Muons production and Neutrino Trapping in Binary Neutron Star mergers

Eleonora Loffredo

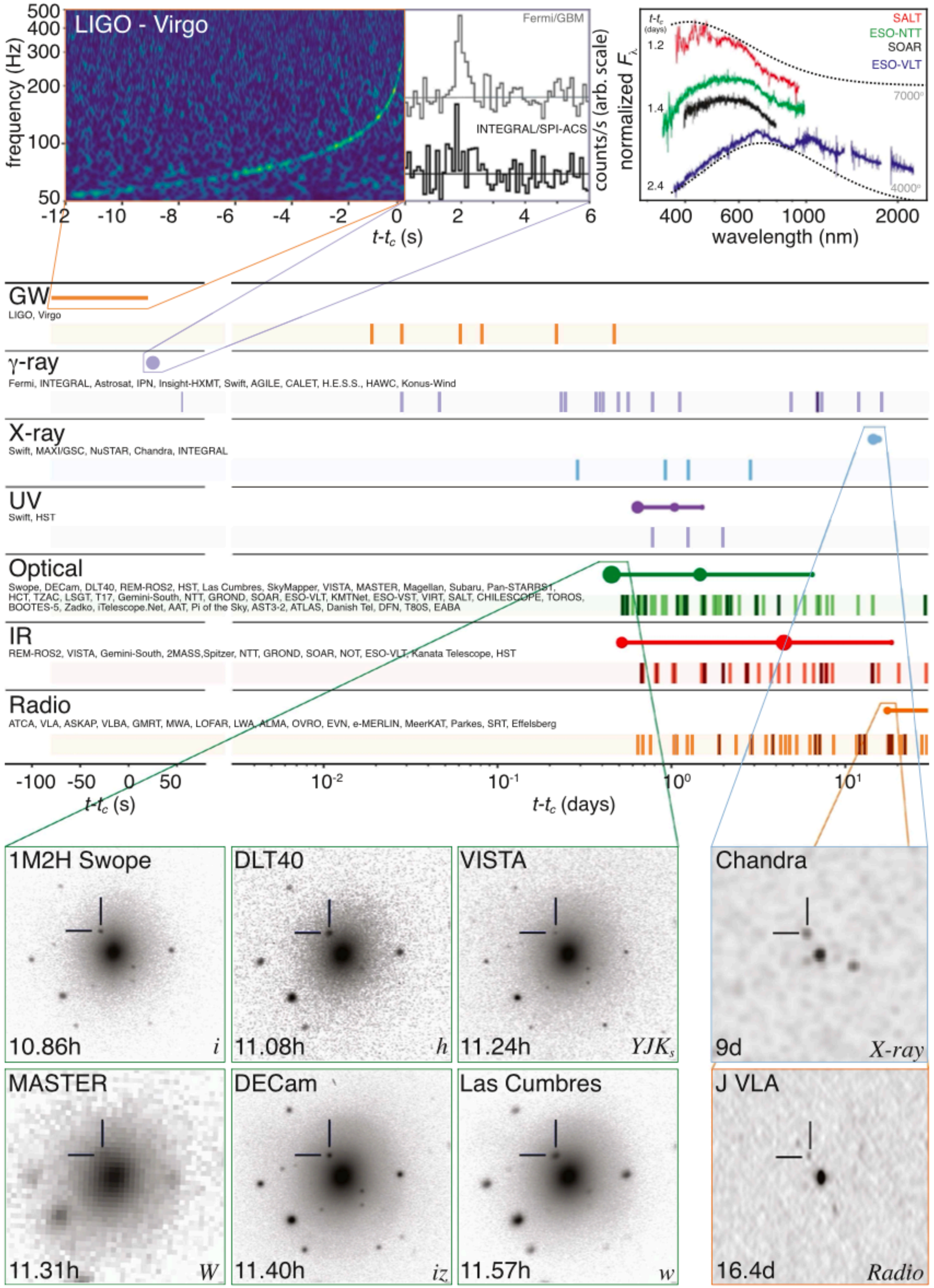
In collaboration with A. Perego, D. Logoteta, and M. Branchesi

