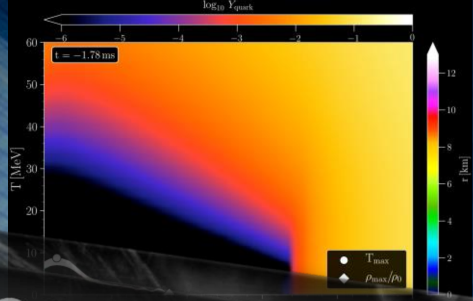
MATTHIAS HANAUSKE
FRANKFURT INSTITUTE FOR ADVANCED STUDIES
JOHANN WOLFGANG GOETHE UNIVERSITÄT
INSTITUT FÜR THEORETISCHE PHYSIK
ARBEITSGRUPPE RELATIVISTISCHE ASTROPHYSIK
D-60438 FRANKFURT AM MAIN



Neutron star collisions and the gravitational collapse

11th. International Workshop on Astronomyand Relativistic Astrophysics

IWARA 2022

Antigua Guatemala, Guatemala., 5. September, 2022

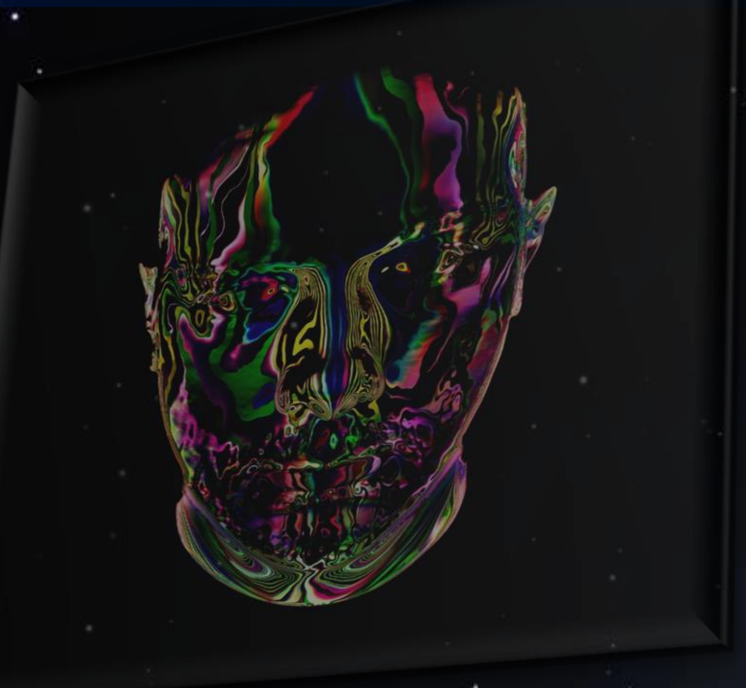
In collaboration with

Lukas Weih, Elias R. Most, Jens Papenfort, Luke Bovard,

Gloria Montana, Laura Tolos, Jan Steinheimer, Anton Motornenko, Veronica Dexheimer,

Horst Stöcker, Luciano Rezzolla and Carsten Greiner

Binary neutron star systems and gravitational waves



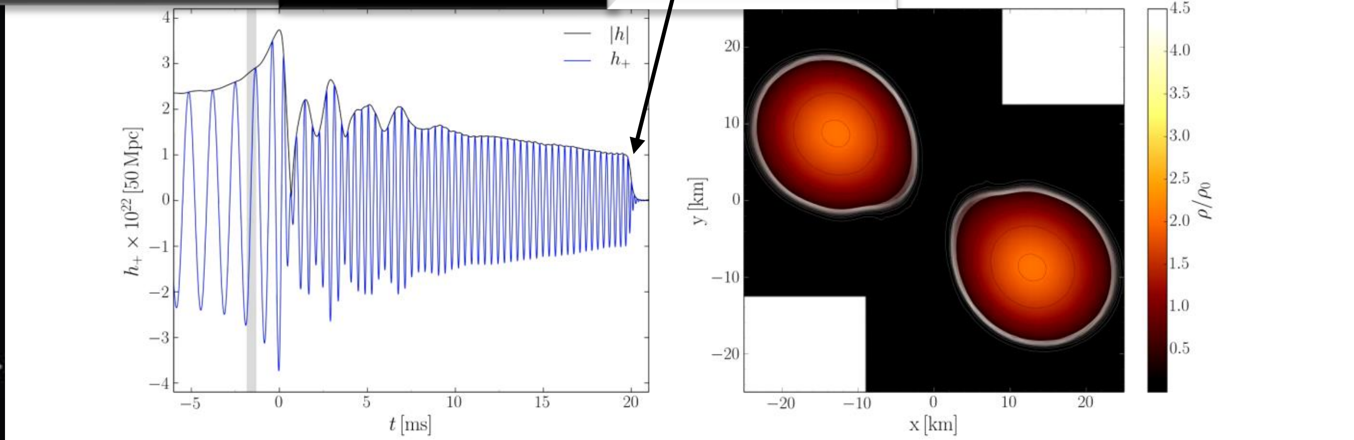
The Double Pulsar
PSR J0737-3039A/B
was discovered in 2003

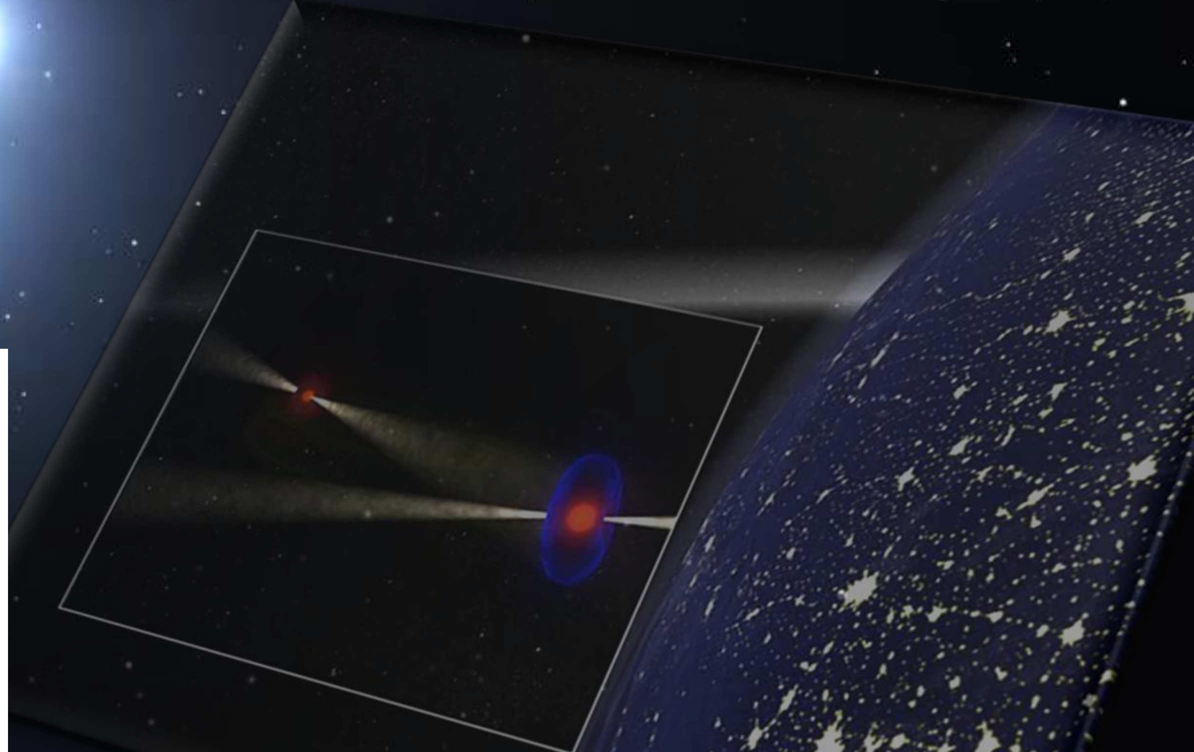
Music by
Eric Prydz
Opus
(9 min, inspiral phase ~1/3)

Inspiral phase

Post-merger phase

Gravitational collaps



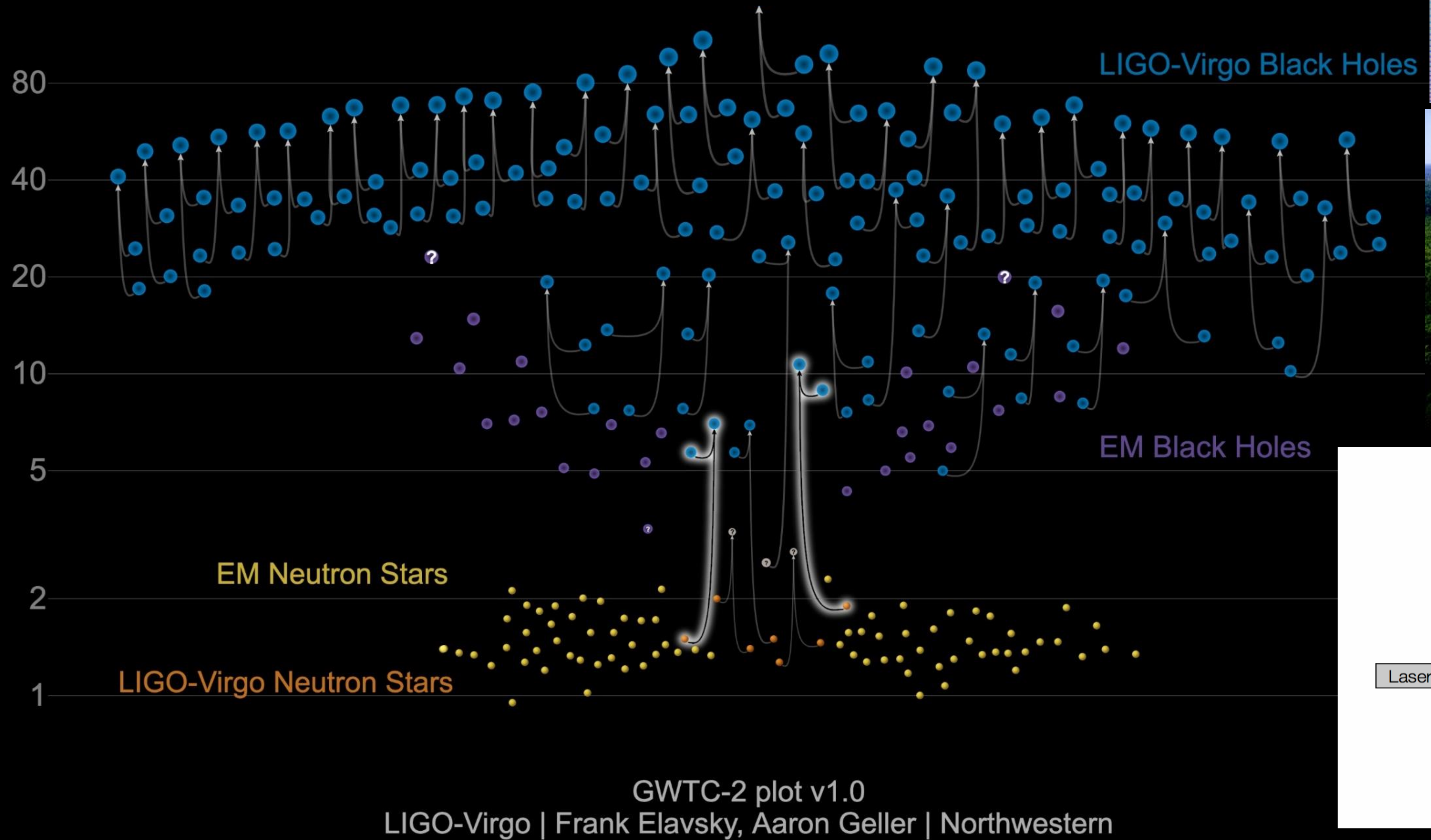


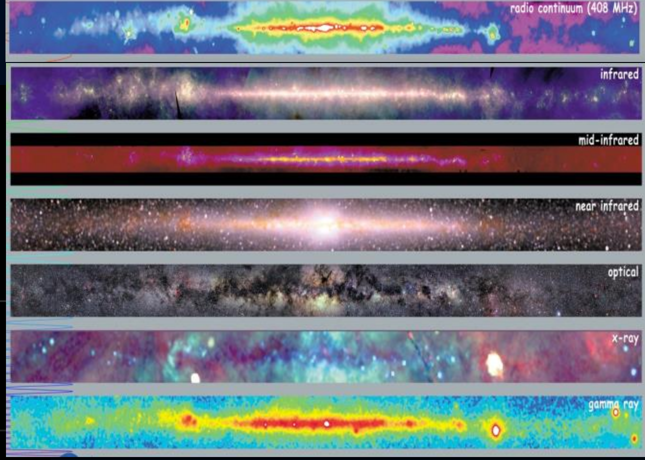
The two neutron stars will collide in 85 million years

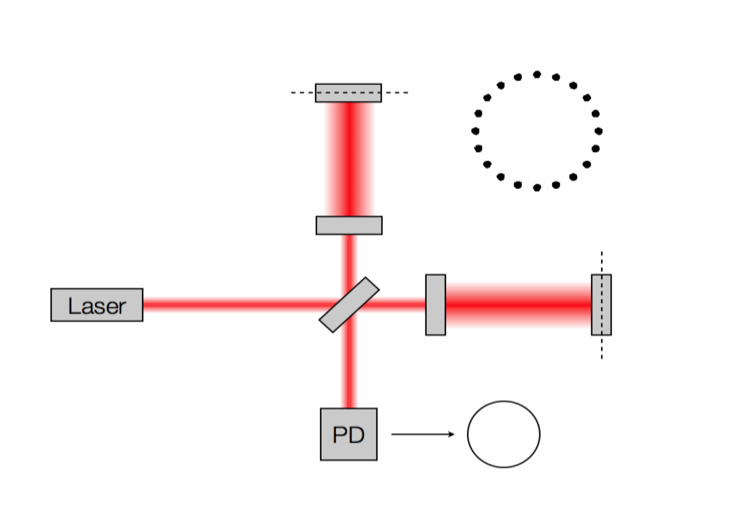
Gravitational Waves (GW): The new way of looking at our universe

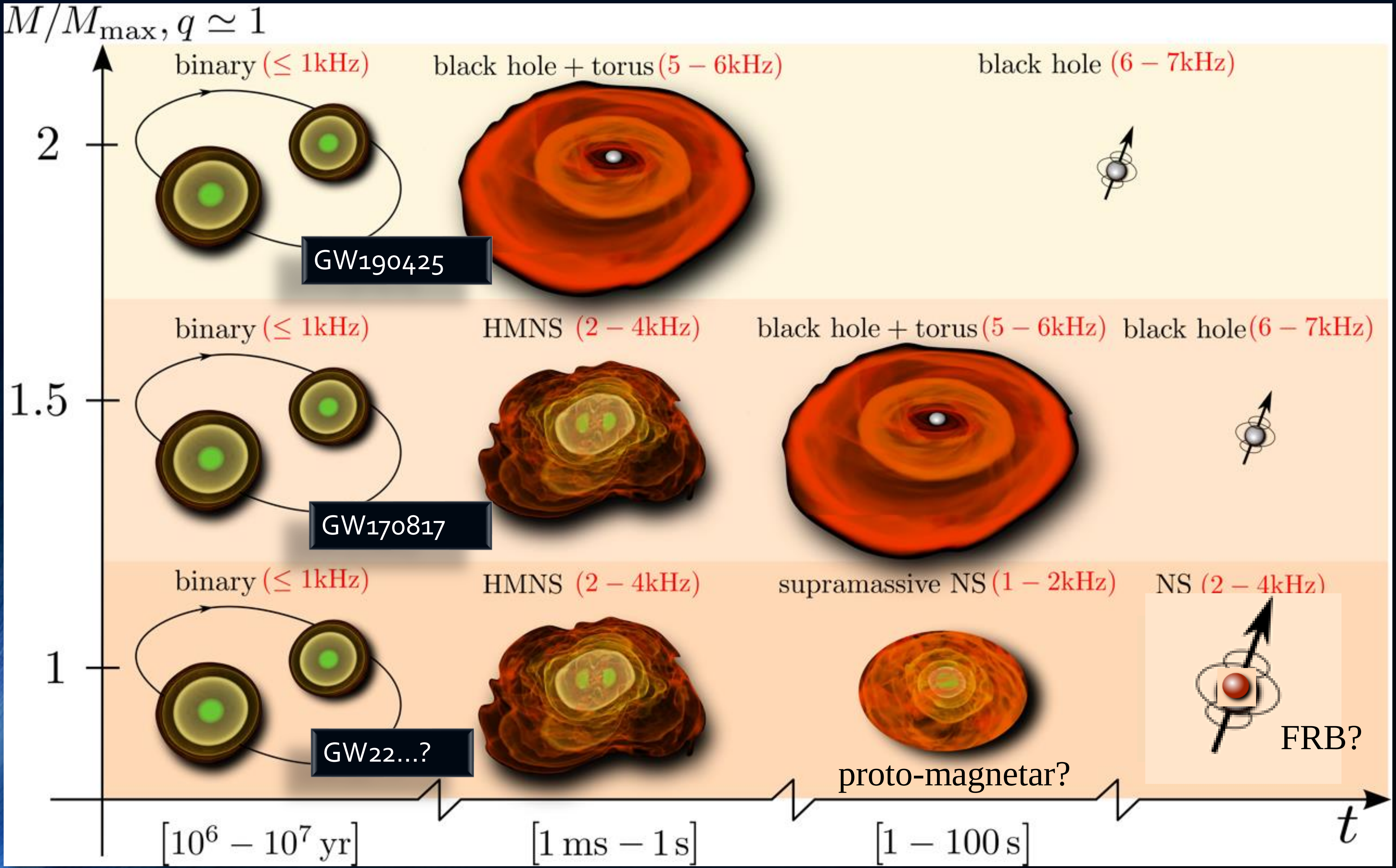
It is as if humanity has wondrous new glasses, a new sensory organ, with which to perceive previously unobservable events in our universe

first GW- detection 2015









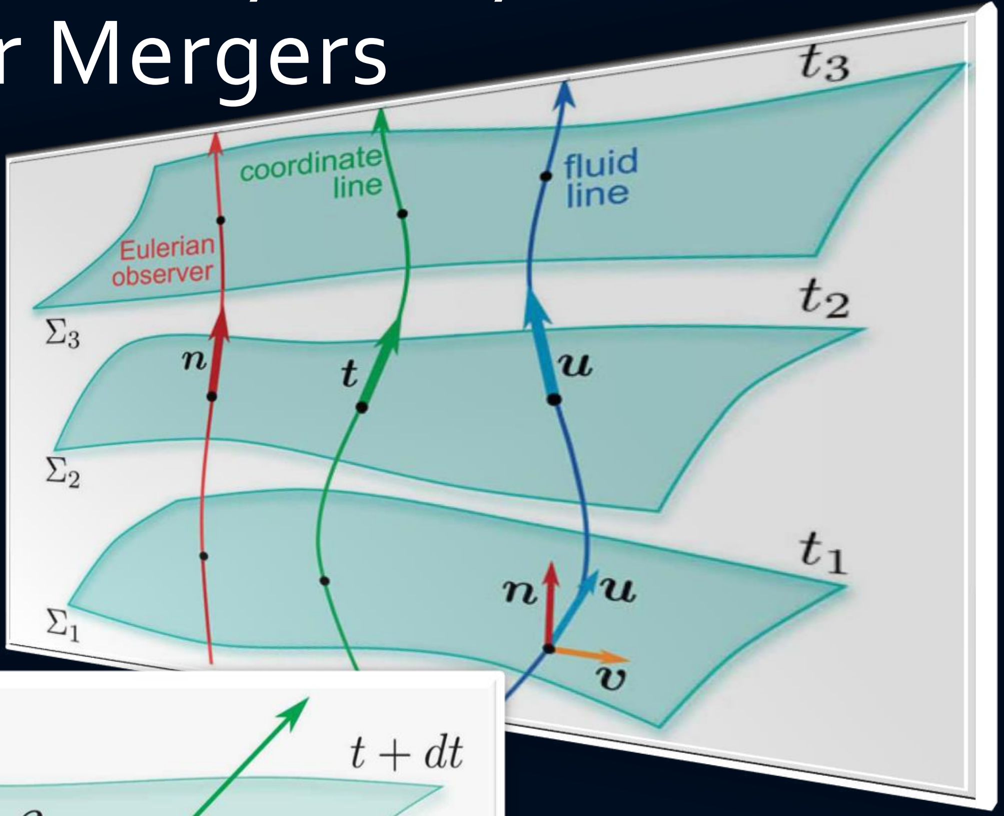
$M/M_{max}, q \simeq 1$
binary (≤ 1kHz)
black hole + torus (5 – 6kHz)
black hole (6 – 7kHz)
2
GW190425
binary (≤ 1kHz)
HMNS (2 – 4kHz)
black hole + torus (5 – 6kHz)
black hole (6 – 7kHz)
1.5
GW170817
binary (≤ 1kHz)
HMNS (2 – 4kHz)
supramassive NS (1 – 2kHz)
NS (2 – 4kHz)
1
GW22...?
proto-magnetar?
FRB?
$[10^6 - 10^7\,yr]$
$[1\,ms - 1\,s]$
$[1 - 100\,s]$
t

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:

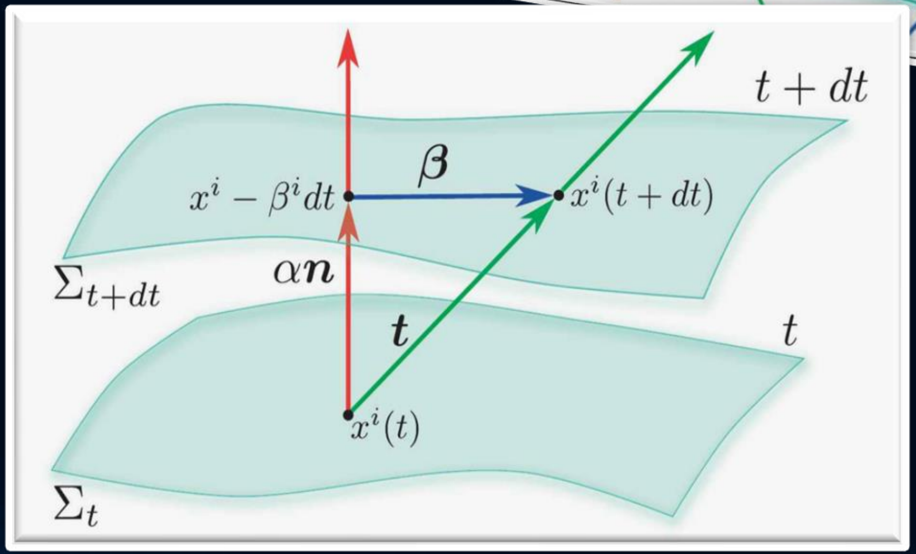
$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = 8\pi T_{\mu\nu}$$

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



(3+1) decomposition of spacetime

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



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

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

Numerical Relativity and Relativistic Hydrodynamics of Binary Neutron Star Mergers

