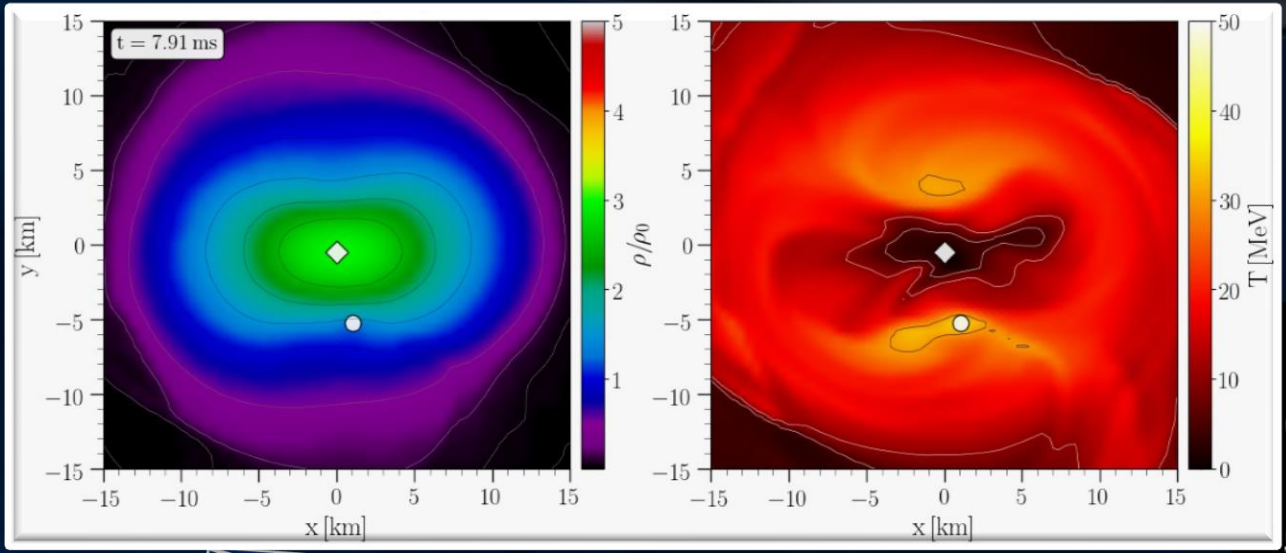
Hypermassive Hybrid Stars

within the

Phase Diagram of Quantum Chromodynamics

30TH TEXAS SYMPOSIUM
PORTSMOUTH, 16 DEZEMBER 2019



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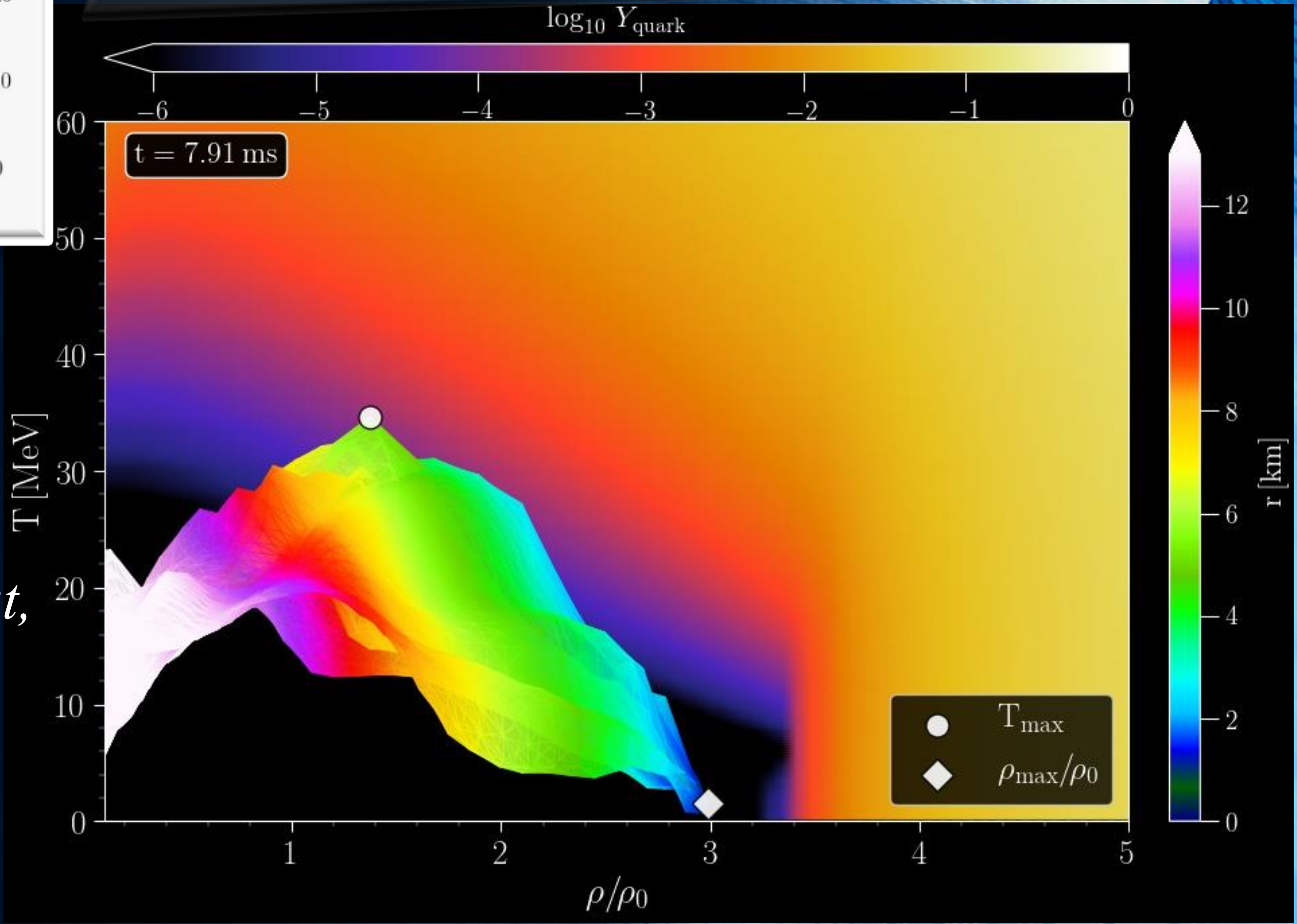
In collaboration with Luke Bovard, Elias R. Most, L. Jens Papenfort, Jan Steinheimer, Veronica Dexheimer, Stefan Schramm, Horst Stöcker and Luciano Rezzolla



The Einstein Equation and the EOS of Compact Stars

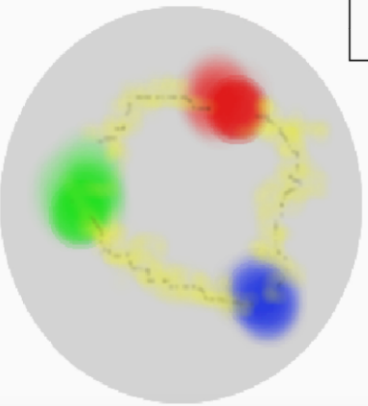
ART	Yang-Mills-Theories
$D_\beta v^\alpha = \partial_\beta\, v^\alpha + \Gamma^\alpha_{\sigma\beta}\, v^\sigma$	$D_{\beta a}{}^{b} = \partial_\beta\, 1_a{}^{b} + ig\, A_{\beta a}{}^{b}$
$R^\delta{}_{\mu\alpha\beta}\, v^\mu = [D_\alpha, D_\beta]\, v^\delta$ $R^\delta{}_{\mu\alpha\beta} = \Gamma^\delta_{\mu\alpha\|\beta} - \Gamma^\delta_{\mu\beta\|\alpha}$ $+\Gamma^\delta_{\nu\beta}\Gamma^\nu_{\mu\alpha} + \Gamma^\delta_{\nu\alpha}\Gamma^\nu_{\mu\beta}$	$F_{\alpha\beta a}{}^{b} = \frac{1}{ig}\left[D_{\alpha a}{}^{c}, D_{\beta c}{}^{b}\right]$ $= A_{\beta a}{}^{b}{}_{\|\alpha} - A_{\alpha a}{}^{b}{}_{\|\beta}$ $+\frac{1}{ig}\left[A_{\alpha a}{}^{c}, A_{\beta c}{}^{b}\right]$
$\mathcal{L}_G = R + \underbrace{\left(c_1\, R_{\mu\nu}R^{\mu\nu} + \ldots\right)}_{\equiv 0 \text{ for ART}}$	$\mathcal{L}_{YM} = \frac{1}{4} F_{\mu\nu a}{}^{b}\, F^{\mu\nu}{}_{a}{}^{b}$

QuantumCromoDynamic:

$(SU(3)_{(c)}$- Color Yang-Mills-Gauge Theory)

$$D_{\beta A}{}^{B} = \partial_\beta\, 1_A{}^{B} + ig\, G_{\beta A}{}^{B}$$

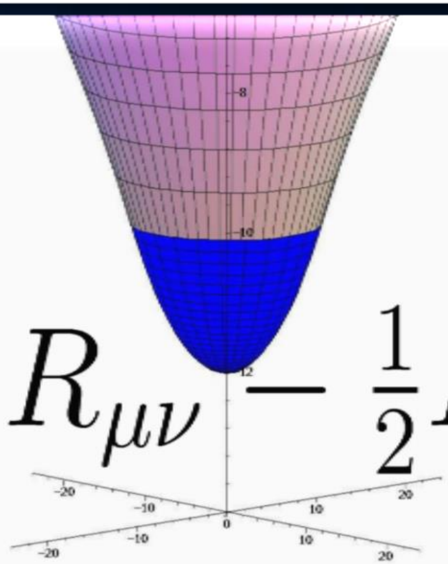
$A, {}^B$ = red, green, blue

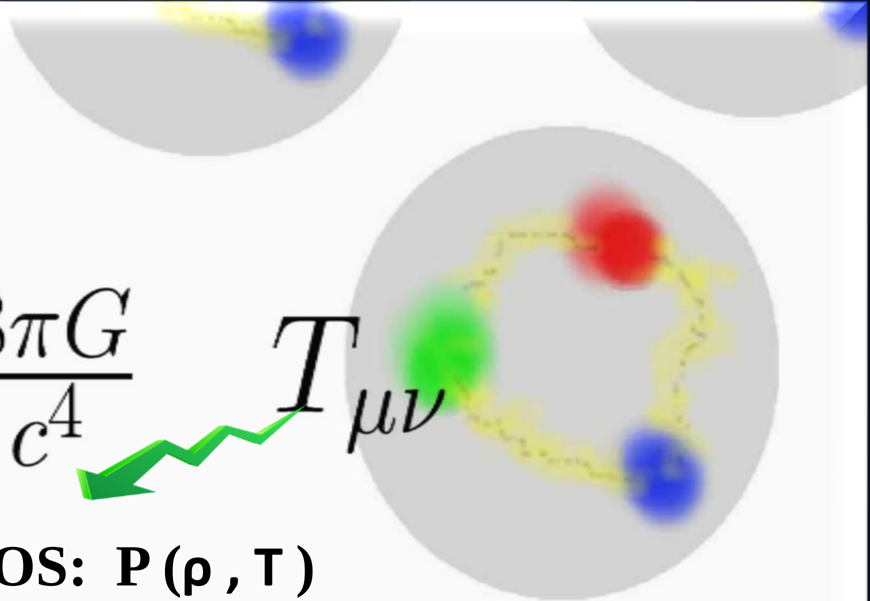


$$\psi^f_A = \begin{pmatrix} \psi^f_r \\ \psi^f_g \\ \psi^f_b \end{pmatrix}$$

Confinement

chiral symmetry, ...



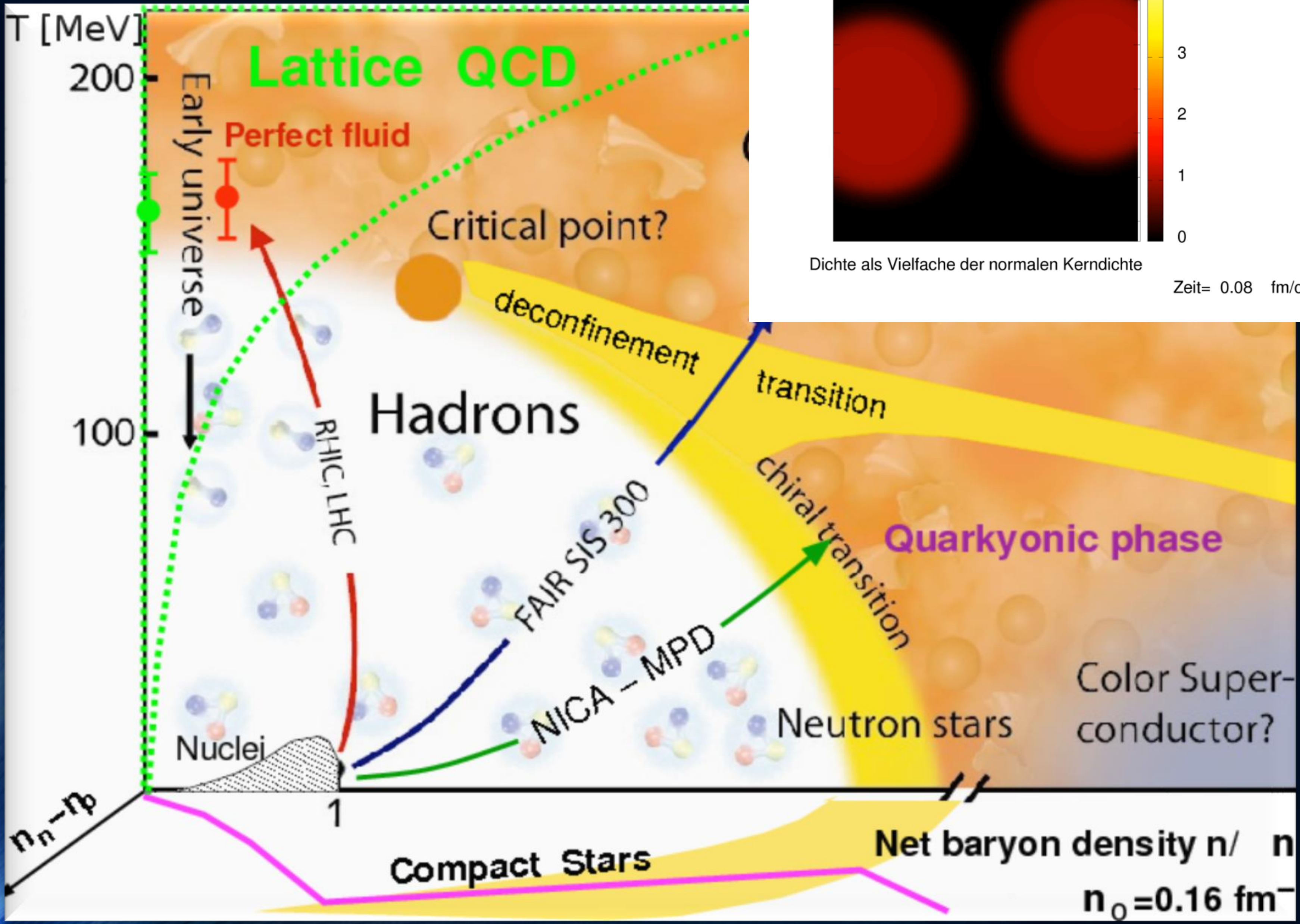


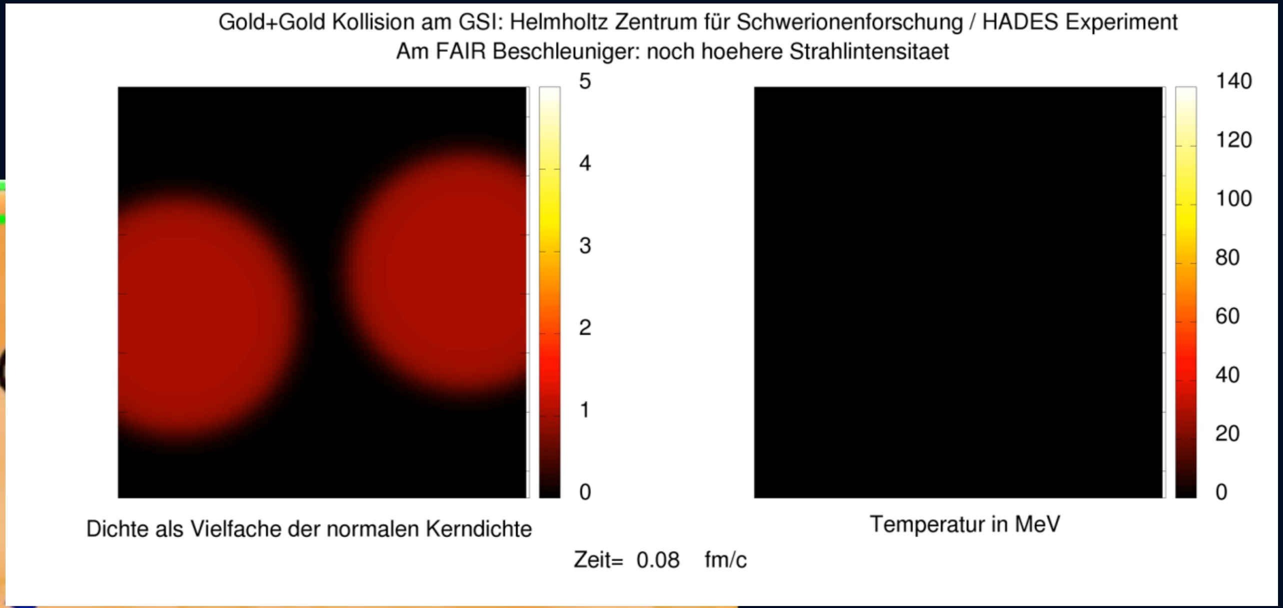
$$R_{\mu\nu} - \frac{1}{2} R\, g_{\mu\nu} = \frac{8\pi G}{c^4}\, T_{\mu\nu}$$

EOS: P (ρ , T)

The Hadron-Quark Phase Transition

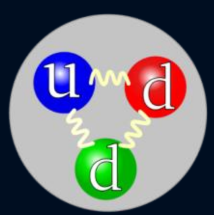
The QCD Phase Diagram



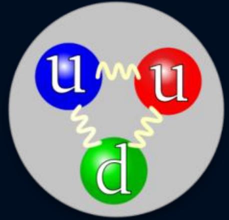


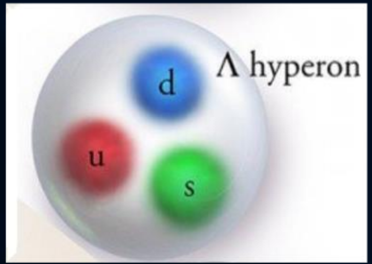
Credits:
Jan Steinheimer

Neutron

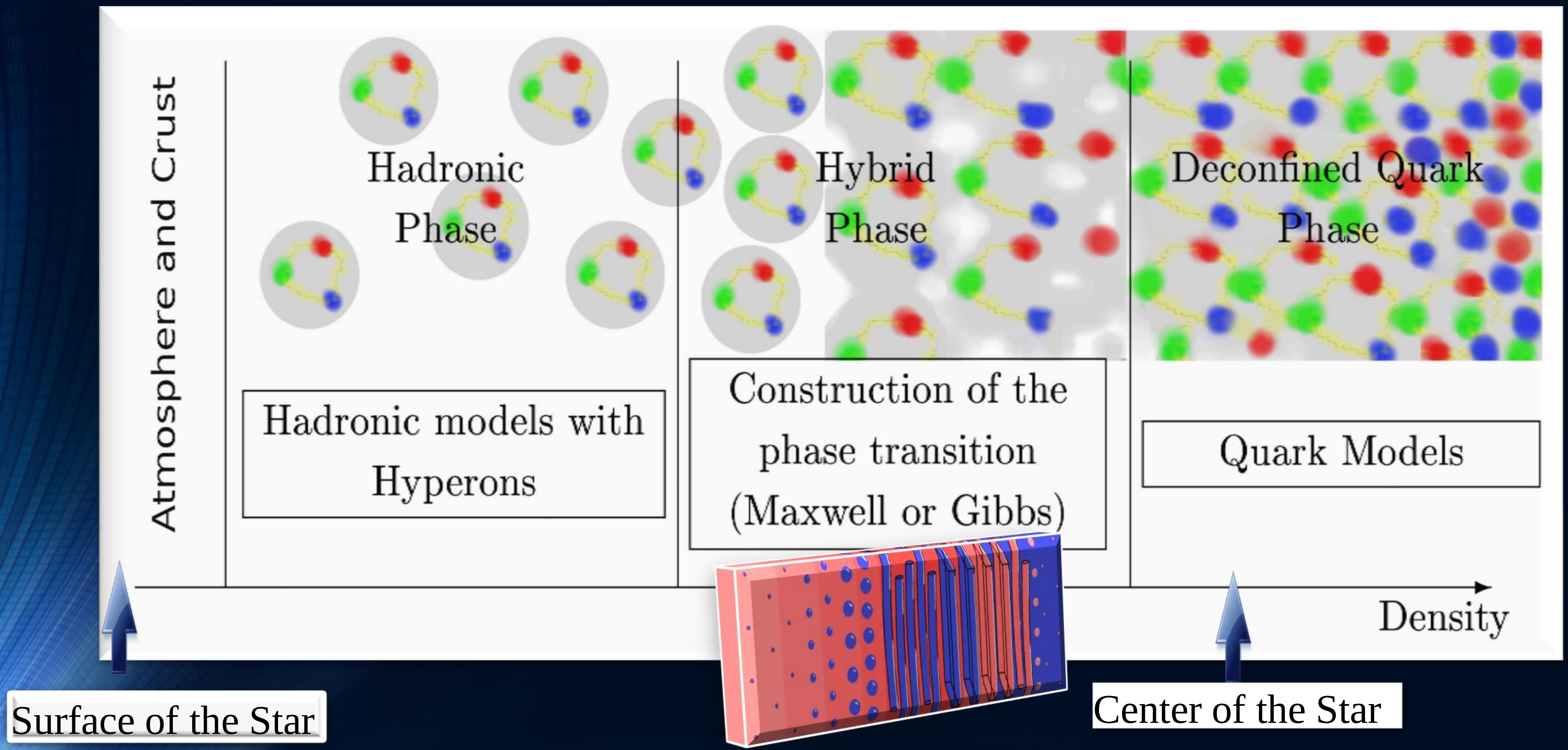


Proton



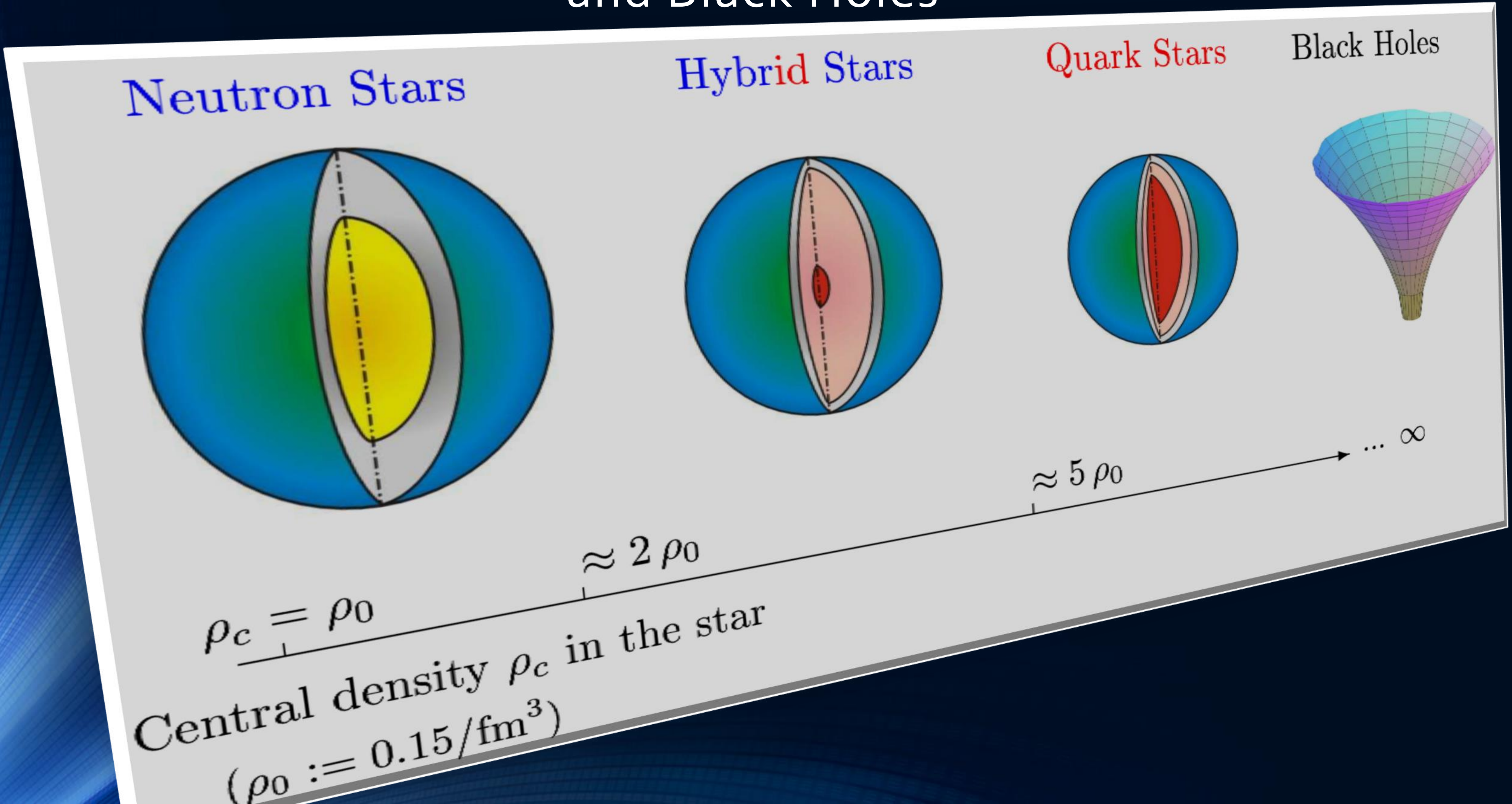


The QCD – Phase Transition and the Interior of a Hybrid Star



Matthias Hanauske; Doctoral Thesis:
Properties of Compact Stars within QCD-motivated Models; University Library Publication Frankfurt (2004)

