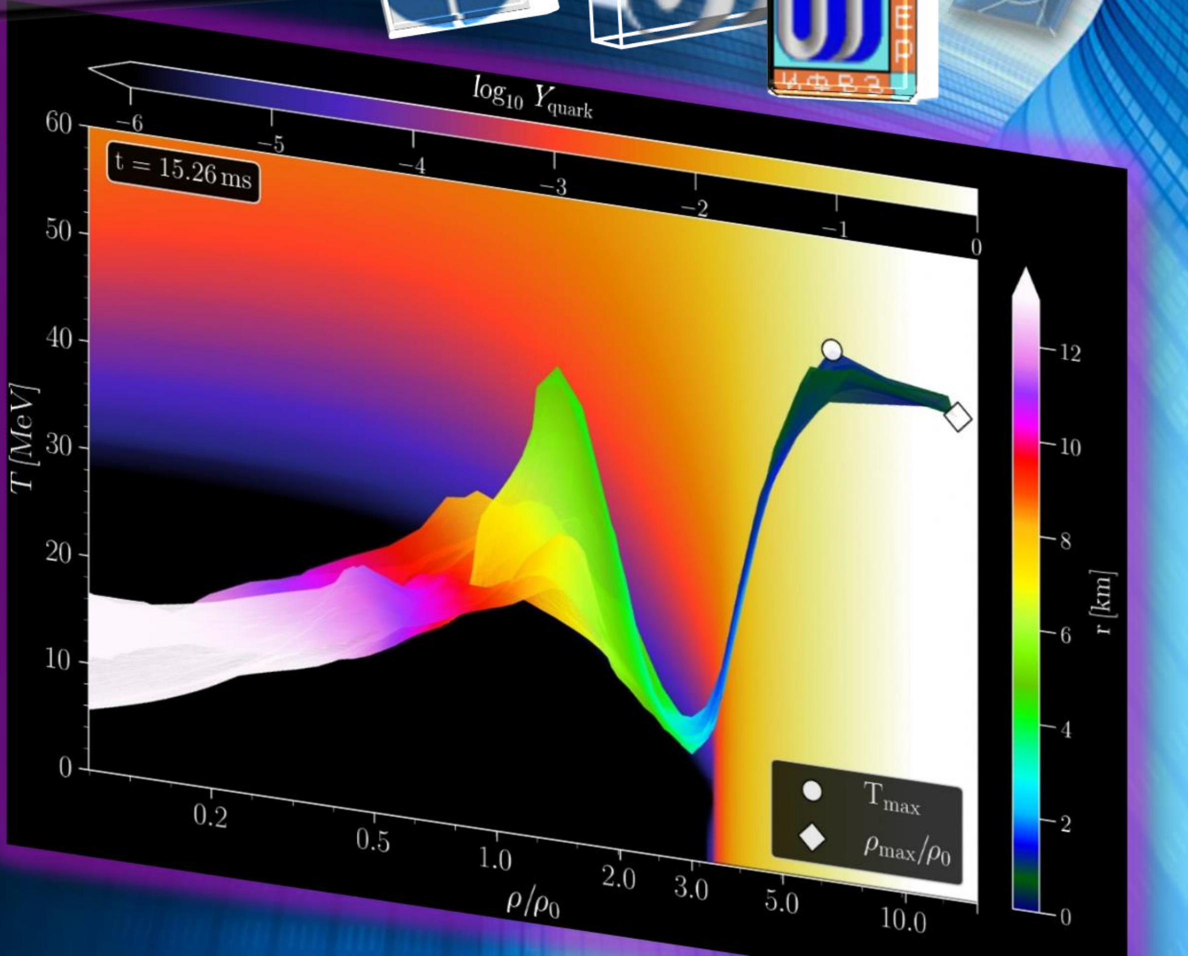
XXXII INTERNATIONAL (ONLINE) WORKSHOP ON HIGH ENERGY PHYSICS "HOT PROBLEMS OF STRONG INTERACTIONS"

Logunov Institute for High Energy Physics of the National Research Centre "Kurchatov Institute" in Russia
10. November 2020

Gravitational-Wave Signatures of the Hadron-Quark Phase Transition in Binary Compact Star Mergers

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 Lukas Weih, Elias R. Most, Jens Papenfort, Luke Bovard, Gloria Montana, Laura Tolos, Jan Steinheimer, Anton Motornenko, Veronica Dexheimer, Horst Stöcker, and Luciano Rezzolla

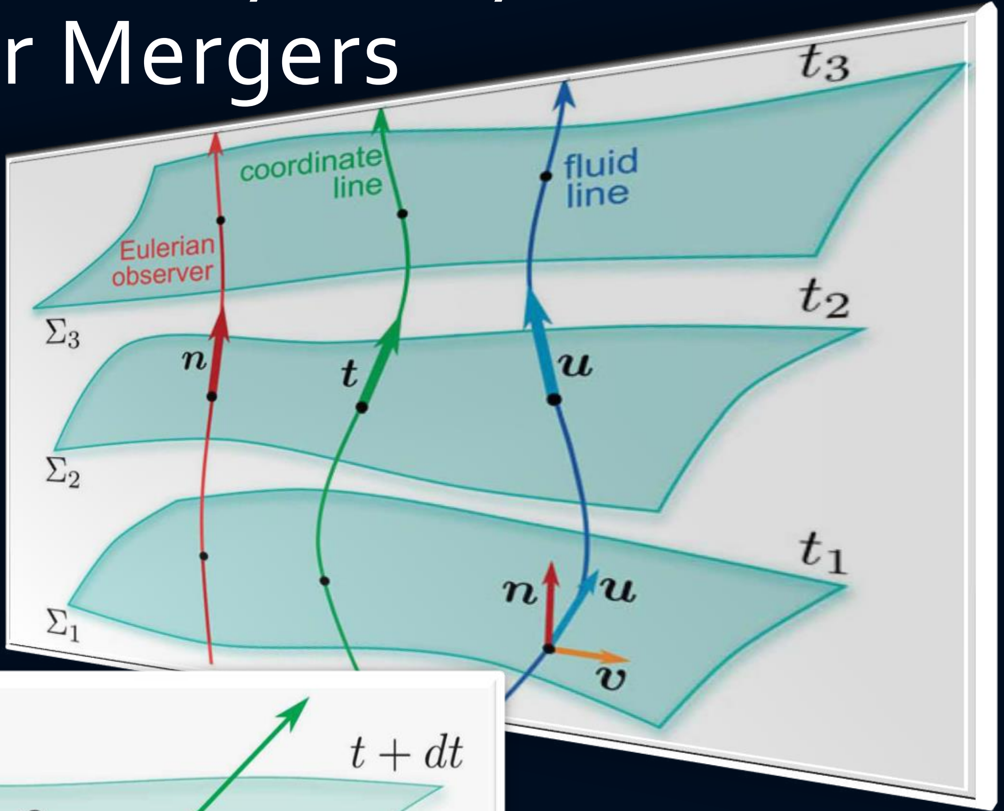


Numerical Relativity and Relativistic Hydrodynamics of Binary Compact Star Mergers

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:

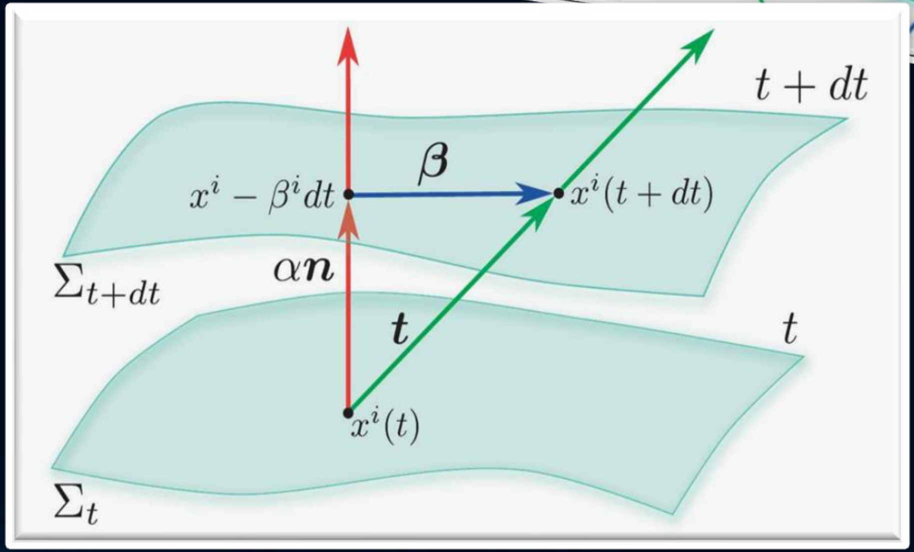
$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = 8\pi T_{\mu\nu}$$

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



(3+1) decomposition of spacetime

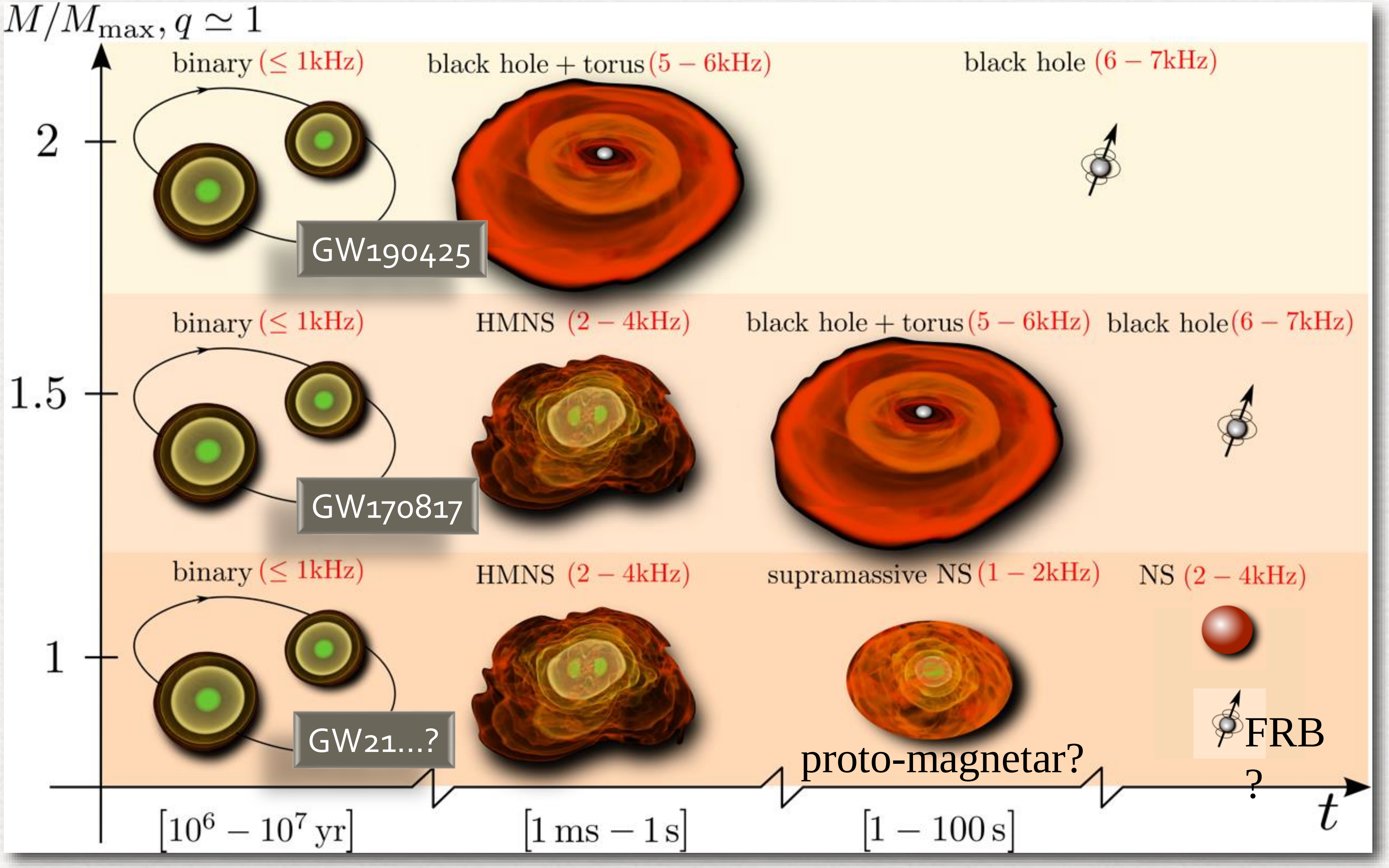
$$g_{\mu\nu} = \begin{pmatrix} -\alpha^2 + \beta_i \beta^i & \beta_i \\ \beta_i & \gamma_{ij} \end{pmatrix}$$



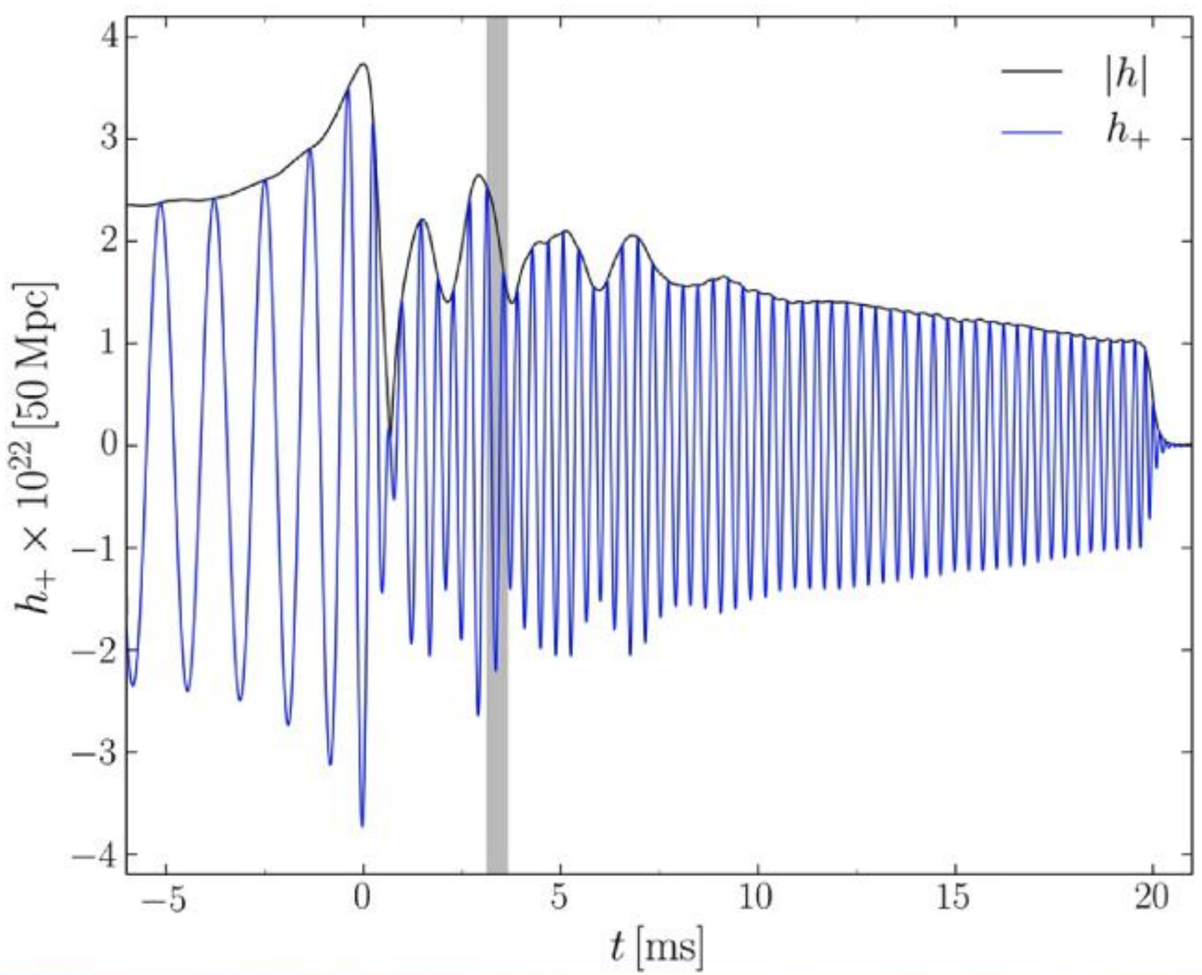
$$d\tau^2 = \alpha^2(t, x^j) dt^2 \qquad x^i_{t+dt} = x^i_t - \beta^i(t, x^j) dt$$

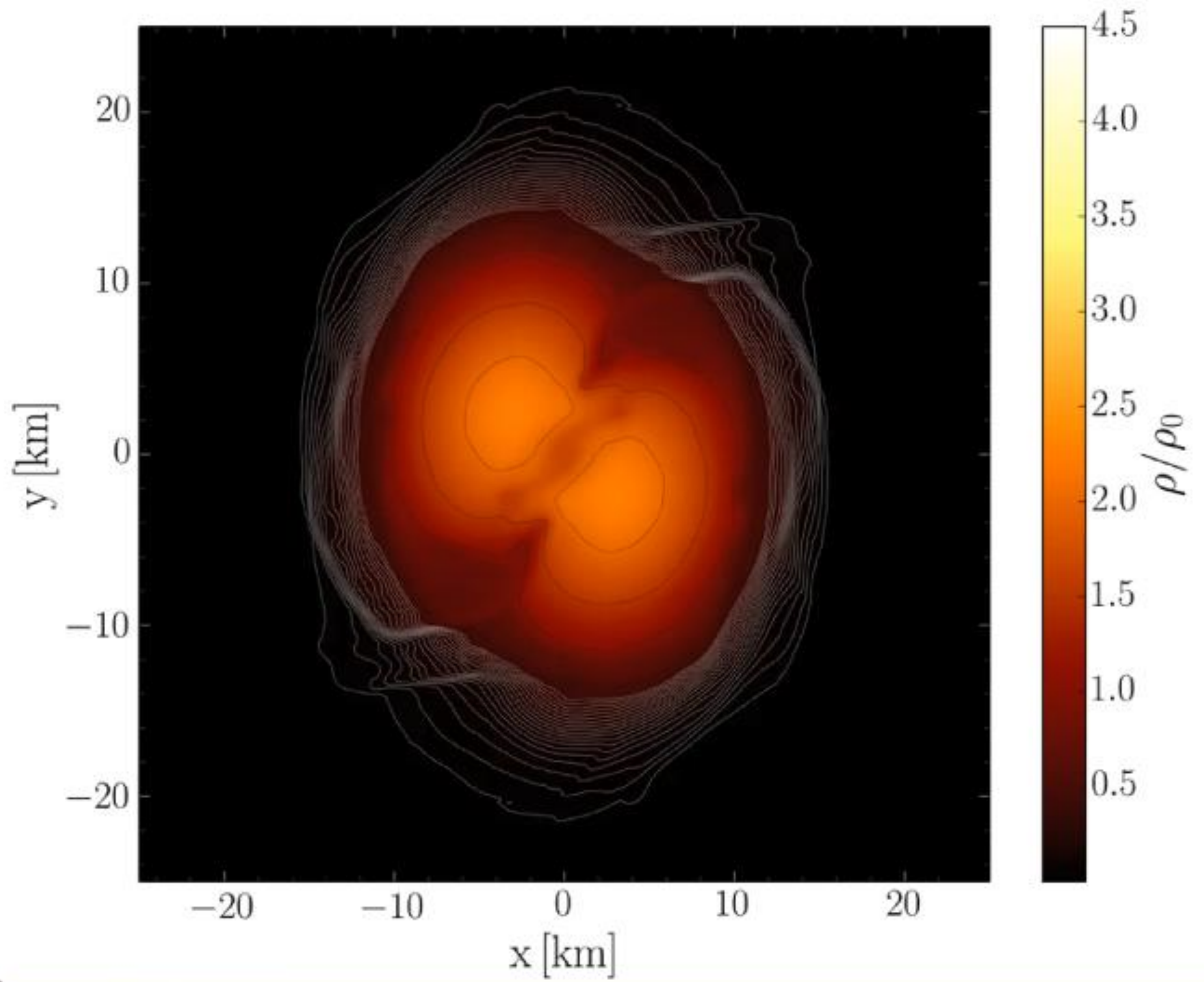
All figures and equations from: Luciano Rezzolla, Olindo Zanotti: Relativistic Hydrodynamics, Oxford Univ. Press, Oxford (2013)

Broadbrush picture



Evolution of the density in the post merger phase





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

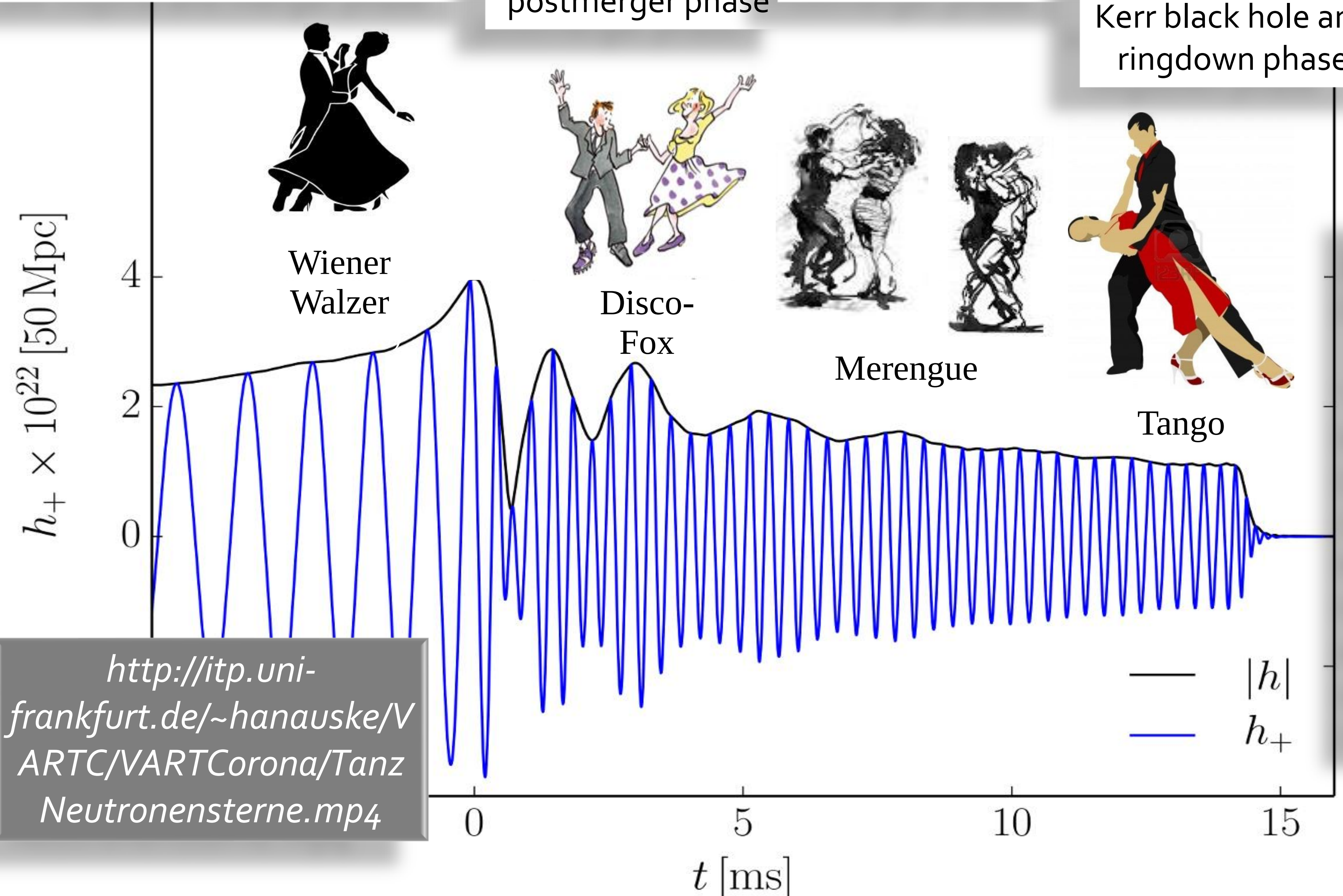
The different Phases of a Binary Compact Star Merger Event

Late inspiral and merger phase

Transient early postmerger phase

Postmerger phase

Collapse to the Kerr black hole and ringdown phase

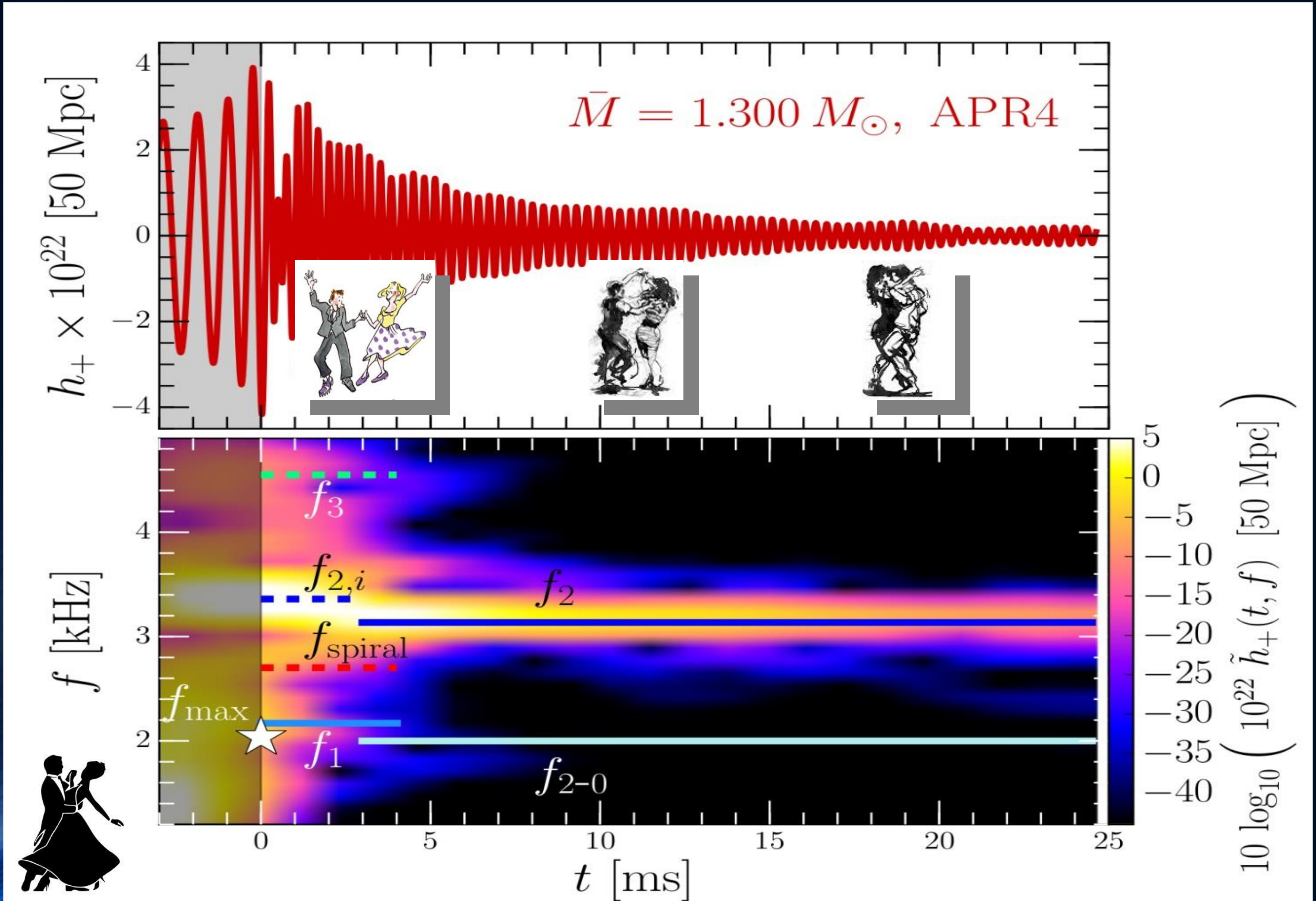


http://itp.uni-frankfurt.de/~hanauske/VARTC/VARTCorona/TanzNeutronensterne.mp4

Wy exactly these dances? Details in

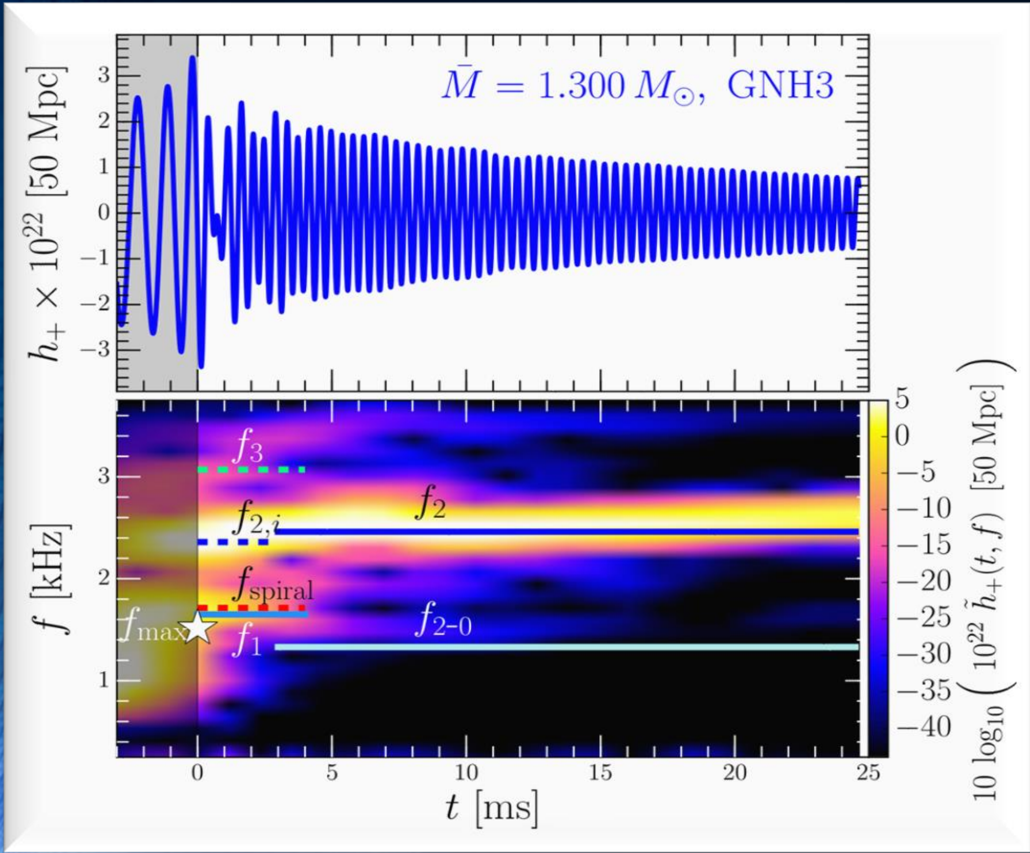
"Binary Compact Star Mergers and the Phase Diagram of Quantum Chromodynamics", Matthias Hanauske and Horst Stöcker, Discoveries at the Frontiers of Science, 107-132; Springer, Cham (2020)

