BIRLA INSTITUTE OF TECHNOLOGY AND SCIENCE, PILANI
HYDERABAD CAMPUS

1-day Online Symposium on Physics of Neutron stars
June 16, 2021

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 gravitational waves

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

Organised by
Sarmistha Banik
Department of Physics, BITS Pilani, Hyderabad Campus, India

meet.google.com/omh-yang-jcq

BITS Pilani
Hyderabad Campus

My first visit at the Saha Institute in Kolkata

Pictures from 2002

Astrophysical Observables of the hadron-quark phase transition

How to detect the Quark-Gluon Plasma with Telescopes

M. Hanauske

Institut für Theoretische Physik, J. W. Goethe–Universität, D-60054 Frankfurt, Germany

Abstract

The appearance of the QCD - phase transition (QPT) at low temperatures and high densities will change the properties of neutron stars (NS). Whether this change will be visible with telescopes and gravitational wave antennas depends strongly on the equation of state (eos) of hadronic and quark matter and on the construction of the phase transition (PT).

1 Introduction

If the onset of the QPT at low temperatures is below $\approx 5\rho_0$, $\rho_0 := 0.15\ \mathrm{fm}^{-3}$ ...
... happen in the
... eory of strong
... n the nonper-
... of QCD on a
... be infinite nu-
... nsities. As an
... s of hadronic
... proposed. By choosing
... /or parameter sets inside the mod-
... the hadronic and quark phase, the composition of particles inside the stars, the eos and as a result, the properties of the stars will change. The construction of

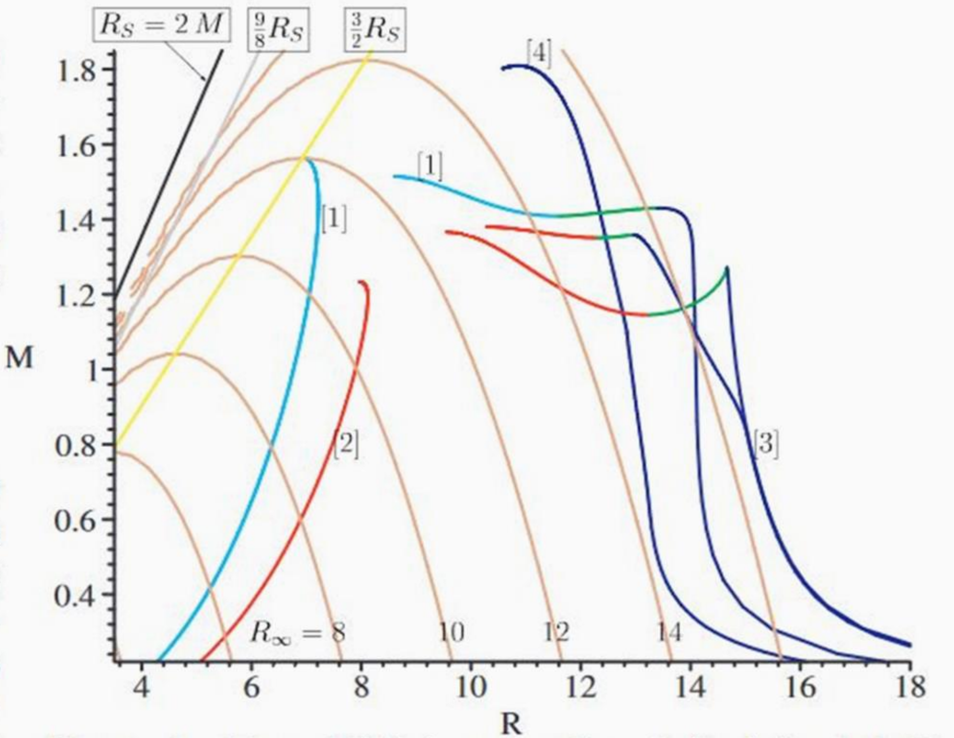


Figure 1: Mass $M[M_\odot]$ and radius R [km] for hybrid, quark and hyperon stars. The Schwarzschild radius $R_S = 2\,M$, the absolute threshold for stable stars ($R = 9/8\,R_S$), the photon surface ($R = 3/2\,R_S$) and R_∞ =const lines.

3 Astrophysical Observables for the QGP

How to detect the Quark-Gluon Plasma with Telescopes

Autoren	Matthias Hanauske
Publikationsdatum	2003
Zeitschrift	GSI Annual Report; GSI: Darmstadt, Germany

First article with Sarmistha and Debades

PHYSICAL REVIEW D
covering particles, fields, gravitation, and cosmology

Rotating compact stars with exotic matter

Sarmistha Banik, Matthias Hanauske, Debades Bandyopadhyay, and Walter Greiner
Phys. Rev. D **70**, 123004 – Published 8 December 2004

ABSTRACT

We have constructed models of uniformly rotating compact stars including hyperons, Bose-Einstein condensates of antikaons, and quarks. First order phase transitions from hadronic to antikaon condensed matter and then to quark matter are considered here. For the equation of state undergoing phase transitions to antikaon condensates, the third family of compact stars are found to exist in the fixed angular velocity sequences. However, the third family solution disappears when the compact stars rotate very fast. For this equation of state, the fixed baryon number supramassive sequence shows a second stable part after the unstable region but no back bending phenomenon. On the other hand, we observe that the rotation gives rise to a second maximum beyond the neutron star maximum for the equation of state involving phase transitions to both antikaon condensed and quark matter. In this case, the back bending phenomenon has been observed in the supramassive sequence as a consequence of the first order phase transition from K^- condensed to quark matter. And the back bending segment contains stable configurations of neutron stars.

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:

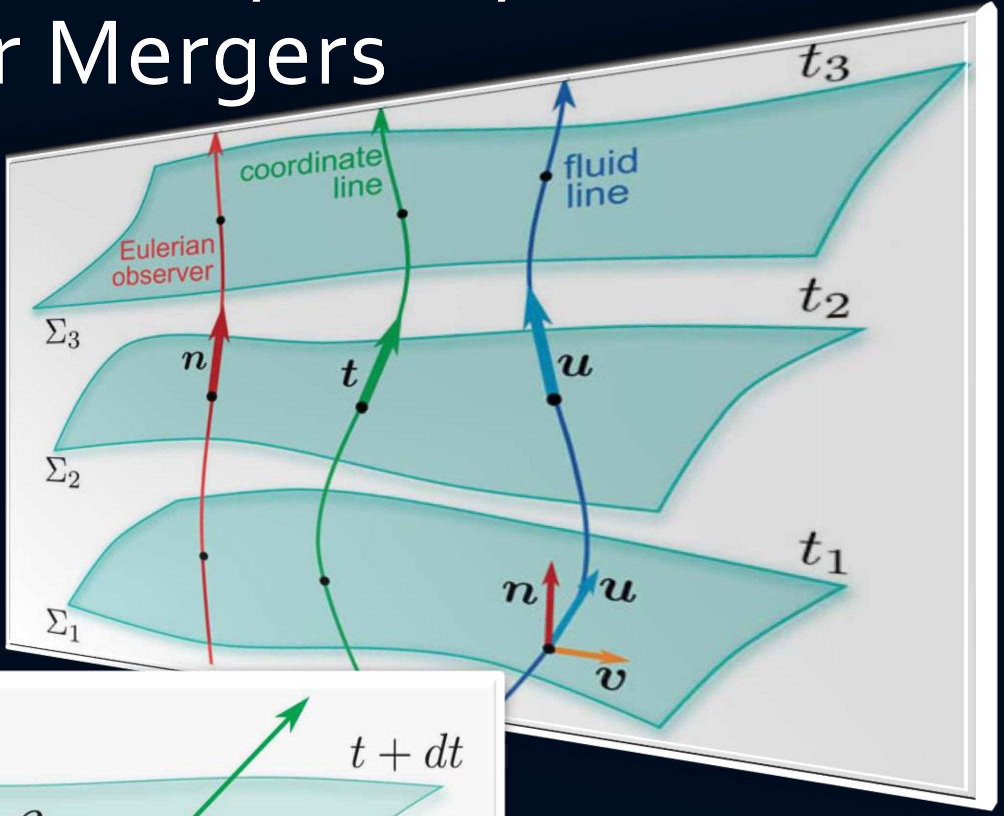
$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = 8\pi T_{\mu\nu}$$

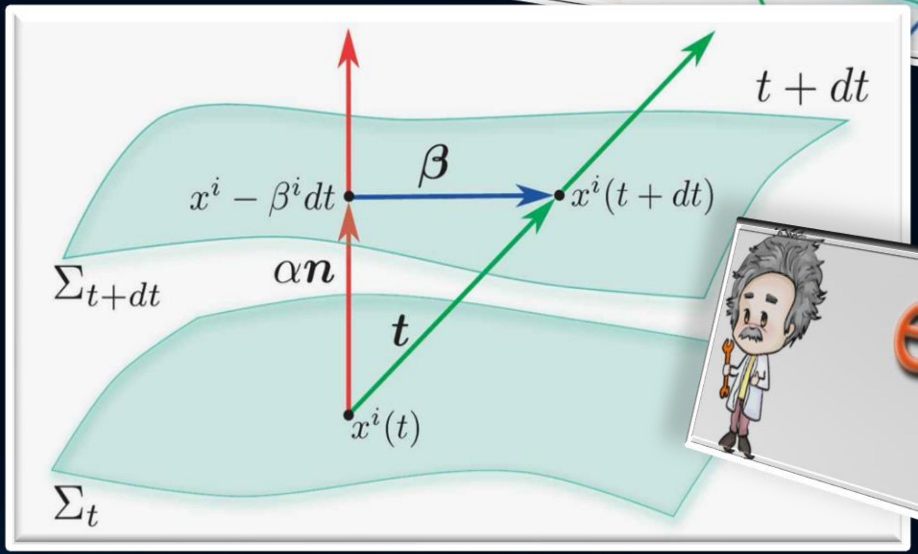
$$\nabla_\mu (\rho u^\mu) = 0\,, \qquad \nabla_\nu T^{\mu\nu} = 0\,.$$

(3+1) decomposition of spacetime

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

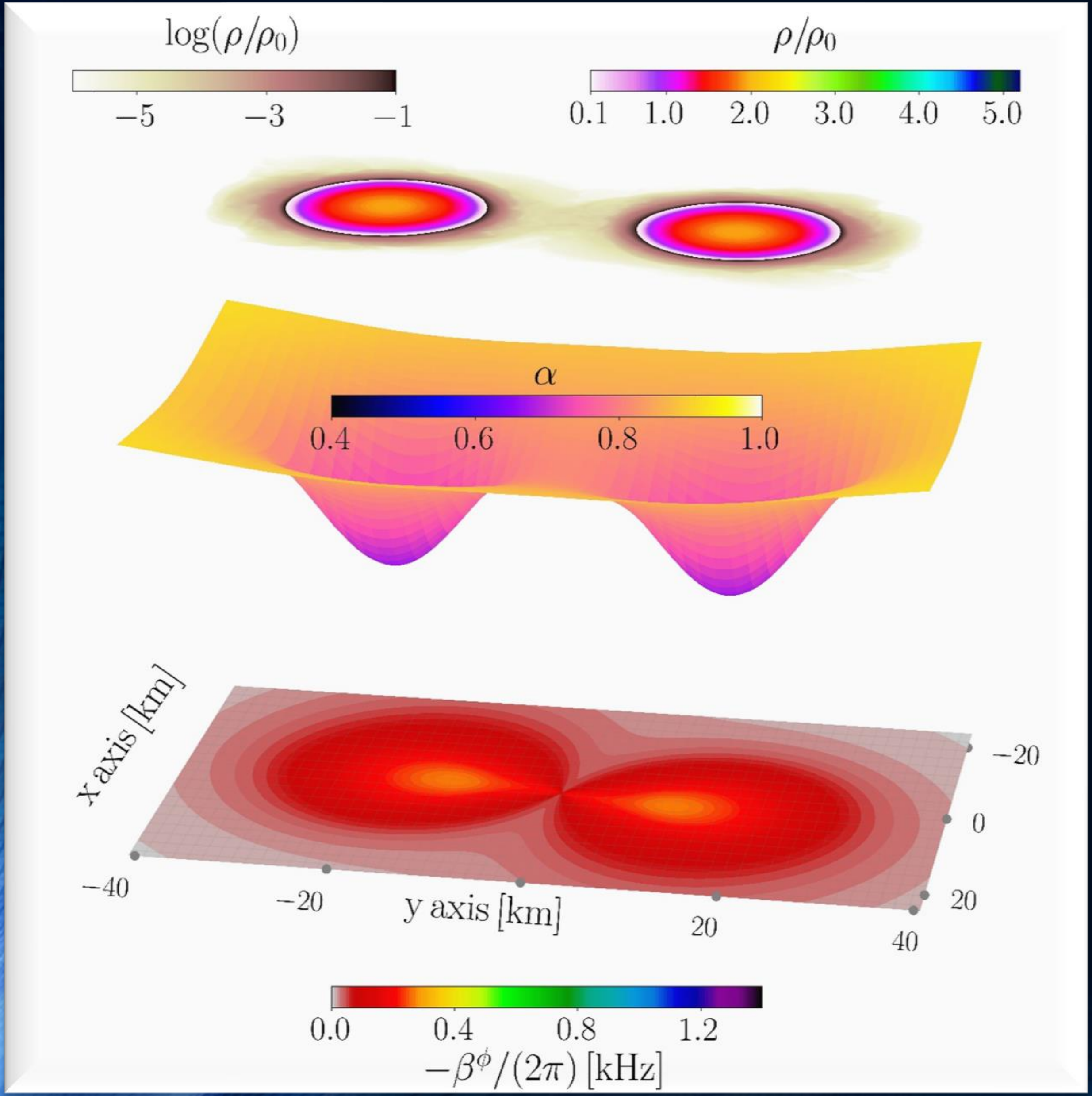
$$d\tau^2 = \alpha^2 (t, x^j) dt^2 \qquad x^i_{t+dt} = x^i_t - \beta^i (t, x^j) dt$$

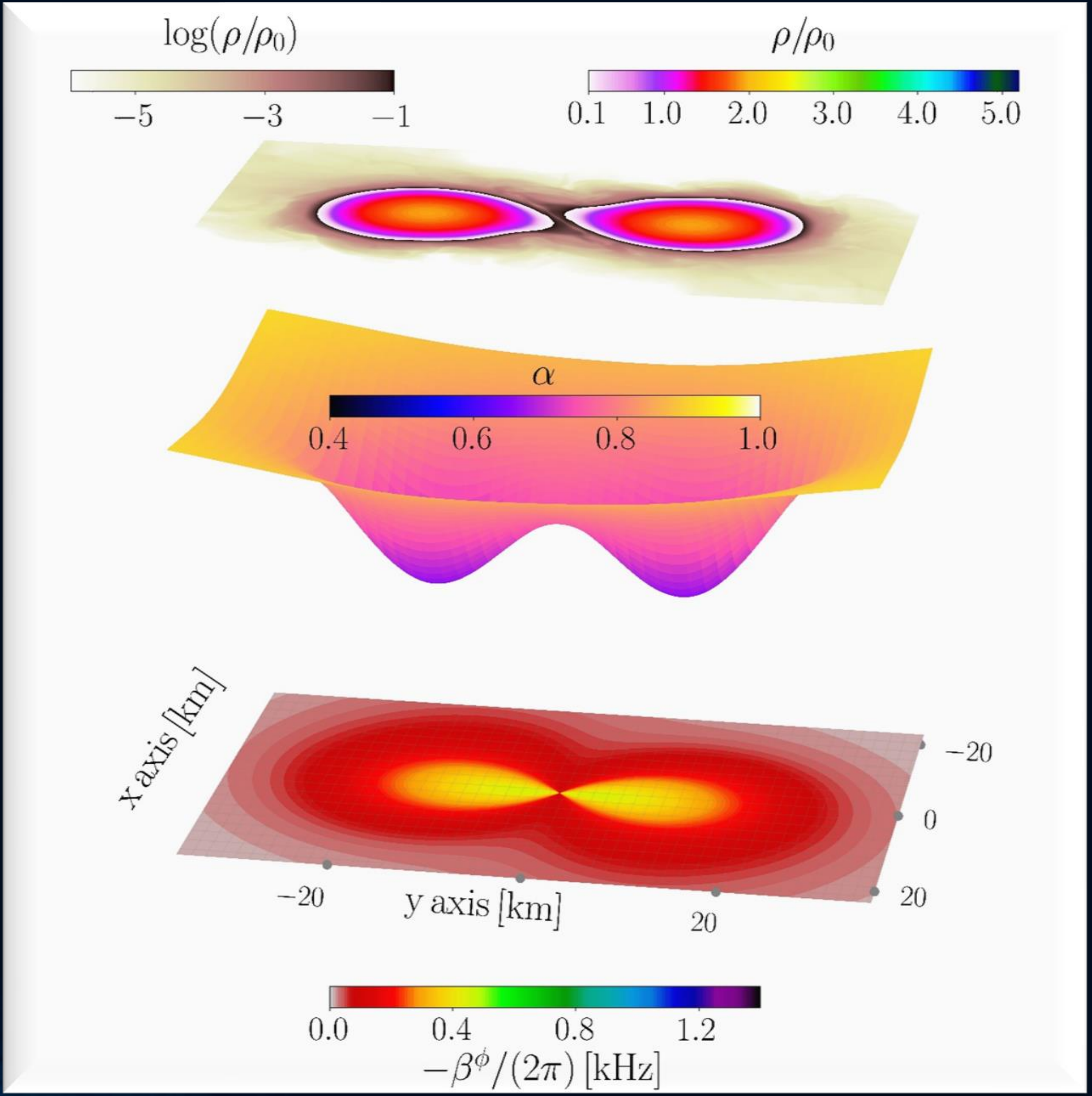




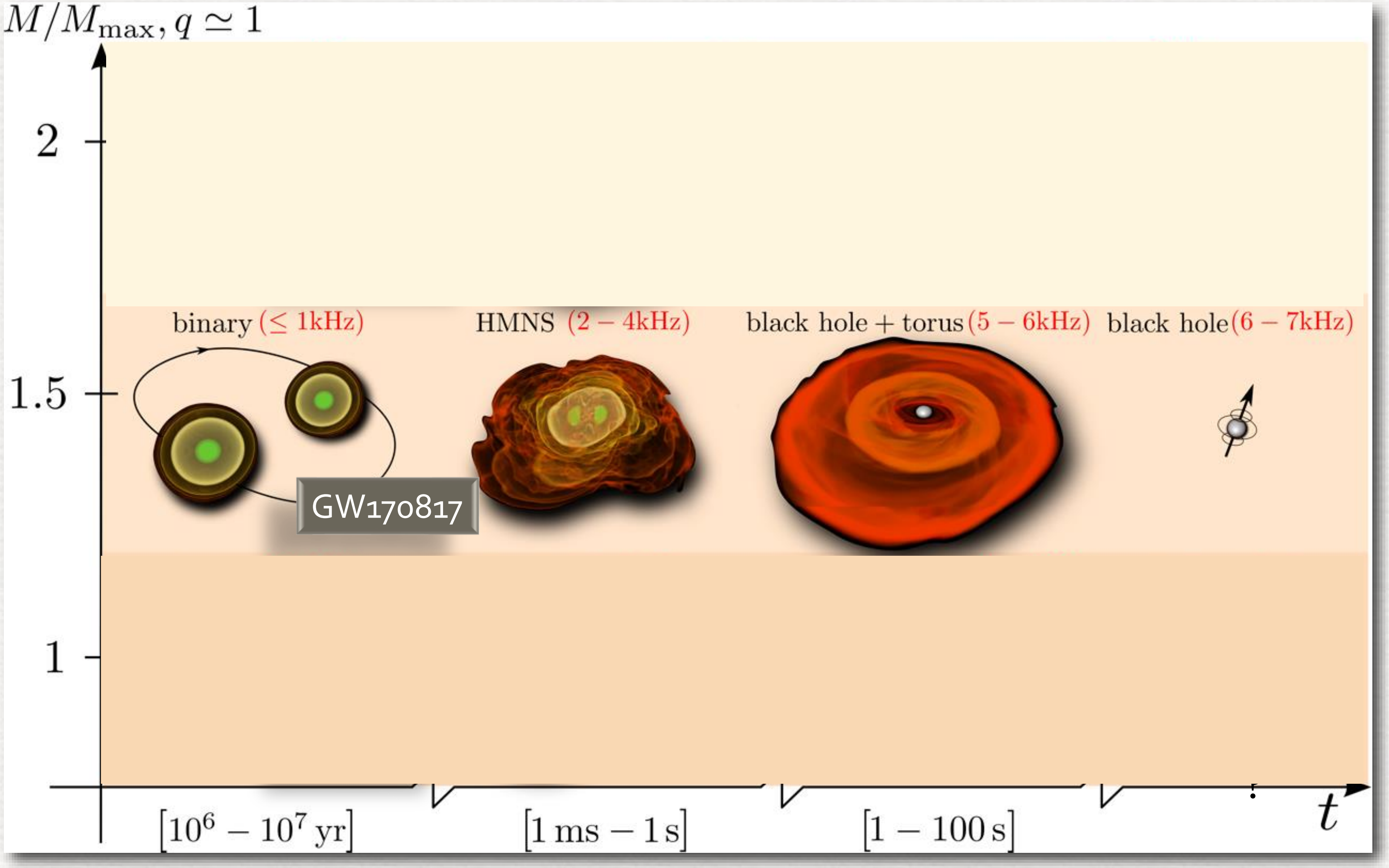
All figures and equations from: Luciano Rezzolla, Olindo Zanotti: Relativistic Hydrodynamics, Oxford Univ. Press, Oxford (2013)

The late inspiral phase (density, lapse and shift)