Neutron Stars, Hybrid Stars, Quark Stars and Black Holes

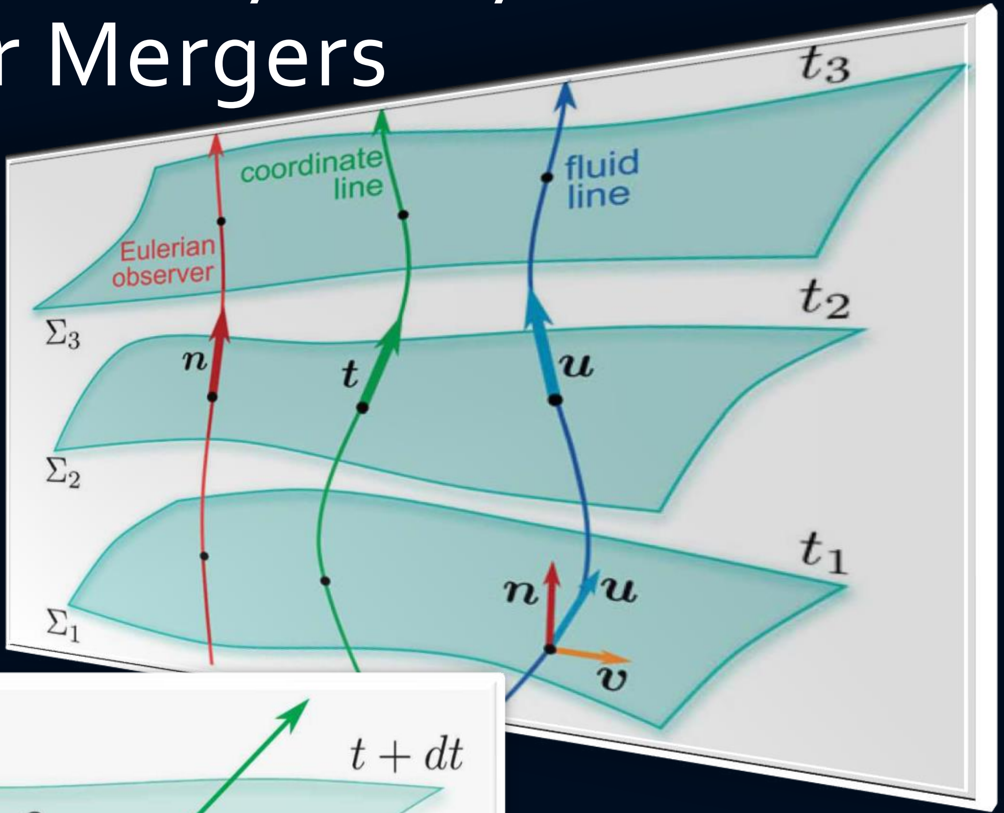


Numerical Relativity and Relativistic Hydrodynamics of Binary Neutron Star Mergers

Einstein's theory of general relativity and the resulting general relativistic conservation laws for energy-momentum in connection with the rest-mass conservation are the theoretical groundings of neutron star binary mergers:

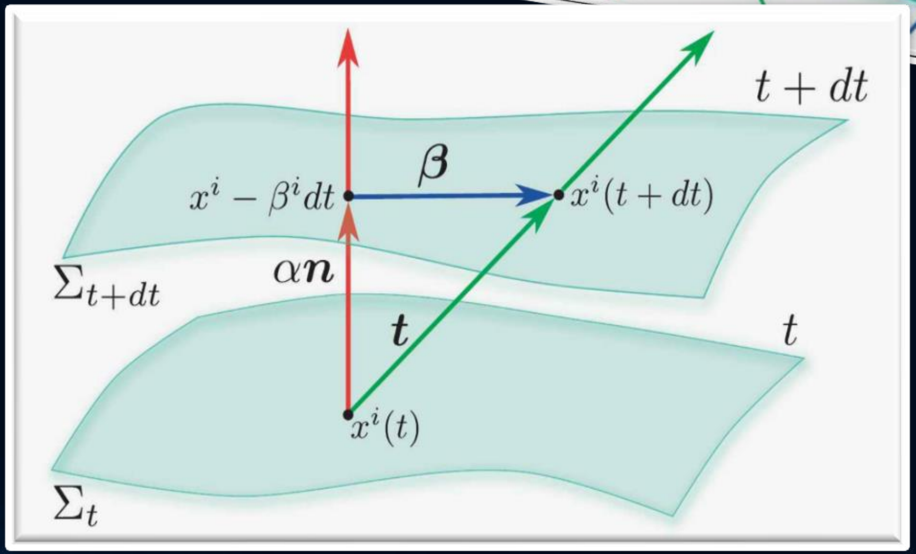
$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = 8\pi T_{\mu\nu}$$

$$\nabla_\mu (\rho u^\mu) = 0\,, \qquad \nabla_\nu T^{\mu\nu} = 0\,.$$



(3+1) decomposition of spacetime

$$g_{\mu\nu} = \begin{pmatrix} -\alpha^2 + \beta_i \beta^i & \beta_i \\ \beta_i & \gamma_{ij} \end{pmatrix}$$



$$d\tau^2 = \alpha^2 (t, x^j) dt^2$$

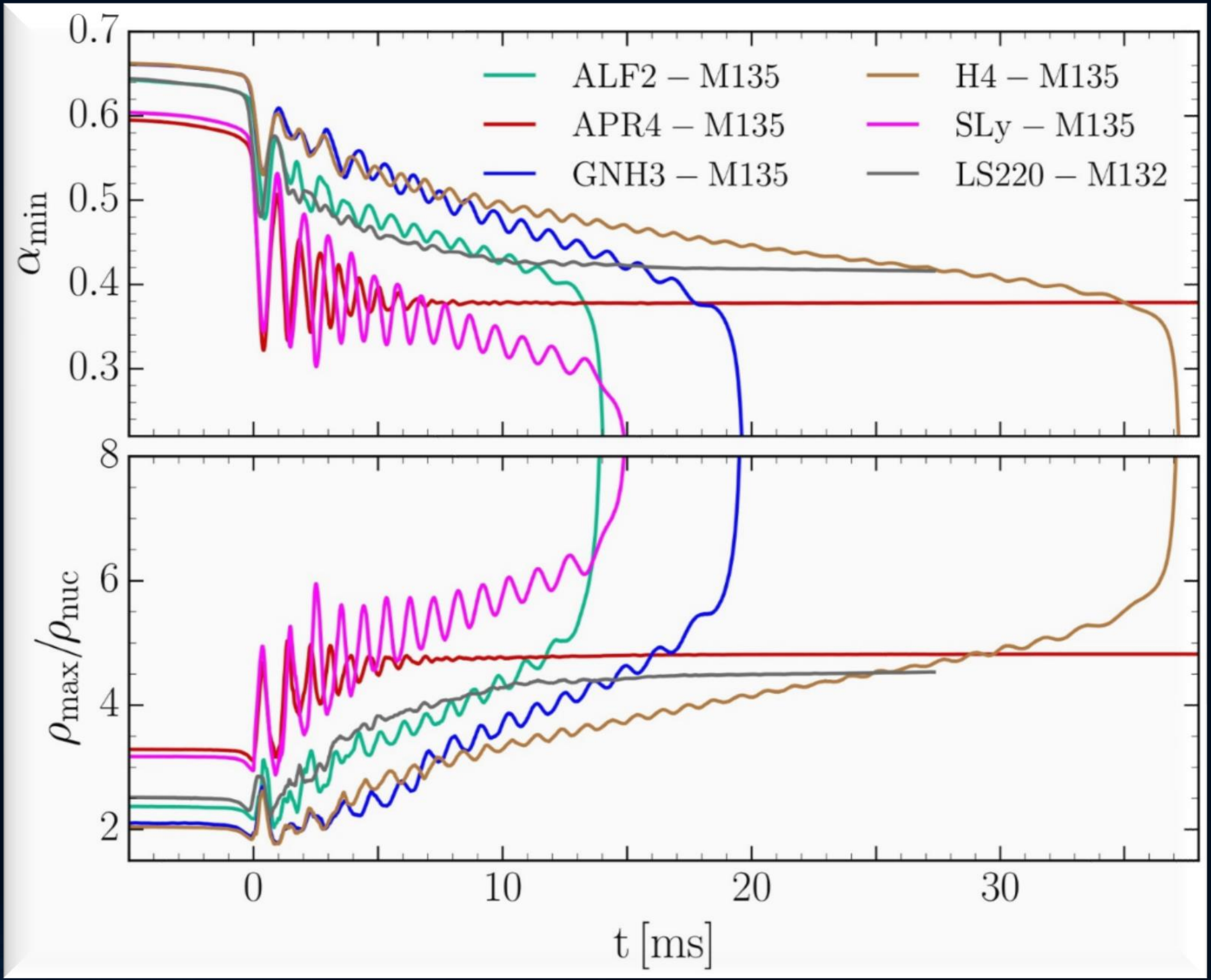
$$x^i_{t+dt} = x^i_t - \beta^i (t, x^j) dt$$

All figures and equations from: Luciano Rezzolla, Olindo Zanotti: Relativistic Hydrodynamics, Oxford Univ. Press, Oxford (2013)

Binary Merger of two Neutron Stars for different EoSs

High mass simulations
(M=1.35 Msolar)

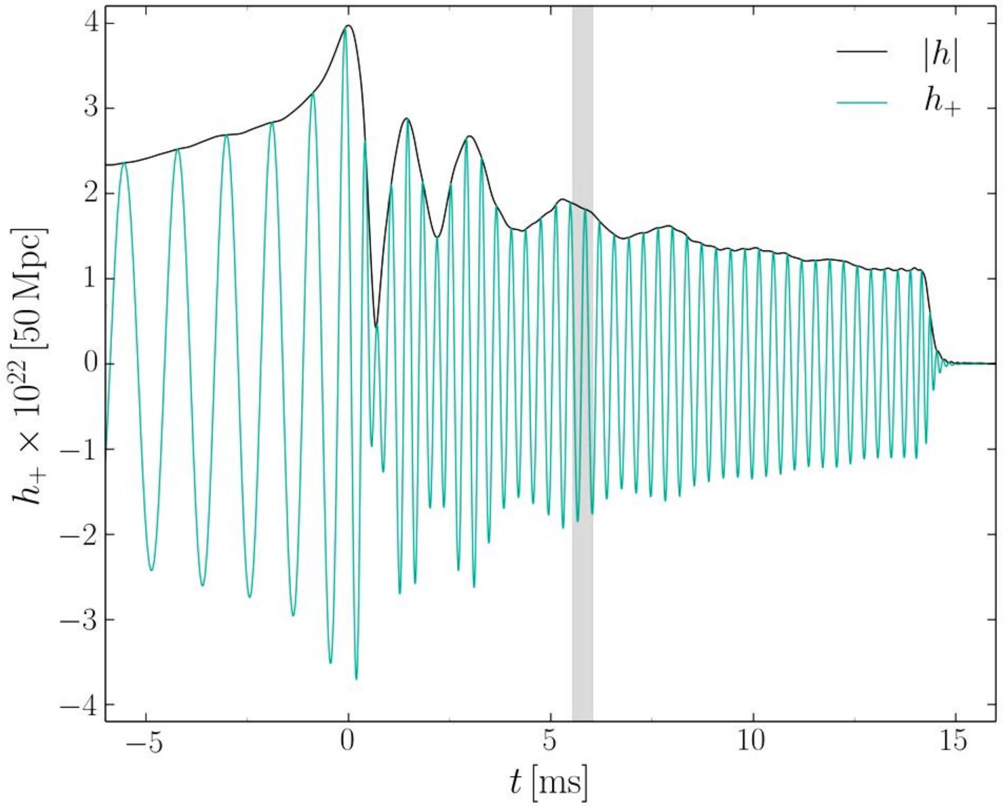
Central value of the lapse function α_c (upper panel) and maximum of the rest mass density ρ_{max} in units of ρ_0 (lower panel) versus time for the high mass simulations.



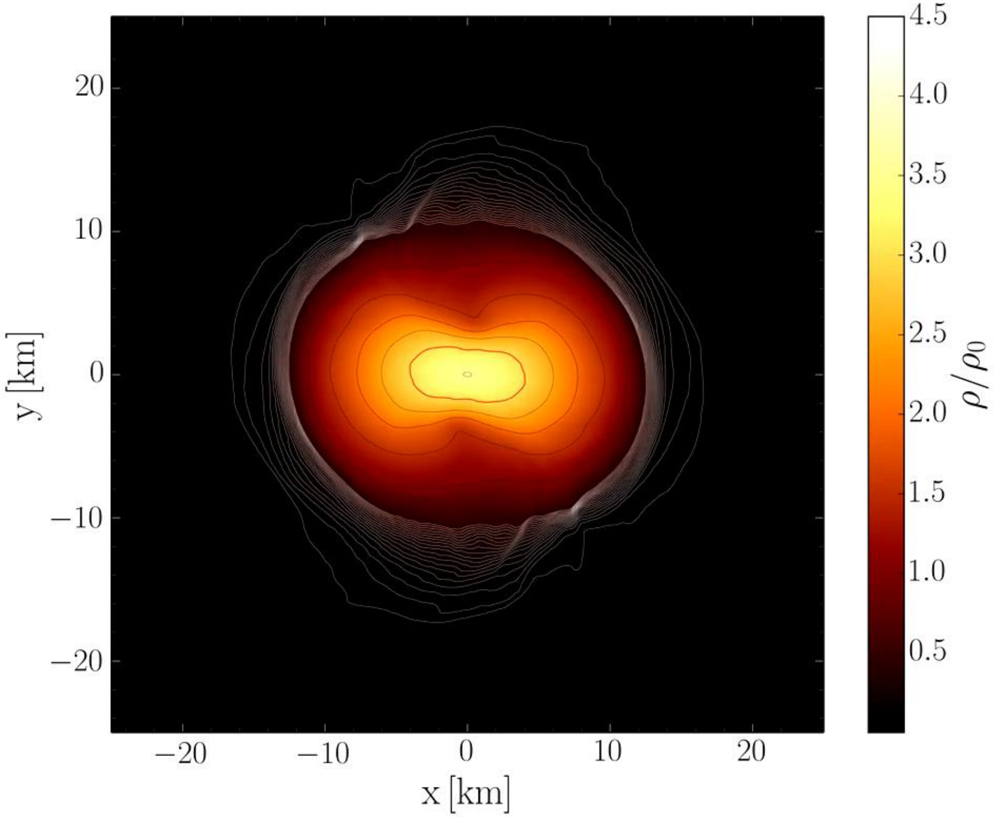
Hanauske, et.al. PRD, 96(4), 043004 (2017)

Evolution of the density in the post merger phase

ALF2-EOS: Mixed phase region starts at $3\rho_0$ (see red curve), initial NS mass: 1.35 M_{solar}

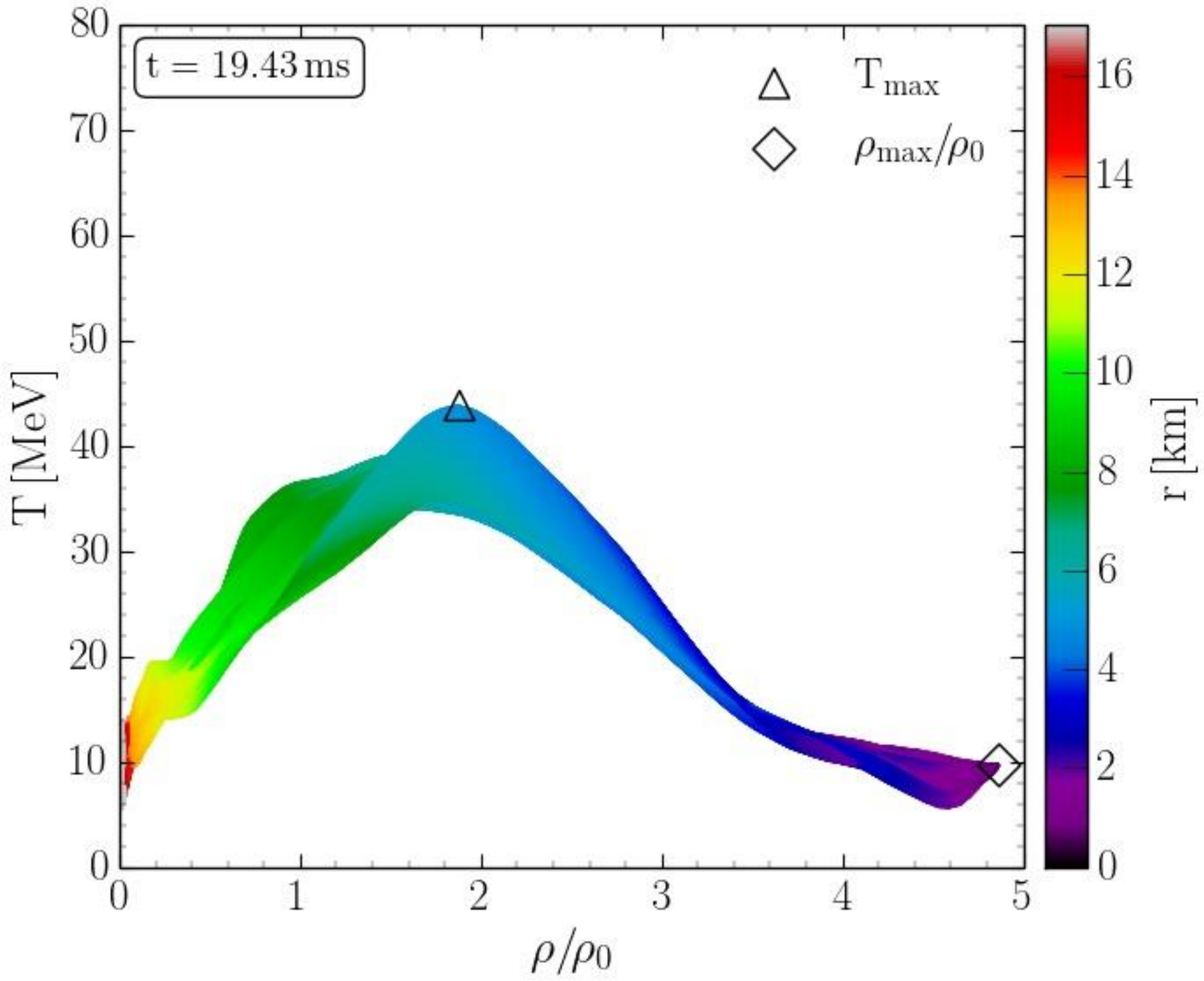


Gravitational wave amplitude
at a distance of 50 Mpc



Rest mass density distribution ρ(x,y)
in the equatorial plane
in units of the nuclear matter density ρ_0

Hypermassive Neutron Stars in the QCD Phase Diagram

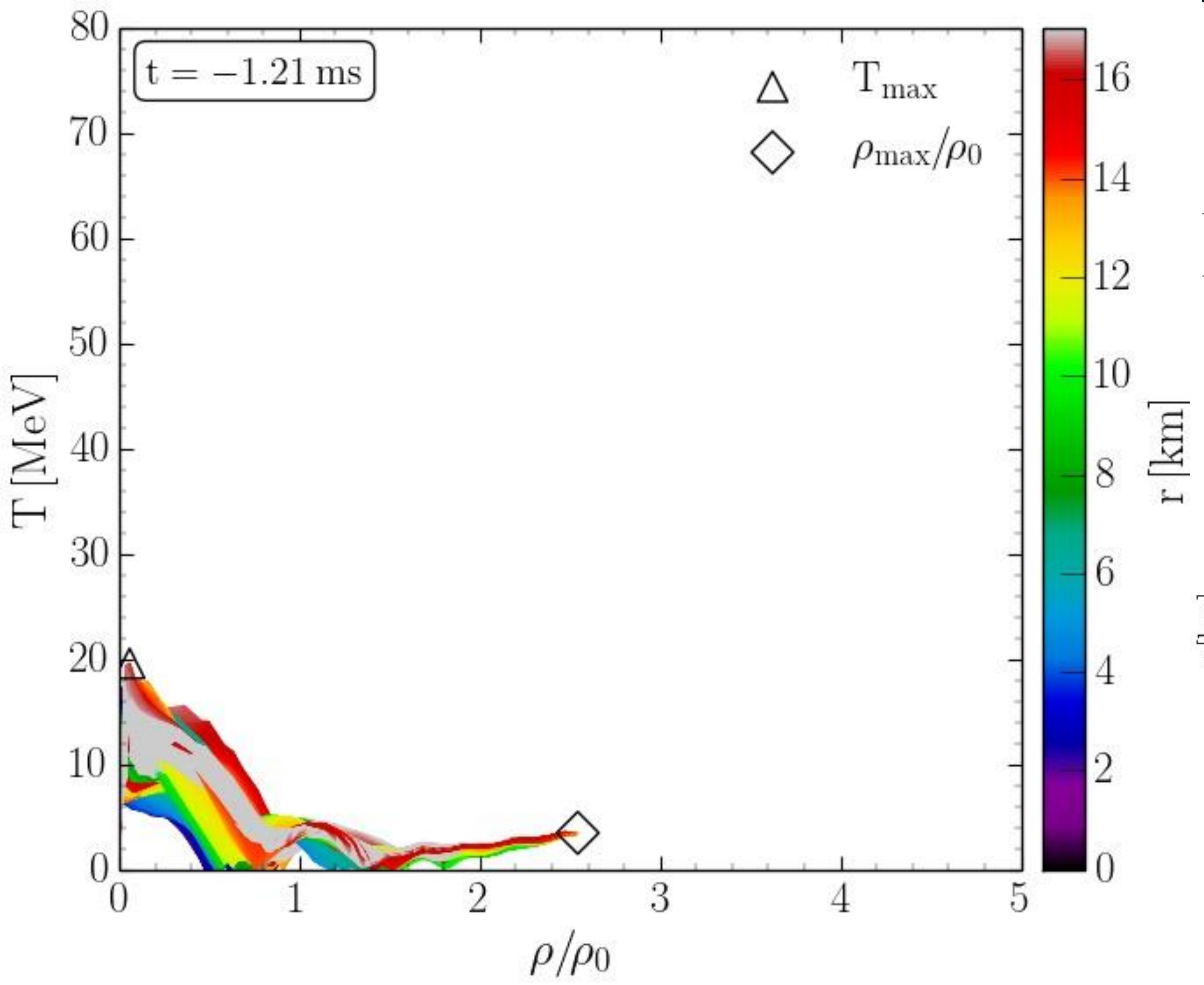


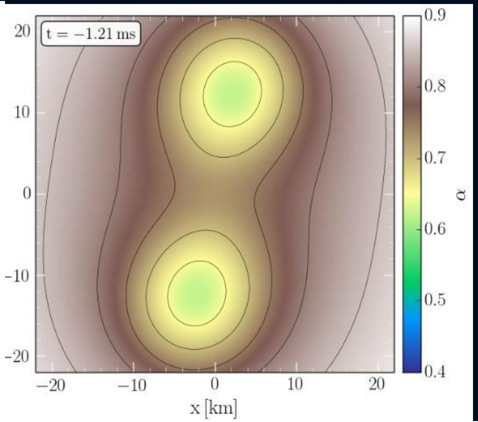
Density-temperature profiles inside the inner area of a hypermassive neutron star simulated within the LS220 EOS with a total mass of M_{total}=2.7 M_{solar} in the style of a (T-ρ) QCD phase diagram plot at t=19.43 ms after the merger.

The color-coding indicate the radial position r of the corresponding (T- ρ) fluid element measured from the origin of the simulation (x , y) = (0 , 0) on the equatorial plane at z = 0.

The open triangle marks the maximum value of the temperature while the open diamond indicates the maximum of the density.

