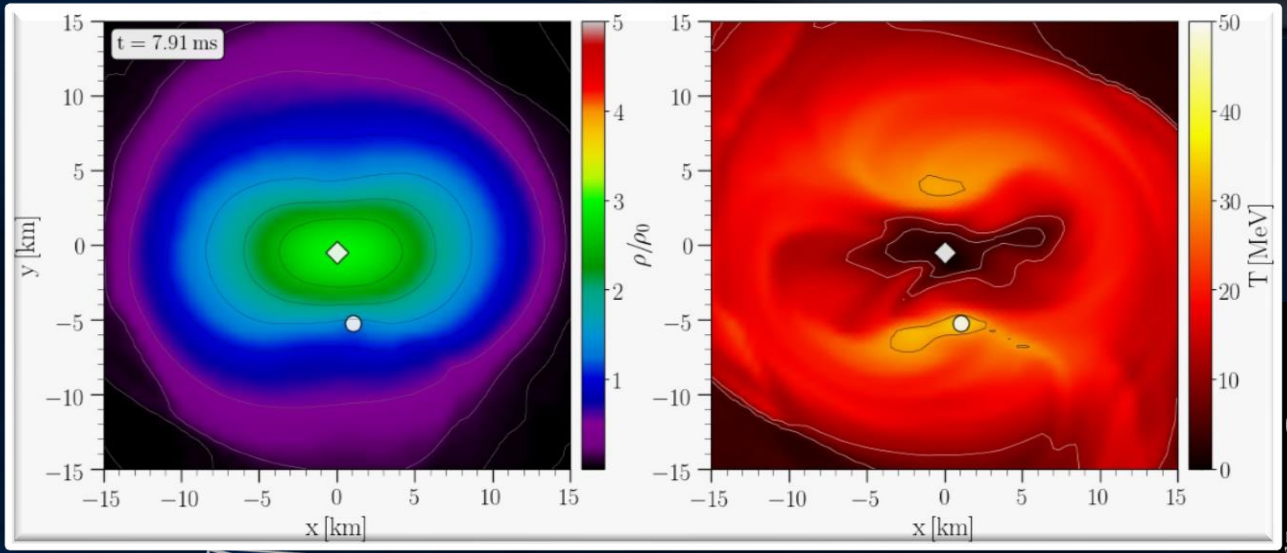
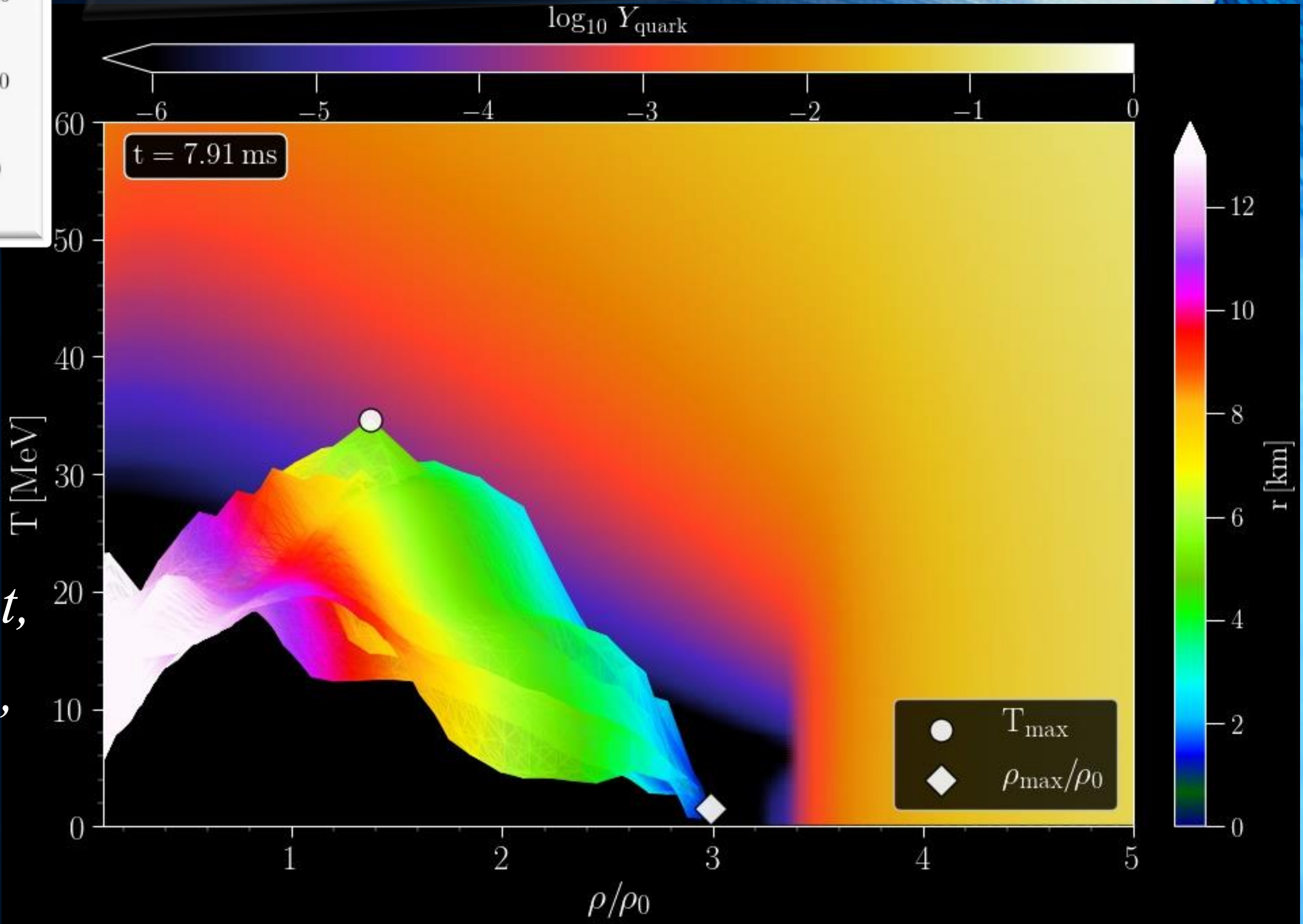
Binary Hybrid Star Mergers and the Phase Diagram of Quantum Chromo Dynamics

GR22 AND AMALDI13
VALENCIA, 09 JULY 2019



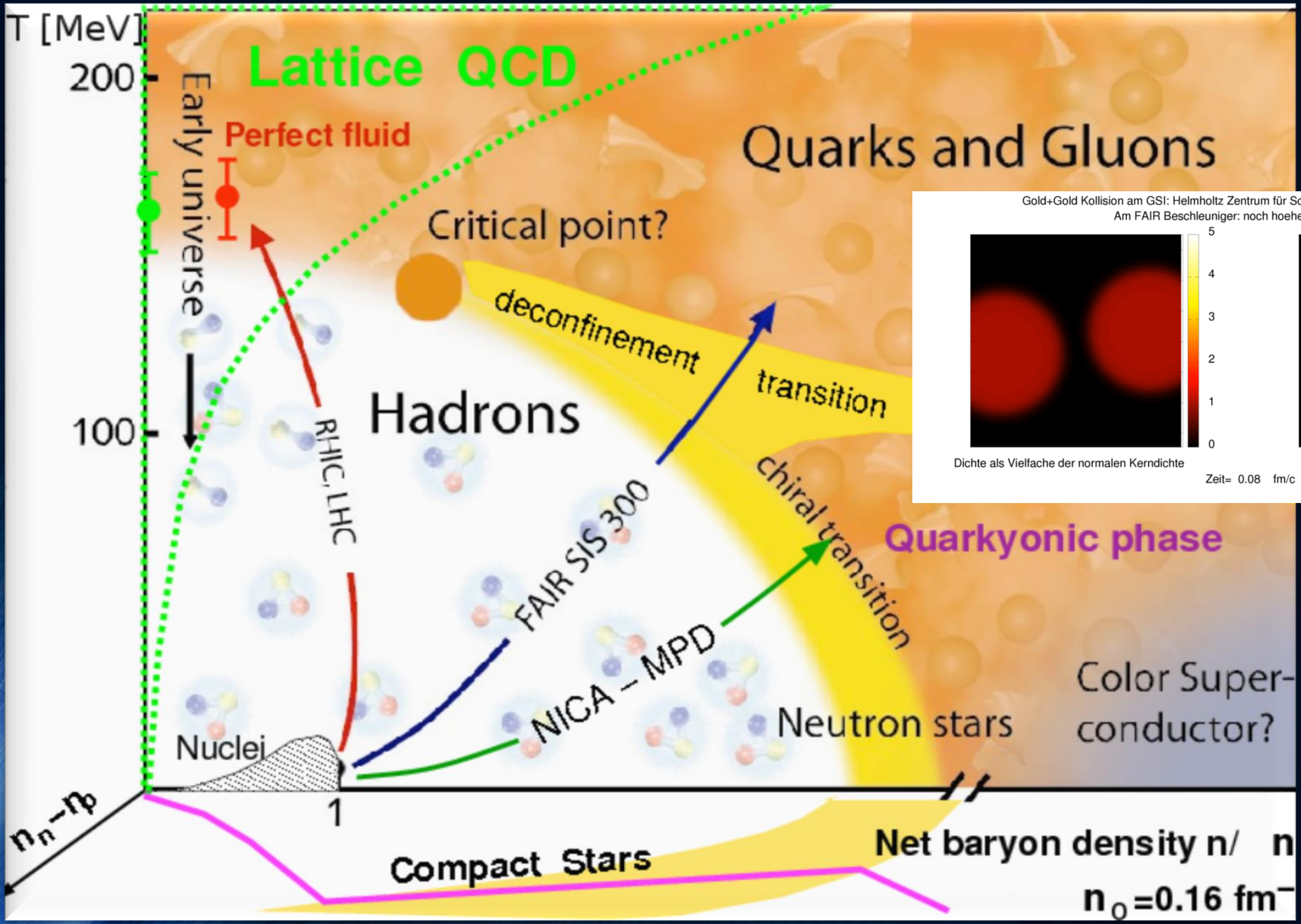
MATTHIAS HANAUSKE
FRANKFURT INSTITUTE FOR ADVANCED STUDIES
JOHANN WOLFGANG GOETHE UNIVERSITÄT
INSTITUT FÜR THEORETISCHE PHYSIK
ARBEITSGRUPPE RELATIVISTISCHE ASTROPHYSIK
D-60438 FRANKFURT AM MAIN