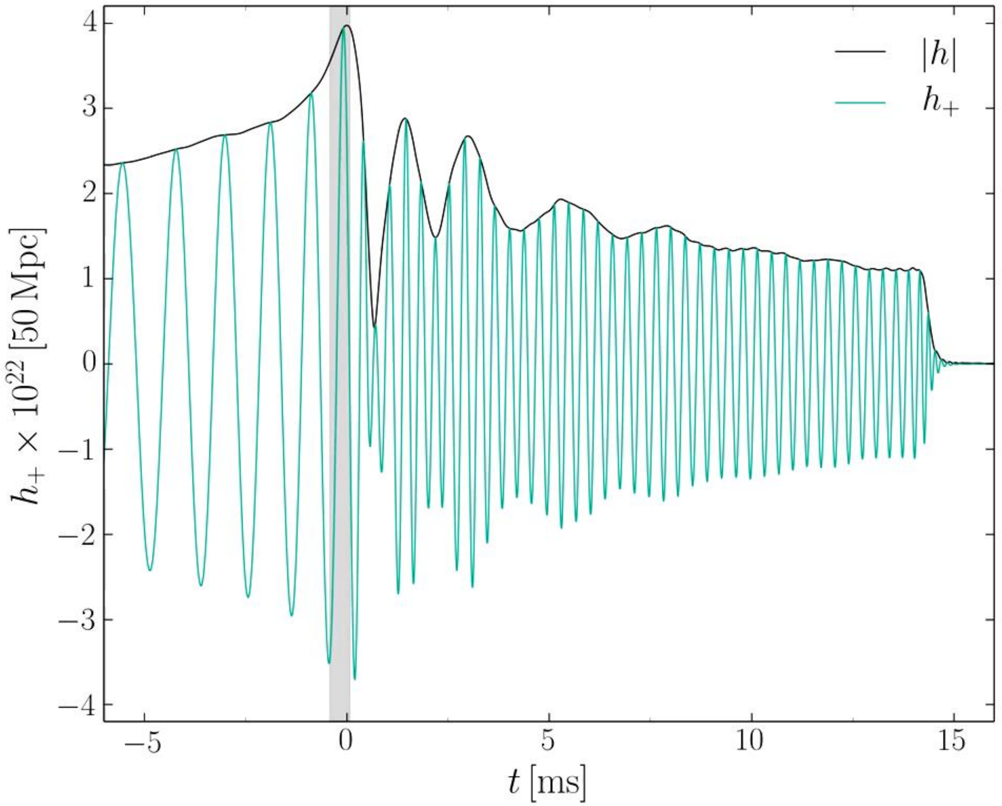
Broadbrush picture

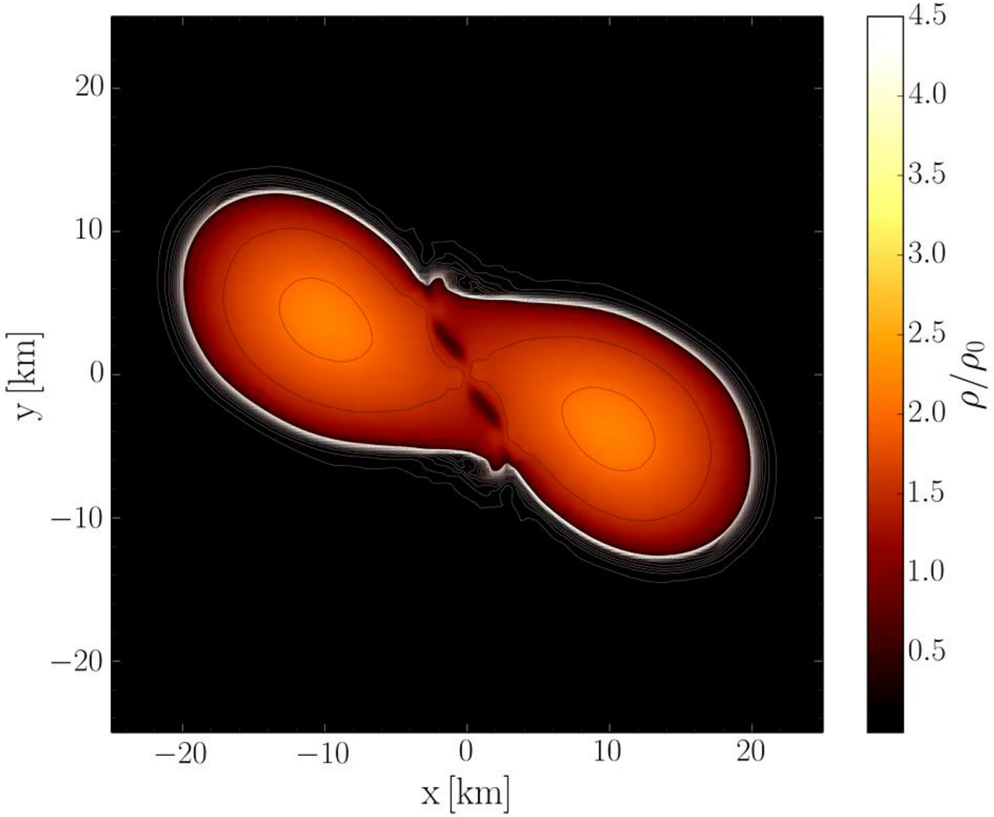


Gravitational Waves and Hypermassive Hybrid Stars

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)



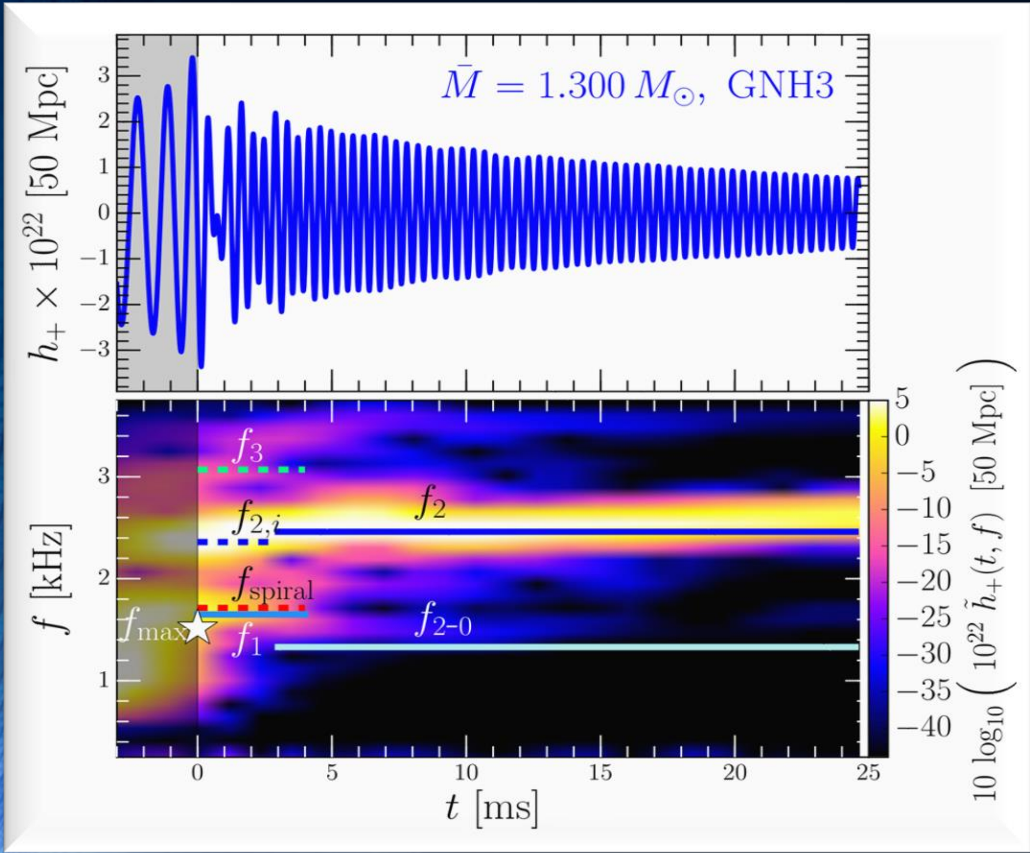


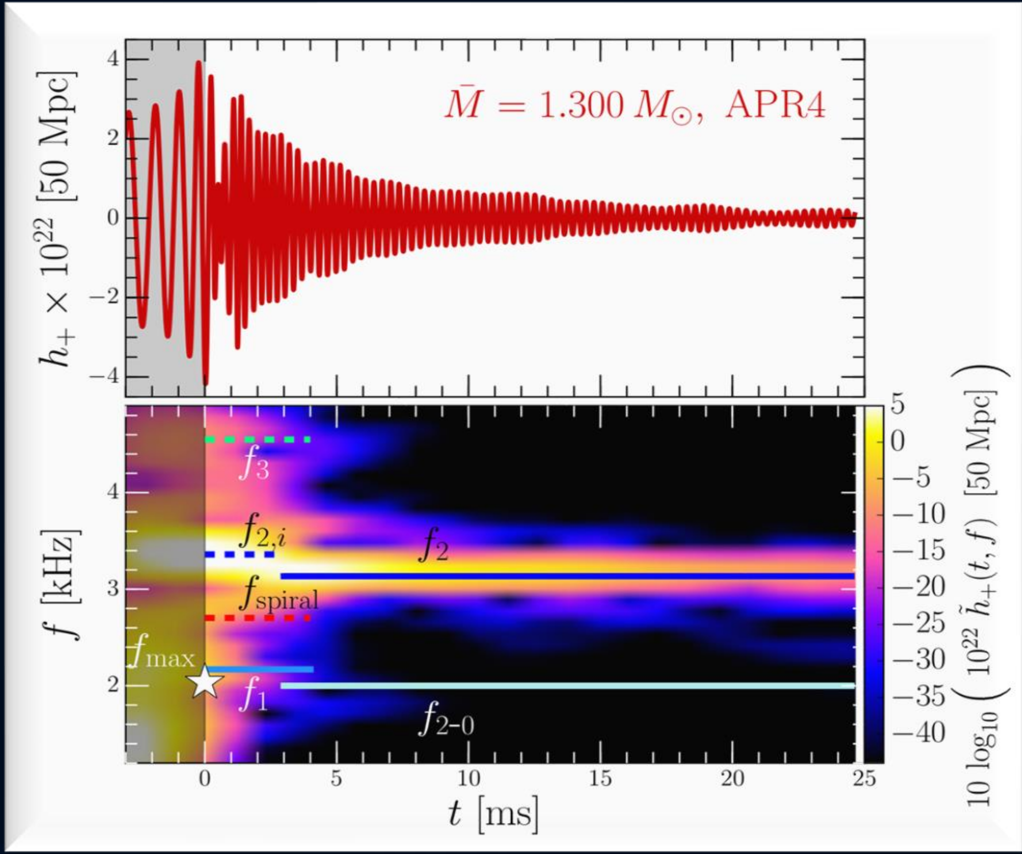
Gravitational wave amplitude
at a distance of 50 Mpc

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

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

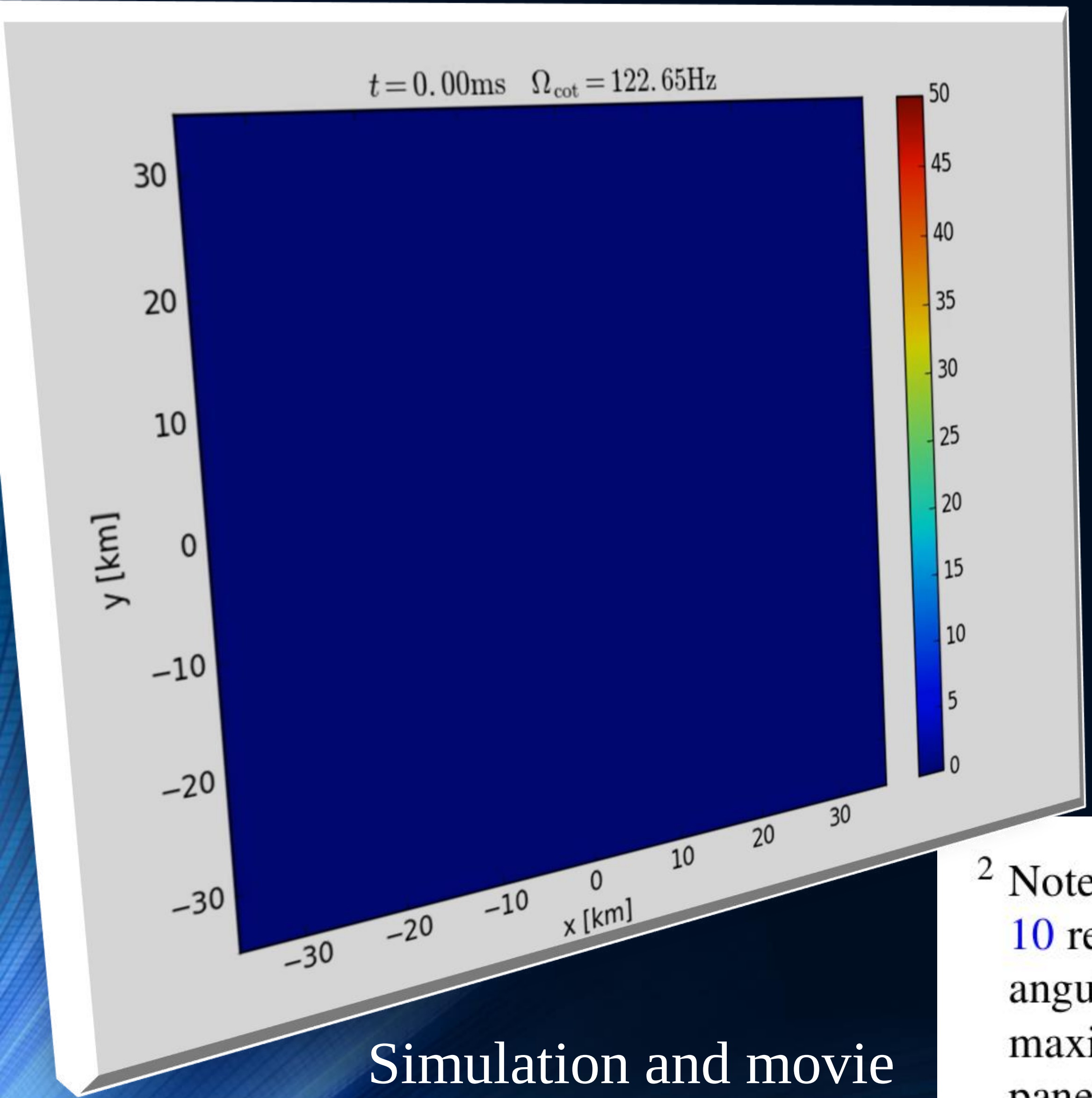
Soft EOS

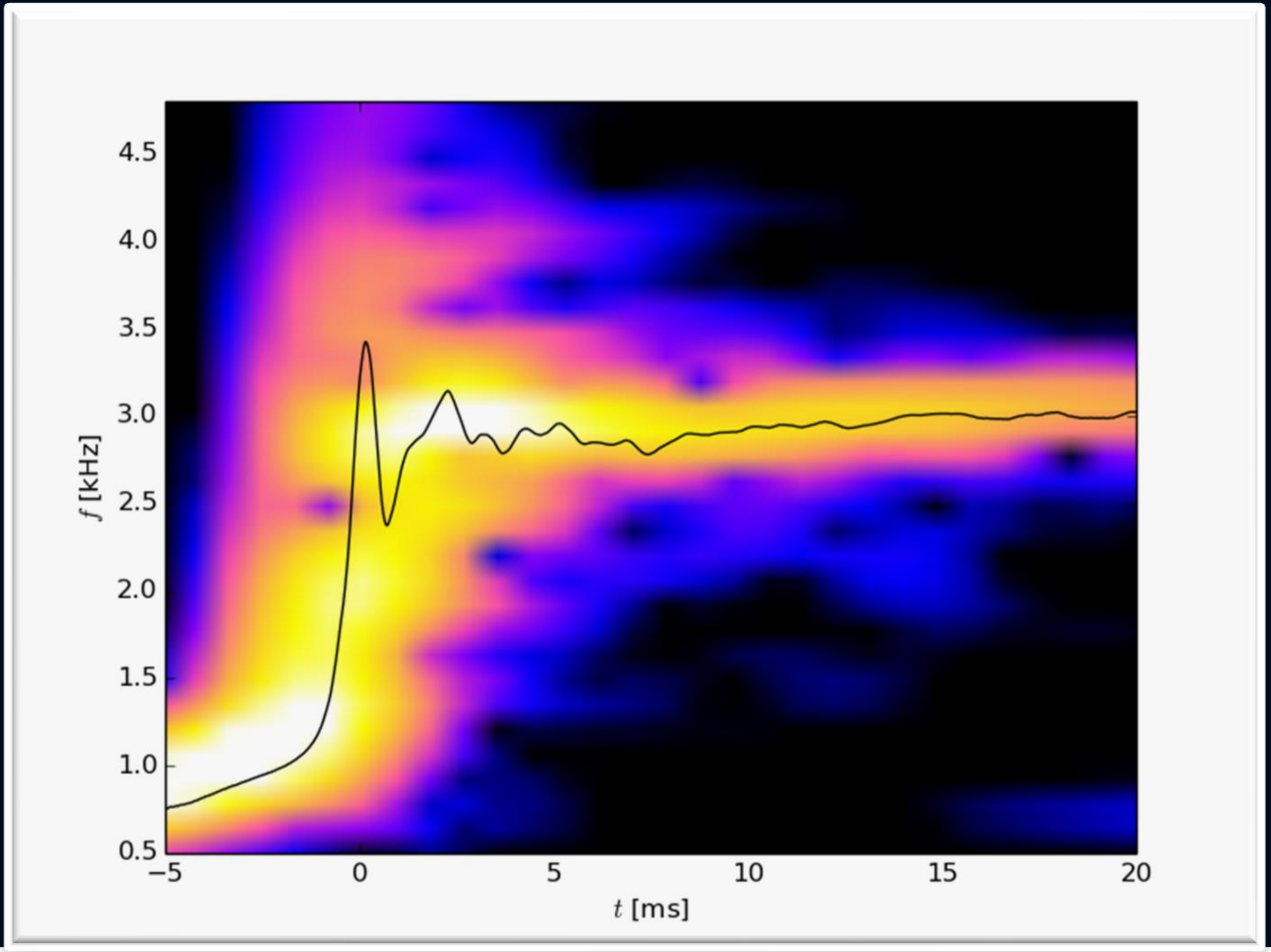
Unfortunately, due to the low sensitivity at high gravitational wave frequencies, no post-merger signal has been found in GW170817.

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.

The Co-Rotating Frame

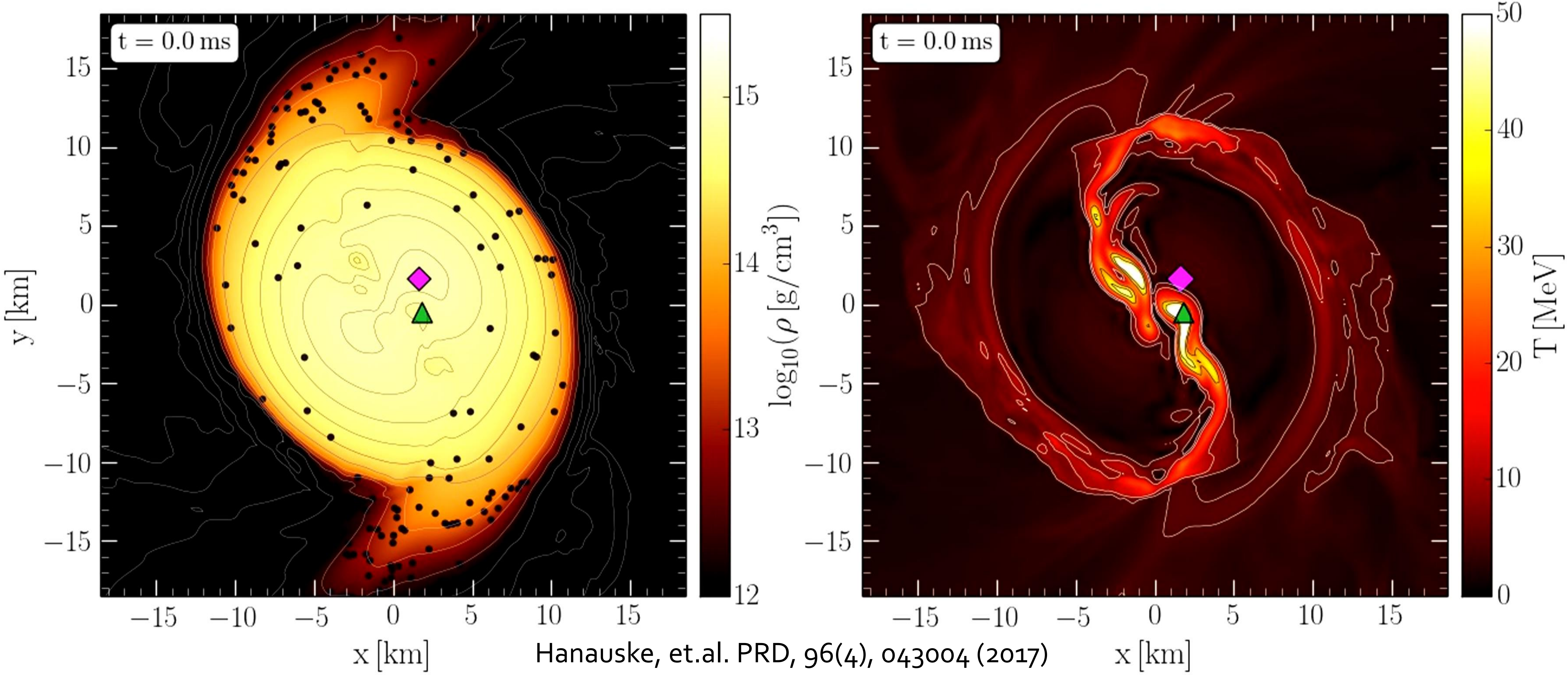




Simulation and movie
has been produced by Luke Bovard

[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 $\Omega_{\rm max}$ 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

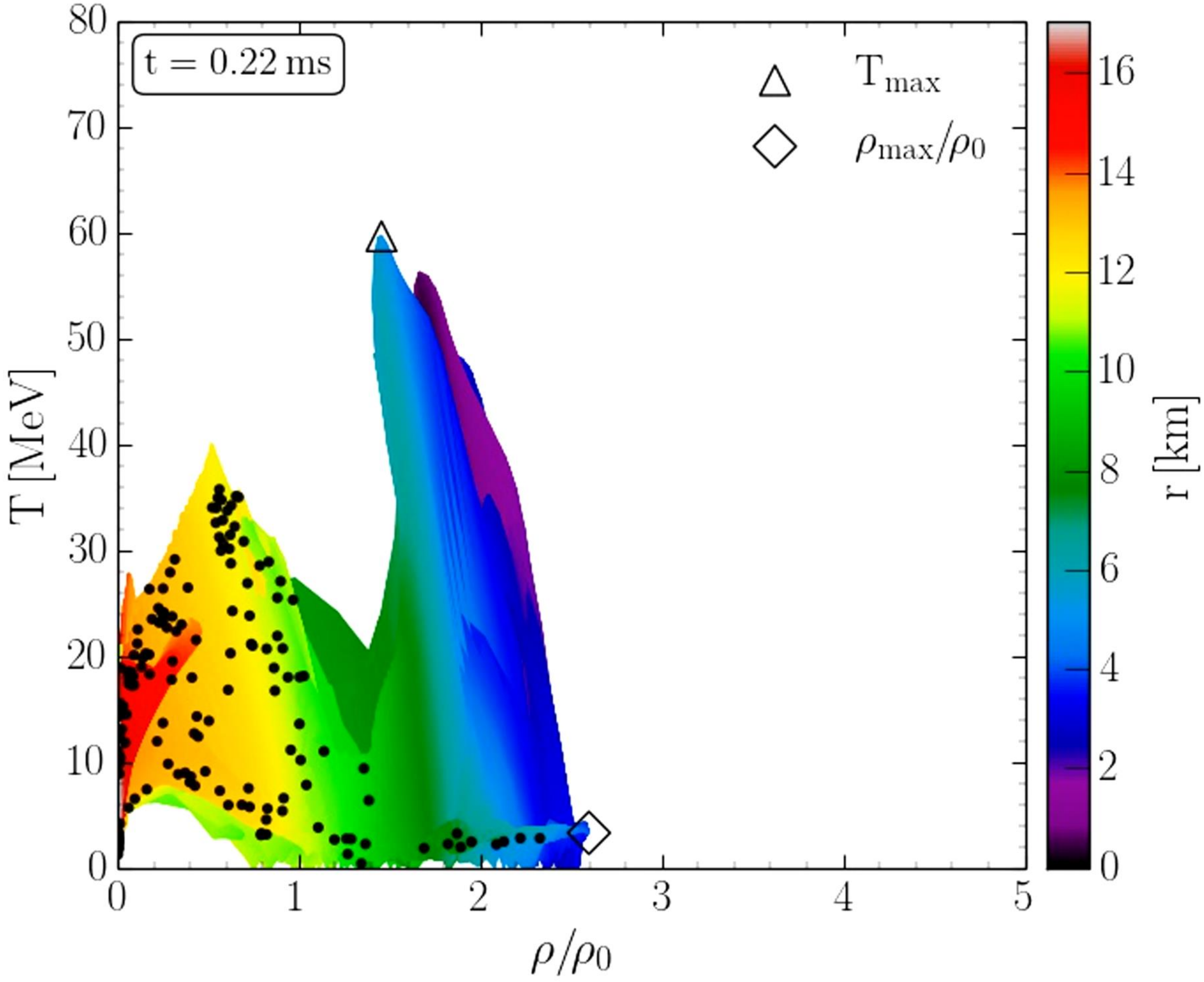


Hanauske, et.al. PRD, 96(4), 043004 (2017)