Quinto incontro Nazionale di Fisica Nucleare - INFN 2022

Binary Neutron Star mergers

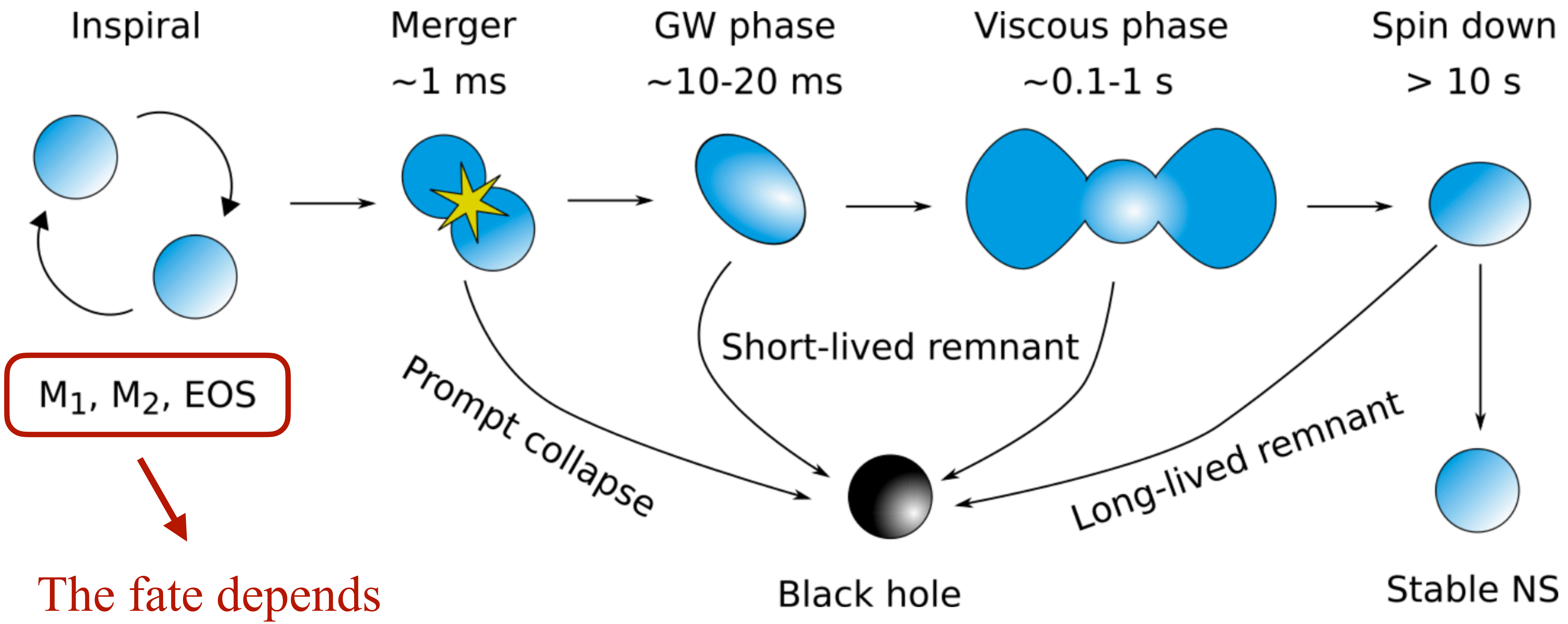
The first detection

- August 2017: first detection of gravitational waves & electromagnetic counterparts from a BNS merger
- New insights on fundamental physics, in particular on Gamma Ray Bursts and Kilonovae



Credits: LVC+astronomers, Abbott et al. 2017, ApJL, 848

Which is the fate of a Binary Neutron Star merger?

