UNIVERSITY OF AMSTERDAM

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Post-merger gravitational-wave signatures of phase transitions in binary mergers of compact stars

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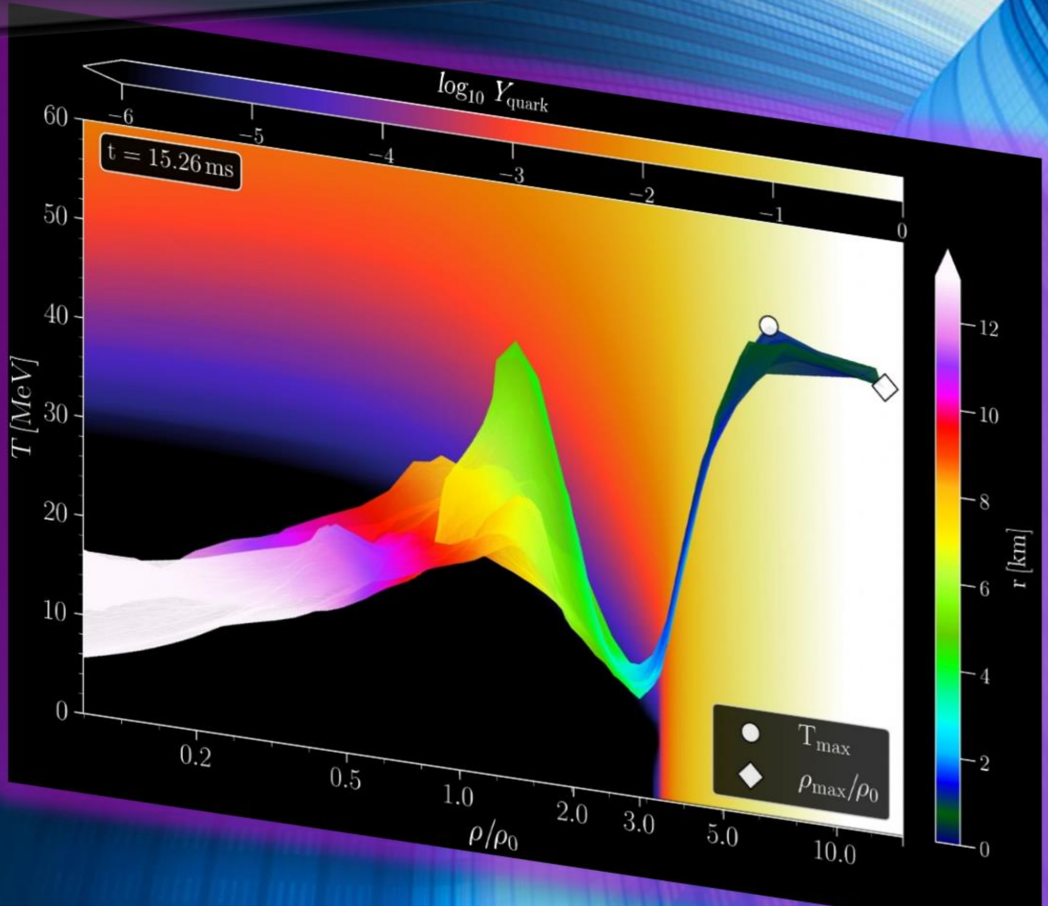
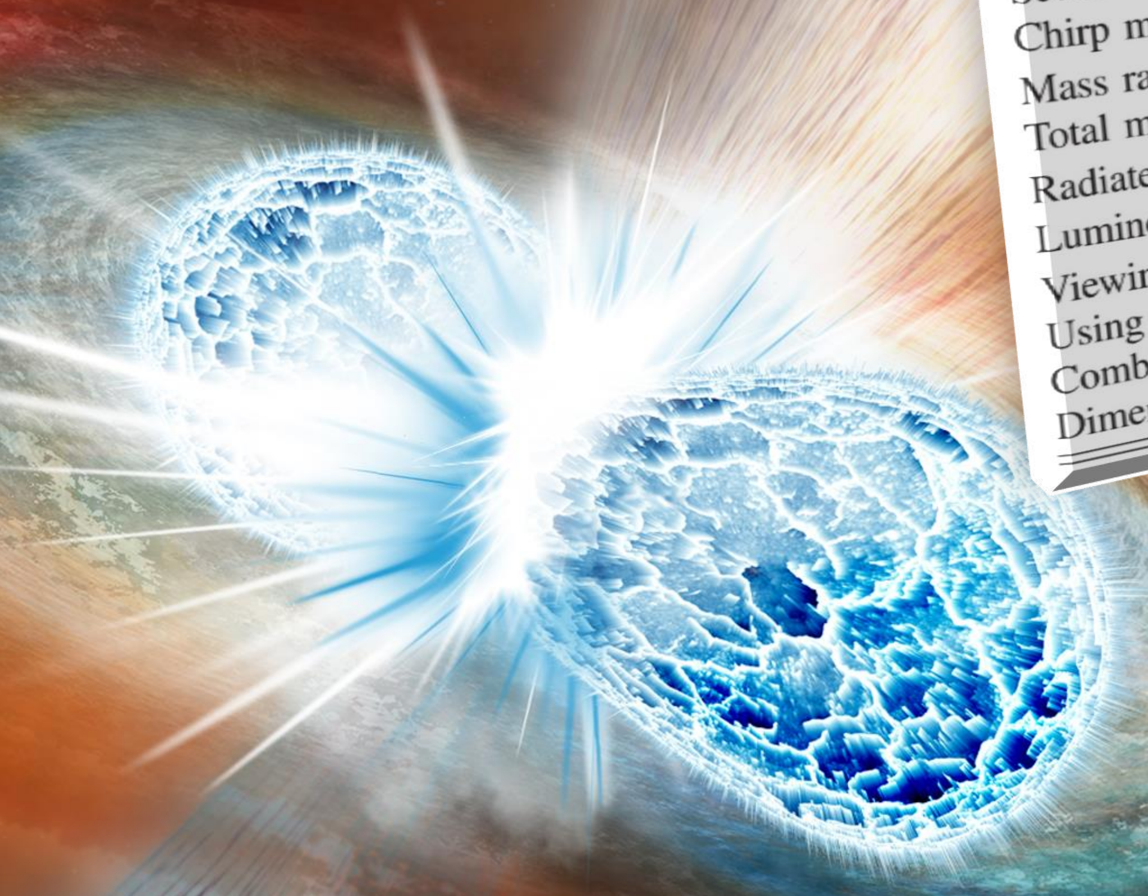
In collaboration with Lukas Weih, Elias R. Most, L. Jens Papenfort, Luke Bovard, Jan Steinheimer, Veronica Dexheimer, Horst Stöcker and Luciano Rezzolla



Post-merger gravitational-wave signatures of phase transitions in binary compact star mergers

- Introduction
  - GW170817 and GW190425 - the long-awaited events
  - Numerical relativity of compact star mergers
  - The equation of state of elementary matter and the hadron-quark phase transition
  - The compact star zoo: neutron stars, hybrid stars and strange quark stars
  - The different phases of a binary compact star merger event
  - Properties of HyperMassive Neutron Stars and the post-merger gravitational wave emission
  - HyperMassive Hybrid Stars
- Detecting the hadron-quark phase transition with gravitational waves
  - Most et.al., PHYSICAL REVIEW LETTERS 122, 061102 (2019)
  - Bauswein et.al., PHYSICAL REVIEW LETTERS 122, 061101 (2019)
  - Weih et.al., arXiv:1912.09340v1 [gr-qc] 19 Dec 2019 (submitted to PHYSICAL REVIEW LETTERS)

The long awaited event GW170817

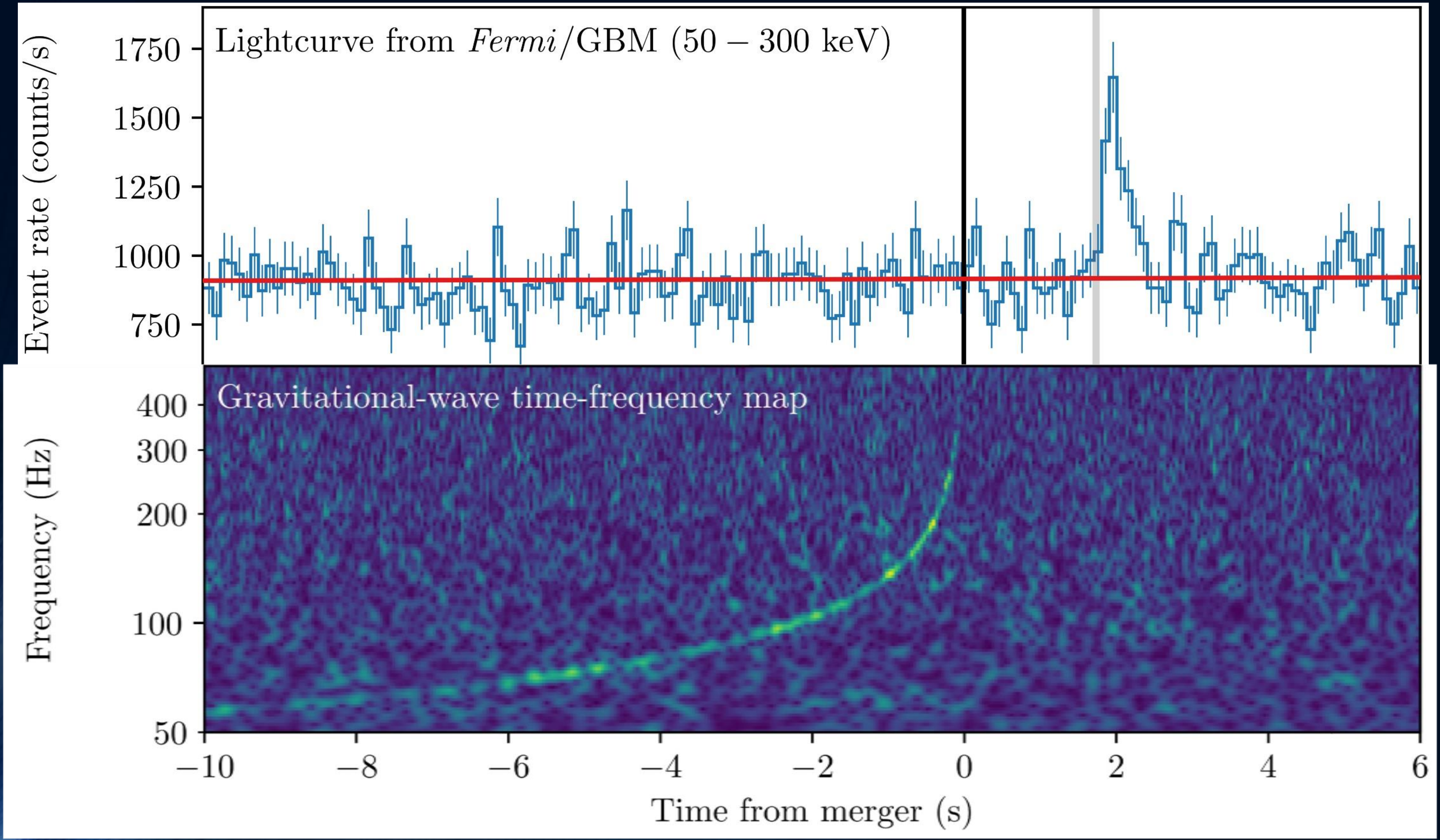


	Low-spin priors ($\|\chi\| \leq 0.05$)	High-spin priors ($\|\chi\| \leq 0.89$)
Primary mass m_1	1.36–1.60 $M_\odot$	1.36–2.26 $M_\odot$
Secondary mass m_2	1.17–1.36 $M_\odot$	0.86–1.36 $M_\odot$
Chirp mass $\mathcal{M}$	$1.188^{+0.004}_{-0.002} M_\odot$	$1.188^{+0.004}_{-0.002} M_\odot$
Mass ratio m_2/m_1	0.7–1.0	0.4–1.0
Total mass m_{tot}	$2.74^{+0.04}_{-0.01} M_\odot$	$2.82^{+0.47}_{-0.09} M_\odot$
Radiated energy E_{rad}	$> 0.025 M_\odot c^2$	$> 0.025 M_\odot c^2$
Luminosity distance D_L	40^{+8}_{-14} Mpc	40^{+8}_{-14} Mpc
Viewing angle Θ	$\leq 55°$	$\leq 56°$
Using NGC 4993 location	$\leq 28°$	$\leq 28°$
Combined dimensionless tidal deformability $\tilde{\Lambda}$	≤ 800	≤ 700
Dimensionless tidal deformability $\Lambda(1.4 M_\odot)$	≤ 800	≤ 1400

17. August 2017

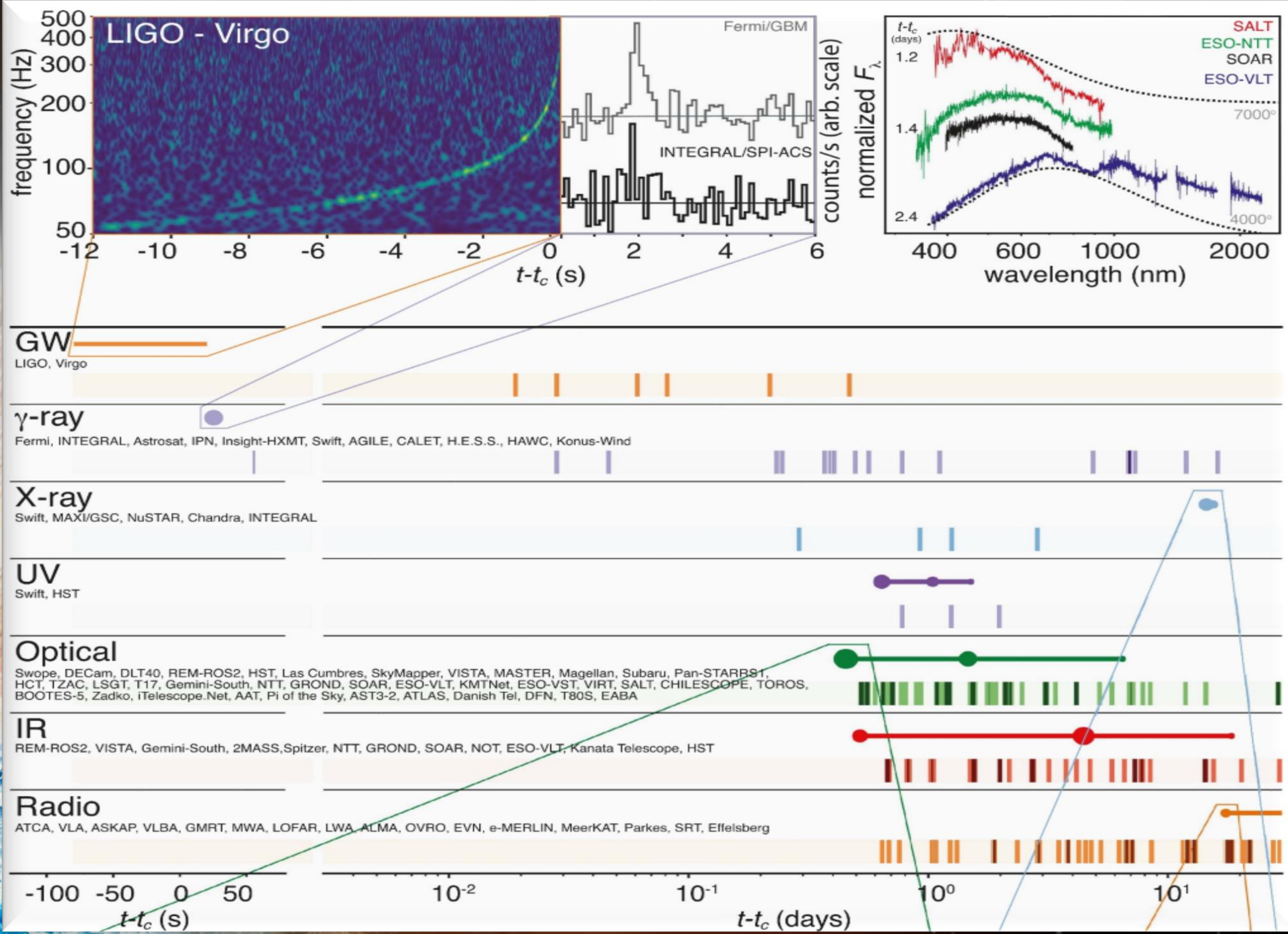
First detection of a gravitational wave from a binary neutron star merger event!

Gravitational Wave GW170817 and Gamma-Ray Emission GRB170817A

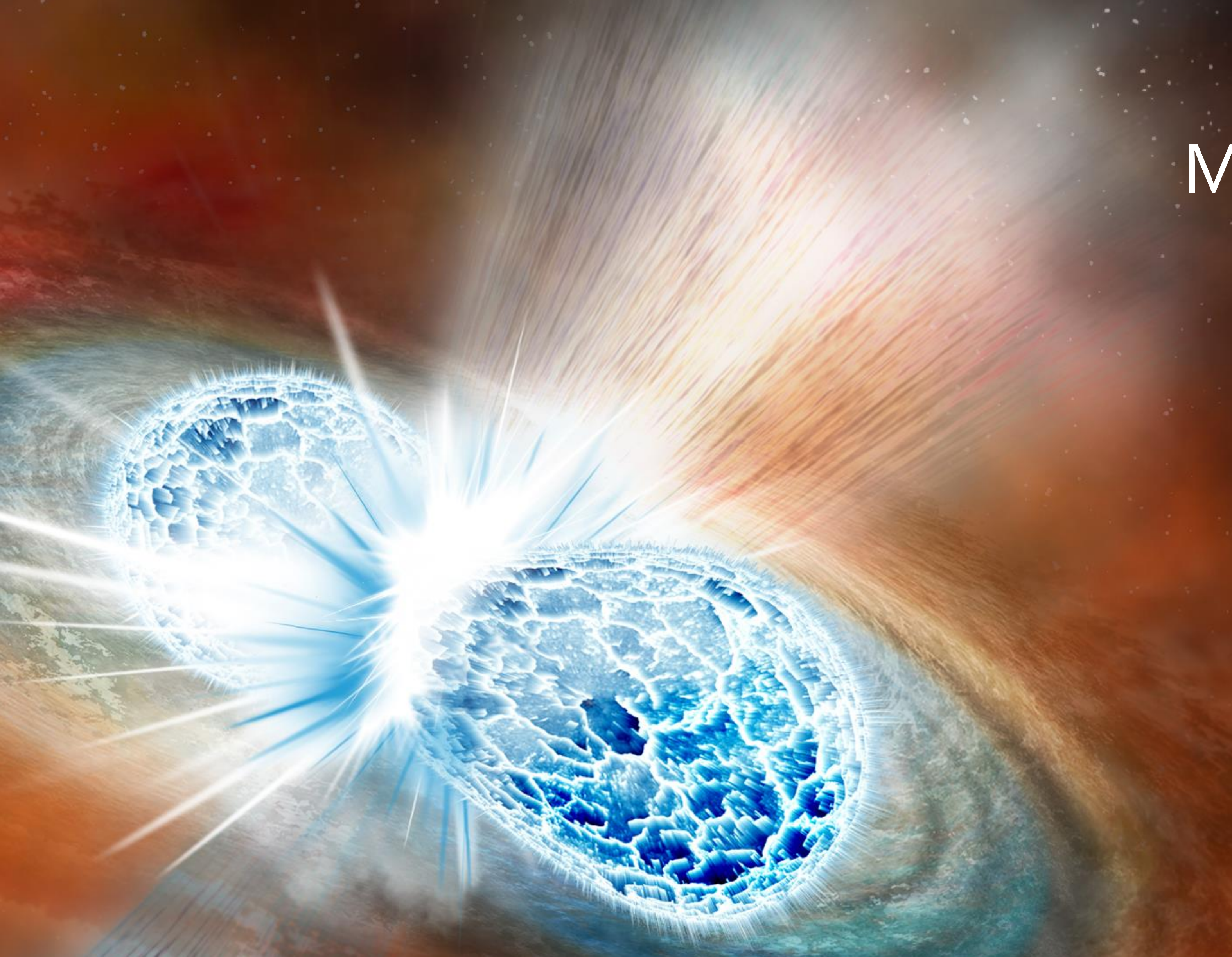


GW170817

Kilonova observed



The second event: GW190425

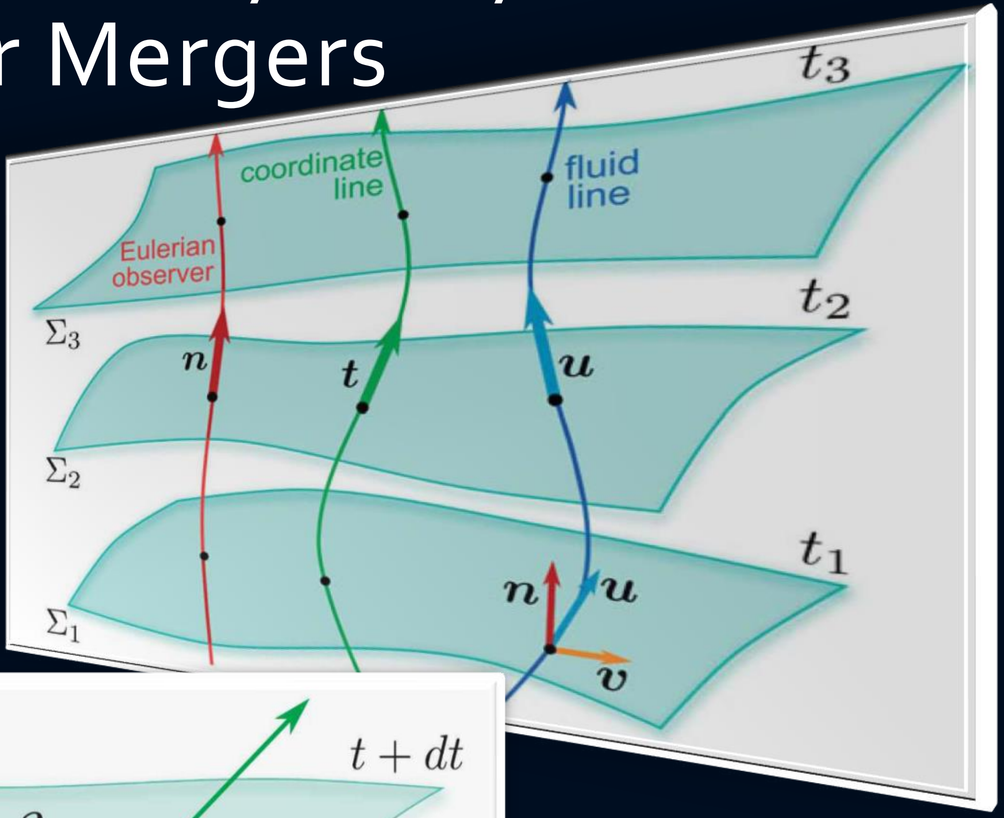


Mass ~ 3.4 $M_\odot$

19. April 2019

Second detection of a gravitational wave from a binary neutron star merger event!

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:

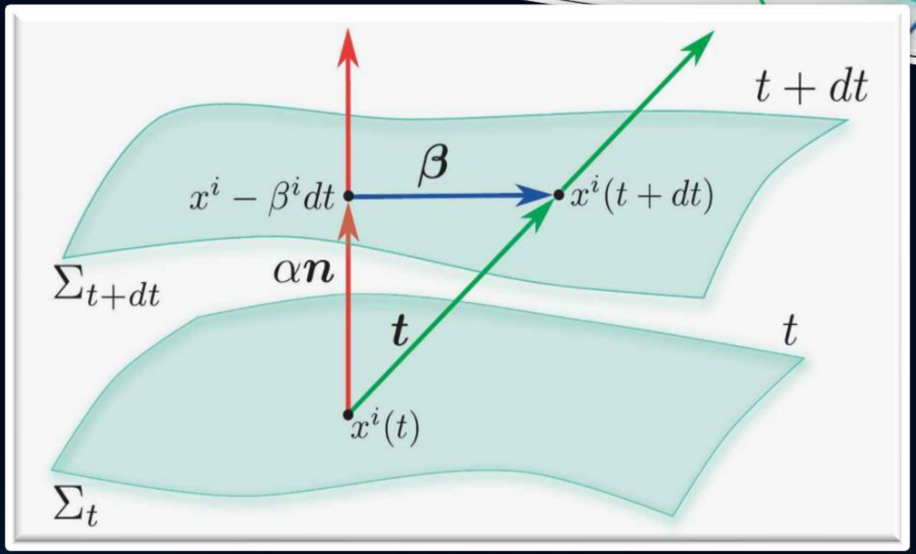
$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = 8\pi T_{\mu\nu}$$

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

(3+1) decomposition of spacetime

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

$$d\tau^2 = \alpha^2(t, x^j) dt^2 \qquad x^i_{t+dt} = x^i_t - \beta^i(t, x^j) dt$$



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

The Einstein Equation and the EOS of Compact Stars

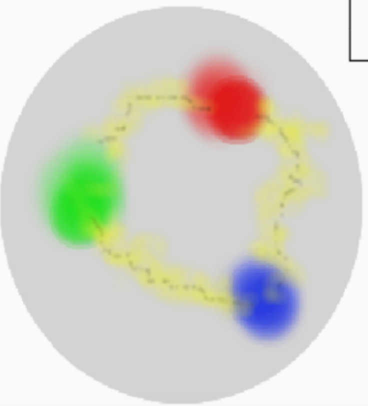
ART	Yang-Mills-Theories
$D_\beta v^\alpha = \partial_\beta\, v^\alpha + \Gamma^\alpha_{\sigma\beta}\, v^\sigma$	$D_{\beta a}{}^{b} = \partial_\beta\, 1_a{}^b + ig\, A_{\beta a}{}^{b}$
$R^\delta{}_{\mu\alpha\beta}\, v^\mu = [D_\alpha, D_\beta]\, v^\delta$ $R^\delta{}_{\mu\alpha\beta} = \Gamma^\delta_{\mu\alpha\|\beta}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

QuantumCromoDynamic:

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

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

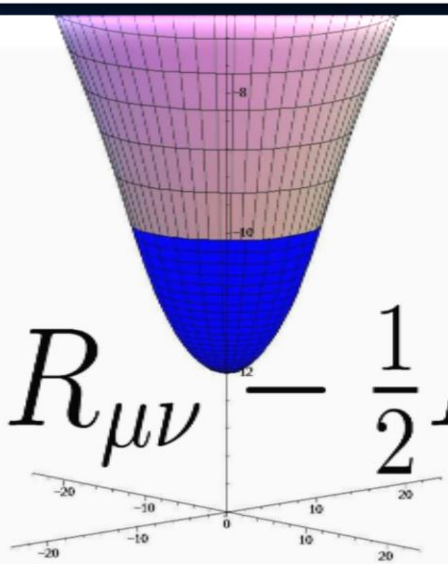
$_{A,}{}^{B}$ =red, green, blue



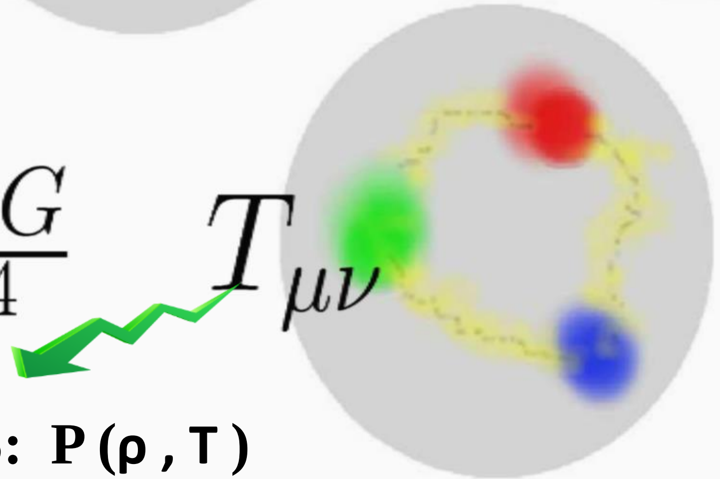
$$\psi^f_A = \begin{pmatrix} \psi^f_r \\ \psi^f_g \\ \psi^f_b \end{pmatrix}$$

Confinement

chiral symmetry, ...