Rest mass density on the equatorial plane

Temperature on the equatorial plane

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}

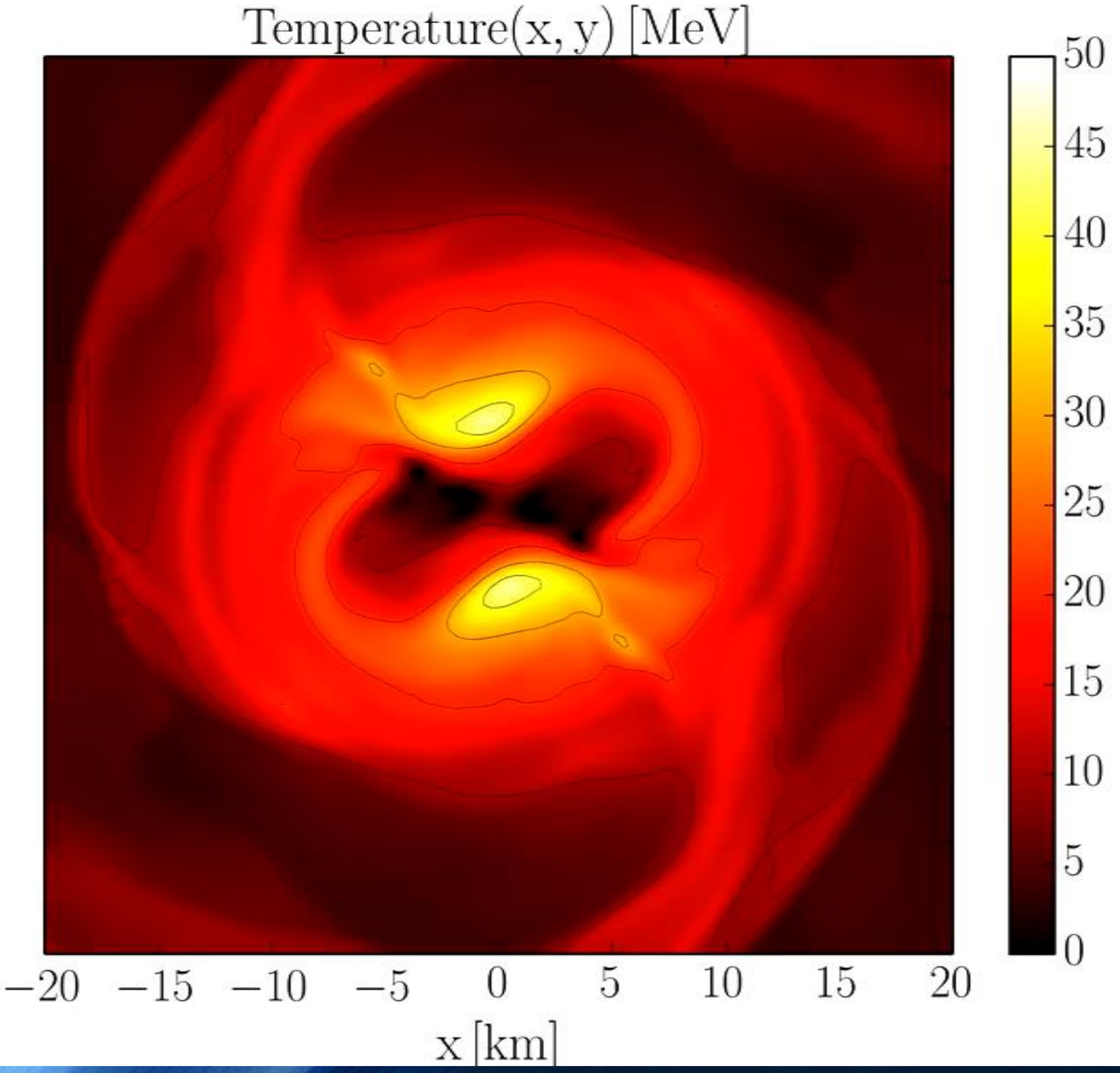
(3+1)-decomposition of spacetime:

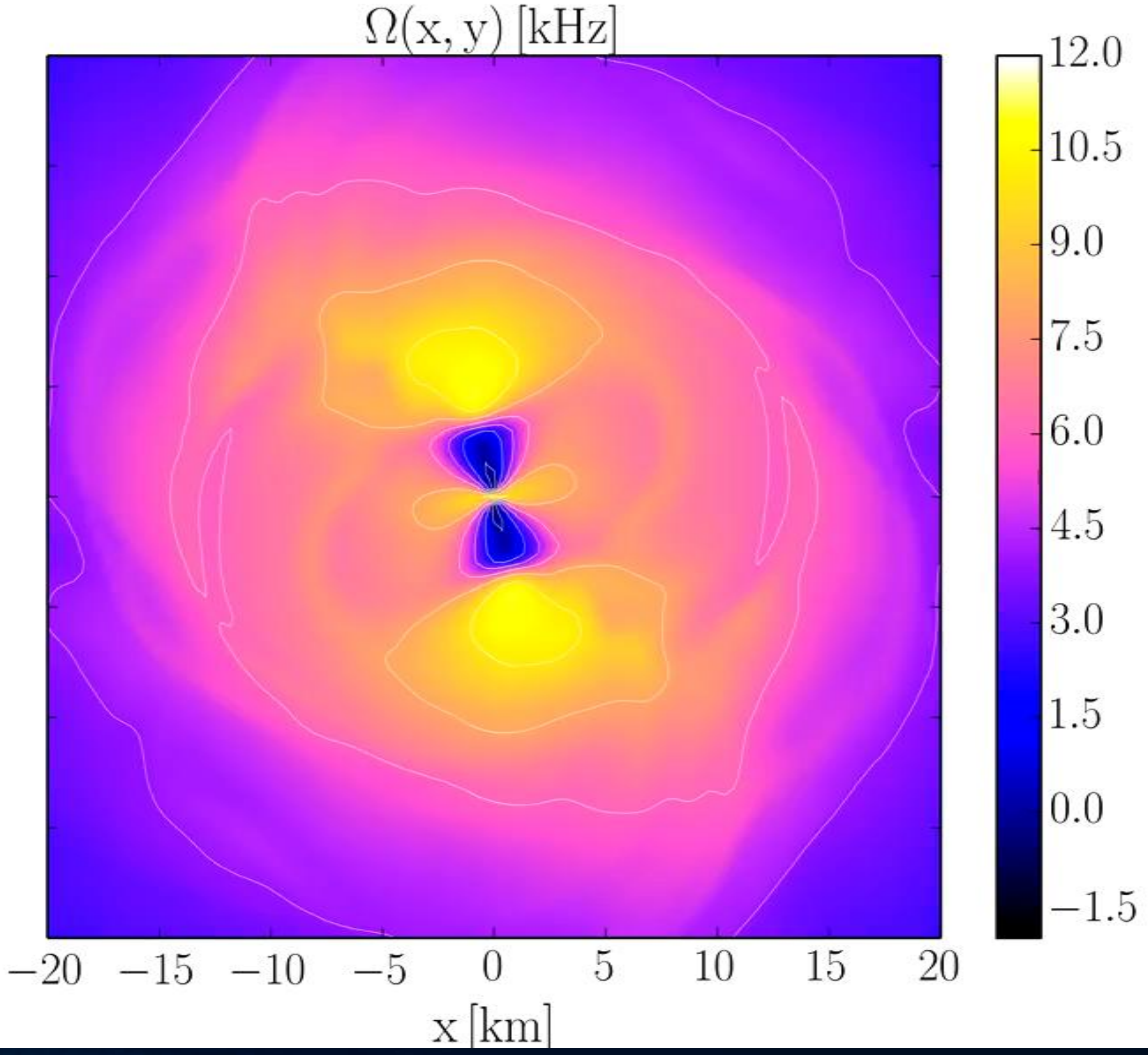
$$g_{\mu\nu} = \begin{pmatrix} -\alpha^2 + \beta_i \beta^i & \beta_i \\ \beta_i & \gamma_{ij} \end{pmatrix}$$

Focus: Inner core of the differentially rotating HMNS

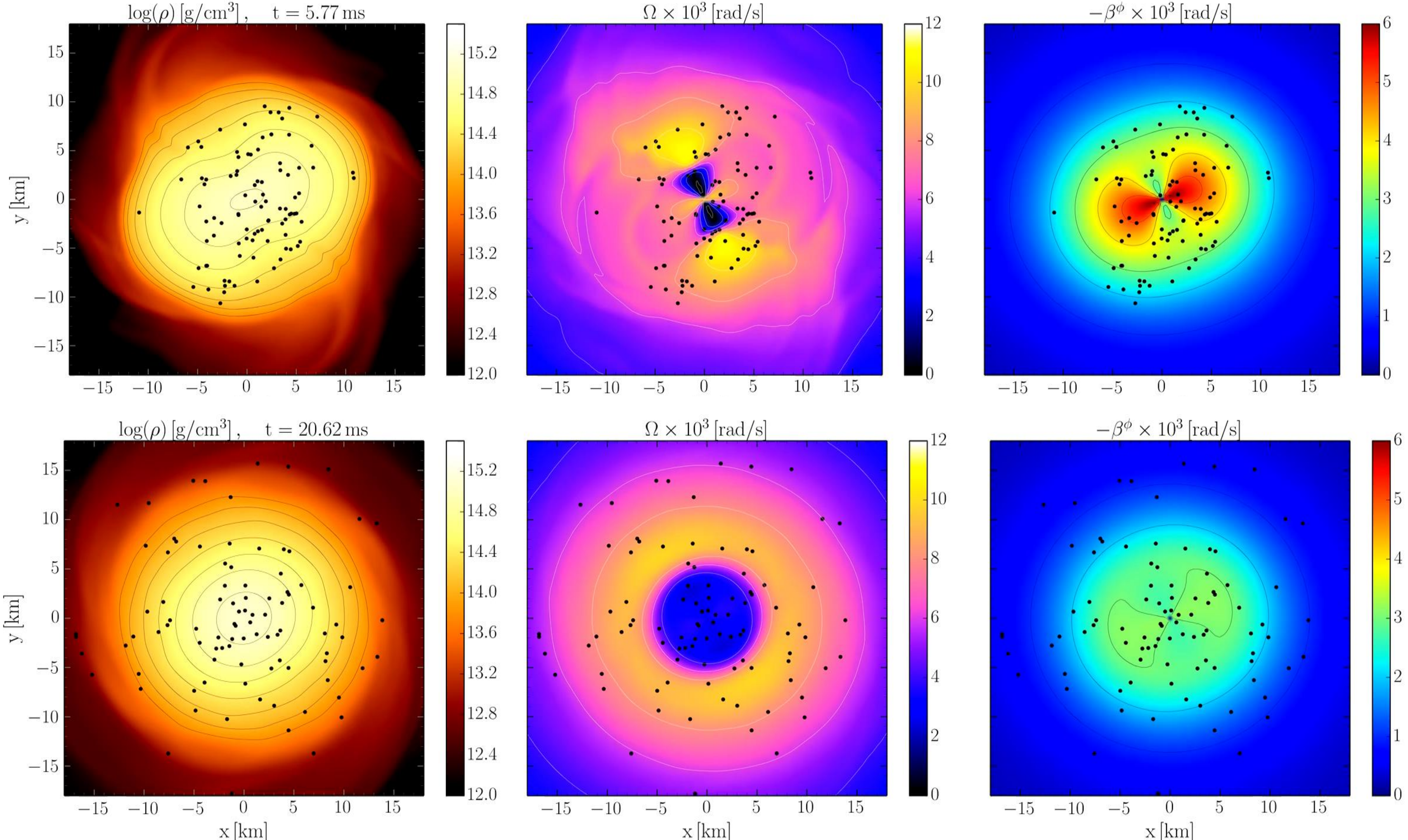
M. Shibata, K. Taniguchi, and K. Uryu, Phys. Rev. D 71, 084021 (2005)
M. Shibata and K. Taniguchi, Phys. Rev. D 73, 064027 (2006)
F. Galeazzi, S. Yoshida and Y. Eriguchi, A&A 541, p. A156 (2012)
W. Kastaun and F. Galeazzi, Phys. Rev. D 91, p. 064027 (2015)

Temperature | Angular Velocity

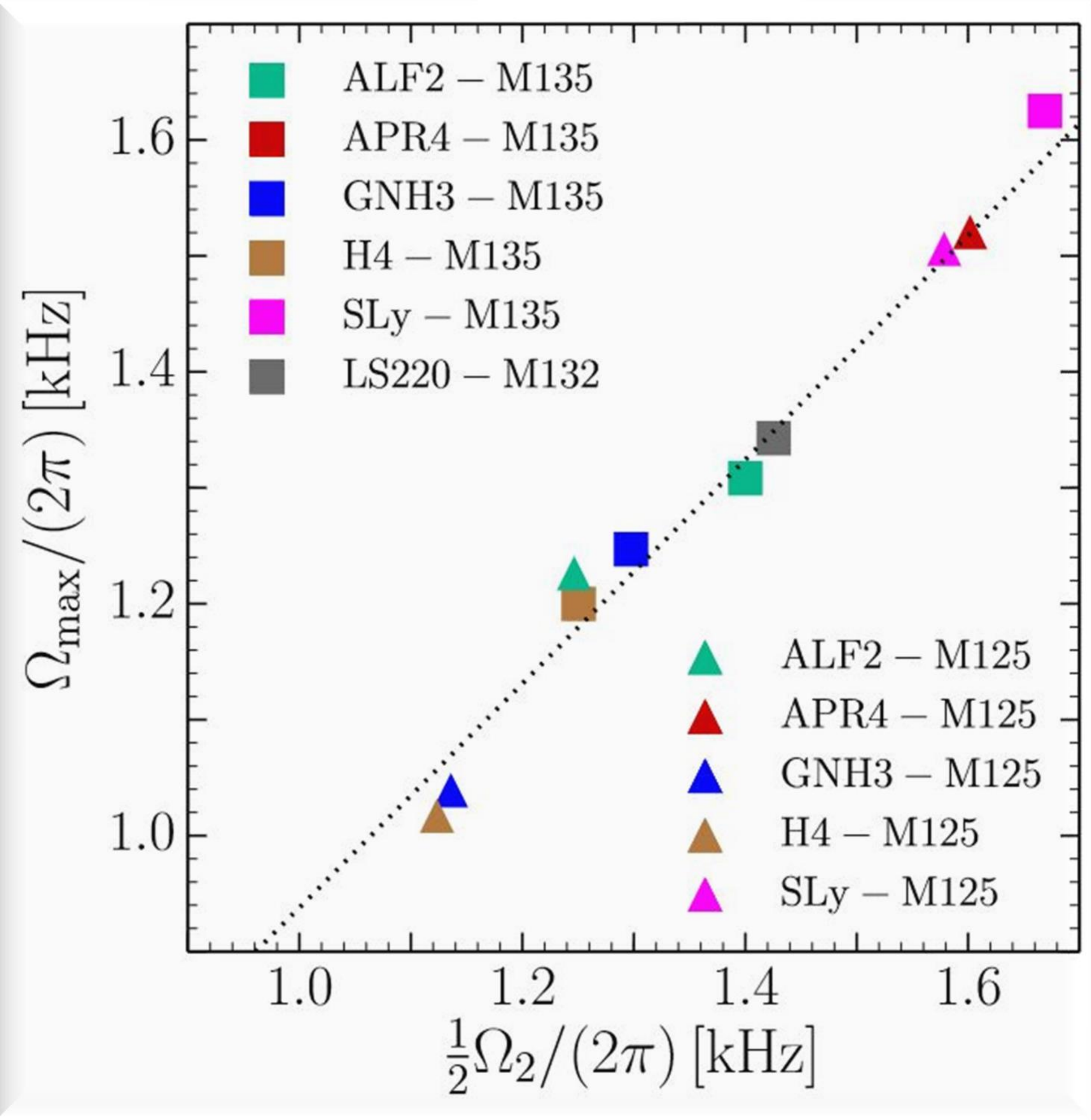


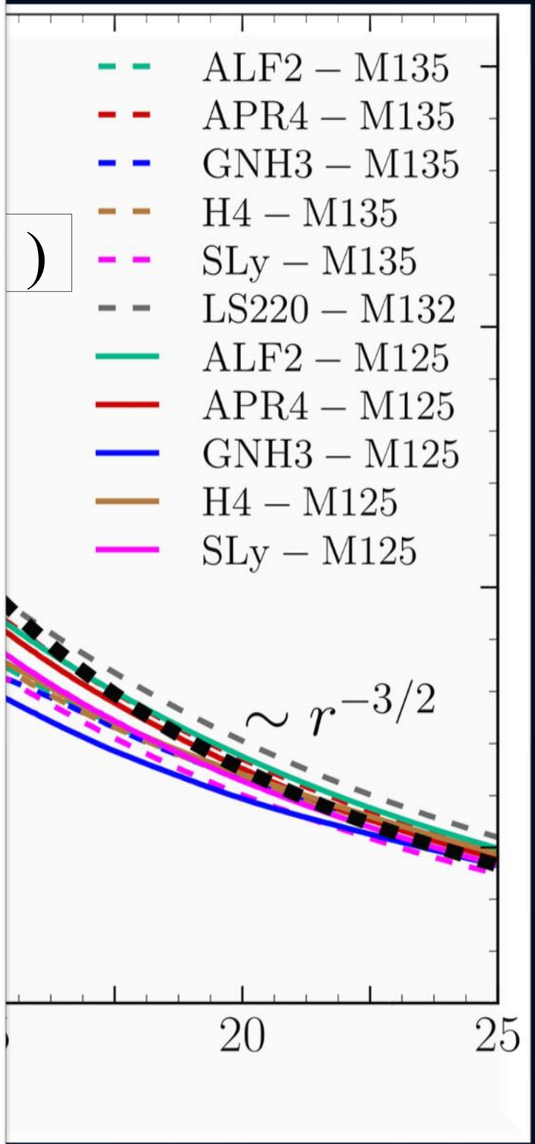


EOS: LS200 , Mass: 1.32 M_{solar} , simulation with Pi-symmetry


log(ρ) [g/cm³], t = 5.77 ms
Ω × 10³ [rad/s]
−β^φ × 10³ [rad/s]
log(ρ) [g/cm³], t = 20.62 ms
Ω × 10³ [rad/s]
−β^φ × 10³ [rad/s]
y [km]
x [km]

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 ph
compact star mergers
  - *Signatures within the late inspiral phase (premerger signals)*
    - Constraining twin stars with GW170817; G Montana, L Tolós, M Han
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 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)
    - **Prompt phase transition scenario**
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)

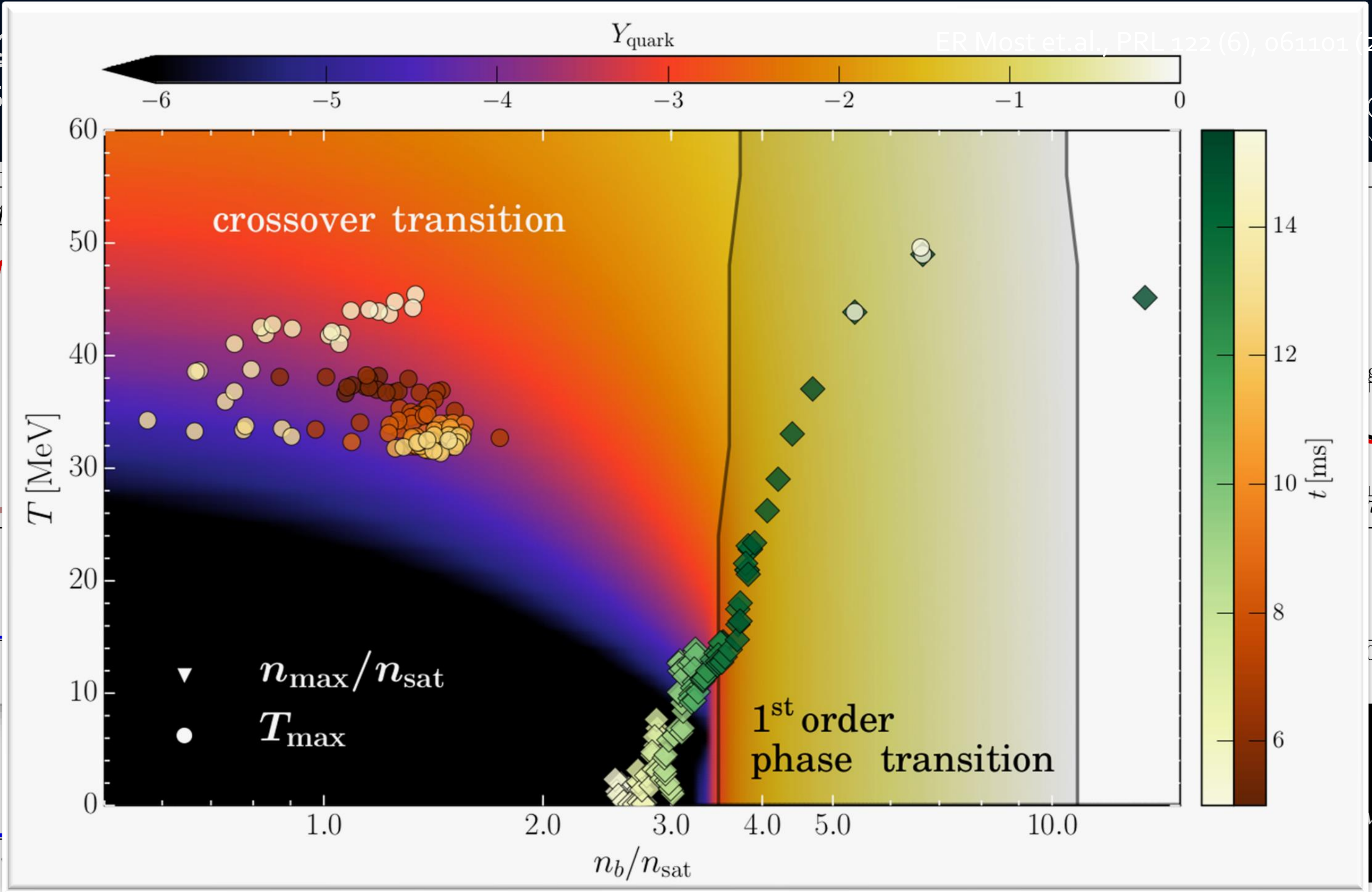
Sig…

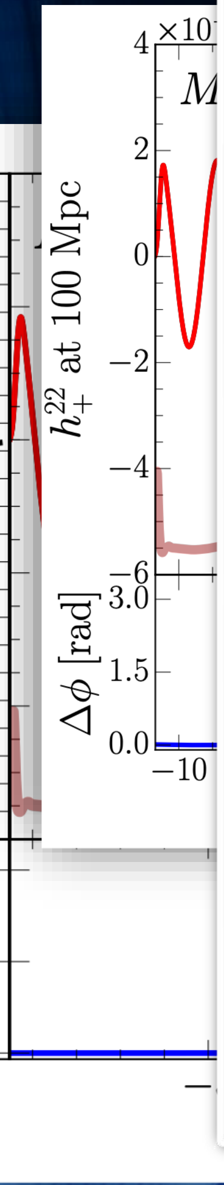
Phas…

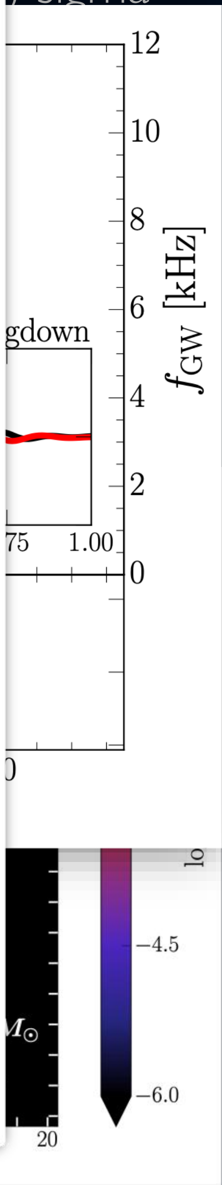
ER Most et al., PRL 122 (6), 061101 (2019)