The different Phases during the Postmergerphase of the HMNS

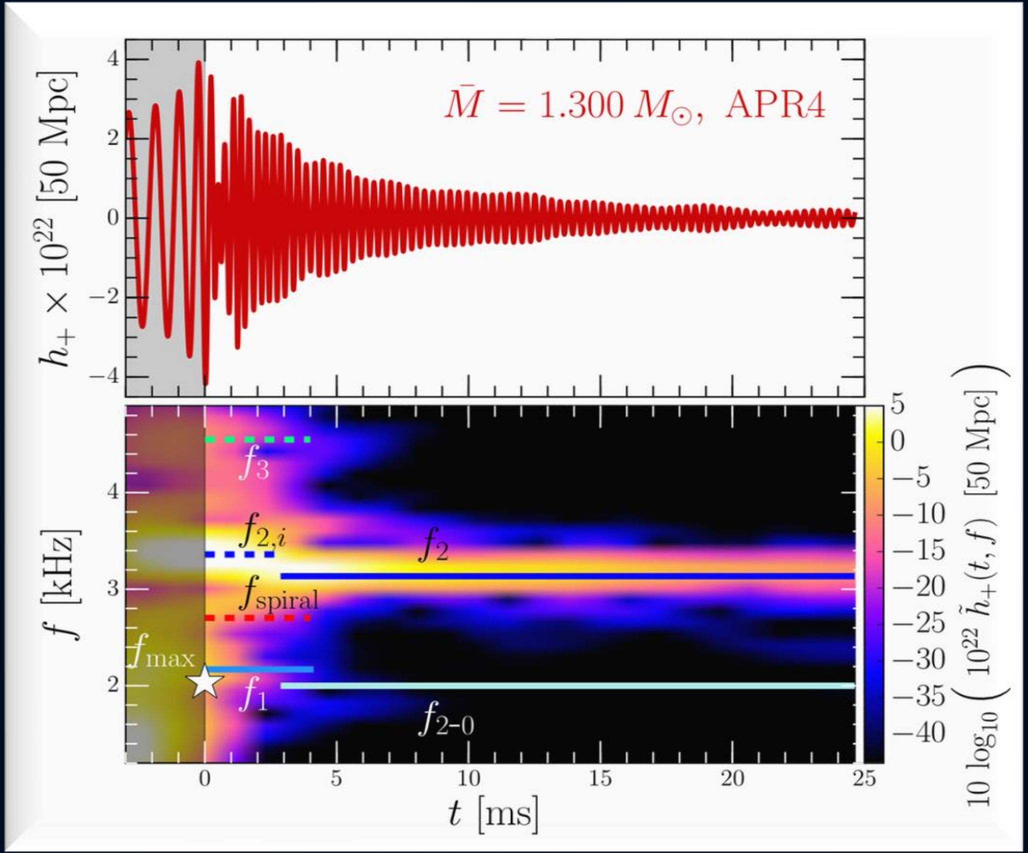


Time Evolution of the GW-Spectrum

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))



<u>Stiff EOS</u>



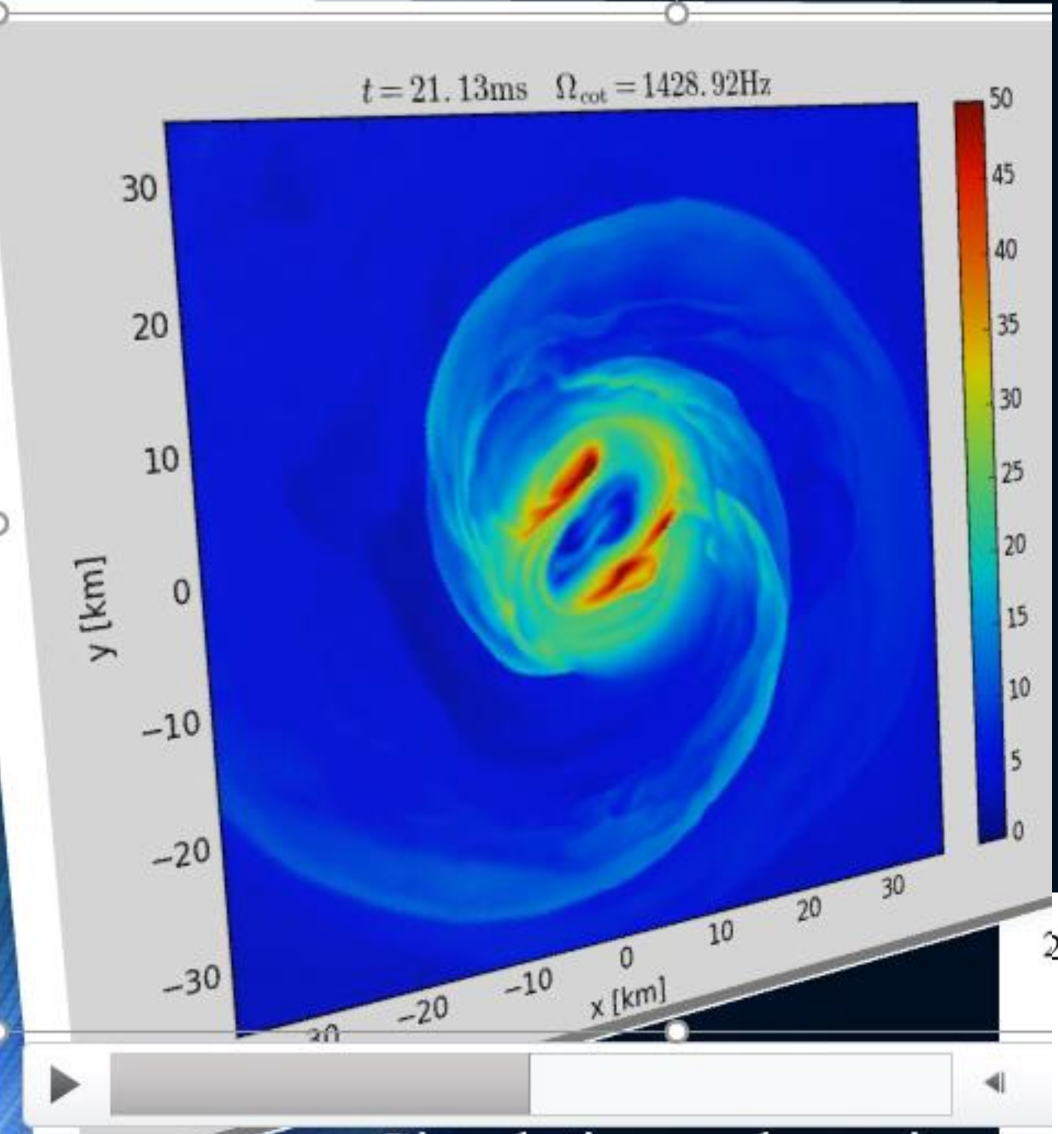
<u>Soft EOS</u>

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

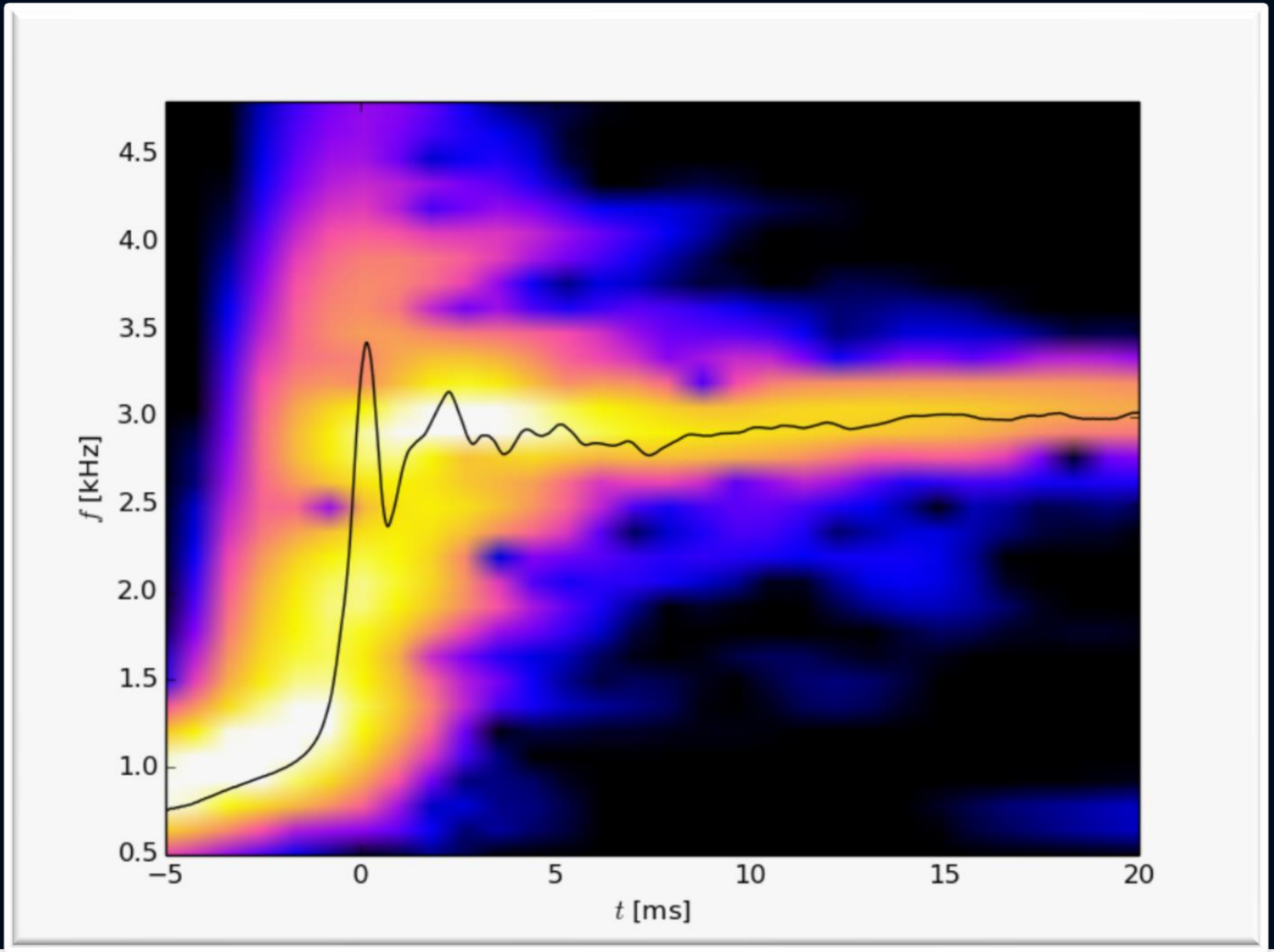
But advanced detectors / next-generation detectors might be able to detect!!?

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

The Co-Rotating Frame

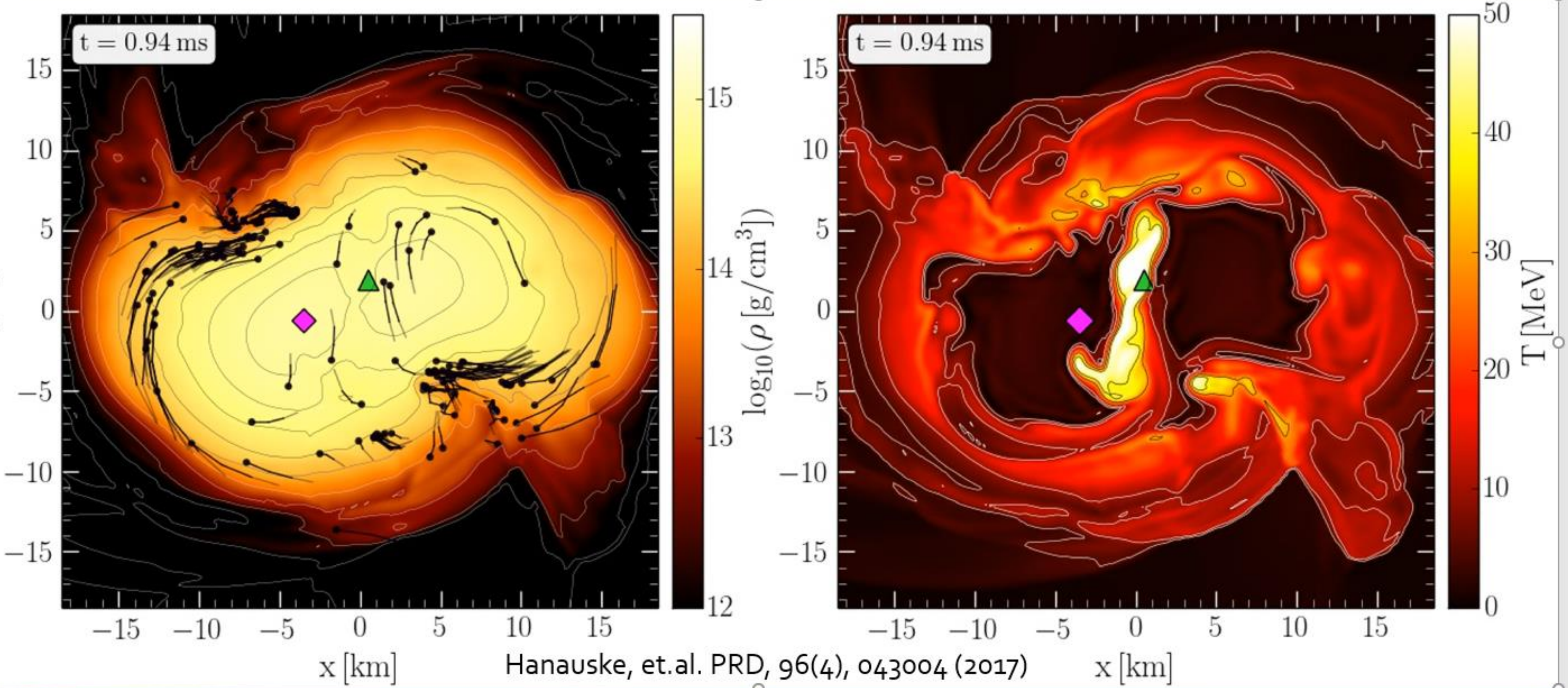


Simulation and movie
has been produced by Luke Bovard



[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, $\Omega_{\rm GW}$. Because the maximum of the angular velocity $\Omega_{\max}$ is of the order of $\Omega_{\rm GW}/2$ (cf. left panel of Fig. 12), the ring structure in this panel is approximately at zero angular velocity.

Density and Temperature Evolution inside the HMNS

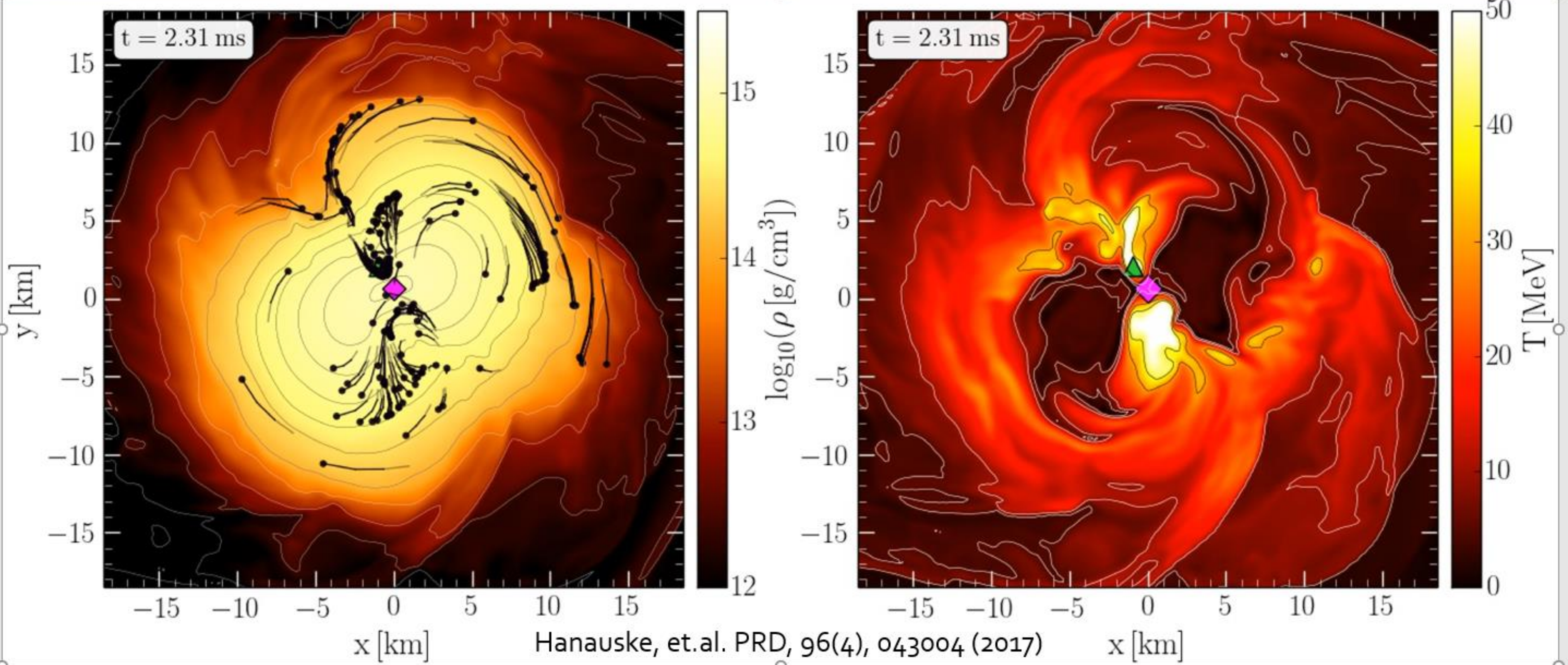


Hanauske, et.al. PRD, 96(4), 043004 (2017)

Rest mass density on the equatorial plane

Temperature on the equatorial plane

Density and Temperature Evolution inside the HMNS



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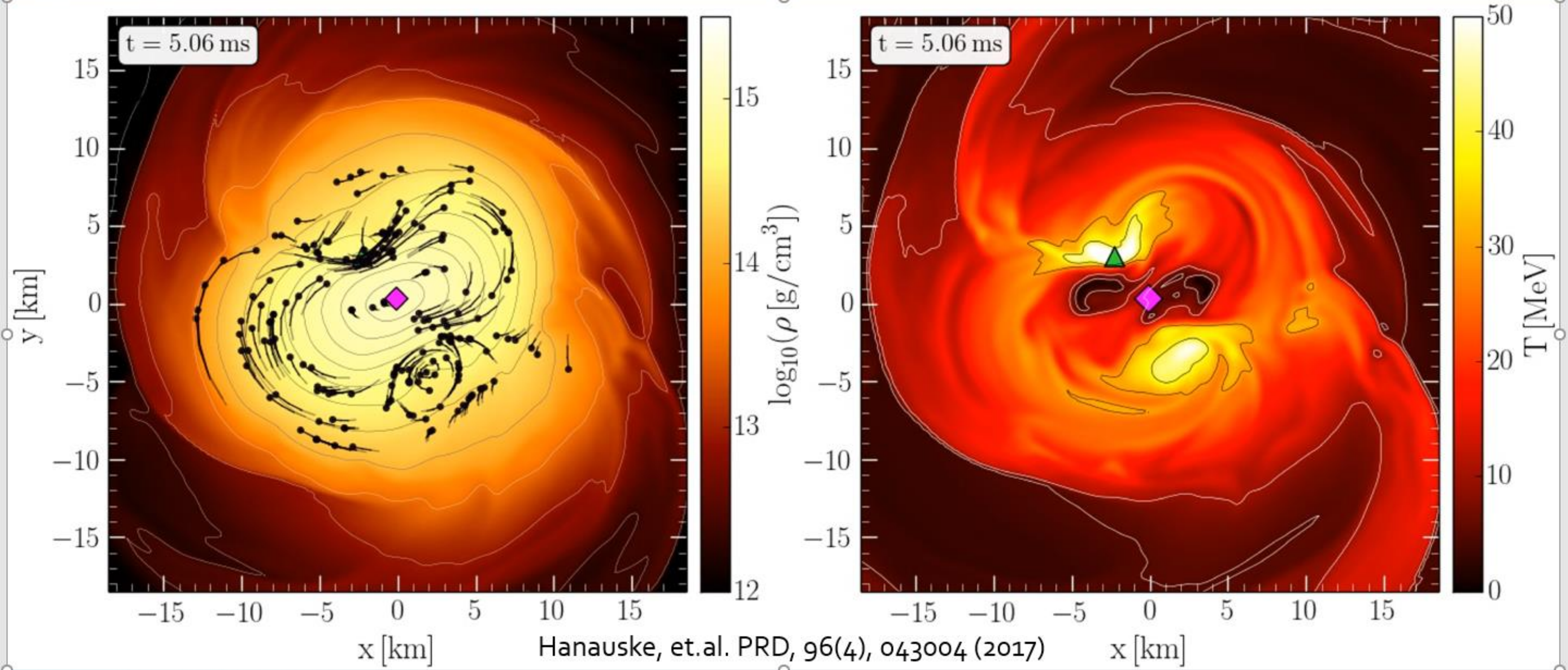

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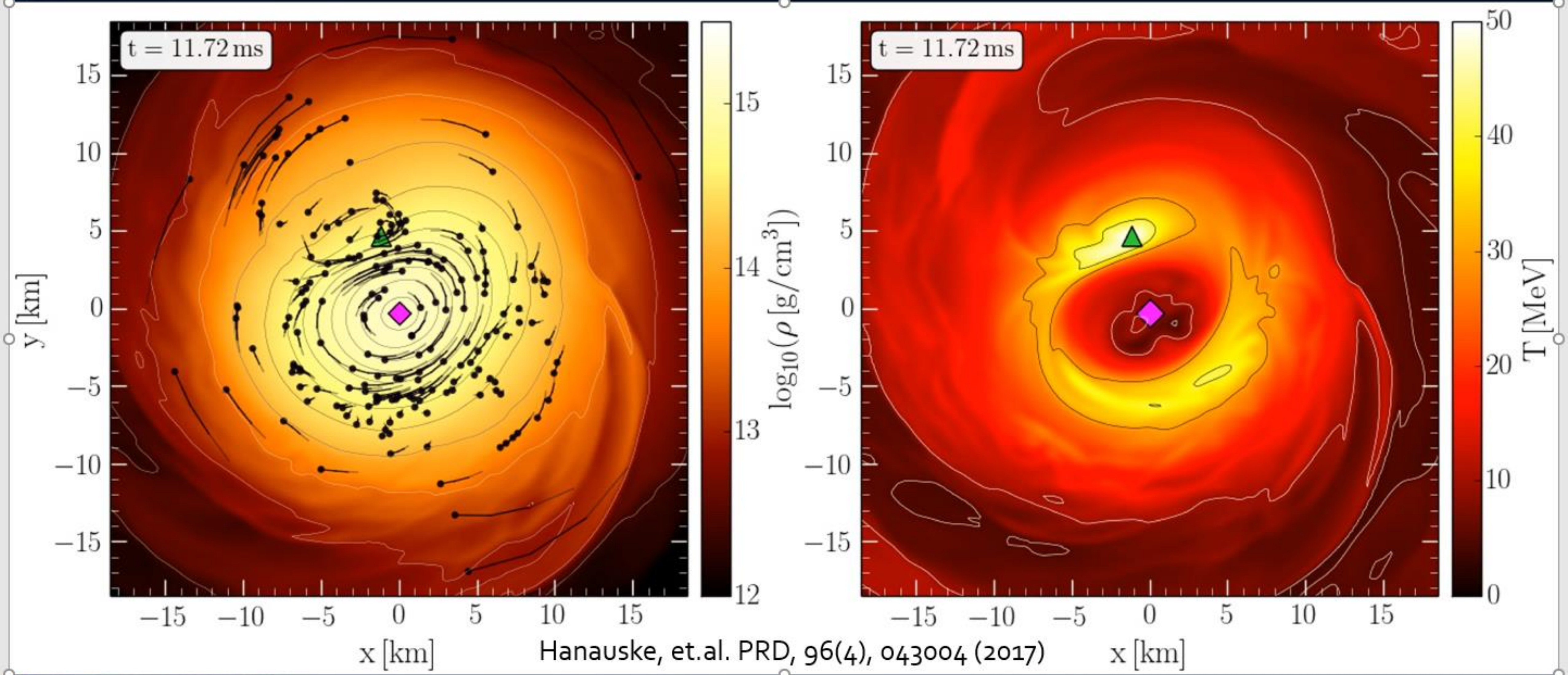

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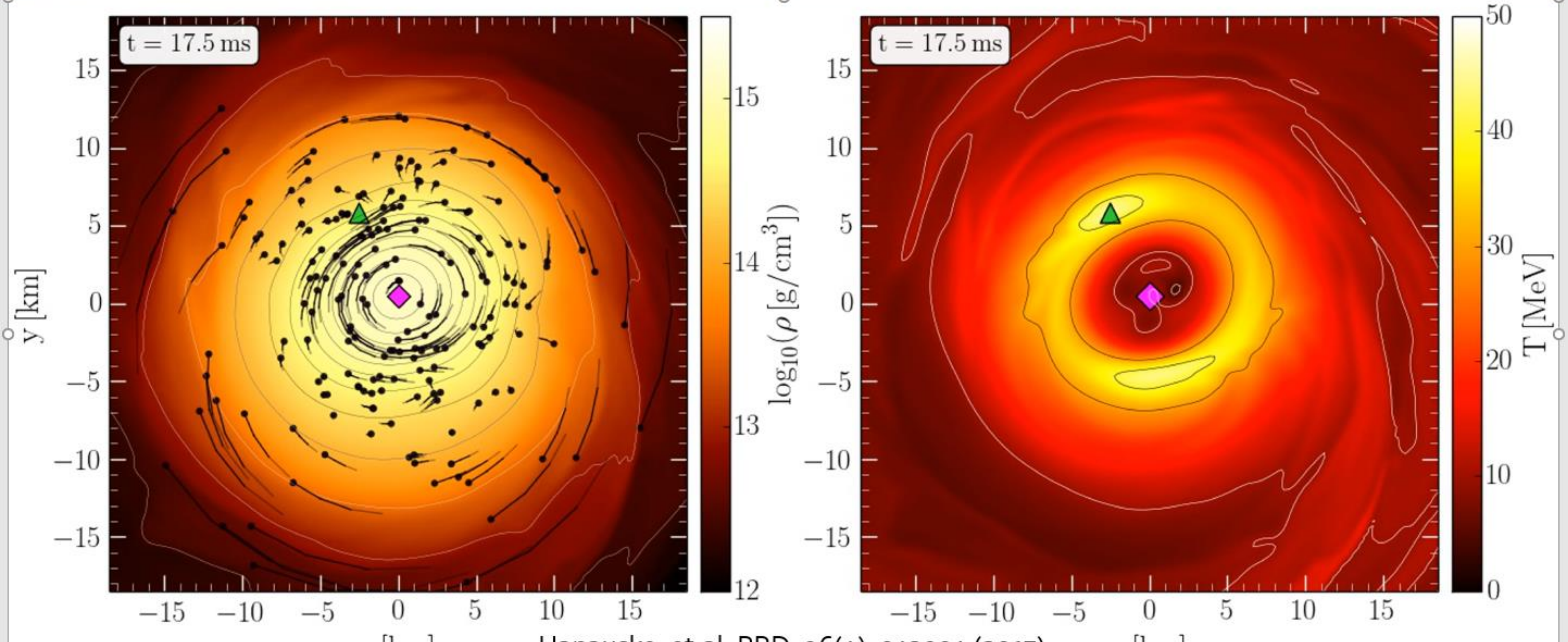

Hanauske, et.al. PRD, 96(4), 043004 (2017)

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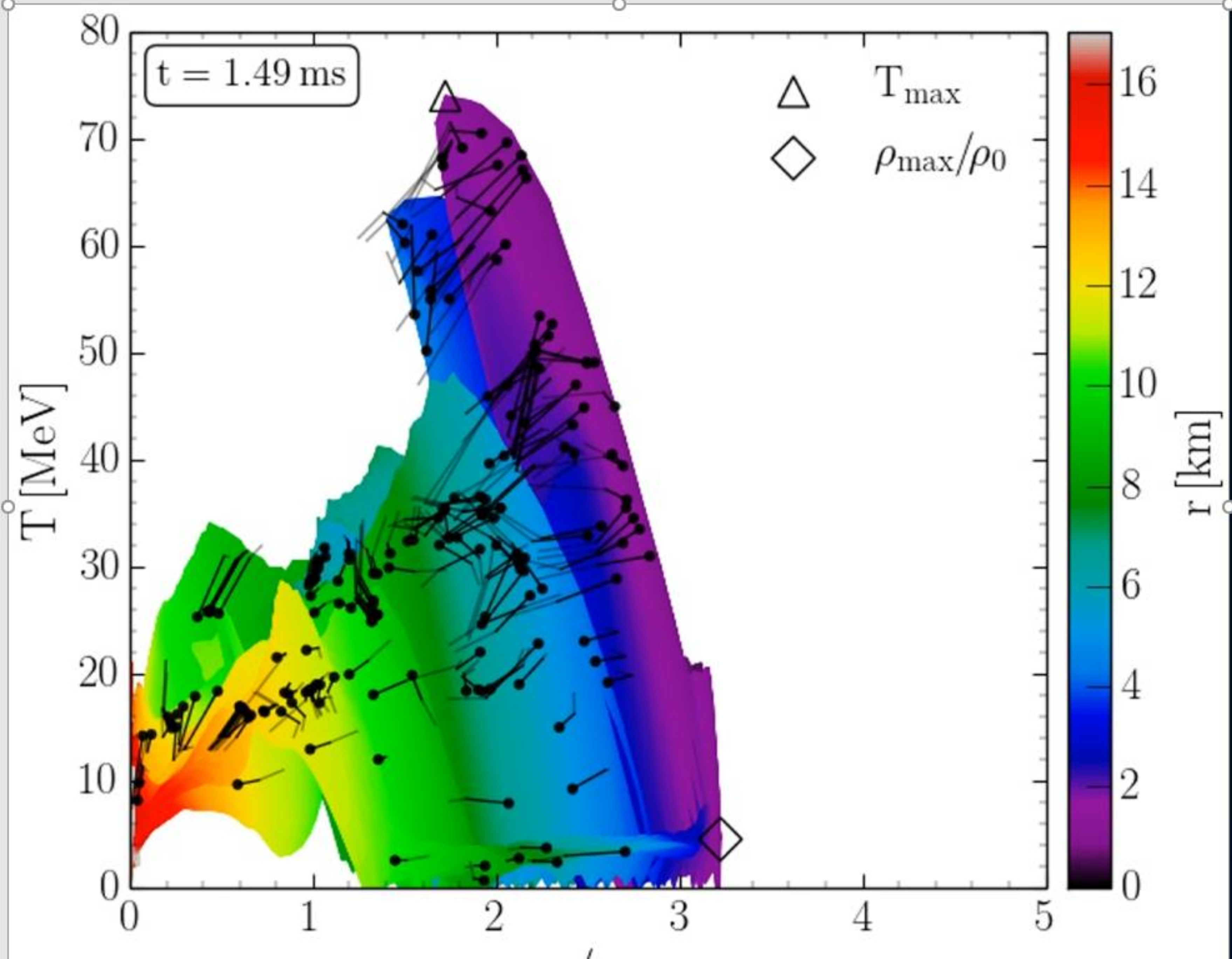
Binary Neutron Star Mergers in the QCD Phase Diagram

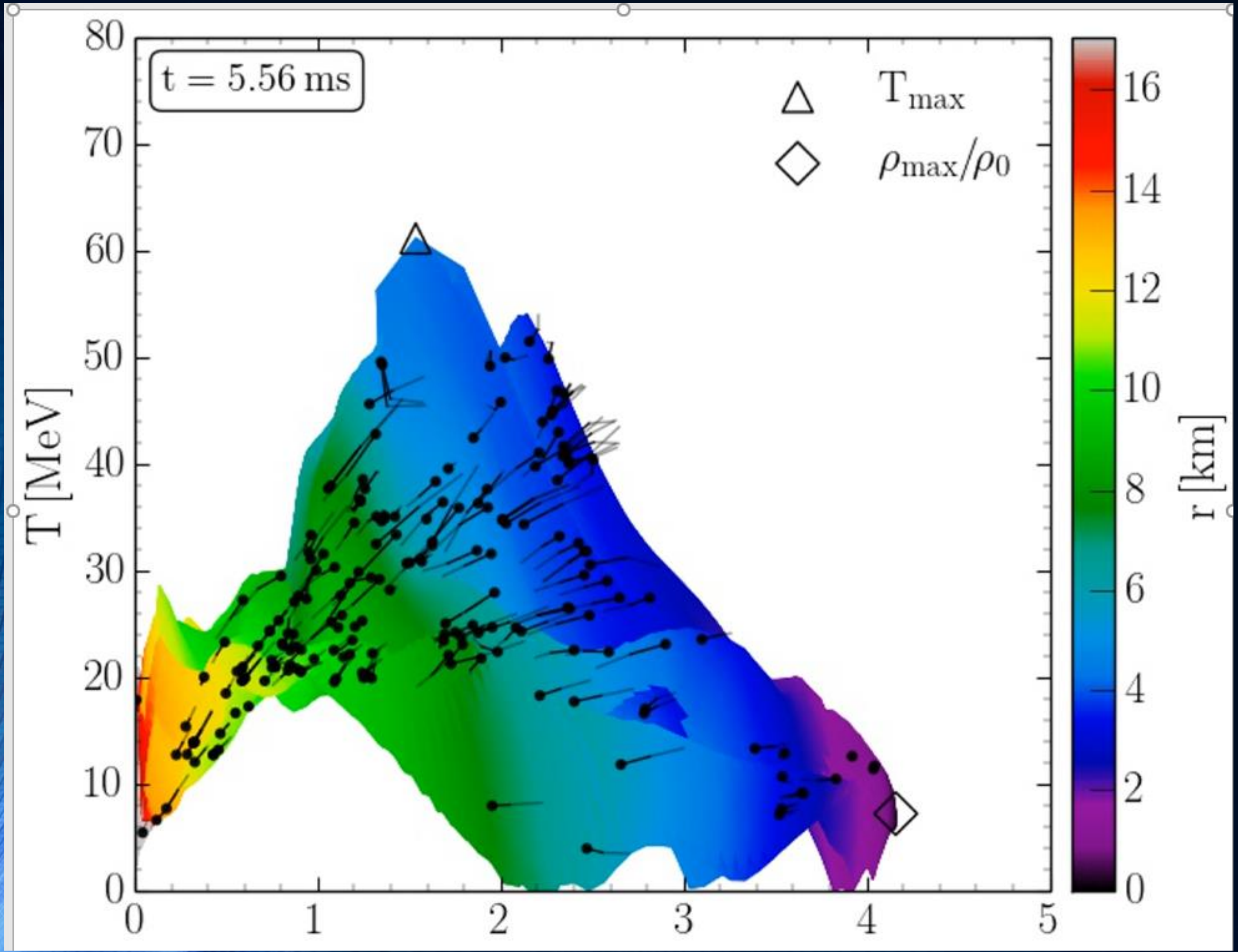


Evolution of hot and dense matter inside the inner area of a hypermassive neutron star simulated within the LS220 EOS with a total mass of $M_{total}=2.7\ M_{\odot}$ in the style of a (T- ρ) QCD phase diagram plot

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.