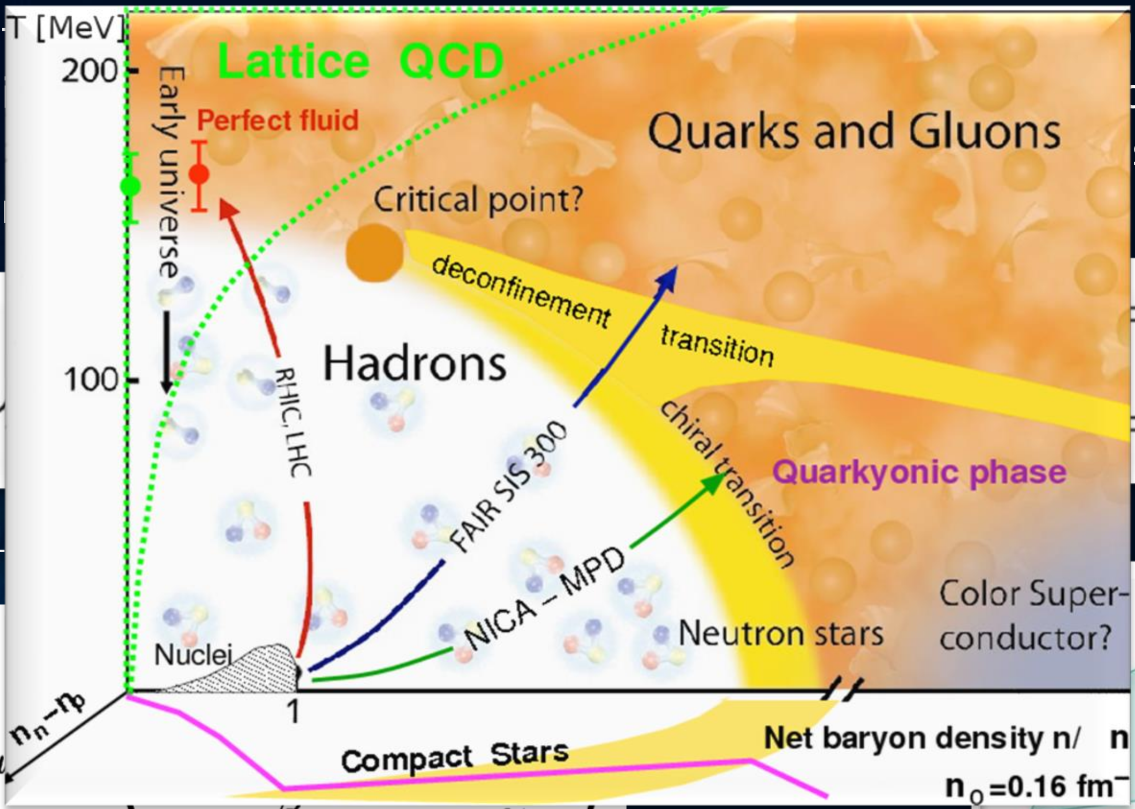
Eins… l
relat… ction
with … s of
neut…

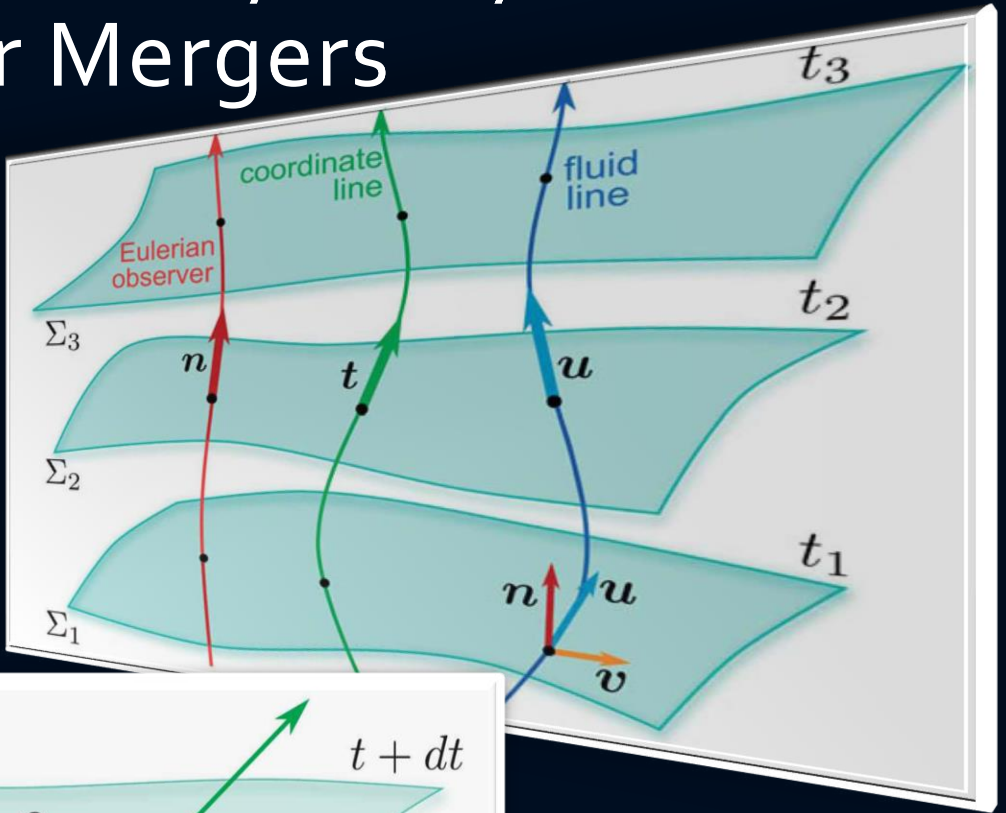
$R_{\mu\nu}$ … $= 0\,,$

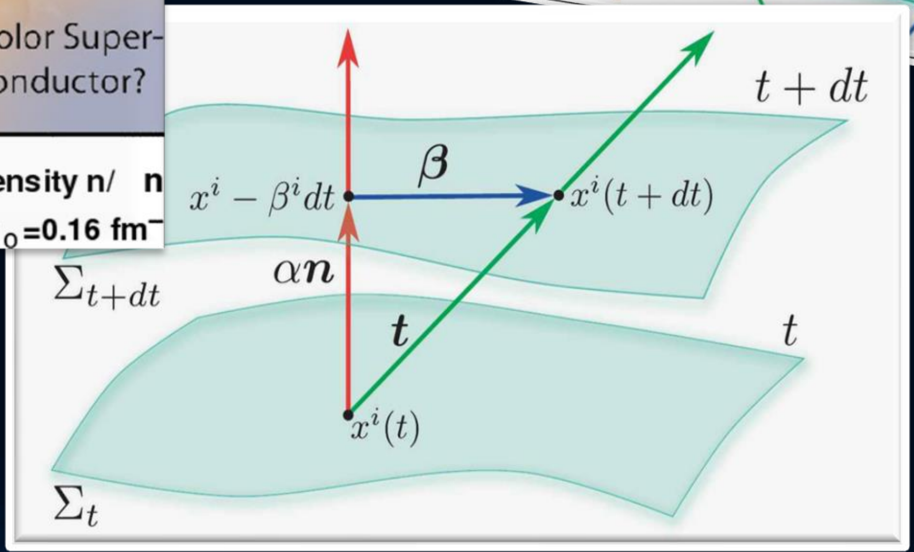
… $= 0\,.$

(3+…

g_{μ} … $\beta_i \quad \gamma_{ij}$ …





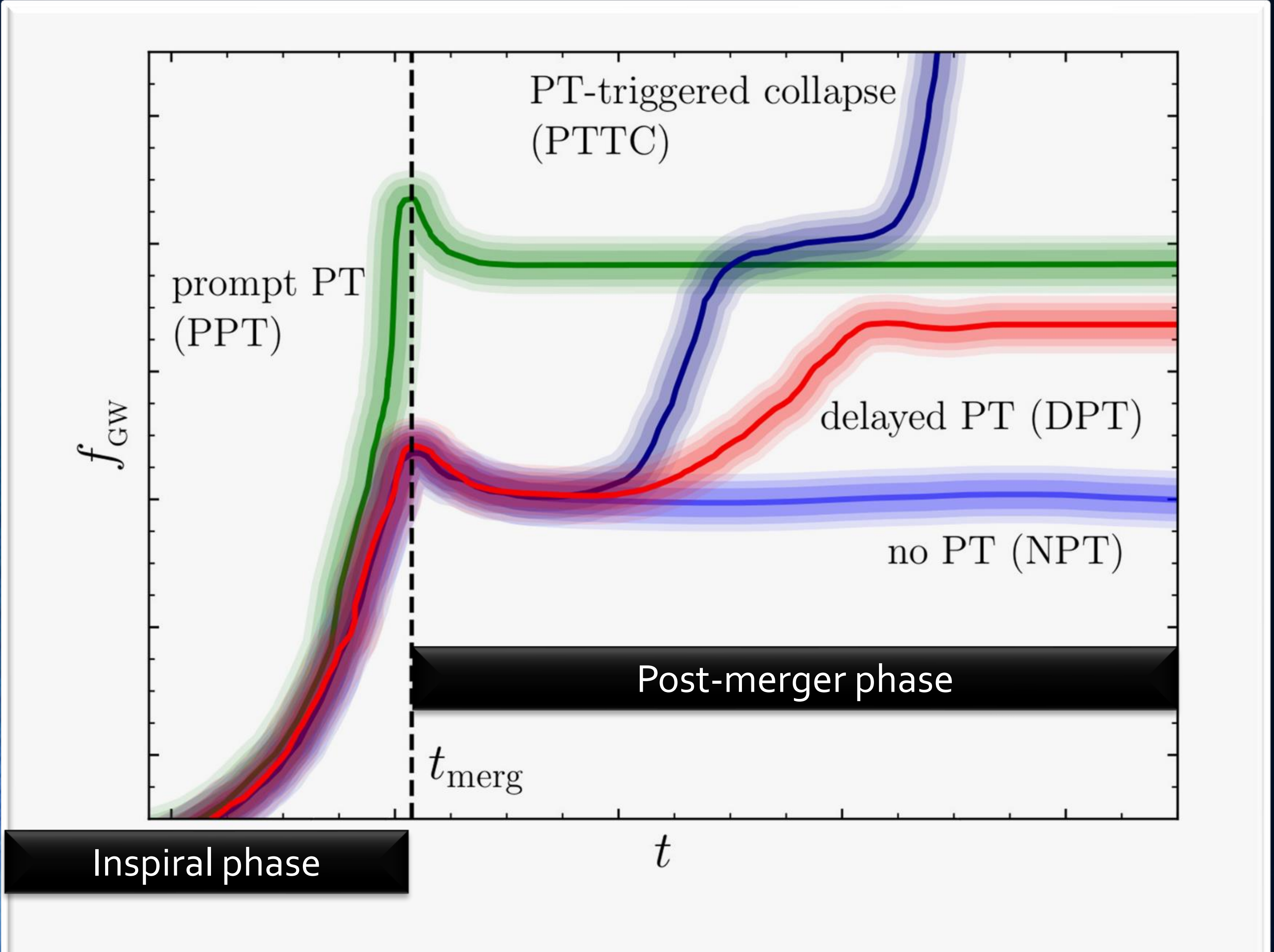


$$d\tau^2 = \alpha^2(t, x^j)dt^2$$

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

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

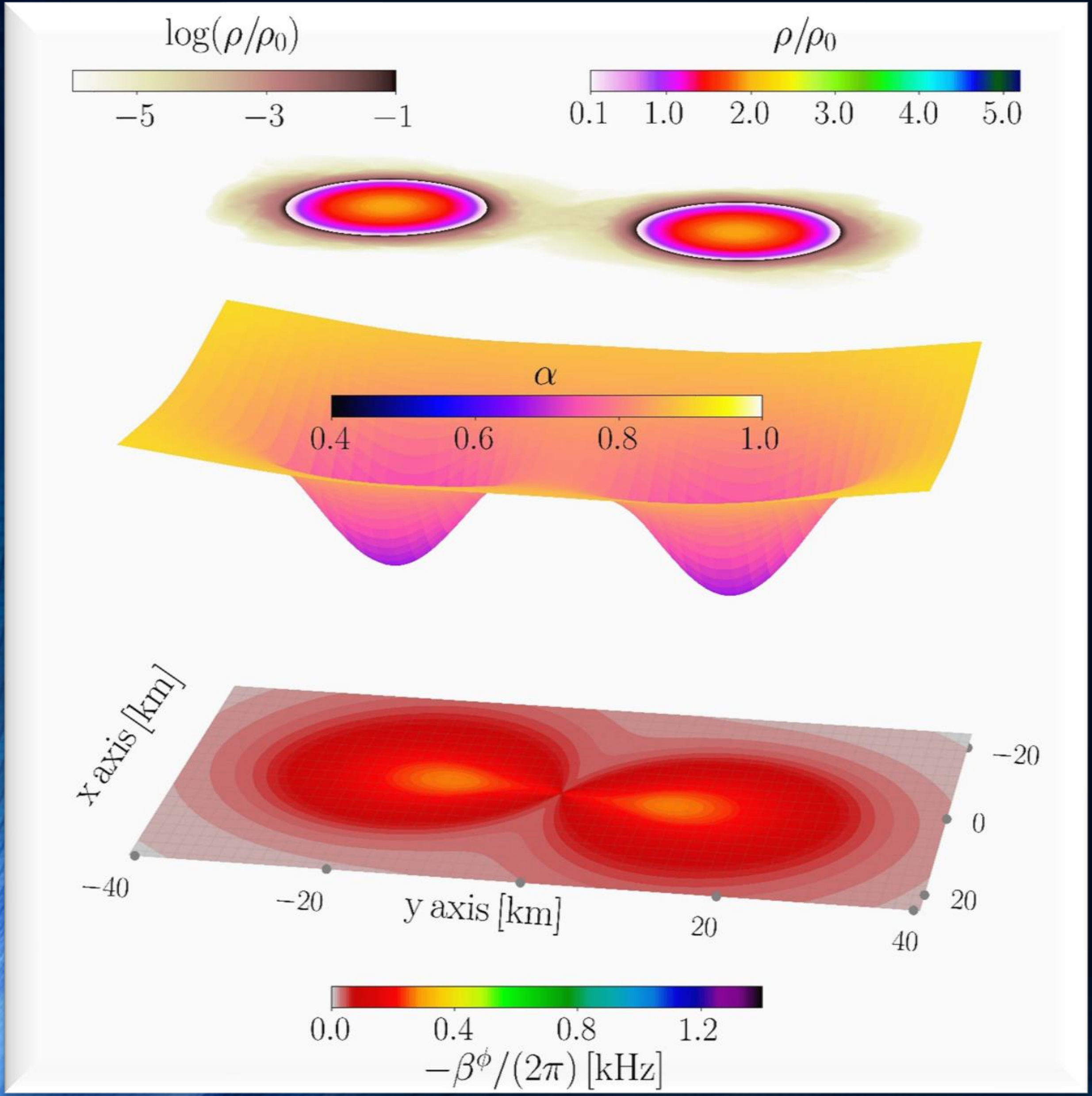
Post-merger gravitational-wave signatures of phase transitions in binary compact star mergers

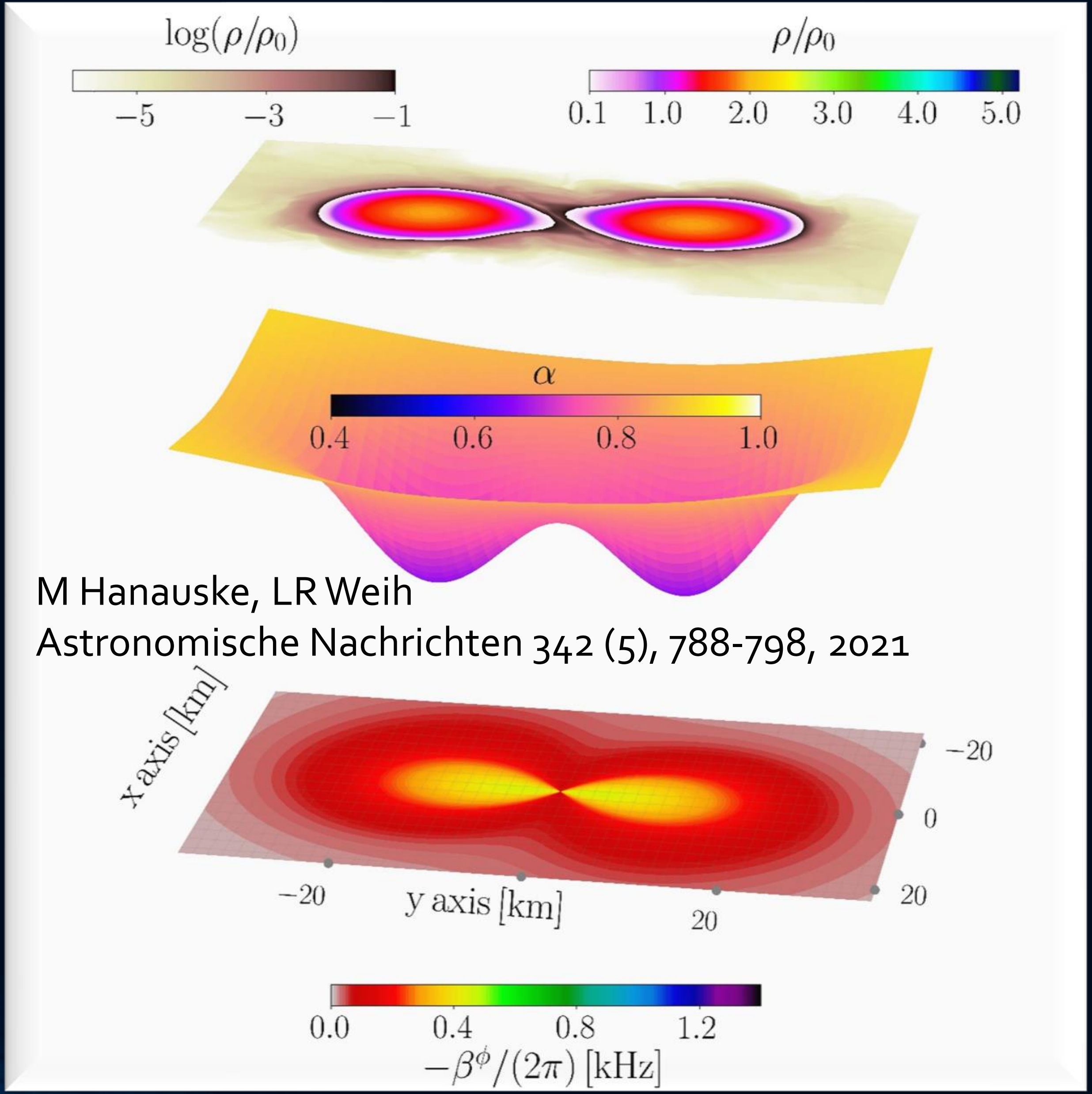


PRL 124, 171103 (2020)

Schematic overview of the instantaneous gravitational wave frequency and how its evolution can be used to classify the different scenarios associated with a hadron-quark phase transition.

The late inspiral phase (density, lapse and shift)

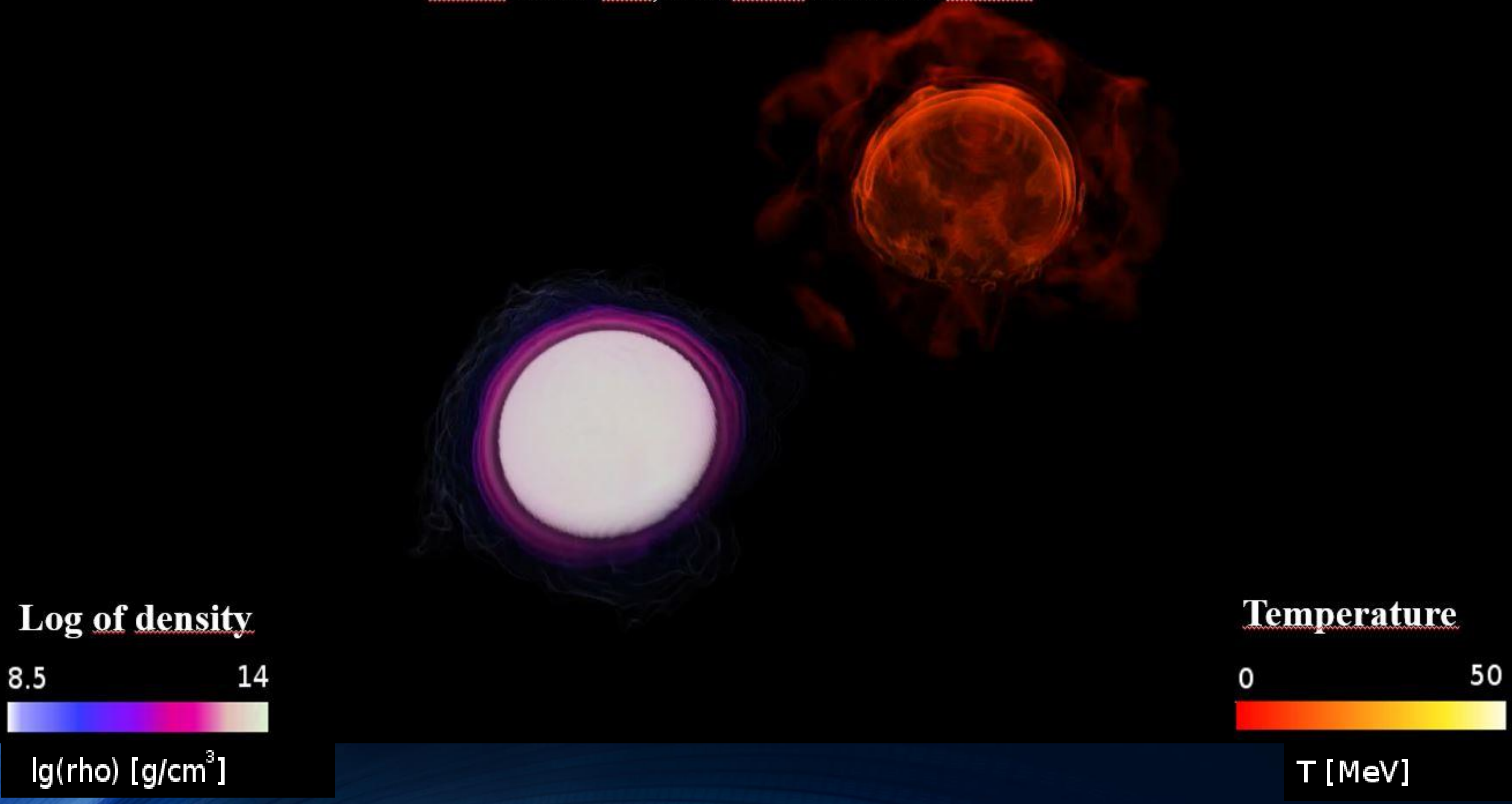




M Hanauske, LR Weih
Astronomische Nachrichten 342 (5), 788-798, 2021

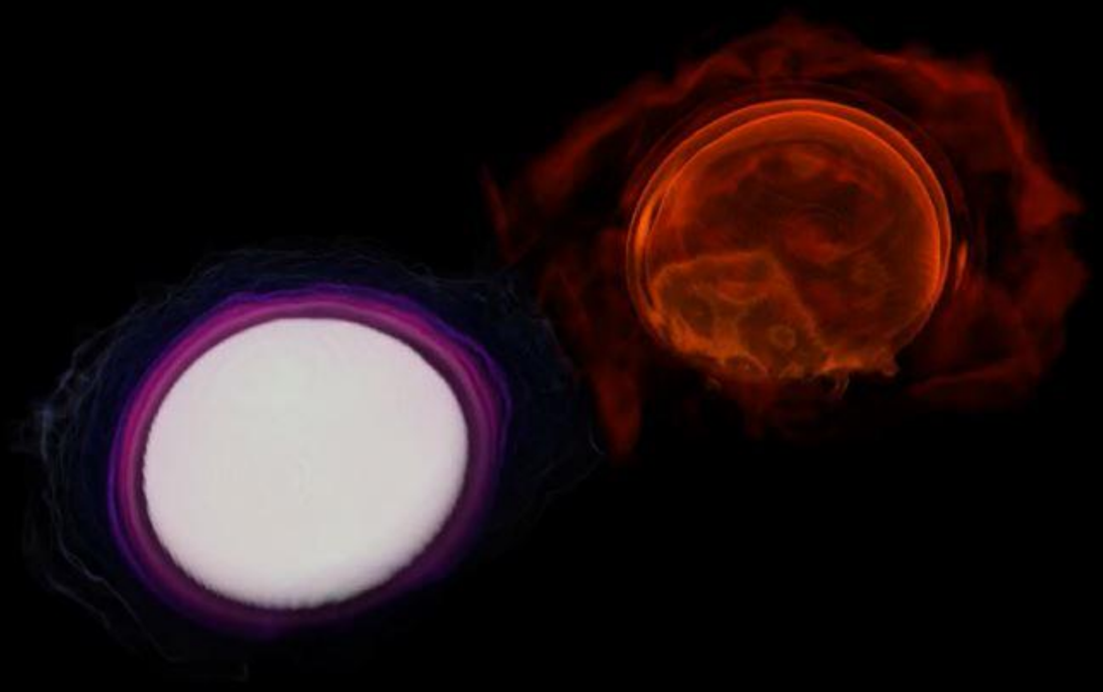
Computer Simulation of a neutron star merger

Credits: Cosima Breu, David Radice und Luciano Rezzolla



Computer Simulation of a neutron star merger

Credits: Cosima Breu, David Radice und Luciano Rezzolla



Log of density

8.5 14

lg(rho) [g/cm^3]

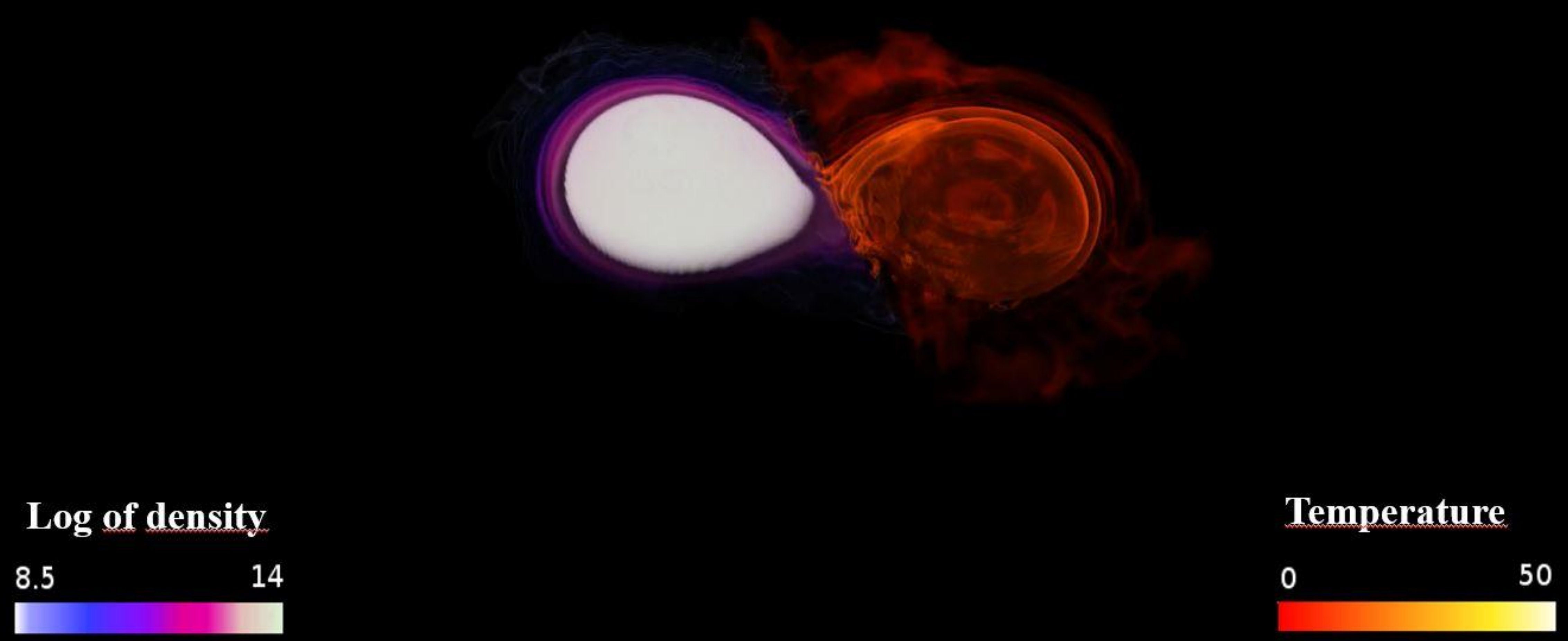
Temperature

0 50

T [MeV]

Computer Simulation of a neutron star merger

Credits: Cosima Breu, David Radice und Luciano Rezzolla



Computer Simulation of a neutron star merger

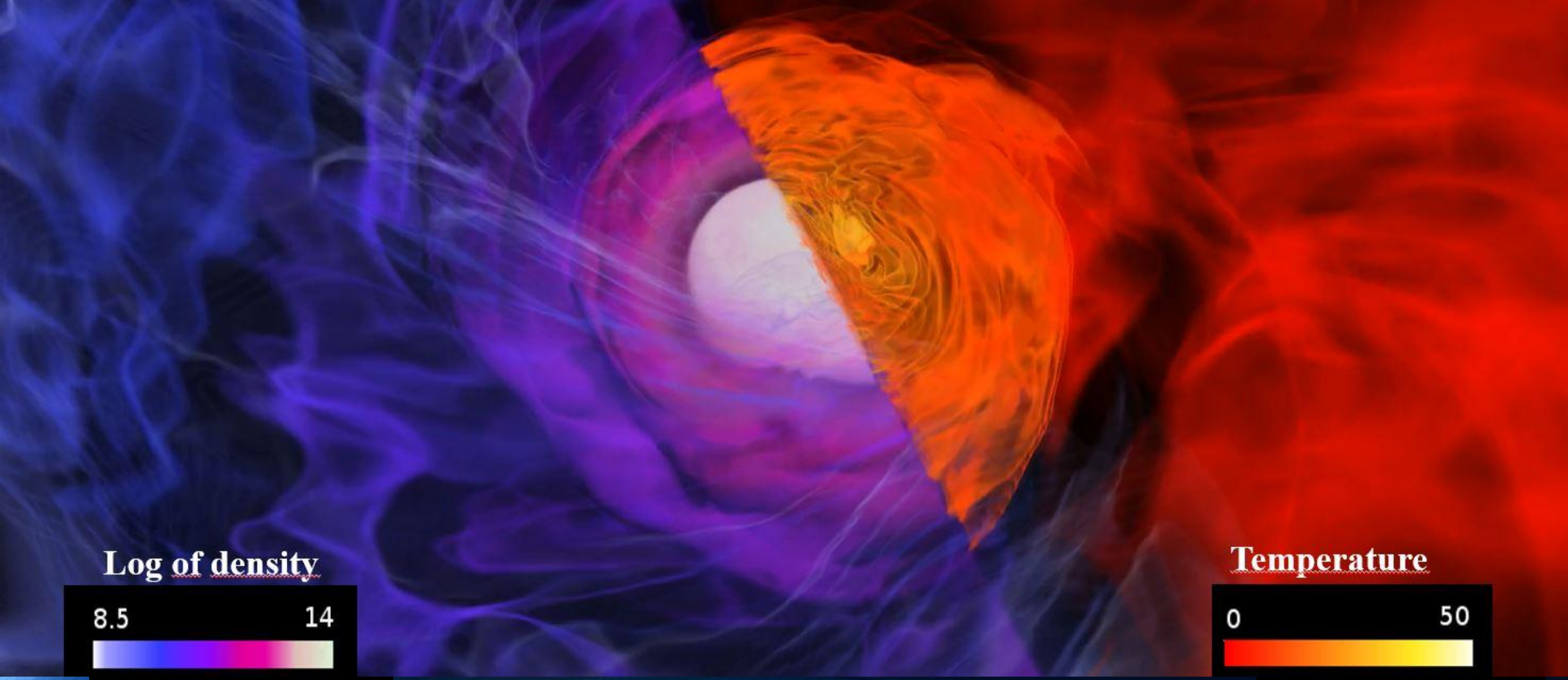
Credits: Cosima Breu, David Radice und Luciano Rezzolla

Computer Simulation of a neutron star merger

Credits: Cosima Breu, David Radice und Luciano Rezzolla

Computer Simulation of a neutron star merger

Credits: Cosima Breu, David Radice und Luciano Rezzolla



Computer Simulation of a neutron star merger

Credits: Cosima Breu, David Radice und Luciano Rezzolla

Computer Simulation of a neutron star merger

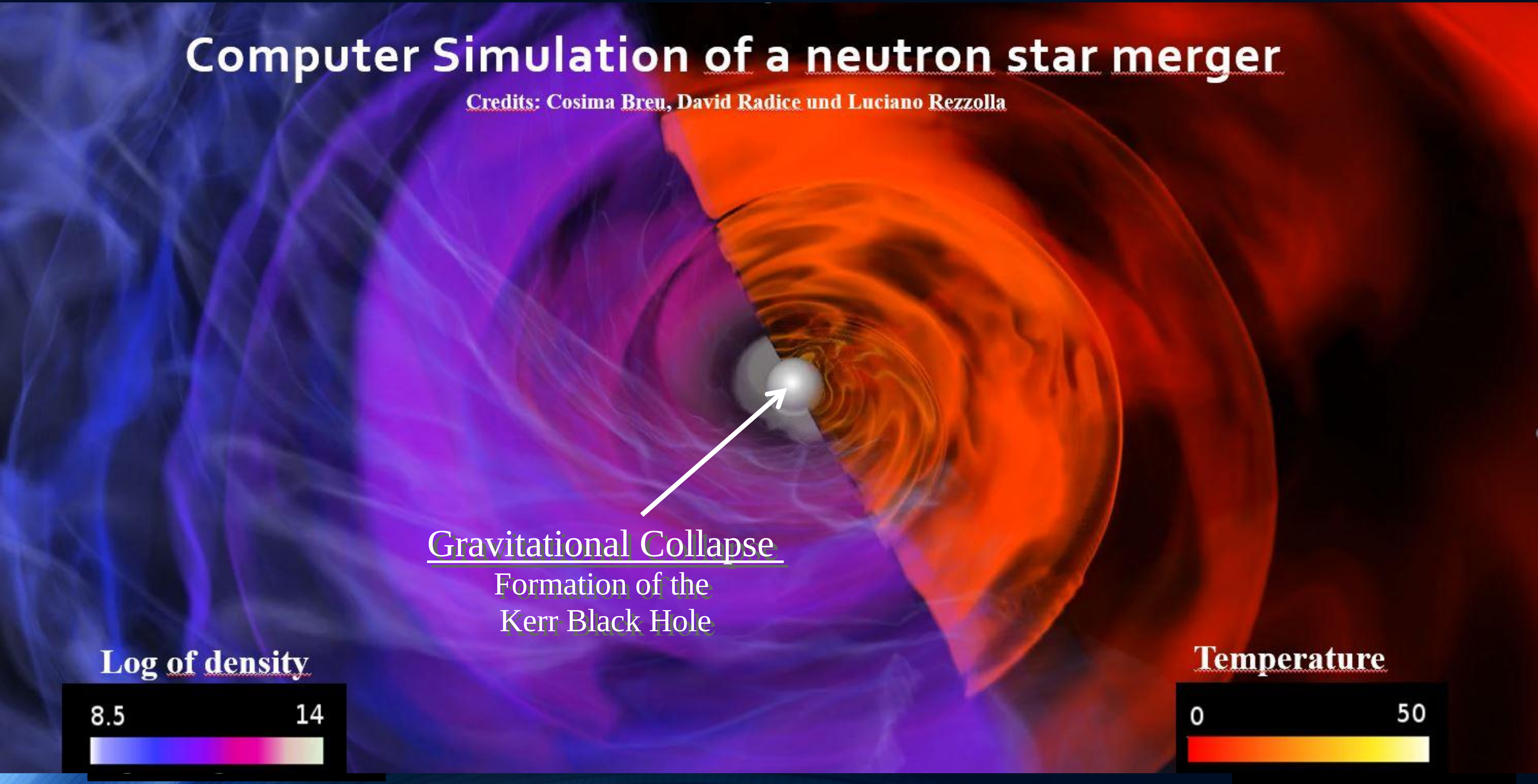
Credits: Cosima Breu, David Radice und Luciano Rezzolla

Computer Simulation of a neutron star merger

Credits: Cosima Breu, David Radice und Luciano Rezzolla

Computer Simulation of a neutron star merger

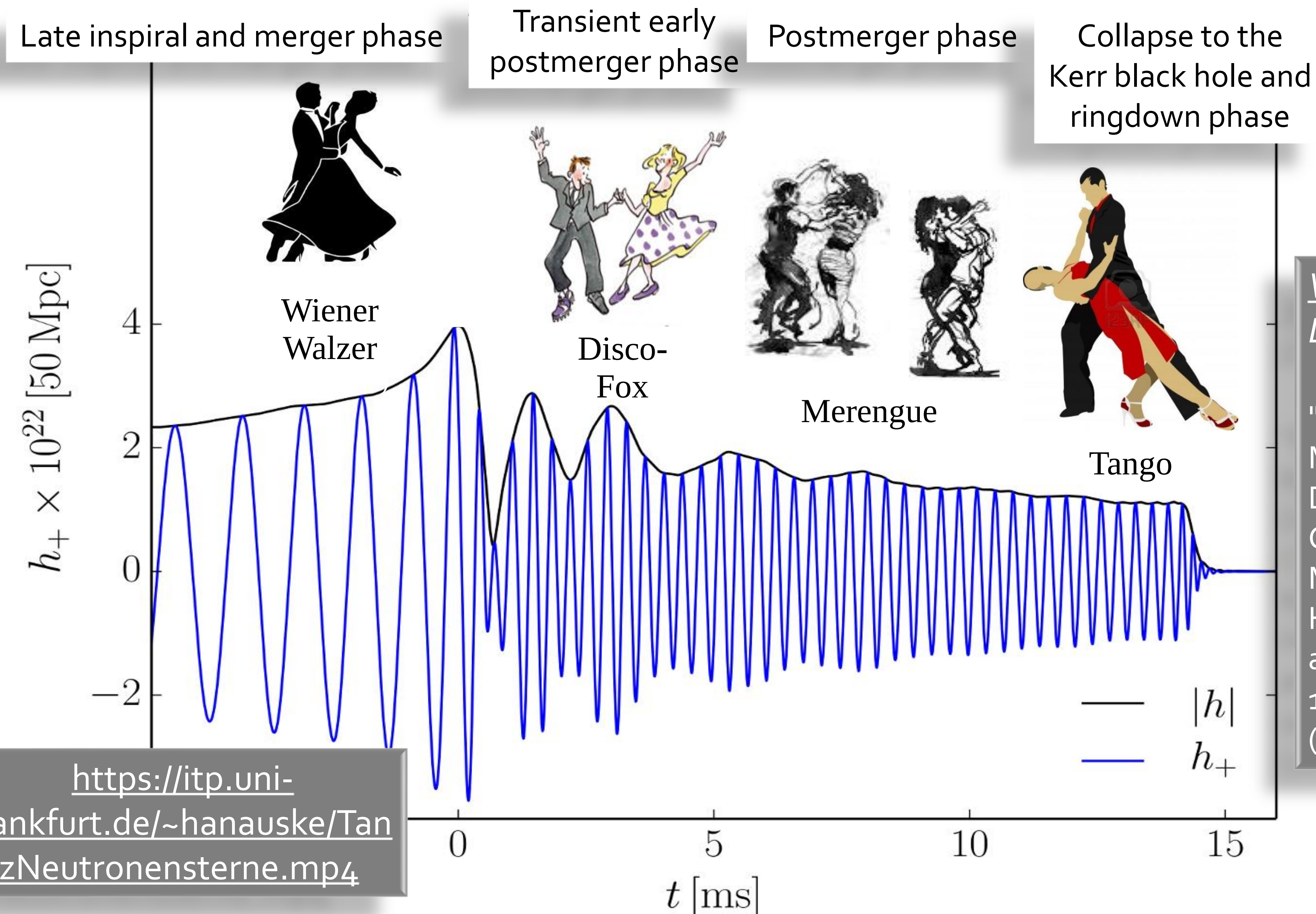
Credits: Cosima Breu, David Radice und Luciano Rezzolla


Computer Simulation of a neutron star merger
Credits: Cosima Breu, David Radice und Luciano Rezzolla
Gravitational Collapse
Formation of the
Kerr Black Hole
Log of density
8.5
14
Temperature
0
50