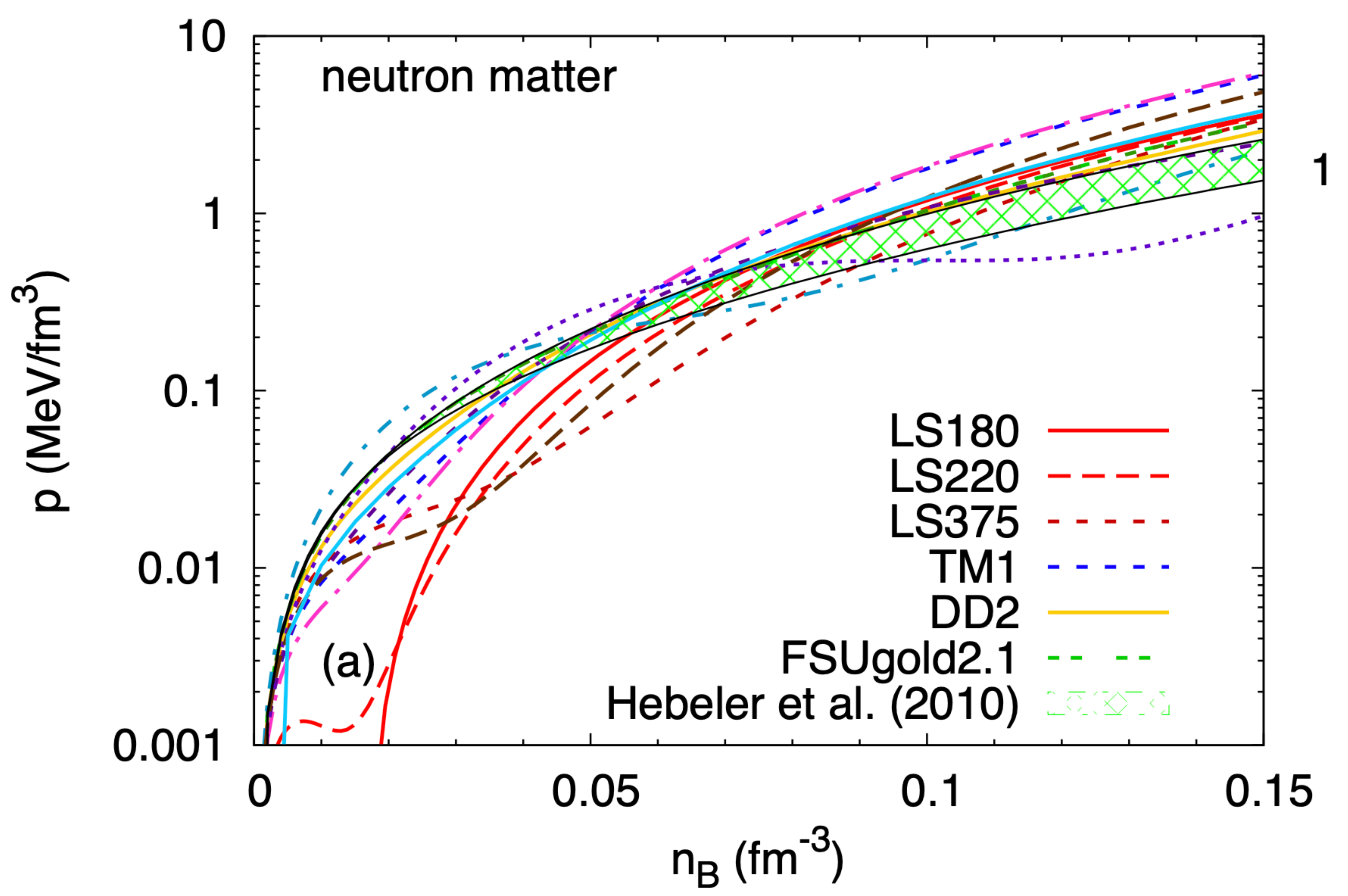


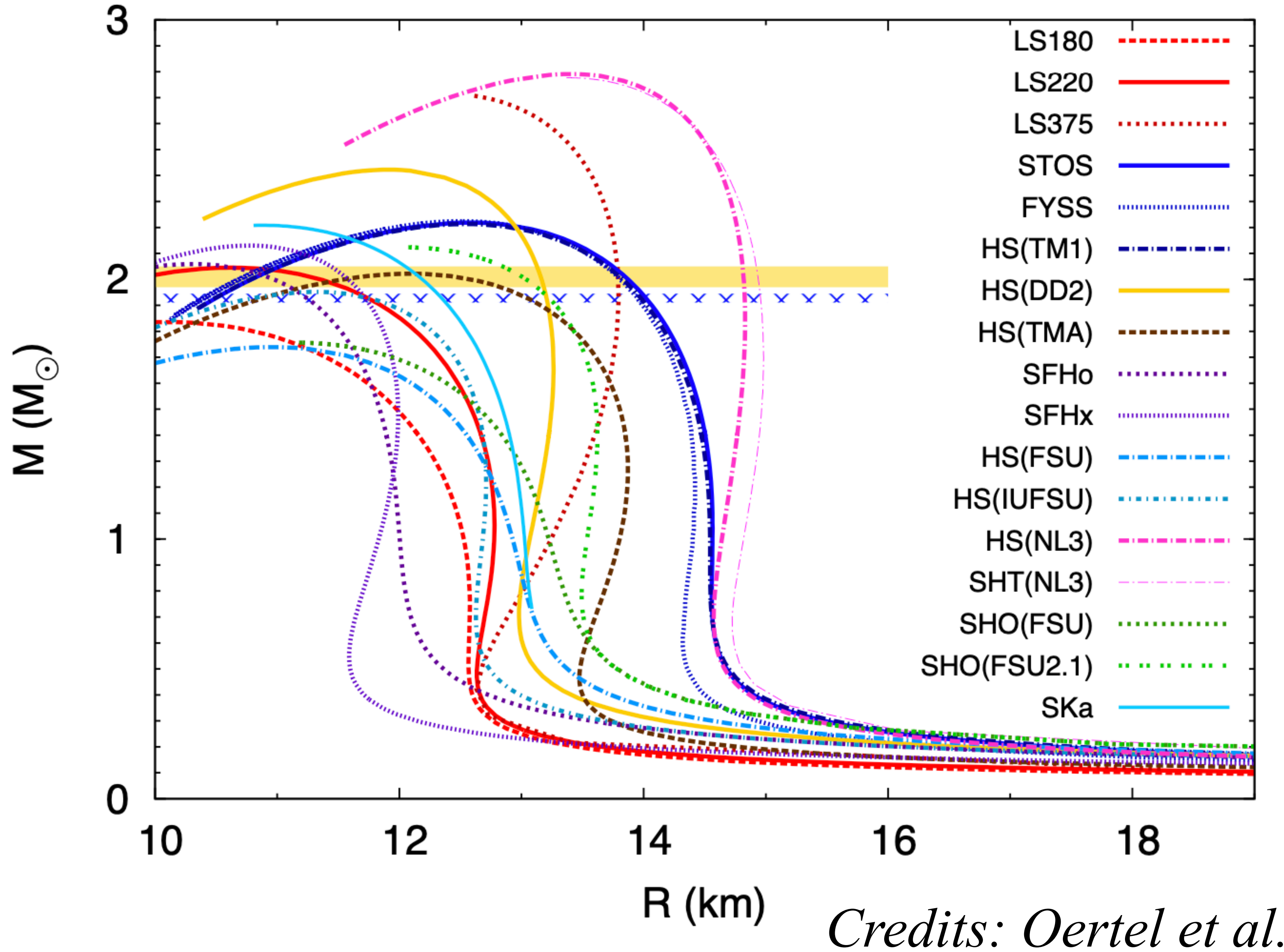
The fate depends
on the masses and
the Equation of State