…CMF)

…) sigma







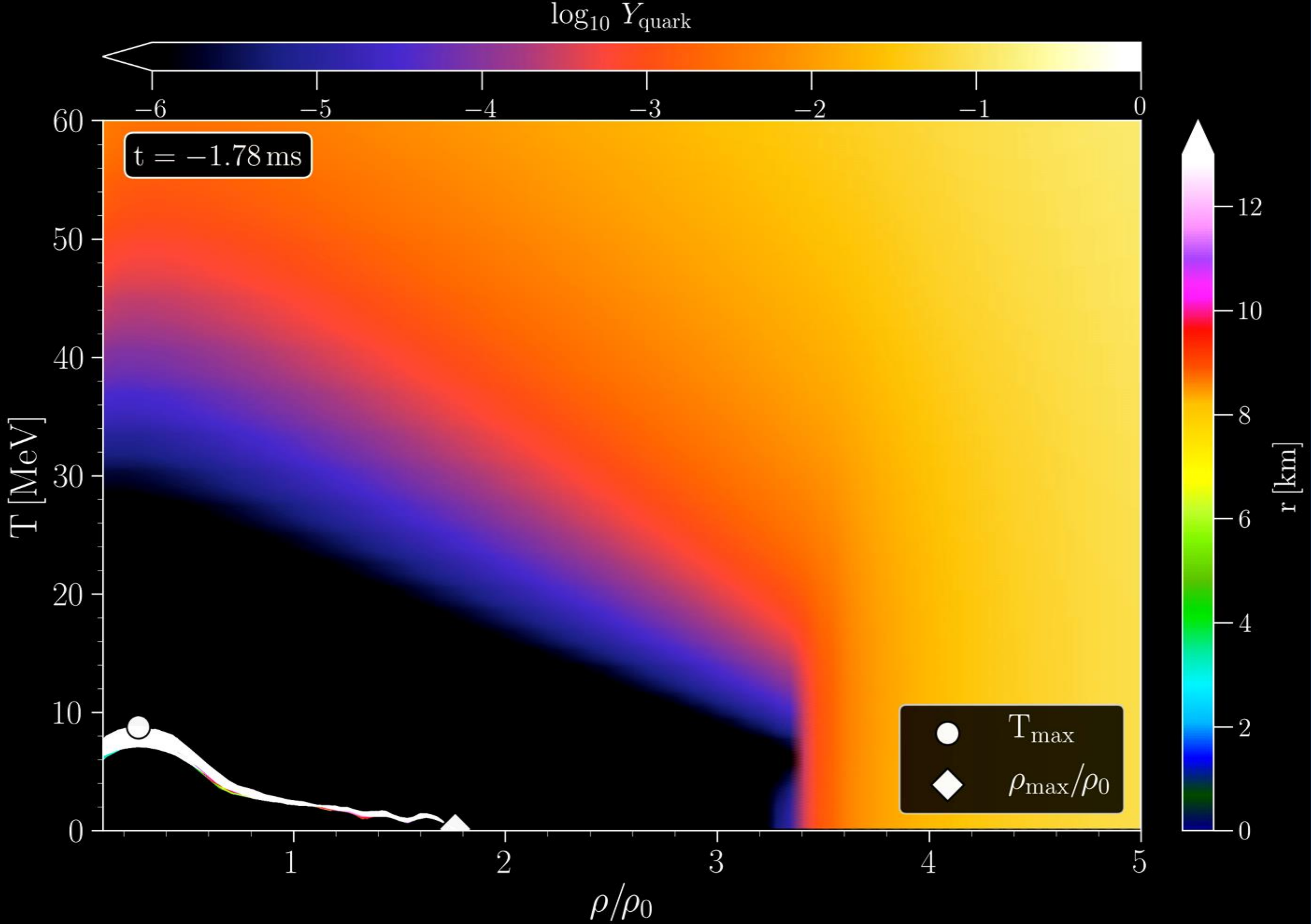
Phase-transition triggered collapse scenario

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

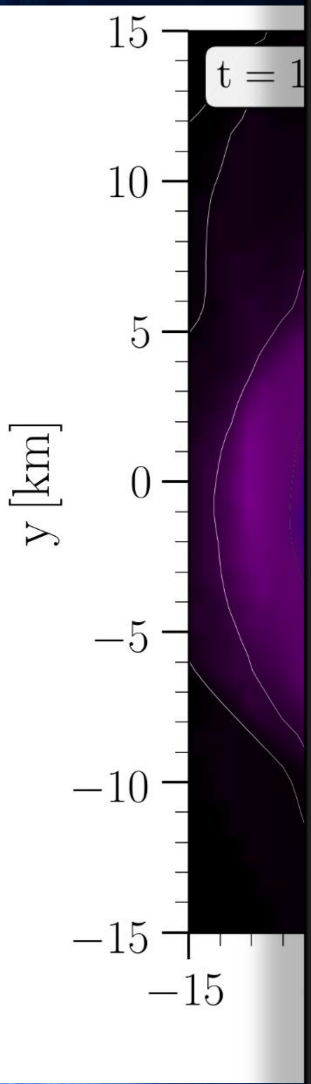
ER Most, LJ Papenfort, V Dexheimer, M Hanauske, S Schramm, H Stöcker and L. Rezzolla

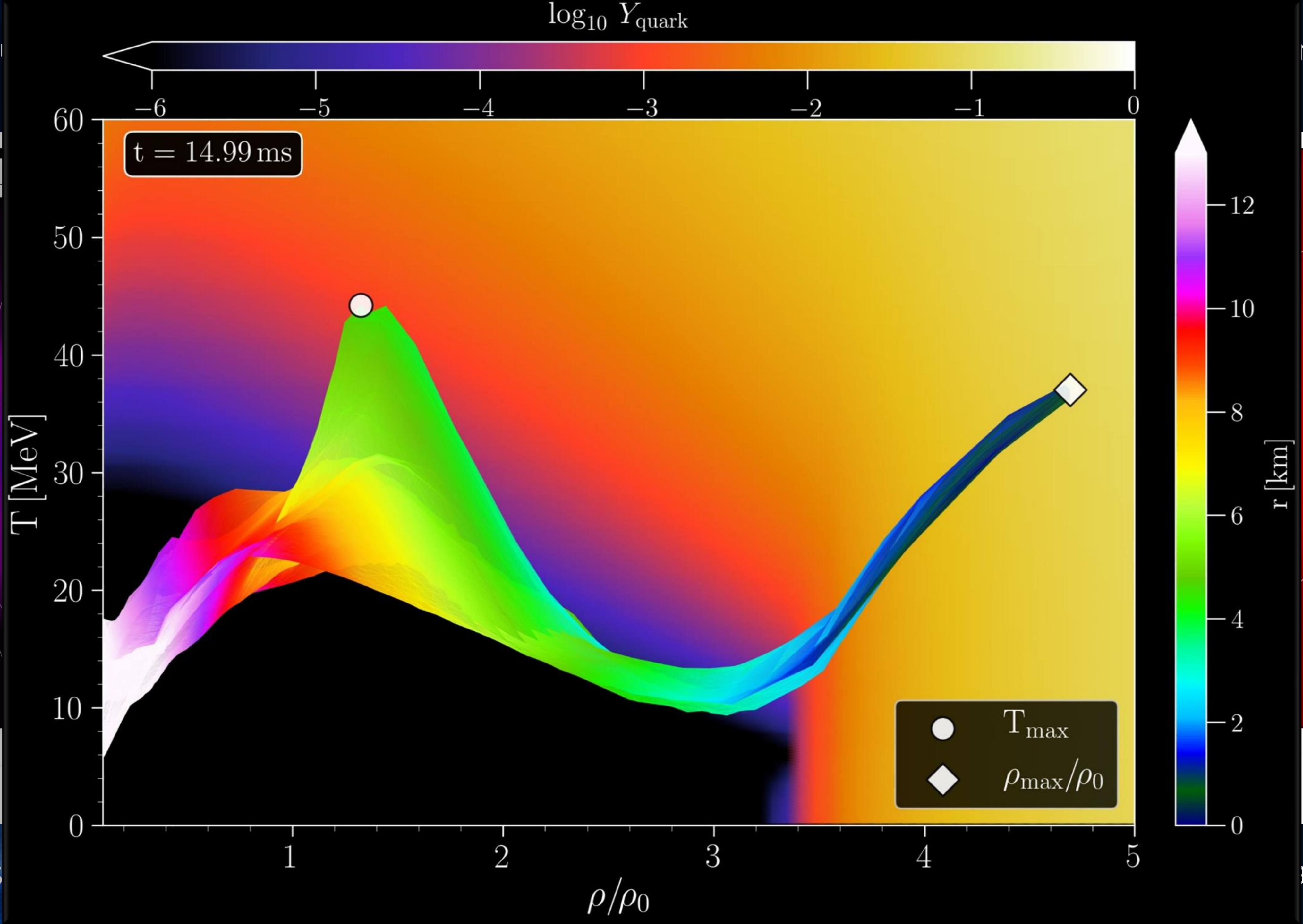
Physical review letters 122 (6), 061101 (2019)

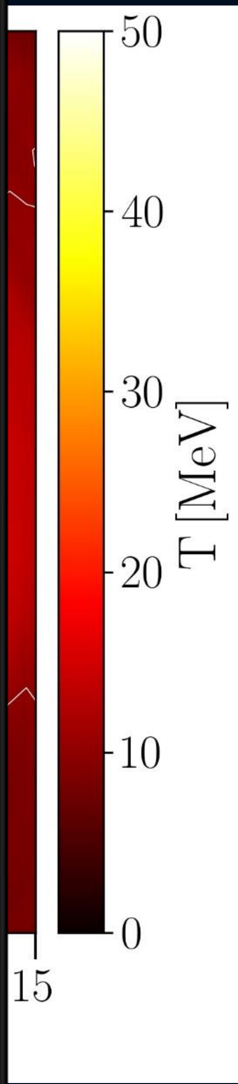
Density-Temperature-Composition dependent EOS within the CMFQ model.



The last simu … r (HMHS)

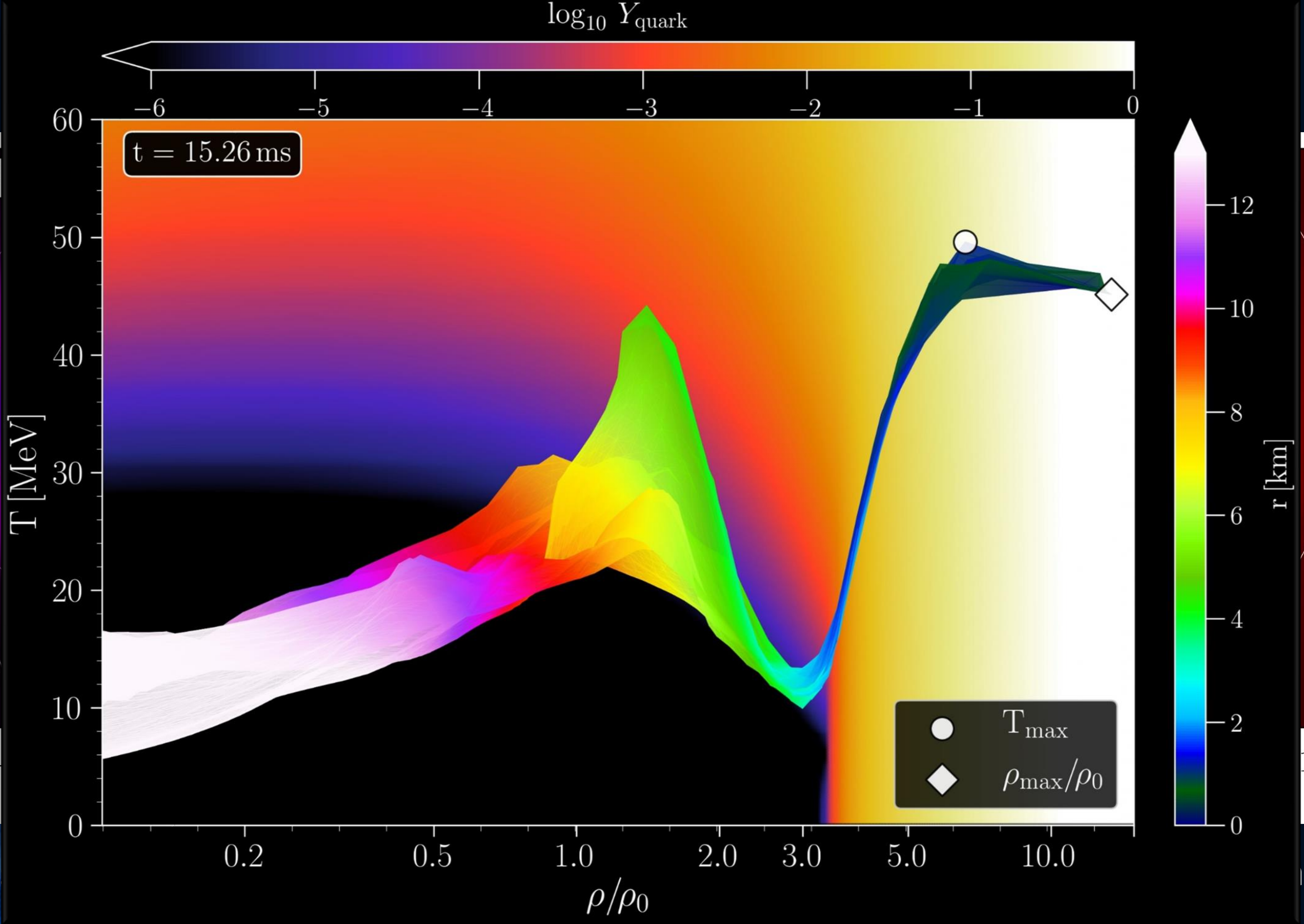






Rest mas … ane

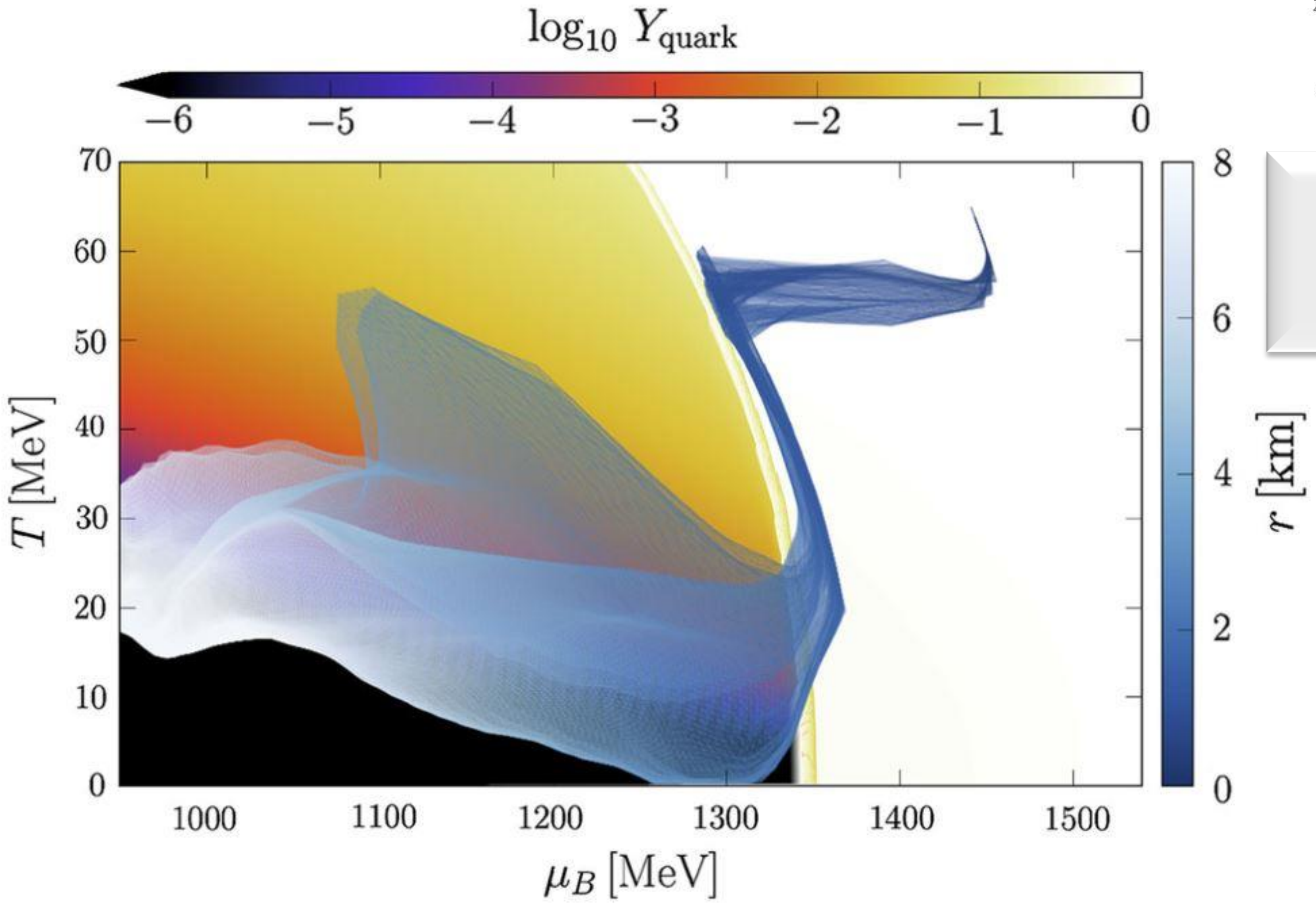
The last sim … (HMHS)



Rest mas … ne

GRAVITATIONAL COLLAPSE AND SPACE- TIME S

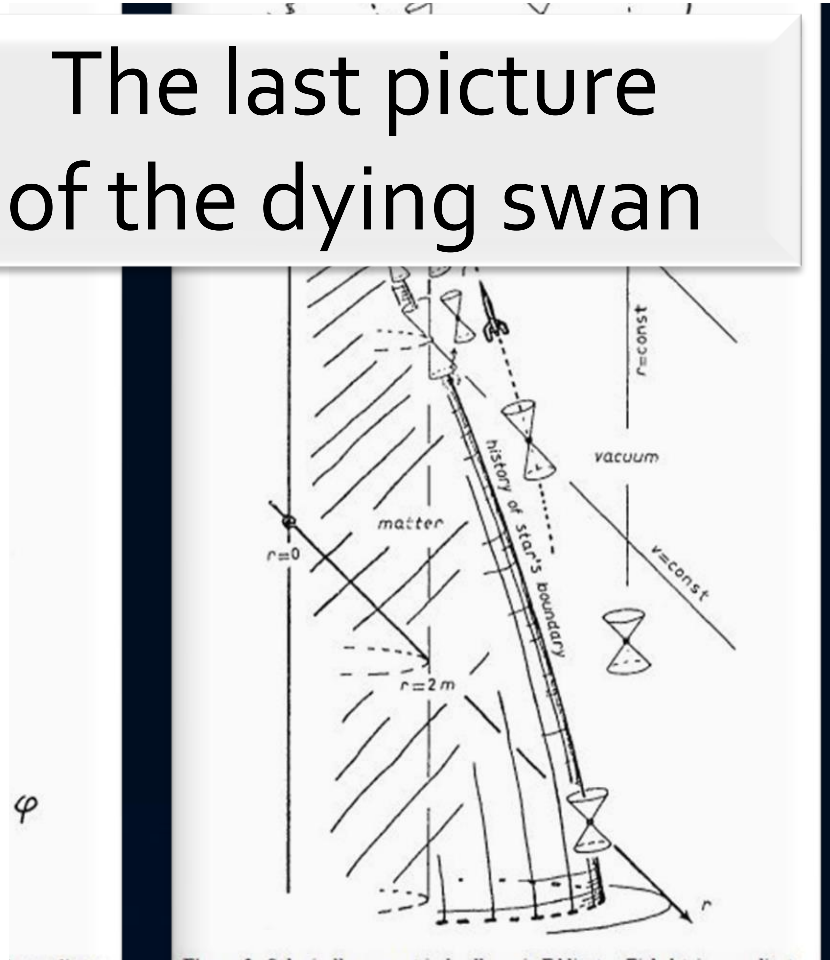
Nobel Price 2020: R.Penrose, PRL Vol.14 No.3



On the deconfinement phase transition in neutron-star mergers

Autoren	Elias R Most, L Jens Papenfort, Veronica Dexheimer, Matthias Hanauske, Horst Stoecker, Luciano Rezzolla
Publikationsdatum	2020/2
Zeitschrift	The European Physical Journal A
Band	56
Ausgabe	2
Seiten	1-11

The last picture of the dying swan



co-ordinates.

