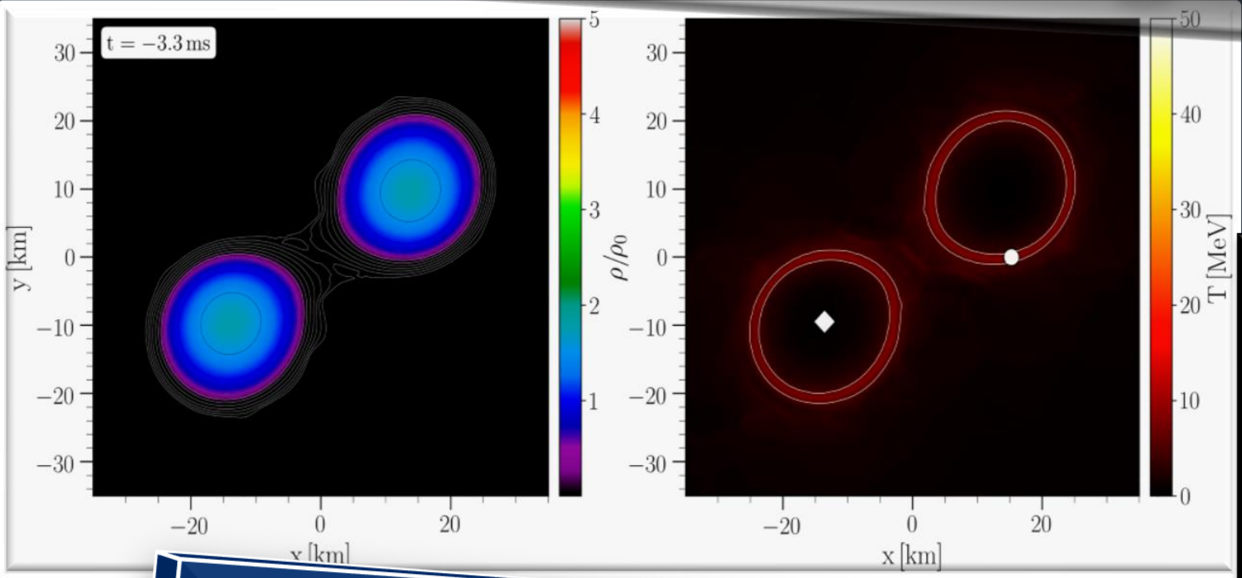
Binary Hybrid Star Mergers and the Phase Diagram of Quantum Chromo Dynamics

DPG-FRÜHJAHRSTAGUNG
MÜNCHEN, 21 MÄRZ 2019



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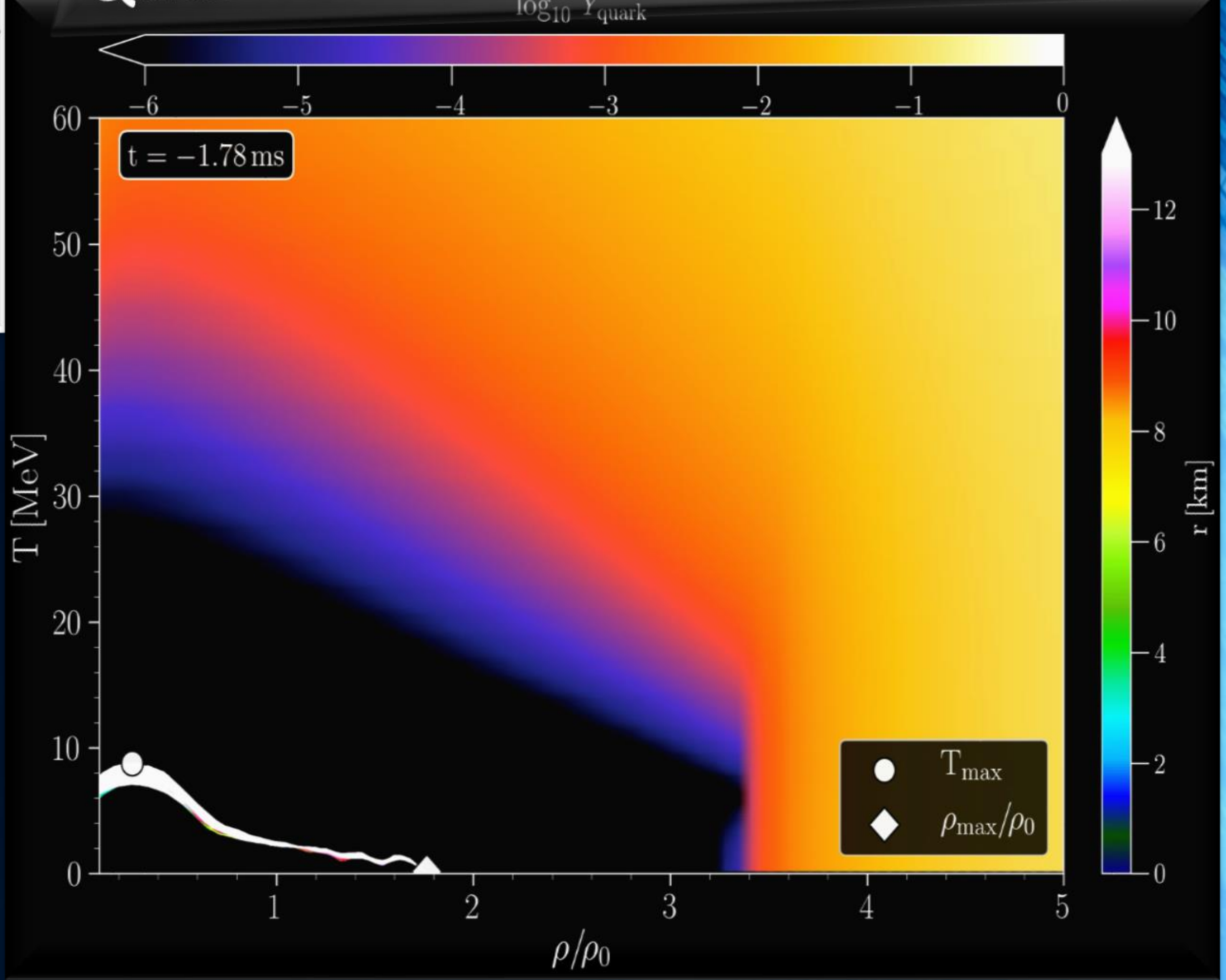
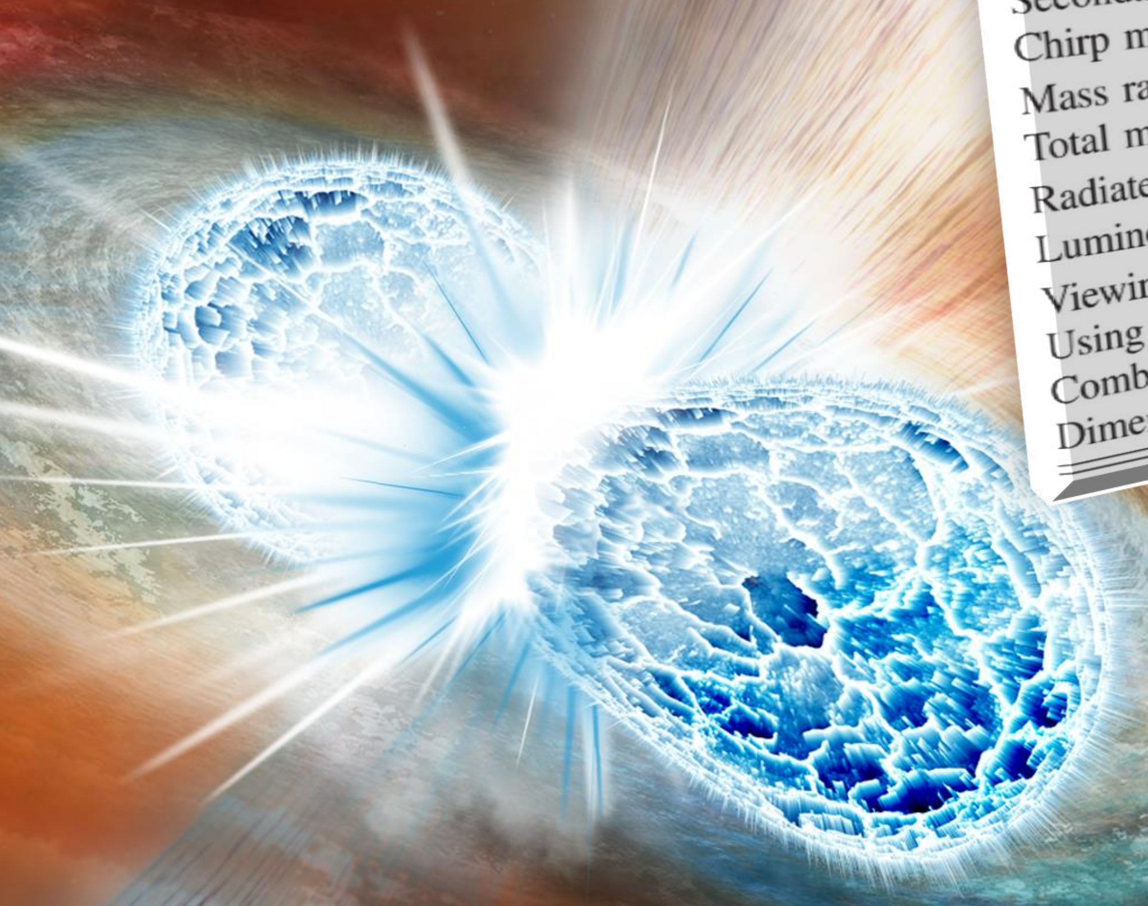
In collaboration with Luke Bovard, Elias R. Most, L. Jens Papenfort, Laura Tolos, Gloria Montaña, Jan Steinheimer, Veronica Dexheimer, Stefan Schramm, Horst Stöcker and Luciano Rezzolla



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 $m_{\rm tot}$	$2.74^{+0.04}_{-0.01} M_\odot$	$2.82^{+0.47}_{-0.09} M_\odot$
Radiated energy $E_{\rm rad}$	$> 0.025 M_\odot c^2$	$> 0.025 M_\odot c^2$
Luminosity distance $D_{\rm L}$	40^{+8}_{-14} Mpc	40^{+8}_{-14} Mpc
Viewing angle Θ	$\lesssim 55°$	$\lesssim 56°$
Using NGC 4993 location	$\lesssim 28°$	$\lesssim 28°$
Combined dimensionless tidal deformability $\tilde{\Lambda}$	$\lesssim 800$	$\lesssim 700$
Dimensionless tidal deformability $\Lambda(1.4 M_\odot)$	$\lesssim 800$	$\lesssim 1400$



17. August 2017

Gravitationswelle einer
Neutronenstern Kollision gemessen!

Constraining the Equation of State by Multimessenger Gravitational Wave Astronomy

DPG Meeting 2002 (17 years ago !)

Über die Möglichkeit mittels Gravitationswellen-Detektion etwas über die starke Wechselwirkung zu lernen

Matthias Hanauske, Walter Greiner und Horst Stöcker

1. Einführung
   - ART ⇔ QCD
   - Confinement
   - Quark-Gluon-Plasma
2. Kompakte Sterne
   - Theoretische Vorhersagen
   - Beobachtbare Größen
3. Emission von Gravitationswellen
   - In welchen Systemen können die von kompakten Sternen emittierten Gravitationswellen von den Eigenschaften der QCD abhängen

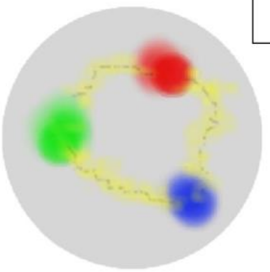
ART ⇔ QCD

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

QuantenCromoDynamik:
$(SU(3)_{(c)}$ Yang-Mills-Theorie der Farbe)

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

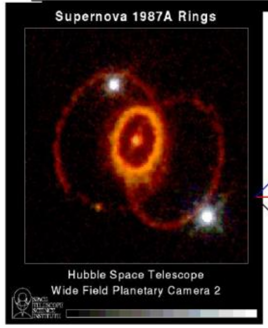
A, B =rot, grün, blau

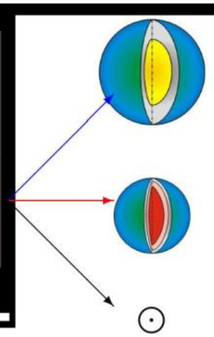


$$\psi^f_A = \begin{pmatrix} \psi^f_r \\ \psi^f_g \\ \psi^f_b \end{pmatrix}$$

Confinement
chirale Symmetrie, ...

Entstehung und Beobachtungsmöglichkeiten von kompakten Sternen

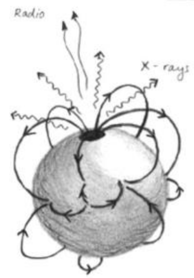




Neutronen Stern

Quark- oder Hyperstern

Schwarzes Loch



Radiowellen Teleskope(ca. 1400)

Optische Teleskope (3)

Röntgen Detektoren (ca. 30)

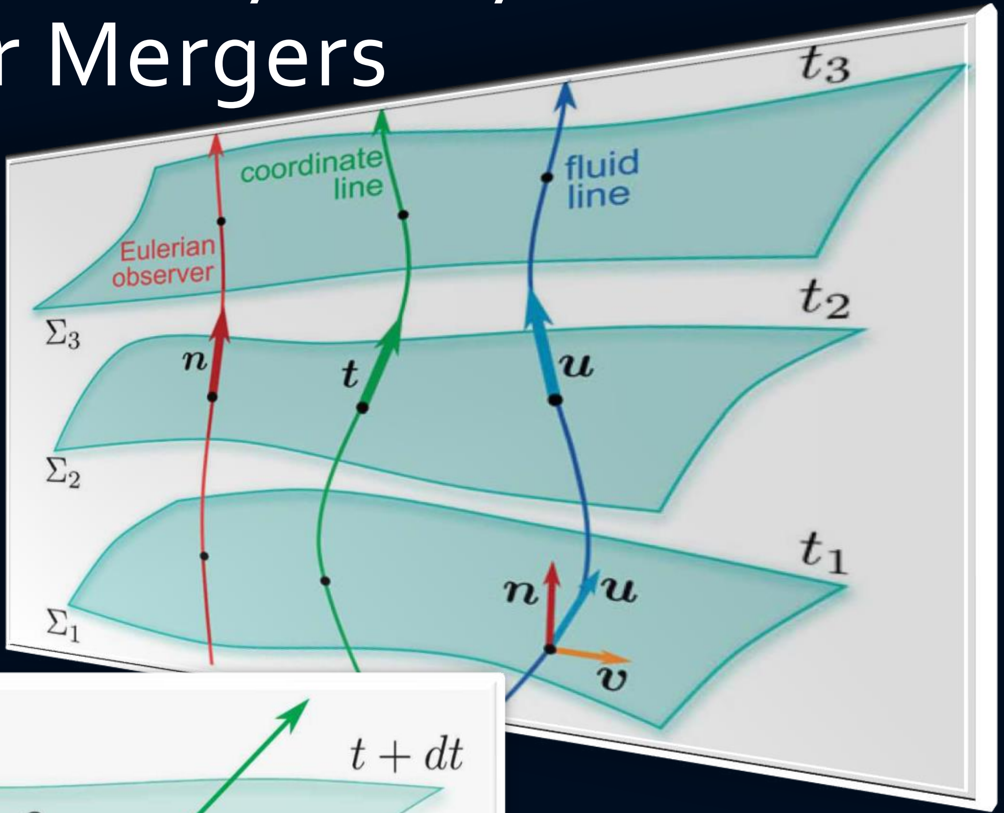
Gravitationswellen Detektoren

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:

