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ICRANet
International Center for Relativistic Astrophysics Network

# 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*

*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*

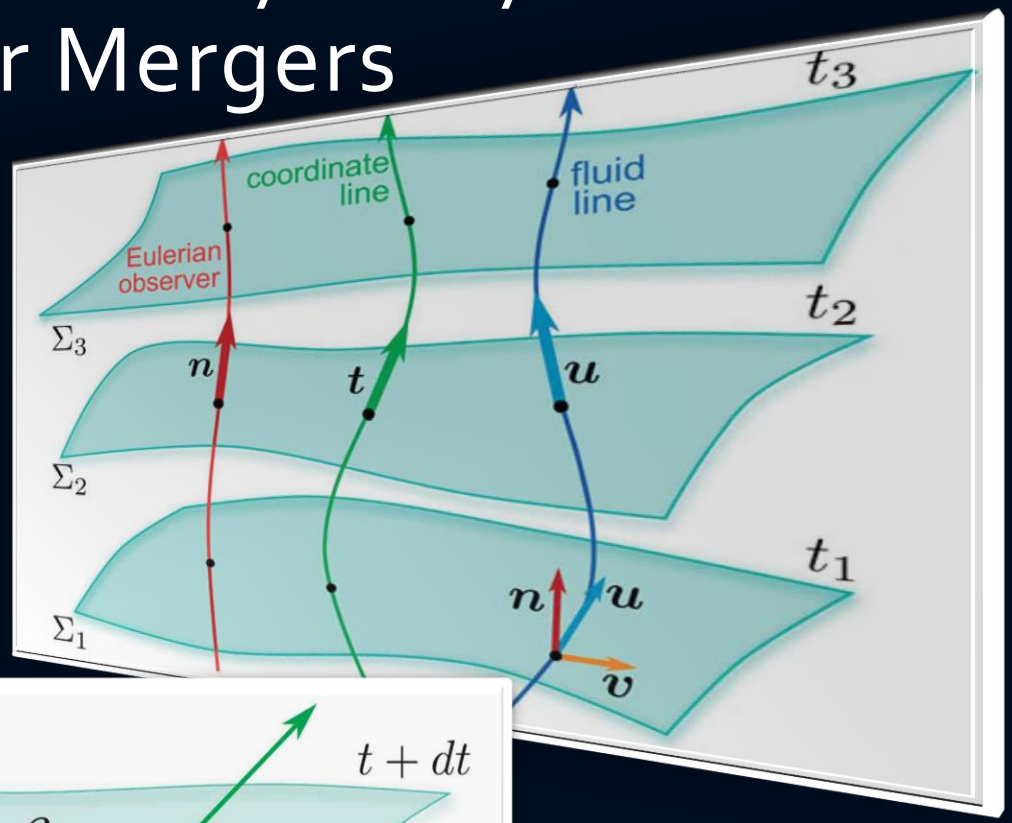
MG16 5-10 JULY 2021
SIXTEENTH MARCEL GROSSMANN MEETING
ON RECENT DEVELOPMENTS IN THEORETICAL AND EXPERIMENTAL GENERAL RELATIVITY, ASTROPHYSICS AND RELATIVISTIC FIELD THEORIES
VIRTUAL MEETING
websites: http://www.icra.it/mg/mg16/ https://indico.icranet.org/event/1/
email: mg16@icranet.org
6:30-19:30 CENTRAL EUROPEAN SUMMER TIME
50TH ANNIVERSARY OF "INTRODUCING THE BLACK HOLE"

# Numerical Relativity and Relativistic Hydrodynamics of Binary Neutron Star Mergers

Einstein's theory of general relativity and the resulting general relativistic conservation laws for energy-momentum in connection with the rest-mass conservation are the theoretical groundings of neutron star binary mergers:

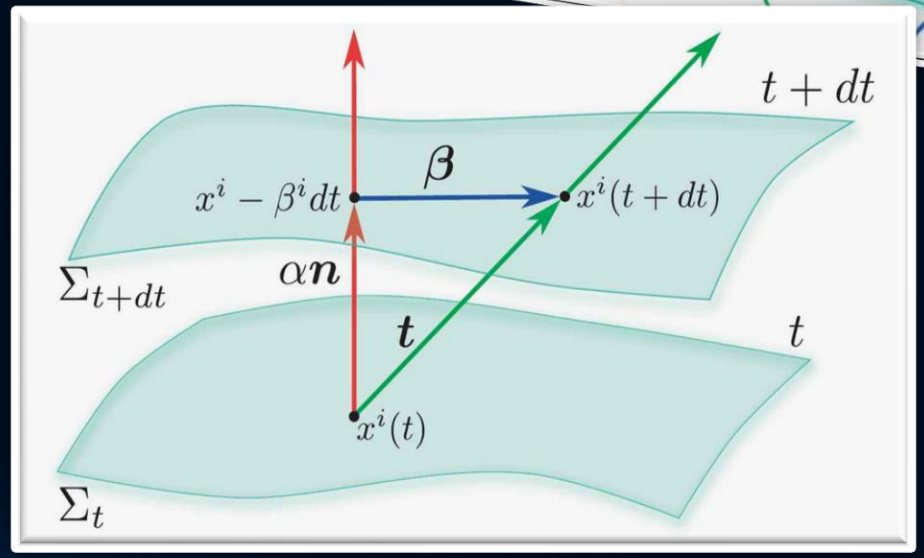
$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = 8\pi T_{\mu\nu}$$

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




(3+1) decomposition of spacetime

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

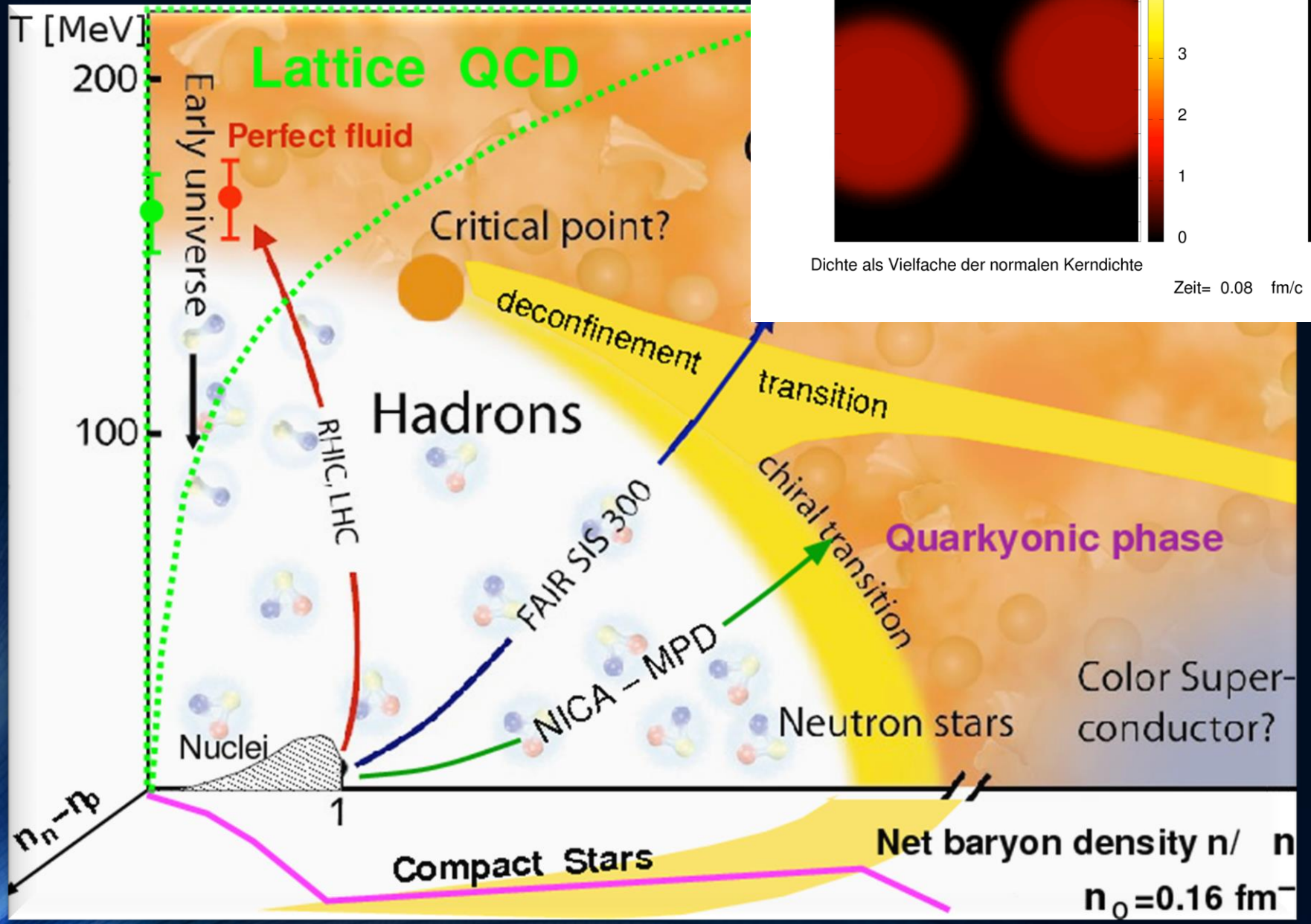


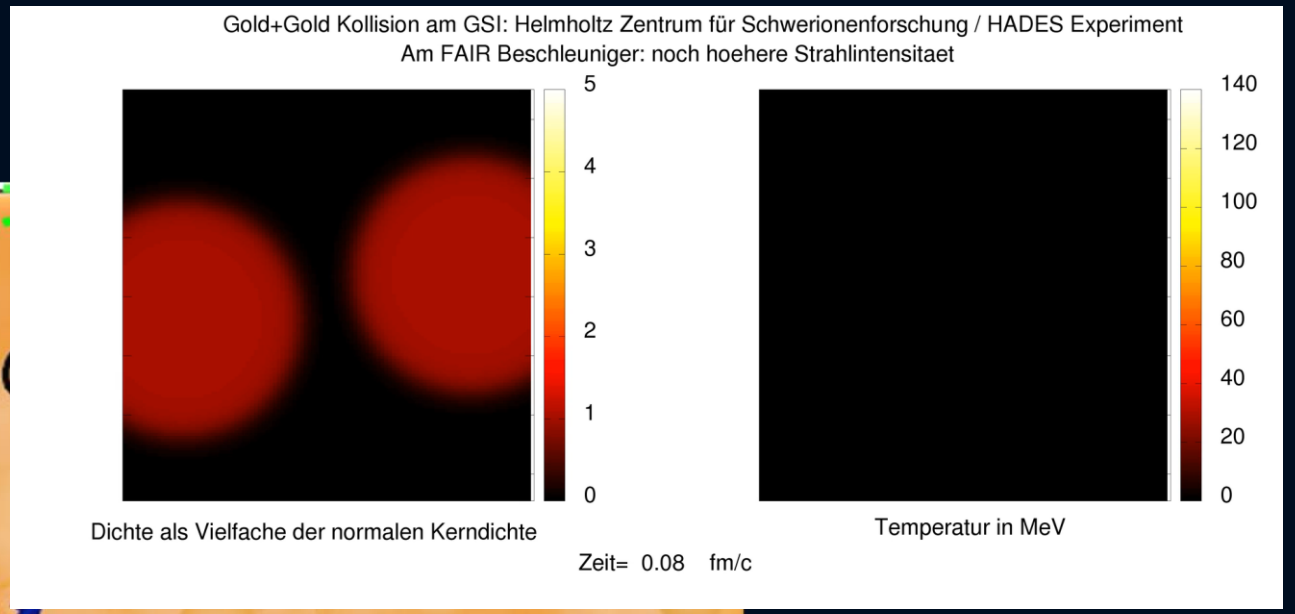

$$d\tau^2 = \alpha^2(t, x^j) dt^2 \qquad x^i_{t+dt} = x^i_t - \beta^i(t, x^j) dt$$