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

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

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

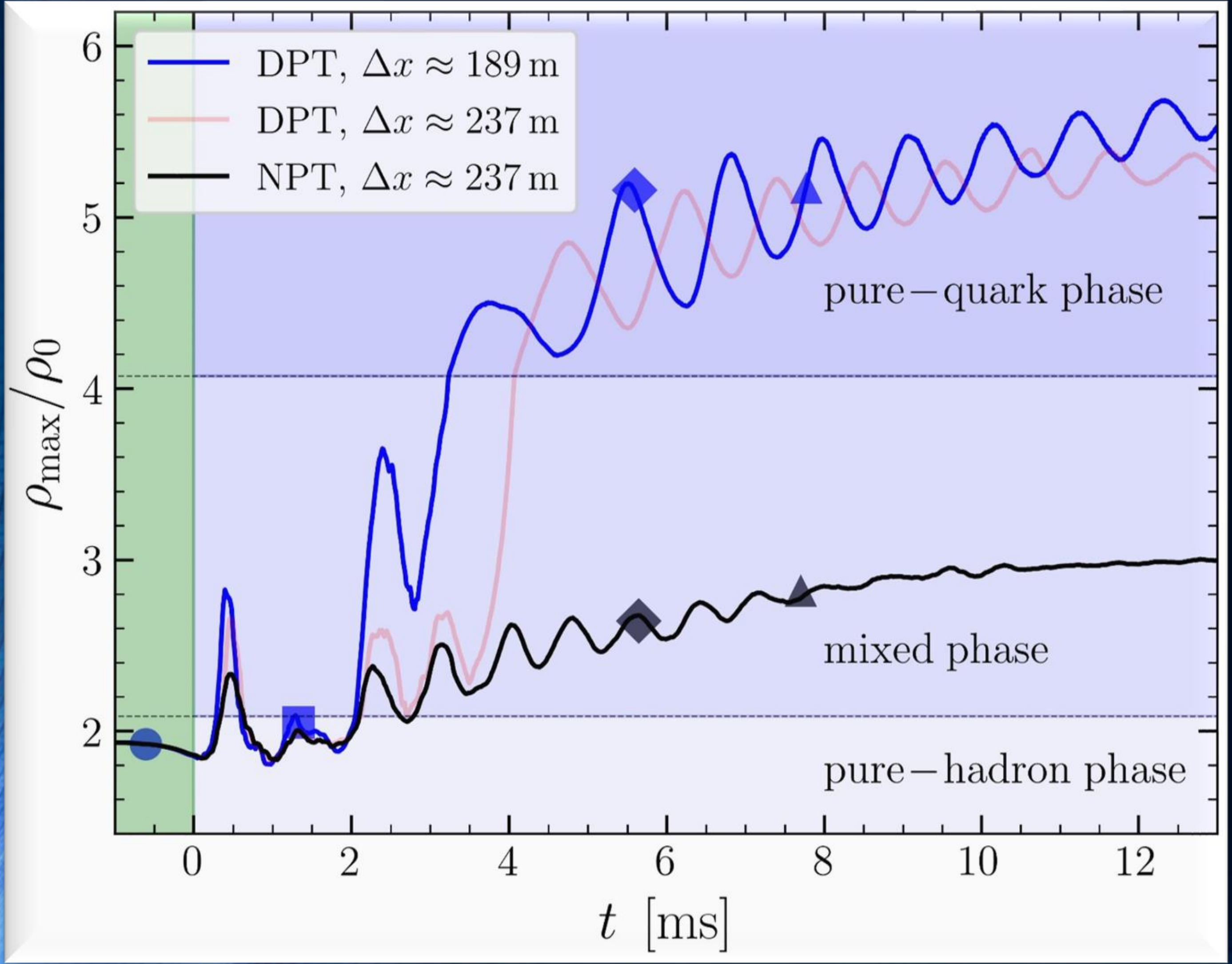
Can we detect the quark-gluon plasma with gravitational waves?

- 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)

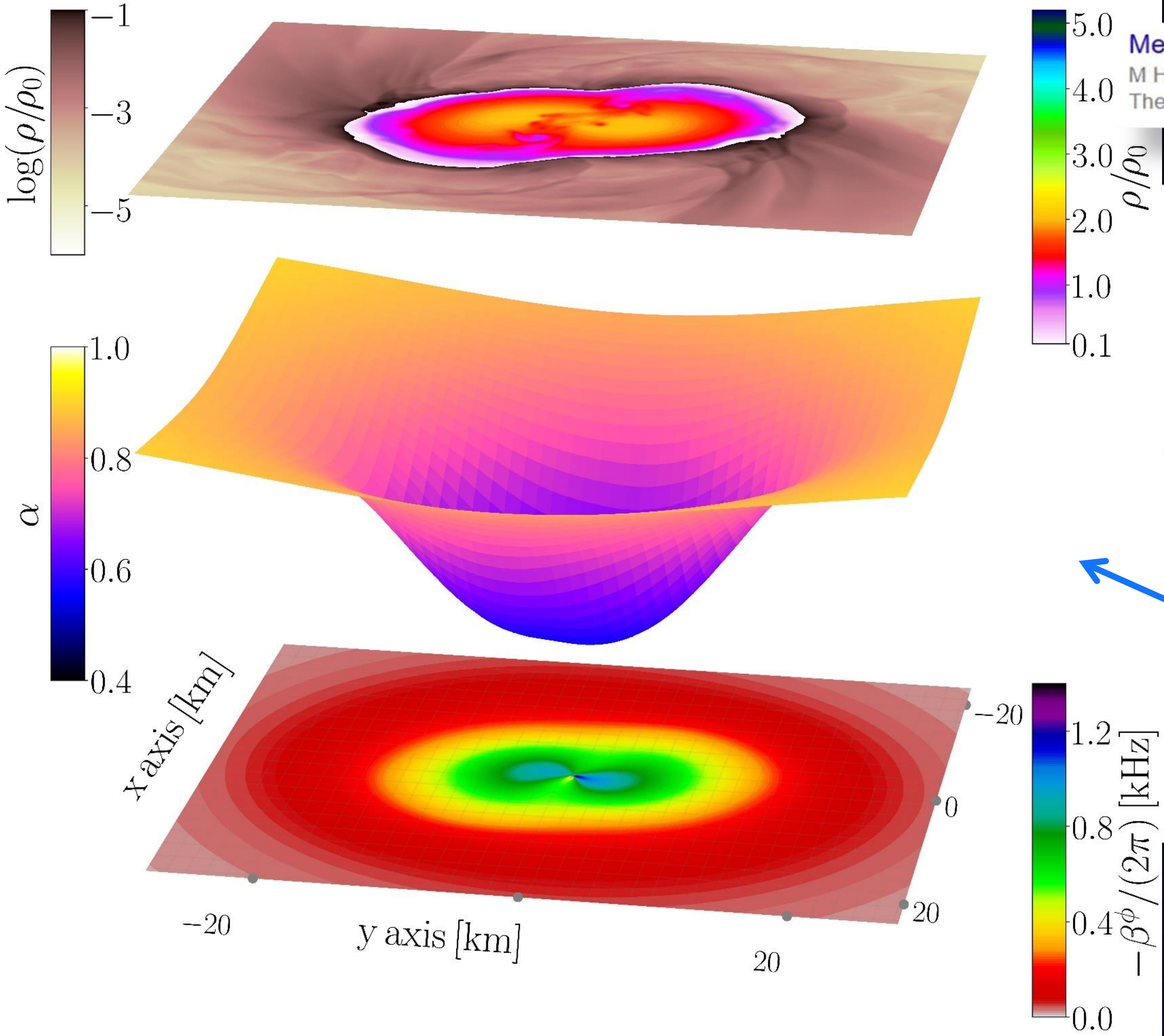
Signatures within the post-merger phase evolution

Delayed phase transition scenario

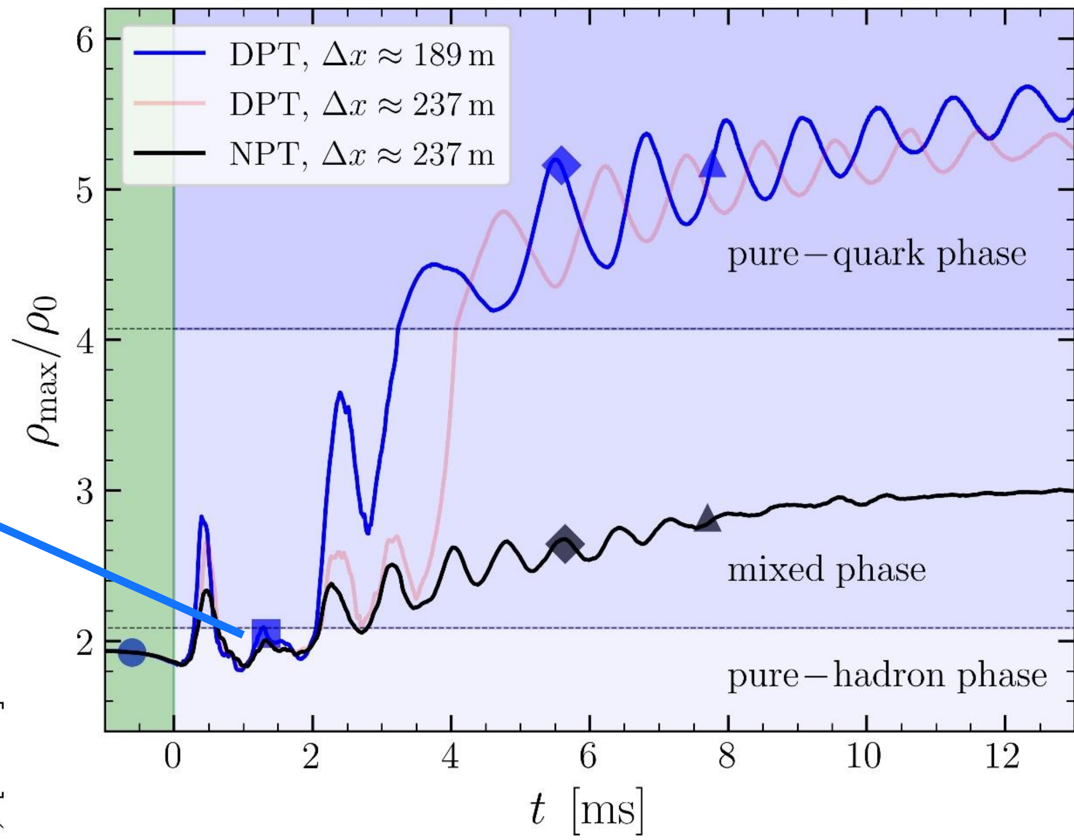
Postmerger Gravitational-Wave Signatures of Phase Transitions in Binary Mergers; LR Weih, M Hanauske, L Rezzolla; Physical Review Letters 124 (17), 171103 (2020)



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.

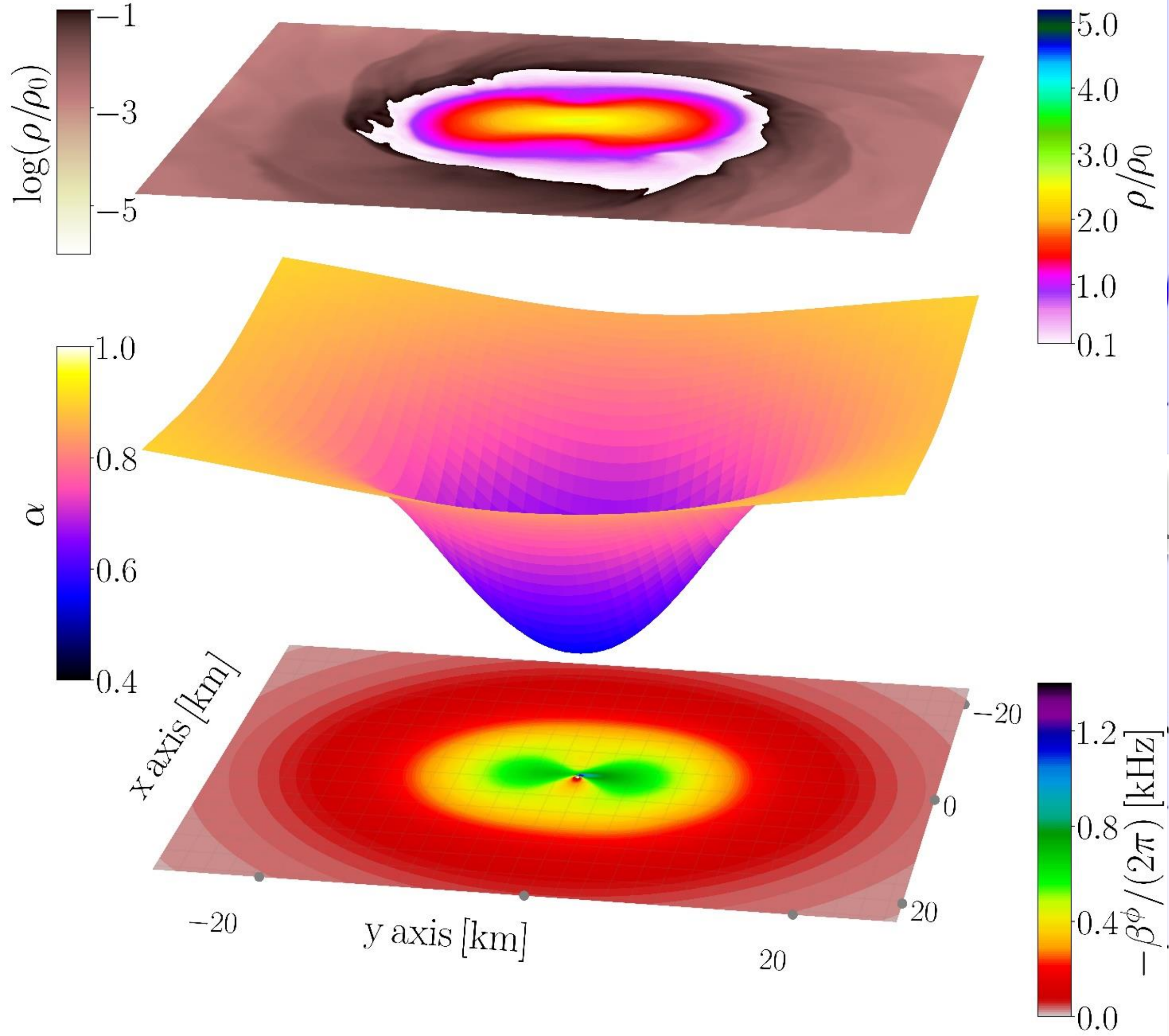


Metastable hypermassive hybrid stars as neutron-star merger remnants
M Hanauske, LR Weih, H Stöcker, L Rezzolla
The European Physical Journal Special Topics, 1-8

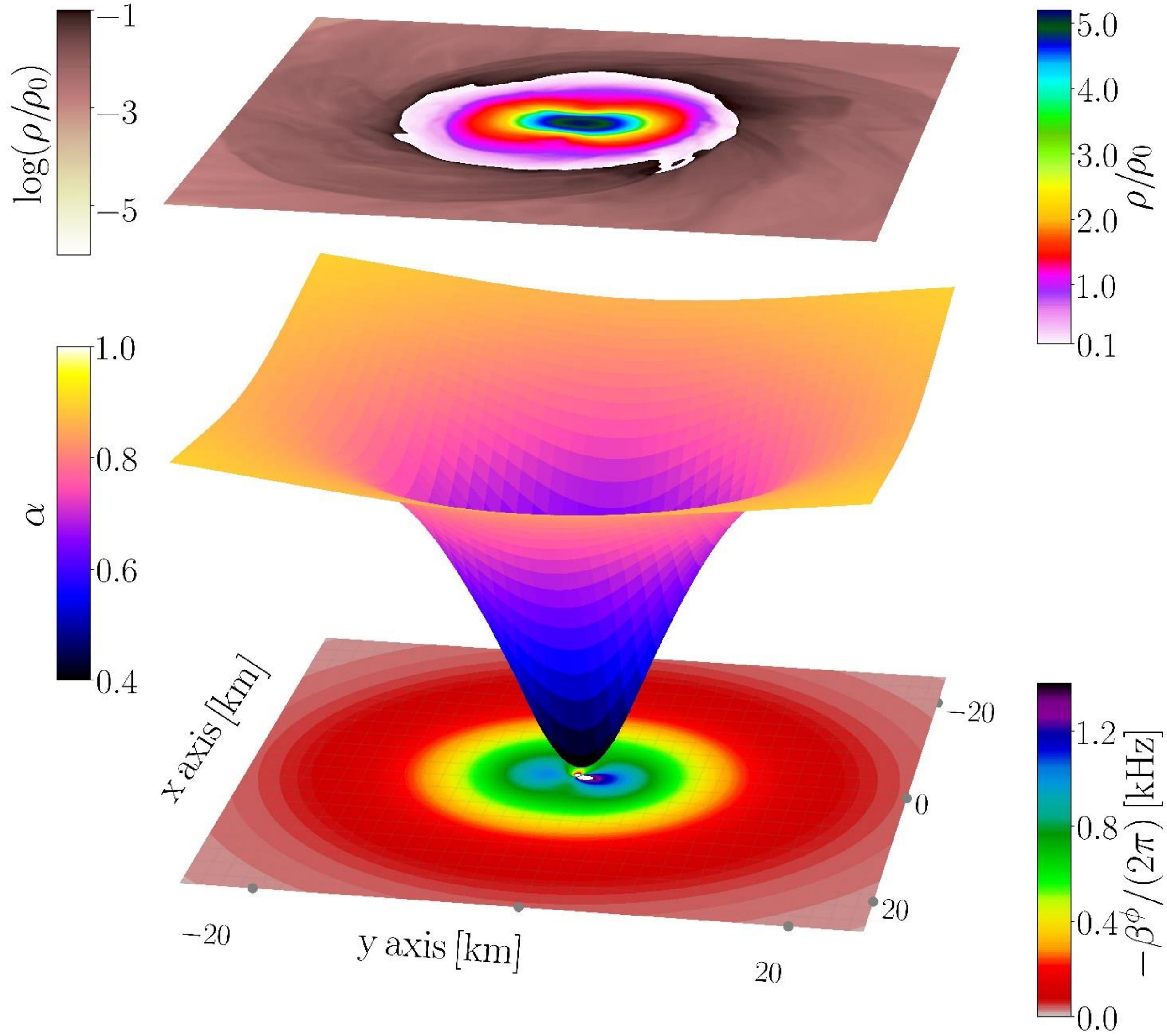


Additional article „ Neutron star collisions and gravitational waves" by M.Hanauske and L.Weih will appear soon in Astronomische Nachrichten (Astronomical Notes)