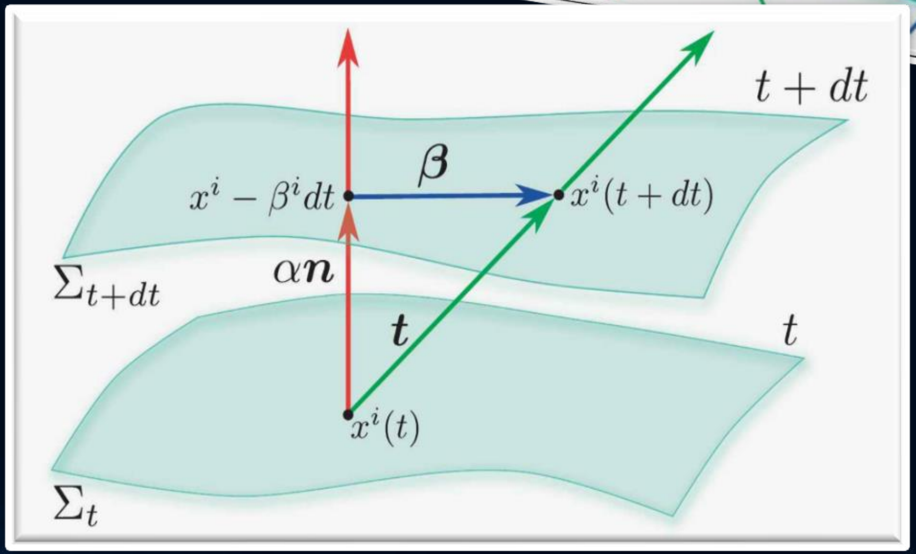
$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = 8\pi T_{\mu\nu}$$

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



(3+1) decomposition of spacetime

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

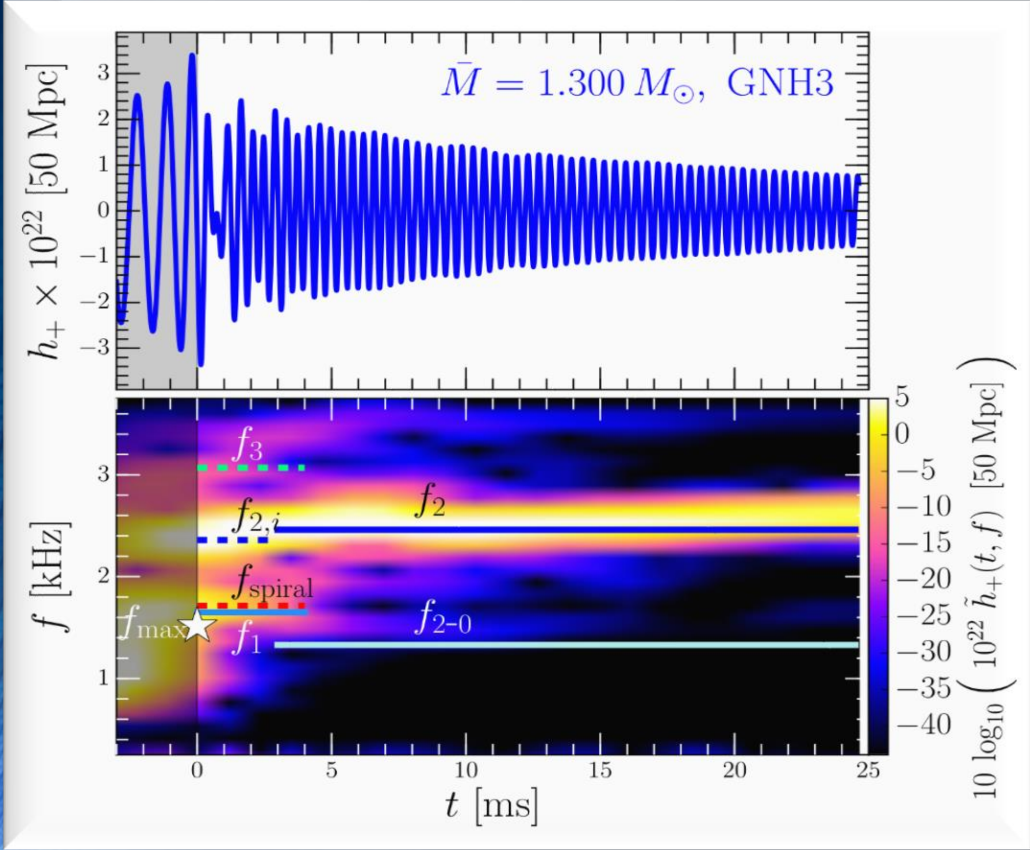


$$d\tau^2 = \alpha^2(t, x^j) dt^2 \qquad x^i_{t+dt} = x^i_t - \beta^i(t, x^j) dt$$

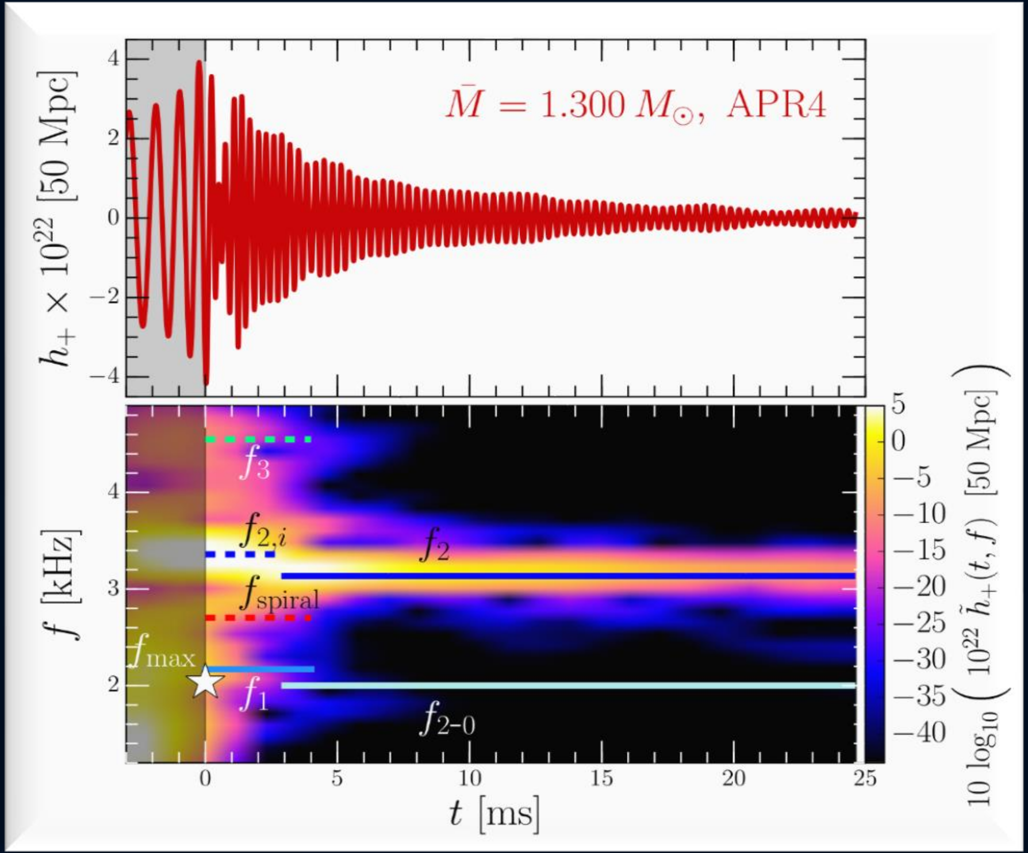
All figures and equations from: Luciano Rezzolla, Olindo Zanotti: Relativistic Hydrodynamics, Oxford Univ. Press, Oxford (2013)

Time Evolution of the GW-Spectrum

The power spectral density profile of the post-merger emission is characterized by several distinct frequencies. After 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



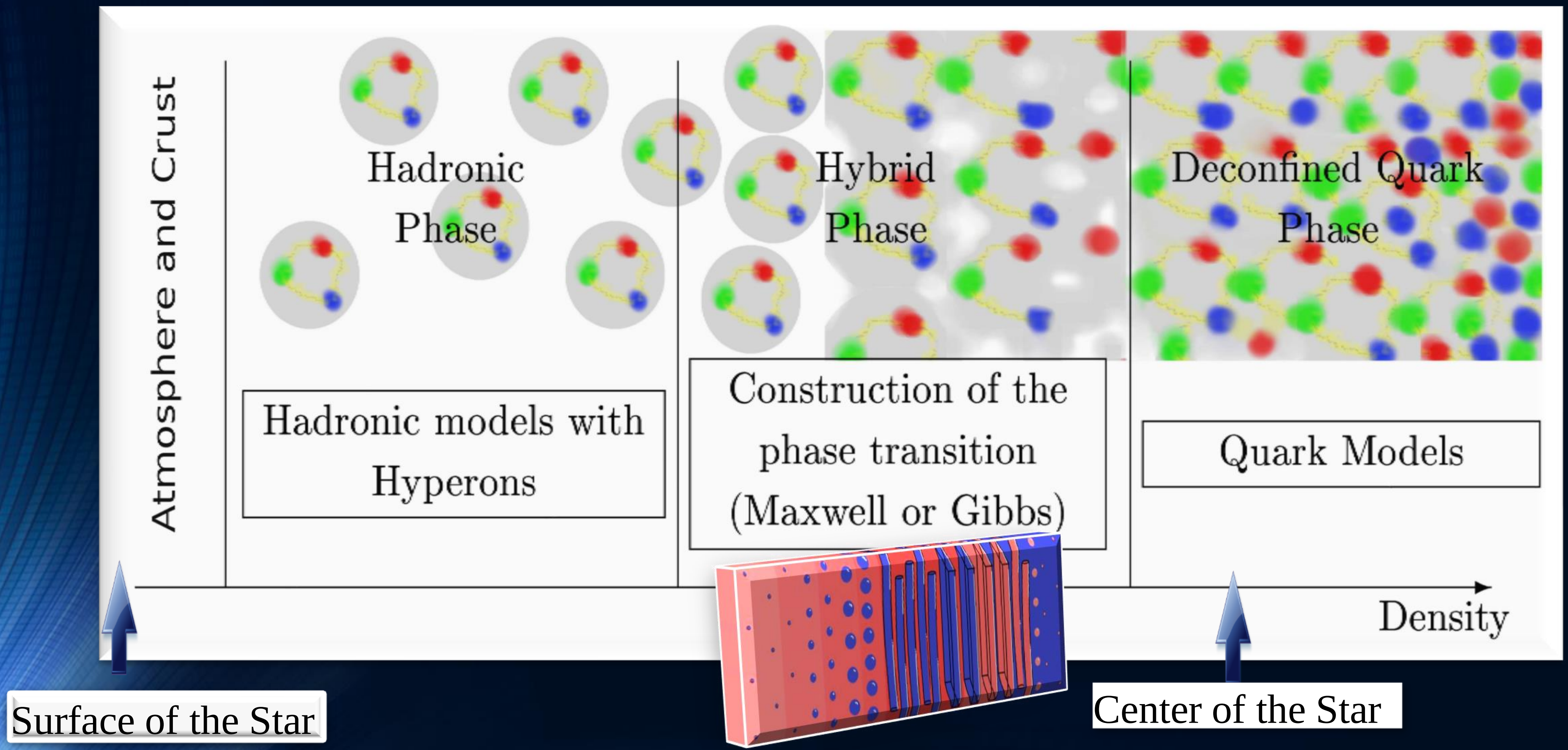
Soft EOS

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.

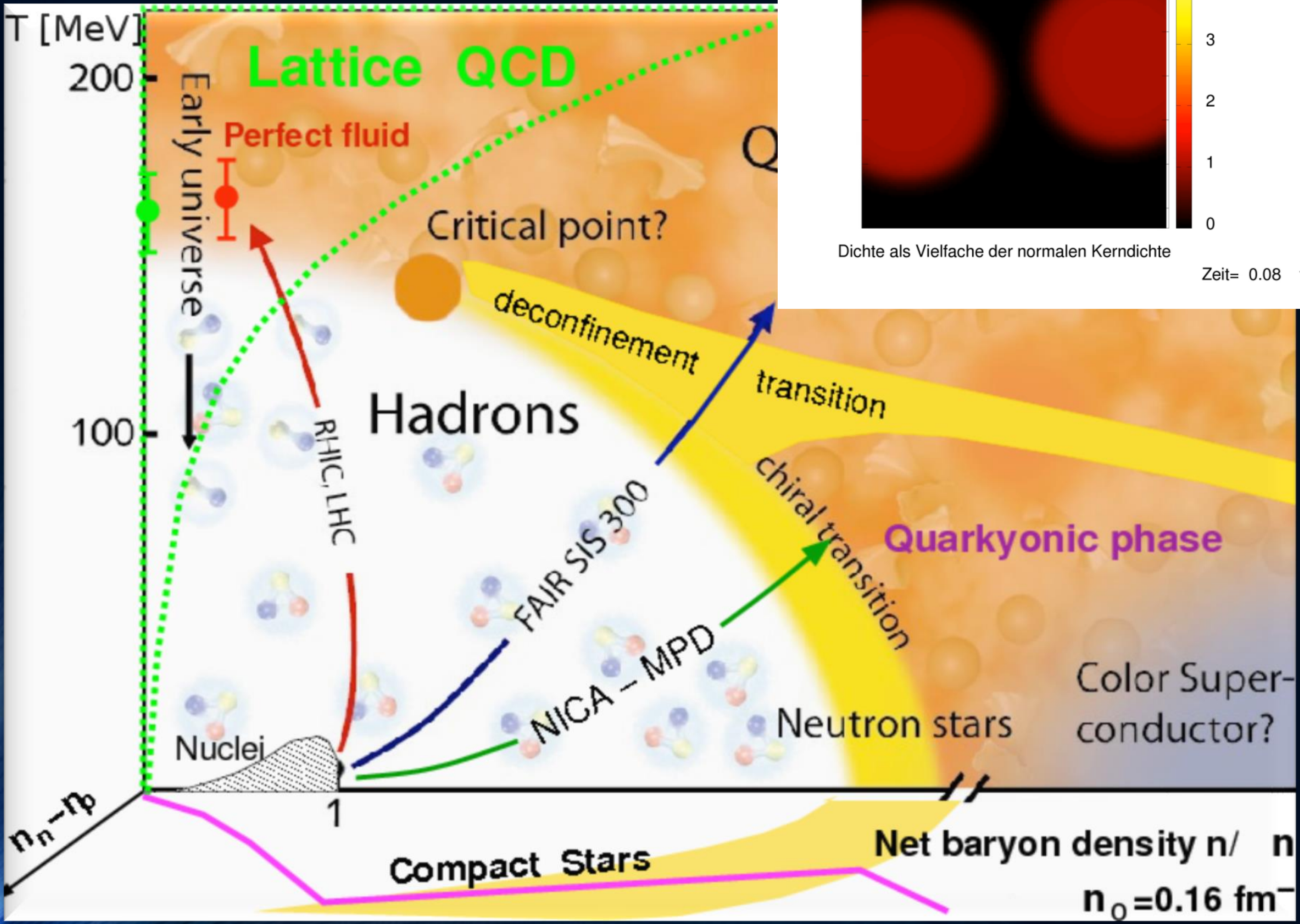
The QCD – Phase Transition and the Interior of a Hybrid Star