Computer Simulation of a neutron star merger

Credits: Cosima Breu, David Radice und Luciano Rezzolla

The different Phases of a Binary Compact Star Merger Event

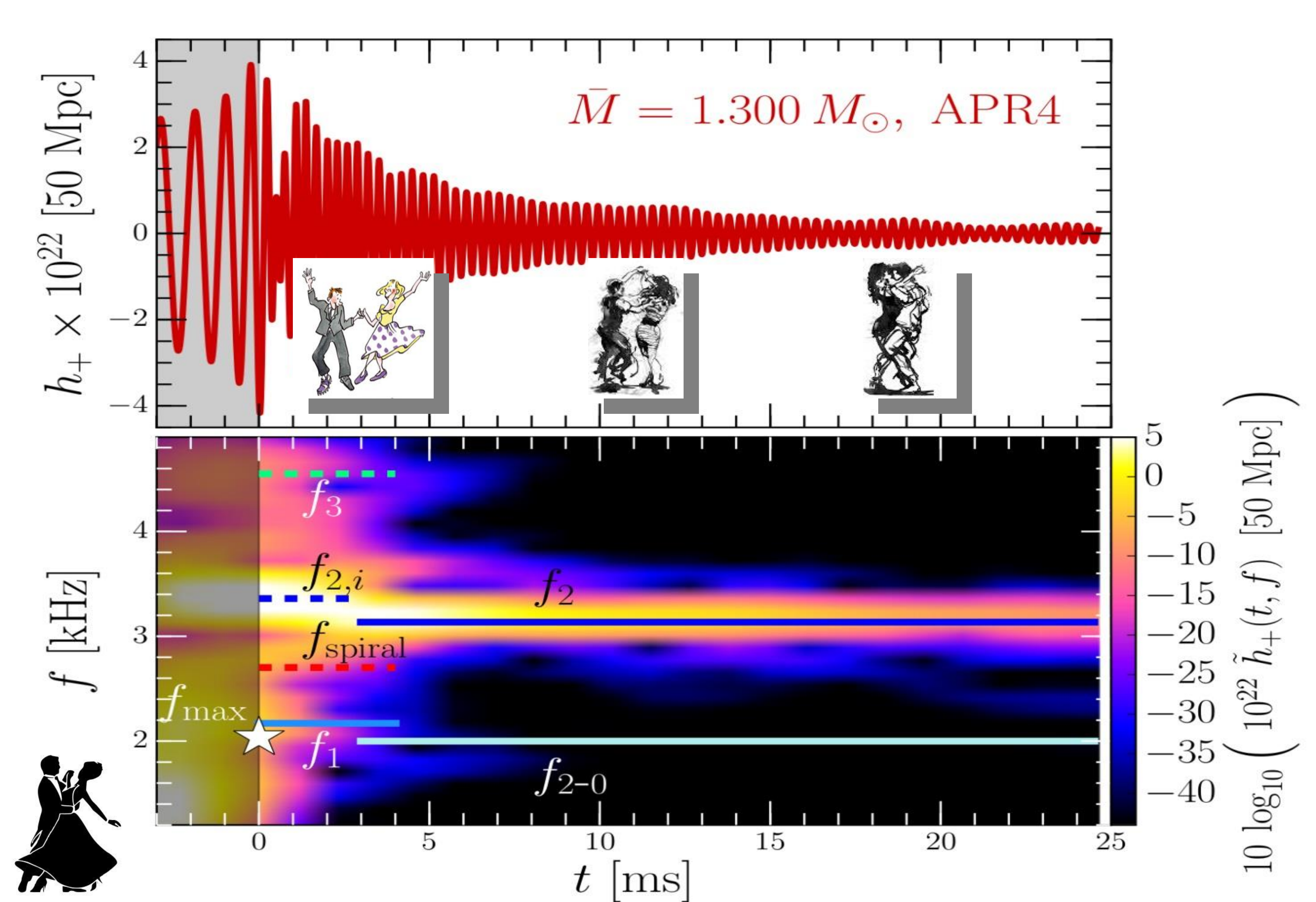


Wy exactly these dances? Details in

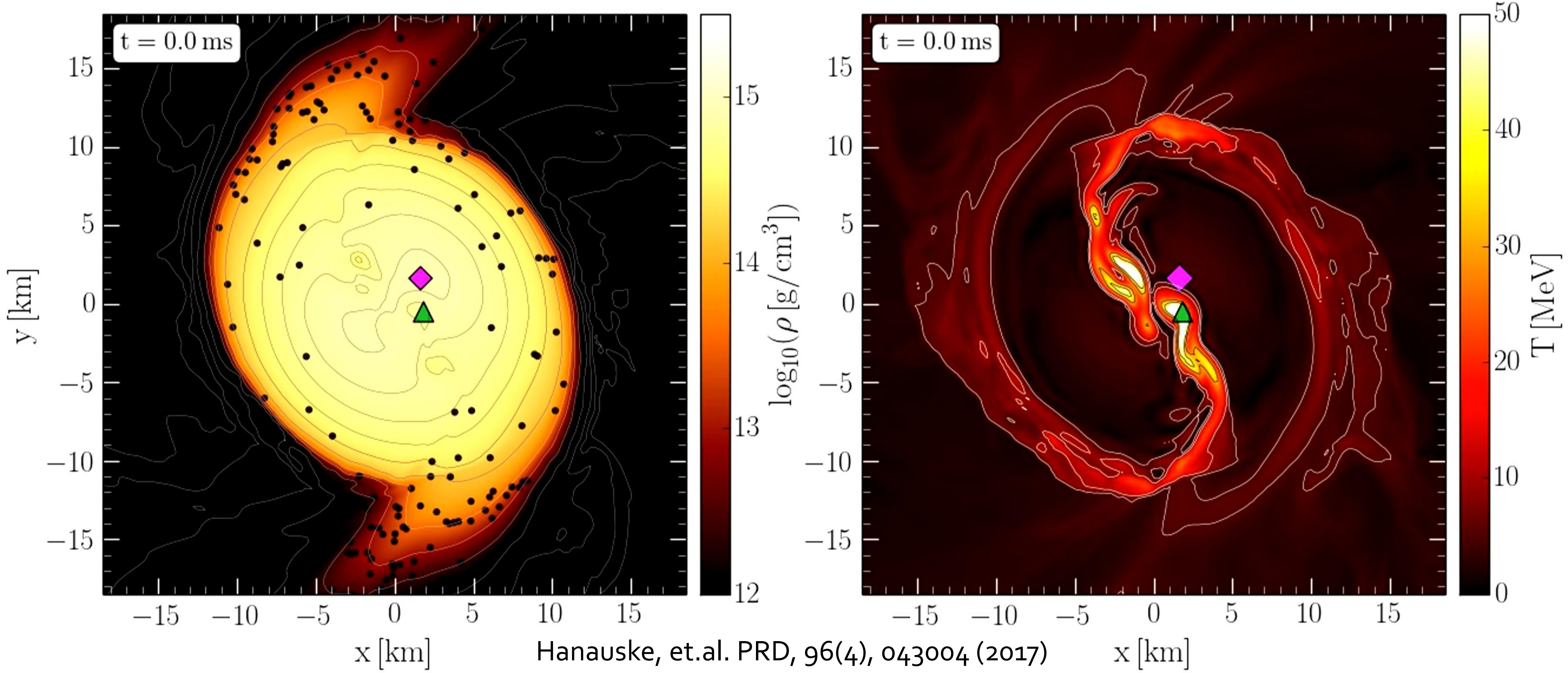
"Binary Compact Star Mergers and the Phase Diagram of Quantum Chromodynamics", Matthias Hanauske and Horst Stöcker, Discoveries at the Frontiers of Science, 107-132; Springer, Cham (2020)

https://itp.uni-frankfurt.de/~hanauske/TanzNeutronensterne.mp4

The different Phases during the Postmergerphase of the HMNS



Density and Temperature Evolution inside the HMNS

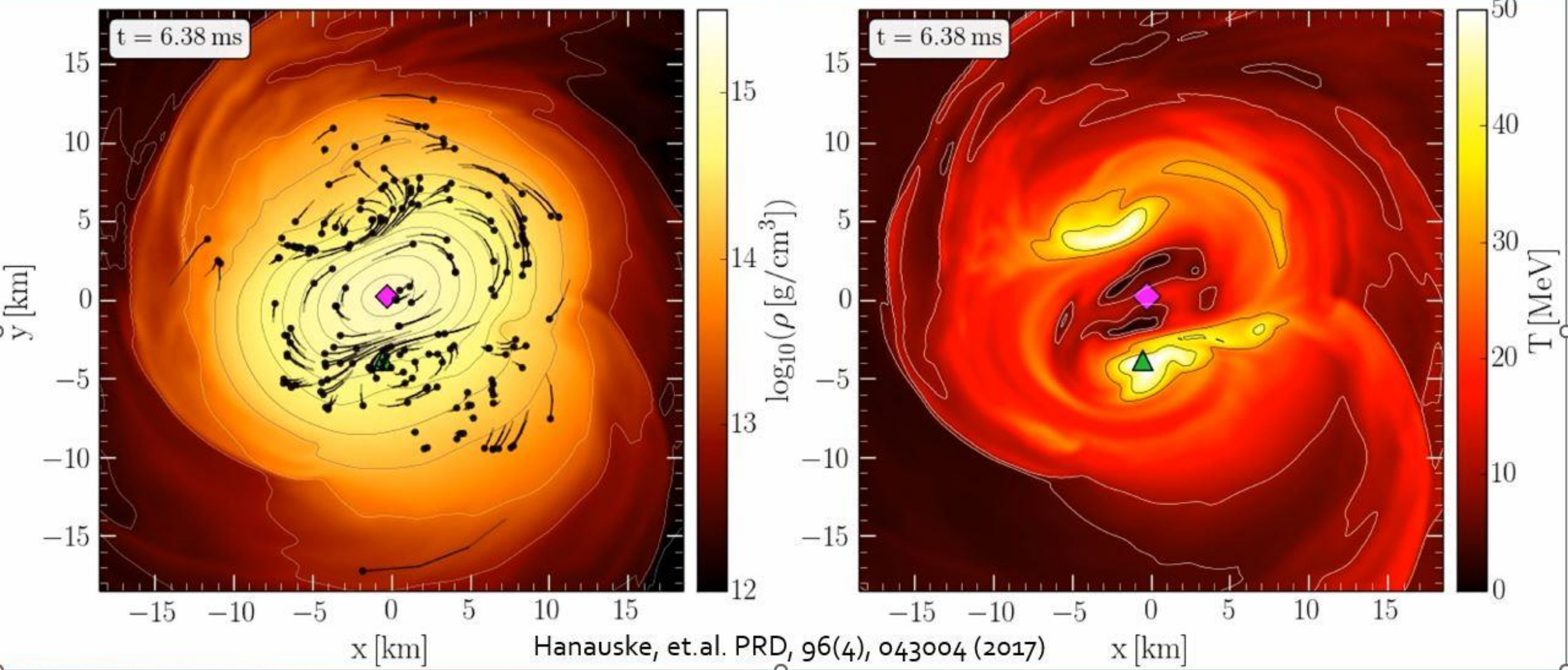


Hanauske, et.al. PRD, 96(4), 043004 (2017)

Rest mass density on the equatorial plane

Temperature on the equatorial plane

Density and Temperature Evolution inside the HMNS



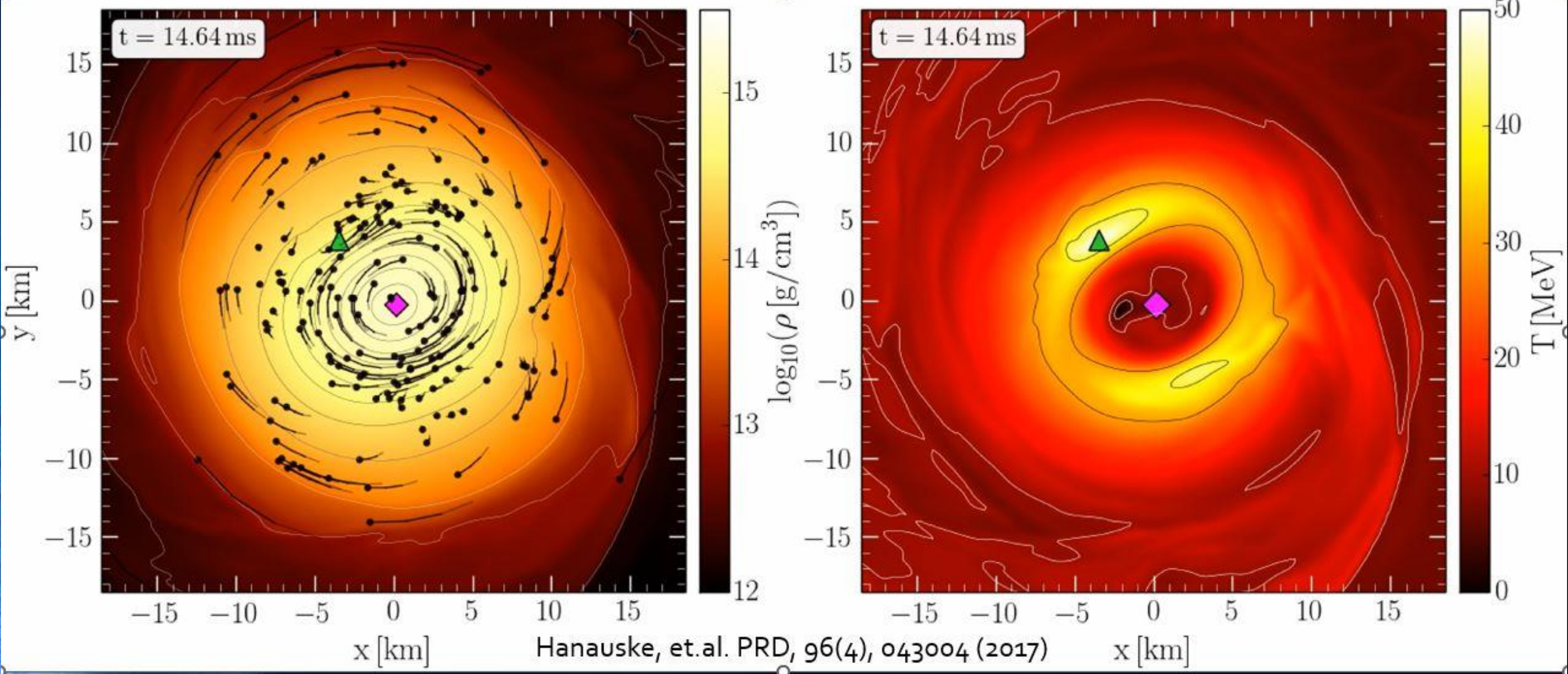
Hanauske, et.al. PRD, 96(4), 043004 (2017)

00:15,12

Rest mass density on the equatorial plane

Temperature on the equatorial plane

Density and Temperature Evolution inside the HMNS



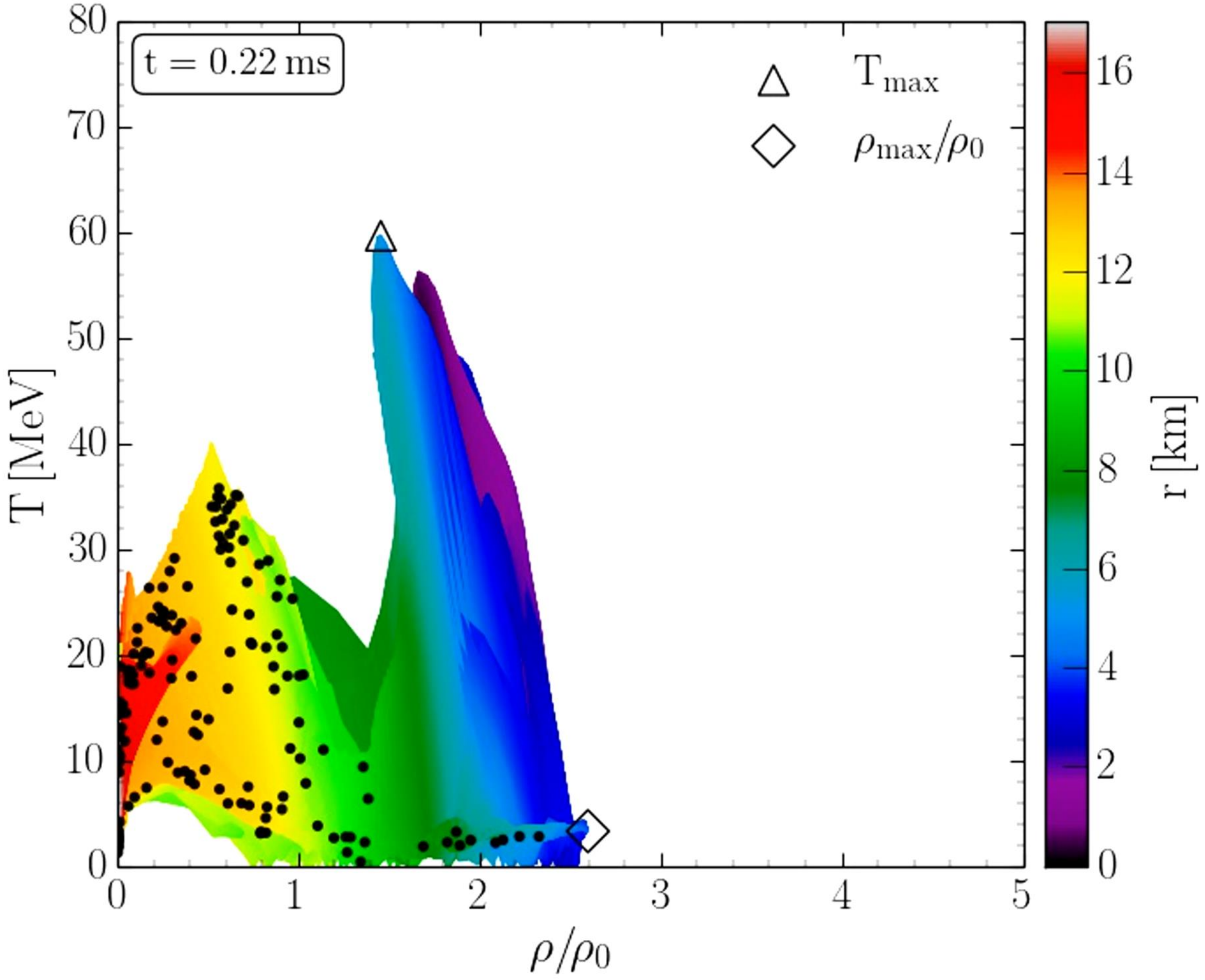
Hanauske, et.al. PRD, 96(4), 043004 (2017)

00:33,76

Rest mass density on the equatorial plane

Temperature on the equatorial plane

Binary Neutron Star Mergers in the QCD Phase Diagram

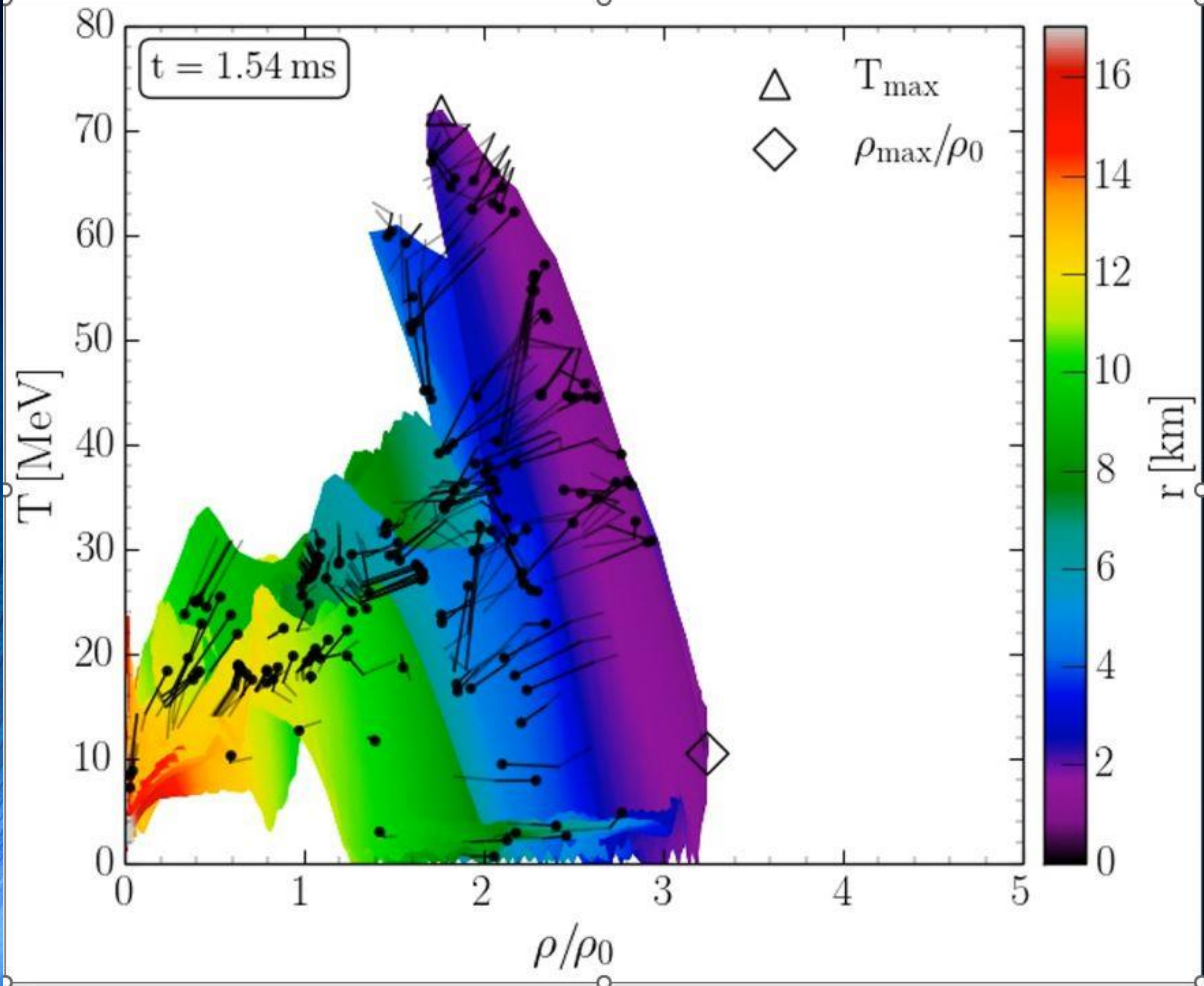


Evolution of hot and dense matter inside the inner area of a hypermassive neutron star simulated within the LS220 EOS with a total mass of $M_{total}=2.7\, M_\odot$ in the style of a (T- ρ) QCD phase diagram plot

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

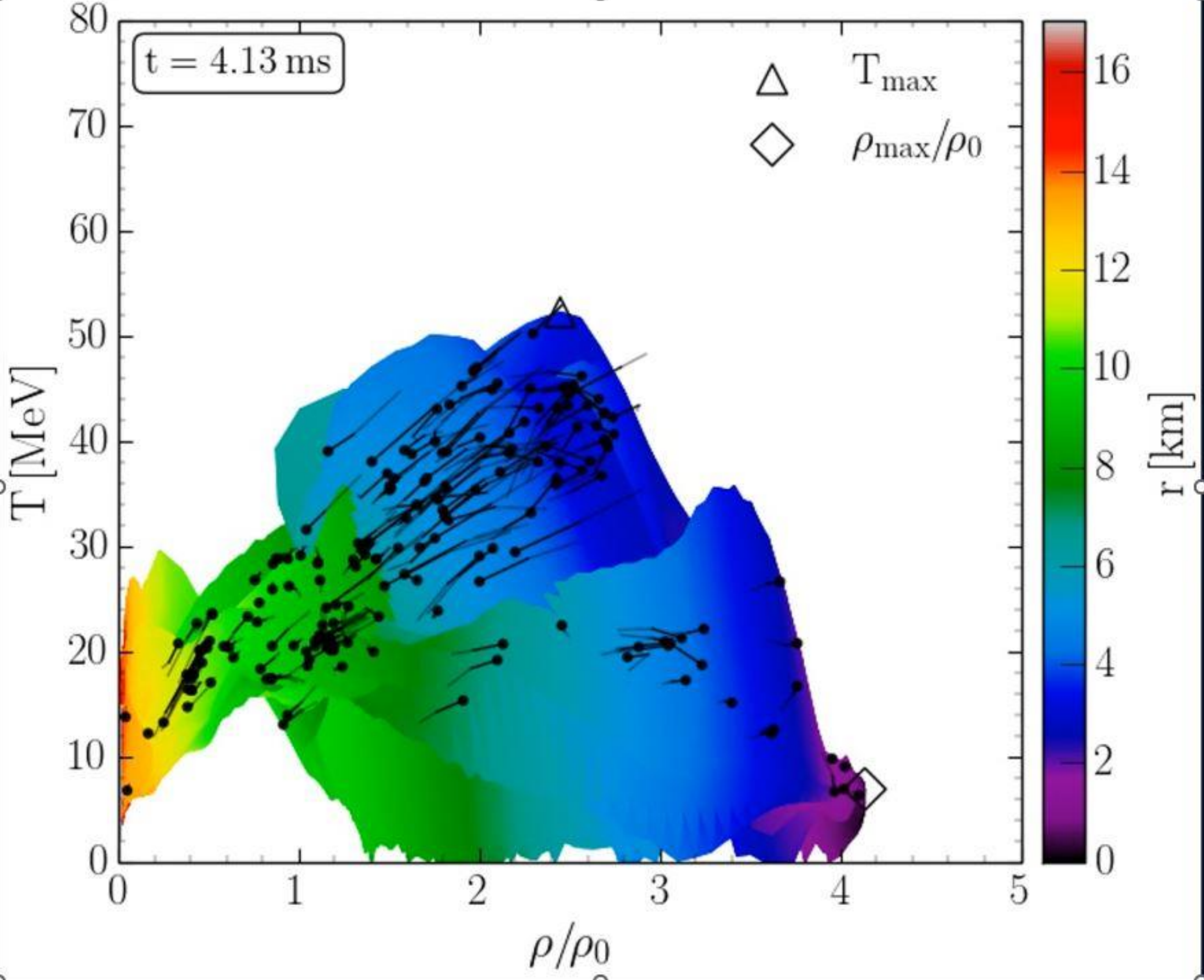


Evolution of hot and dense matter inside the inner area of a hypermassive neutron star simulated within the LS220 EOS with a total mass of M_{total}=2.7 $M_{\odot}$ in the style of a (T- ρ) QCD phase diagram plot

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

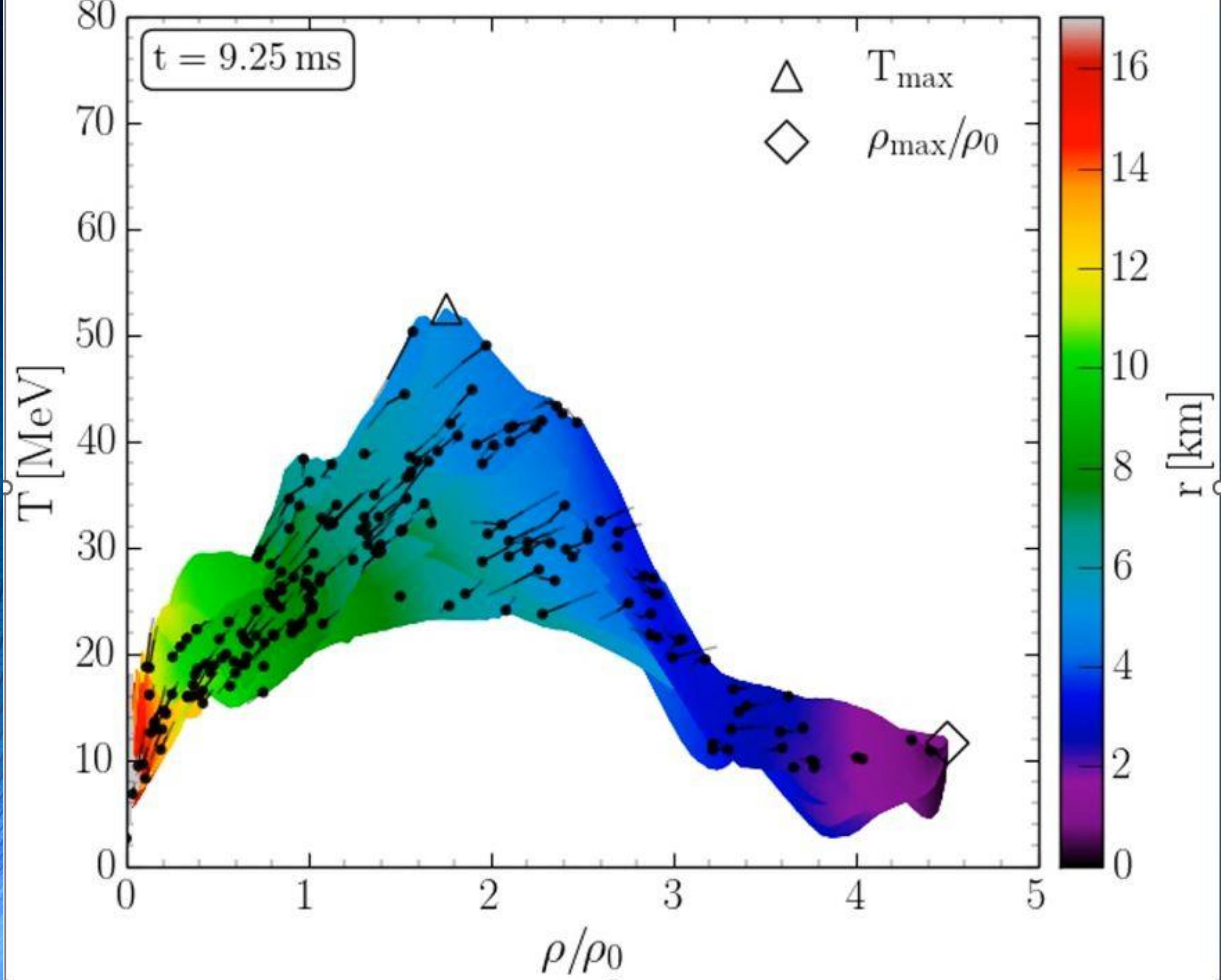


Evolution of hot and dense matter inside the inner area of a hypermassive neutron star simulated within the LS220 EOS with a total mass of M_{total}=2.7 $M_{\odot}$ in the style of a (T- ρ) QCD phase diagram plot

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

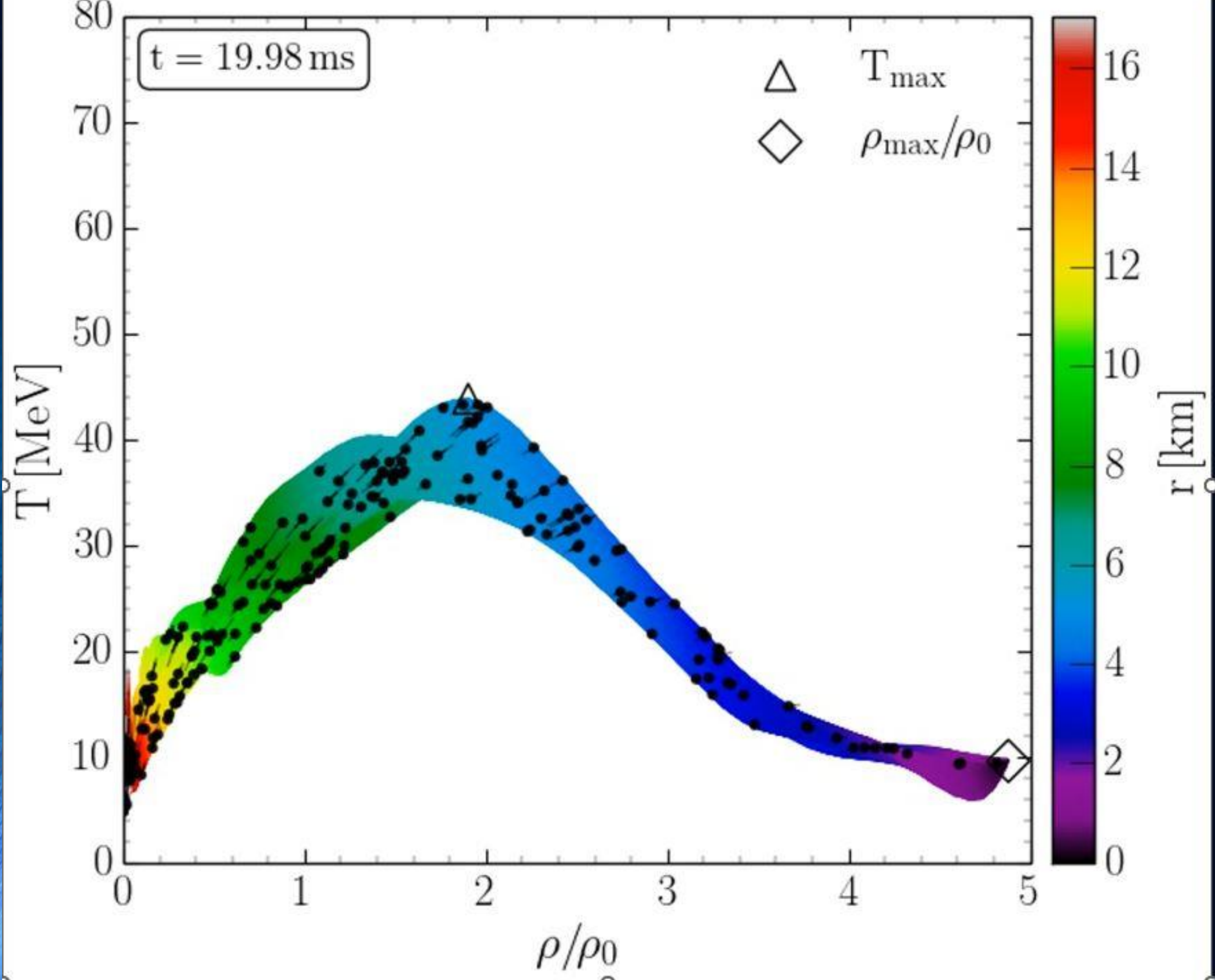


Evolution of hot and dense matter inside the inner area of a hypermassive neutron star simulated within the LS220 EOS with a total mass of M_{total}=2.7 $M_\odot$ in the style of a (T- ρ) QCD phase diagram plot

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



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.