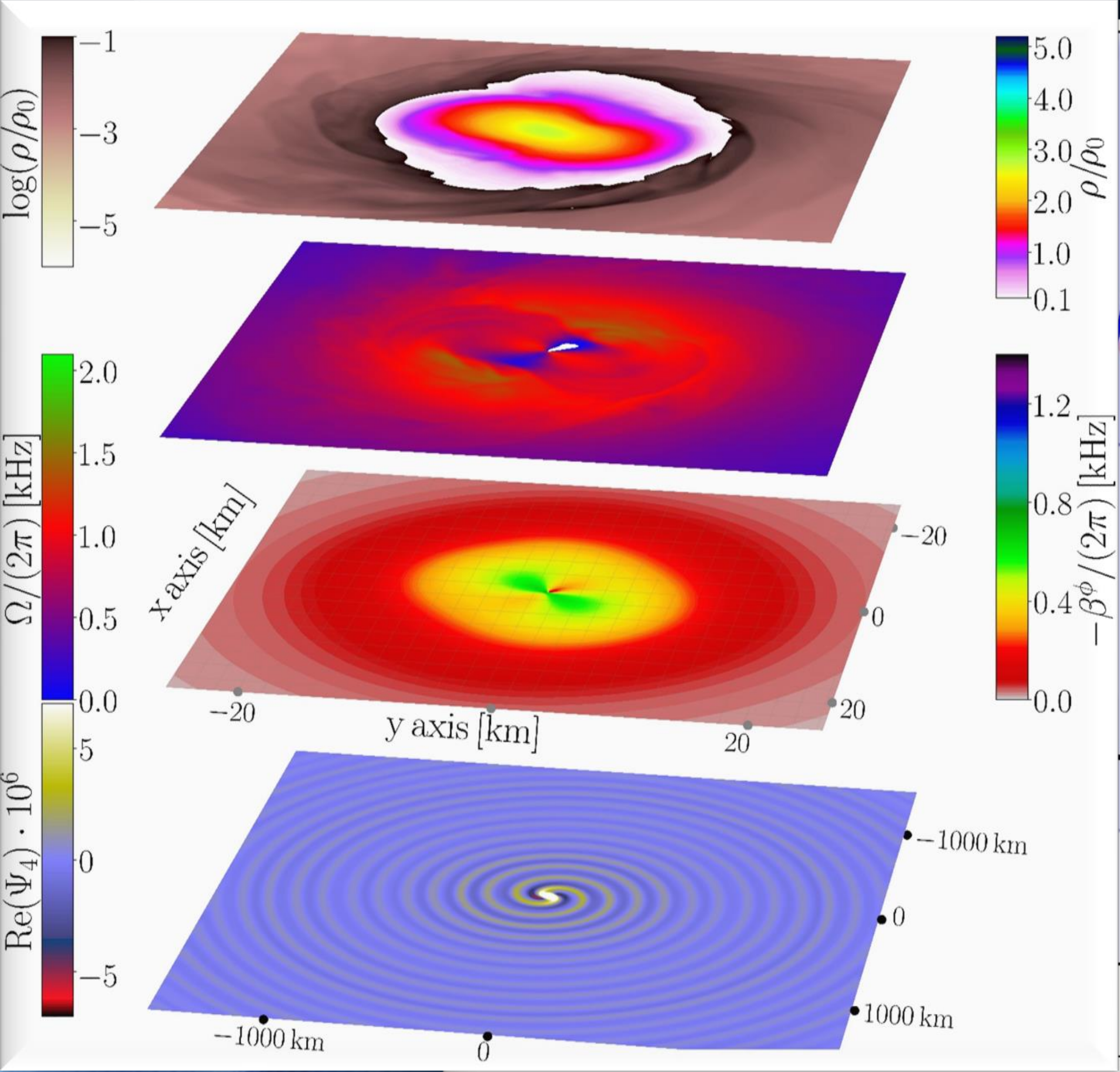
Without Phase Transition



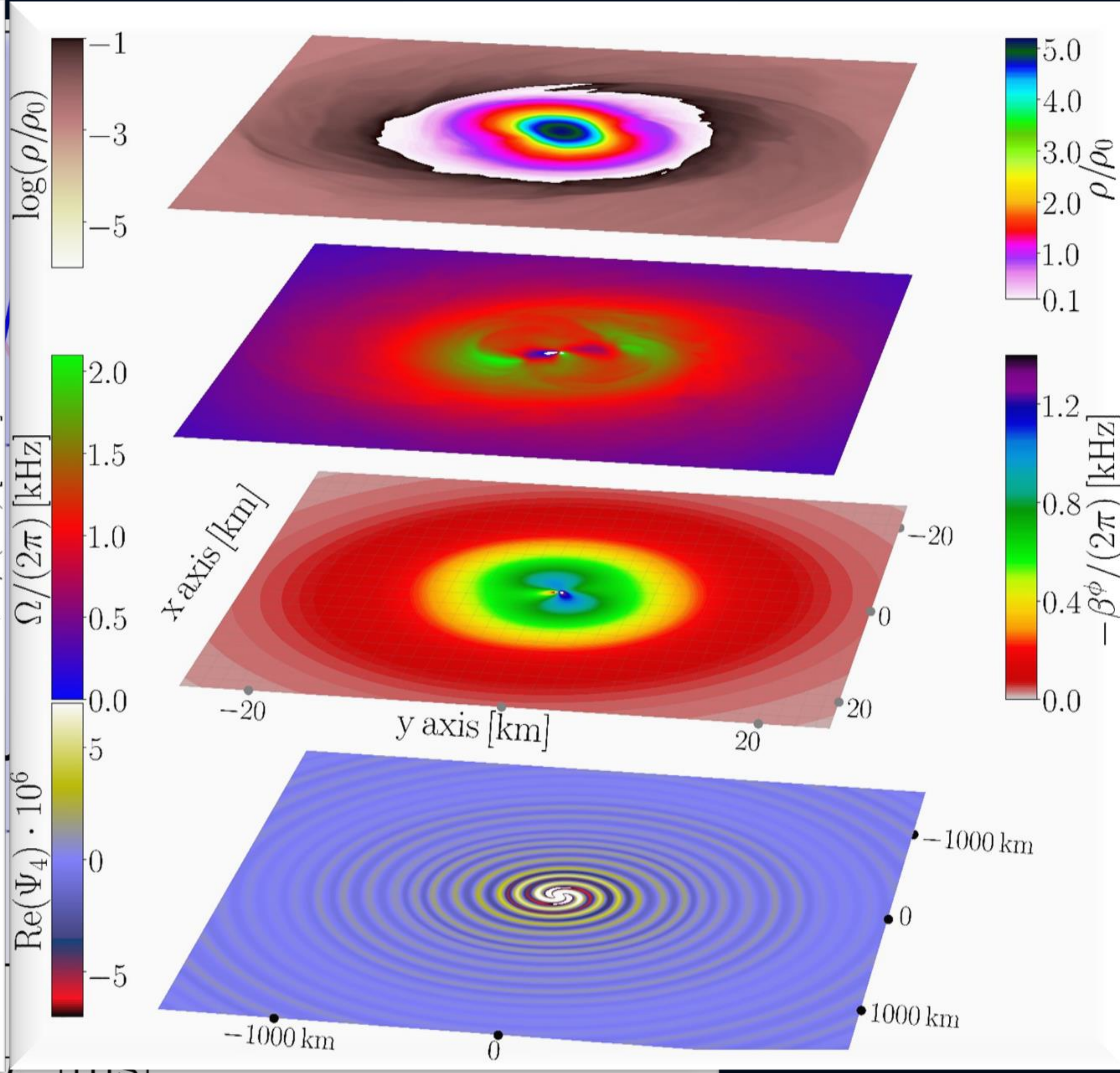
With Phase Transition

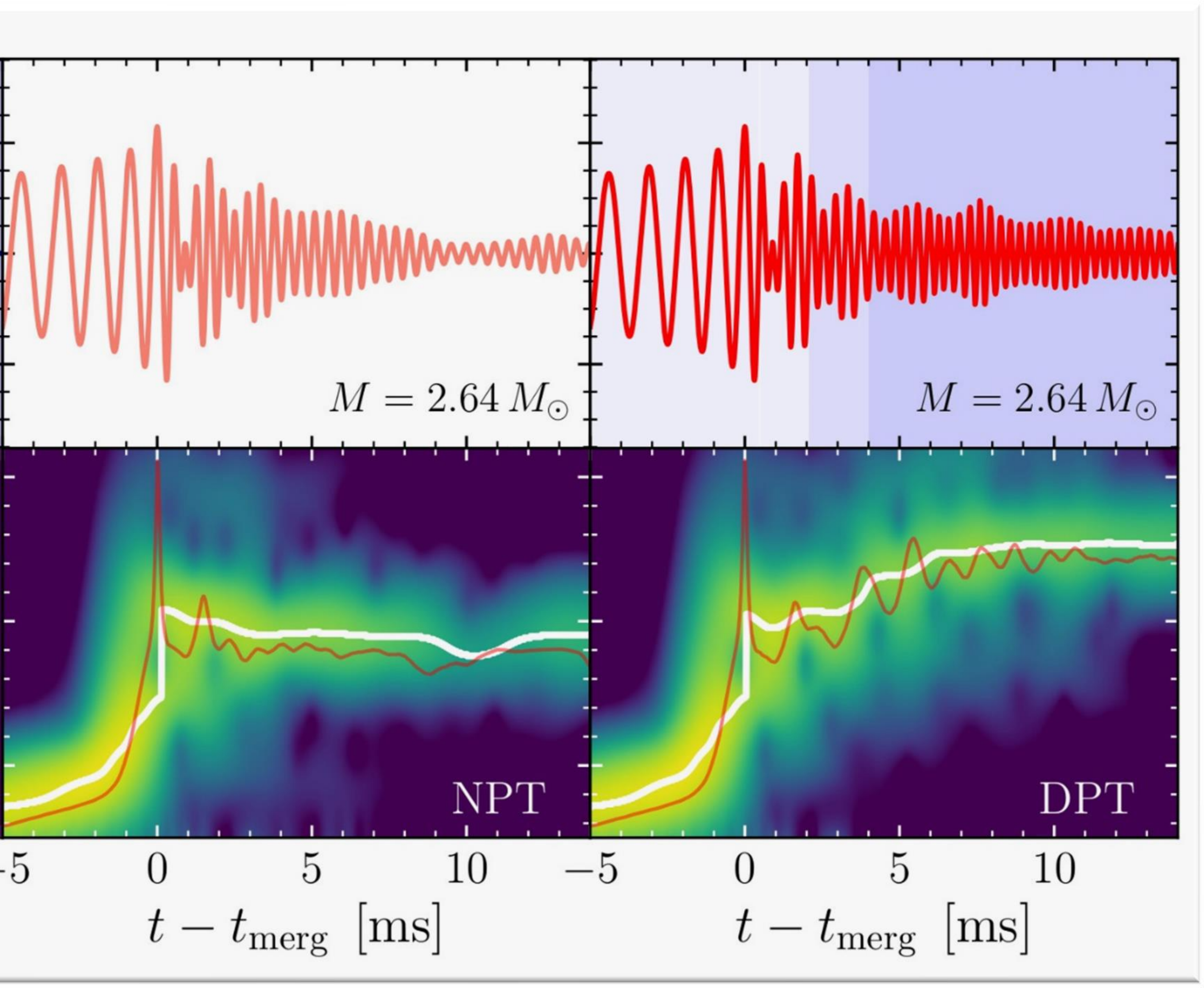


Without Phase Transition

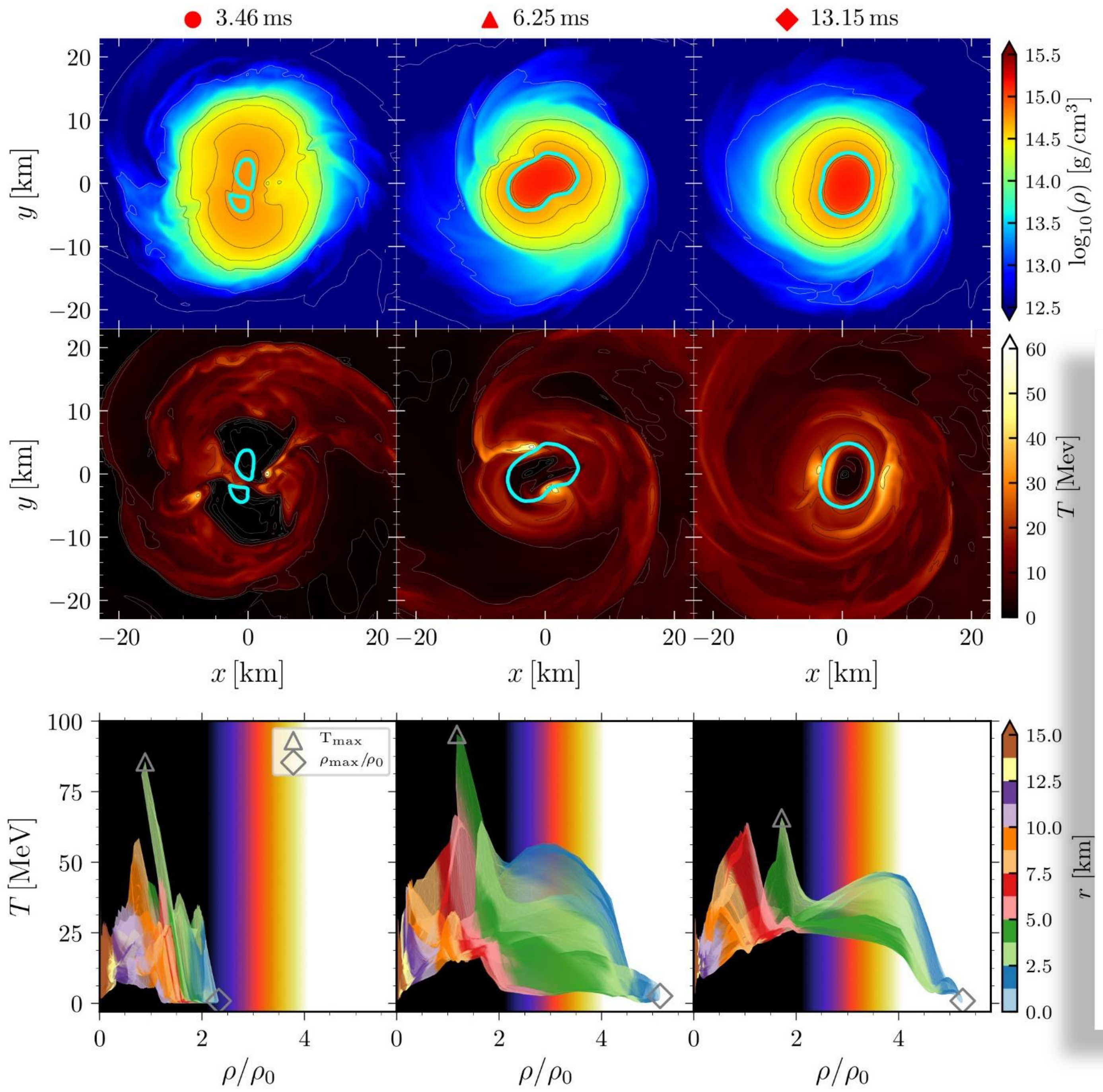


With Phase Transition



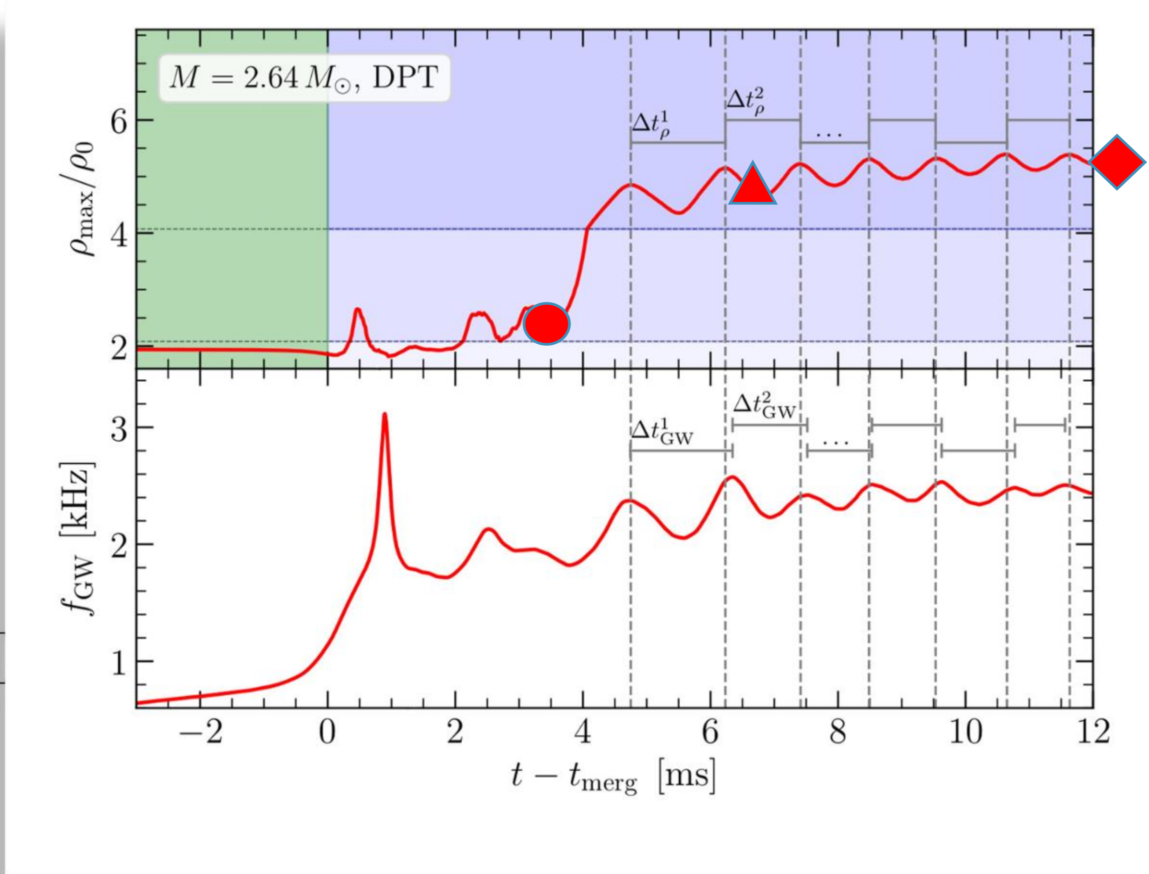


Strain h+ (top) and its spectrogram (bottom) for the binary neutron star simulation of the delayed phase transition scenario. In the top panel the different shadings mark the times when the HMNS core enters the mixed and pure quark phases.. In the bottom panels, the white lines trace the maximum of the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

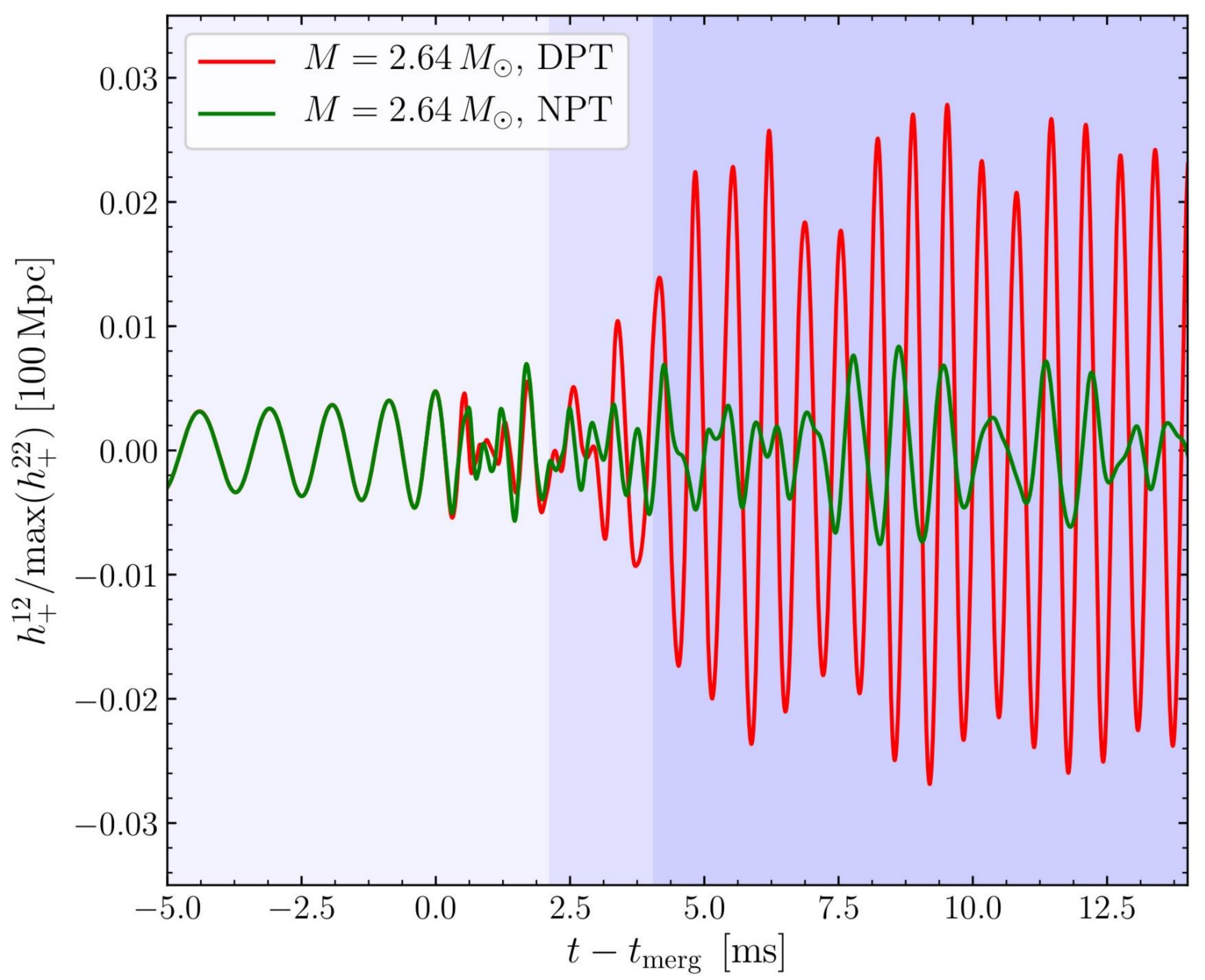


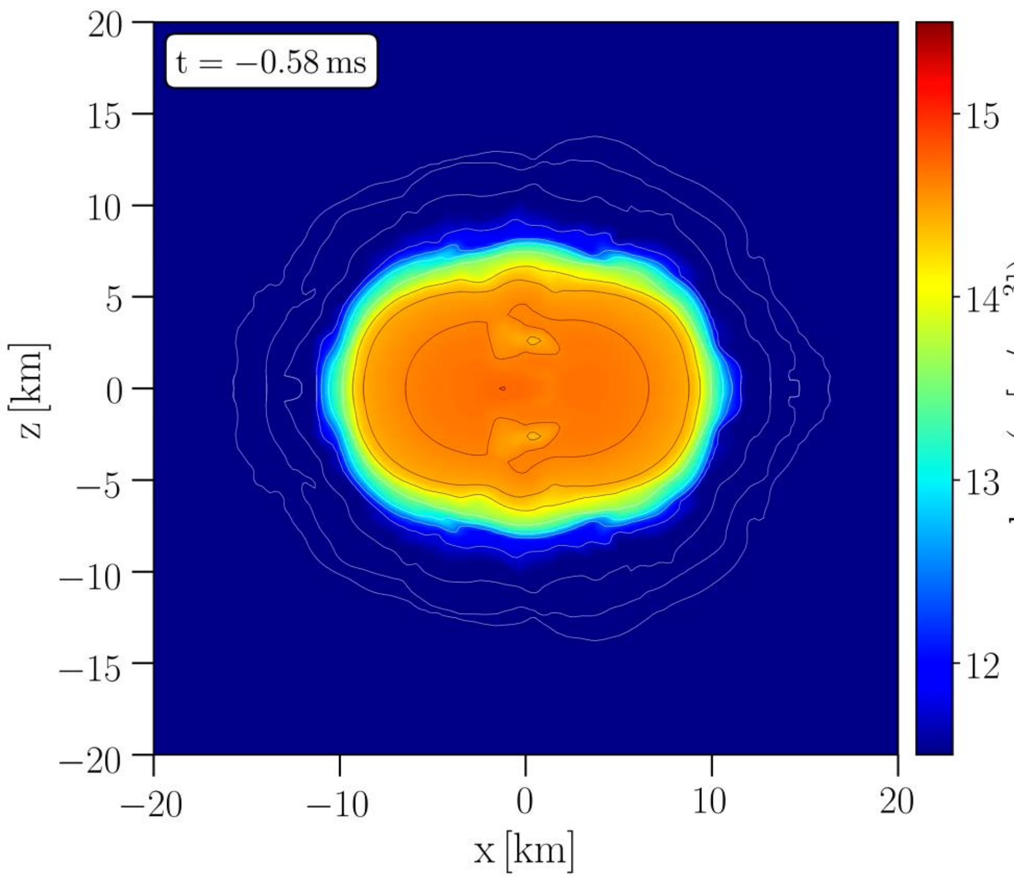
Article will appear in

EPJ Special Topics on "Nuclear Astrophysics in Our Time: Supernovae, Neutron Stars and Binary Neutron Star Mergers"

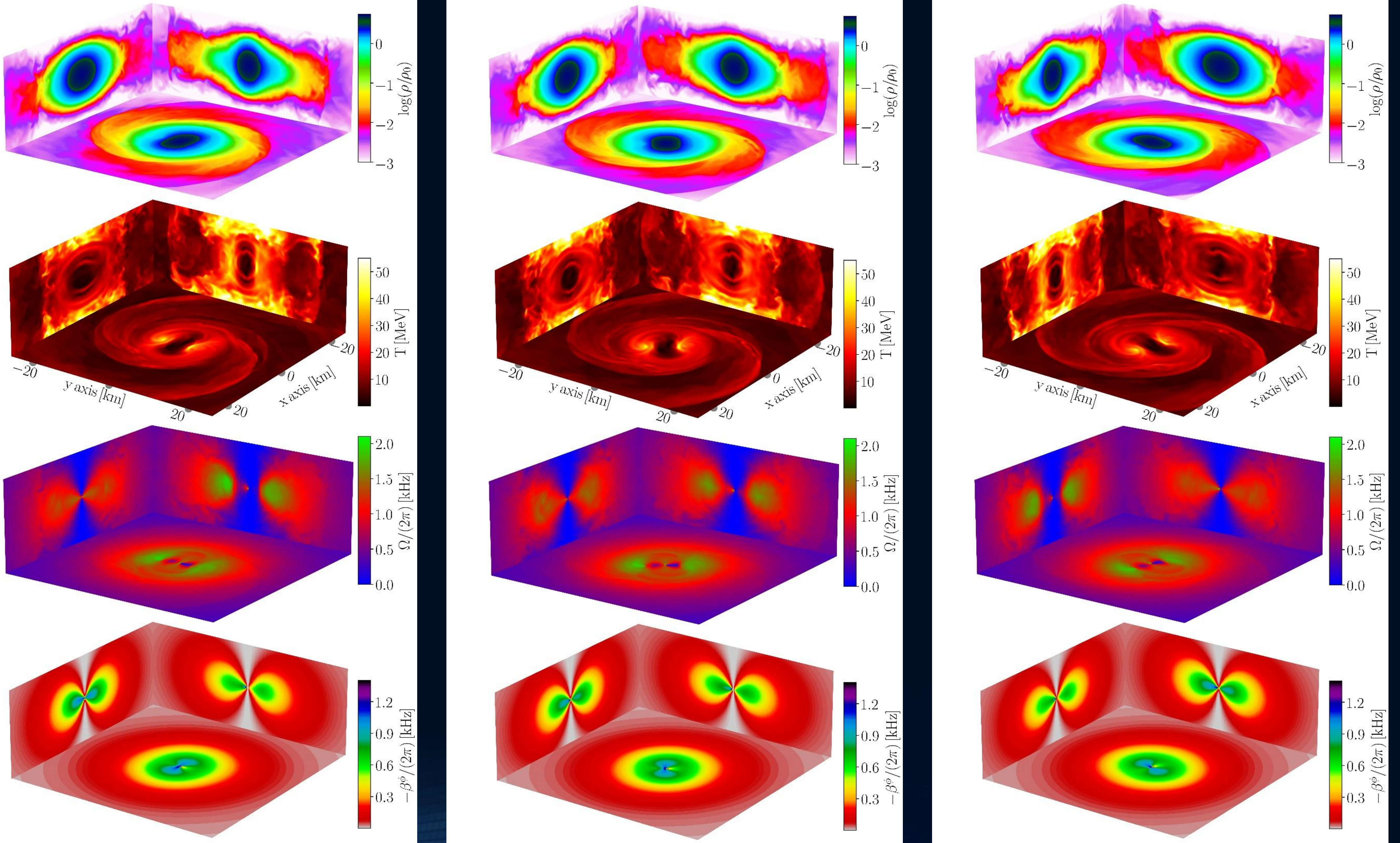


Difference in the h_+^{12} – gravitational wave mode





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.


