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JOHANN WOLFGANG GOETHE UNIVERSITÄT
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JOHANN WOLFGANG GOETHE UNIVERSITÄT FRANKFURT AM MAIN

ICRANet International Center for Relativistic Astrophysics Network

On the properties of metastable hypermassive hybrid stars

Parallel session

Neutron stars: Dense matter in compact stars, 08.07.2021, 18:10

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

MG16 5-10 JULY 2021
SIXTEENTH MARCEL GROSSMANN MEETING
ON RECENT DEVELOPMENTS IN THEORETICAL AND EXPERIMENTAL GENERAL RELATIVITY, ASTROPHYSICS AND RELATIVISTIC FIELD THEORIES

VIRTUAL MEETING
websites: http://www.icra.it/mg/mg16/ https://indico.icranet.org/event/1/
email: mg16@icranet.org
6:30-19:30 CENTRAL EUROPEAN SUMMER TIME

50TH ANNIVERSARY OF "INTRODUCING THE BLACK HOLE"

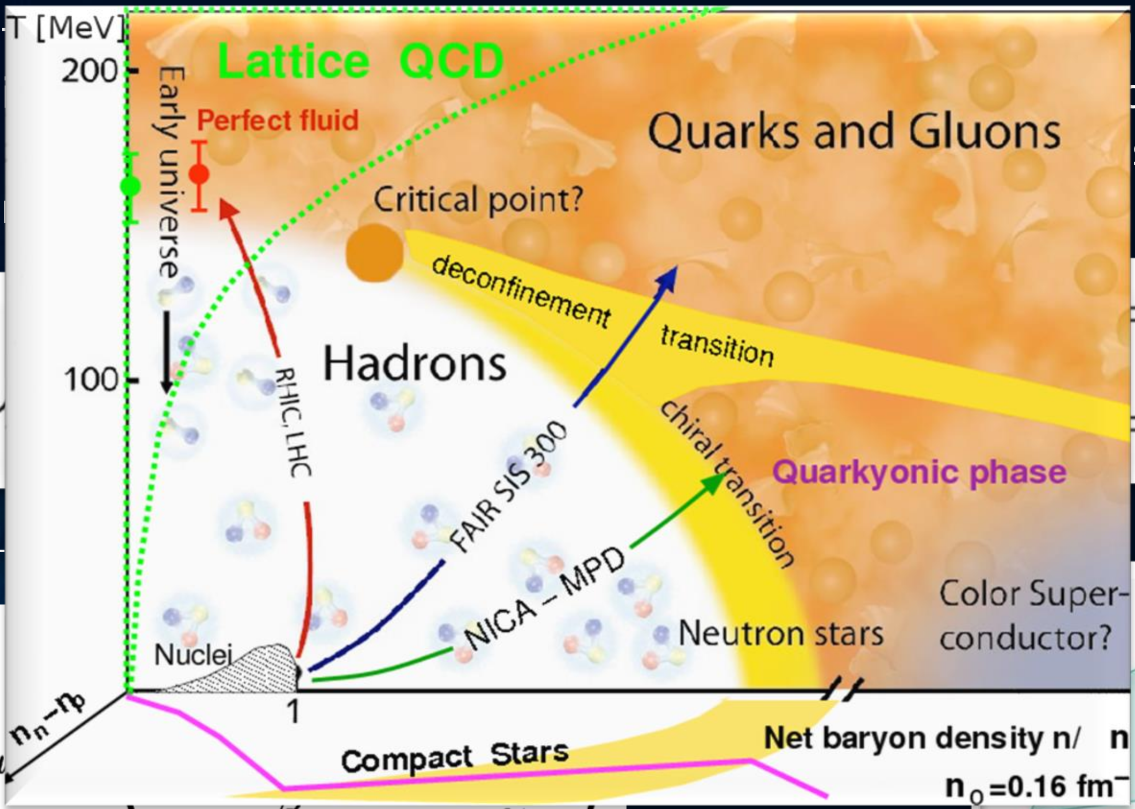
Numerical Relativity and Relativistic Hydrodynamics of Binary Neutron Star Mergers

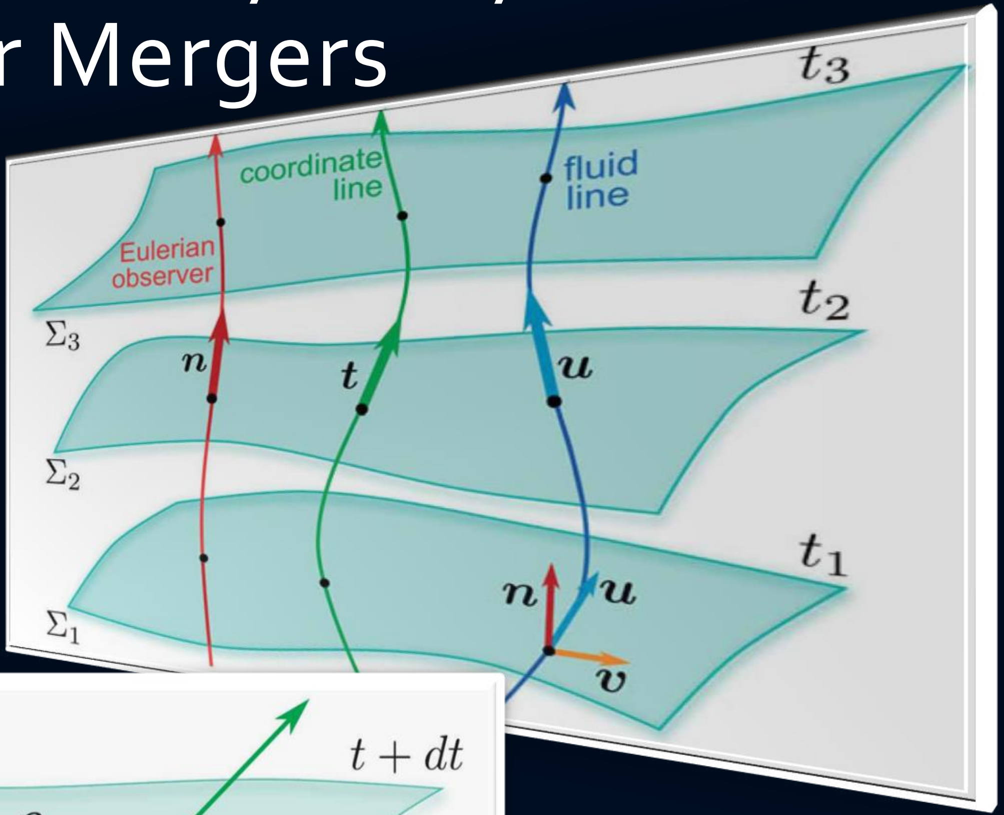
Eins… relat… with… neut… …l …ction …s of

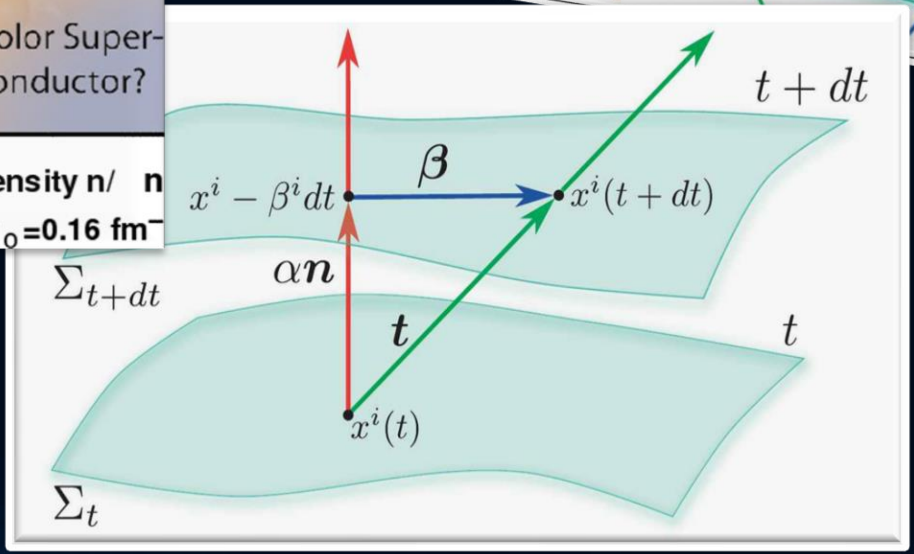
$R_{\mu\nu}$ … $= 0\,,$ … $= 0\,.$

(3+…

g_{μ} … β_i … γ_{ij}





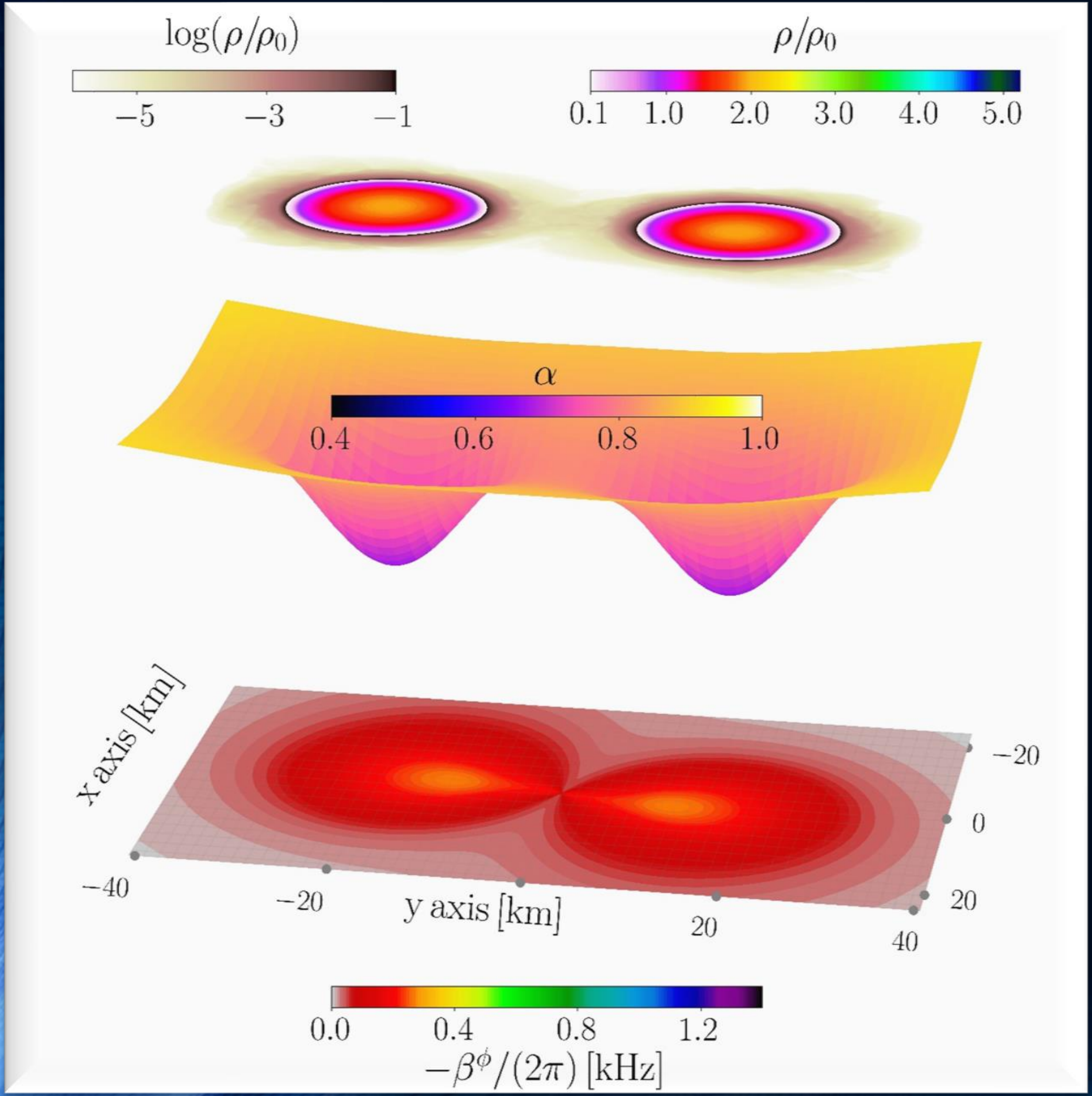


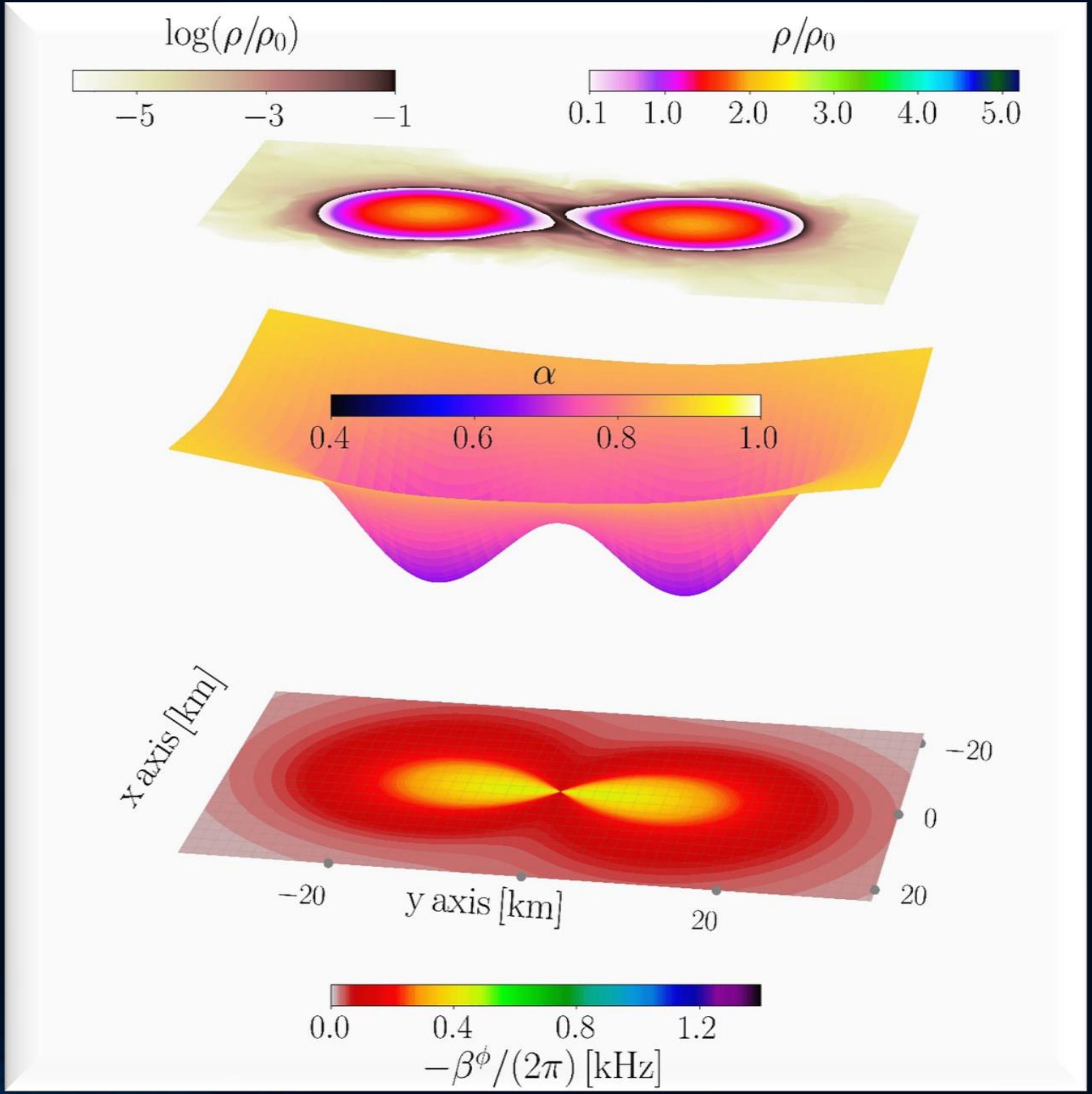
$$d\tau^2 = \alpha^2(t,x^j)dt^2$$

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

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

The late inspiral phase (density, lapse and shift)

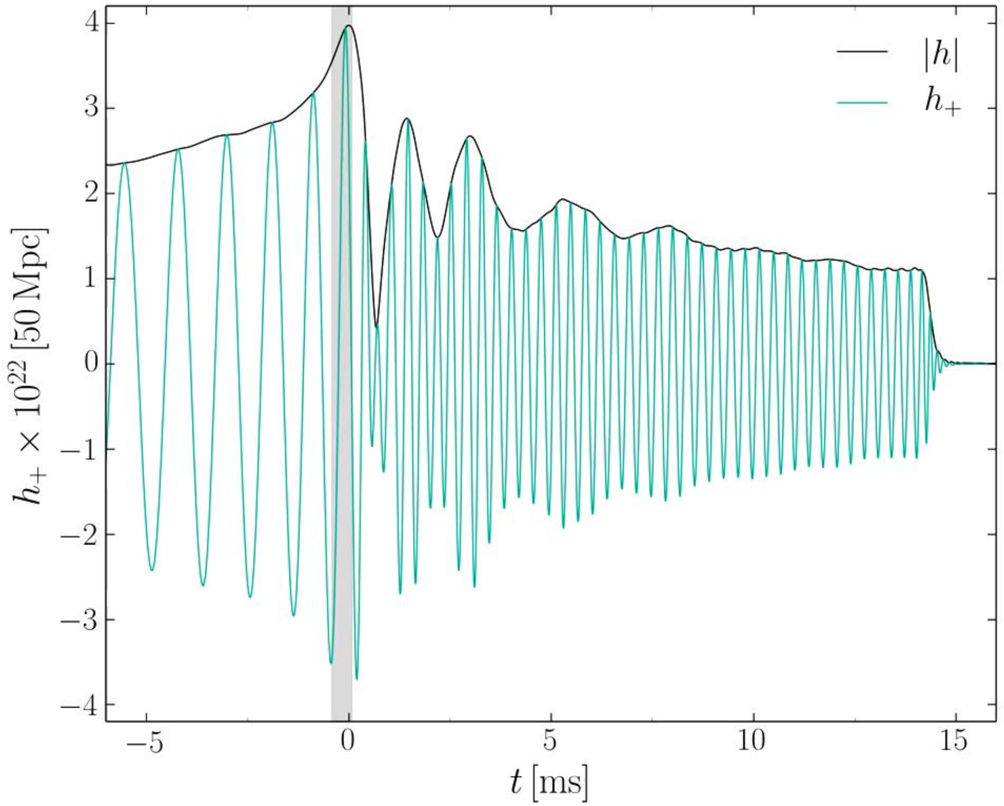


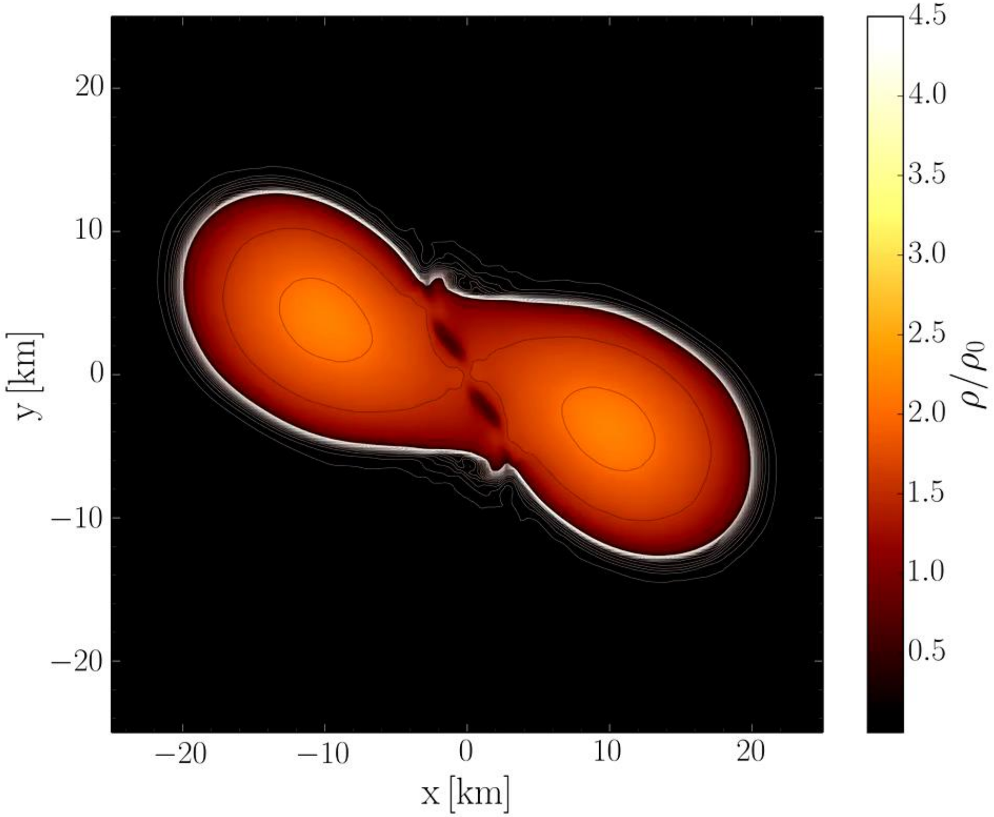


Gravitational Waves and Hypermassive Hybrid Stars

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)

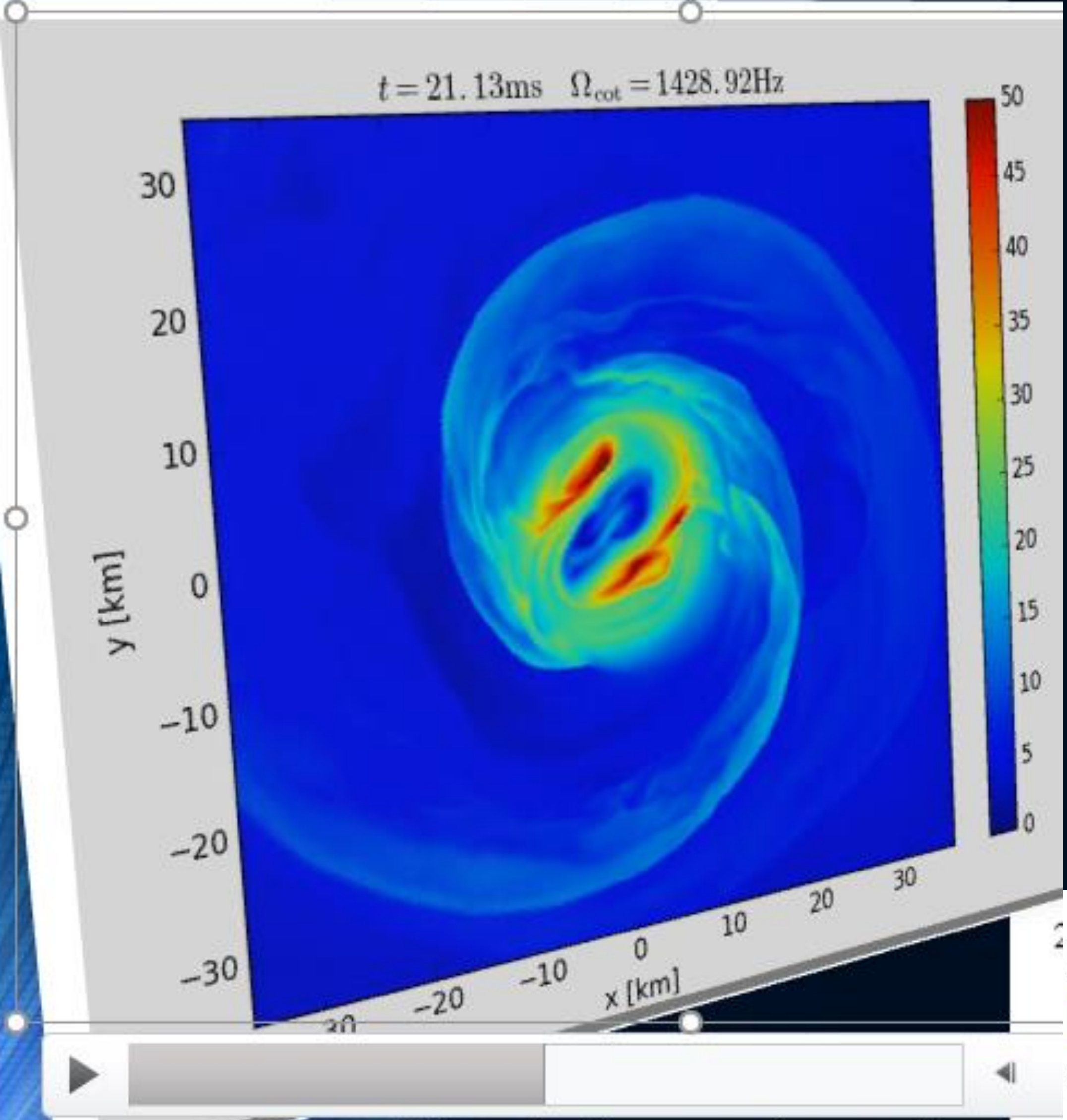




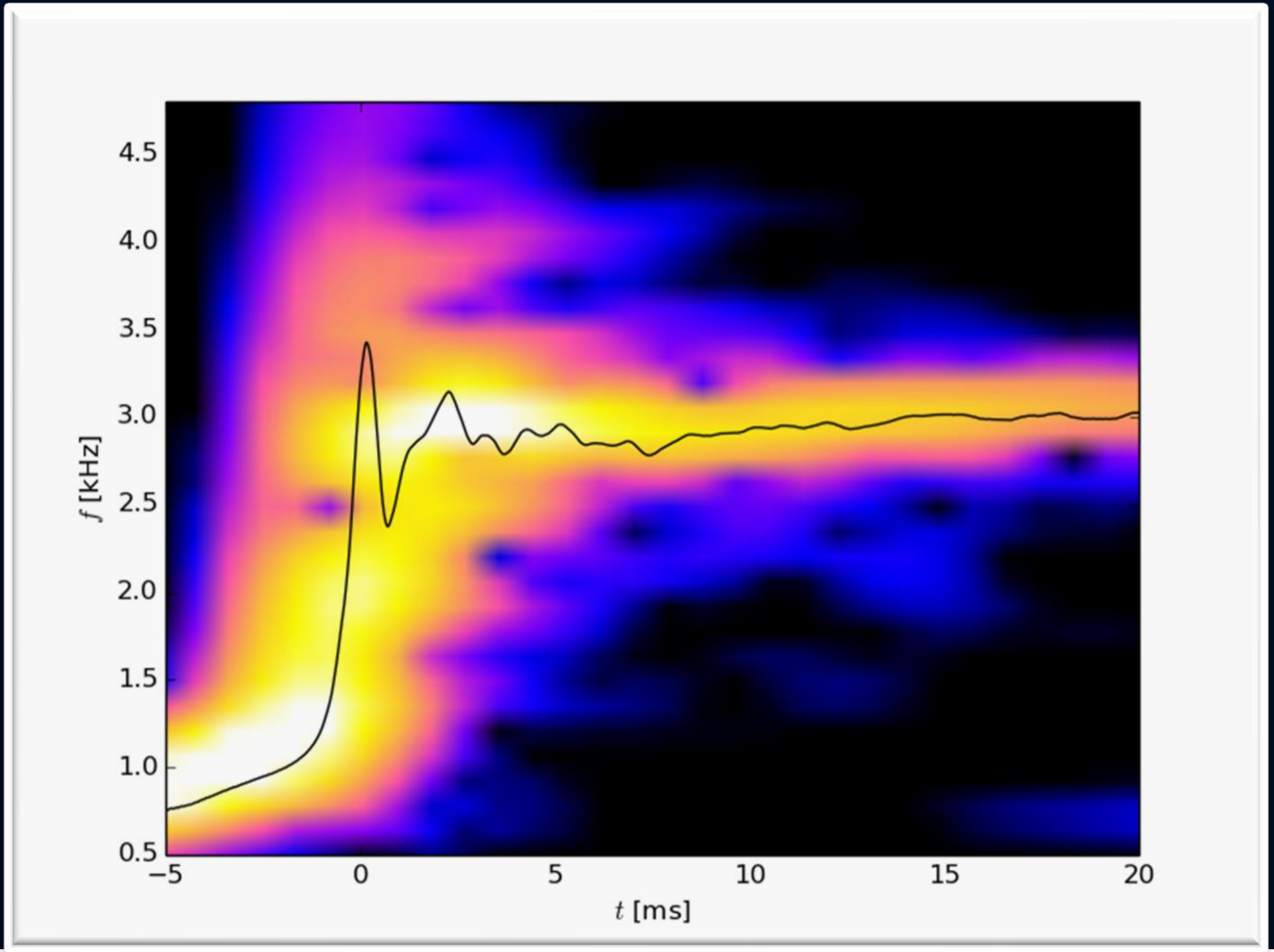
Gravitational wave amplitude
at a distance of 50 Mpc