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 unknown
- 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

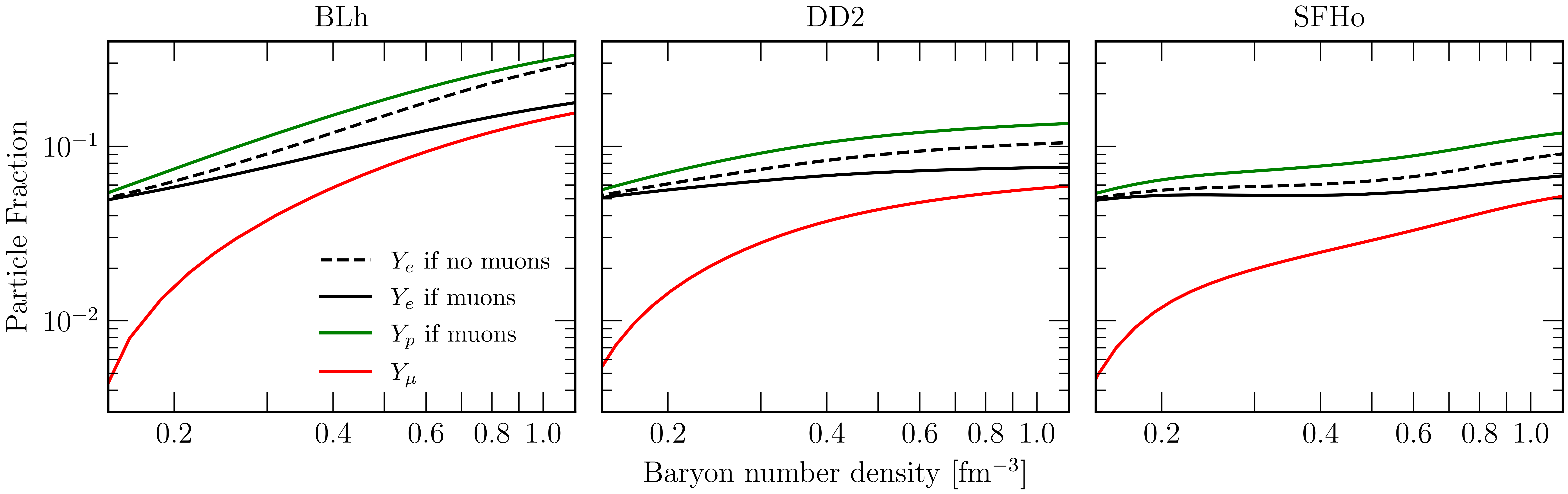




Credits: Oertel et al. 2016

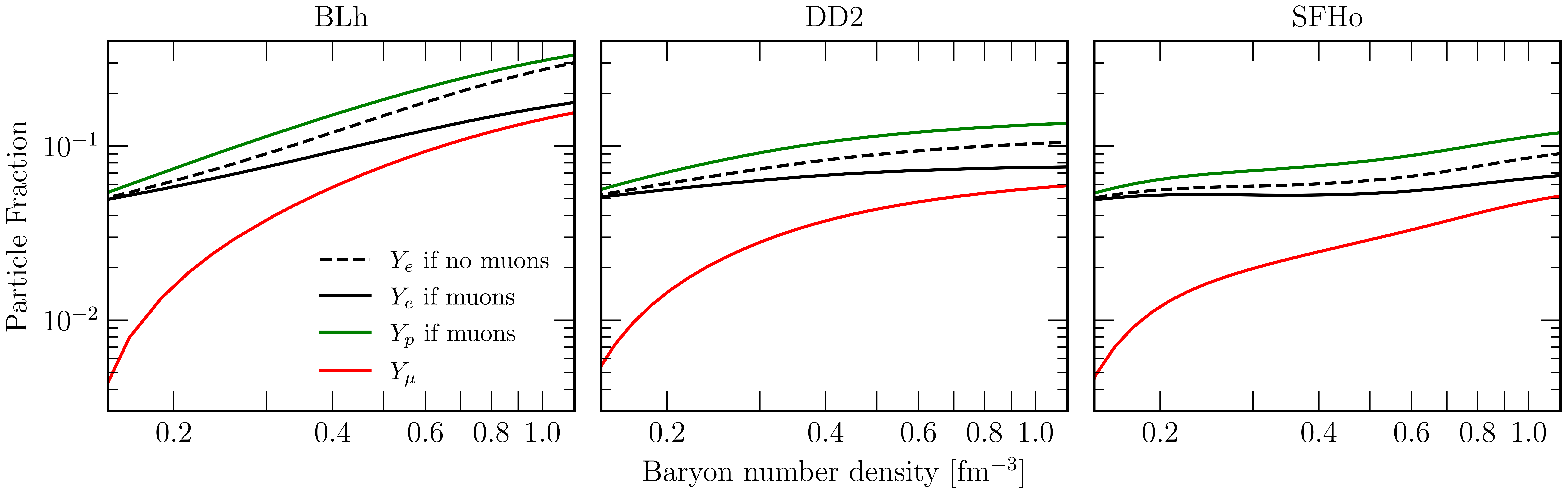
The relevance of muons and trapped neutrinos

- 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



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 merger remnant.