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

# The Hadron-Quark Phase Transition

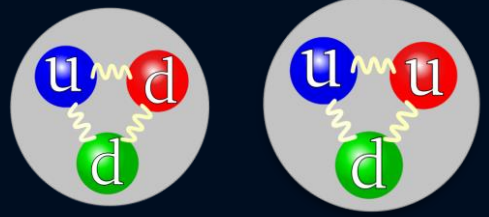
## The QCD Phase Diagram

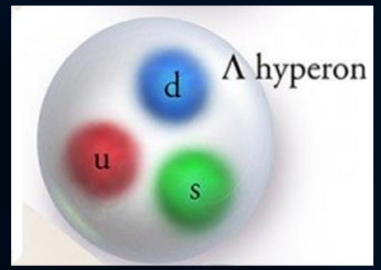


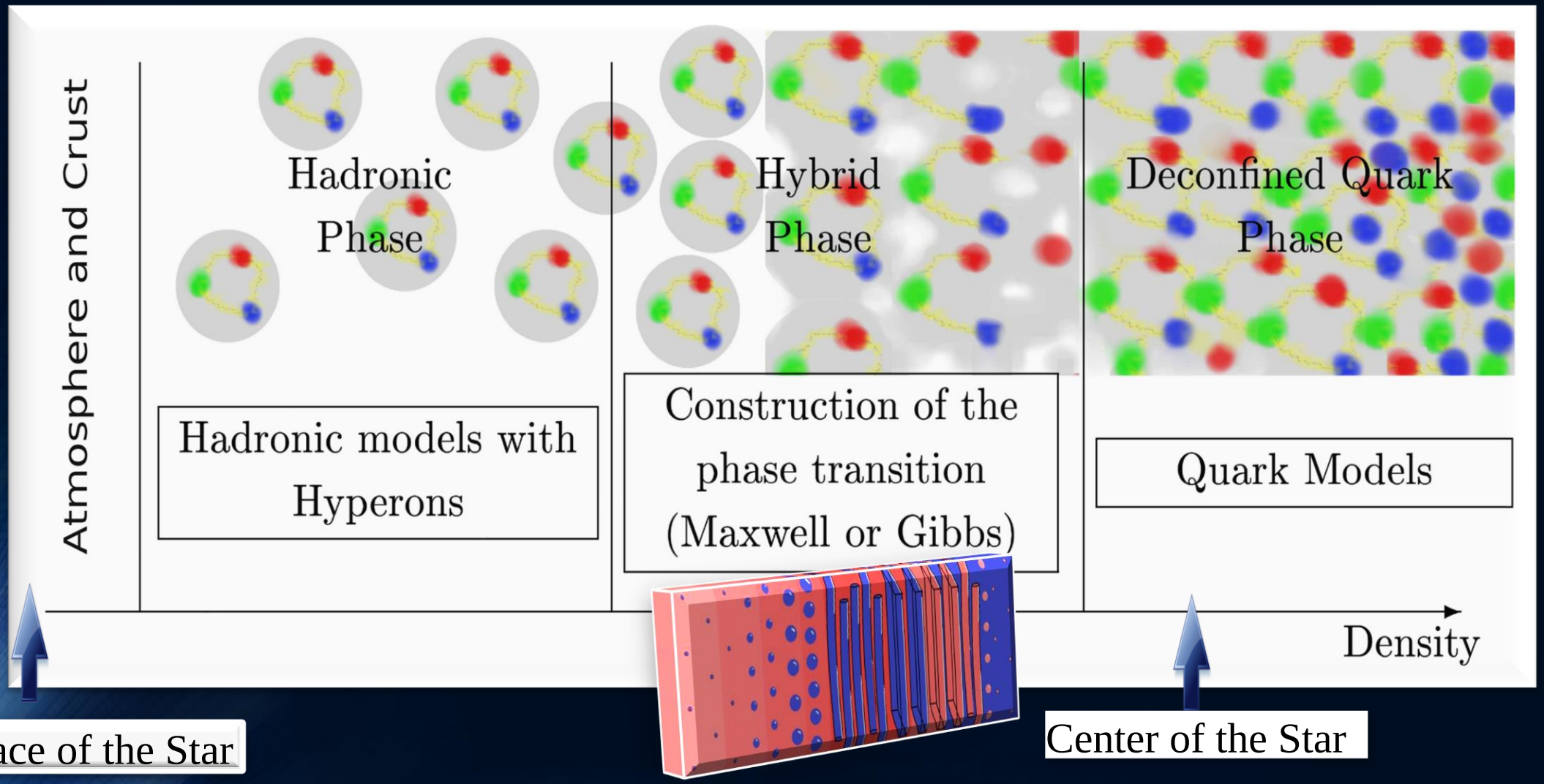

Credits:
Jan Steinheimer

neutron proton



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

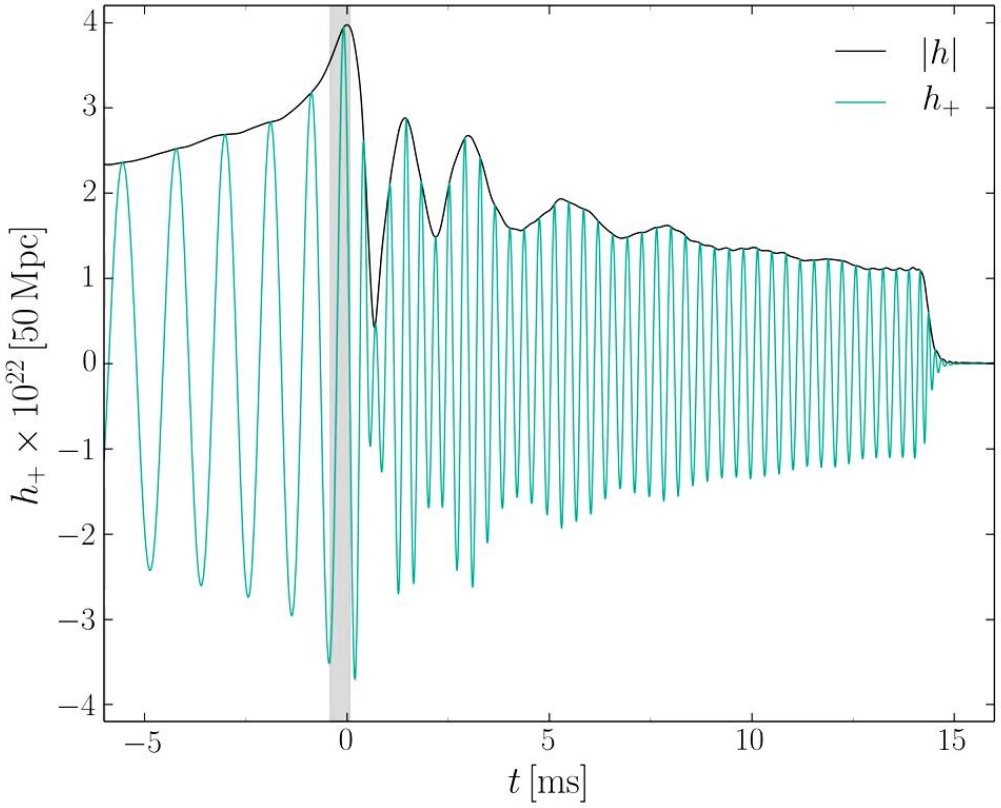


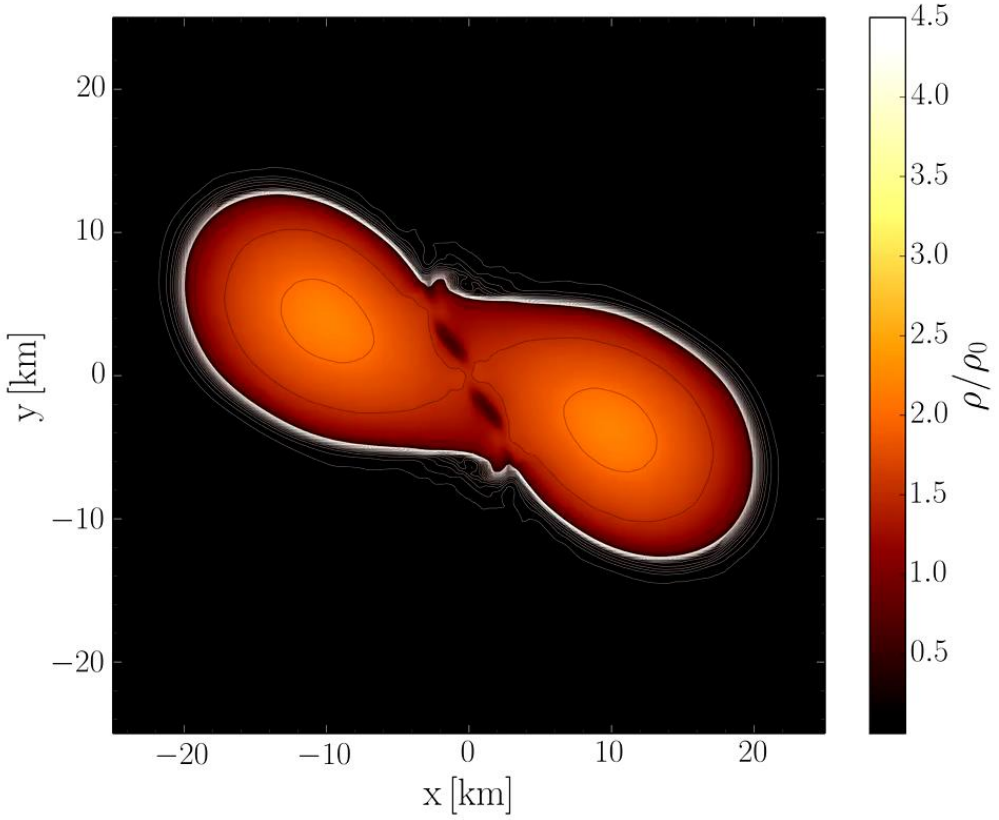

*Matthias Hanauske; Doctoral Thesis:*
*Properties of Compact Stars within QCD-motivated Models; University Library Publication Frankfurt (2004)*

# 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)



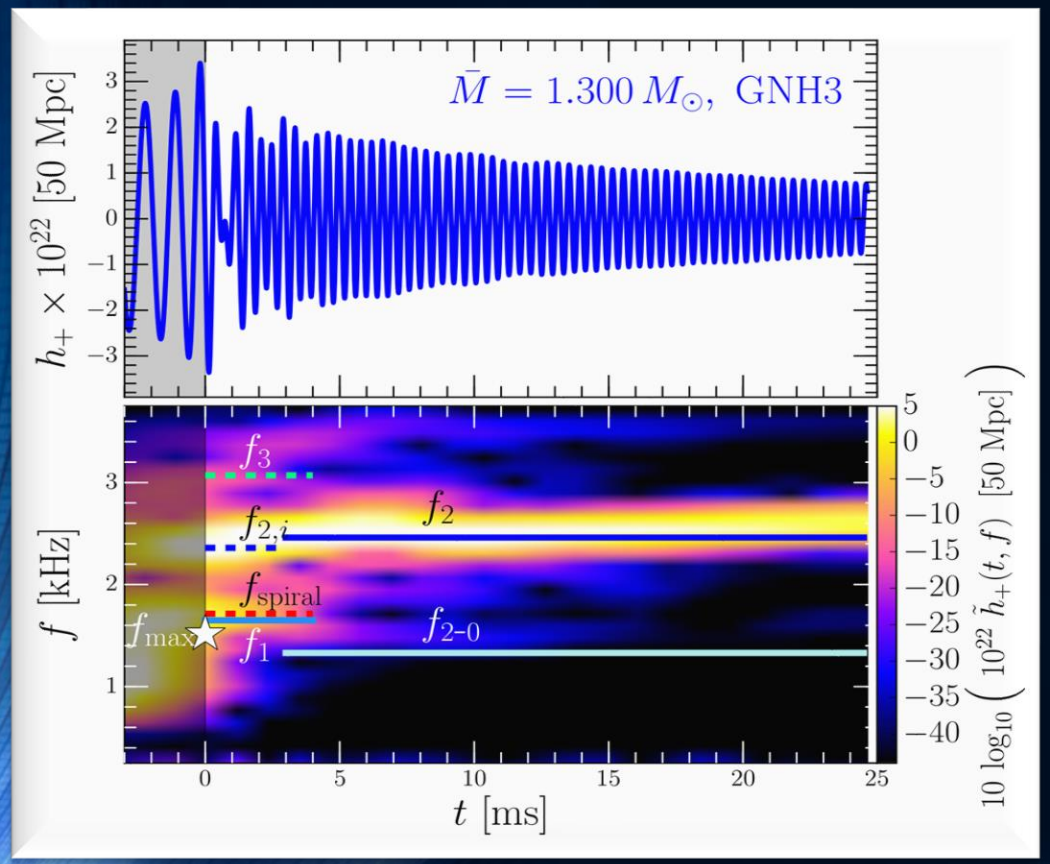

Gravitational wave amplitude
at a distance of 50 Mpc

Rest mass density distribution ρ(x,y)
in the equatorial plane

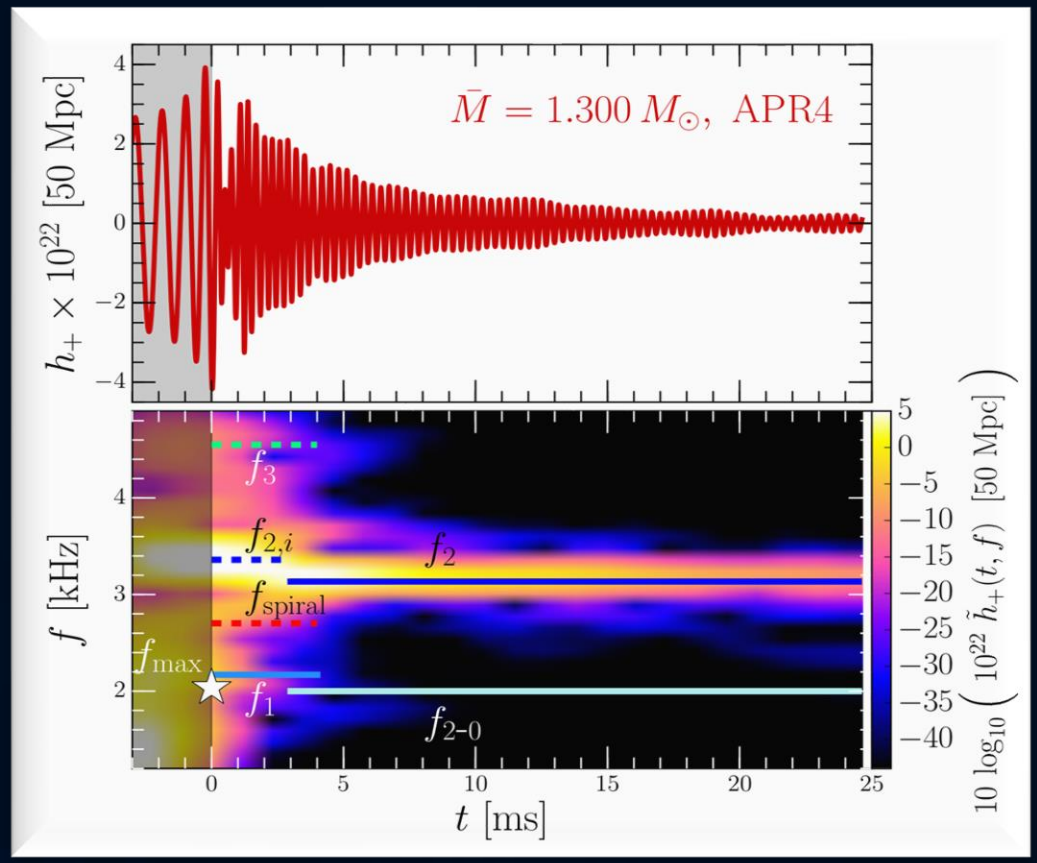
in units of the nuclear matter density $\rho_0$

# Time Evolution of the GW-Spectrum

The power spectral density profile of the post-merger emission is characterized by several distinct frequencies. After approximately 5 ms after merger, the only remaining dominant frequency is the $f_2$-frequency (See e.g. L.Rezzolla and K.Takami, PRD, 93(12), 124051 (2016))




Stiff EOS




Soft EOS

Unfortunately, due to the low sensitivity at high gravitational wave frequencies, no post-merger signal has been found in GW170817.

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

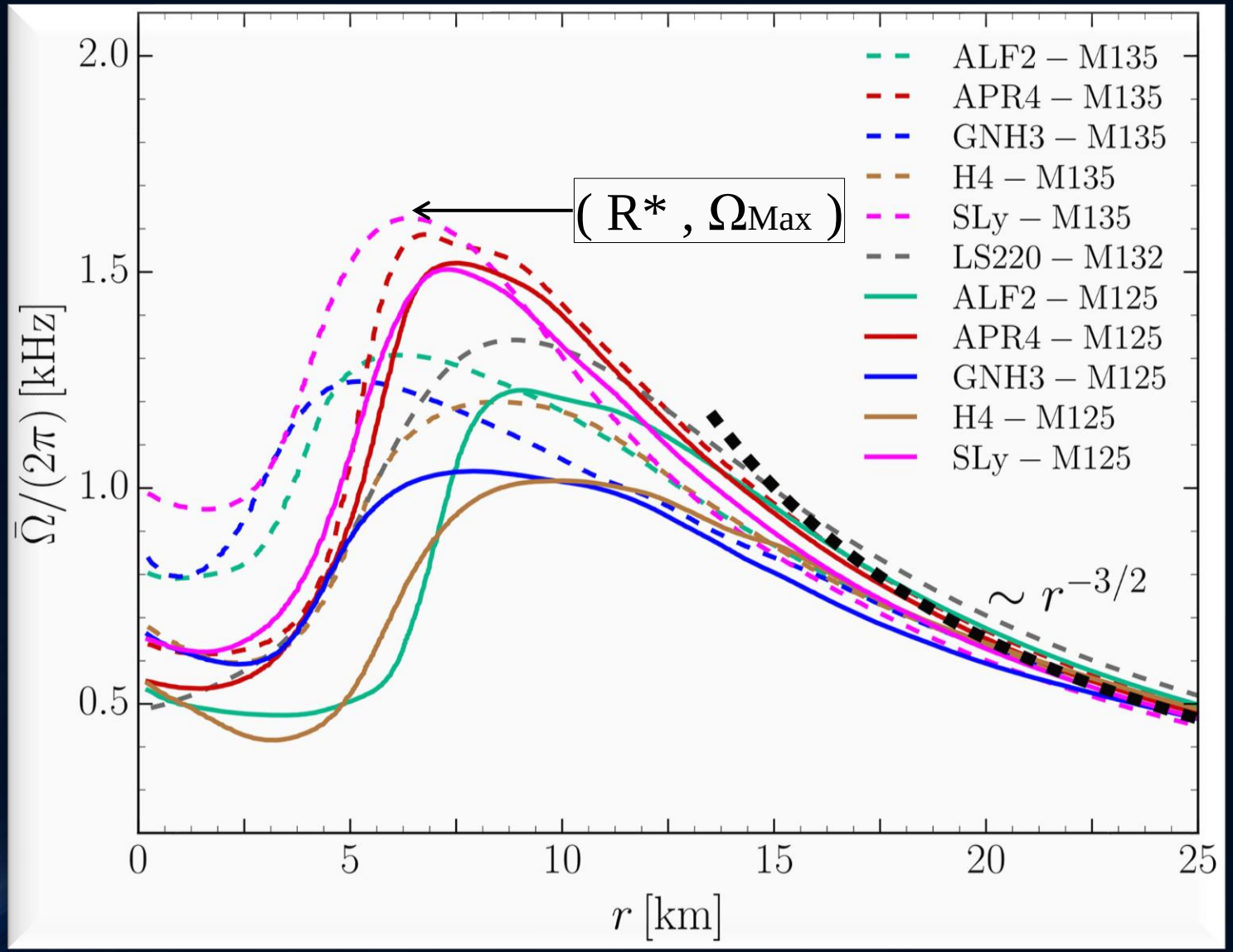
Evolution of the frequency spectrum of the emitted gravitational waves for the stiff GNH3 (left) and soft APR4 (right) EOS.