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

The Co-Rotating Frame

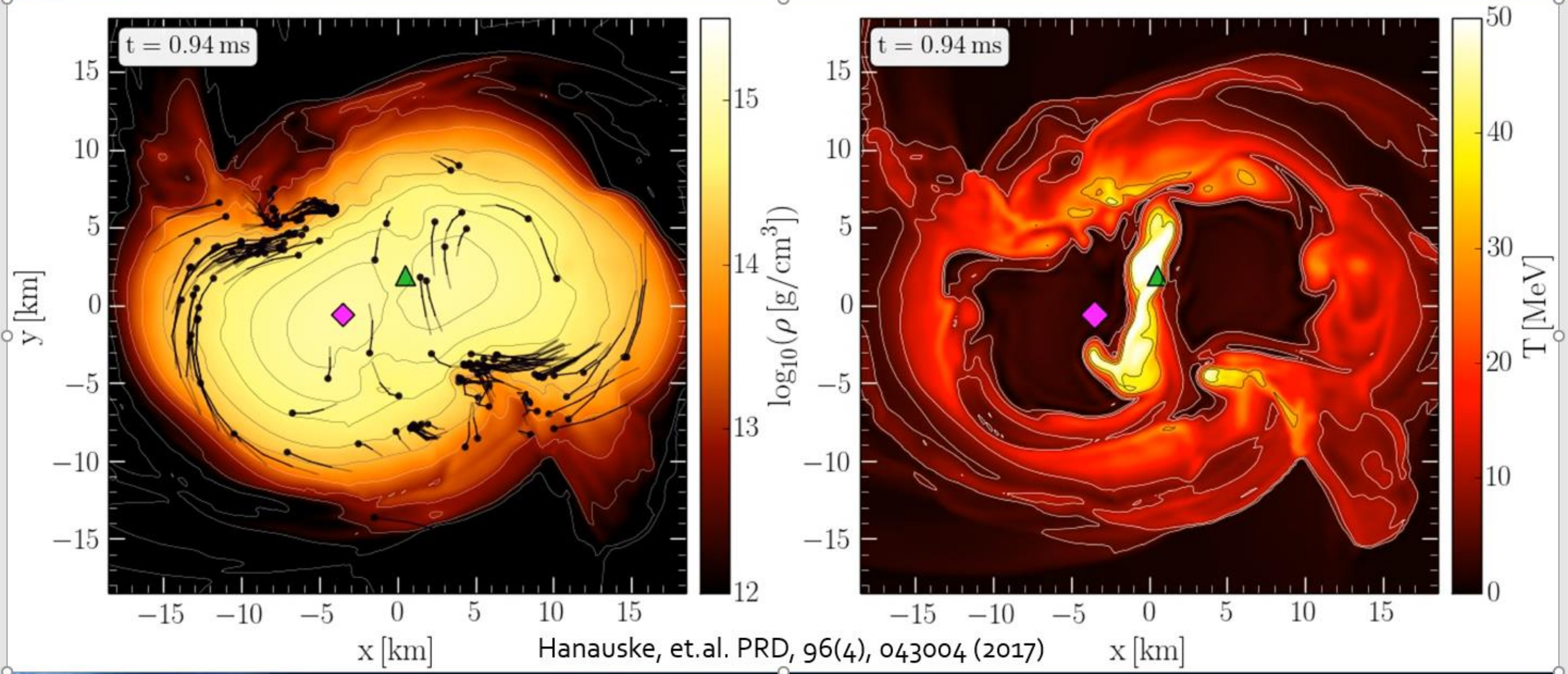


Simulation and movie has been produced by Luke Bovard



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.

Density and Temperature Evolution inside the HMNS

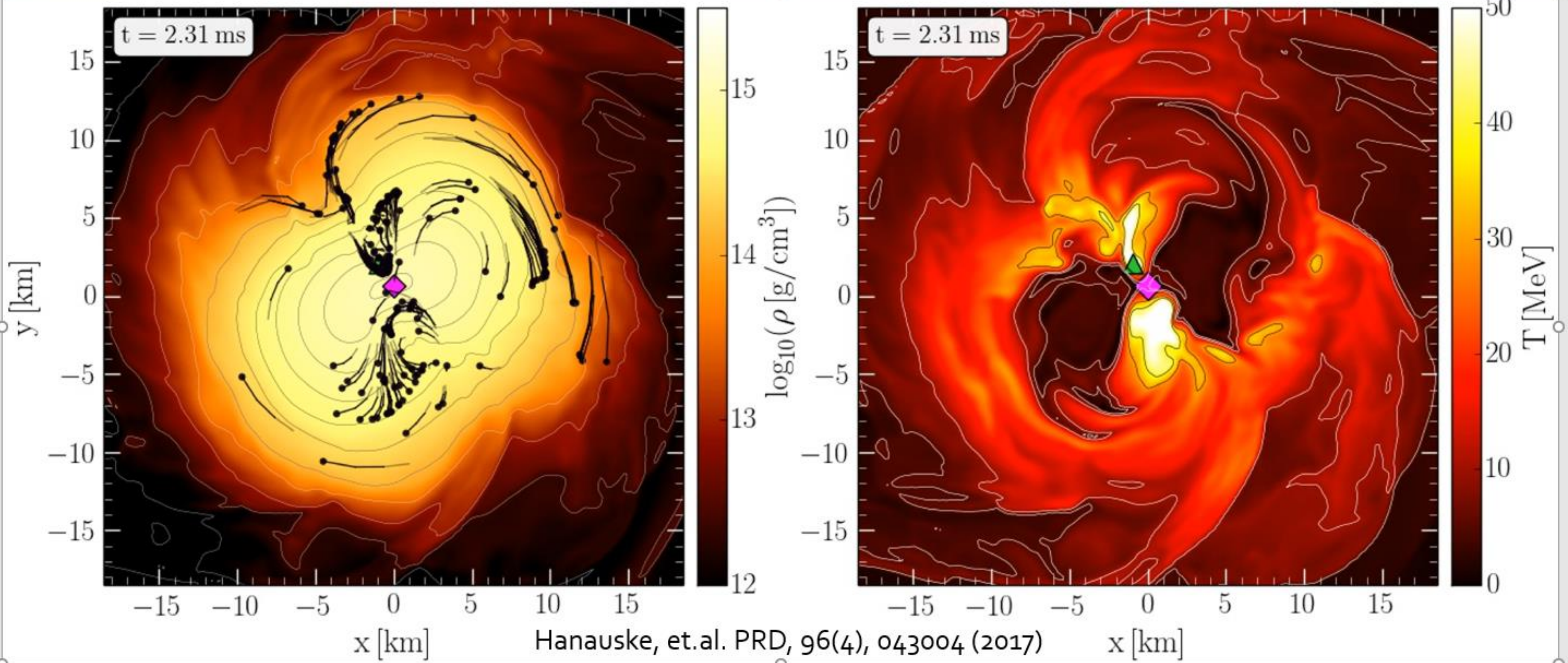


Hanauske, et.al. PRD, 96(4), 043004 (2017)

Rest mass density on the equatorial plane

Temperature on the equatorial plane

Density and Temperature Evolution inside the HMNS



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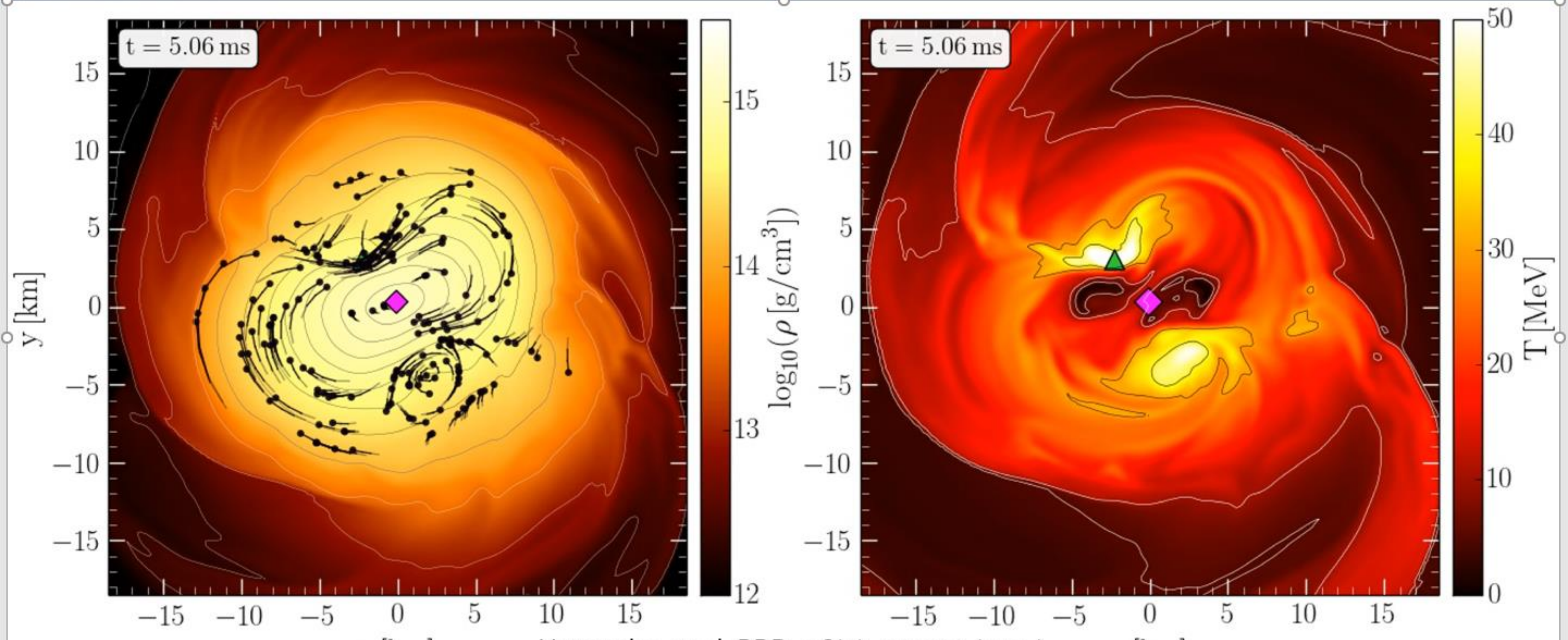

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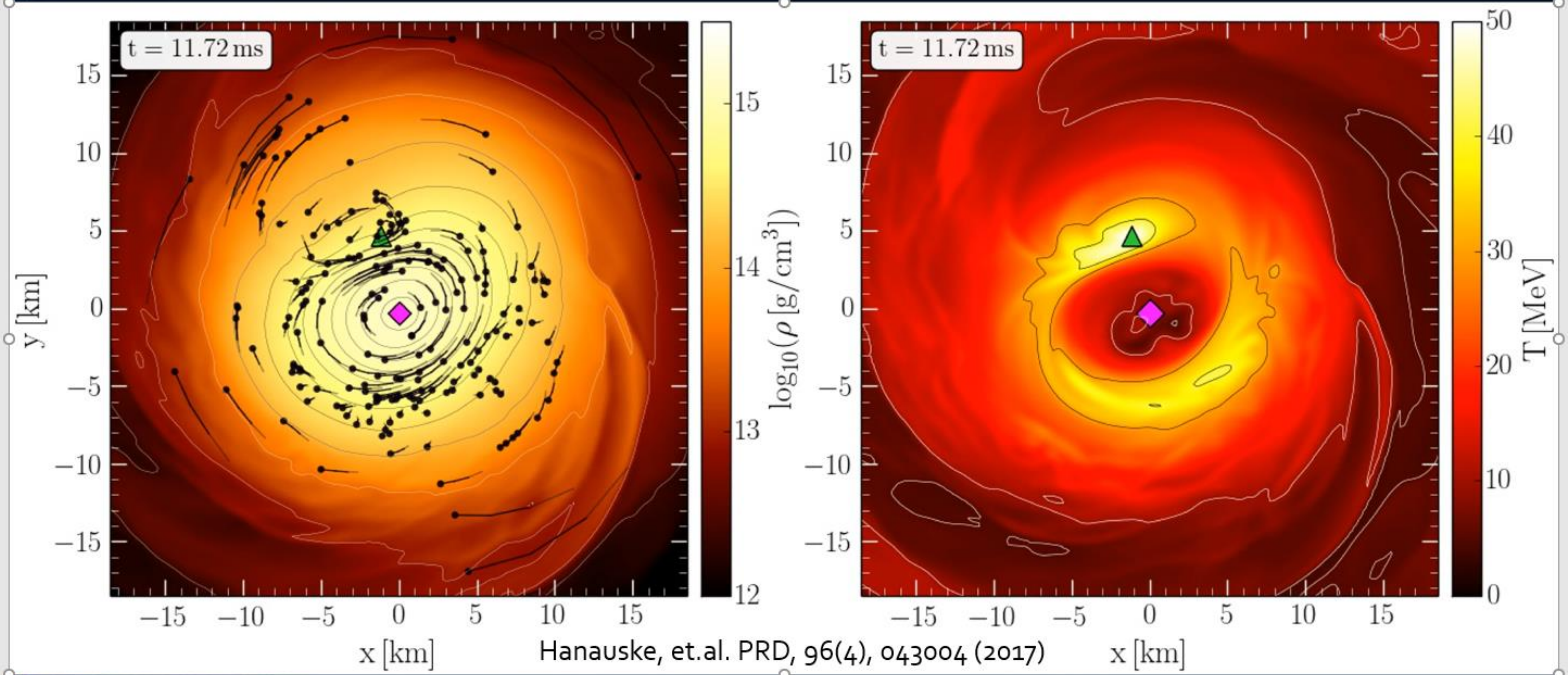

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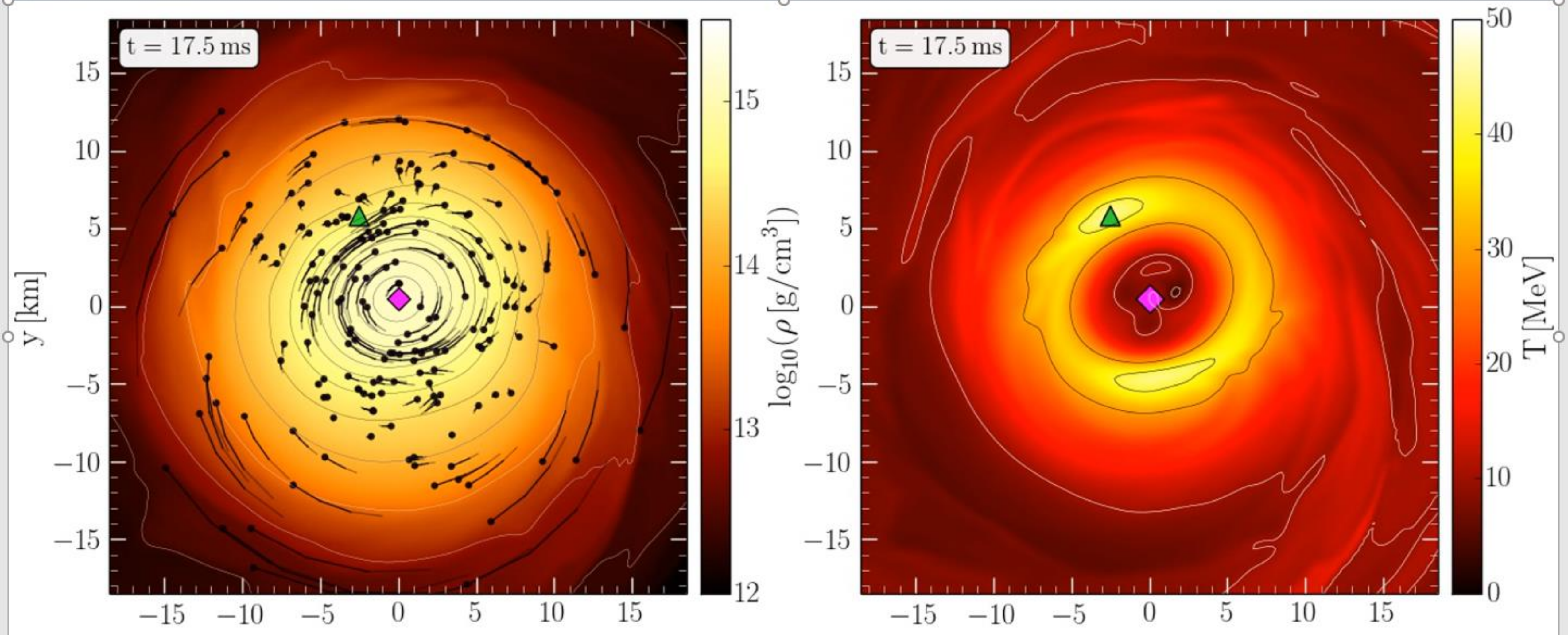
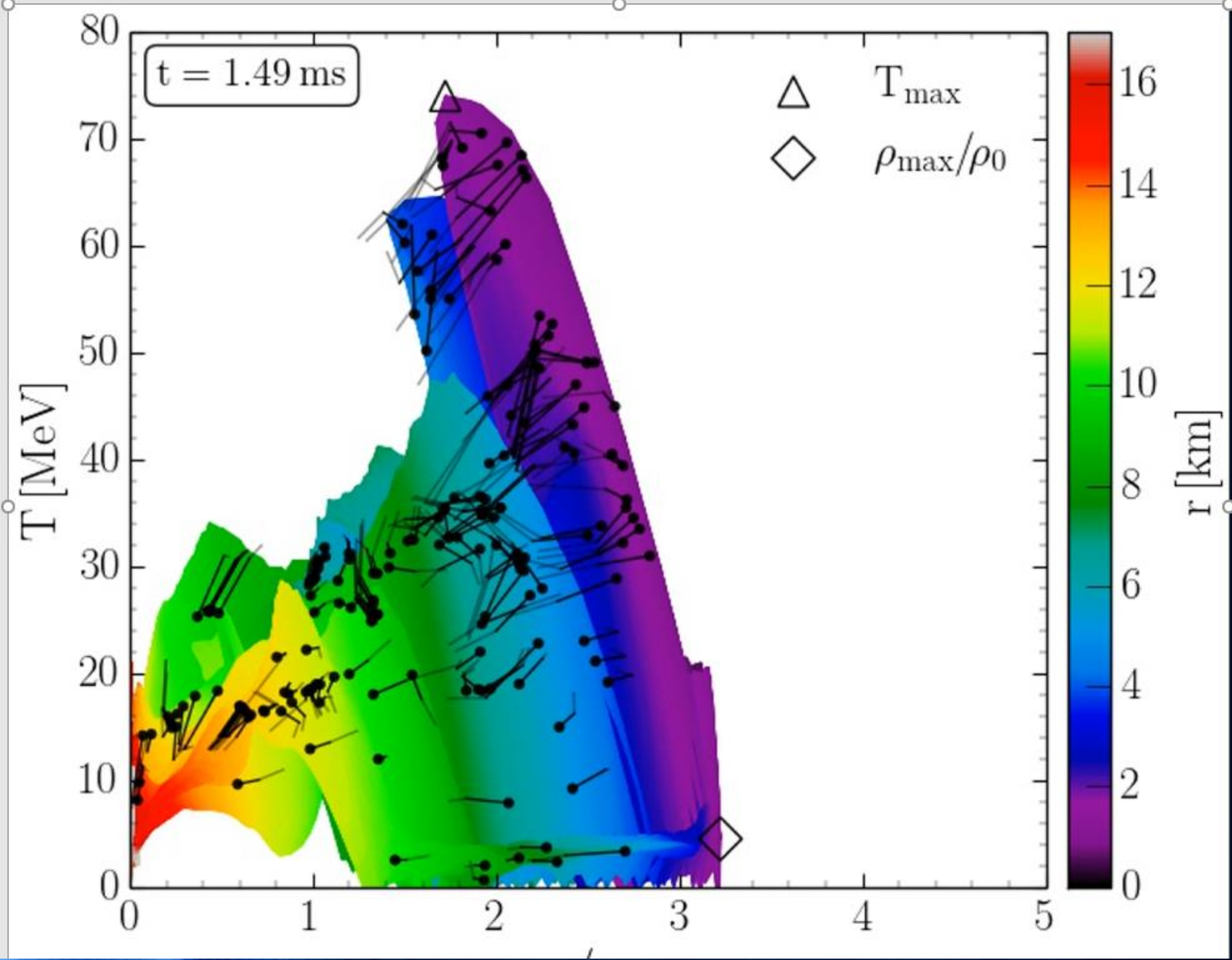


Hanauske, et.al. PRD, 96(4), 043004 (2017)