Improving the microphysics modelling

Method

- 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 $i = p, e^-, e^+, \mu^- \dots$
- 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

Improving the microphysics modelling

Method - The post-processing technique

- During the merger the temperature of fluid elements increase → 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

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

- 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

Typical outcome of a BNS merger simulation

Matter Density

$t - t_{\mathrm{merger}} \sim 1$ ms $t - t_{\mathrm{merger}} \sim 3$ ms $t - t_{\mathrm{merger}} \sim 5$ ms

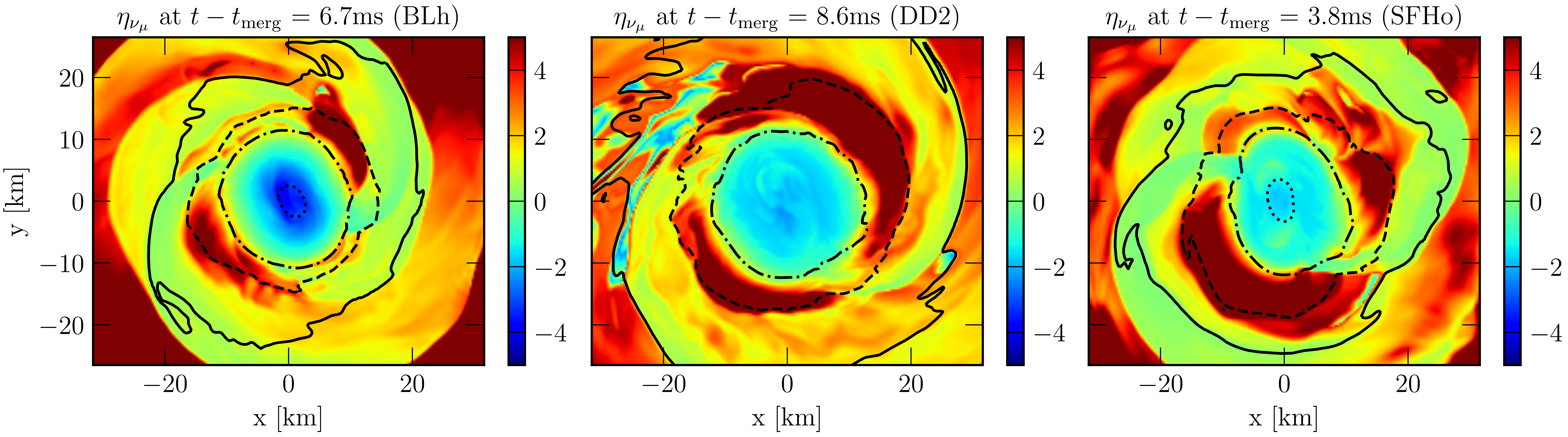
Credits: Simulation from Nedora et al., ApJ 2021

The appearance of muons

Results for 3 simulations with same binary mass ratio $M_1/M_2 = 1$ but different EOS (BLh, DD2, SFHo)