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

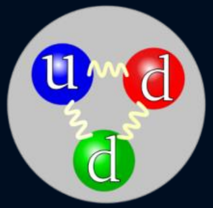


The Hadron-Quark Phase Transition

The QCD Phase Diagram

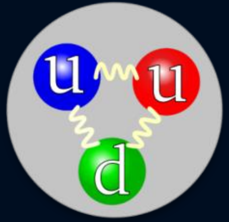


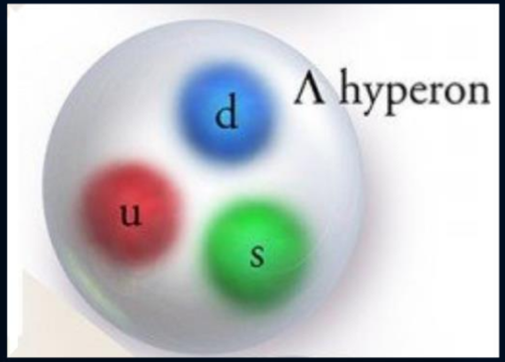
Neutron

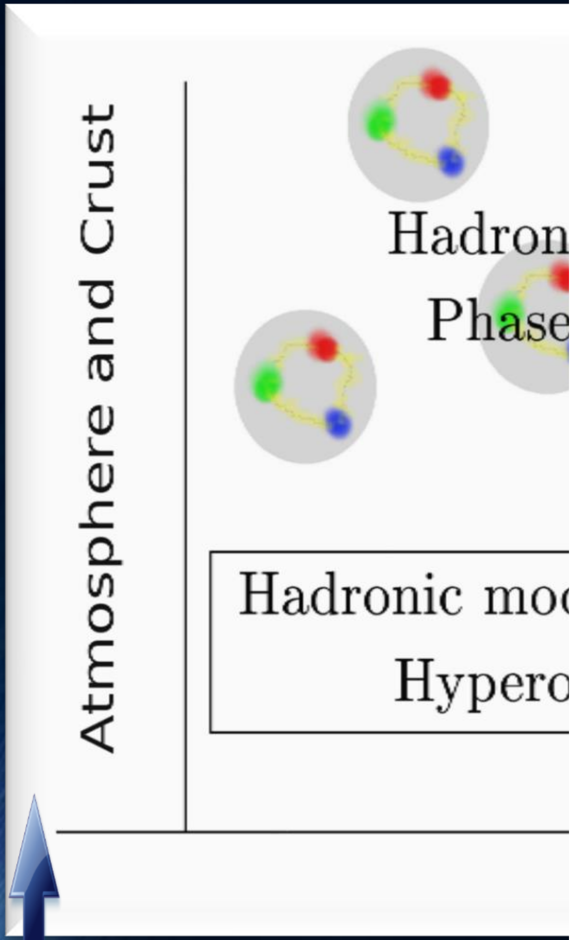


Credits:
Jan Steinheimer

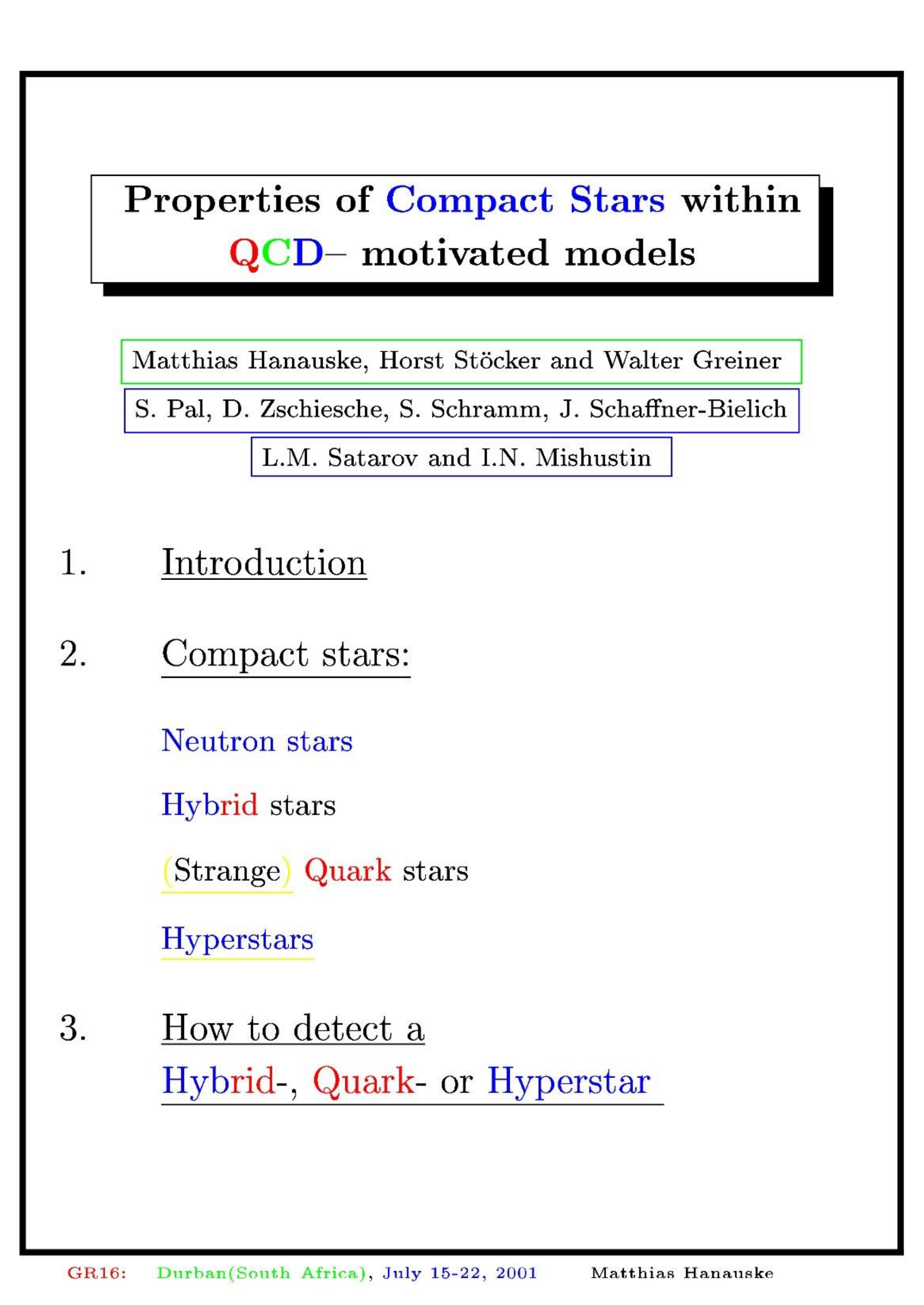
Proton







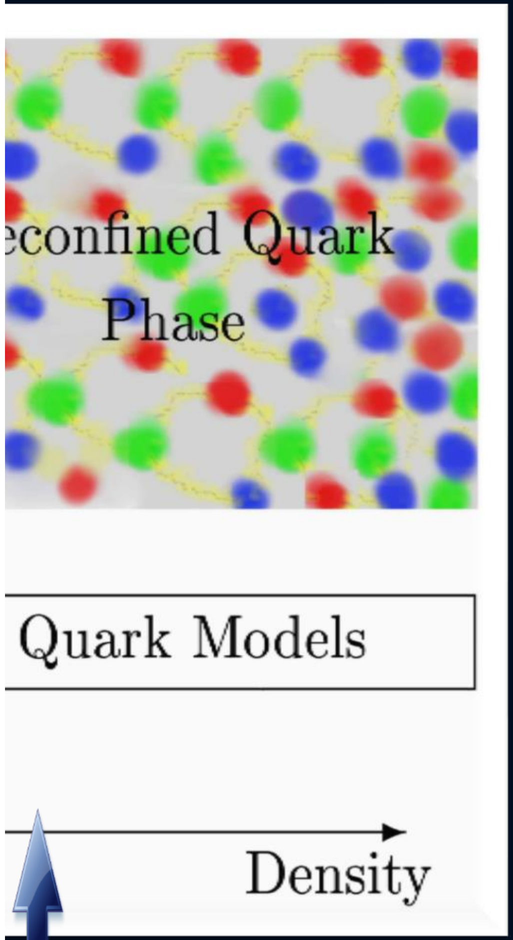
Surface of the Star



Properties of Compact Stars within QCD– motivated models

Matthias Hanauske, Horst Stöcker and Walter Greiner
S. Pal, D. Zschiesche, S. Schramm, J. Schaffner-Bielich
L.M. Satarov and I.N. Mishustin

1. Introduction
2. Compact stars:
   - Neutron stars
   - Hybrid stars
   - (Strange) Quark stars
   - Hyperstars
3. How to detect a Hybrid-, Quark- or Hyperstar



of the Star

Properties of Compact Stars ... Publication Frankfurt (2004)

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:

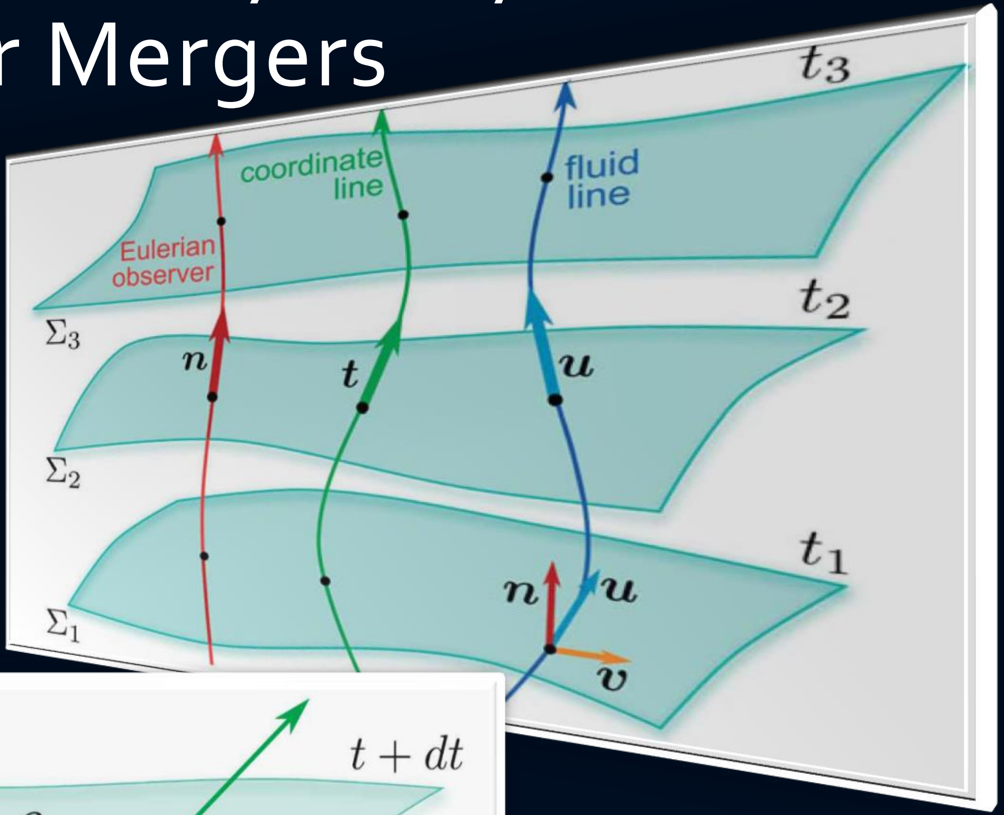
$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = 8\pi T_{\mu\nu}$$

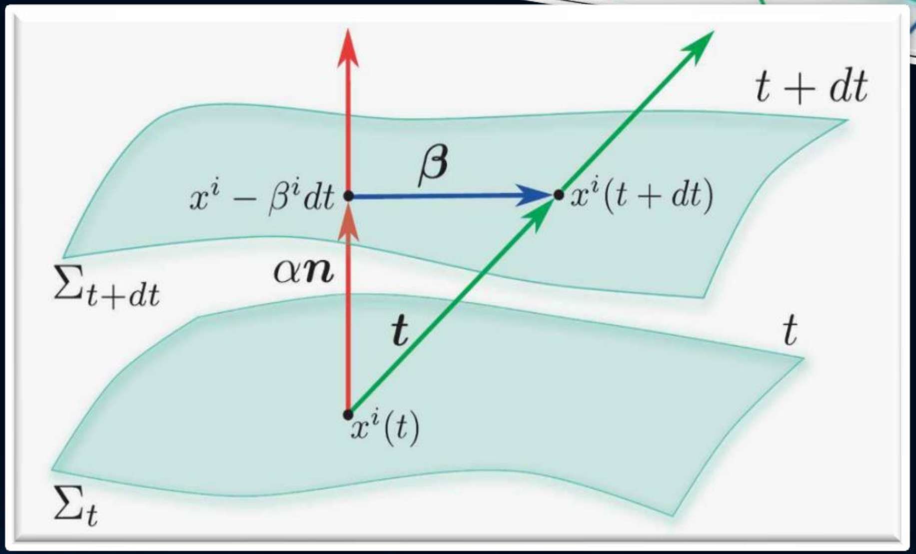
$$\nabla_\mu(\rho u^\mu) = 0\,, \qquad \nabla_\nu T^{\mu\nu} = 0\,.$$

(3+1) decomposition of spacetime

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

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

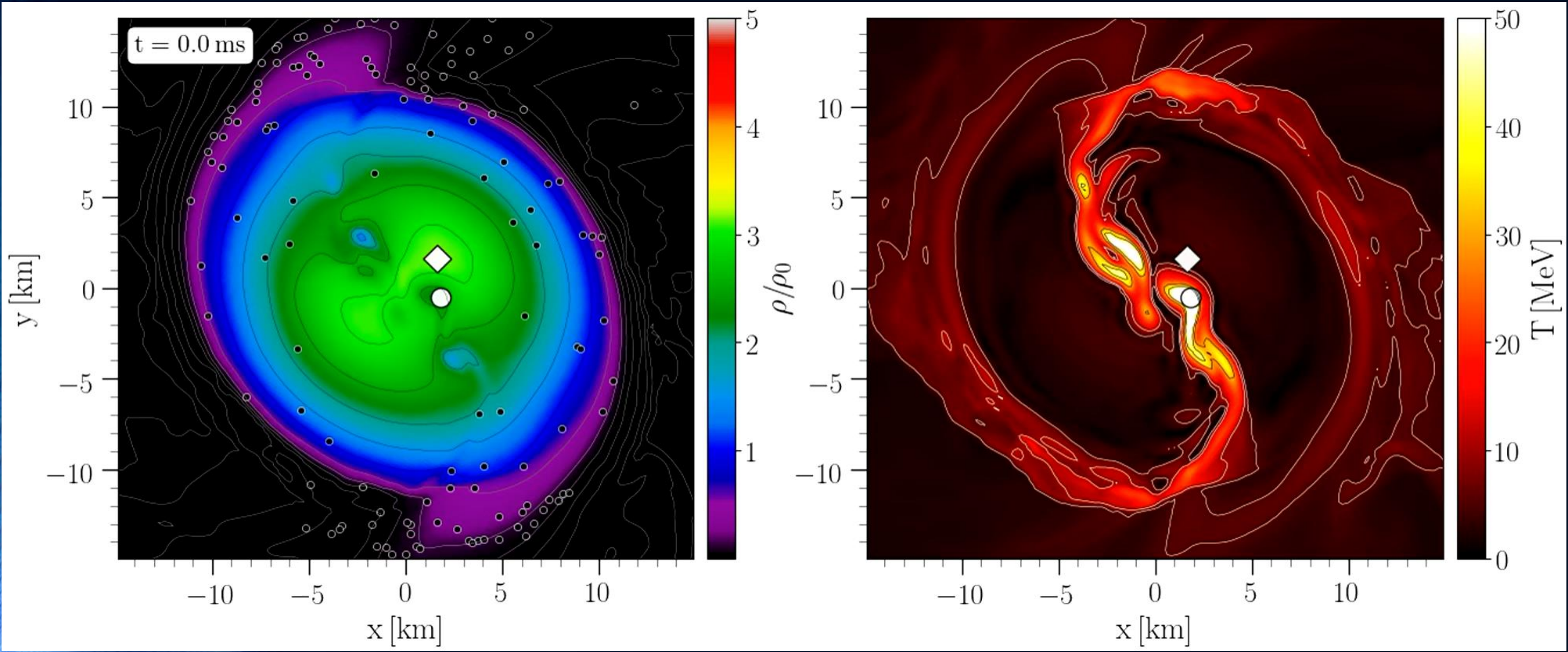




All figures and equations from: Luciano Rezzolla, Olindo Zanotti: Relativistic Hydrodynamics, Oxford Univ. Press, Oxford (2013)

Density and Temperature Evolution inside a HMNS

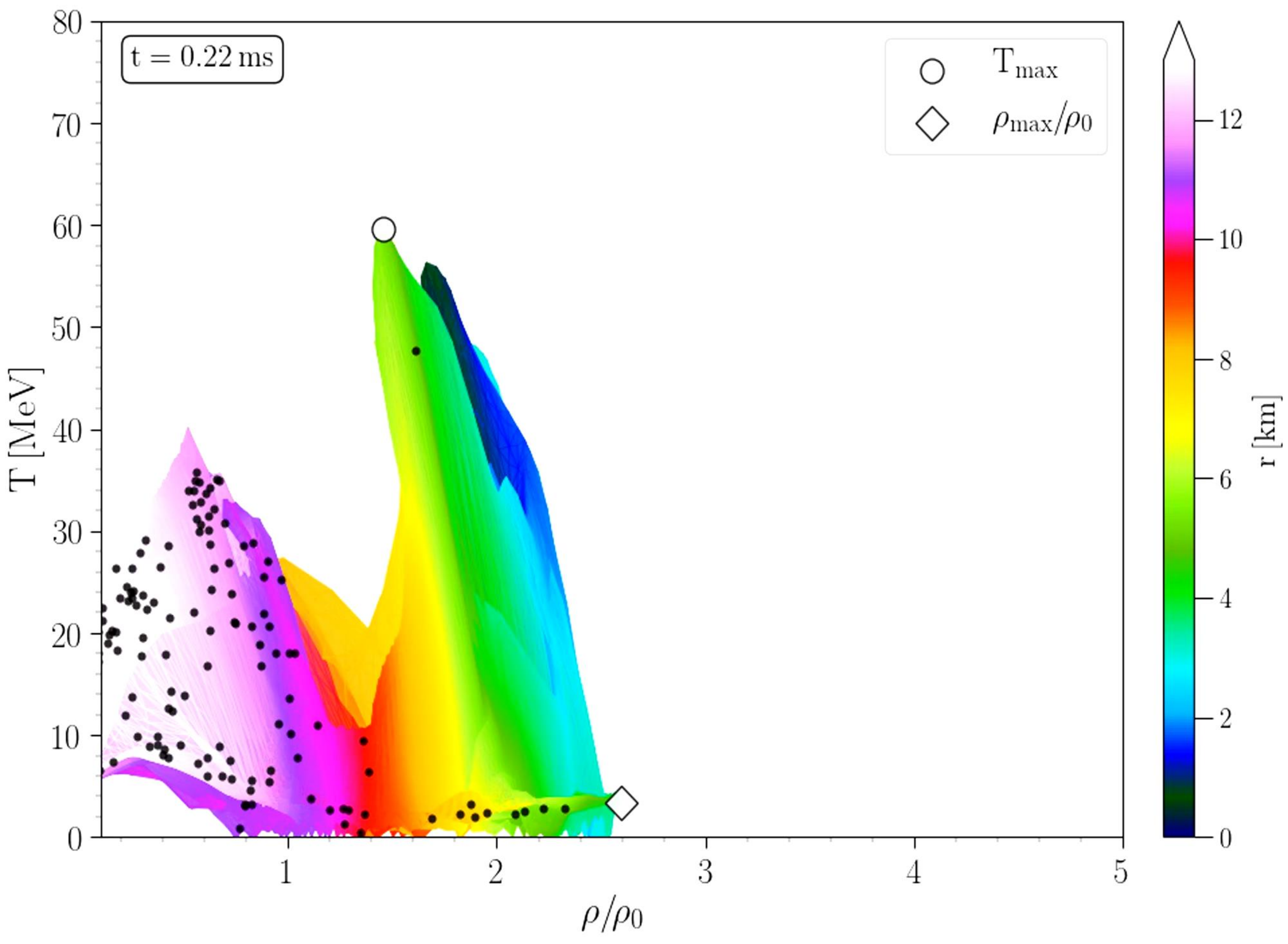
Purely hadronic, no phase transition (LS220 EOS), corotating frame