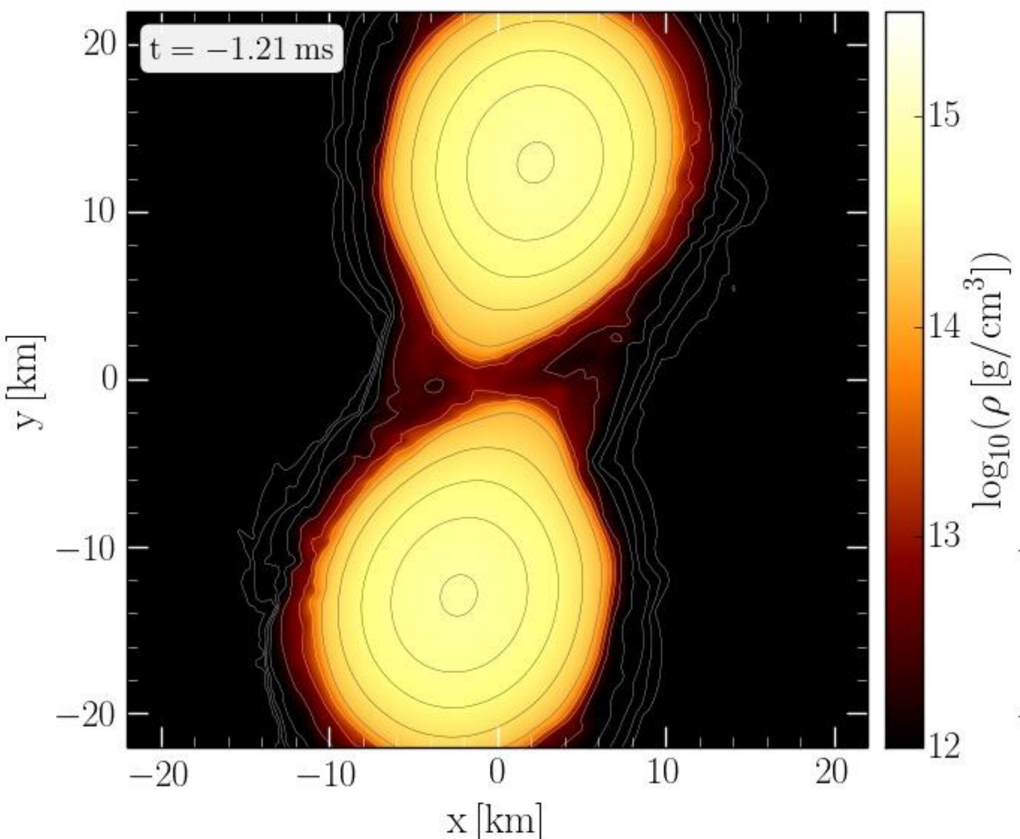
QCD Phase Diagram: The Late Inspiral Phase



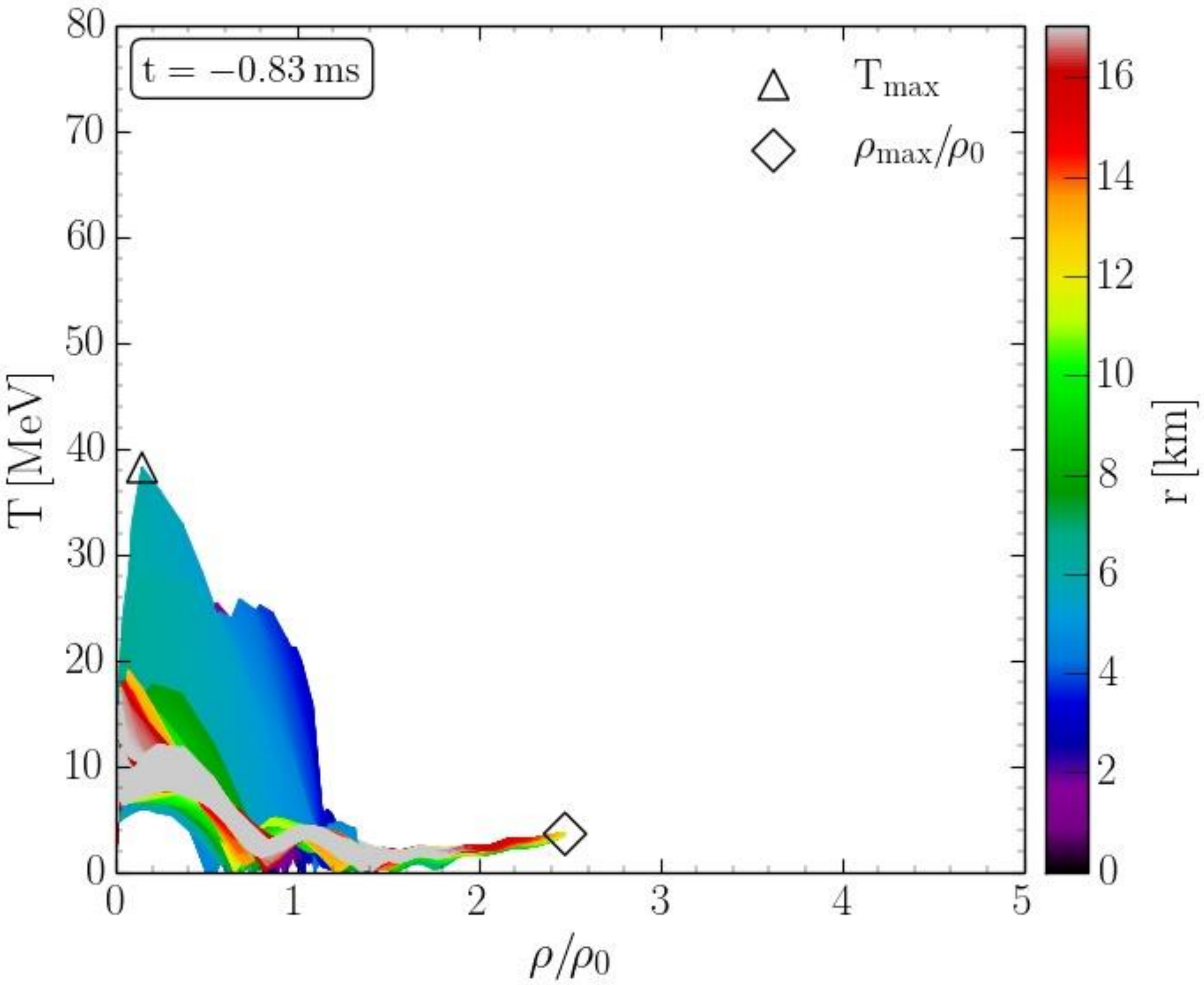


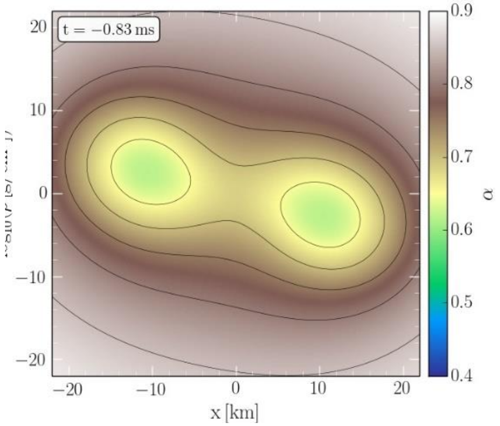
Lapse function α (left)

rest mass density ρ



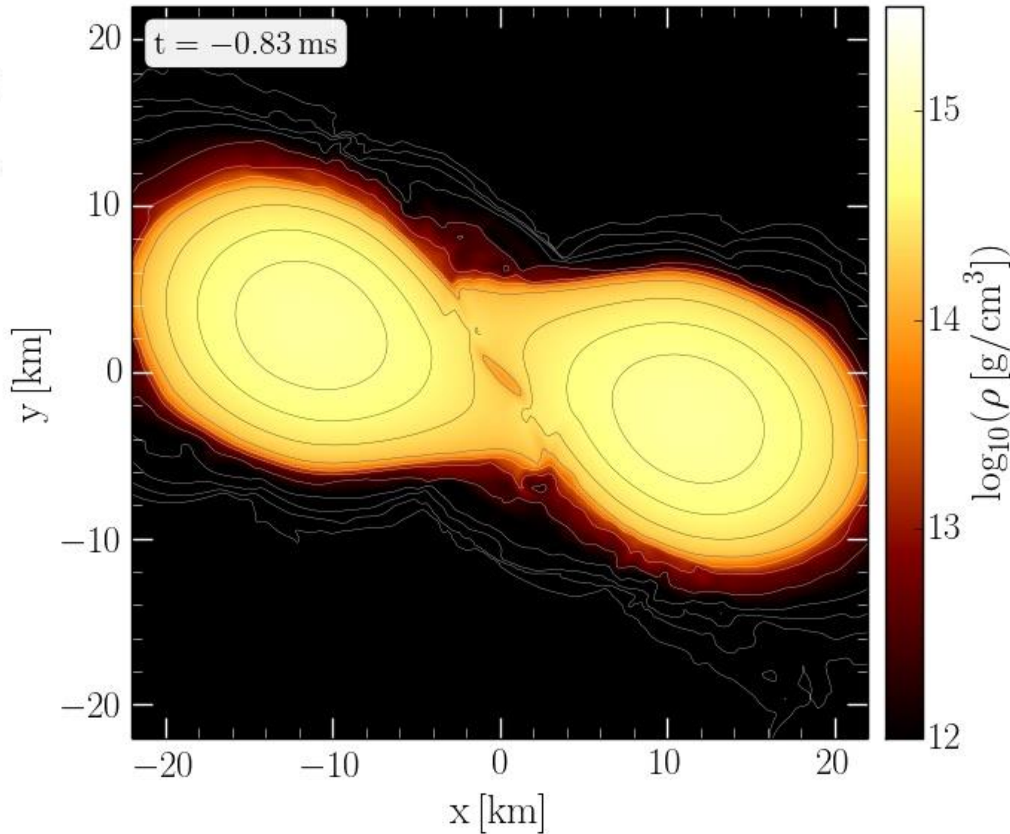
QCD Phase Diagram: The Late Inspiral Phase



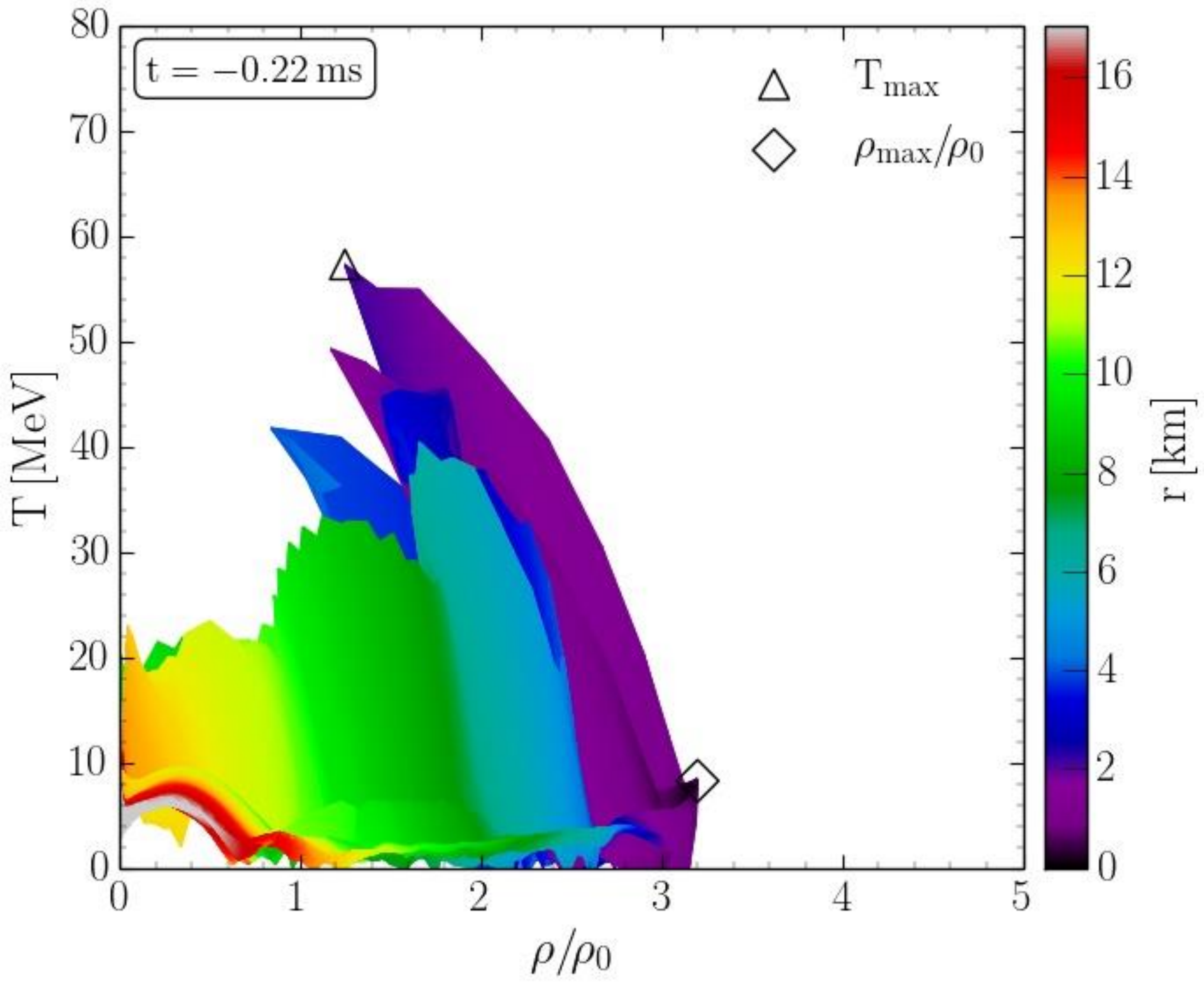


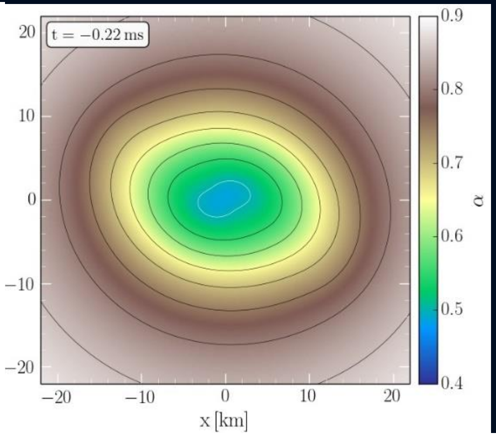
Lapse function α (left)

rest mass density ρ



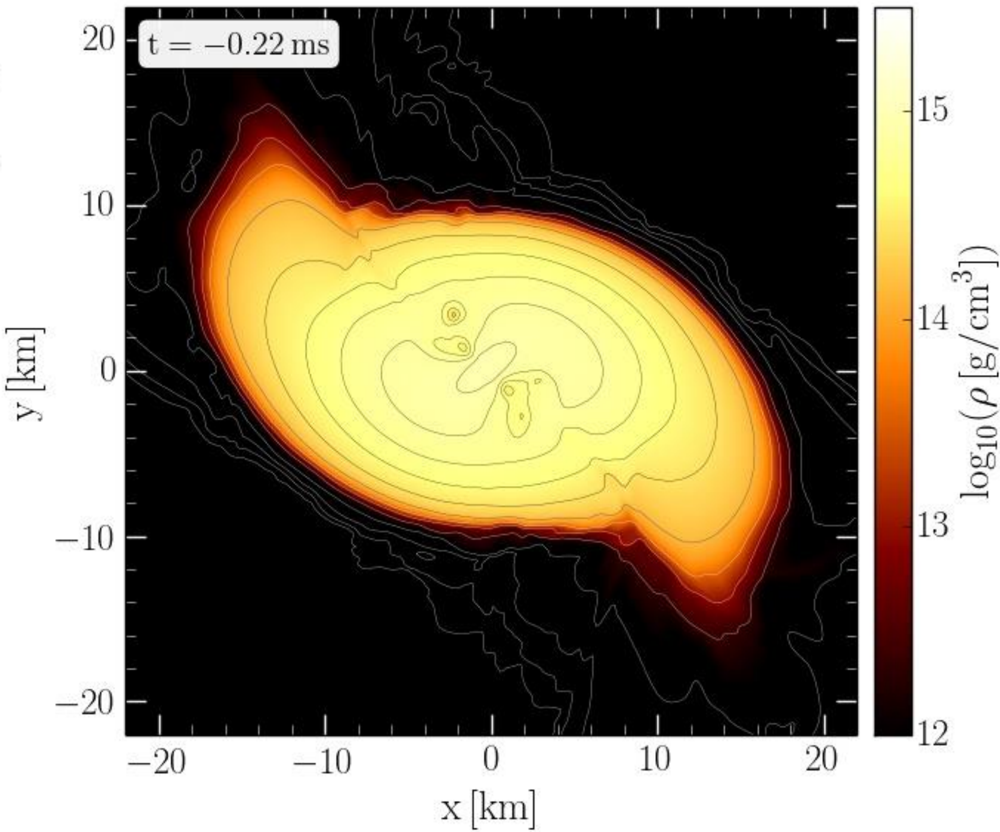
QCD Phase Diagram: The Late Inspiral Phase



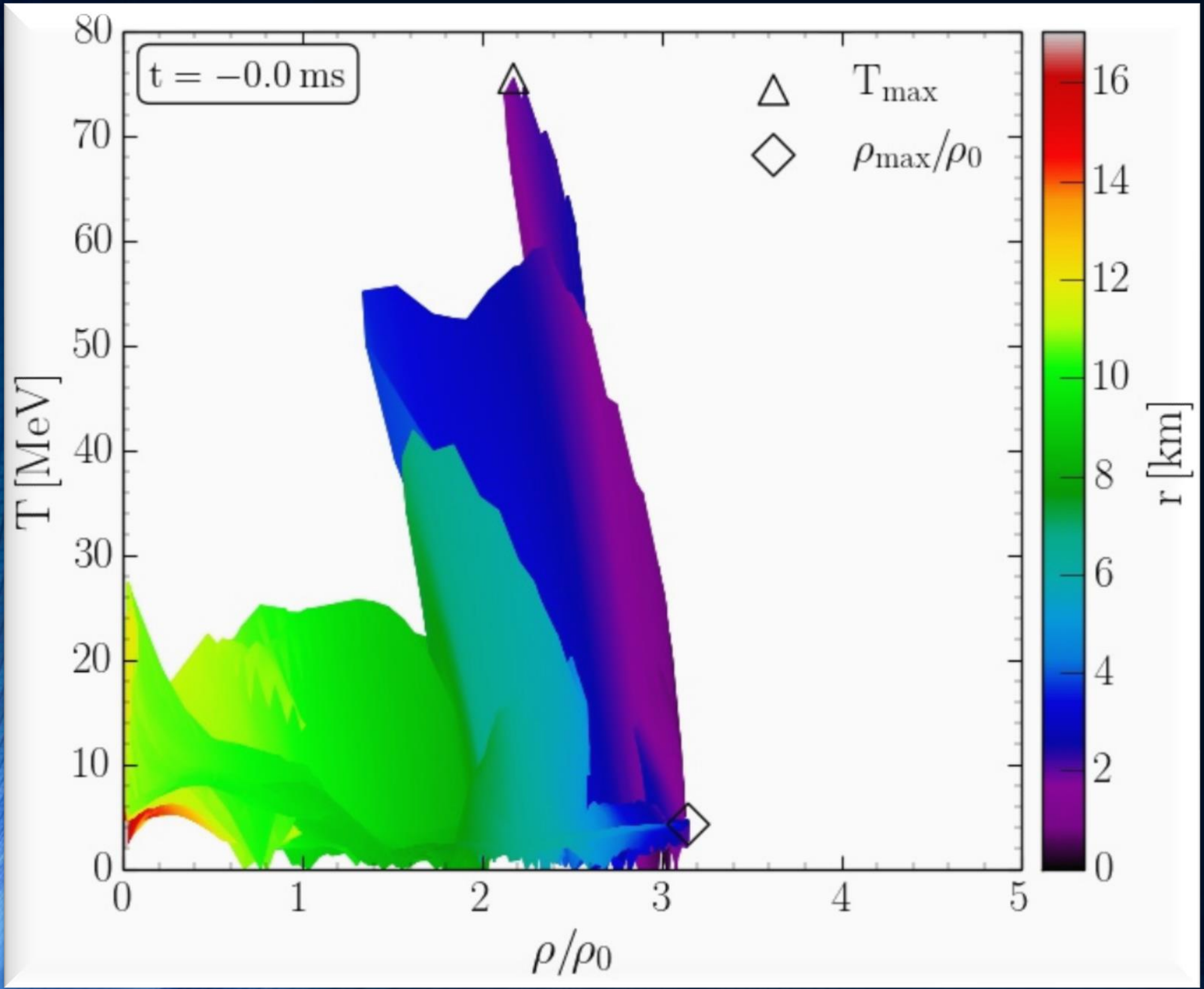


Lapse function α (left)

rest mass density ρ



Binary Neutron Star Mergers in the QCD Phase Diagram

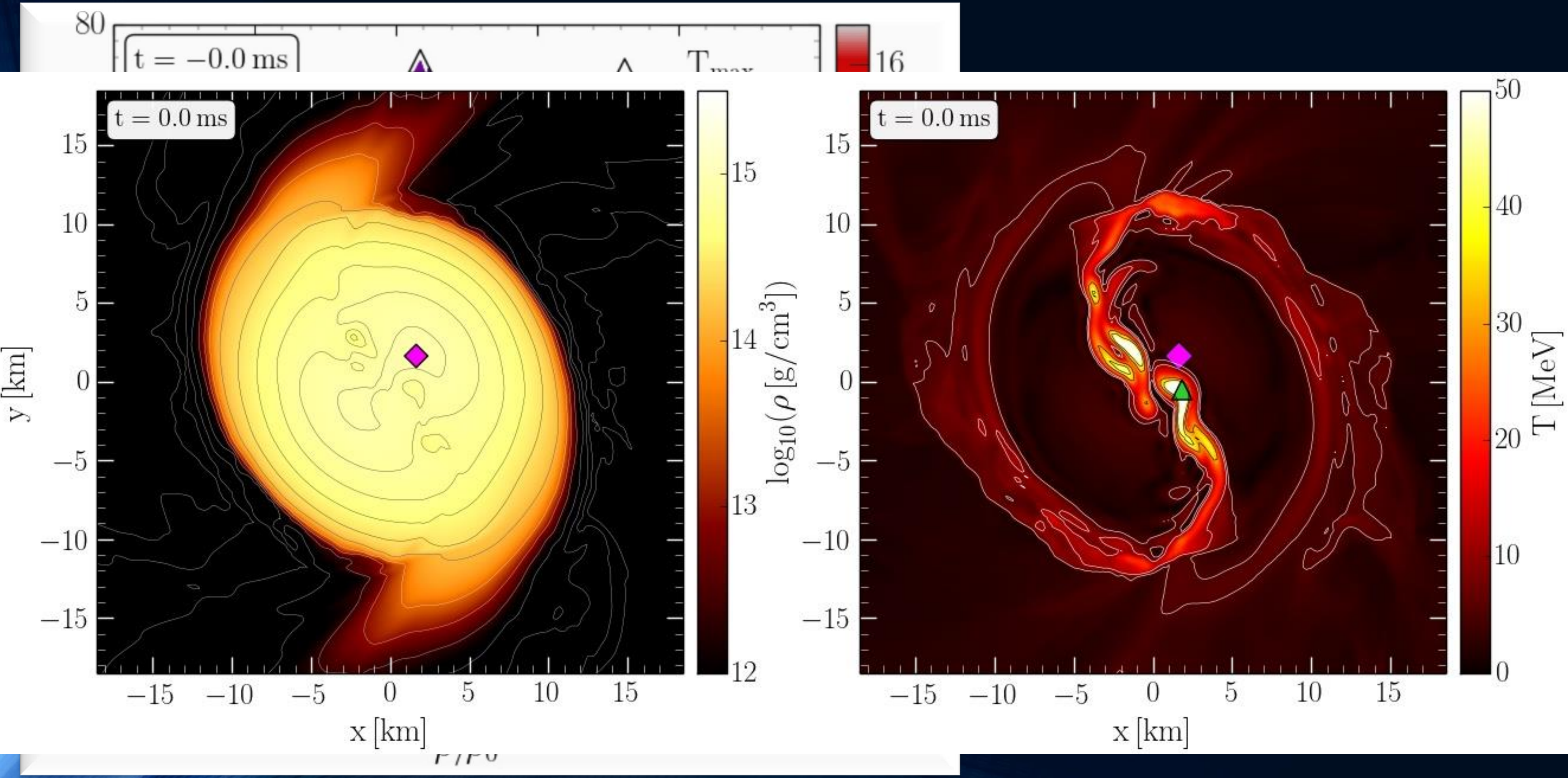


Density-temperature profiles inside the inner area of the LS220-M135 simulation in the style of a (T- ρ) QCD phase diagram plot at merger time (t=0 ms).

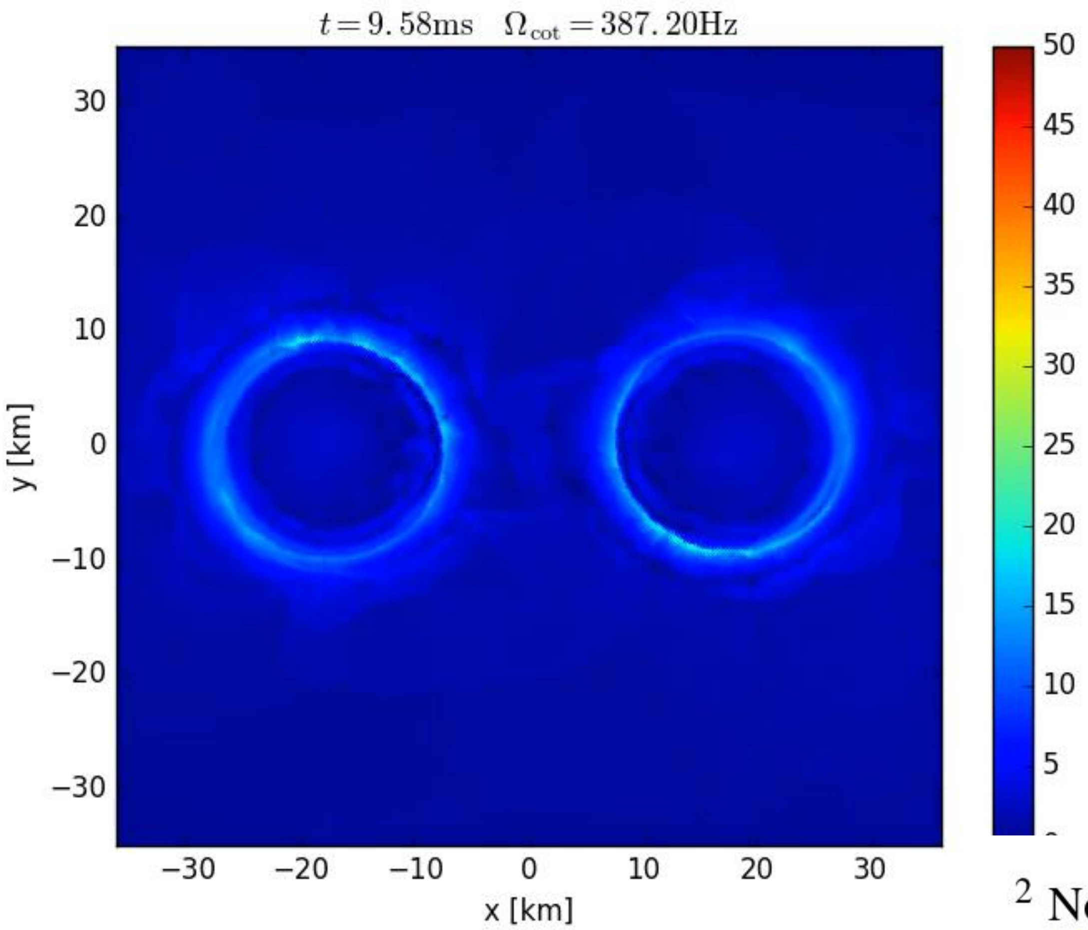
The color-coding indicate the radial position r of the corresponding (T- ρ) fluid element measured from the origin of the simulation (x,y) = (0,0) on the equatorial plane (z = 0).

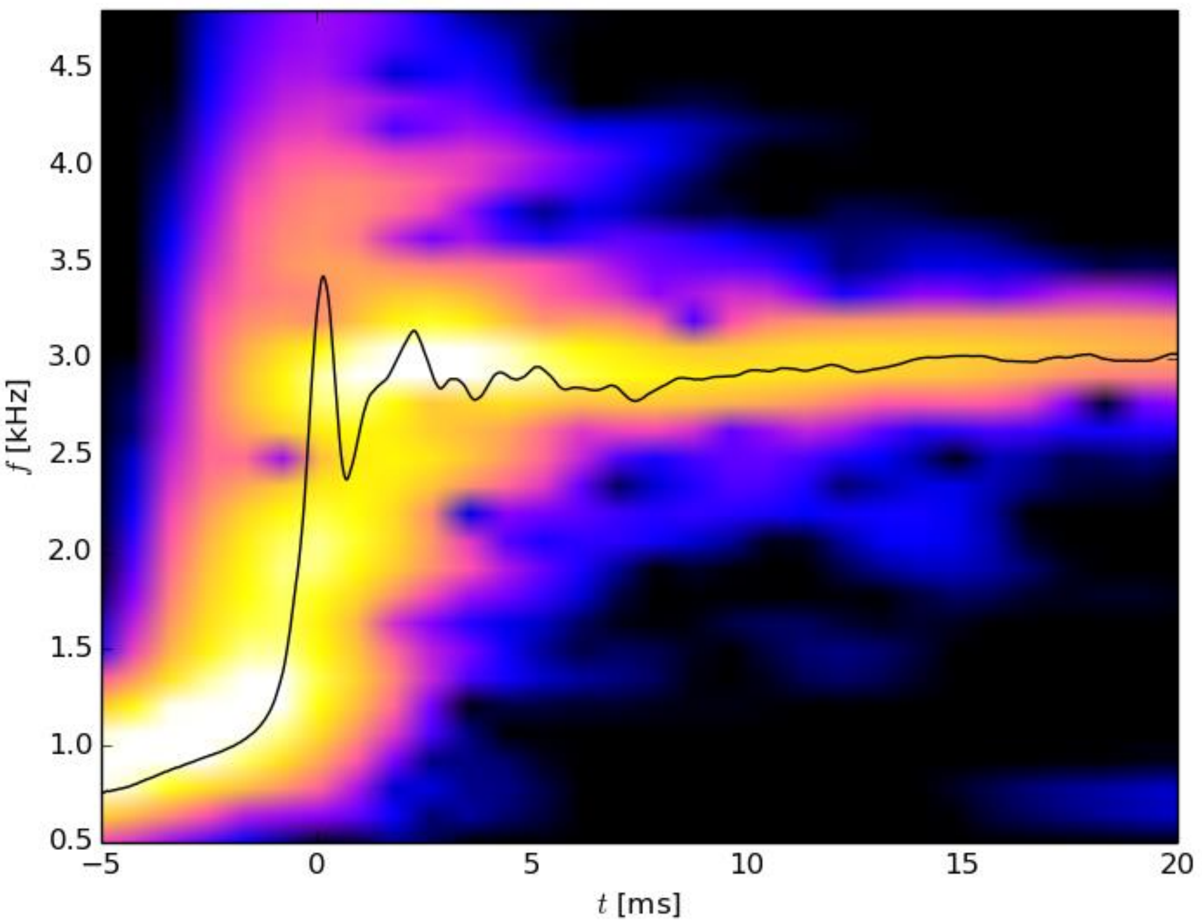
The open triangle marks the maximum value of the temperature while the open diamond indicates the maximum of the density.