Rest mass density on the equatorial plane

Temperature on the equatorial plane

Binary Neutron Star Mergers in the QCD Phase Diagram

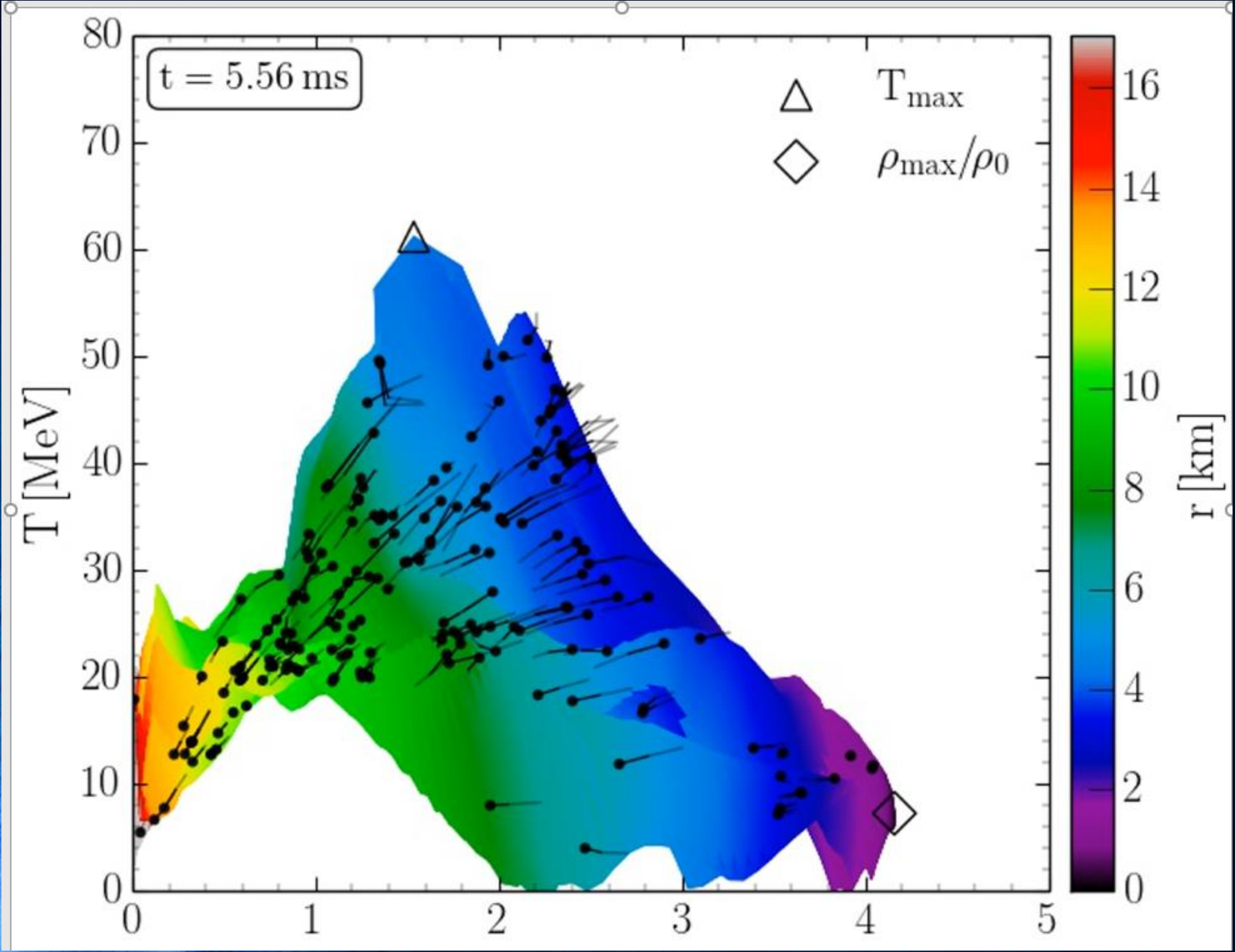


Evolution of hot and dense matter inside the inner area of a hypermassive neutron star simulated within the LS220 EOS with a total mass of $M_{total}=2.7\ M_\odot$ in the style of a (T- ρ) QCD phase diagram plot

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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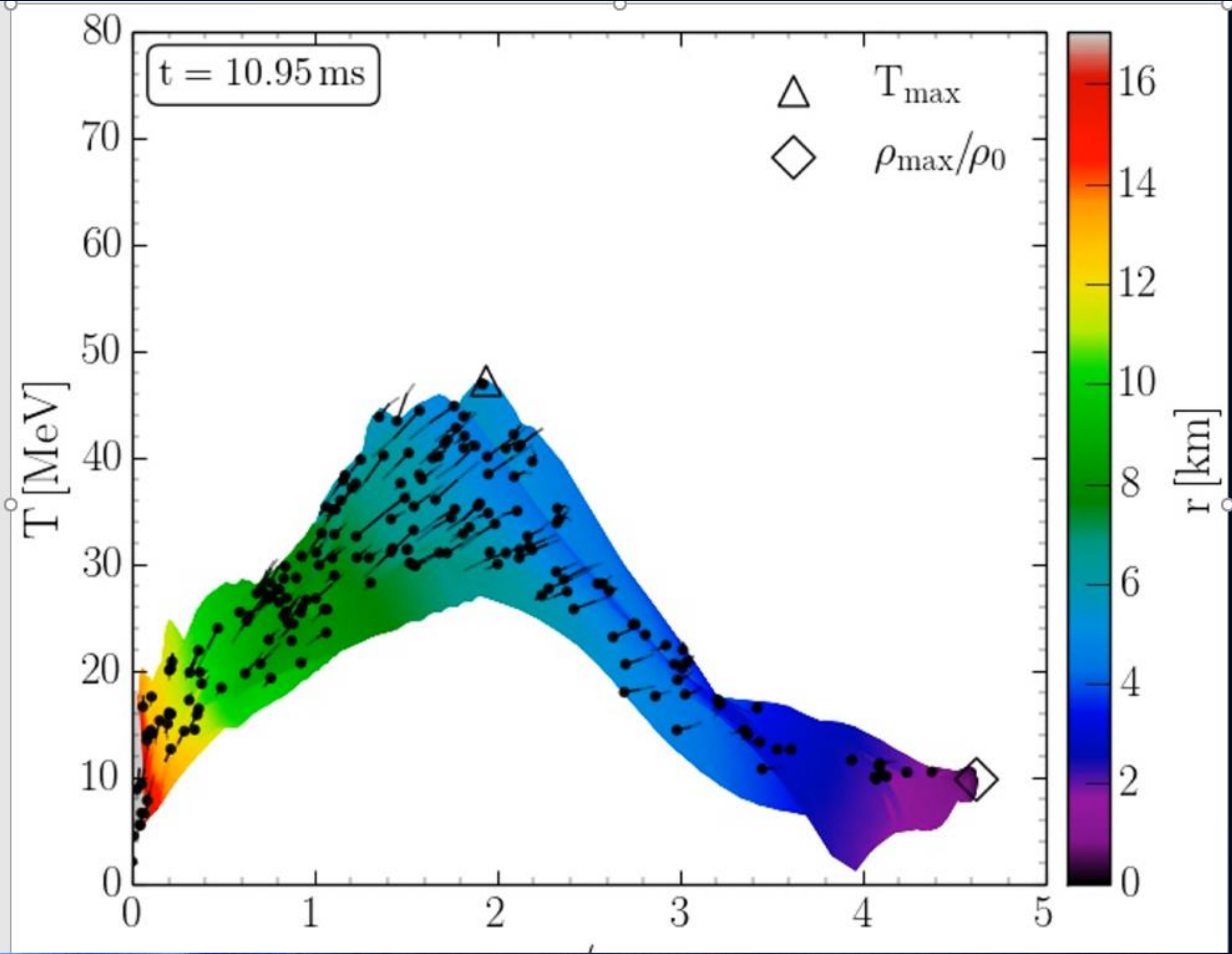

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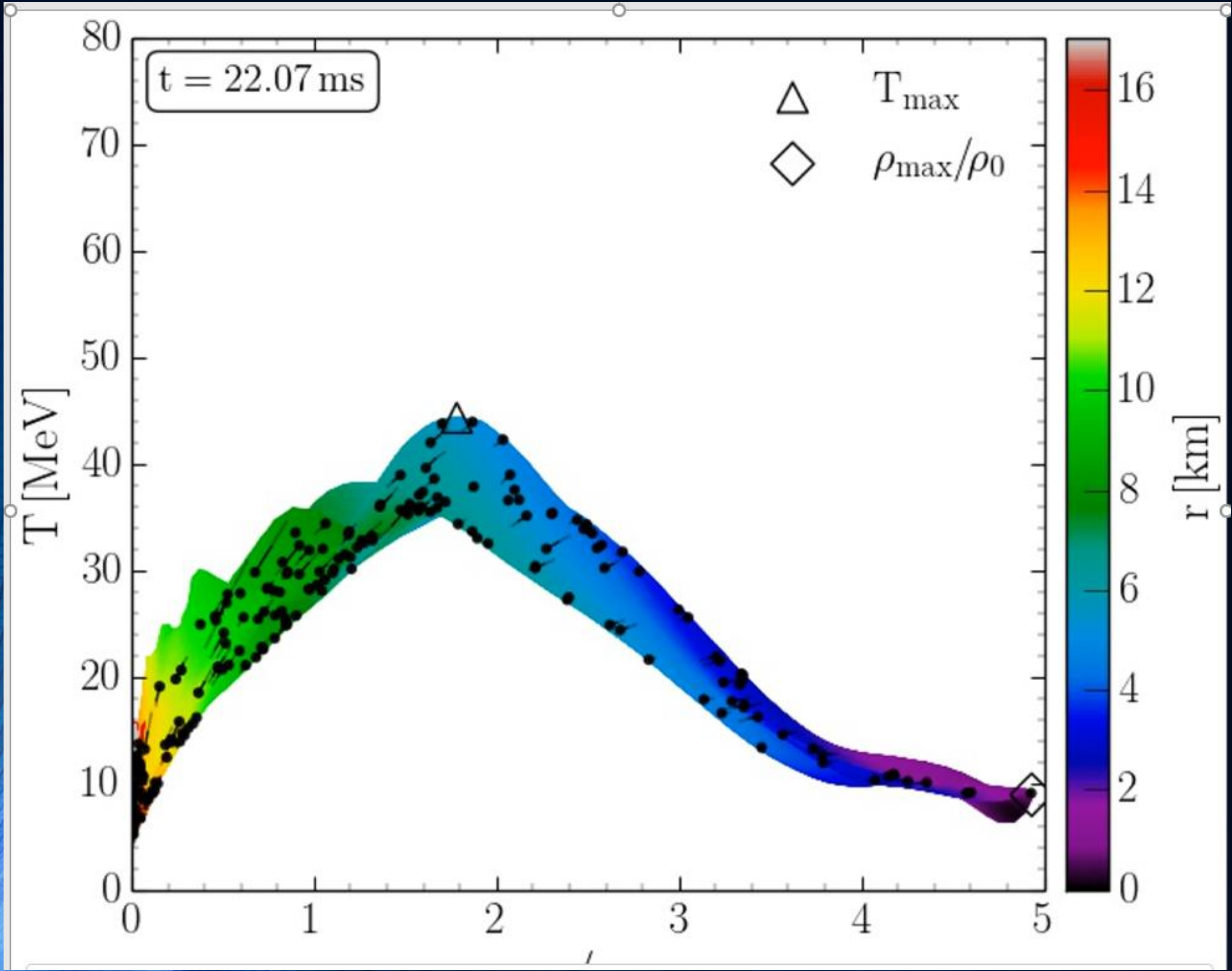

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The Angular Velocity in the (3+1)-Split

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**):

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

Angular velocity Ω

Lapse function α

Φ-component of 3-velocity v^{φ}

Frame-dragging β^{φ}

$g_{\mu\nu}$

Today's plenary talk

Ignazio Ciufolini

University of Salento

Frame-Dragging And ITS Tests With LASER Relativity And Geodesy Satellites

Gravity Probe B, LARES, …

Focus: Inner core of the differentially rotating HMNS

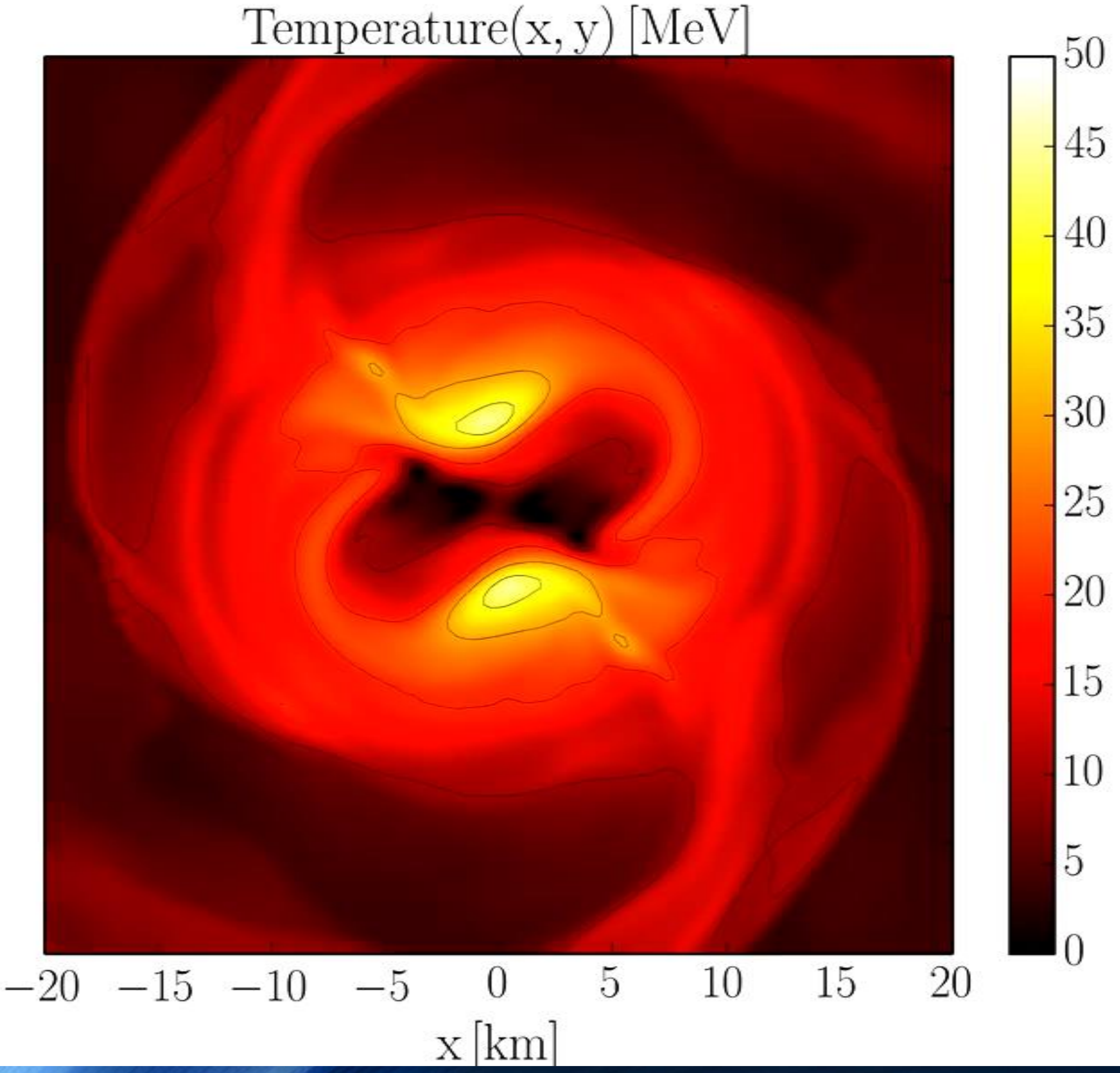
M. Shibata, K. Taniguchi, and K. Uryu, Phys. Rev. D 71, 084021 (2005)

M. Shibata and K. Taniguchi, Phys. Rev. D 73, 064027 (2006)

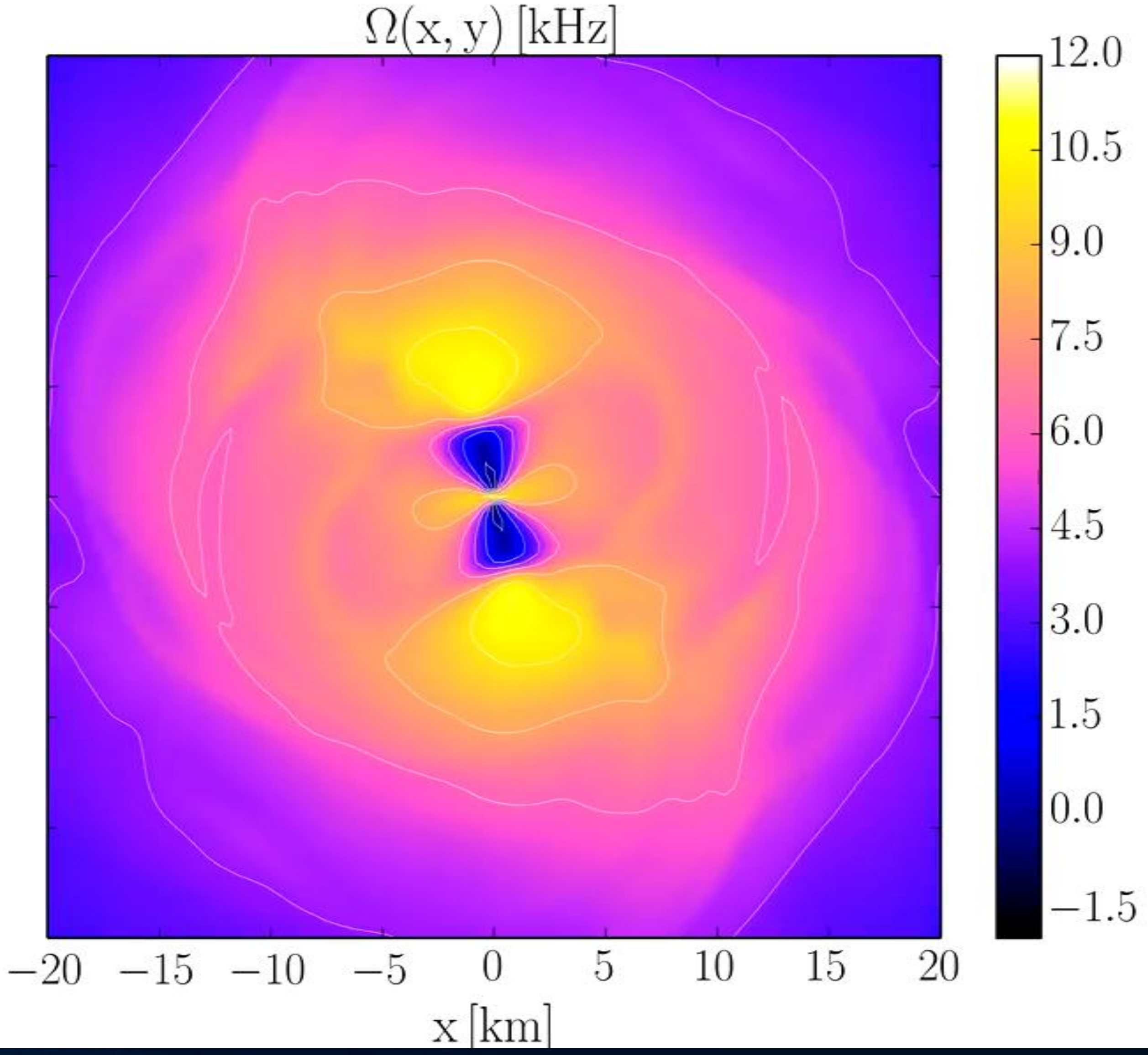
F. Galeazzi, S. Yoshida and Y. Eriguchi, A&A 541, p. A156 (2012)

W. Kastaun and F. Galeazzi, Phys. Rev. D 91, p. 064027 (2015)

Temperature

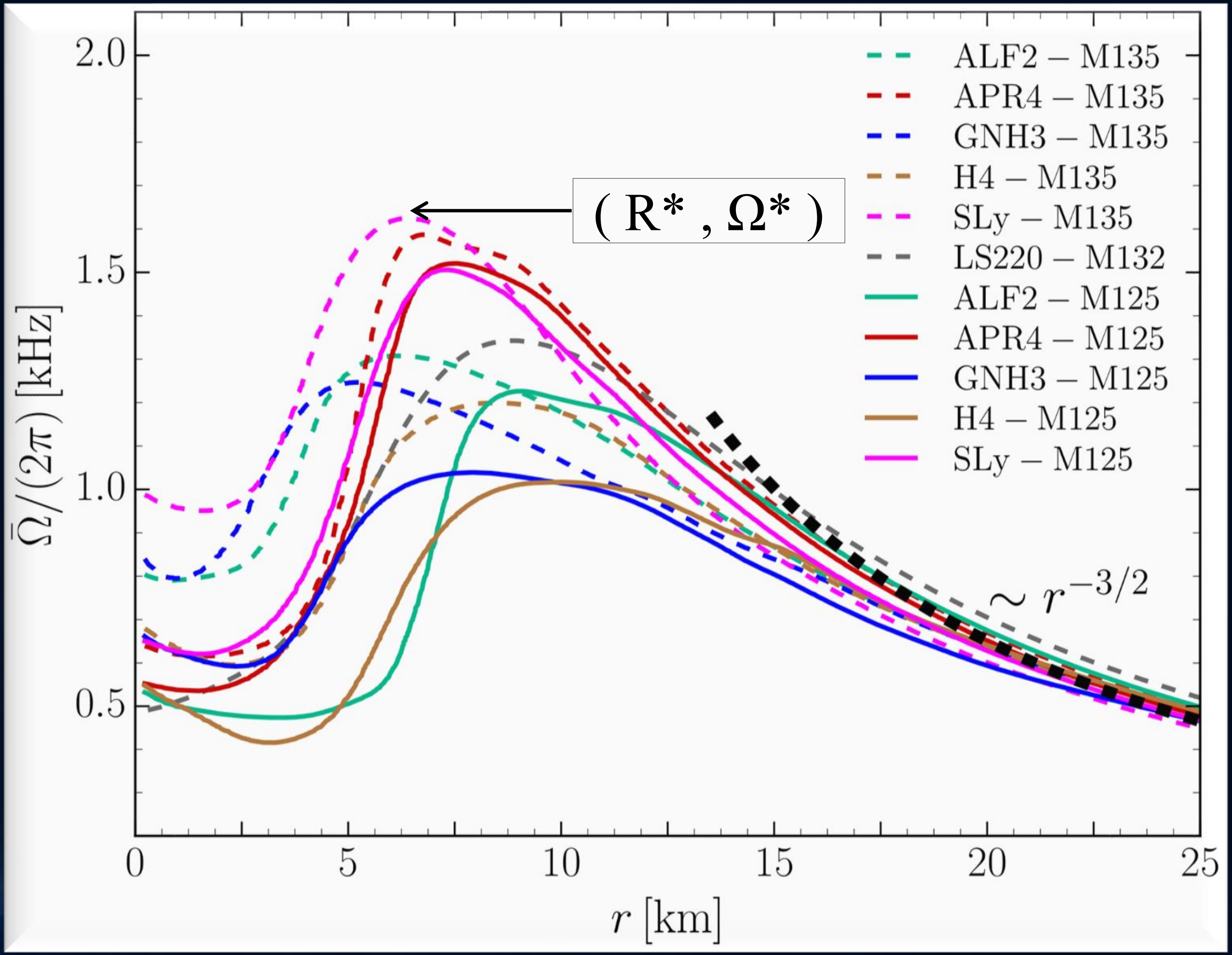


Angular Velocity



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

Time-averaged Rotation Profiles of the HMNSs

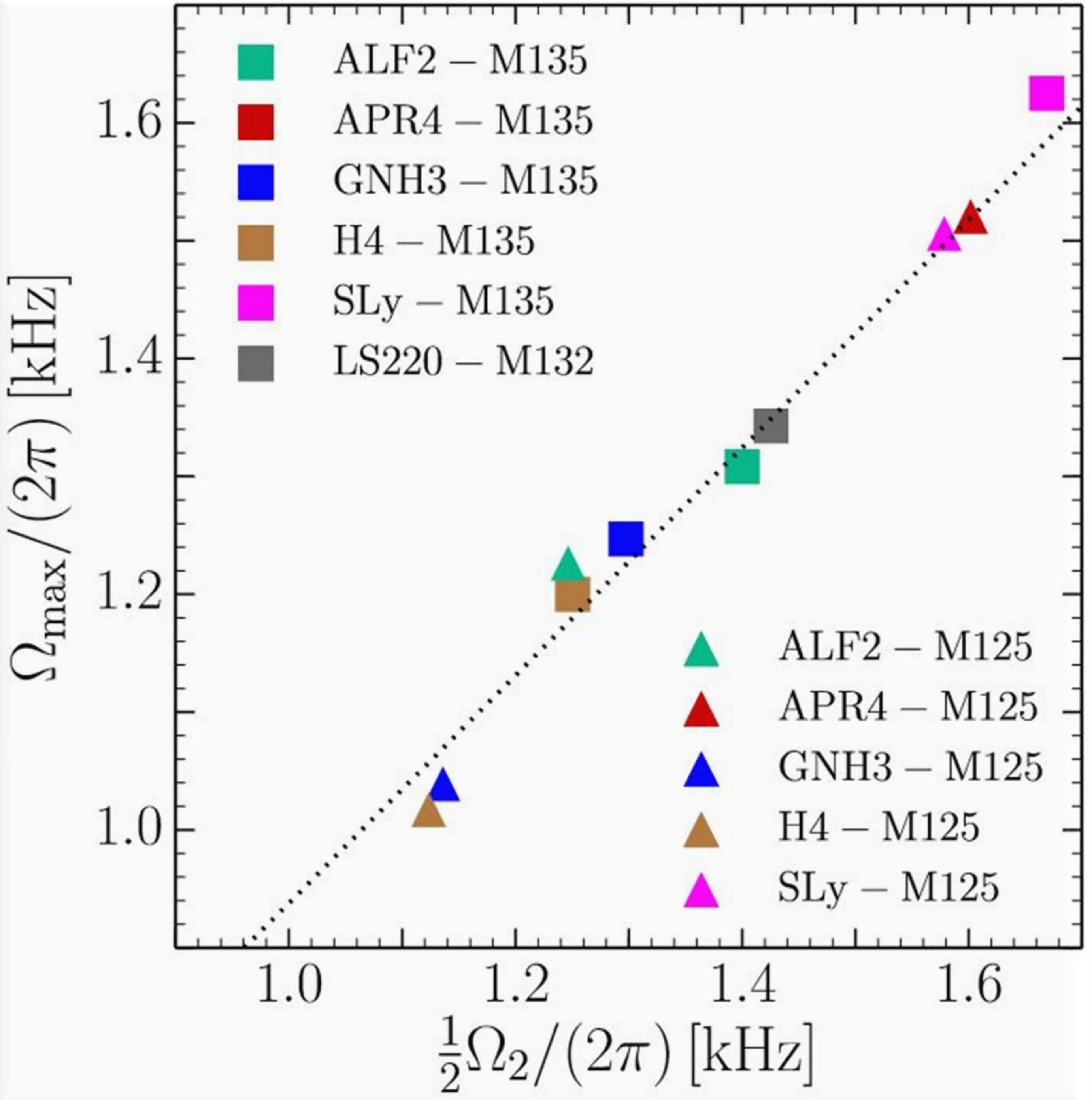


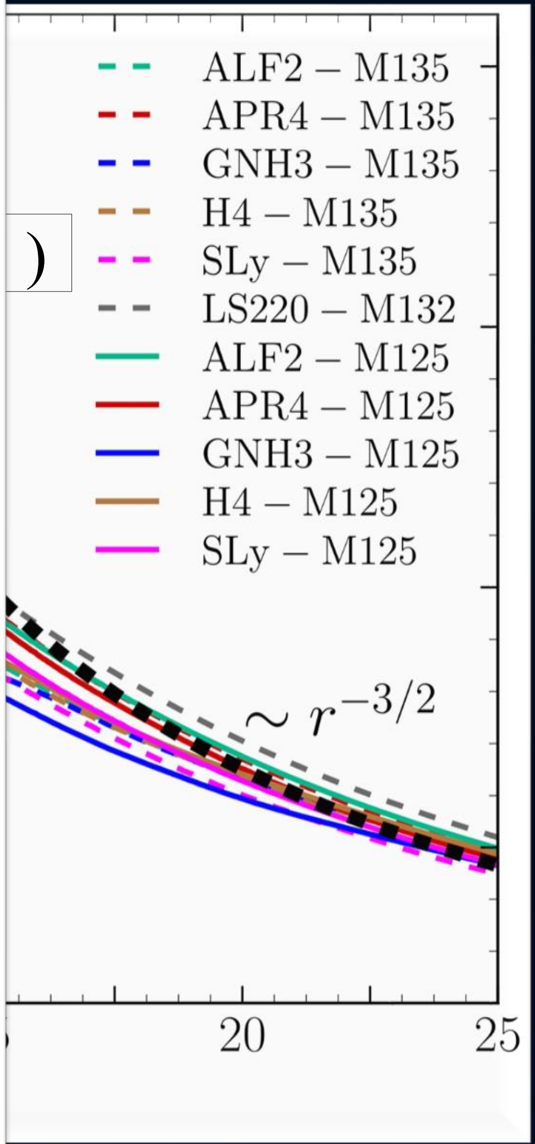
Soft EoSs:
Sly
APR4

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) files of the HMNSs





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

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

S

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

lashed curves).