Rest mass density on the equatorial plane

Temperature on the equatorial plane

Binary Neutron Star Mergers and the QCD Phase Diagram

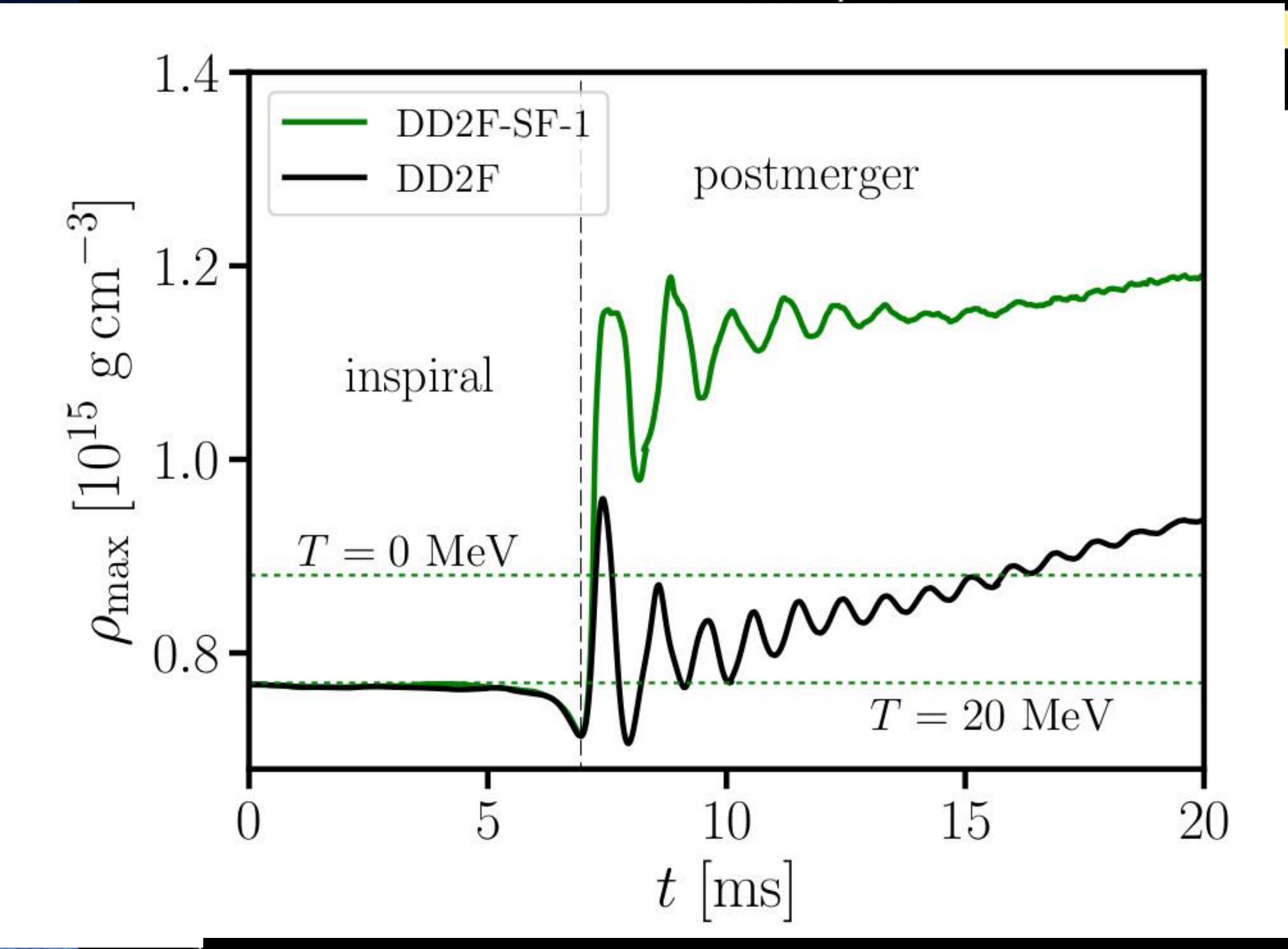


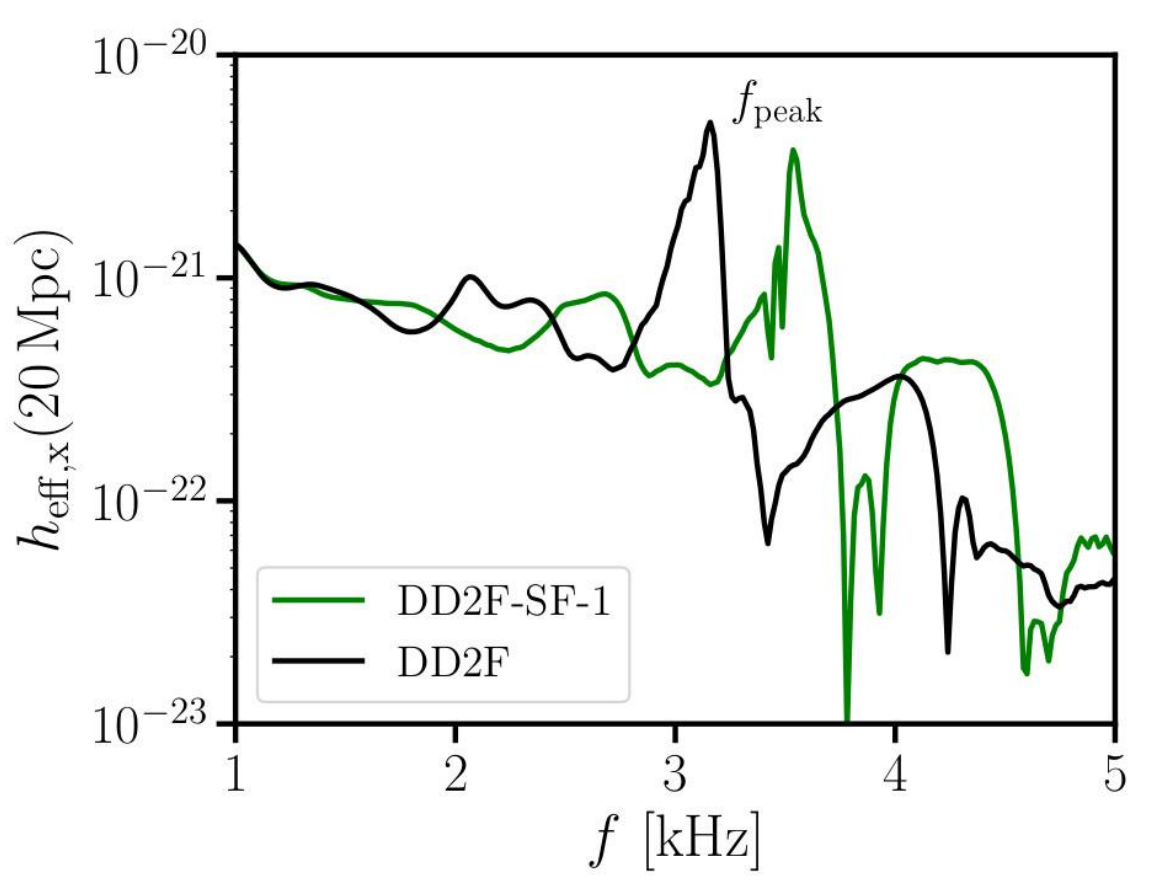
Hot and dense matter inside the inner area of a hypermassive neutron star in the style of a (T- ρ) QCD phase diagram plot.
The color-coding (right side) indicate the radial position r of the corresponding (T- ρ) fluid element measured from the origin of the simulation (x , y) = (0 , 0) on the equatorial plane at z = 0.
The open triangle marks the maximum value of the temperature while the open diamond indicates the maximum of the density.
Additionally, several tracer particle are shown, indicating the motion of fluid cells.

G. Alford, L. Bovard, M. Hanauske, L. Rezzolla, and K. Schwenzer „Viscous Dissipation and Heat Conduction in Binary Neutron-Star Mergers" PRL. 120, 041101 (2018)

Binary Hybrid Star Mergers and the QCD Phase Diagram

Hot and dense matter inside the inner area of a hypermassive

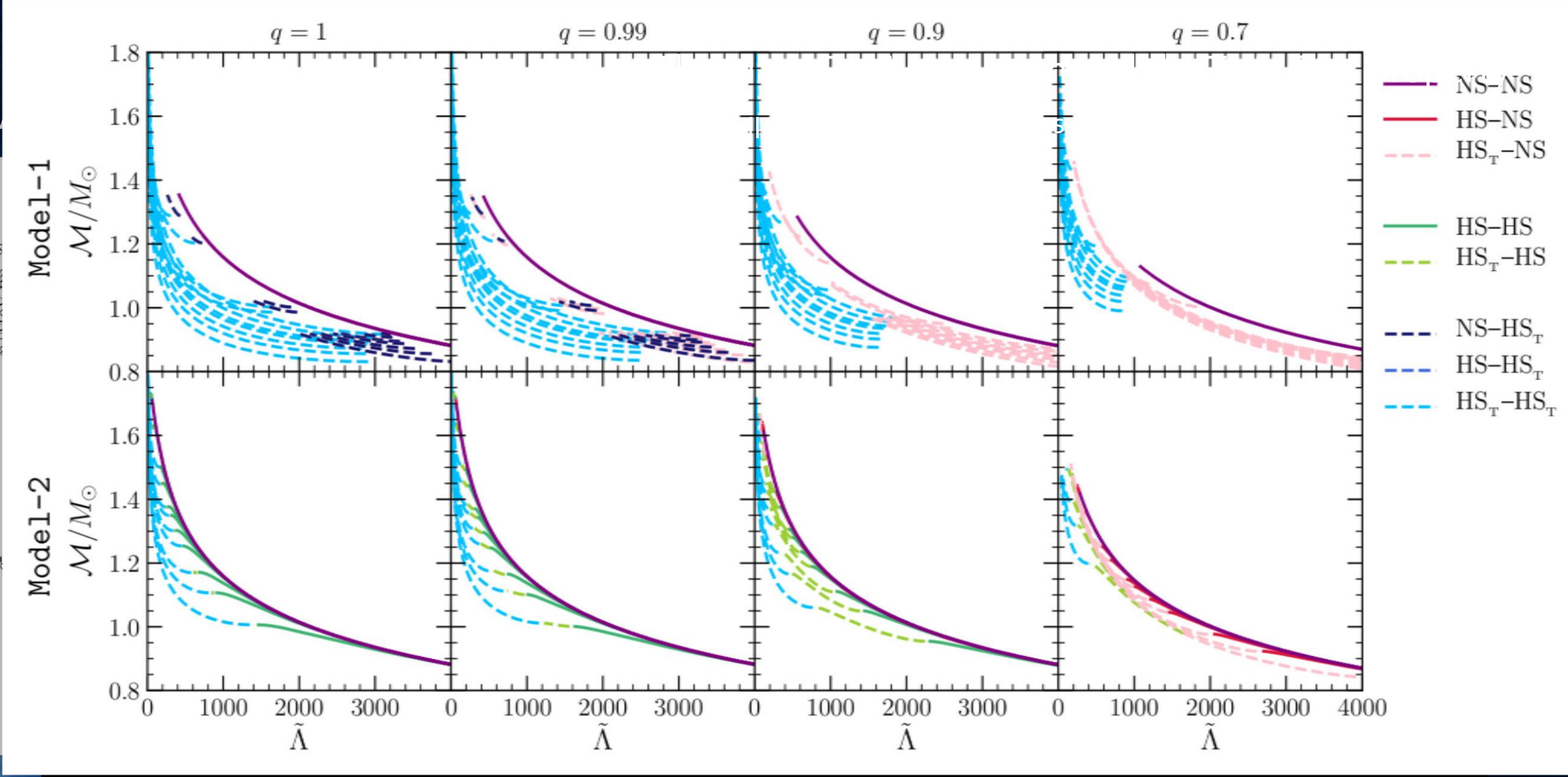




A.Bauswein, N.U.F. Bastian, D.B.Blaschke, K.Chatziioannou, J.A.Clark, T.Fischer and M.Oertel
„Identifying a first-order transition in neutron star mergers through gravitational waves“, PRL 2019

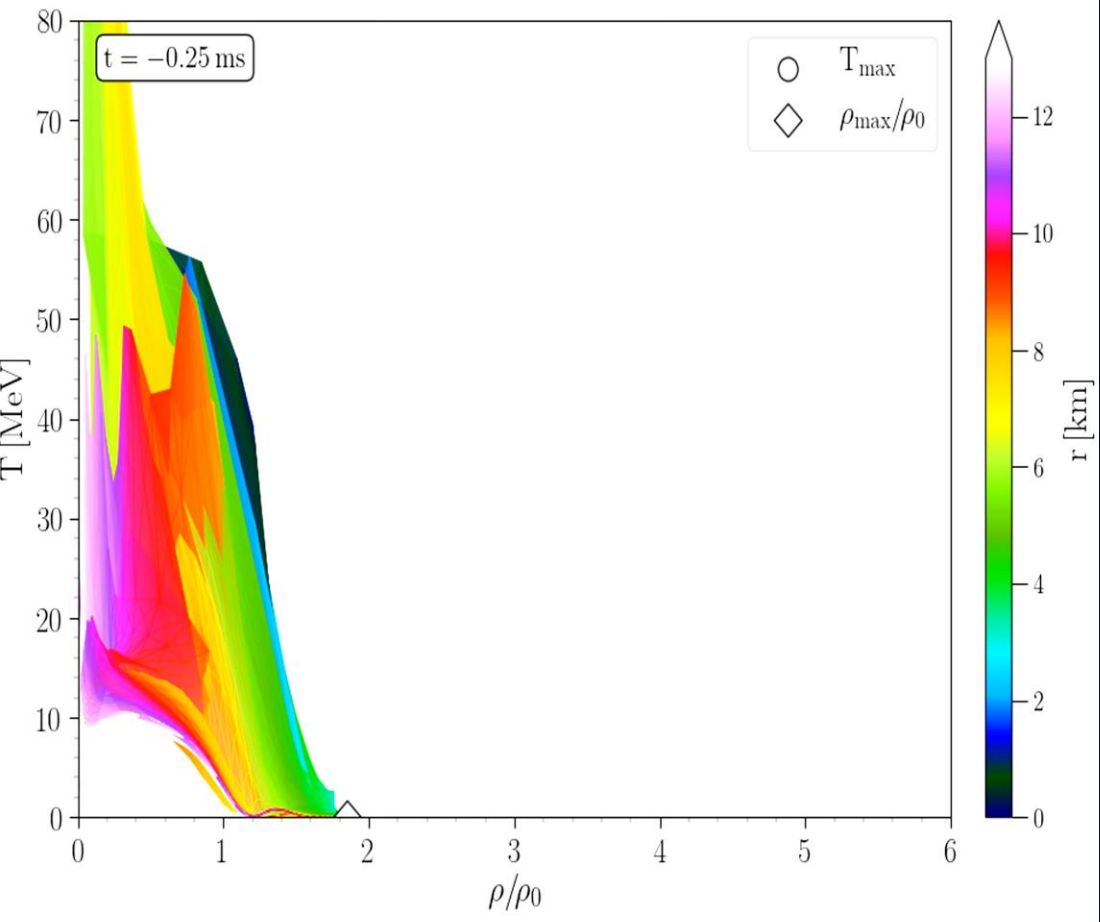
E.R.Most, L.J.Papenfort, V.Dexheimer, M.Hanauske, S.Schramm, H.Stöcker and L.Rezzolla
„Signatures of quark-hadron phase transitions in general-relativistic neutron-star mergers„, PRL 2019

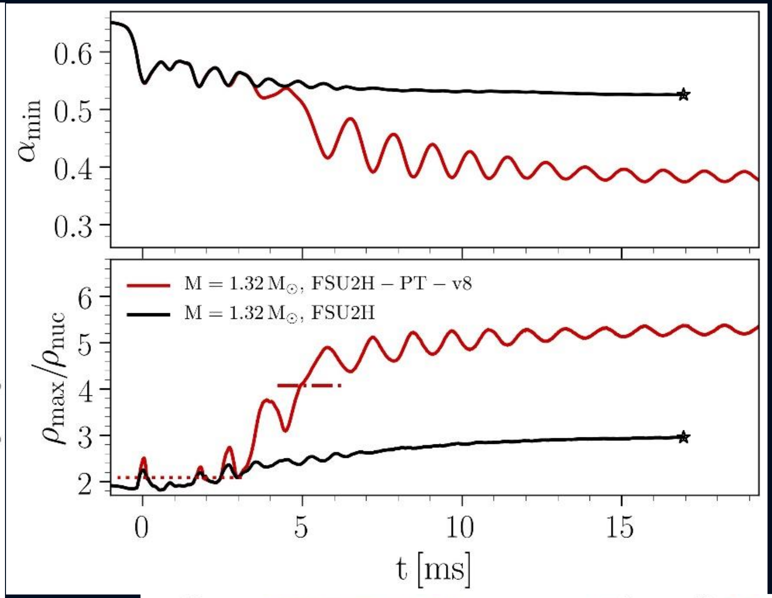
Binary Hybrid Star Mergers and the Twin Star Possibility