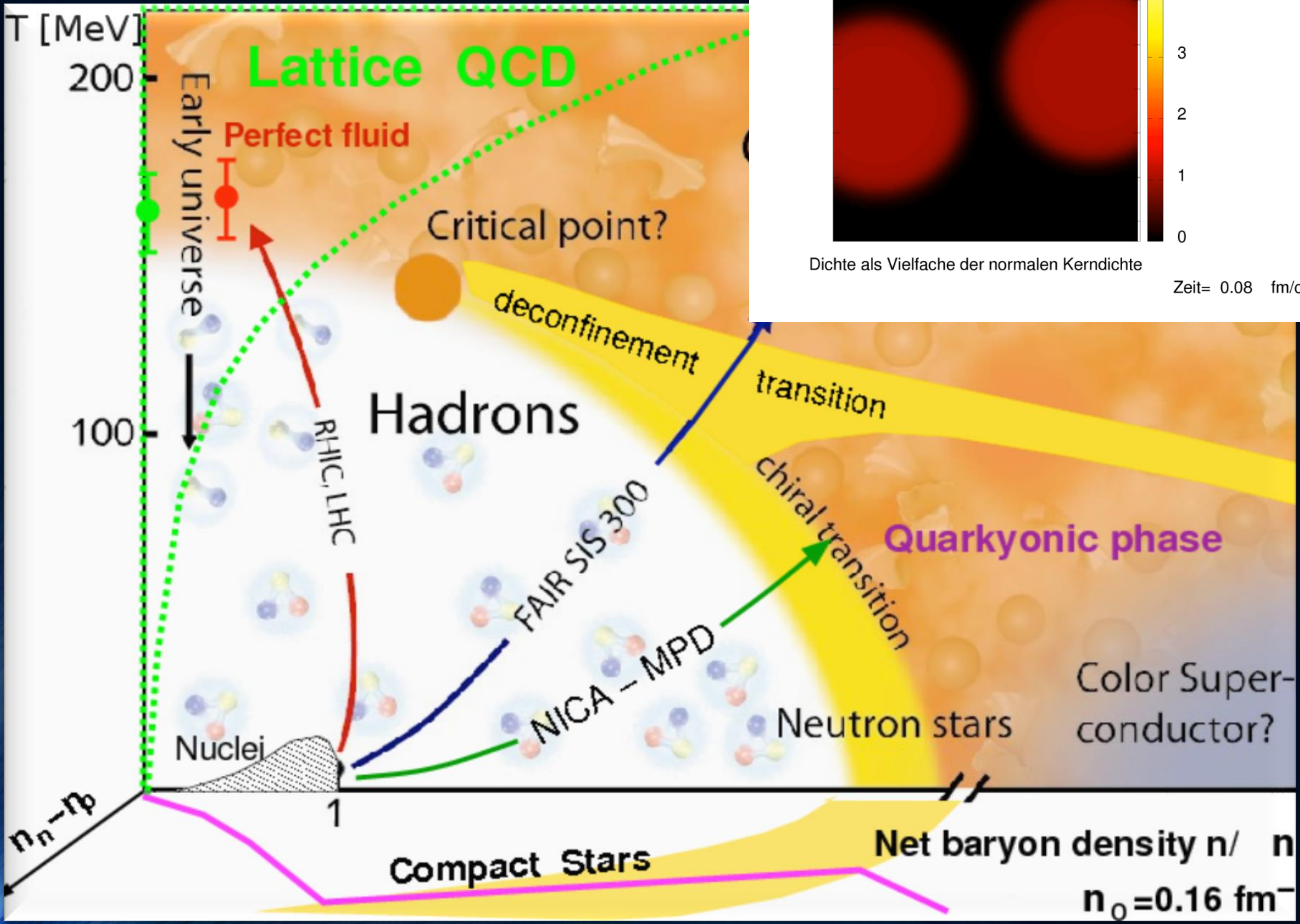
$$R_{\mu\nu} - \frac{1}{2} R\, g_{\mu\nu} = \frac{8\pi G}{c^4}\, T_{\mu\nu}$$

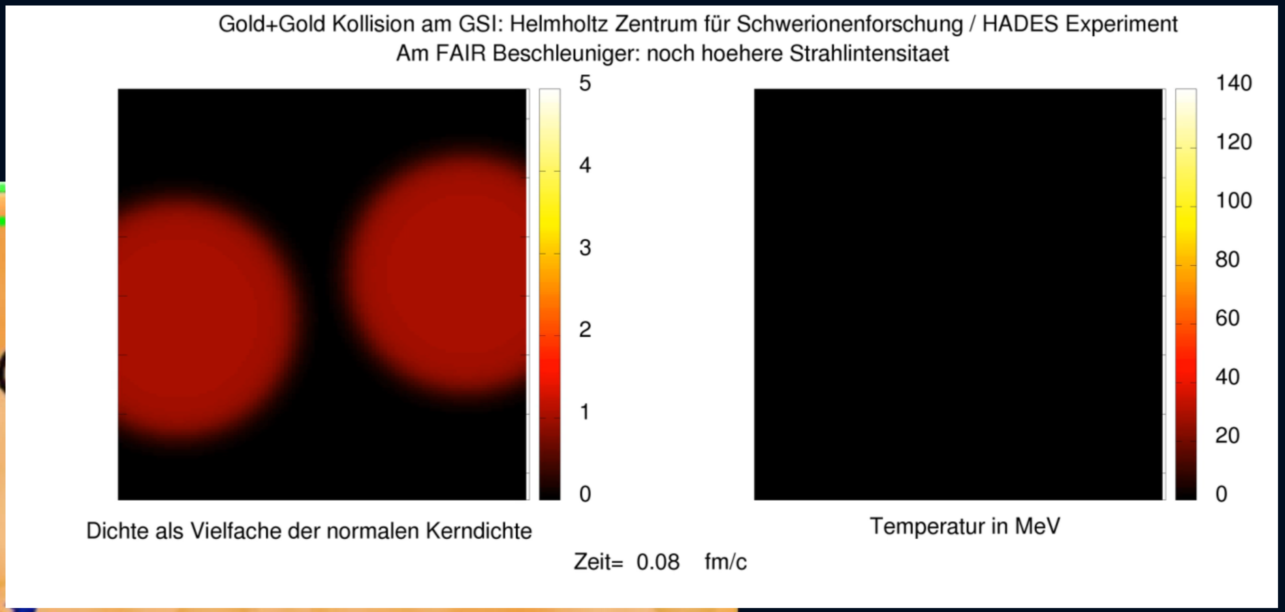


EOS: P (ρ , T)

The Hadron-Quark Phase Transition

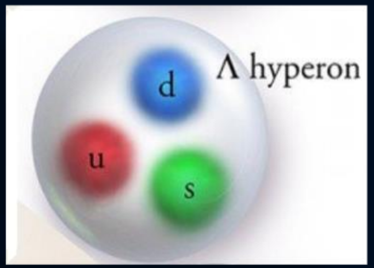
The QCD Phase Diagram



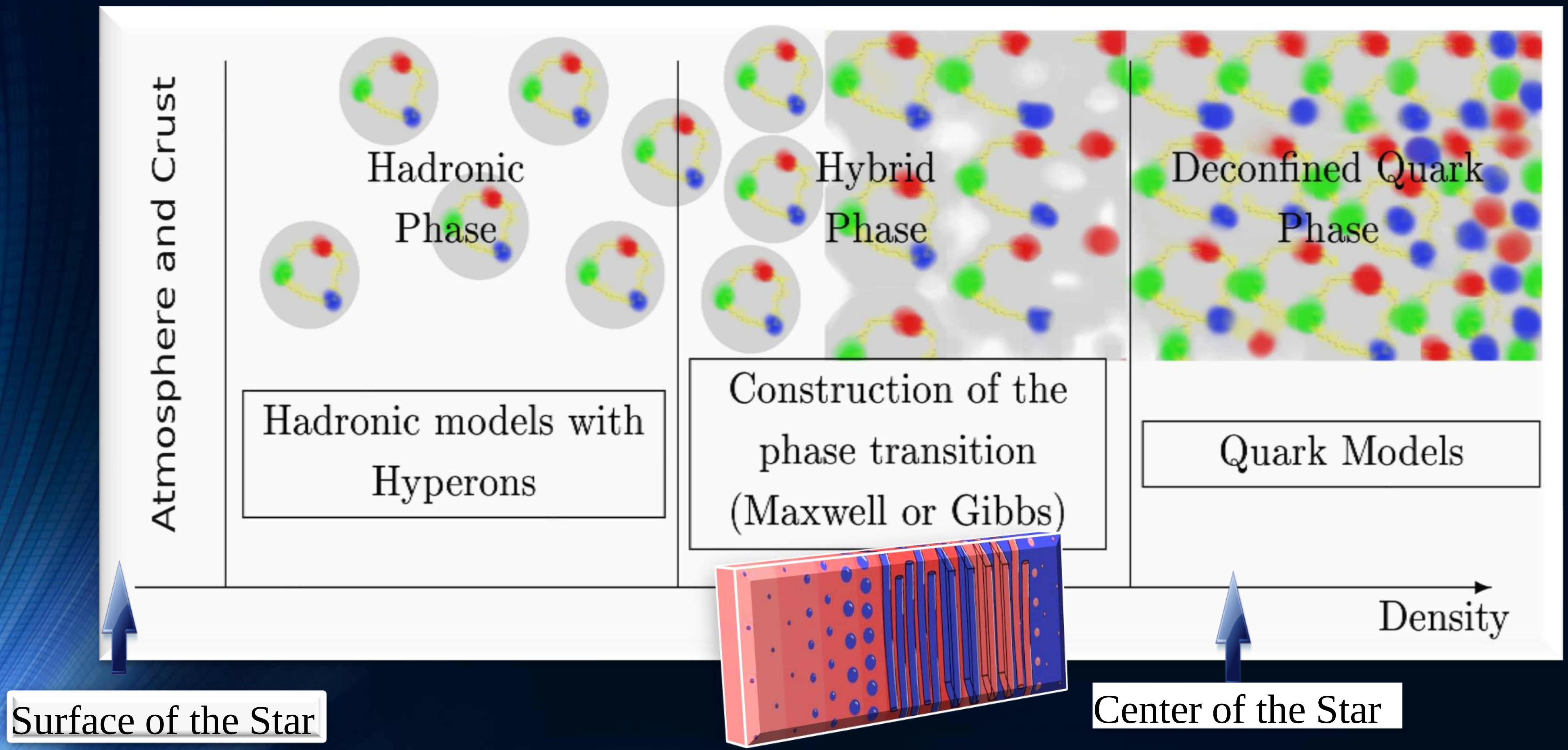


Credits:
Jan Steinheimer

Neutron Proton

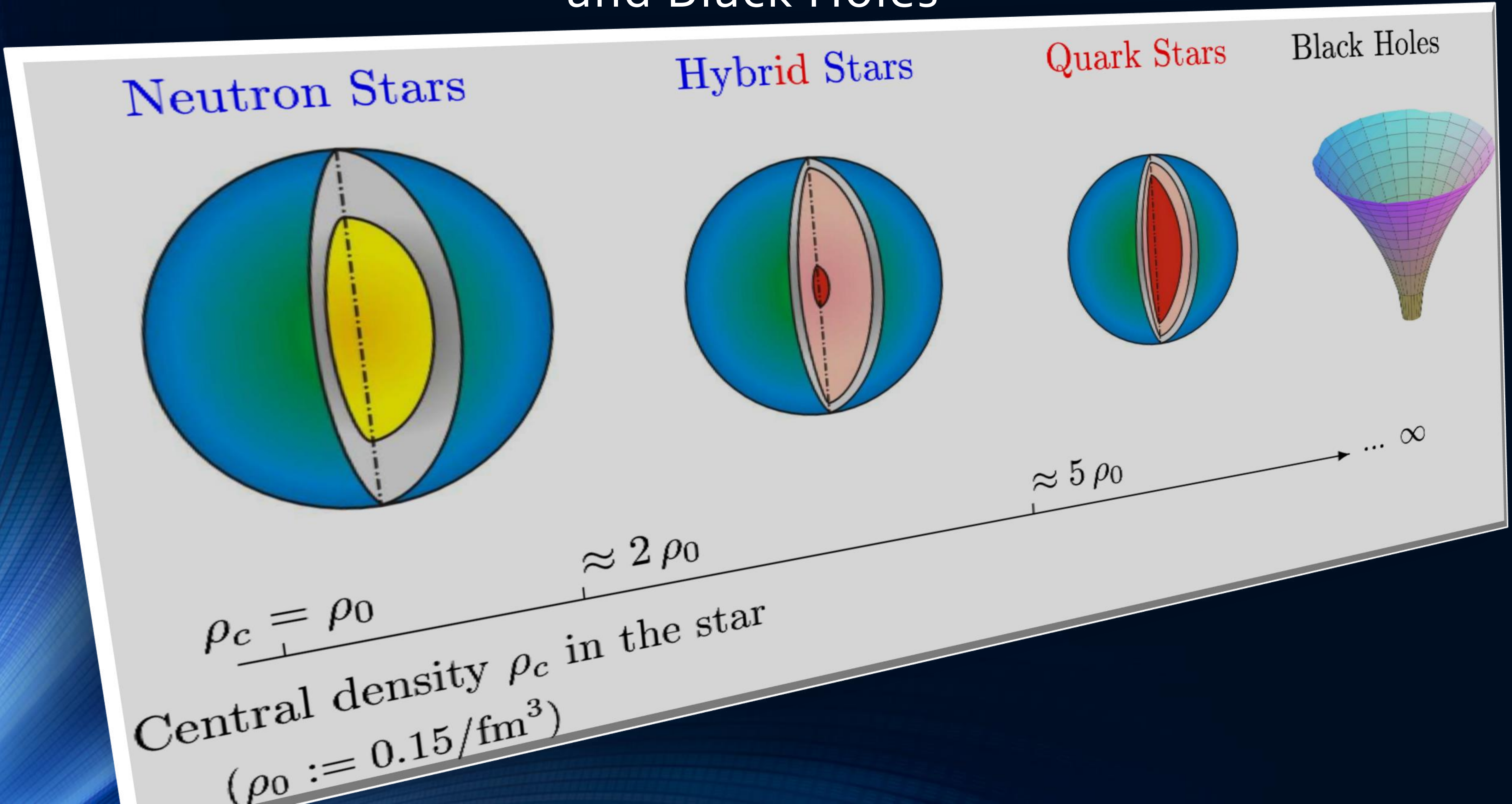


The QCD – Phase Transition and the Interior of a Hybrid Star

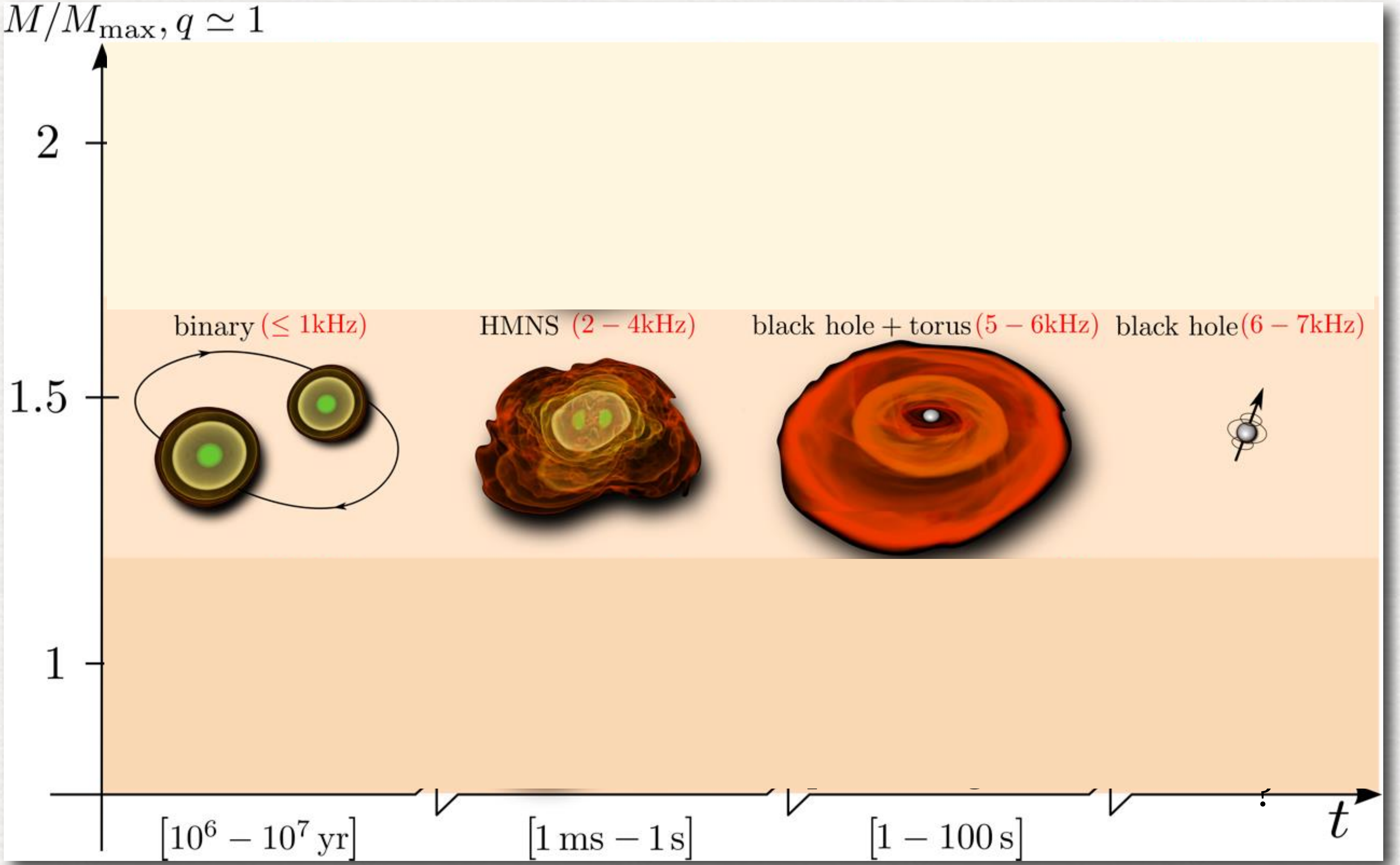


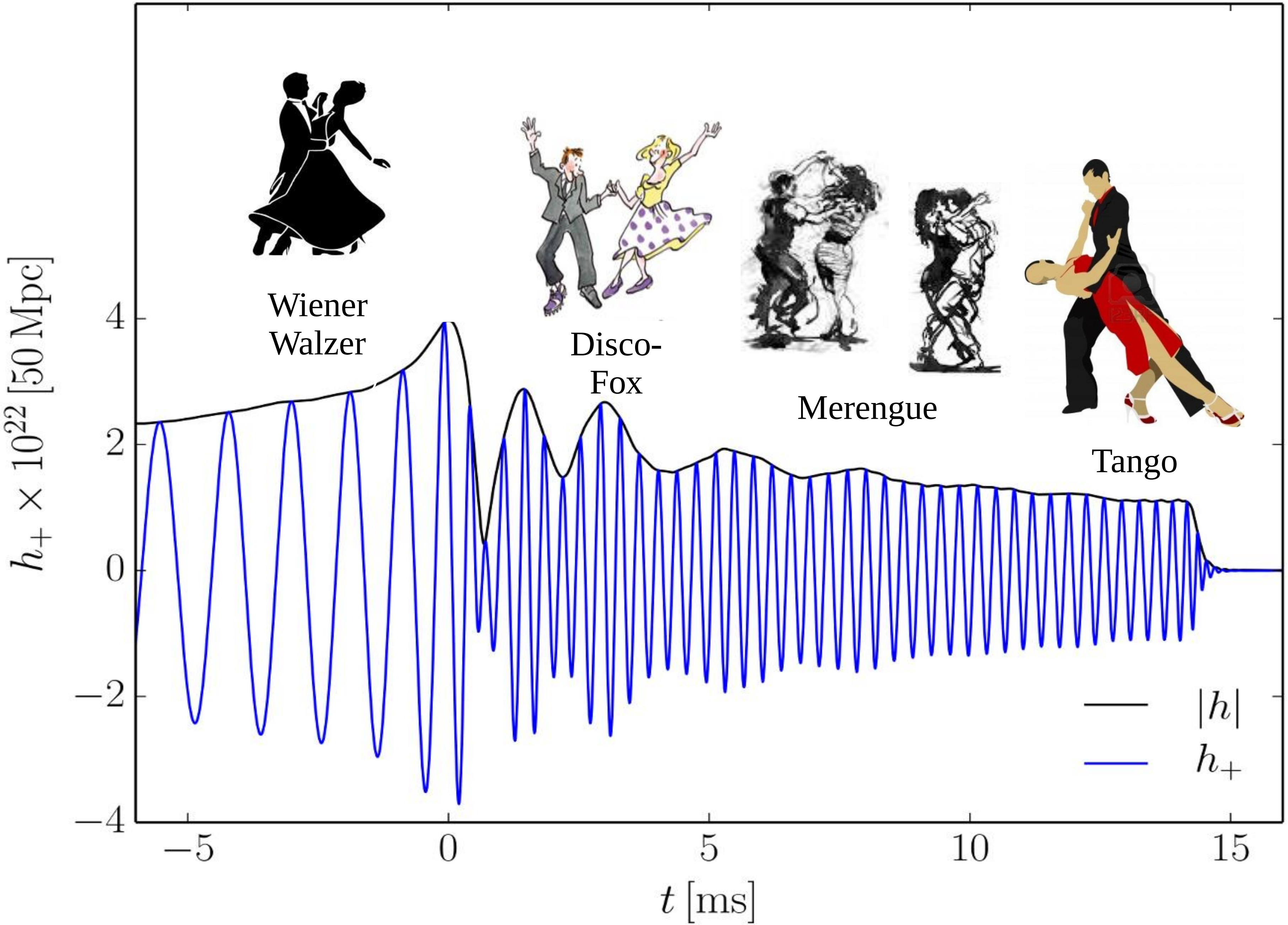
Matthias Hanauske; Doctoral Thesis:
Properties of Compact Stars within QCD-motivated Models; University Library Publication Frankfurt (2004)

Neutron Stars, Hybrid Stars, Quark Stars and Black Holes



Broadbrush picture



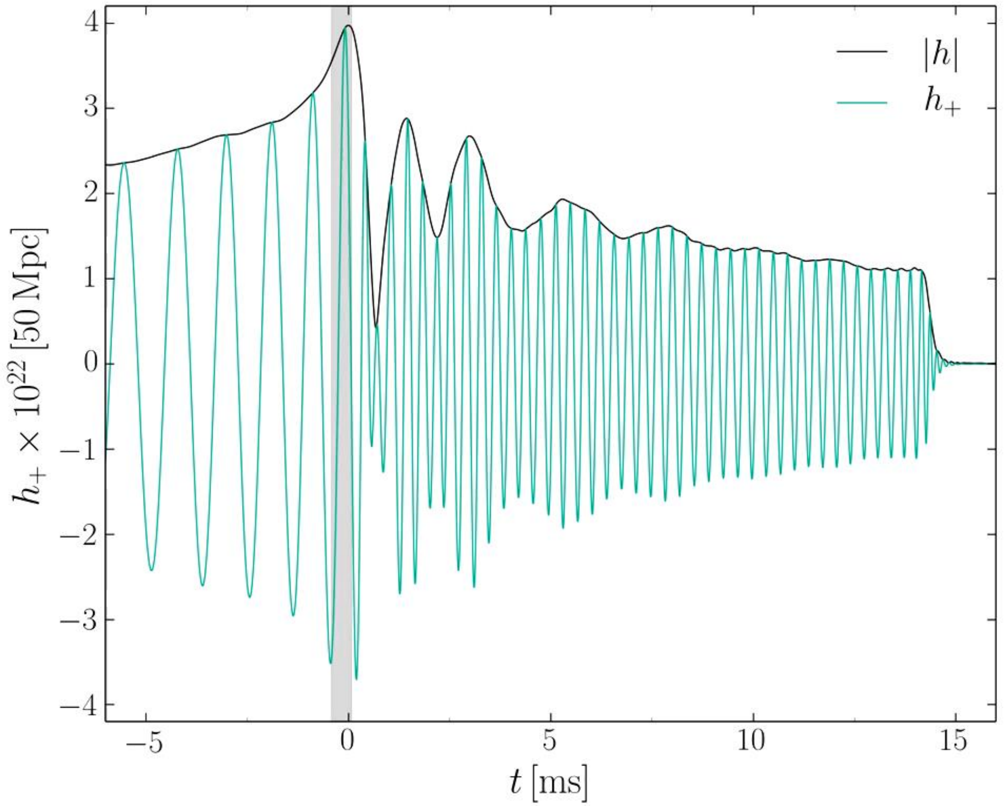


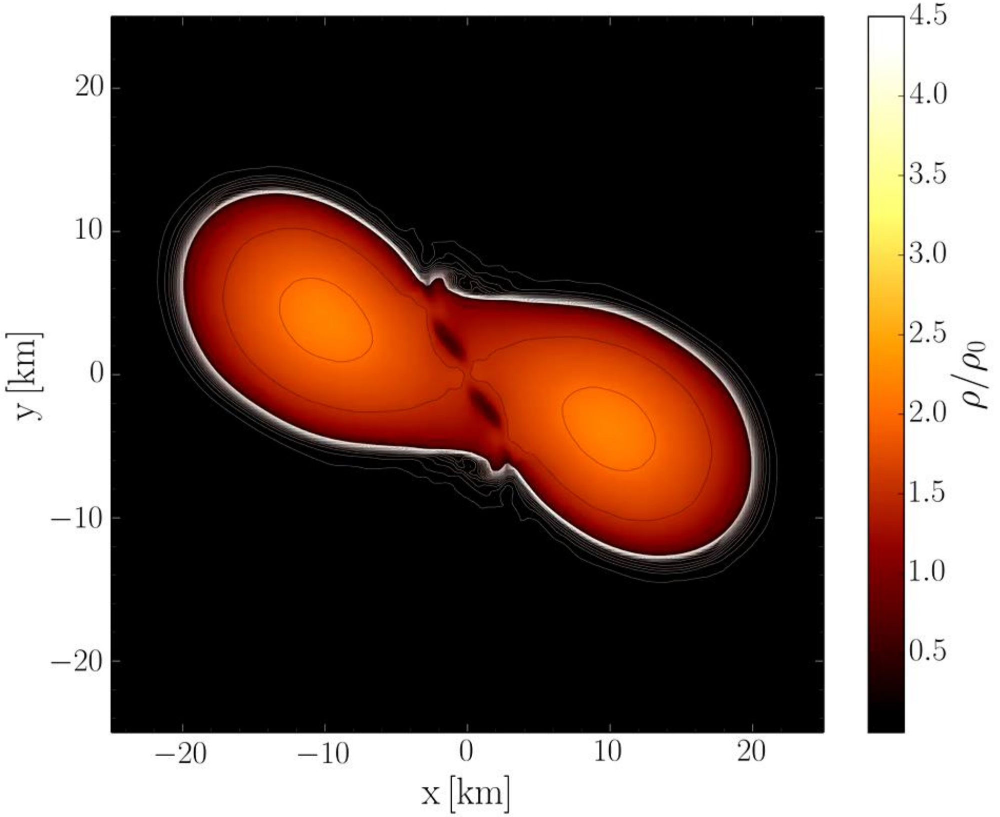
Wiener
Walzer
Disco-
Fox
Merengue
Tango
$h_+ \times 10^{22}\,[50\,\mathrm{Mpc}]$
$t\,[\mathrm{ms}]$
$|h|$
h_+
4
2
0
−2
−4
−5
0
5
10
15

