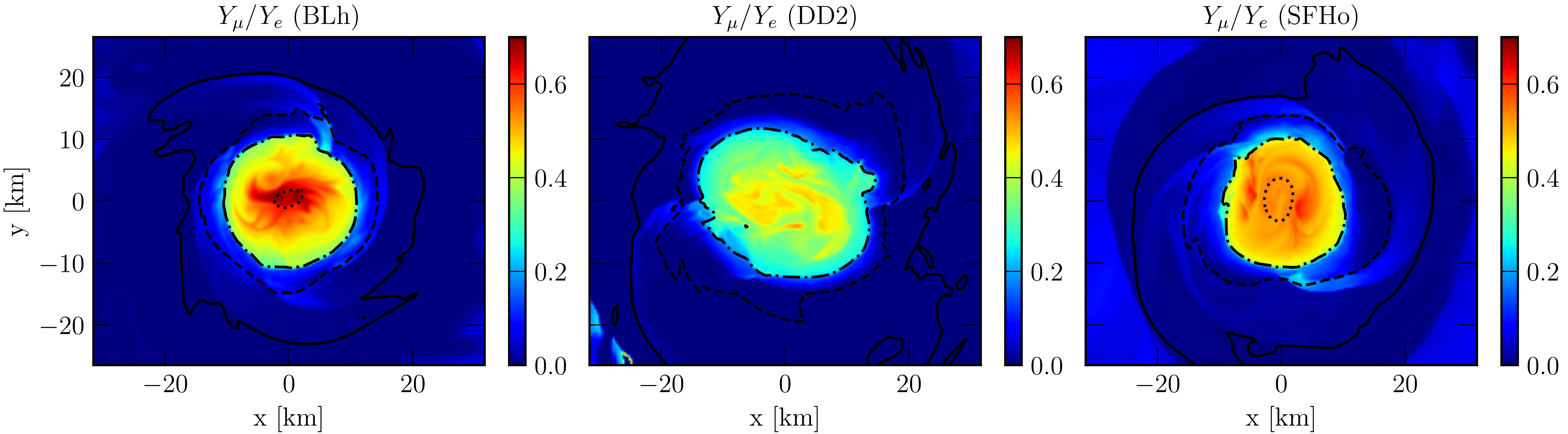
- Antineutrinos dominate in the core $\rho > 10^{14}$ g cm^{-3}, and $\bar{\nu}_\mu$ are the most abundant (see *Foucart et al. 2016*)

- Neutrinos dominate in the outer layer $\rho \sim 10^{13} \div 10^{14}$ g cm^{-3} , and ν_μ are the most abundant



The relevance of muons

Ratio between muon and electron fractions

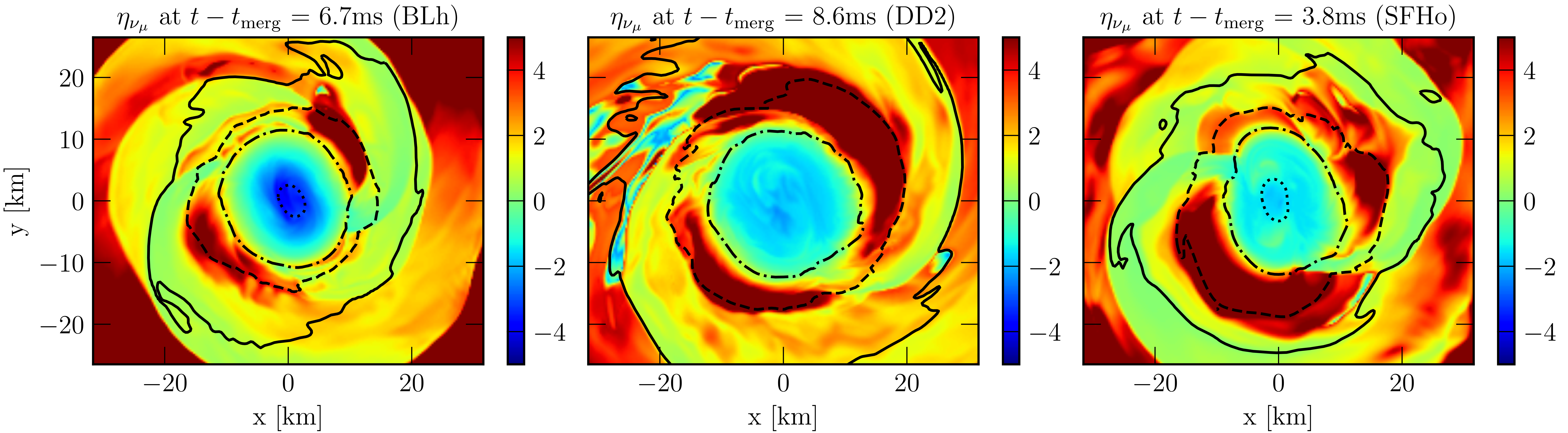


$Y_\mu^{\rm max} \sim 0.7\ Y_e$ $\qquad$ $Y_\mu^{\rm max} \sim 0.5\ Y_e$ $\qquad$ $Y_\mu^{\rm max} \sim 0.6\ Y_e$

The fraction of muons is relevant compared to electrons.