log(ρ/ρ₀)
0
−1
−2
−3
T [MeV]
50
40
30
20
10
−20
y axis [km]
20
0
x axis [km]
Ω/(2π) [kHz]
2.0
1.5
1.0
0.5
0.0
−β^φ/(2π) [kHz]
1.2
0.9
0.6
0.3

The new NICER observation

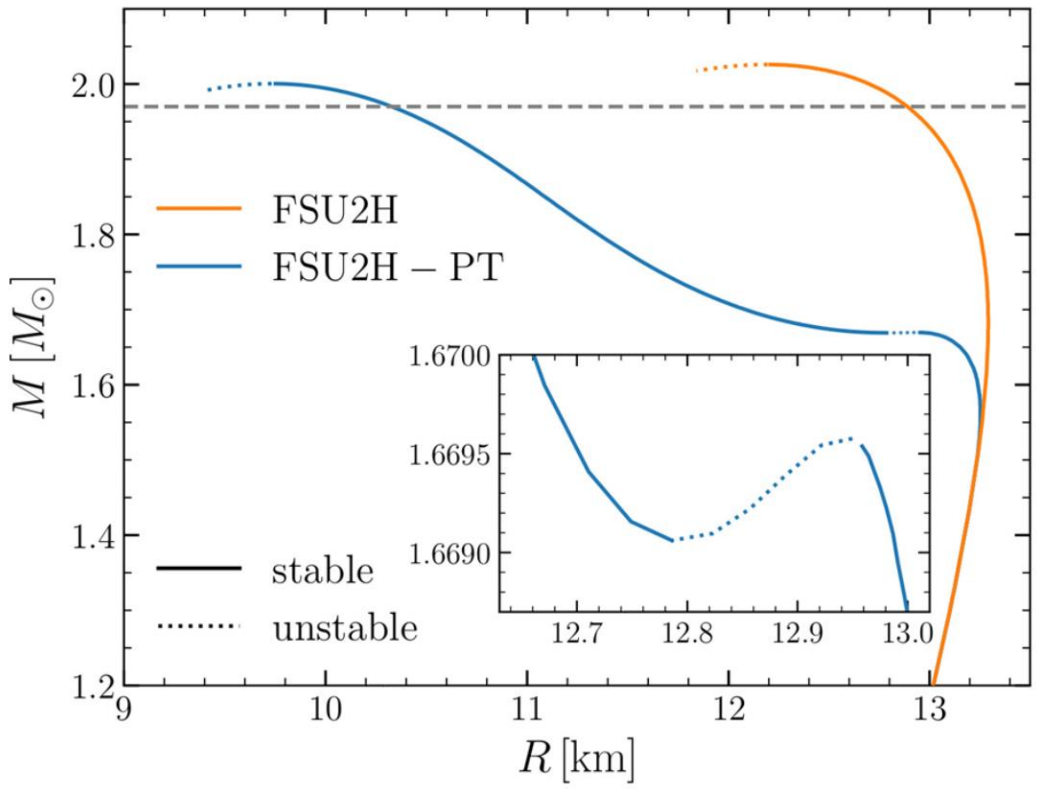


FIG. 1. Mass-radius relation for the purely hadronic EOS (FSU2H) and its modified version (FSU2H-PT). The latter shows a second stable (solid lines) branch after a small region of instability (dotted). The grey dashed line marks the limit of 1.97 $M_\odot$.

EOS in our PRL 124, 171103 (2020)

A *NICER* VIEW OF THE MASSIVE PULSAR PSR J0740+6620 INFORMED BY RADIO TIMING AND *XMM-NEWTON* SPECTROSCOPY

Thomas E. Riley,[1] Anna L. Watts,[1] Paul S. Ray,[2] Slavko Bogdanov,[3] Sebastien Guillot,[4,5] Sharon M. Morsink,[6] Anna V. Bilous,[7] Zaven Arzoumanian,[8] Devarshi Choudhury,[1] Julia S. Deneva,[9] Keith C. Gendreau,[8] Alice K. Harding,[10] Wynn C. G. Ho,[11] James M. Lattimer,[12] Michael Loewenstein,[13,14] Renee M. Ludlam,[15,16] Craig B. Markwardt,[8] Takashi Okajima,[8] Chanda Prescod-Weinstein,[17] Ronald A. Remillard,[18] Michael T. Wolff,[2] Emmanuel Fonseca,[19,20,21,22] H. Thankful Cromartie,[23,16] Matthew Kerr,[2] Timothy T. Pennucci,[24,25] Aditya Parthasarathy,[26] Scott Ransom,[24] Ingrid Stairs,[27] Lucas Guillemot,[28,29] and Ismael Cognard[28,29]

[1] *Anton Pannekoek Institute for Astronomy, University of Amsterdam, Science Park 904, 1090GE Amsterdam, the Netherlands*
[2] *Space Science Division, U.S. Naval Research Laboratory, Washington, DC 20375, USA*
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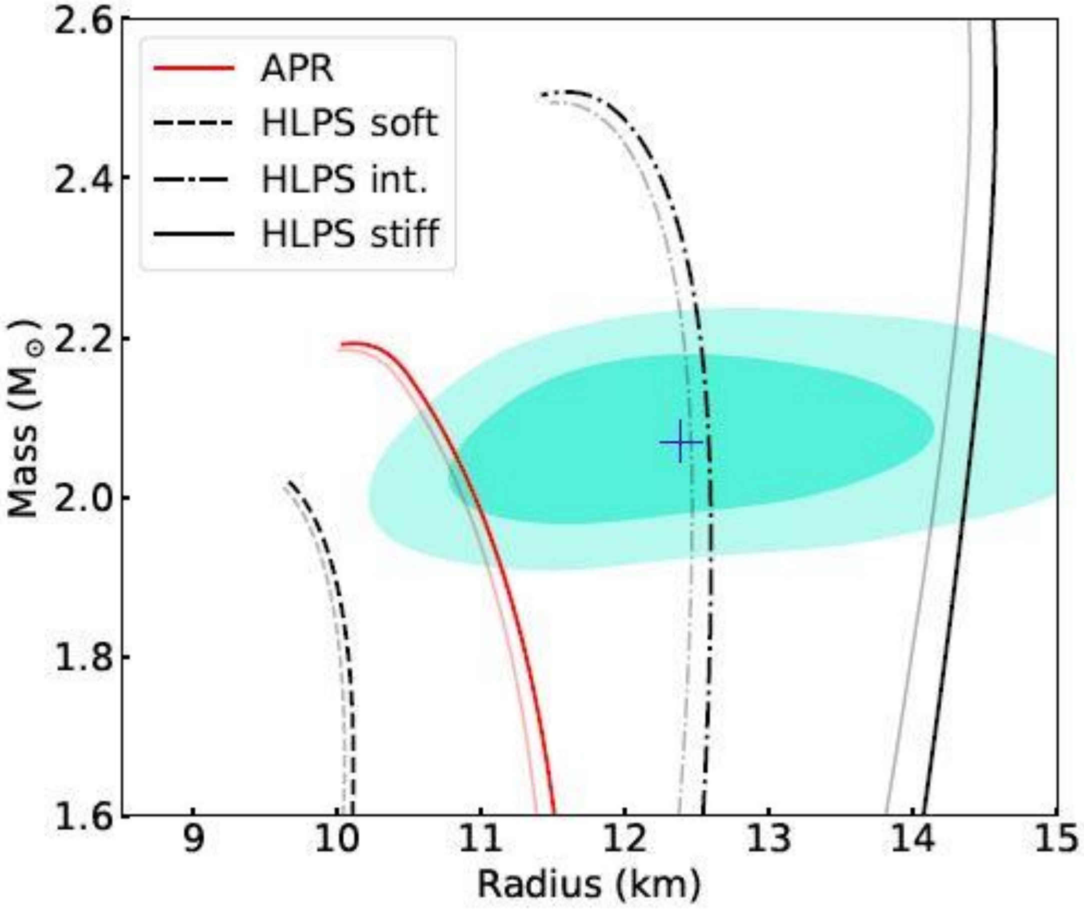
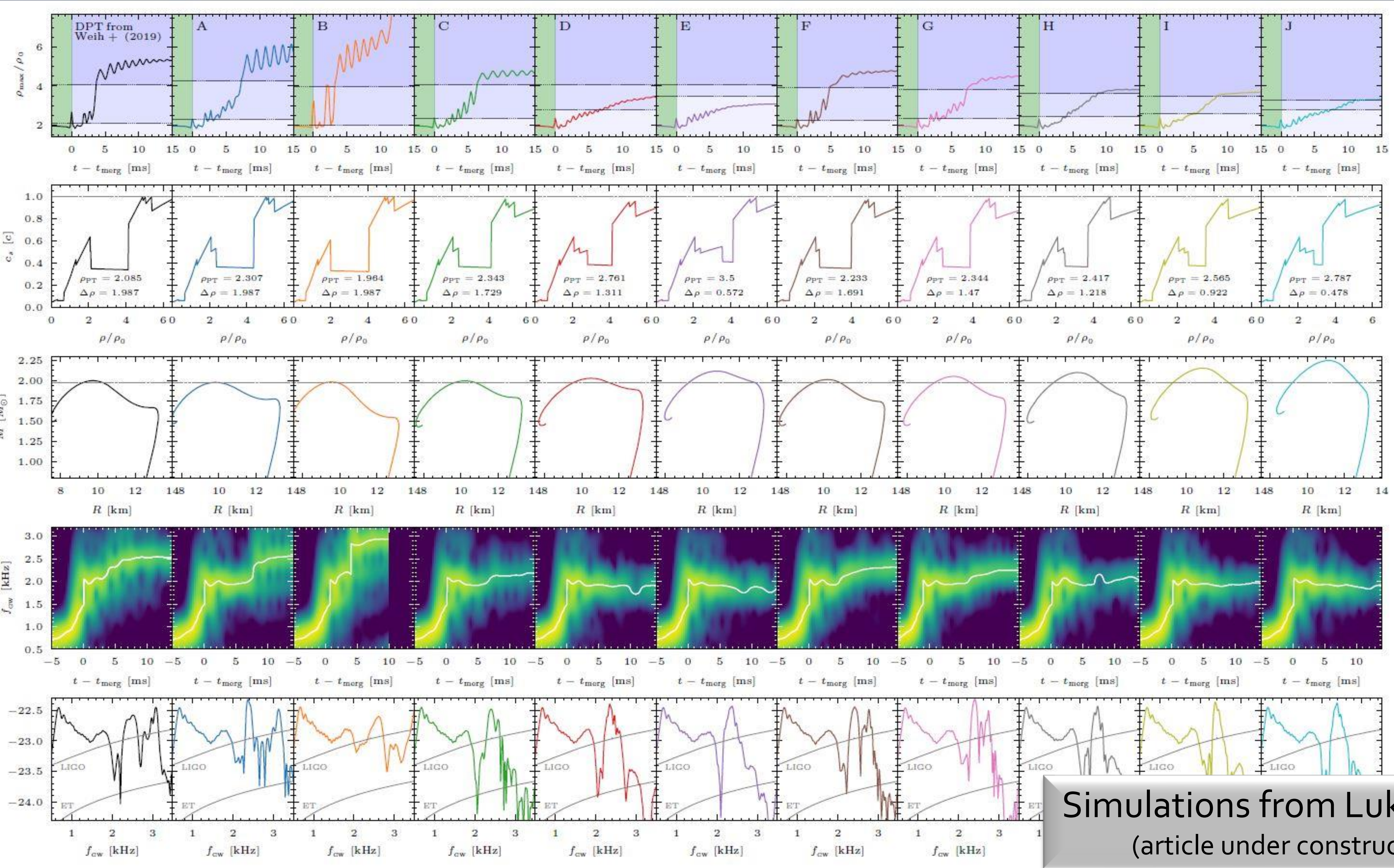
[4] *IRAP, CNRS, 9 avenue du Colonel Roche, BP 44346, F-31028 Toulouse Cedex 4, France*
[5] *Université de Toulouse, CNES, UPS-OMP, F-31028 Toulouse, France.*
[6] *Department of Physics, University of Alberta, 4-183 CCIS, Edmonton, AB, T6G 2E1, Canada*
[7] *ASTRON, the Netherlands Institute for Radio Astronomy, Postbus 2, 7990 AA Dwingeloo, The Netherlands*

14 May 2021





Simulations from Lukas Weih
(article under construction)

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

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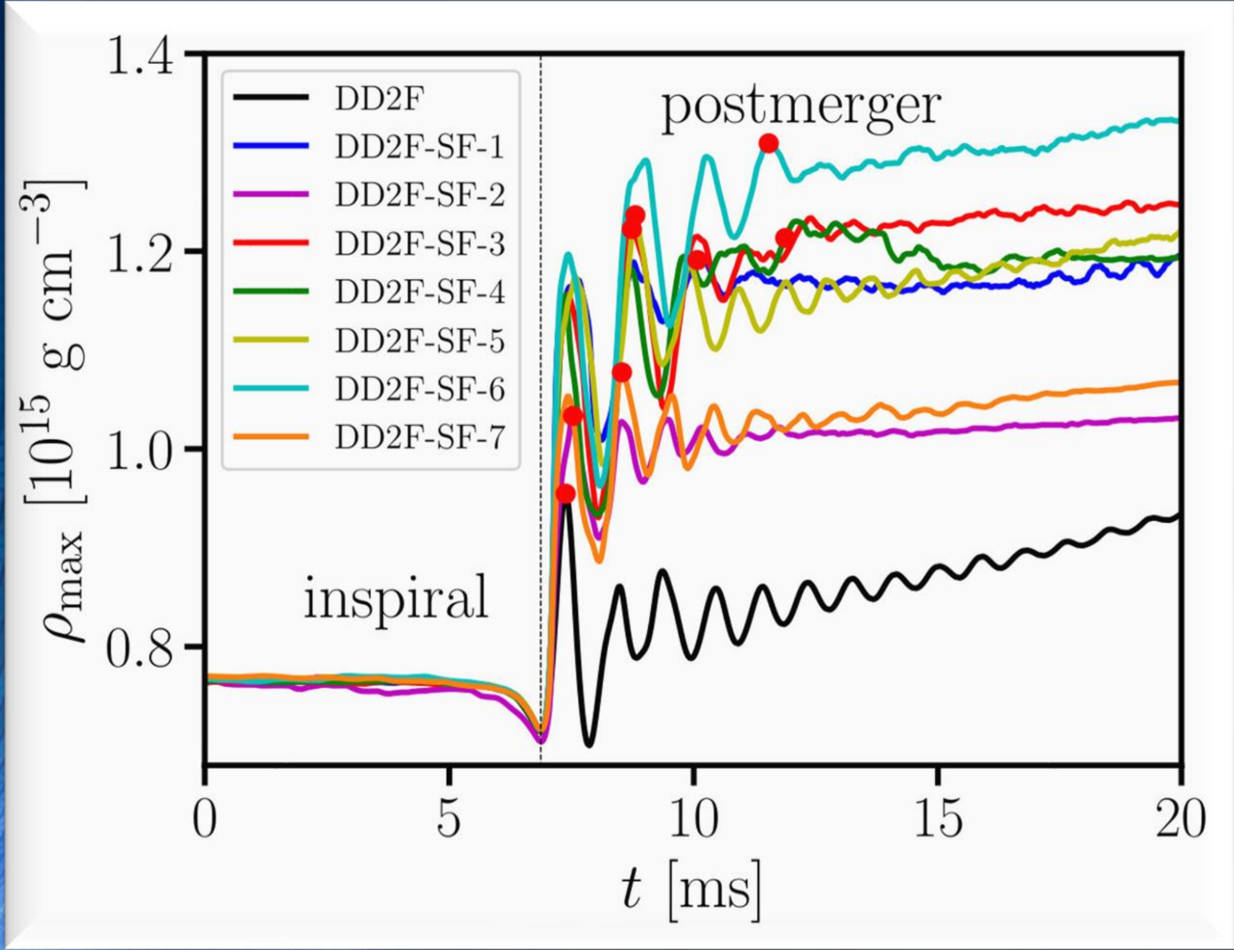