Binary Neutron Star Mergers in the QCD Phase Diagram



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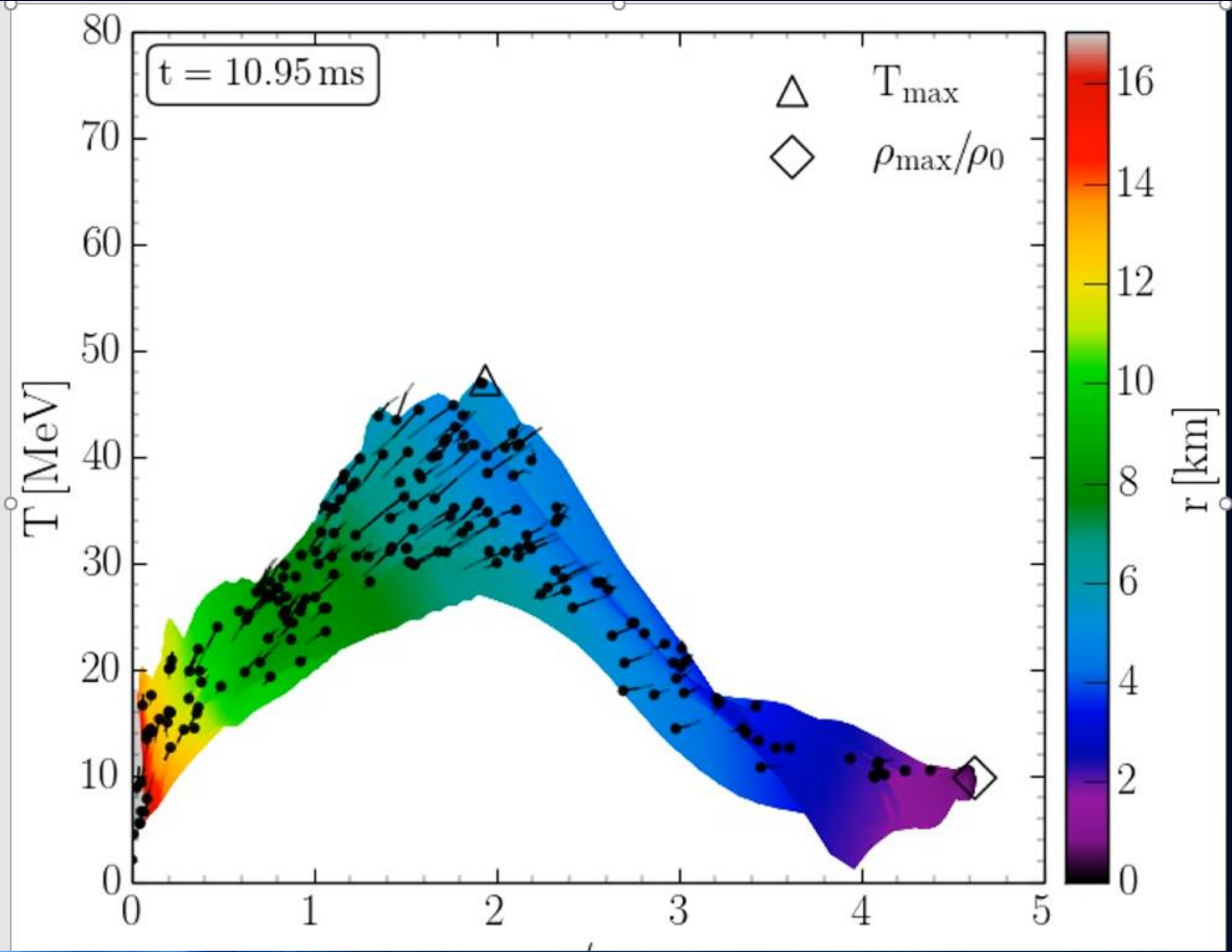

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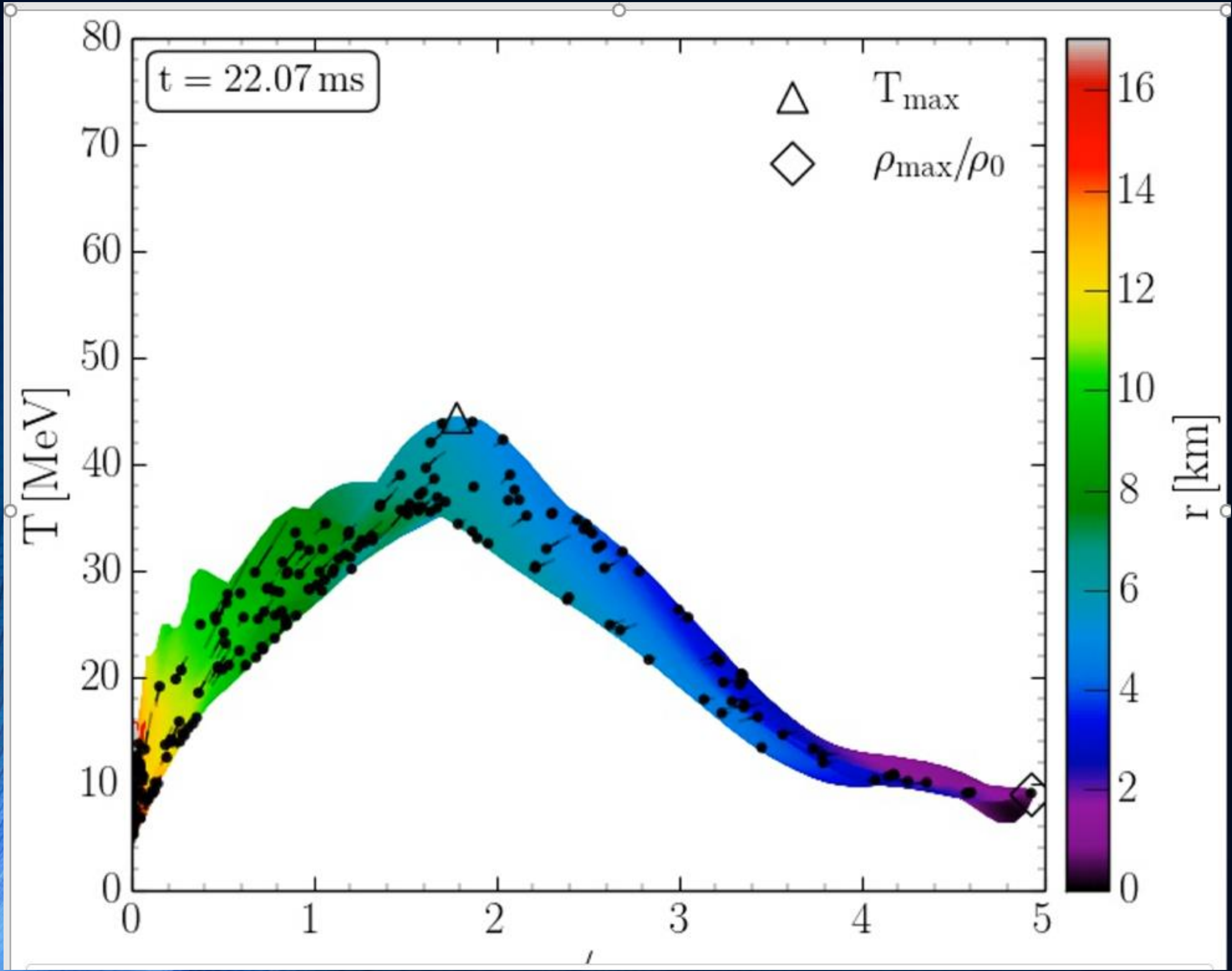

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The Angular Velocity in the (3+1)-Split

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:

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

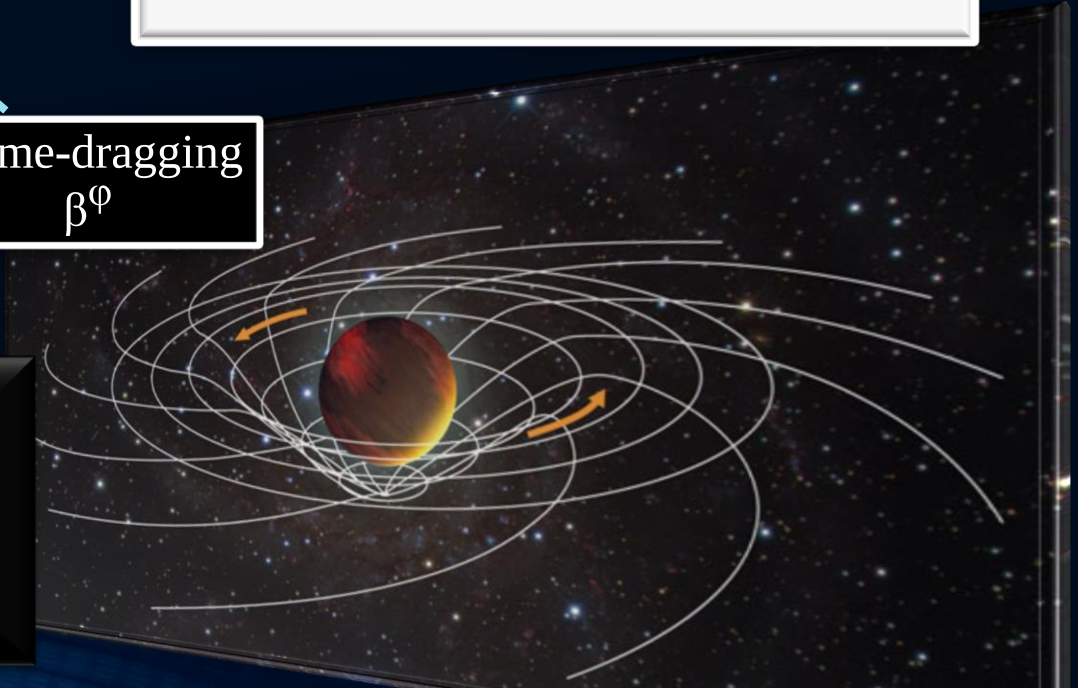
$$\Omega(x, y, z, t) = \frac{u^{\phi}}{u^{t}} = \alpha\, v^{\phi} - \beta^{\phi}$$

Angular velocity Ω

Lapse function α

Φ-component of 3-velocity v^{φ}

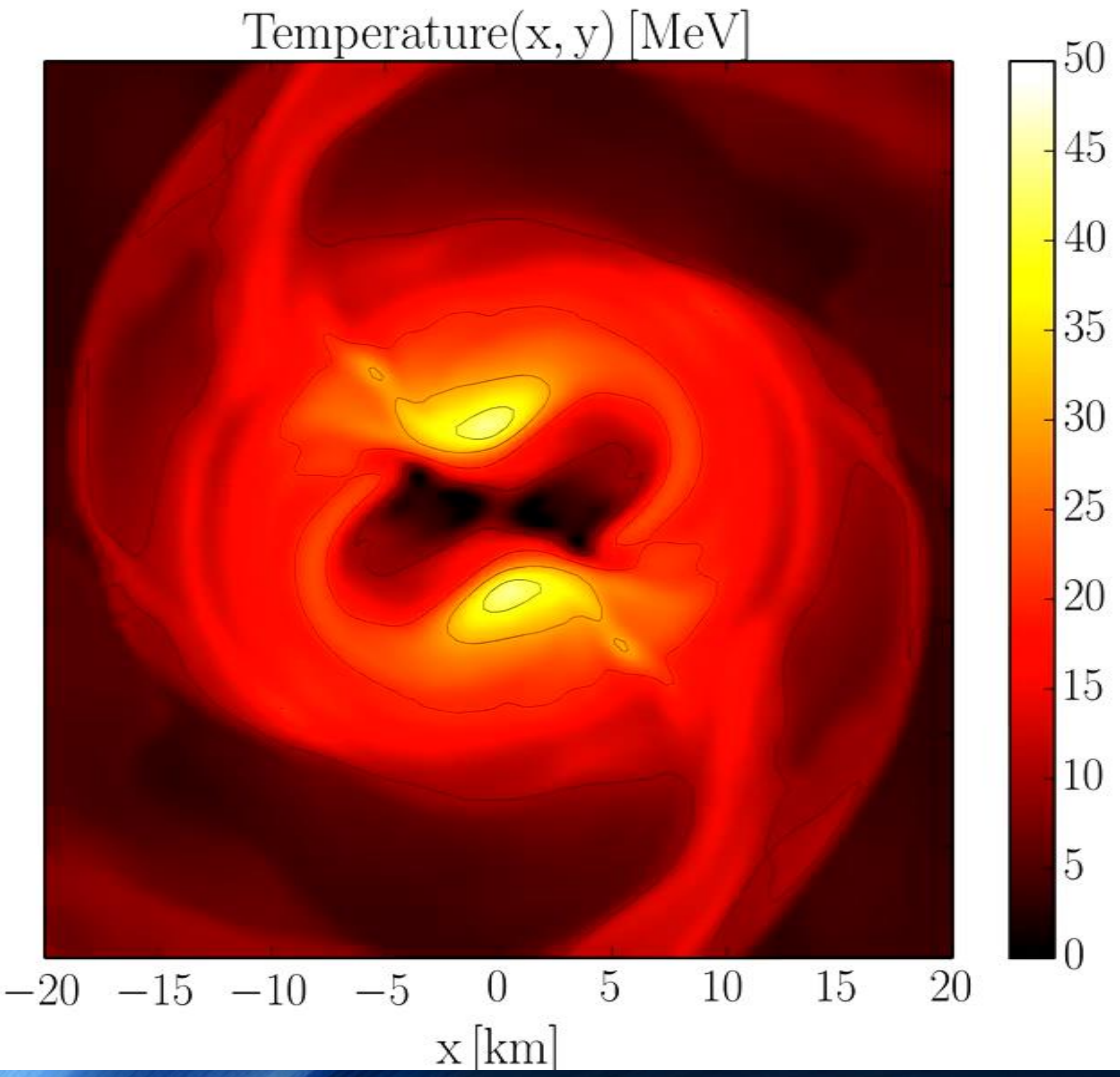
Frame-dragging β^{φ}

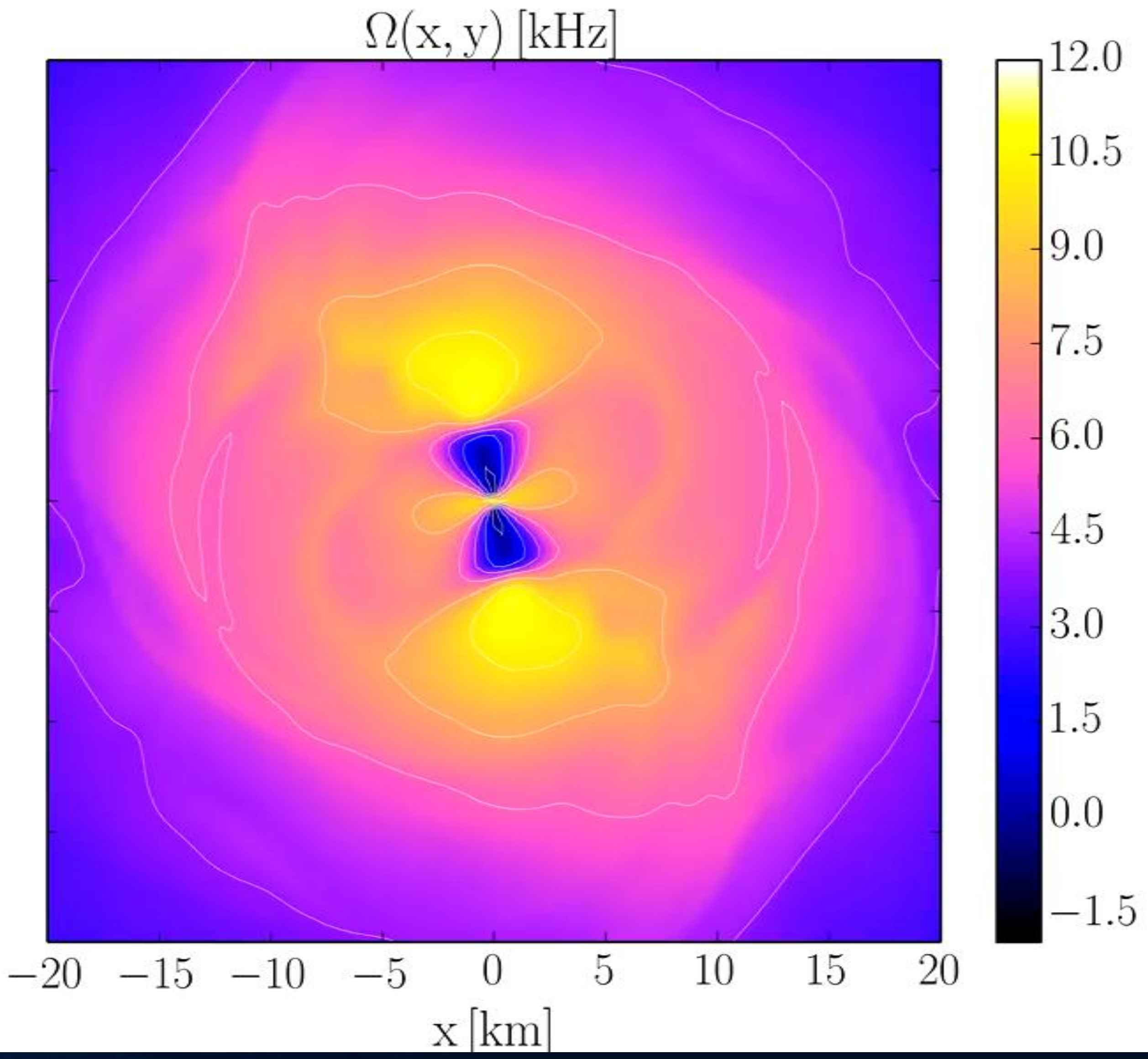


Focus: Inner core of the differentially rotating HMNS

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)