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

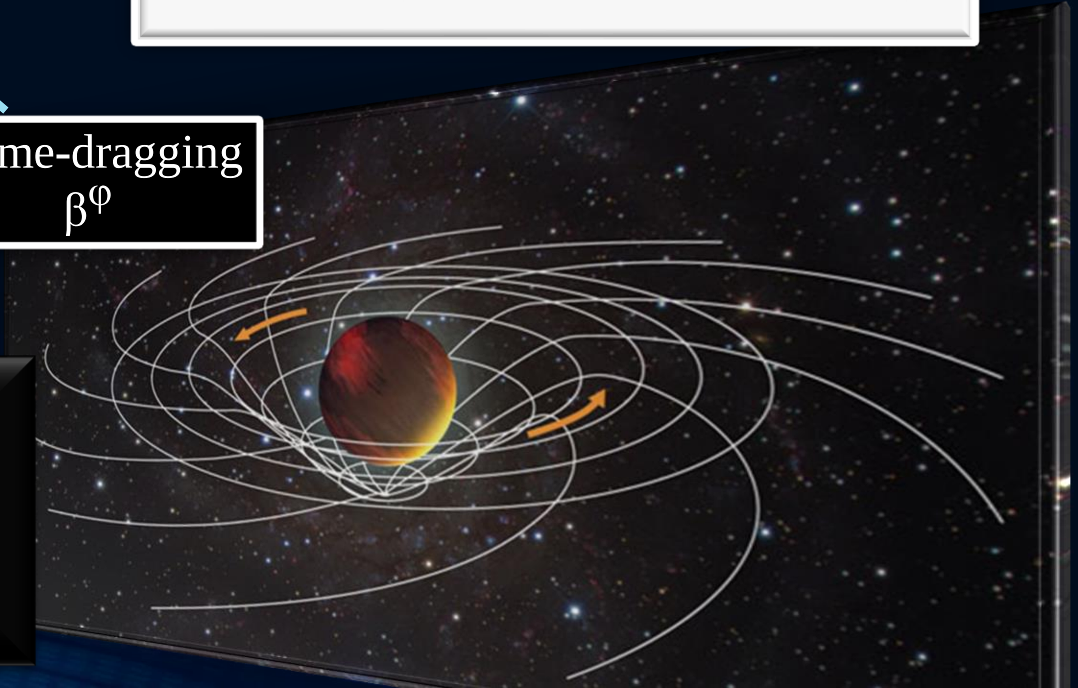
Lapse function
α

Φ-component of
3-velocity v^φ

Frame-dragging
β^φ

(3+1)-decomposition of spacetime:

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



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)

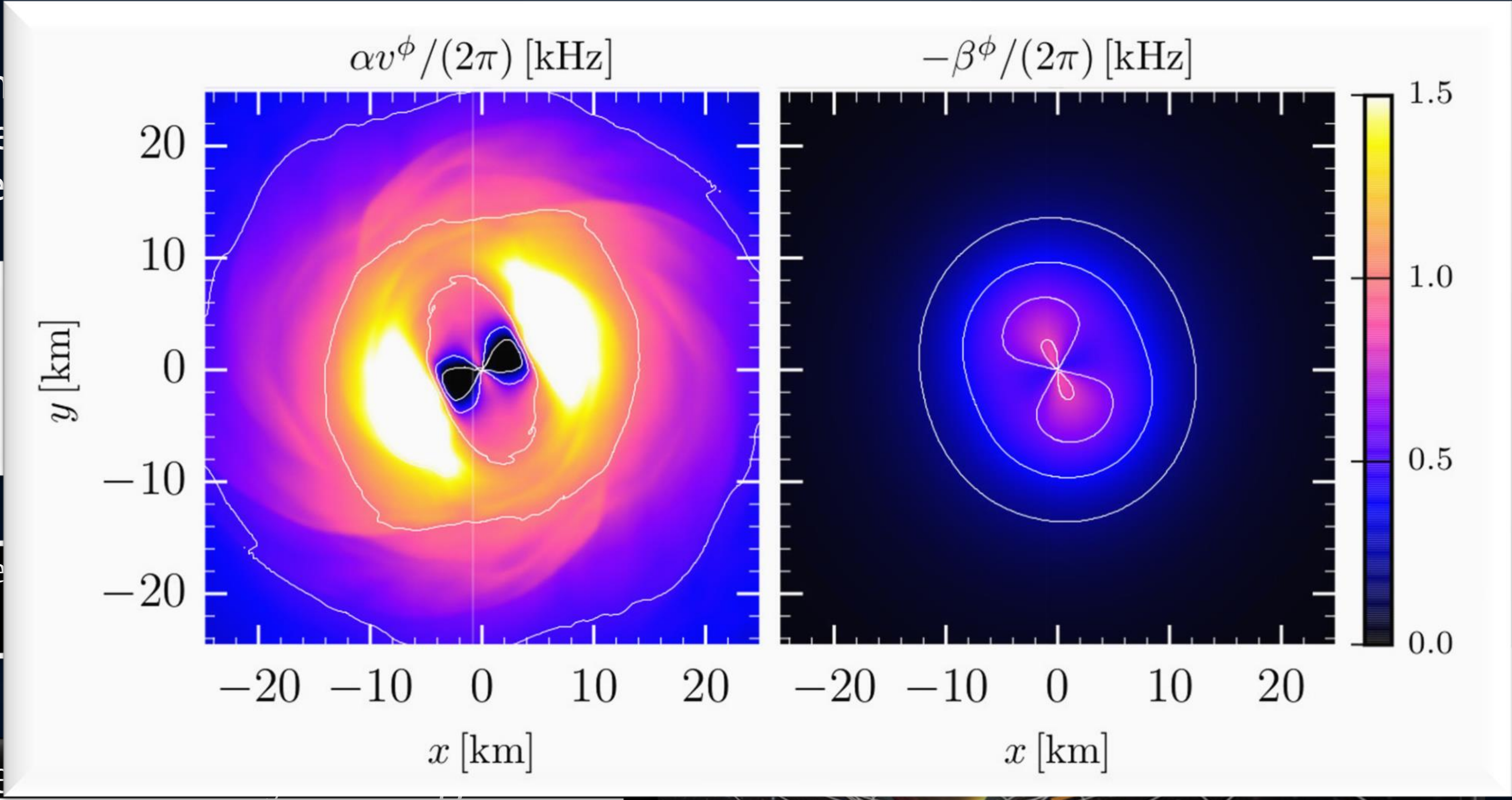
The Angular Velocity in the (3+1)-Split

The angular velocity Ω in th
function α , the ϕ-compone
v^{ϕ} of the fluid (spatial proje

$$\Omega(x, y, z, t) =$$

Angular velocity
Ω

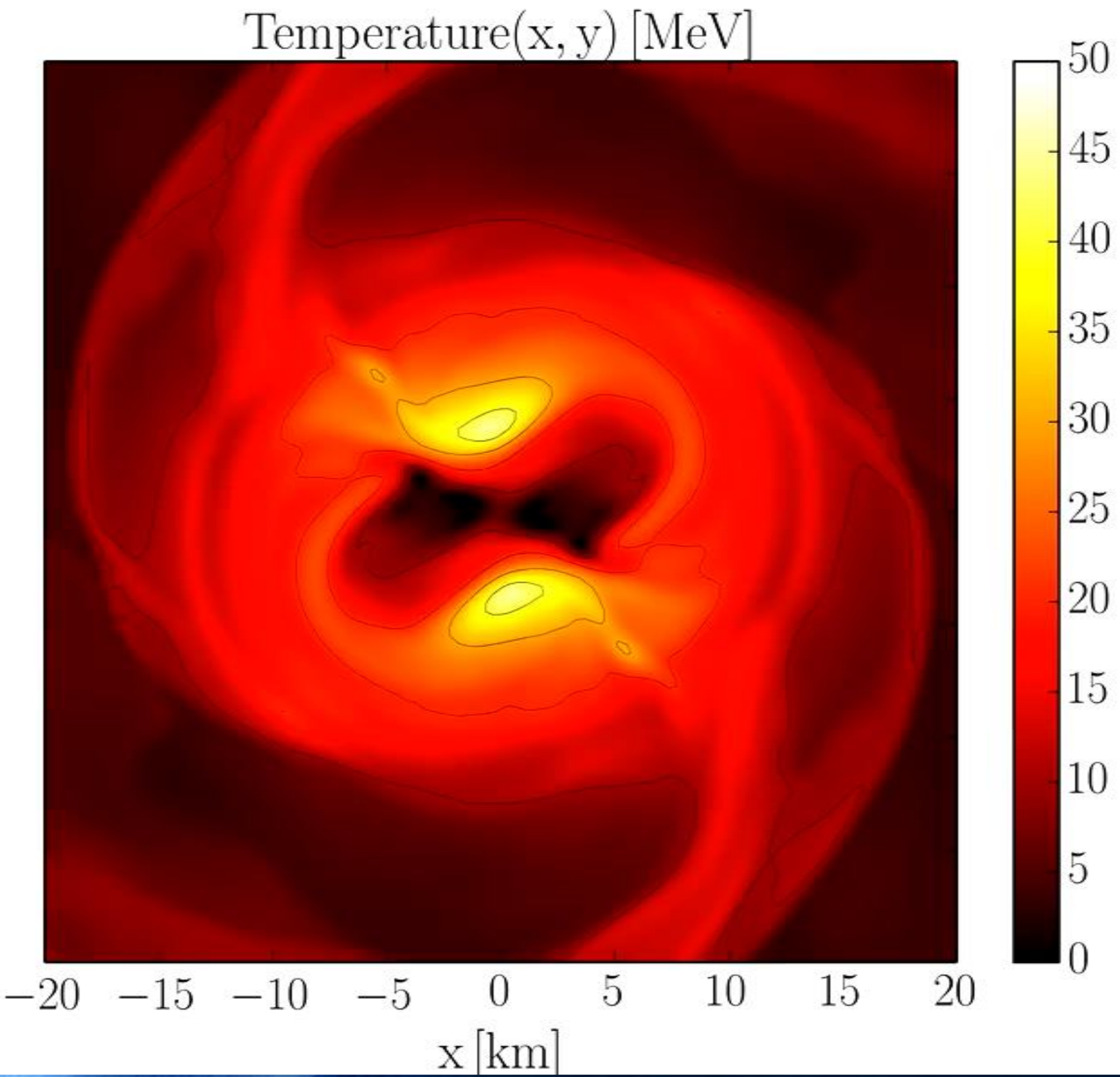
Lapse



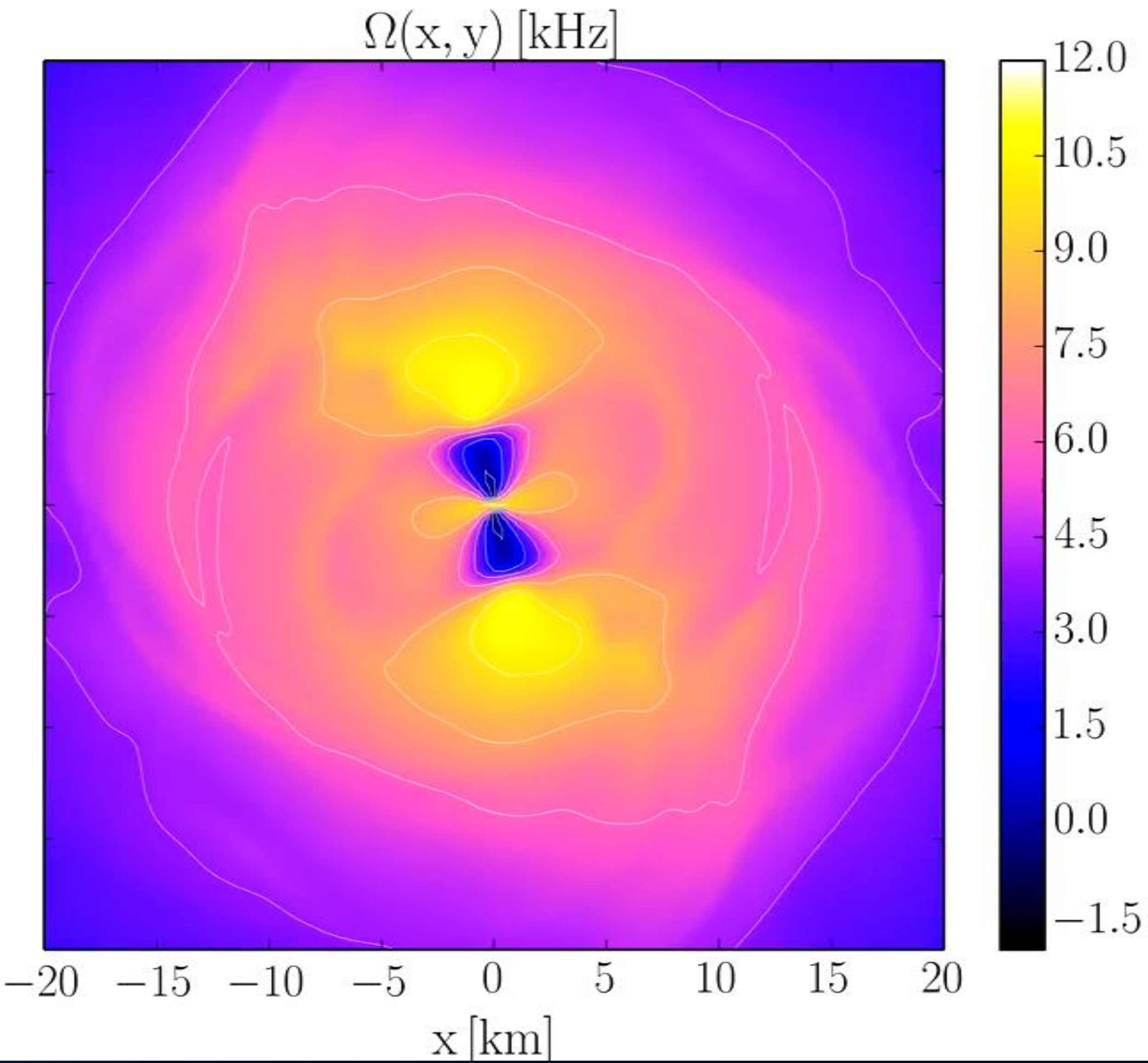
Focus: Inner core of the

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

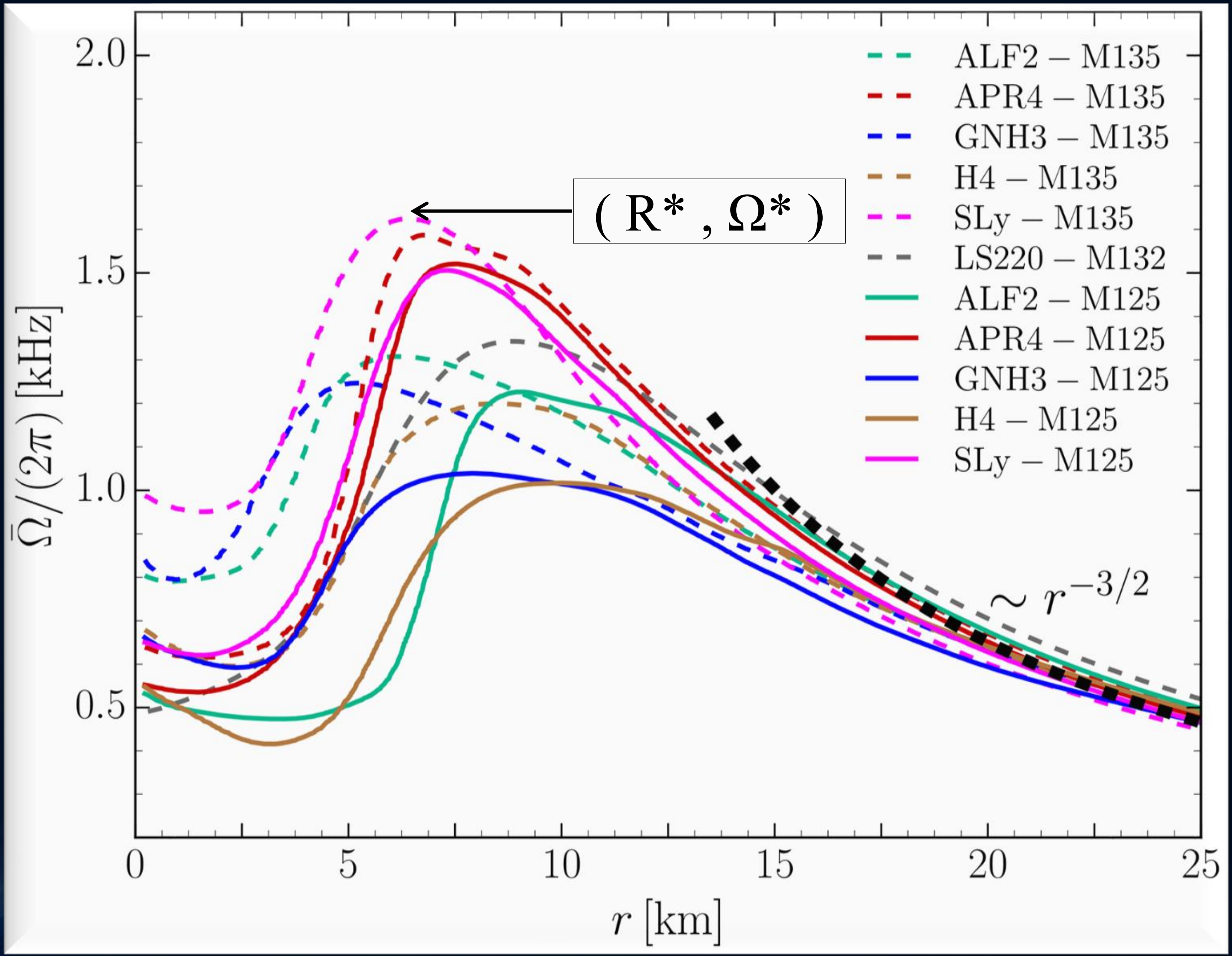


Angular Velocity



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

Time-averaged Rotation Profiles of the HMNSs



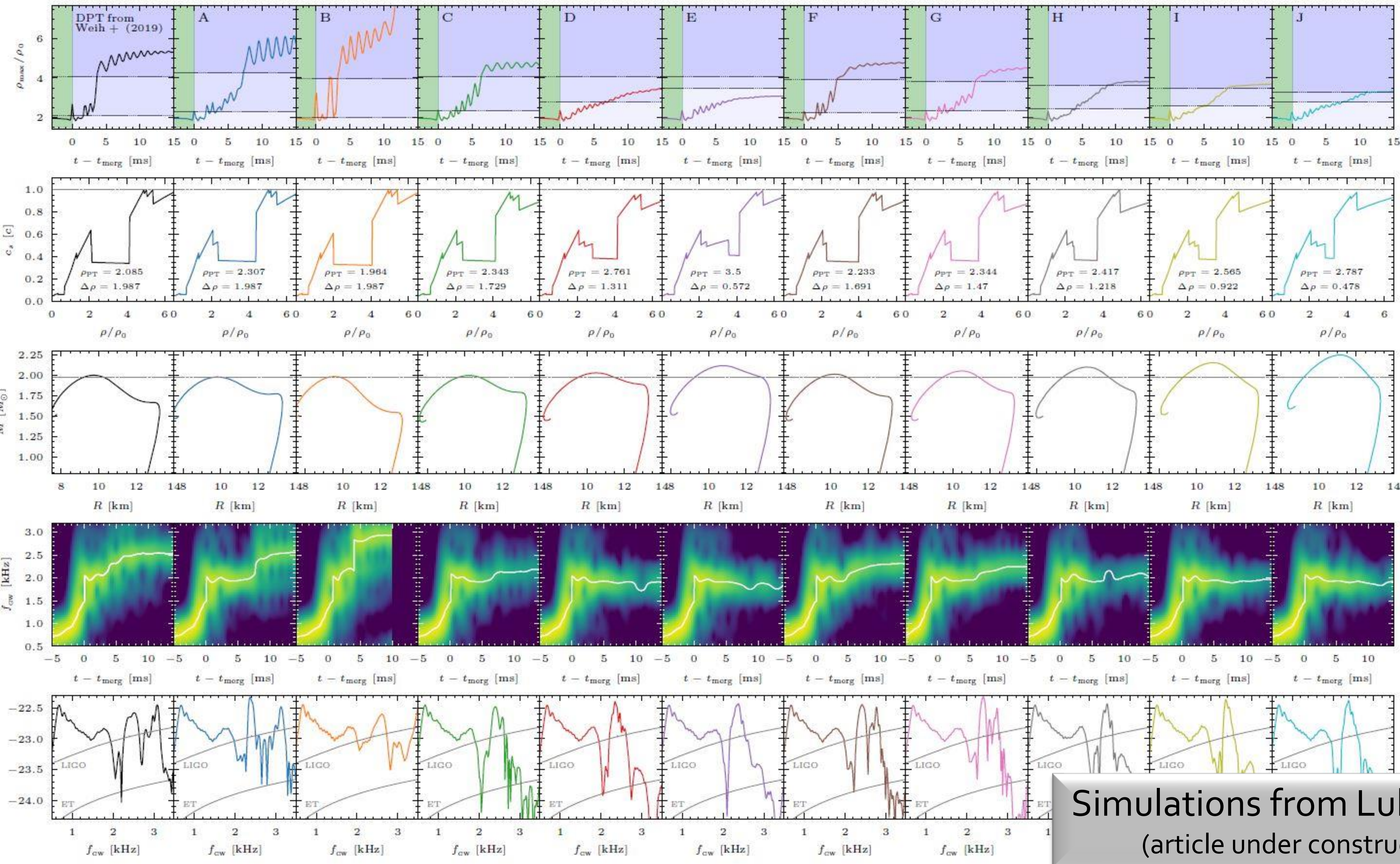
Soft EoSs:
Sly
APR4

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)

Analysis of the impact of phase transitions

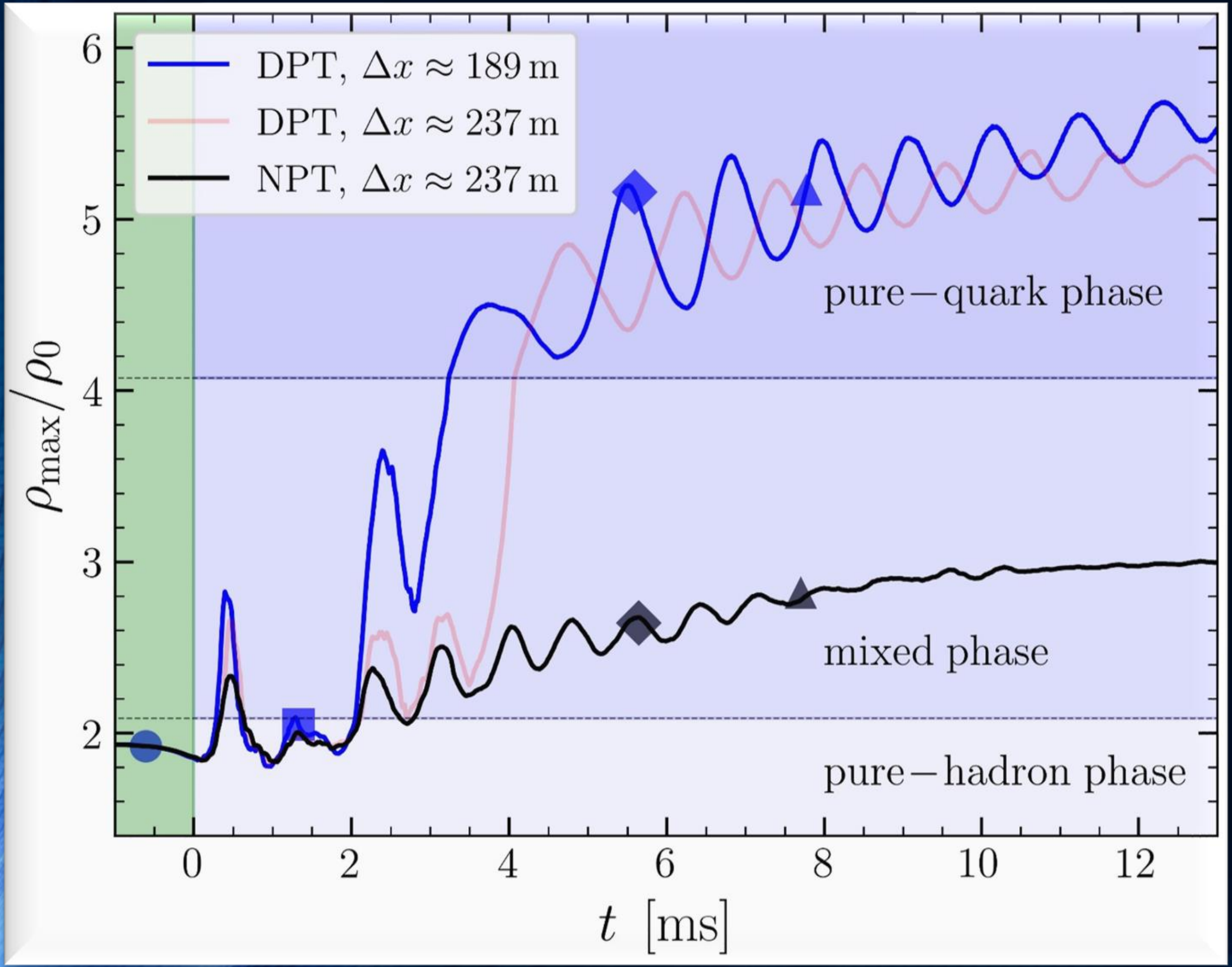


Simulations from Lukas Weih
(article under construction)

Signatures within the post-merger phase evolution

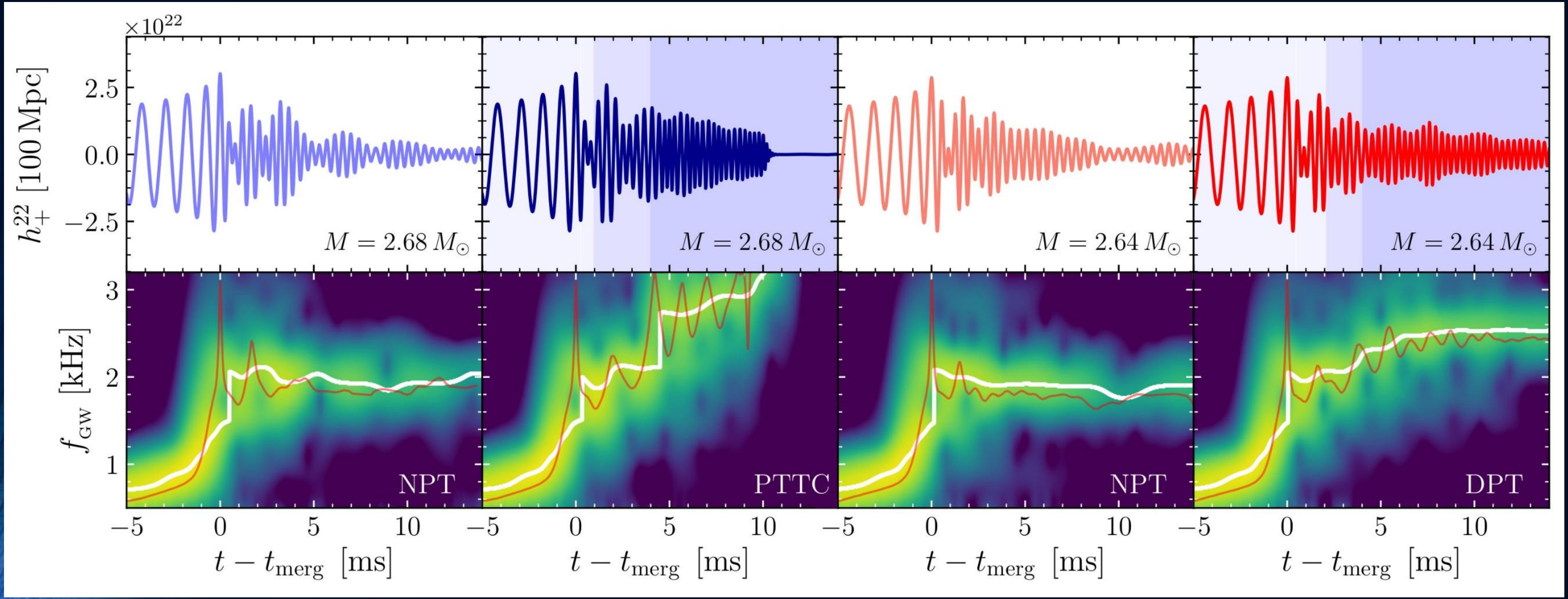
DPT: Delayed phase transition scenario

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



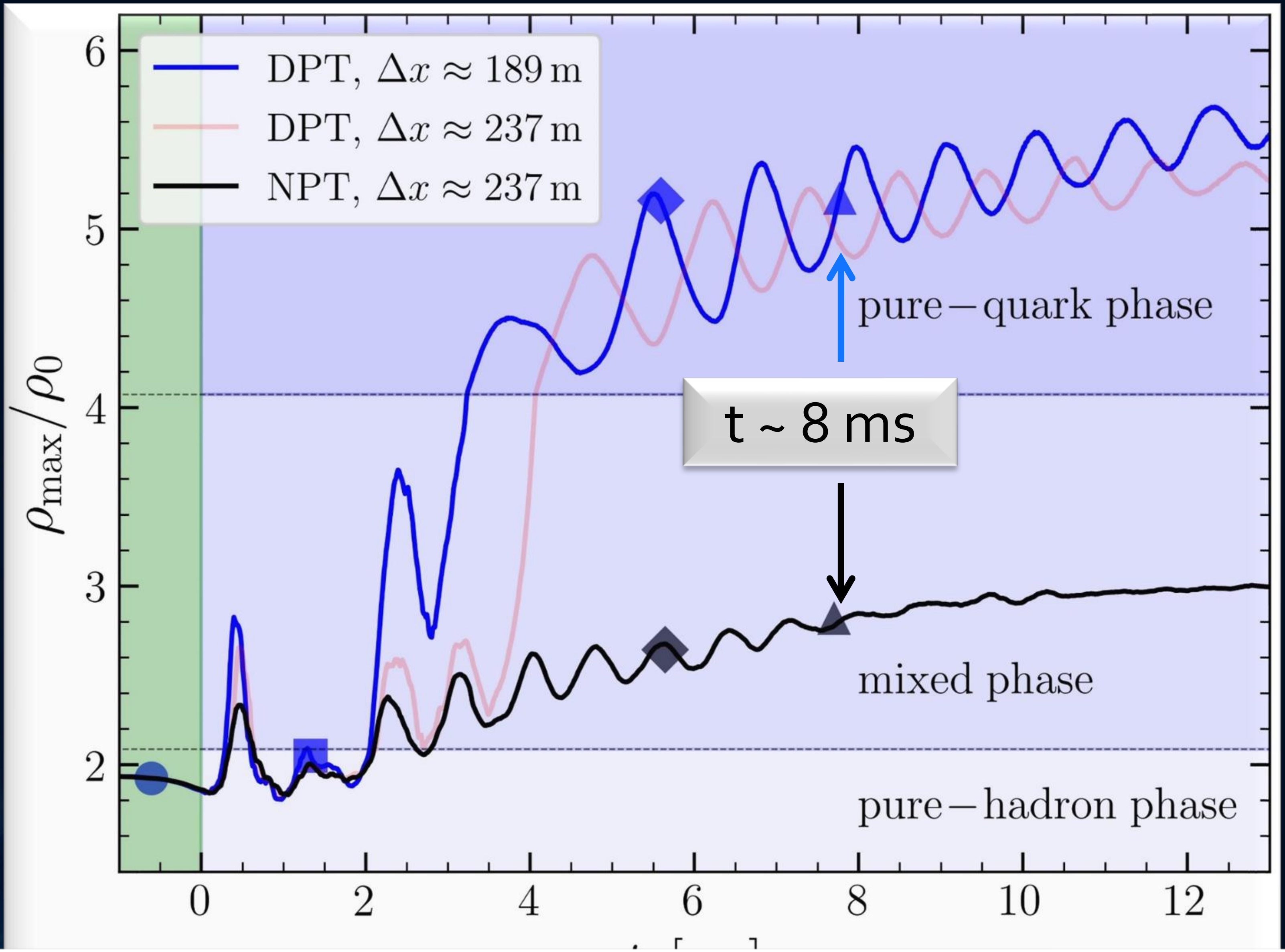
Maximum value of the rest-mass density vs time for three binary neutron star simulations. Black curve without a phase transition (NPT) and blue/red with a Gibbs-like hadron-quark phase transition (DPT: standard/low resolution). Blue-shaded regions mark the different phases of the EOS (mixed phase and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