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

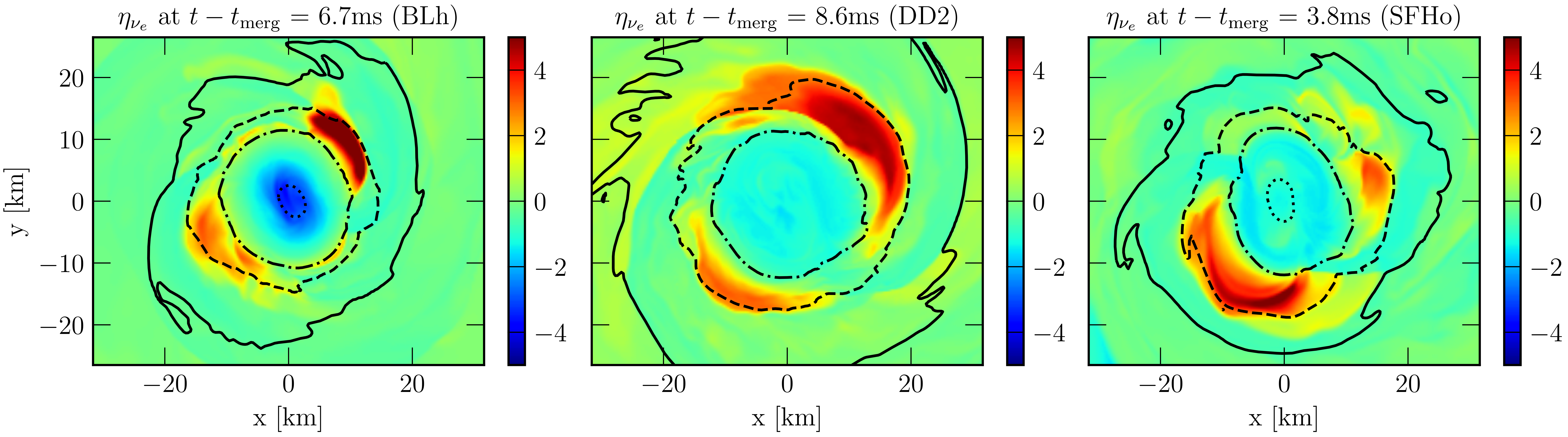
The trapping of Muon Neutrinos



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

Trapped Anti-neutrinos as probe of the nuclear chemical potentials

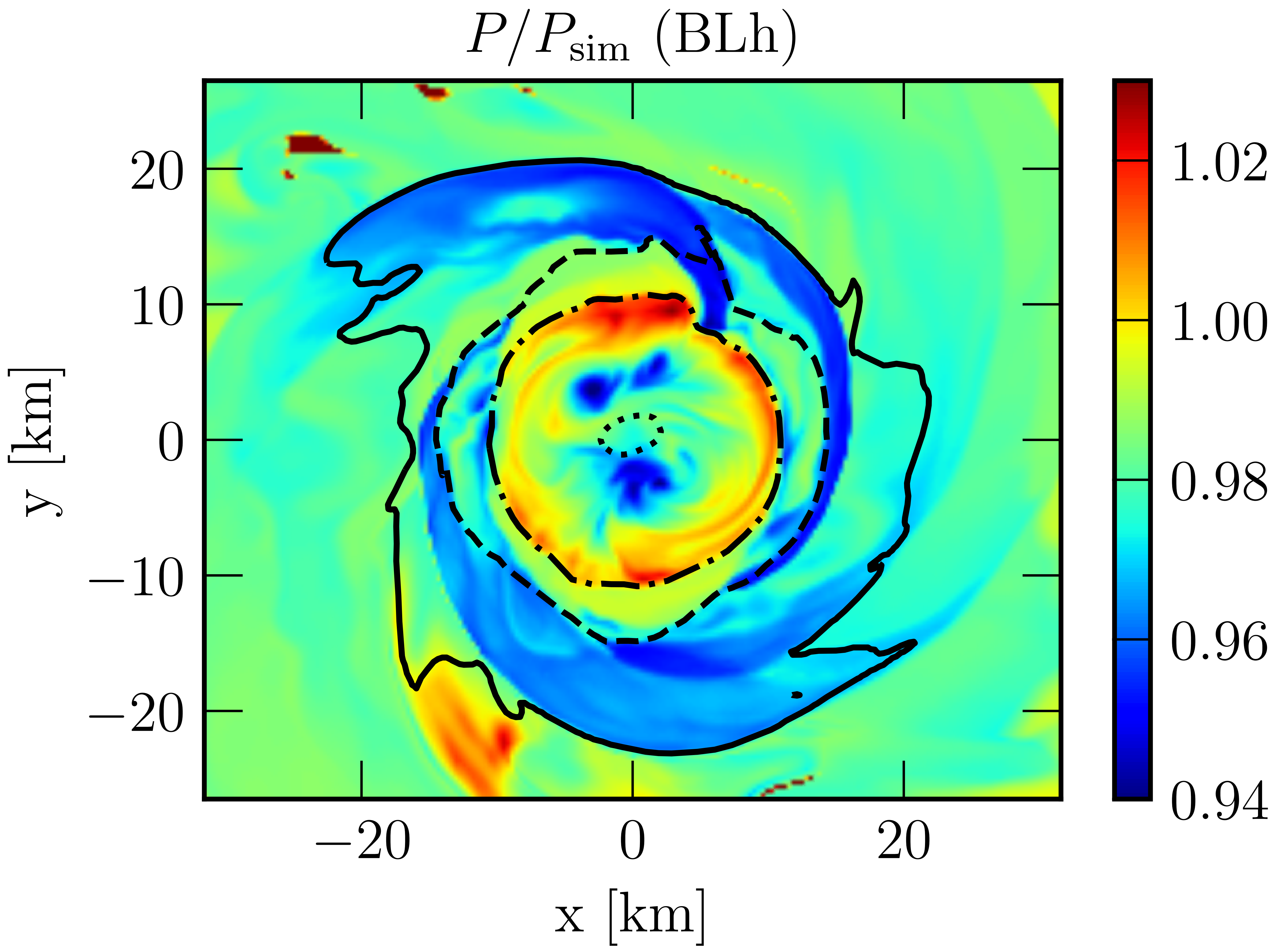
The trapping of Electron Neutrinos



Trapped neutrinos in the outer layers irrespective of the EoS.

Possibility of Neutrino bursts during the evolution.