# Time-averaged Rotation Profiles of the HMNSs

**Talk on Thursday**

*On the properties of metastable hypermassive hybrid stars*

*Parallel session Neutron stars: Dense matter in compact stars, 08.07.2021, 18:10*



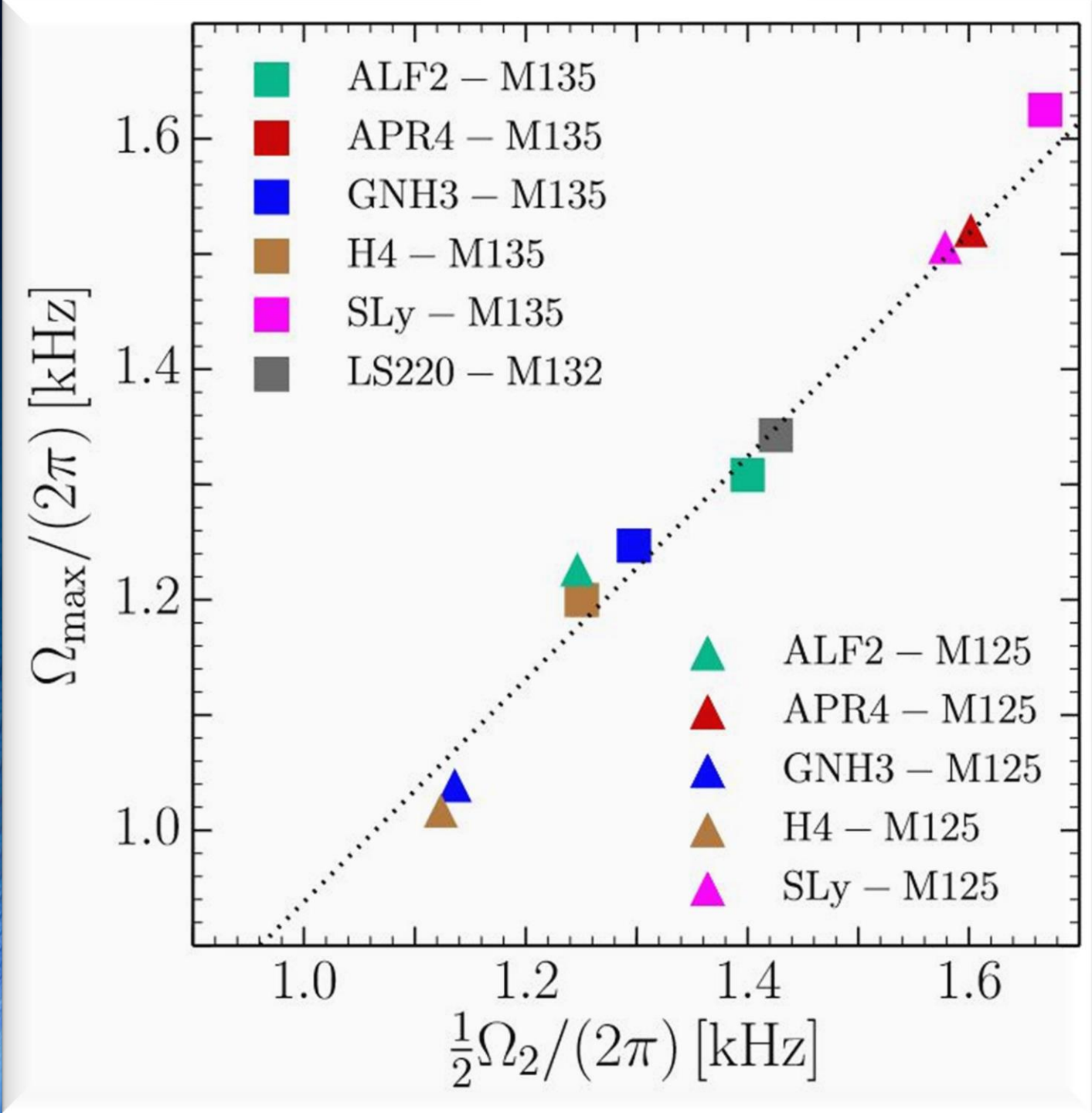

Time-averaged rotation profiles for different EoS
Low mass runs (solid curves), high mass runs (dashed curves).

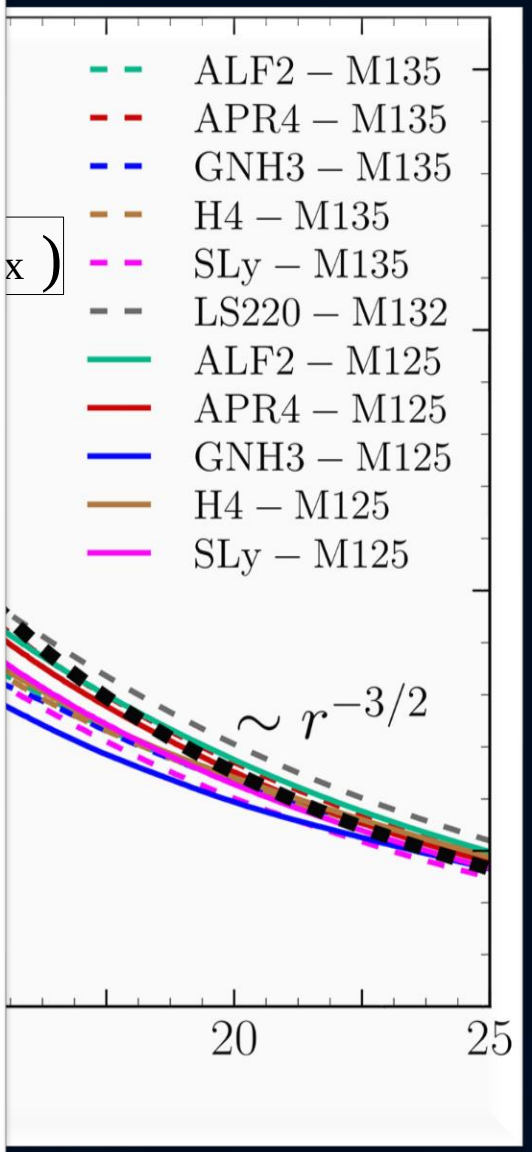
Hanauske, et.al. PRD, 96(4), 043004 (2017)

**Soft EoSs:**
Sly
APR4

**Stiff EoSs:**
GNH3
H4

# files of the HMNSs




Soft EoSs:
Sly
APR4

Stiff EoSs:
GNH3
H4

S Hanauske, et.al. PRD, 96(4), 043004 (2017)
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# 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)
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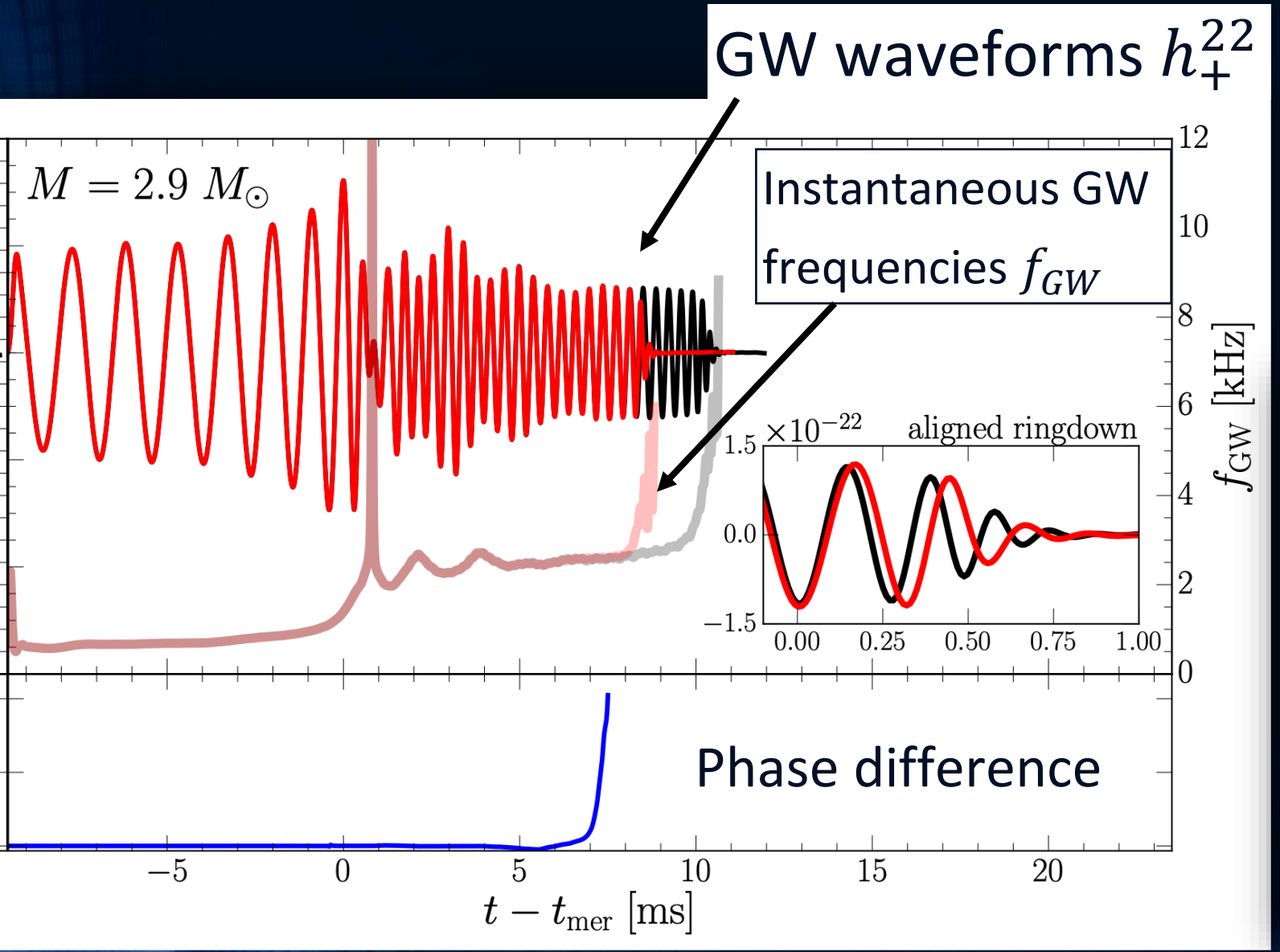
# *Signatures within the post-merger phase*

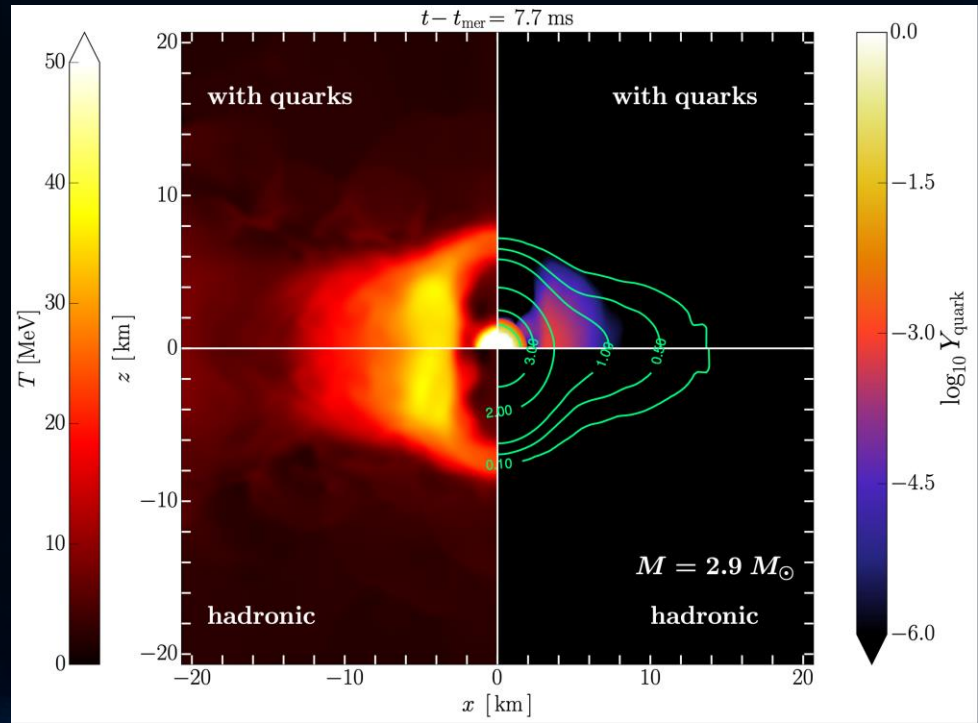
## Phase-transition triggered collapse scenario