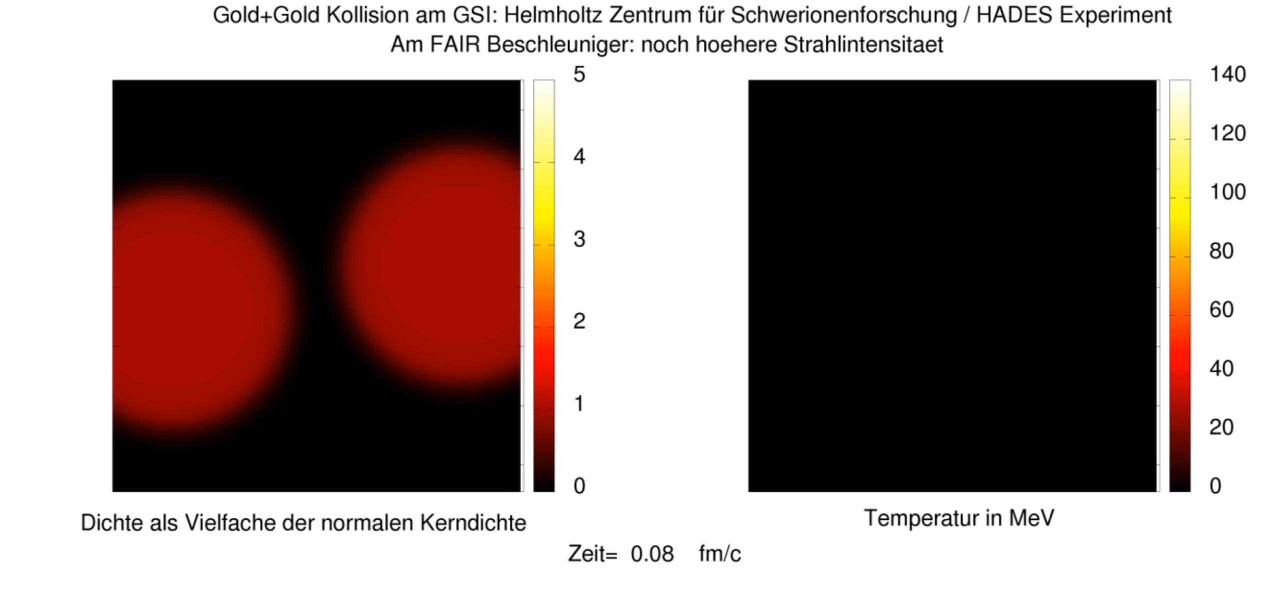


Matthias Hanauske; Doctoral Thesis:
Properties of Compact Stars within QCD-motivated Models; University Library Publication Frankfurt (2004)

The Hadron-Quark Phase Transition

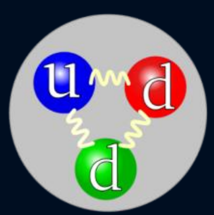
The QCD Phase Diagram



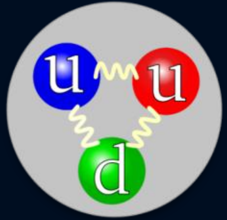


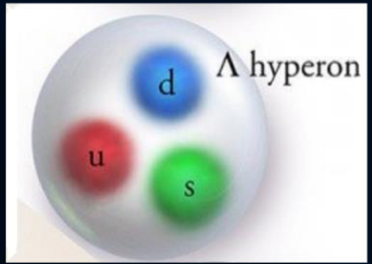
Credits:
Jan Steinheimer

Neutron

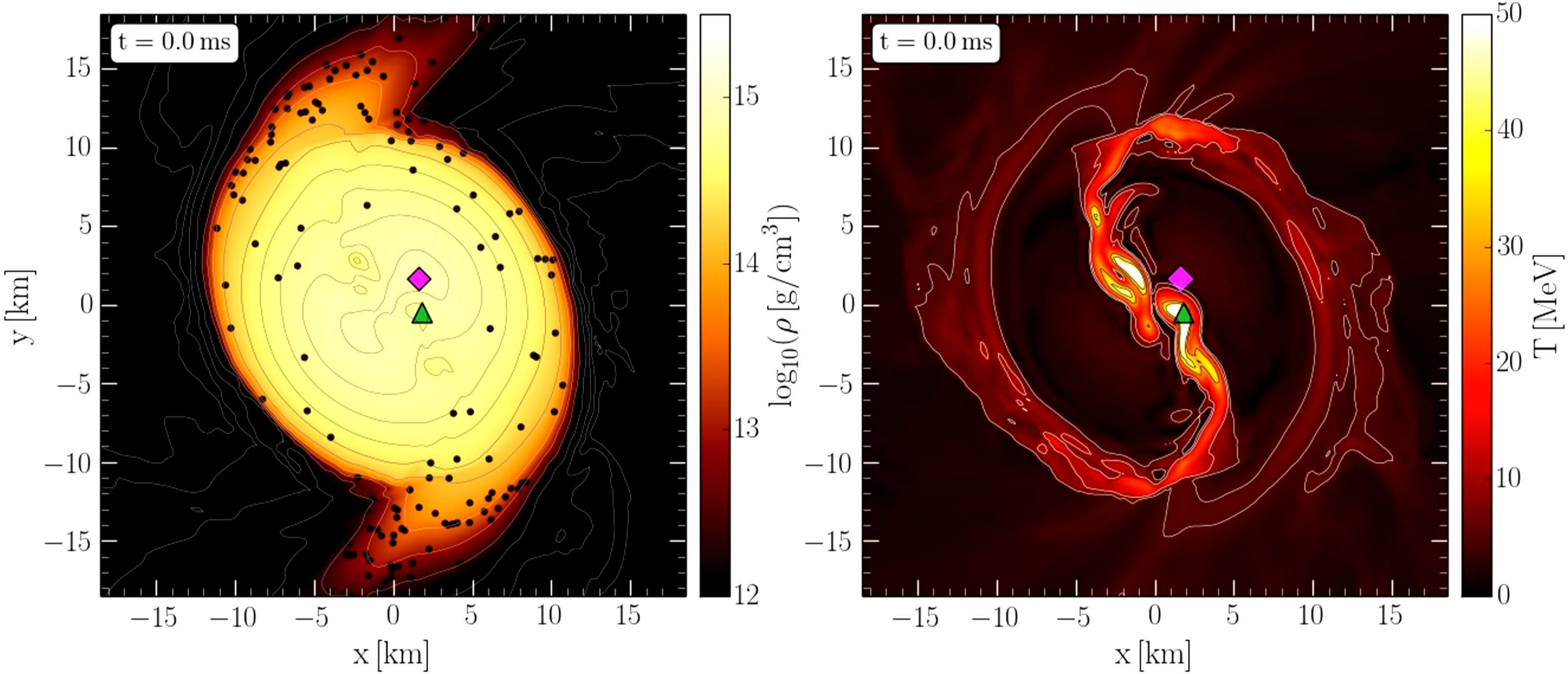


Proton



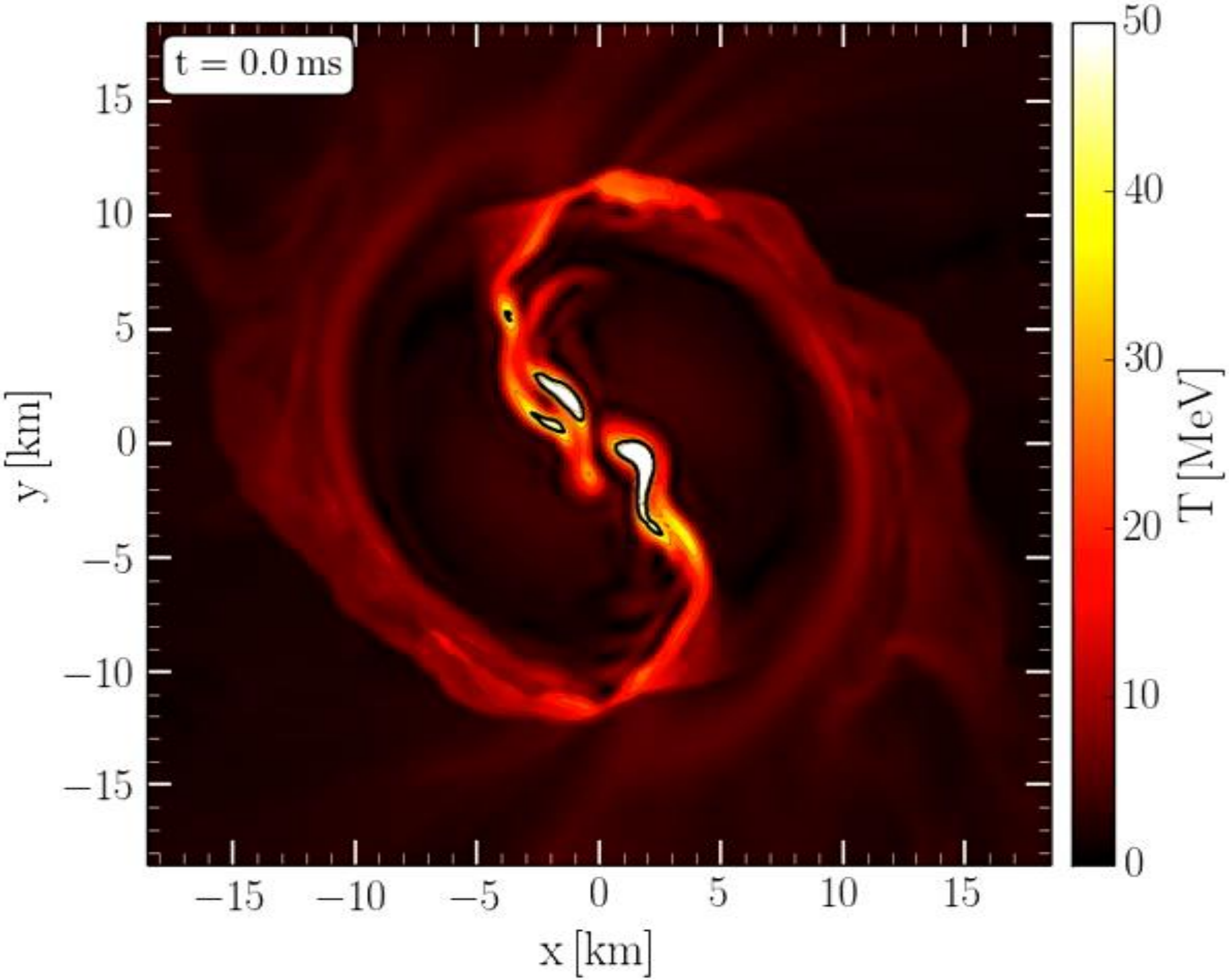


Density and Temperature Evolution inside the HMNS



Rest mass density on the equatorial plane

Temperature on the equatorial plane



Evolution of the Temperature in the post merger phase

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

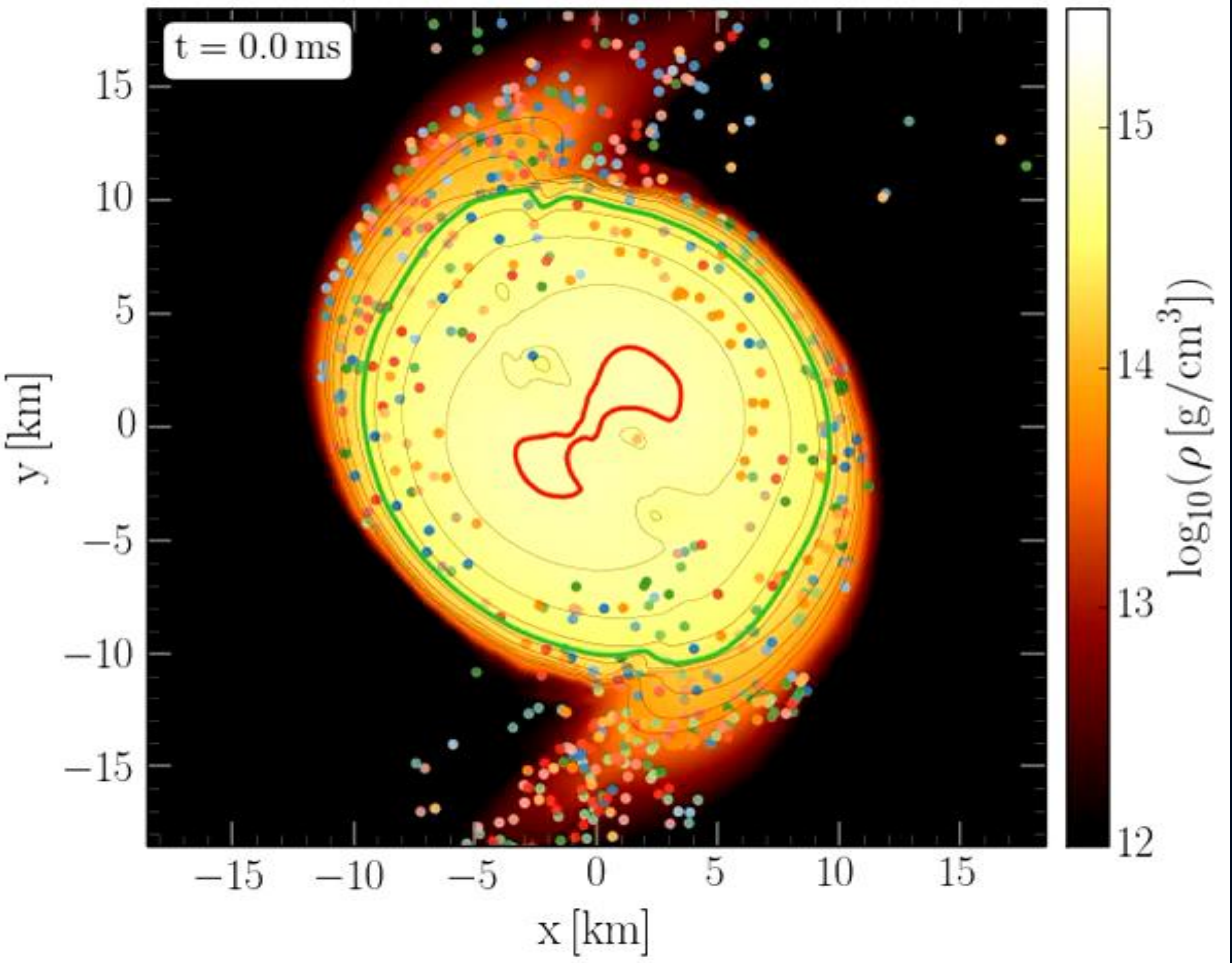
Kastaun, W., Ciolfi, R., Endrizzi, A., & Giacomazzo, B. (2017). Structure of stable binary neutron star merger remnants: Role of initial spin. Physical Review D, 96(4), 043019