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

- Gravitational-wave signatures of the hadron-quark phase transition in binary compact star mergers
  - *Signatures within the late inspiral phase (premerger signals)*
    - Constraining twin stars with GW170817; G Montana, L Tolós, M Hanauske, L Rezzolla; Physical Review D 99 (10), 103009 (2019)
  - *Signatures within the post-merger phase evolution*
    - **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, L. Rezzolla; Physical review letters 122 (6), 061101 (2019)
    - **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)
    - **Prompt phase transition scenario**
      Identifying a first-order phase transition in neutron-star mergers through gravitational waves; A Bauswein, NUF Bastian, DB Blaschke, K Chatziioannou, JA Clark, JA Clark, T Fischer, M Oertel; Physical review letters 122 (6), 061102 (2019)

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Papenfort, V Dexheimer, M Hanauske, S S
(2019)
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Rezzolla; Physical Review Letters 124 (17
    - **Prompt phase transition scenario**
Identifying a first-order phase transition in n
Bastian, DB Blaschke, K Chatziioannou, JA C
(2019)

Talk on Monday

M.Hanauske

Gravitational-wave signatures of the hadron-quark phase transition in binary compact star mergers

Parallel session: Numerical Relativity and Gravitational Wave Observations

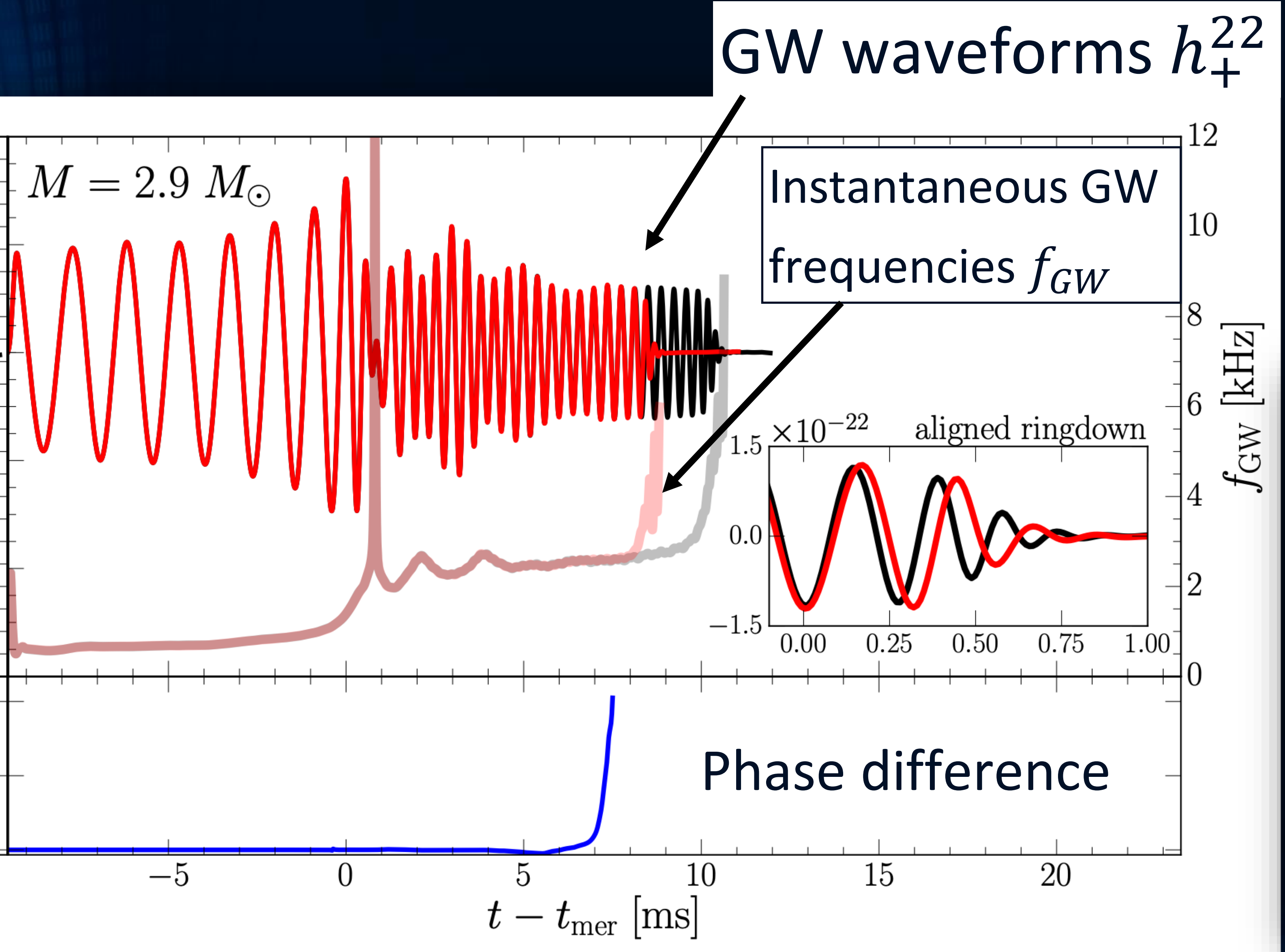
05.07.2021, 17:50

YES WE CAN

(6), 061102

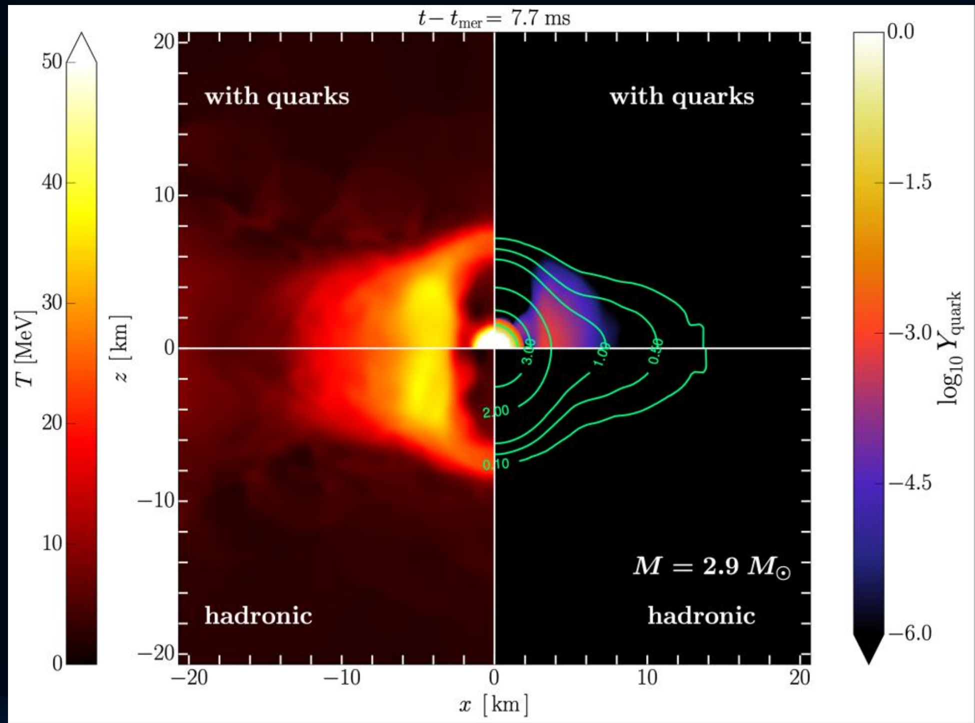
Signatures within the post-merger phase
Phase-transition triggered collapse scenario

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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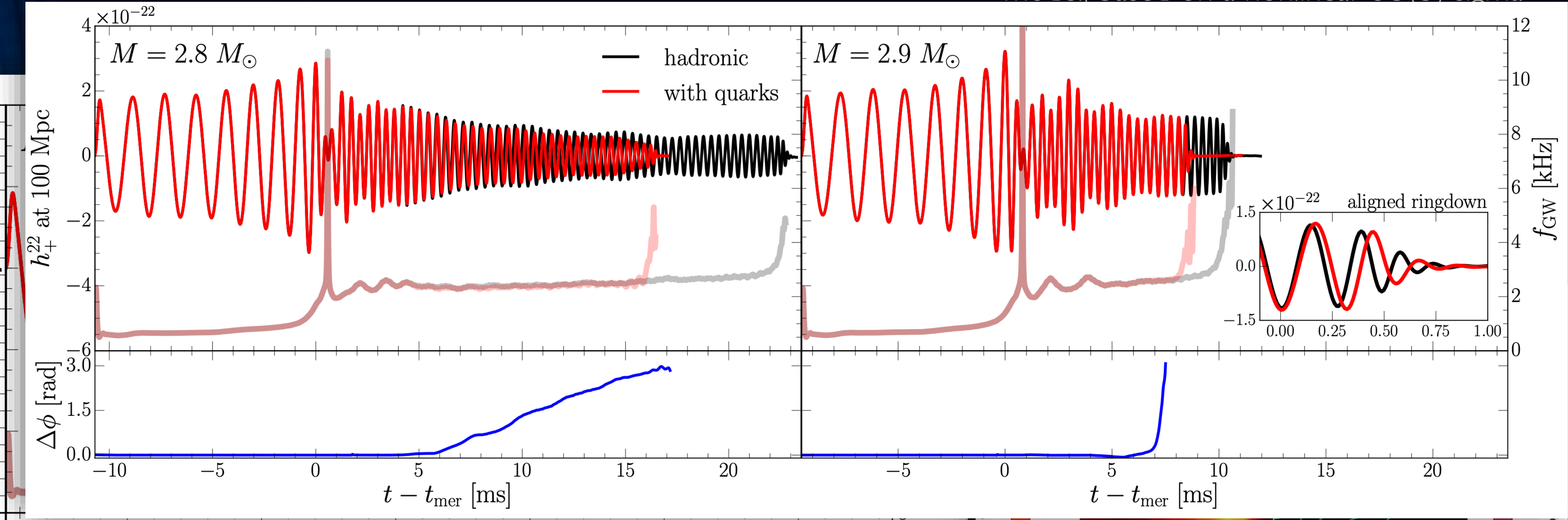
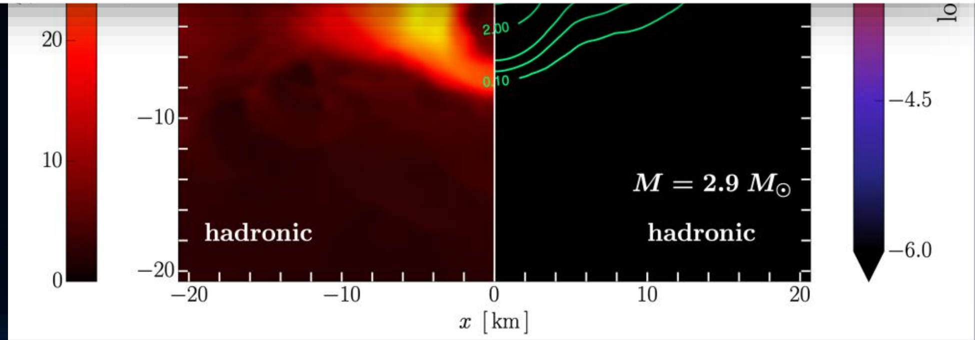


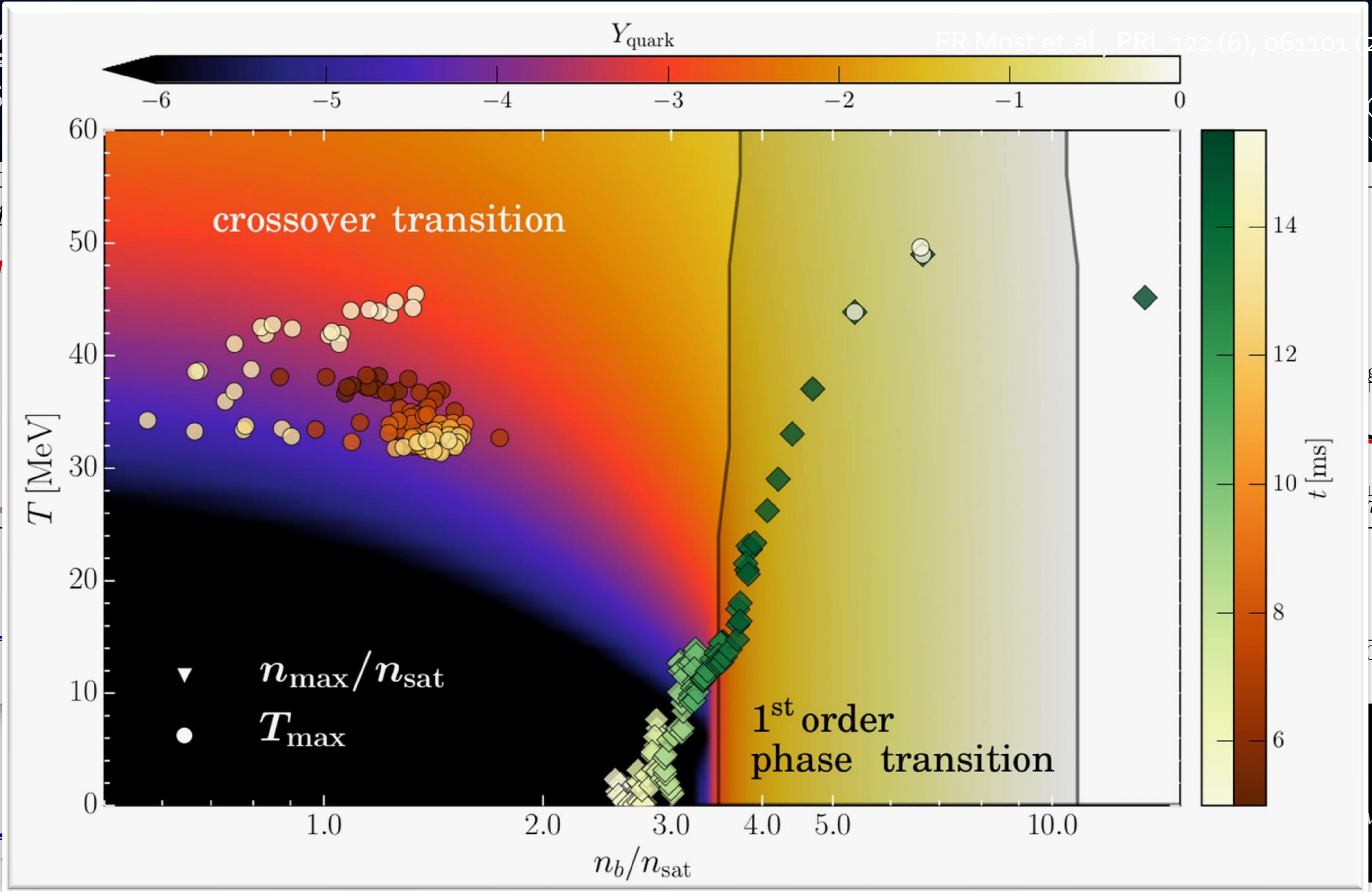
Phase difference



Sig
Phas

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

CMF)
) sigma



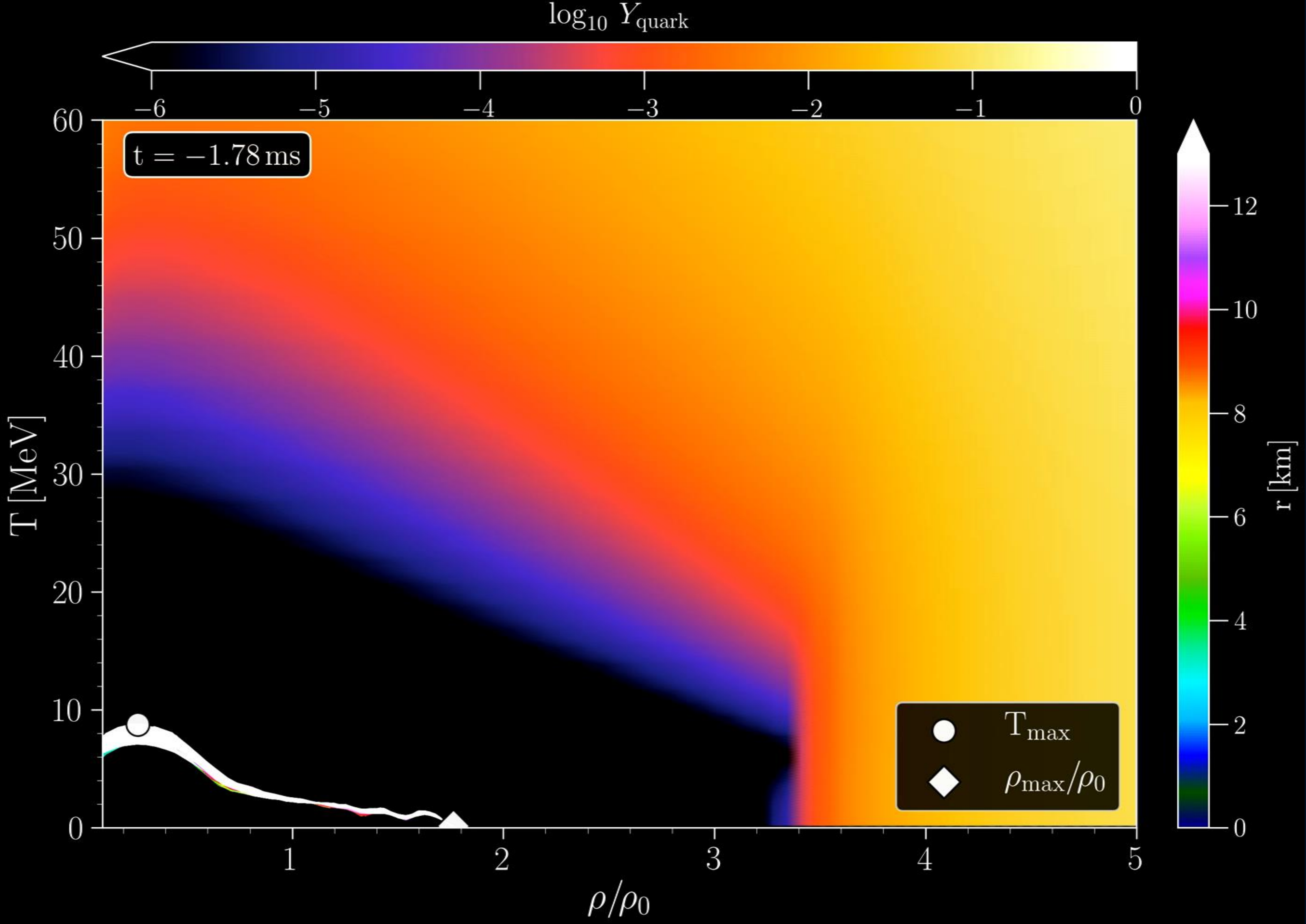
Phase-transition triggered collapse scenario

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

Physical review letters 122 (6), 061101 (2019)

Density-Temperature-Composition dependent EOS within the CMFQ model. Simulation of total mass M=2.8 Msolar



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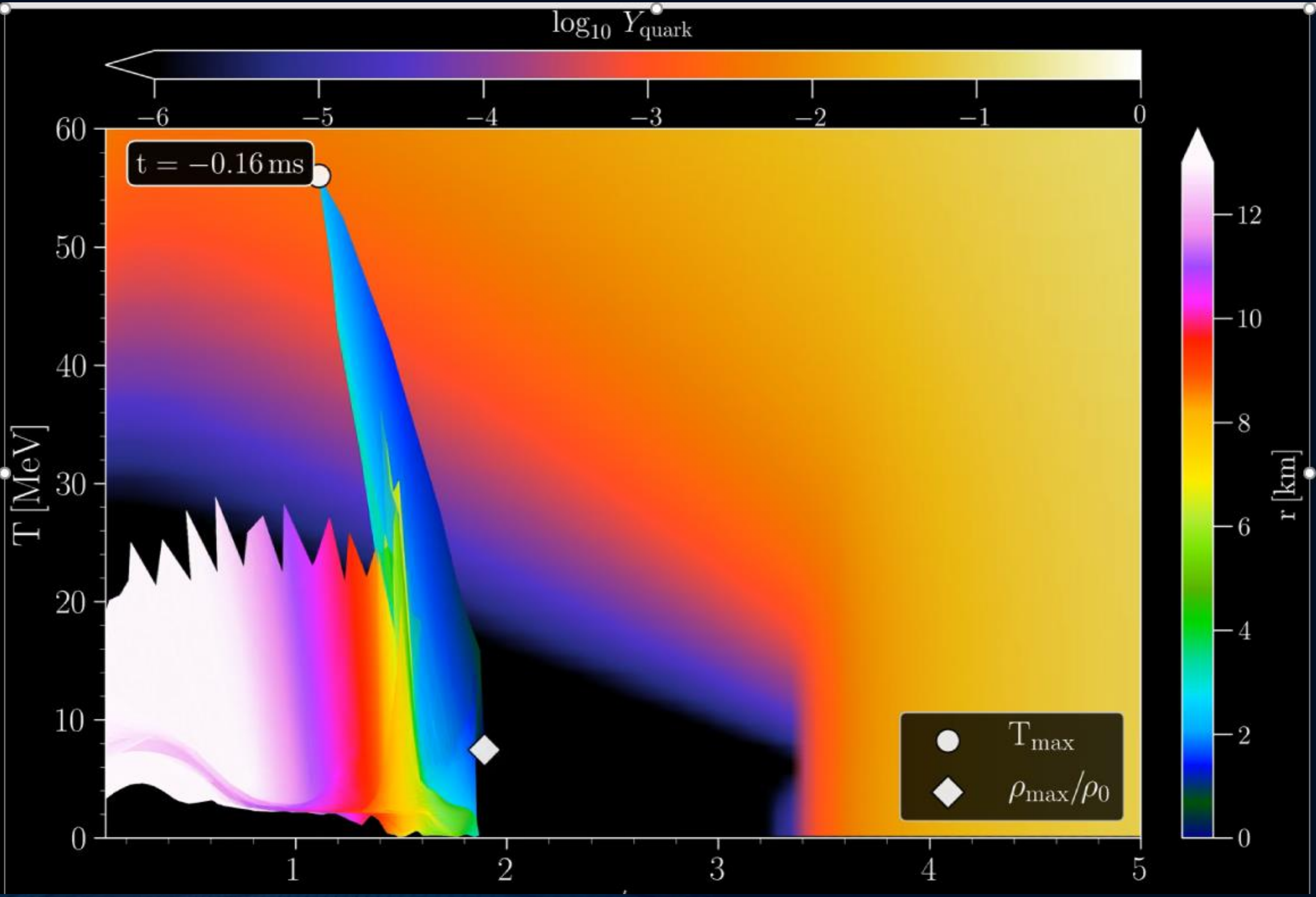