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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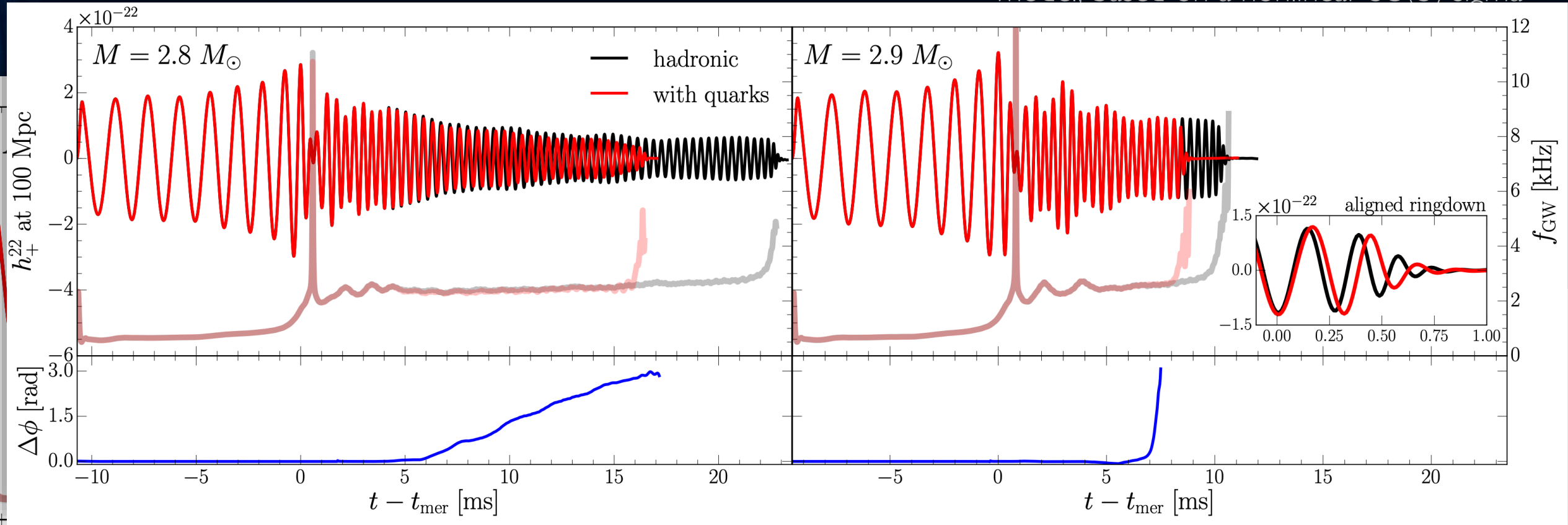
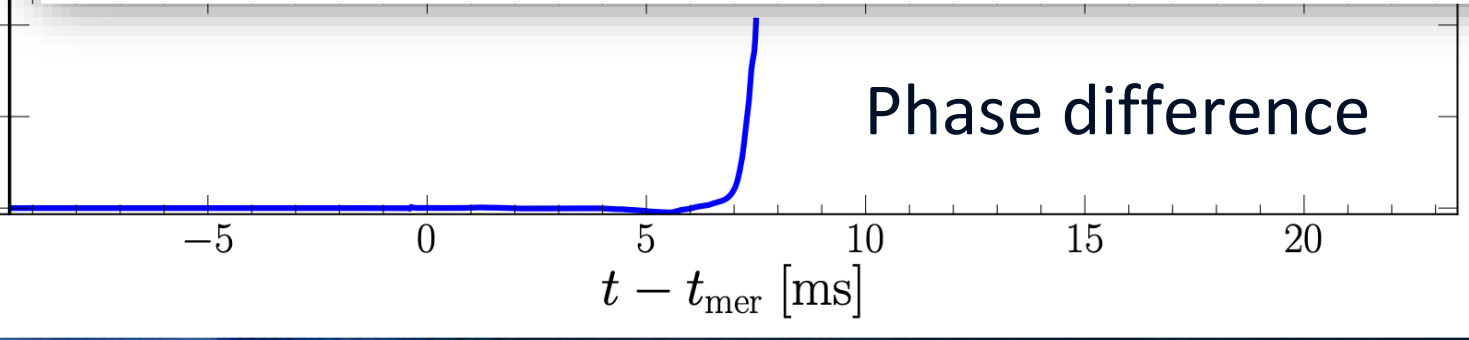
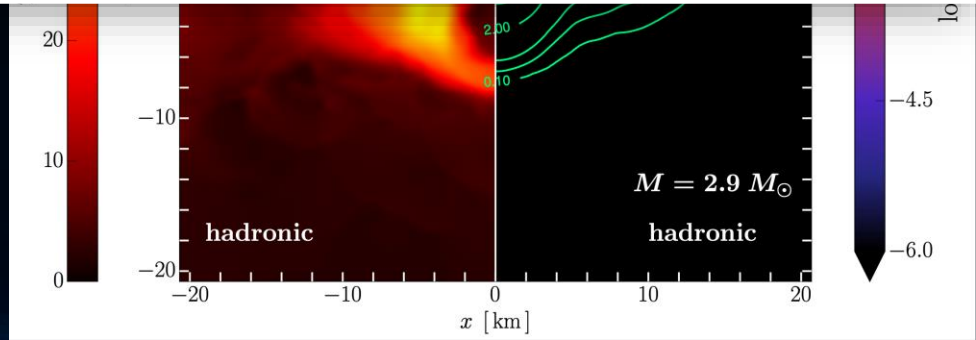
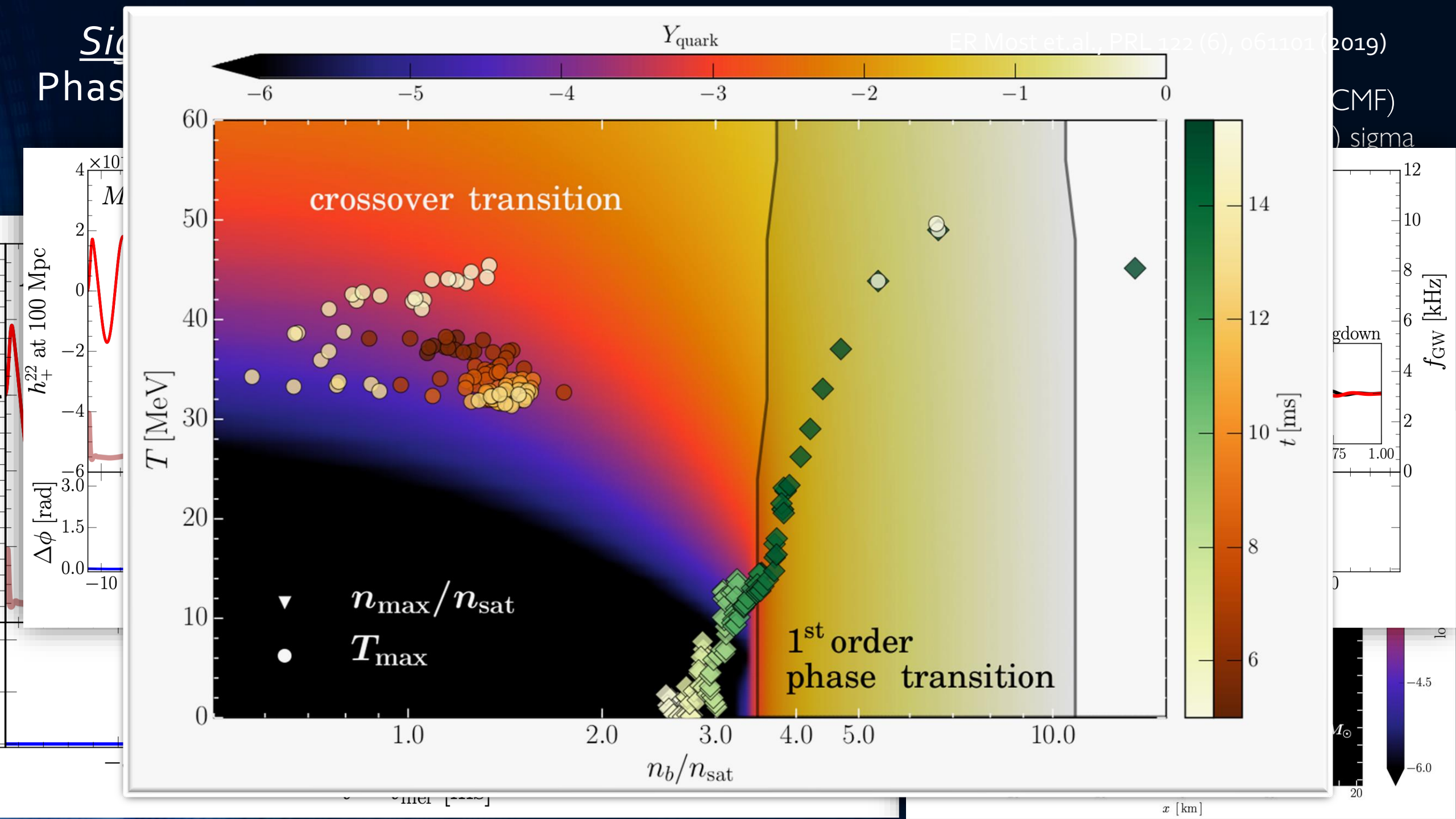



$Y_{\rm quark}$
−6
−5
−4
−3
−2
−1
0
crossover transition
1st order
phase transition
$n_{\rm max}/n_{\rm sat}$
$T_{\rm max}$
$T$ [MeV]
$n_b/n_{\rm sat}$
$t$ [ms]
$h_+^{22}$ at 100 Mpc
$\Delta\phi$ [rad]
$f_{\rm GW}$ [kHz]
$x$ [km]

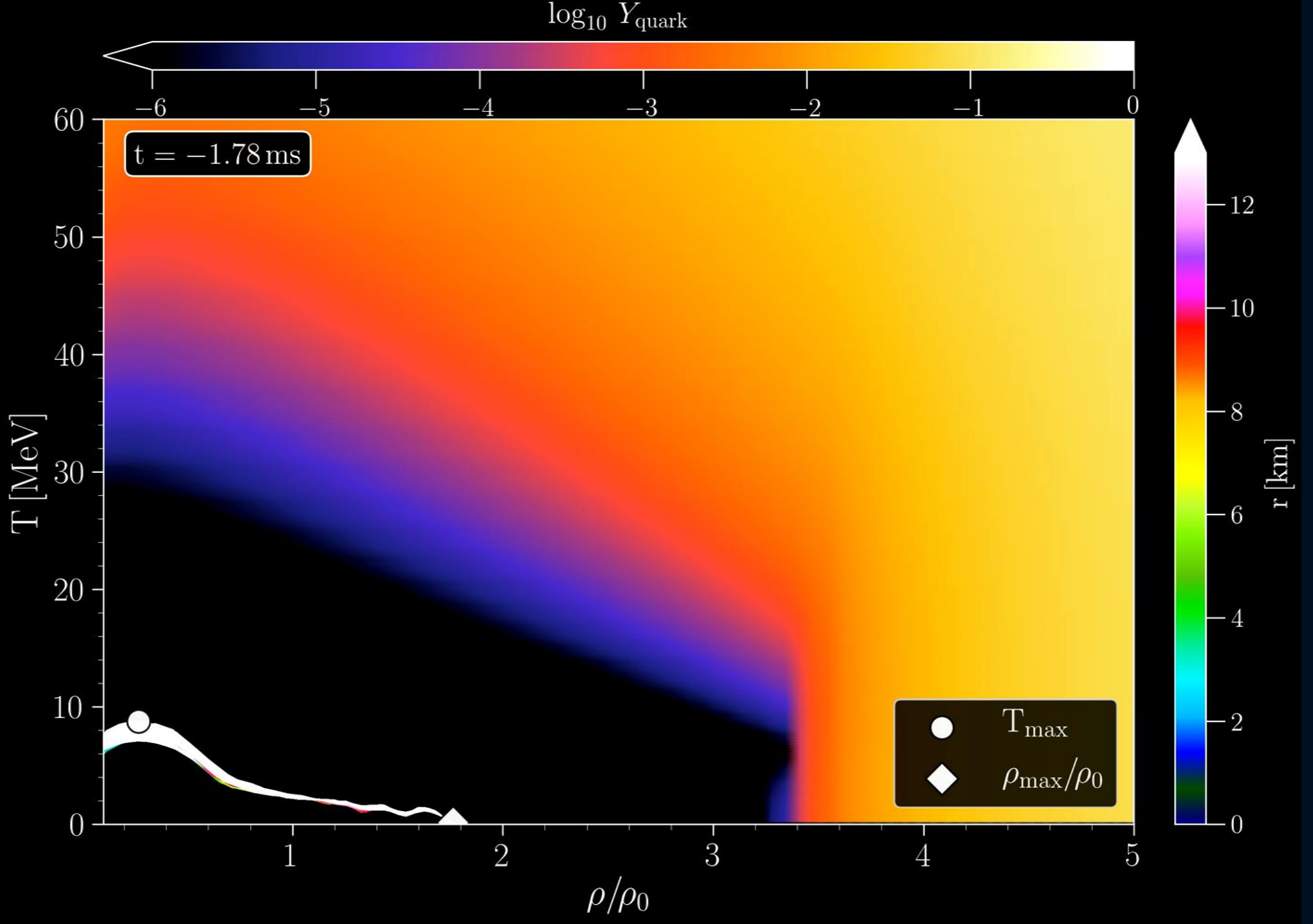
**Phase-transition triggered collapse scenario**

*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 $M_{solar}$



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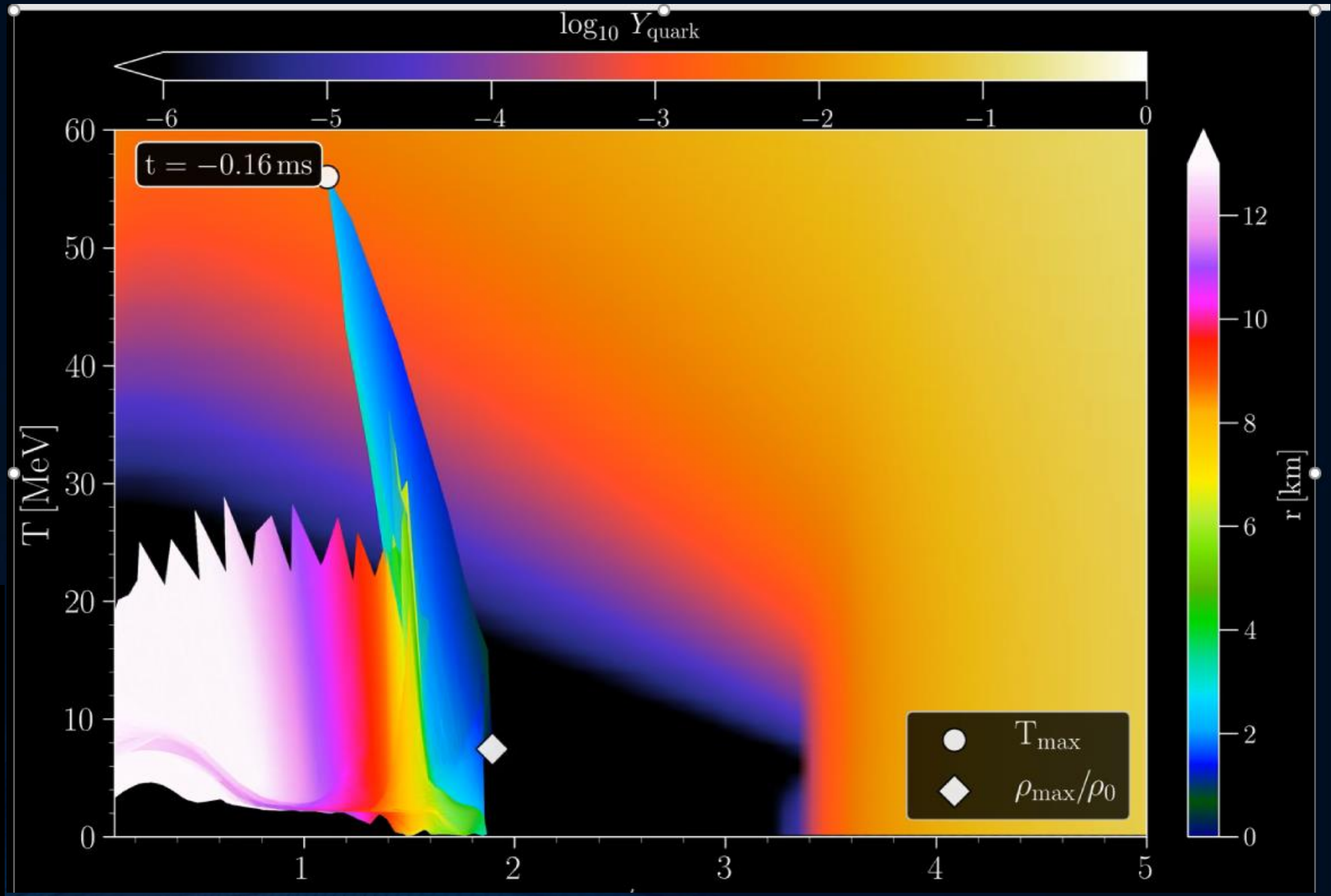