Binary Neutron Star Mergers in the QCD Phase Diagram



The Co-Rotating Frame

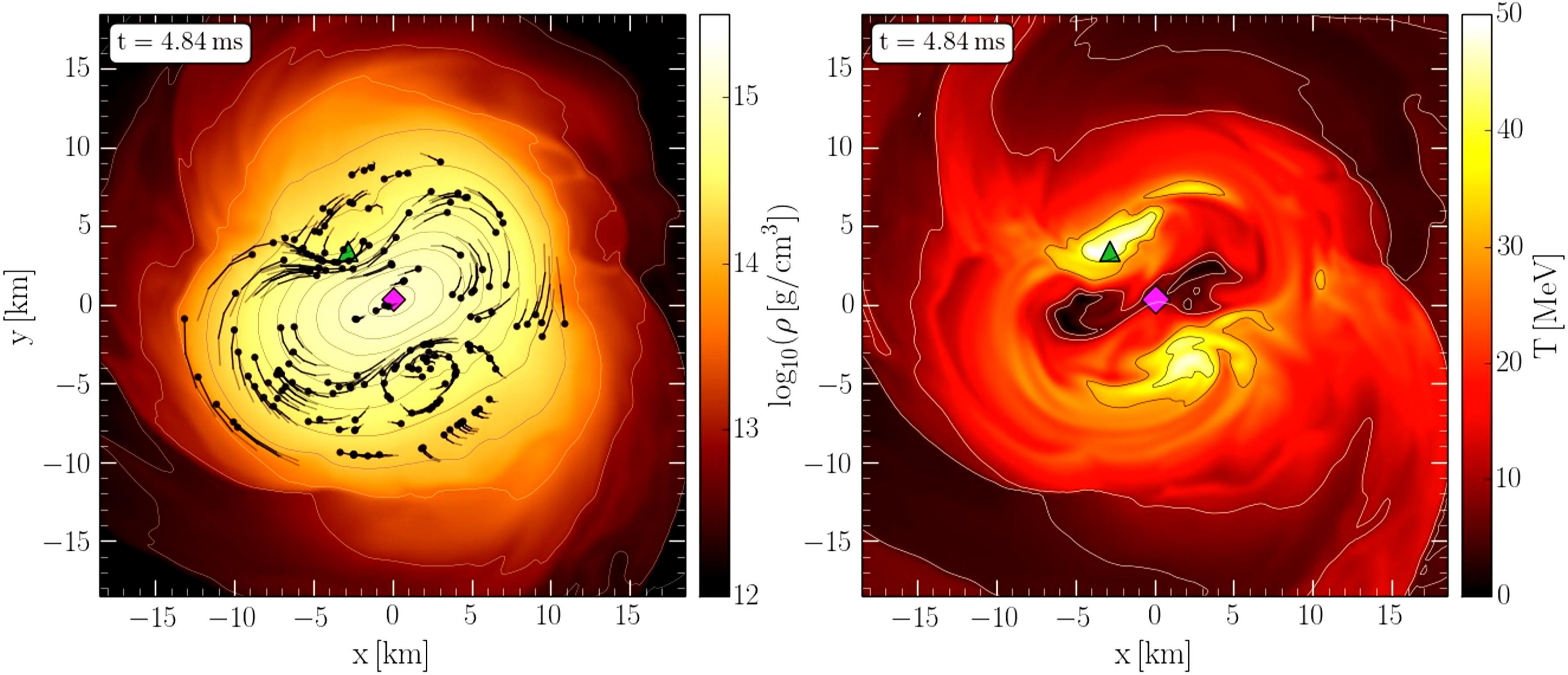




[2] Note that the angular-velocity distribution in the lower central panel of Fig. 10 refers to the corotating frame and that this frame is rotating at half the angular frequency of the emitted gravitational waves, Ω_{GW}. Because the maximum of the angular velocity Ω_{max} is of the order of $\Omega_{GW}/2$ (cf. left panel of Fig. 12), the ring structure in this panel is approximately at zero angular velocity.

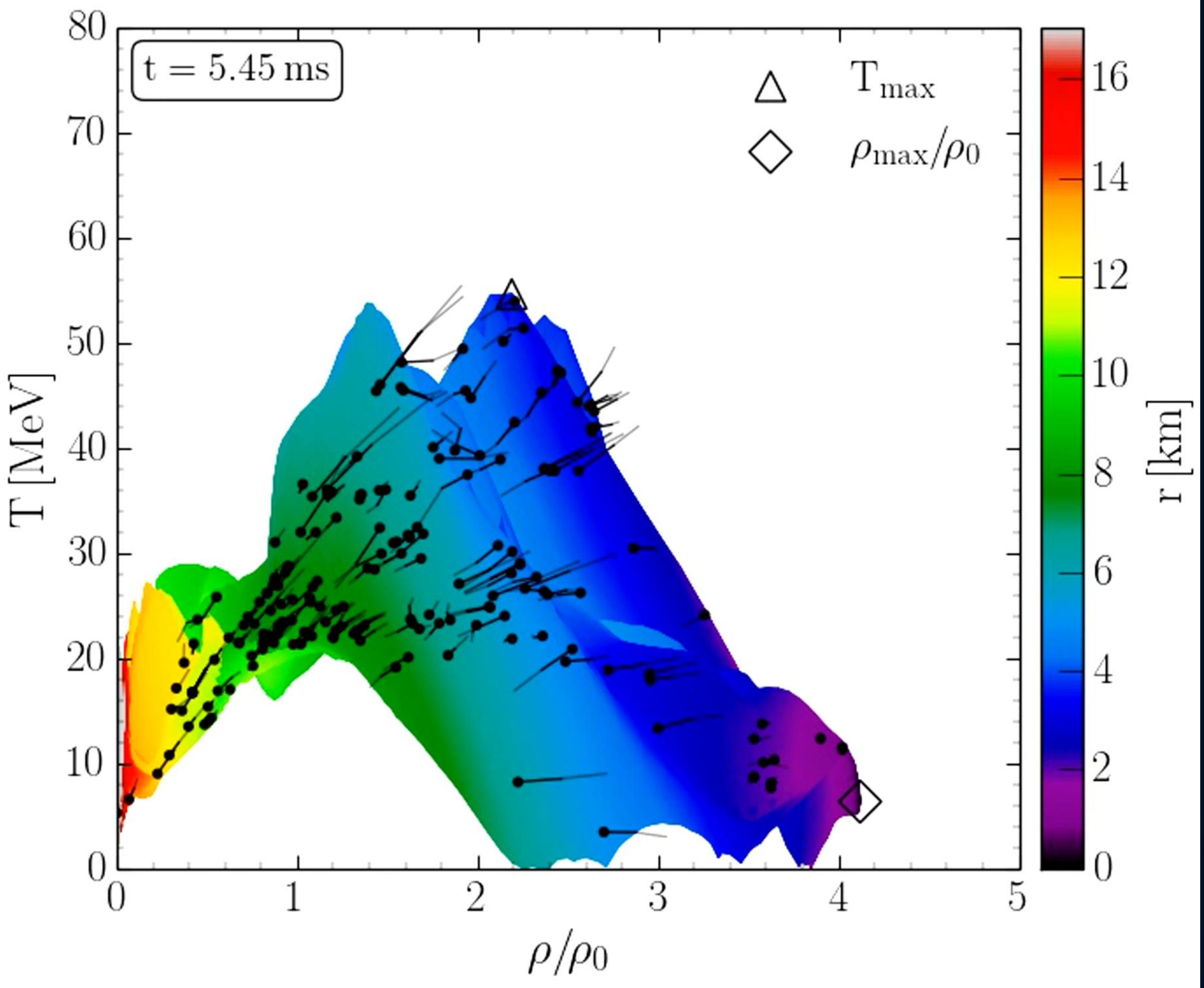
Simulation and movie has been produced by Luke Bovard

Density and Temperature Evolution inside the HMNS



Rest mass density on the equatorial plane

Temperature on the equatorial plane



Binary Neutron Star Mergers in the QCD Phase Diagram

Evolution of hot and dense matter inside the inner area of a hypermassive neutron star simulated within the LS220 EOS with a total mass of M_{total}=2.7 M_{solar} in the style of a (T- ρ) QCD phase diagram plot

The color-coding indicate the radial position r of the corresponding (T- ρ) fluid element measured from the origin of the simulation (x , y) = (0 , 0) on the equatorial plane at z = 0.

The open triangle marks the maximum value of the temperature while the open diamond indicates the maximum of the density.

The Angular Velocity in the (3+1)-Split

The angular velocity Ω in the (3+1)-Split is a combination of the lapse function α , the ϕ-component of the shift vector β^{ϕ} and the 3-velocity v^{ϕ} of the fluid (spatial projection of the 4-velocity **u**):

$$\Omega(x,y,z,t) = \frac{u^{\phi}}{u^{t}} = \alpha\, v^{\phi} \; - \; \beta^{\phi}$$

Angular velocity Ω

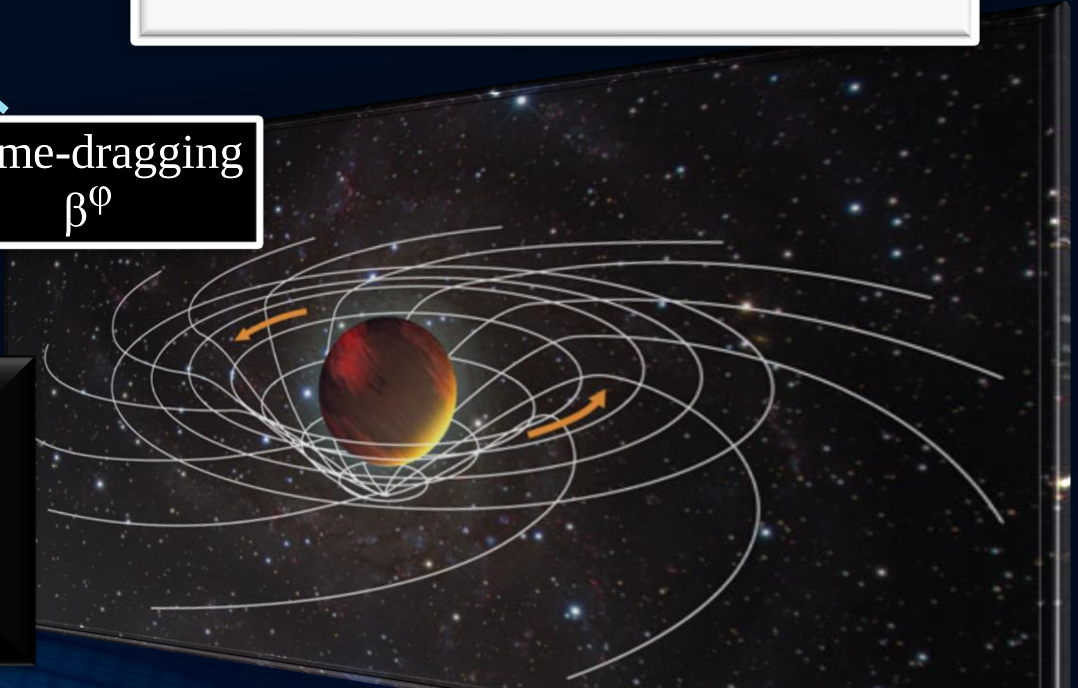
Lapse function α

Φ-component of 3-velocity v^{φ}

Frame-dragging β^{φ}

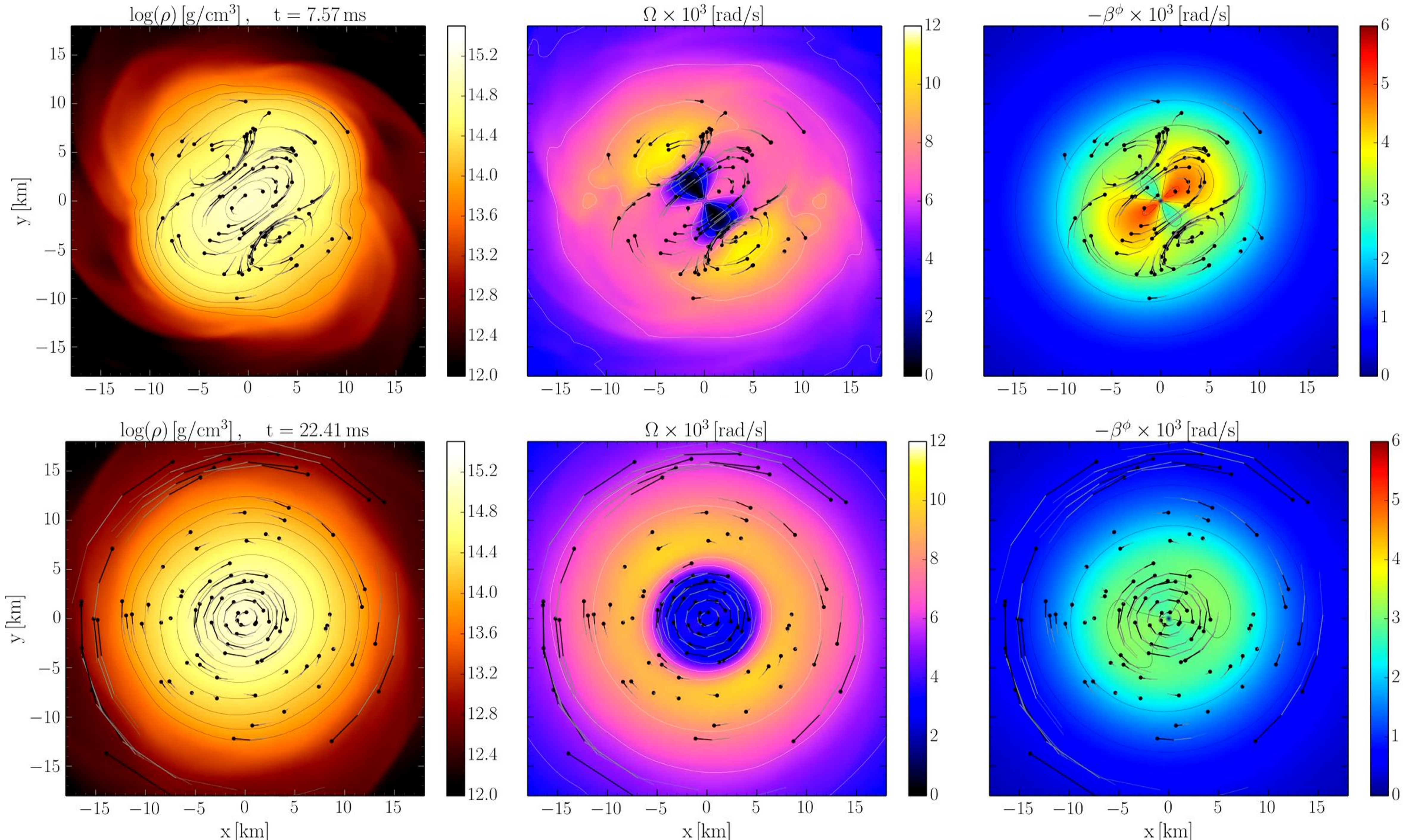
(3+1)-decomposition of spacetime:

$$g_{\mu\nu} = \begin{pmatrix} -\alpha^2 + \beta_i \beta^i & \beta_i \\ \beta_i & \gamma_{ij} \end{pmatrix}$$



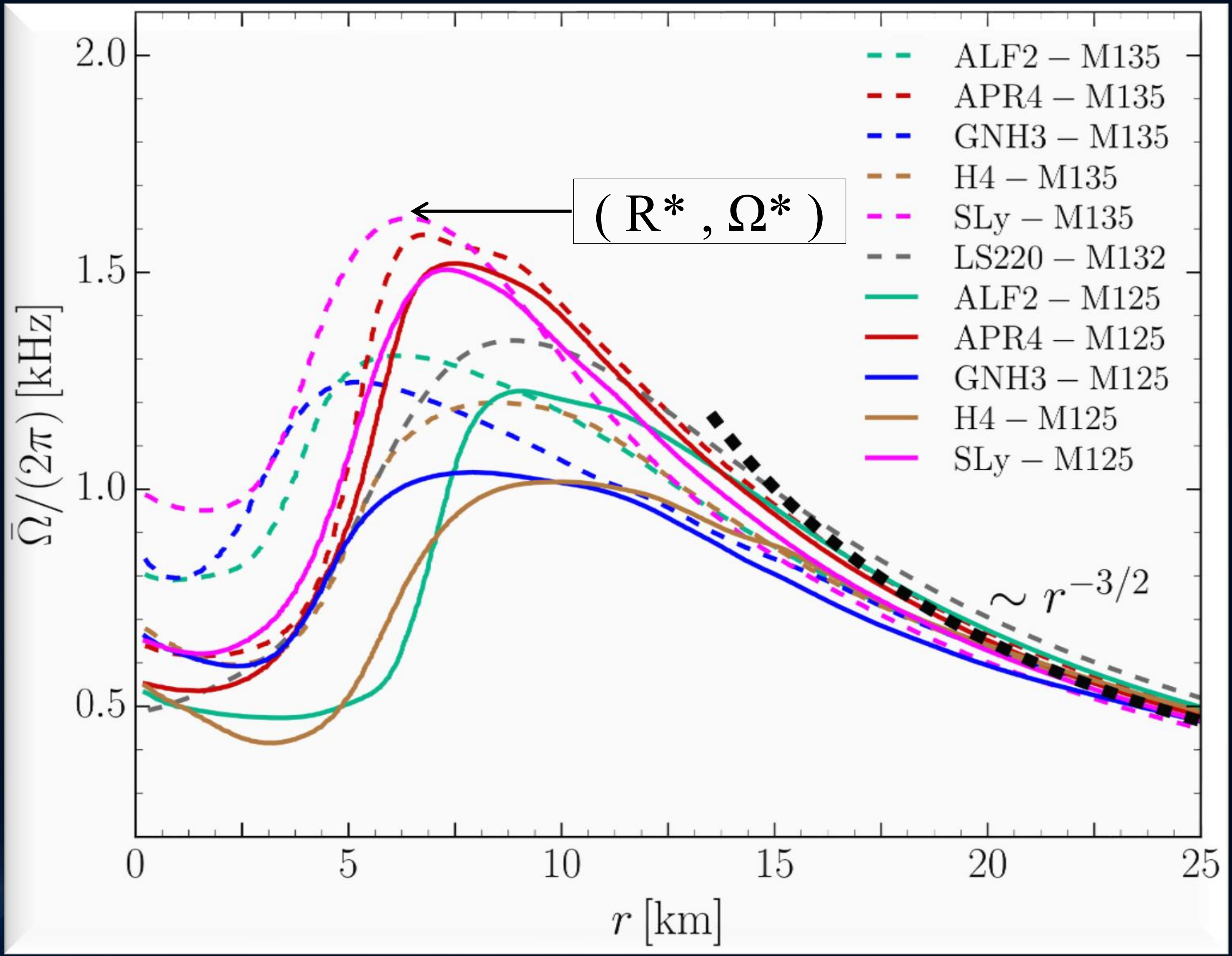
Focus: Inner core of the differentially rotating HMNS

M. Shibata, K. Taniguchi, and K. Uryu, Phys. Rev. D 71, 084021 (2005)
M. Shibata and K. Taniguchi, Phys. Rev. D 73, 064027 (2006)
F. Galeazzi, S. Yoshida and Y. Eriguchi, A&A 541, p. A156 (2012)
W. Kastaun and F. Galeazzi, Phys. Rev. D 91, p. 064027 (2015)



log(ρ) [g/cm³], t = 7.57 ms
Ω × 10³ [rad/s]
−β^φ × 10³ [rad/s]
log(ρ) [g/cm³], t = 22.41 ms
Ω × 10³ [rad/s]
−β^φ × 10³ [rad/s]
y [km]
x [km]

Time-averaged Rotation Profiles of the HMNSs



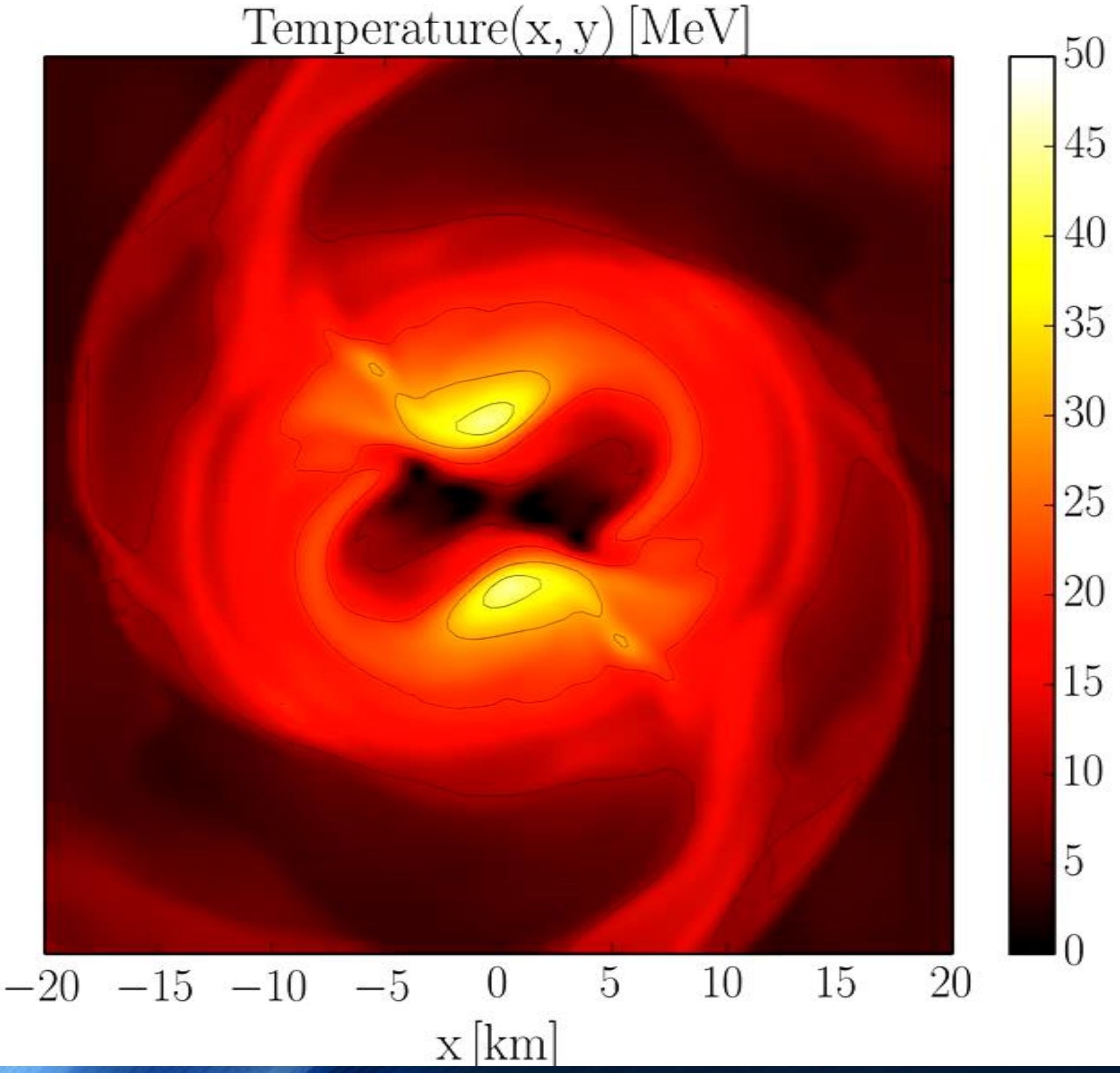
Soft EoSs:
Sly
APR4

Stiff EoSs:
GNH3
H4

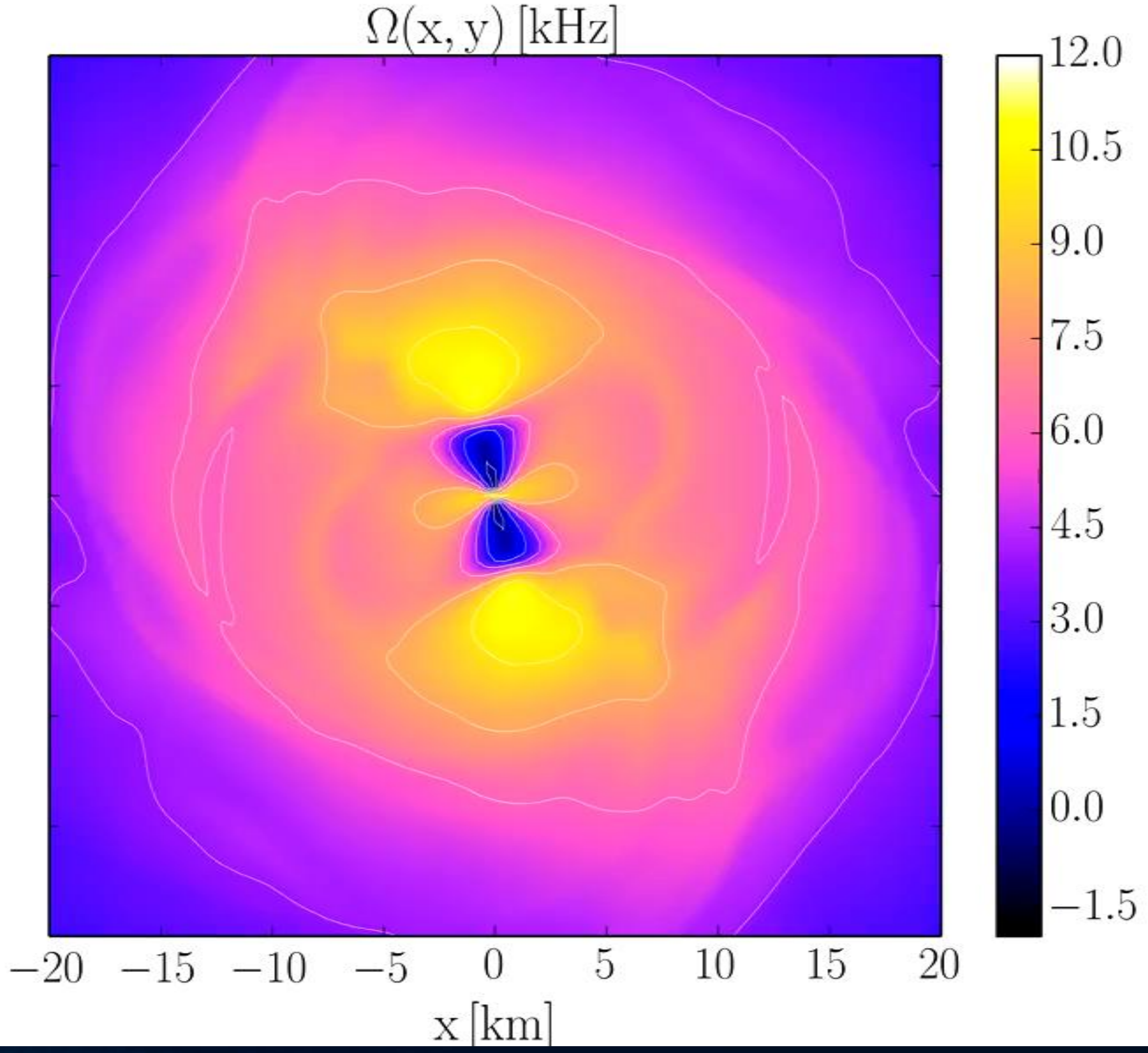
Time-averaged rotation profiles for different EoS
Low mass runs (solid curves), high mass runs (dashed curves).