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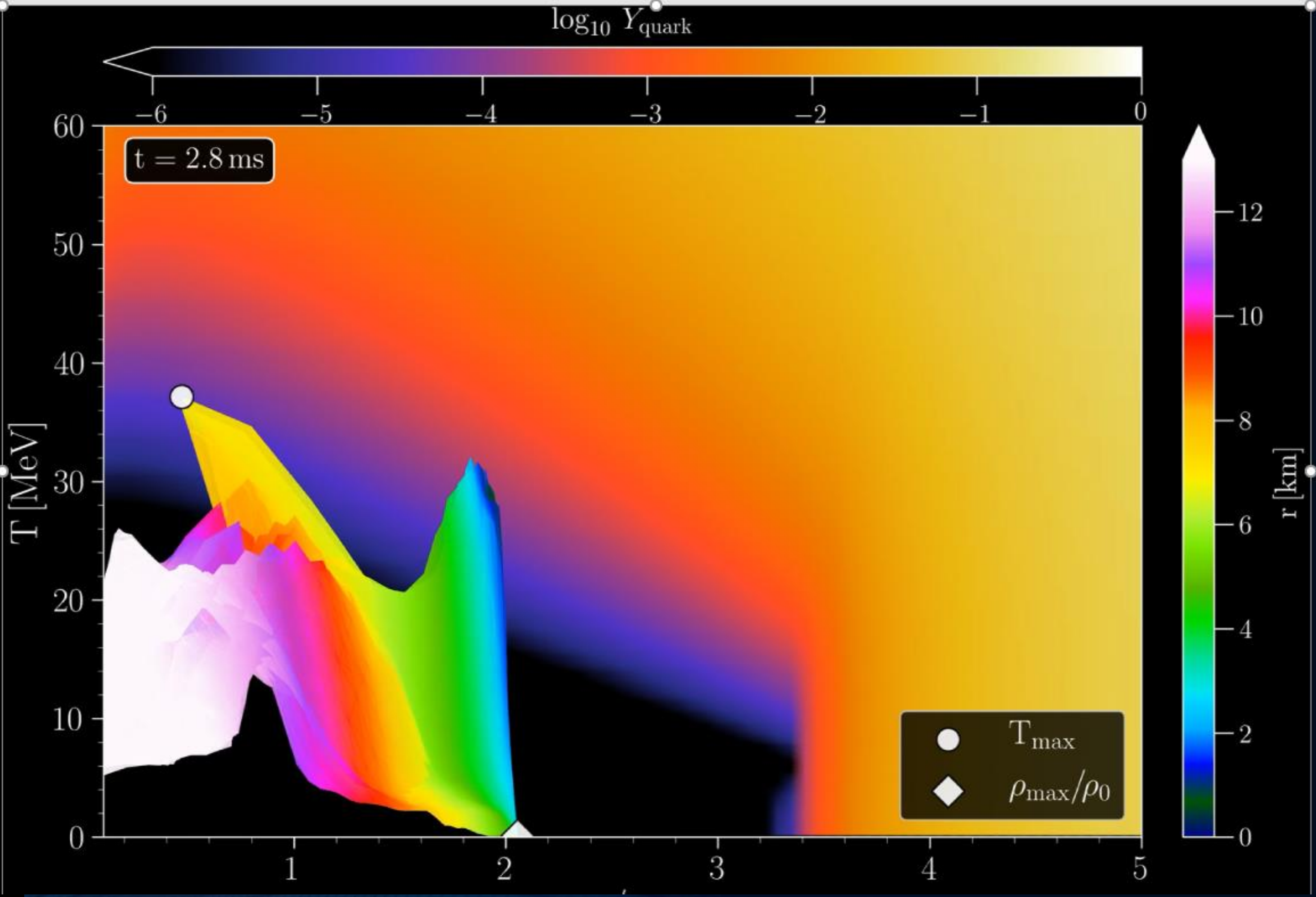

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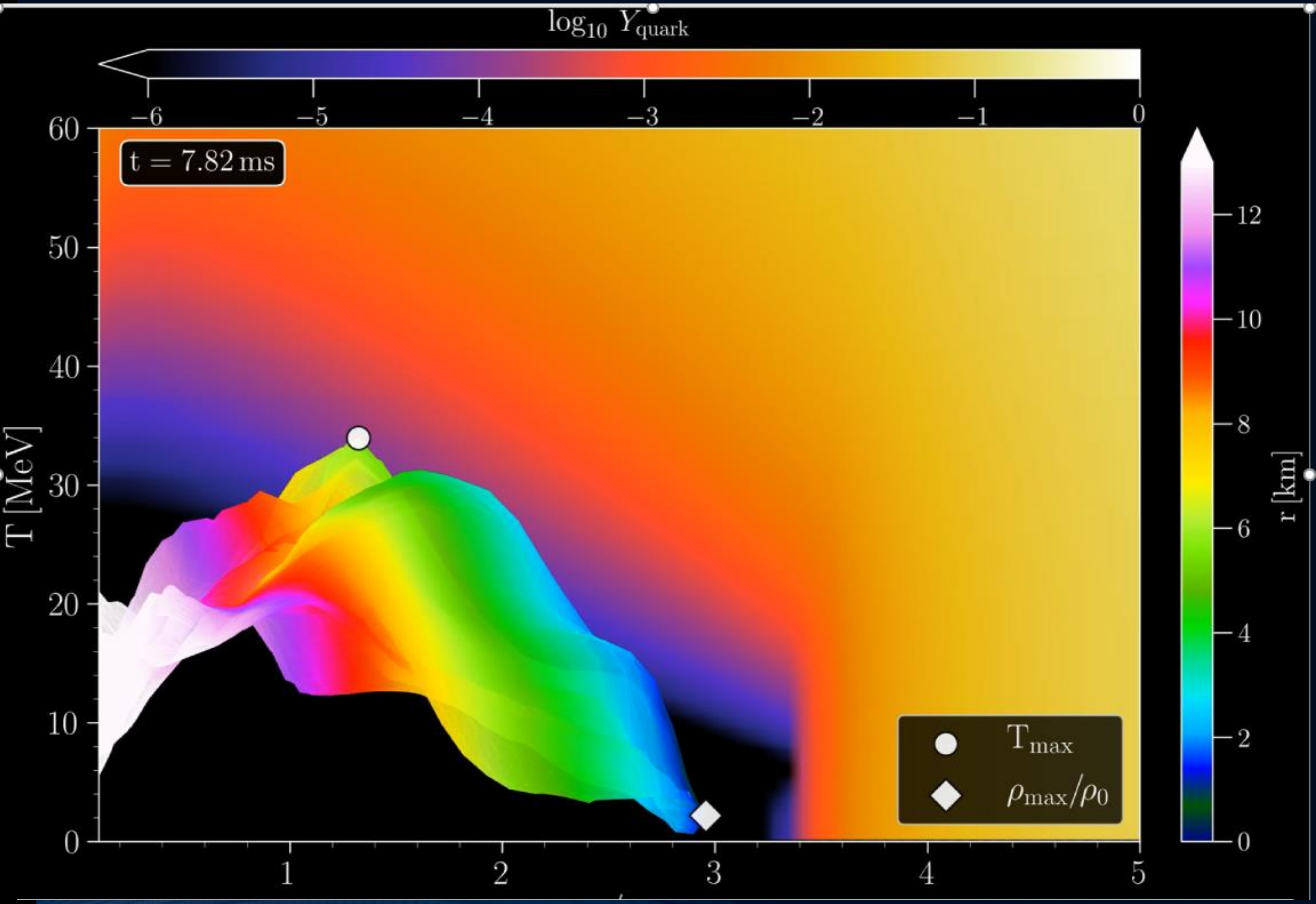

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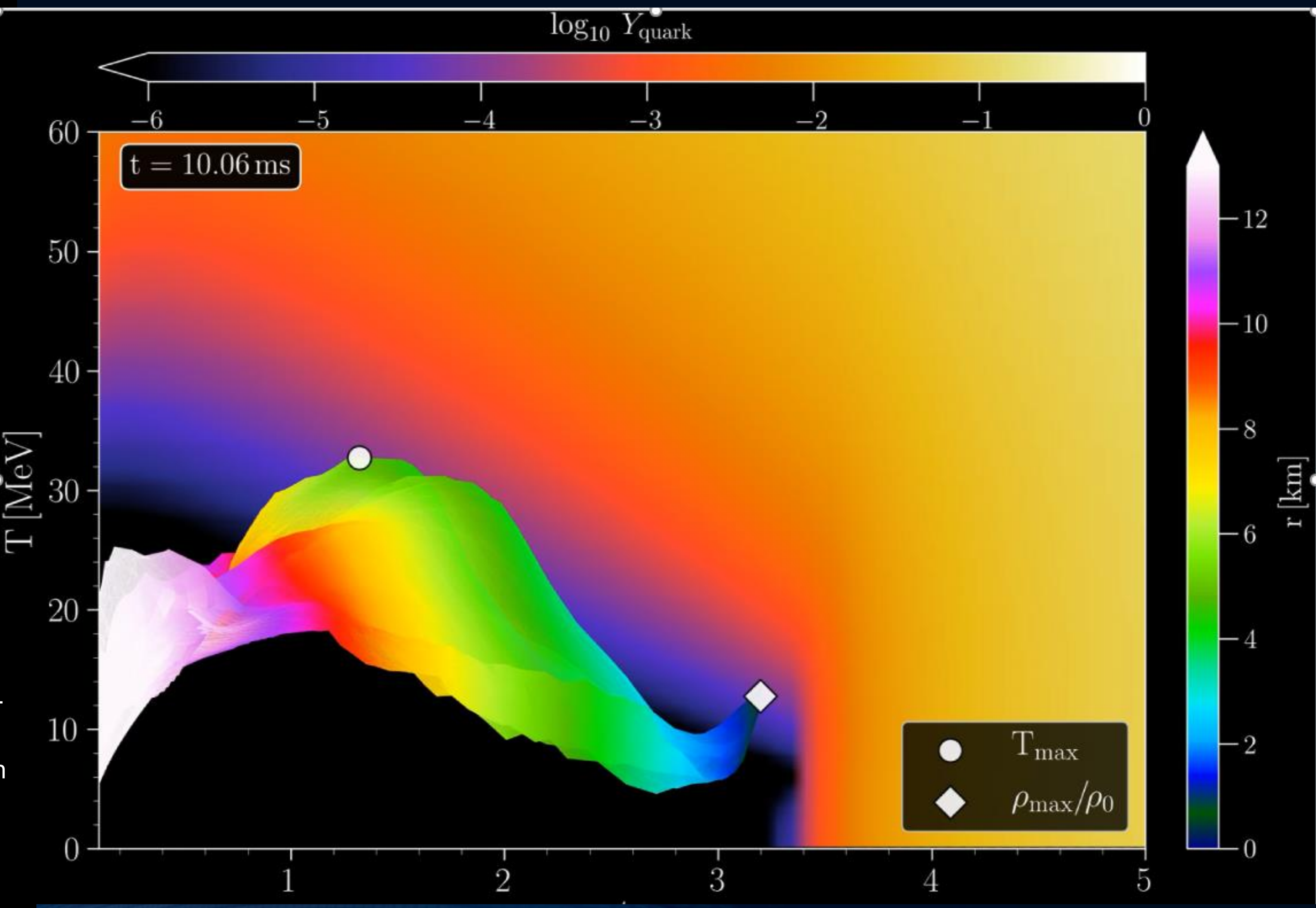
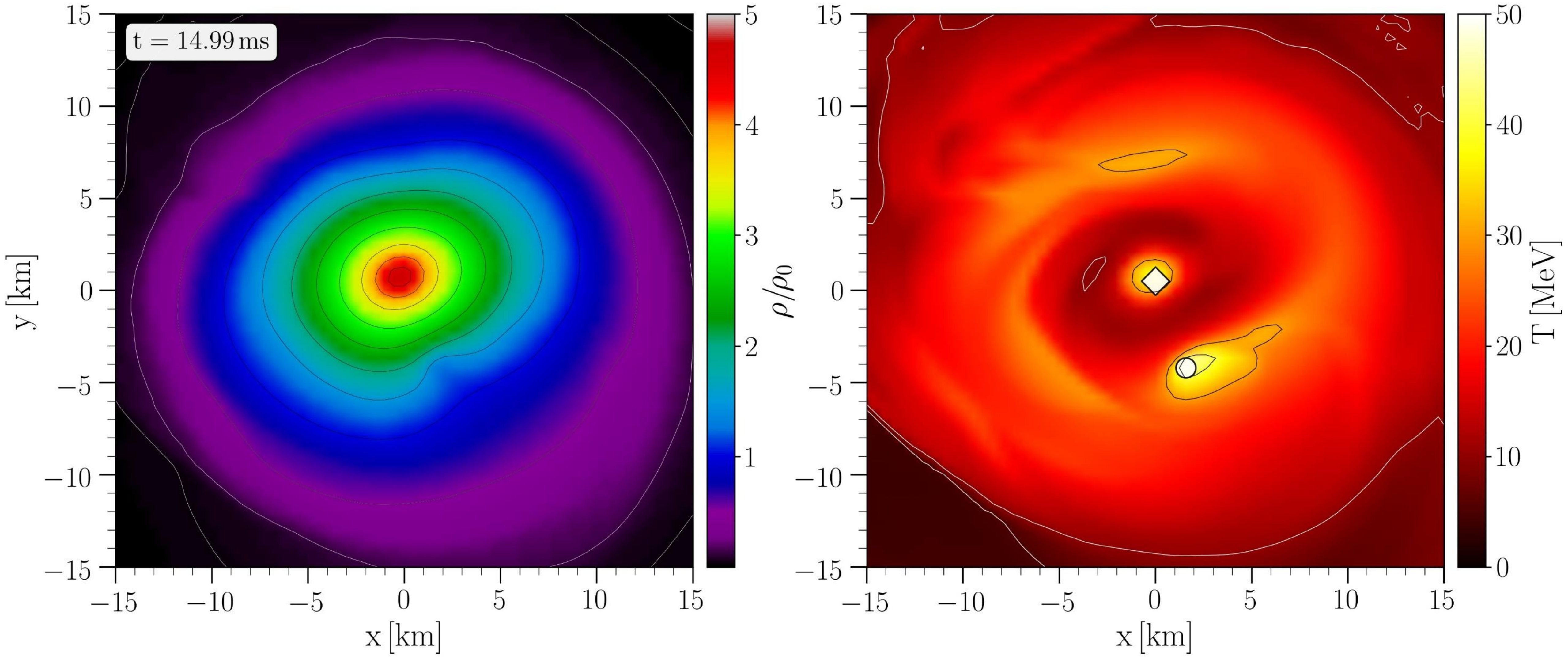


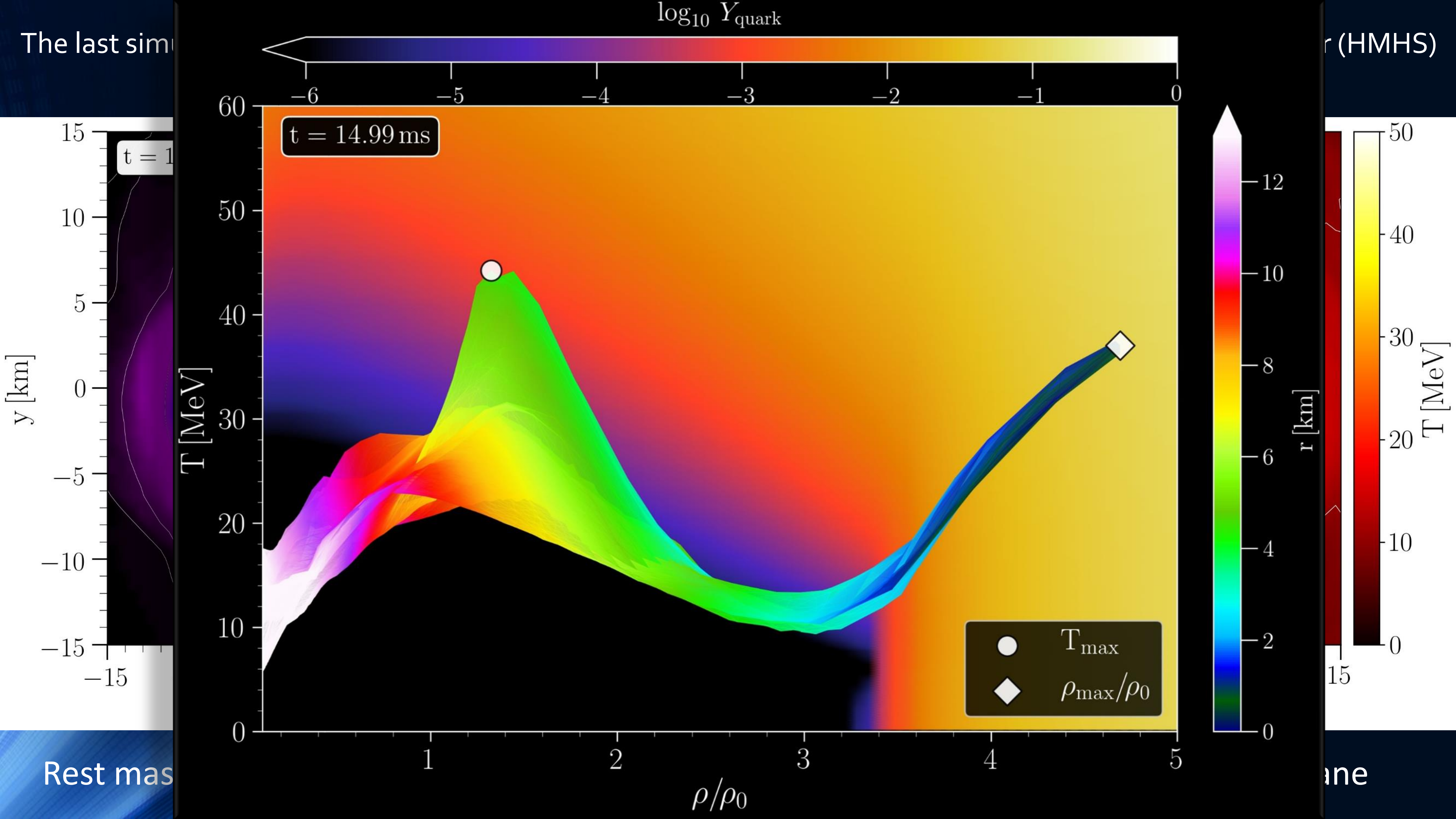
The last simulation snapshots before the apparent horizon is formed inside the HyperMassive Hybrid Star (HMHS)



Rest mass density on the equatorial plane

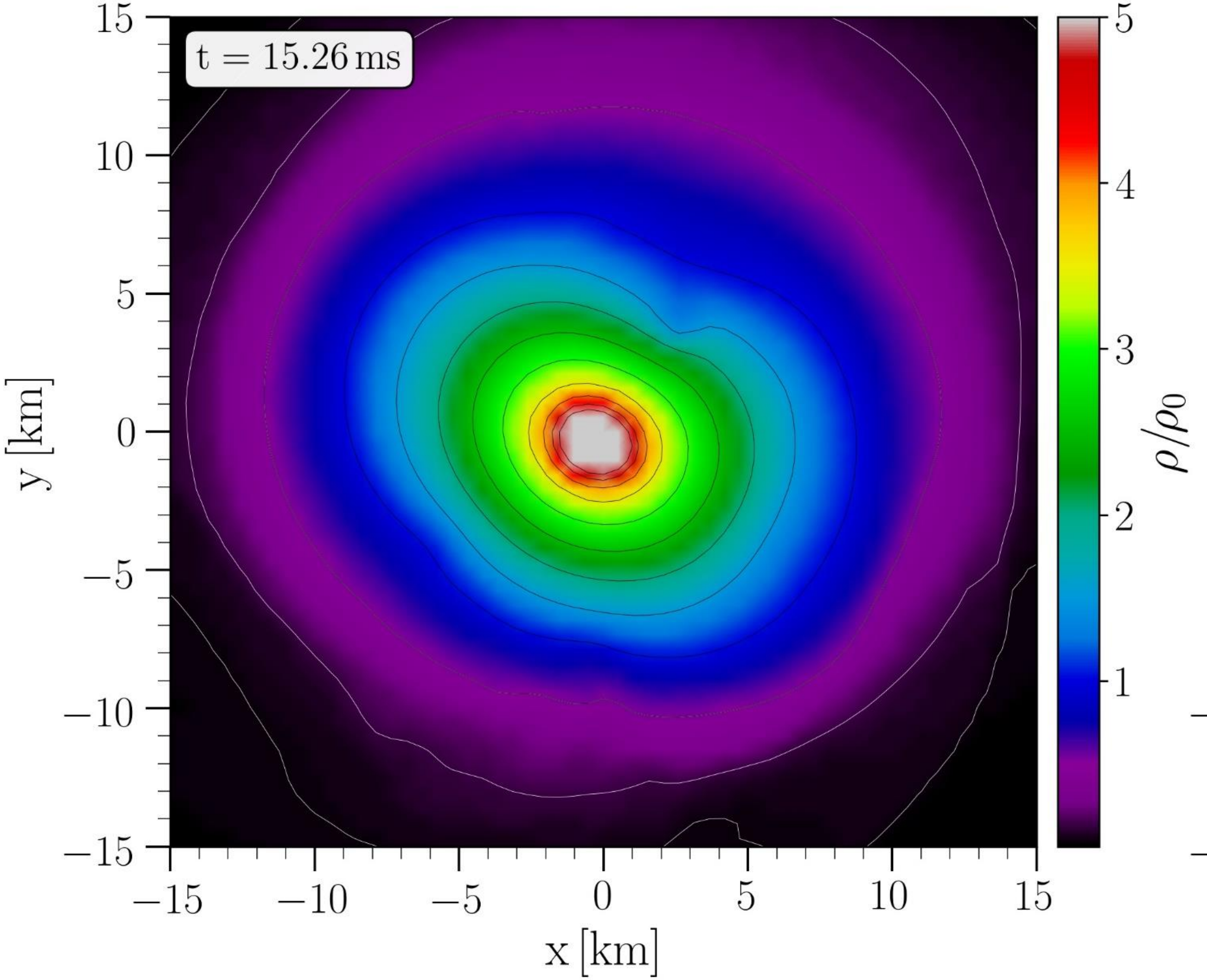
Temperature on the equatorial plane

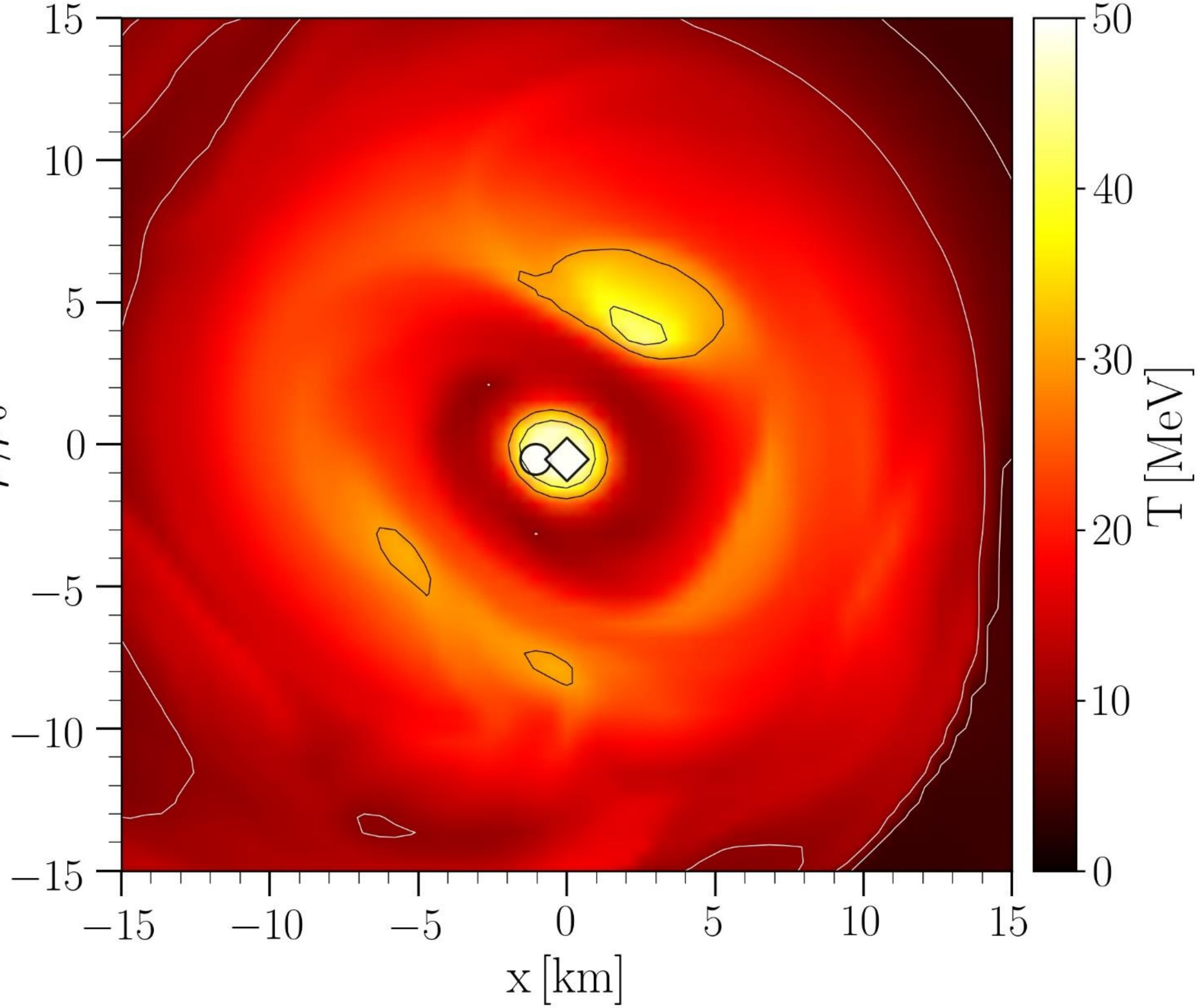
The last simu… r (HMHS)