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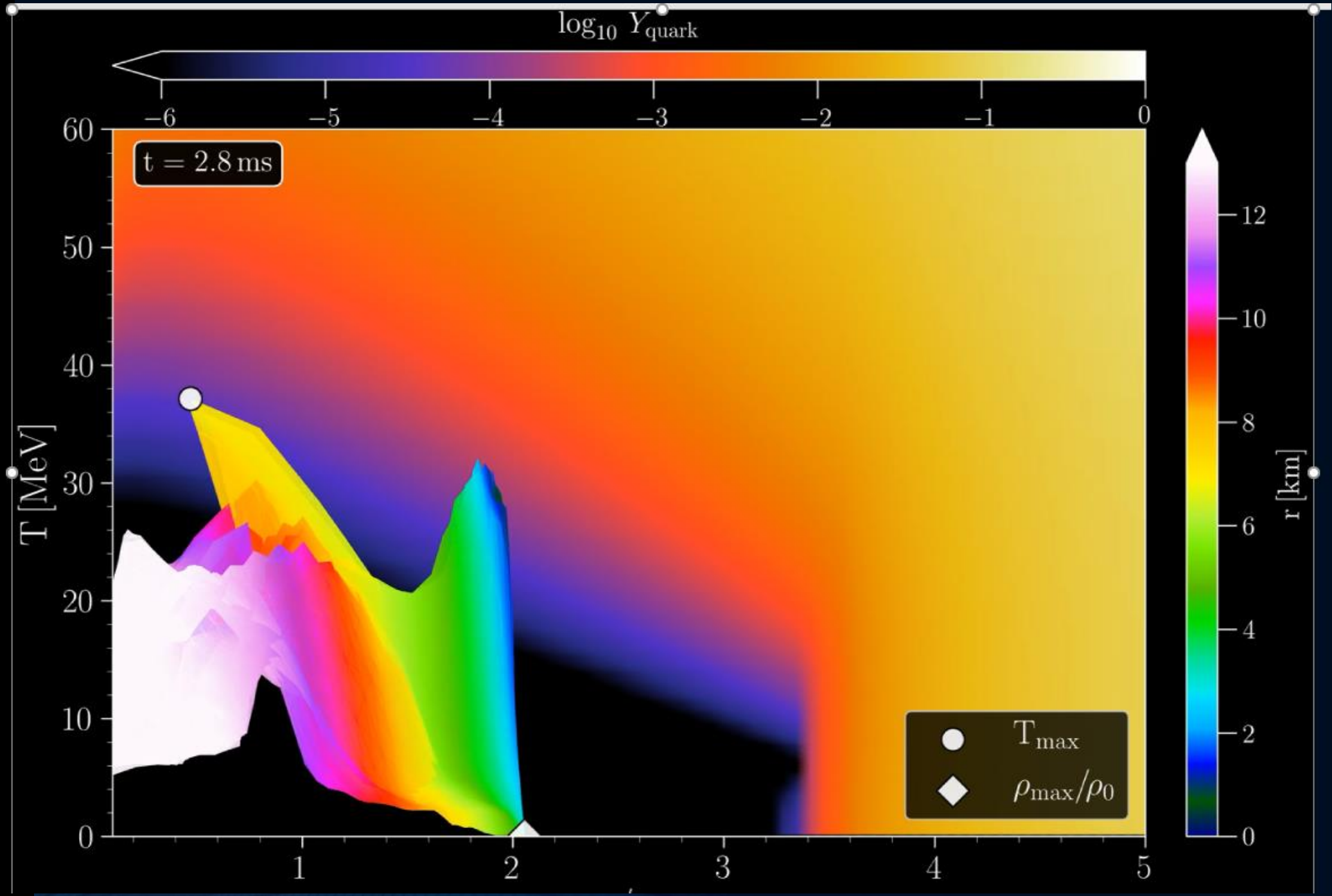

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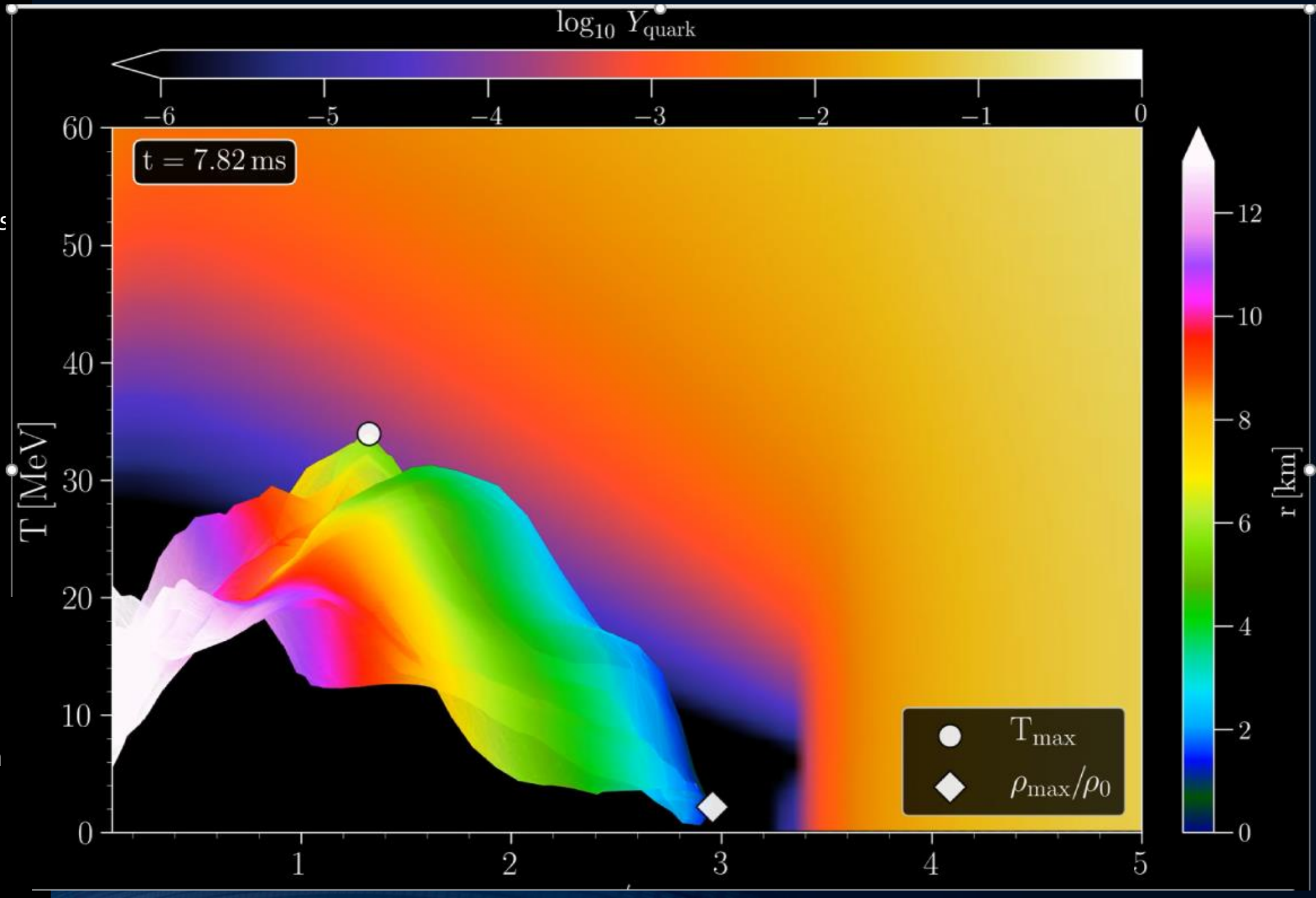

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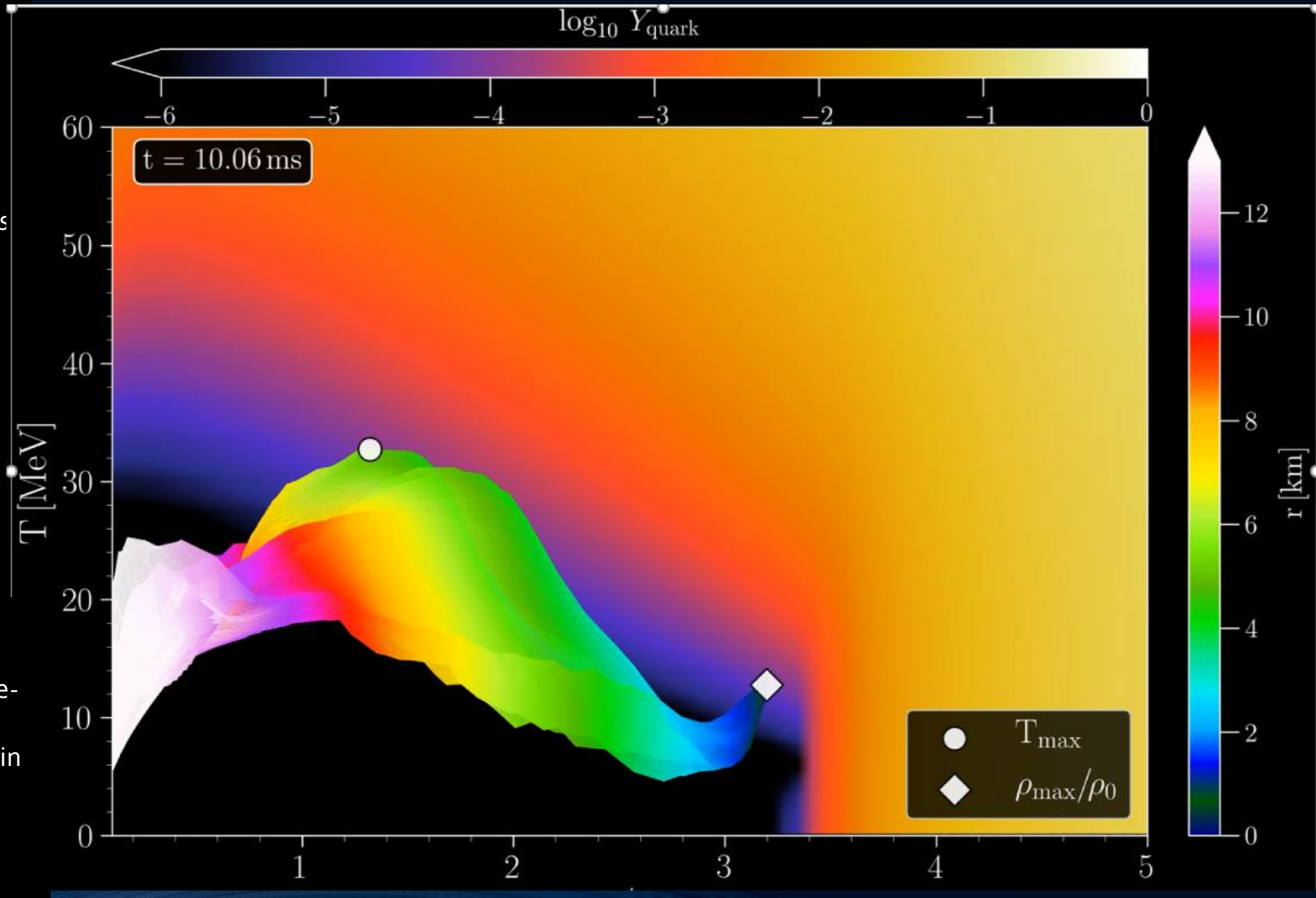
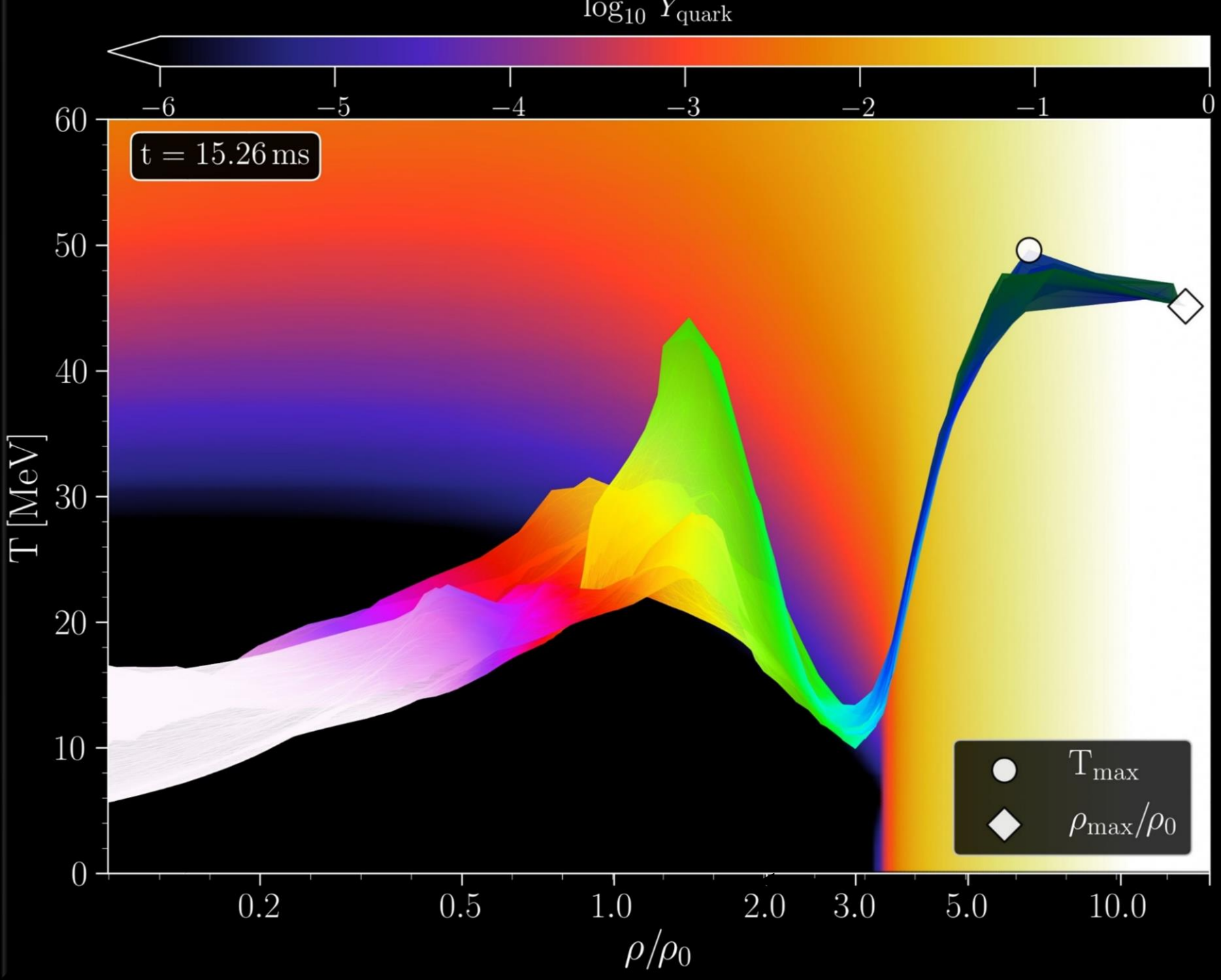