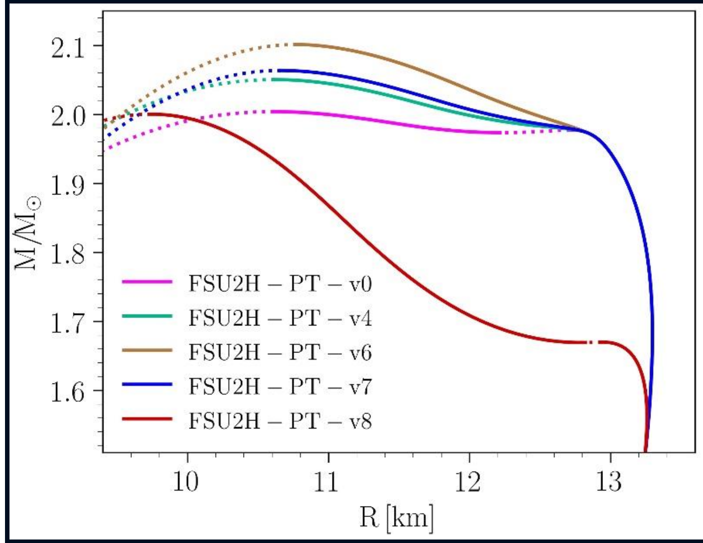


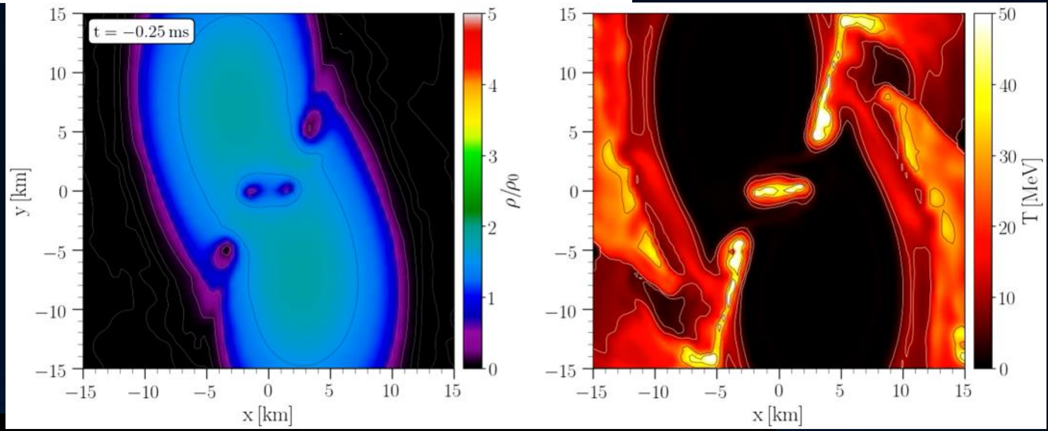
G. Montana, L.Tolos, M.Hanauske and L.Rezzolla „Constraining twin stars with GW170817„, PRD 99(10), 2019

Binary Hybrid Star Mergers and the Spin-Up Effect using Twin Star EOSs









, M.Hanauske ,G. Montana, L.Tolos, L.Rezzolla ... and H.Stöcker (in preparation)

The Neutron Star Merger Dance

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

Literature

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 (2017)

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.

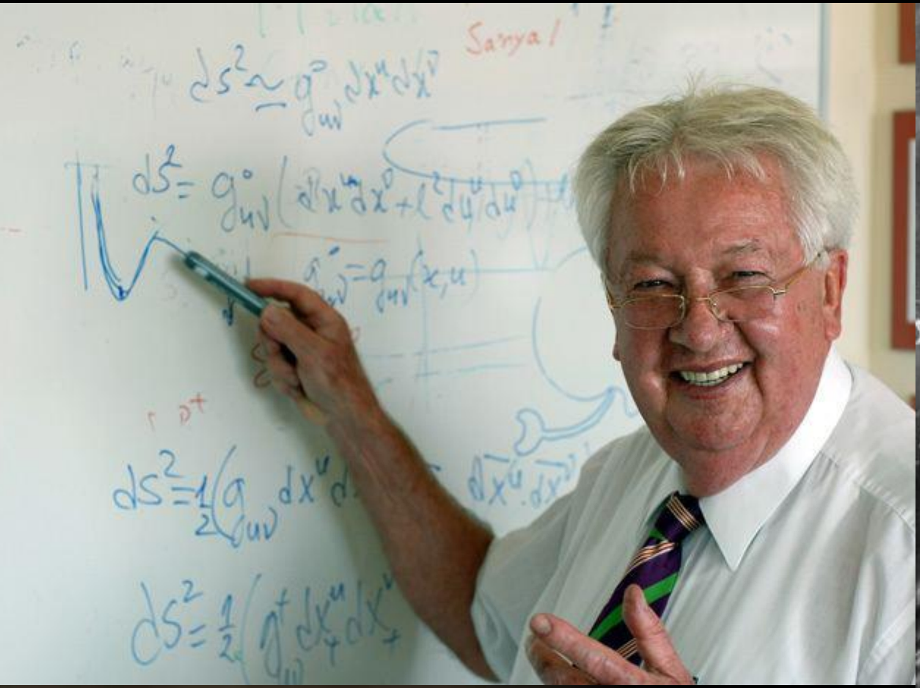
Hanauske, Matthias, et al. "Neutron Star Mergers: Probing the EoS of Hot, Dense Matter by Gravitational Waves." *Particles* 2.1 (2019): 44-56.

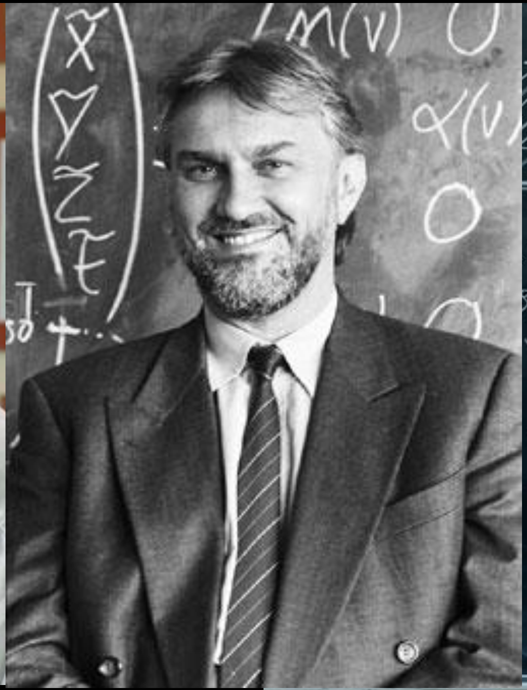
M.Hanauske,L.Bovard,E.Most,J.Papenfort,J.Steinheimer, A. Motornenko, V. Vovchenko, V. Dexheimer, S. Schramm, and H. Stöcker „Detecting the Hadron-Quark Phase Transition with Gravitational Waves „ Universe 5 (2019), 10.3390/universe5060156

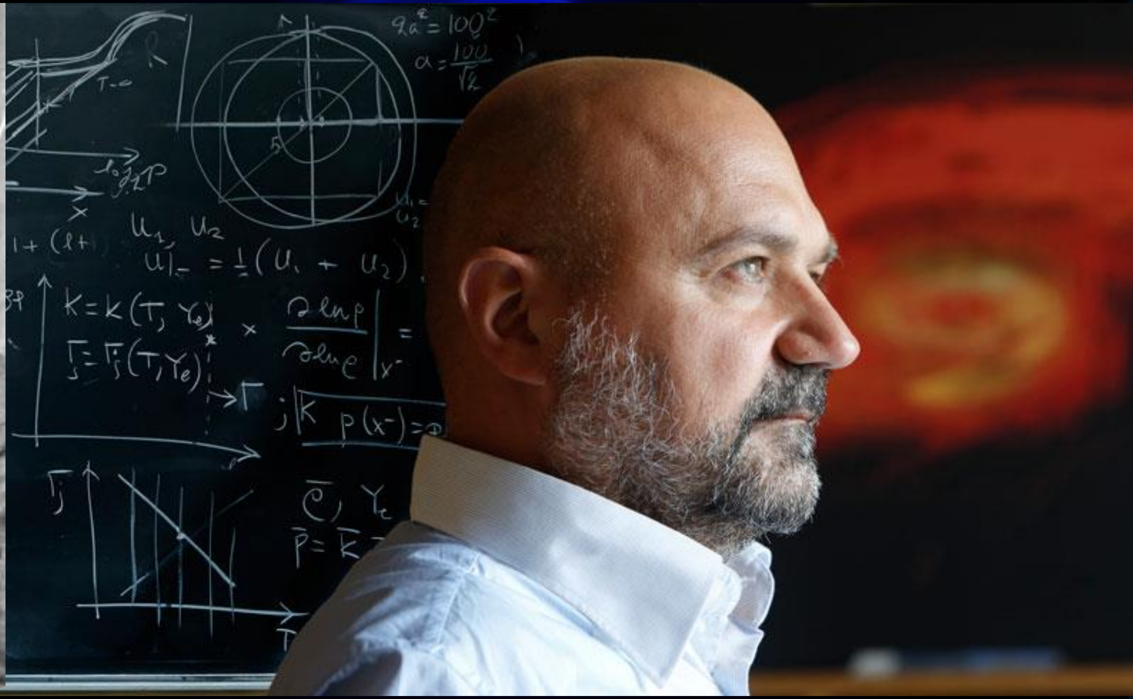
Credits to …

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

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

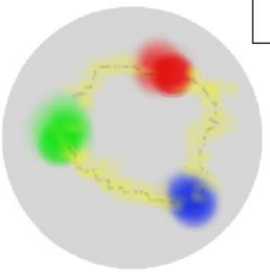
ART ⇔ QCD

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)

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

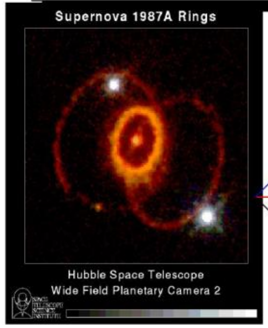
A, B = rot, grün, blau

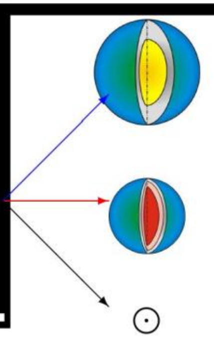


$$\psi^f_A = \begin{pmatrix} \psi^f_r \\ \psi^f_g \\ \psi^f_b \end{pmatrix}$$

Confinement
chirale Symmetrie, ...

Entstehung und Beobachtungsmöglichkeiten von kompakten Sternen

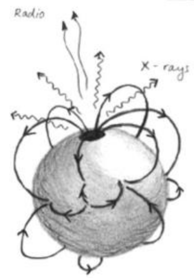




Neutronen Stern

Quark- oder Hyperstern

Schwarzes Loch



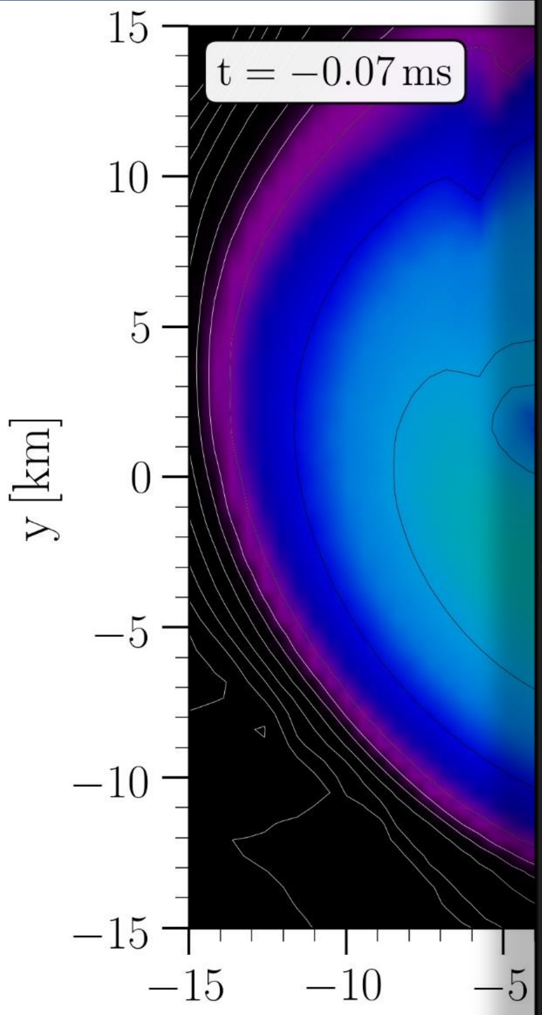
Radiowellen Teleskope(ca. 1400)

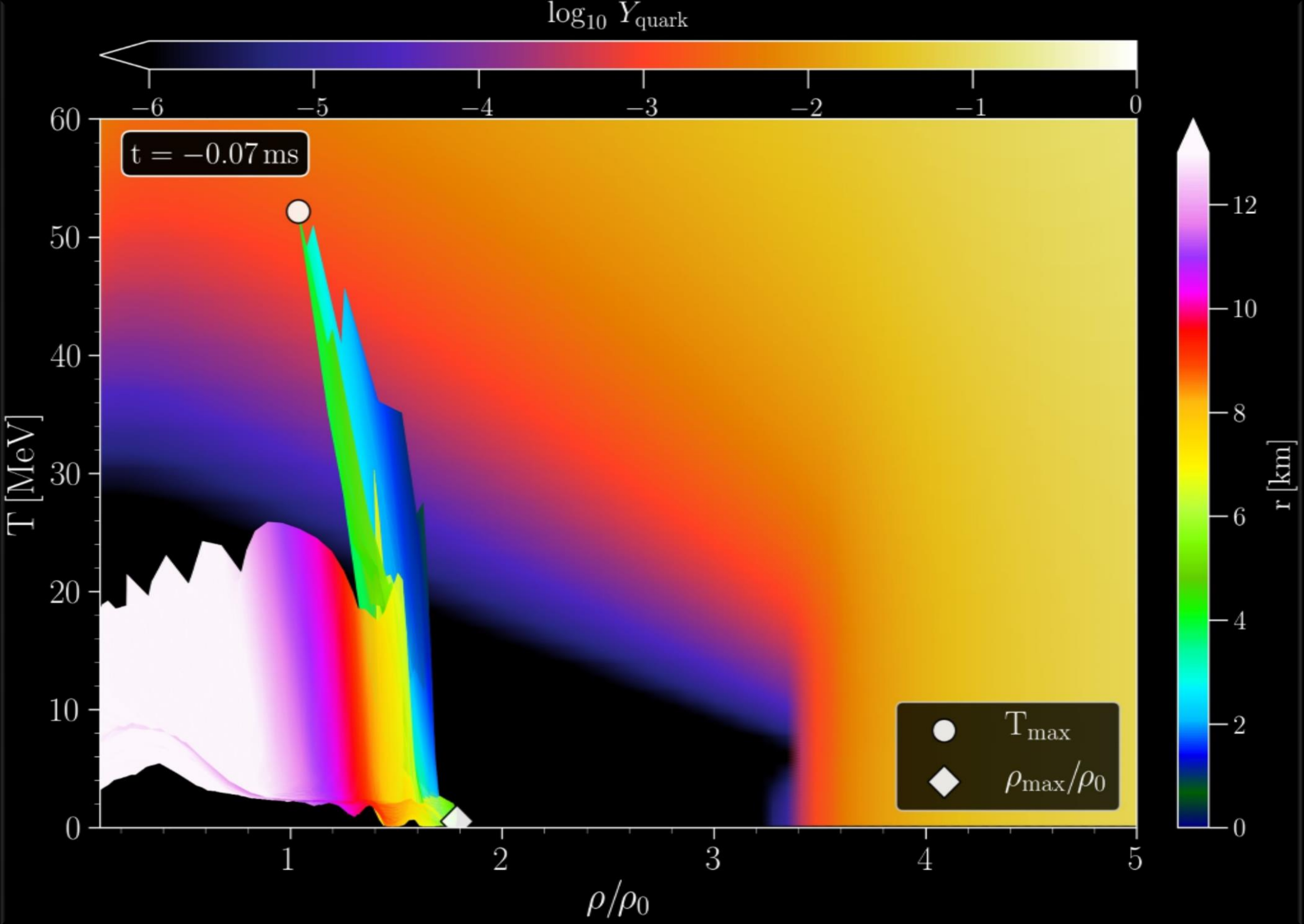
Optische Teleskope (3)

Röntgen Detektoren (ca. 30)