Temperature | Angular Velocity

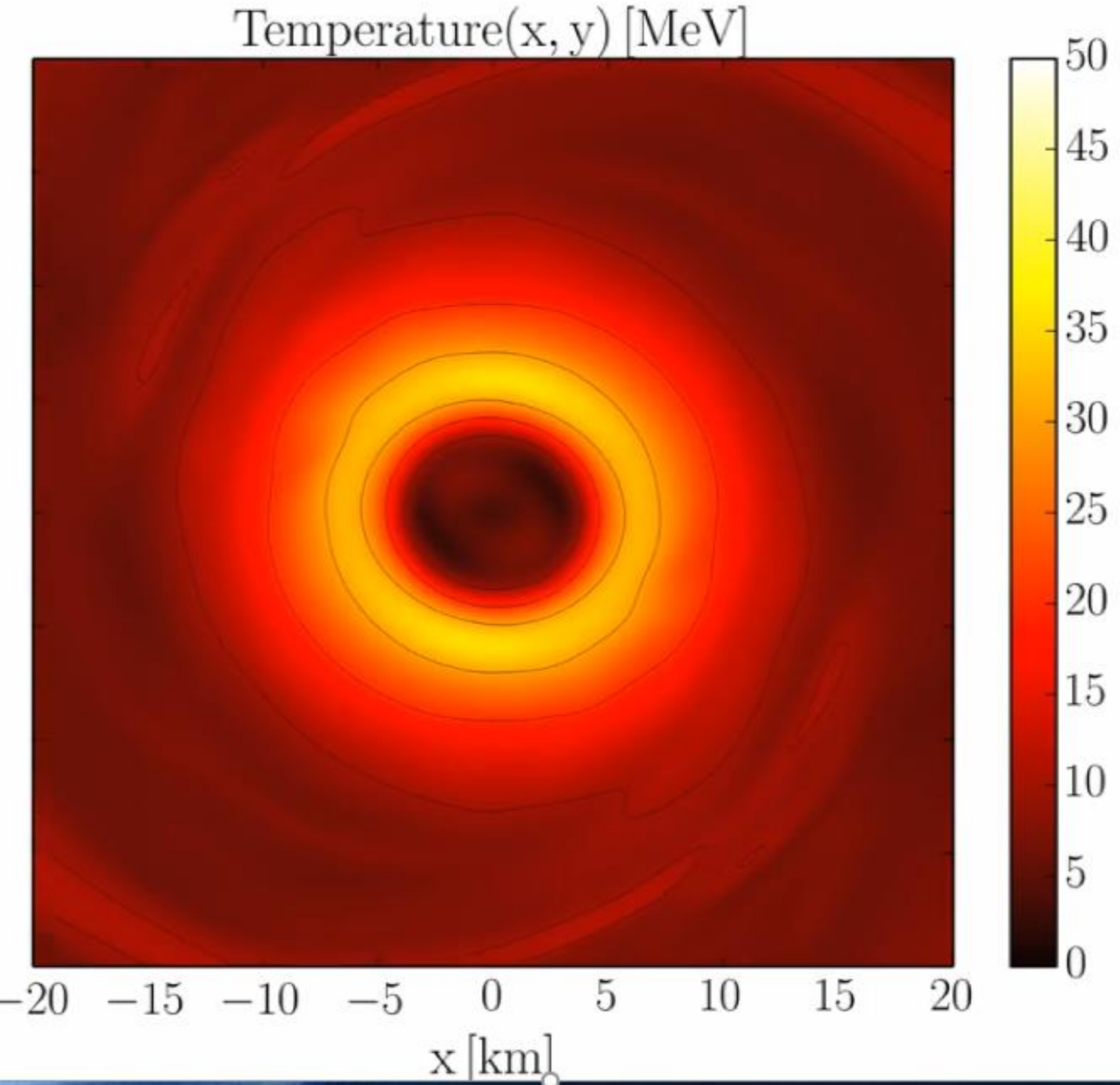


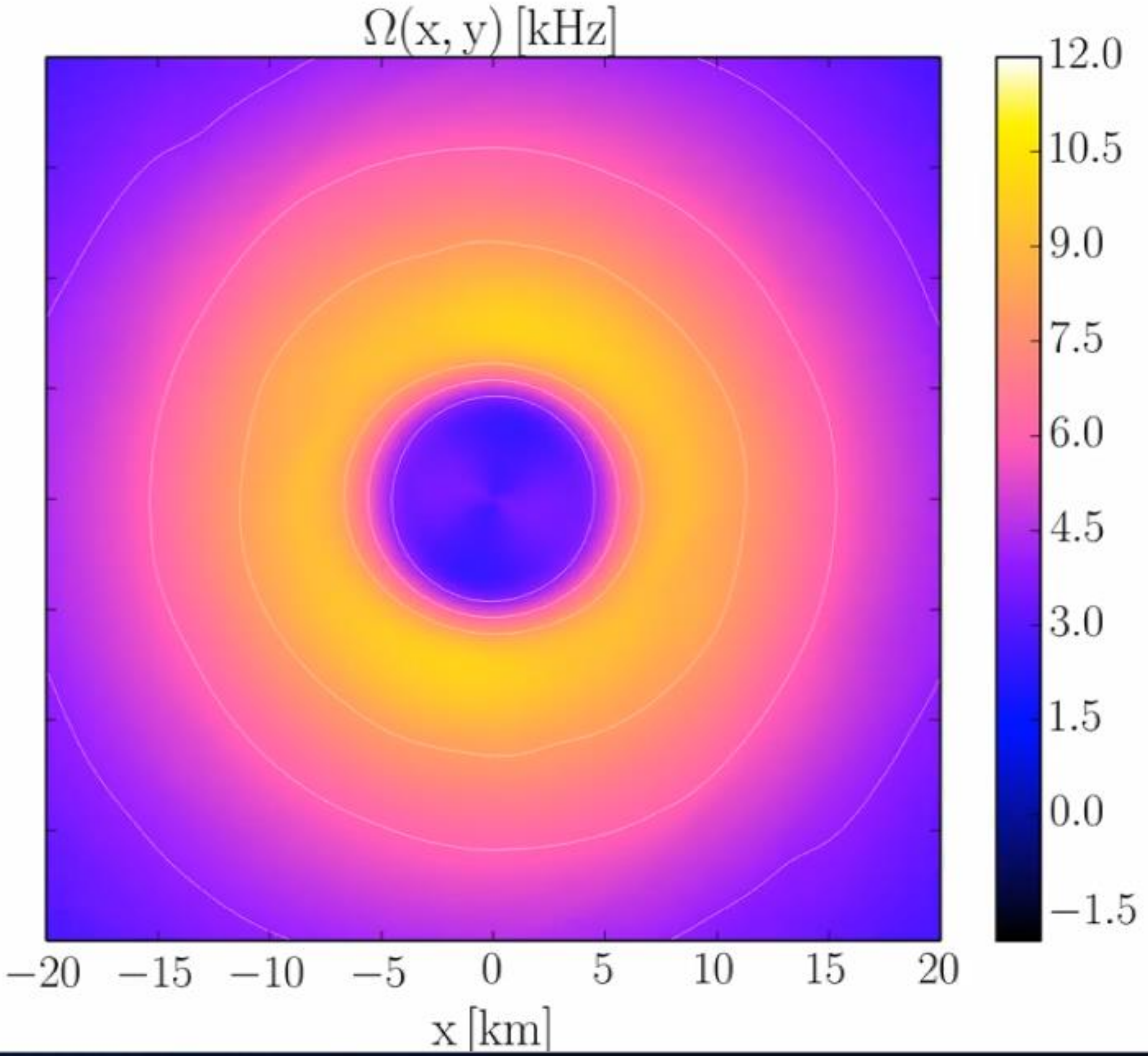


EOS: LS200 , Mass: 1.32 M_{solar} , simulation with Pi-symmetry

Temperature

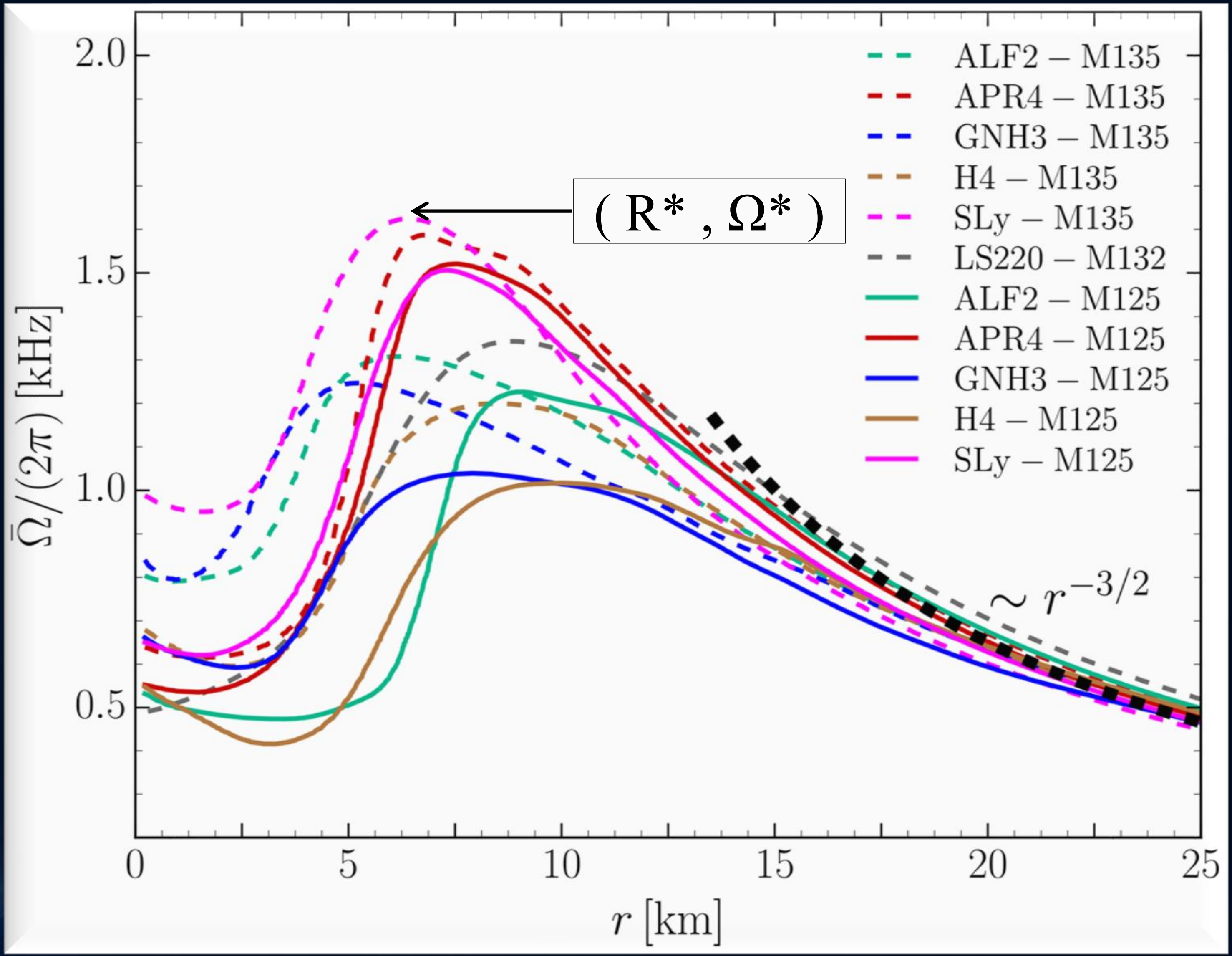
Angular Velocity





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

Time-averaged Rotation Profiles of the HMNSs



<u>Soft EoSs</u>:
Sly
APR4

<u>Stiff EoSs</u>:
GNH3
H4

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

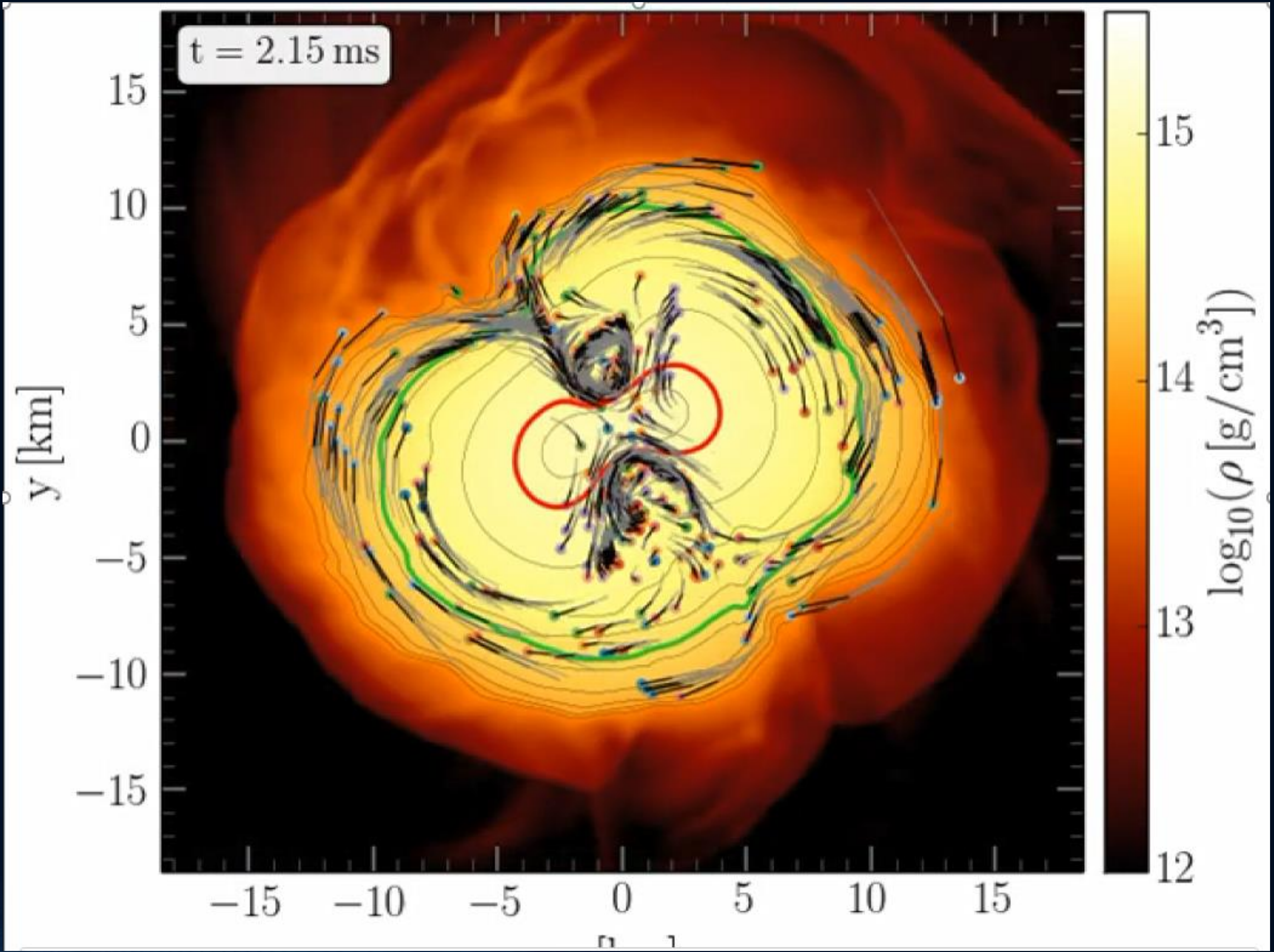
Hanauske, et.al. PRD, 96(4), 043004 (2017)

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

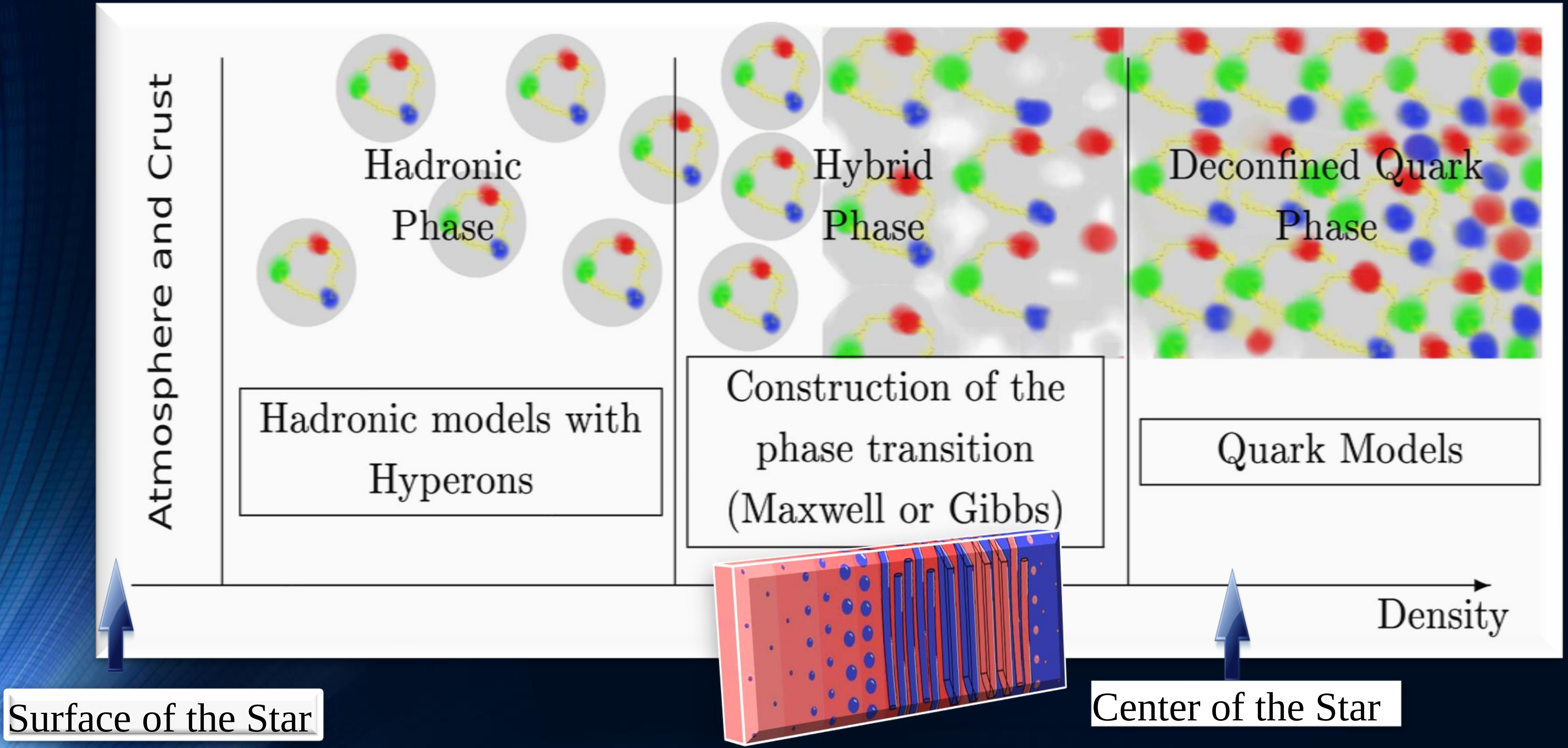
Mark G. Alford, Luke Bovard, Matthias Hanauske, Luciano Rezzolla, and Kai Schwenzer (2018) Viscous Dissipation and Heat Conduction in Binary Neutron-Star Mergers. Phys. Rev. Lett. 120, 041101

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



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)

Can we detect the quark-gluon plasma with gravitational waves?

- Gravitational-wave signatures of the hadron-quark ph
compact star mergers
  - *Signatures within the late inspiral phase (premerger signals)*
    - Constraining twin stars with GW170817; G Montana, L Tolós, M Han
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Signatures of quark-hadron phase transitions in general-relativistic neu
Papenfort, V Dexheimer, M Hanauske, S Schramm, H Stöcker, L. Rezzol
(2019)
    - **Delayed phase transition scenario**
Postmerger Gravitational-Wave Signatures of Phase Transitions in Bina
Rezzolla; Physical Review Letters 124 (17), 171103 (2020)
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Identifying a first-order phase transition in neutron-star mergers through gr
Bastian, DB Blaschke, K Chatziioannou, JA Clark, JA Clark, T Fischer, M Oerte … 061102
(2019)

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Phase-transition triggered collapse scenario

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

ER Most, LJ Papenfort, V Dexheimer, M Hanauske, S Schramm, H Stöcker and L. Rezzolla

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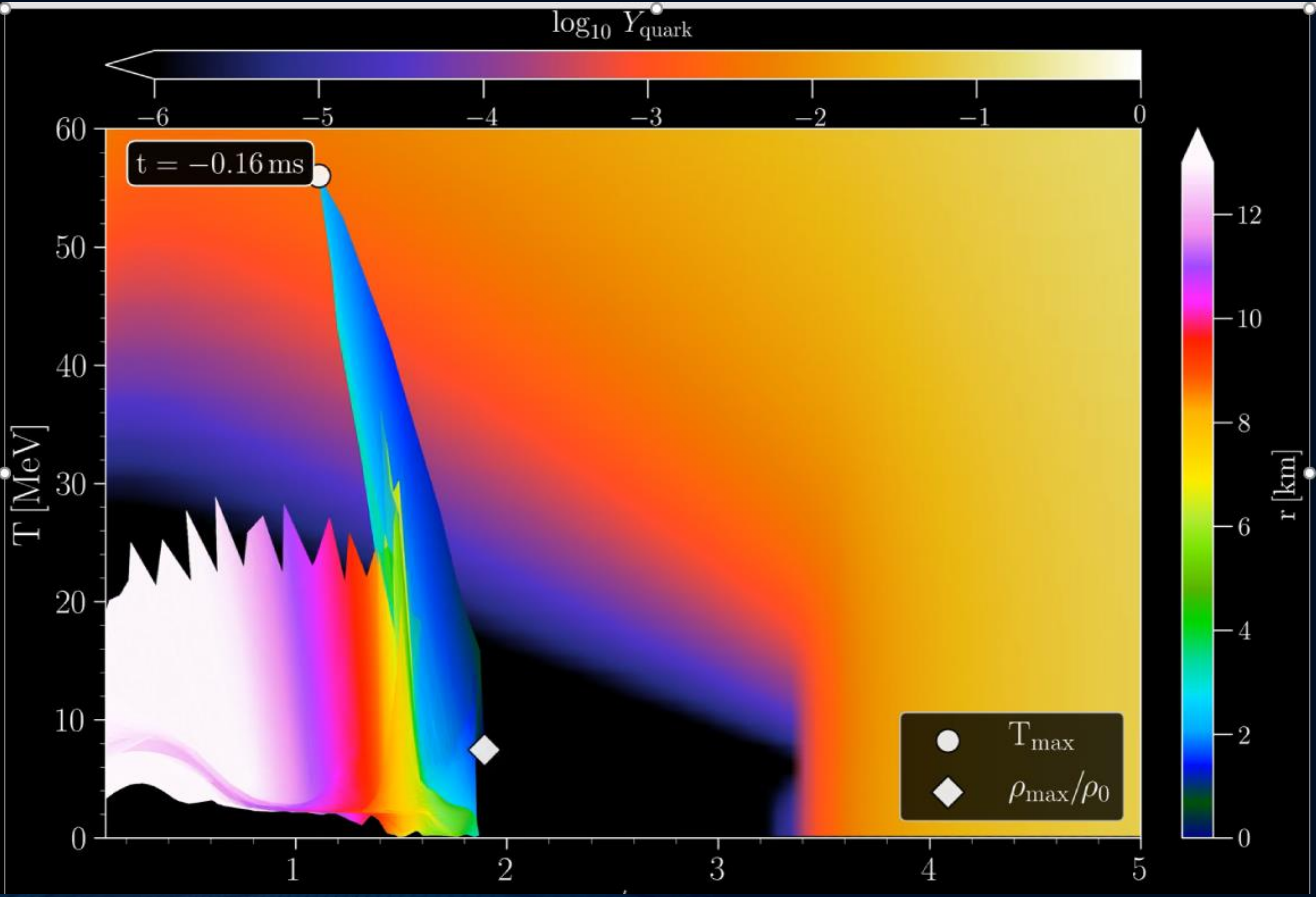
Density-Temperature-Composition dependent EOS within the CMFQ model.



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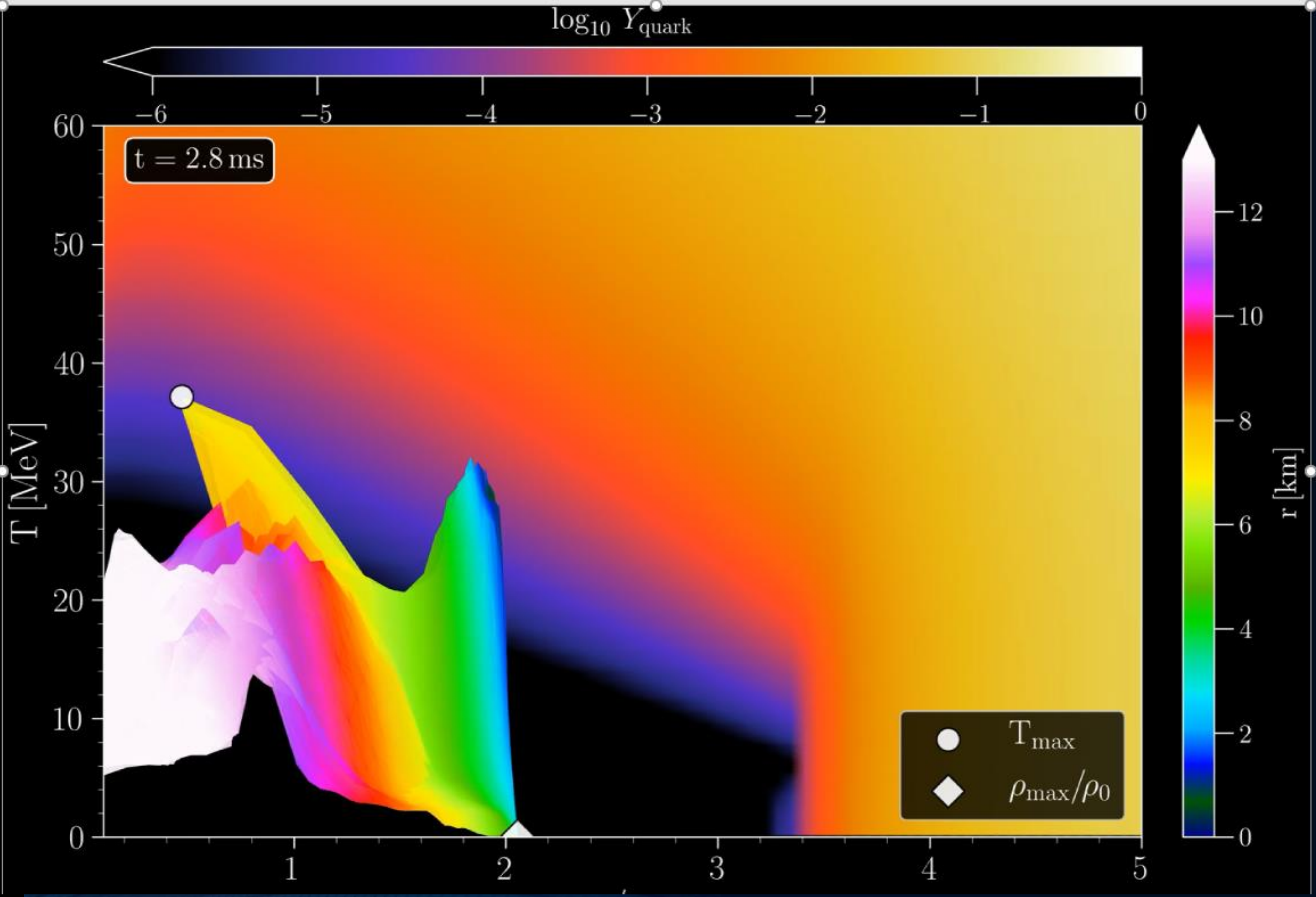

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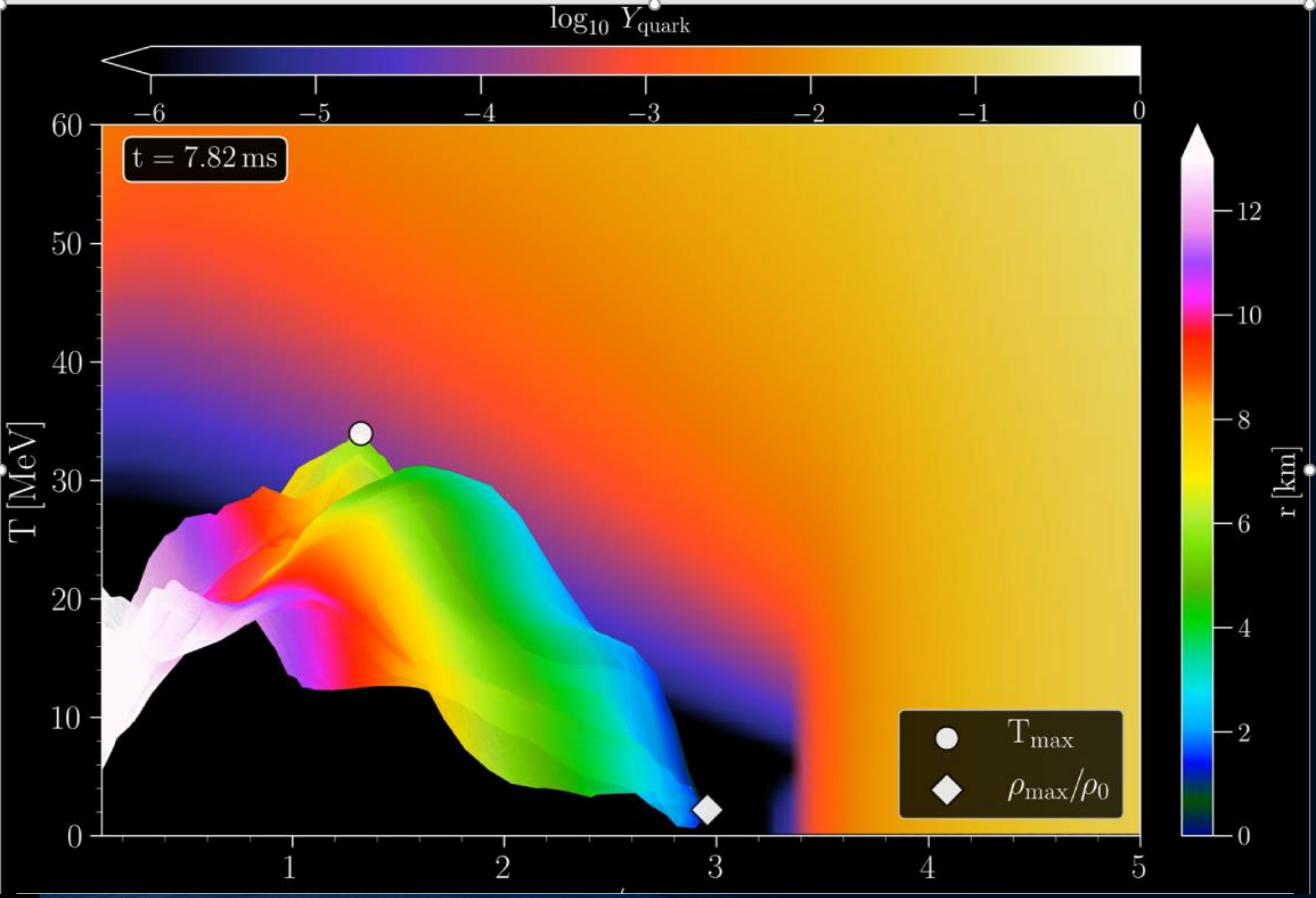

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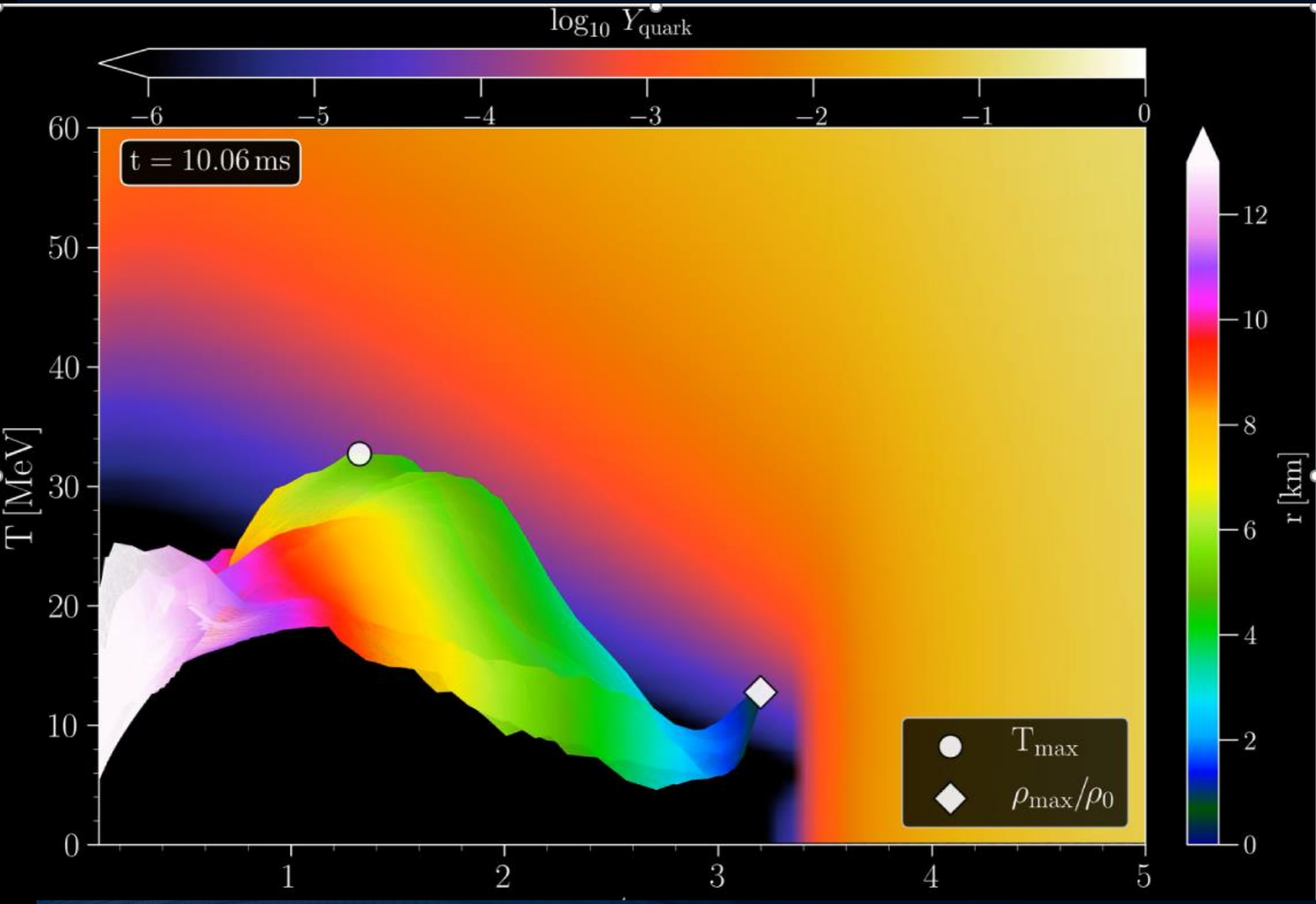

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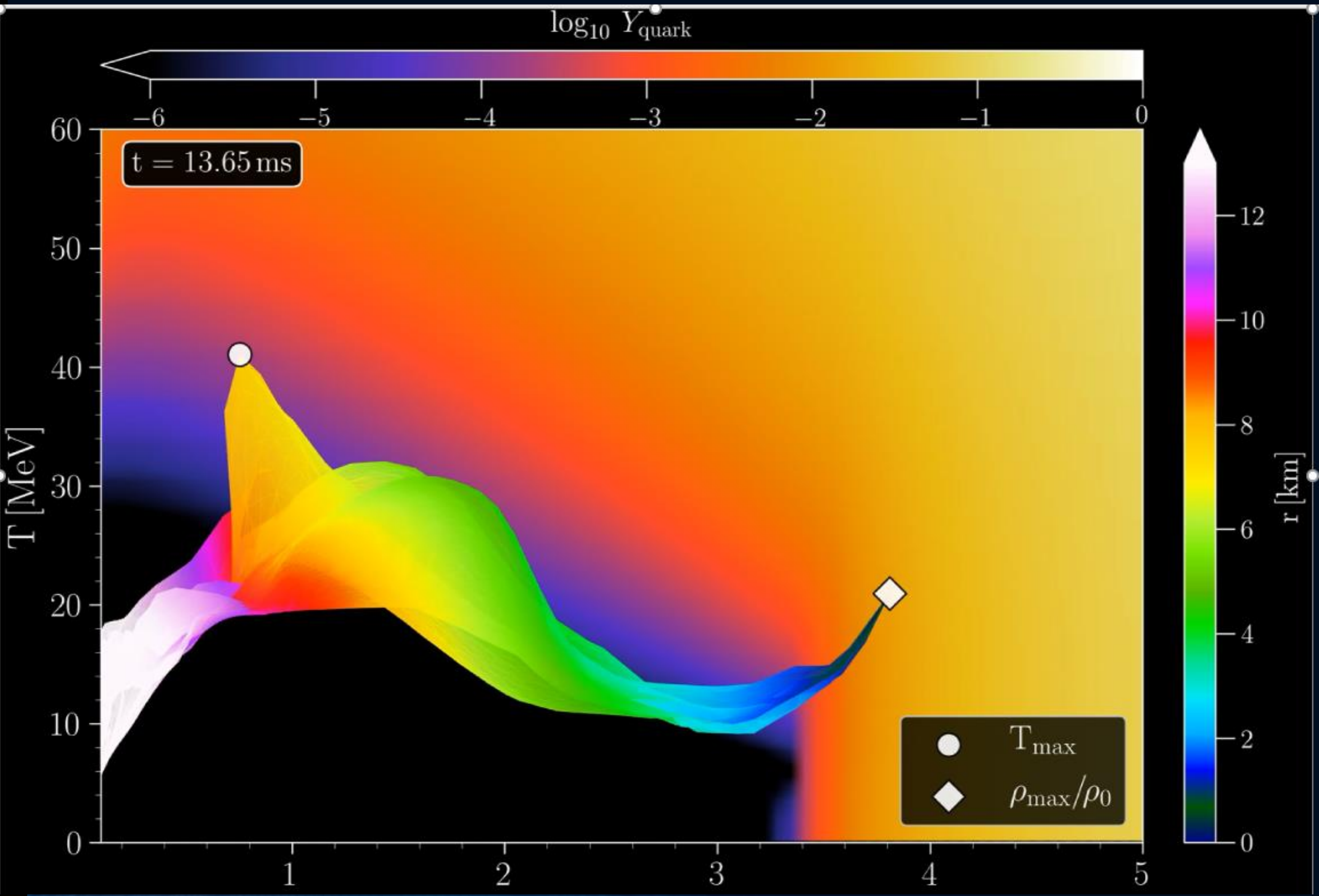
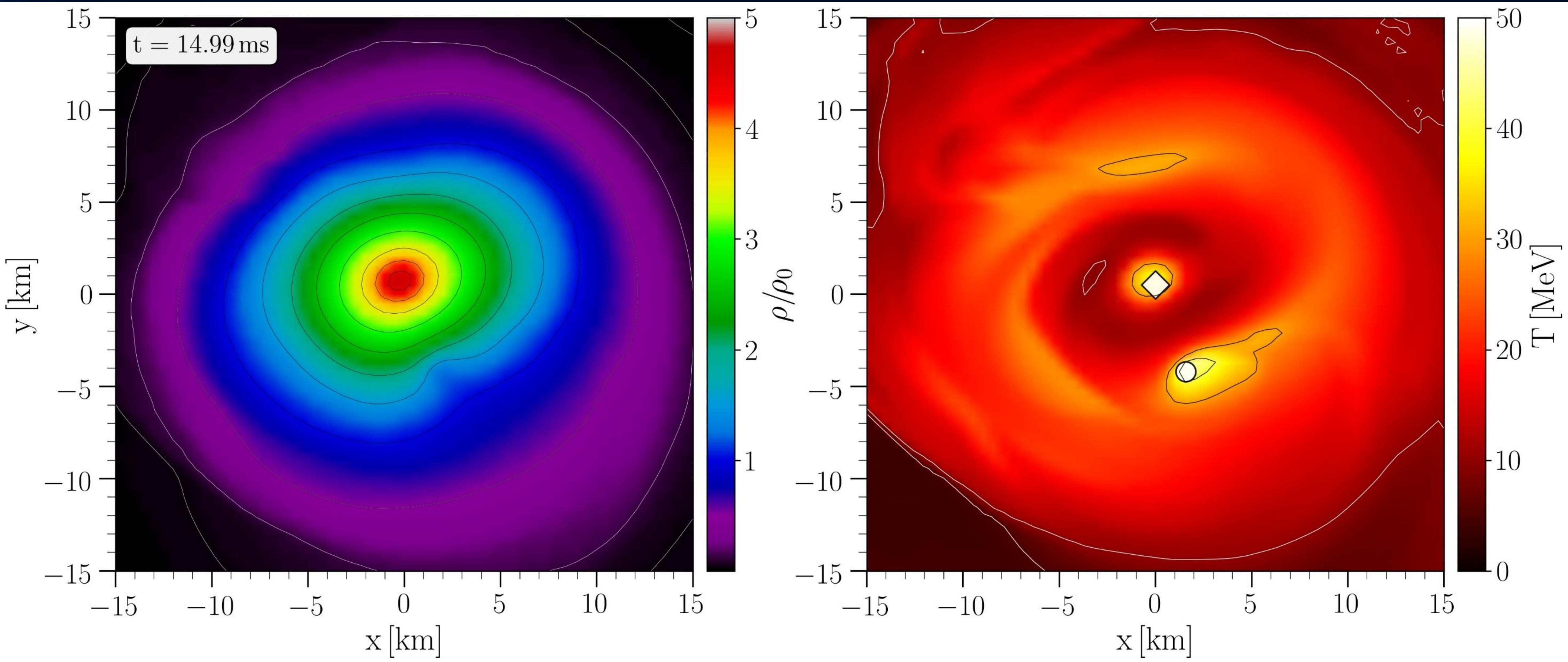


Density-Temperature-Composition dependent EOS within the CMFQ model.