# The Strange Bird Plot

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E.Most, J. Papenfort, V.Dexheimer, M.Hanauske, H.Stöcker and L.Rezzolla,
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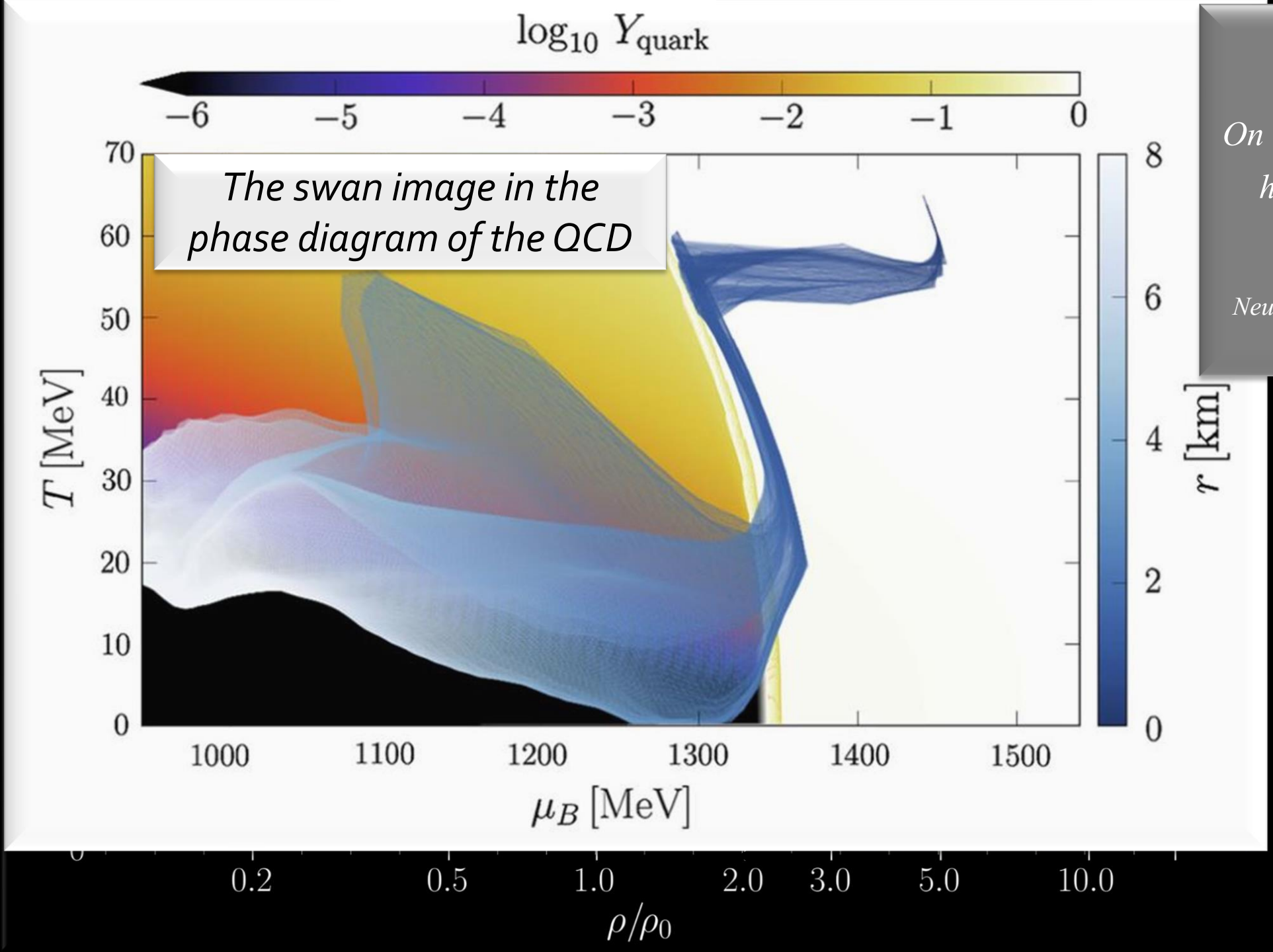
The European Physical Journal A
56 (2), 1-11 (2020)

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)

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*On the properties of metastable hypermassive hybrid stars*

*Parallel session*

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

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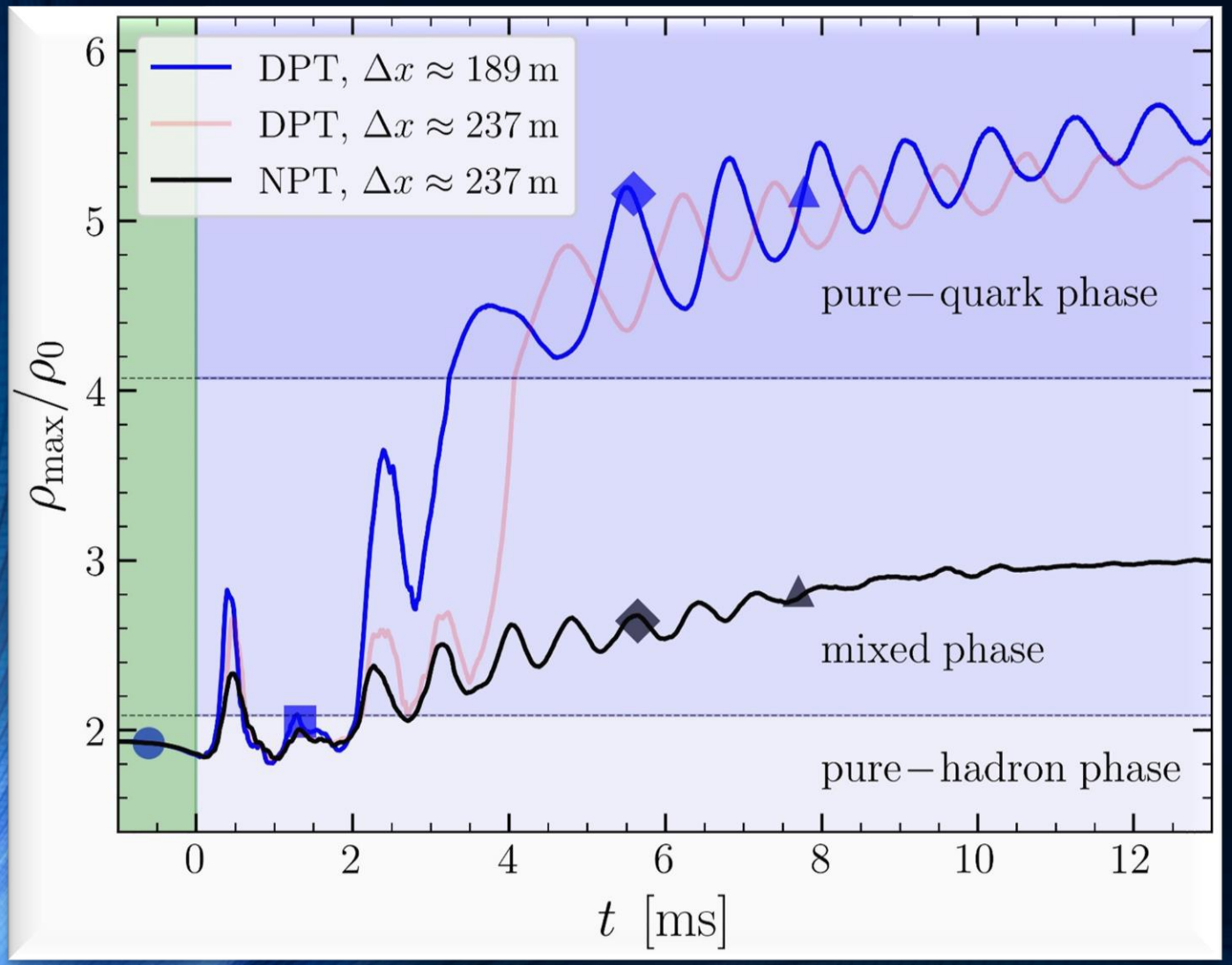
# *Signatures within the post-merger phase evolution*

## DPT: Delayed phase transition scenario

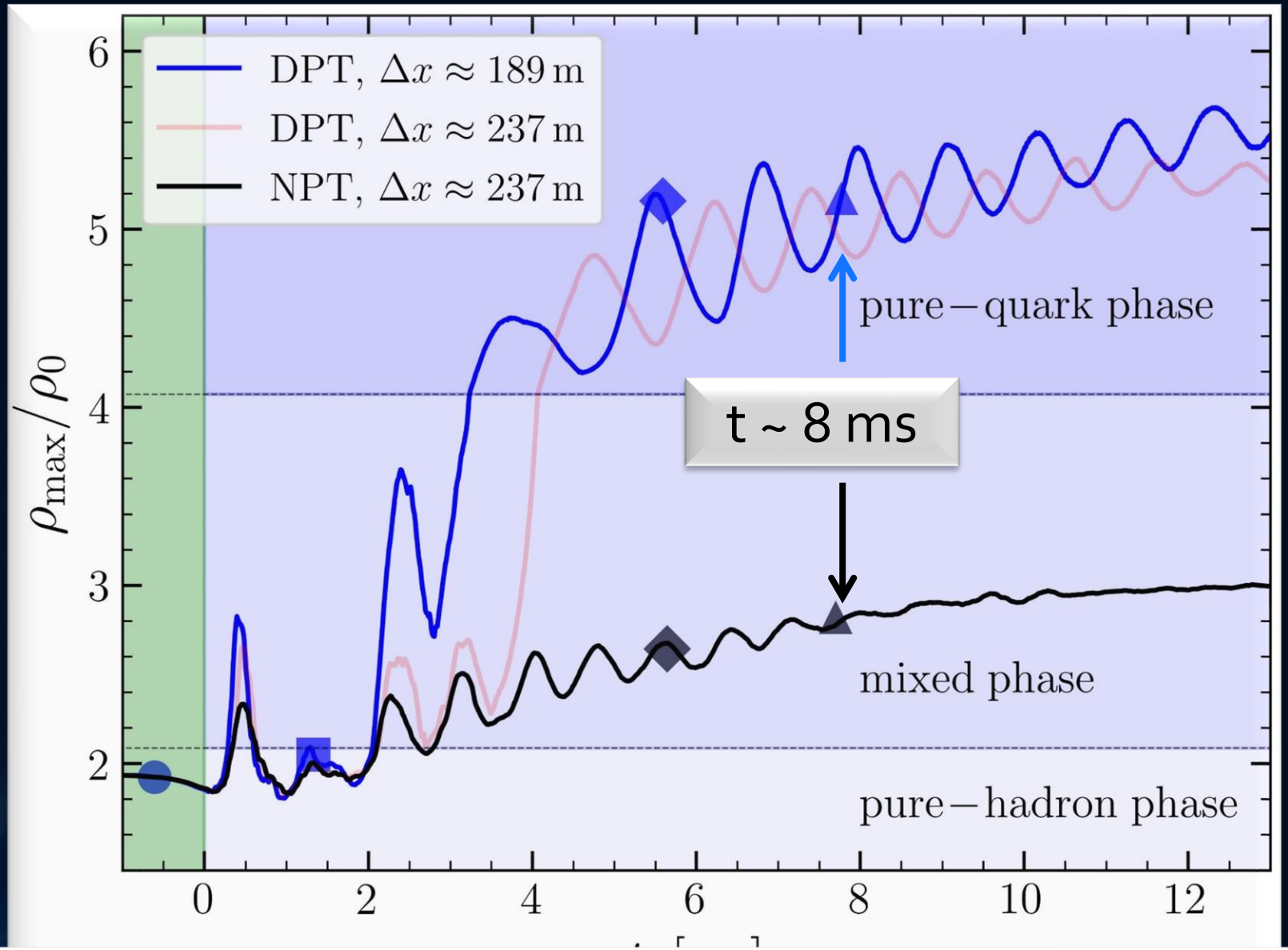
Postmerger Gravitational-Wave Signatures of Phase Transitions in Binary Mergers; LR Weih, M Hanauske, L Rezzolla; Physical Review Letters 124 (17), 171103 (2020)




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).