Hanauske, et.al. PRD, 96(4), 043004 (2017)

Temperature



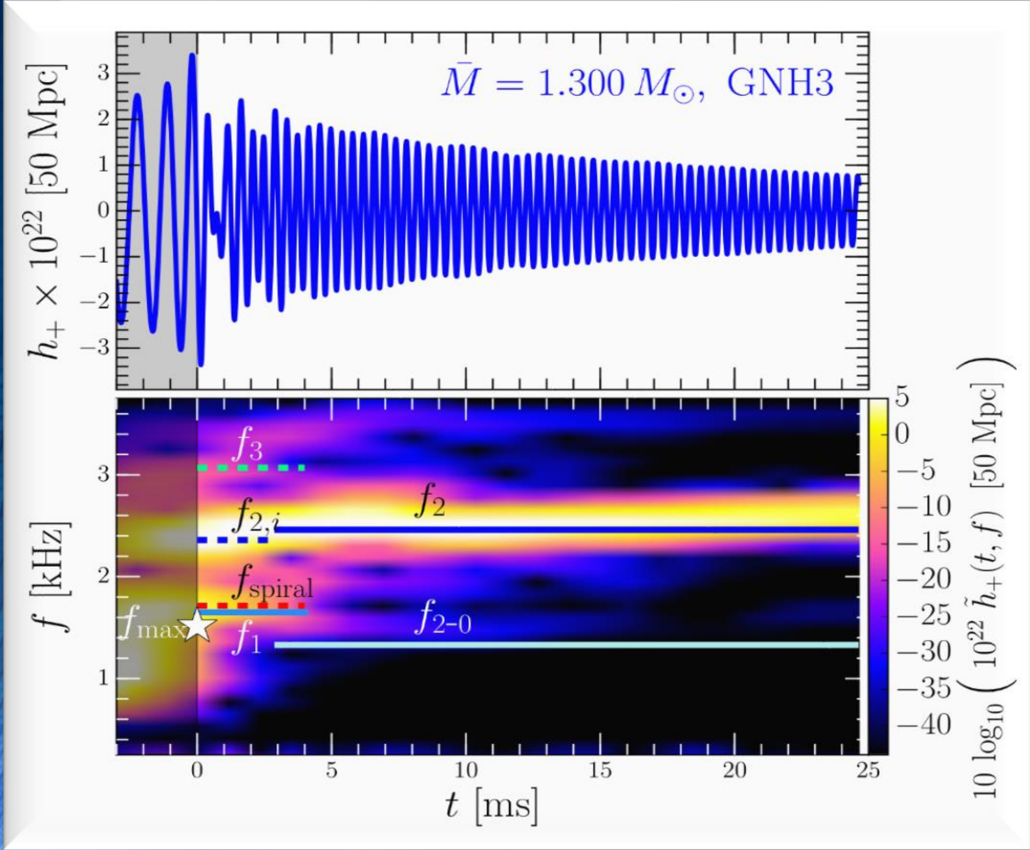
Angular Velocity



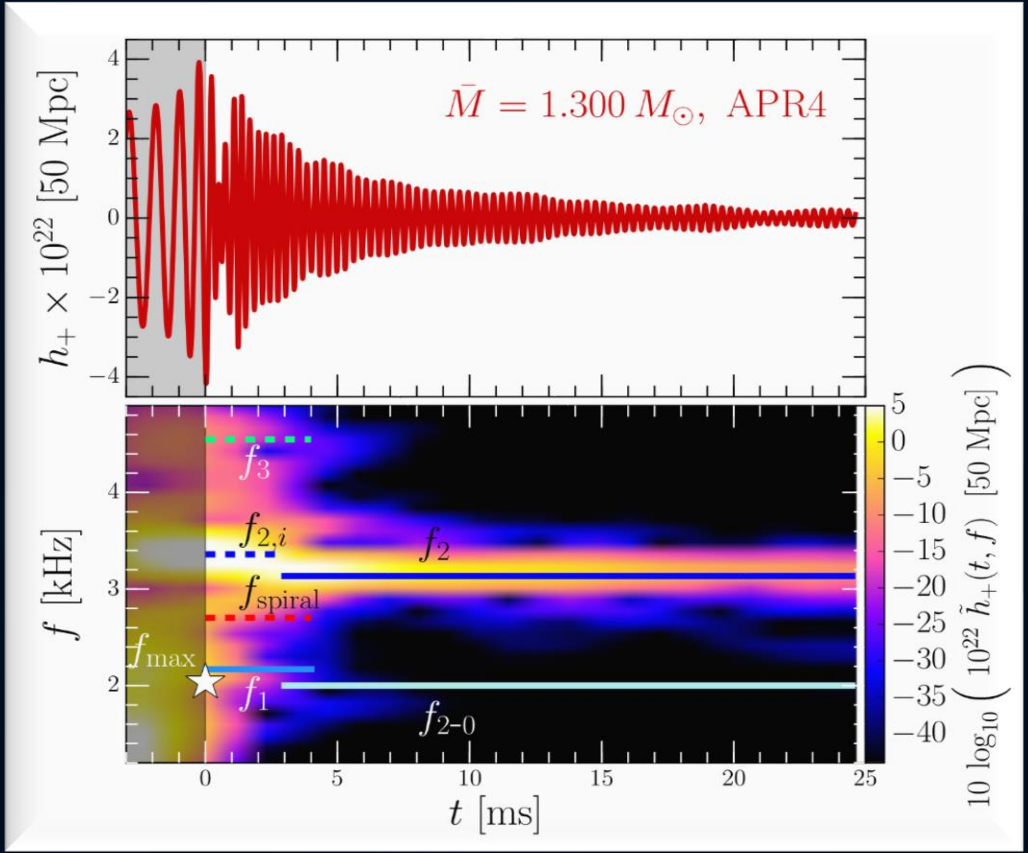
EOS: LS200 , Mass: 1.32 M_{solar} , simulation with Pi-symmetry

Time Evolution of the GW-Spectrum

The power spectral density profile of the post-merger emission is characterized by several distinct frequencies. Approximately 5 ms after merger, the only remaining dominant frequency is the f_2-frequency (see e.g. L.Rezzolla and K.Takami, PRD, 93(12), 124051 (2016))



Stiff EOS



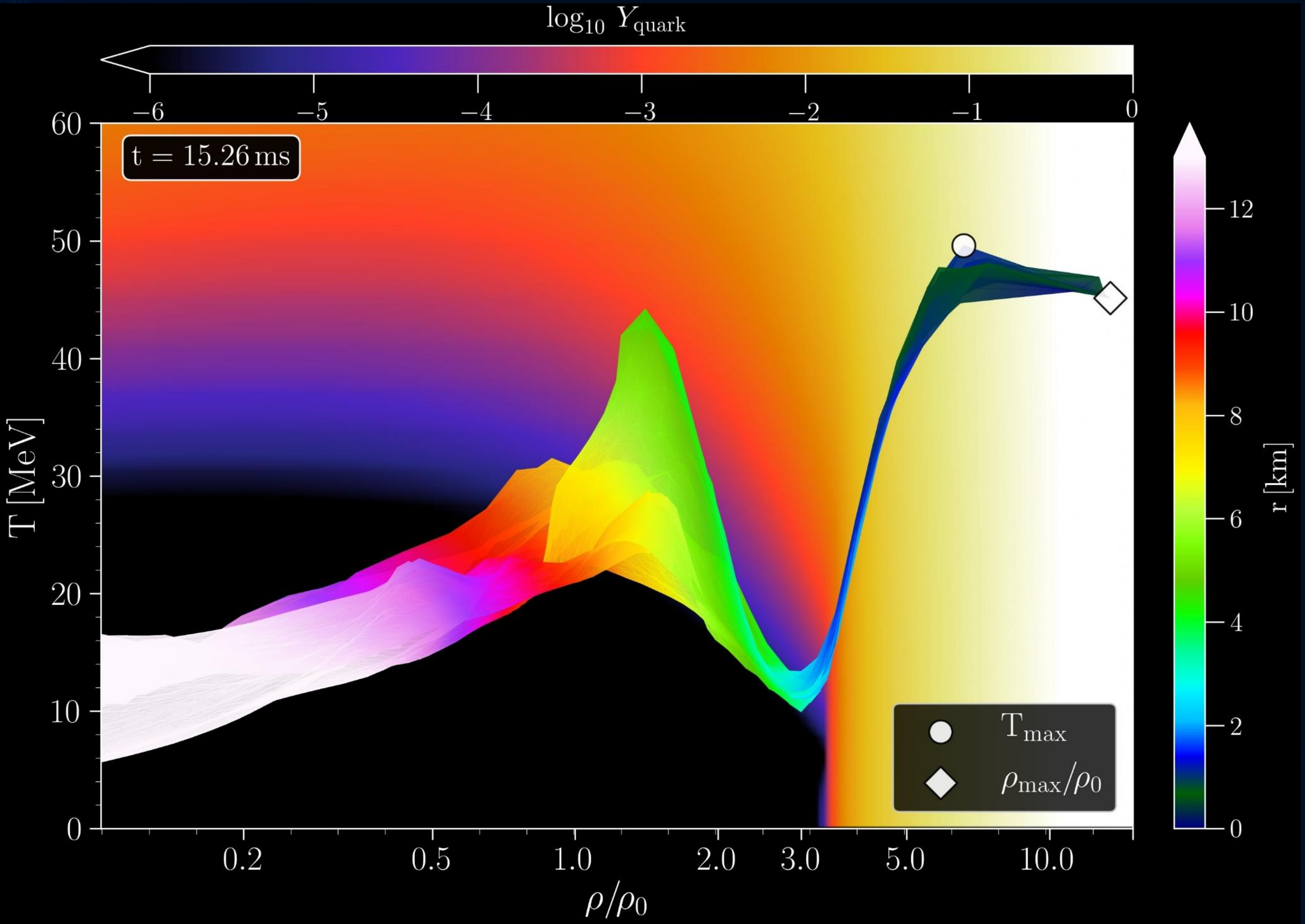
Soft EOS

Unfortunately, due to the low sensitivity at high gravitational wave frequencies, no post-merger signal has been found in GW170817.

But advanced detectors / next-generation detectors might be able to detect!!?

Evolution of the frequency spectrum of the emitted gravitational waves for the stiff GNH3 (left) and soft APR4 (right) EOS.

Binary Hybrid Star Mergers and the QCD Phase Diagram

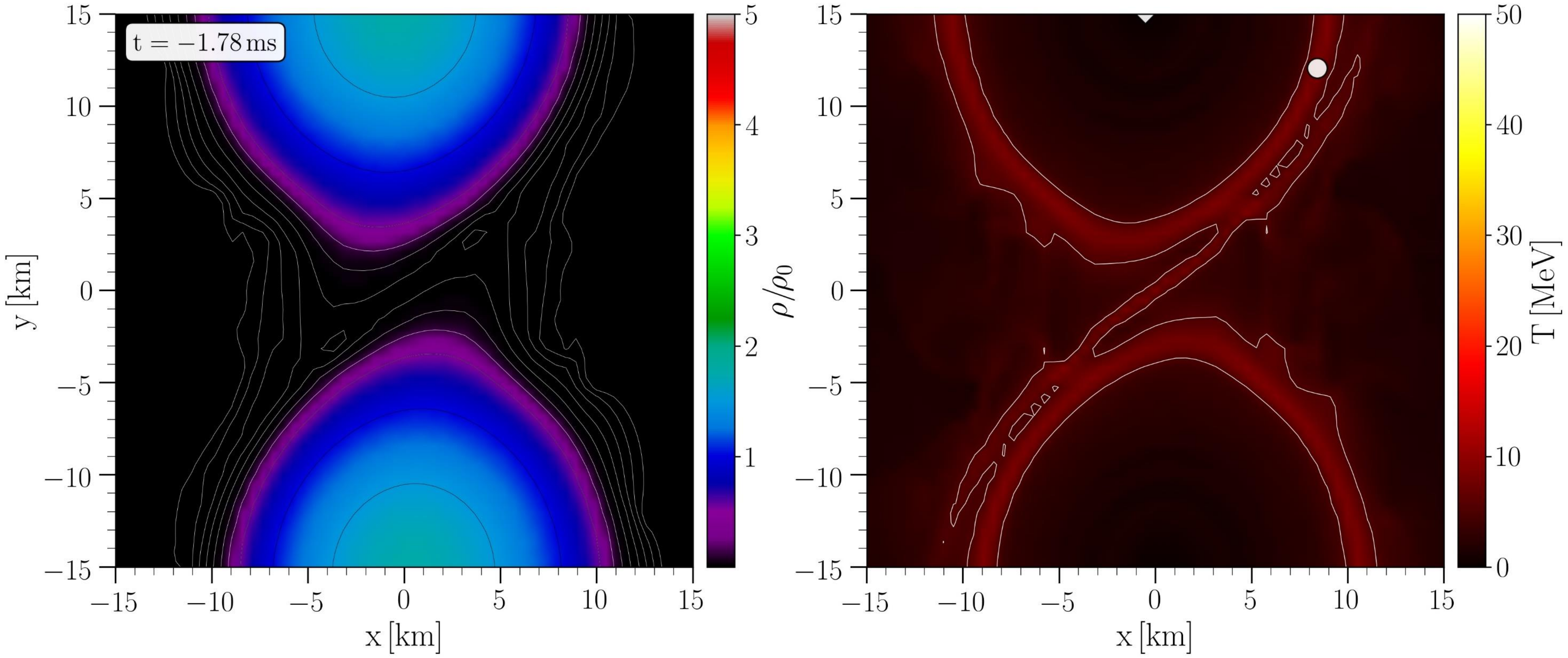


Hot and dense matter inside the inner area of a collapsing hypermassive hybrid star in the style of a (T- ρ) QCD phase diagram plot at a time right before the apparent horizont is formed in its center

The color-coding (right side) indicate the radial position r of the corresponding (T- ρ) fluid element measured from the origin of the simulation (x , y) = (0 , 0) on the equatorial plane at z = 0.
The color-coding (top) indicates the fraction of deconfined quarks.

The open triangle marks the maximum value of the temperature while the open diamond indicates the maximum of the density.