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}

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

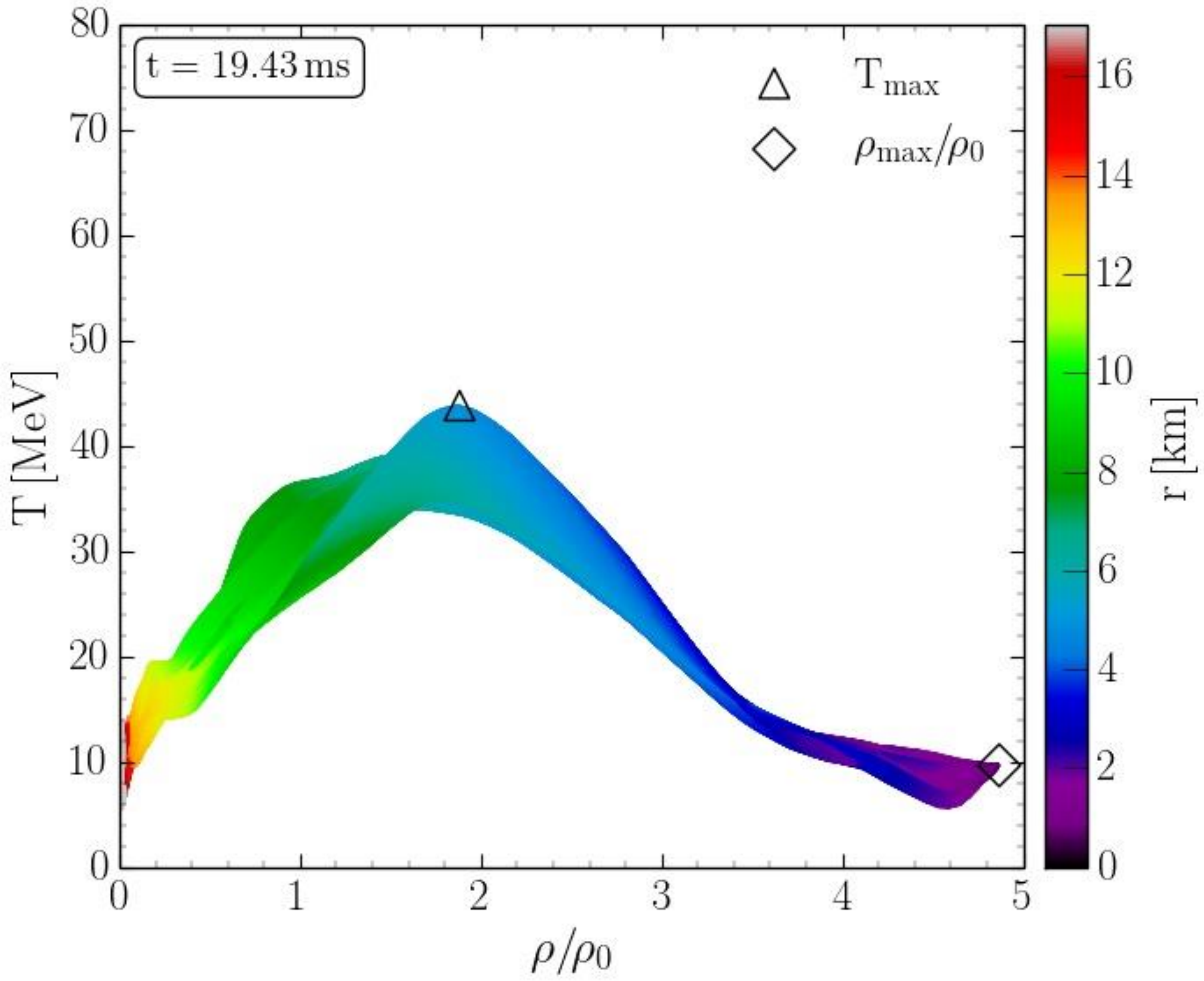




Gravitational wave amplitude
at a distance of 50 Mpc

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

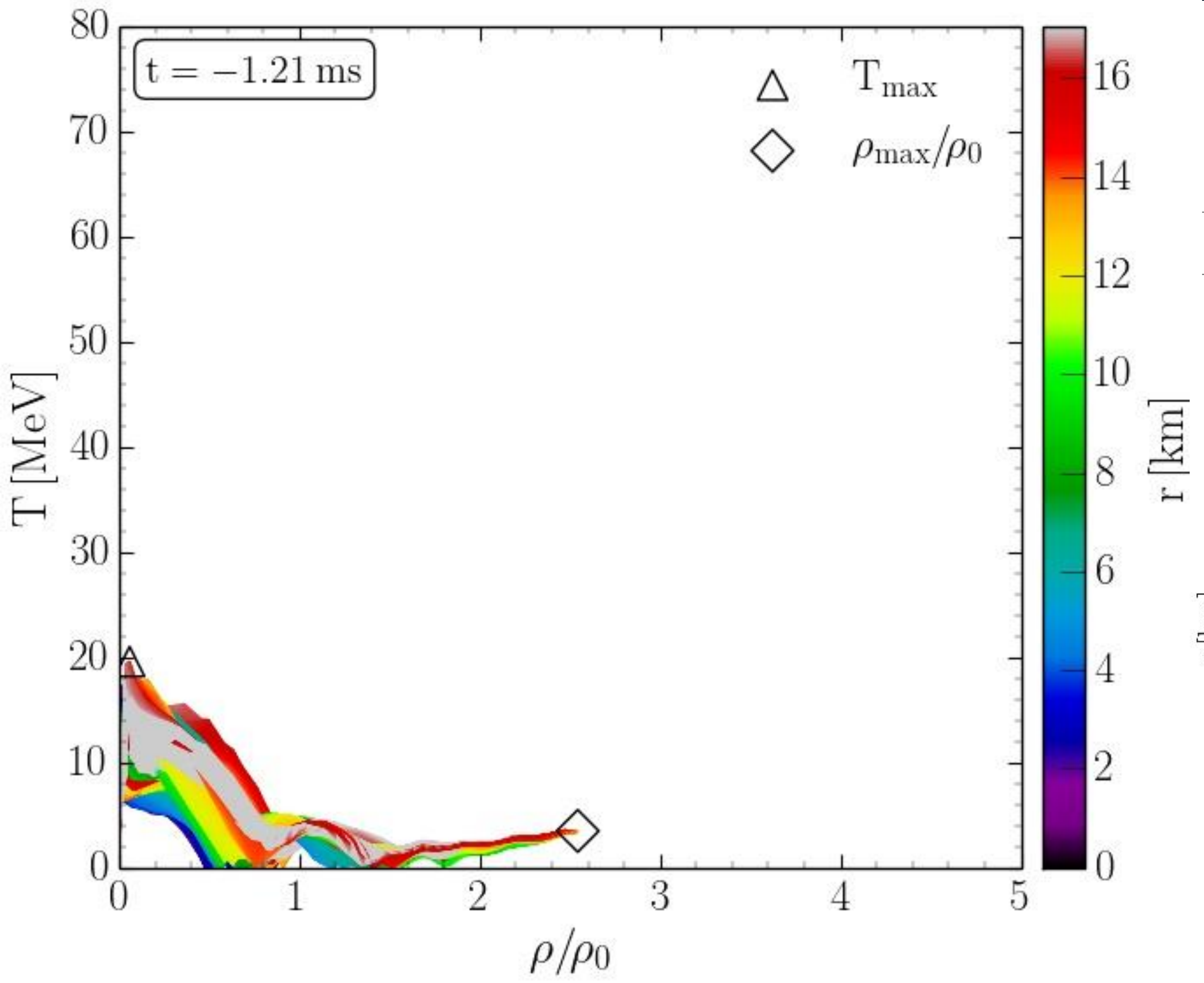


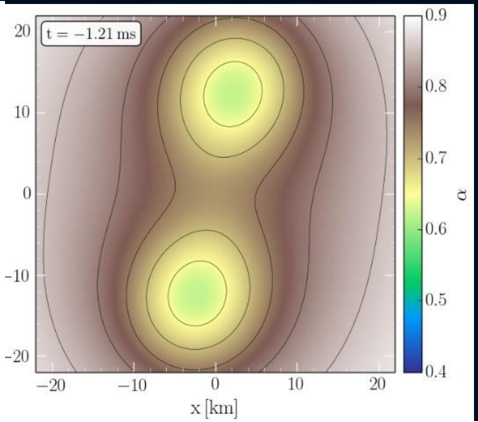
Density-temperature profiles inside the inner area of a hypermassive neutron star simulated within the LS220 EOS with a total mass of M_{total}=2.7 M_{solar} in the style of a (T-ρ) QCD phase diagram plot at t=19.43 ms after the merger.

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.

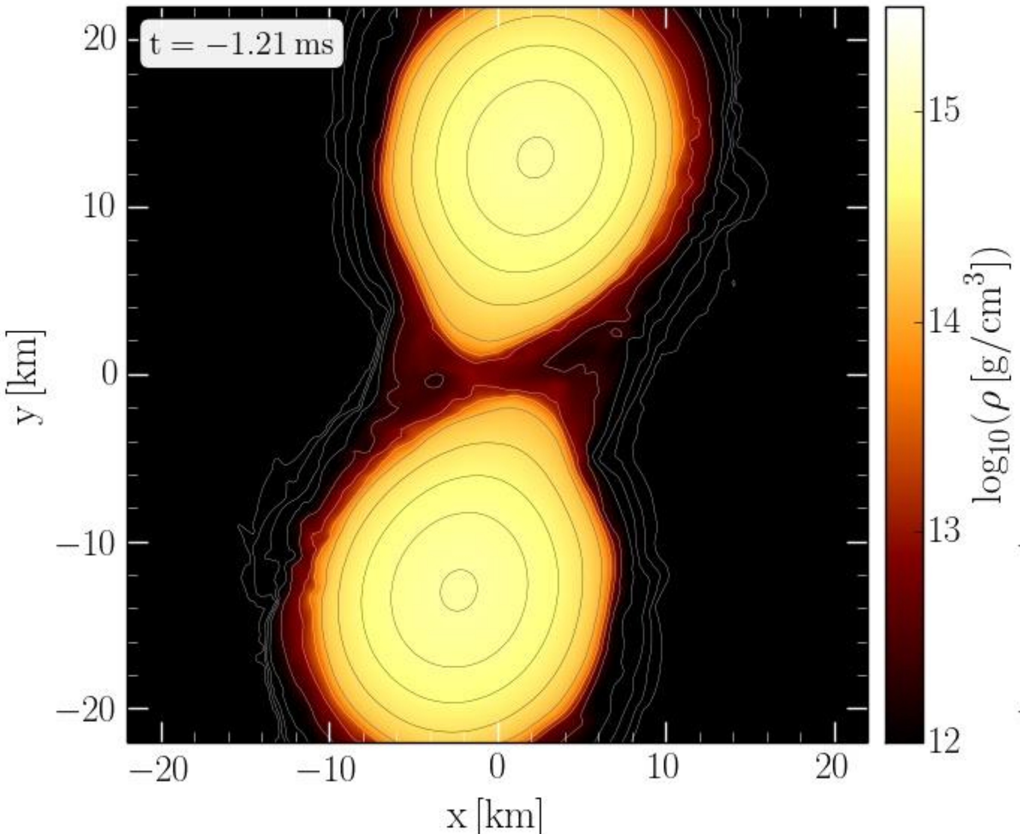
QCD Phase Diagram: The Late Inspiral Phase



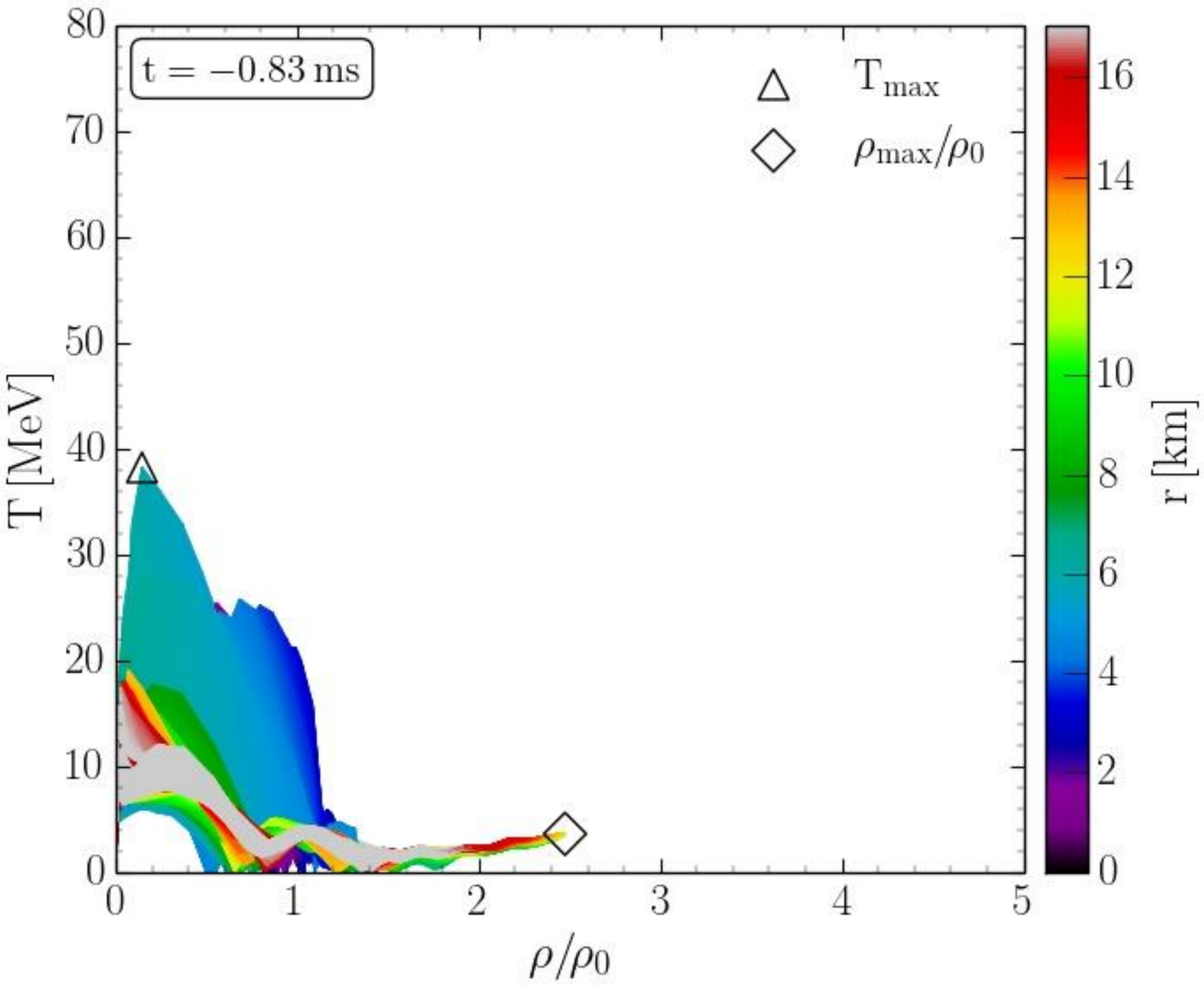


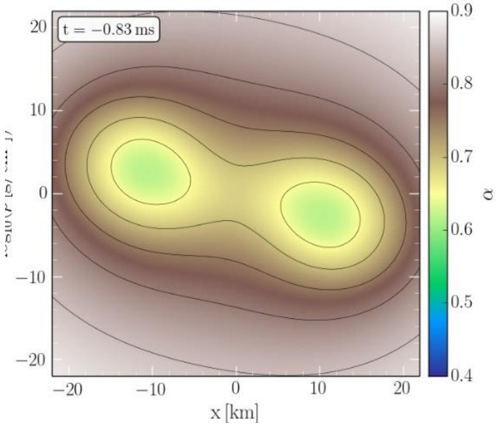
Lapse function α (left)

rest mass density ρ



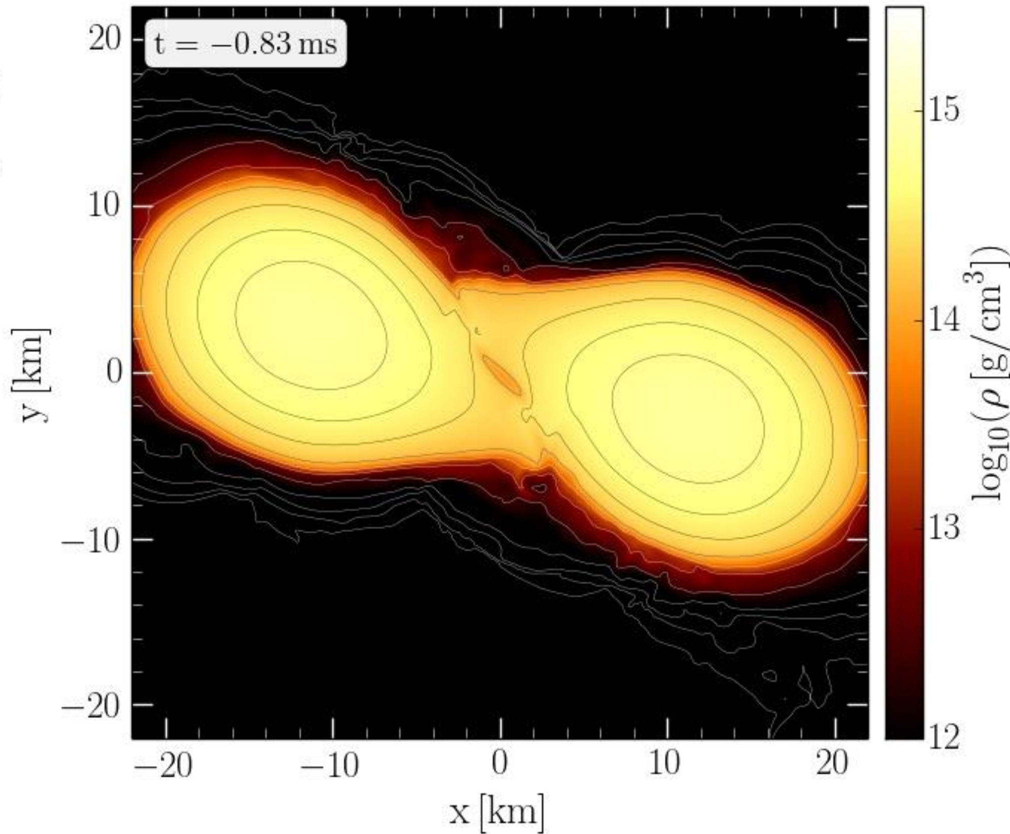
QCD Phase Diagram: The Late Inspiral Phase



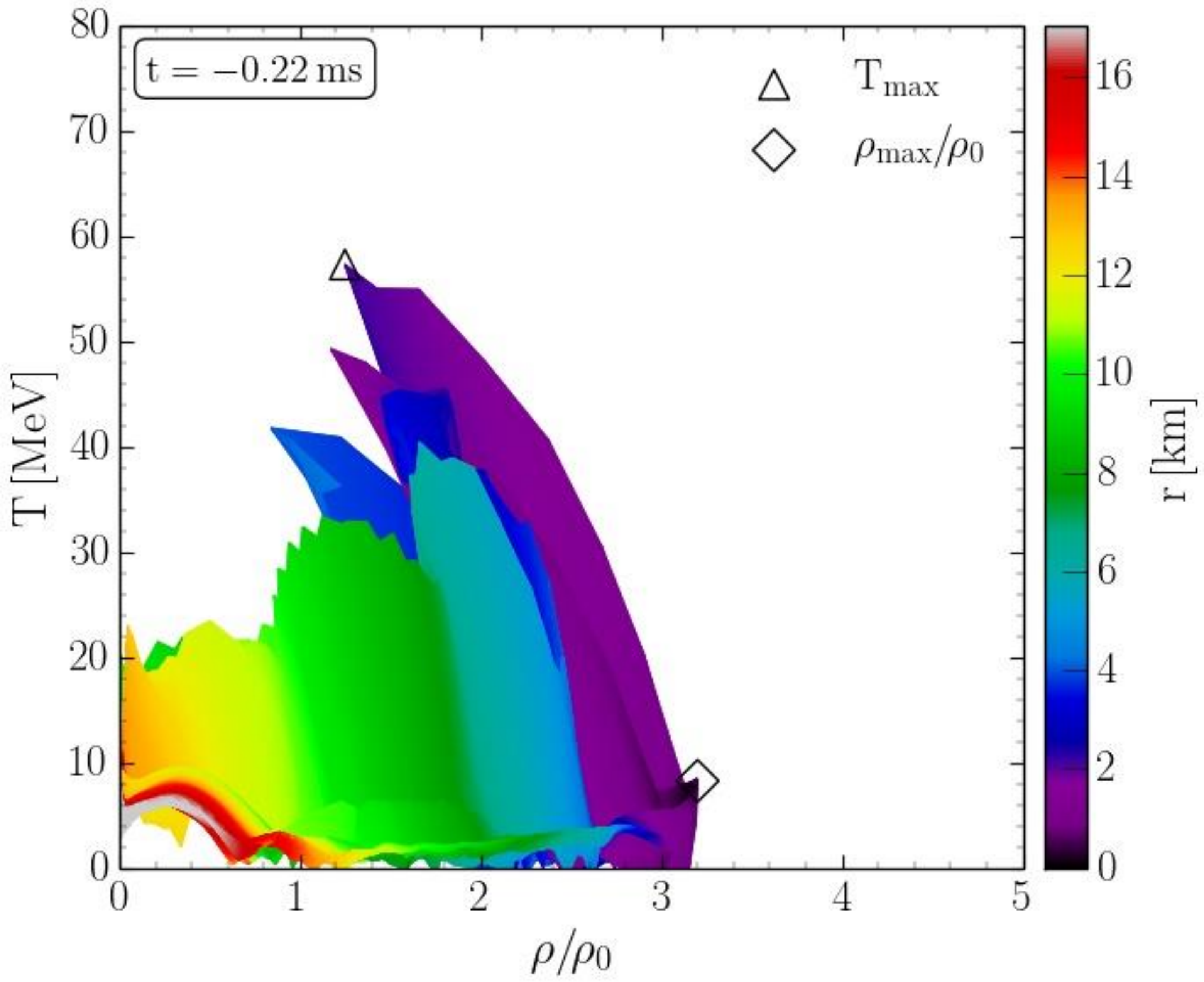


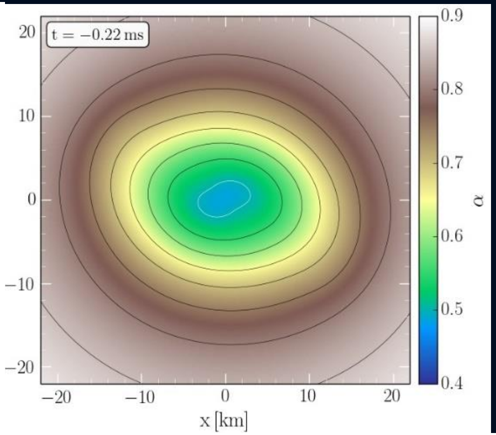
Lapse function α (left)

rest mass density ρ



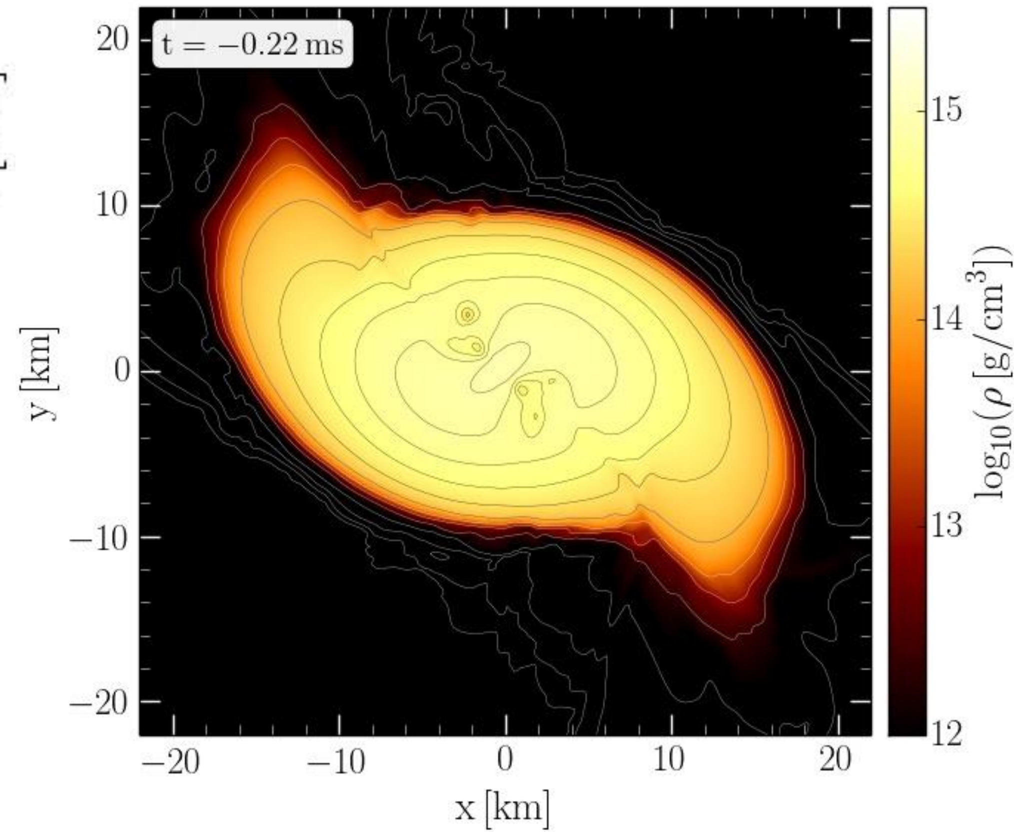
QCD Phase Diagram: The Late Inspiral Phase



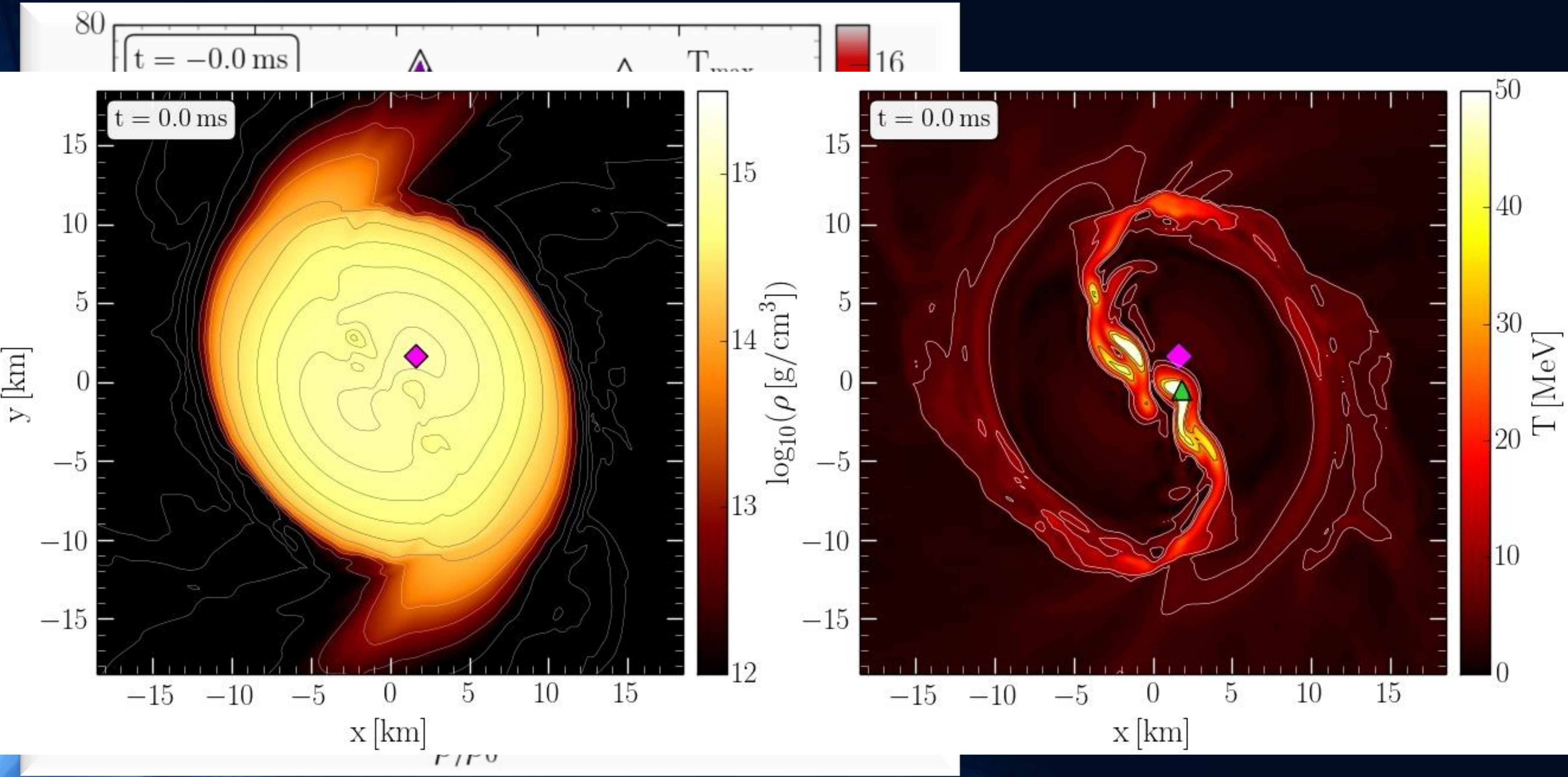


Lapse function α (left)