# Without Phase Transition

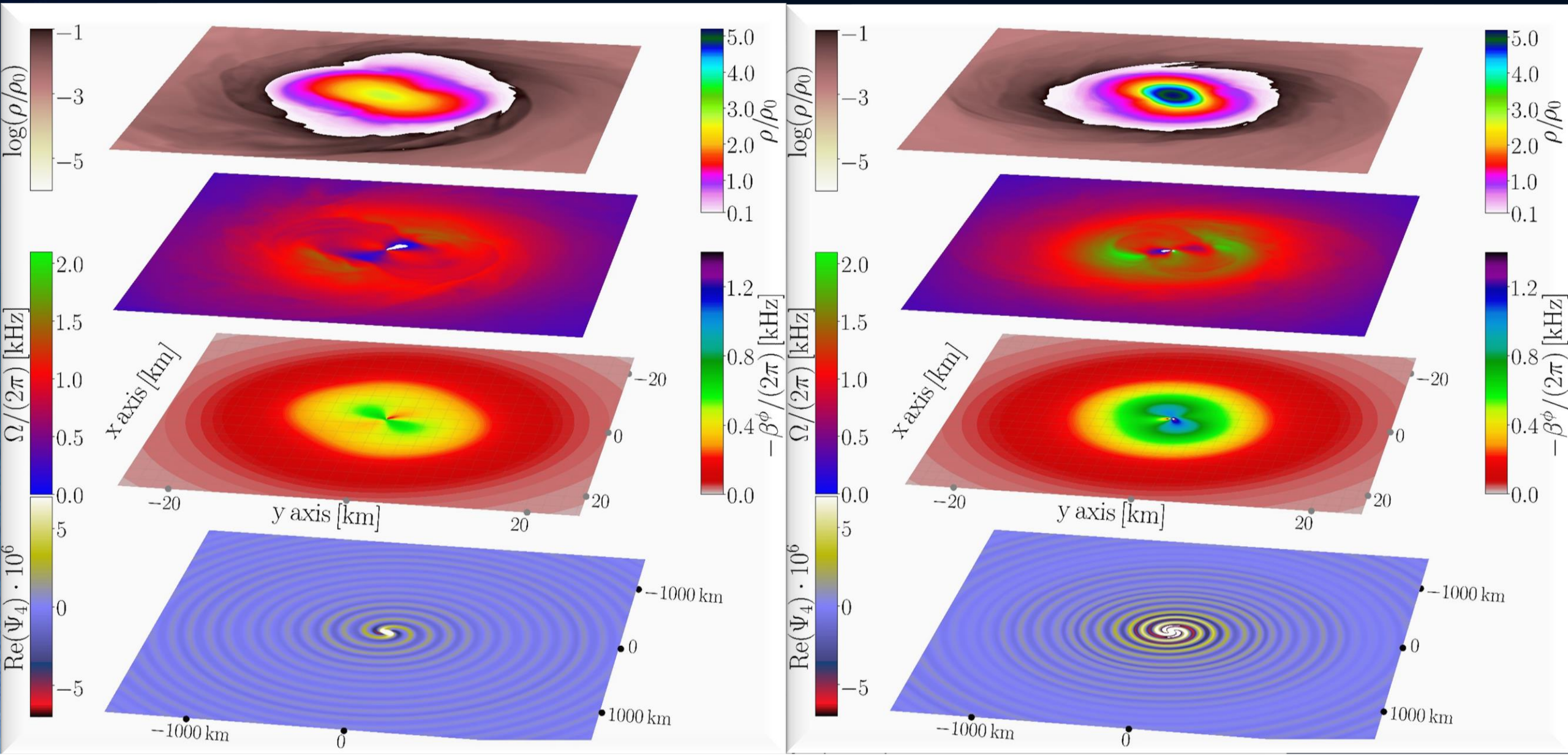
# With Phase Transition




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

# Without Phase Transition

# With Phase Transition

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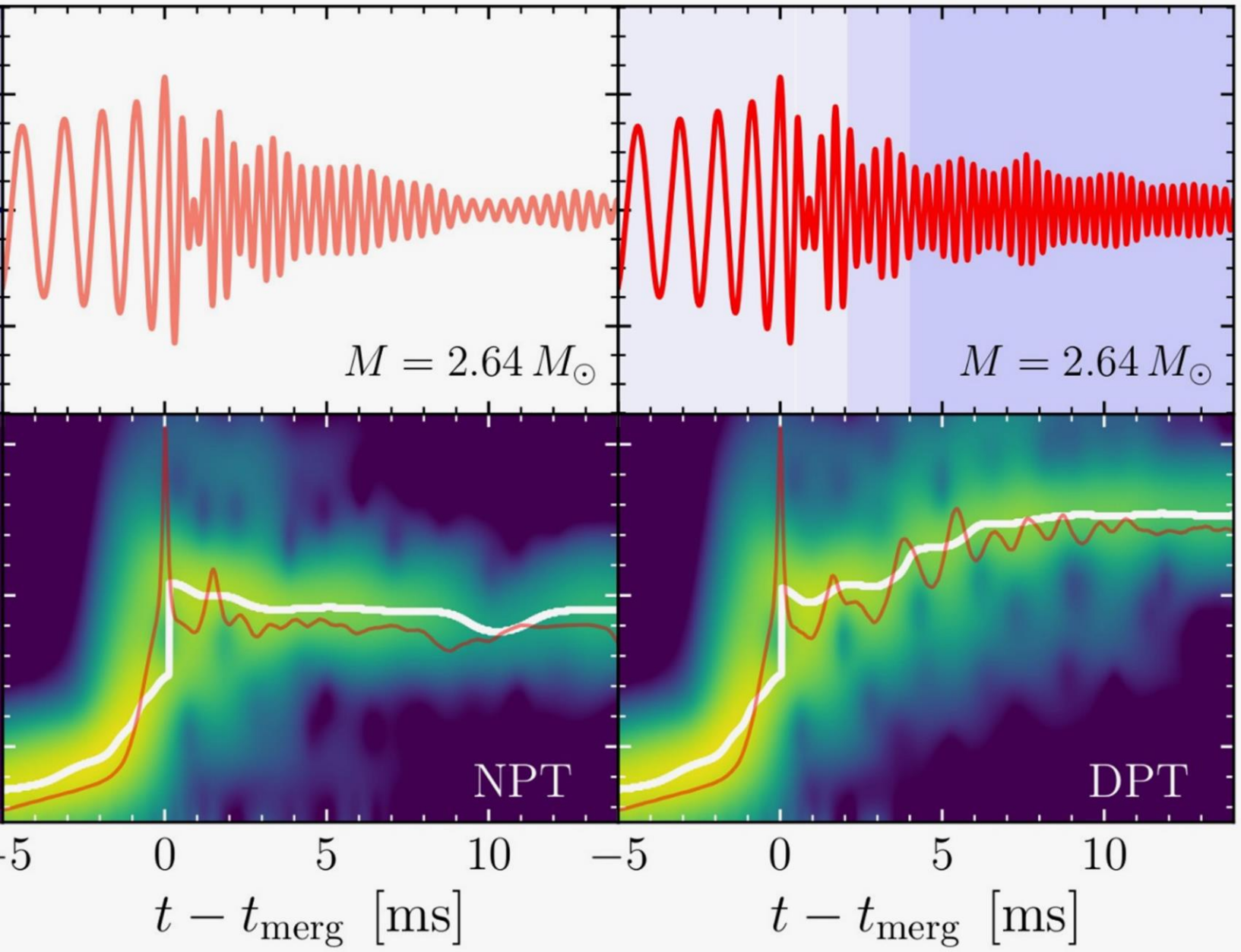
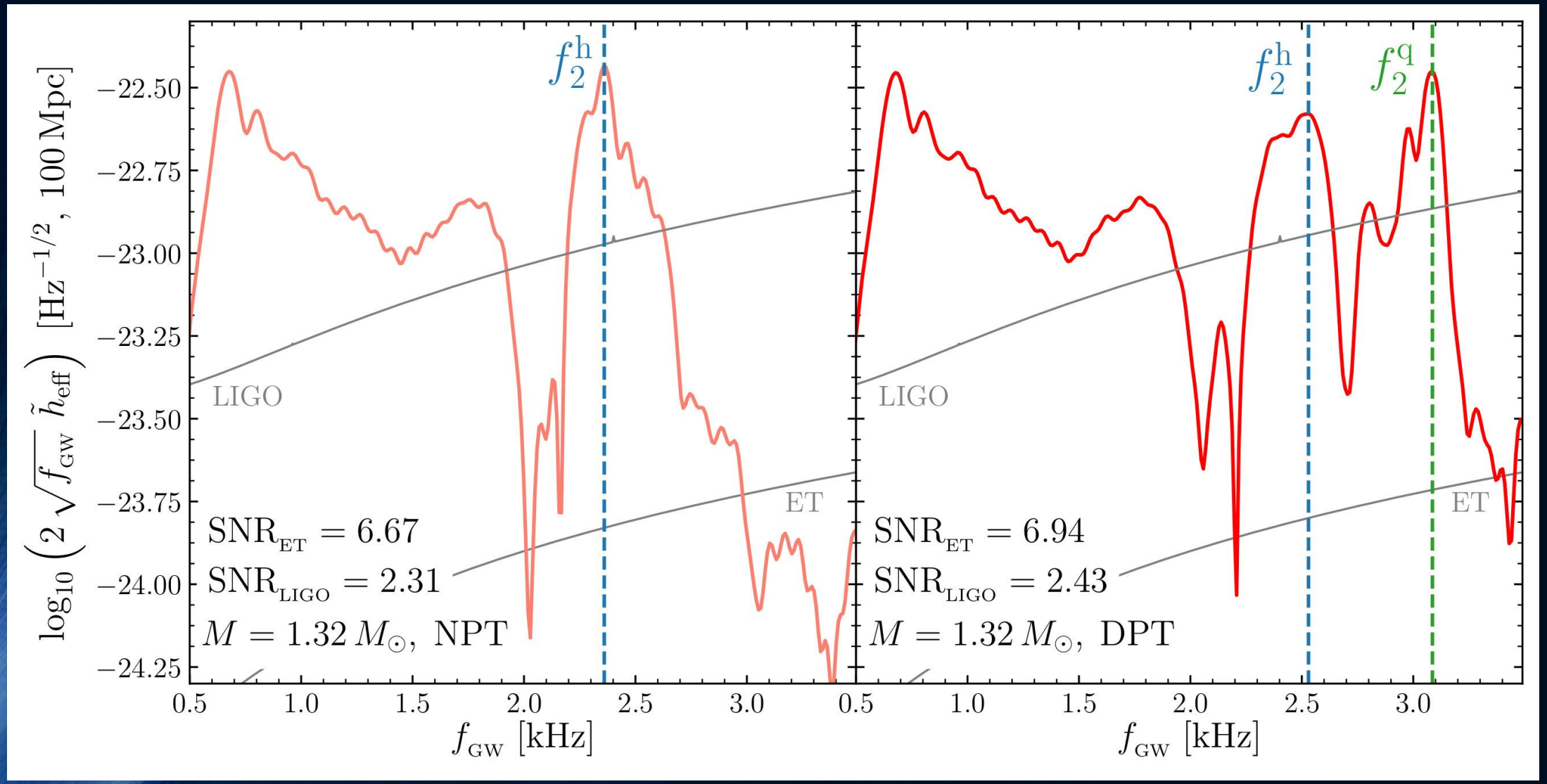



Strain h+ (top) and its spectrogram (bottom) for the binary neutron star simulation of the delayed phase transition scenario. In the top panel the different shadings mark the times when the HMHS core enters the mixed and pure quark phases. In the bottom panels, the white lines trace the maximum of the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

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

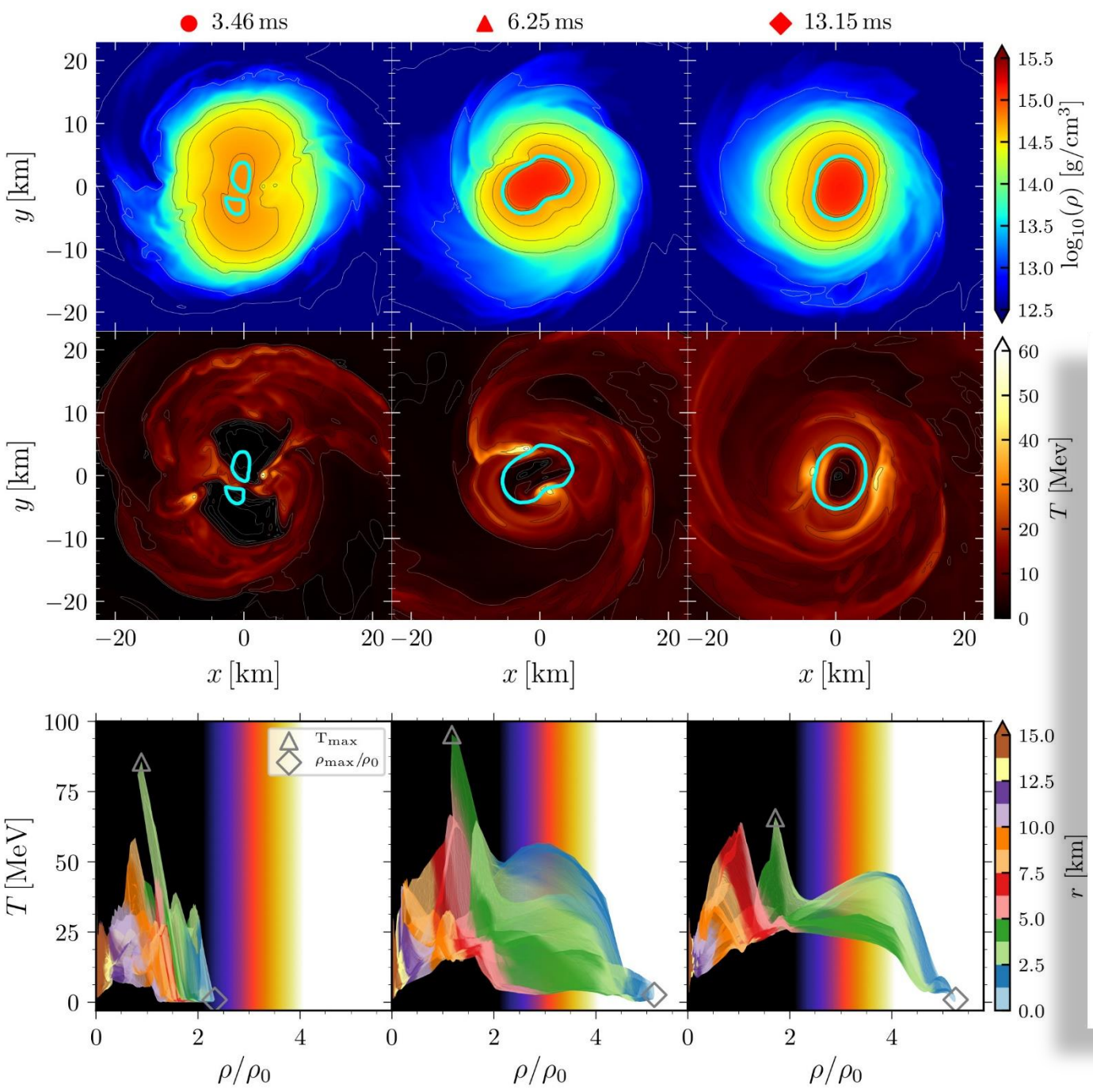


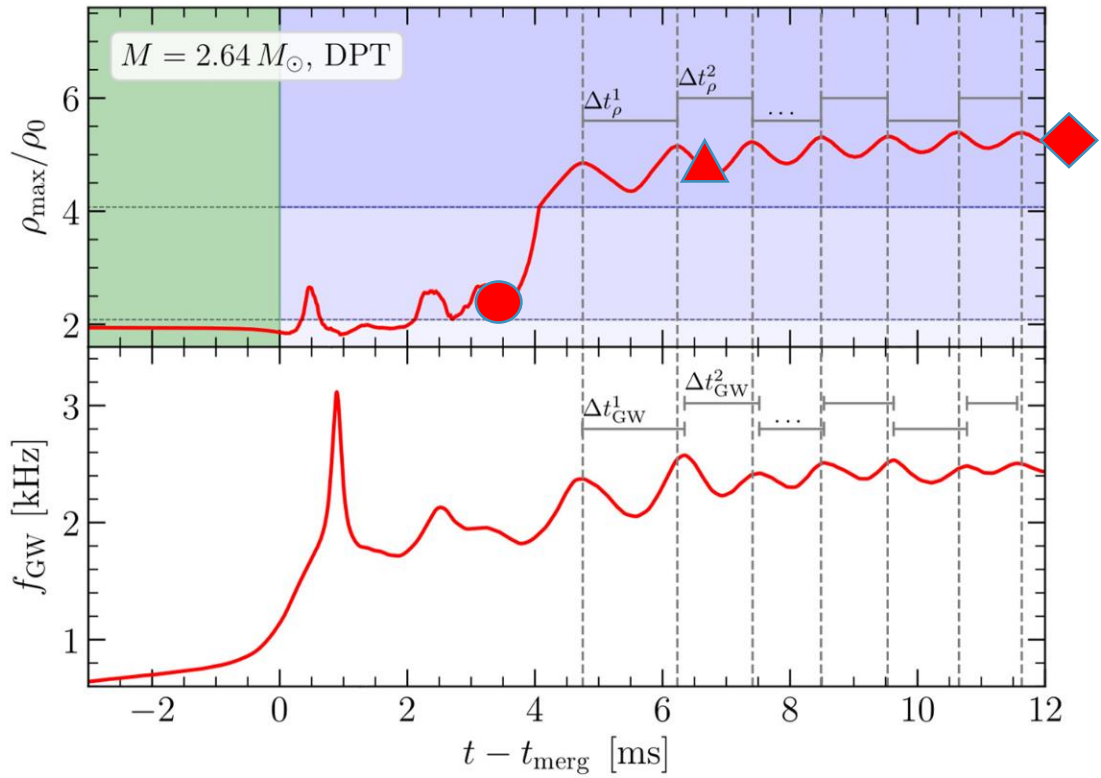

Total gravitational wave spectrum (left NPT, right DPT), PRL 124, 171103 (2020)

M. Hanauske, L. Weih, H. Stöcker and L. Rezzolla

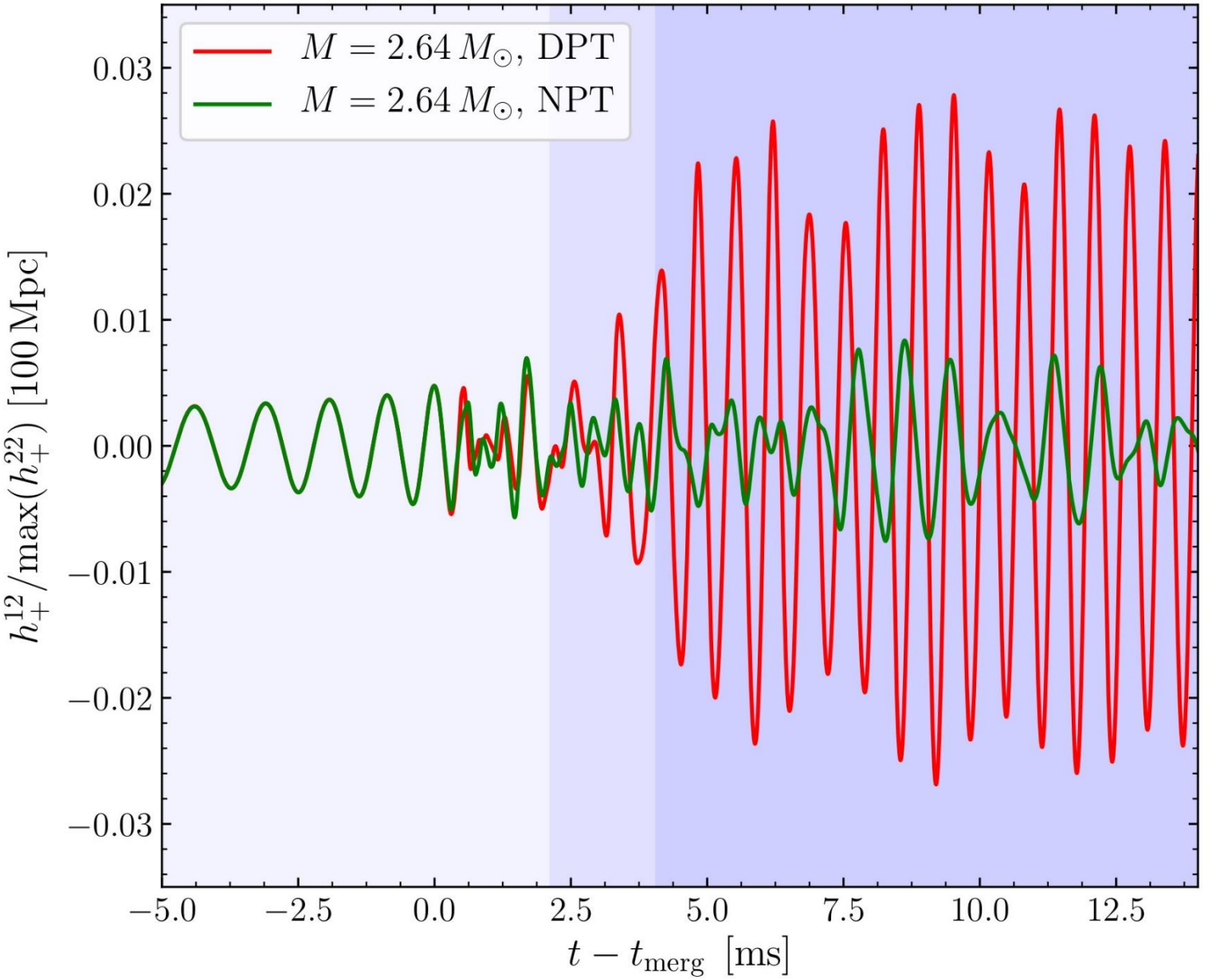
*Metastable hypermassive hybrid stars as neutron-star merger remnants*