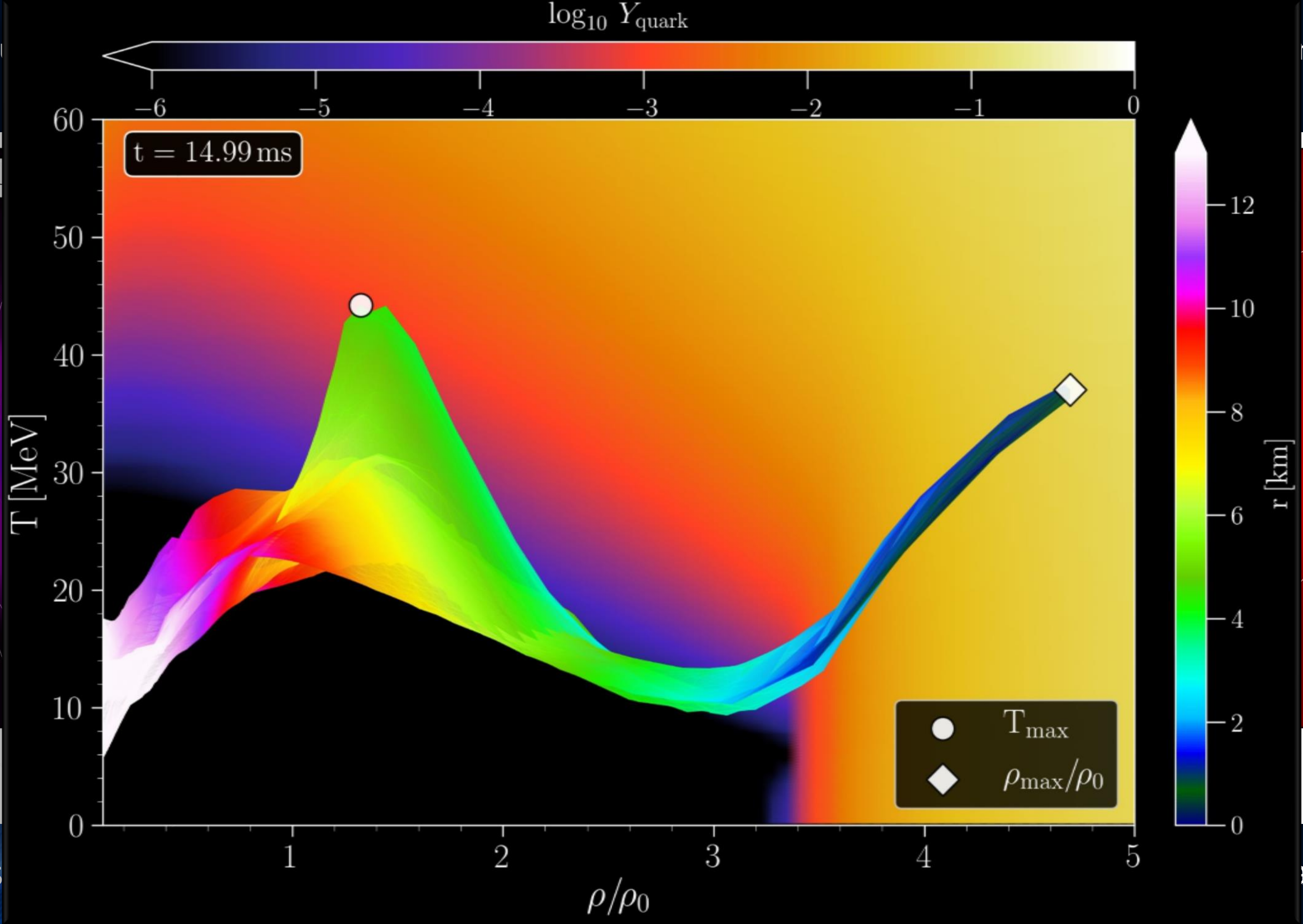
The last simulation snapshots before the apparent horizon is formed inside the HyperMassive Hybrid Star (HMHS)



Rest mass density on the equatorial plane

Temperature on the equatorial plane

The last simu… r (HMHS)



Rest mas… ane

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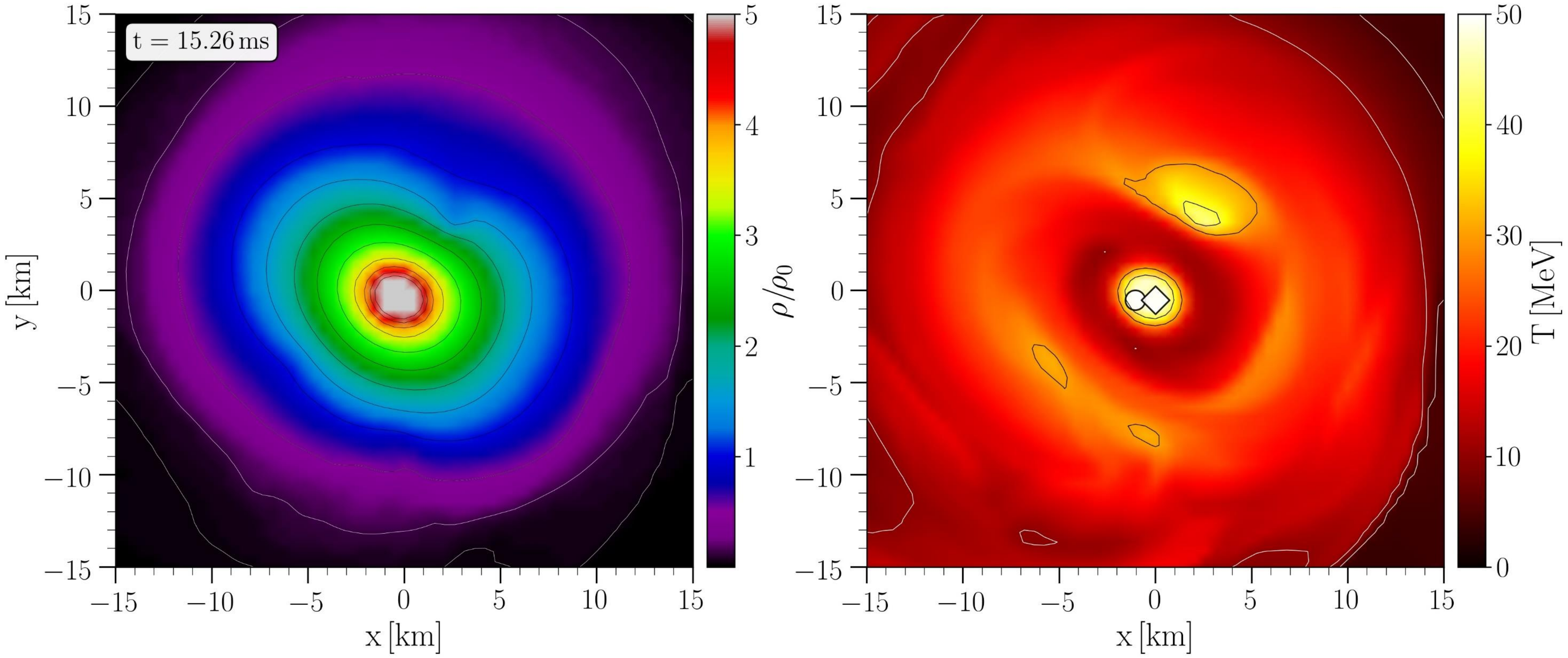

Rest mass density on the equatorial plane

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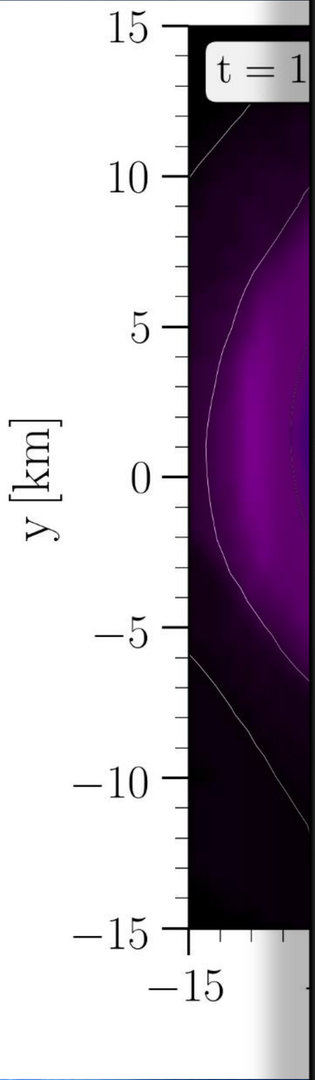
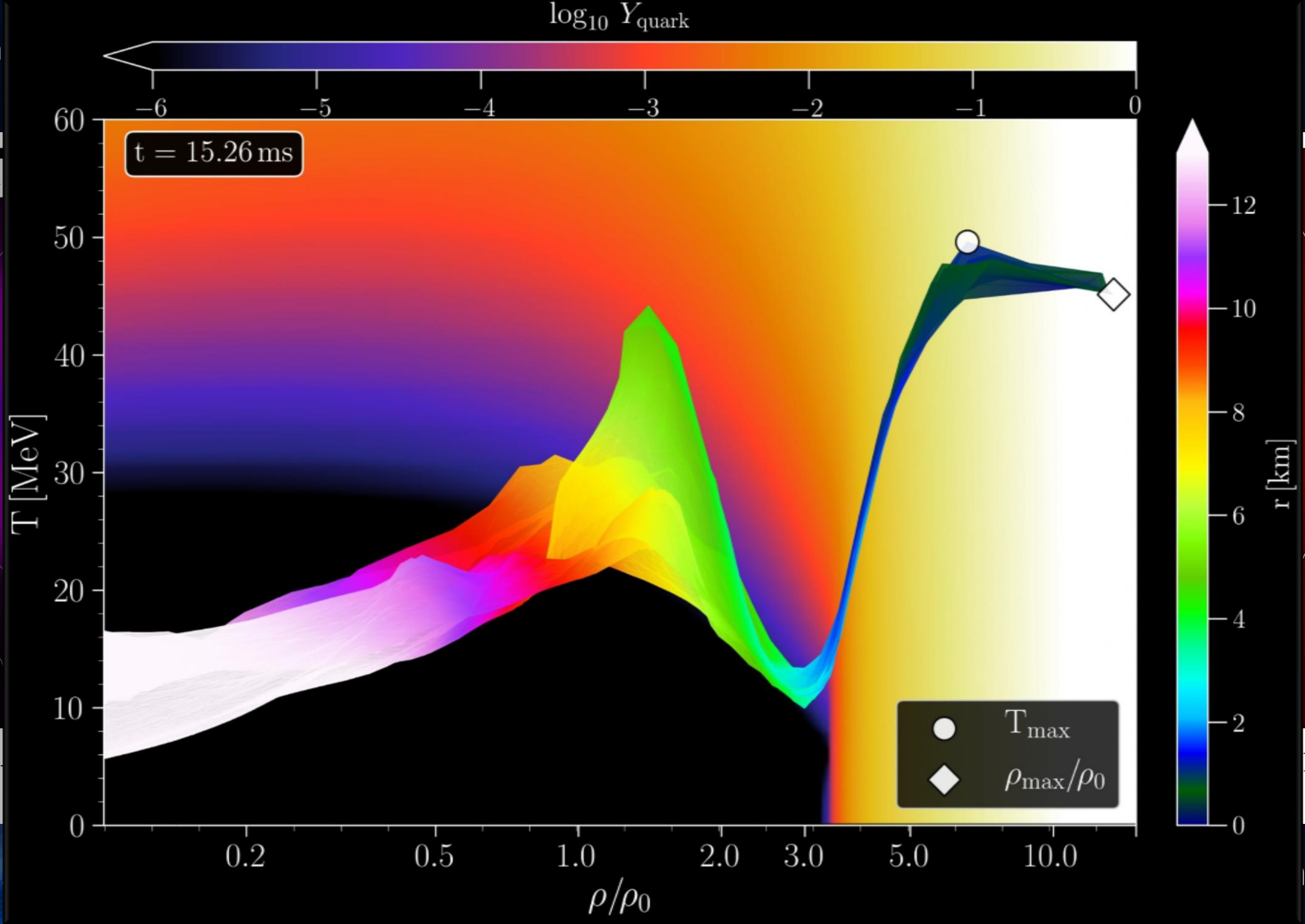
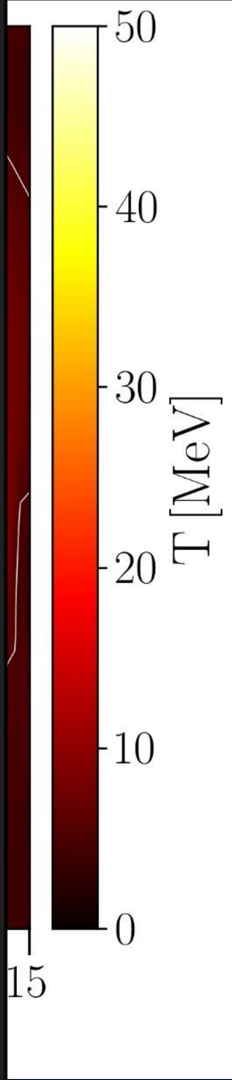
The last sim … (HMHS)



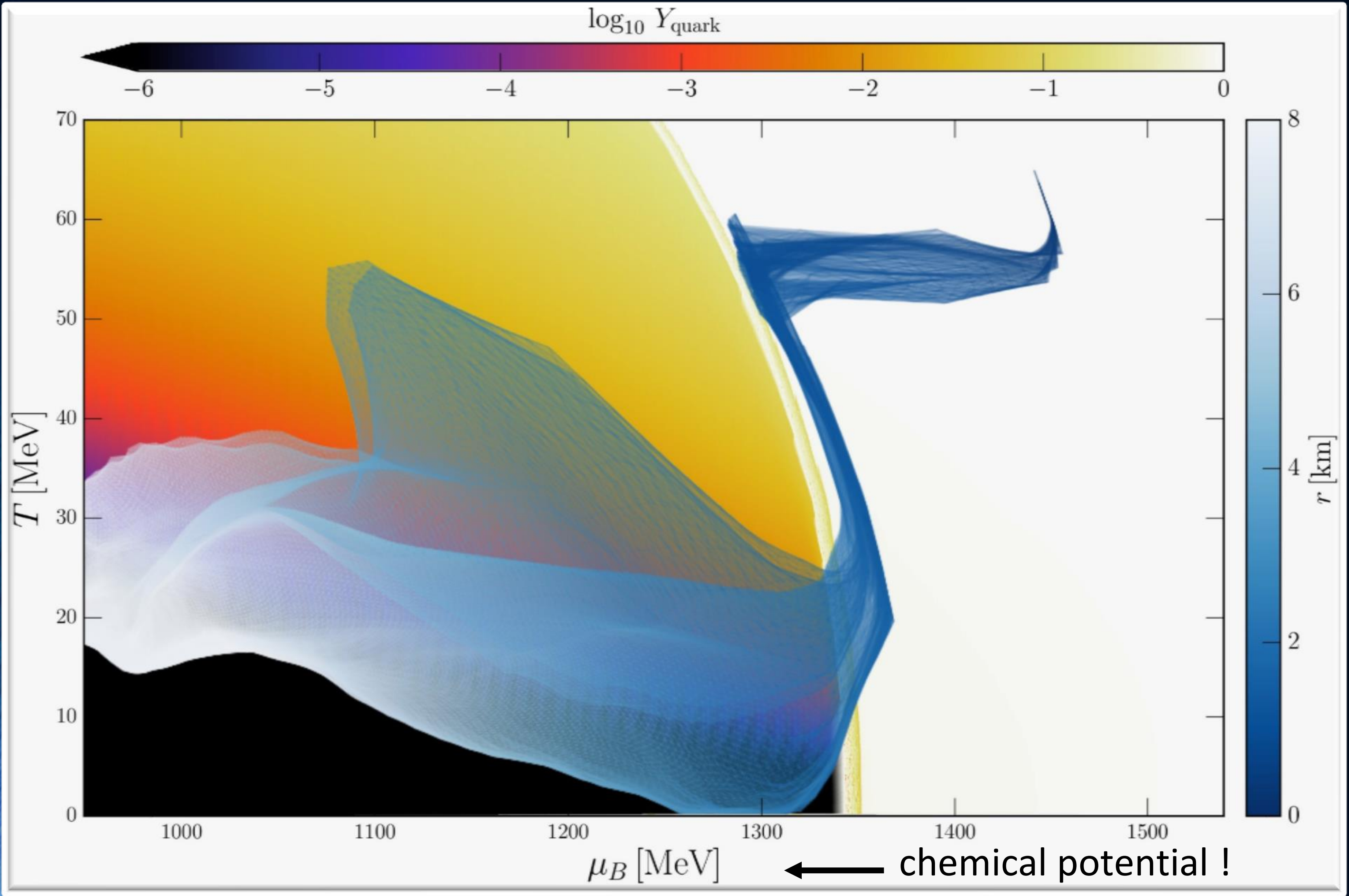




Rest mas … ne

The Pelican Plot

The Strange Bird 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. (high mass simulation M = 2.9 M☉)

E.Most, J. Papenfort, V.Dexheimer, M.Hanauske, H.Stöcker and L.Rezzolla
„On the deconfinement phase transition in neutron-star mergers„; The European Physical Journal A 56 (2), 1-11 (2020)

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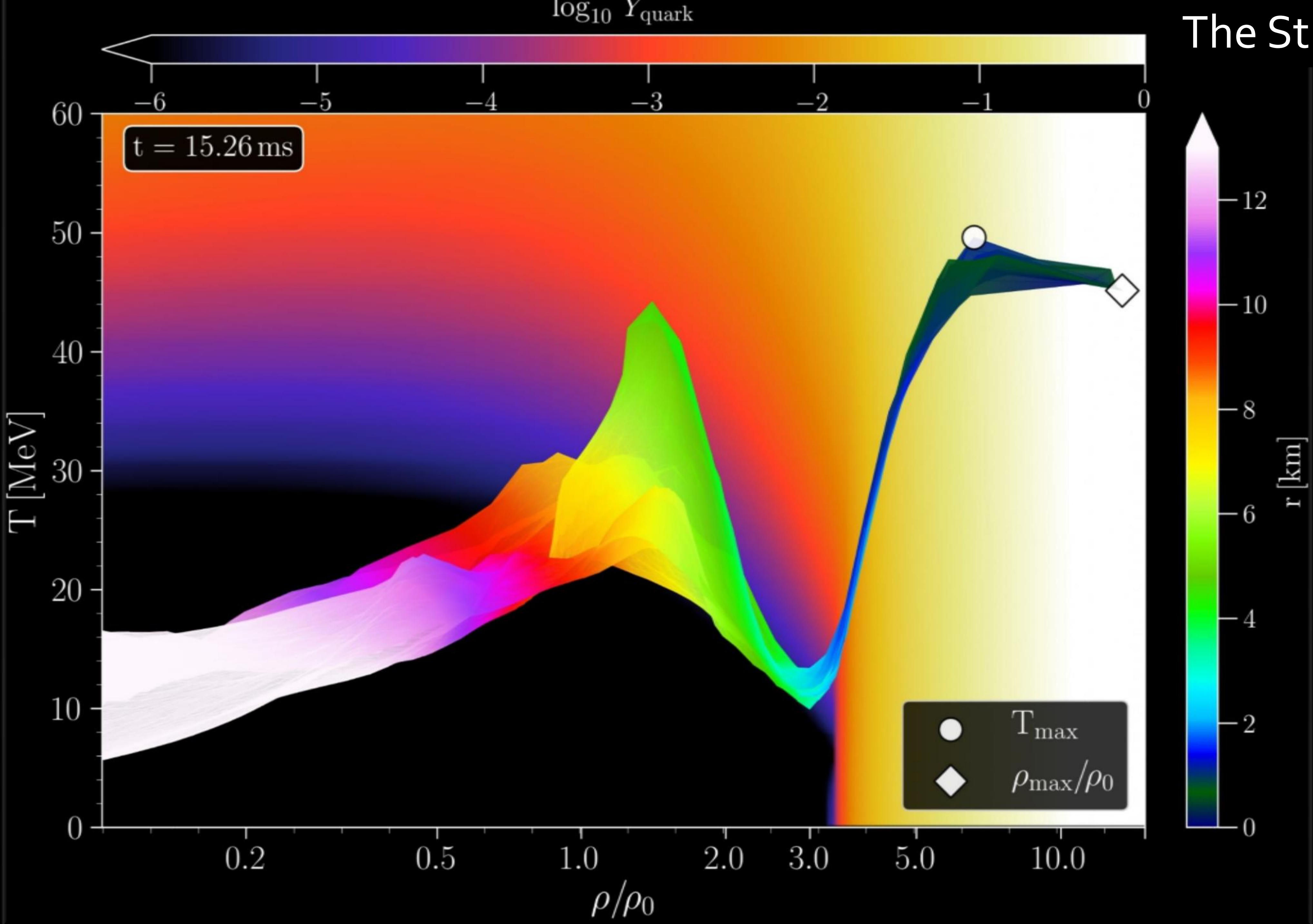


While the quarks in the pelican's head have already rescued themselves from their confinement cage, his body still largely consists of hadronic particles. It is precisely at this point in time that the apparent horizon is formed around the dense and hot head of the strange bird and the free strange quark matter is macroscopically confined by the formation of the black hole.

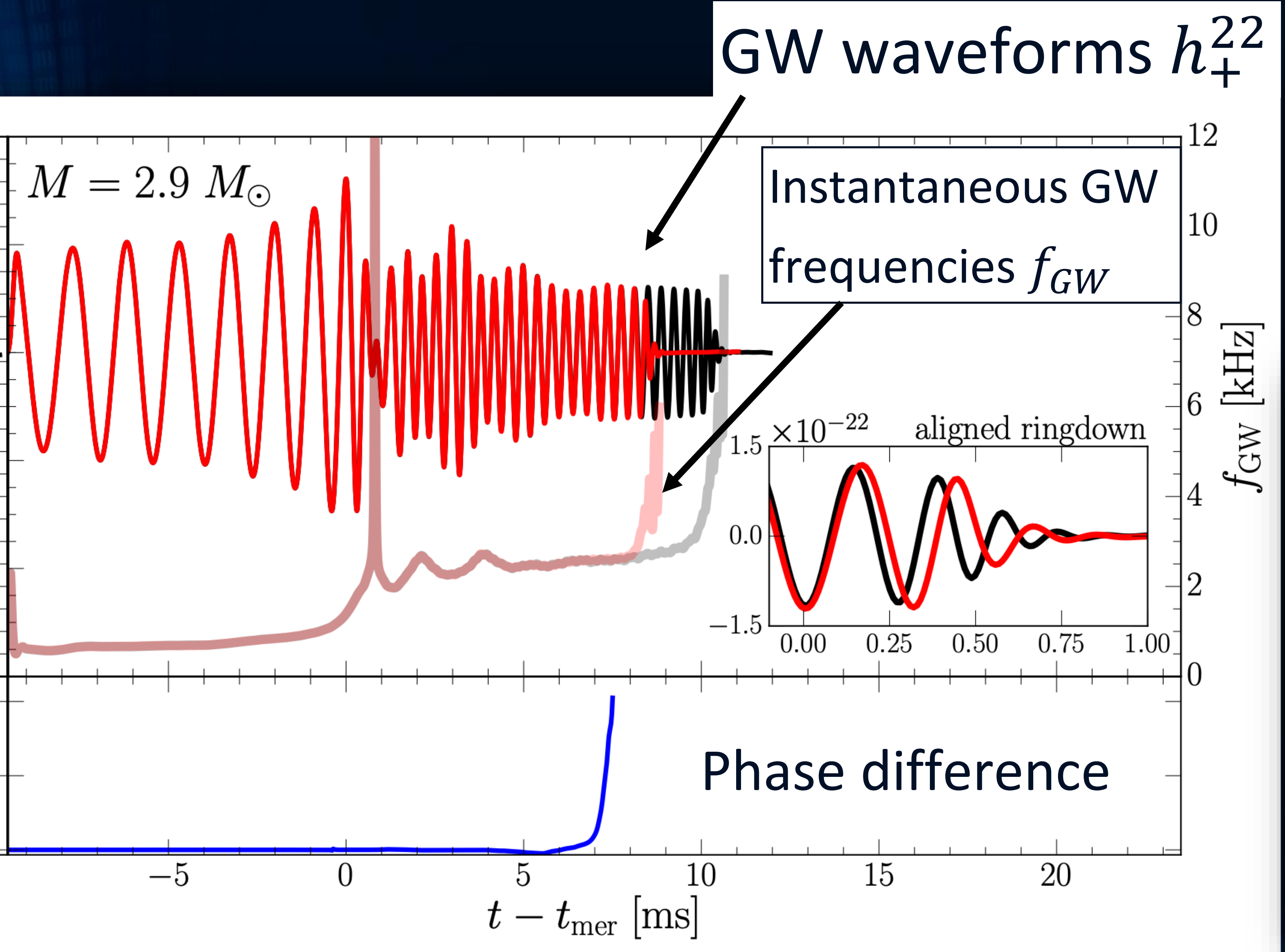
Signatures within the post-merger phase

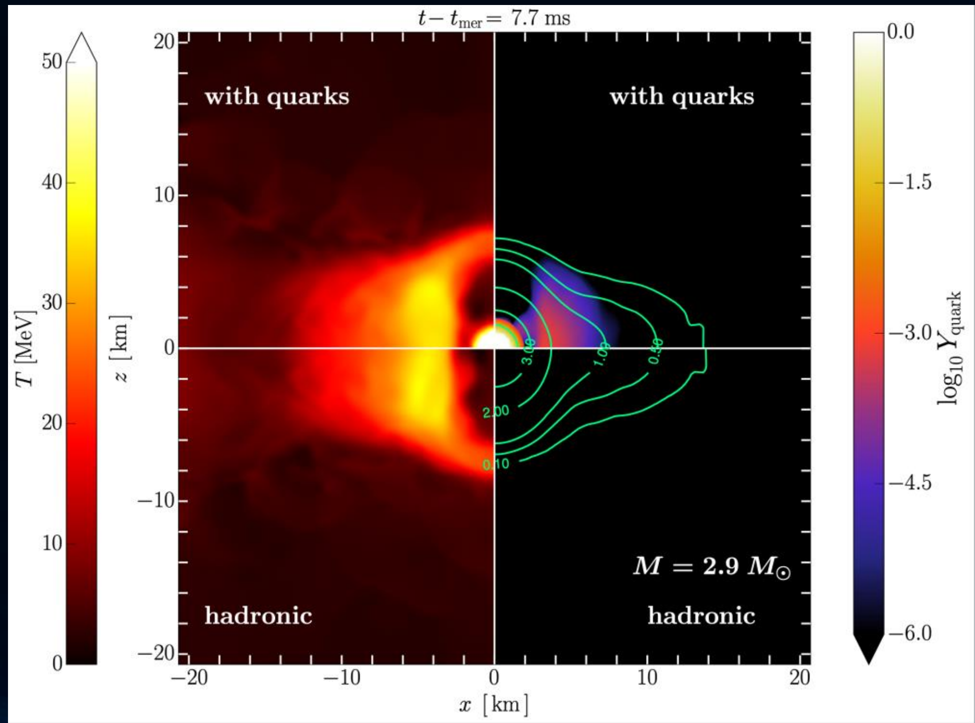
Phase-transition triggered collapse scenario

ER Most et.al., PRL 122 (6), 061101 (2019)

EOS based on Chiral Mean Field (CMF) model, based on a nonlinear SU(3) sigma model with (red) and without (black) phase transition.

Phase transition leads to a very hot and dense quark core that, when it collapses to a black hole, produces a ringdown signal different from the hadronic one.