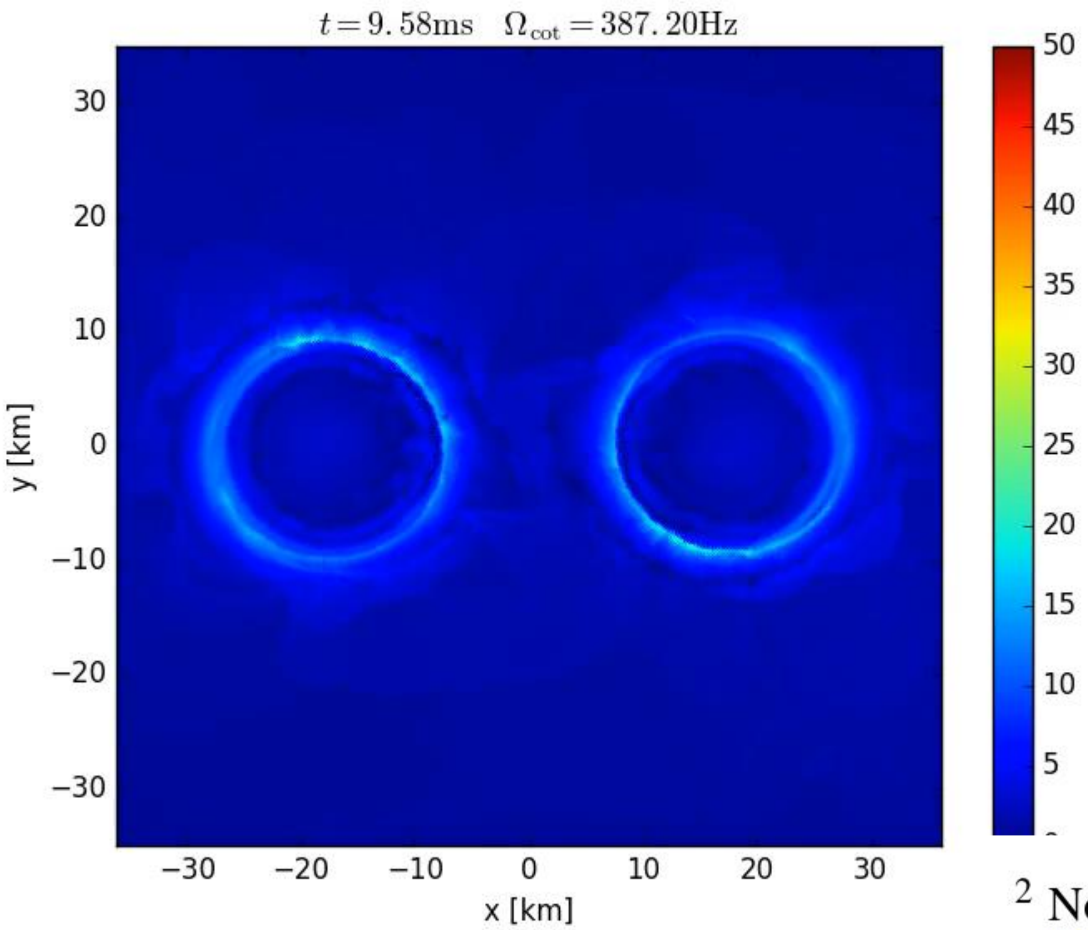
rest mass density ρ

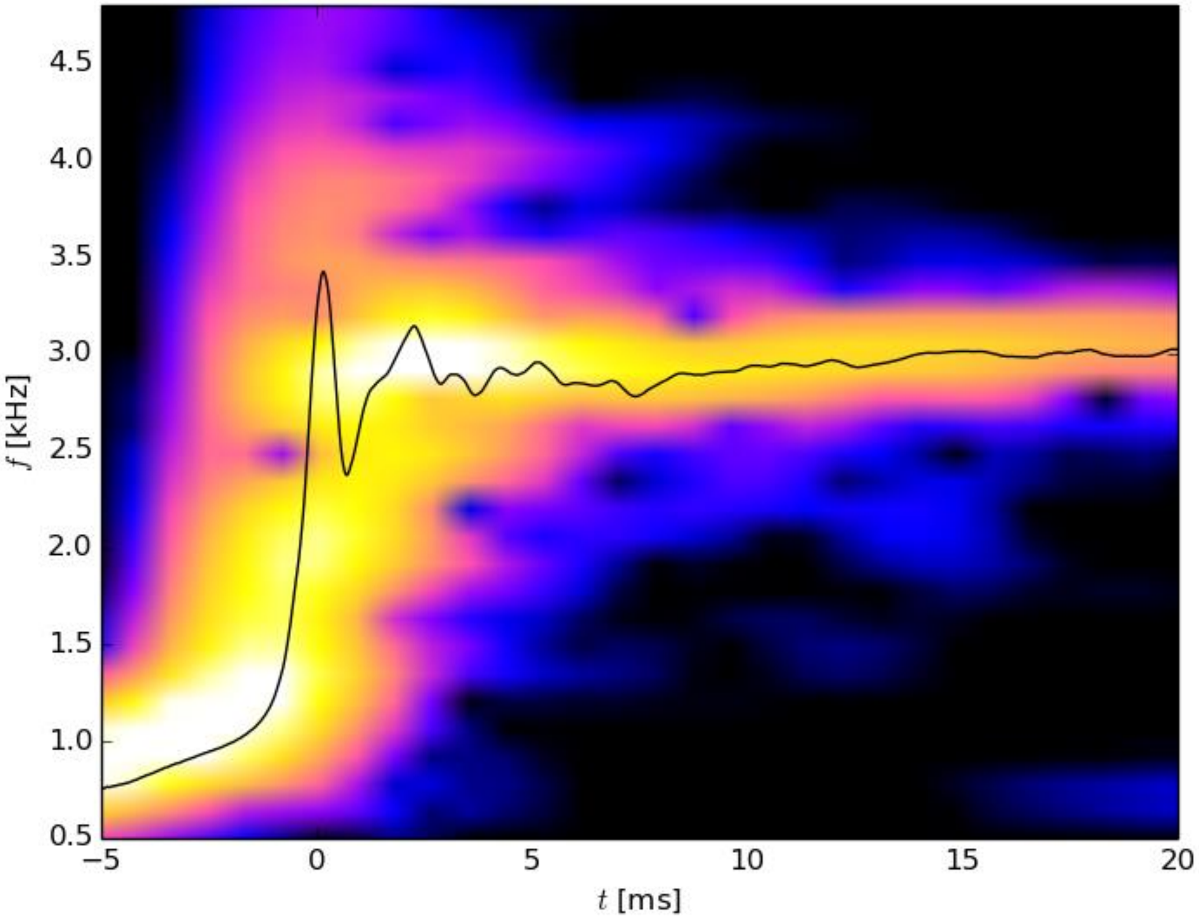


Binary Neutron Star Mergers in the QCD Phase Diagram



The Co-Rotating Frame

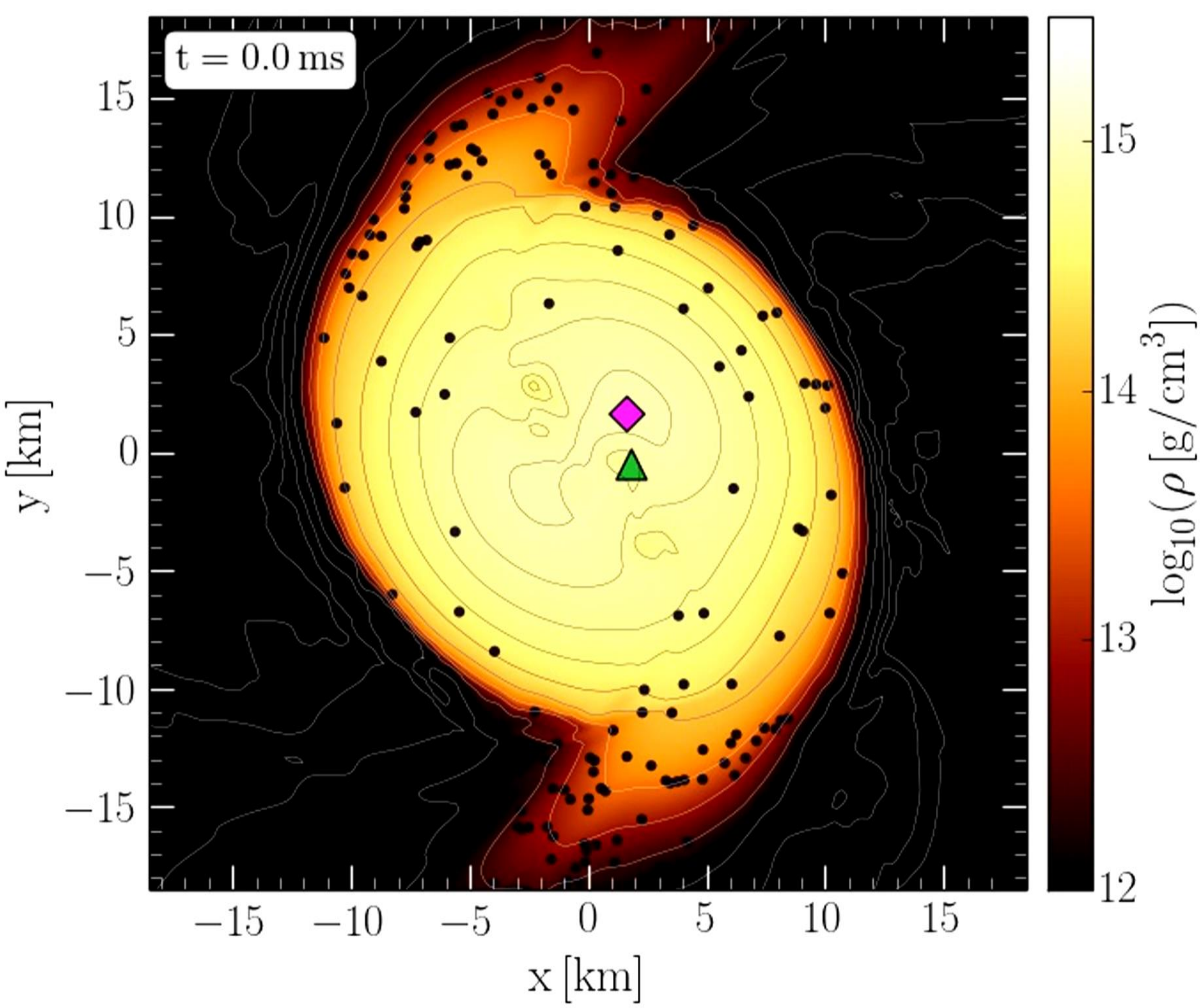


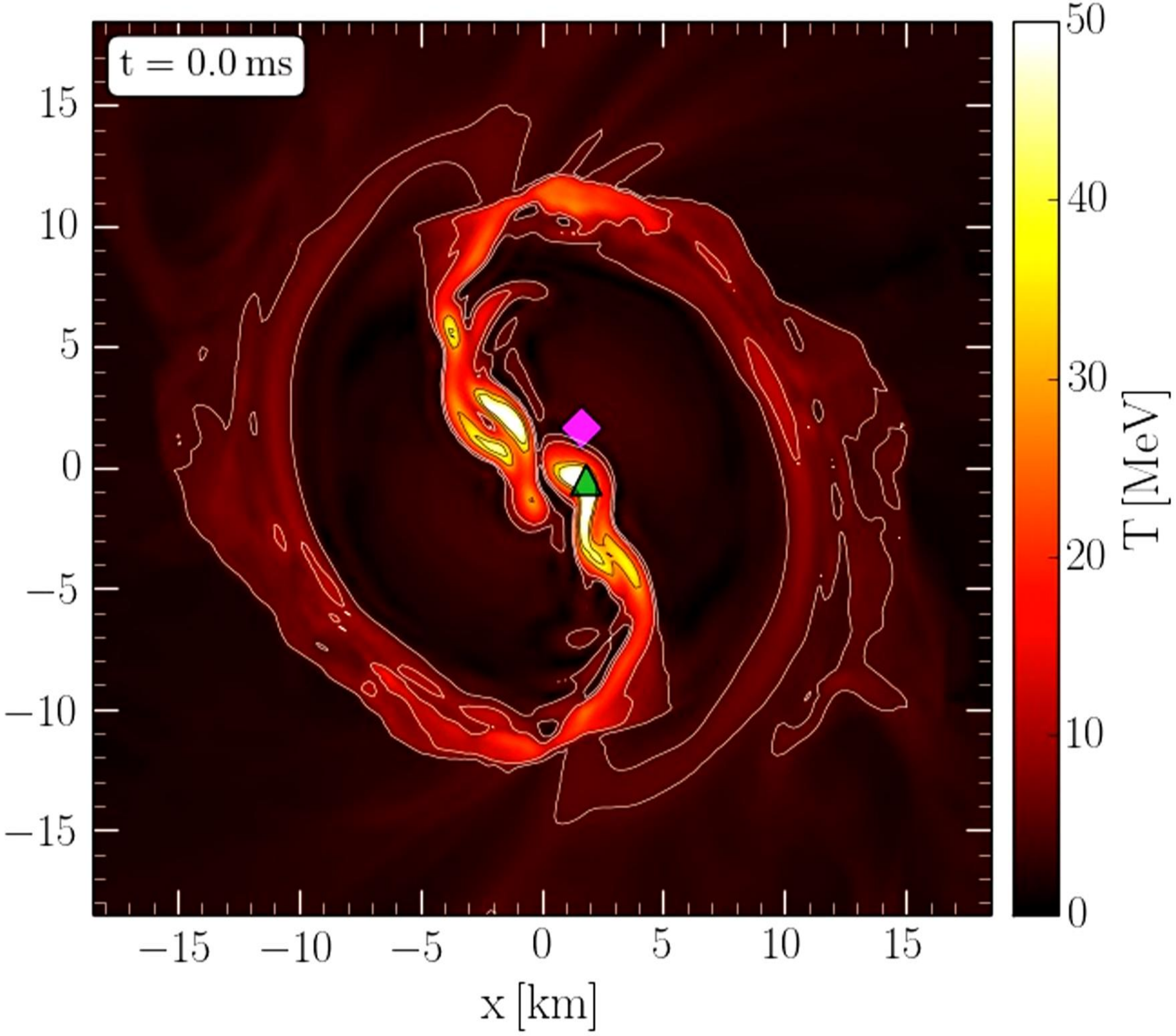


[2] Note that the angular-velocity distribution in the lower central panel of Fig. 10 refers to the corotating frame and that this frame is rotating at half the angular frequency of the emitted gravitational waves, Ω_{GW}. Because the maximum of the angular velocity Ω_{max} is of the order of $\Omega_{GW}/2$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

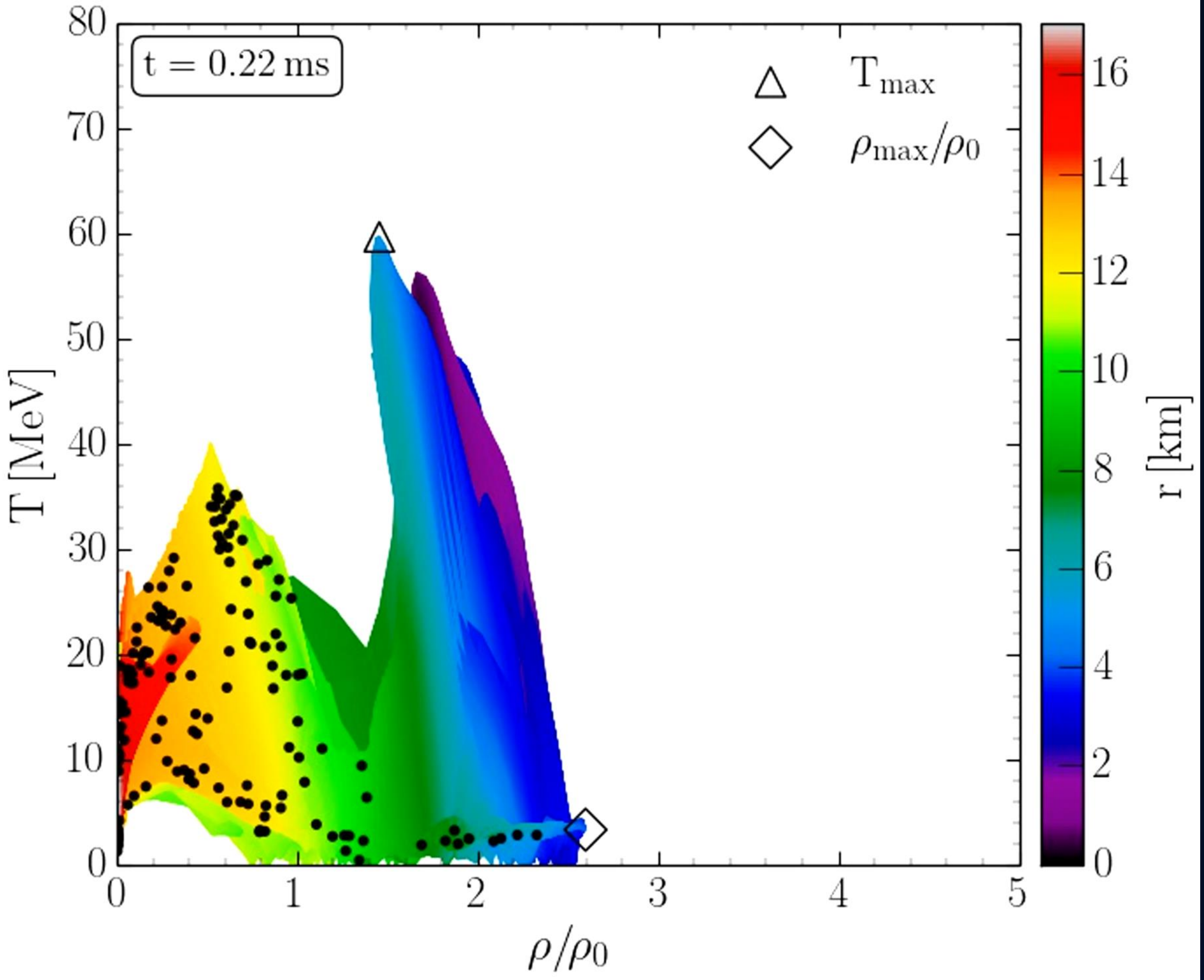




Rest mass density on the equatorial plane

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**):

(3+1)-decomposition of spacetime:

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

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

Angular velocity Ω

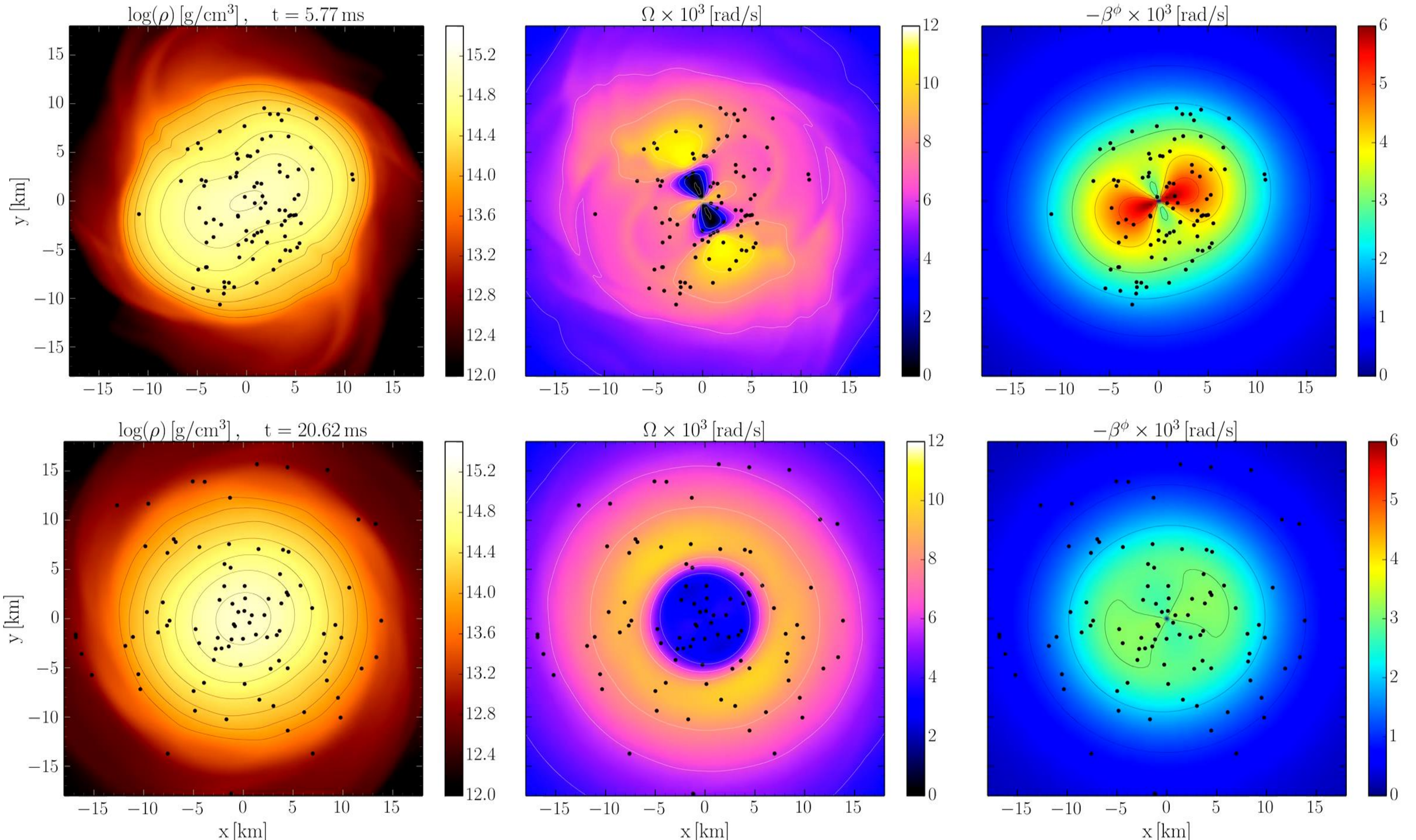
Lapse function α

Φ-component of 3-velocity v^φ

Frame-dragging β^φ

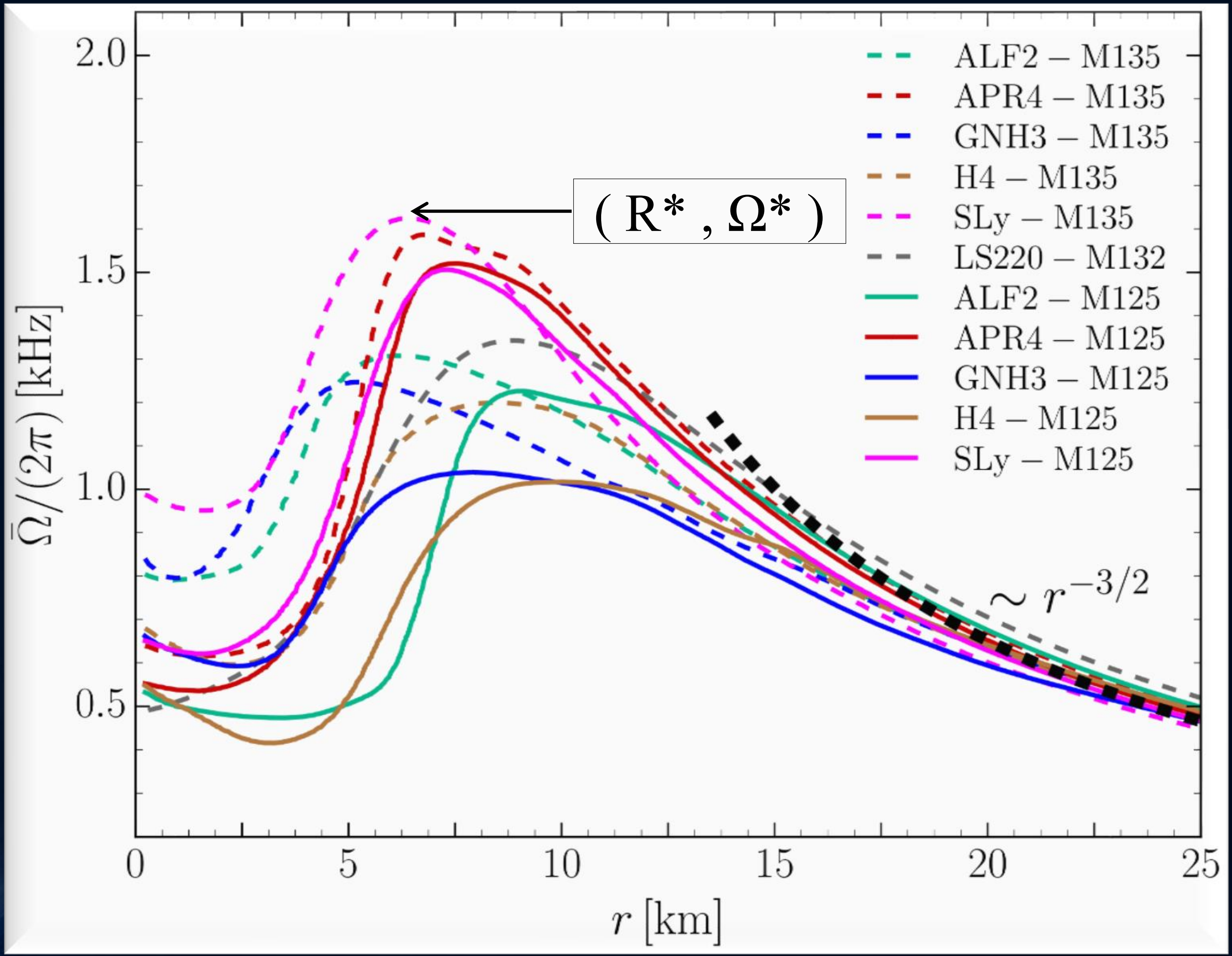
Focus: Inner core of the differentially rotating HMNS

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 = 5.77 ms
Ω × 10³ [rad/s]
−β^φ × 10³ [rad/s]
log(ρ) [g/cm³], t = 20.62 ms
Ω × 10³ [rad/s]
−β^φ × 10³ [rad/s]
y [km]
x [km]

Time-averaged Rotation Profiles of the HMNSs



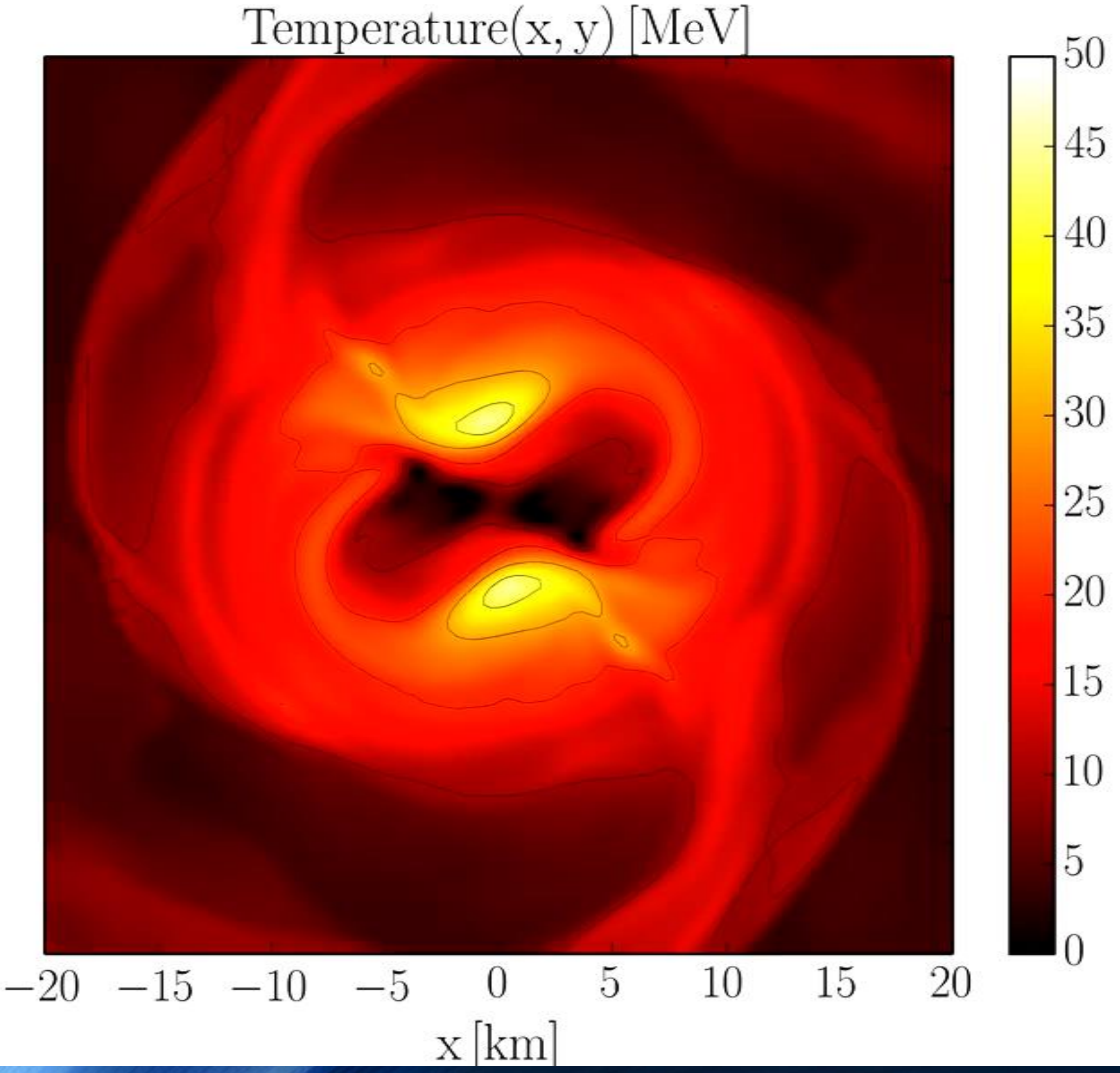
Soft EoSs:
Sly
APR4

Stiff EoSs:
GNH3
H4

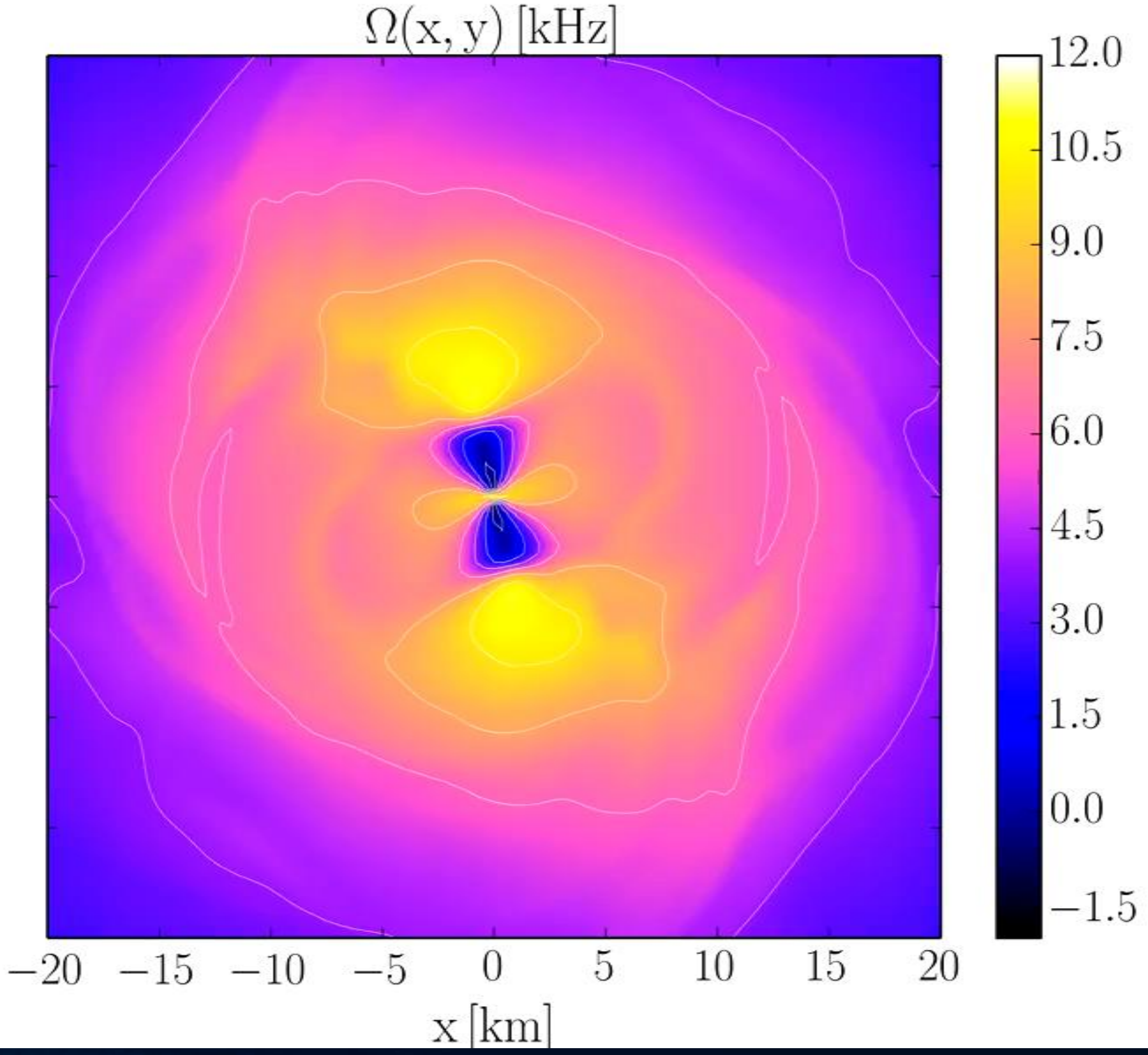
Time-averaged rotation profiles for different EoS
Low mass runs (solid curves), high mass runs (dashed curves).