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)

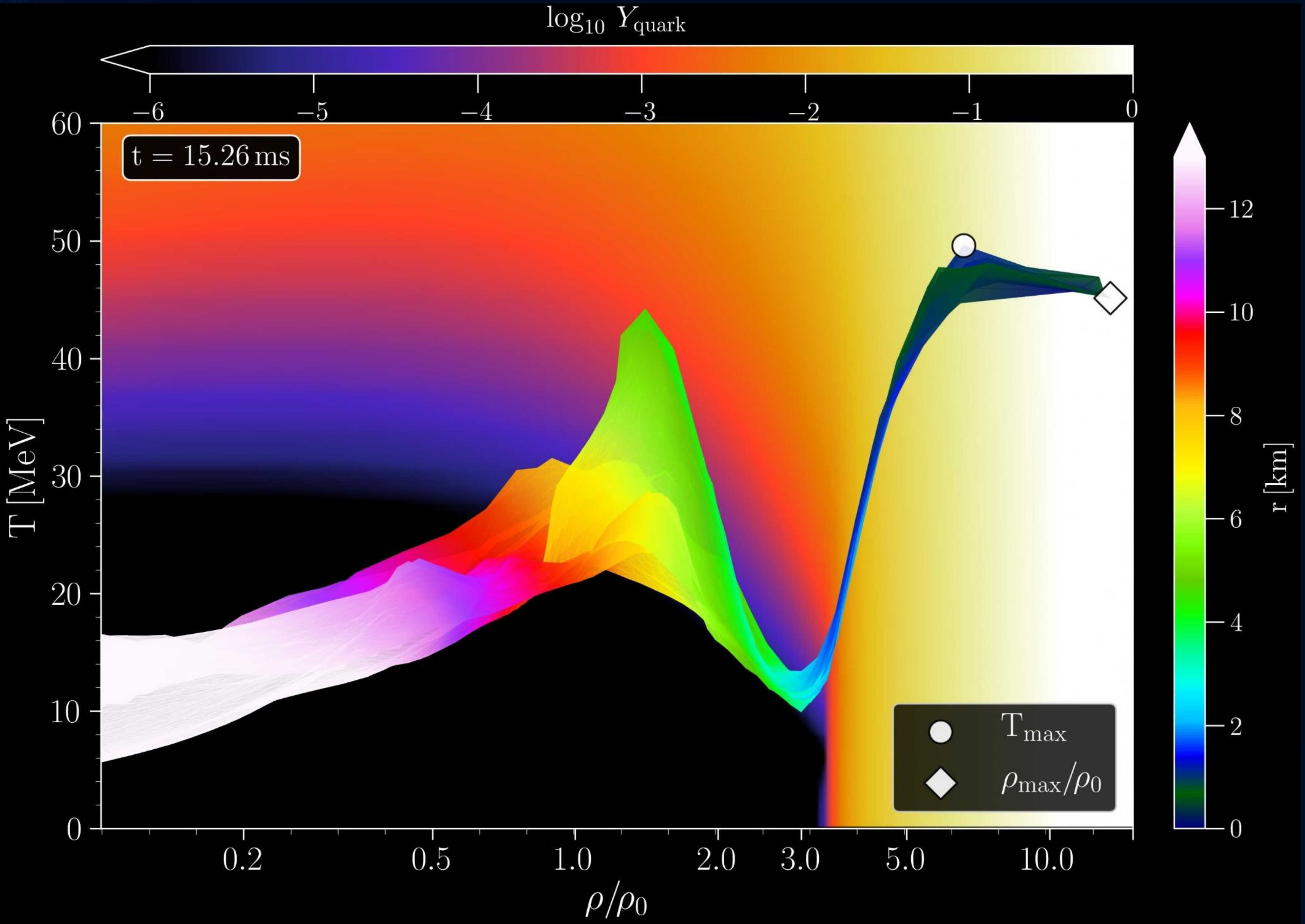
Evolution of Tracer-particles tracking individual fluid elements in the equatorial plane of the HMNS at post-merger times

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

Different rotational behaviour of the quark-gluon-plasma produced in non-central ultra-relativistic heavy ion collisions
L. Adamczyk et.al., "Global Lambda-hyperon polarization in nuclear collisions: evidence for the most vortical fluid", Nature 548, 2017



Binary Hybrid Star Mergers and the QCD Phase Diagram

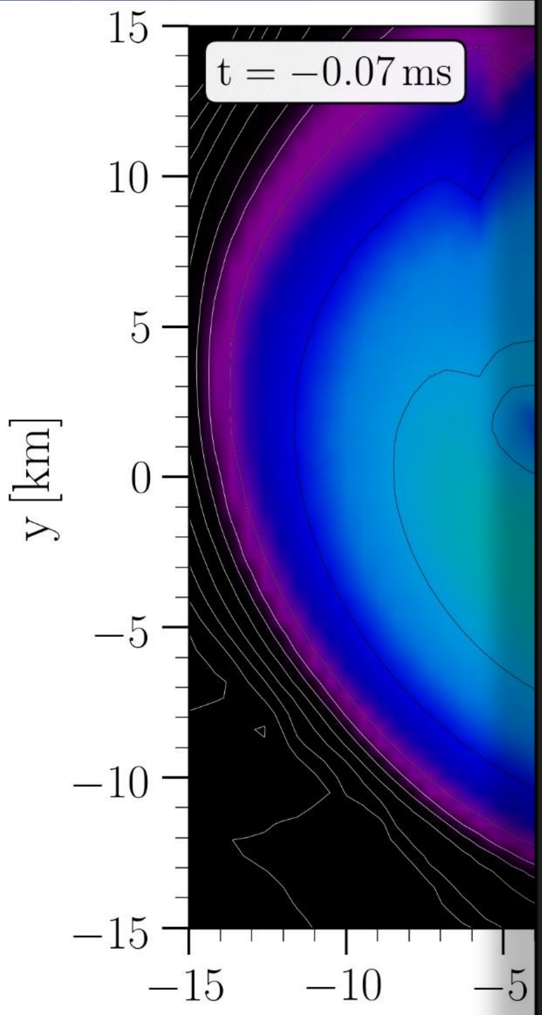


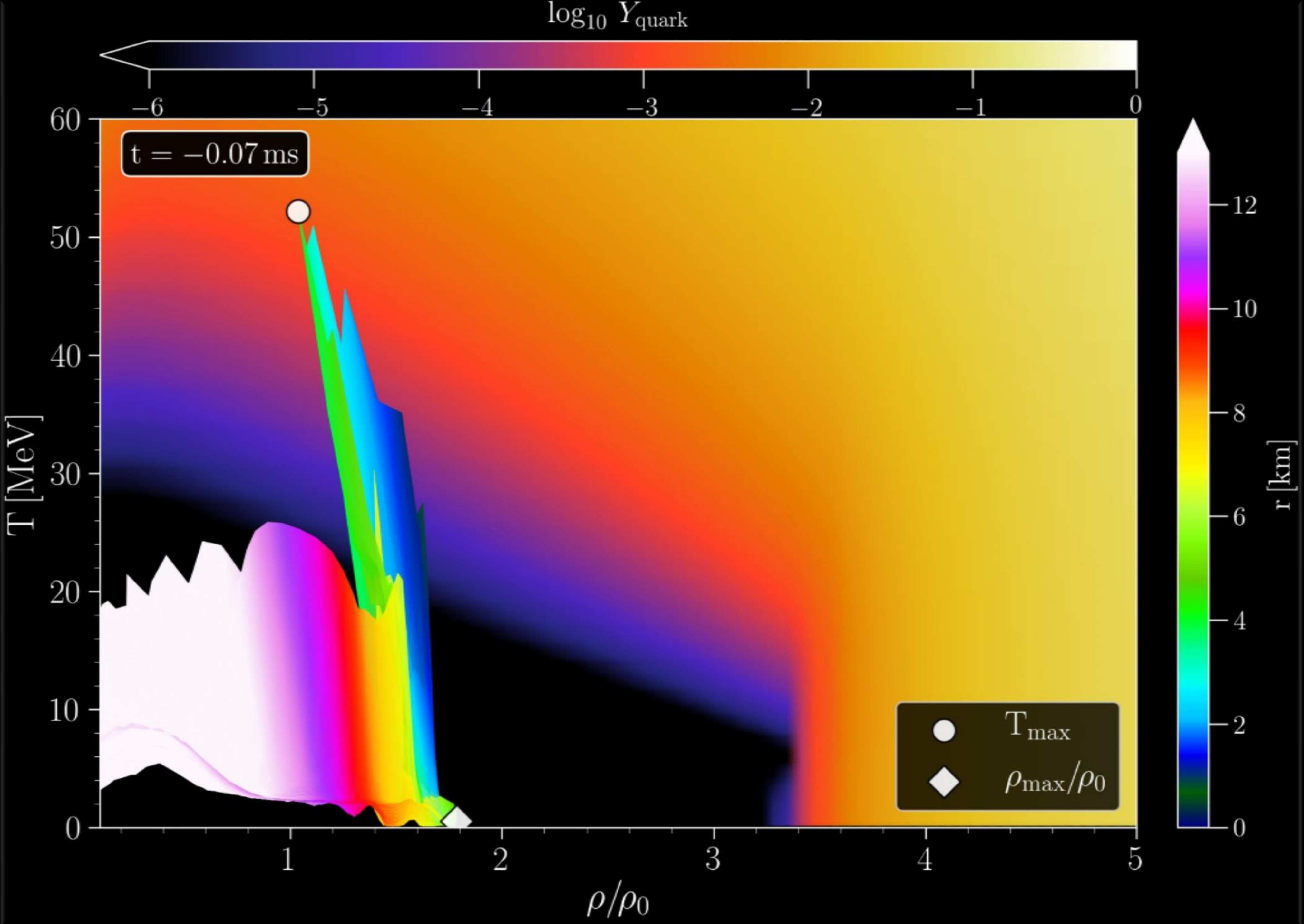
Hot and dense matter inside the inner area of a collapsing hypermassive hybrid star in the style of a (T- ρ) QCD phase diagram plot at a time right before the apparent horizont is formed in its center

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.