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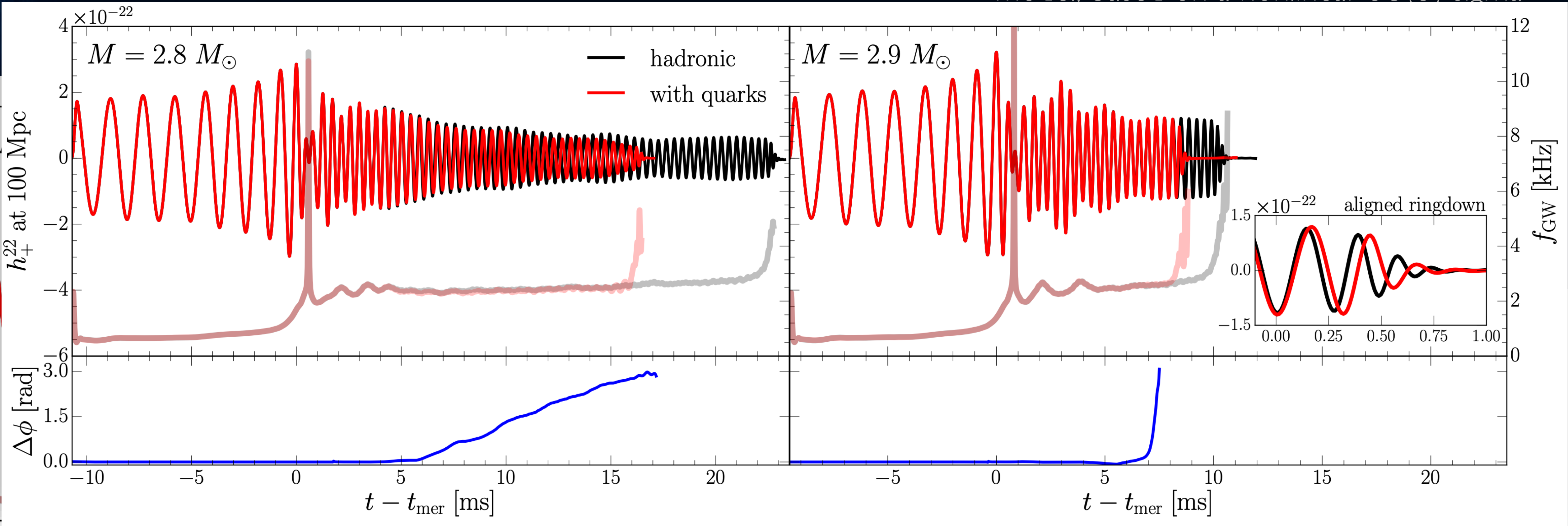
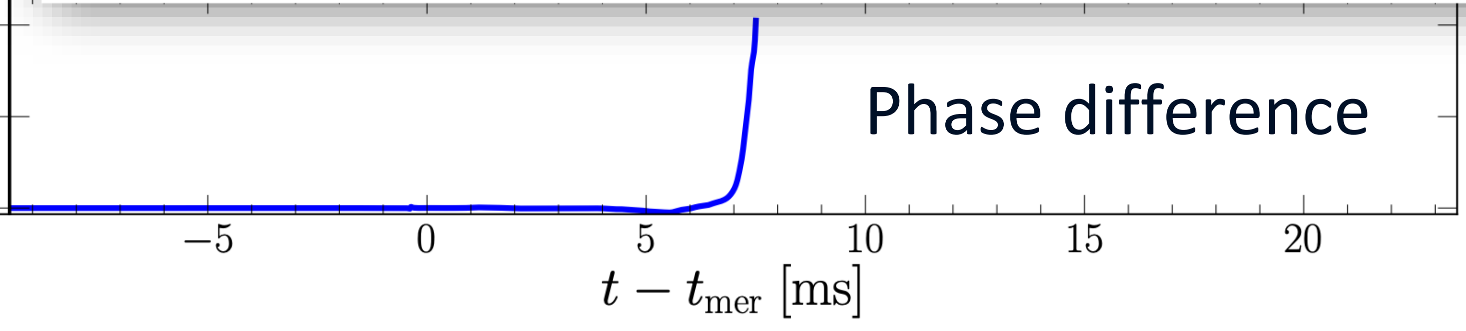
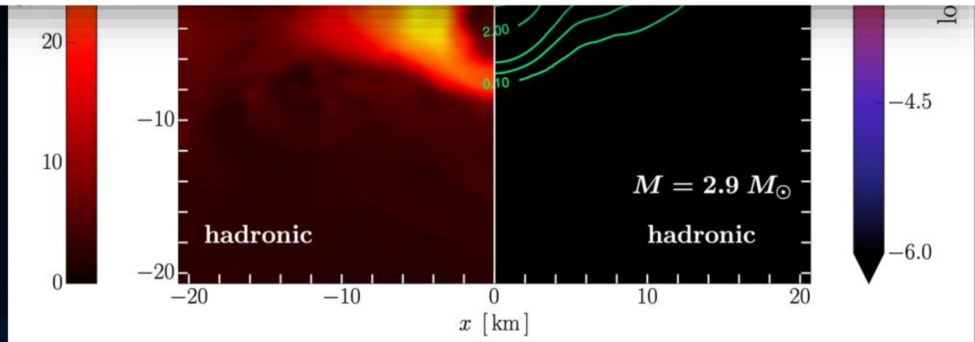




Phase difference



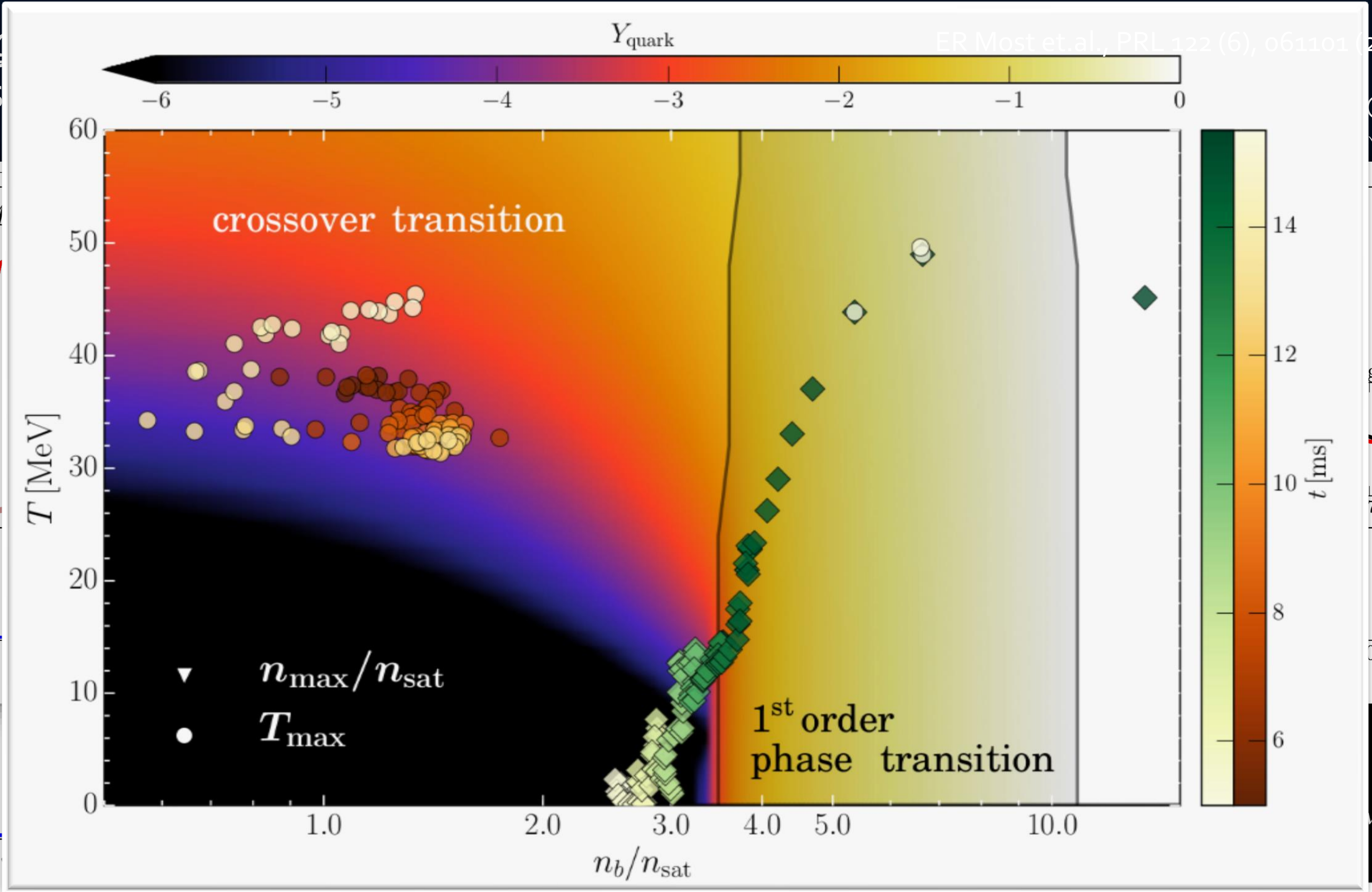
Sig…

Phas…

ER Most et al., PRL 122 (6), 061101 (2019)

…CMF)

…) sigma



Can we detect the quark-gluon plasma with gravitational waves?

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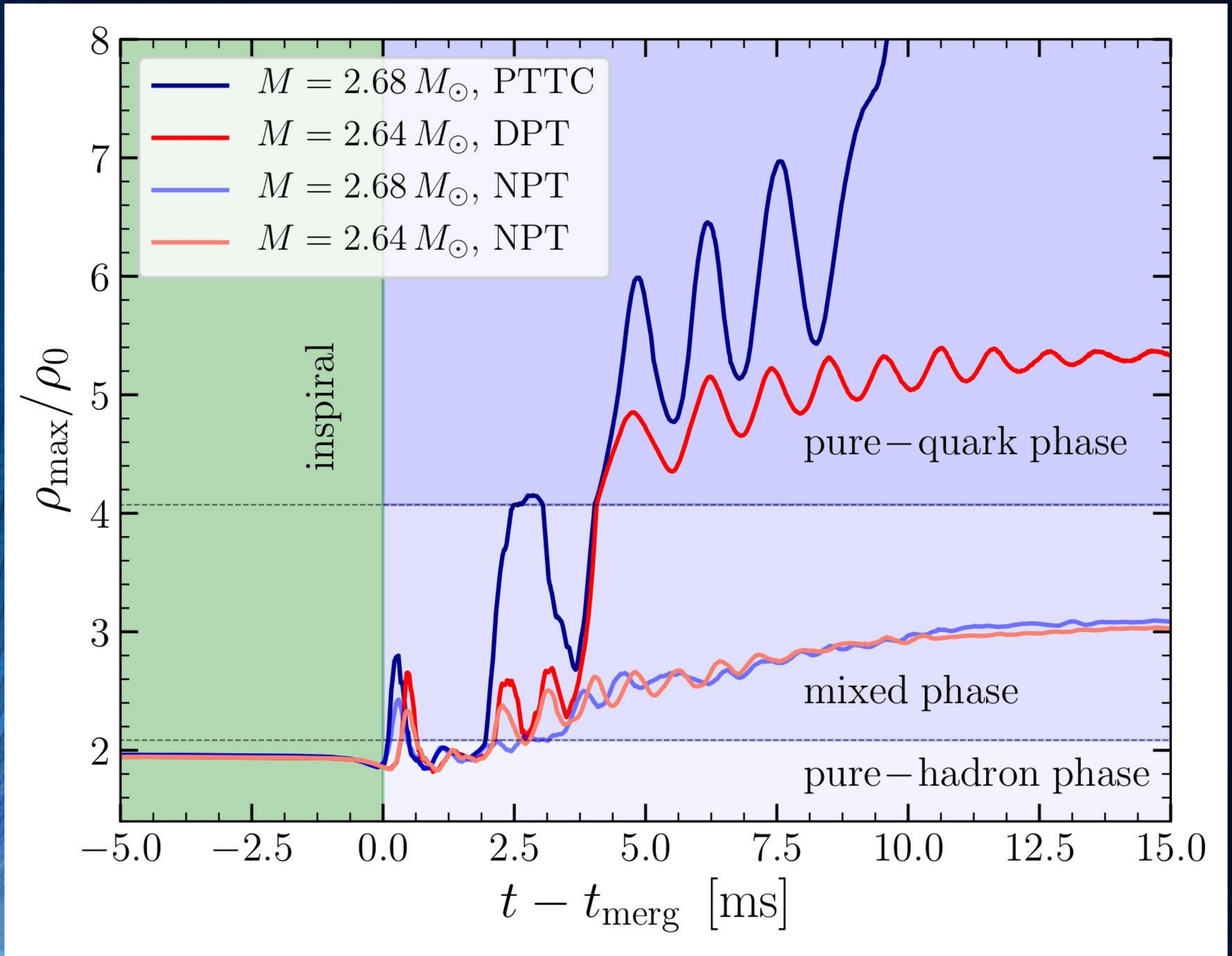
Postmerger Gravitational-Wave Signatures of Phase Transitions in Binary Mergers; LR Weih, M Hanauske, L Rezzolla; Physical Review Letters 124 (17), 171103 (2020)

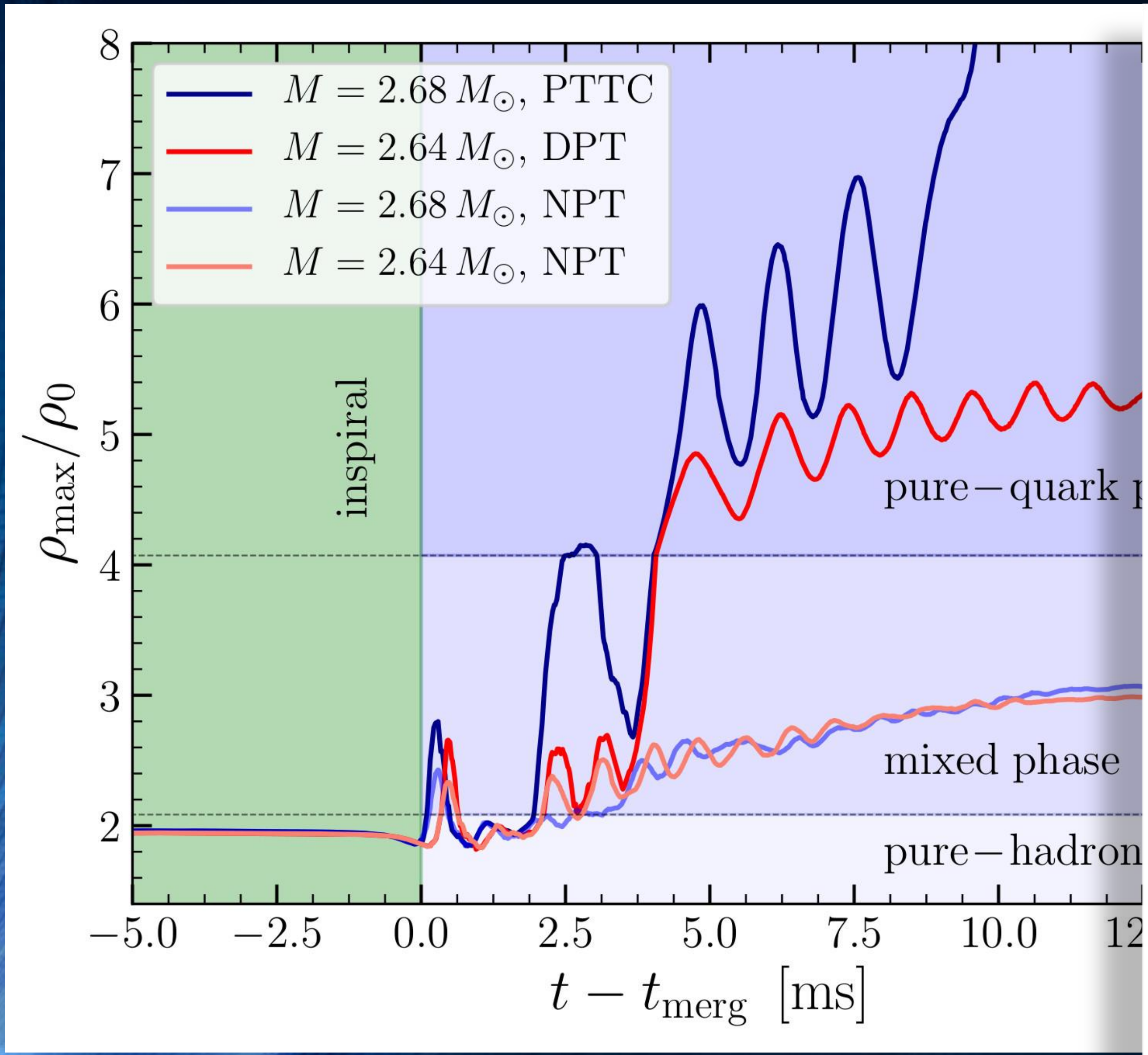


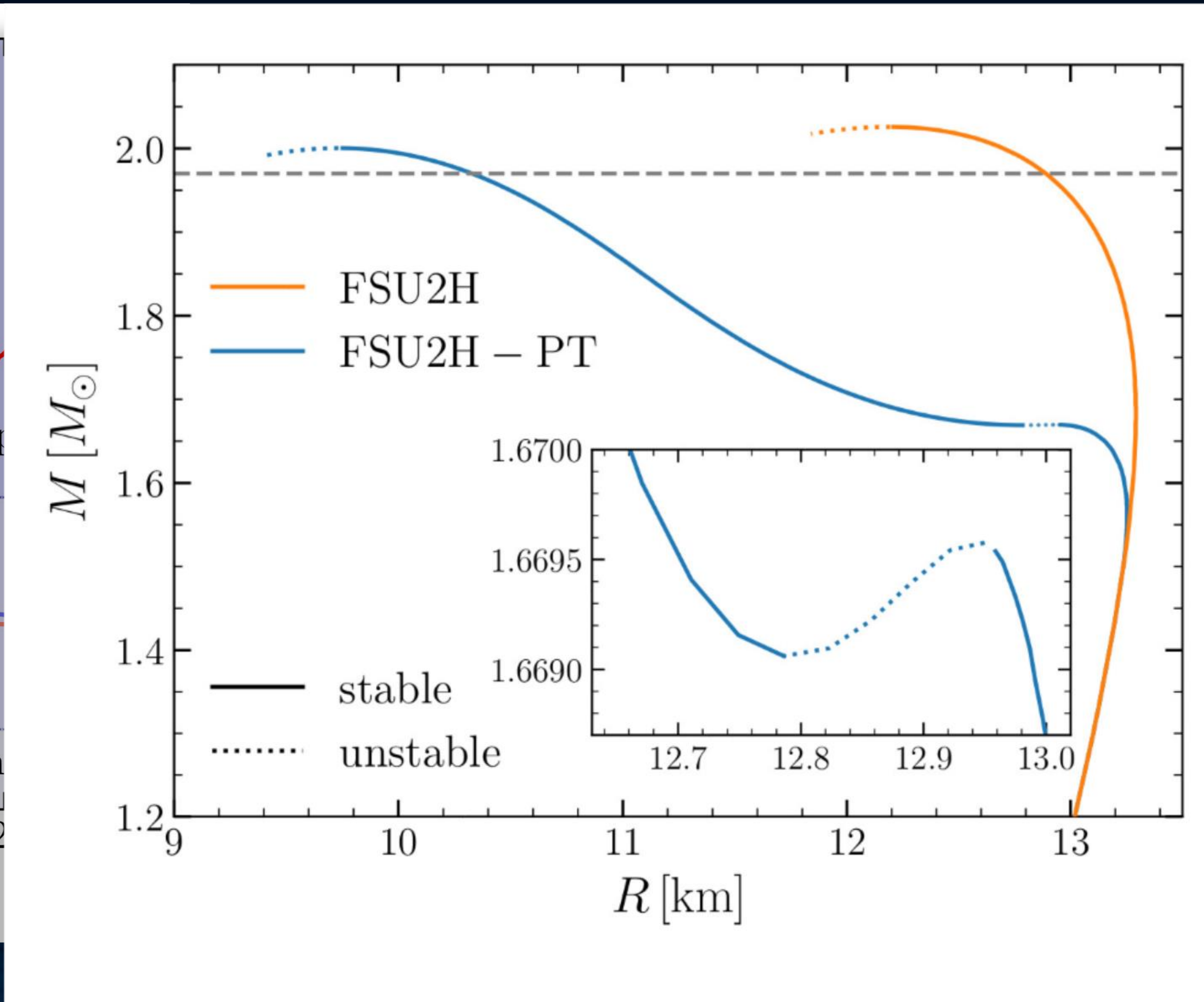
Evolution of the central rest-mass density for four binary neutron star configurations, simulated with/without a Gibbs-like hadron-quark phase transition. Blue-shaded regions mark the different phases of the EOS and apply to the DPT (Delayed phase transition) and PTTC (Phase-transition triggered collaps) scenarios only, since the NPT (No phase transition) binaries are always purely hadronic.

Signatures within the post-merger phase evolution

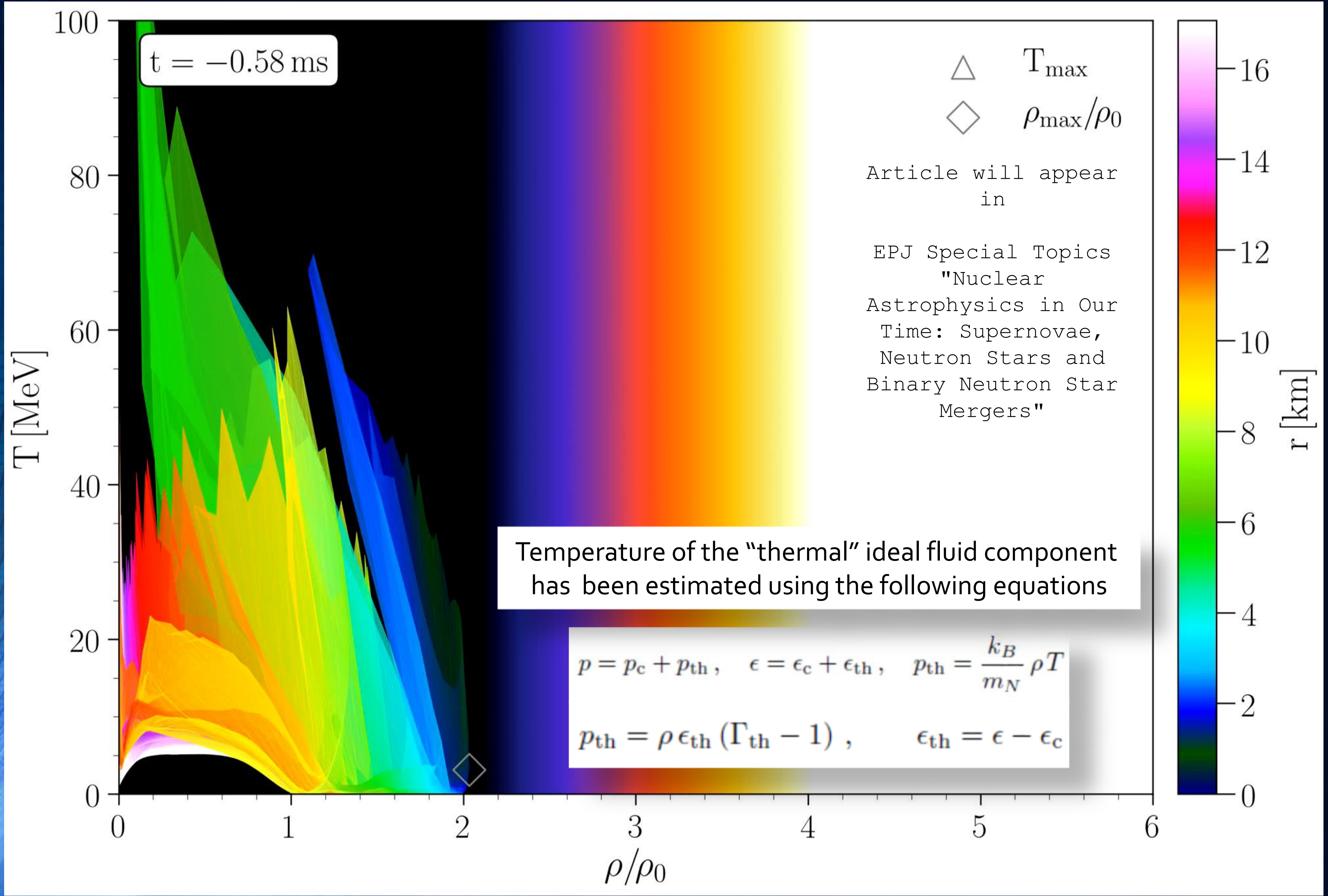
Delayed phase transition scenario

Postmerger Gravitational-Wave Signatures of Phase Transitions in Binary Mergers; LR Weih, M Hanauske, L Rezzolla; Physical Review Letters 124 (17), 171103 (2020)





Binary Neutron Star Mergers in the QCD Phase Diagram



Temperature of the "thermal" ideal fluid component has been estimated using the following equations

$$p = p_c + p_{th}\,, \quad \epsilon = \epsilon_c + \epsilon_{th}\,, \quad p_{th} = \frac{k_B}{m_N}\rho T$$

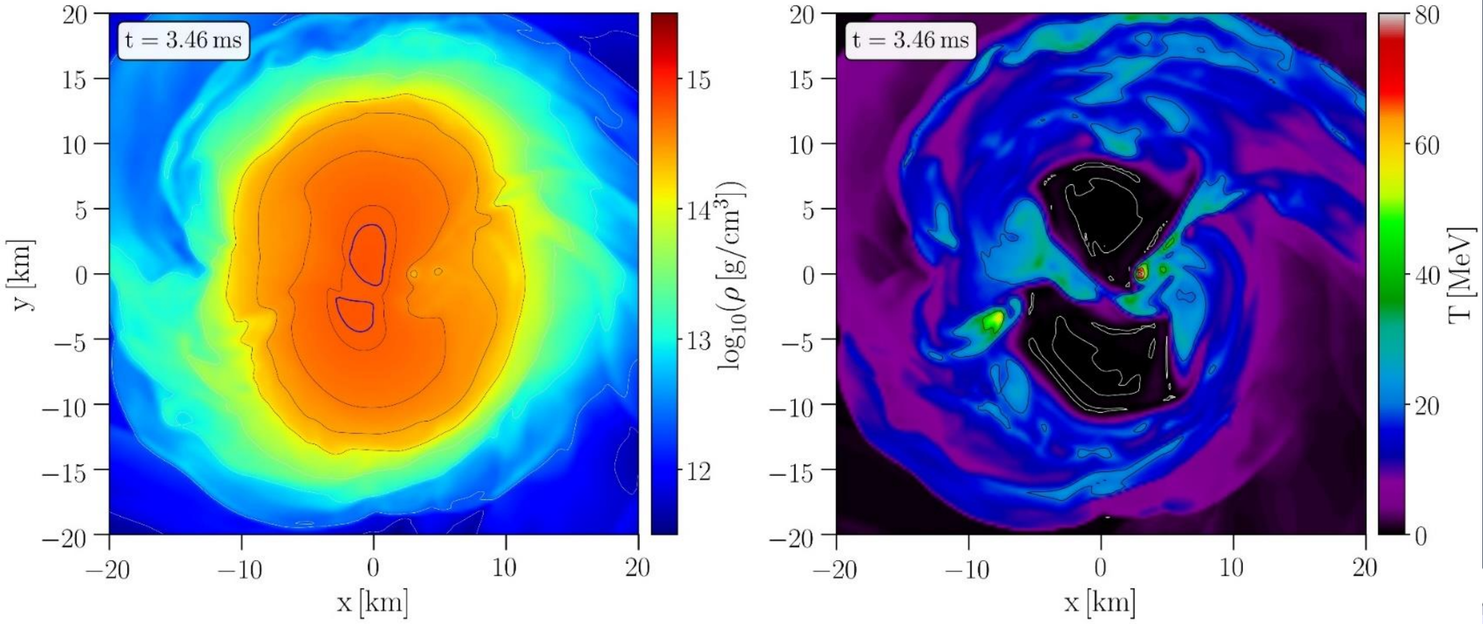
$$p_{th} = \rho\, \epsilon_{th}\,(\Gamma_{th} - 1)\,, \qquad \epsilon_{th} = \epsilon - \epsilon_c$$

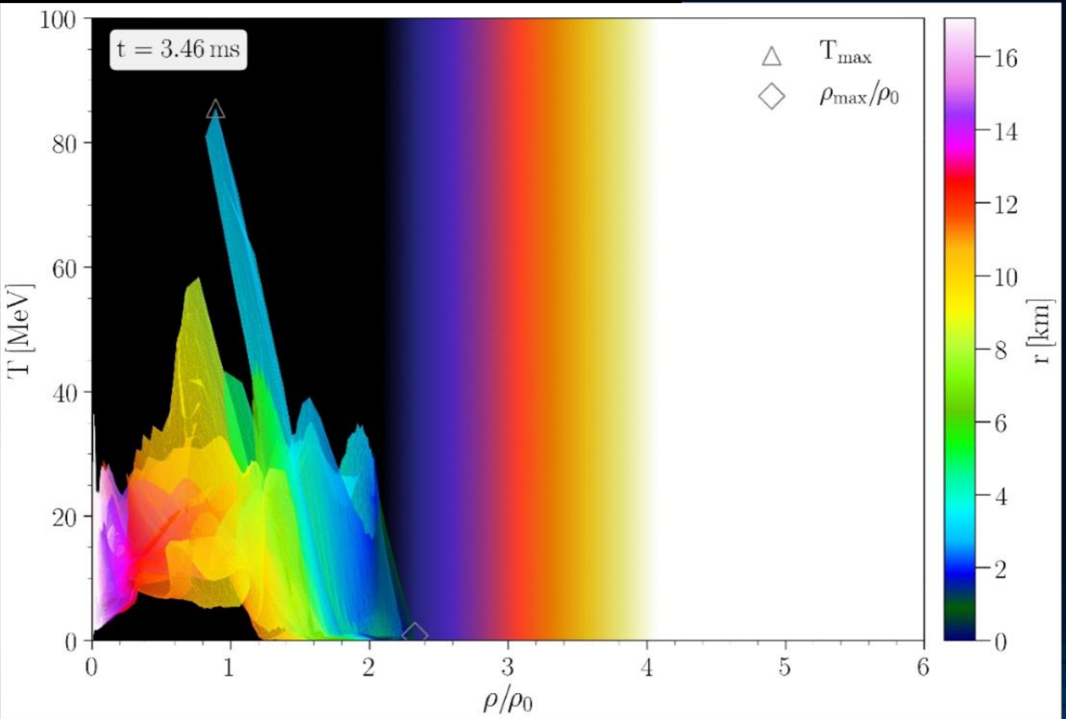
Evolution of hot and dense matter inside the inner area of a hypermassive hybrid star simulated within the (FSU2H-PT + thermal ideal fluid) EOS with a total mass of M_{total}=2.64 $M_\odot$ in the style of a (T- ρ) QCD phase diagram plot

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.

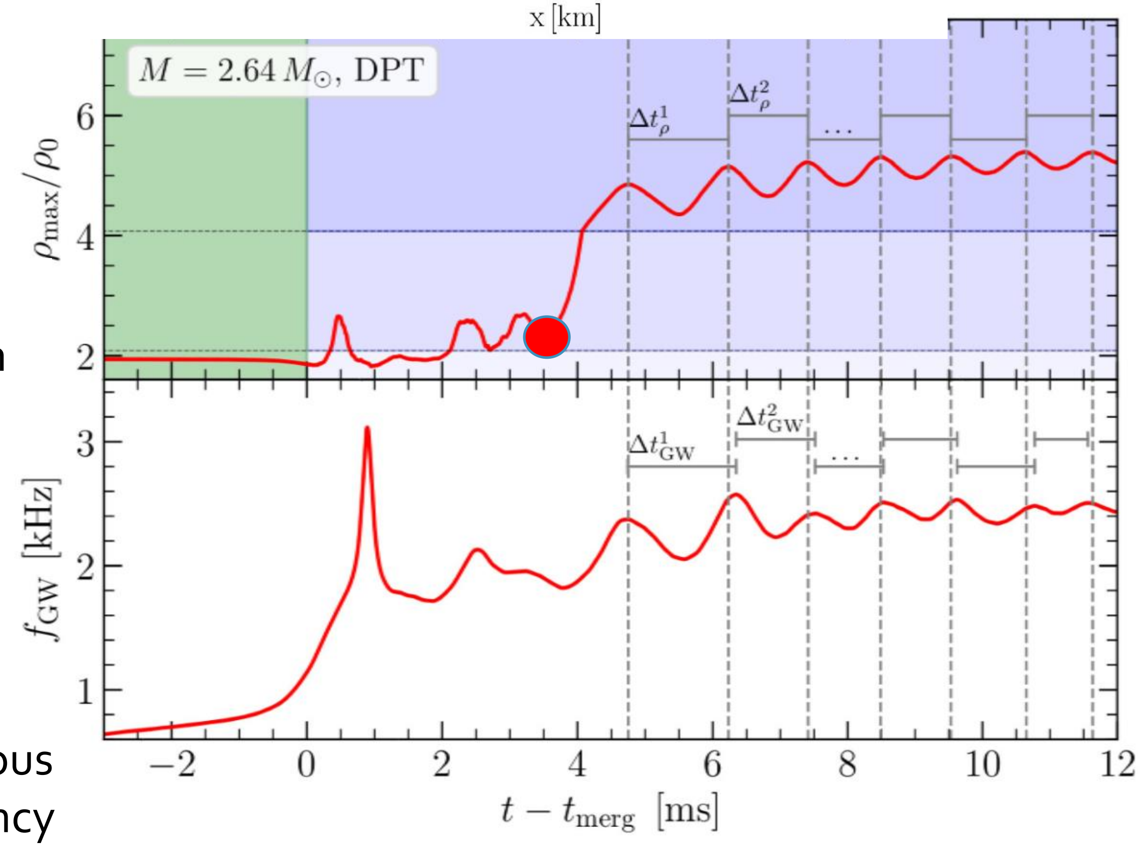
The open triangle marks the maximum value of the temperature while the open diamond indicates the maximum of the density.

These figures show the configuration of the HMHS at a time right before the collapse to the more compact star. The small asymmetry in the density profile and especially the double-core structure is amplified by the collapse resulting in a large one-sided asymmetry (i.e., an m = 1 asymmetry in a spherical-harmonics decomposition), which triggers a sizeable h21 GW strain.