Gravitationswellen Detektoren

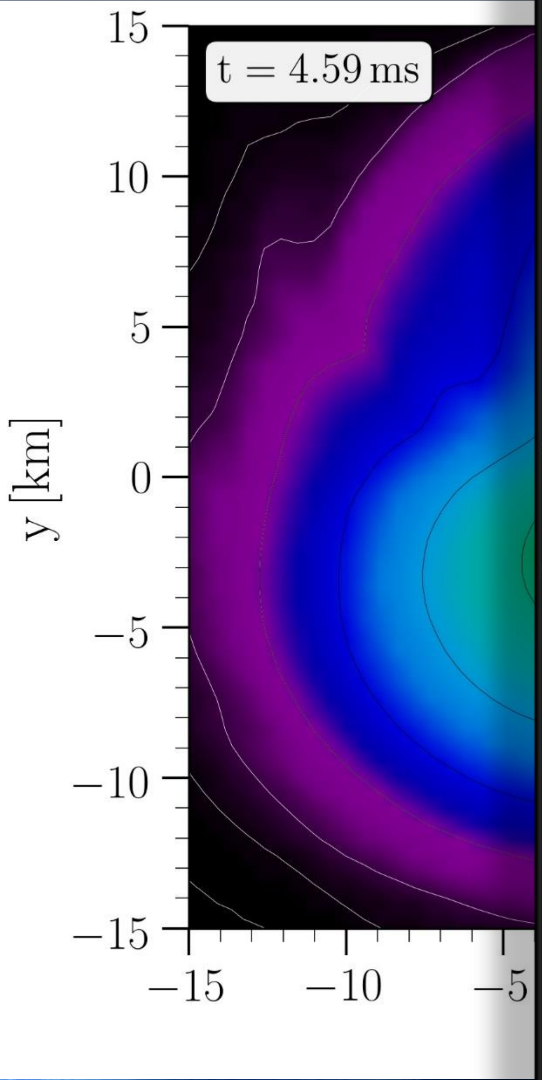
Merger Phase



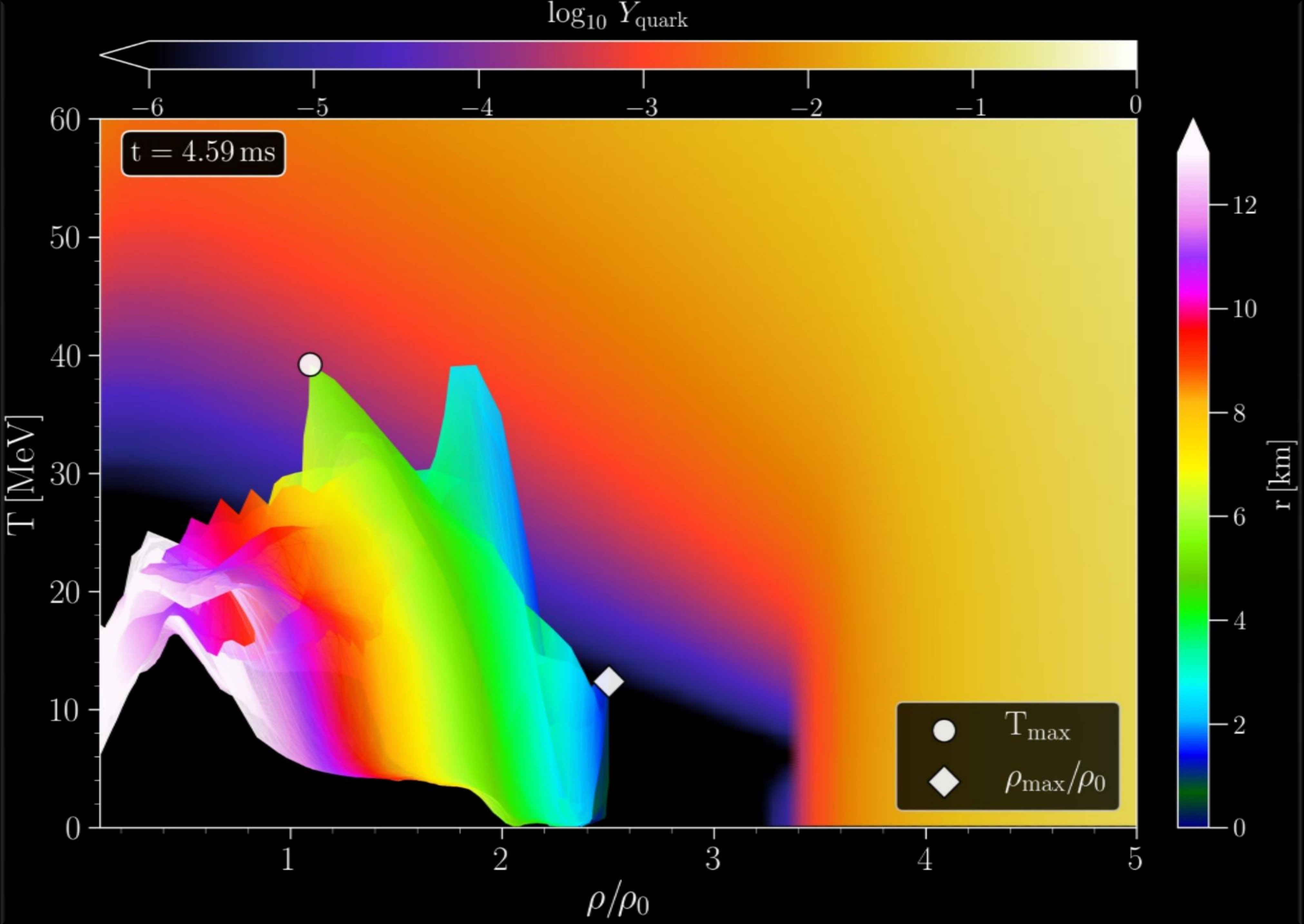


Rest mass density

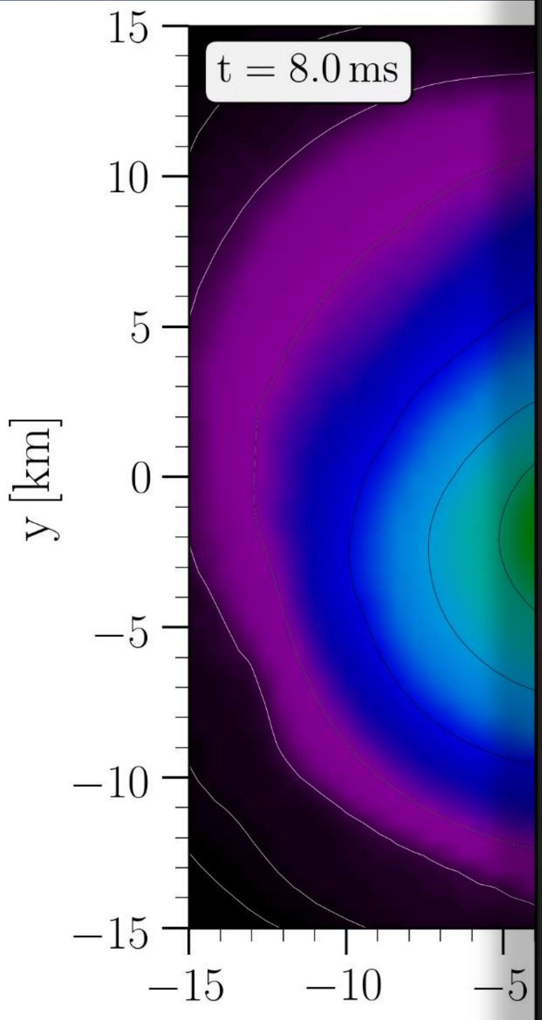
Post Merger Phase



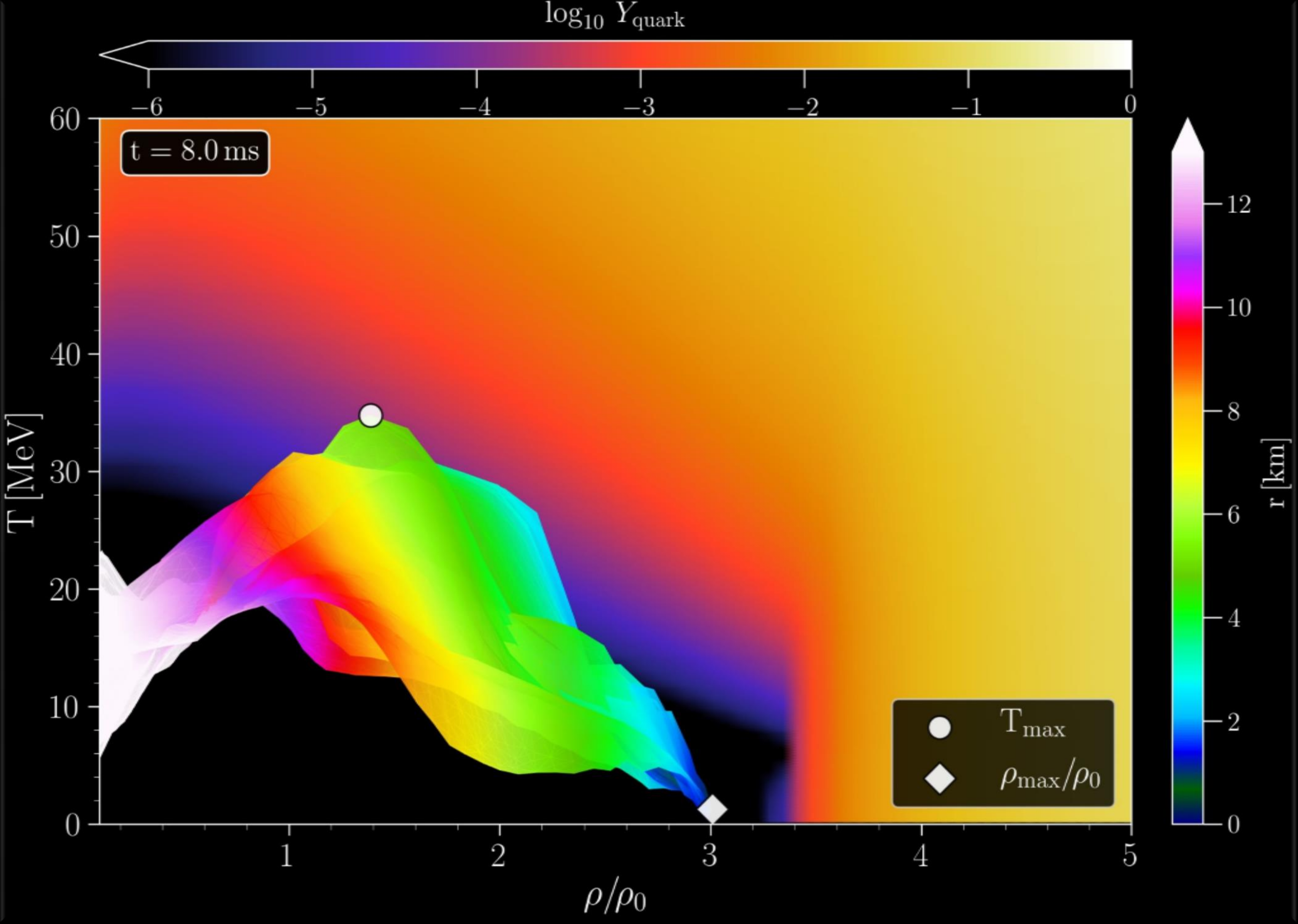
Rest mass density



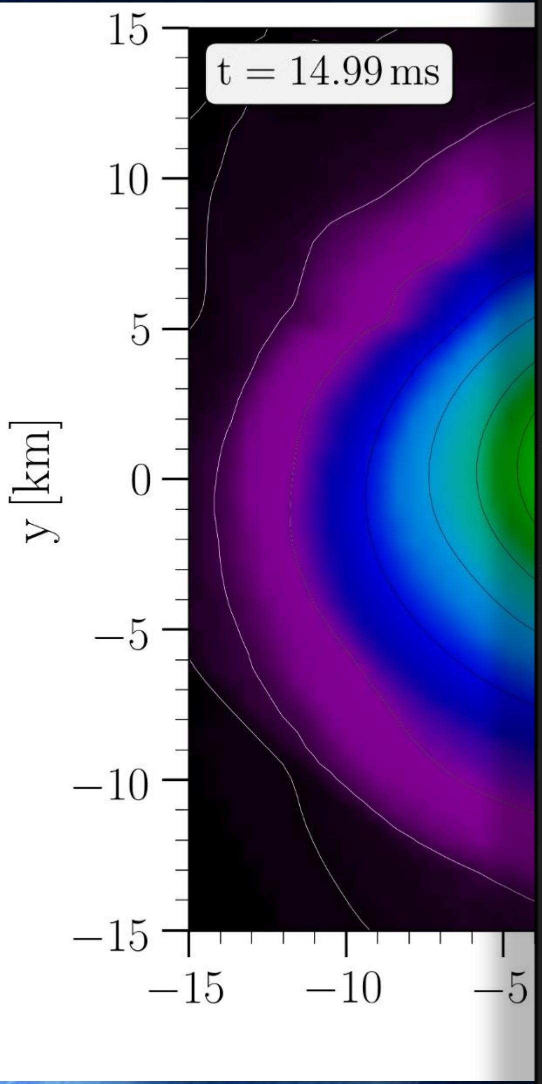
Merger Phase



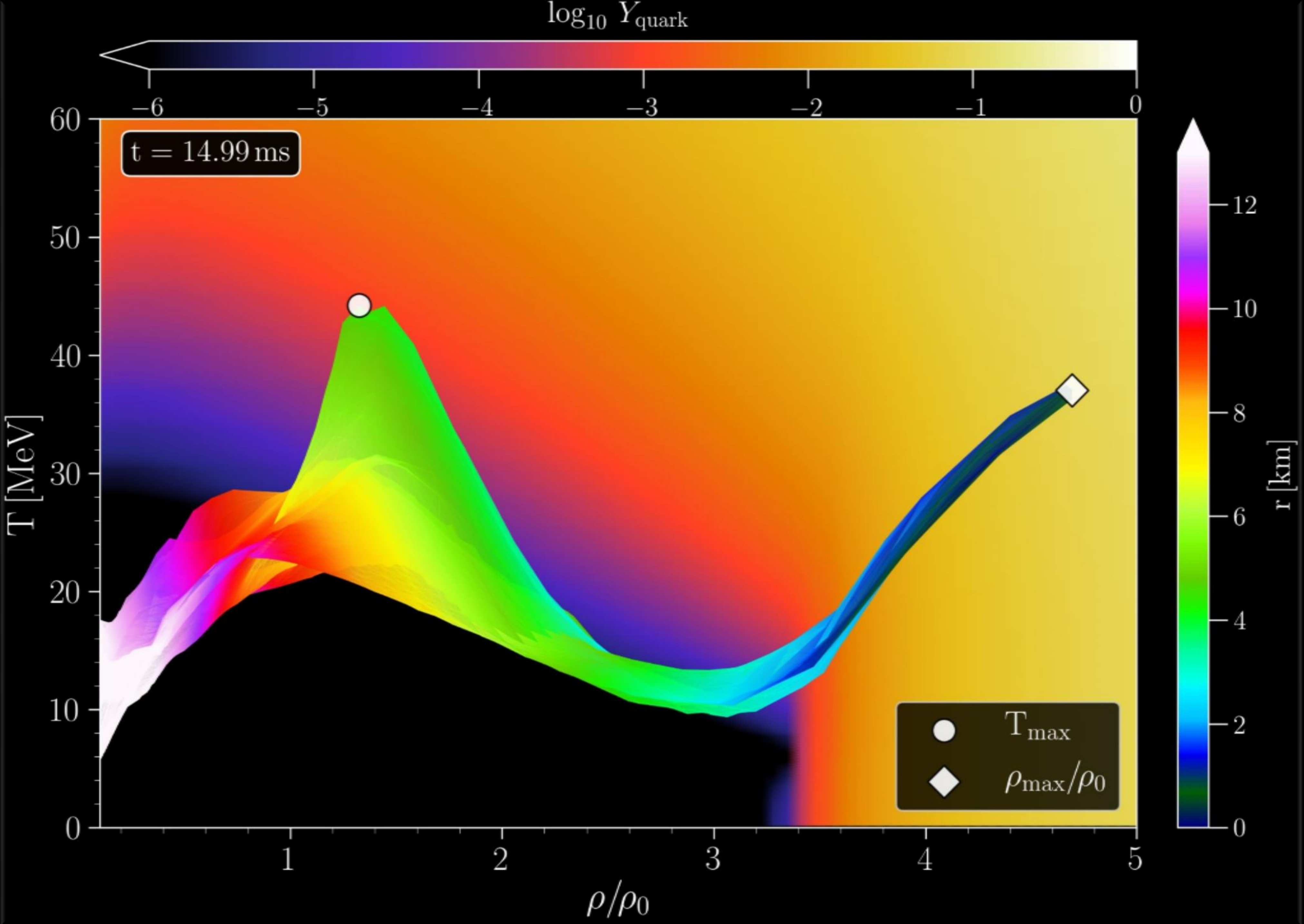
Rest mass density



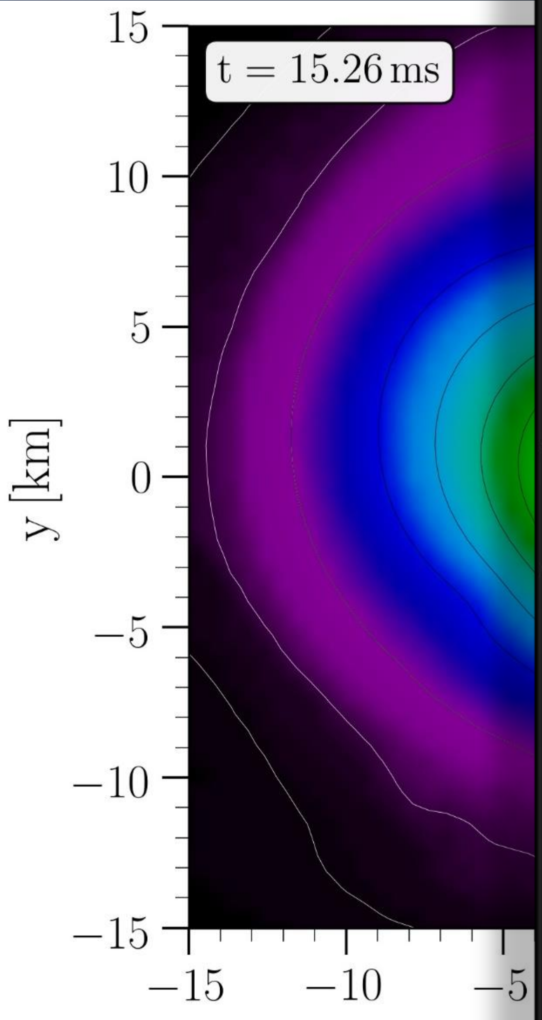
Merger Phase



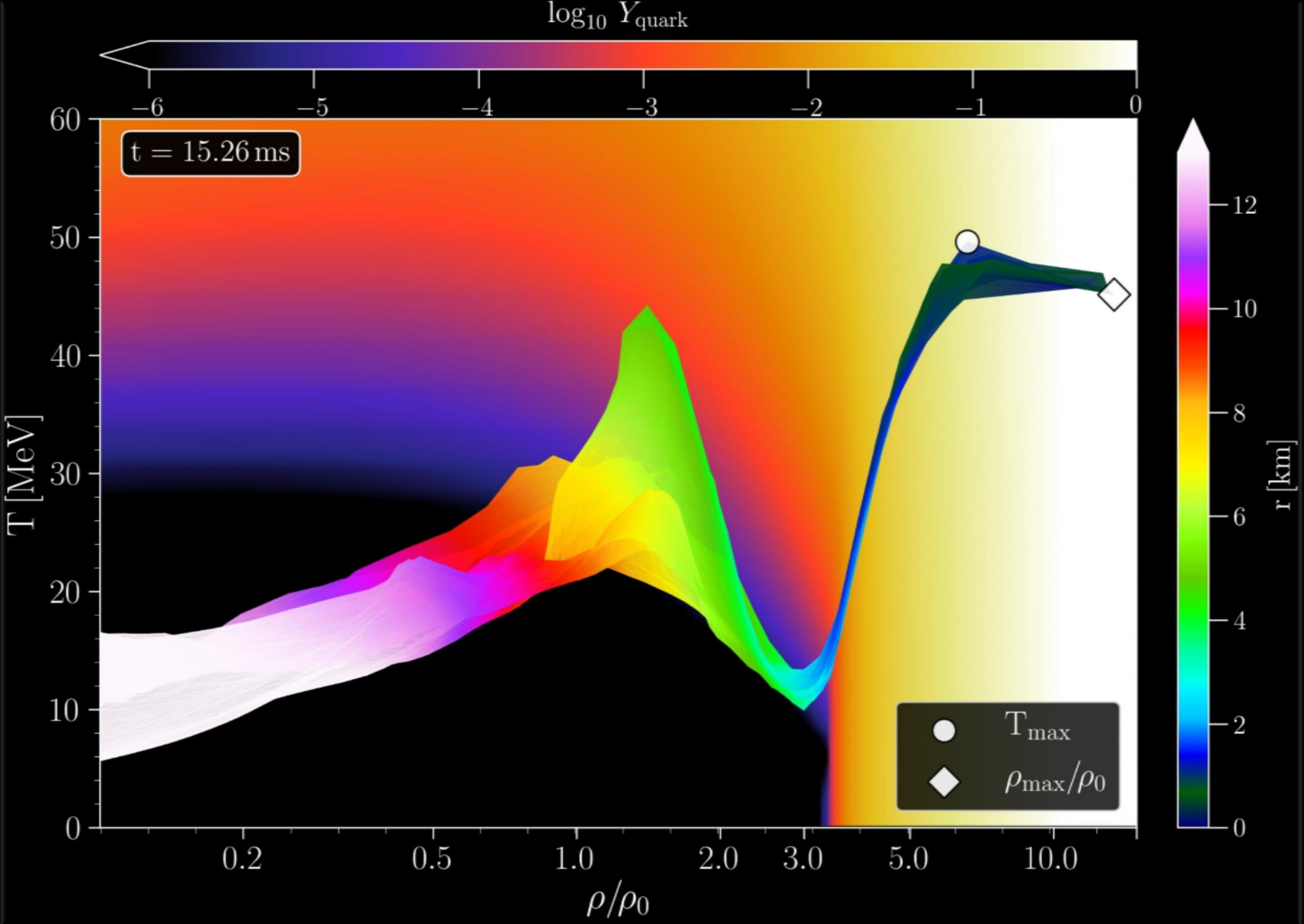