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



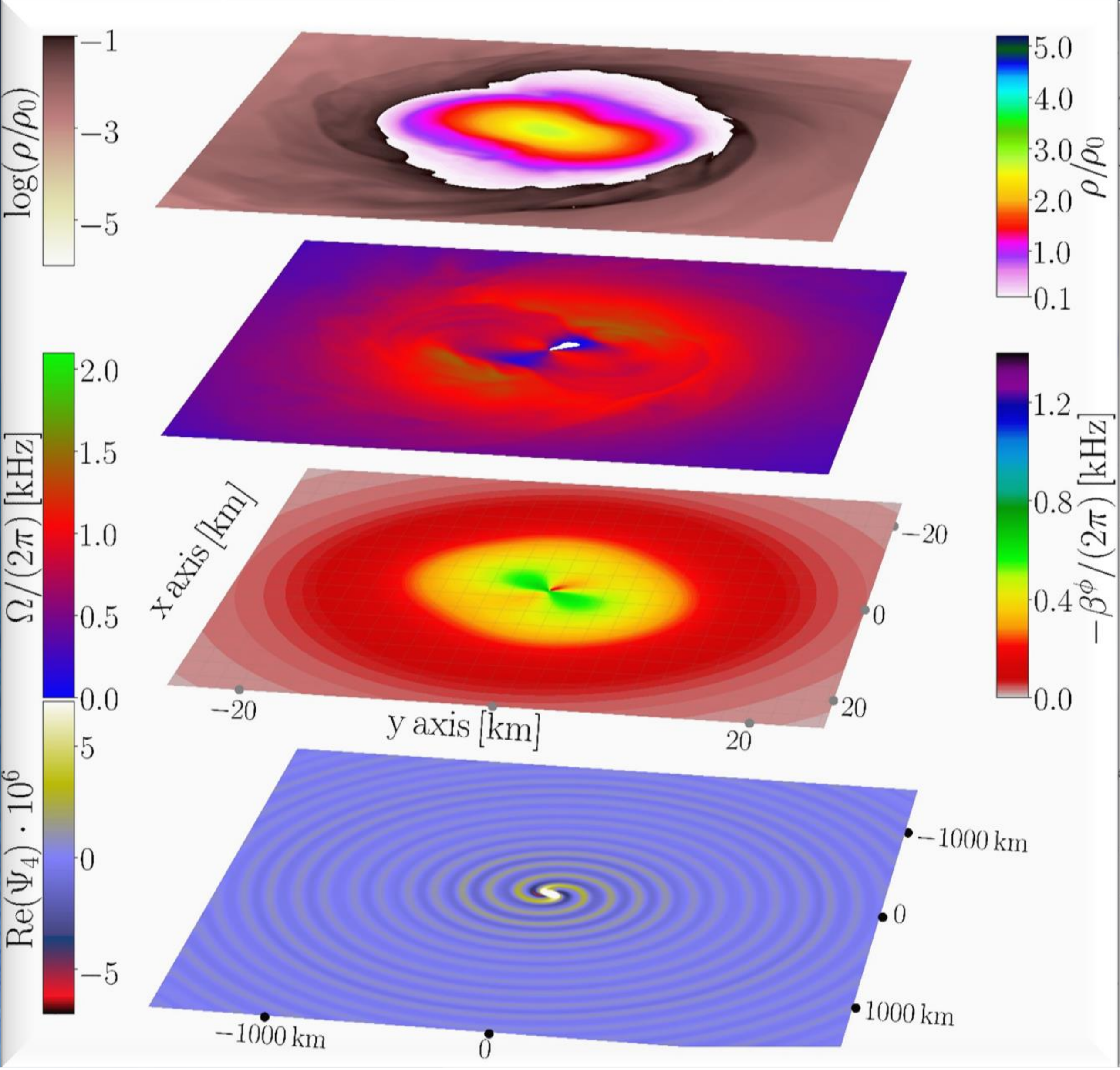
Strain h+ (top) and its spectrogram (bottom) for the four BNSs considered. In the top panels the different shadings mark the times when the HMNS core enters the mixed and quark phases the NPT models are always purely hadronic. In the bottom panels, the white lines trace the maximum of the spectrograms,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

Without Phase Transition With Phase Transition

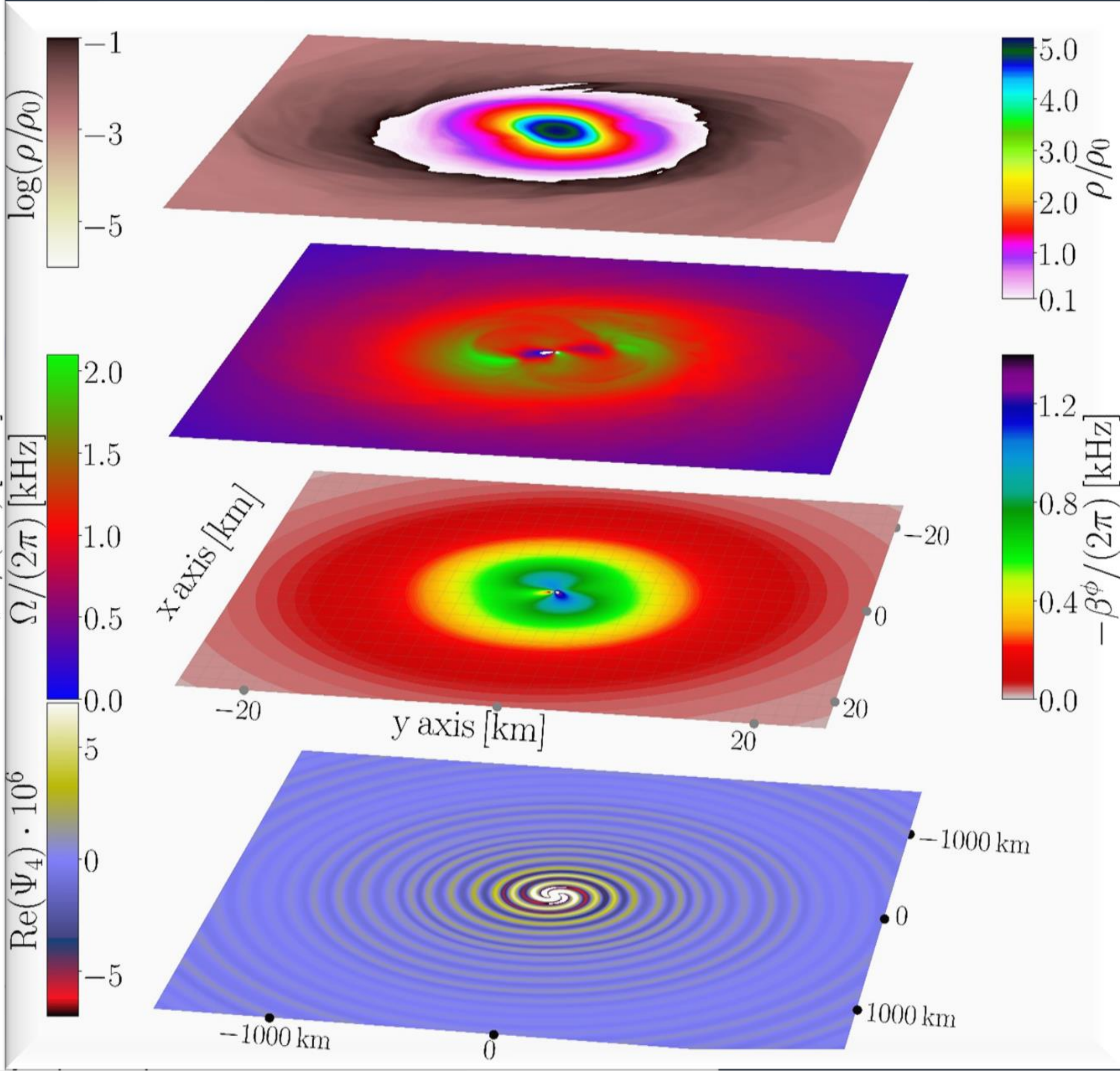


Matthias Hanauske and Lukas Weih. "Neutron star collisions and gravitational waves." *Astronomische Nachrichten* (2021)

Without Phase Transition

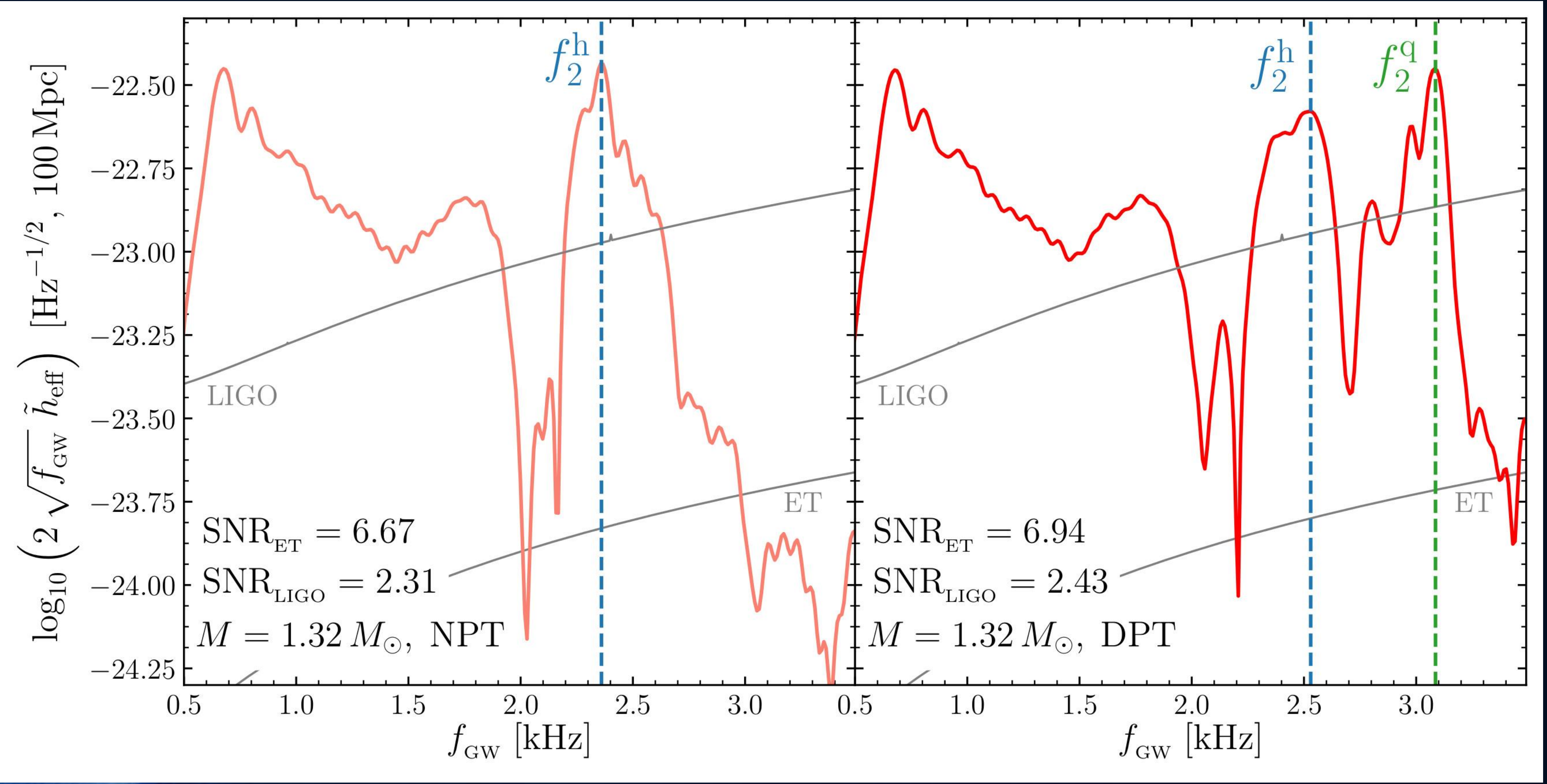


With Phase Transition

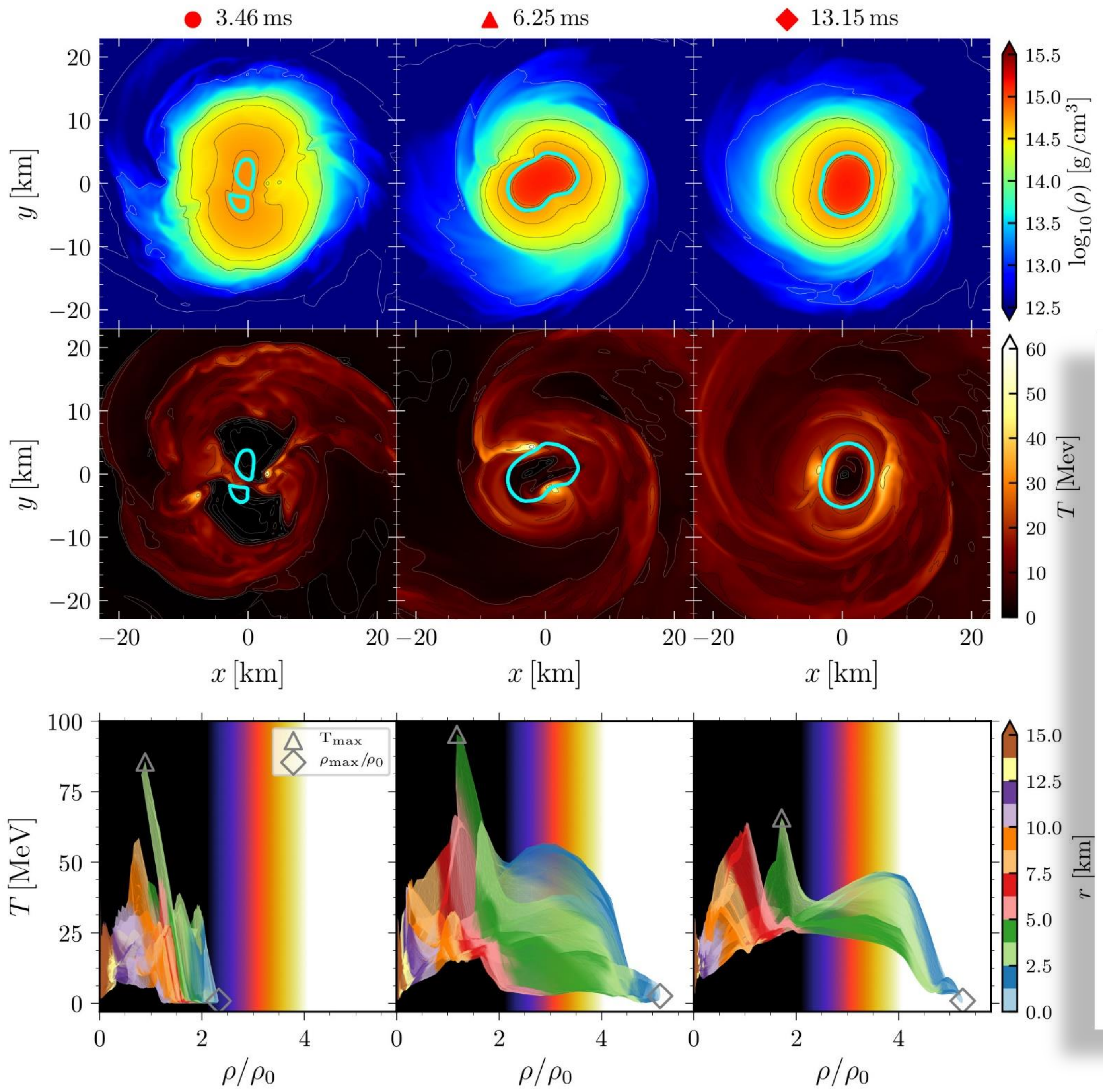


Matthias Hanauske and Lukas Weih. "Neutron star collisions and gravitational waves." *Astronomische Nachrichten* (2021)

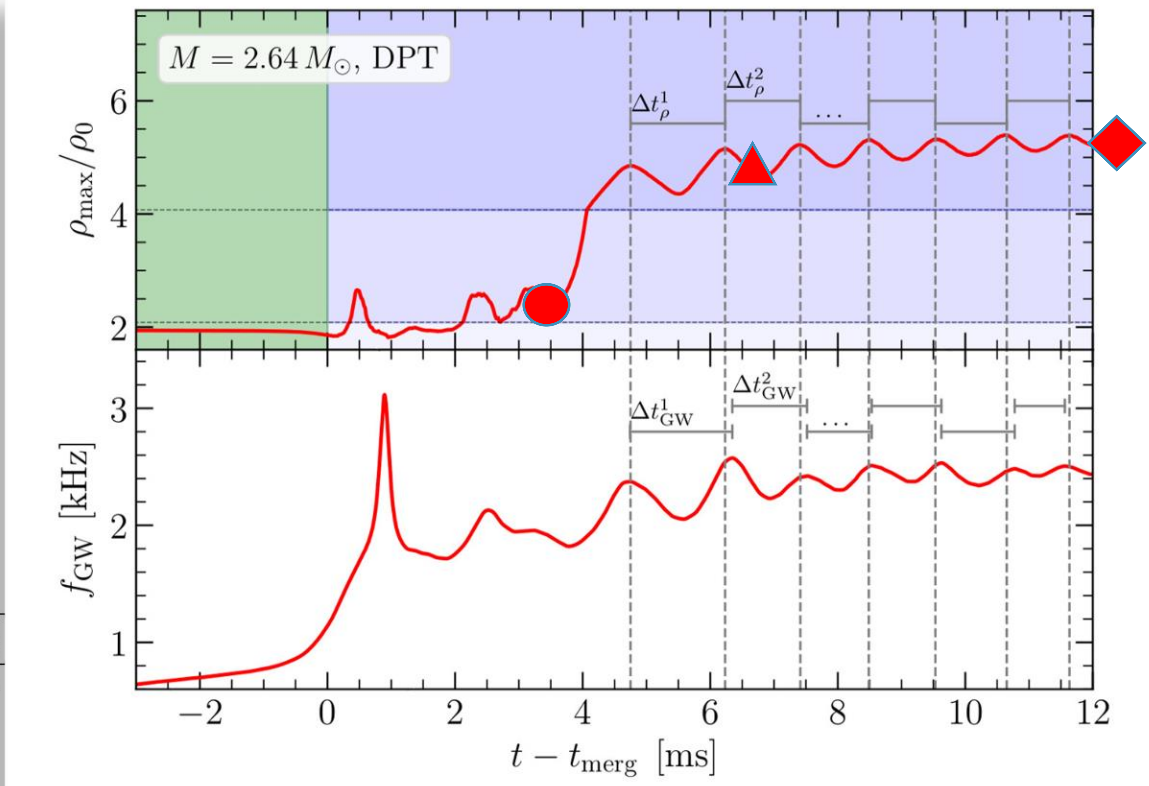
How to detect the hadron-quark phase transition with gravitational waves



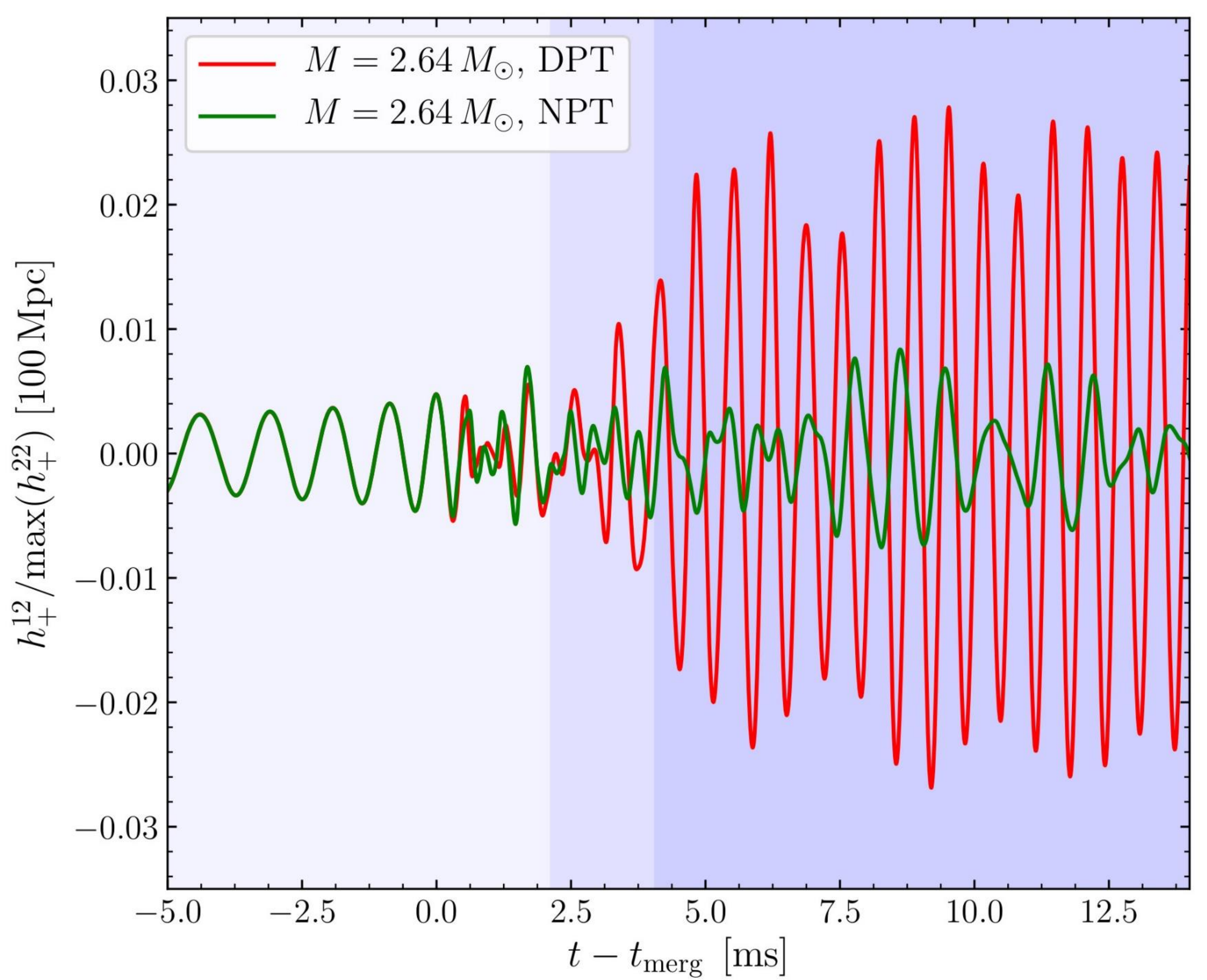
Total gravitational wave spectrum (left NPT, right DPT), PRL 124, 171103 (2020)

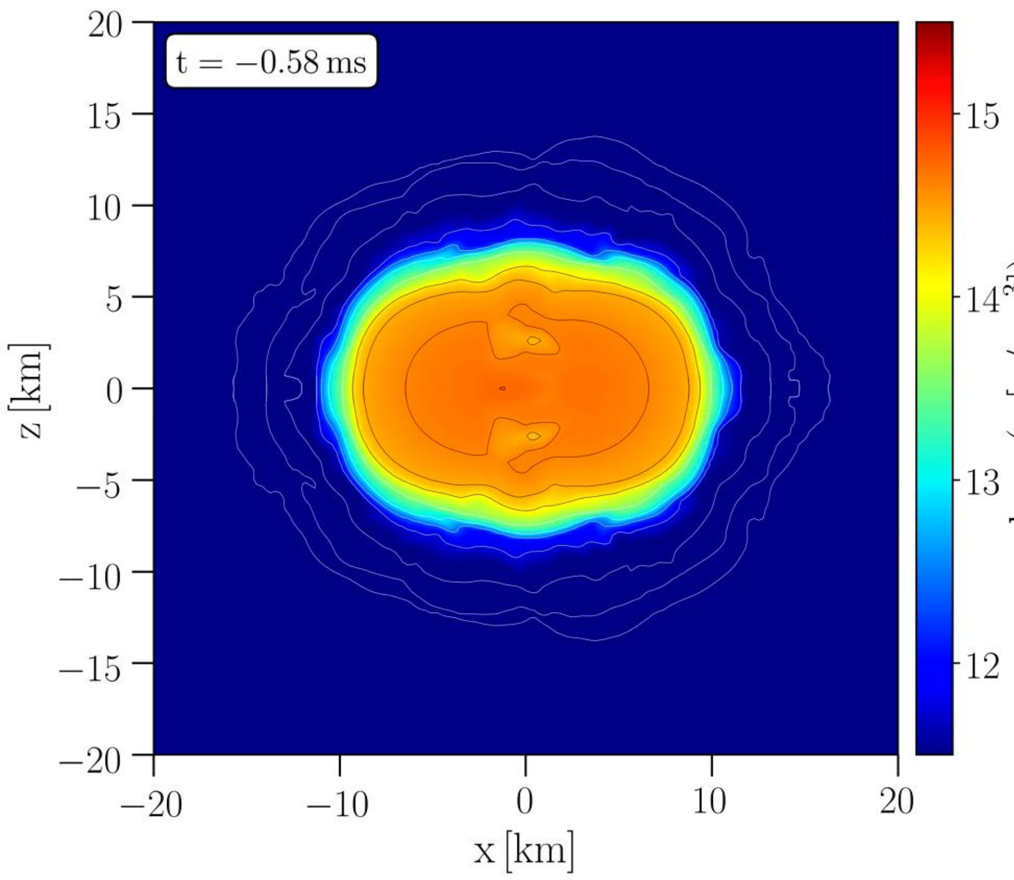


M. Hanauske, L. Weih, H. Stöcker
and L. Rezzolla
Metastable hypermassive hybrid stars as neutron-star merger remnants
The European Physical Journal Special Topics: 1-8 (2021)

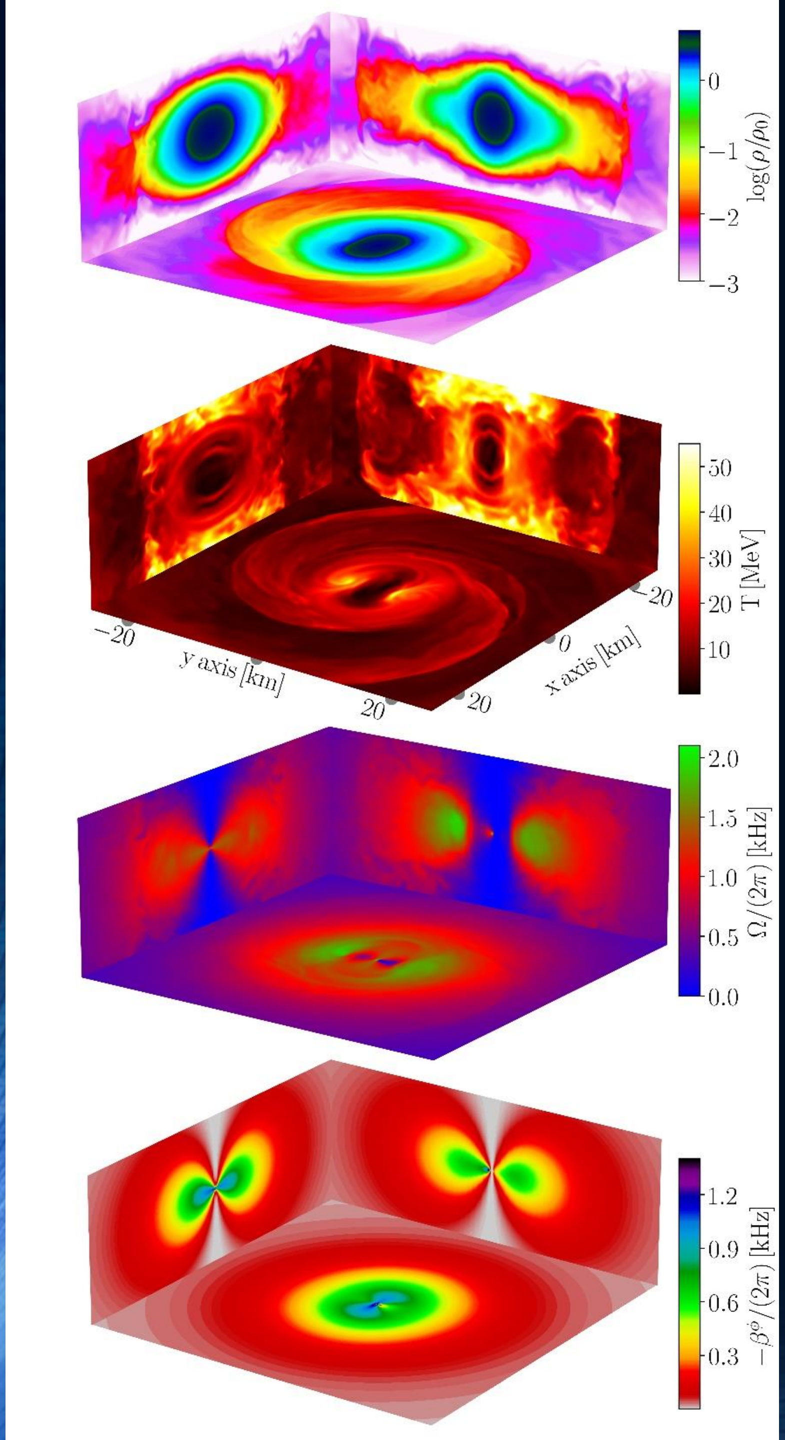


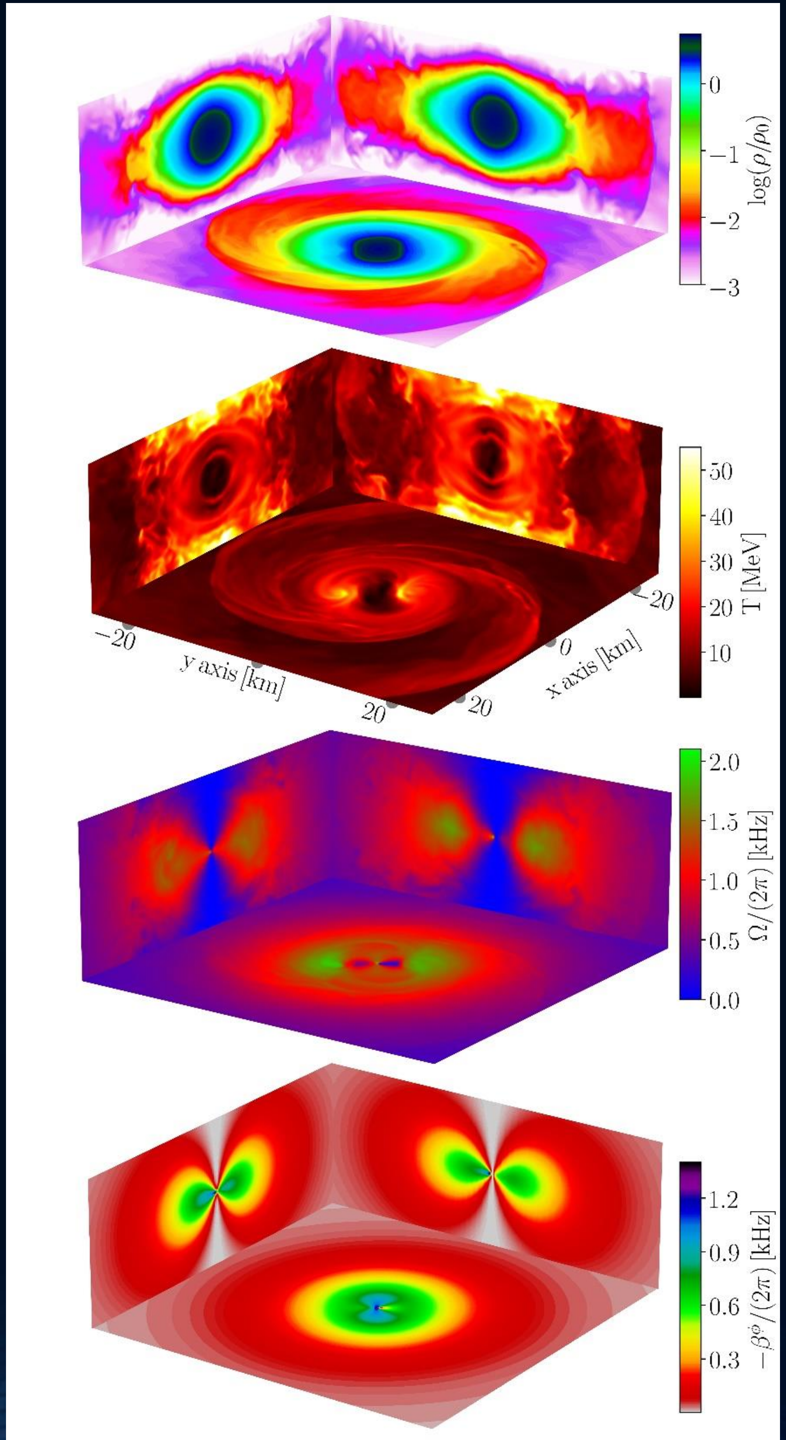
Difference in the h_+^{12} − gravitational wave mode