Trapped muon (anti)neutrinos

The degeneracy parameter

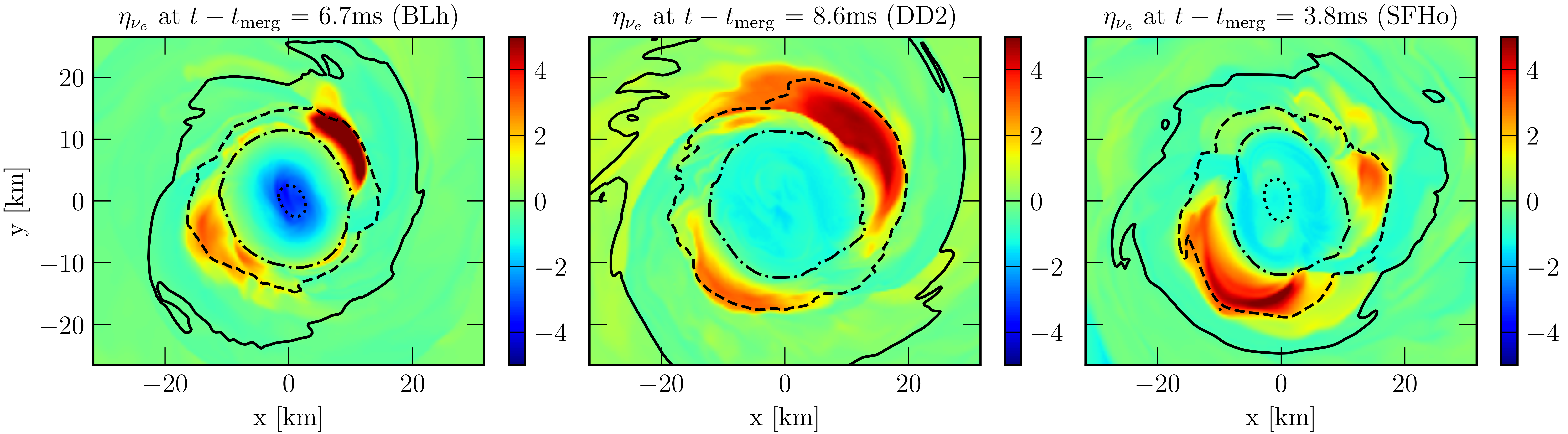


$\mu_n - \mu_p \sim 325$ MeV $\quad\quad$ $\mu_n - \mu_p \sim 200$ MeV $\quad\quad$ $\mu_n - \mu_p \sim 245$ MeV

Trapped Anti-neutrinos as probe of the nuclear chemical potentials and merger dynamics.

Trapped electron (anti)neutrinos

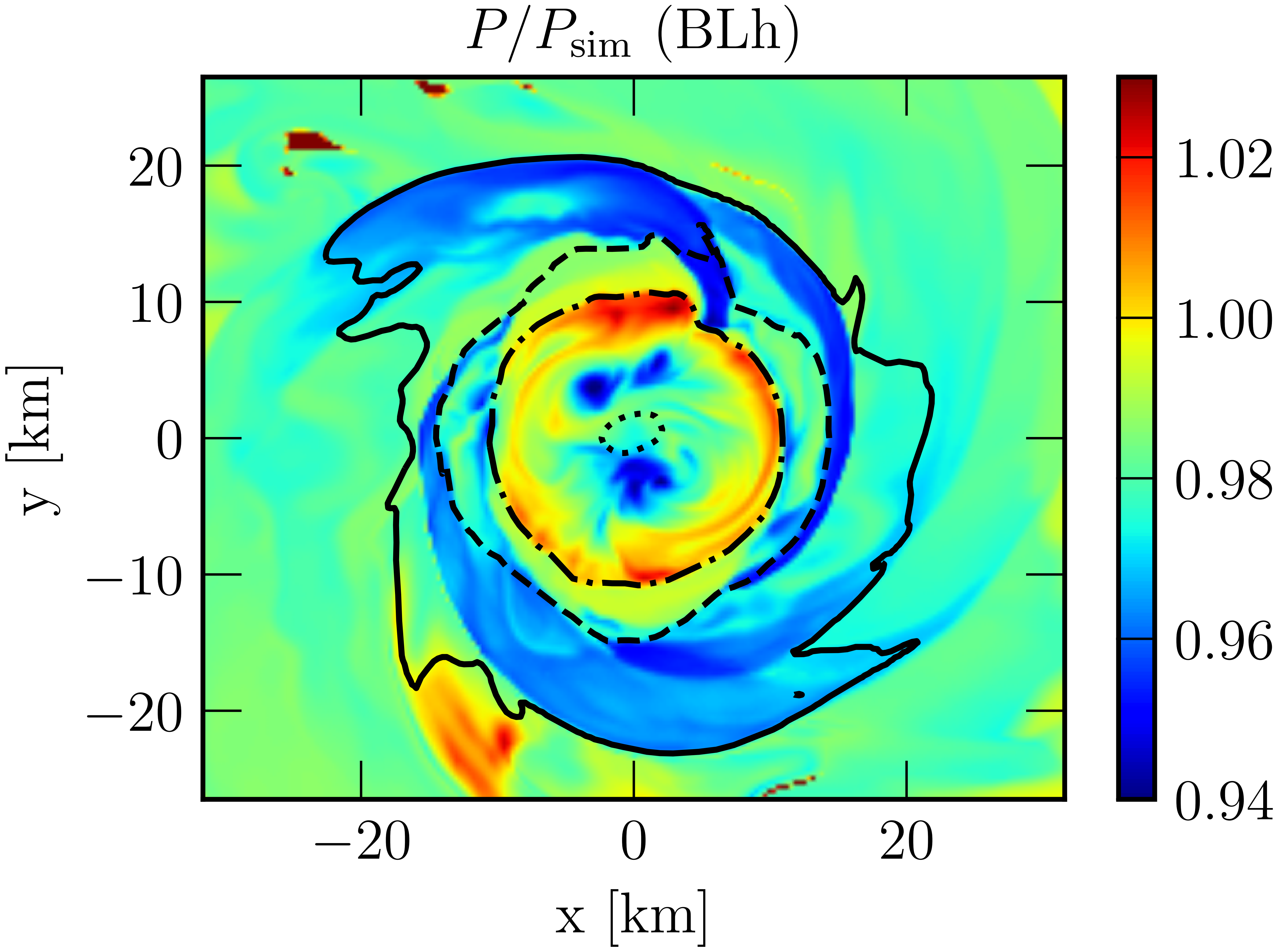
The degeneracy parameter



Trapped neutrinos in the outer layers → possible ν-bursts during the evolution.