Rest mass density



Merger Phase



Rest mass density

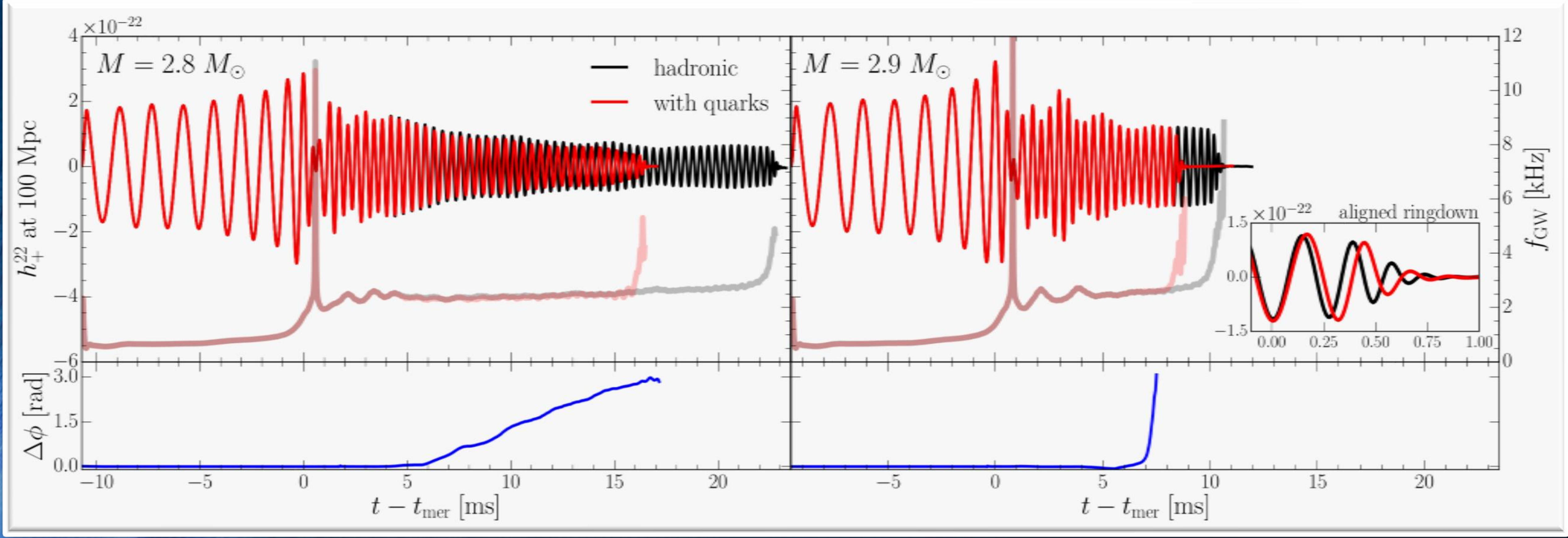


Hybrid Star Mergers with T-dependent EOS *(PRL paper 1)*

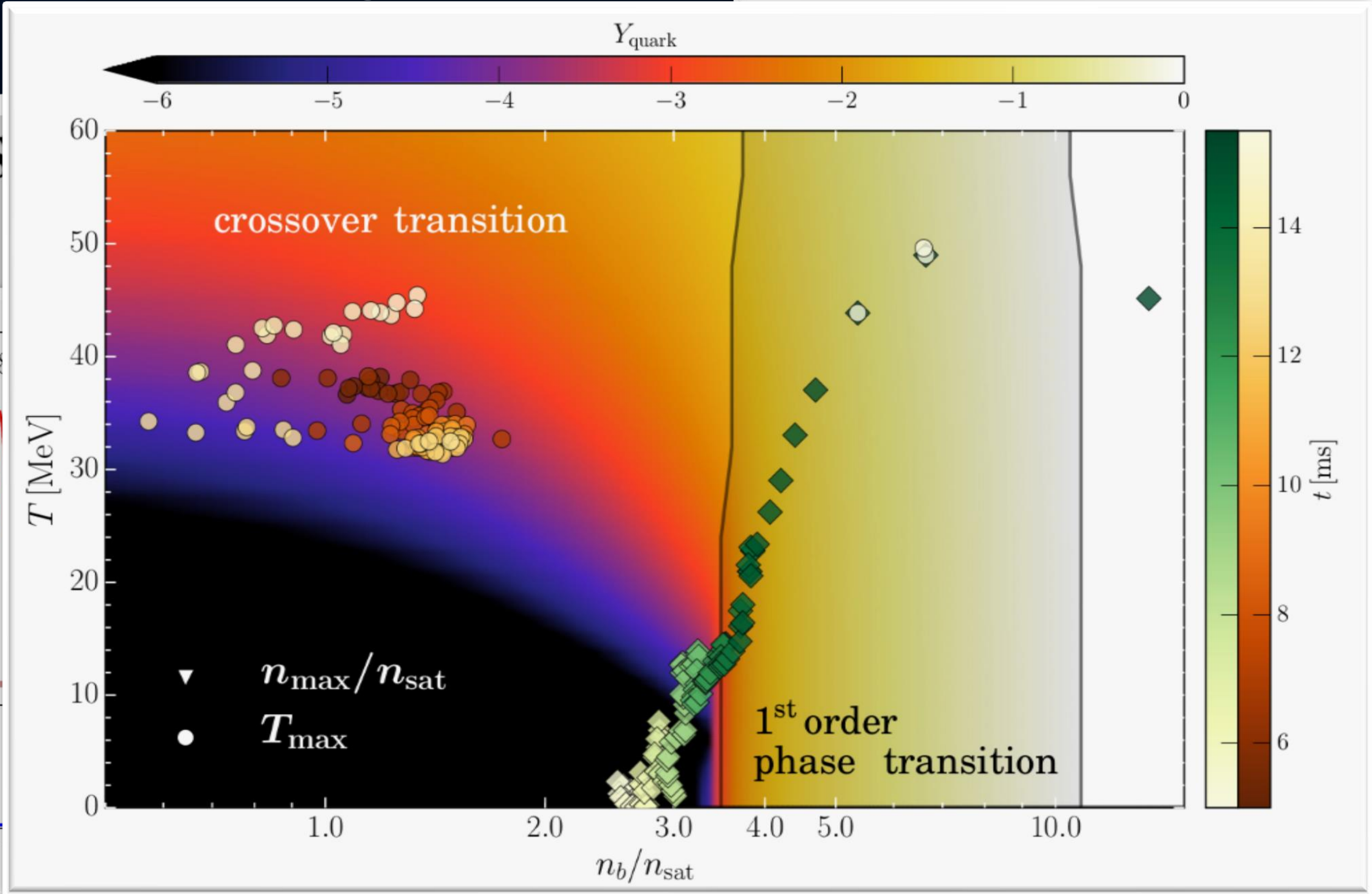

Signatures of quark-hadron phase transitions in general-relativistic neutron-star mergers

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]

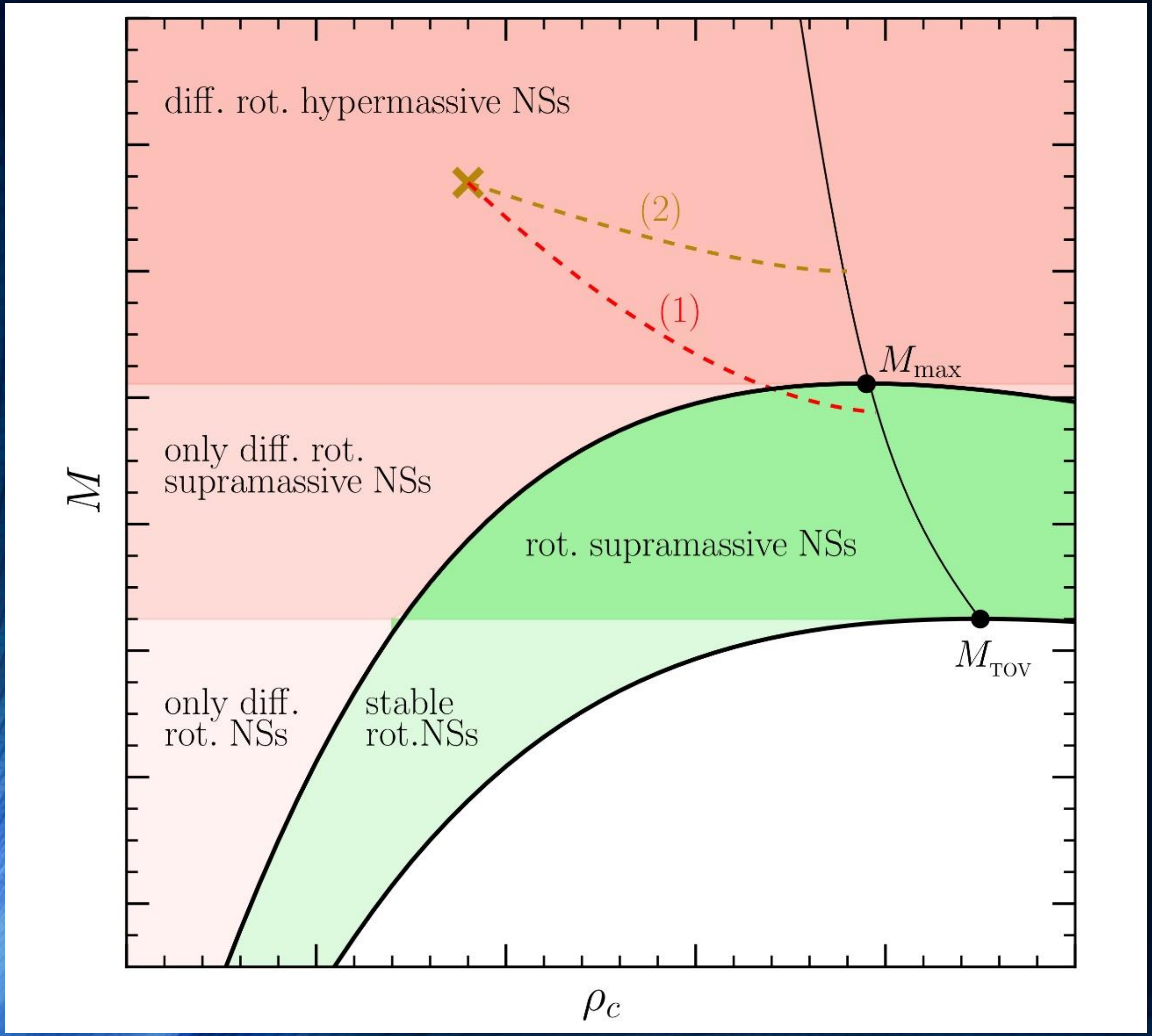
Max-von-Laue-Straße 1, 60438 Frankfurt, Germany
Kent, OH 44243 USA
Frankfurt, Germany