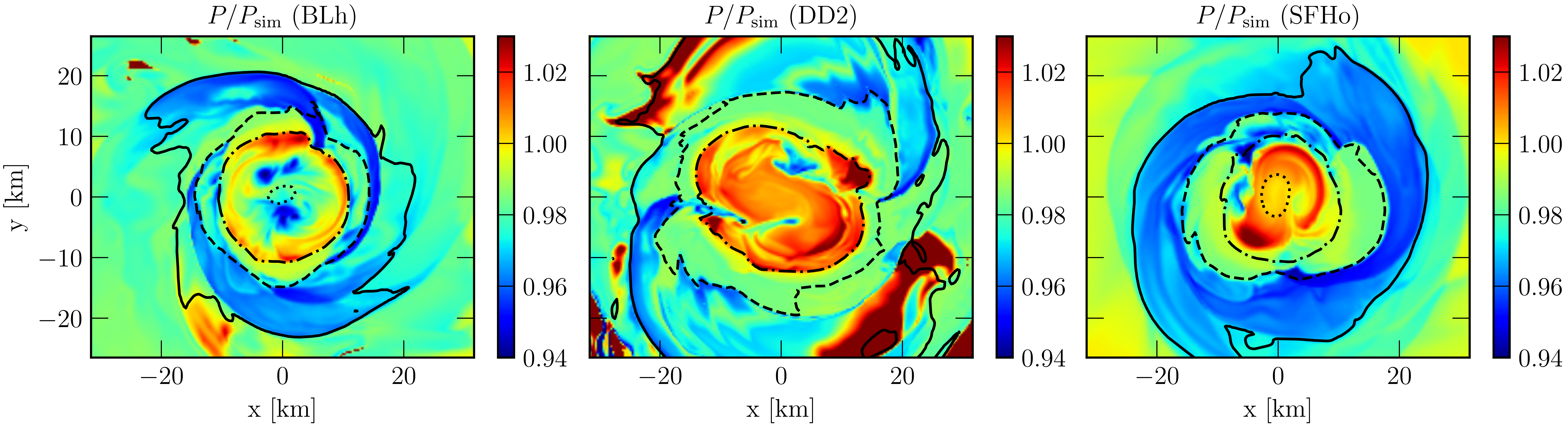
The variation of Pressure



- 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 EoSs



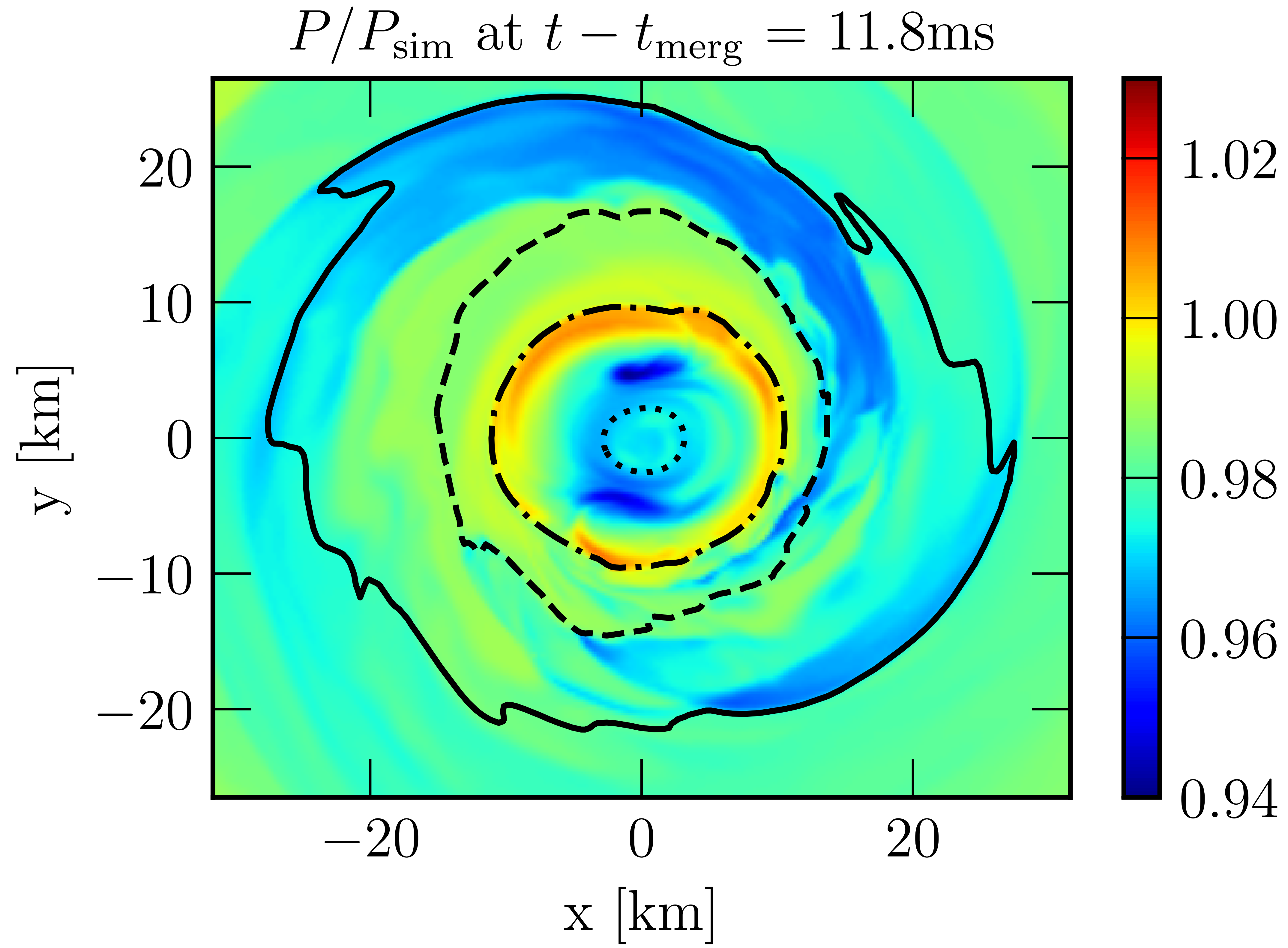
$0.93 \lesssim dP \lesssim 1.03$ $\quad$ $0.94 \lesssim dP \lesssim 1.05$ $\quad$ $0.93 \lesssim dP \lesssim 1.04$