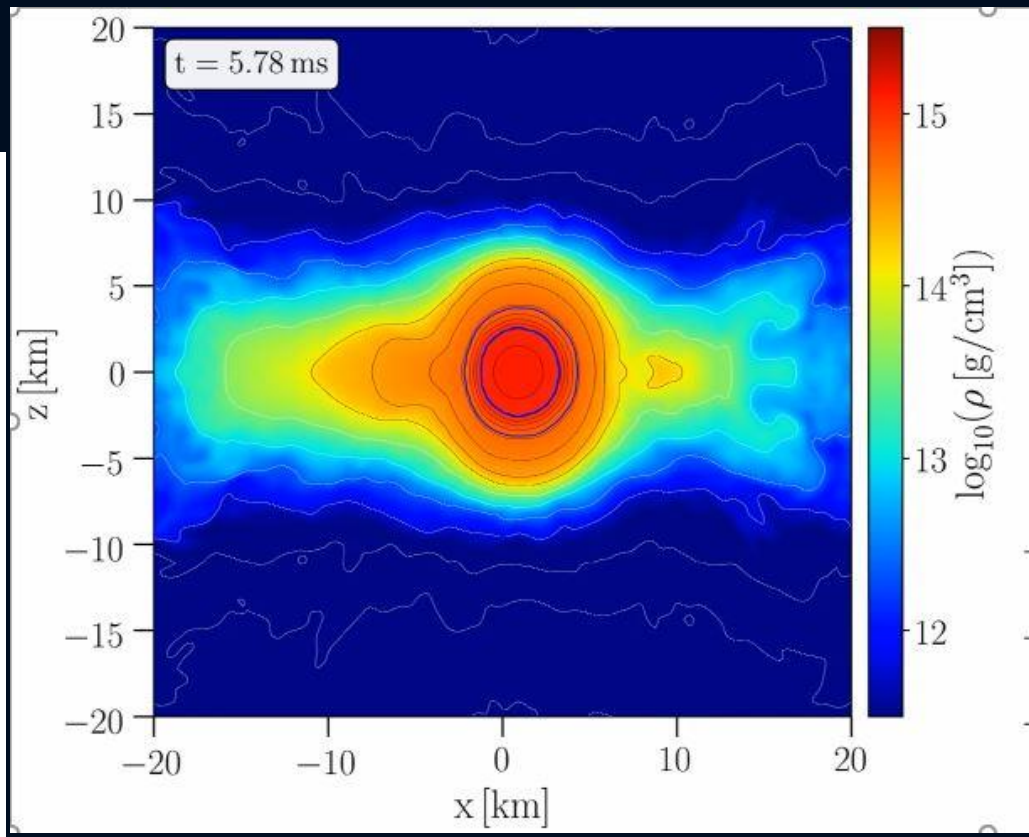
The European Physical Journal Special Topics: 1-8 (2021)



# 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.

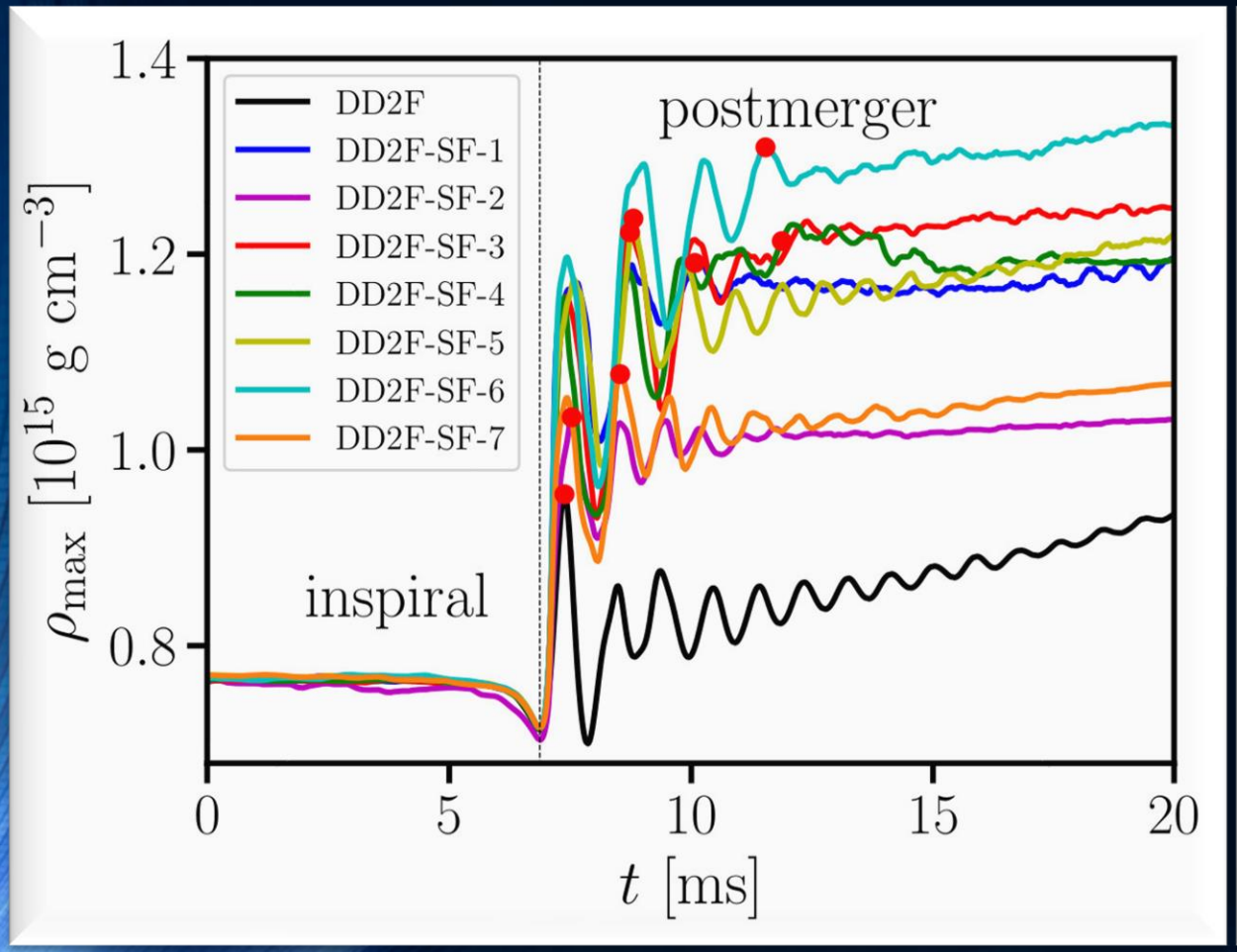
# Can we detect the quark-gluon plasma with gravitational waves?

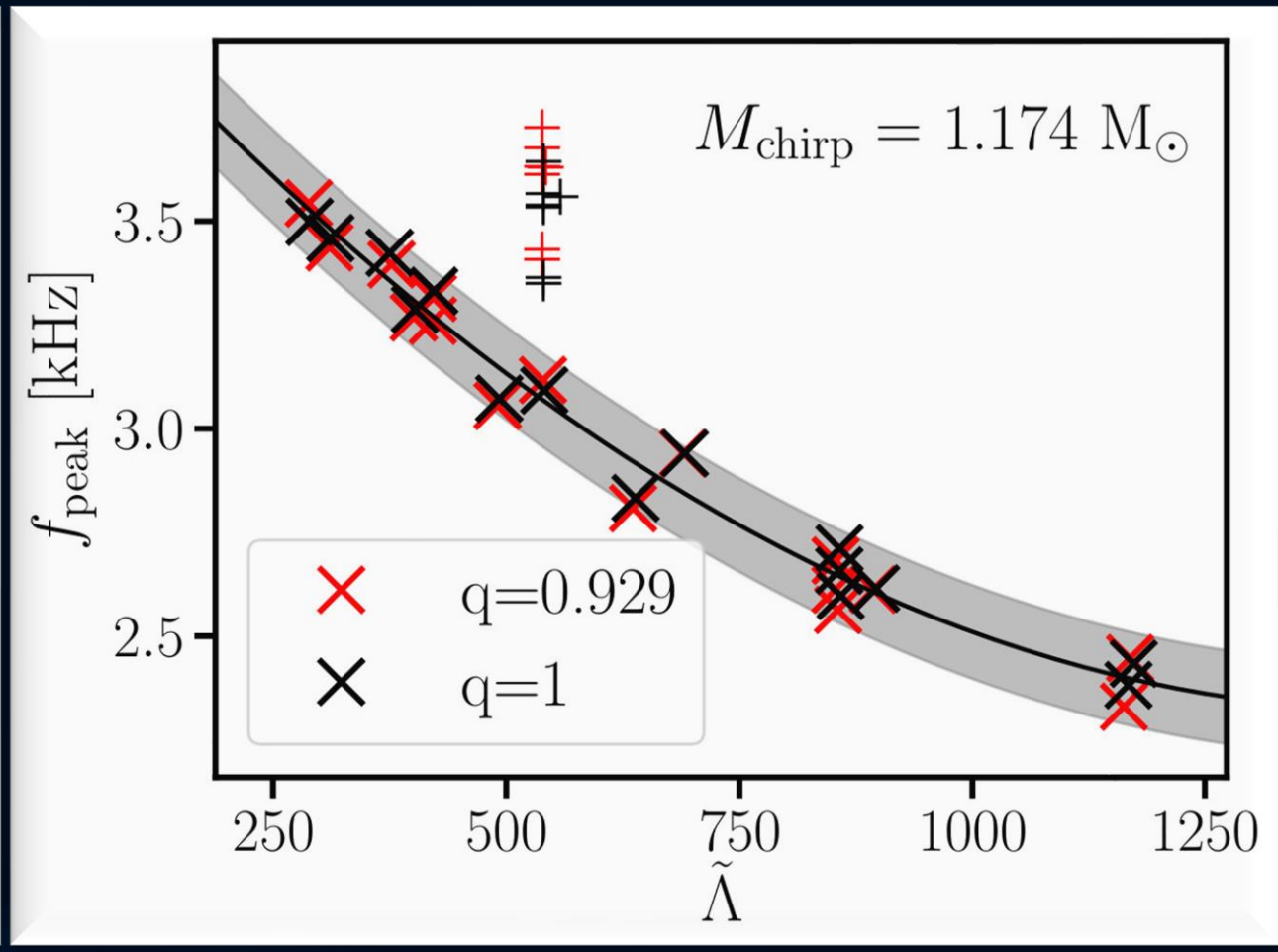
- Gravitational-wave signatures of the hadron-quark phase transition in binary compact star mergers
  - *Signatures within the late inspiral phase (premerger signals)*
    - Constraining twin stars with GW170817; G Montana, L Tolós, M Hanauske, L Rezzolla; Physical Review D 99 (10), 103009 (2019)
  - *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*

## 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)

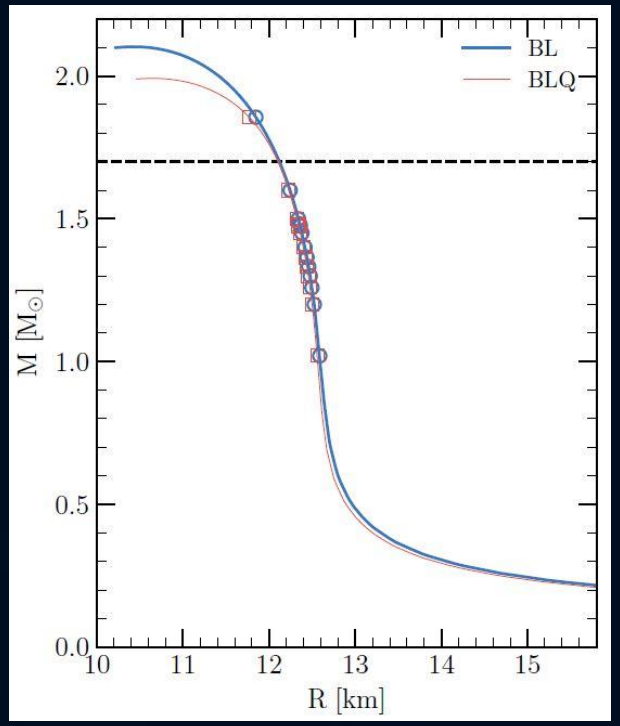


# *Gravitational-wave signatures of the hadron-quark phase transition in binary compact star mergers*

## Two *brand new articles*

Aviral Prakash, David Radice, Domenico Logoteta, Albino Perego, Vsevolod Nedora, Ignazio Bombaci, Rahul Kashyap, Sebastiano Bernuzzi, Andrea Endrizzi.
*Signatures of deconfined quark phases in binary neutron star mergers*. *arXiv:2106.07885* (2021).



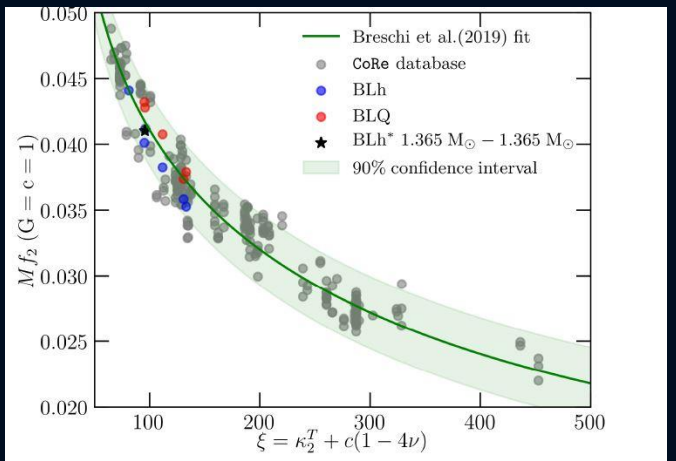




FIG. 10. Correlations between the total mass-scaled post-merger peak frequency $Mf_2$ and the tidal parameter $\xi$. Also shown is the fit from the quasi universal relation presented in [25] along with its 90% confidence interval. The grey points correspond to simulations catalogued in the CoRe database [84]. It can be seen that deviations in $f_2$ (red circles) by virtue of phase transitions are not large enough to violate the quasi-universal relation.

Liebling, Steven L., Carlos Palenzuela, and Luis Lehner.
*Effects of high density phase transitions on neutron star dynamics.*
*Classical and Quantum Gravity* 38.11 (2021): 115007.

# 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

Wiener Walzer

Disco-Fox

Merengue

Tango




*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)

*Talk on Thursday*
*General Relativity in the Theater of the Absurd*
*Parallel session: Education*
*Teaching Einsteinian Physics to School Students*
*08.07.2021, 17:20*

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