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

Temperature



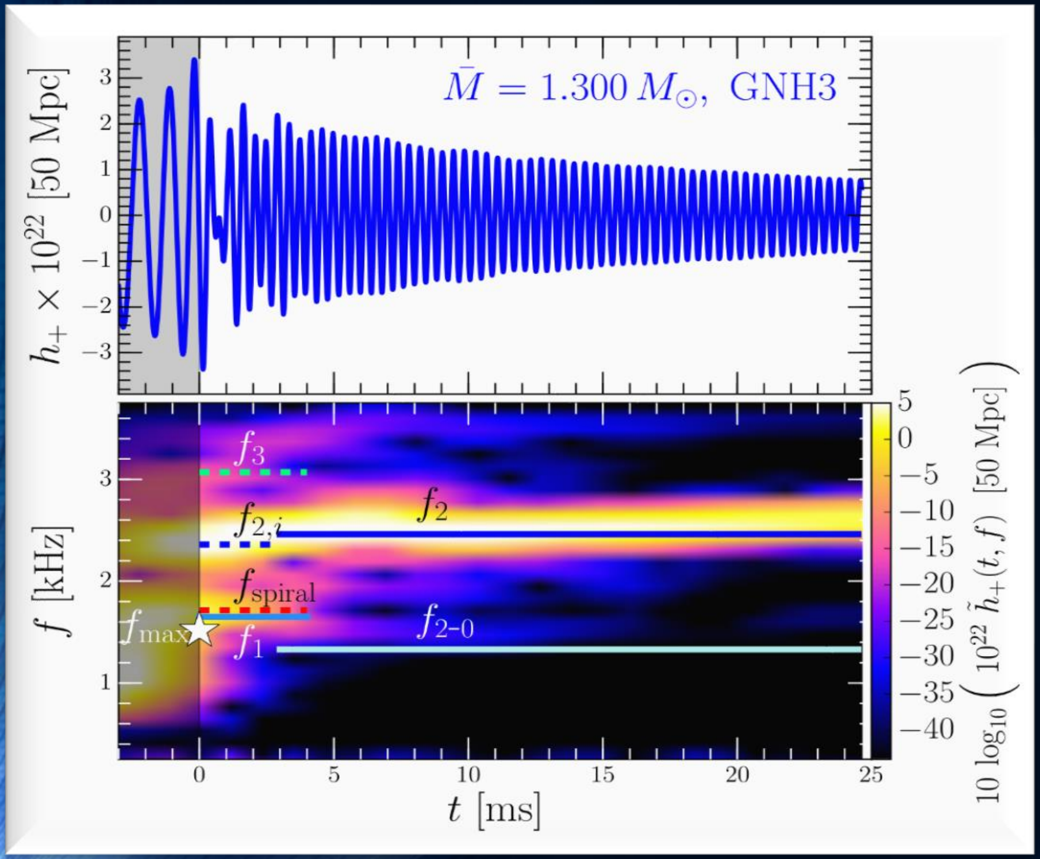
Angular Velocity



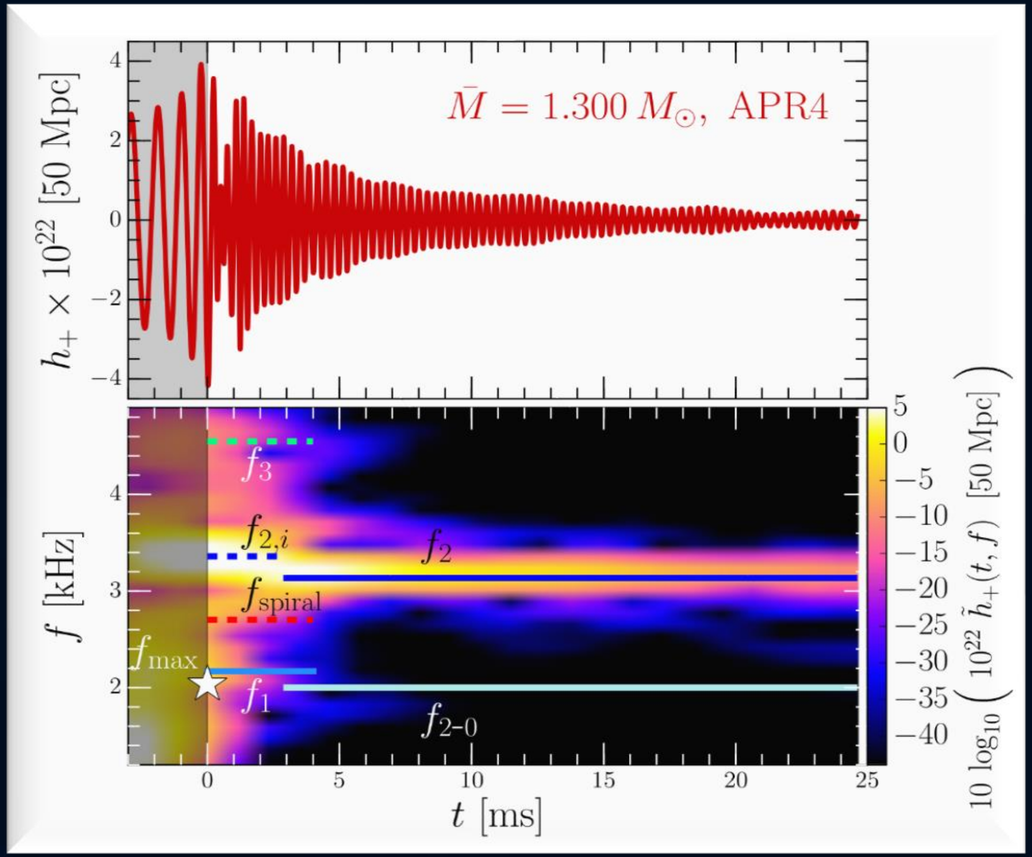
EOS: LS200 , Mass: 1.32 M_{solar} , simulation with Pi-symmetry

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

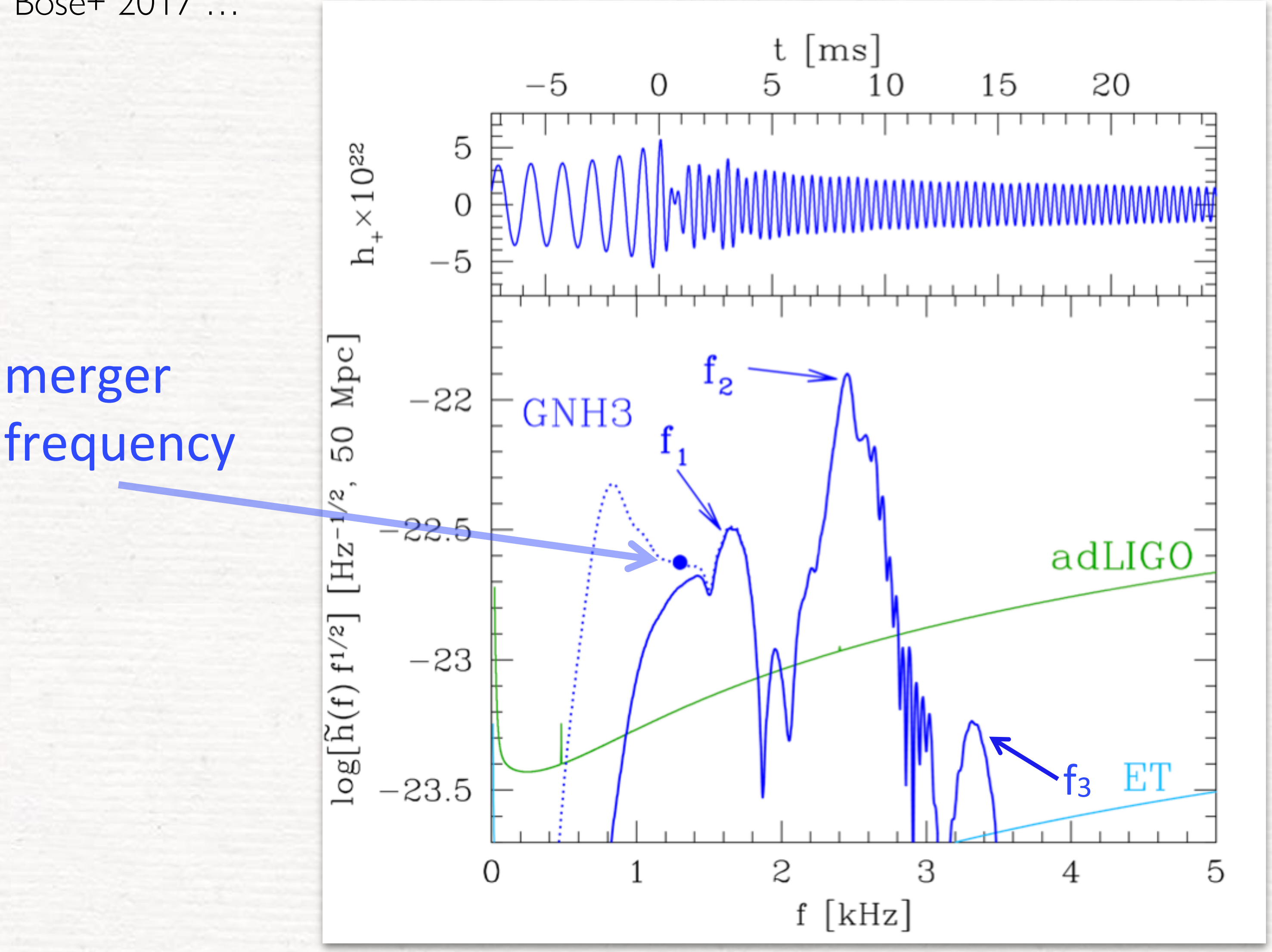
Unfortunately, clow sensitivity at high gravitational wave frequencies, no post-merger signal has been found in GW170817.

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.

A new approach to constrain the EOS

Oechslin+2007, Baiotti+2008, Bauswein+ 2011, 2012, Stergioulas+ 2011, Hotokezaka+ 2013, Takami 2014, 2015, Bernuzzi 2014, 2015, Bauswein+ 2015, Clark+ 2016, LR+2016, de Pietri+ 2016, Feo+ 2017, Bose+ 2017 …

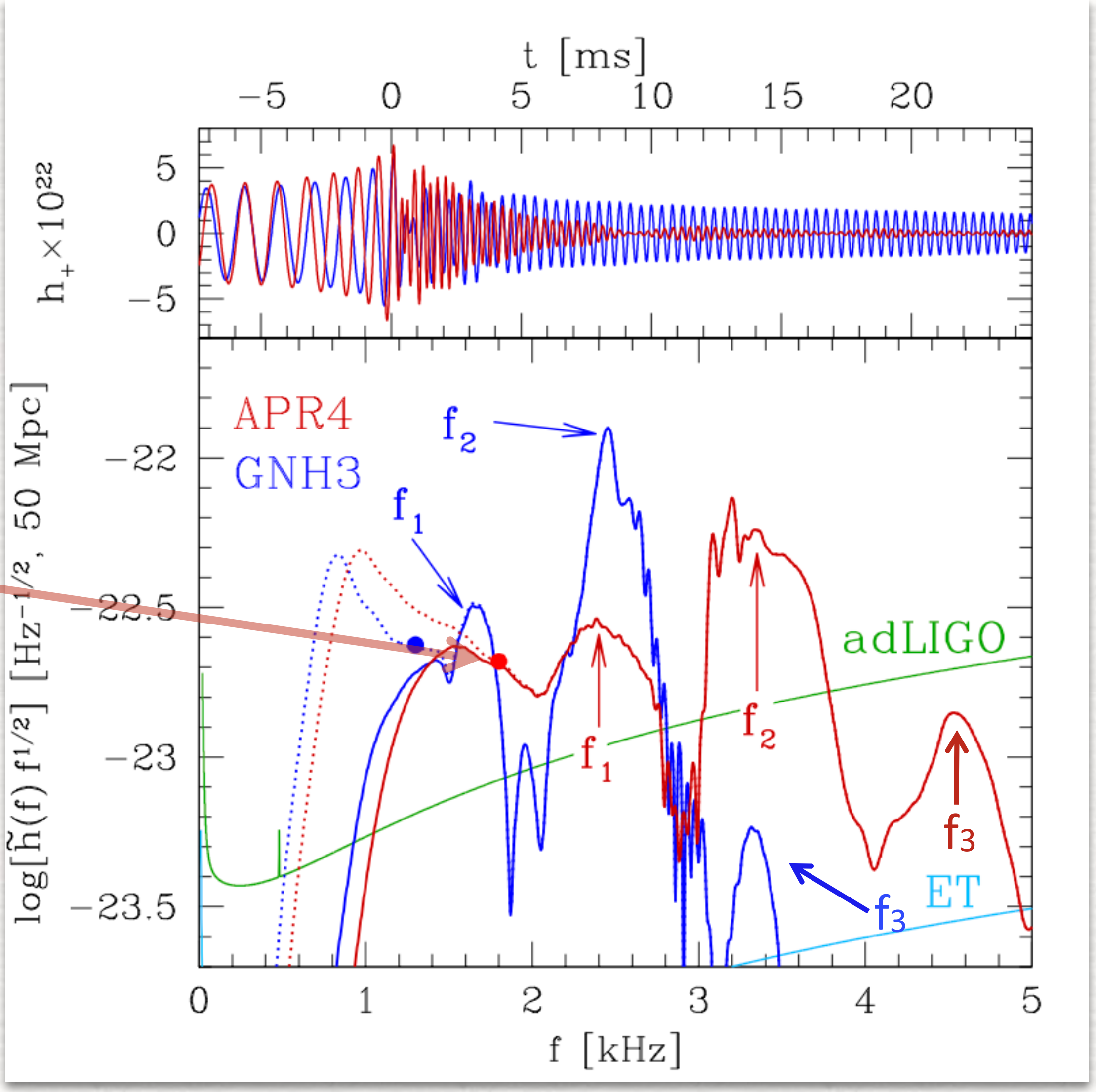


Slide from Luciano Rezzolla

A spectroscopic approach to the EOS

Oechslin+2007, Baiotti+2008, Bauswein+ 2011, 2012, Stergioulas+ 2011, Hotokezaka+ 2013, Takami 2014, 2015, Bernuzzi 2014, 2015, Bauswein+ 2015, Clark+ 2016, LR+2016, de Pietri+ 2016, Feo+ 2017, Bose+ 2017 …

merger frequency



Slide from Luciano Rezzolla

Post-merger gravitational-wave signatures of phase transitions in binary compact star mergers

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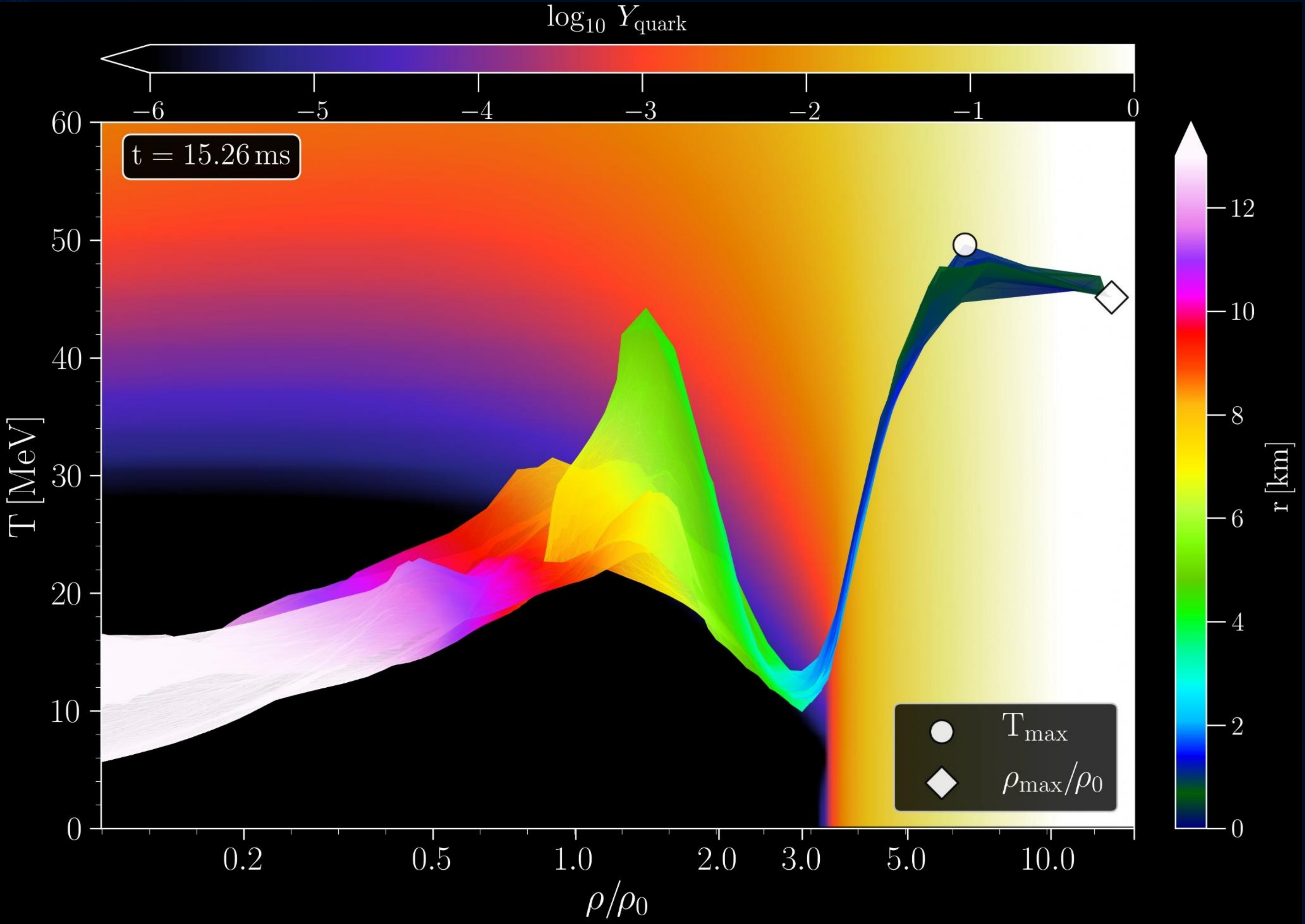
  - Properties of HyperMassive Neutron Stars and the post-merger gravitational wave emission
  - HyperMassive Hybrid Stars
- Detecting the hadron-quark phase transition with gravitational waves
  - Most et.al., PHYSICAL REVIEW LETTERS 122, 061102 (2019)
  - Bauswein et.al., PHYSICAL REVIEW LETTERS 122, 061101 (2019)
  - Weih et.al., arXiv:1912.09340v1 [gr-qc] 19 Dec 2019 (submitted to PHYSICAL REVIEW LETTERS)

Binary Hybrid Star Mergers and the QCD Phase Diagram

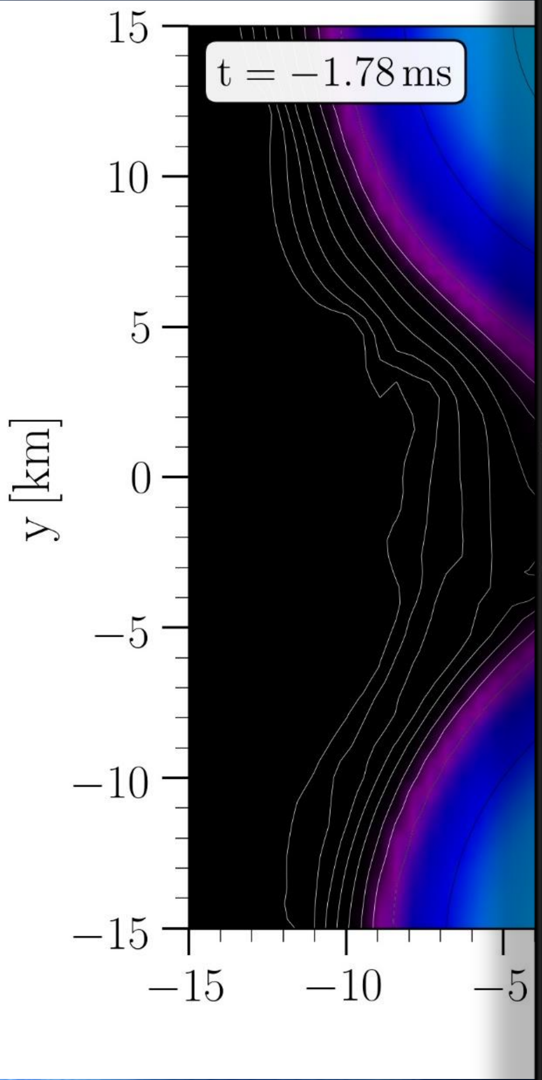


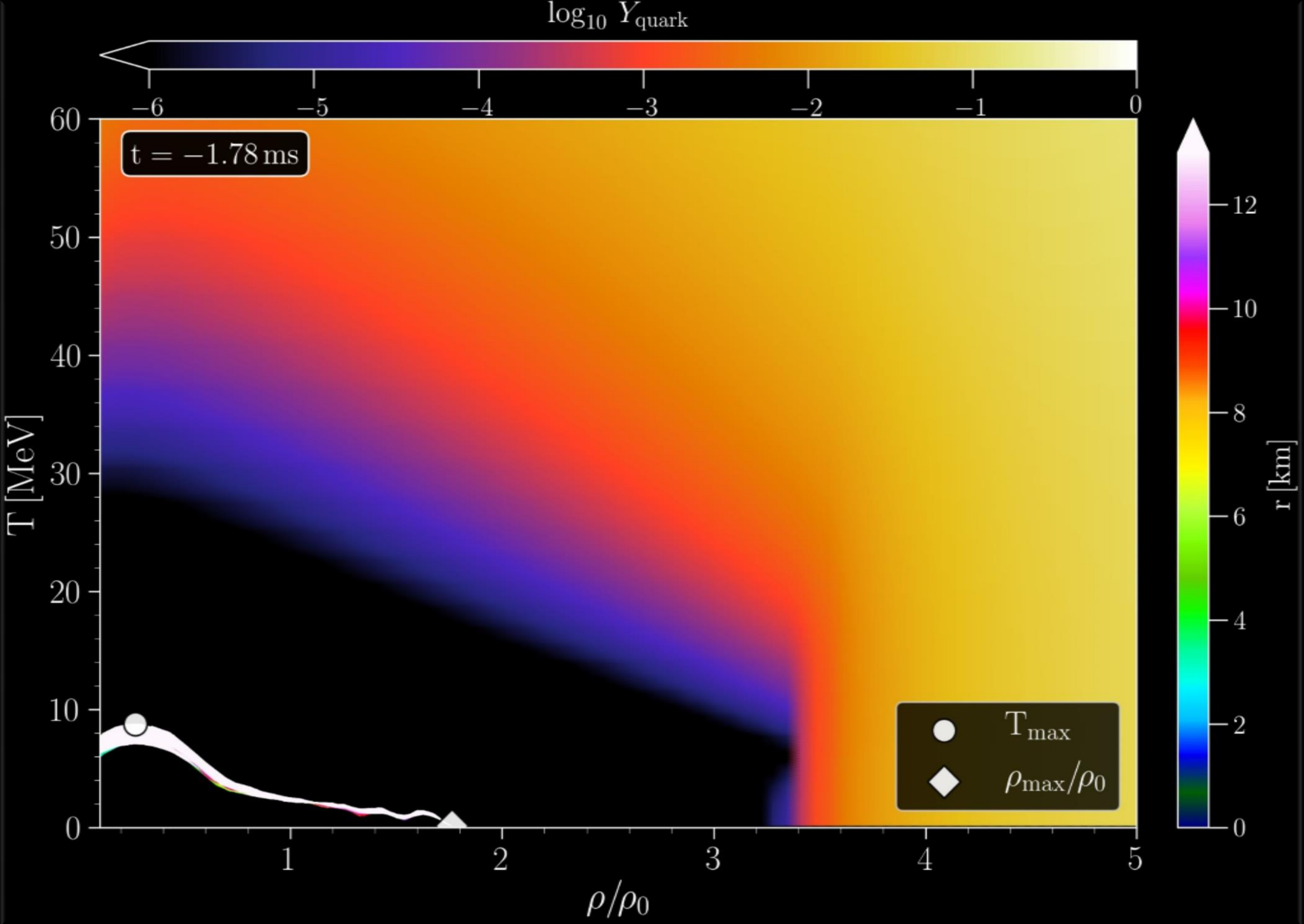
Hot and dense matter inside the inner area of a collapsing hypermassive hybrid star in the style of a (T- ρ) QCD phase diagram plot at a time right before the apparent horizont is formed in its center

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.