The variation of Pressure

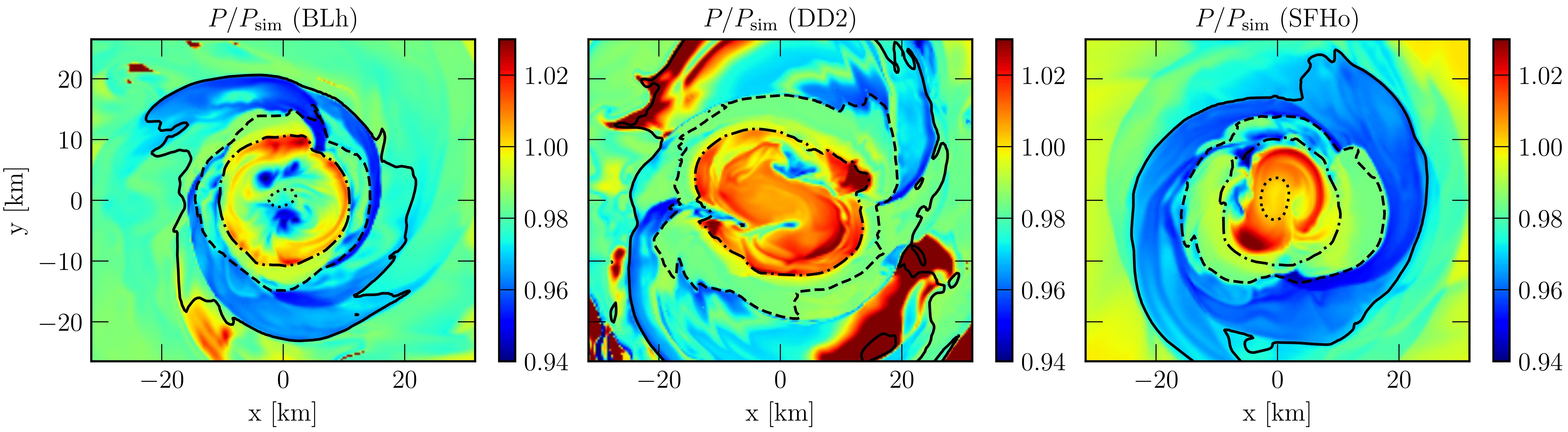
Negative vs positive variation



- Plot of ratio between pressure P computed in post-processing and simulation pressure $P_{\rm sim}$
- $P/P_{\rm sim} < 1 \ \rightarrow$ driven by $n \rightarrow p + e^- + \bar{\nu}_e$ and $n \rightarrow p + \mu^- + \bar{\nu}_\mu$, favoured at high temperature
- $P/P_{\rm sim} > 1 \ \rightarrow$ driven by muons already present in the cold Neutron Stars, favoured at low temperature

The variation of Pressure

Comparing different EOS

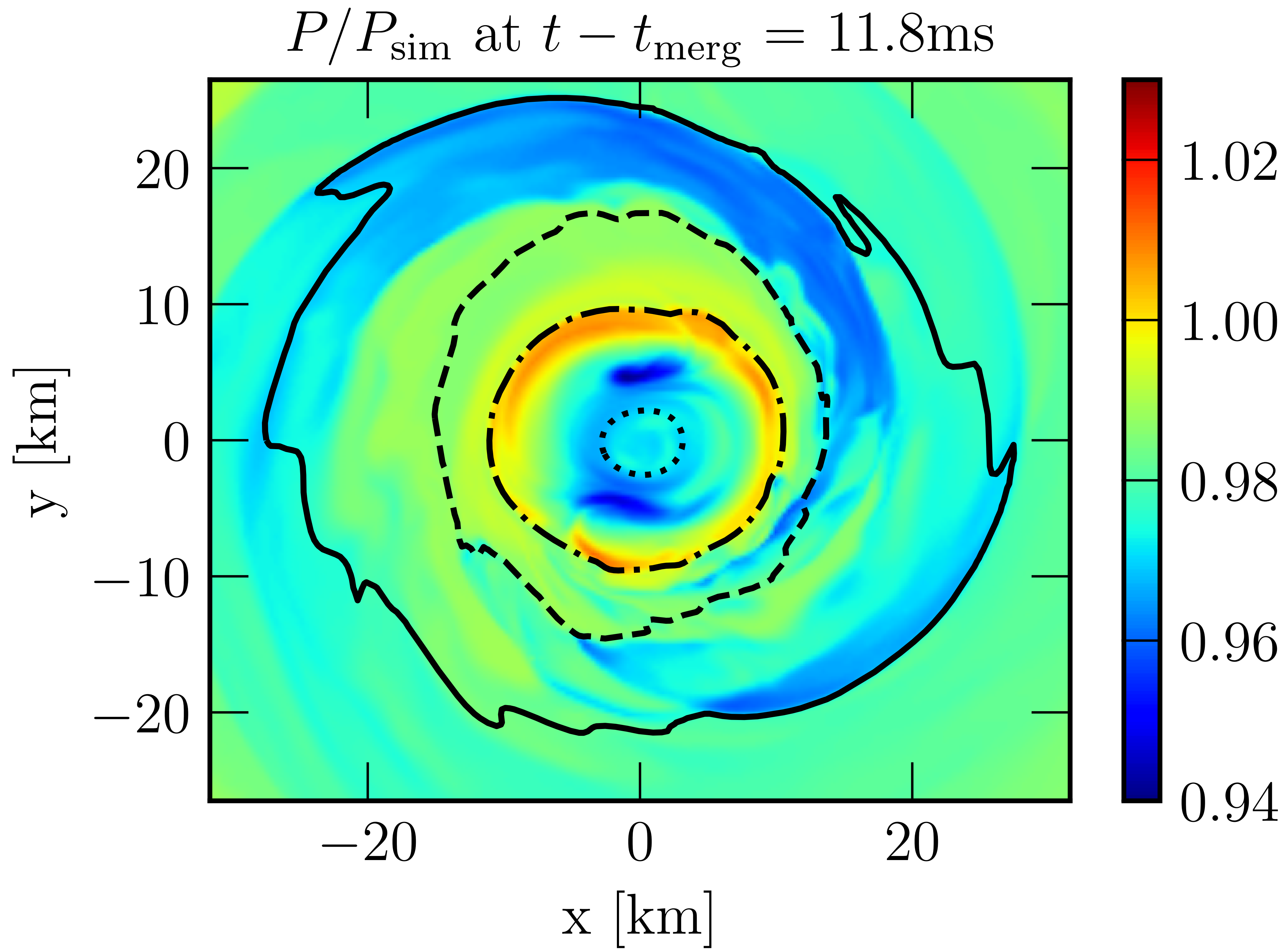


$0.93 \lesssim P/P_{\rm sim} \lesssim 1.03$ $0.94 \lesssim P/P_{\rm sim} \lesssim 1.05$ $0.93 \lesssim P/P_{\rm sim} \lesssim 1.04$