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



GW170817: Constraining the maximum mass of Neutron Stars

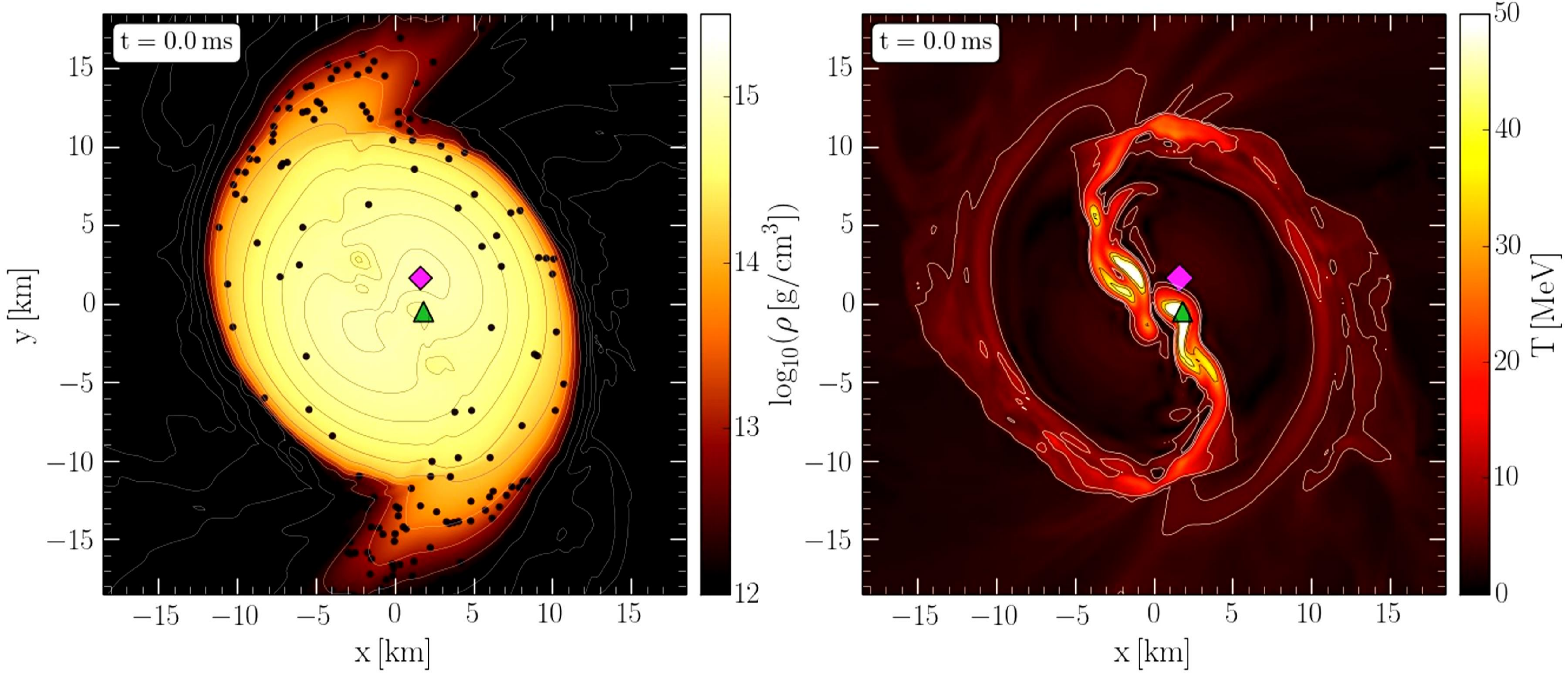


The highly differentially rotating hypermassive/supramassive neutron star will spin down and redistribute its angular momentum (e.g. due to viscosity effects, magnetic braking). After ~1 second it will cross the stability line as a uniformly rotating supramassive neutron star (close to M_{max}) and collapse 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):
$2.01 +/- 0.04 < M_{TOV} < 2.16 +/- 0.17$

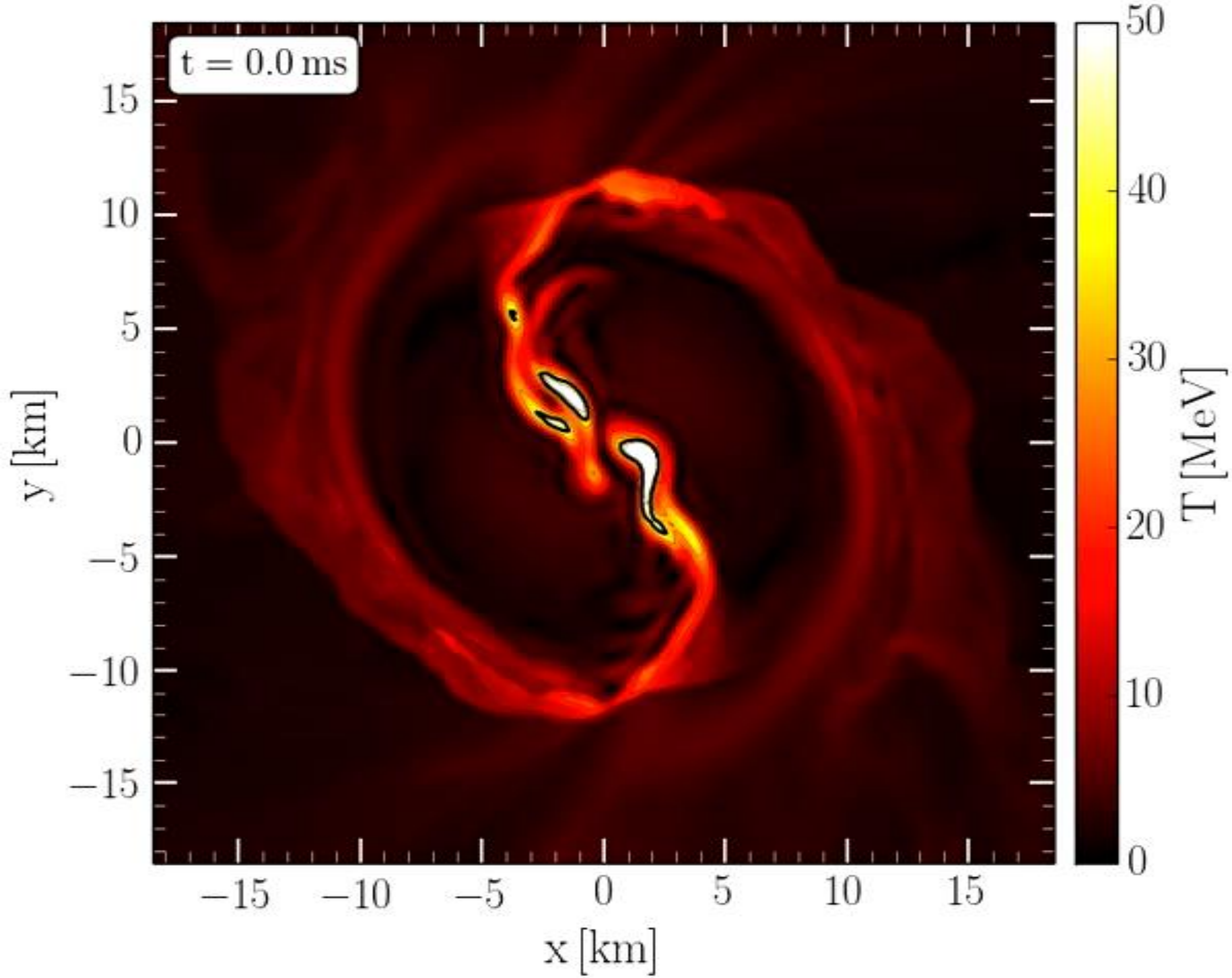
See also: S.Lawrence et al. ,APJ808,186, 2015
Margalit & Metzger, The Astrophysical Journal Letters 850, L19 (2017): $M_{TOV} < 2.17$ (90%)
Zhou, Zhou, Li, PRD 97, 083015 (2018)
Ruiz, Shapiro, Tsokaros, PRD 97,021501 (2018)

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

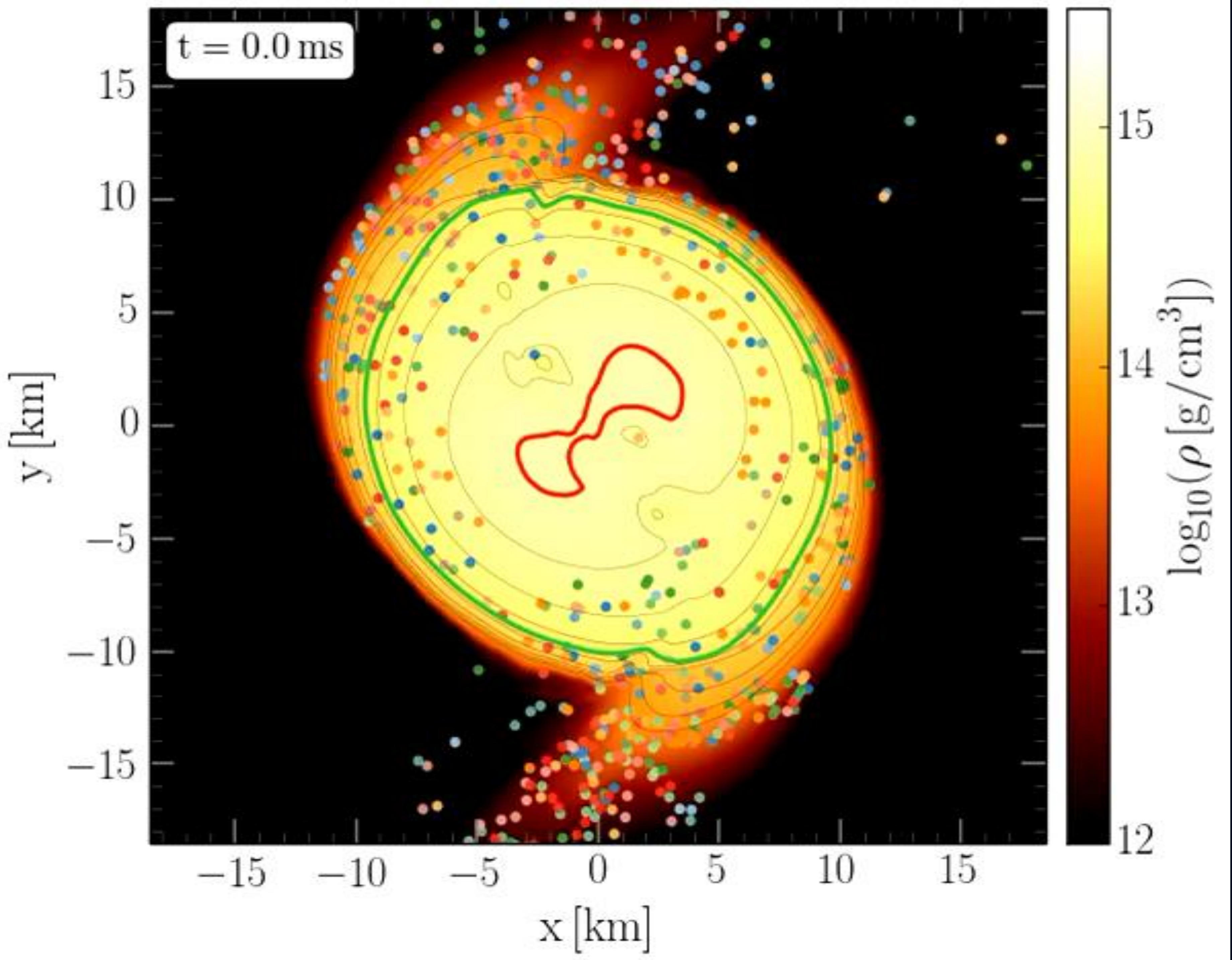
Kastaun, W., Ciolfi, R., Endrizzi, A., & Giacomazzo, B. (2017). Structure of stable binary neutron star merger remnants: Role of initial spin. Physical Review D, 96(4), 043019

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)

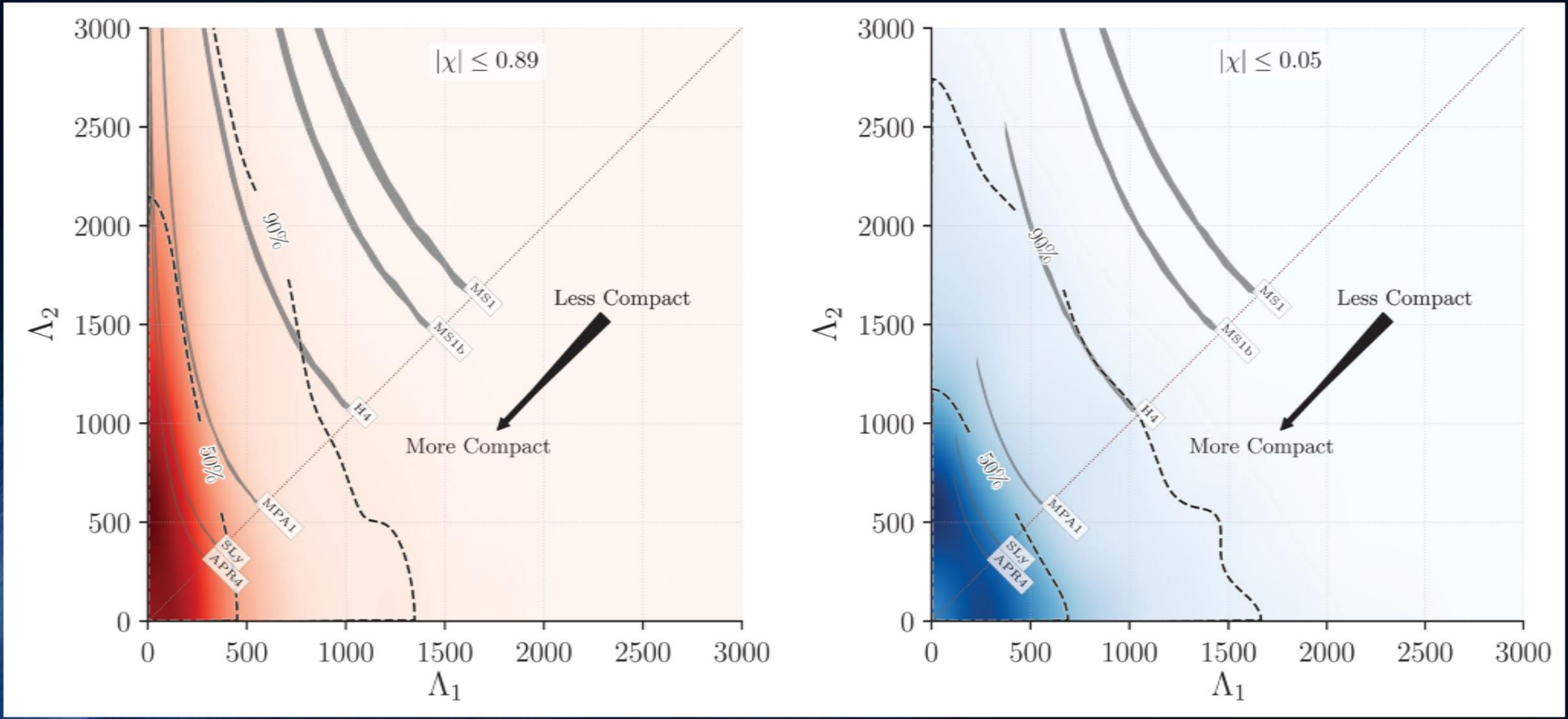
Evolution of Tracer-particles tracking individual fluid elements in the equatorial plane of the HMNS at post-merger times