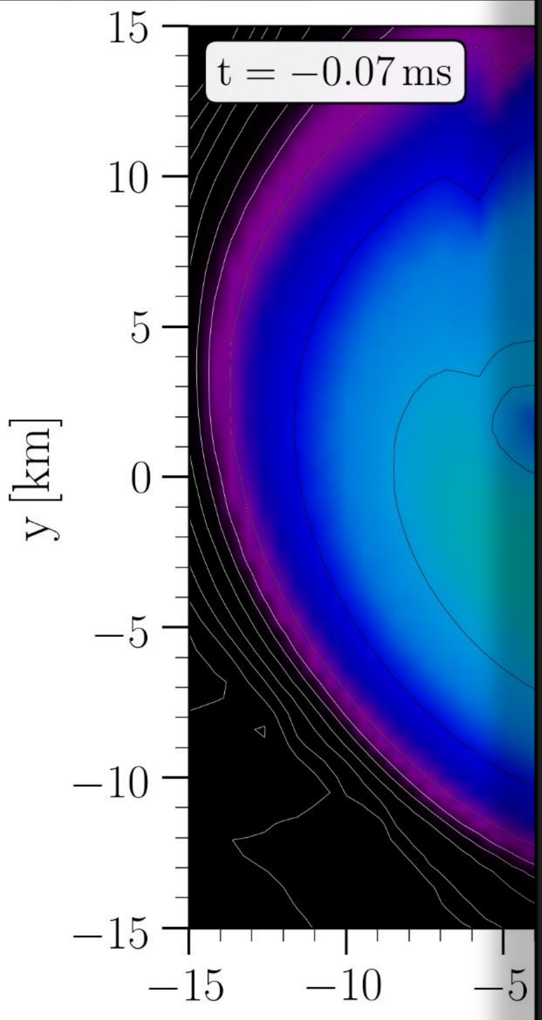
Late Inspiral Phase



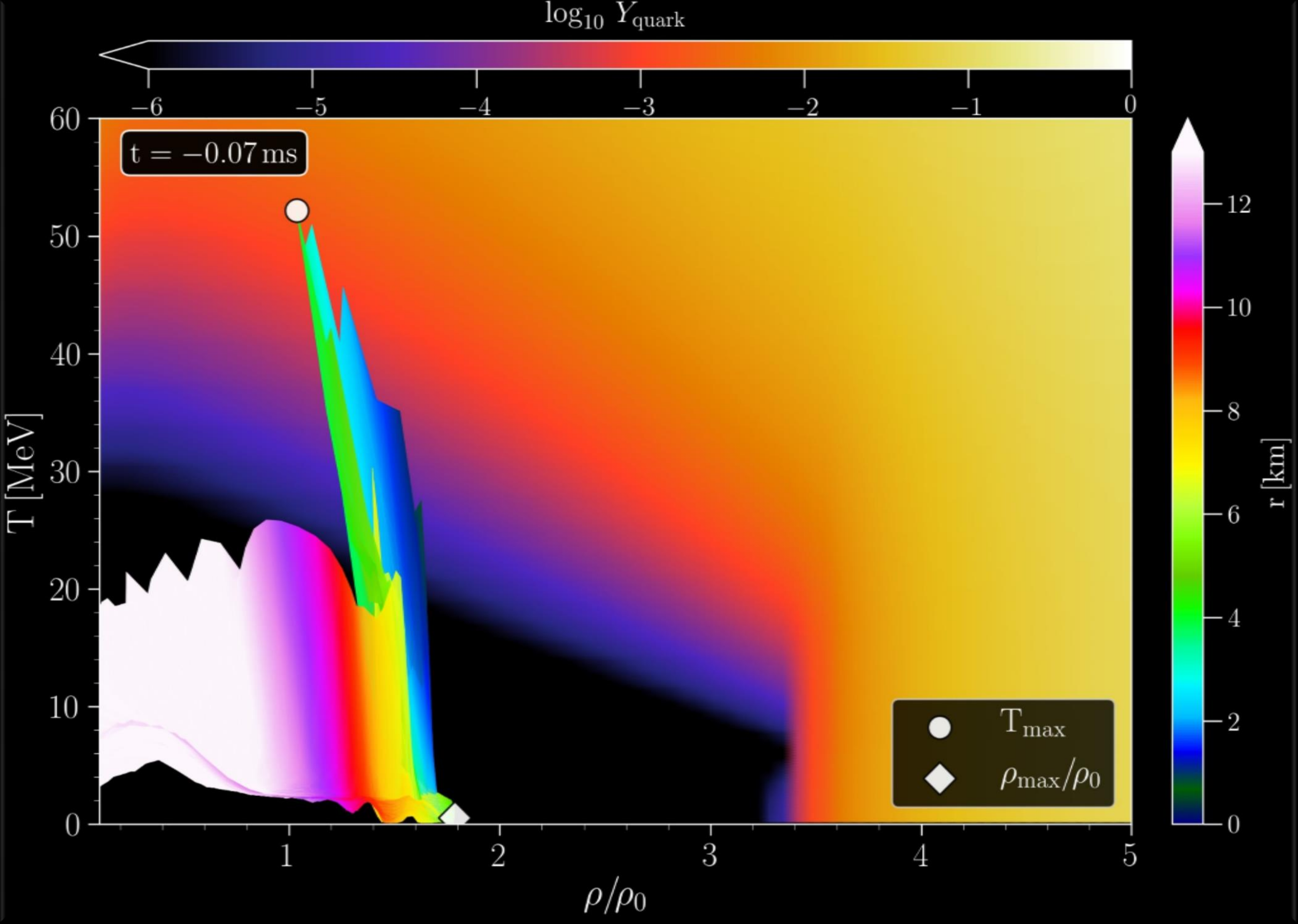


Rest mass density

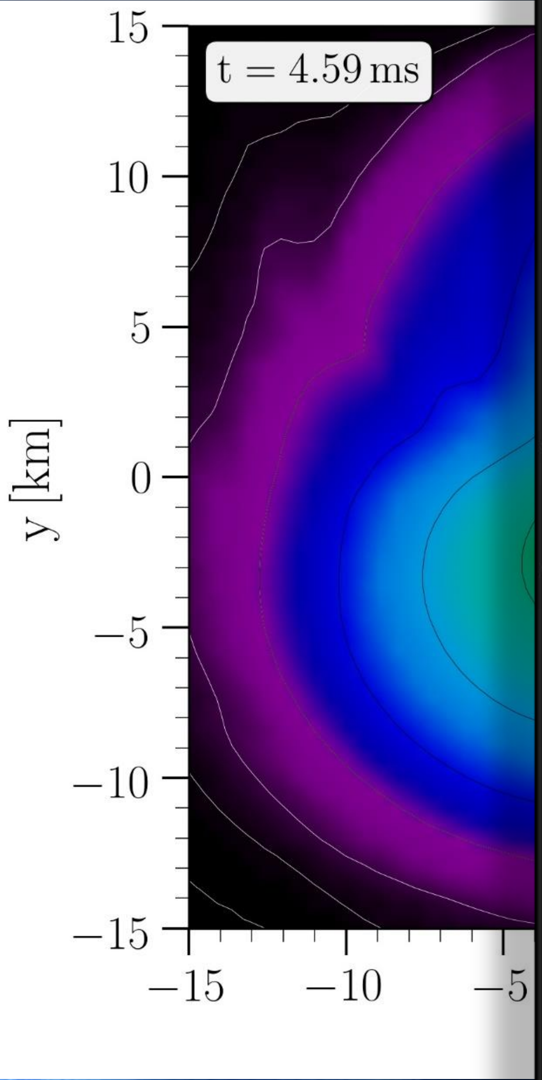
Merger Phase



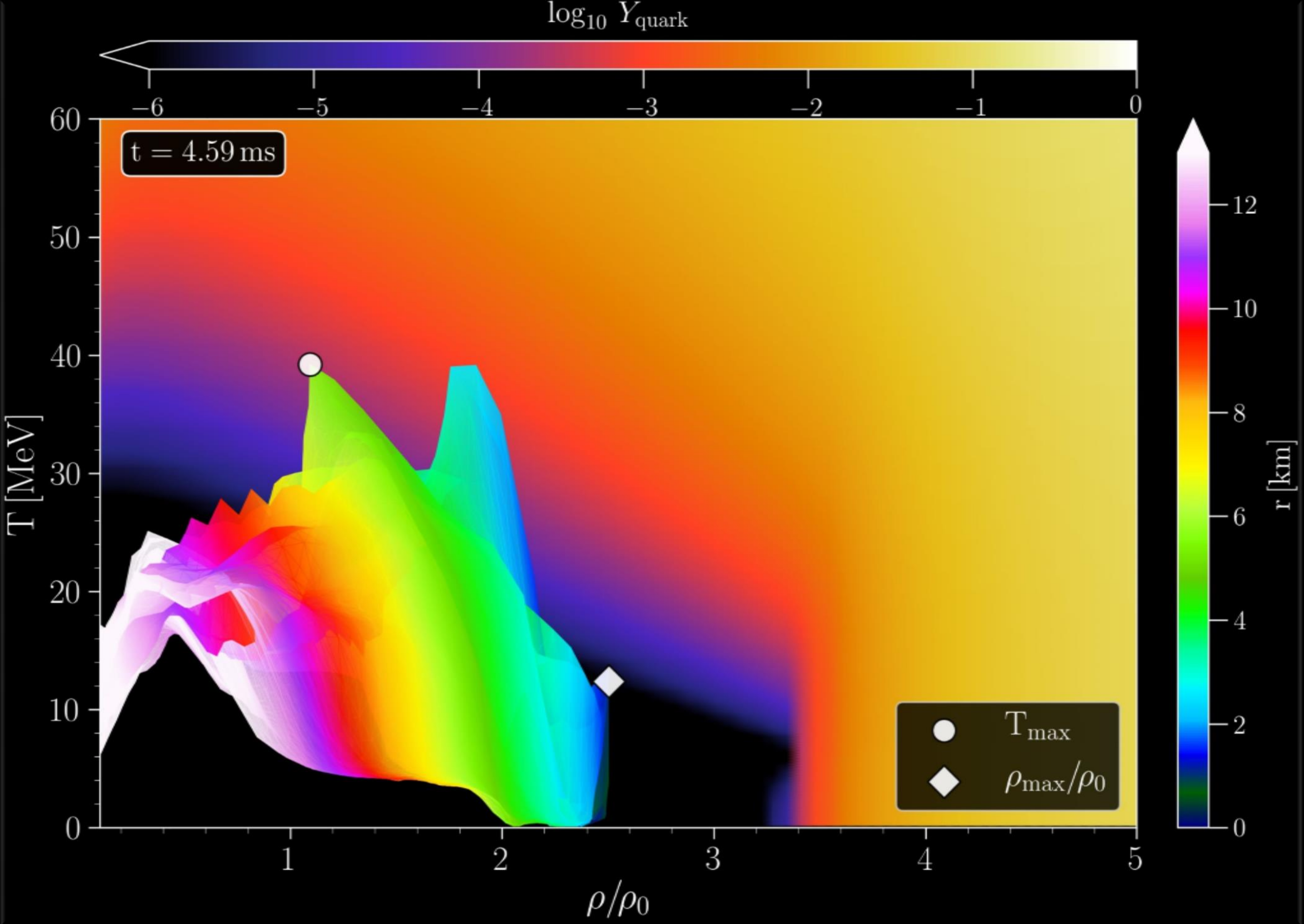
Rest mass density



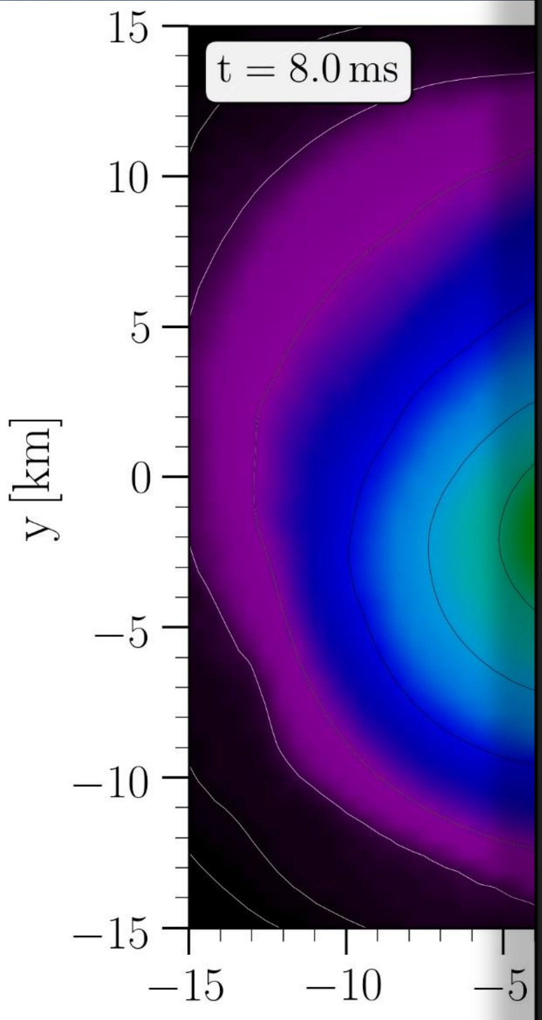
Post Merger Phase

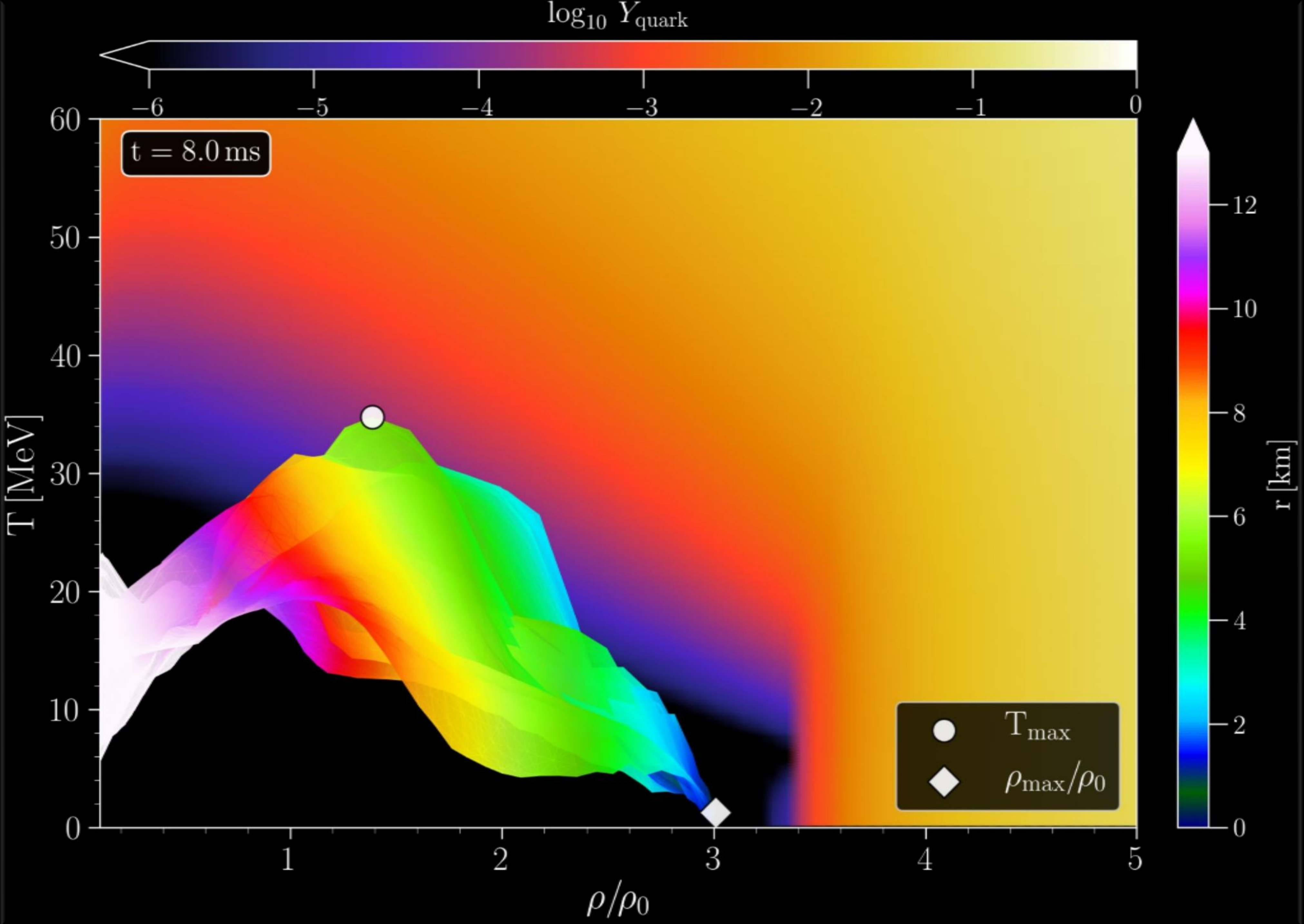


Rest mass density



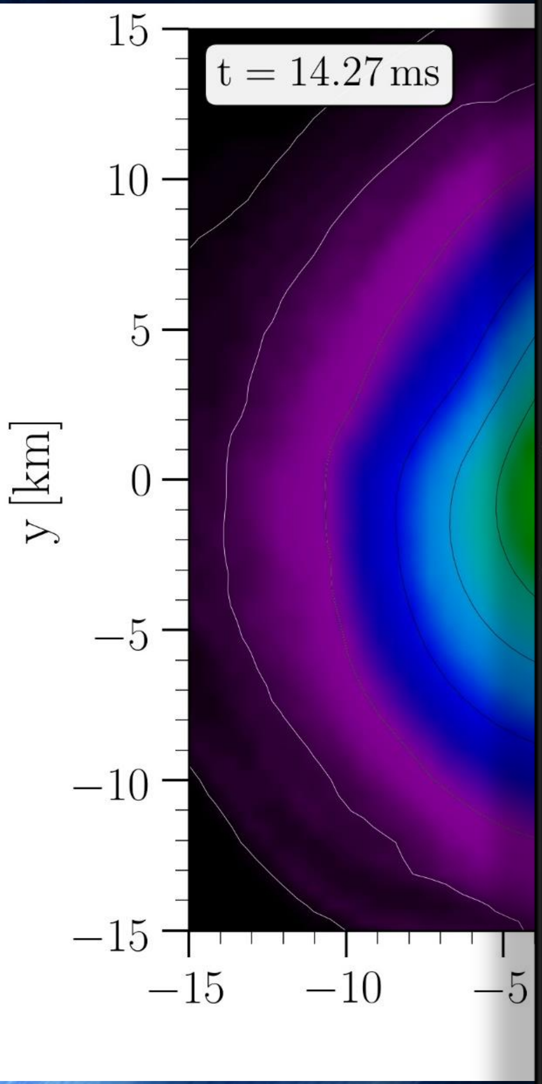
Merger Phase

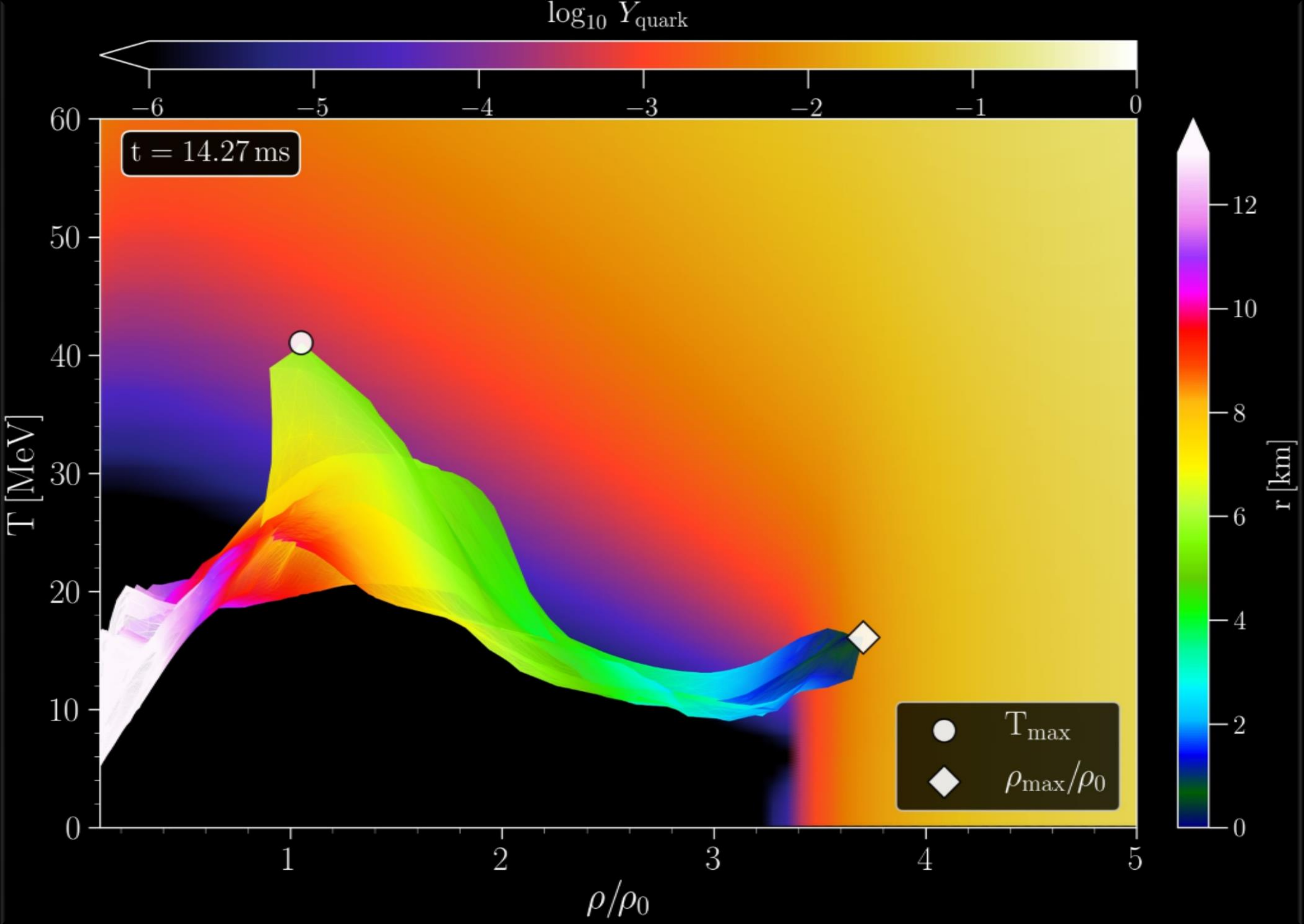




Rest mass density

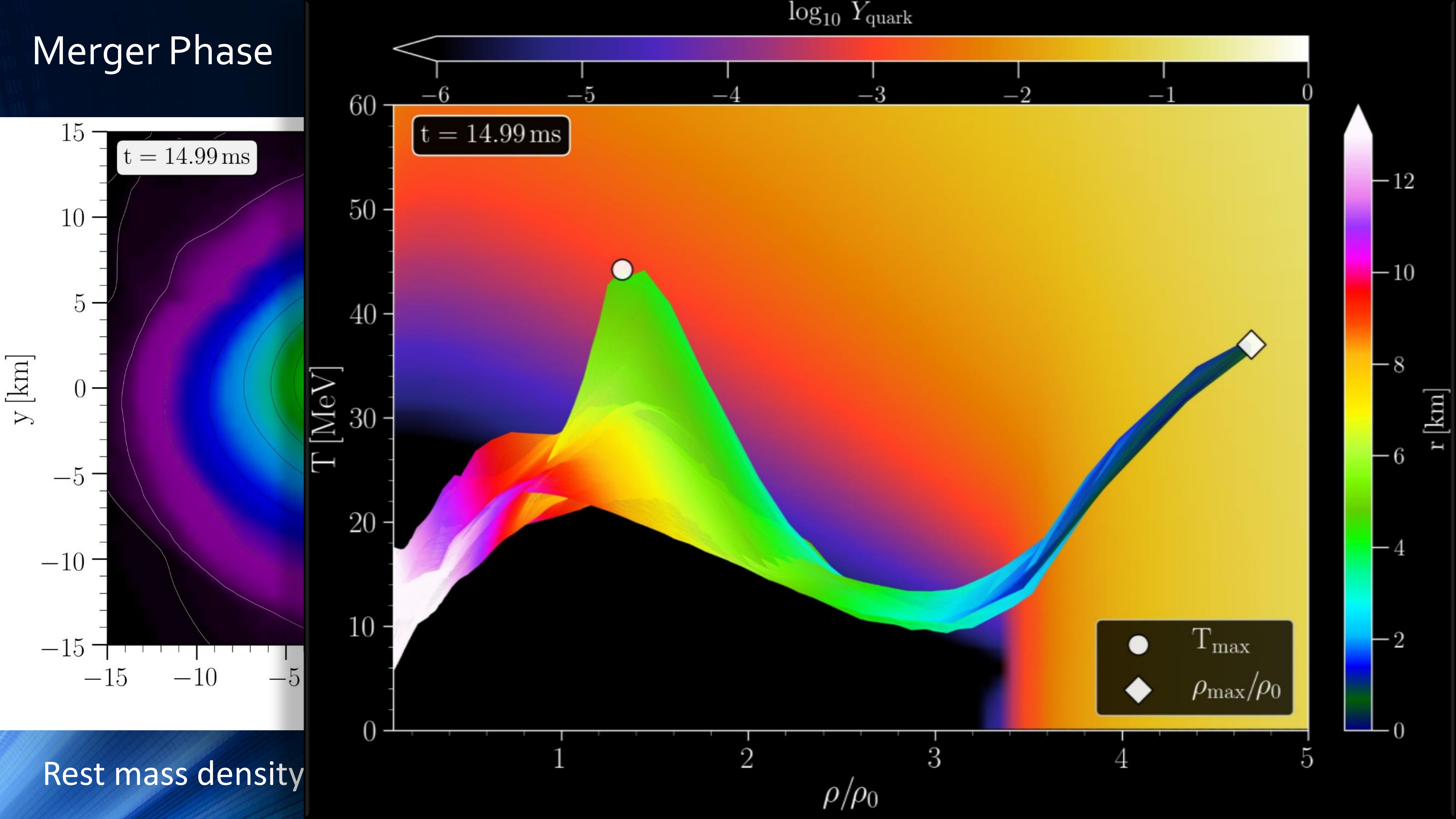
Merger Phase





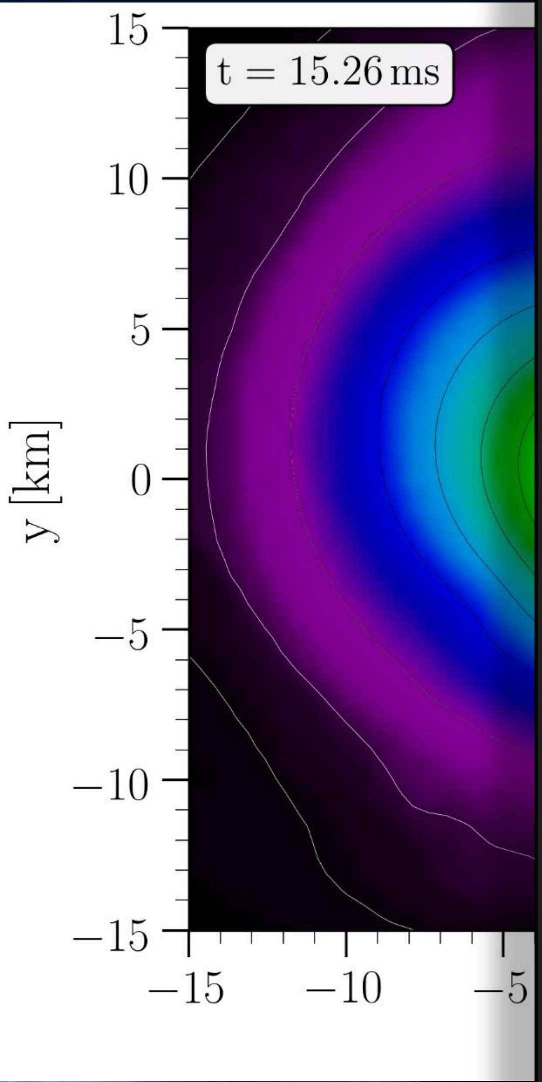
Rest mass density

Merger Phase

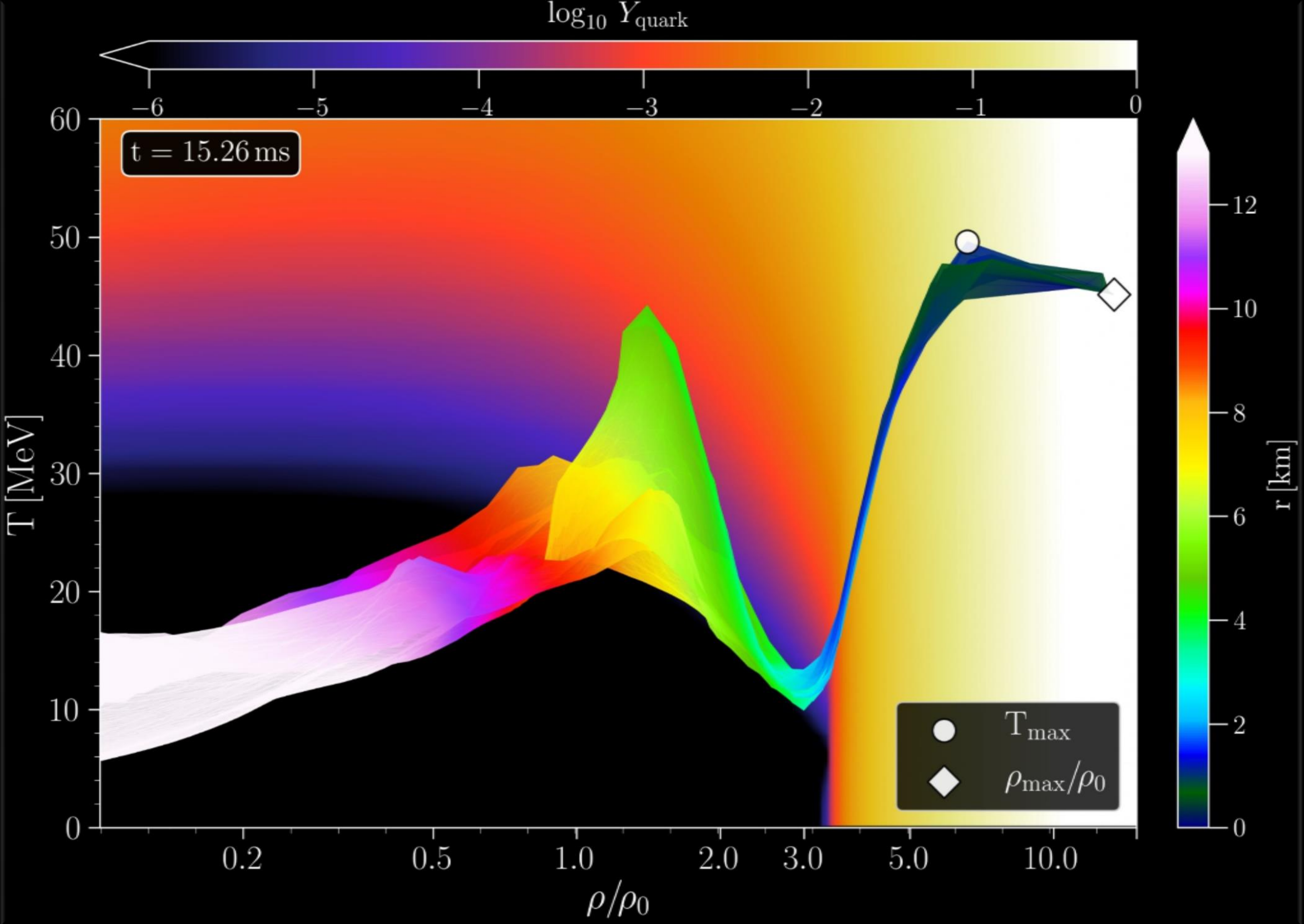


Rest mass density

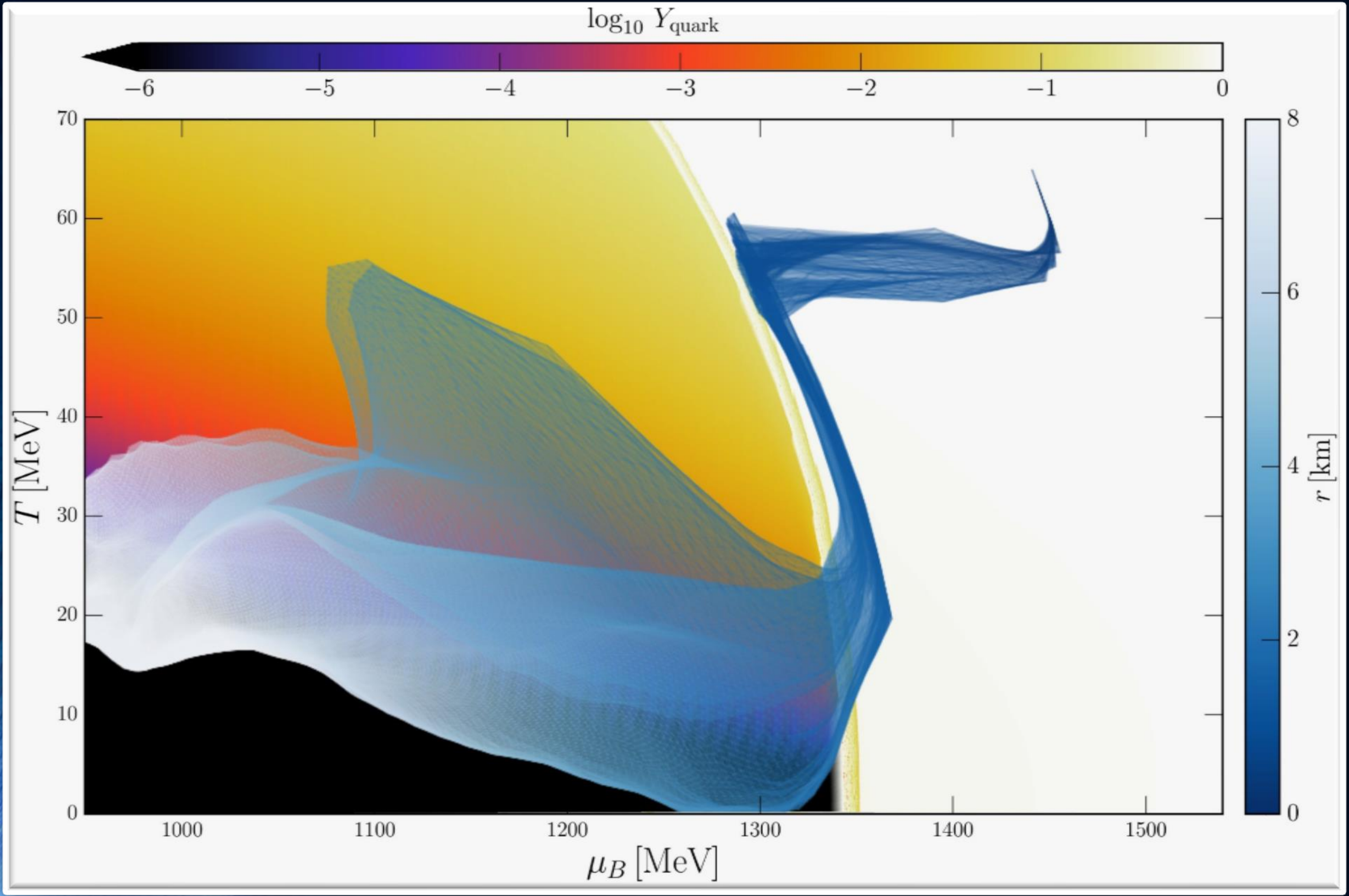
Merger Phase



Rest mass density



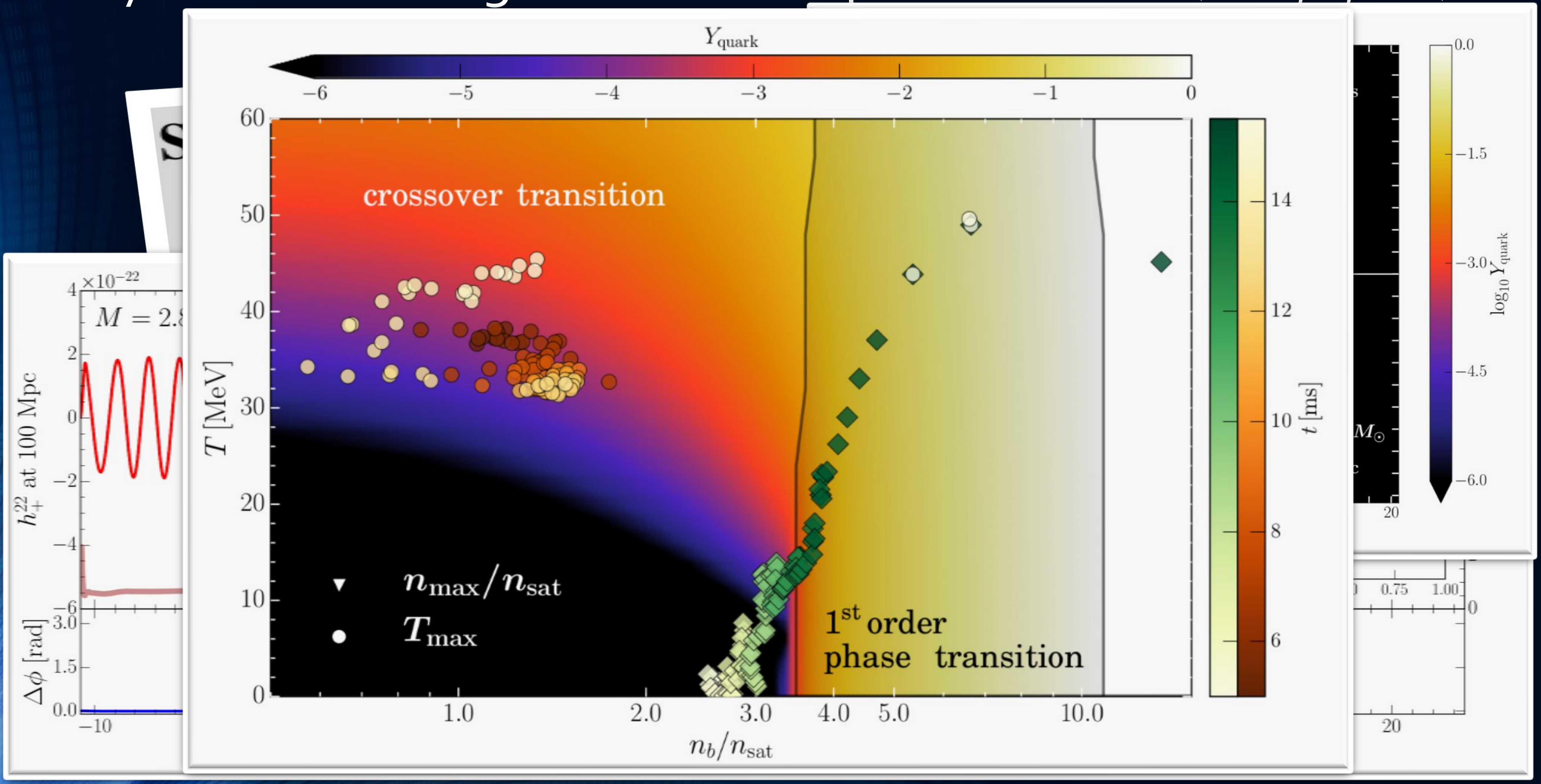
The Pelican Plot



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)*



Post-merger gravitational-wave signatures of phase transitions in binary compact star mergers

- Introduction
  - GW170817 and GW190425 - the long-awaited events
  - Numerical relativity of compact star mergers
  - The equation of state of elementary matter and the hadron-quark phase transition
  - The compact star zoo: neutron stars, hybrid stars and strange quark stars
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  - Properties of HyperMassive Neutron Stars and the post-merger gravitational wave emission
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Hybrid Star Mergers with T-dependent EOS *(PRL paper 2)*

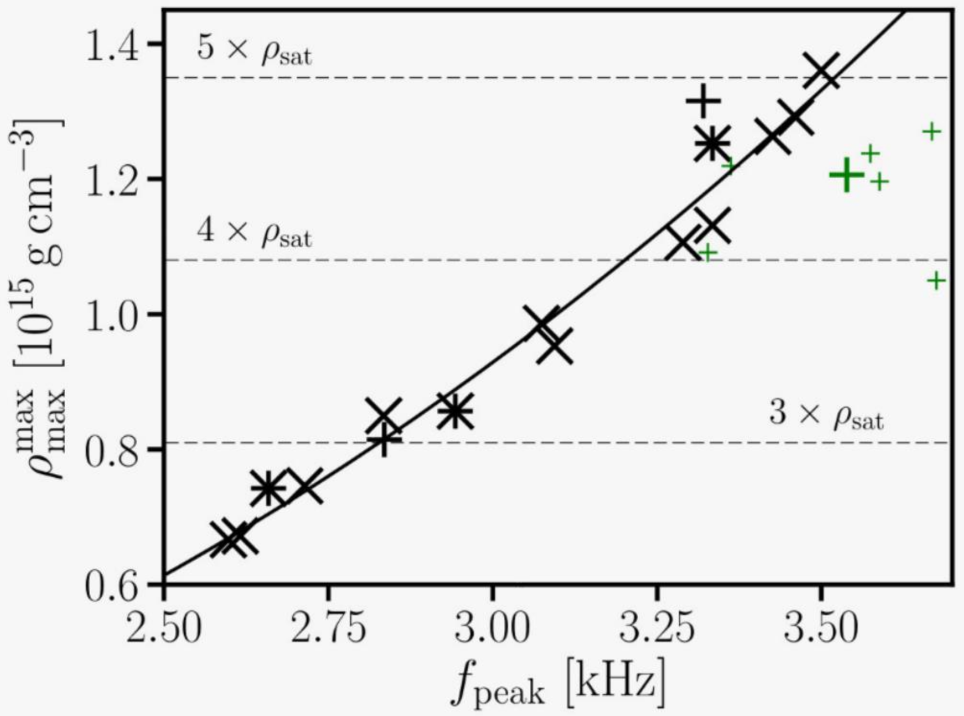

FIG. 4: Maximum rest-mass density ρ_{max}^{max} during the first milliseconds of the postmerger phase as function of the dominant postmerger GW frequency f_{peak} for 1.35-1.35 $M_\odot$ mergers. Green symbols display results for DD2F-SF (big symbol for DD2F-SF-1). Asterisks indicate models with hyperons.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

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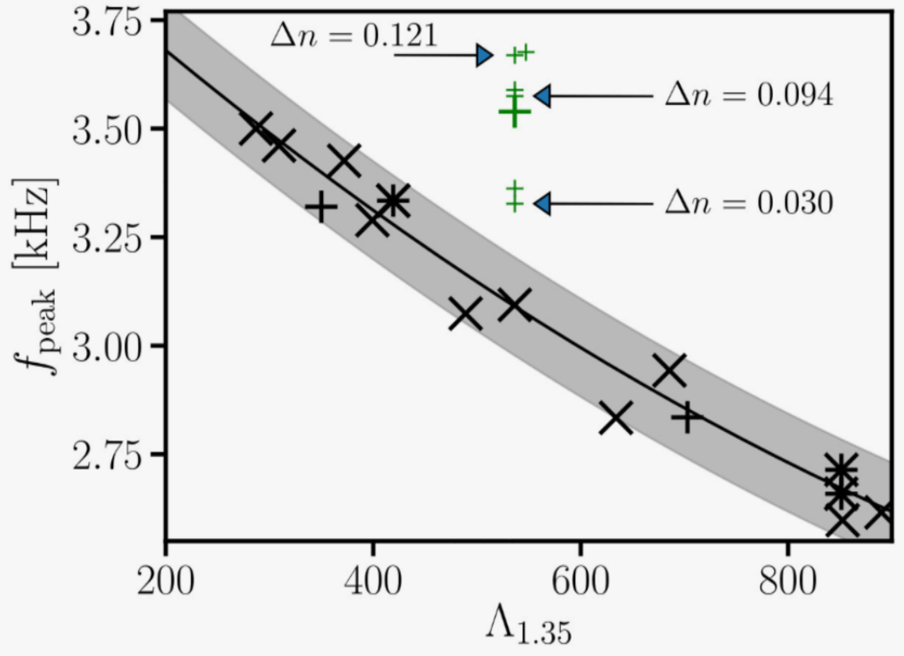