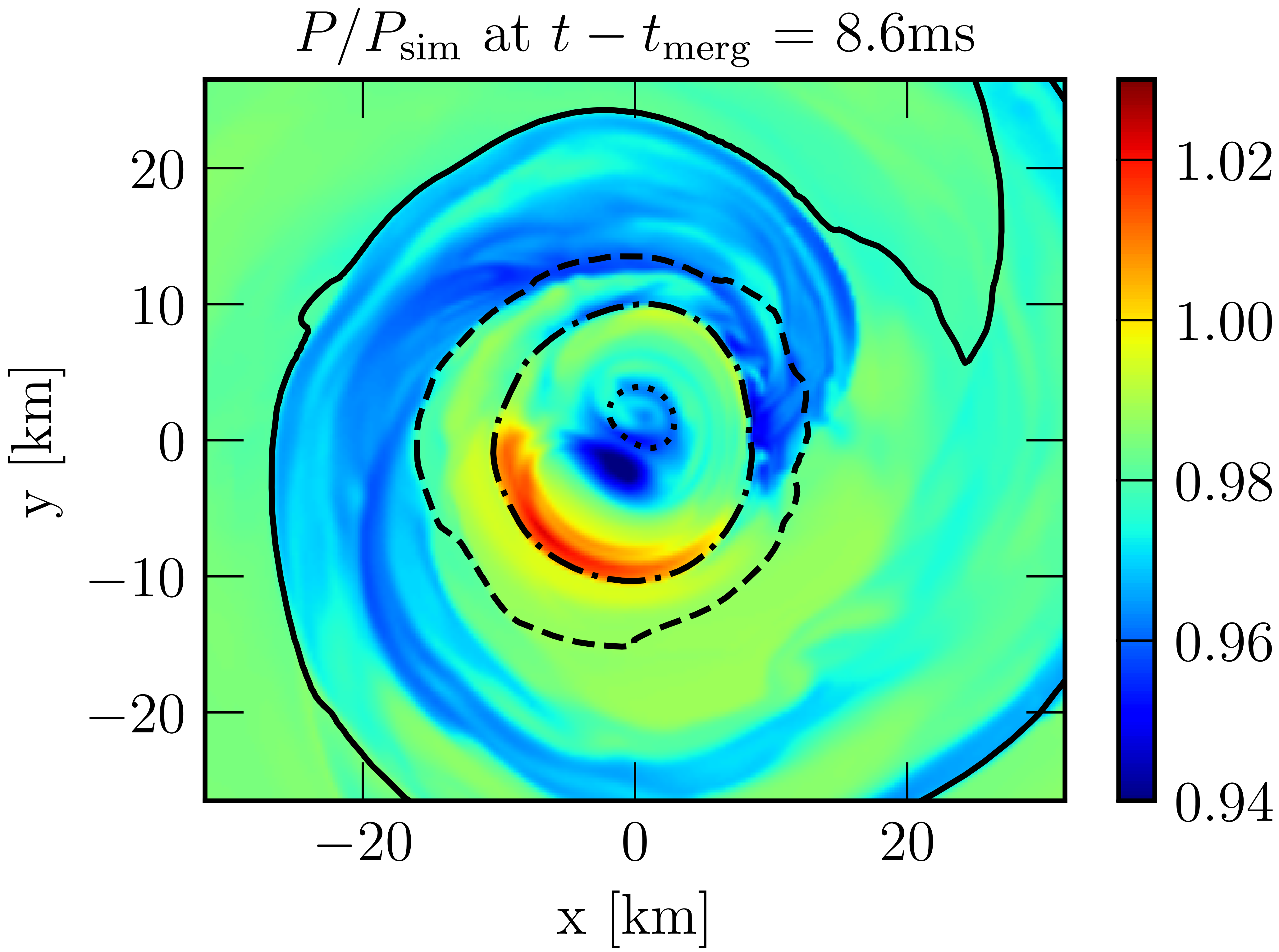
Possible impact on the remnant stability and collapse time.

The variation of Pressure

Comparing different binary mass ratios



$M_1/M_2 = 1.0$



$M_1/M_2 = 1.4$

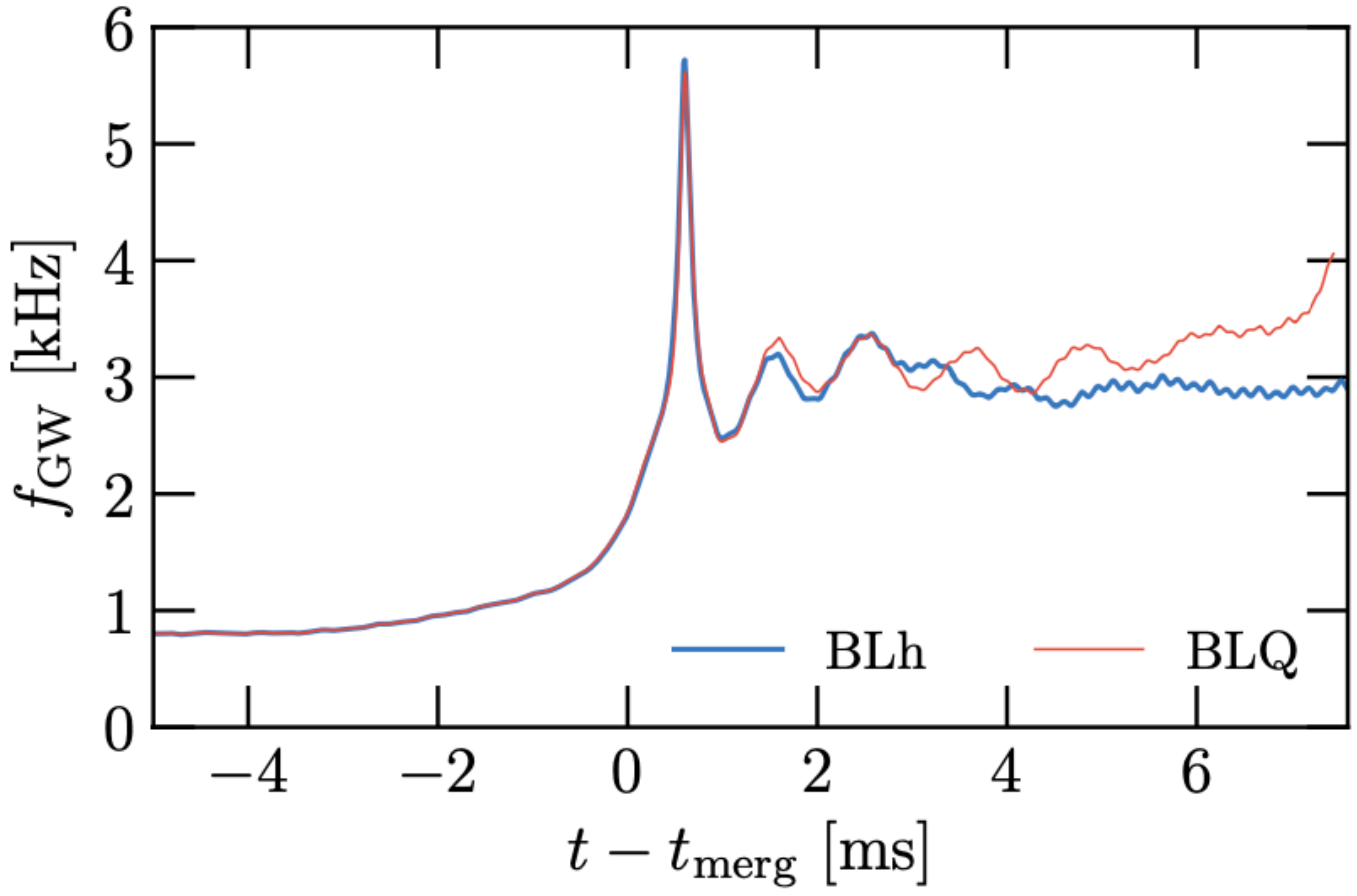
Asymmetry in pressure variation for $M_1/M_2 > 1$. Possibility of kicks?