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



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



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

1. WHAT ARE HYBRID STARS?
2. HYPERMASSIVE NEUTRON STARS
3. HYPERMASSIVE HYBRID STARS
4. TWIN STAR MERGERS

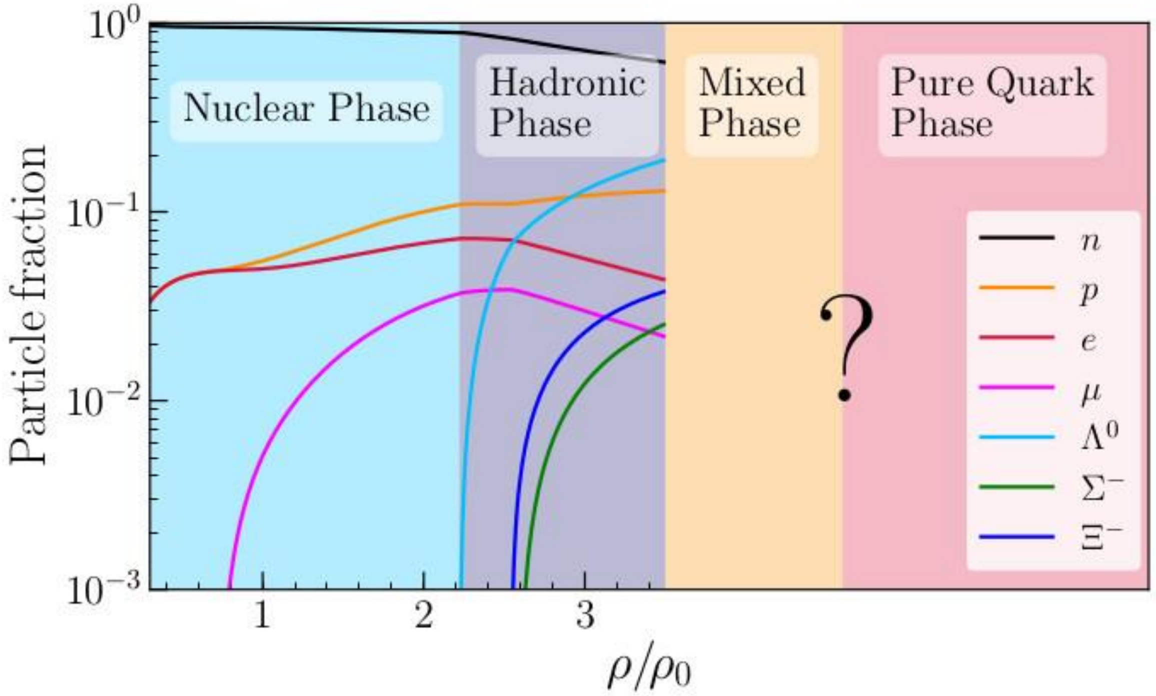
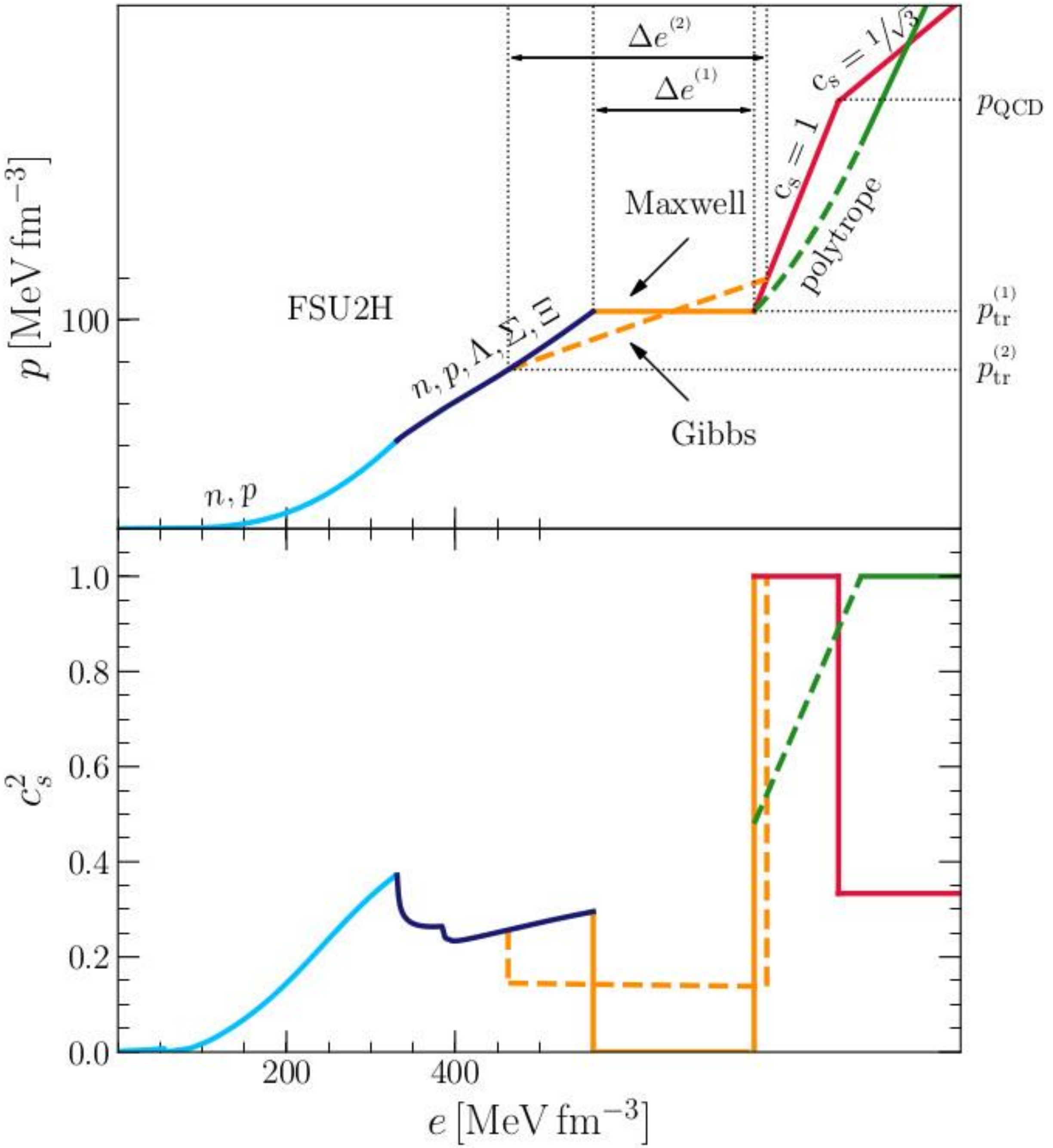
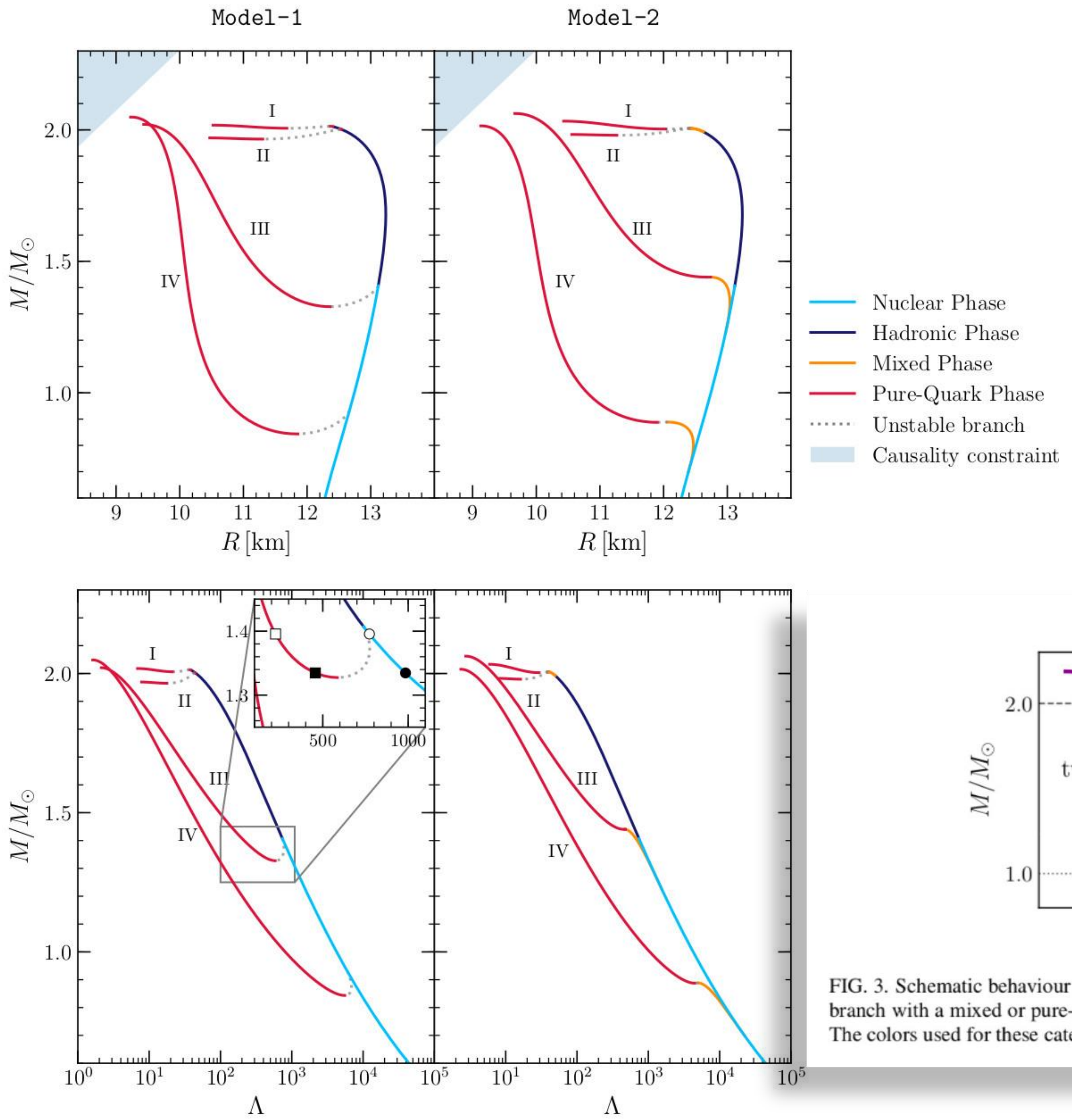


FIG. 1. Particle fractions as functions of the baryonic density for the FSU2H model [69, 70] up to the point where the HQPT is implemented, giving rise to a phase of deconfined quark matter which can be separated from the nuclear (or hadronic) phase by a mixed phase of hadrons and quarks. We note that 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.



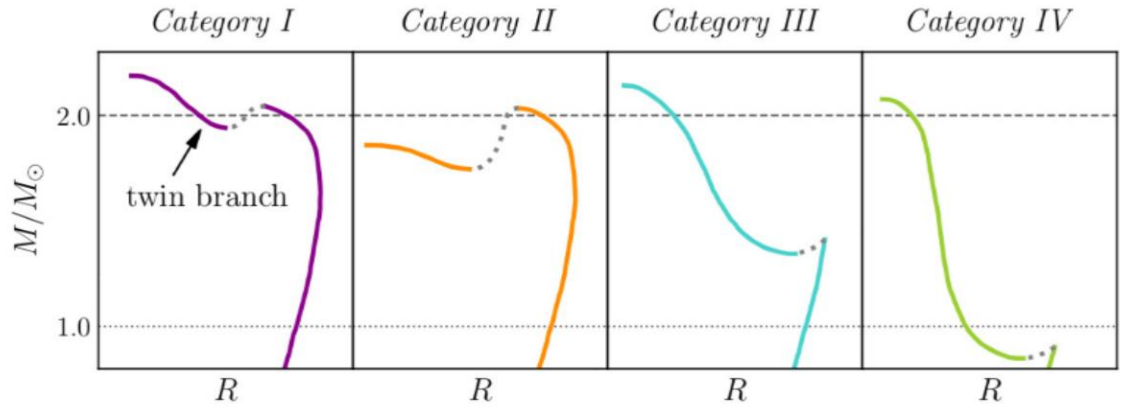
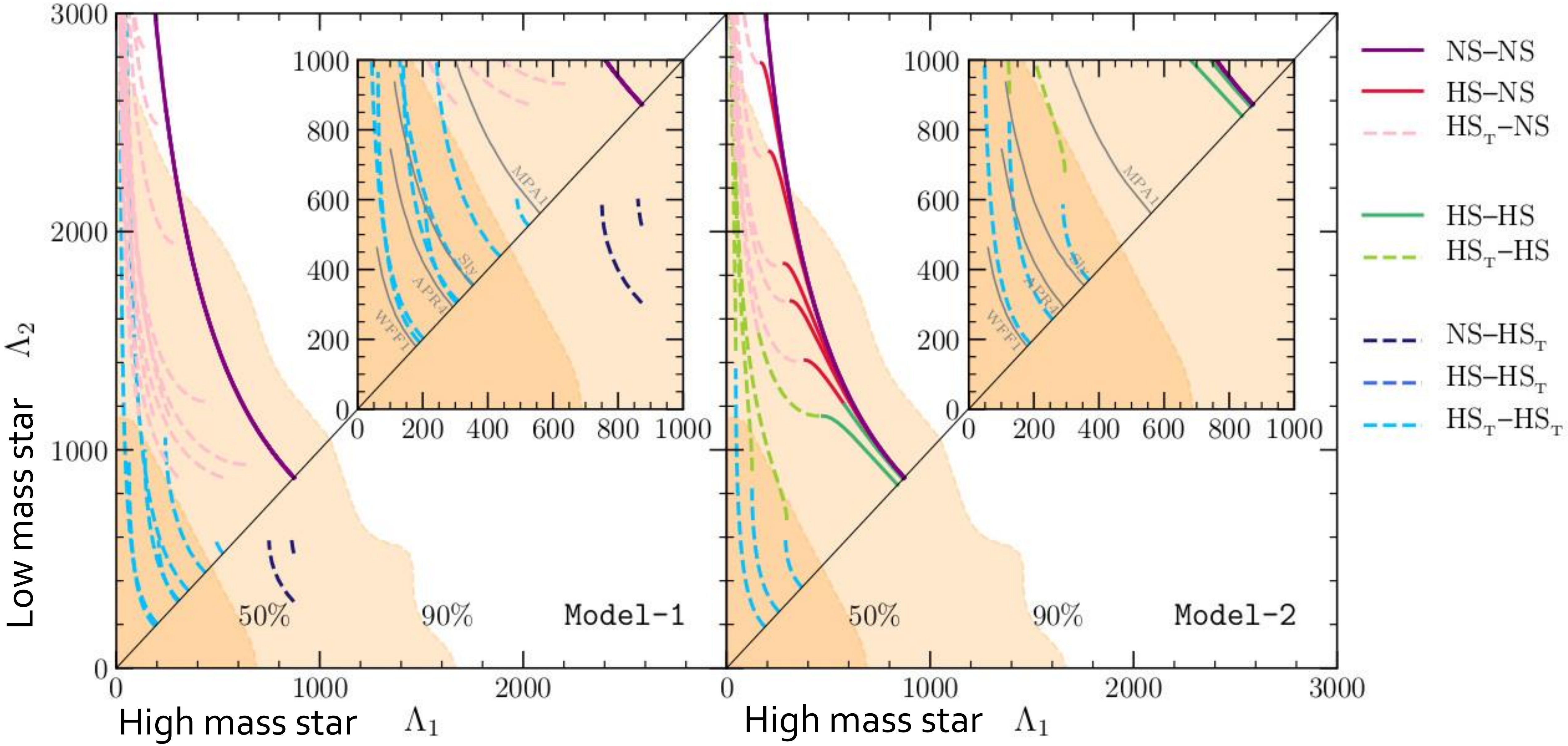


FIG. 3. Schematic behaviour of the mass–radius relation for the twin-star categories *I–IV* defined in the text. Note the appearance of a "twin" branch with a mixed or pure-quark phase; the twin branch has systematically smaller radii than the branch with a nuclear or hadronic phase. The colors used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