Possible impact on the remnant stability and collapse time.

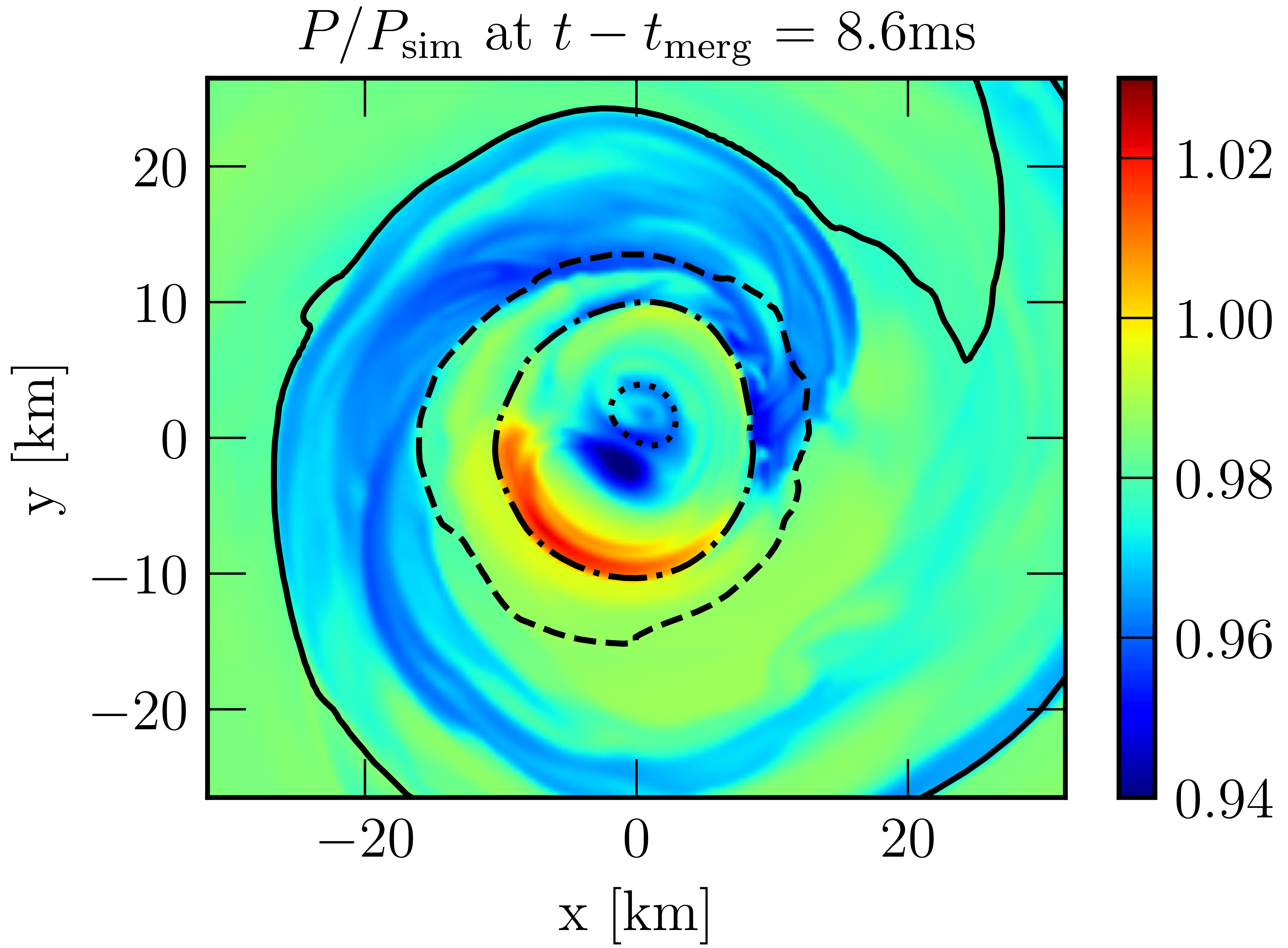
The variation of Pressure: different mass ratio

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 → 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 and features of EM counterparts.
- Asymmetry in pressure variation → possibility of kicks.

THANK YOU FOR YOUR KIND ATTENTION