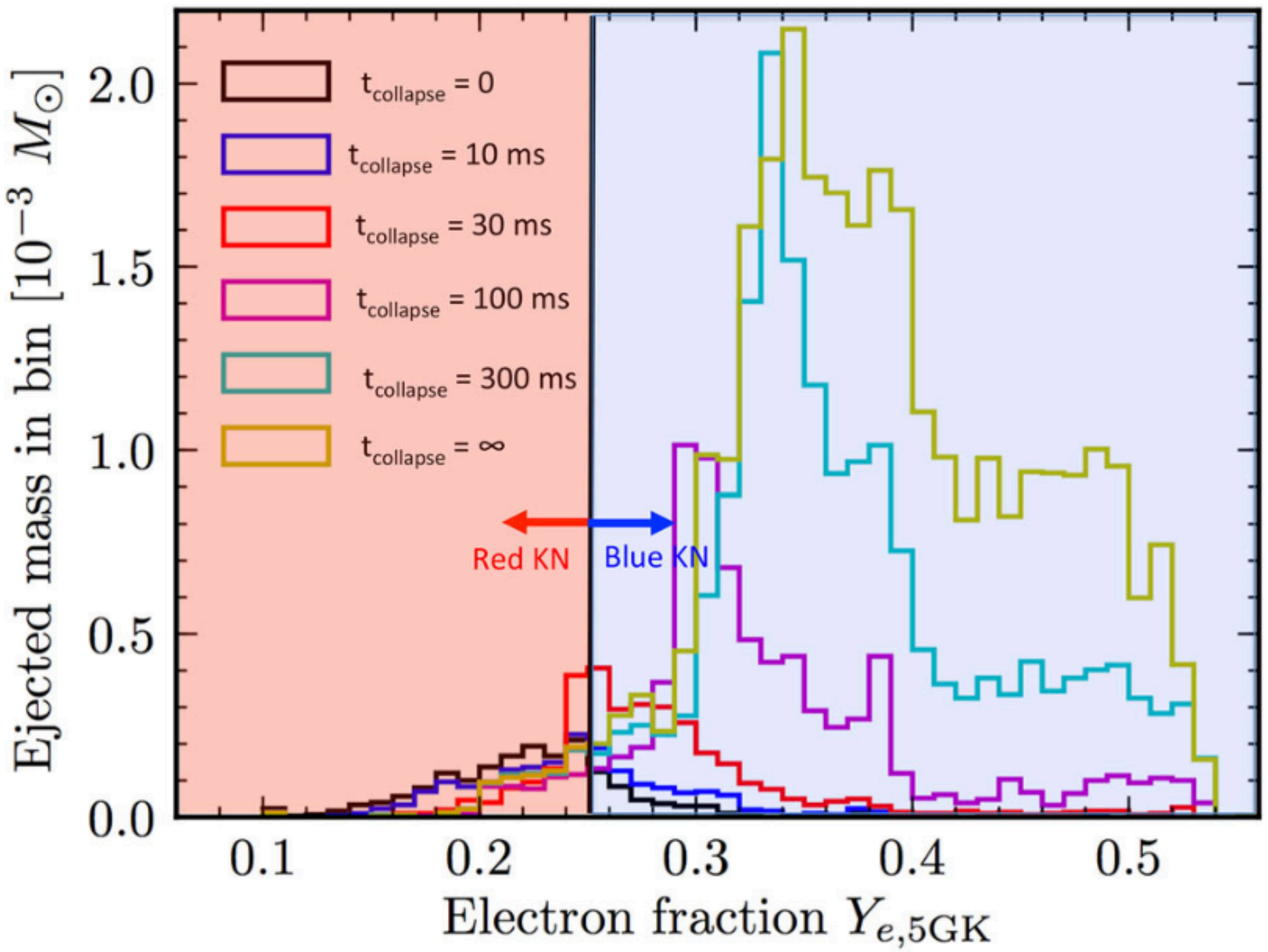
Conclusions

- The fraction of muons is between $\sim 30\% \div 70\,\%$ of the electron fraction. The inclusion of muons will improve state of the art simulations.
- $\bar{\nu}_e$ and $\bar{\nu}_\mu$ form trapped degenerate gases in the core with a degeneracy depending on the nuclear chemical potentials → probe of $\mu_n - \mu_p$
- ν_e and ν_μ form trapped degenerate gases in the outer layers → possibility of bursts
- The pressure variation is positive or negative depending on the spatial region considered → implications for collapse time
- Asymmetry in pressure variation for asymmetric binaries → possibility of kicks?

Outlook

Muons and trapped neutrinos change the EOS stiffness and the collapse time → possibly implications for post-merger GWs and Kilonova.