FIG. 3: Dominant postmerger GW frequency f_{peak} as function of tidal deformability Λ for 1.35-1.35 $M_\odot$ mergers. The DD2F-SF models with a phase transition to deconfined quark matter (green symbols) appear as clear outliers (big symbol for DD2F-SF-1). Solid curve displays the least square fit 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.

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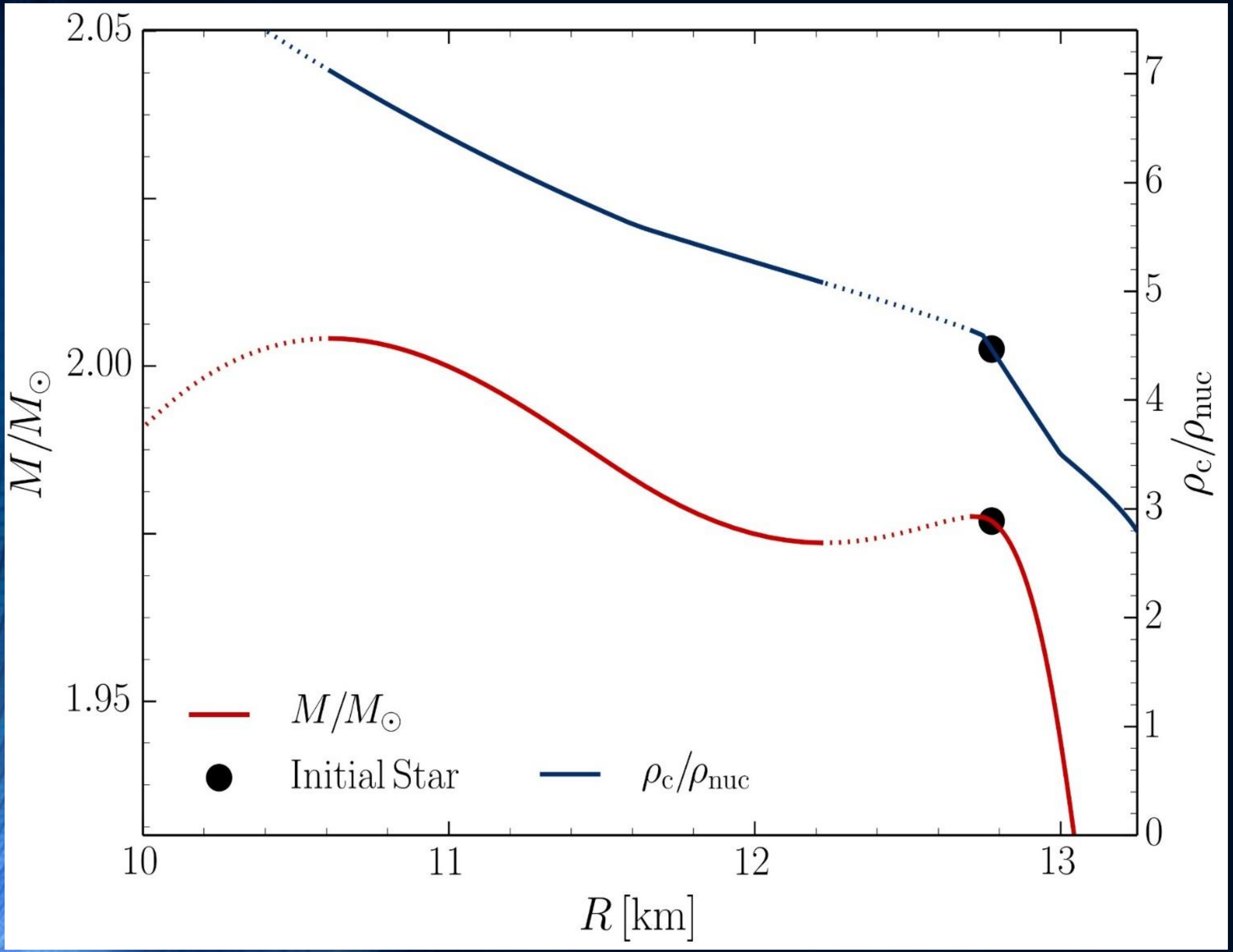
The Hadron-Quark Phase Transition and the Third Family of Compact Stars (Twin Stars)



Glendenning, N. K., & Kettner, C. (1998). Nonidentical neutron star twins. Astron. Astrophys., 353(LBL-42080), L9.

Sarmistha Banik, Matthias Hanauske, Debades Bandyopadhyay and Walter Greiner, Rotating compact stars with exotic matter, Phys.Rev.D 70 (2004) p.12304

I.N. Mishustin, M. Hanauske, A. Bhattacharyya, L.M. Satarov, H. Stöcker, and W. Greiner, Catastrophic rearrangement of a compact star due to quark core formation, Physics Letters B 552 (2003) p.1-8

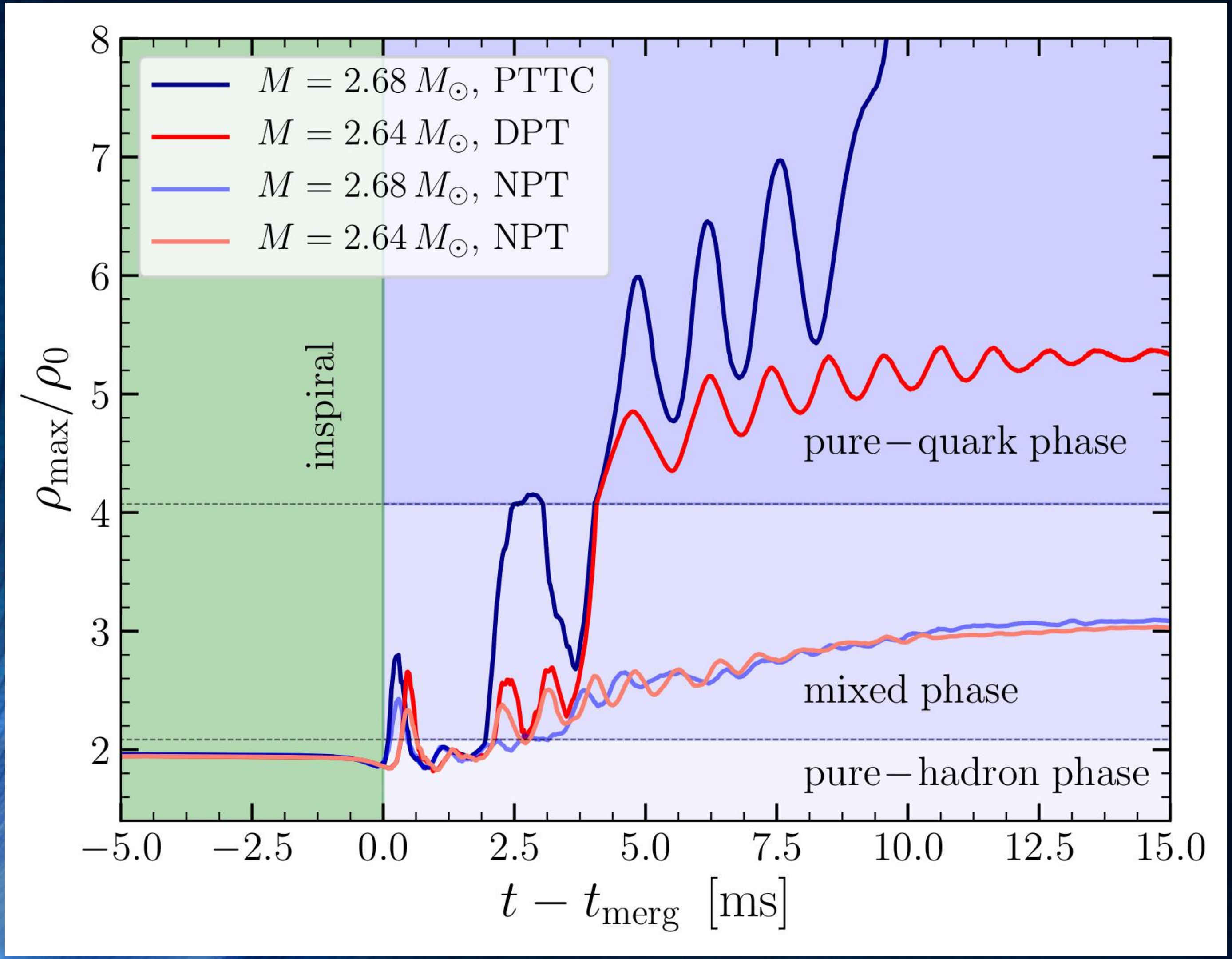
M.Alford and A. Sedrakian, Compact stars with sequential QCD phase transitions. Physical review letters, 119(16), 161104 (2017)..

D.Alvarez-Castillo and D.Blaschke, High-mass twin stars with a multipolytrope equation of state. Physical Review C, 96(4), 045809 (2017) .

A. Ayriyan, N.-U. Bastian, D. Blaschke, H. Grigorian, K. Maslov, D. N. Voskresensky, How robust is a third family of compact stars against pasta phase effects?, arXiv:1711.03926 [nucl-th]

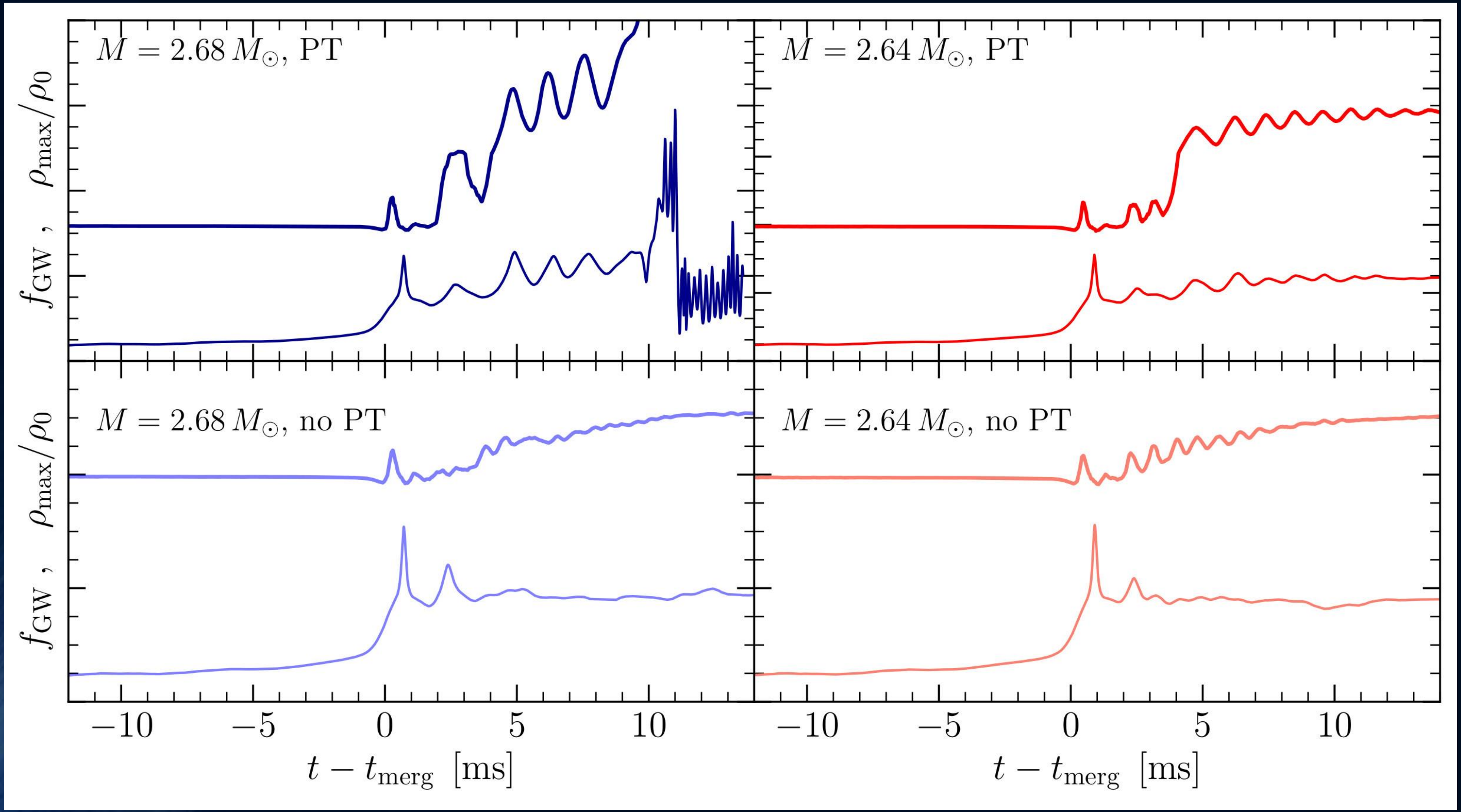
Post-merger gravitational-wave signatures of phase transitions in binary compact star mergers

(Weih et.al., arXiv:1912.09340v1)



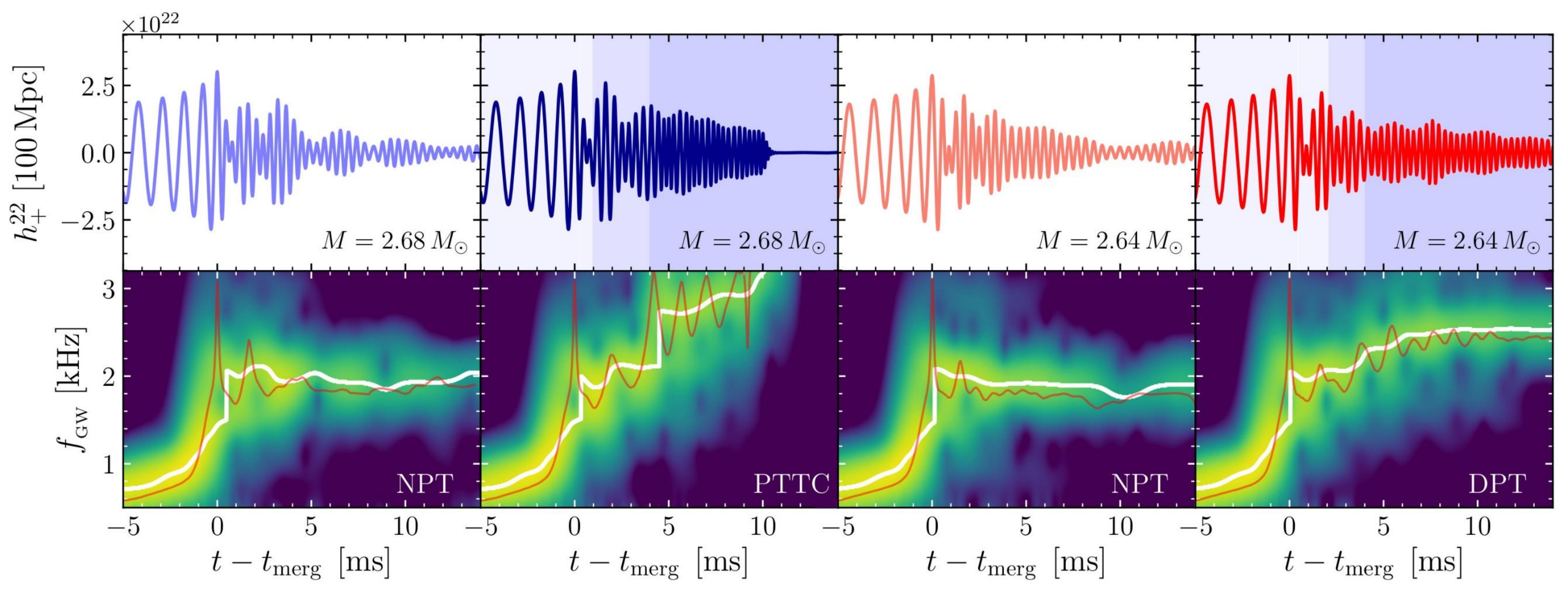
Evolution of the central rest-mass density for the four BNS configurations we have simulated. Blue-shaded regions mark the different phases of the EOS and apply to the DPT (Delayed phase transition) and PTTC (Phase-transition triggered collaps) scenarios only since the NPT (No phase transition) binaries are always purely hadronic.