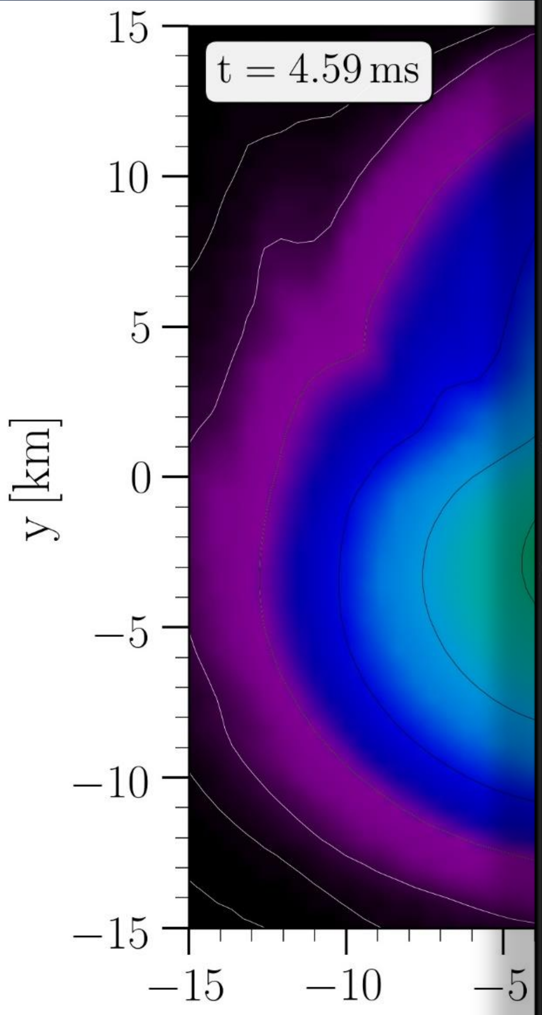
Merger Phase



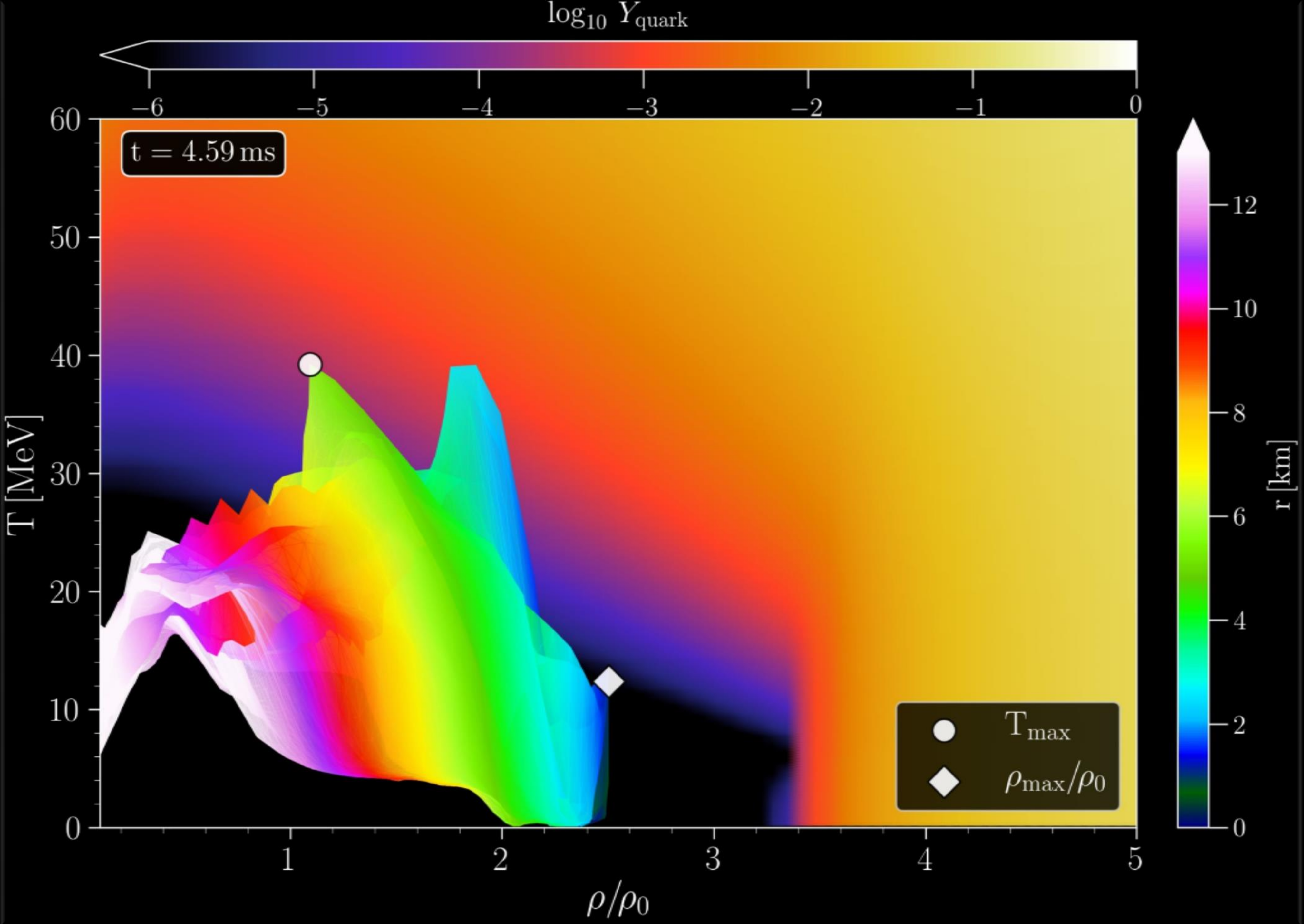


Rest mass density

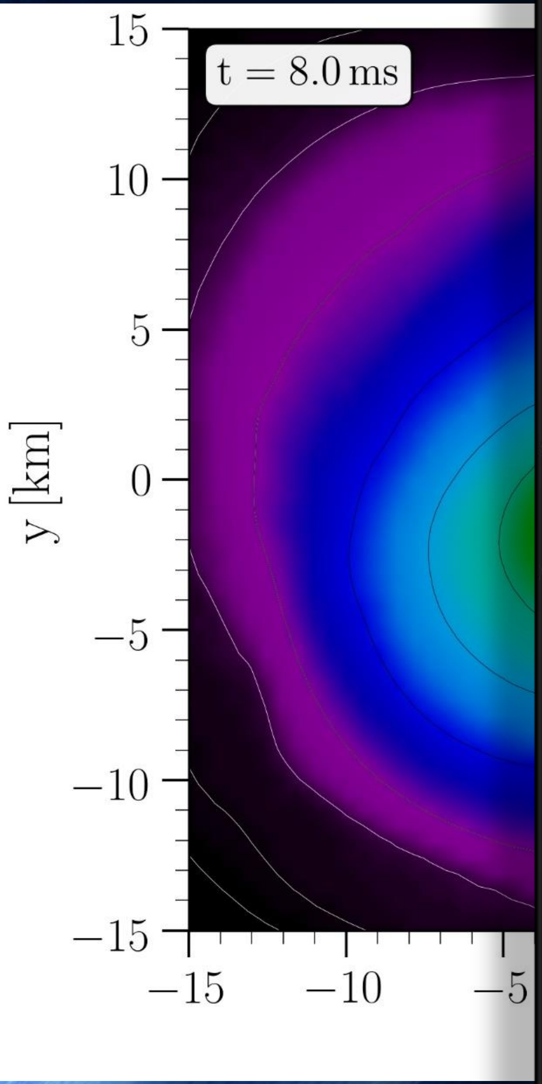
Post Merger Phase

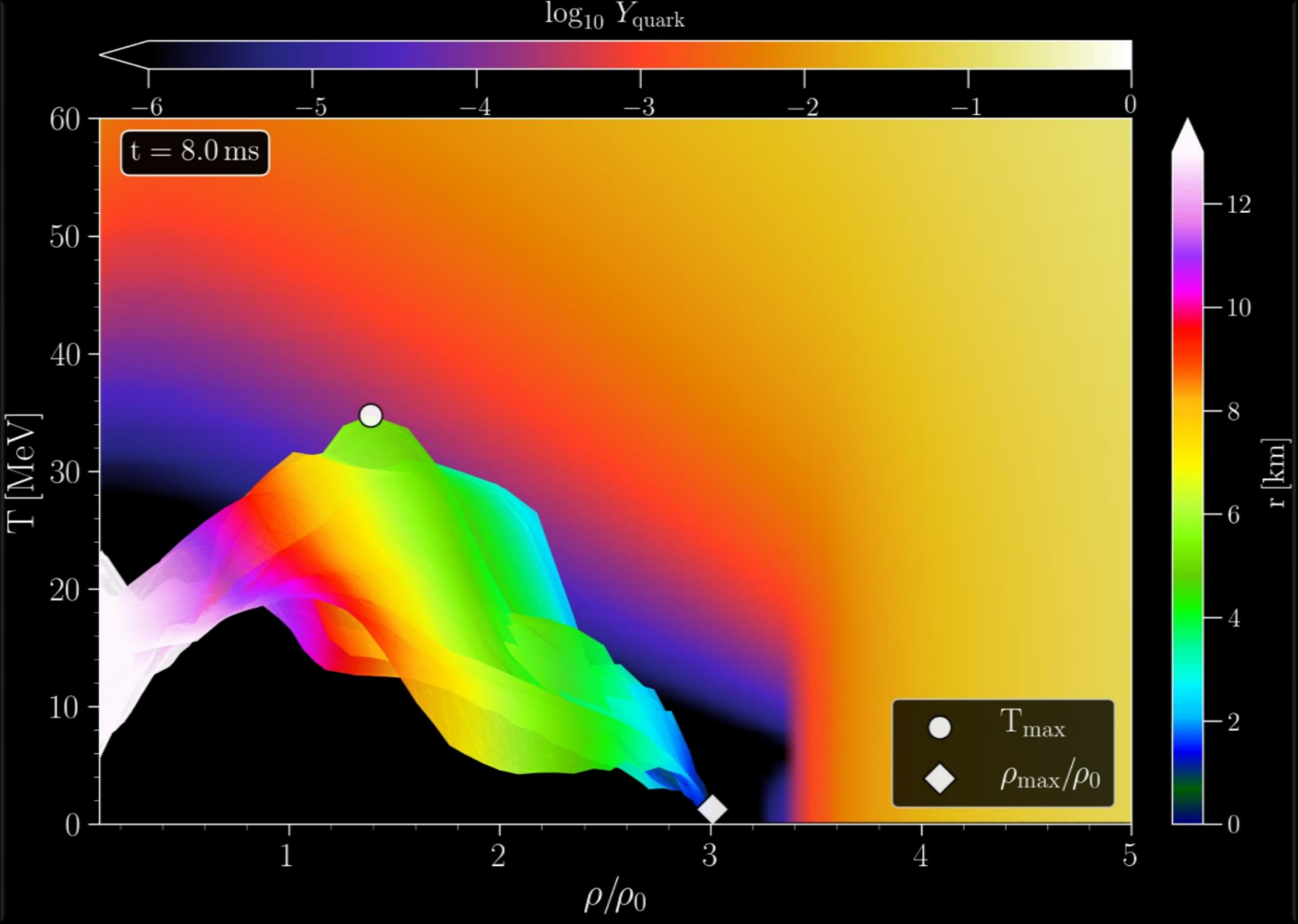


Rest mass density



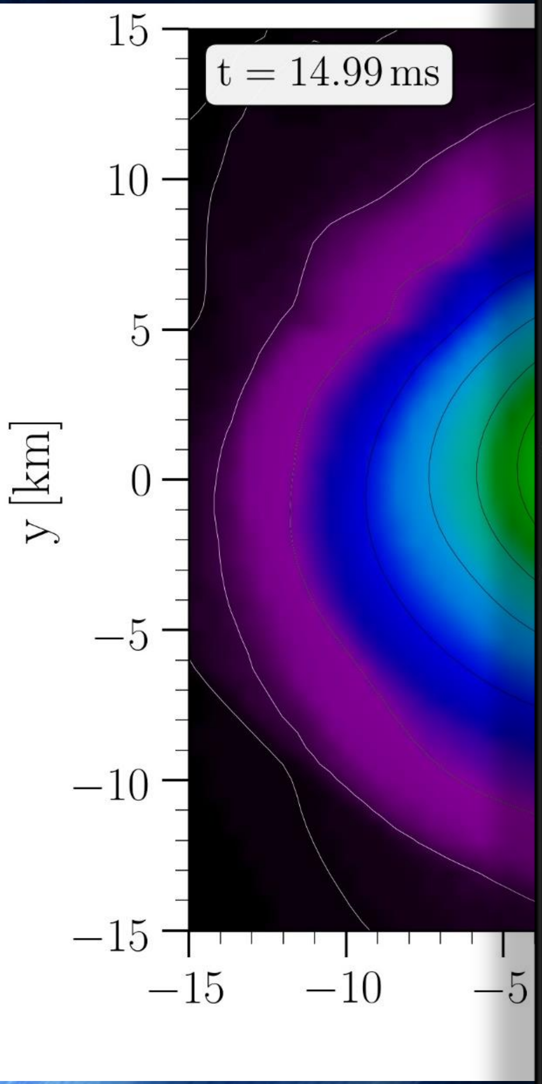
Merger Phase

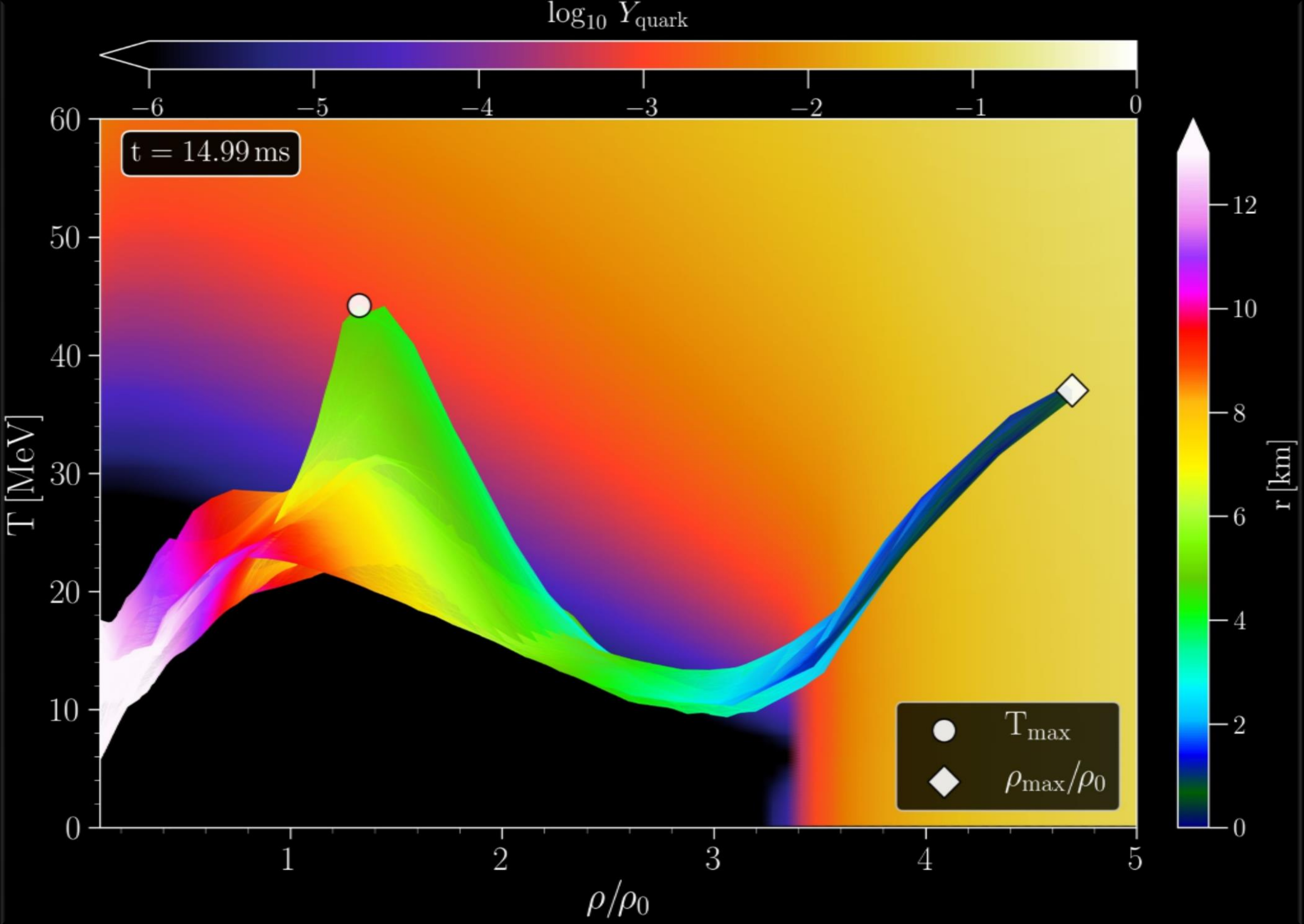




Rest mass density

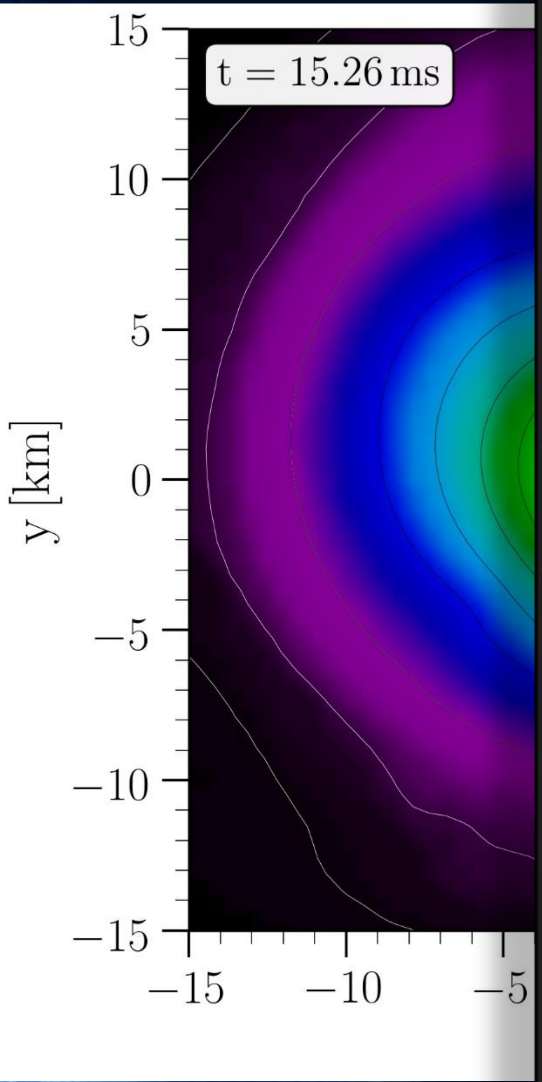
Merger Phase



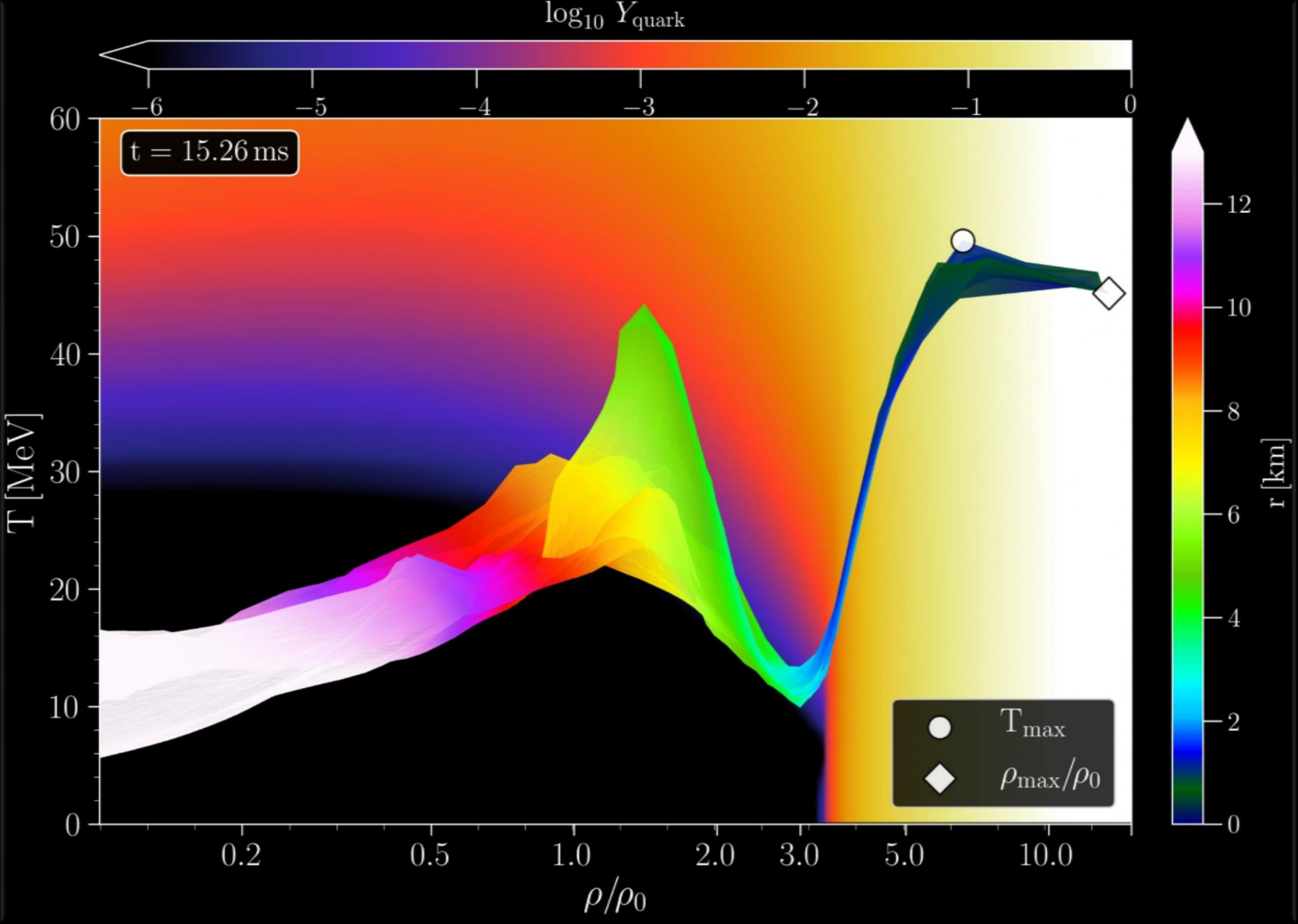