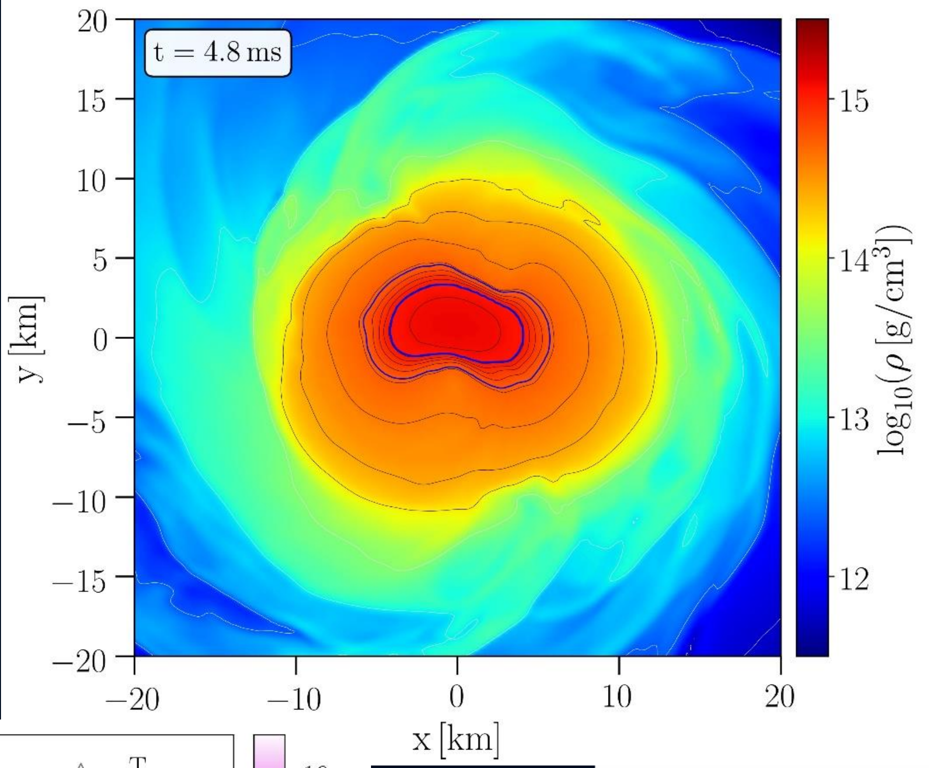


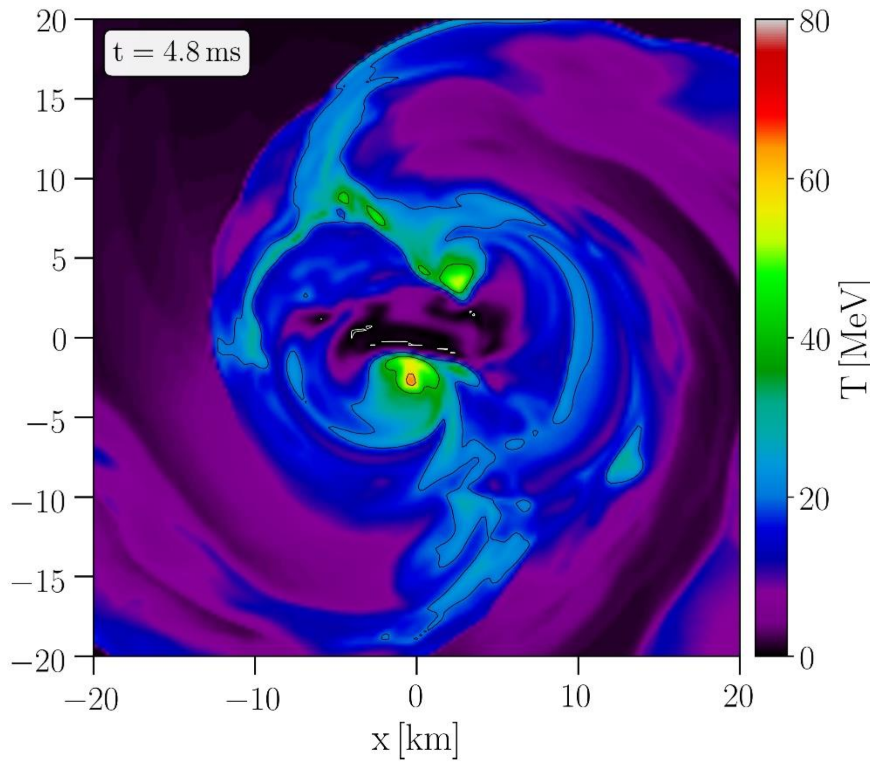
Density maximum

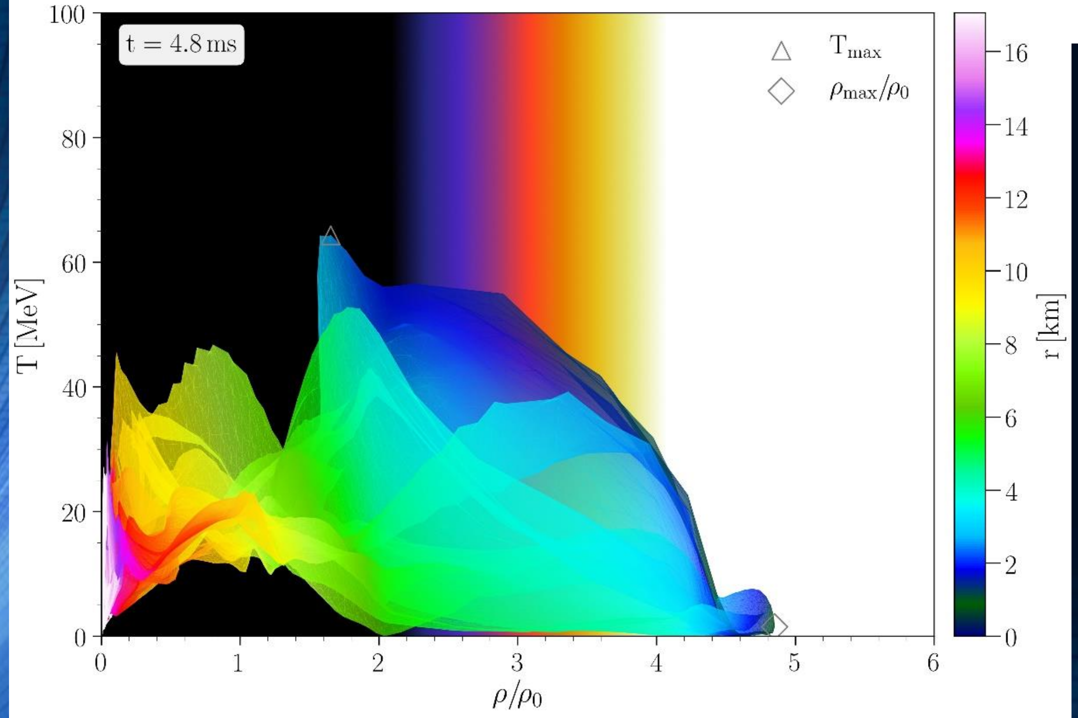


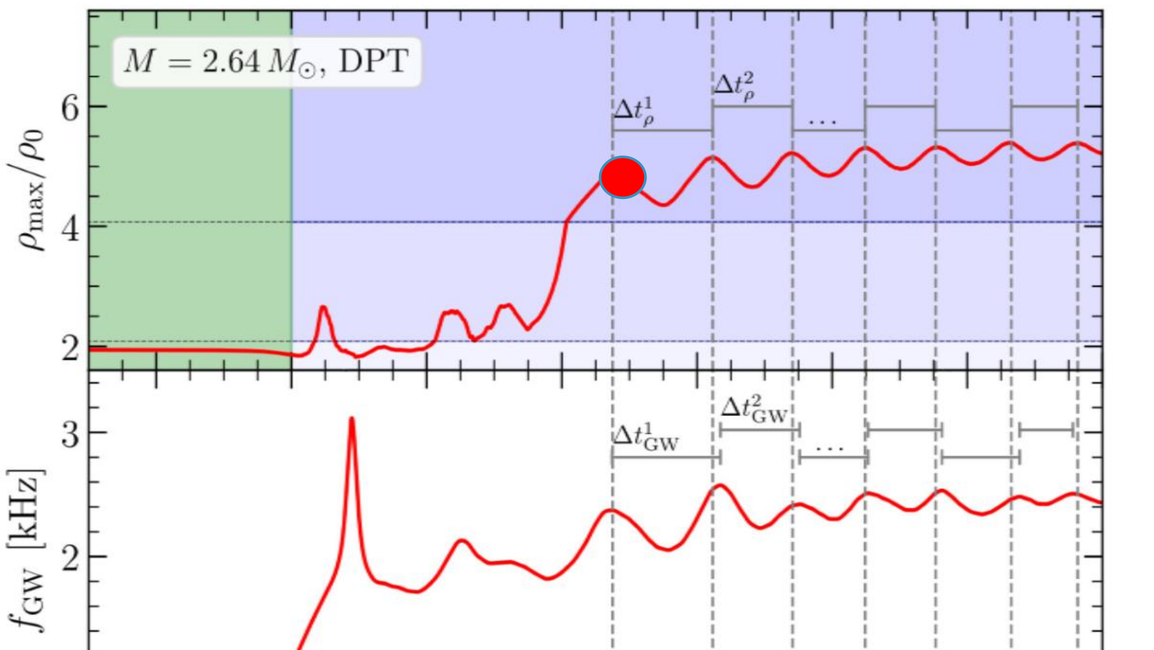
Instantaneous GW frequency

The figures correspond to a time near the first density maximum at t = 4.8ms (see red marker). The large m = 1 contribution can be seen by looking at the asymmetry of the spatial location of the quark core, which is marked with the second blue contour line. As a result of this asymmetry, the location of the two temperature are at different radial distances from the grid center.

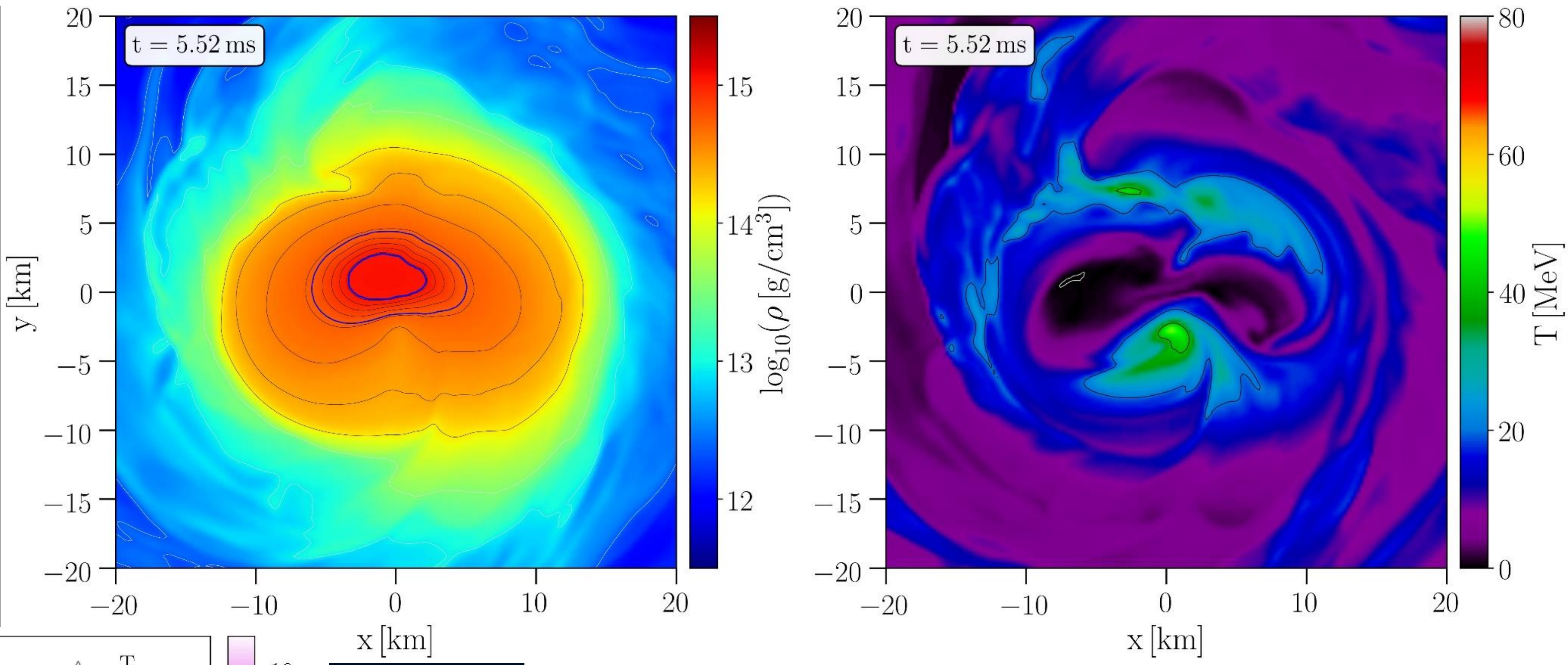


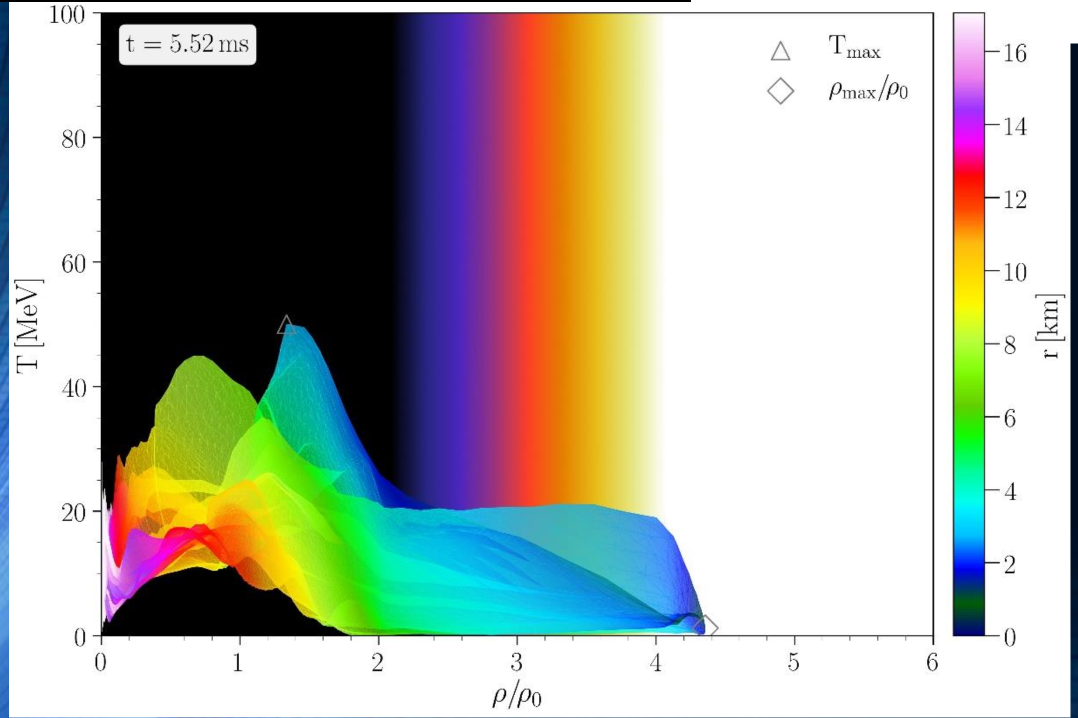


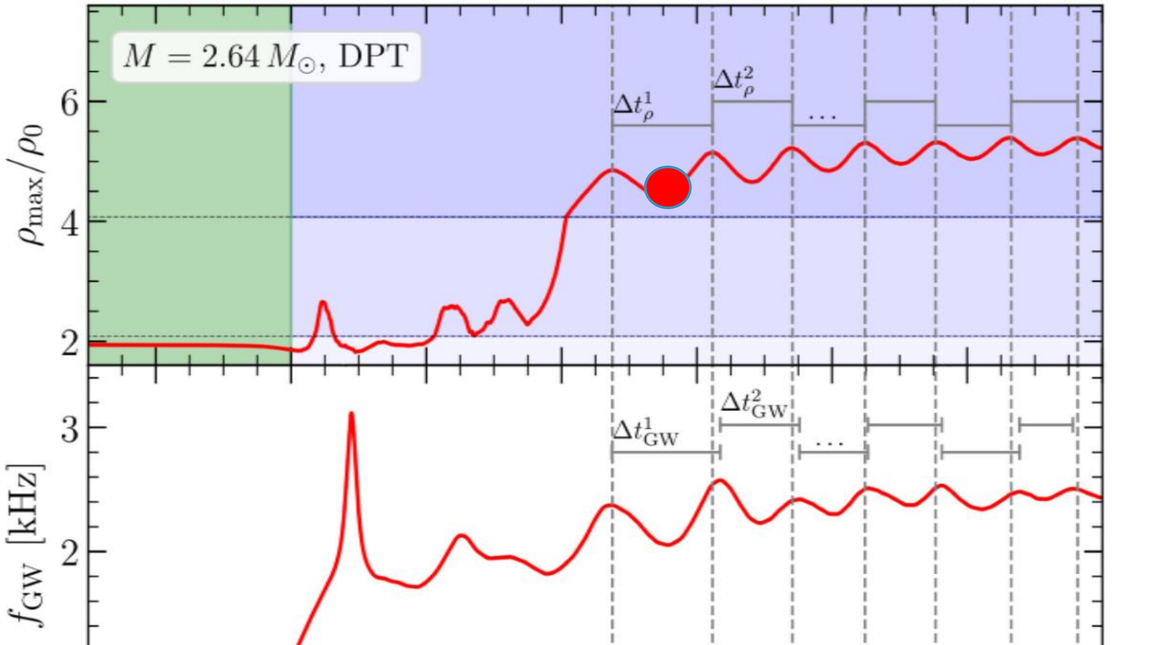




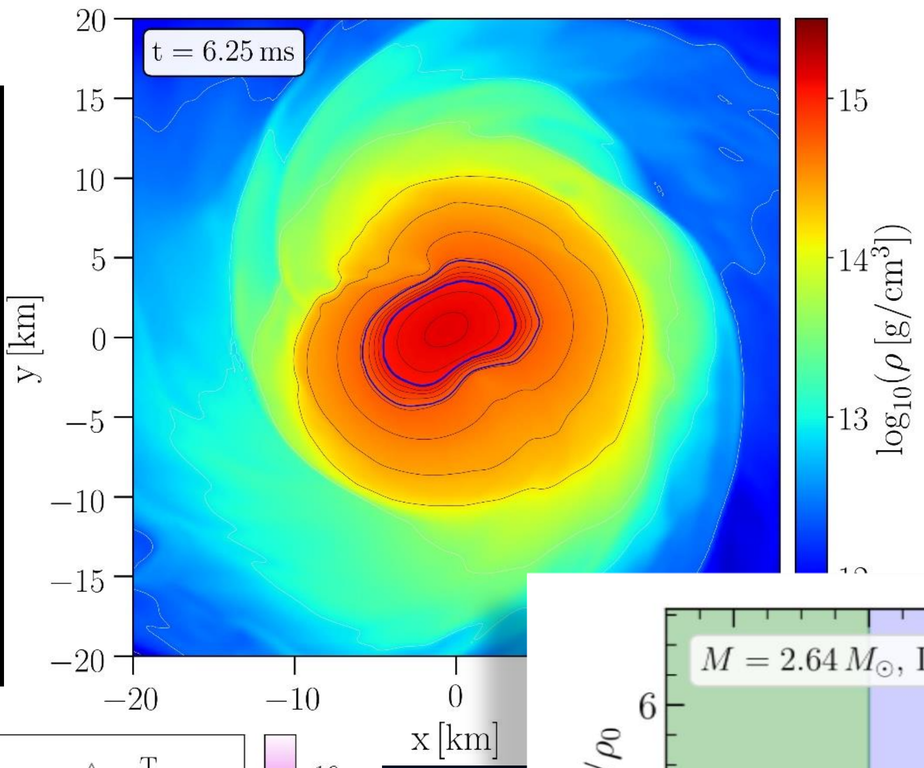
The figures correspond to a time near the first density minimum at t = 5.52ms (see red marker). The large m = 1 contribution can be seen by looking at the asymmetry of the spatial location of the quark core, which is marked with the second blue contour line. As a result of this asymmetry, the location of the two temperature are at different radial distances from the grid center.

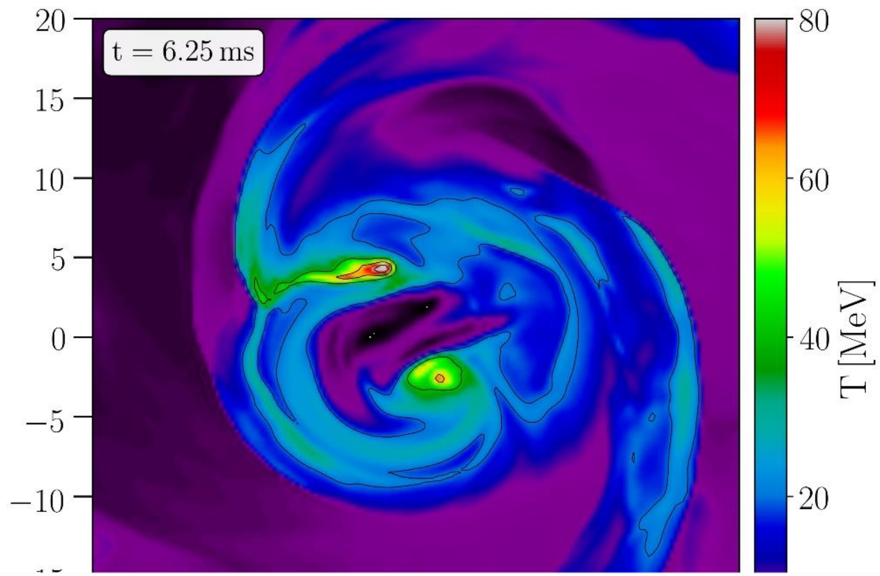


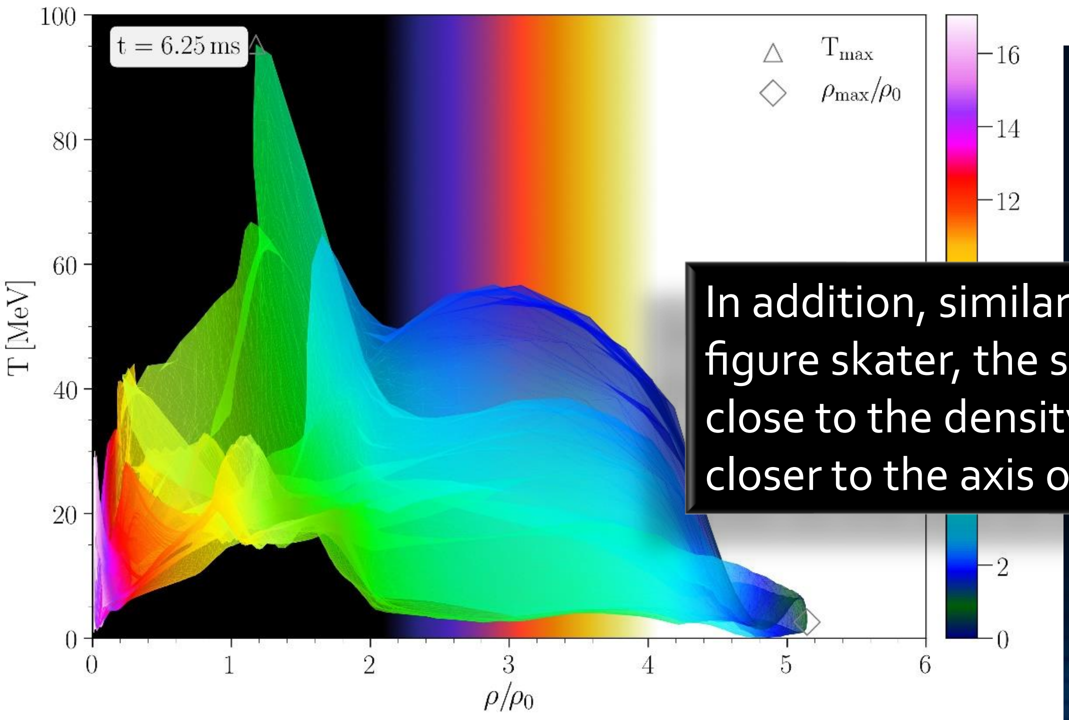


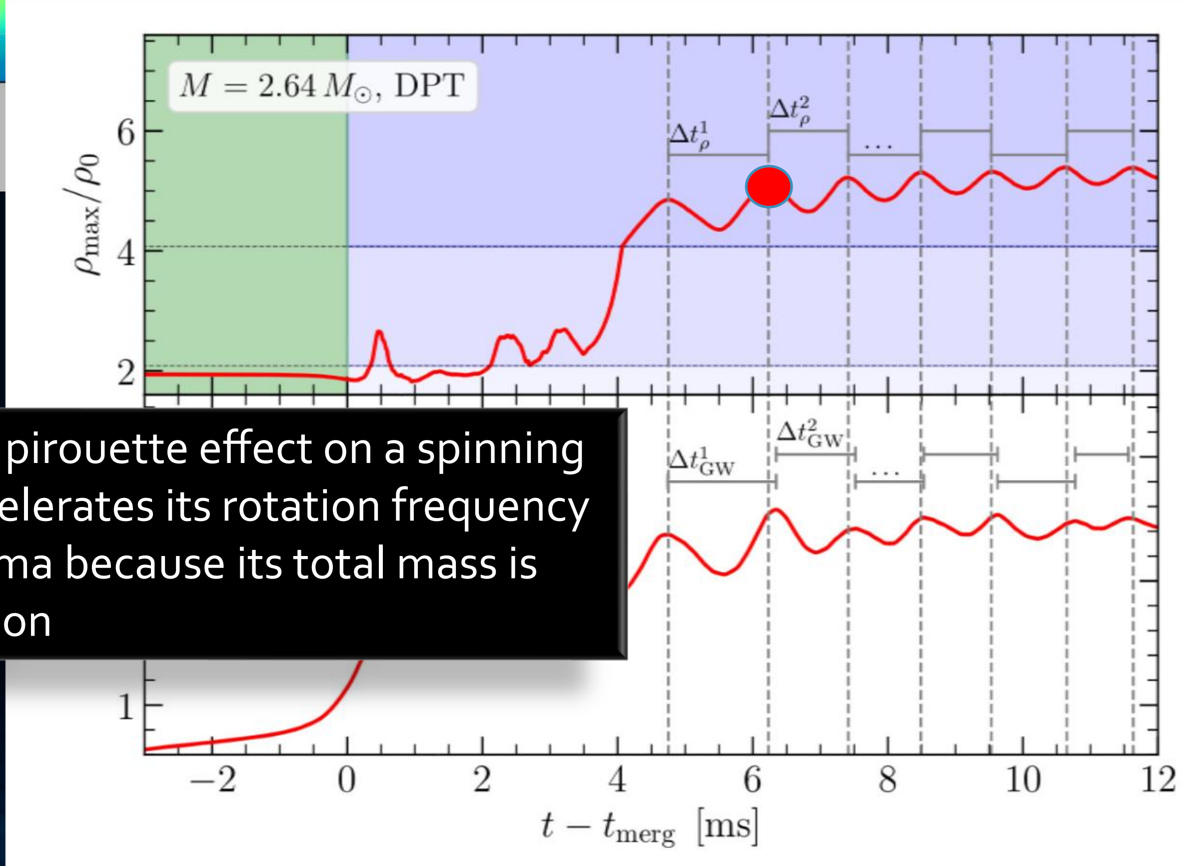


The collapse of the HMNS to the HMHS causes the system to vibrate. At the times when the maximum of the central density is reached, the pure quark core with its stiffer equation of state presses violently against the gravitational pressure and the star expands again and, as a result, its central density decreases.