arXiv:1912.09340v1



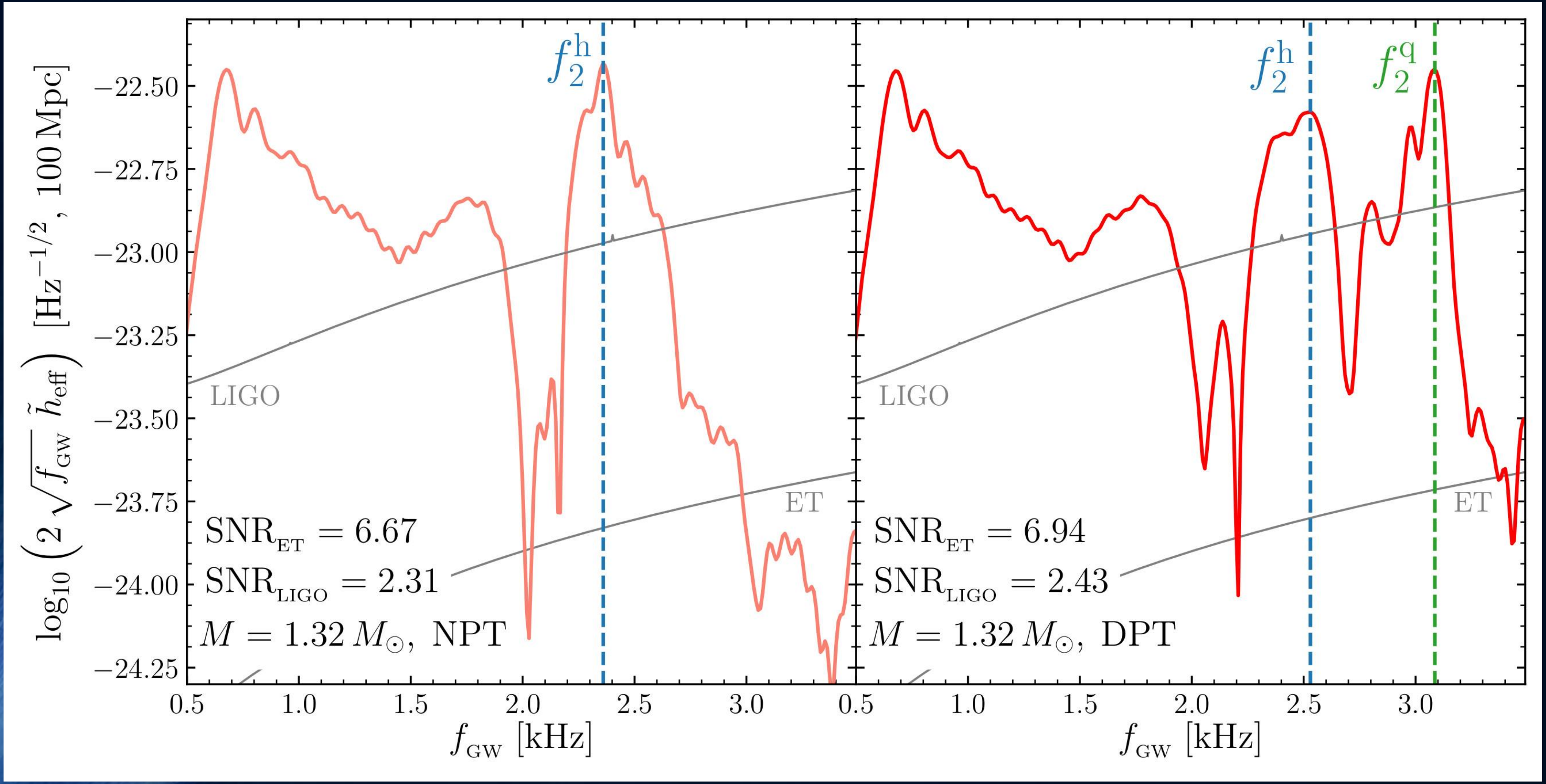
Evolution of the central rest-mass density (top) and instantaneous gravitational wave frequency (bottom).

arXiv:1912.09340v1

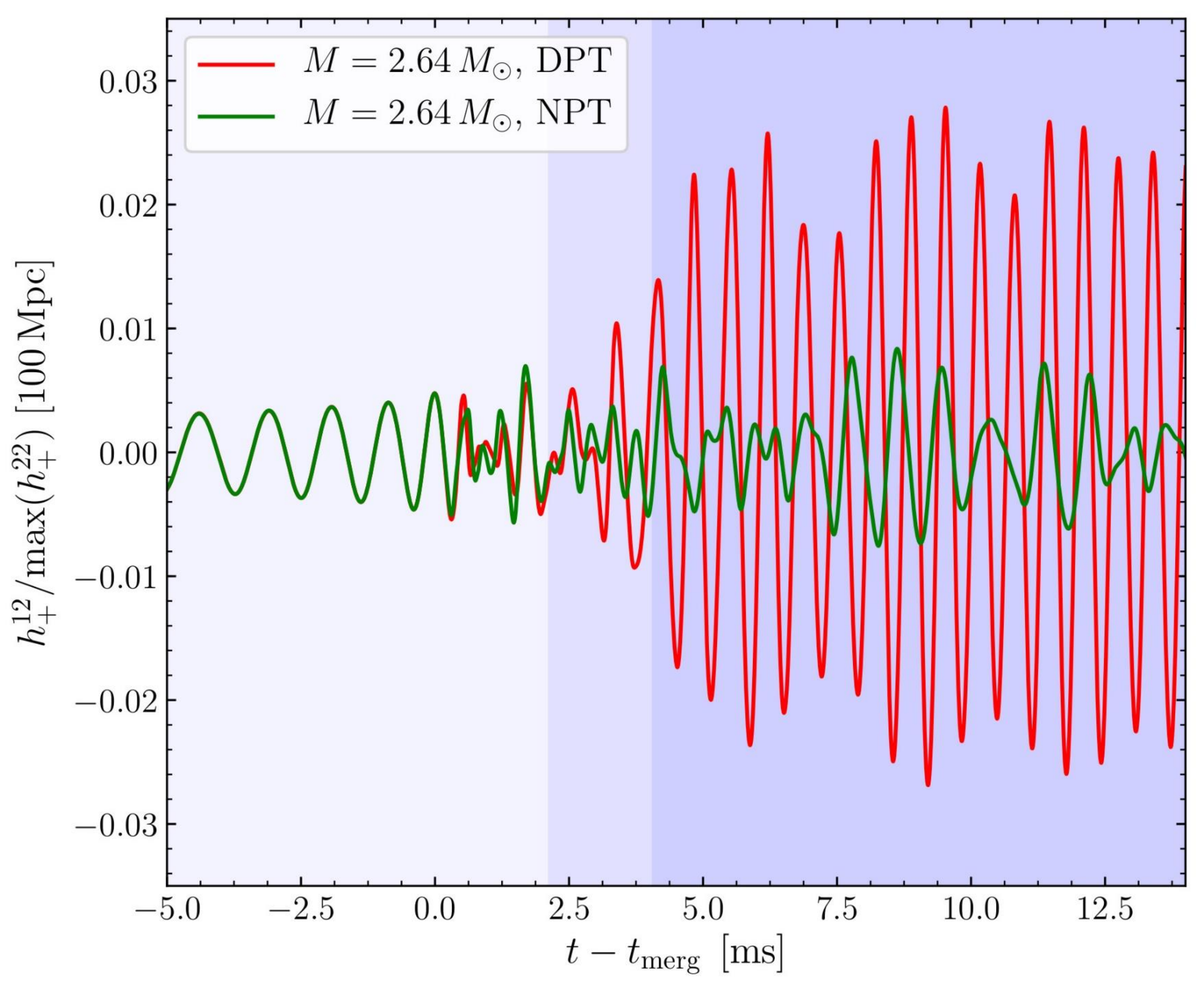


Strain h+ (top) and its spectrogram (bottom) for the four BNSs considered. In the top panels the different shadings mark the times when the HMNS core enters the mixed and quark phases the NPT models are always purely hadronic. In the bottom panels, the white lines trace the maximum of the spectrograms, while the red lines show the instantaneous gravitational-wave frequency.

arXiv:1912.09340v1

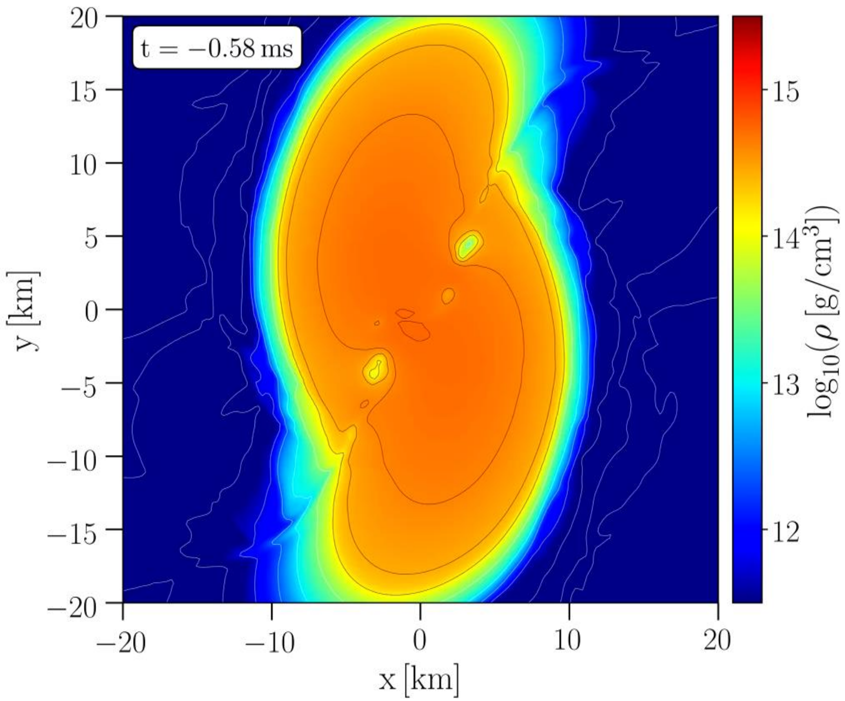


Total gravitational wave spectrum (left NPT, right DPT).

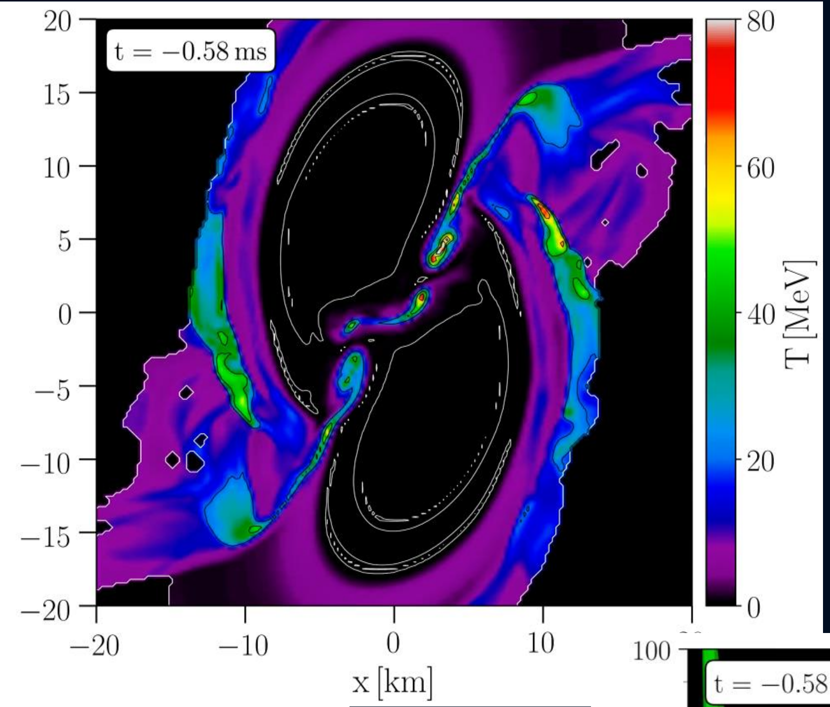


Due to the large m=1 mode of the emitted gravitational wave in the DPT case, a qualitative difference to the NPT scenario might be observable in future by focusing on the h12-gravitational wave mode during the post-merger evolution.

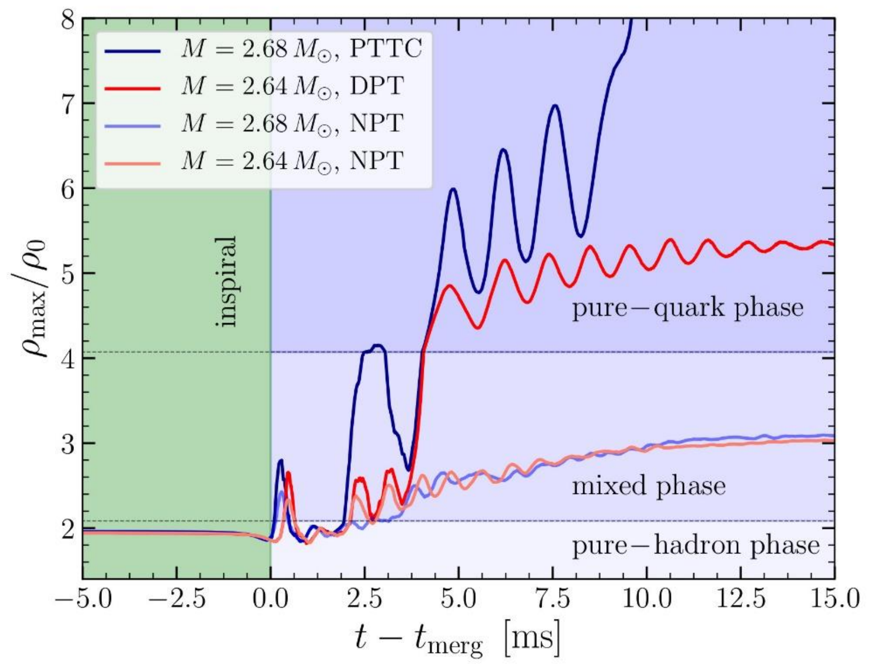
DPT



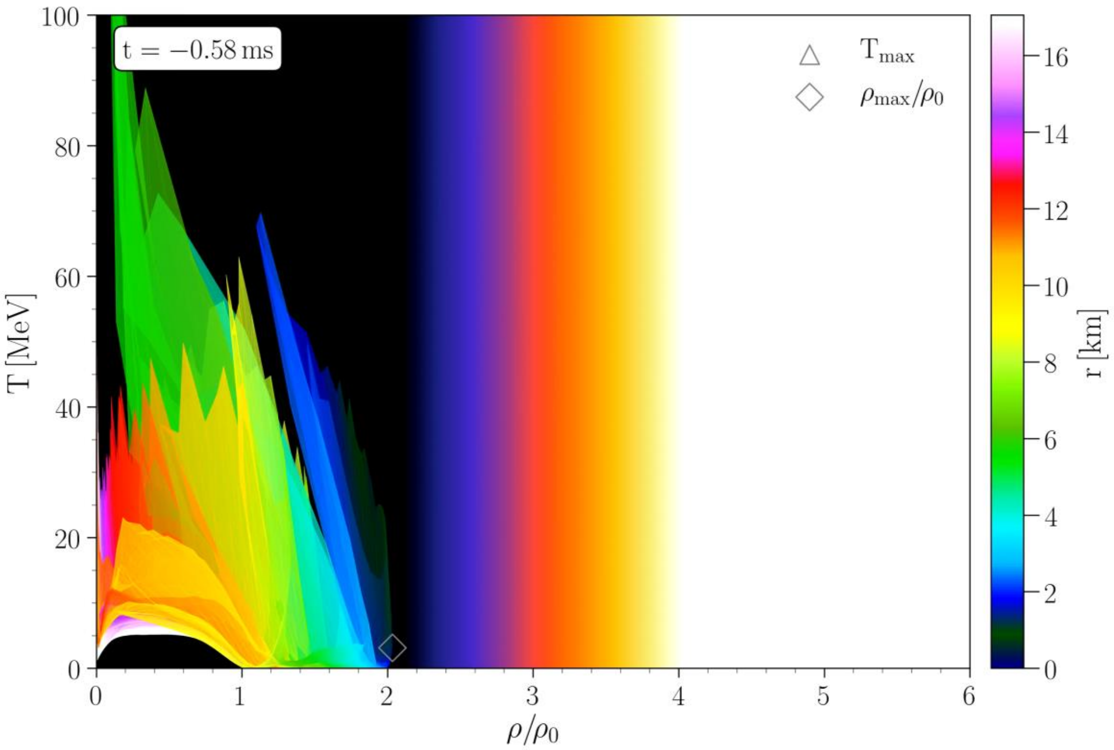
t = −0.58 ms
y [km]
x [km]
log10(ρ [g/cm3])



t = −0.58 ms
x [km]
T [MeV]

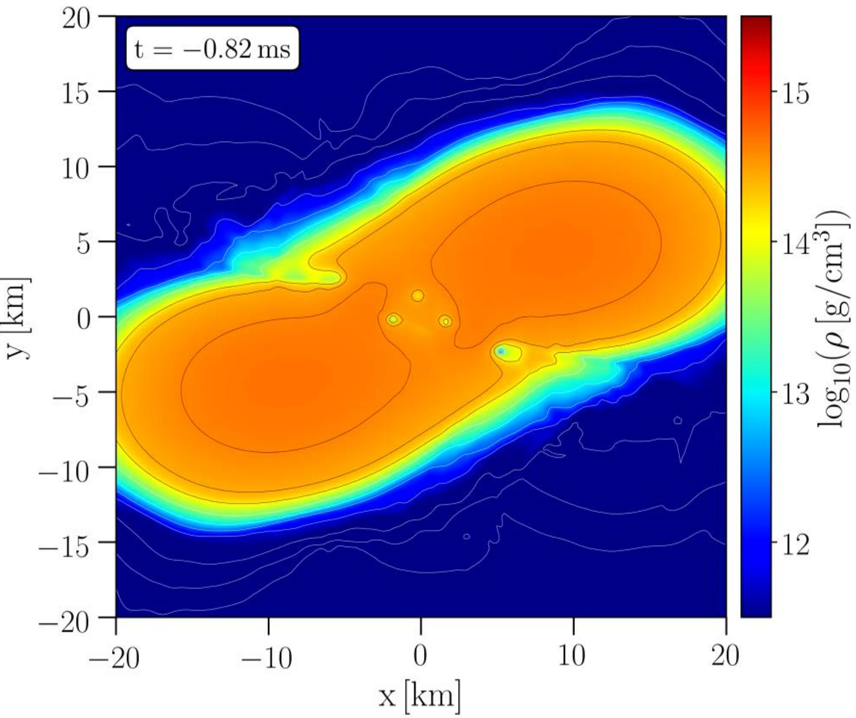


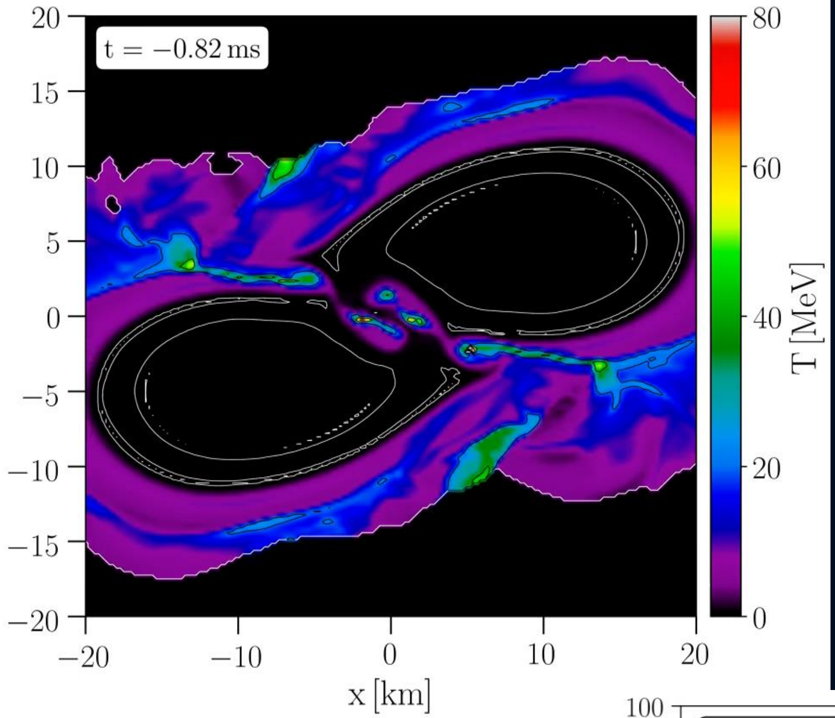
M = 2.68 M⊙, PTTC
M = 2.64 M⊙, DPT
M = 2.68 M⊙, NPT
M = 2.64 M⊙, NPT
inspiral
pure−quark phase
mixed phase
pure−hadron phase
ρmax/ρ0
t − tmerg [ms]

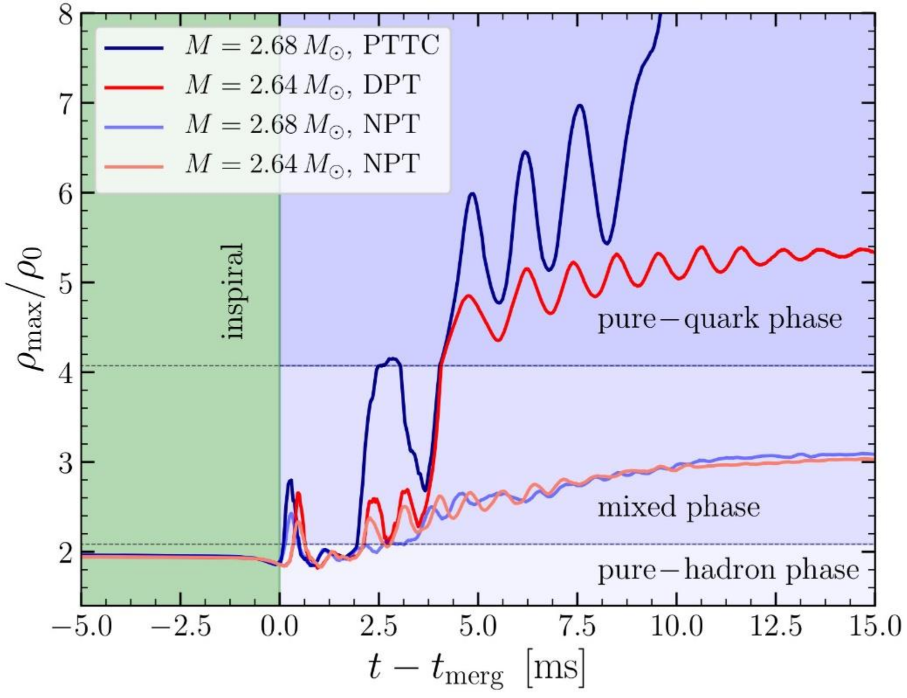


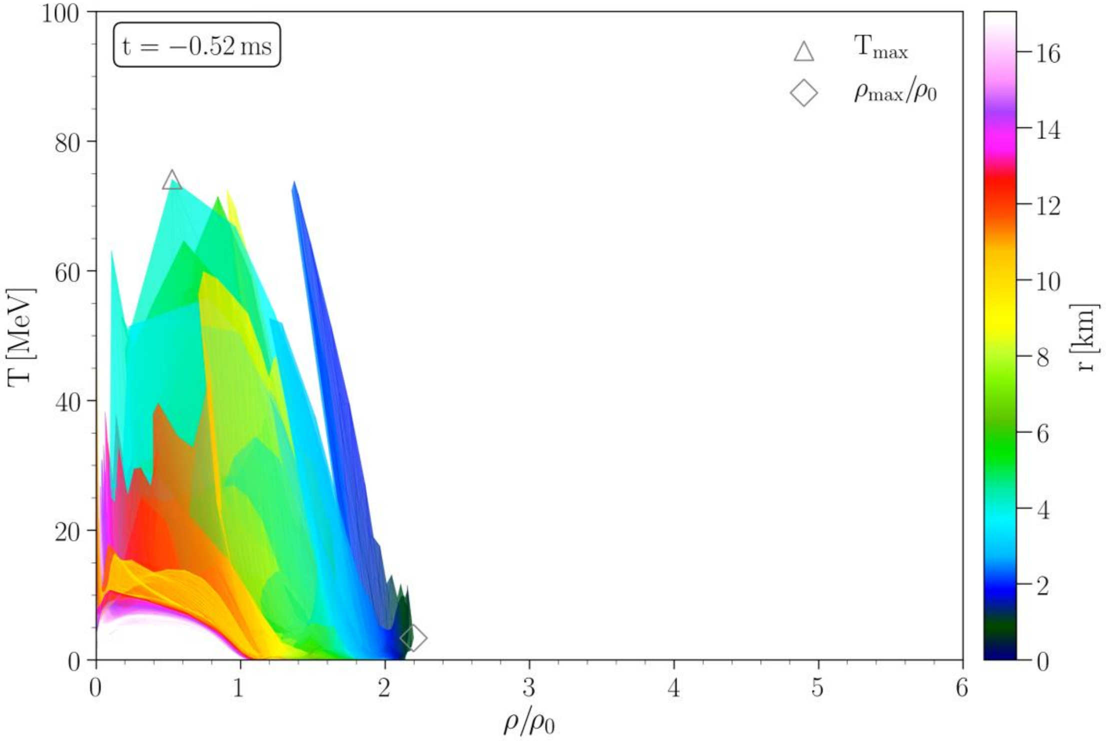
t = −0.58 ms
Tmax
ρmax/ρ0
T [MeV]
ρ/ρ0
r [km]

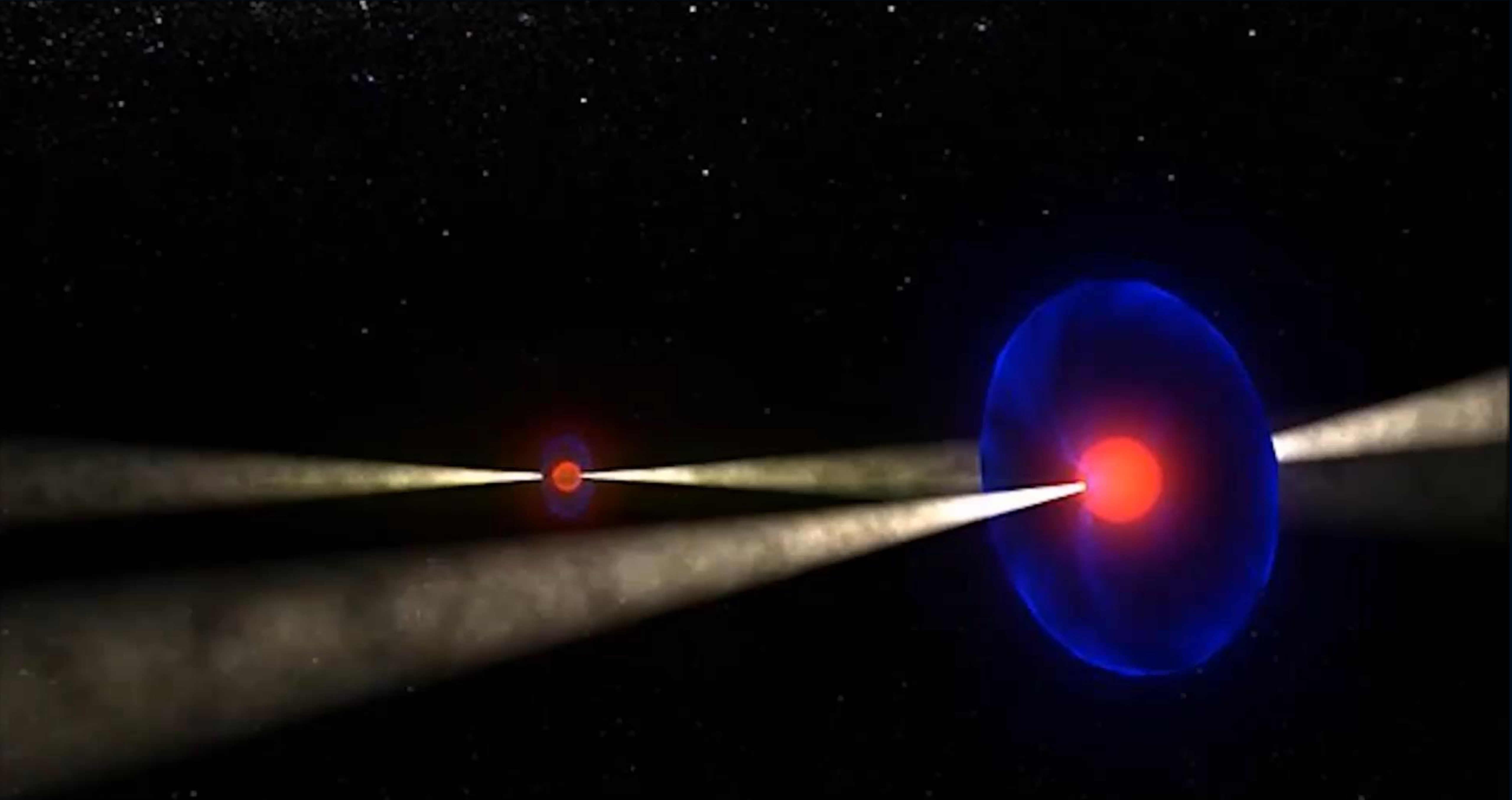
NPT


t = −0.82 ms
y [km]
x [km]
log10(ρ [g/cm3])


t = −0.82 ms
x [km]
T [MeV]


M = 2.68 M⊙, PTTC
M = 2.64 M⊙, DPT
M = 2.68 M⊙, NPT
M = 2.64 M⊙, NPT
inspiral
pure−quark phase
mixed phase
pure−hadron phase
ρmax/ρ0
t − tmerg [ms]


t = −0.52 ms
Tmax
ρmax/ρ0
T [MeV]
ρ/ρ0
r [km]



The Neutronstar Merger Dance

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.