Rest mas… ane

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

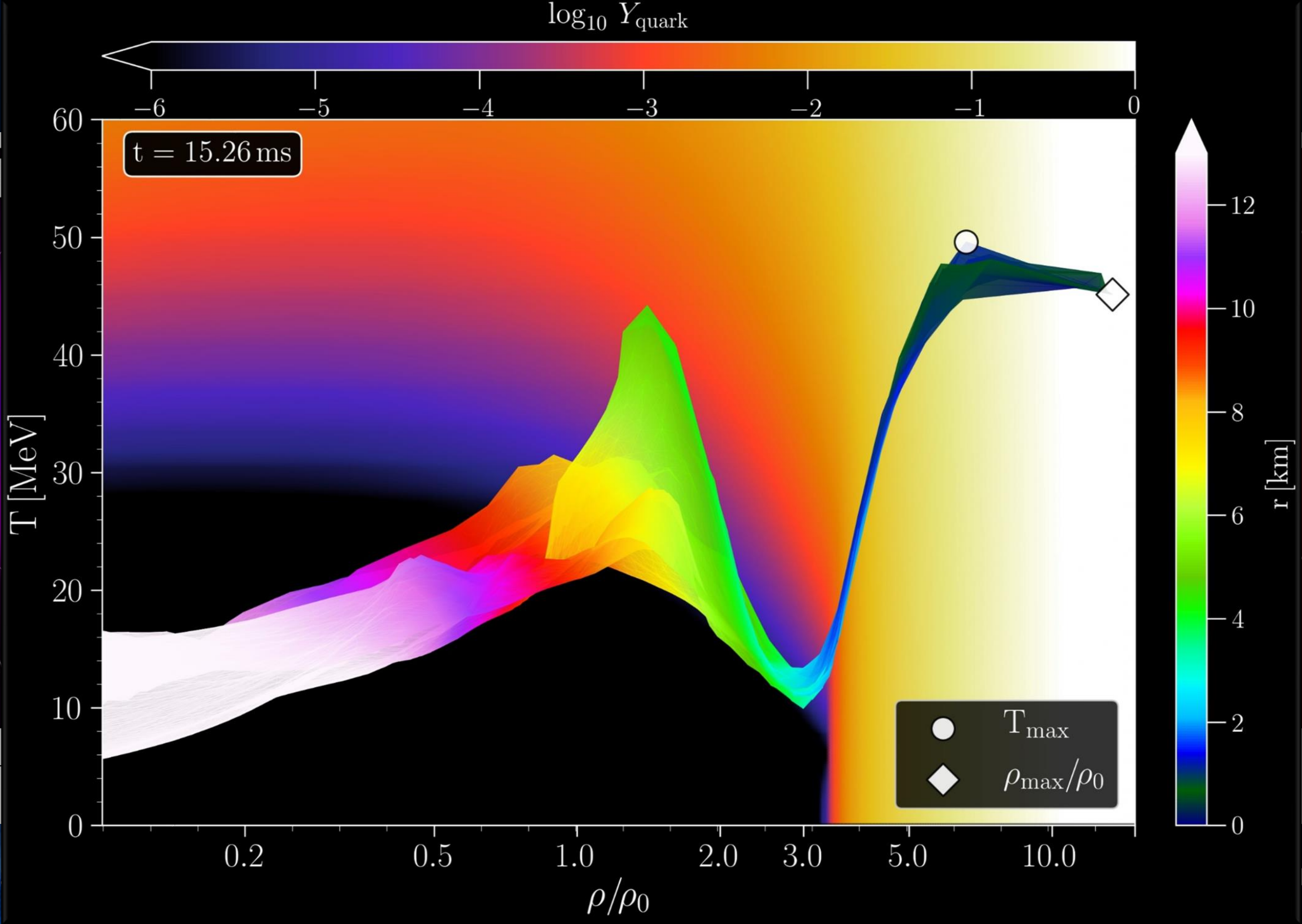




Rest mass density on the equatorial plane

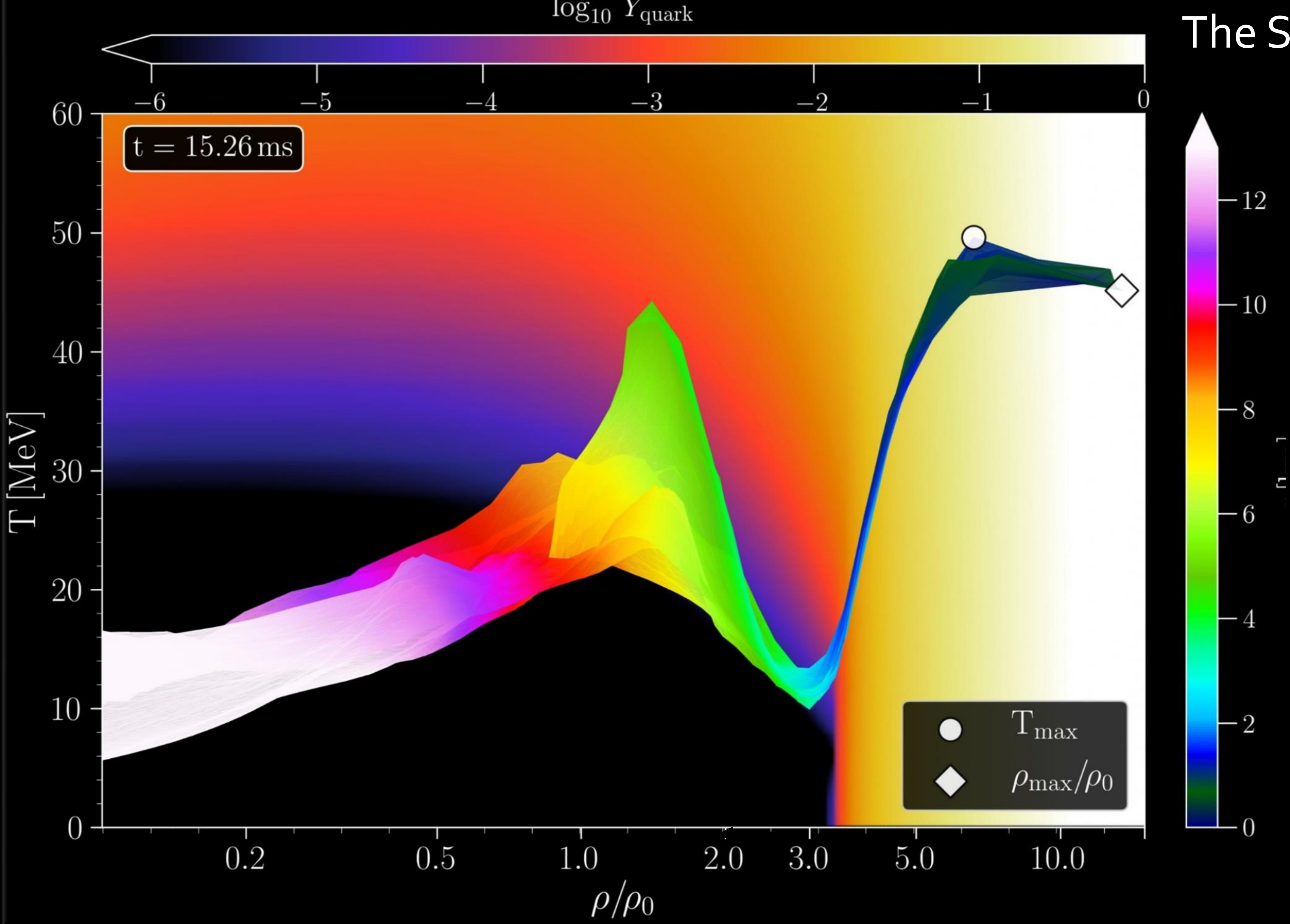
Temperature on the equatorial plane

The last sim (HMHS)



Rest mas ane

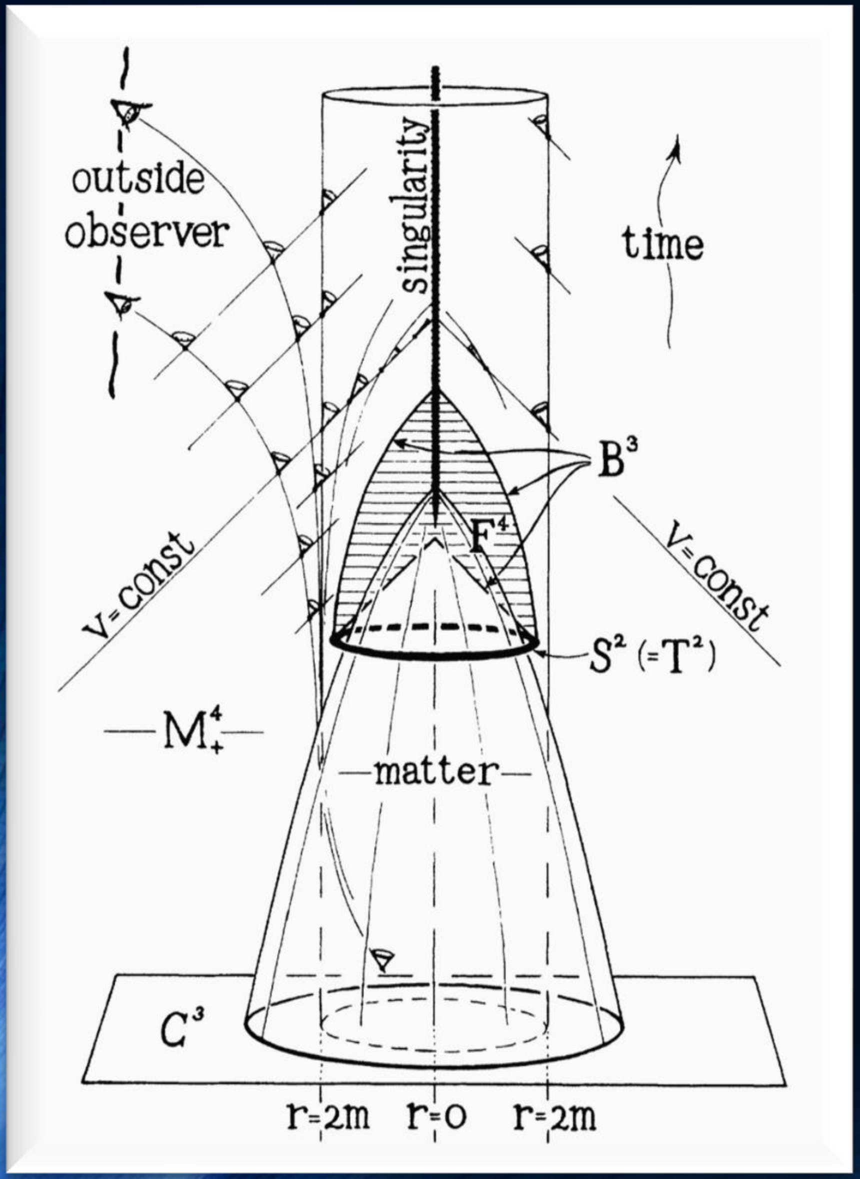
The Strange Bird Plot



While the quarks in the bird'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.

GRAVITATIONAL COLLAPSE AND SPACE- TIME SINGULARITIES

Nobel Price 2020: R.Penrose, PRL Vol.14 No.3 (1965)



Self-drawn space-time diagram by R.Penrose (1965)

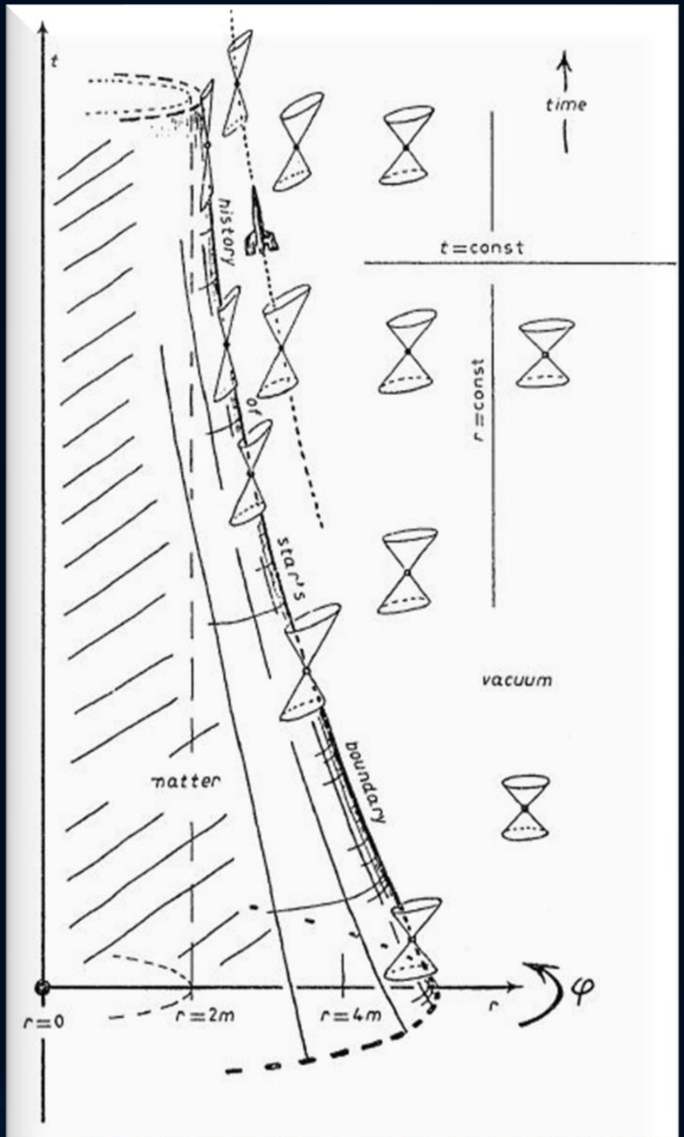


Figure 1. Spherically symmetrical collapse in the usual Schwarzschild co-ordinates.

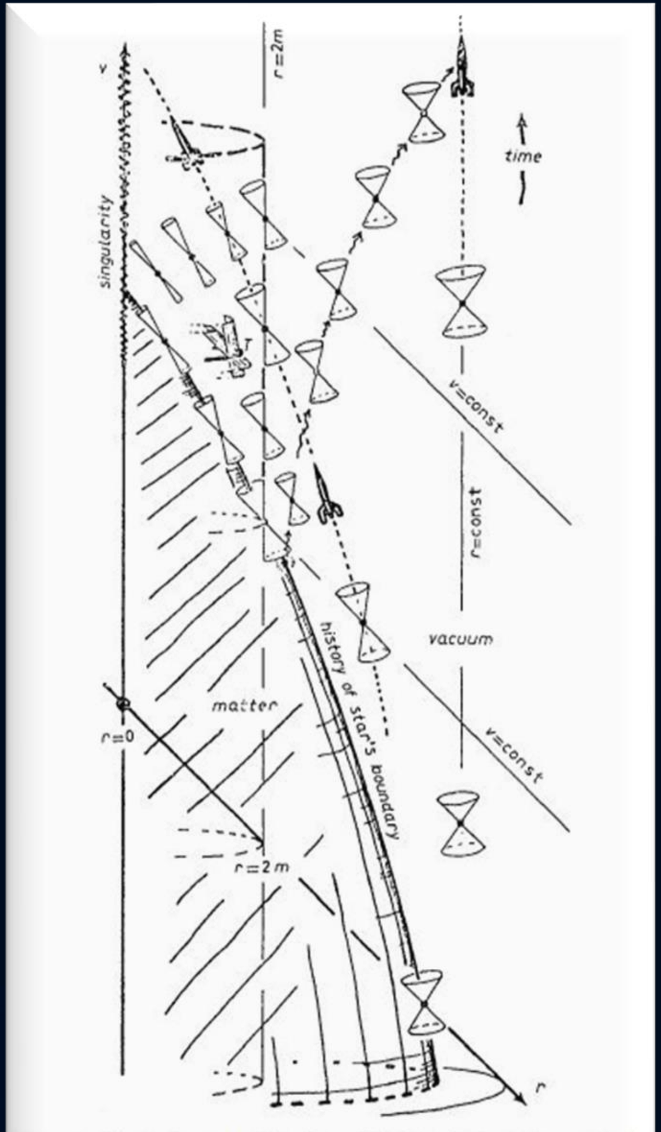
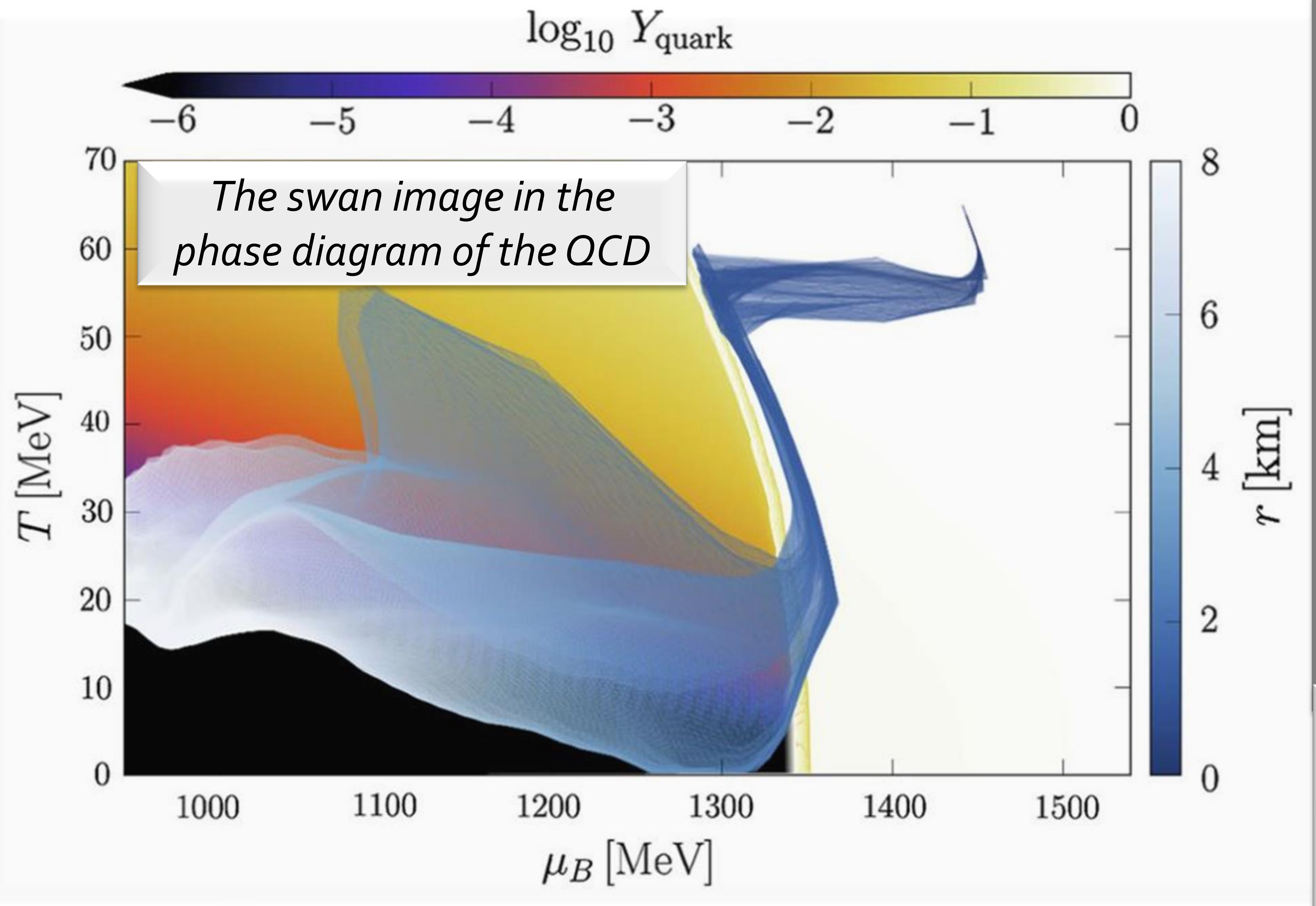
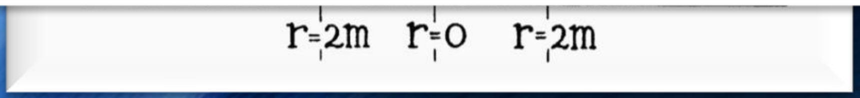


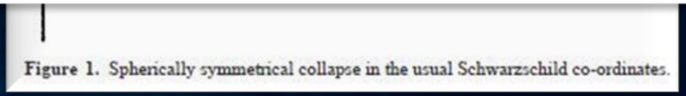
Figure 2. Spherically symmetrical collapse in Eddington-Finkelstein co-ordinates.

R.Penrose in Rivista del Nuovo Cimento, Num.Spez. I, 257 (1969)





Self-drawn space-time diagram by R.Penrose (1965)



R.Penrose in Rivista del Nuovo Ci

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)

A.Motornenko, M.Hanauske , L.Weih, J.Steinheimer and H.Stöcker, *MAGIC: Matter in Astrophysics, Gravitational Waves, and Ion Collisions*. *原子核物理评论*, 37(3), 272-282 (2020)

The last picture what an outside observer sees is the frozen picture of a dying swan

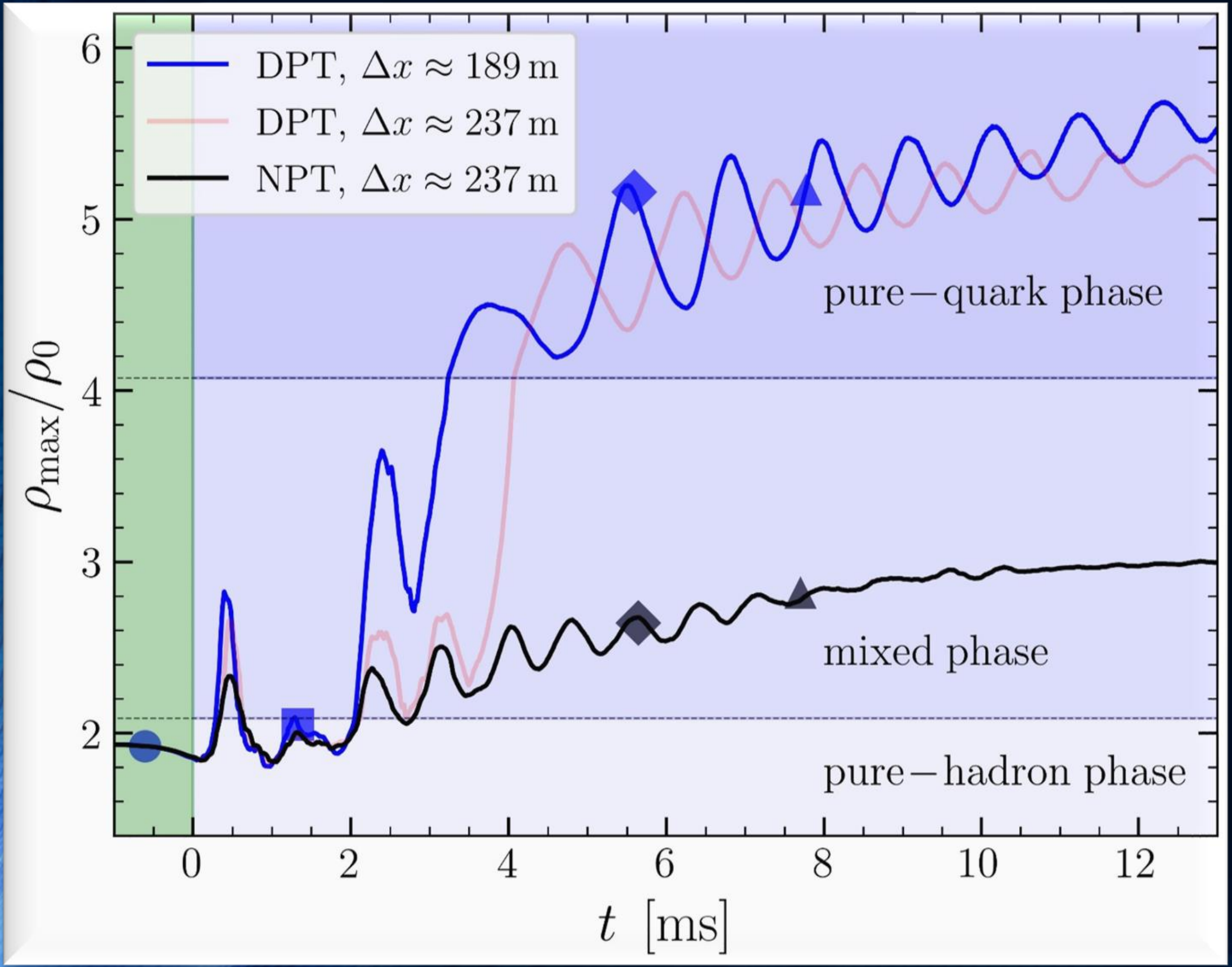
Can we detect the quark-gluon plasma with gravitational waves?