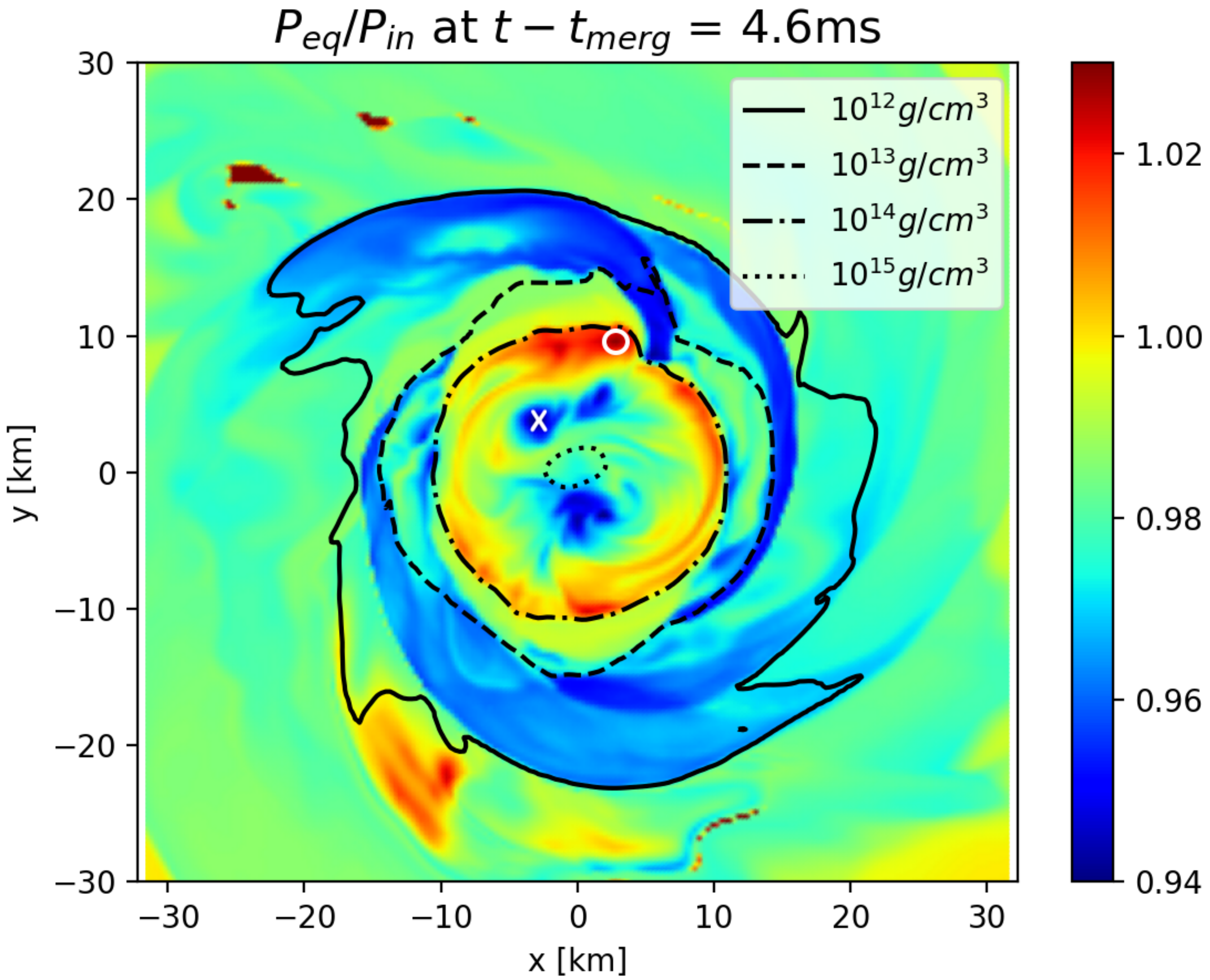


Credits: A. Prakash et al, 2021

Credits: Metzger, 2019

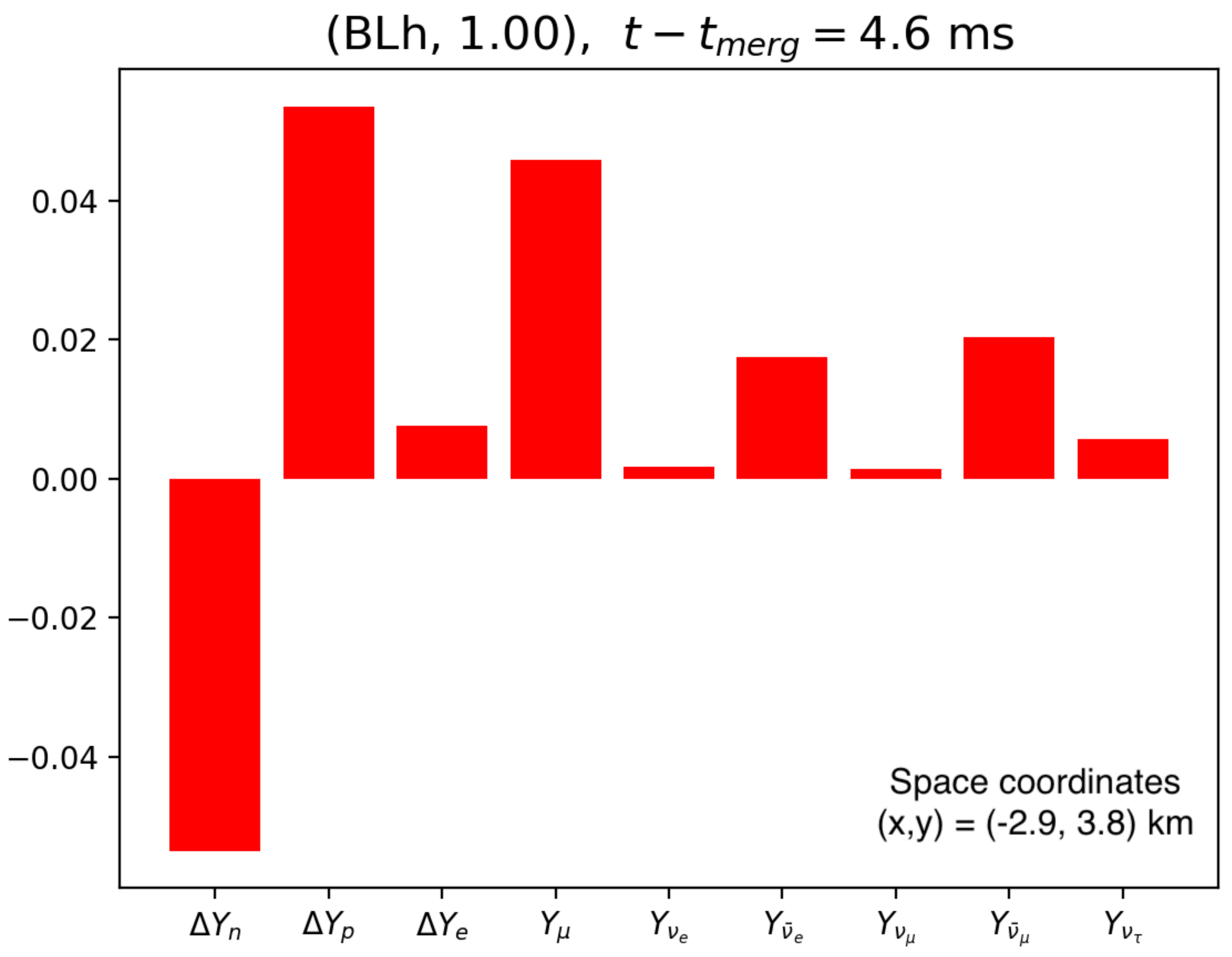