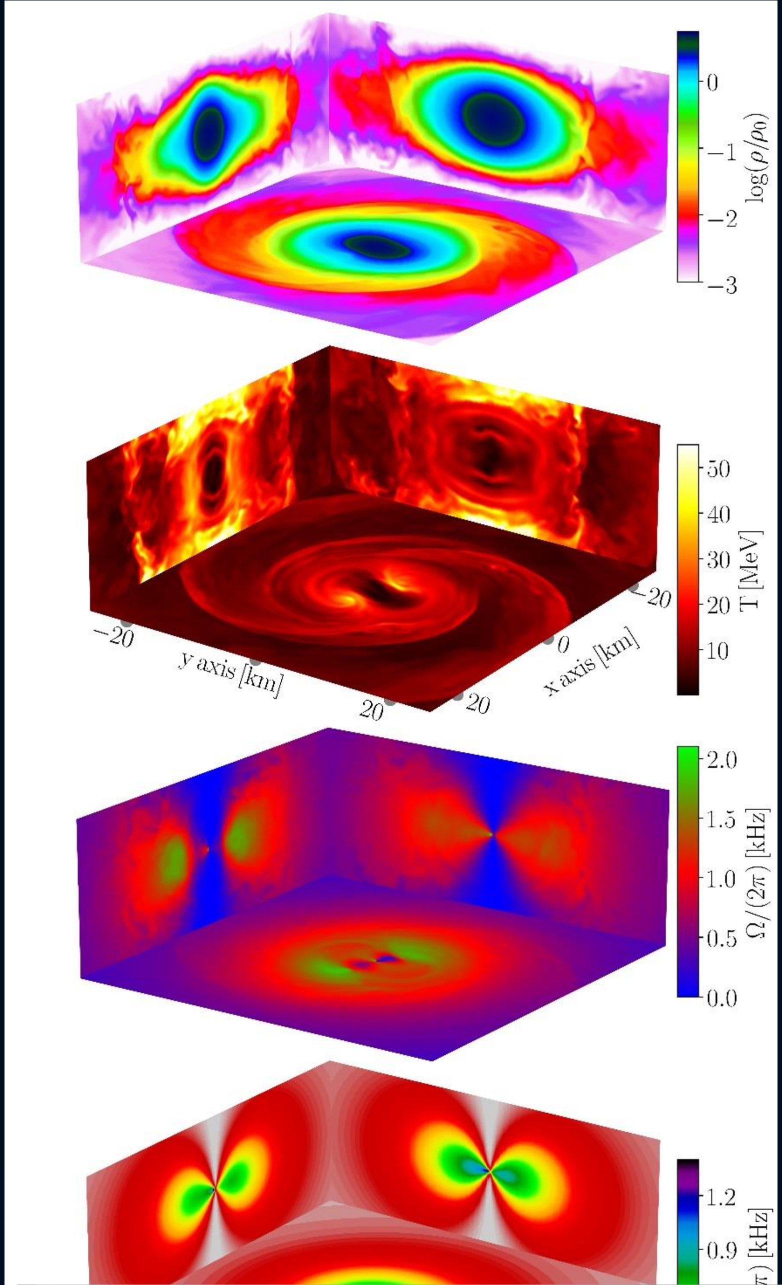




Due to the large m=1 mode of the emitted gravitational wave in the DPT case, a qualitative difference to the NPT scenario might be observable in future by focusing on the h_+^{12} − gravitational wave mode during the post-merger evolution.



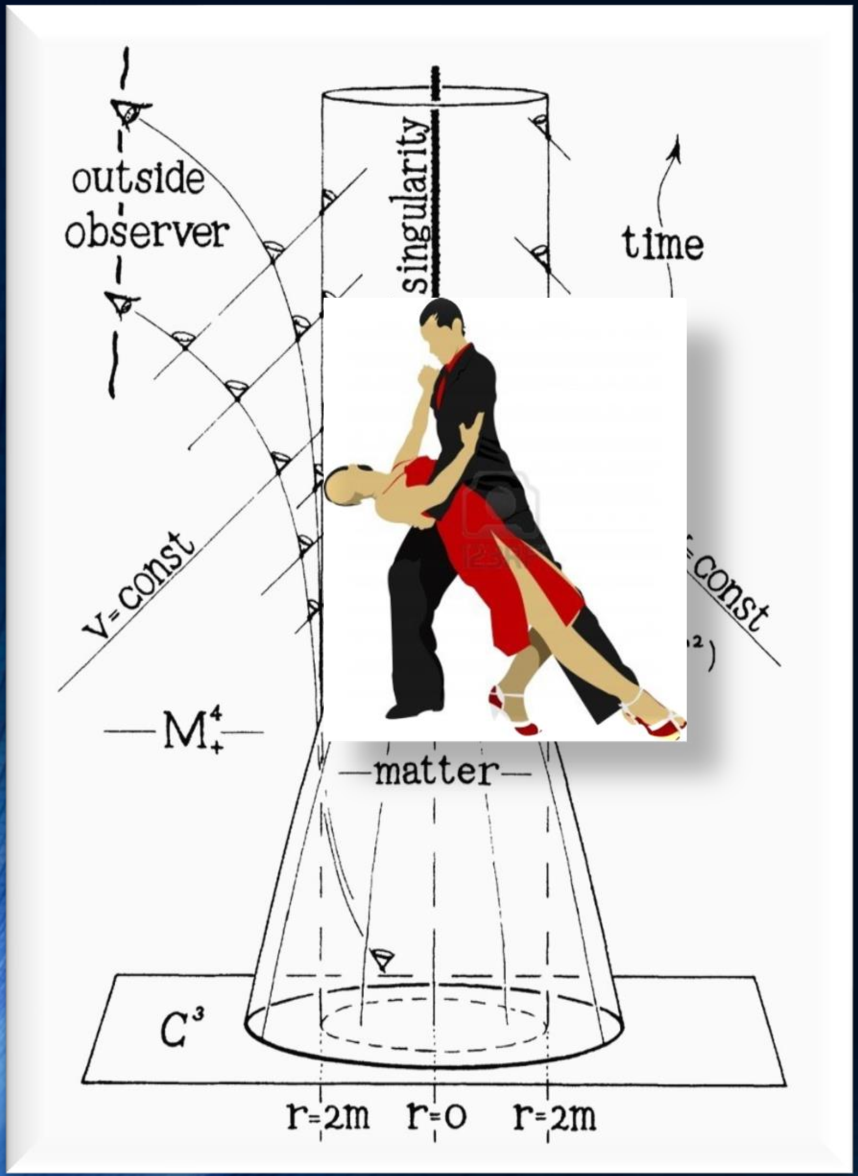




Simulations from Lukas Weih
(article under construction)

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)

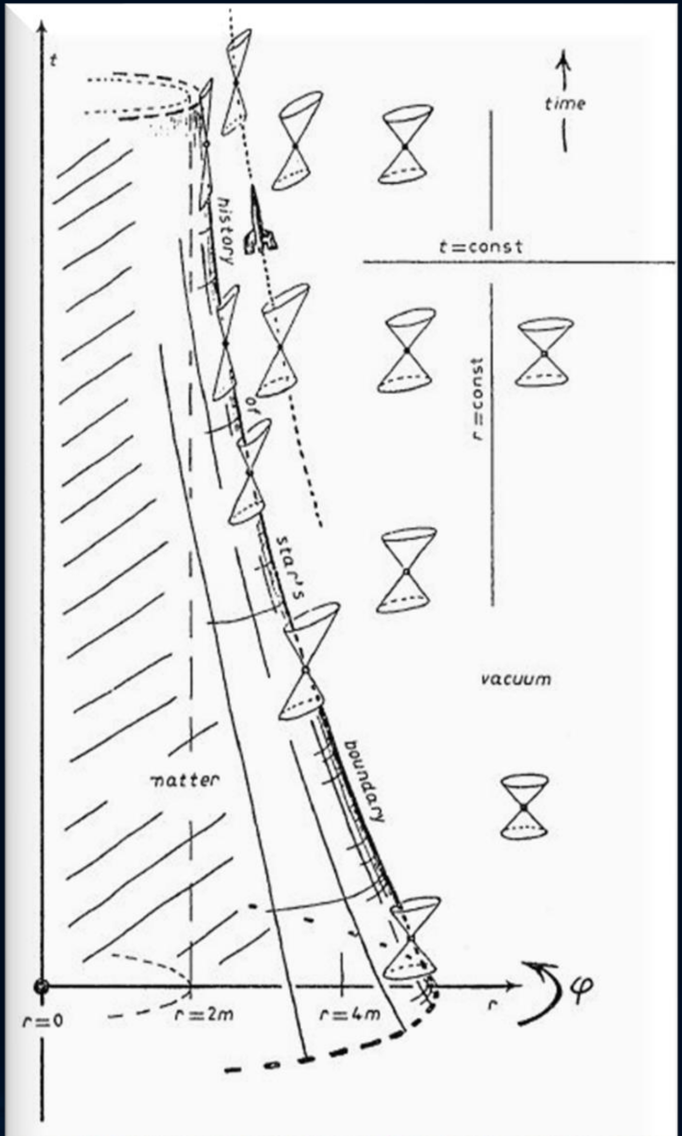


Figure 1. Spherically symmetrical collapse in the usual Schwarzschild co-ordinates.

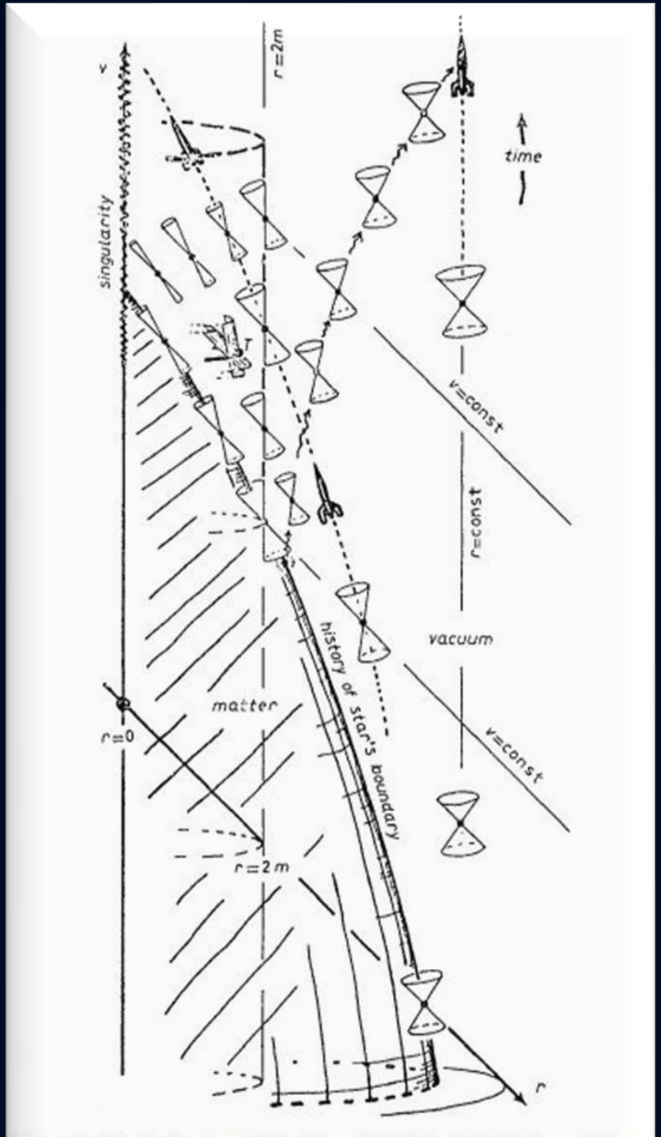


Figure 2. Spherically symmetrical collapse in Eddington-Finkelstein co-ordinates.

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

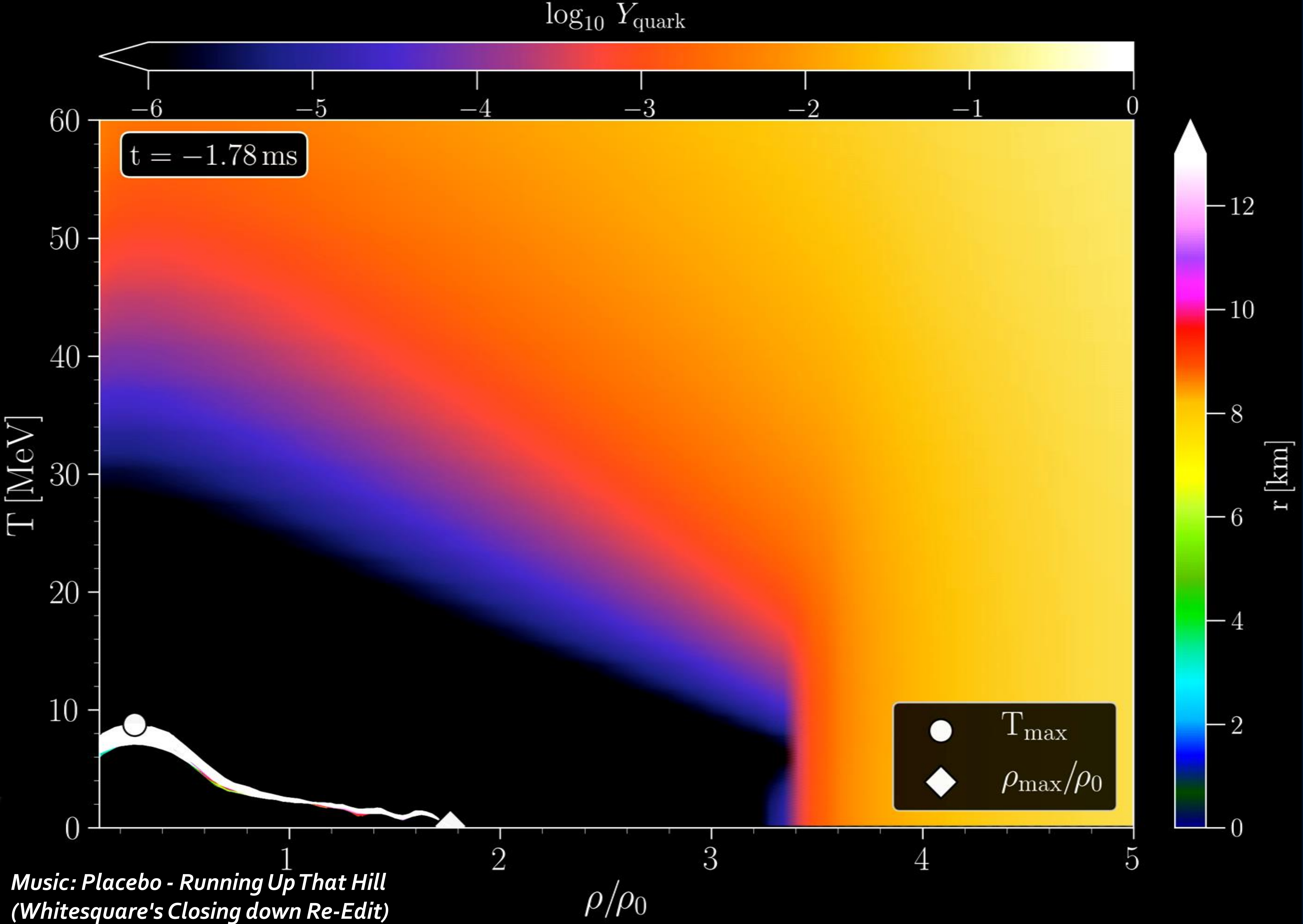
Phase-transition triggered collapse scenario

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.



Music: Placebo - Running Up That Hill (Whitesquare's Closing down Re-Edit)

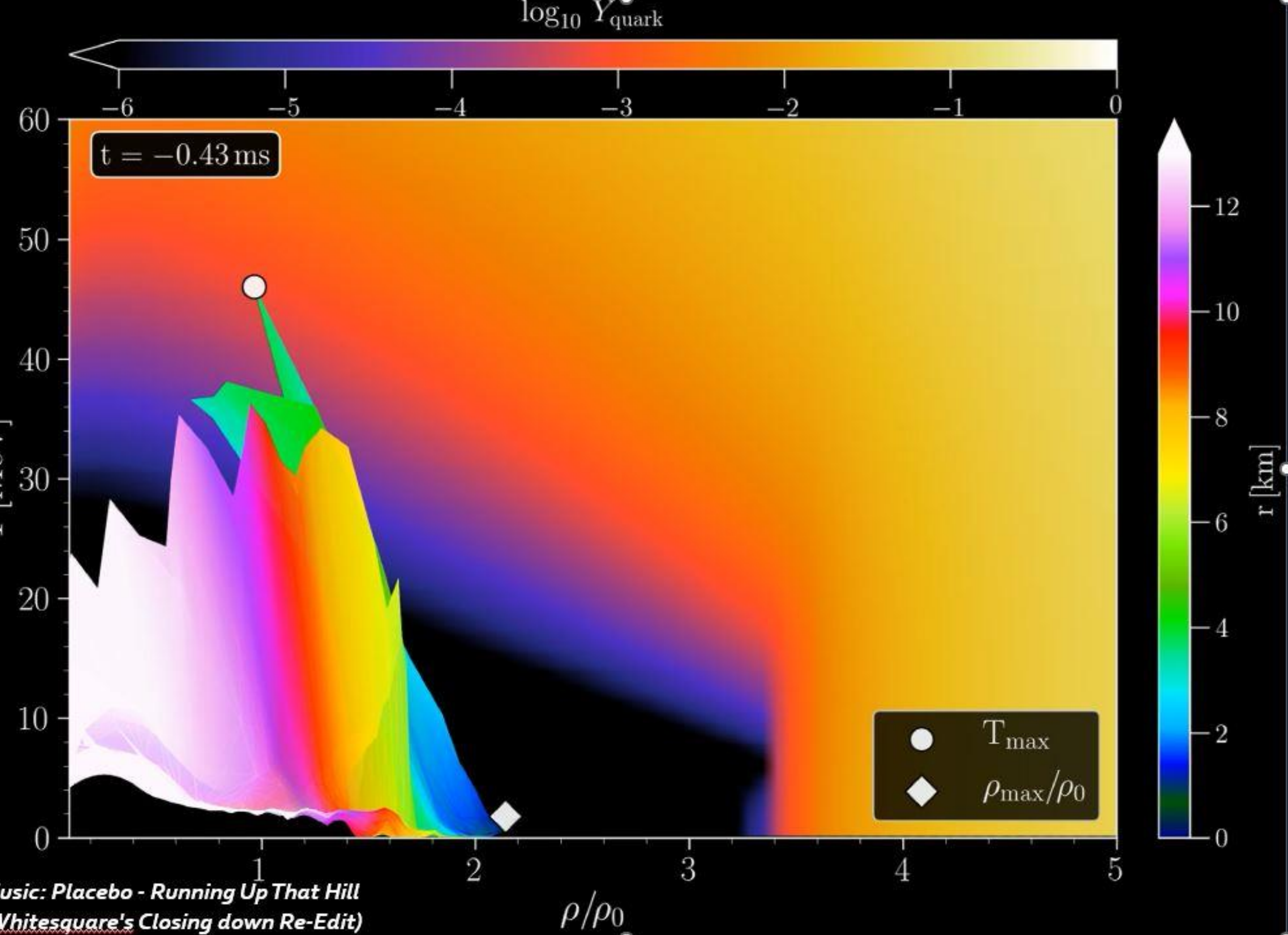
Phase-transition triggered collapse scenario

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 CMF$_Q$ model.



Music: Placebo - Running Up That Hill (Whitesquare's Closing down Re-Edit)

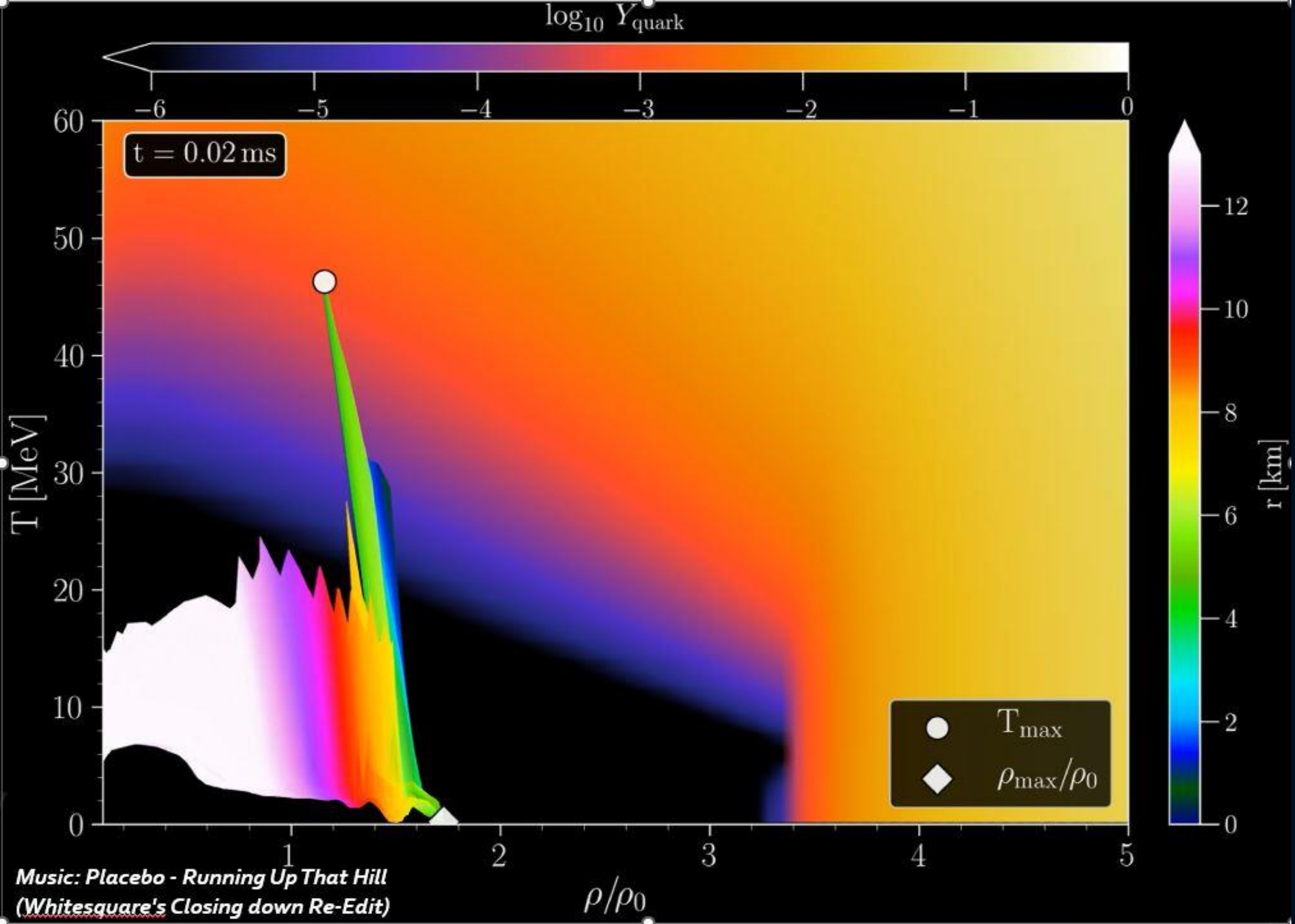
Phase-transition triggered collapse scenario

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.



Music: Placebo - Running Up That Hill (Whitesquare's Closing down Re-Edit)

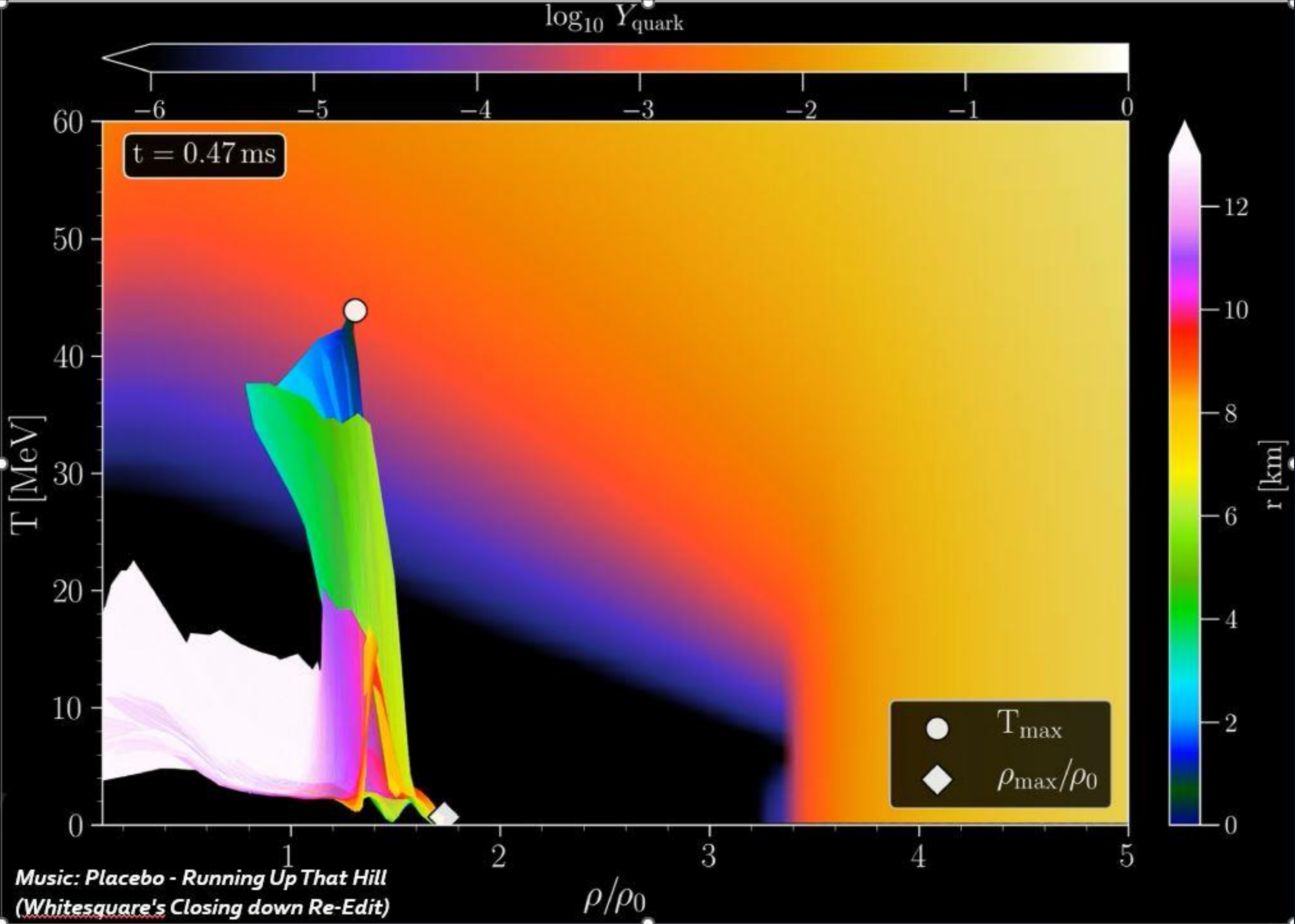
Phase-transition triggered collapse scenario

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.