Rest mass density

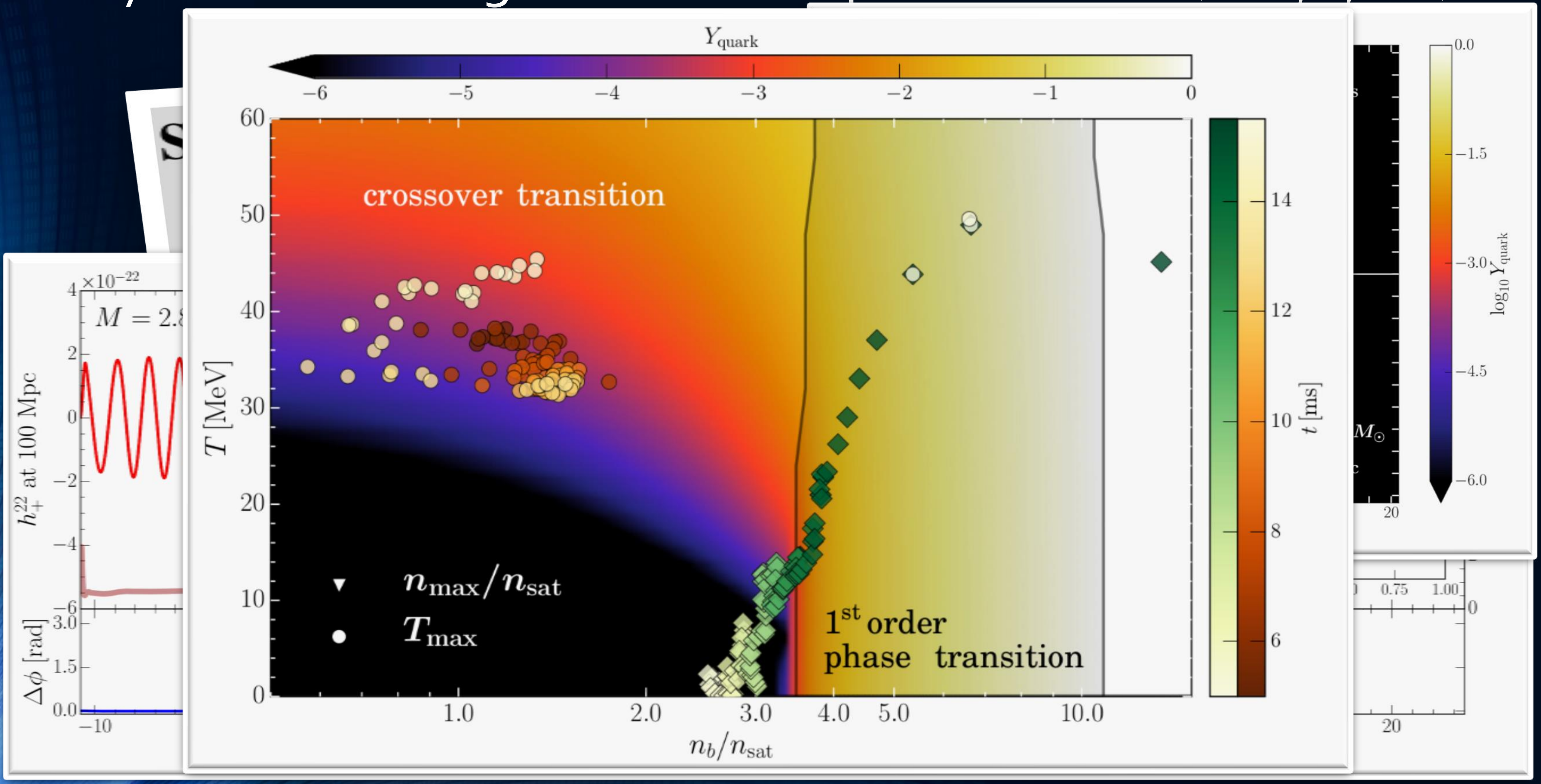
Merger Phase



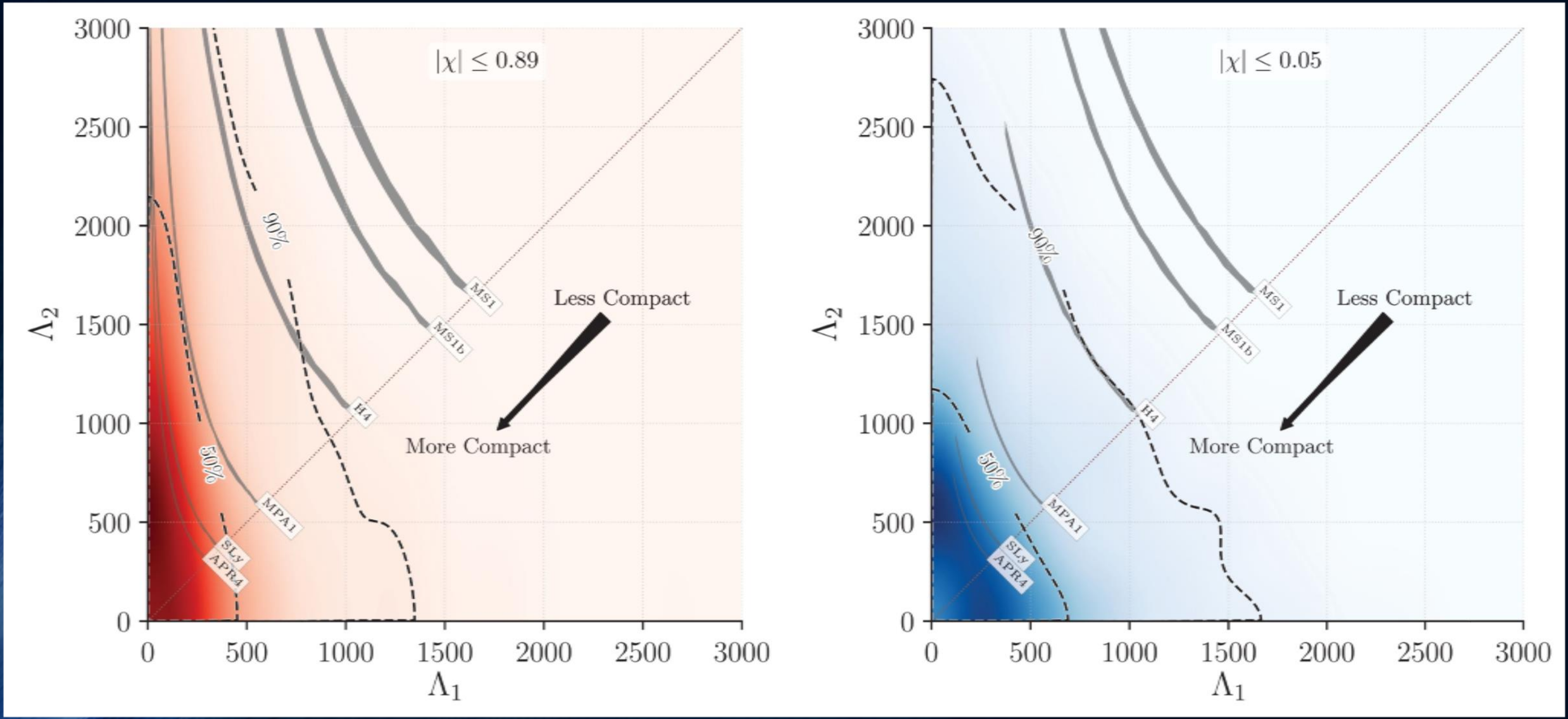
Rest mass density



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



GW170817: Tidal Deformability Restrictions on the Equation of State (EOS) (for high and low spin assumption)



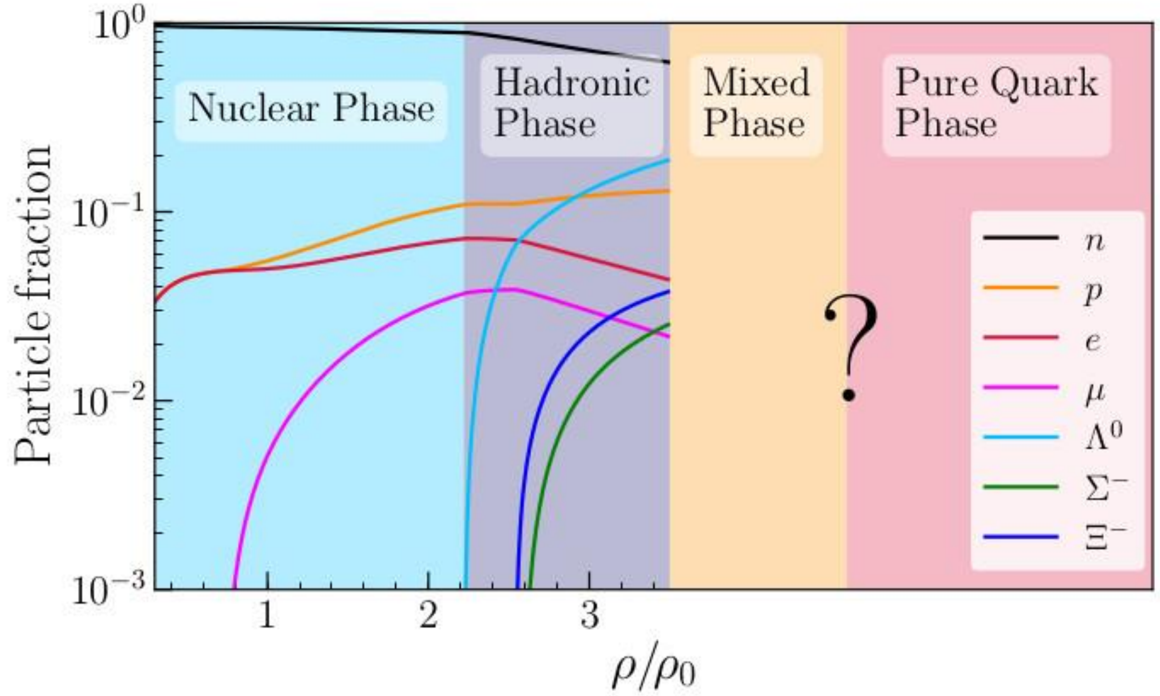
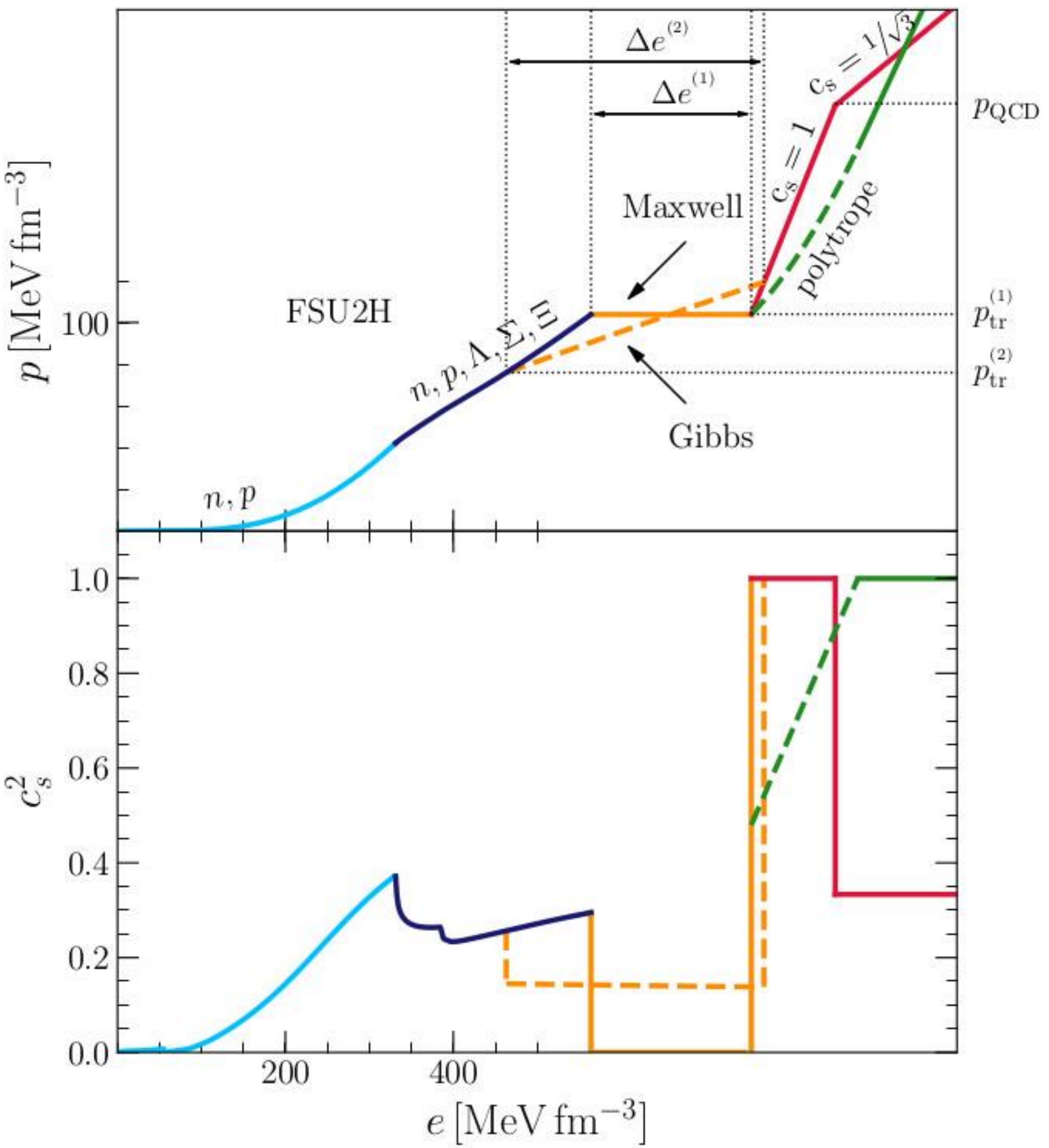
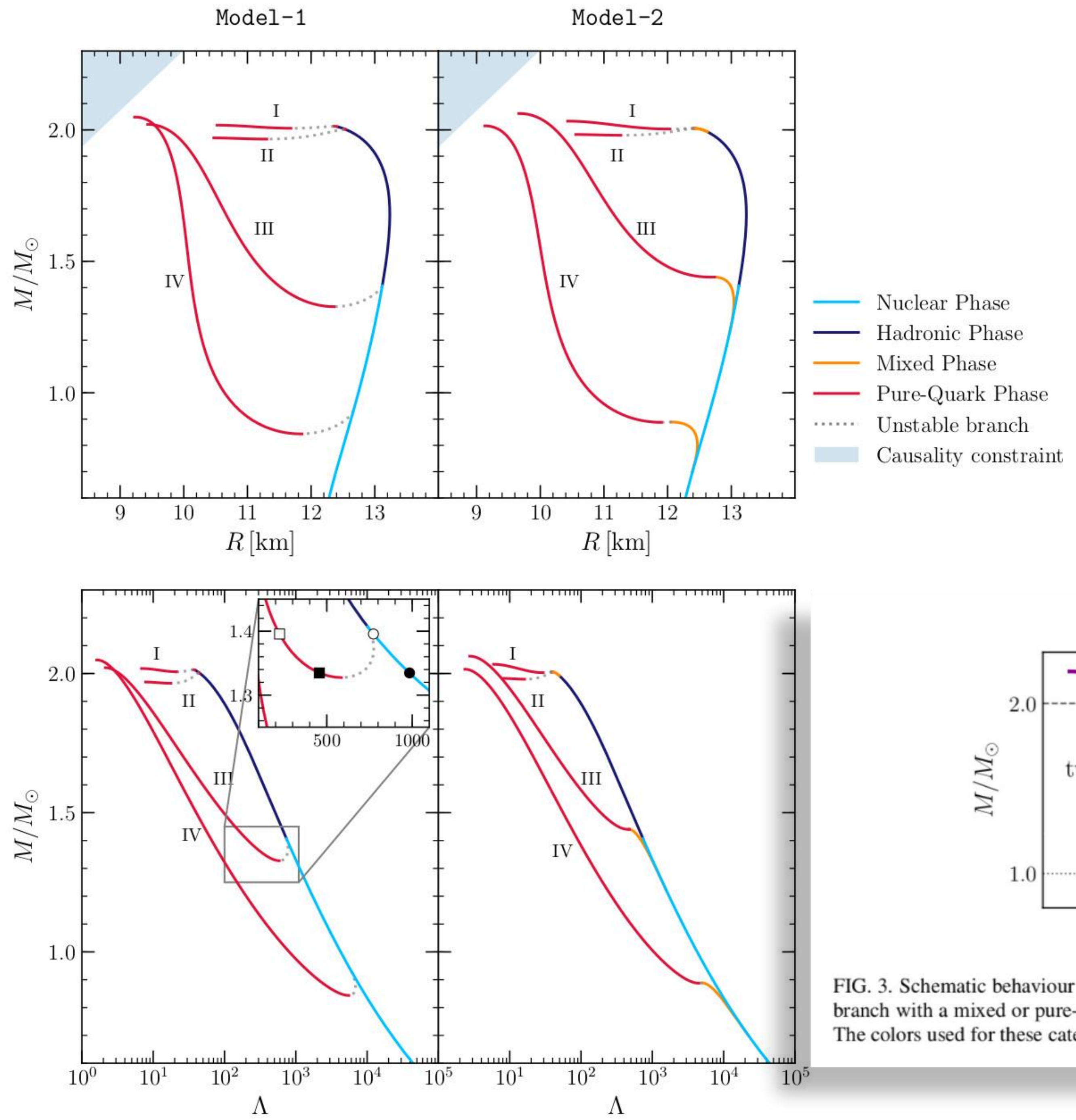