Backup Slides

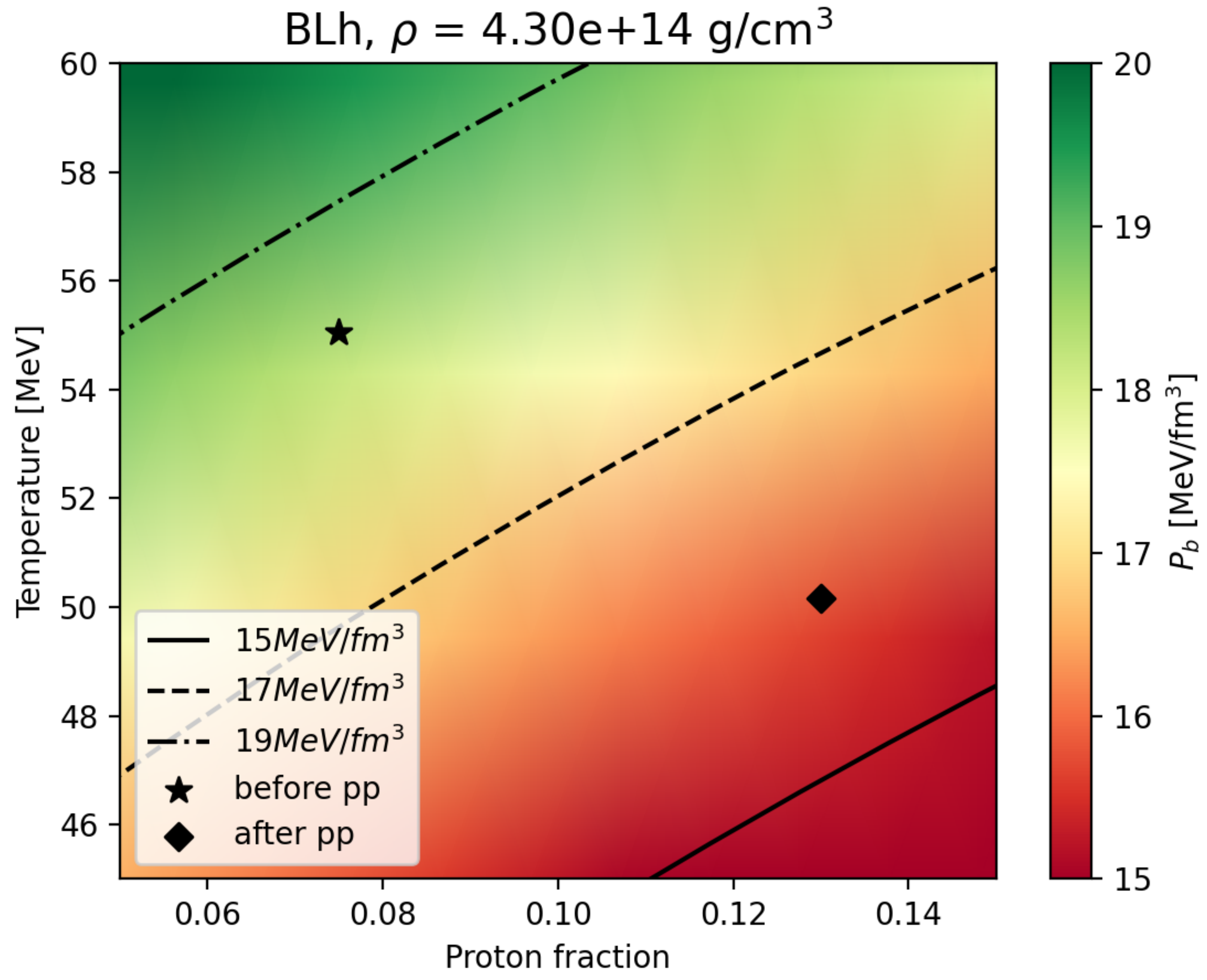
Pressure variation: two representative examples