Music: Placebo - Running Up That Hill (Whitesquare's Closing down Re-Edit)

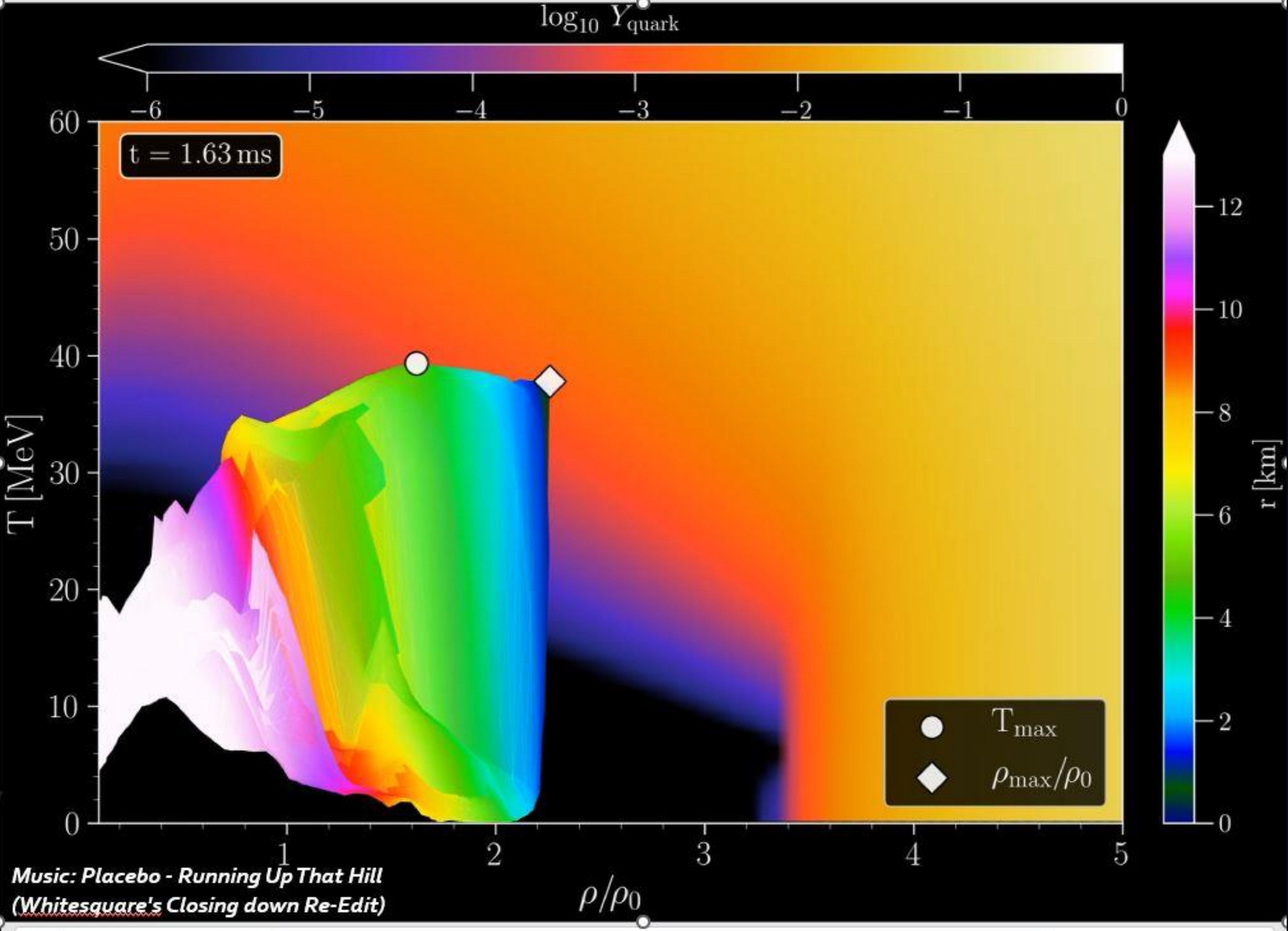
Phase-transition triggered collapse scenario

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.



Music: Placebo - Running Up That Hill (Whitesquare's Closing down Re-Edit)

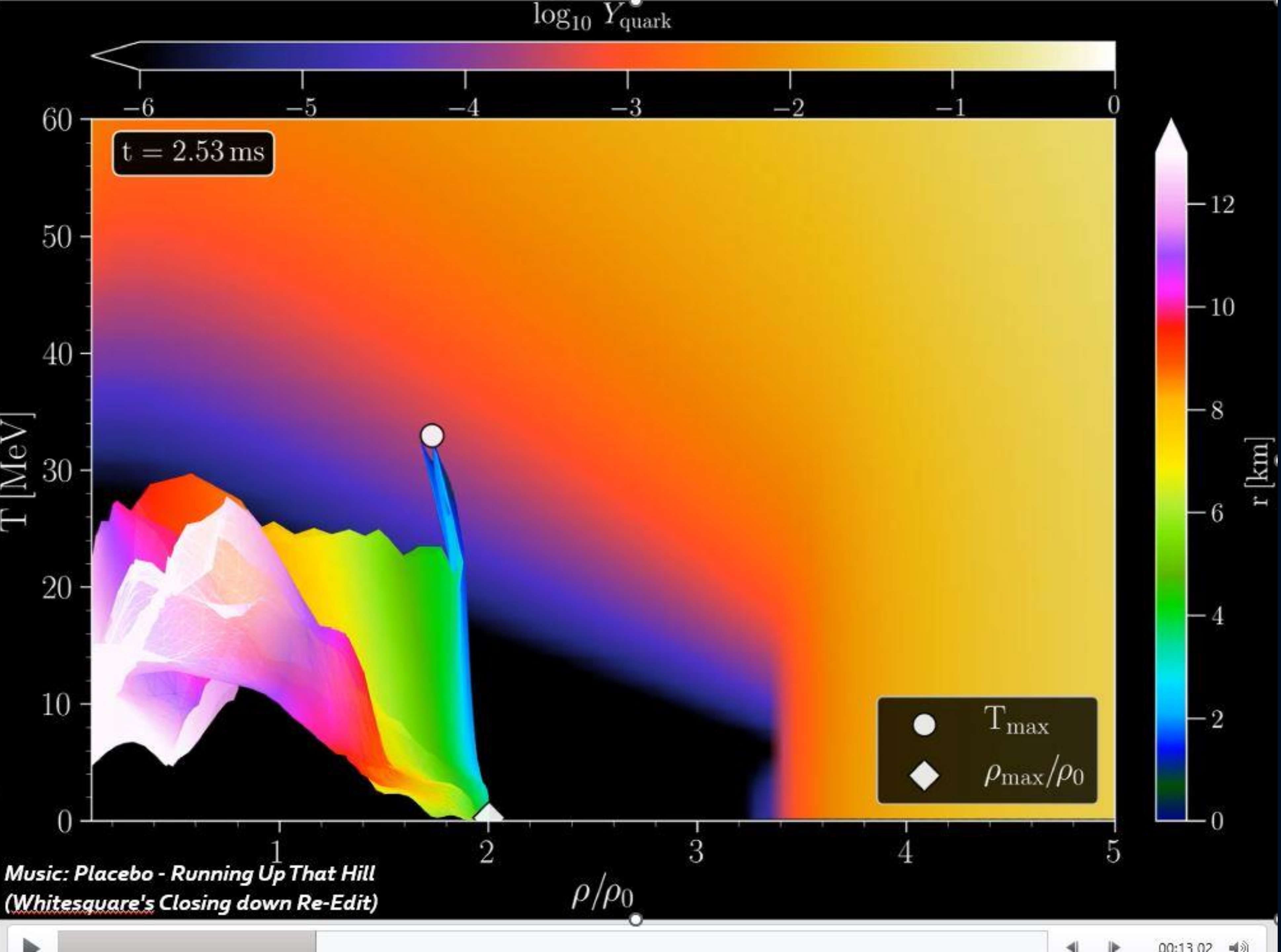
Phase-transition triggered collapse scenario

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 CMF$_{Q}$ model.



Music: Placebo - Running Up That Hill
(Whitesquare's Closing down Re-Edit)

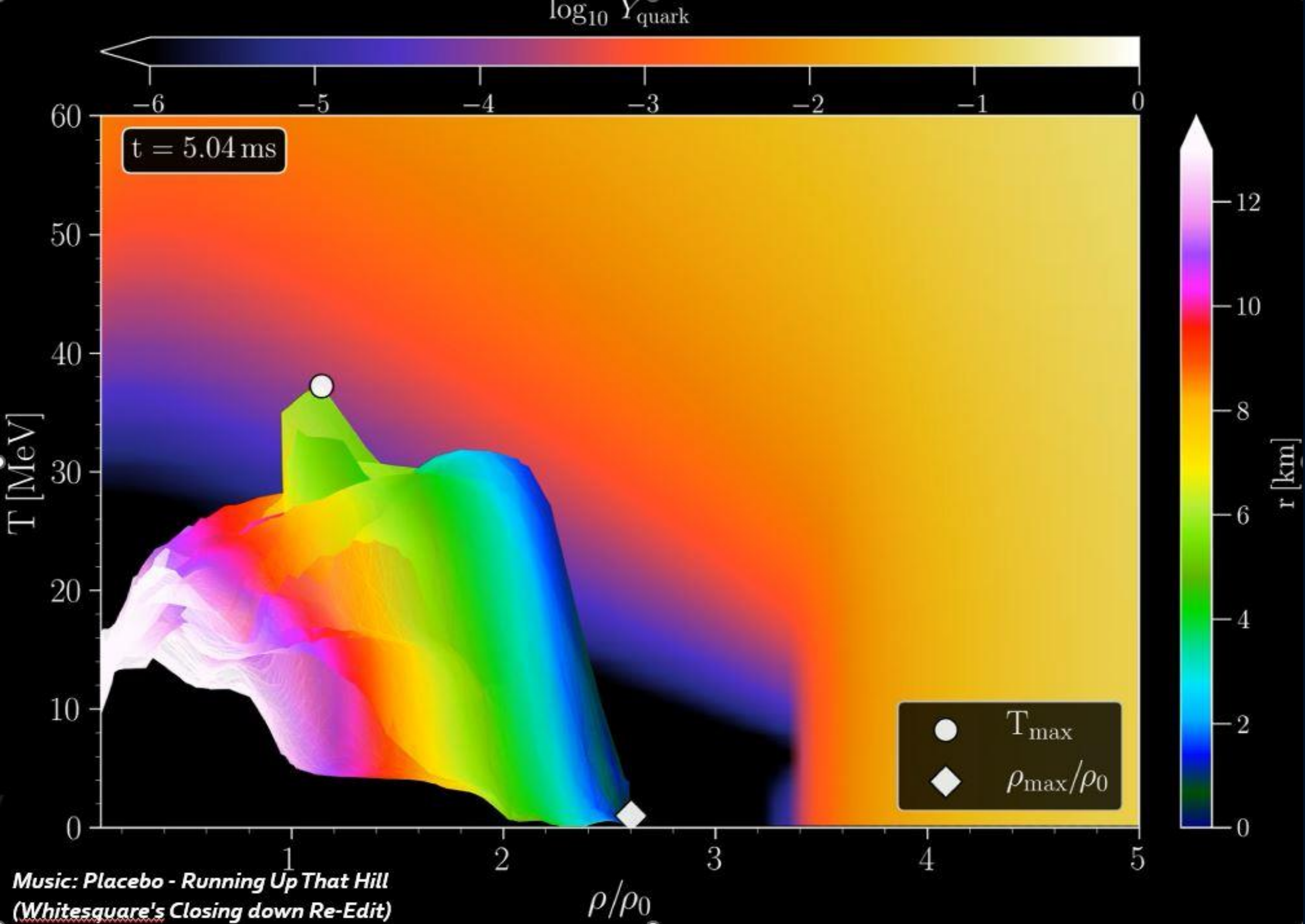
Phase-transition triggered collapse scenario

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 CMF$_Q$ model.



Music: Placebo - Running Up That Hill (Whitesquare's Closing down Re-Edit)

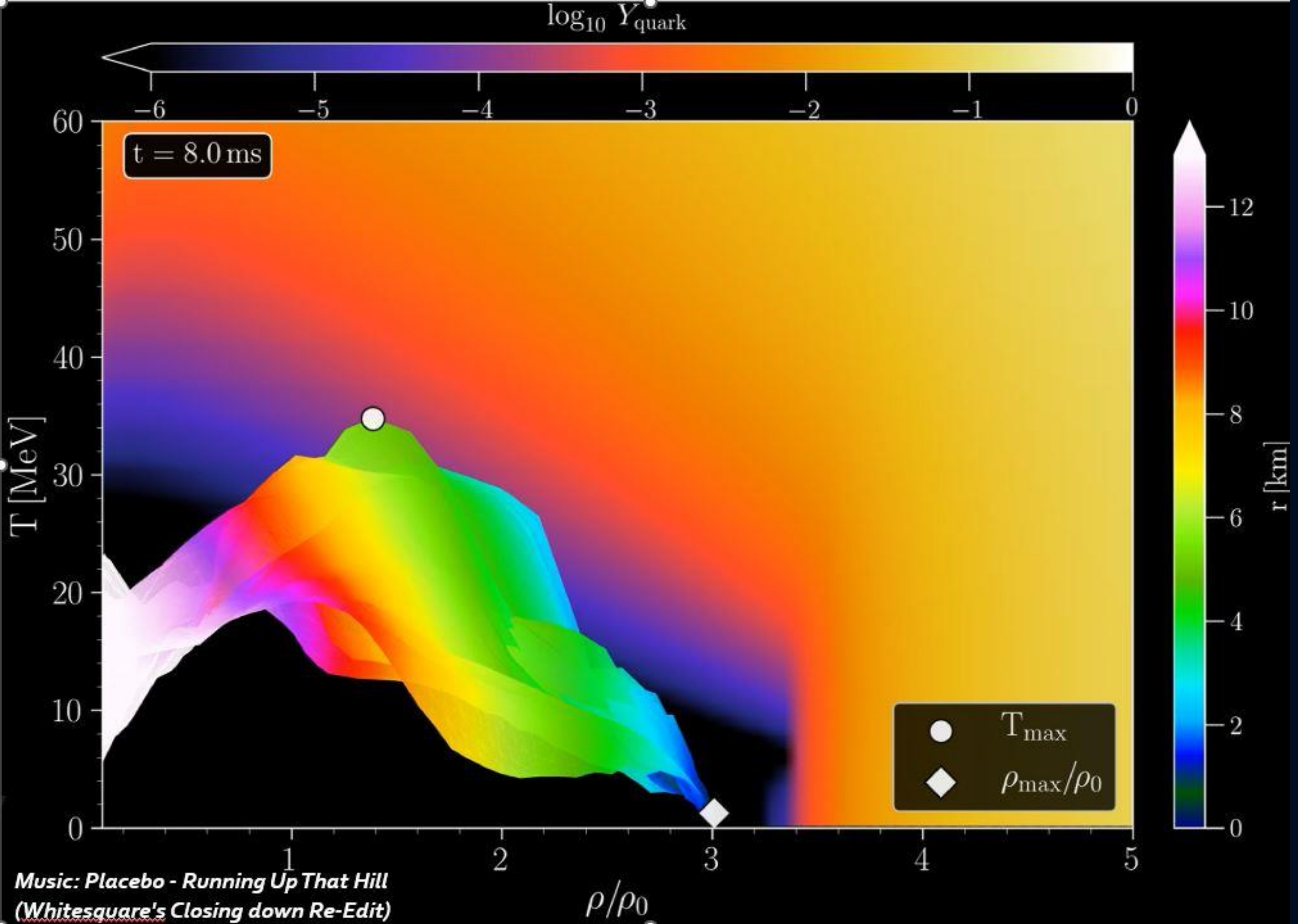
Phase-transition triggered collapse scenario

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.



Music: Placebo - Running Up That Hill (Whitesquare's Closing down Re-Edit)

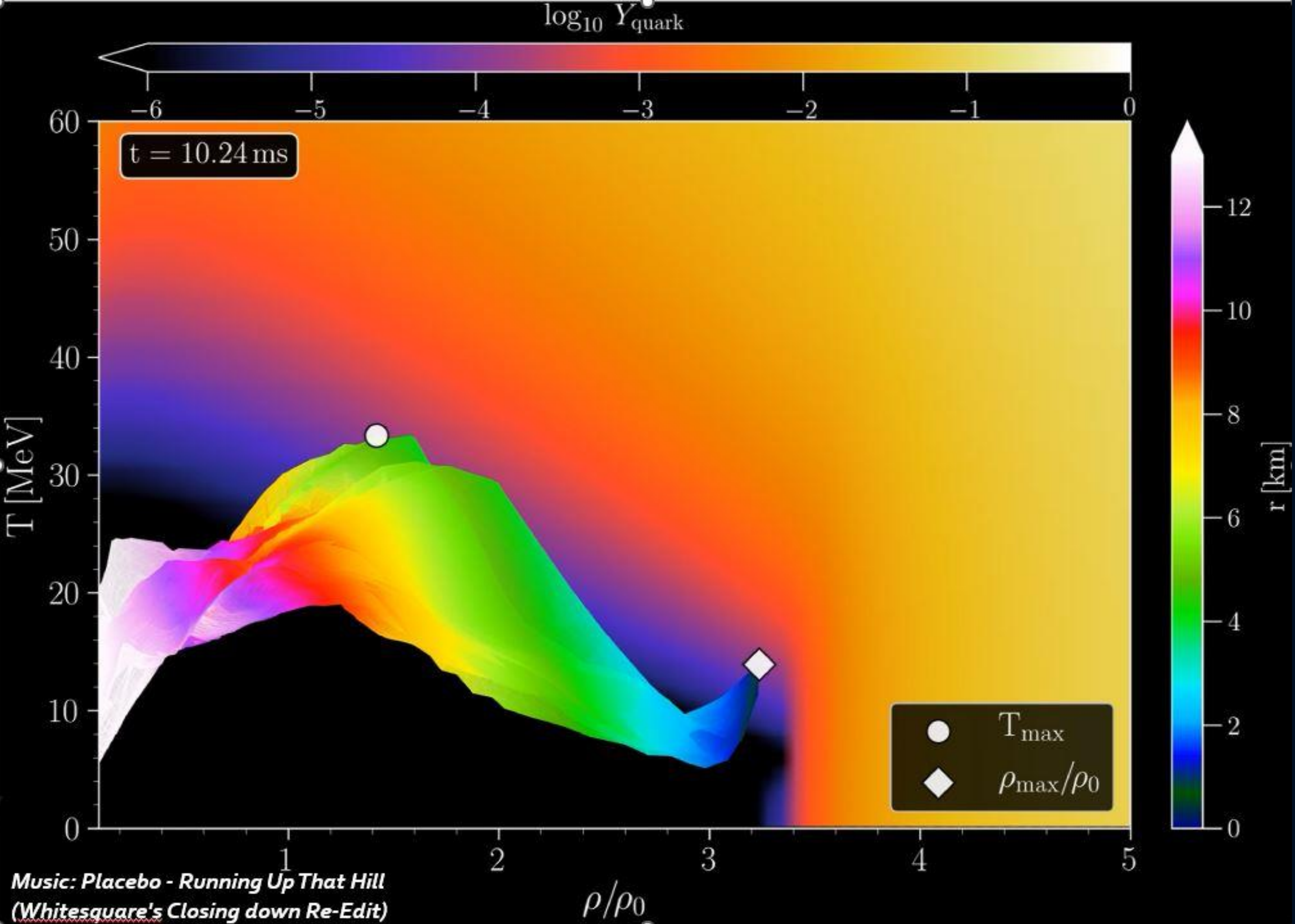
Phase-transition triggered collapse scenario

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.



Music: Placebo - Running Up That Hill (Whitesquare's Closing down Re-Edit)

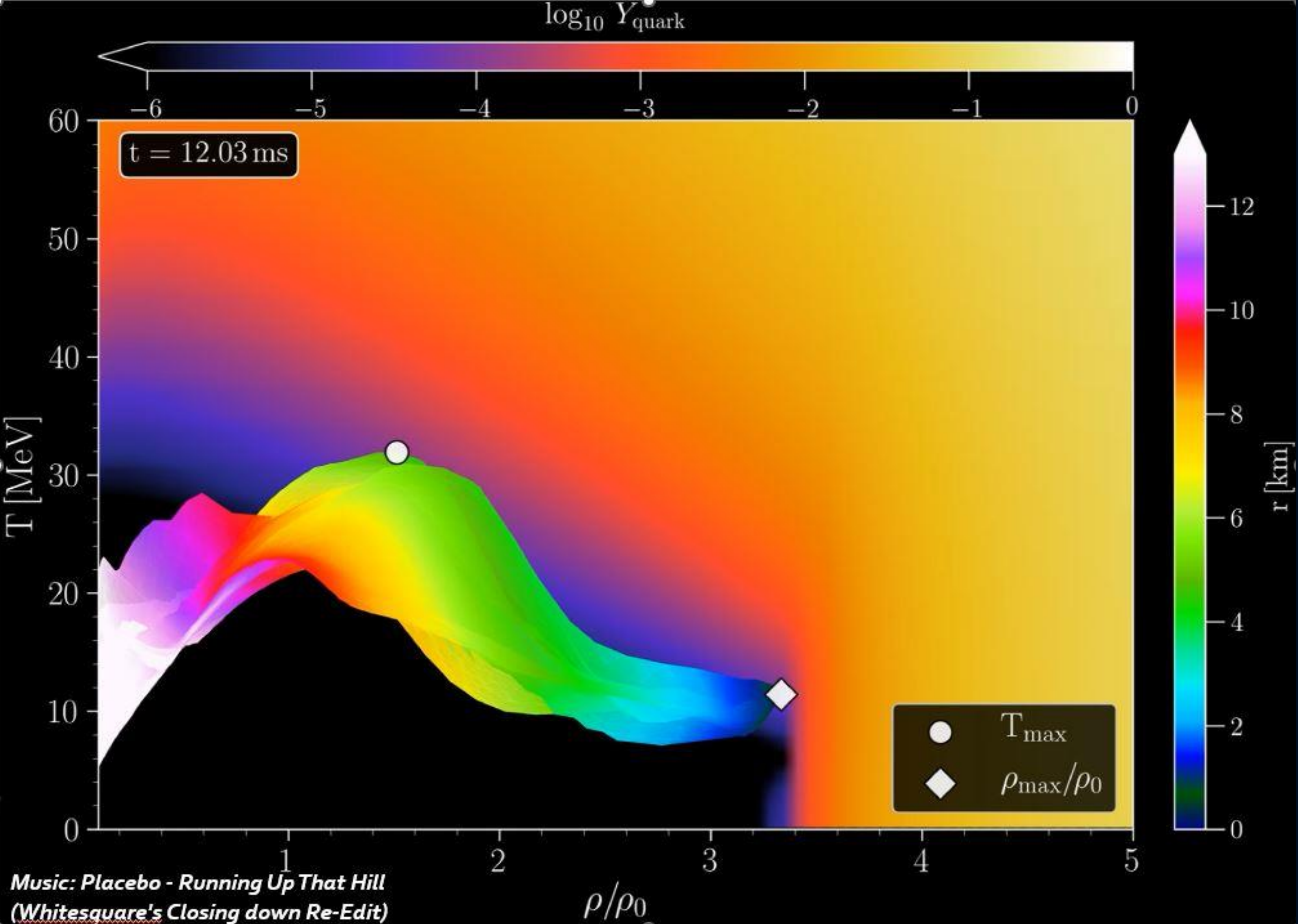
Phase-transition triggered collapse scenario

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.



Music: Placebo - Running Up That Hill (Whitesquare's Closing down Re-Edit)

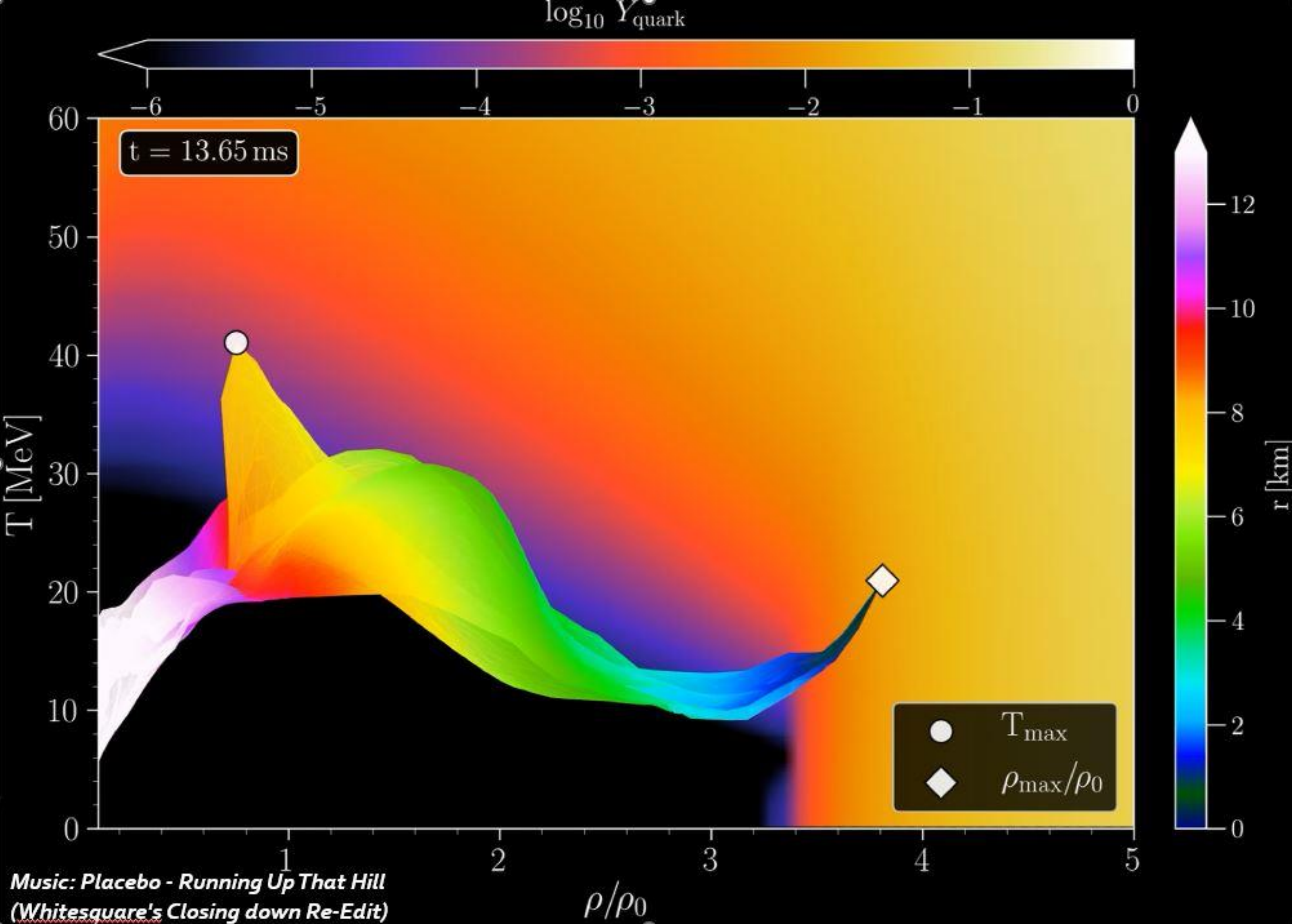
Phase-transition triggered collapse scenario

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 CMF$_Q$ model.



Music: Placebo - Running Up That Hill (Whitesquare's Closing down Re-Edit)

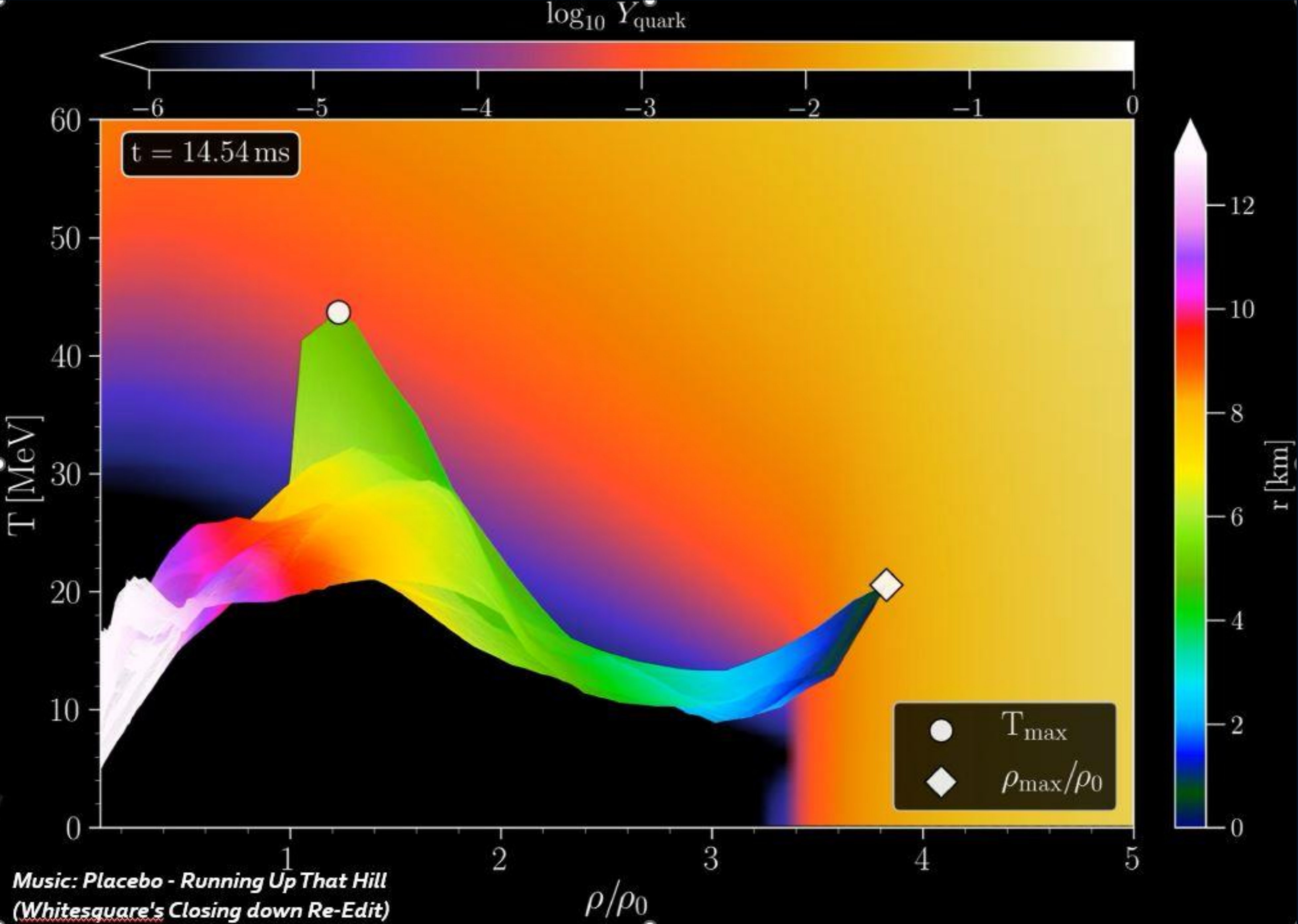
Phase-transition triggered collapse scenario

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.



Music: Placebo - Running Up That Hill (Whitesquare's Closing down Re-Edit)

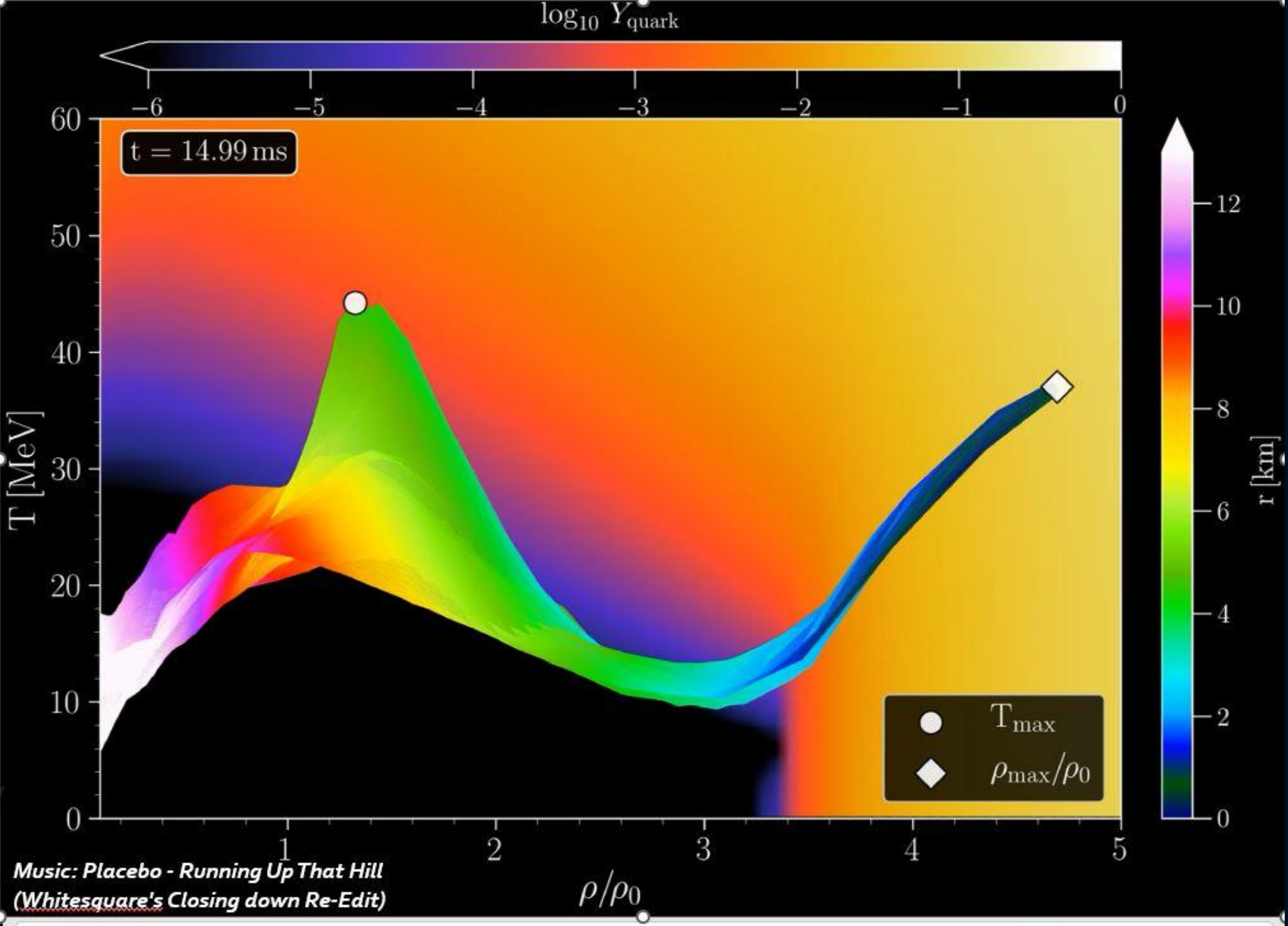
Phase-transition triggered collapse scenario

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.