FIG. 1. Particle fractions as functions of the baryonic density for the FSU2H model [69, 70] up to the point where the HQPT is implemented, giving rise to a phase of deconfined quark matter which can be separated from the nuclear (or hadronic) phase by a mixed phase of hadrons and quarks. We note that the actual fractions of nucleons/hyperons and quarks u, d, s in the mixed and quark phases cannot be determined with the parametrizations used in this work.



Mass-Radius Relations for Twin-Star EOSs

The mass and radius of a single, non-rotating and spherically symmetric neutron star can be easily calculated by solving the static TOV equation numerically for a given EOS.



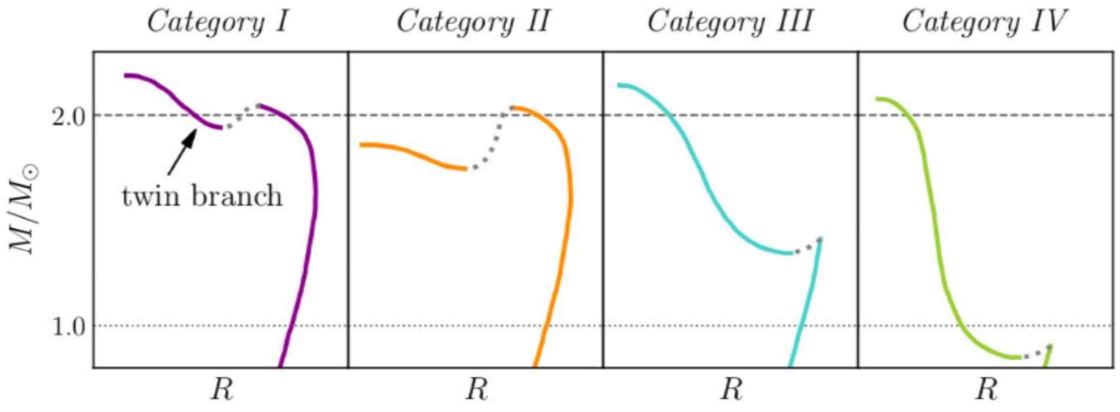
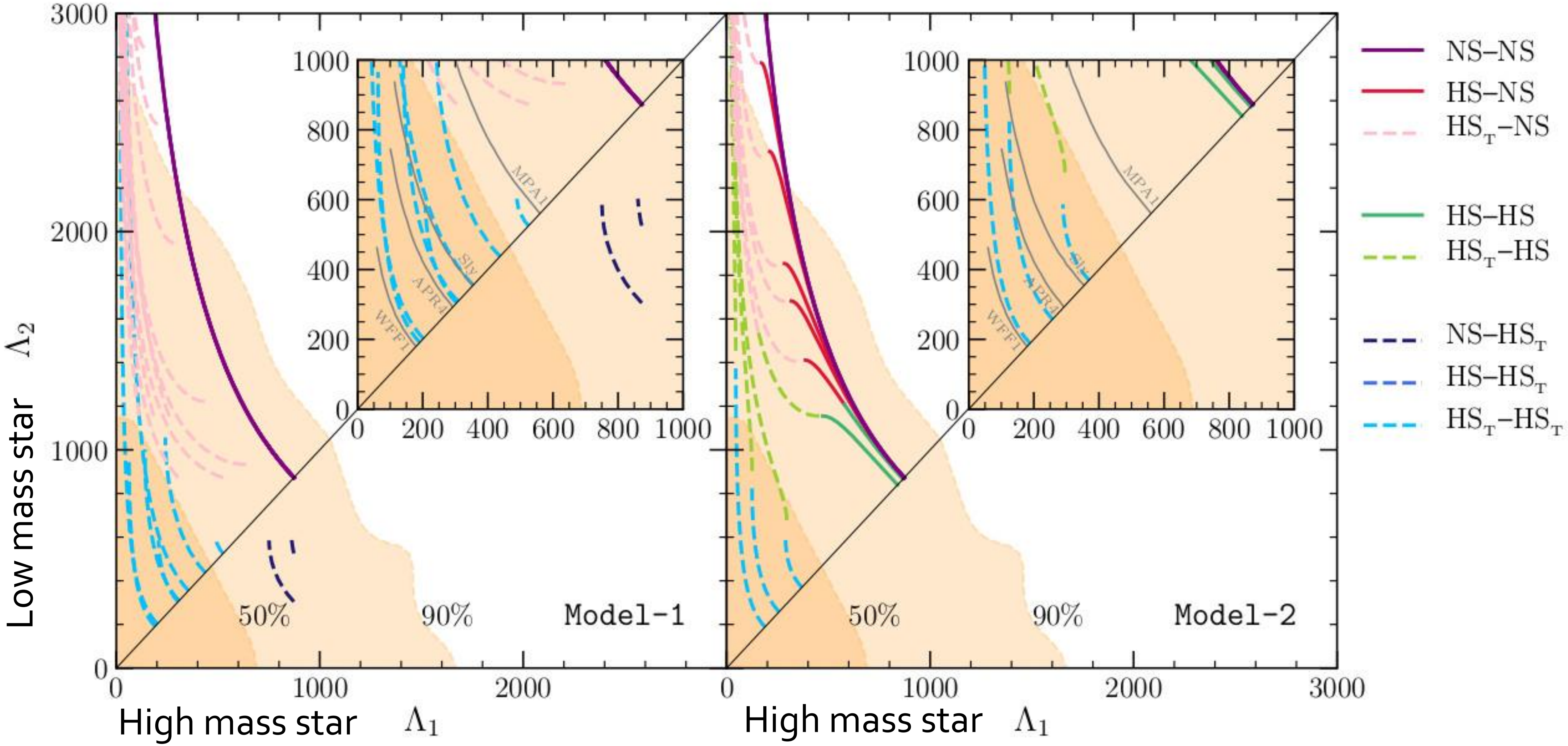
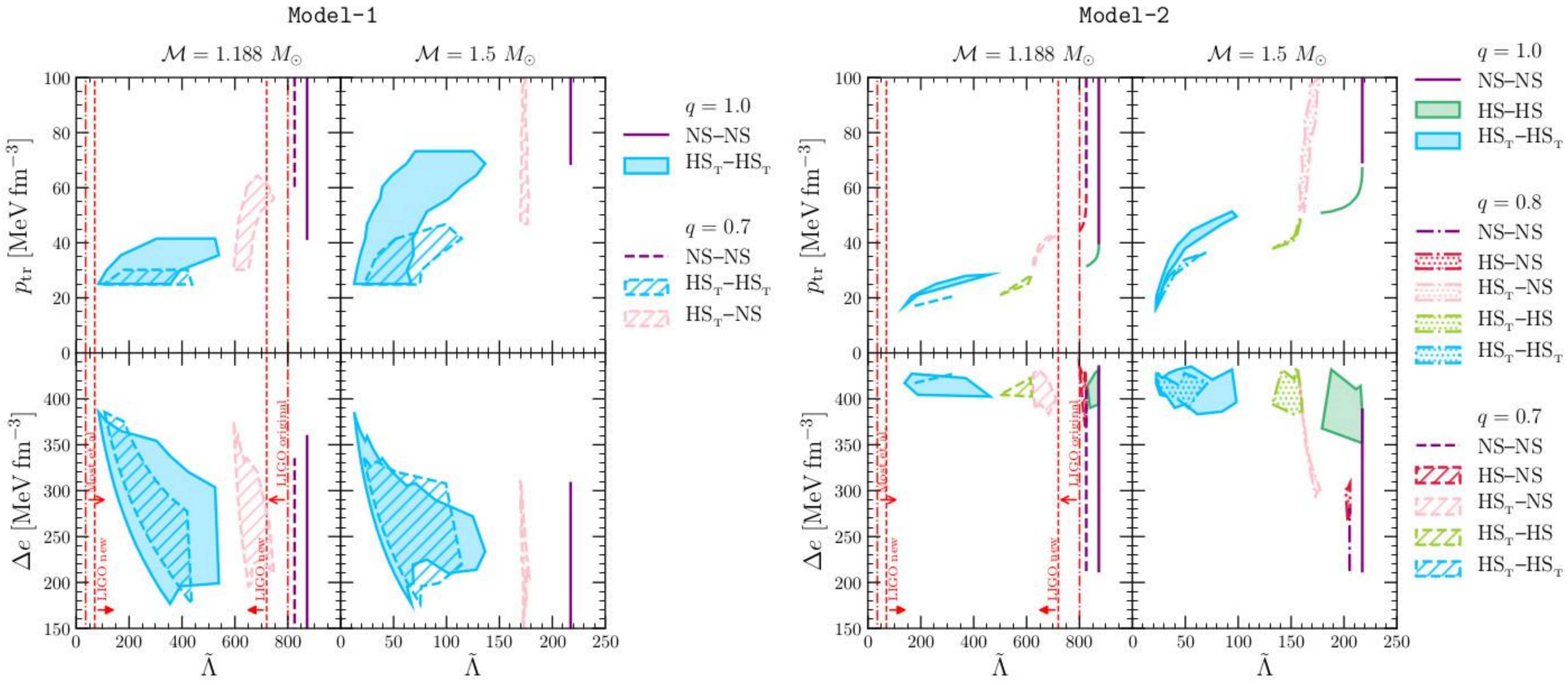


FIG. 3. Schematic behaviour of the mass–radius relation for the twin-star categories *I–IV* defined in the text. Note the appearance of a "twin" branch with a mixed or pure-quark phase; the twin branch has systematically smaller radii than the branch with a nuclear or hadronic phase. The colors used for these categories will be employed also in the subsequent figures.