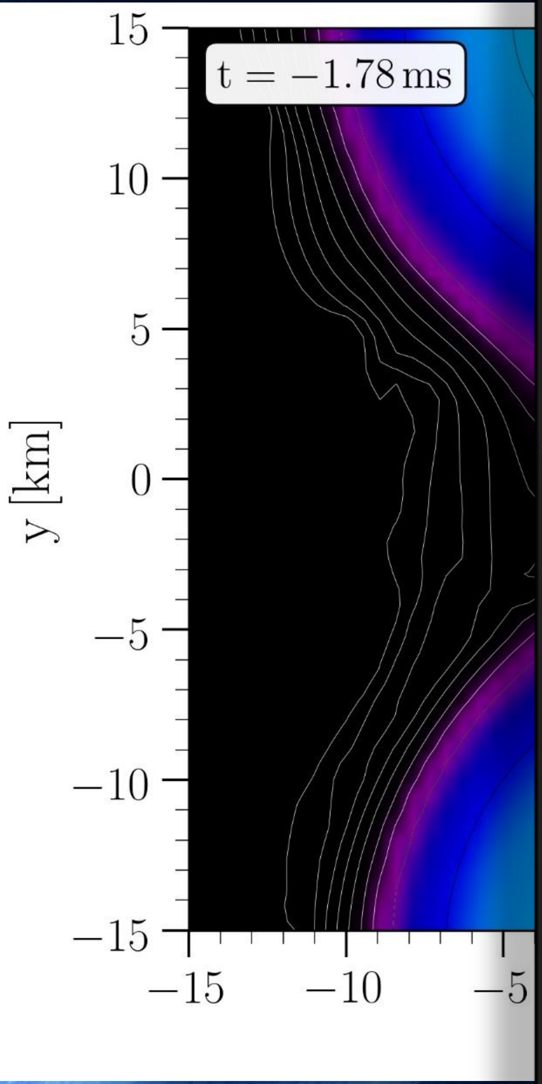
Late Inspiral Phase

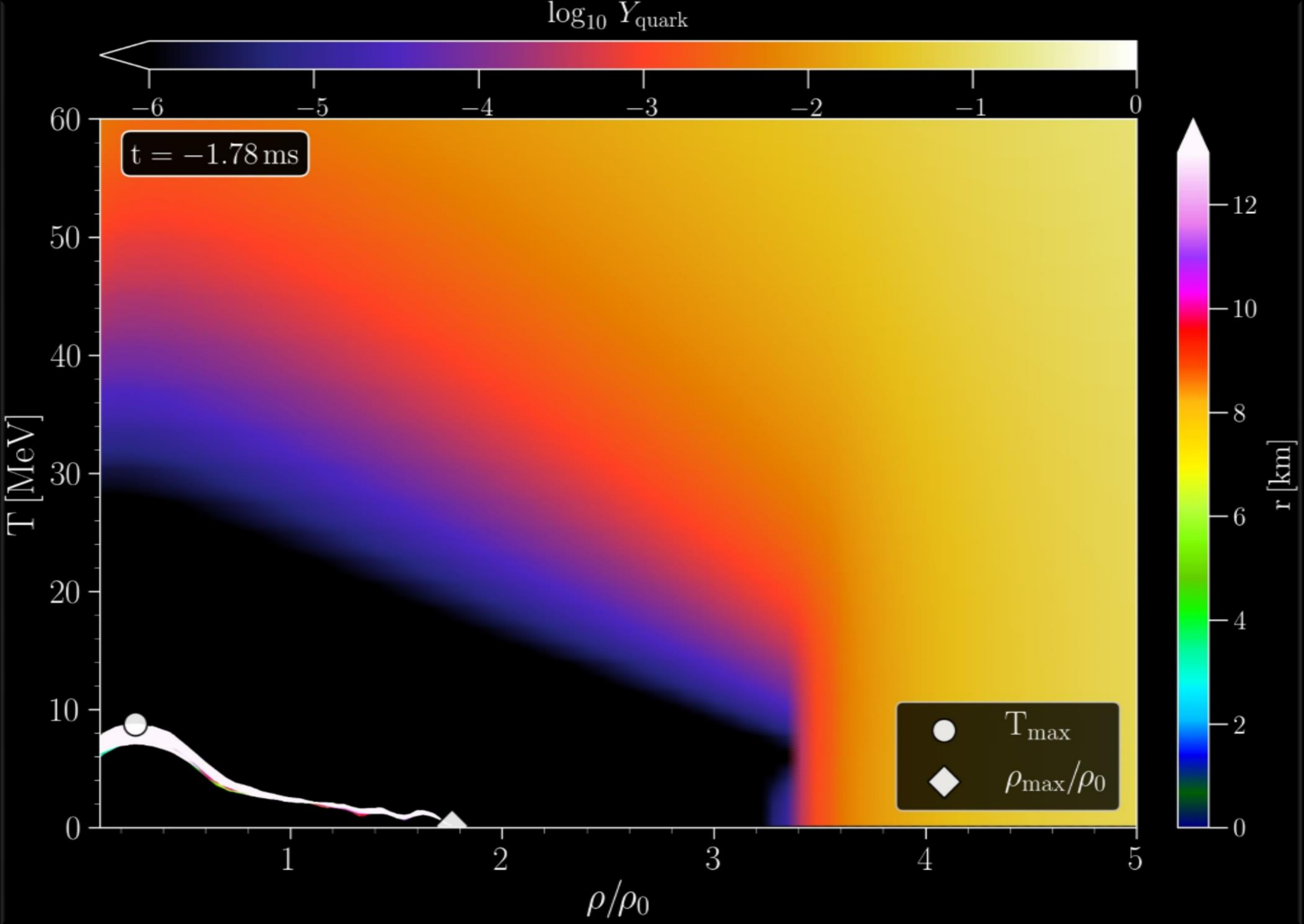


Rest mass density on the equatorial plane

Temperature on the equatorial plane

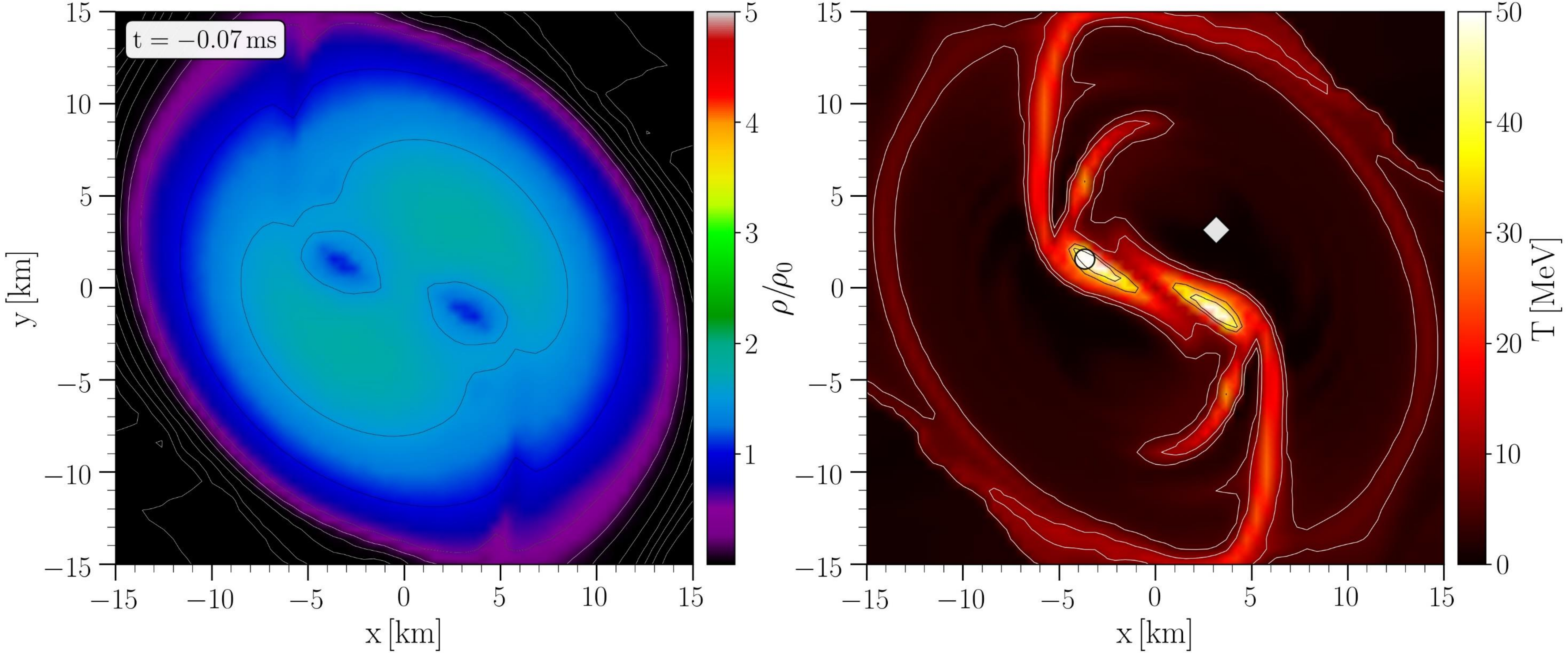
Late Inspiral Phase





Rest mass density

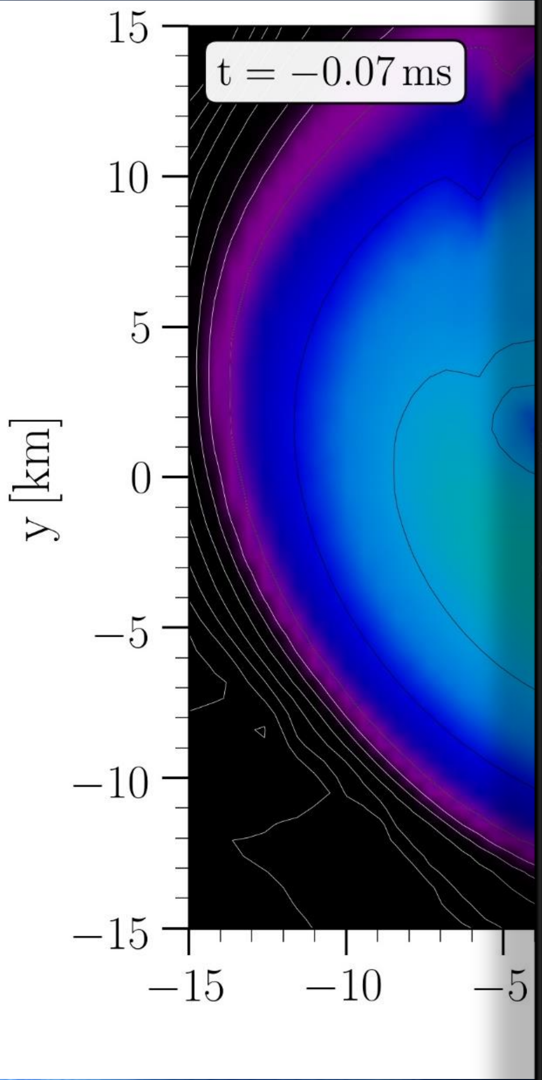
Merger Phase

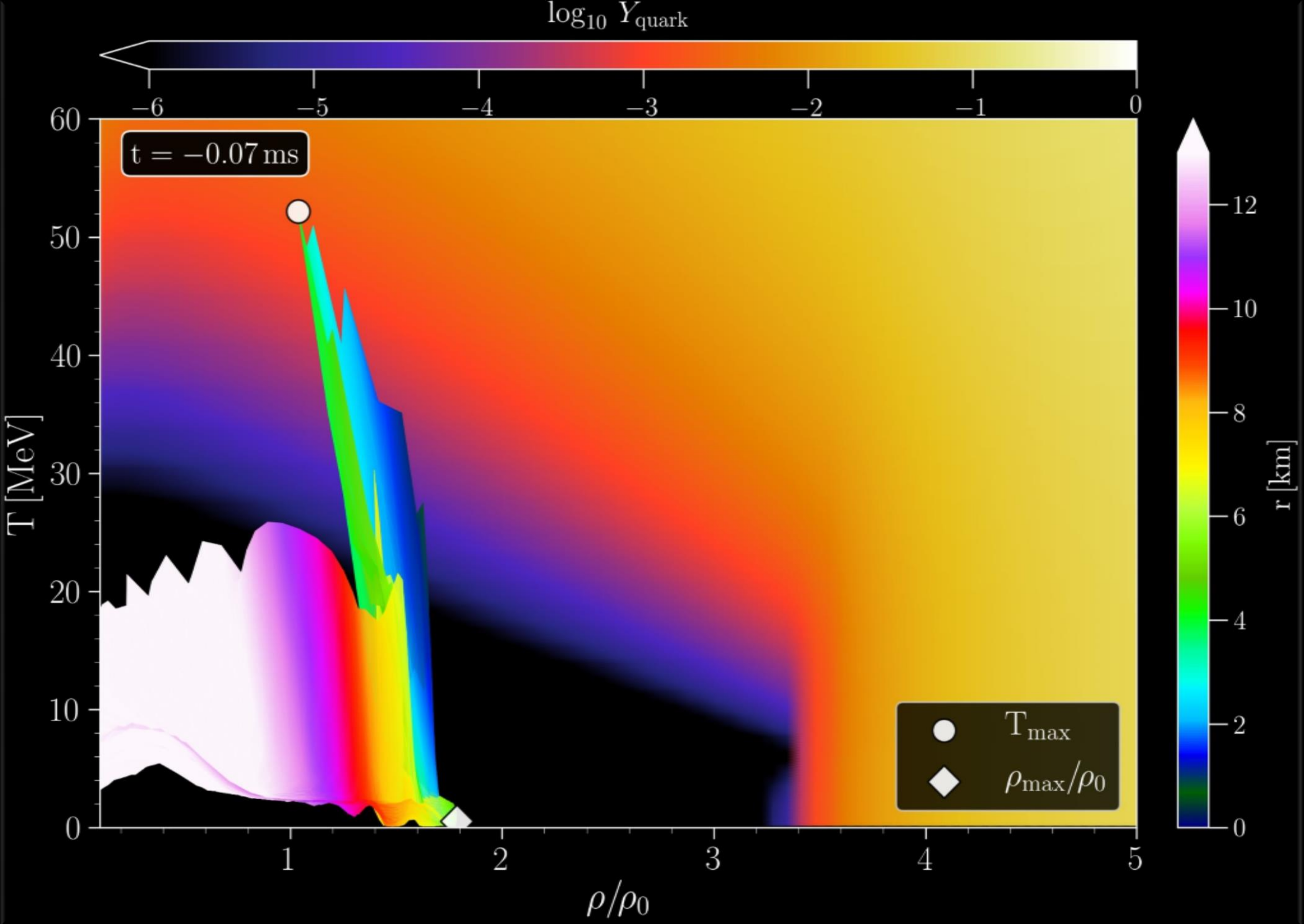


Rest mass density on the equatorial plane

Temperature on the equatorial plane

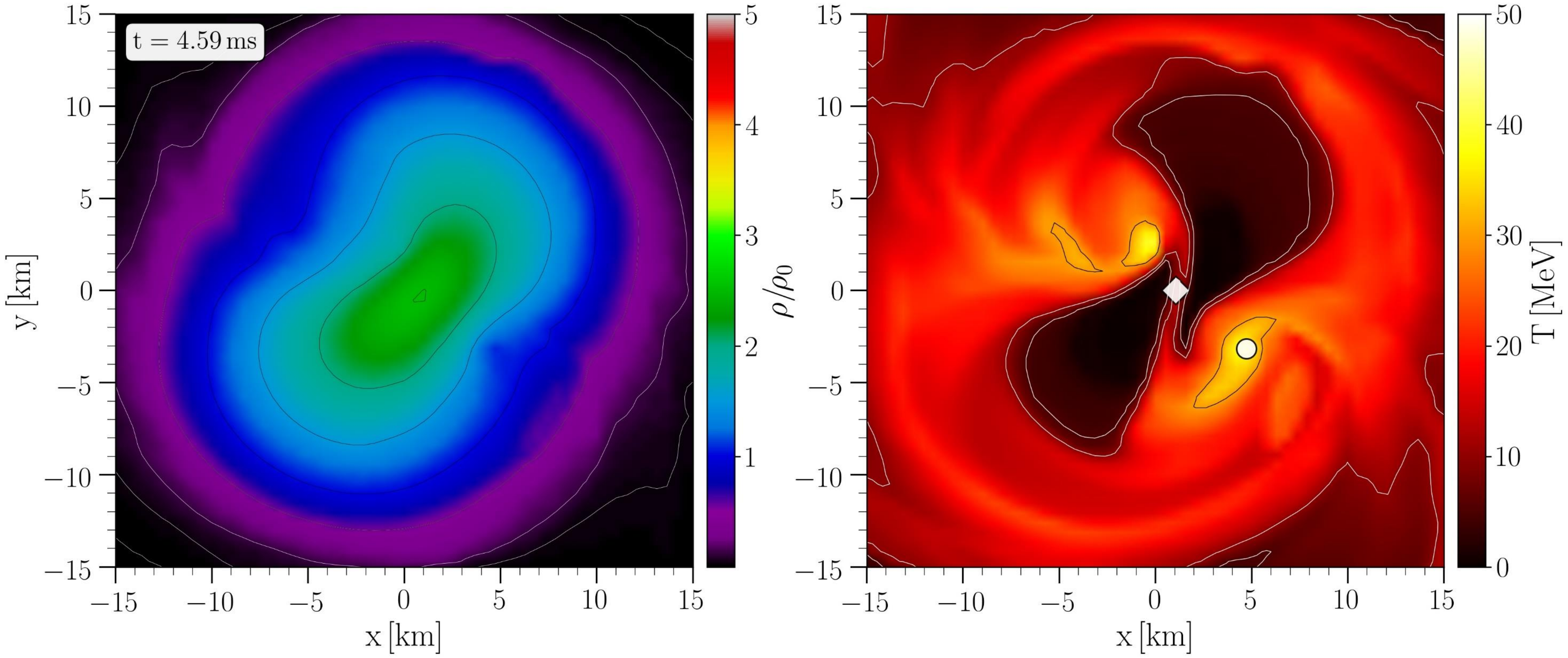
Merger Phase





Rest mass density

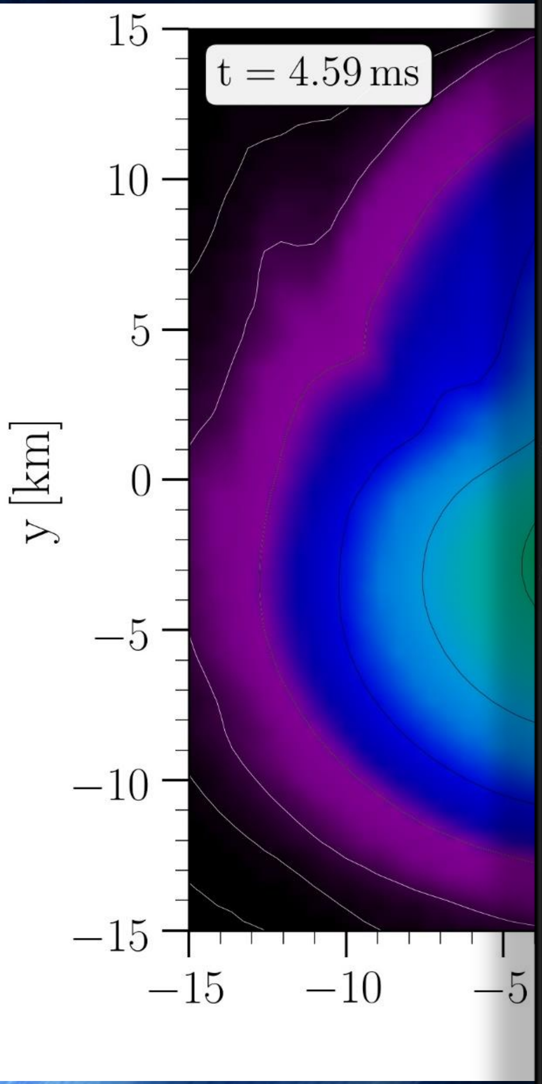
Post Merger Phase

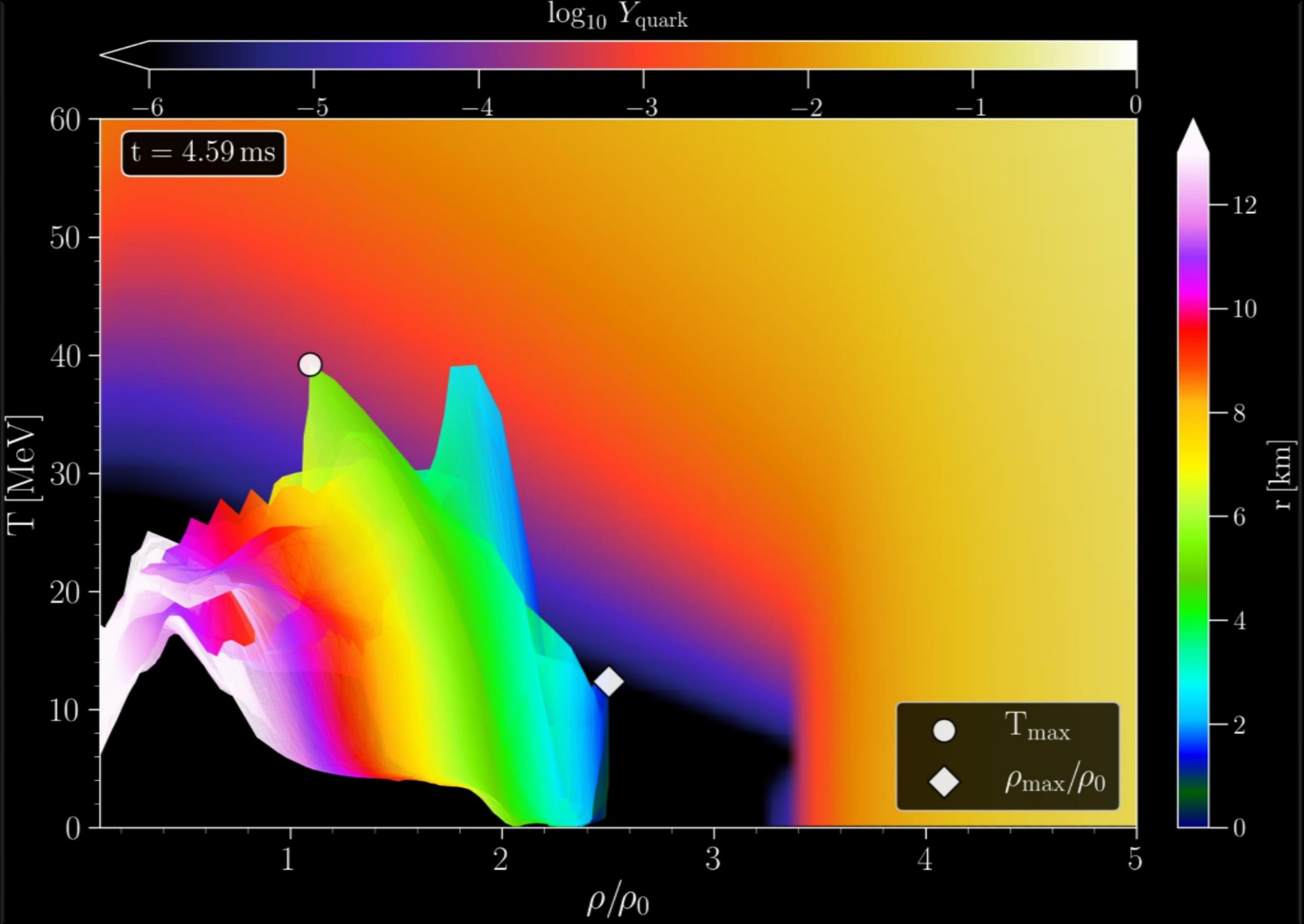


Rest mass density on the equatorial plane

Temperature on the equatorial plane

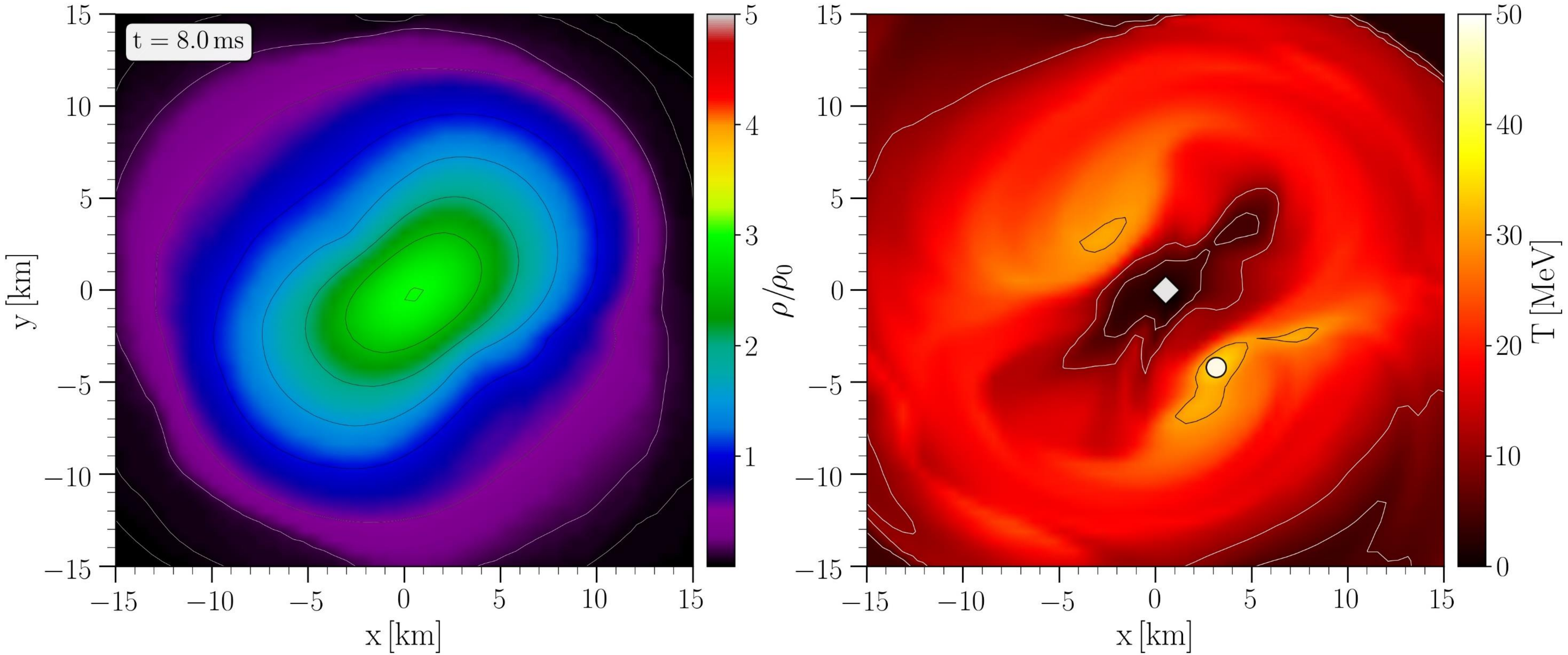
Post Merger Phase





Rest mass density

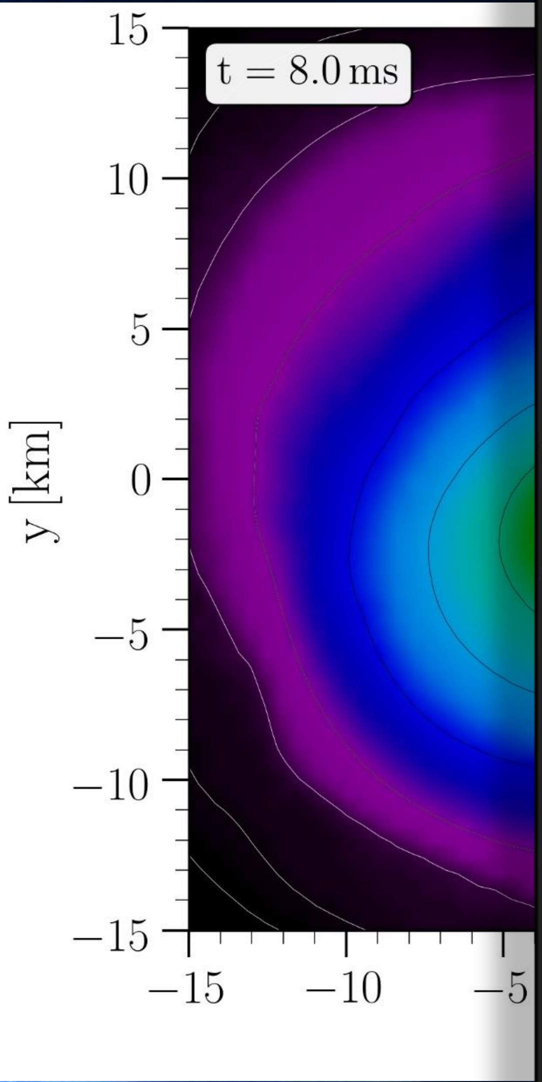
Merger Phase

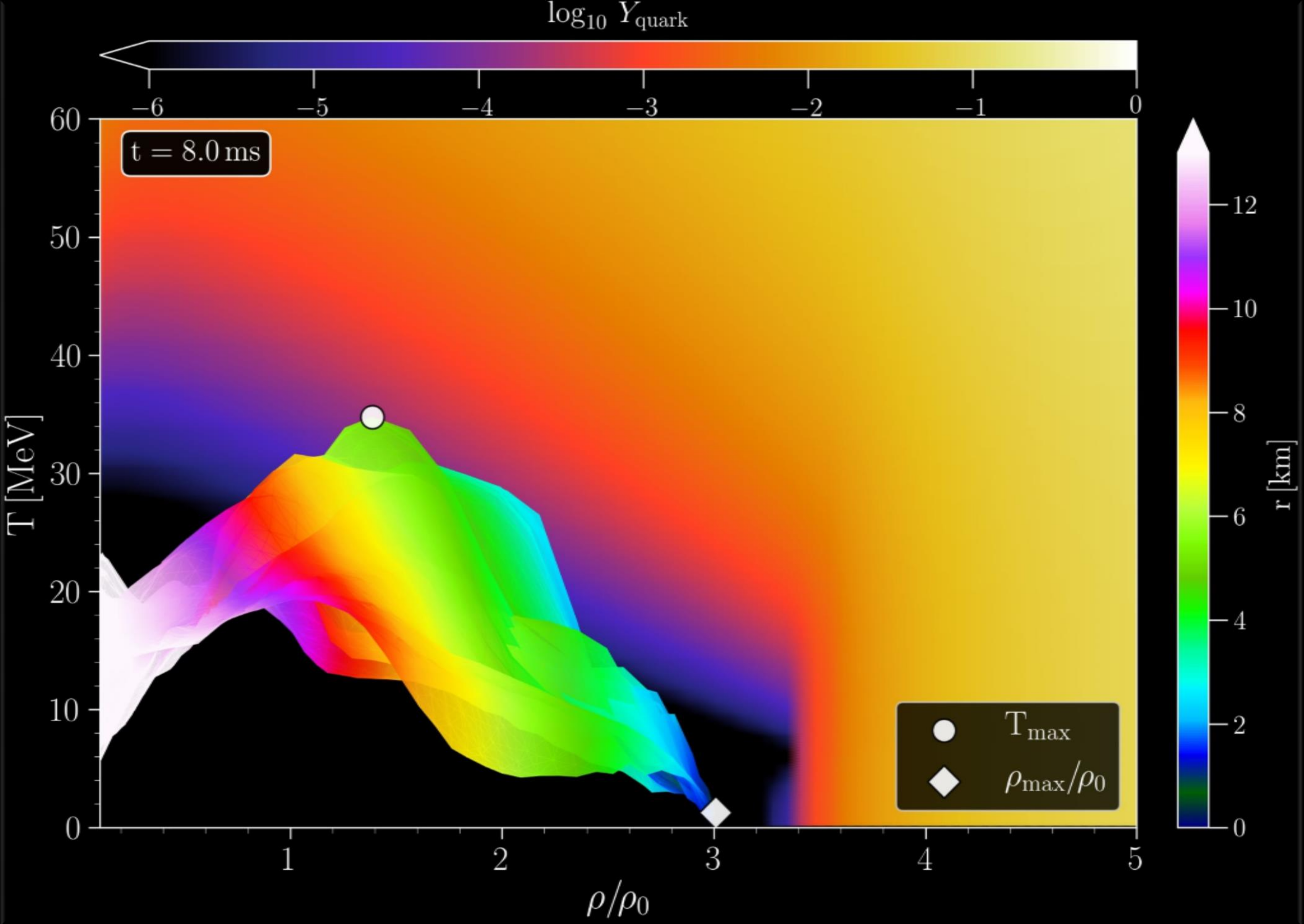