Music: Placebo - Running Up That Hill (Whitesquare's Closing down Re-Edit)

00:47.87

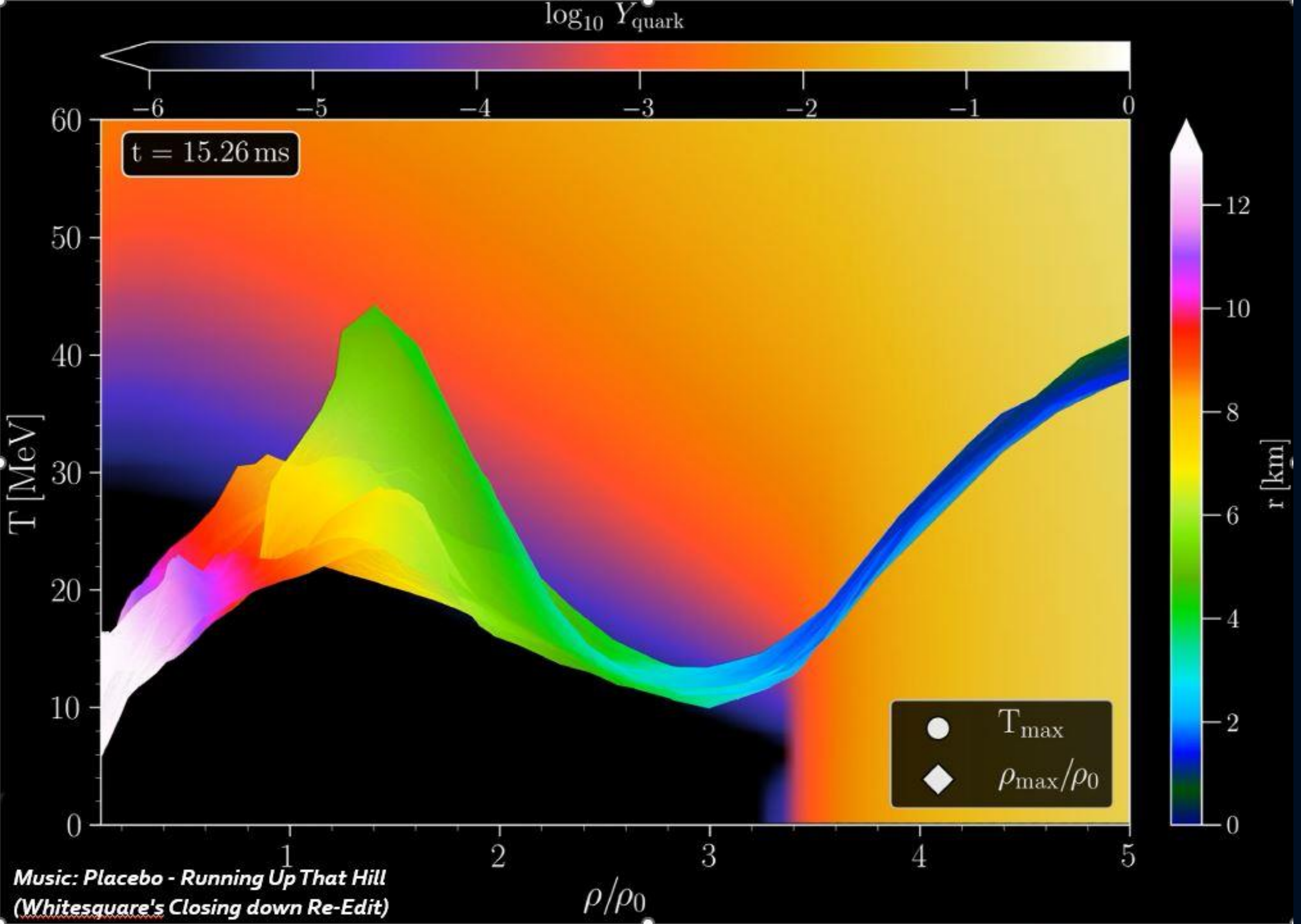
Phase-transition triggered collapse scenario

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.



Music: Placebo - Running Up That Hill (Whitesquare's Closing down Re-Edit)

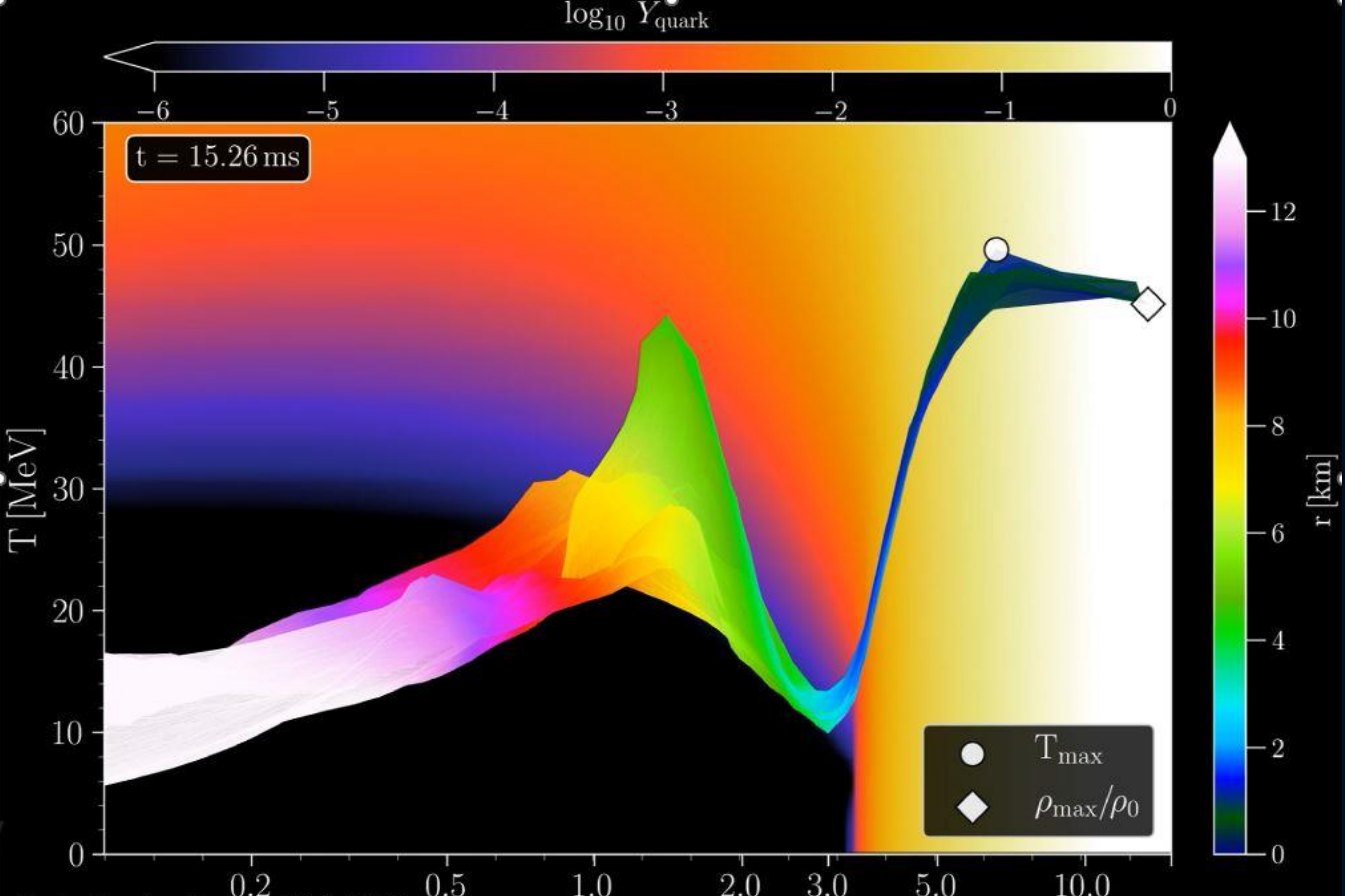
Phase-transition triggered collapse scenario

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)

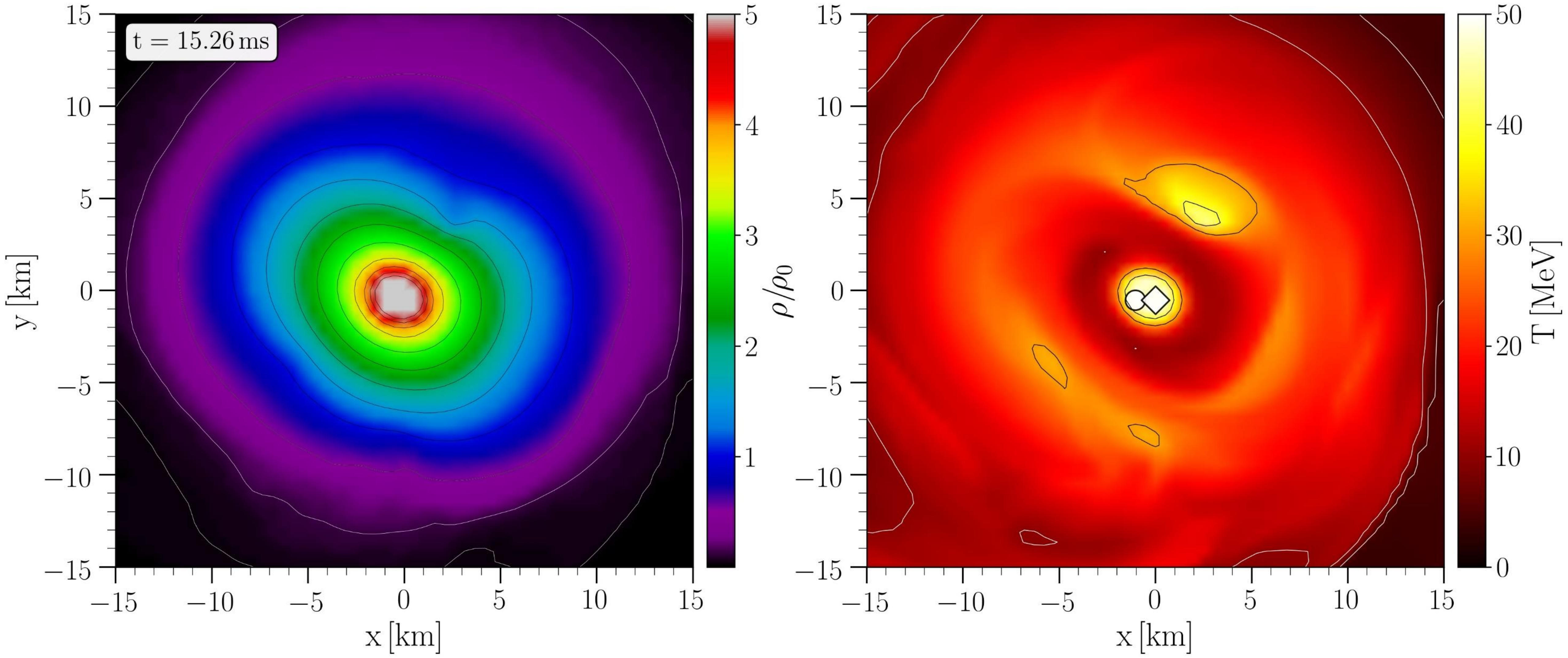
Density-Temperature-Composition dependent EOS within the CMF$_\Omega$ model.



Music: Placebo - Running Up That Hill (Whitesquare's Closing down Re-Edit)

00:48,90

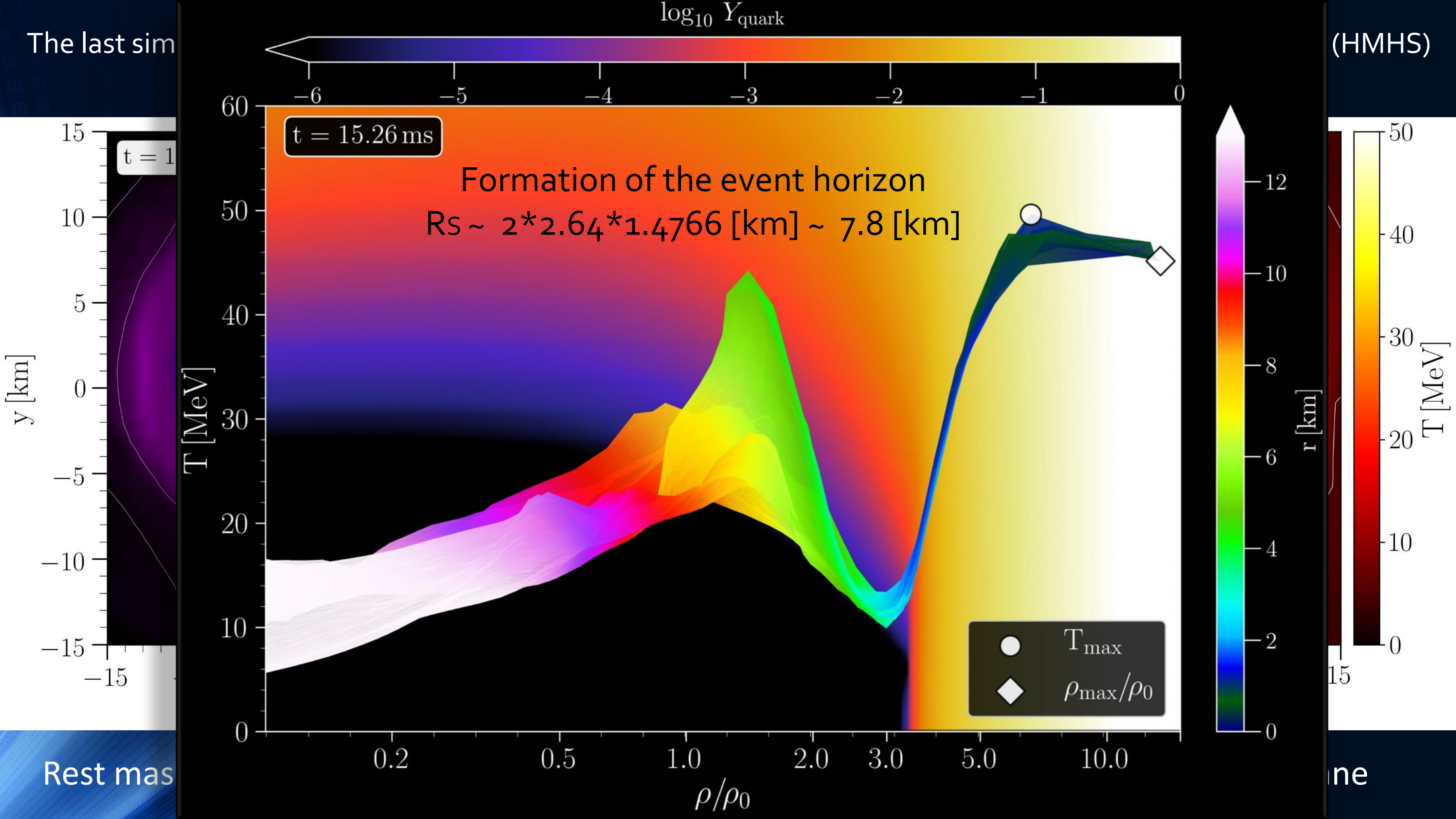
The last simulation snapshot before the apparent horizon is formed inside the HyperMassive Hybrid Star (HMHS)



Rest mass density on the equatorial plane

Temperature on the equatorial plane

The last sim (HMHS)

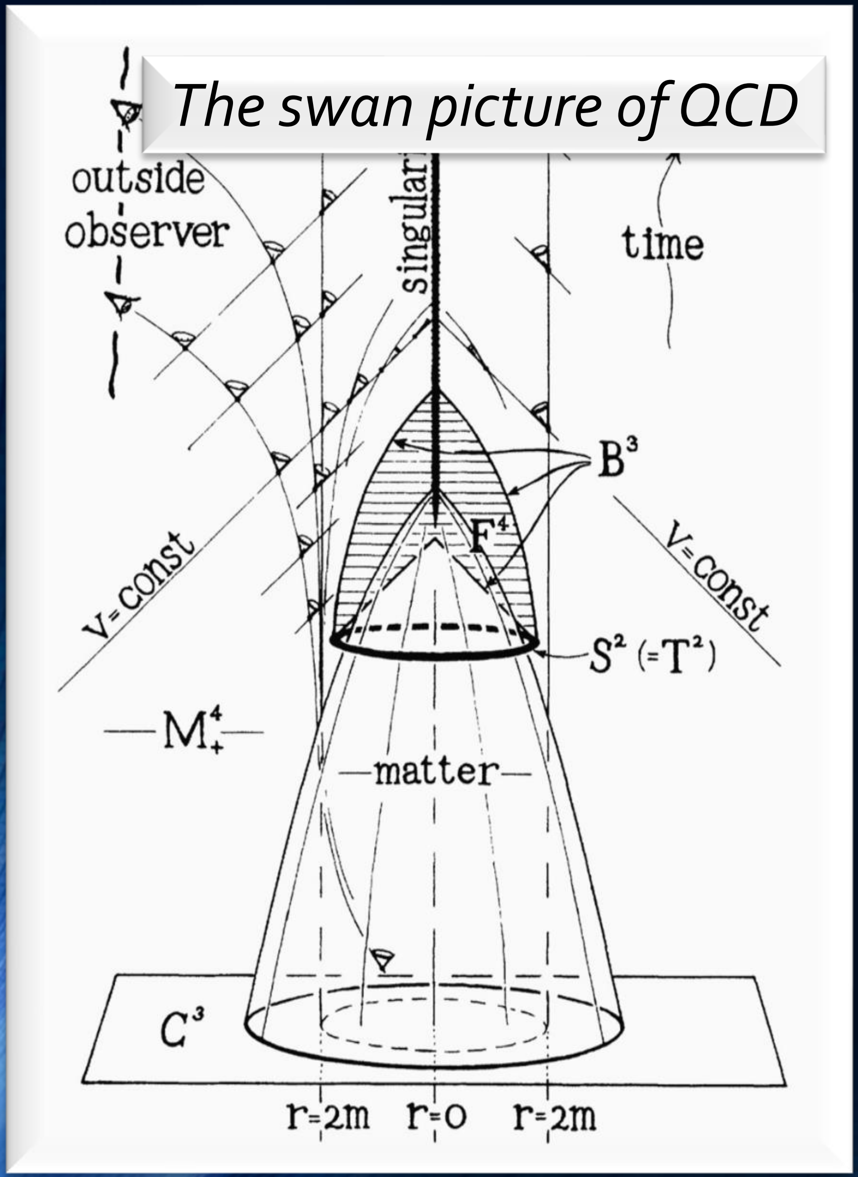


Rest mas ne

GRAVITATIONAL COLLAPSE AND SPACE- TIME SINGULARITIES

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

The swan picture of QCD



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

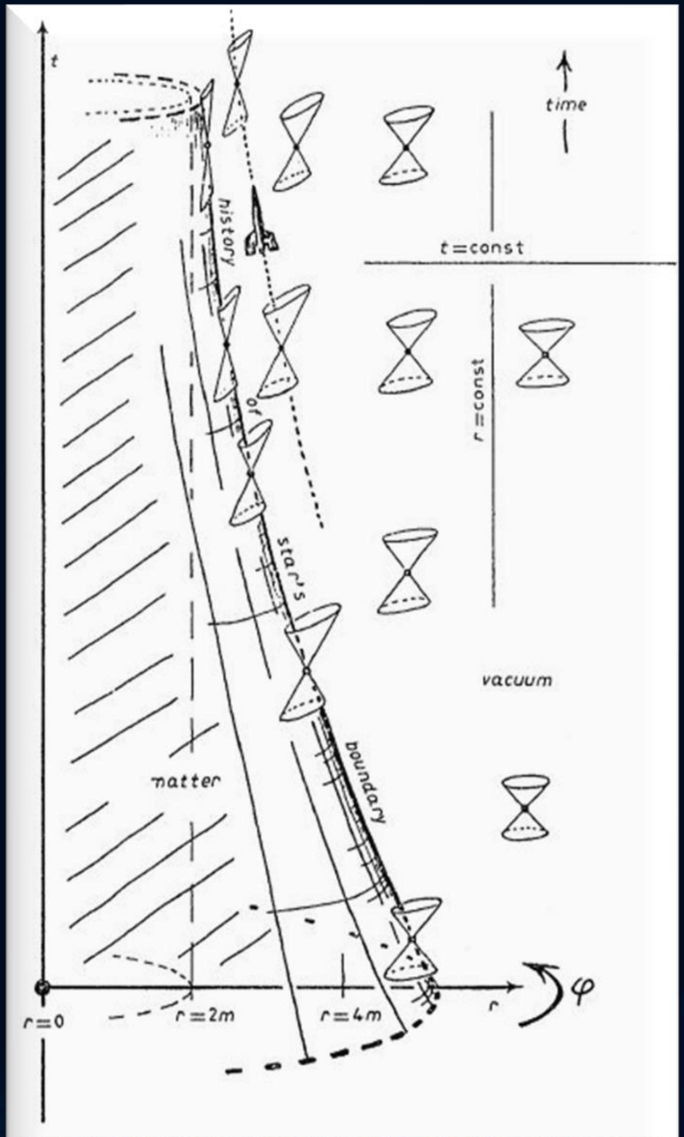
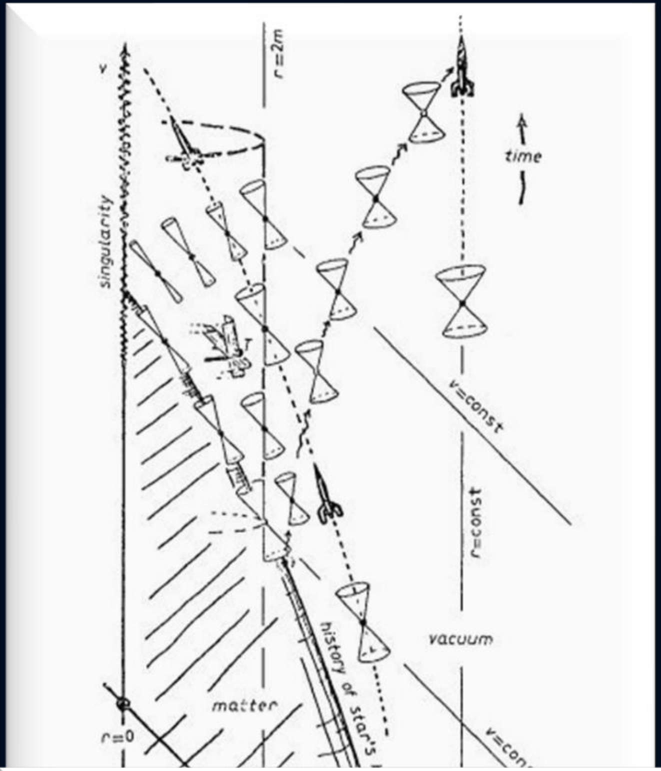
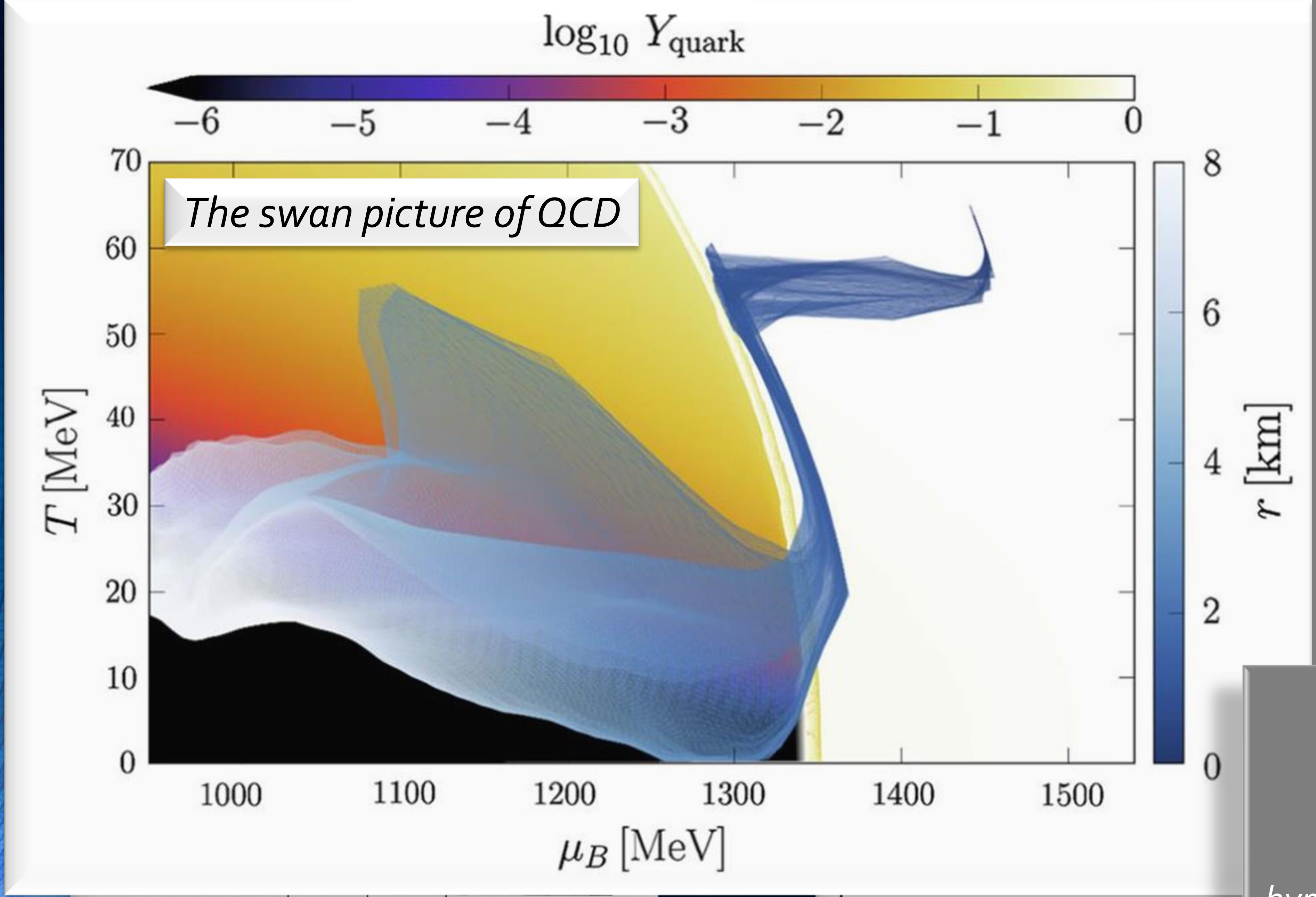


Figure 1. Spherically symmetrical collapse in the usual Schwarzschild co-ordinates.

R.Penrose in Rivista del Nuovo Ci



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

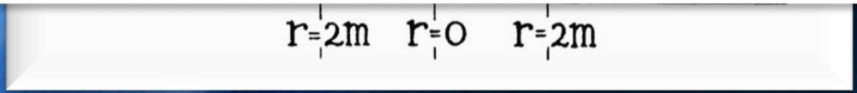


E.Most, J. Papenfort, V.Dexheimer, M.Hanauske, H.Stöcker and L.Rezzolla, *On the deconfinement phase transition in neutron-star mergers* The European Physical Journal A 56 (2), 1-11 (2020)

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)

<u>Project together with Prof. Carsten Greiner</u>

Simulations: Collapse of a hypermassive hybrid compact star to a Kerr Black hole



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

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

R.Penrose in Rivista del Nuovo Ci

YES WE CAN

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)

Lateral Thoughts, Popular Science Articles:
http://itp.uni-frankfurt.de/~hanauske/new/etc/pdf/LateralThoughts.pdf
http://itp.uni-frankfurt.de/~hanauske/new/etc/pdf/MG16-Hanauske.pdf
The neutronstar merger dance:
https://itp.uni-frankfurt.de/~hanauske/TanzNeutronensterne.mp4
https://www.physikalischer-verein.de/veranstaltung/der-tanz-der-neutronensterne.html
Recent scientific articles:
https://onlinelibrary.wiley.com/doi/full/10.1002/asna.202113994
https://inspirehep.net/files/1bd749e8d48a948b39aa6498a63d0ecd
https://link.springer.com/article/10.1140/epjs/s11734-021-00003-5
https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.124.171103
https://journals.aps.org/prd/abstract/10.1103/PhysRevD.99.103009
https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.122.061101
https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.120.041101
https://journals.aps.org/prd/abstract/10.1103/PhysRevD.96.043004
https://arxiv.org/pdf/2201.13150.pdf

Probing neutron-star matter in the lab: connecting binary mergers to heavy-ion collisions

Elias R. Most,[1,2,3] Anton Motornenko,[4,5] Jan Steinheimer,[5] Veronica Dexheimer,[6] Matthias Hanauske,[4,5] Luciano Rezzolla,[4,5,7] and Horst Stoecker[4,5,8]

[1]*Princeton Center for Theoretical Science, Princeton University, Princeton, NJ 08544, USA*
[2]*Princeton Gravity Initiative, Princeton University, Princeton, NJ 08544, USA*
[3]*School of Natural Sciences, Institute for Advanced Study, Princeton, NJ 08540, USA*
[4]*Institut für Theoretische Physik, Goethe Universität, D-60438 Frankfurt am Main, Germany*
[5]*Frankfurt Institute for Advanced Studies, Giersch Science Center, D-60438 Frankfurt am Main, Germany*
[6]*Department of Physics, Kent State University, Kent, OH 44243, USA*
[7]*School of Mathematics, Trinity College, Dublin 2, Ireland*
[8]*GSI Helmholtzzentrum für Schwerionenforschung GmbH, D-64291 Darmstadt, Germany*

(Dated: February 1, 2022)

As a way to find analogies and differences in the dynamics of hot and dense matter under extreme conditions, we present the first self-consistent relativistic-hydrodynamic calculations of both neutron-star mergers and low-energy heavy-ion collisions employing the same equation of state. By a direct comparison of the evolution of quantities such as temperature, entropy, and density, we show that neutron-star collision regimes can be probed directly at GSI beam energies. We provide concrete evidence that the physical conditions reached in binary neutron-star mergers can be studied in present and future laboratory experiments, thus bridging 18 orders of magnitude in length scale, from microscopic ion collisions to macroscopic astrophysical compact objects