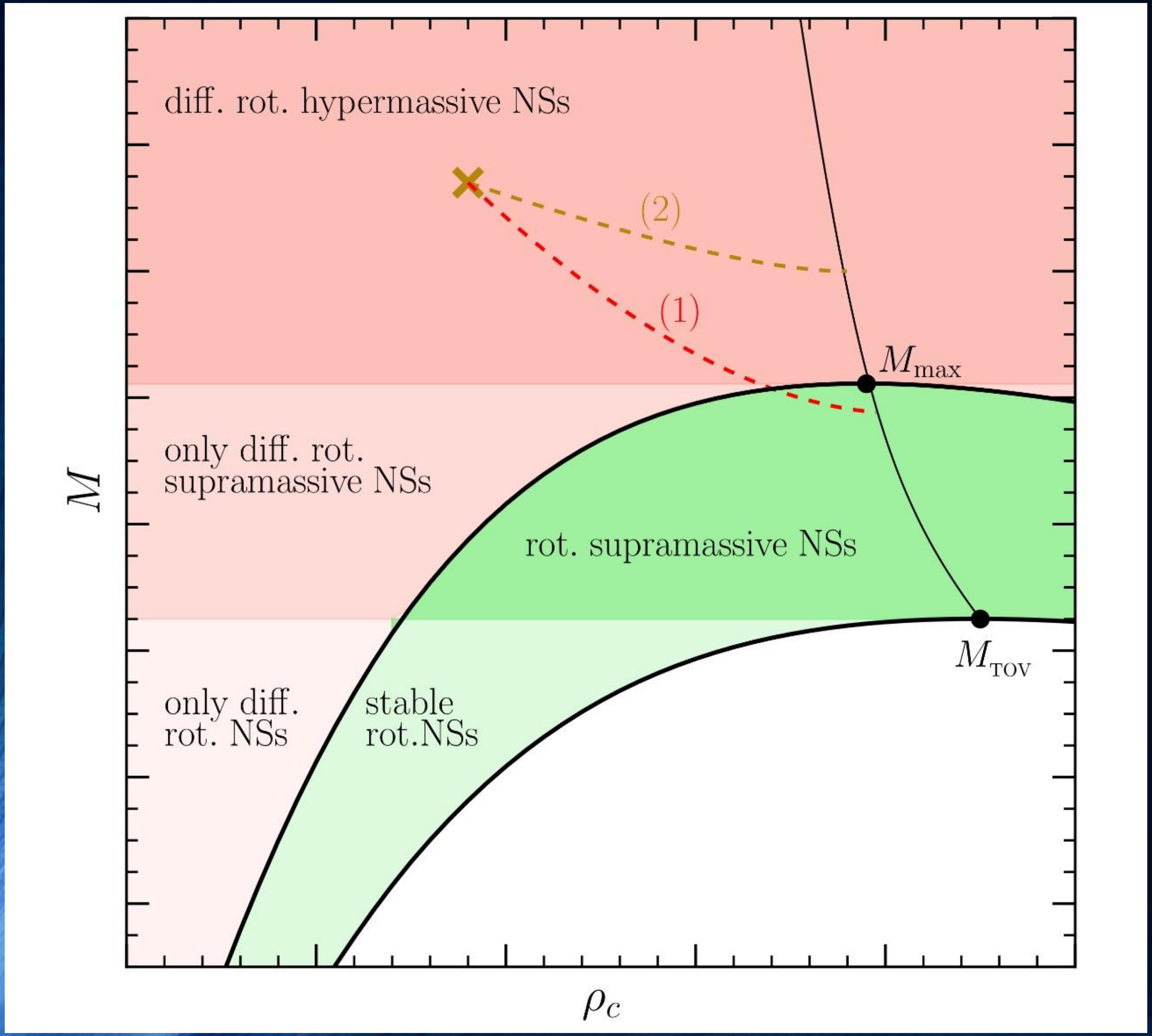


In a binary hybrid star merger the two masses of the individual stars can be different (q<1). As a result, the tidal deformability and the stars composition can be different. In this plot the total mass of the binary system has been fixed to the measured chirp mass of GW170817 (M=1.188 M_{solar}) and the different curve show results for EOSs of Category III.

Constraining the global parameters of the phase transition with GW170817



GW170817: Constraining the maximum mass of Neutron Stars



The highly differentially rotating hypermassive/supramassive neutron star will spin down and redistribute its angular momentum (e.g. due to viscosity effects, magnetic braking). After ~1 second it will cross the stability line as a uniformly rotating supramassive neutron star (close to M_{max}) and collapse to a black hole. Parts of the ejected matter will fall back into the black hole producing the gamma-ray burst.

L.Rezzolla, E.Most, L.Weih, "Using Gravitational Wave Observations and Quasi-Universal Relations to constrain the maximum Mass of Neutron Stars",The Astrophysical Journal Letters 852, L25 (2018): $2.01 \pm 0.04 < M_{TOV} < 2.16 \pm 0.17$

See also: S.Lawrence et al. ,APJ808,186, 2015
Margalit & Metzger, The Astrophysical Journal Letters 850, L19 (2017): $M_{TOV} < 2.17$ (90%)
Zhou, Zhou, Li, PRD 97, 083015 (2018)
Ruiz, Shapiro, Tsokaros, PRD 97,021501 (2018)

Literature

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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)

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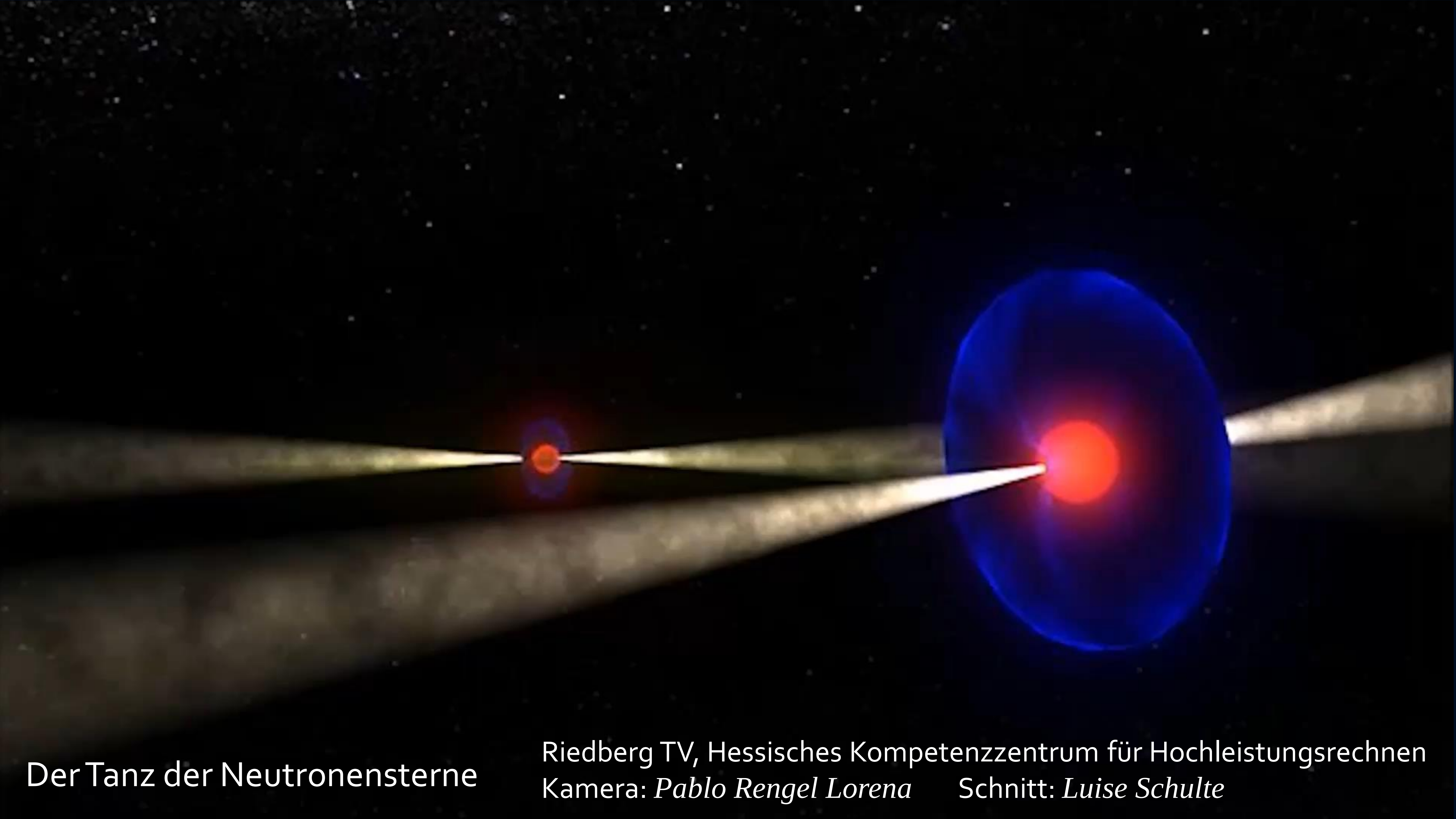
Mark G. Alford, Luke Bovard, Matthias Hanauske, Luciano Rezzolla, and Kai Schwenzer (2018), Viscous Dissipation and Heat Conduction in Binary Neutron-Star Mergers. Phys. Rev. Lett. 120, 041101

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.



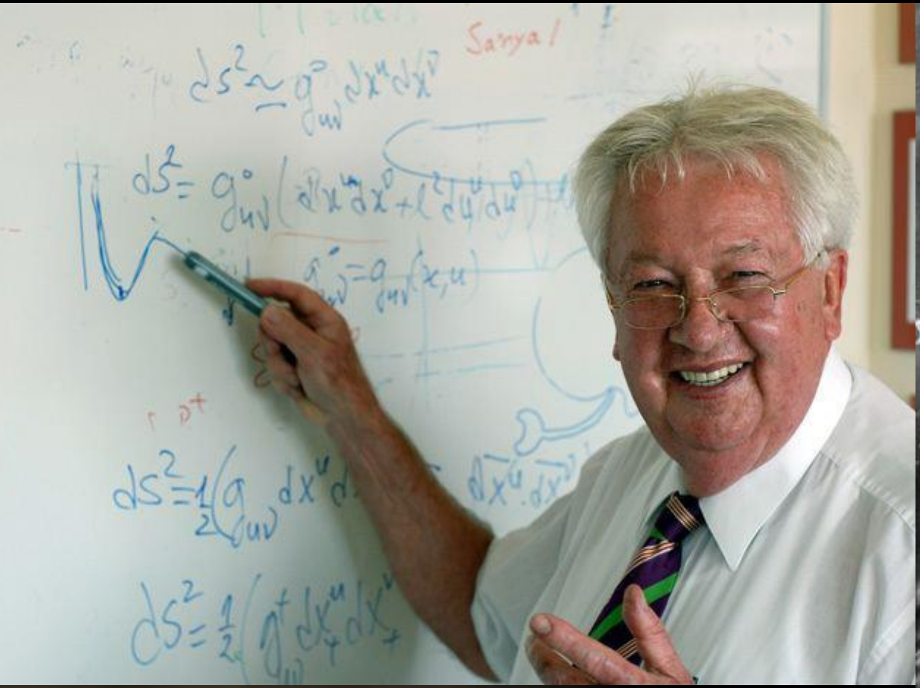
Der Tanz der Neutronensterne

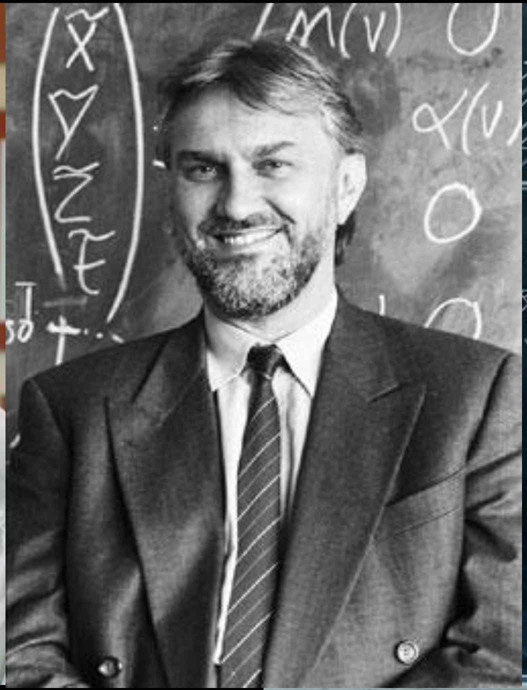
Riedberg TV, Hessisches Kompetenzzentrum für Hochleistungsrechnen
Kamera: *Pablo Rengel Lorena* Schnitt: *Luise Schulte*

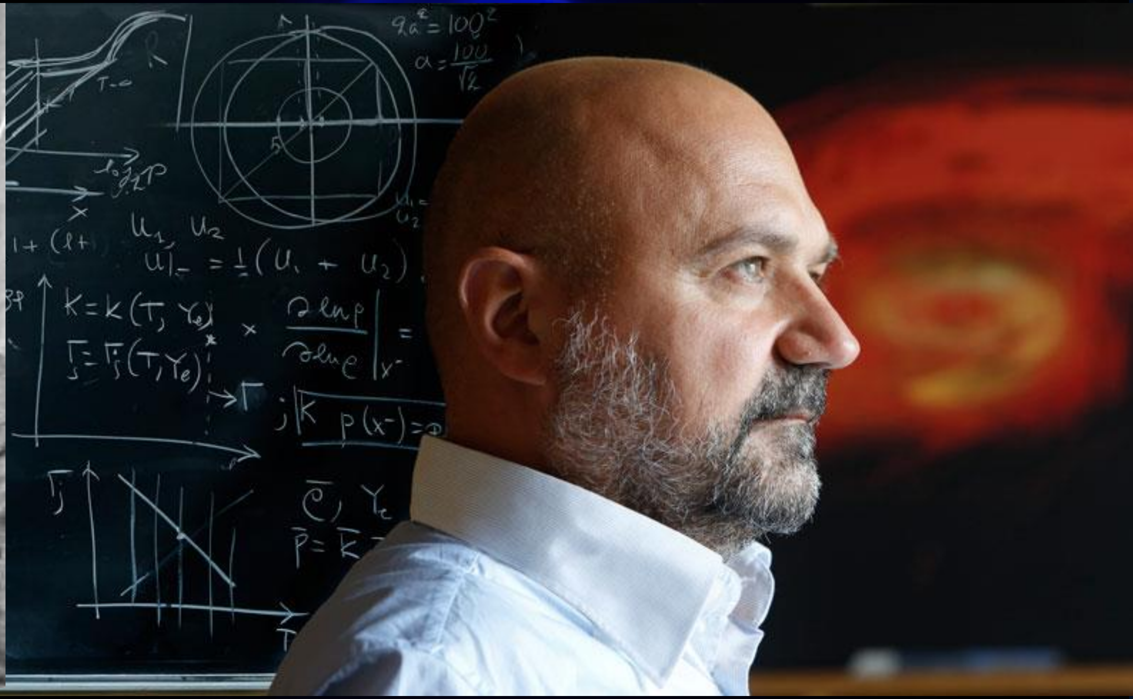
Credits to …

Kentaro Takami, Luke Bovard, Jose Font, Filippo Galeazzi, Jens Papenfort, Lukas Weih, Elias Most, Cosima Breu, Federico Guercilena, Natascha Wechselberger, Zekiye Simay Yilmaz, Christina Mitropoulos, Jan Steinheimer, Stefan Schramm, David Blaschke, Mark Alford, Kai Schwenzer, Antonios Nathanail, Roman Gold, Alejandro Cruz Osorio, Andreas Zacchi, Jürgen Schaffner-Bielich, Laura Tolos, Sven Köppel, Gloria Montaña, Michael Rattay, Debades Bandopadhyay,

Walter Greiner *Horst Stöcker* *Luciano Rezzolla*







Riedberg TV, Hessisches Kompetenzzentrum für Hochleistungsrechnen und Tanzschule Wernecke

Kamera: *Pablo Rengel Lorena* Schnitt: *Luise Schulte*

Der Tanz der Neutronensterne: Vortrag an der Sternwarte Darmstadt am Sa. 16.02., 20.00 Uhr