Rest mass density on the equatorial plane

Temperature on the equatorial plane

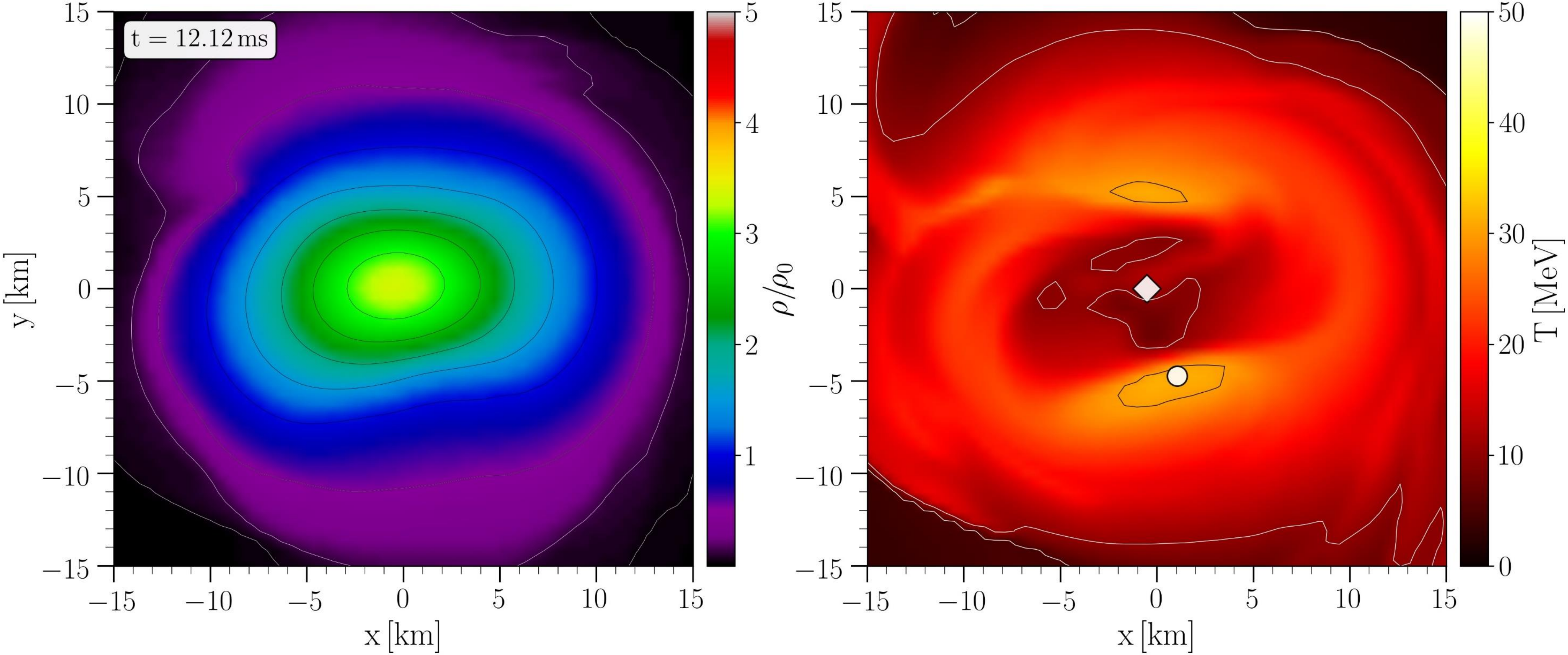
Merger Phase





Rest mass density

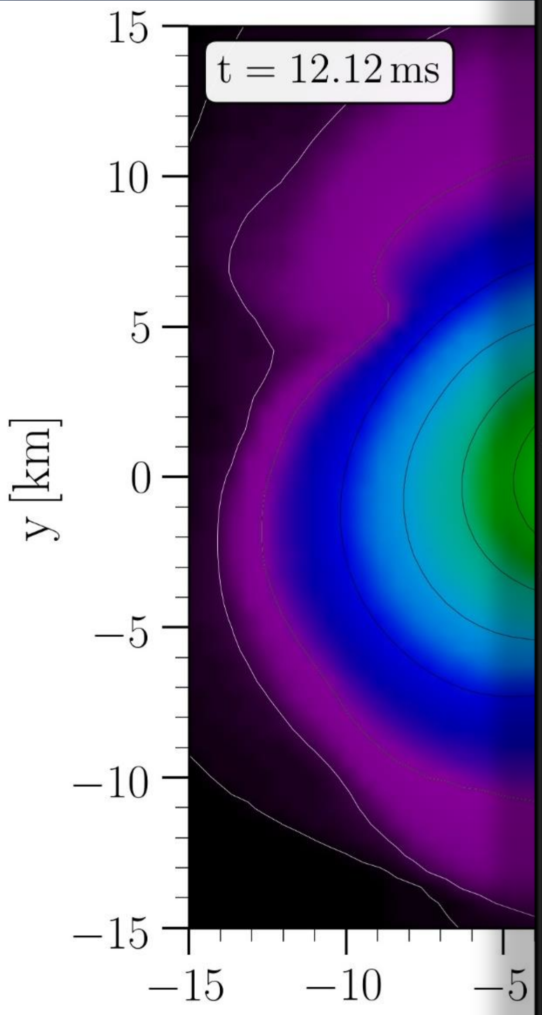
Merger Phase



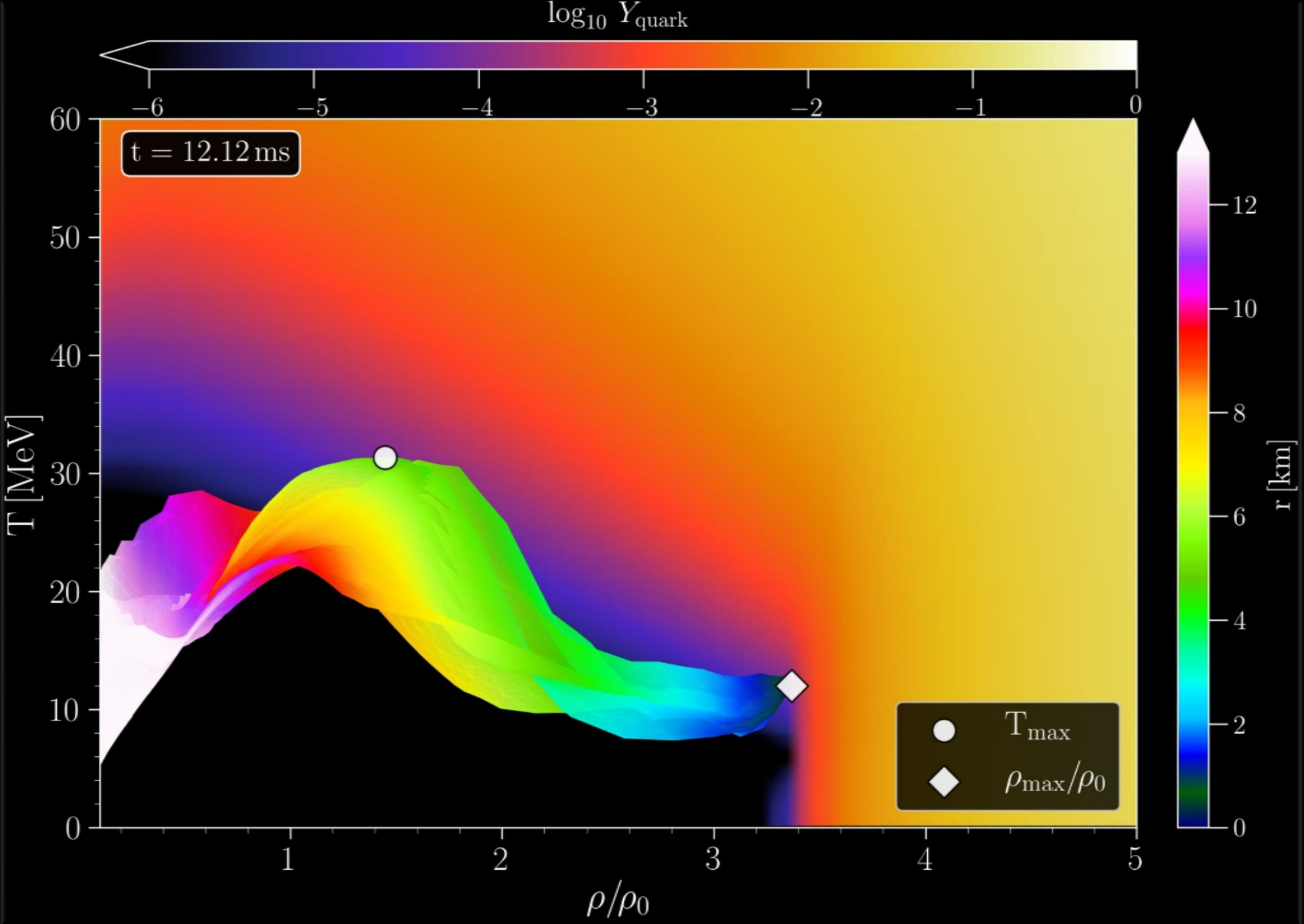
Rest mass density on the equatorial plane

Temperature on the equatorial plane

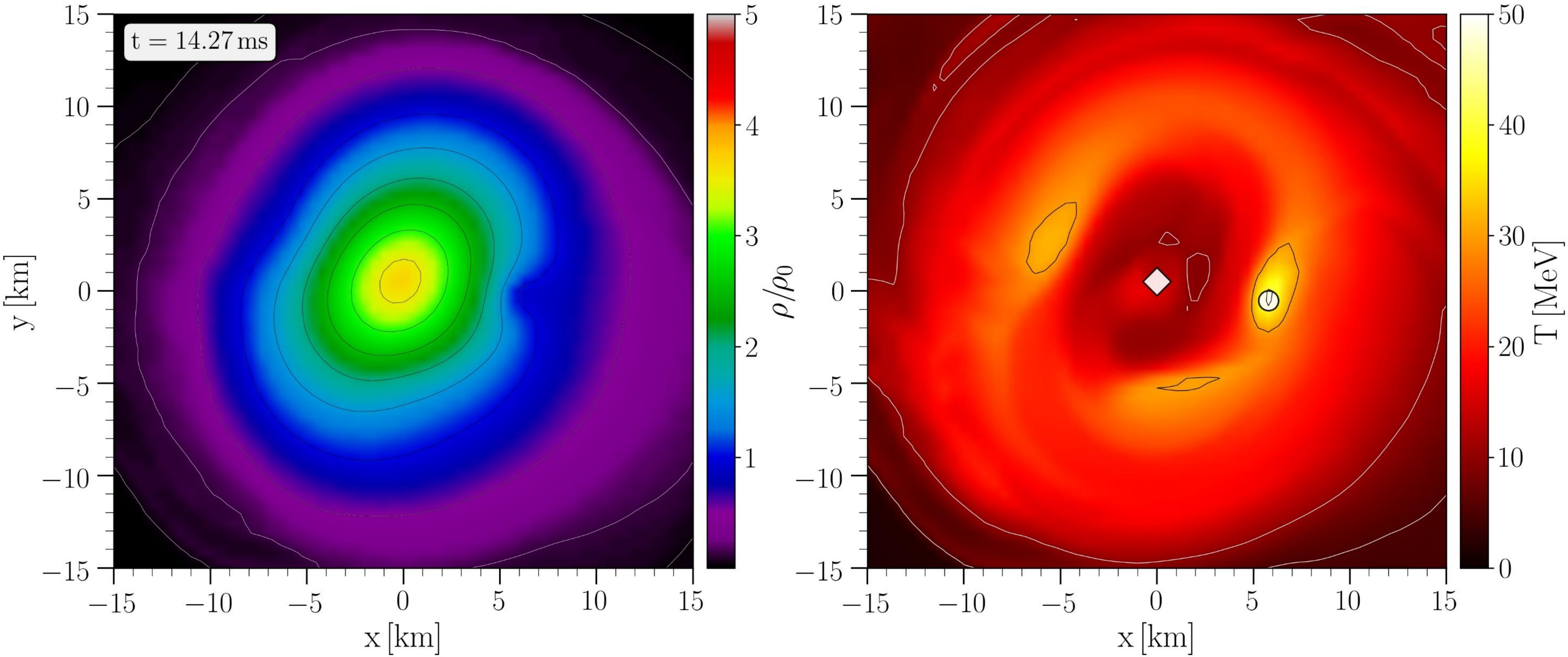
Merger Phase



Rest mass density



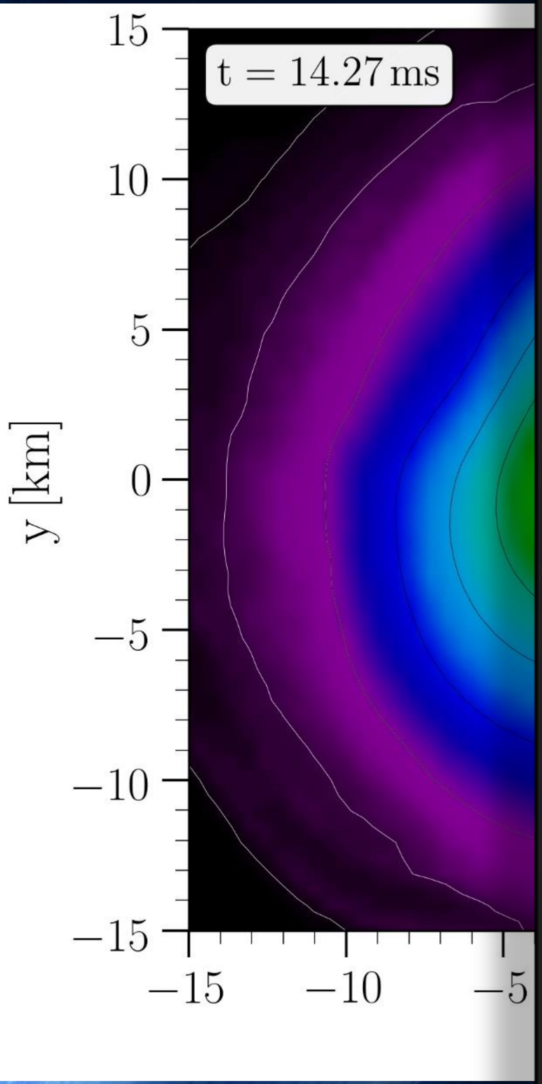
Merger Phase

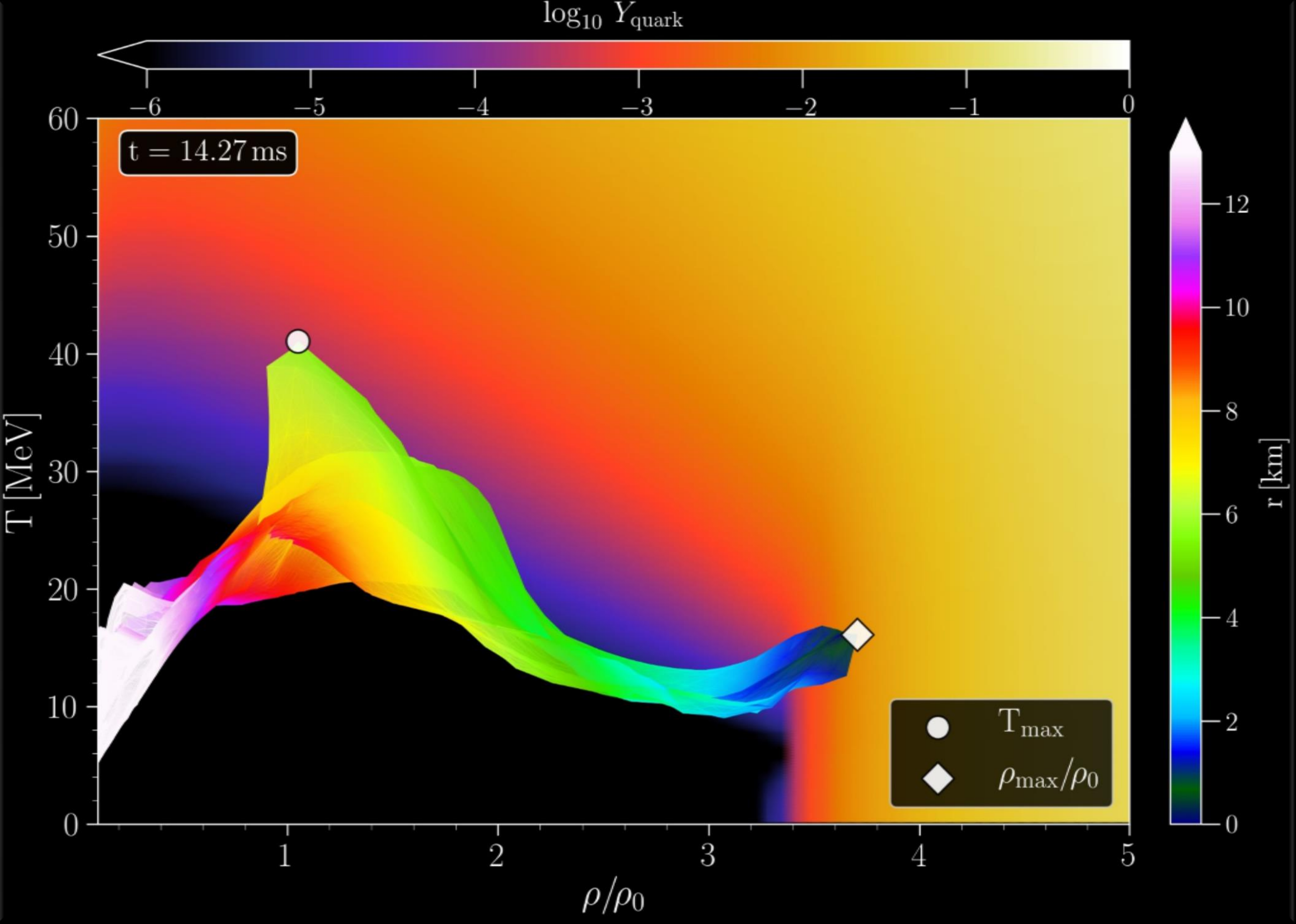


Rest mass density on the equatorial plane

Temperature on the equatorial plane

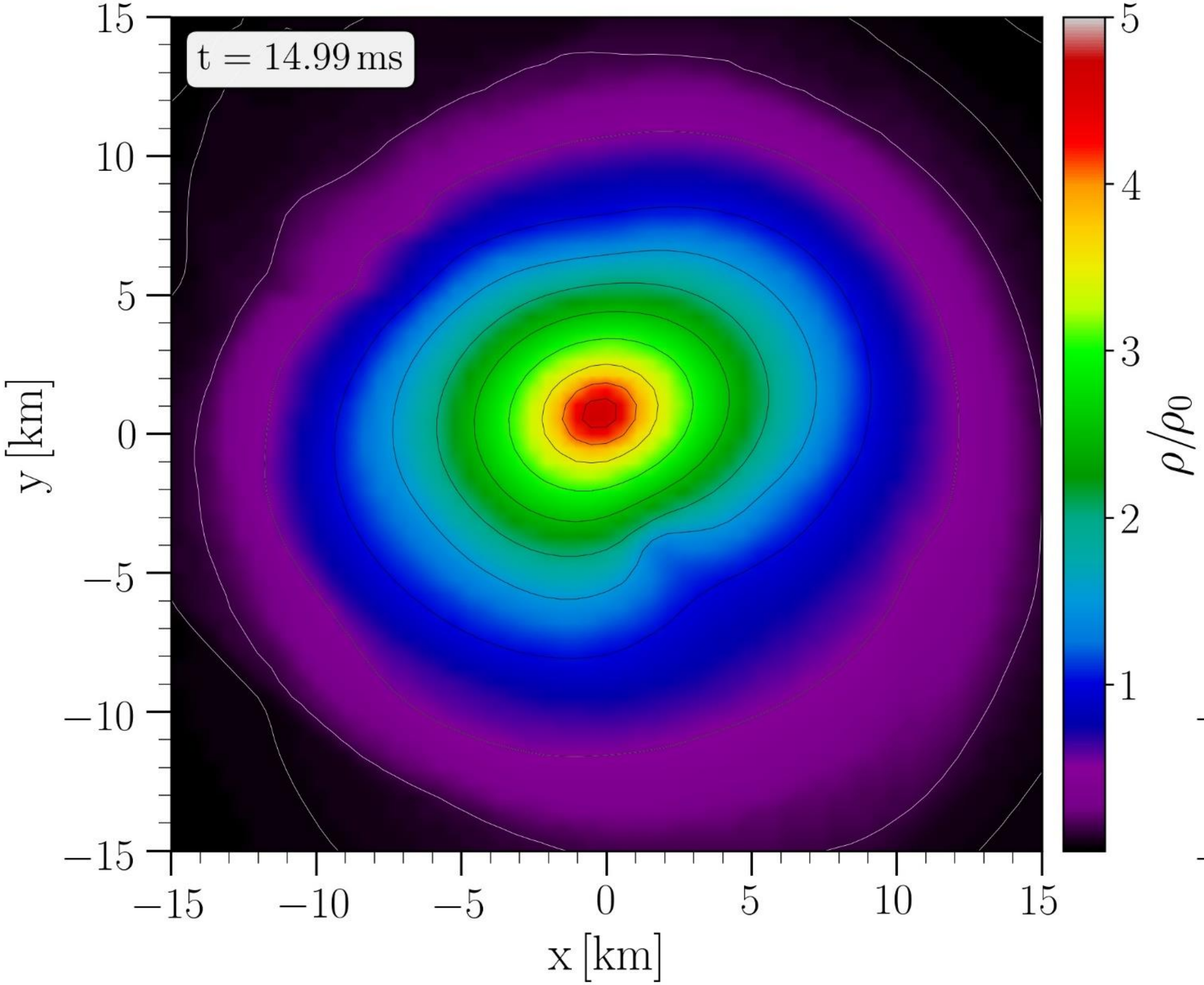
Merger Phase



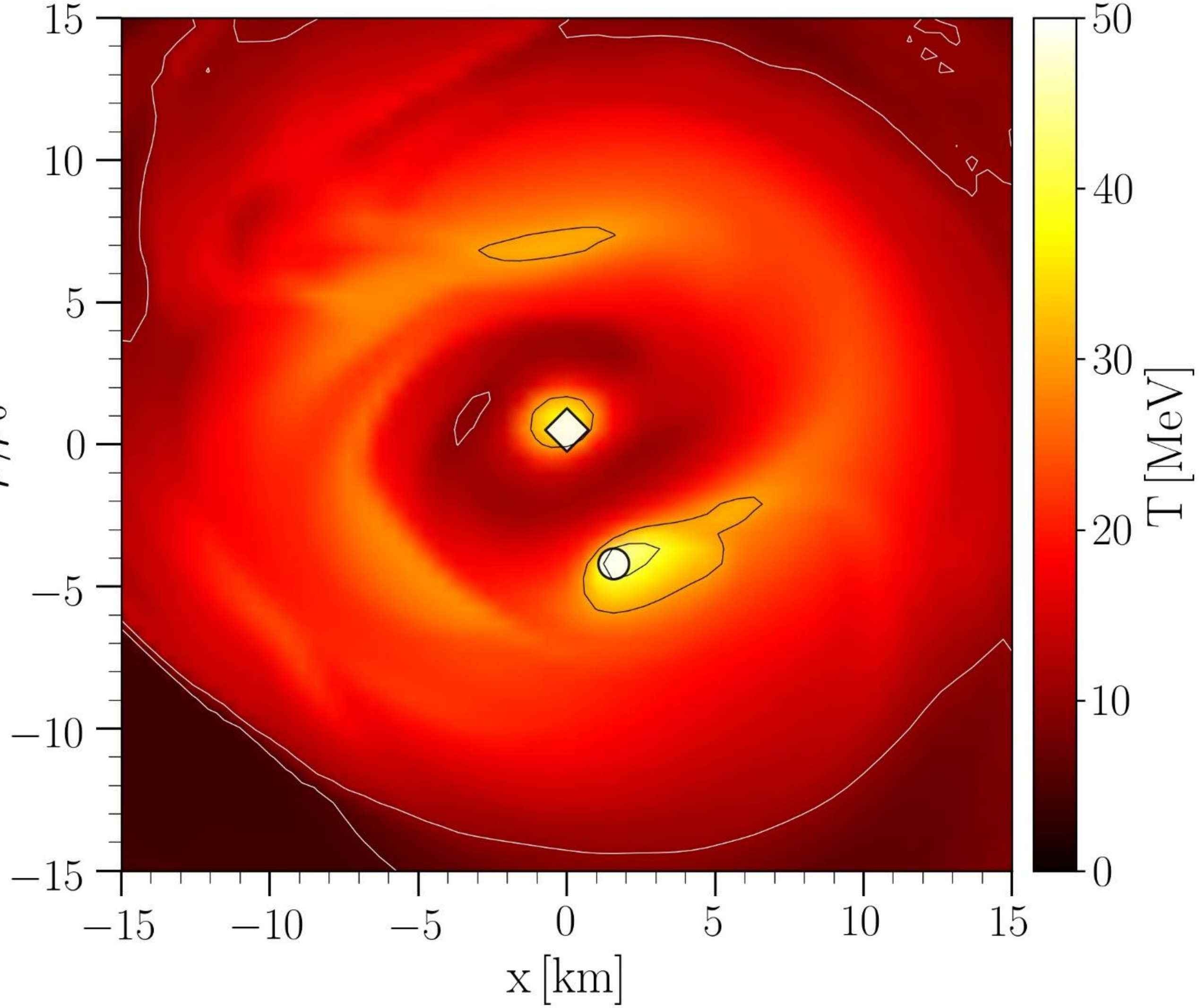


Rest mass density

Merger Phase

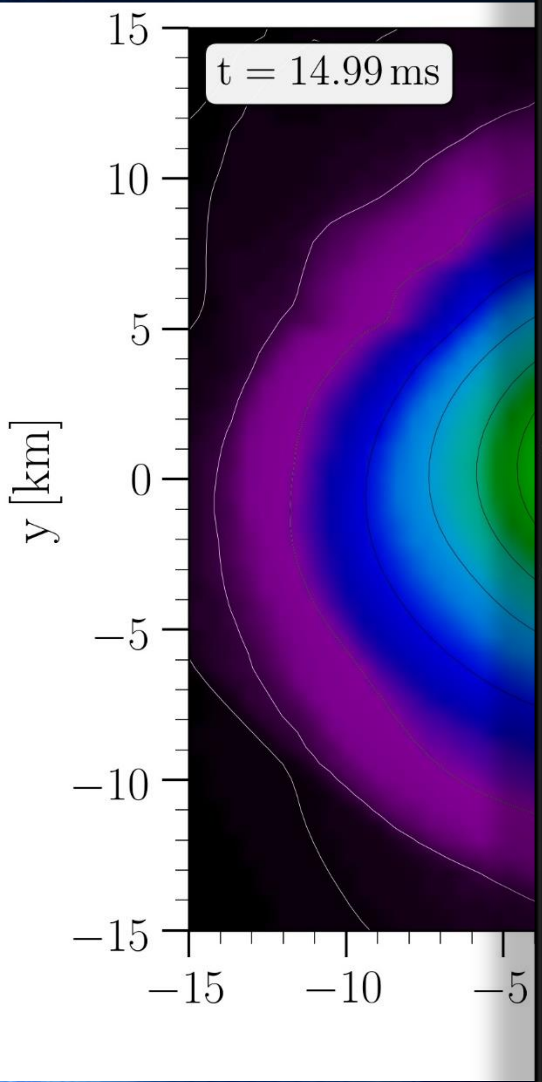


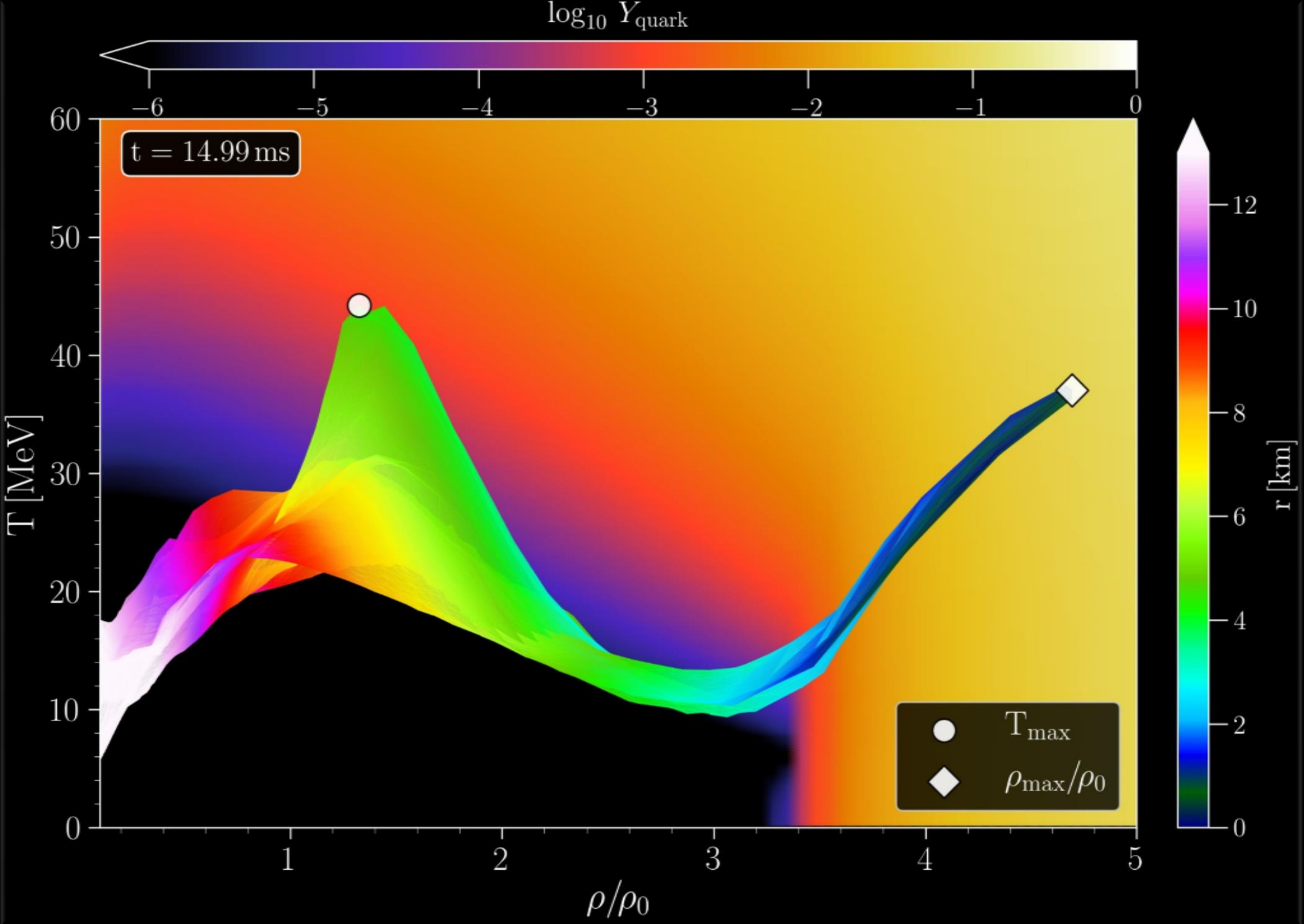
Rest mass density on the equatorial plane