- Gravitational-wave signatures of the hadron-quark phase transition in binary compact star mergers
  - *Signatures within the late inspiral phase (premerger signals)*
    - Constraining twin stars with GW170817; G Montana, L Tolós, M Hanauske, L Rezzolla; Physical Review D 99 (10), 103009 (2019)
  - *Signatures within the post-merger phase evolution*
    - **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, L. Rezzolla; Physical review letters 122 (6), 061101 (2019)
    - **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)
    - **Prompt phase transition scenario**
      Identifying a first-order phase transition in neutron-star mergers through gravitational waves; A Bauswein, NUF Bastian, DB Blaschke, K Chatziioannou, JA Clark, JA Clark, T Fischer, M Oertel; Physical review letters 122 (6), 061102 (2019)

Signatures within the post-merger phase evolution

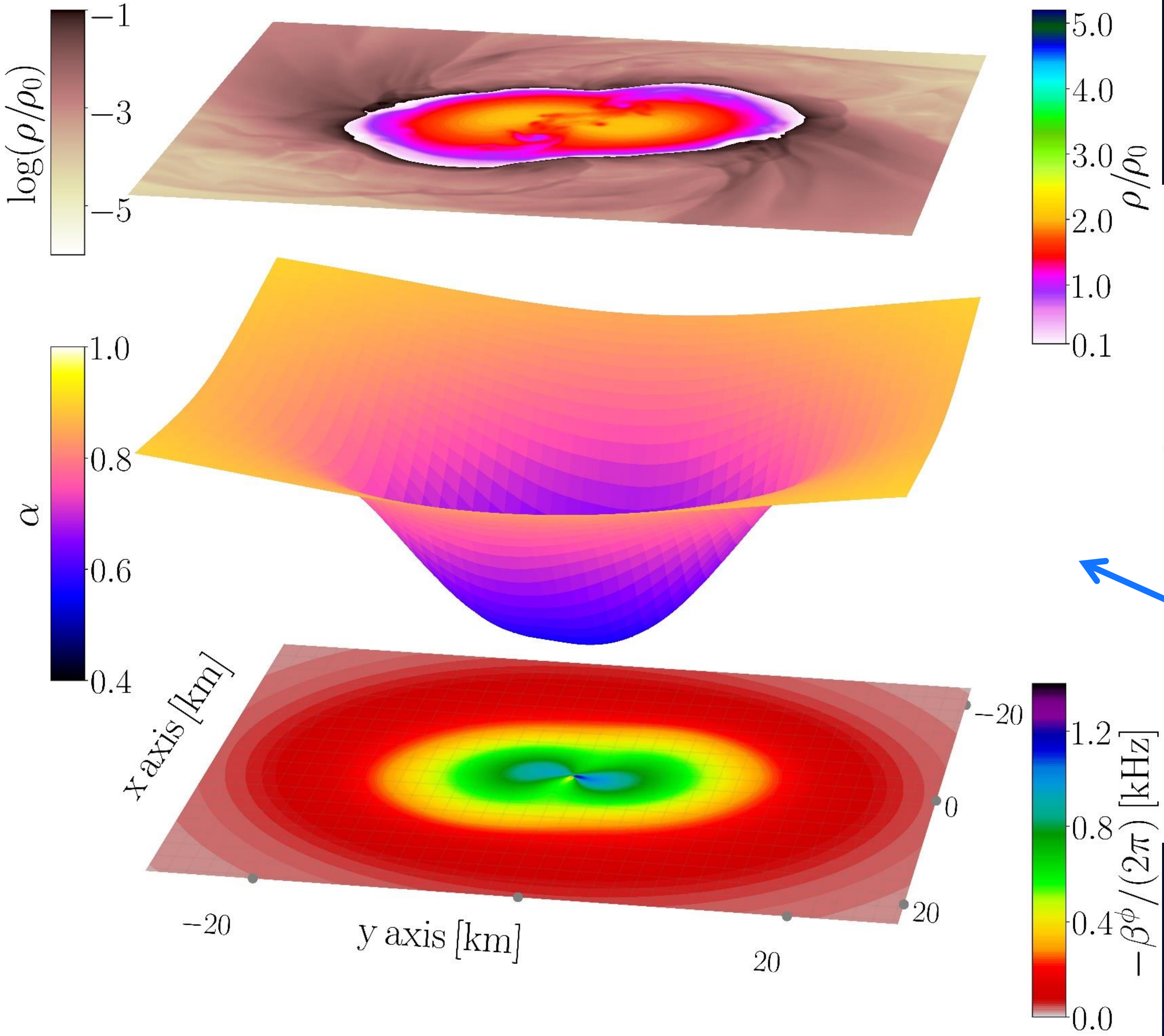
Delayed phase transition scenario

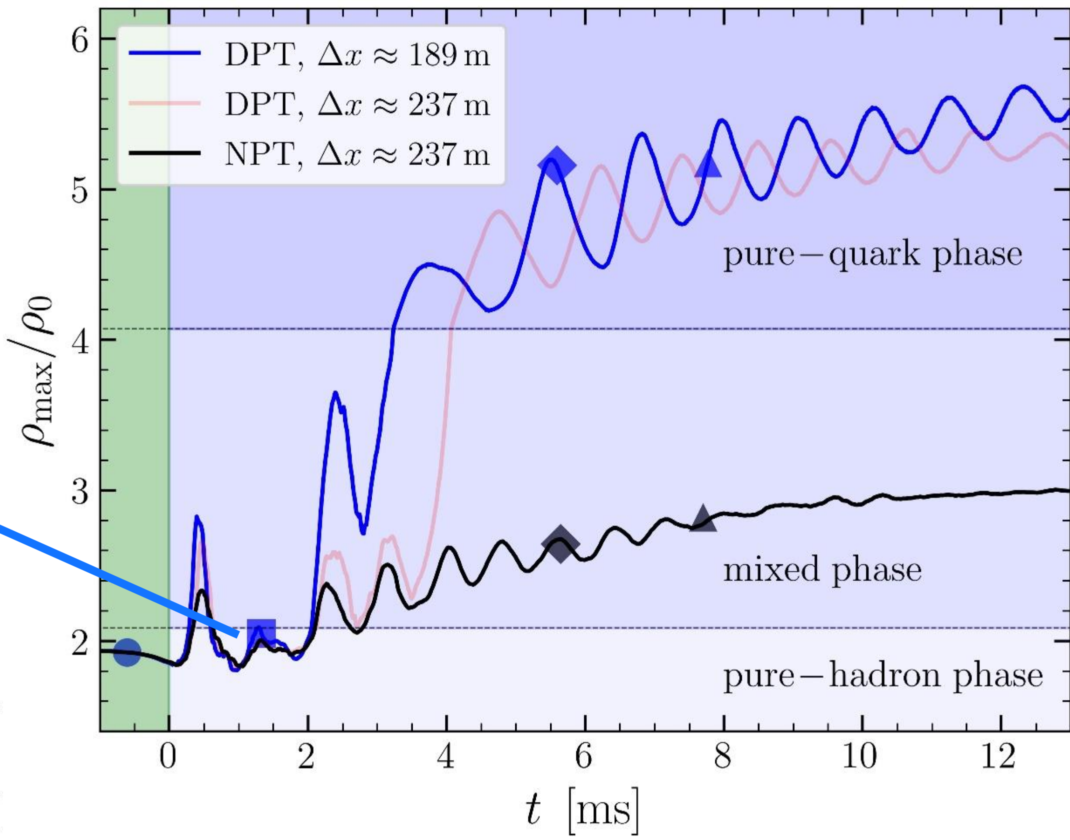
Postmerger Gravitational-Wave Signatures of Phase Transitions in Binary Mergers; LR Weih, M Hanauske, L Rezzolla; Physical Review Letters 124 (17), 171103 (2020)



Maximum value of the rest-mass density vs time for three binary neutron star simulations. Black curve without a phase transition (NPT) and blue/red with a Gibbs-like hadron-quark phase transition (DPT: standard/low resolution). Blue-shaded regions mark the different phases of the EOS (mixed phase and pure-quark phase).

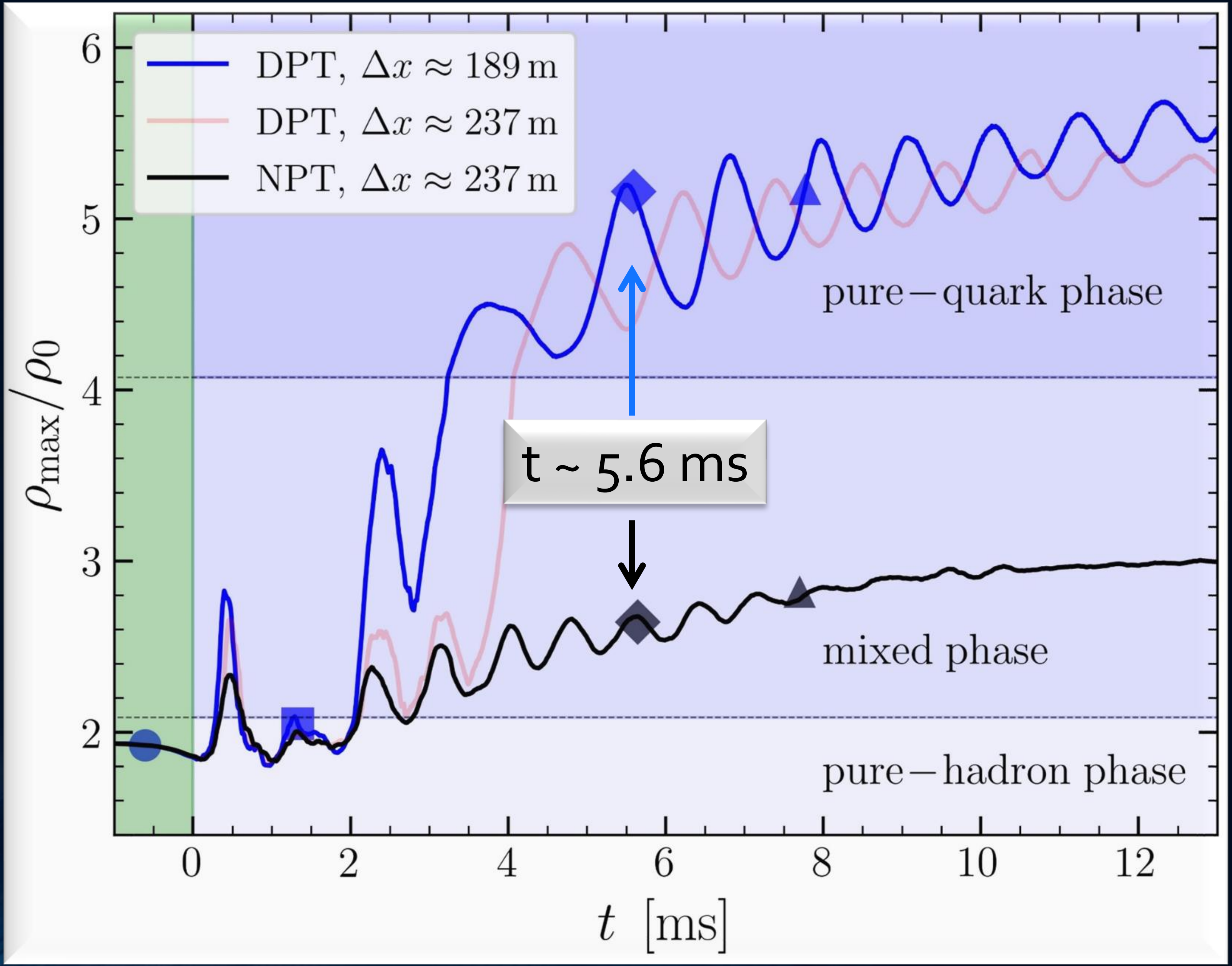
M. Hanauske, L. Weih, H. Stöcker, L. Rezzolla
Metastable hypermassive hybrid stars as neutron-star merger remnants
The European Physical Journal Special Topics: 1-8 (2021)



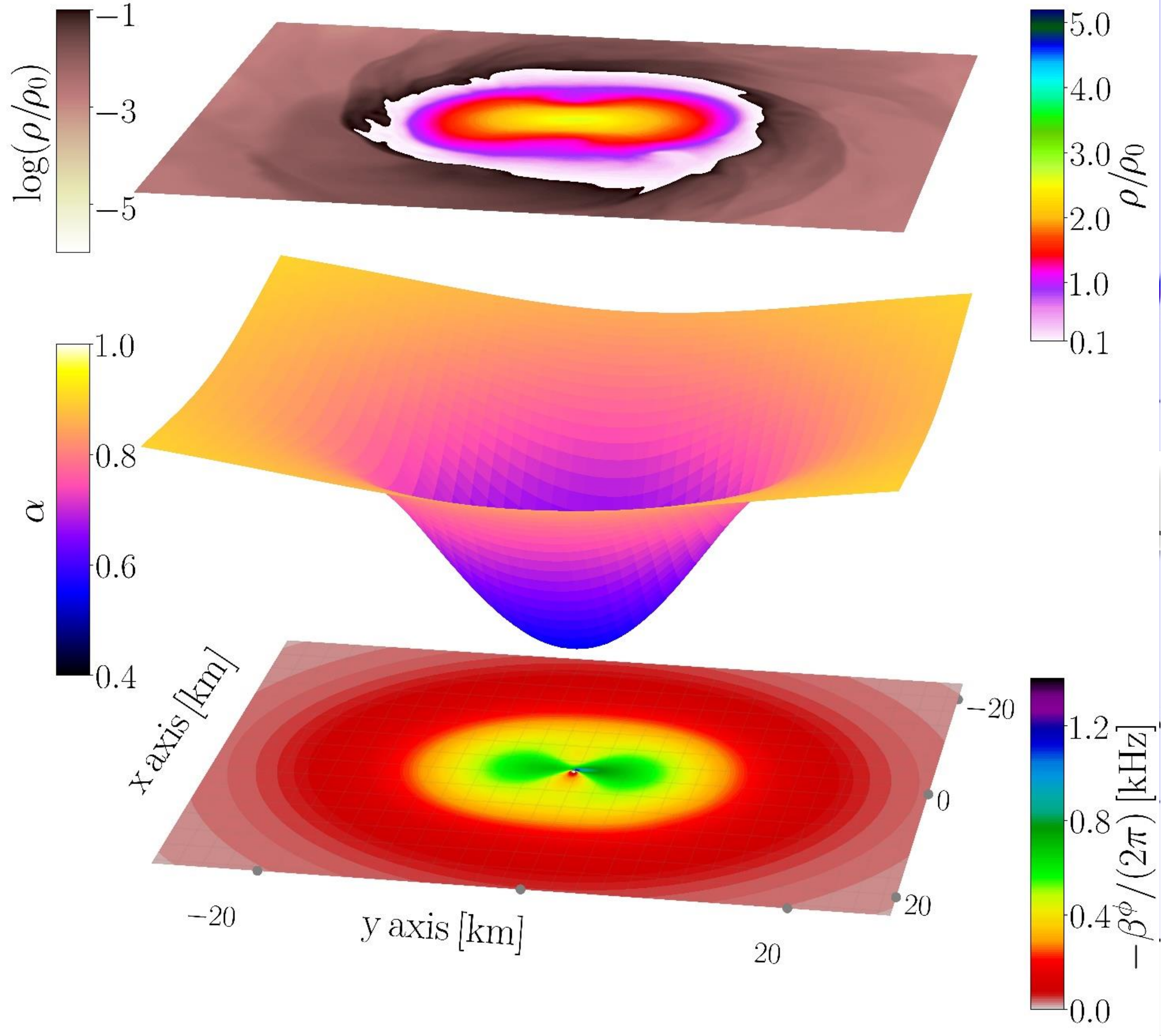


Matthias Hanauske and Lukas Weih
Neutron star collisions and gravitational waves
Astronomische Nachrichten (2021)

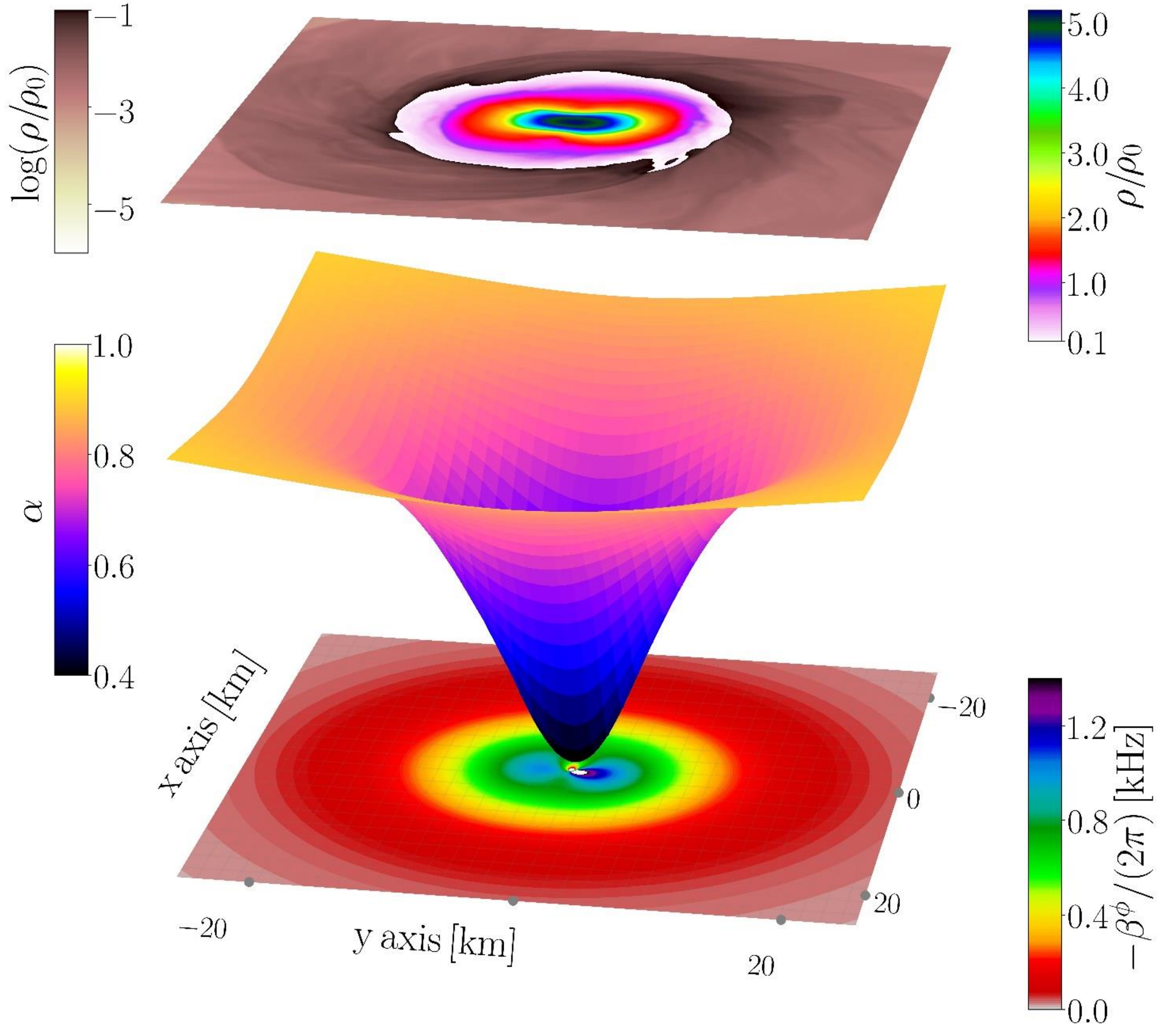
Without Phase Transition   With Phase Transition