Pressure variation: two representative examples

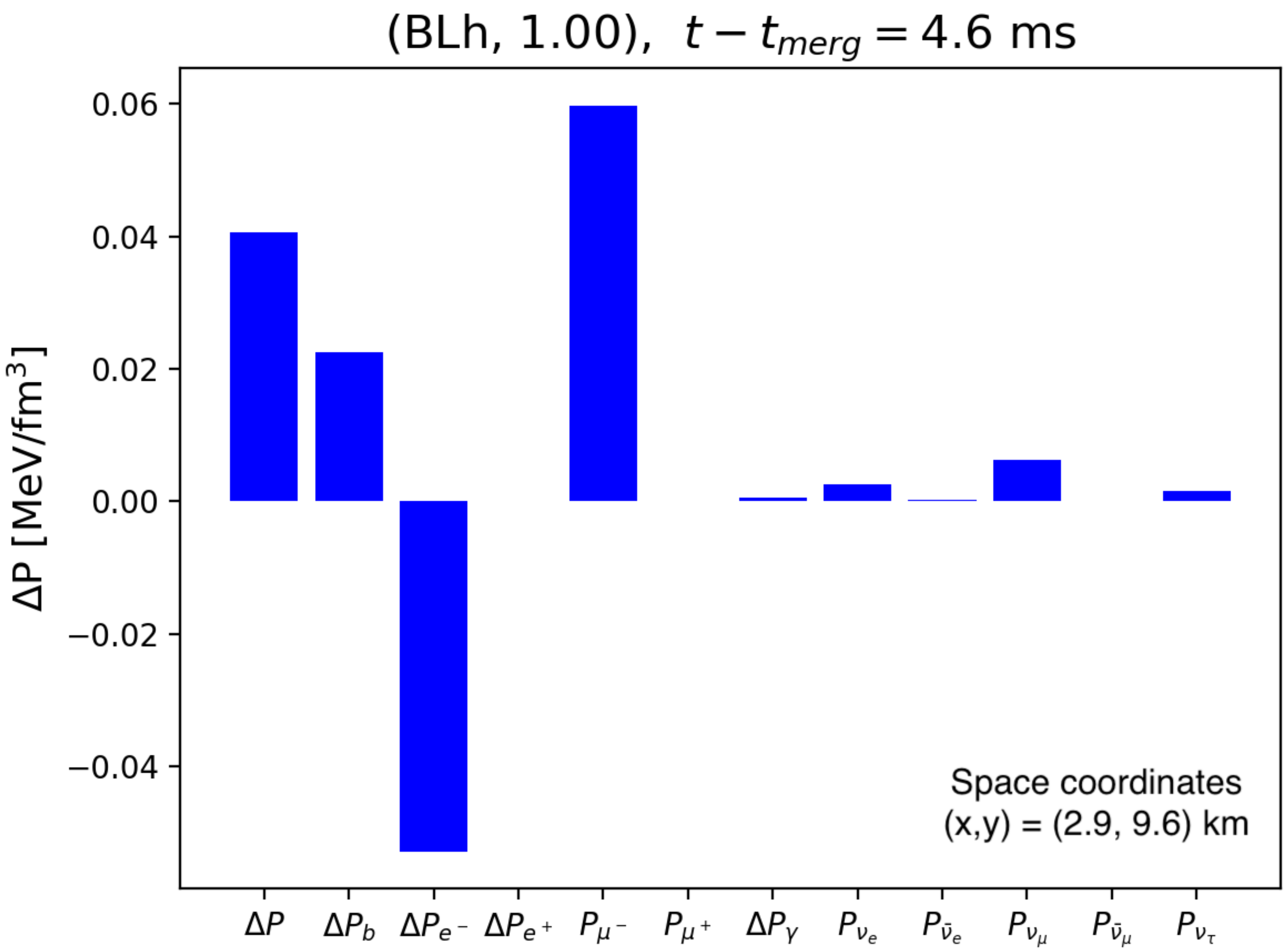
Negative pressure variation

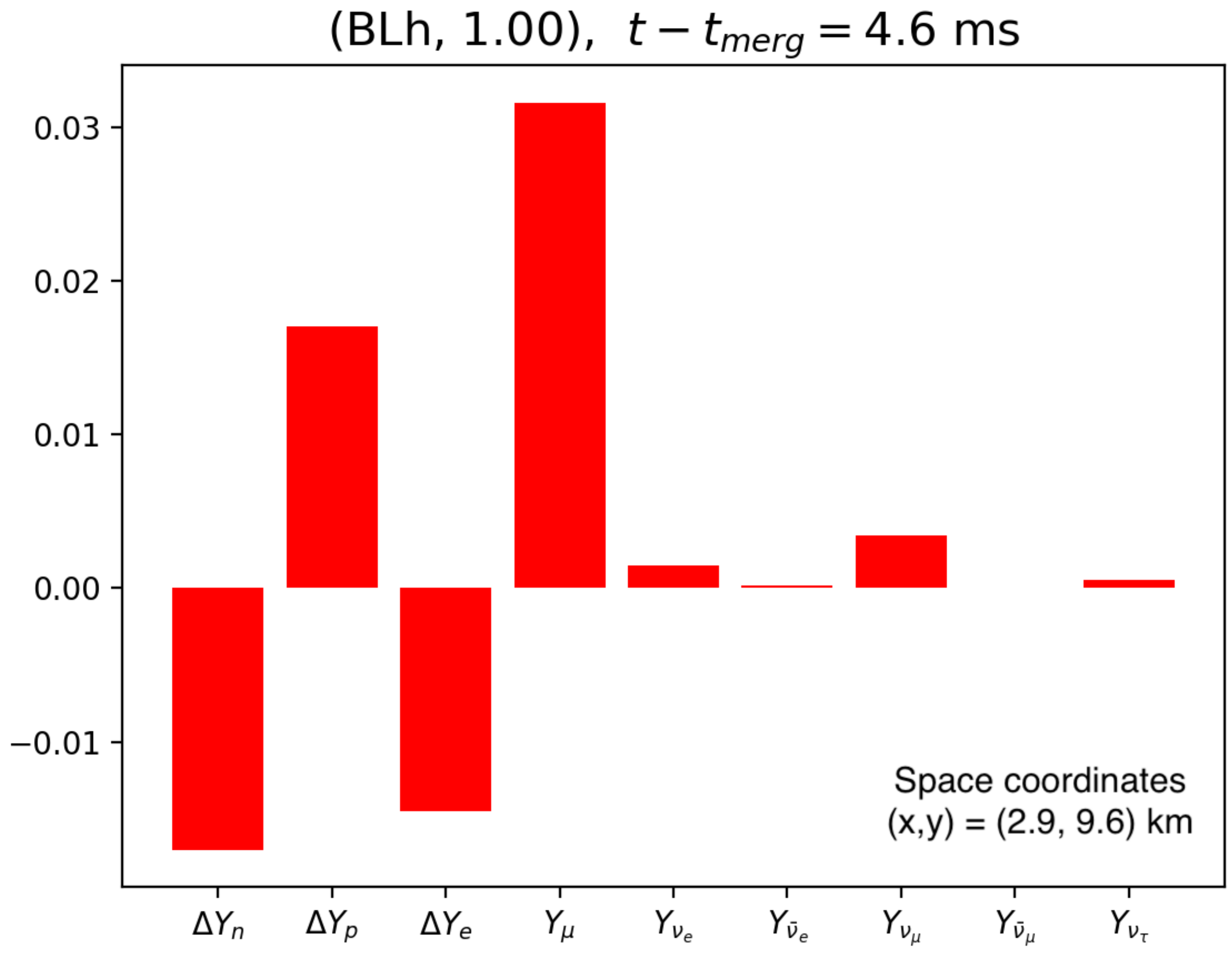




Pressure variation: two representative examples

Positive pressure variation





Pressure variation: two representative examples

Positive pressure variation