Temperature on the equatorial plane

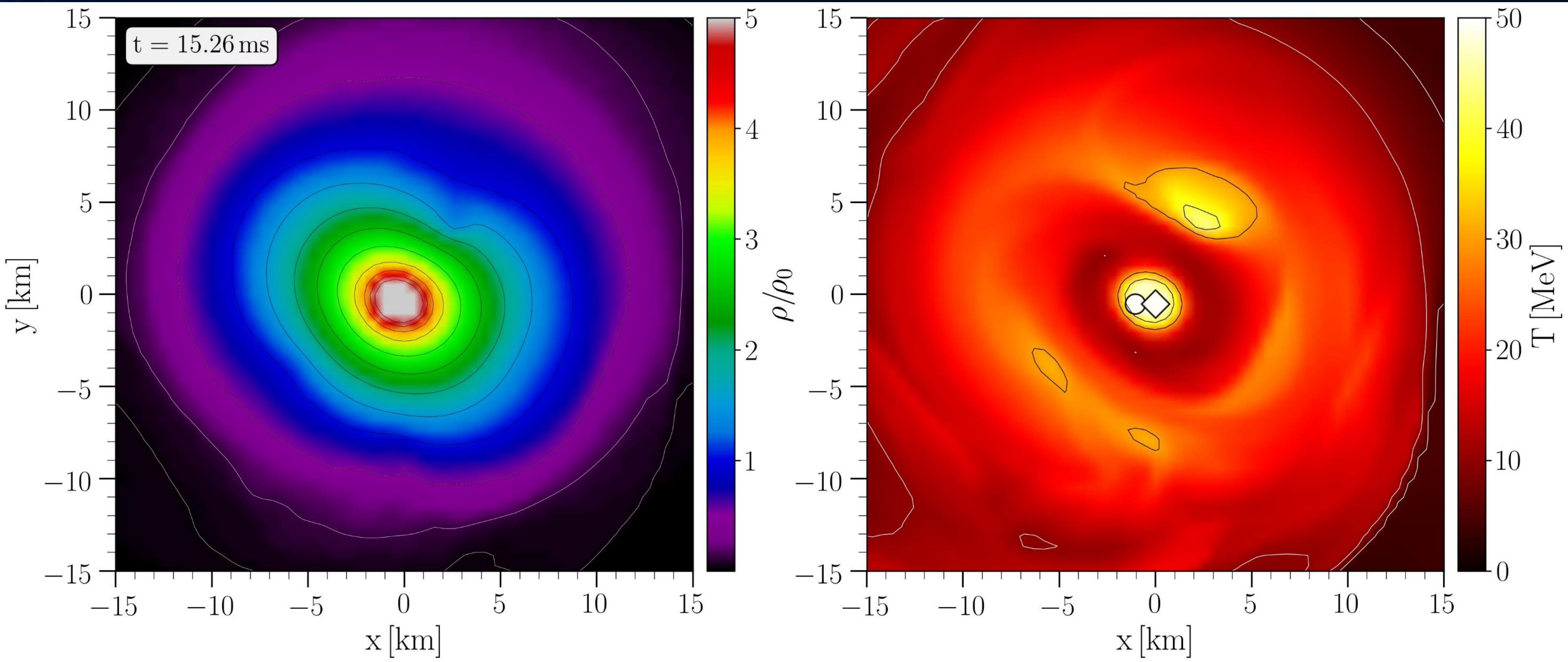
Merger Phase





Rest mass density

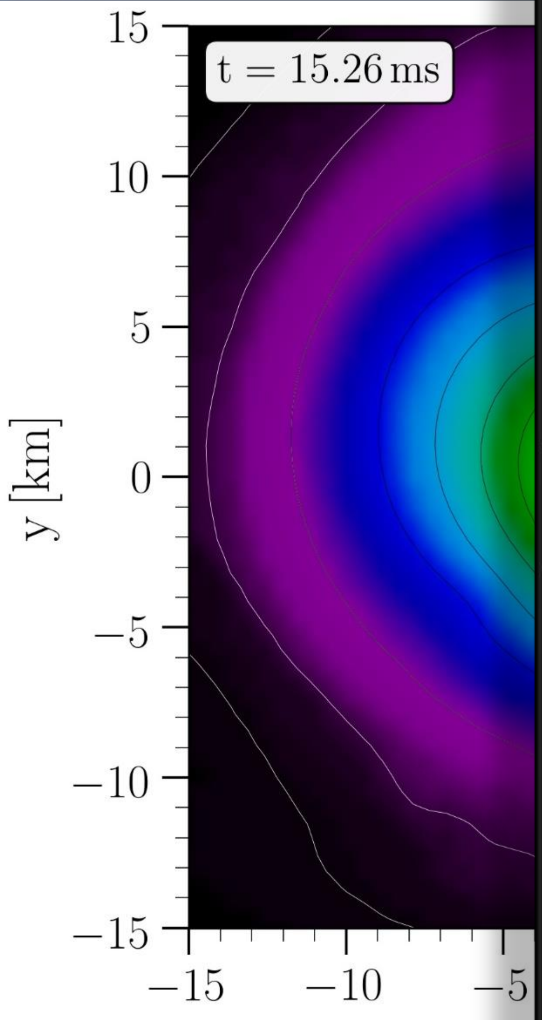
Merger Phase

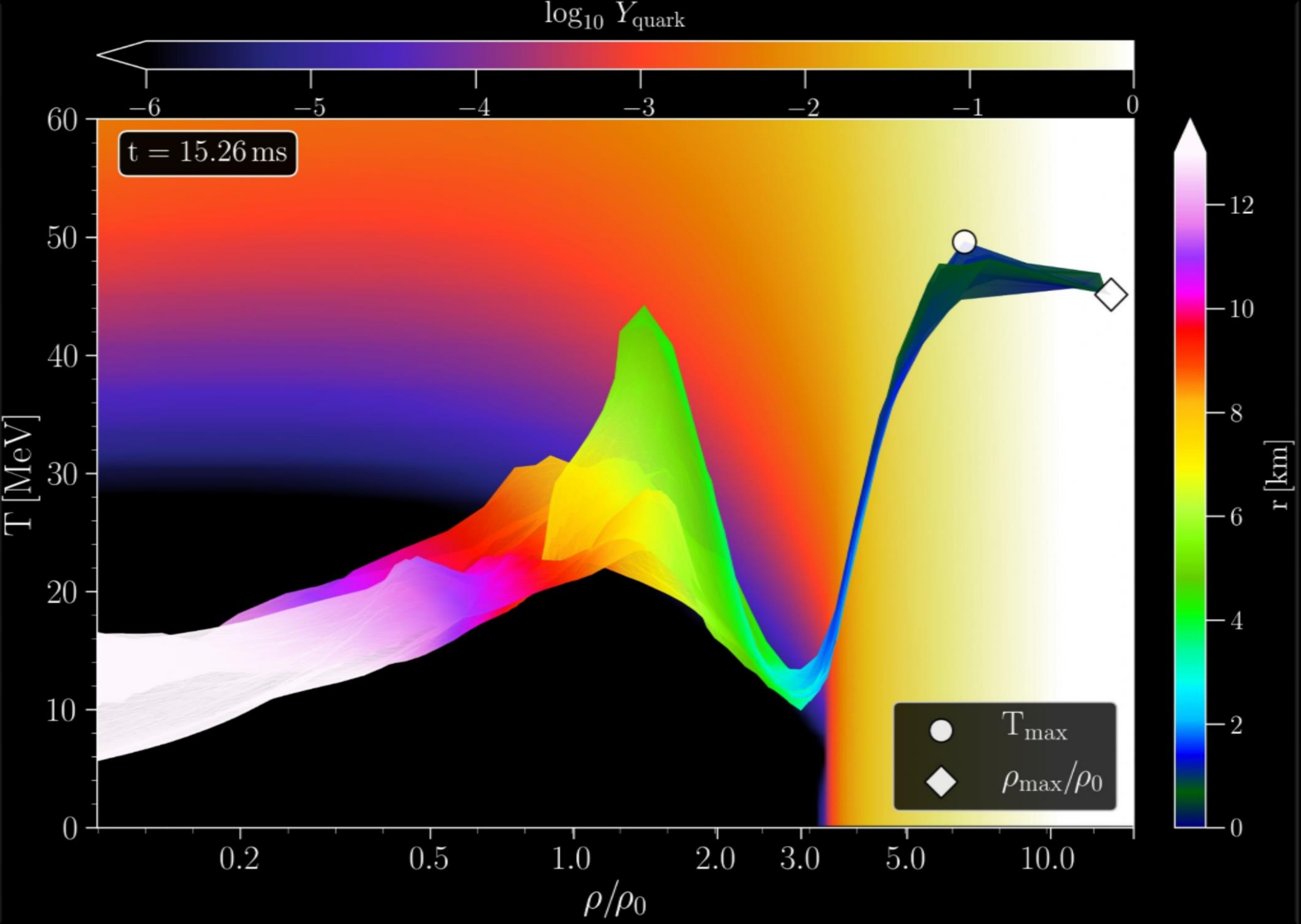


Rest mass density on the equatorial plane

Temperature on the equatorial plane

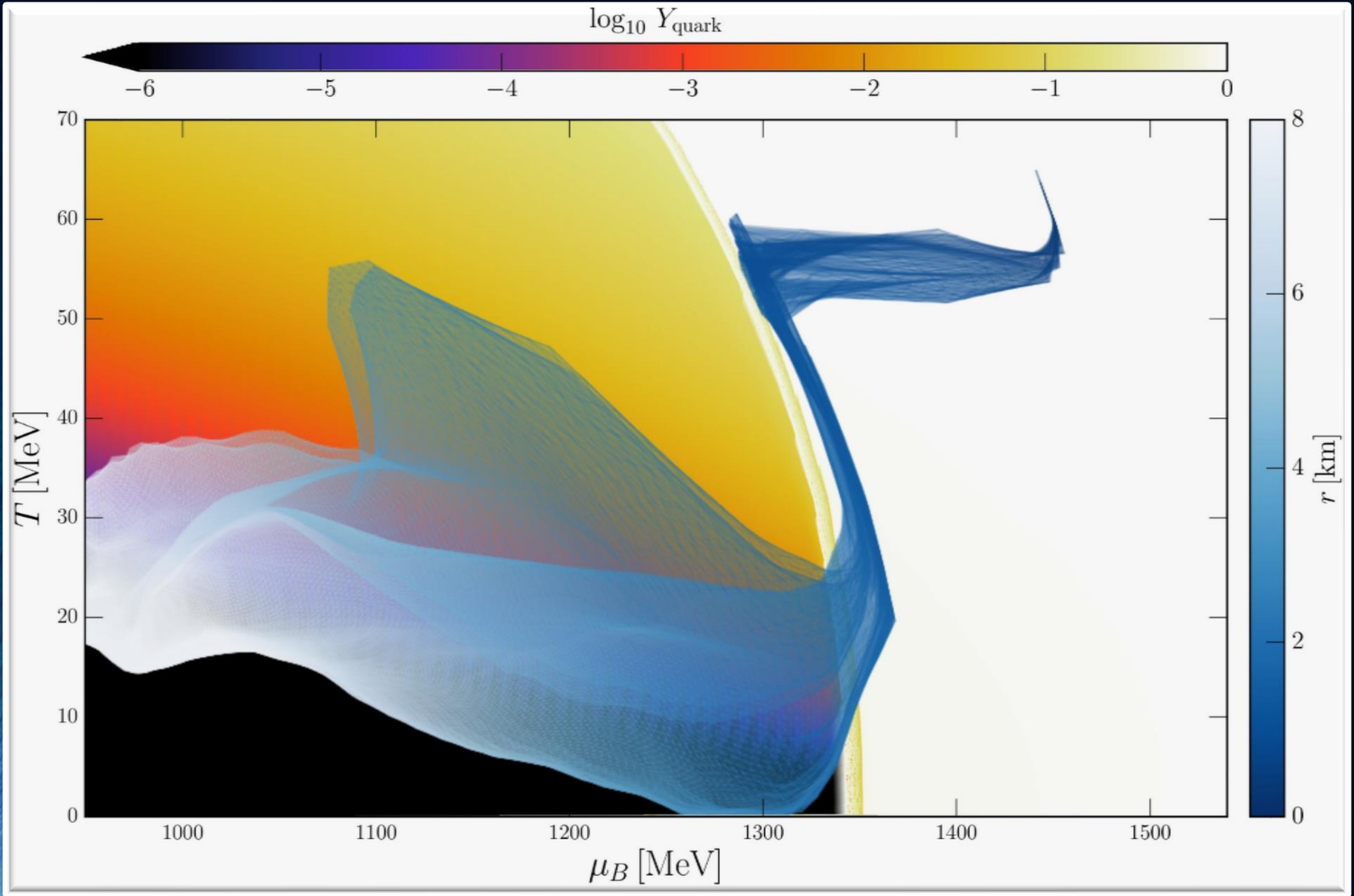
Merger Phase





Rest mass density

The Pelican Plot



The shadowy blue image resembles the shape of a strange bird, e.g. a pelican, wherein the hot head of a pelican contains a high amount of strange quark matter, its thin neck follows the QCD phase boundary, while its hot wings (local temperature maxima) contain mostly hadronic matter at much lower densities.

The maximum tempearture and density points correspond to the head of the pelican where pure strange quark is present. Due to the stiffening of the EOS in the pure quark phase, the temperature stops rising and the high pressure in the central region pushes against the hudge gravitational force.

E.Most, J. Papenfort, V.Dexheimer, M.Hanauske, H.Stöcker and L.Rezzolla;
„On the deconfinement phase transition in neutron-star mergers„; arXiv:*1910.13893*

Hybrid Star Mergers with T-dependent EOS *(PRL paper 1)*

Signatures of quark-hadron phase transitions in general-relativistic neutron-star mergers

Elias R. Most,[1] L. Jens Papenfort,[1] Veronica Dexheimer,[2] Matthias Hanauske,[1,3]
Stefan Schramm,[1,3] Horst Stöcker,[1,3,4] and Luciano Rezzolla[1,3]

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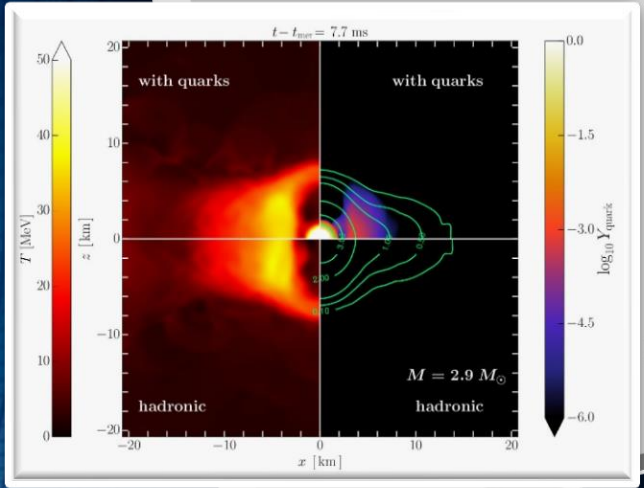

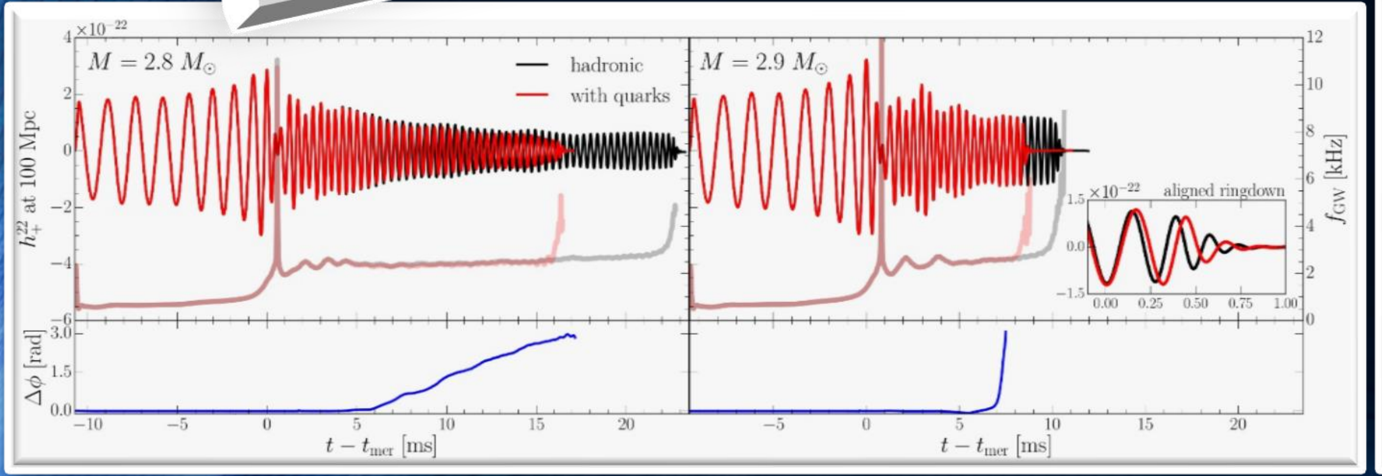

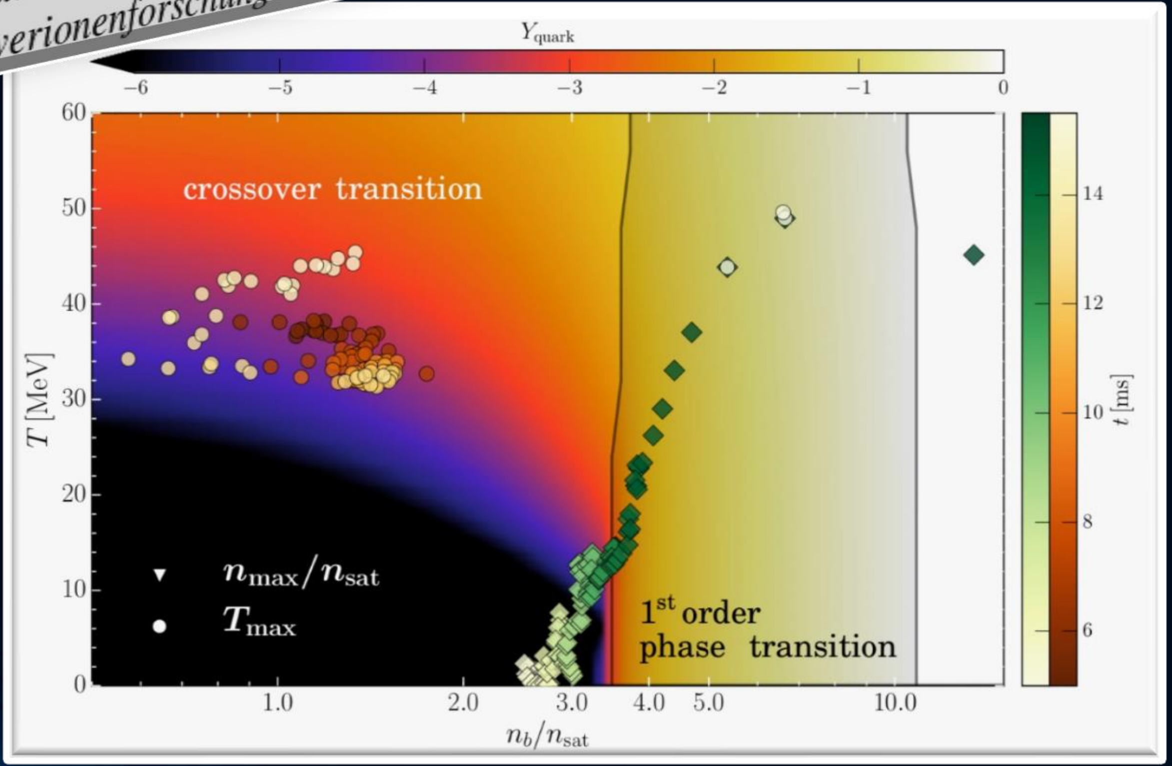

Hybrid Star Mergers with T-dependent EOS *(PRL paper 2)*

Identifying a first-order phase transition in neutron star mergers through gravitational waves

Andreas Bauswein,[1,2] Niels-Uwe F. Bastian,[3] David B. Blaschke,[3,4,5] Katerina Chatziioannou,[6] James A. Clark,[7] Tobias Fischer,[3] and Micaela Oertel[8]

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Laboratory for Theore… 141980 Dubna, Russia
[6] Canadian Insti…
Univers…
[7] Center…
Georgia In…
…TH, Observatoire de…
Sorbonne Pa…

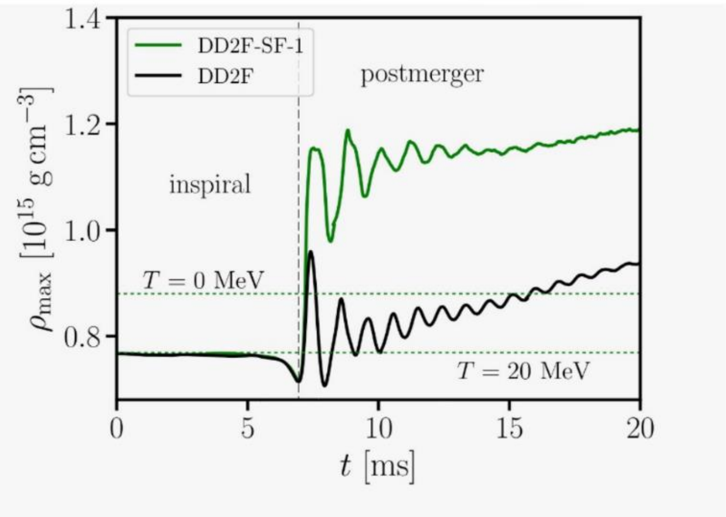

FIG. 1: Evolution of the maximum rest-mass density comparing DD2F-SF-1 (green) and DD2F (black) for 1.35-1.35 $M_\odot$ mergers (solid curves). Horizontal dotted green lines mark the onset density $\rho_{\rm onset}$ of the phase transition for DD2F-SF-1 at $T = 0$ and at 20 MeV.

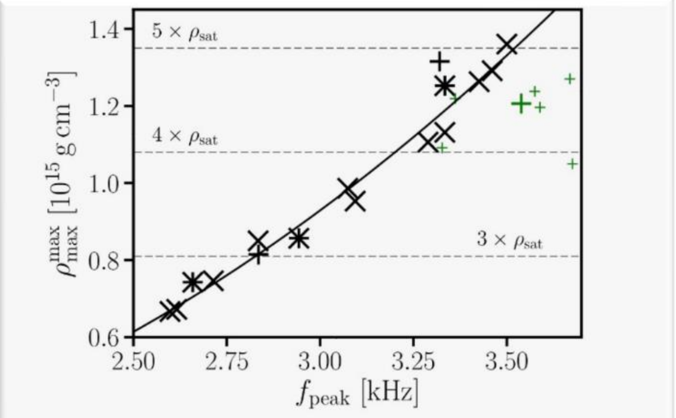

FIG. 4: Maximum rest-mass density $\rho^{\rm max}_{\rm max}$ during the first milliseconds of the postmerger phase as function of the dominant postmerger GW frequency $f_{\rm peak}$ for 1.35-1.35 $M_\odot$ mergers. Green symbols display results for DD2F-SF (big symbol for DD2F-SF-1). Asterisks indicate models with hyperons. Black plus signs display ALF2/4. Solid curve is a second order polynomial least square fit to the data excluding hybrid EOSs.

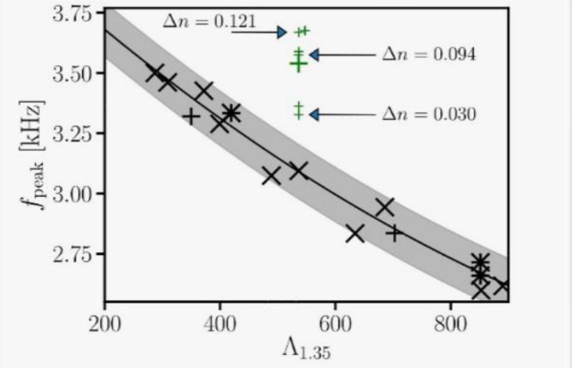

FIG. 3: Dominant postmerger GW frequency $f_{\rm peak}$ as function of tidal deformability Λ for 1.35-1.35 $M_\odot$ mergers. The DD2F-SF models with a phase transition to deconfined quark matter (green symbols) appear as clear outliers (big symbol for DD2F-SF-1). Solid curve displays the least square fit Eq. (1) for all purely hadronic EOSs (including three models with hyperons marked by asterisks). ALF2 and ALF4 are marked by black plus signs. EOSs incompatible with GW170817 are not shown. Arrows mark DD2F-SF models 3, 6 and 7, which feature differently strong density jumps Δn (in fm^{-3}) with roughly the same onset density and stiffness of quark matter.

Literature

Plenary talk (Tuesday, 09:40) by Luciano Rezzolla:
"Binary Neutron Stars: Einstein's richest laboratory"

Hanauske, Matthias, and Walter Greiner.
"Neutron star properties in a QCD-motivated model." *General Relativity and Gravitation* 33.5 (2001): 739-755.

Hanauske, Matthias. "How to detect the Quark-Gluon Plasma with Telescopes." *GSI Annual Report* (2003): 96.

Hanauske, M., Takami, K., Bovard, L., Rezzolla, L., Font, J. A., Galeazzi, F., & Stöcker, H. (2017). Rotational properties of hypermassive neutron stars from binary mergers. Physical Review D, 96(4), 043004

M. Hanauske, et.al., Connecting Relativistic Heavy Ion Collisions and Neutron Star Mergers by the Equation of State of Dense Hadron-and Quark Matter as signalled by Gravitational Waves, Journal of Physics: Conference Series, 878(1), p.012031 (2017)

Hanauske, Matthias, et al. "Gravitational waves from binary compact star mergers in the context of strange matter." *EPJ Web of Conferences*. Vol. 171. EDP Sciences, 2018.

Mark G. Alford, Luke Bovard, Matthias Hanauske, Luciano Rezzolla, and Kai Schwenzer (2018), Viscous Dissipation and Heat Conduction in Binary Neutron-Star Mergers. Phys. Rev. Lett. 120, 041101

Hanauske, Matthias, and Luke Bovard. "Neutron star mergers in the context of the hadron–quark phase transition." *Journal of Astrophysics and Astronomy* 39.4 (2018): 45.

Hanauske, Matthias, et al. "Neutron Star Mergers: Probing the EoS of Hot, Dense Matter by Gravitational Waves." *Particles* 2.1 (2019): 44-56.