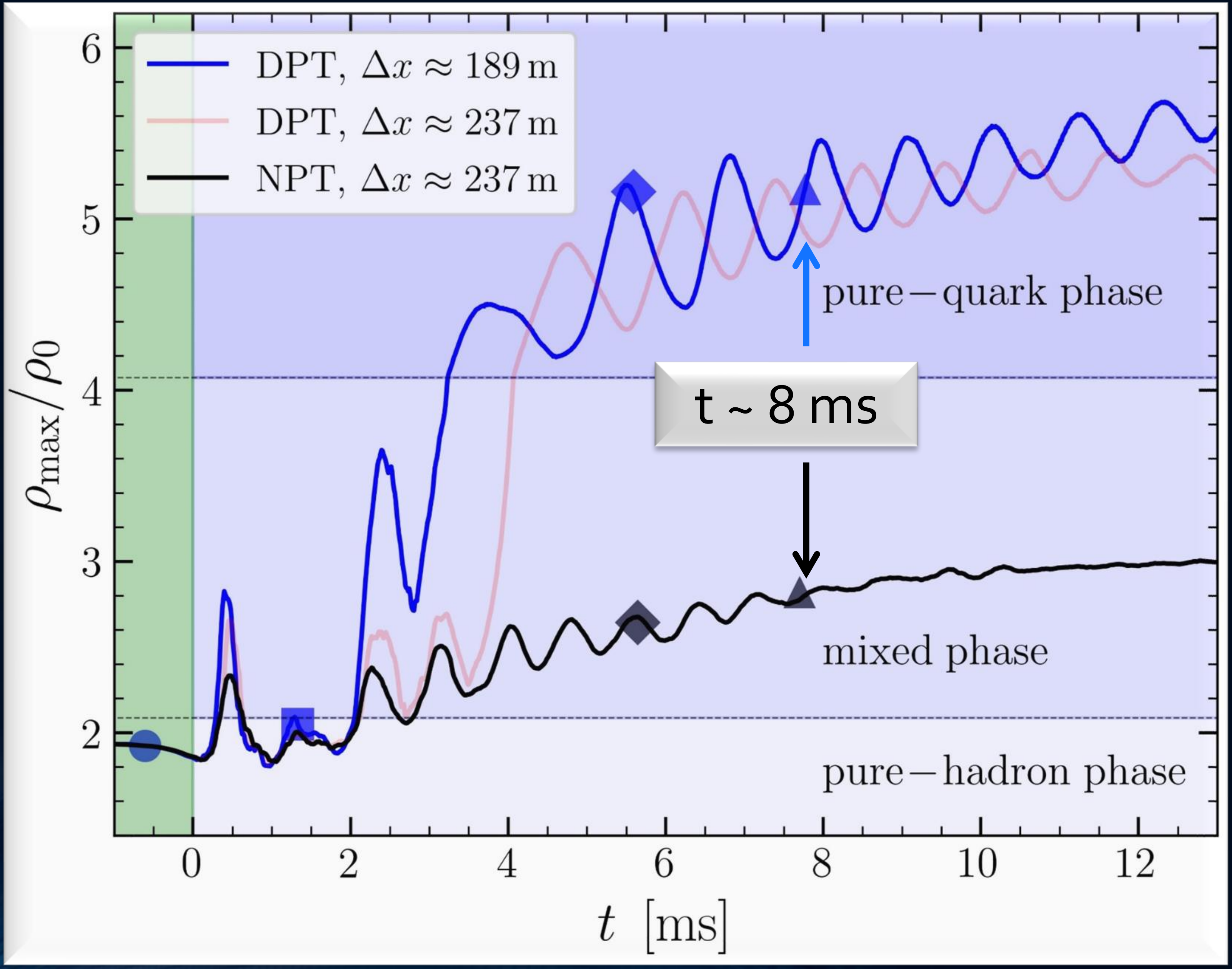
Without Phase Transition



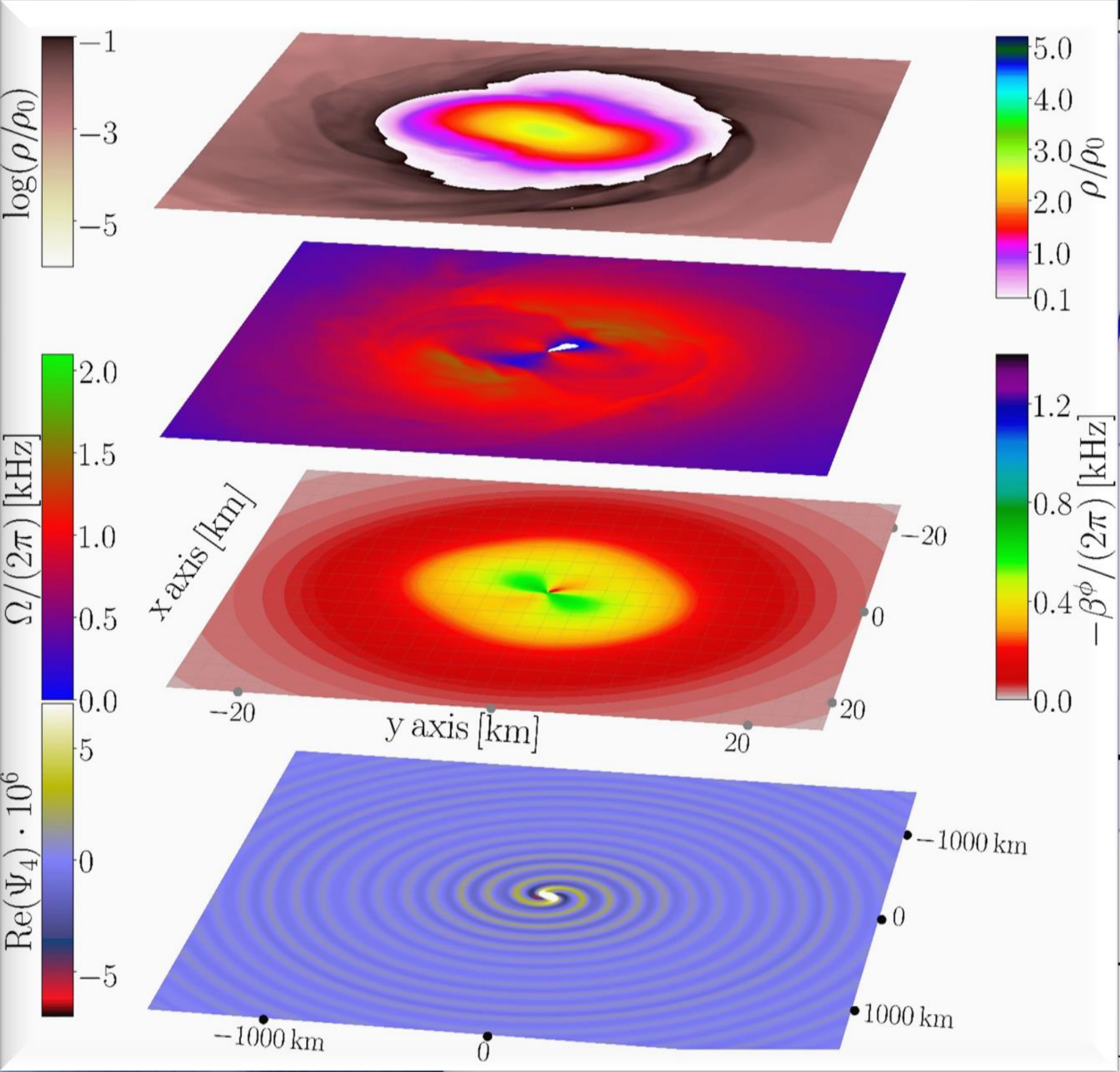
With Phase Transition



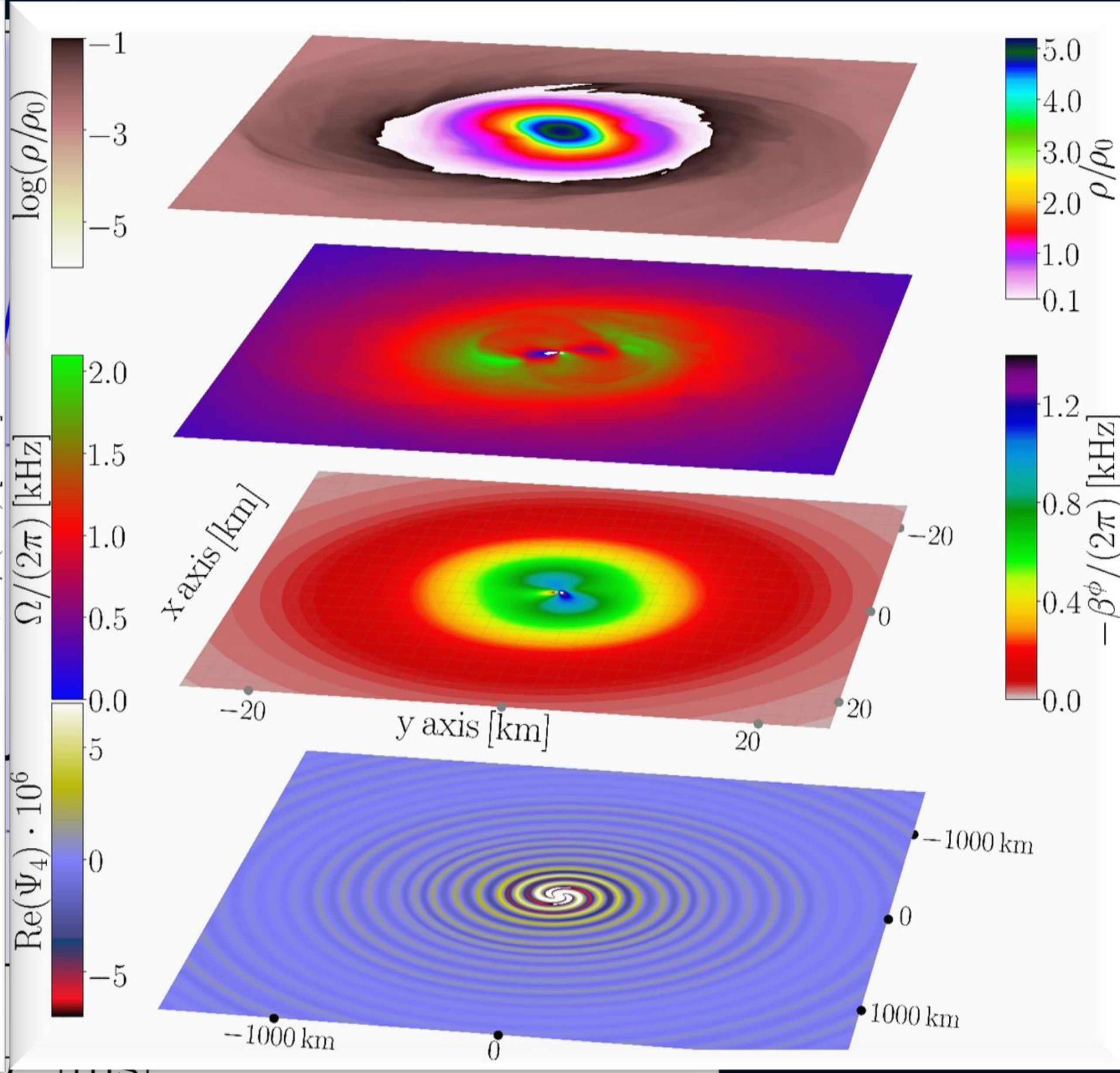
Without Phase Transition With Phase Transition

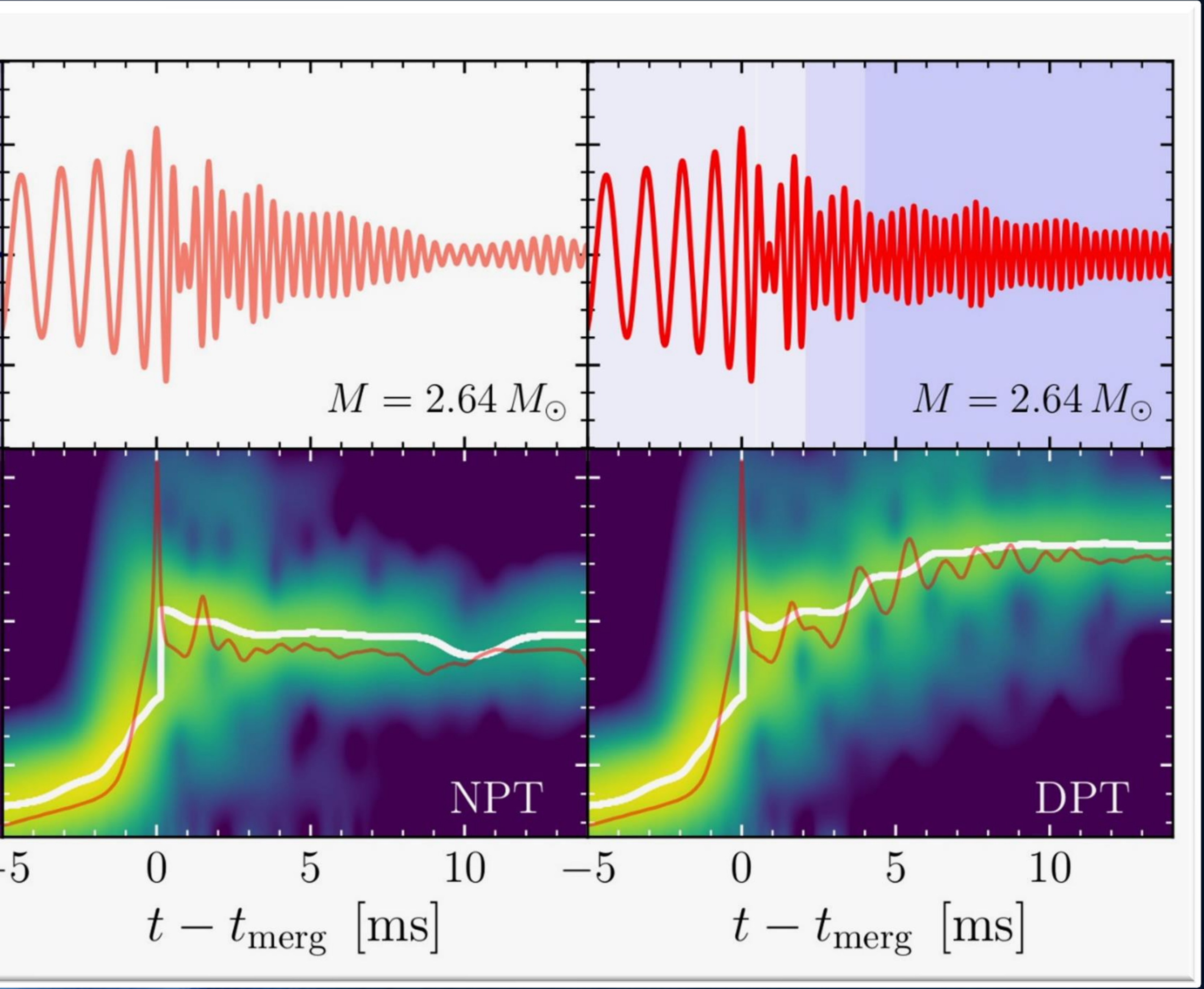


Without Phase Transition



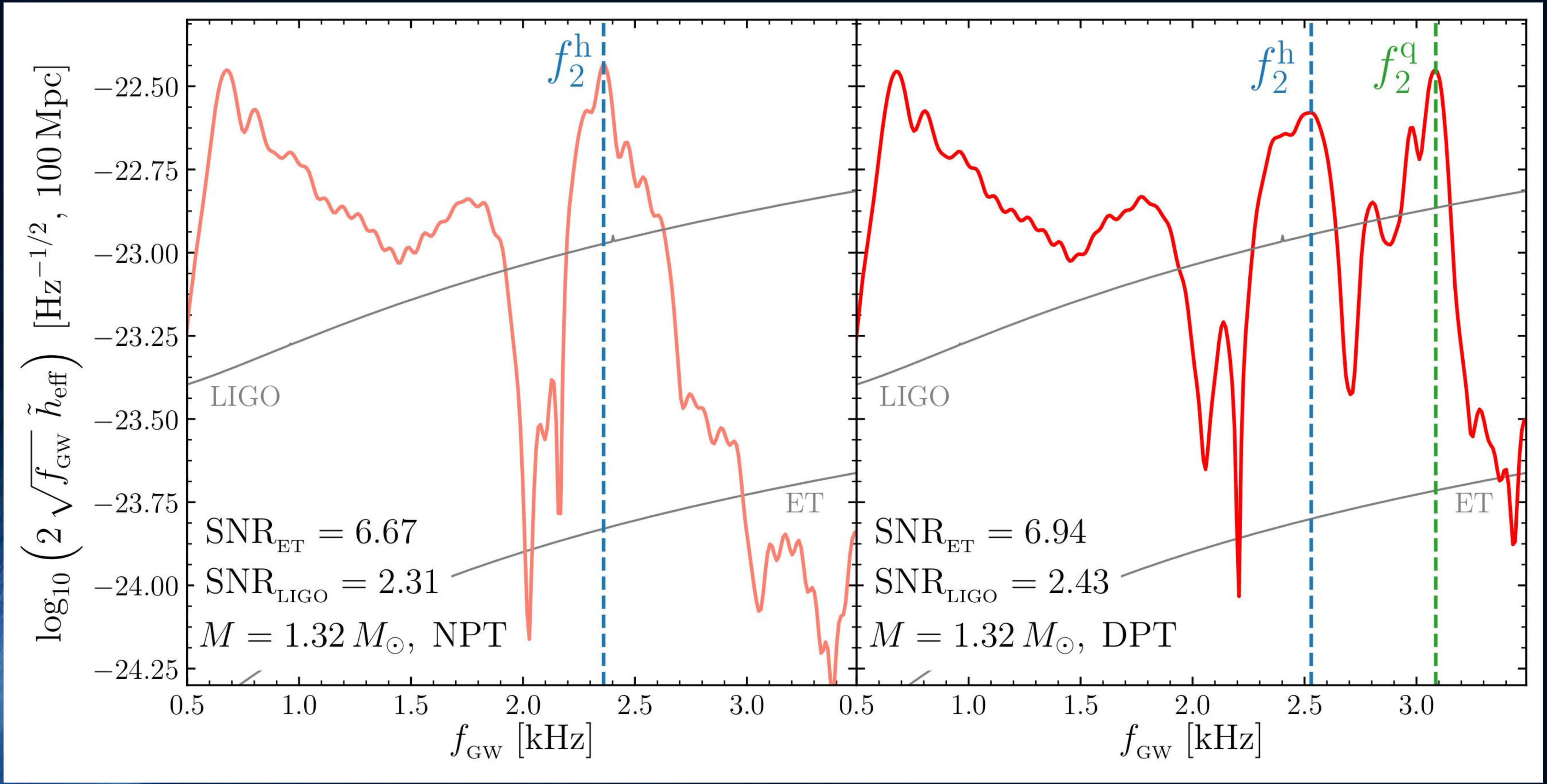
With Phase Transition



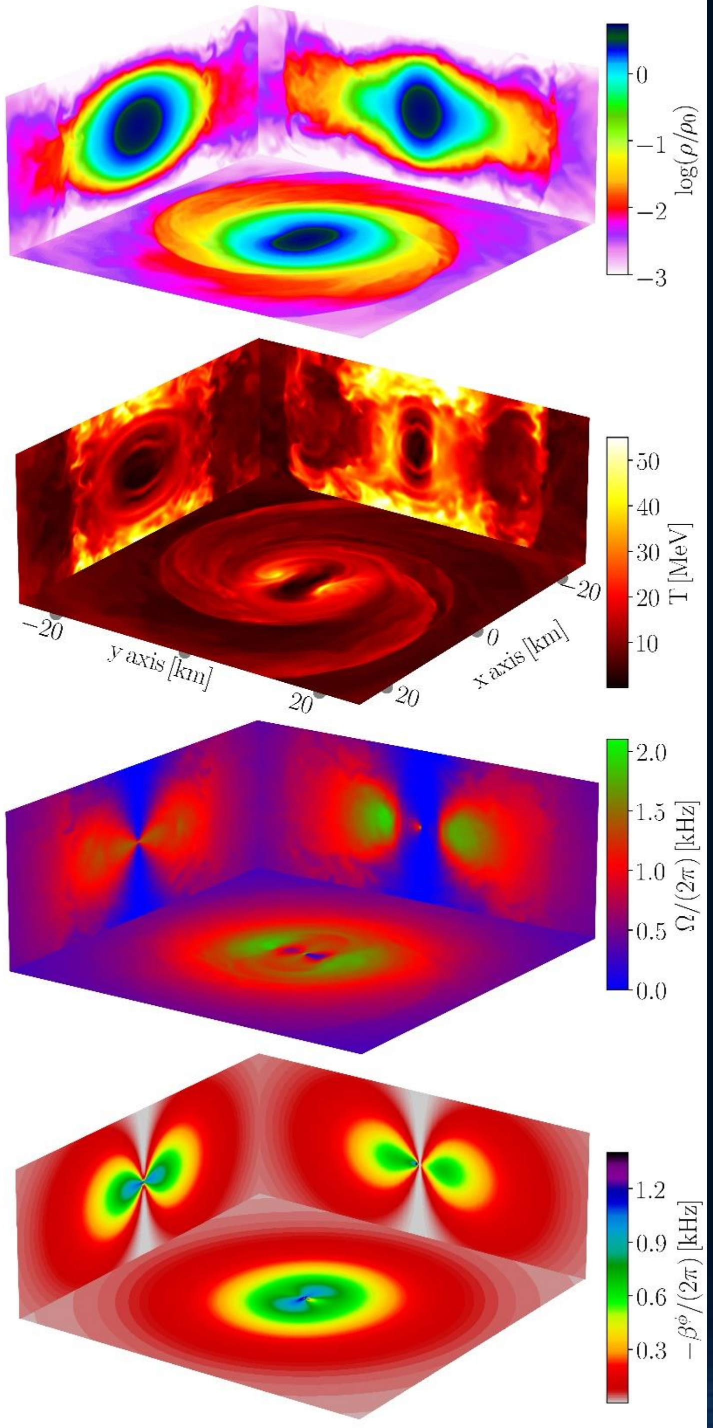


Strain h+ (top) and its spectrogram (bottom) for the binary neutron star simulation of the delayed phase transition scenario. In the top panel the different shadings mark the times when the HMHS core enters the mixed and pure quark phases. In the bottom panels, the white lines trace the maximum of the spectrograms, while the red lines show the instantaneous gravitational-wave frequency.

How to detect the hadron-quark phase transition with gravitational waves



Total gravitational wave spectrum (left NPT, right DPT), PRL 124, 171103 (2020)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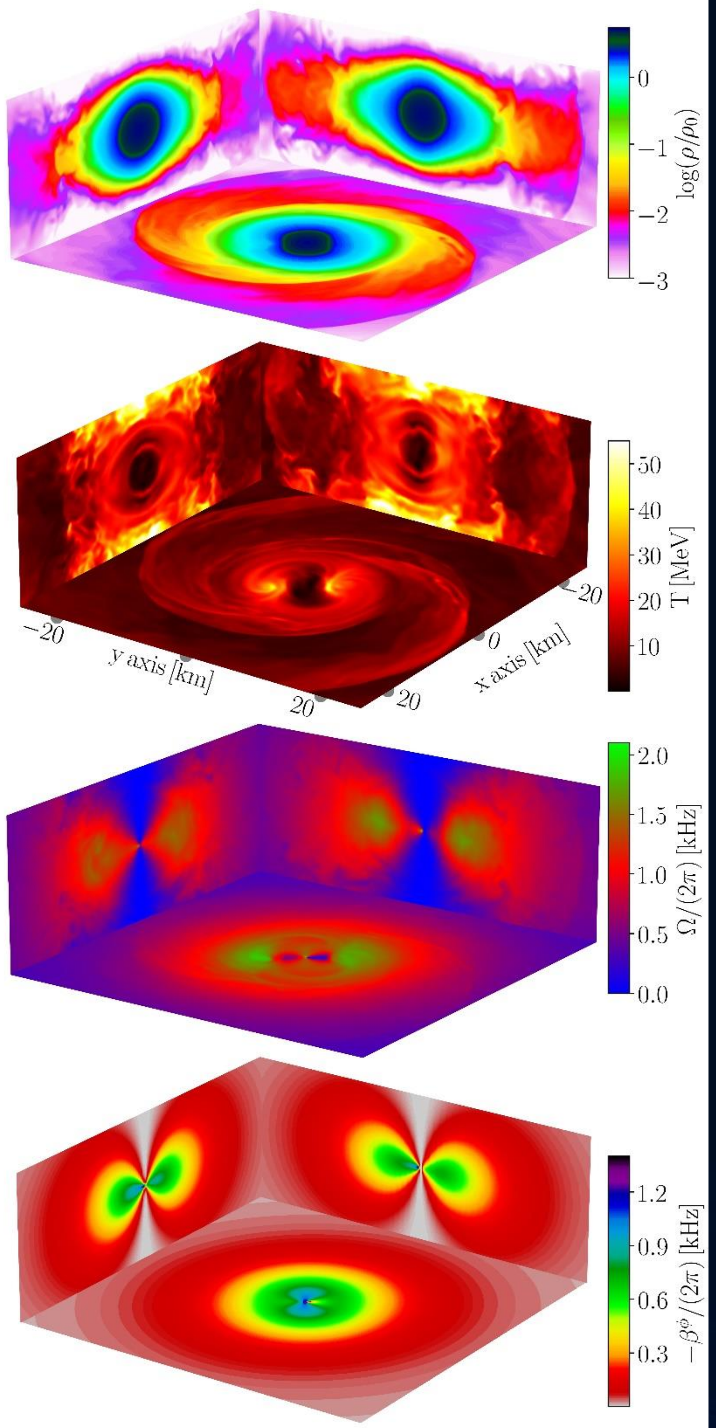
T [MeV]
y axis [km]
x axis [km]
Ω/(2π) [kHz]
−β^φ/(2π) [kHz]

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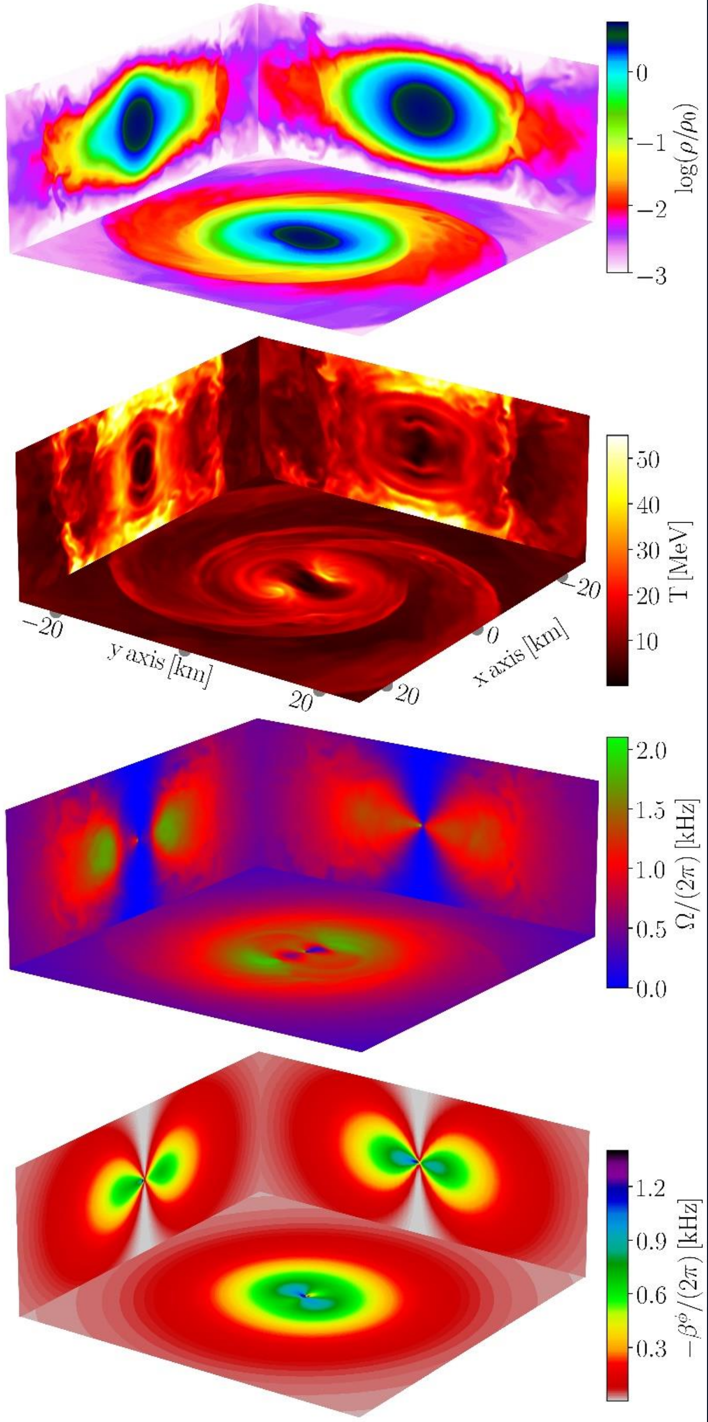
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