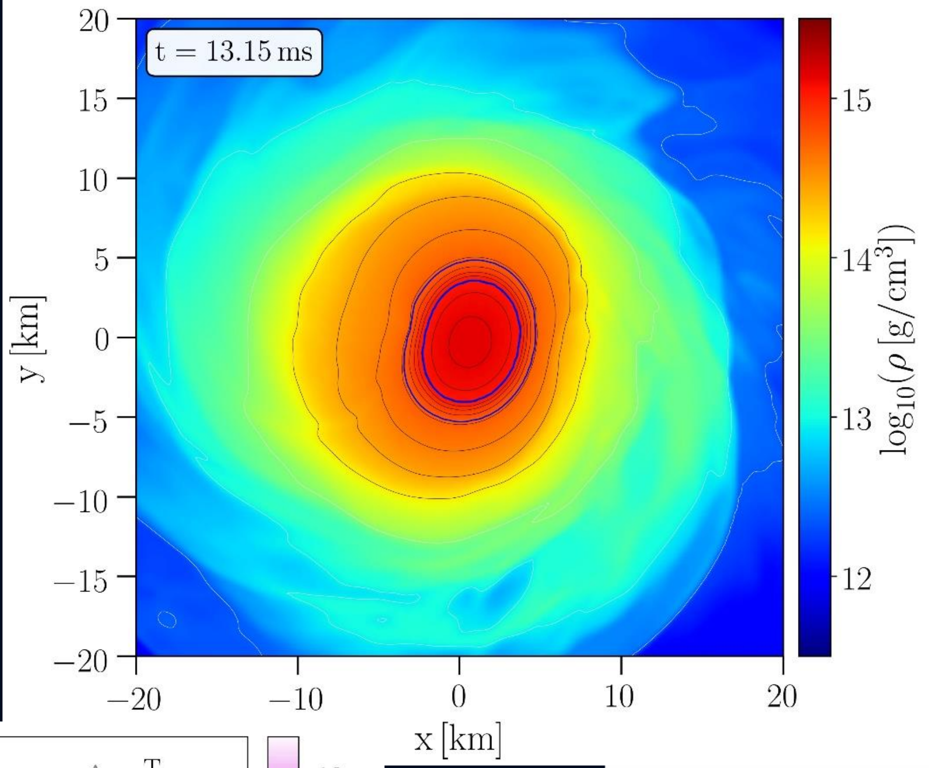


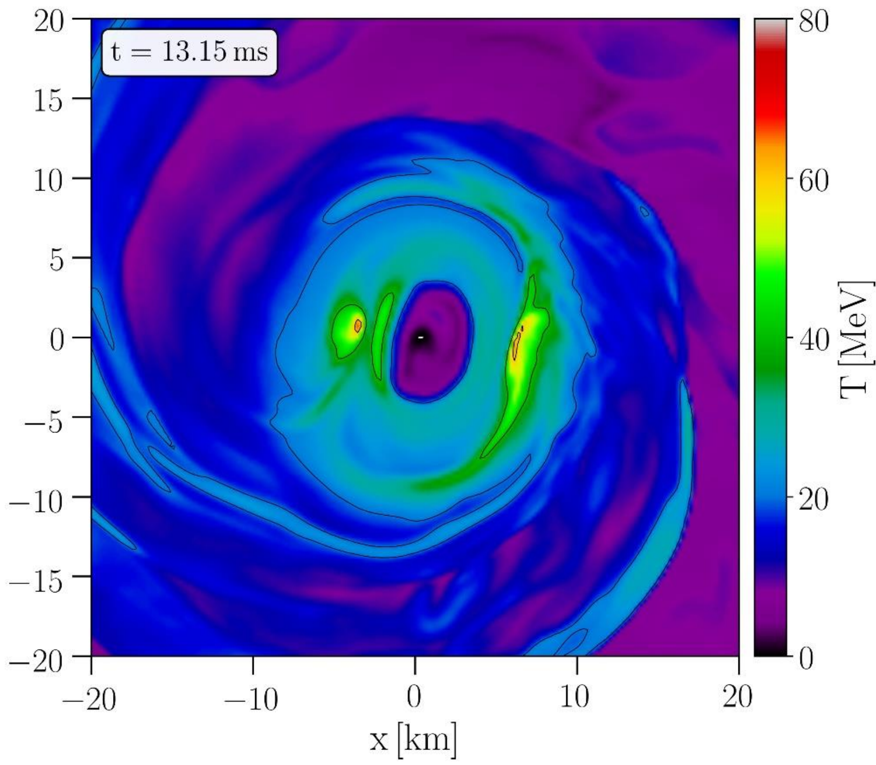


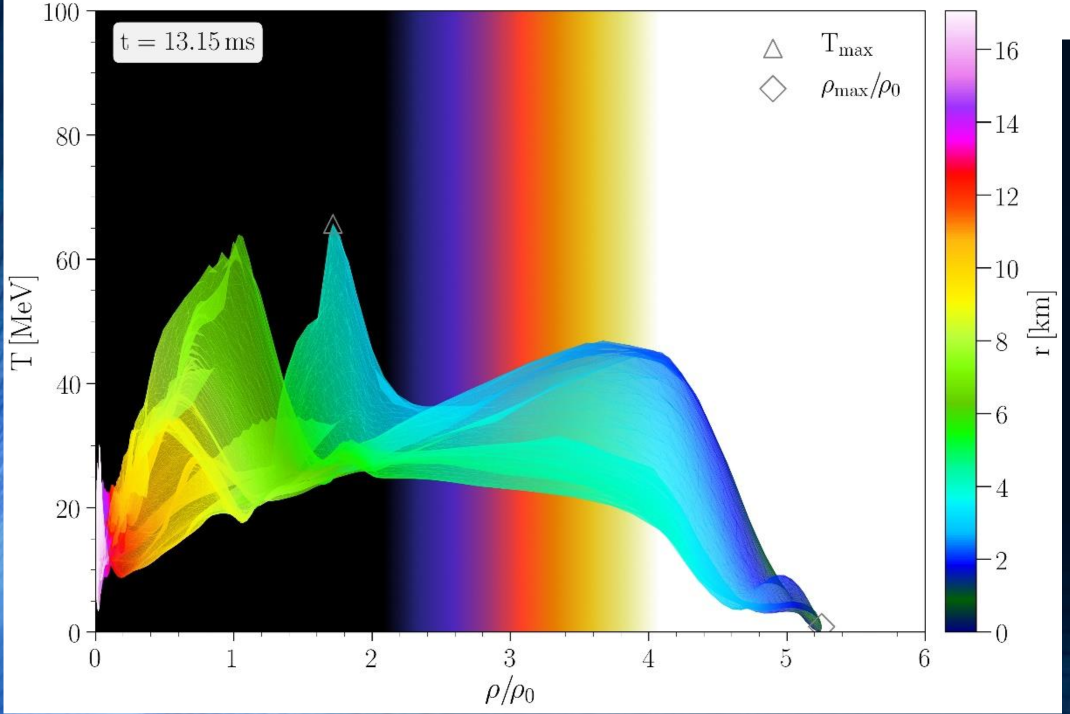


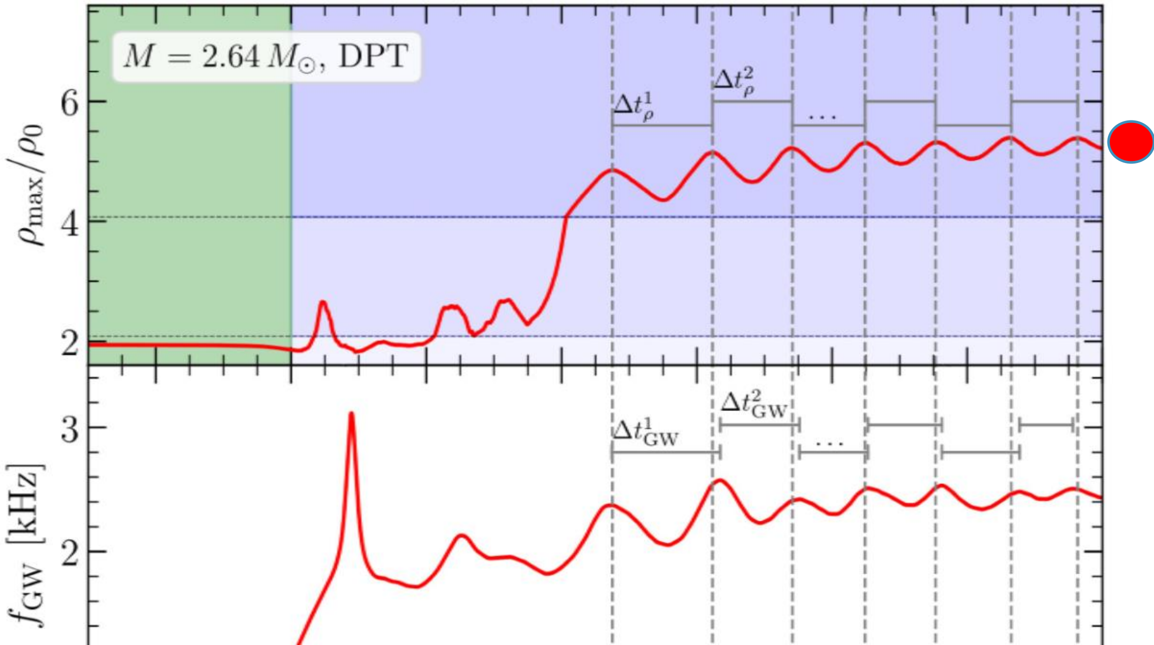
In addition, similar to the pirouette effect on a spinning figure skater, the star accelerates its rotation frequency close to the density maxima because its total mass is closer to the axis of rotation

These figures report the HMHS properties at t = 13.15 ms and shows that in addition to the two temperature hot-spots, a new high temperature shell surrounding a cold core appears within the mixed phase region of the remnant . For subsequent post-merger times, the two temperature hot-spots will be smeared out to become a ring like structure on the equatorial plane

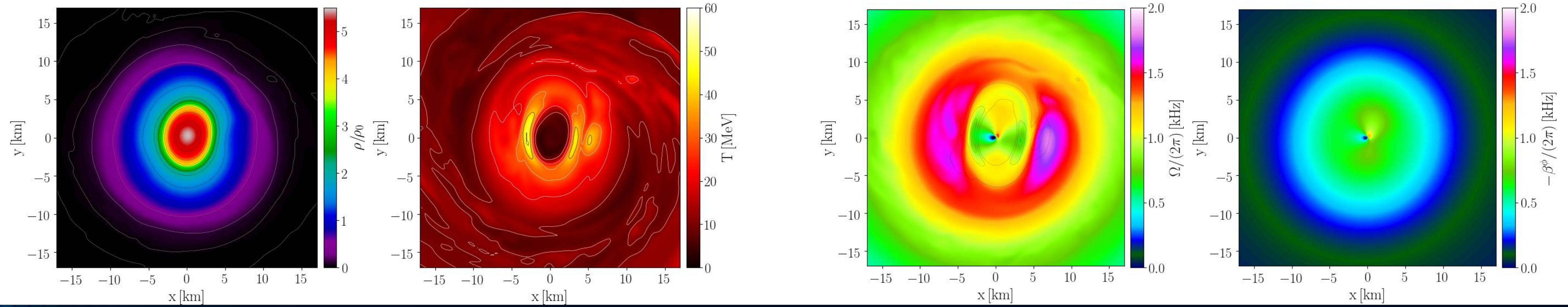




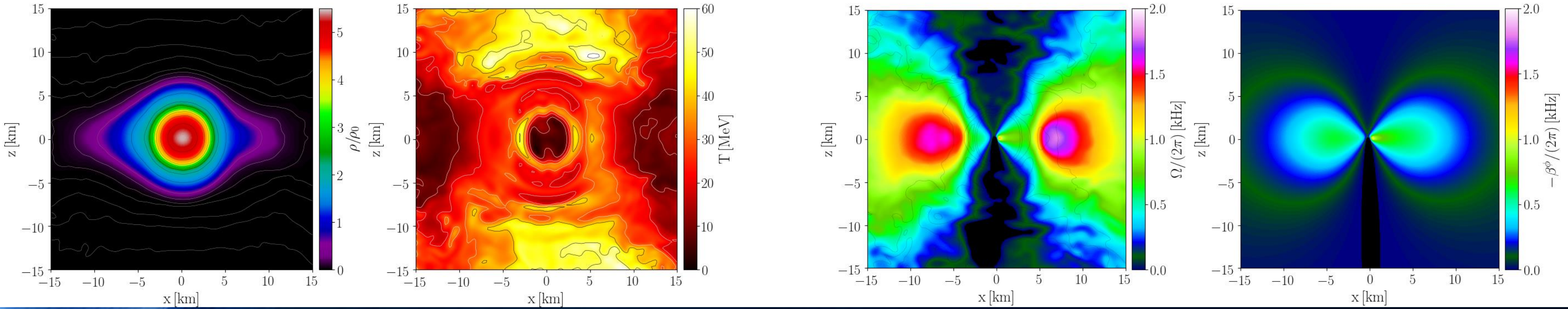




Density | Temperature | Rotation-profile | Frame dragging

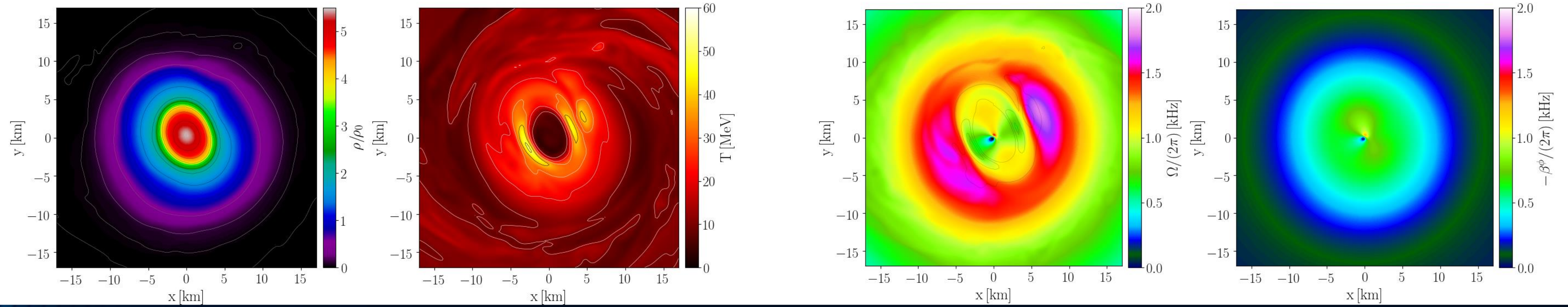


xy-plane

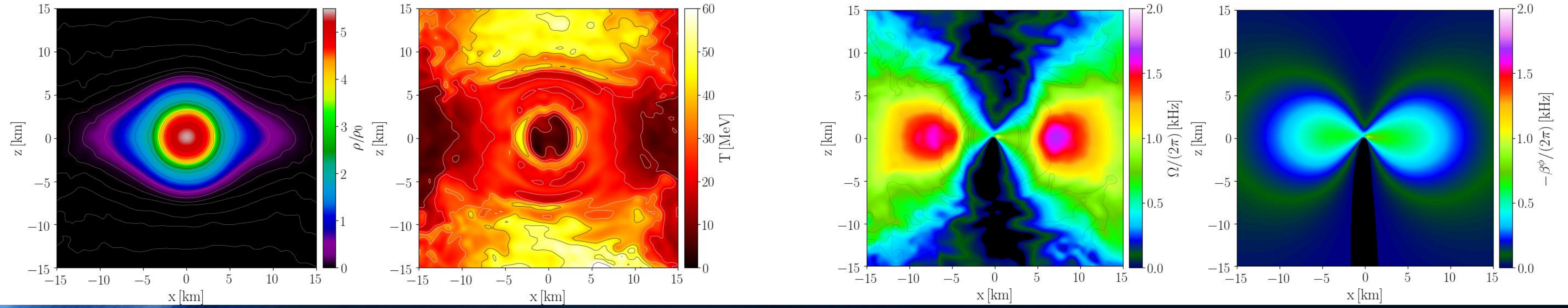


xz-plane

Density Temperature Rotation-profile Frame dragging

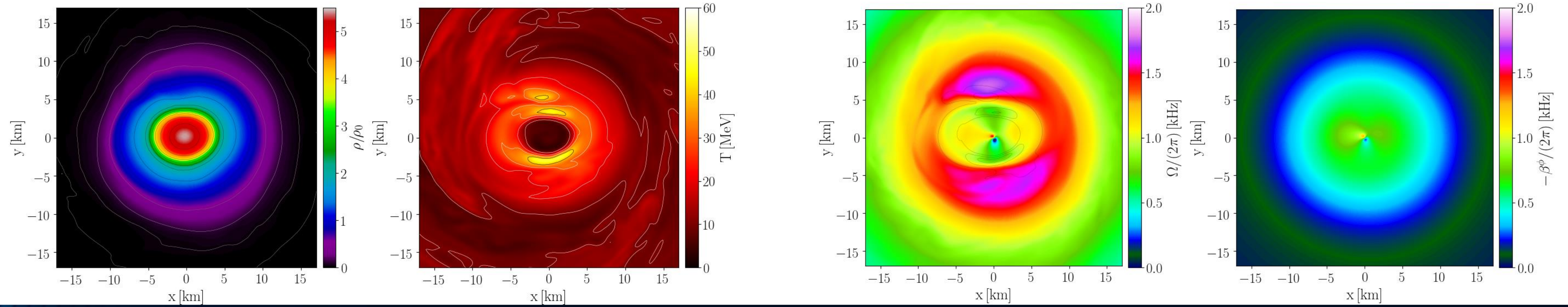


xy-plane



xz-plane

Density | Temperature | Rotation-profile | Frame dragging



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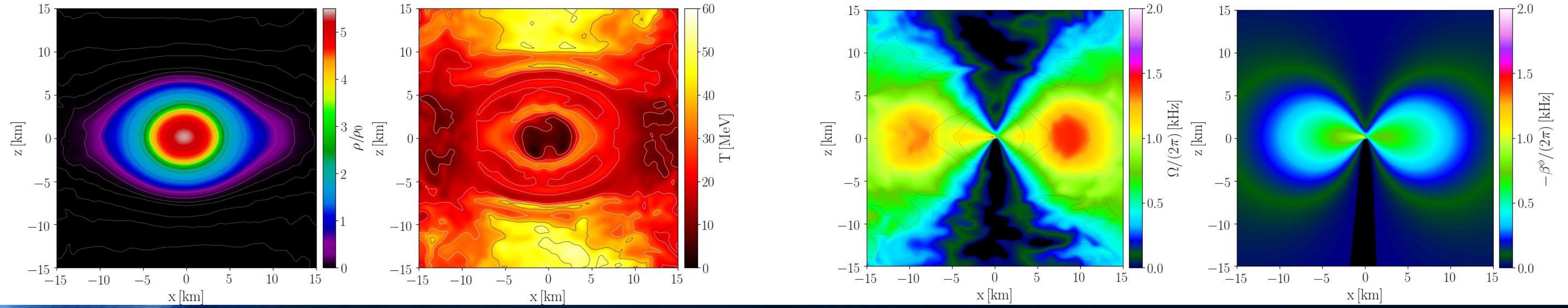

xz-plane

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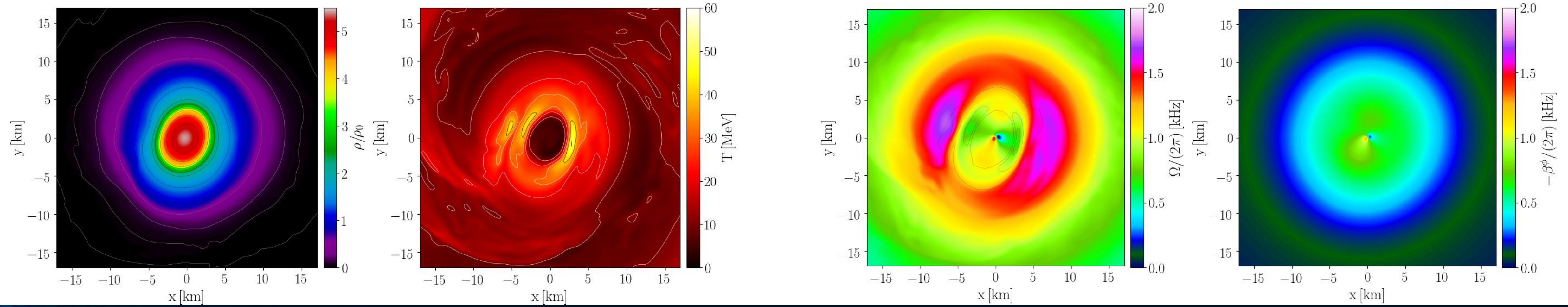

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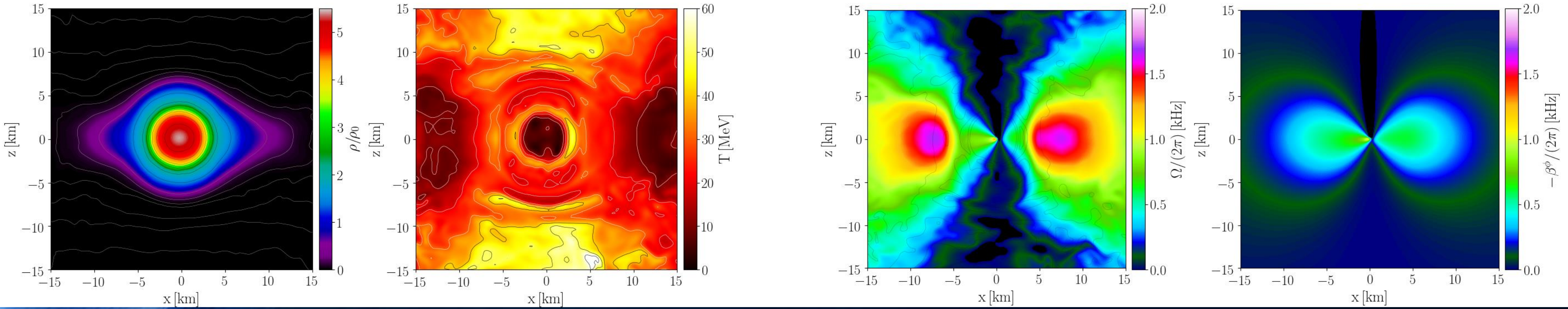
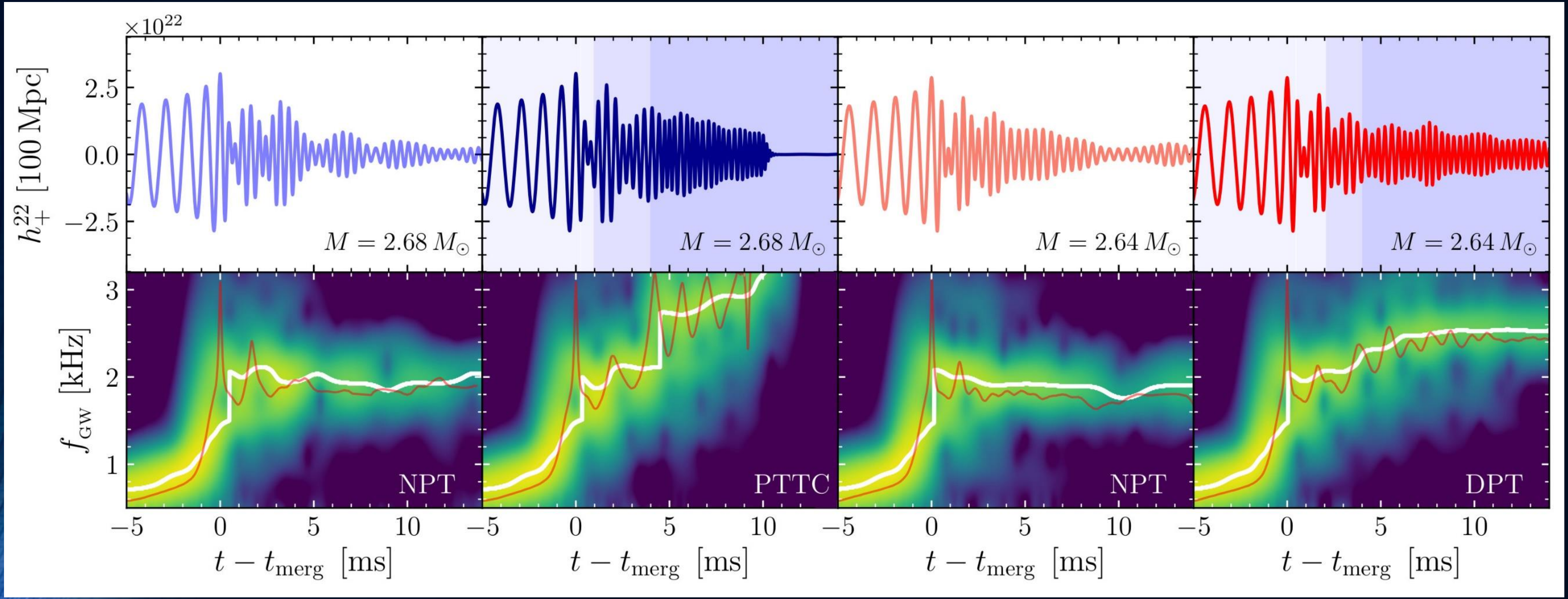


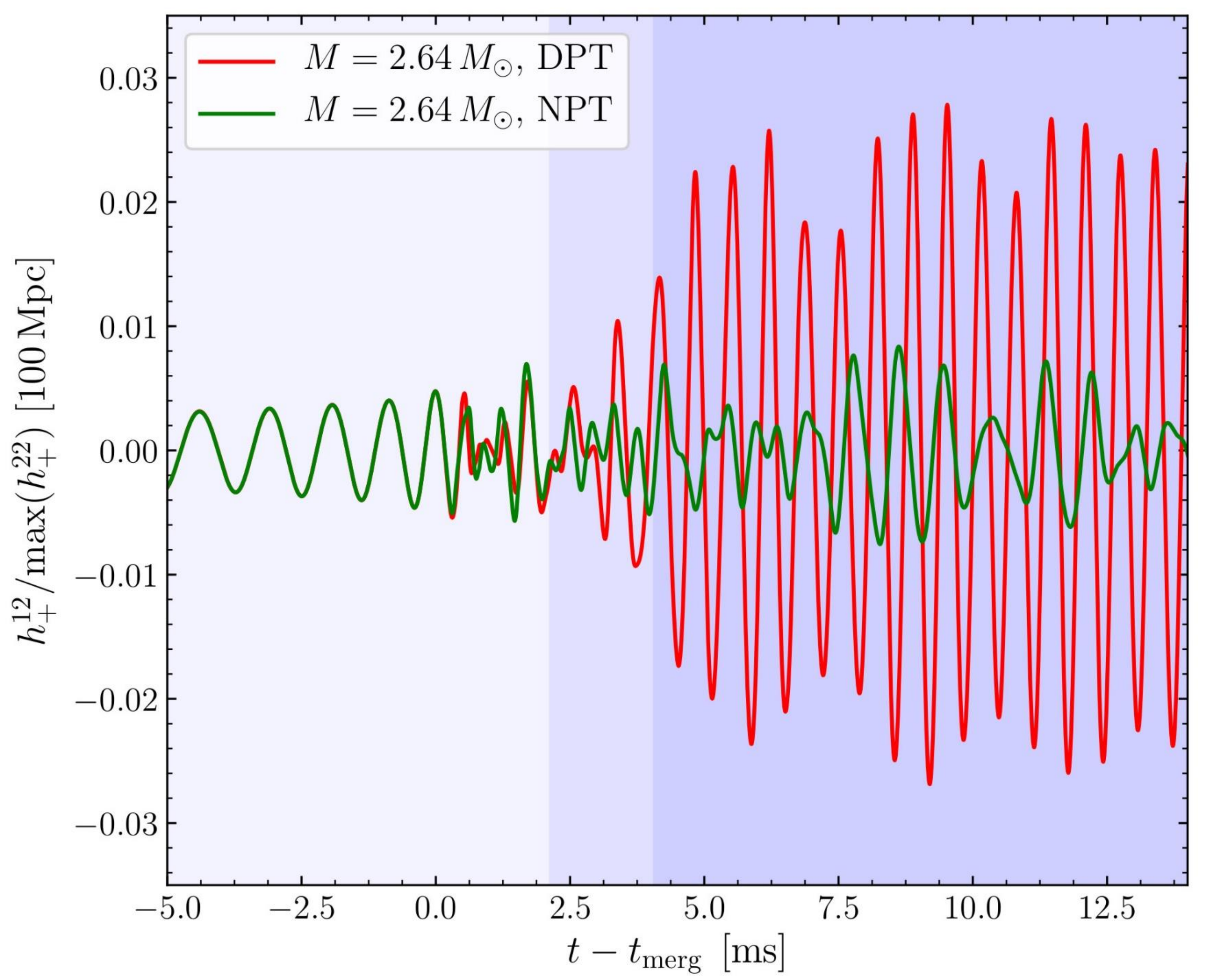
xz-plane

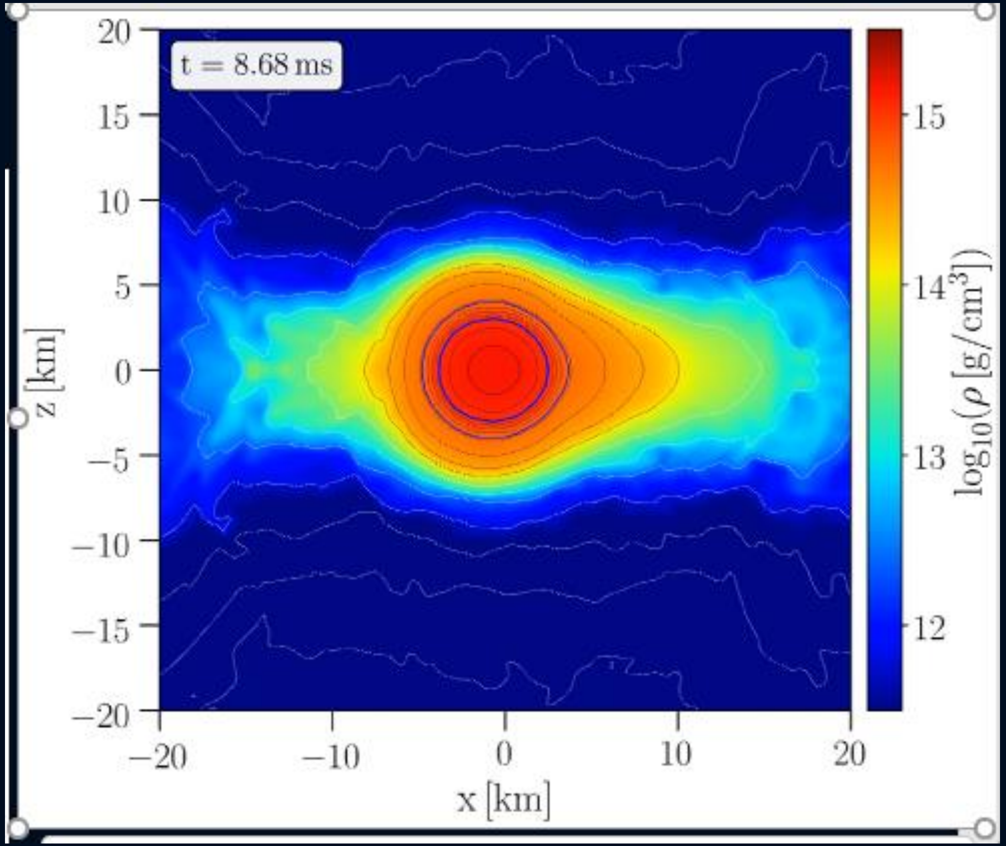
Postmerger Gravitational-Wave Signatures of Phase Transitions in Binary Mergers; LR Weih, M Hanauske, L Rezzolla; Physical Review Letters 124 (17), 171103 (2020)



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.

Differnce in the h_+^{12} – gravitational wave mode





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 h_+^{12} – gravitational wave mode during the post-merger evolution.

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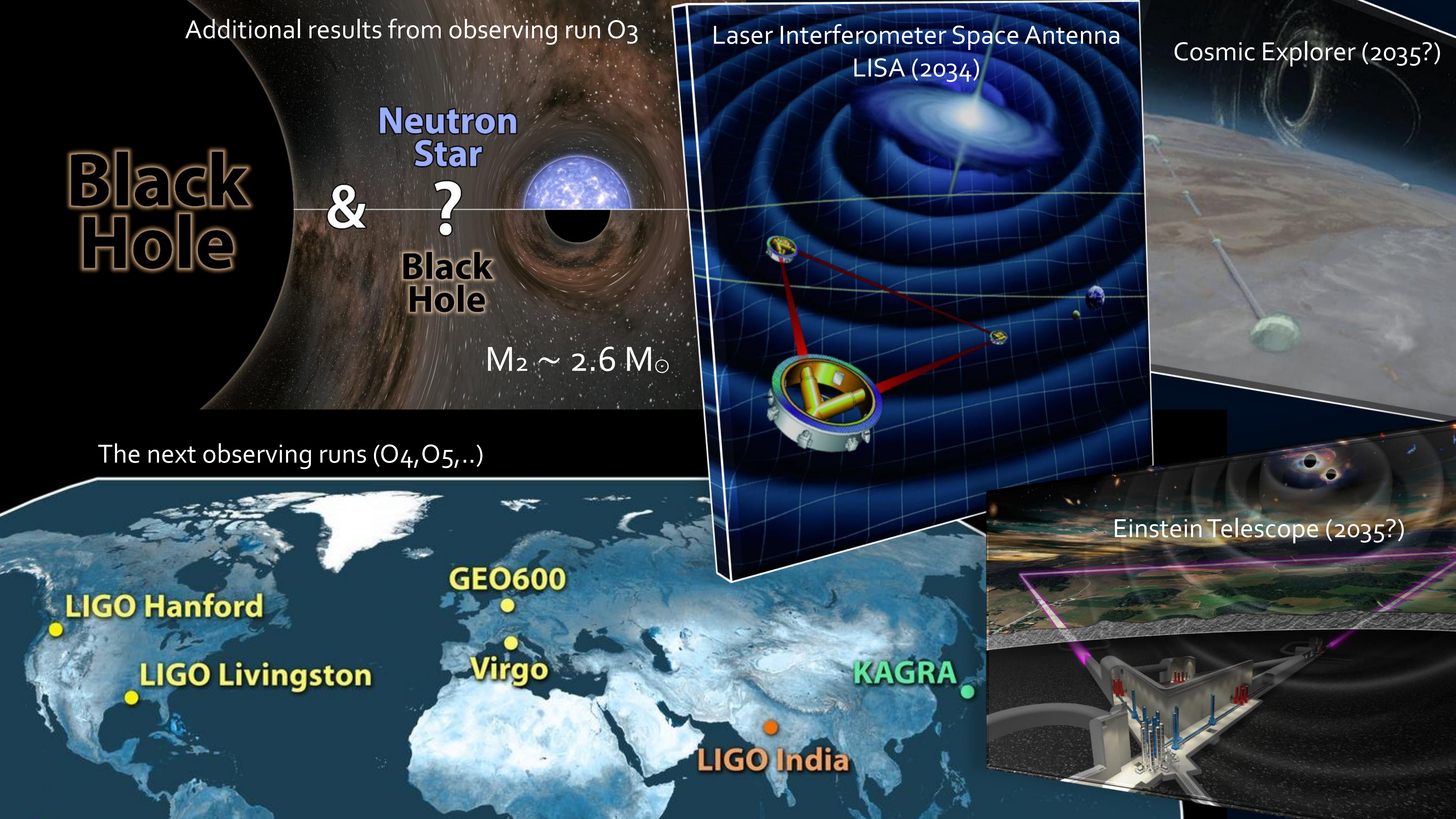
Additional results from observing run O3
Black Hole
&
Neutron Star
?
Black Hole
M2 ~ 2.6 M☉
Laser Interferometer Space Antenna
LISA (2034)
Cosmic Explorer (2035?)
The next observing runs (O4,O5,..)
LIGO Hanford
LIGO Livingston
GEO600
Virgo
KAGRA
LIGO India
Einstein Telescope (2035?)