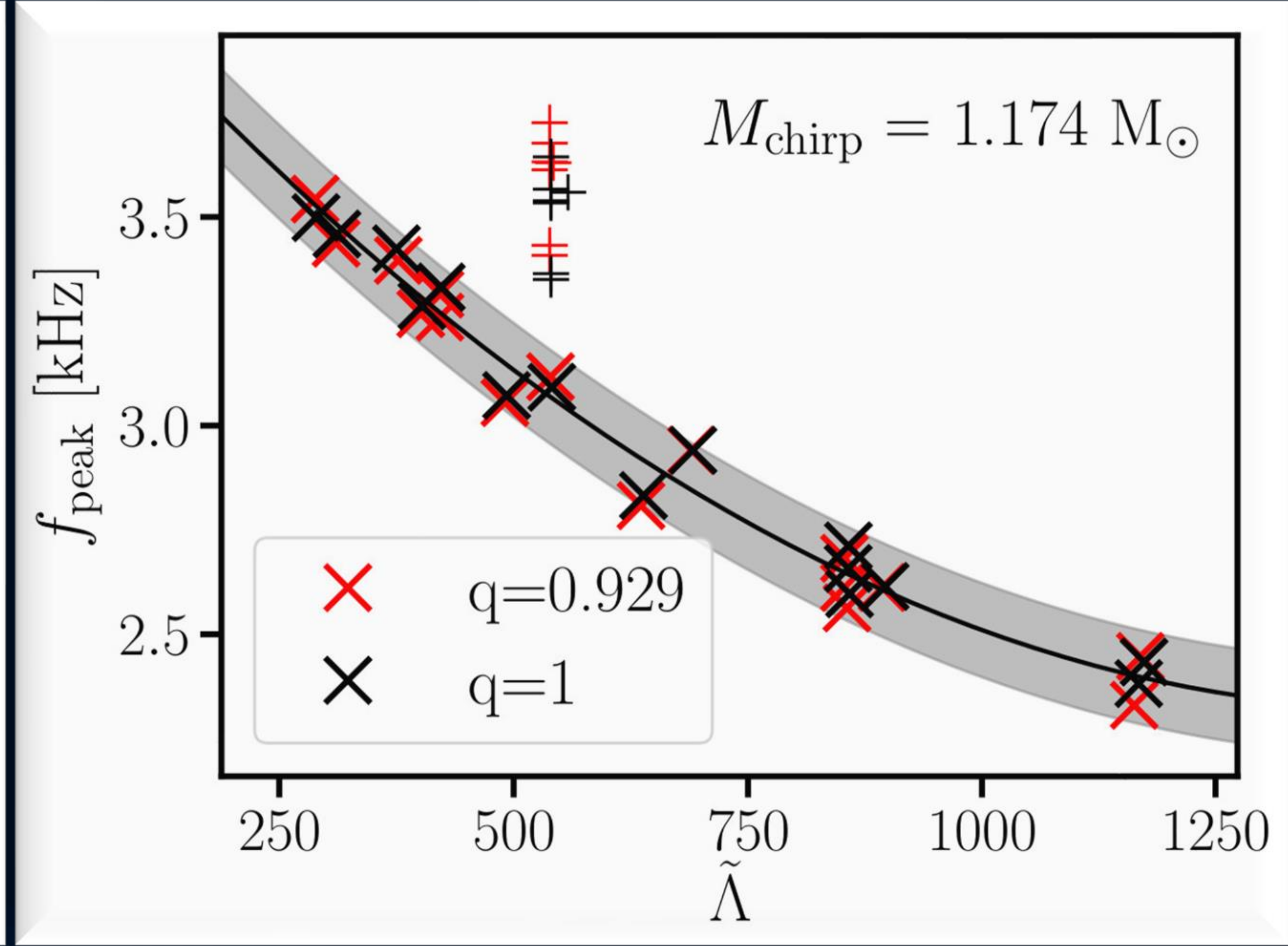

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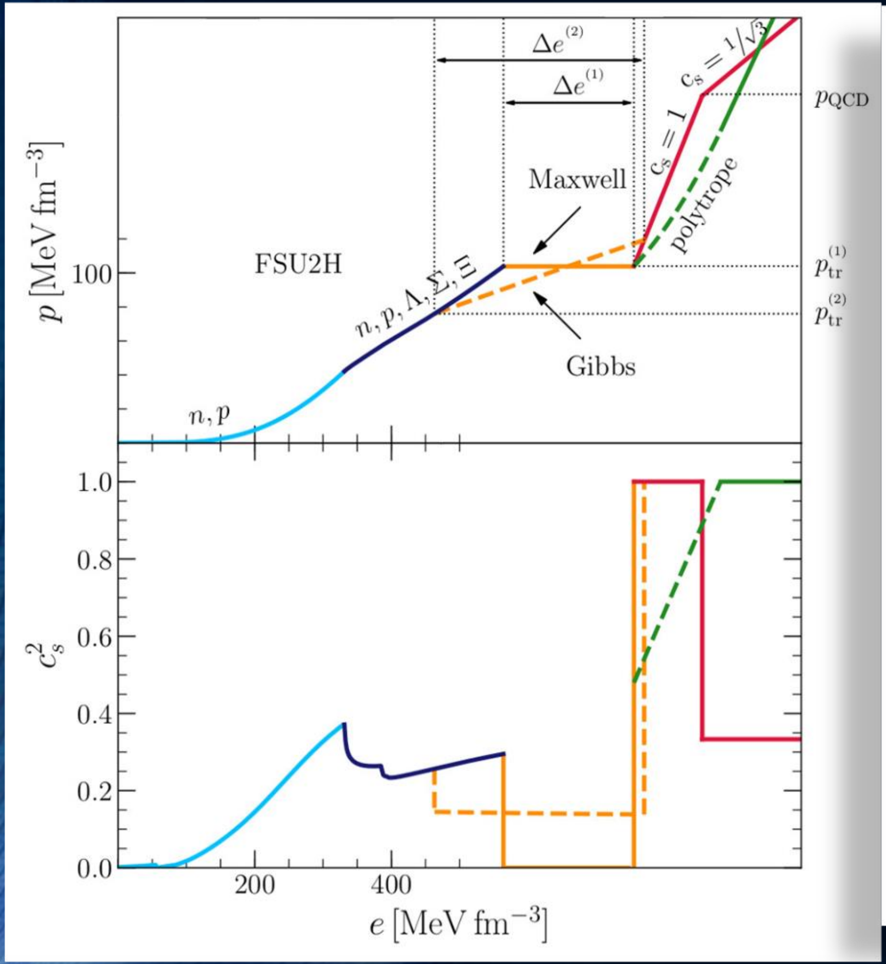
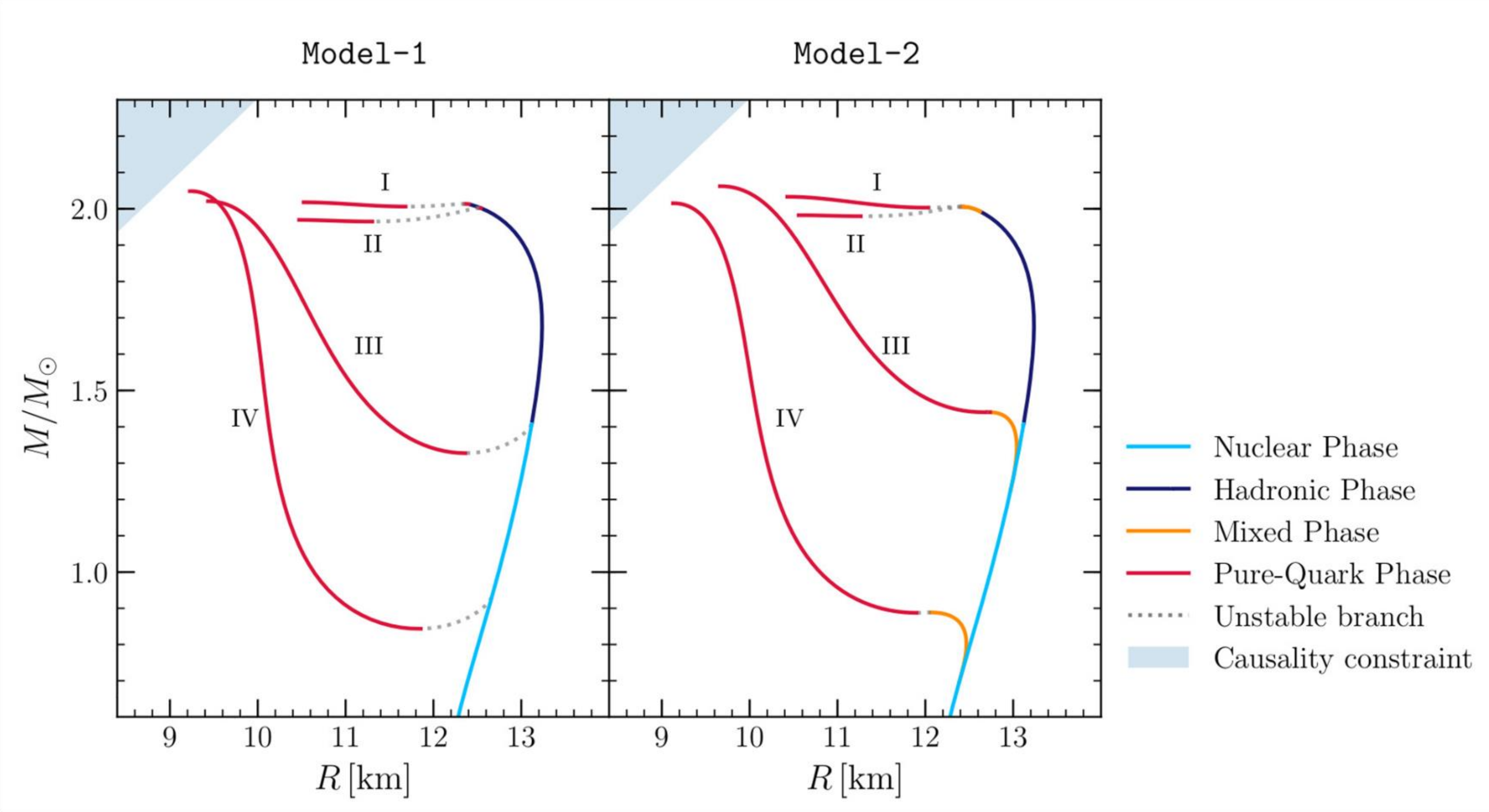
Gravitational-wave signatures within the late inspiral phase

Construction of the EOS with a hadron-quark phase transition



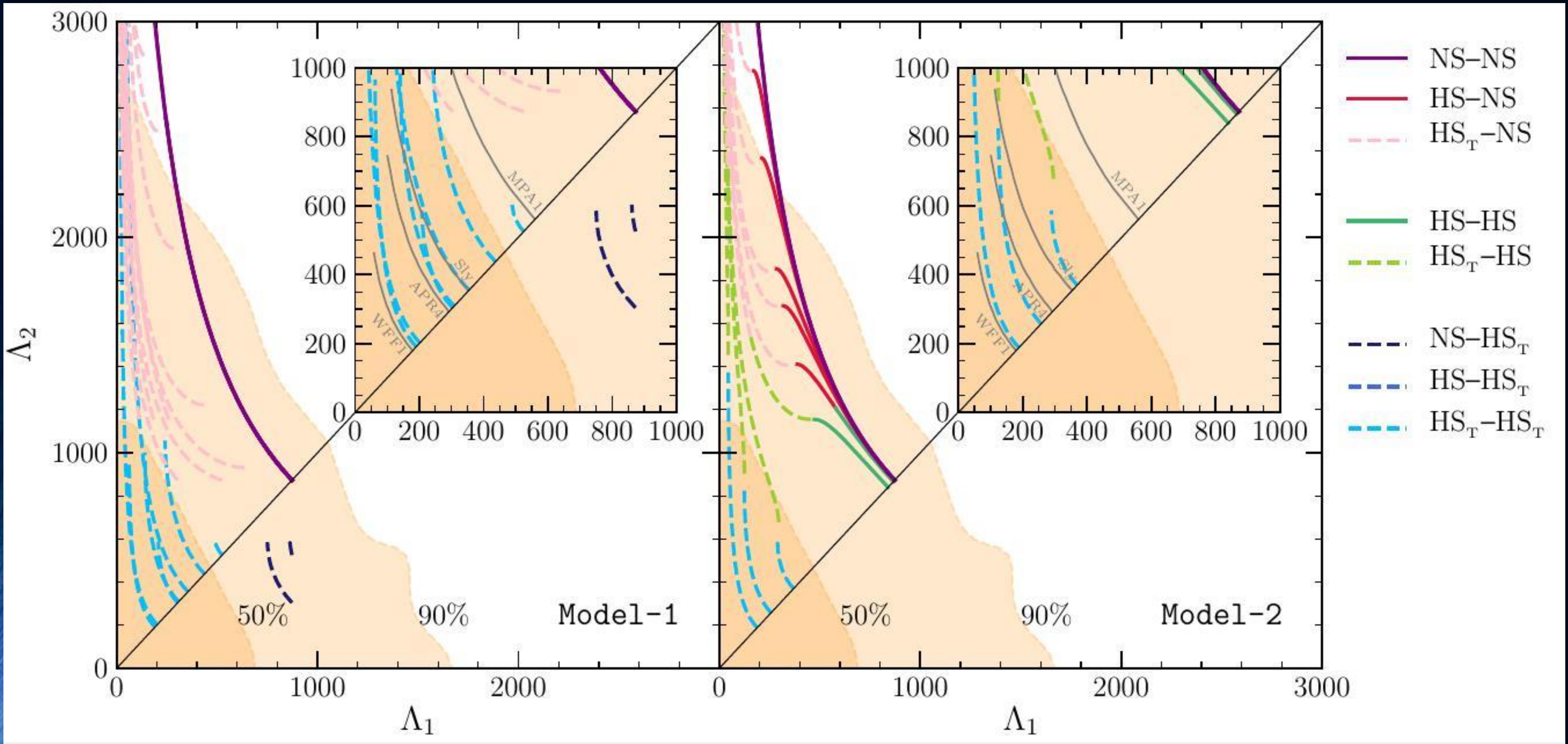
The Mass-Radius relation and the twin star property

Maxwell Construction Gibbs Construction



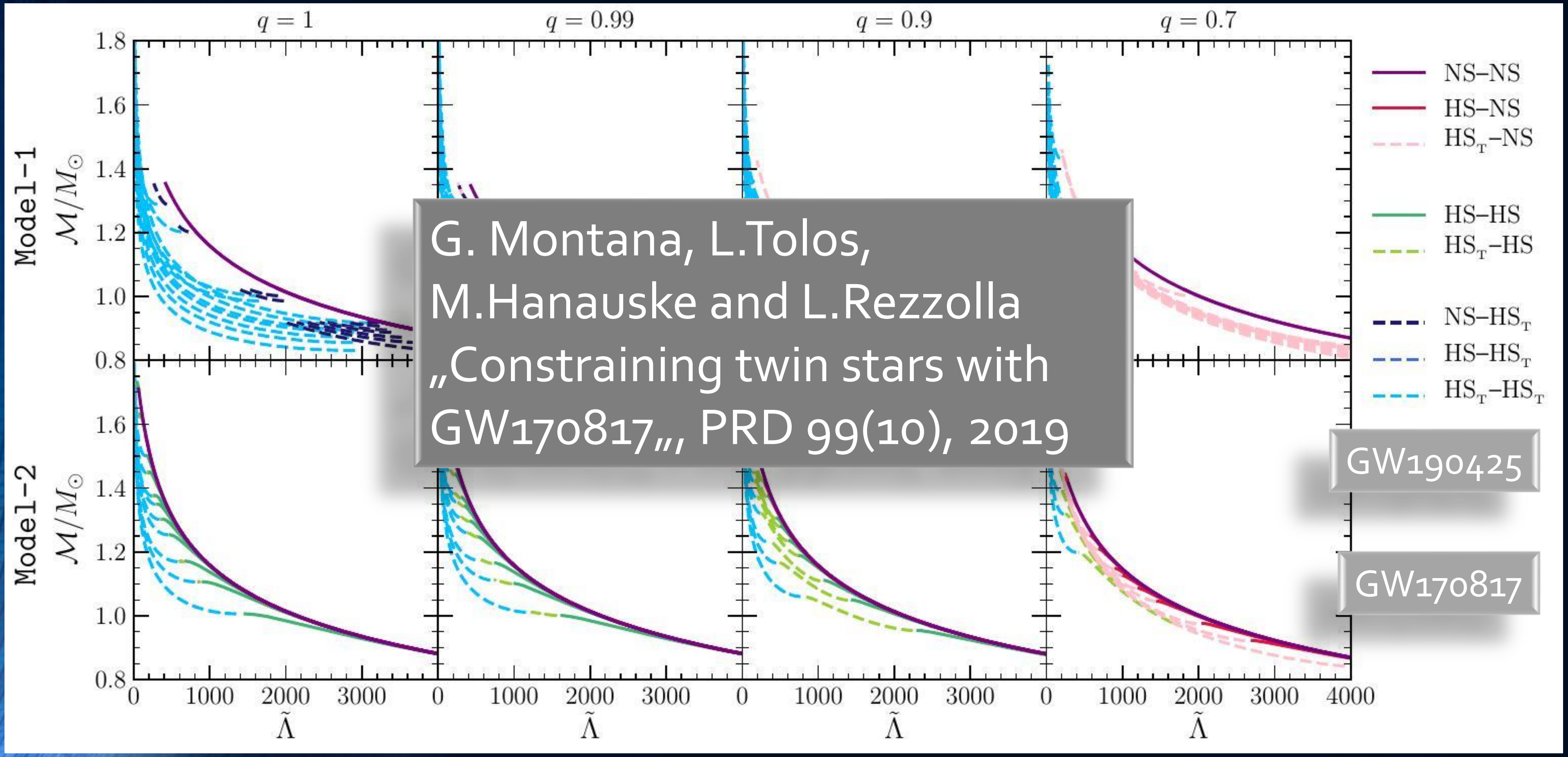
G. Montana, L.Tolos, M.Hanauske and L.Rezzolla
„Constraining twin stars with GW170817", PRD 99(10), 2019

Constraining the hadron-quark phase transition with GW170817



Assuming that the hadronic part of the EOS is given by the FSU2H model, the phase transition takes place already in the inspiral phase -> GW170817 was a hybrid star merger

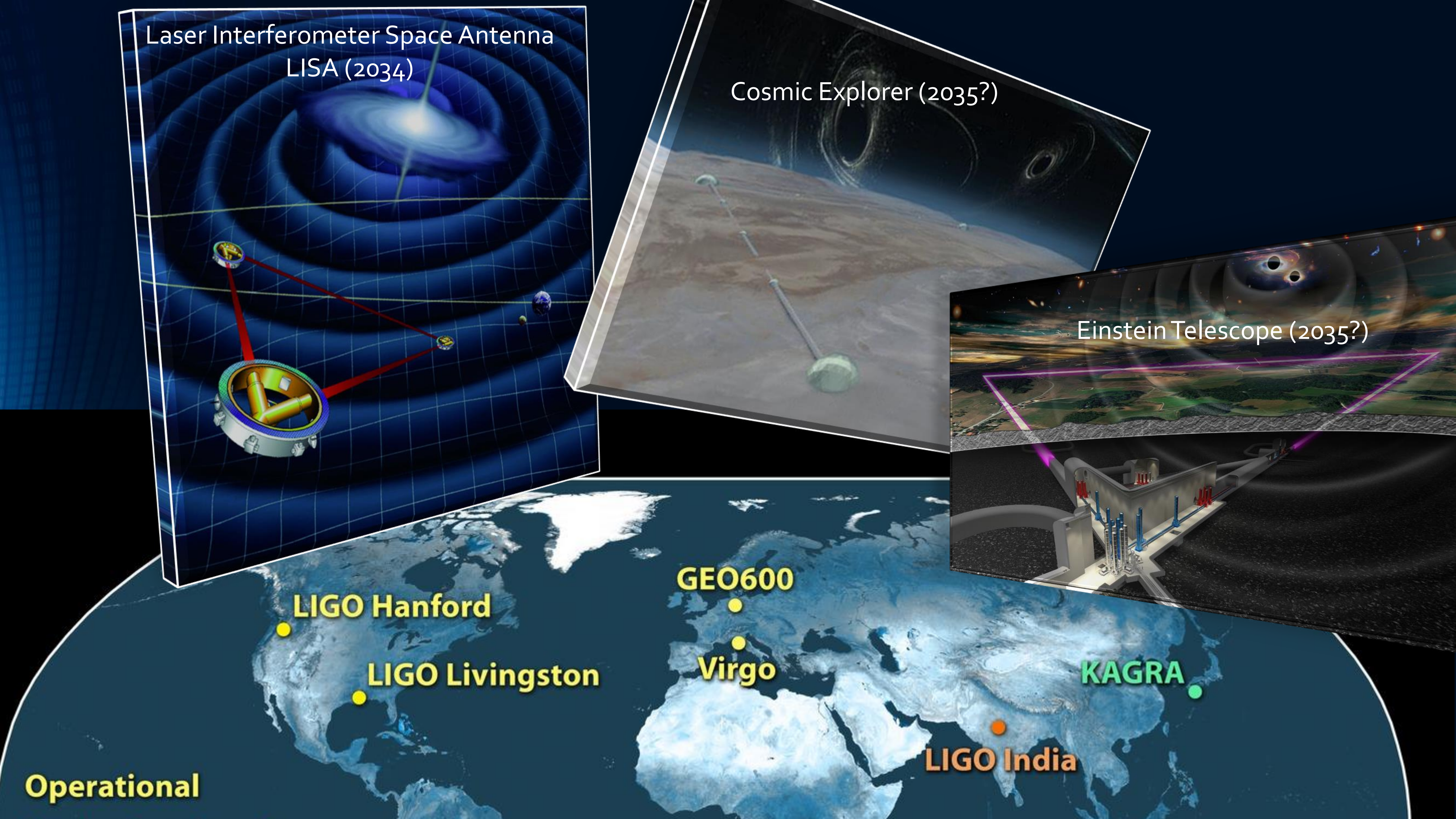
Pre-merger signatures of the hadron-quark phase transition



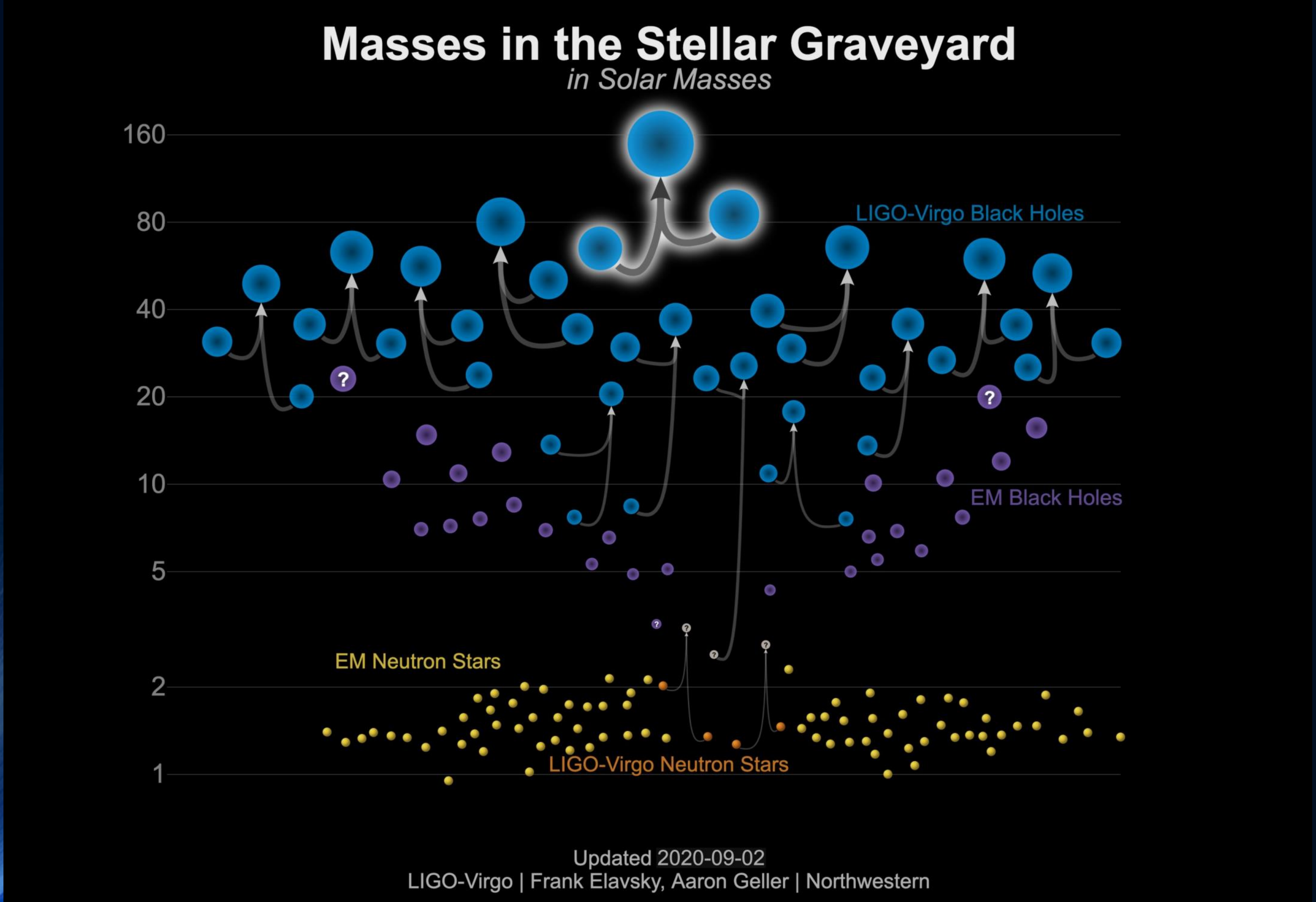
G. Montana, L.Tolos, M.Hanauske and L.Rezzolla „Constraining twin stars with GW170817„, PRD 99(10), 2019

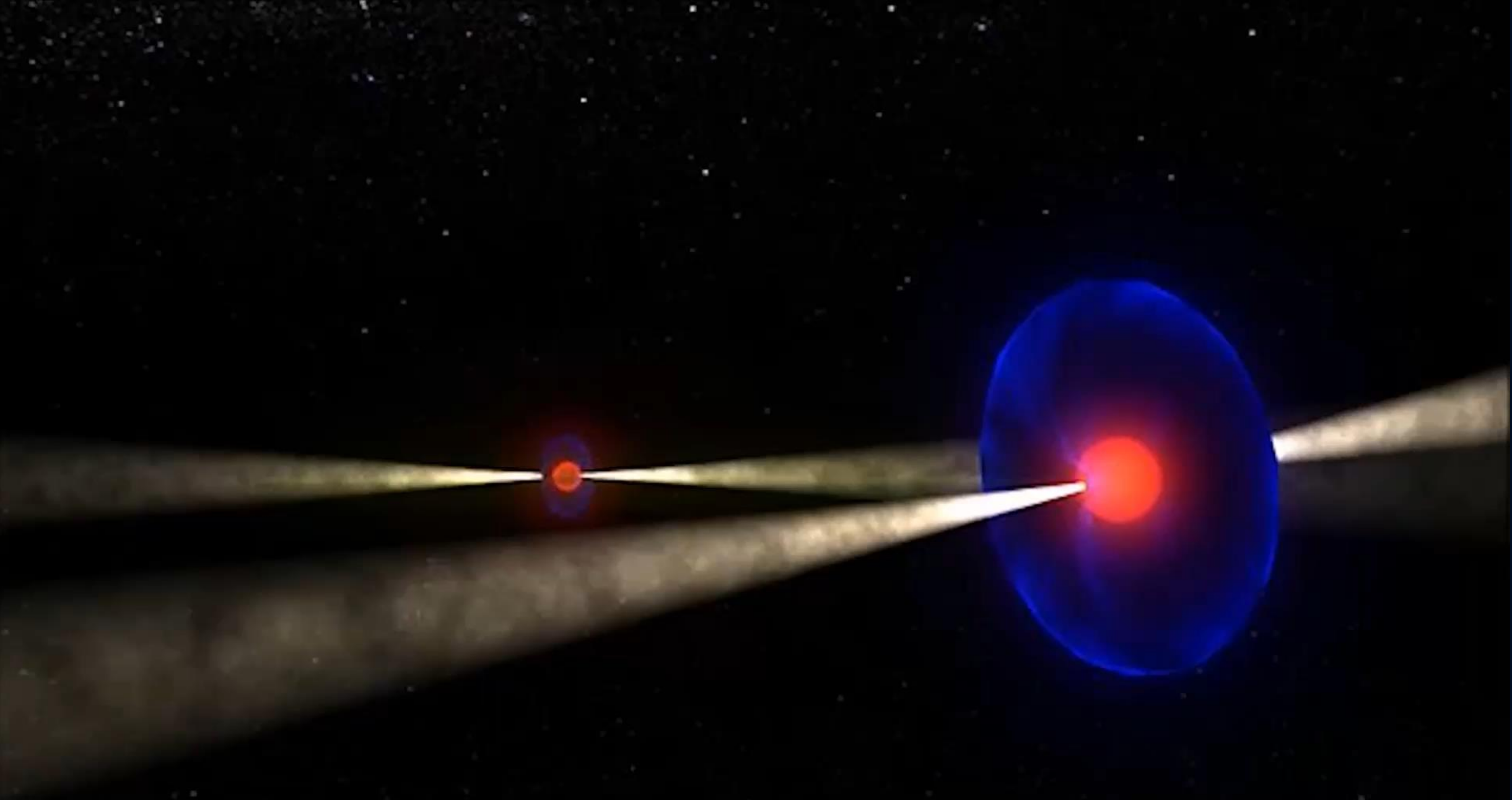
Chirp mass set to Mch as a function of the weighted dimensionless tidal deformability $\widetilde{\Lambda} = \widetilde{\Lambda}$ (M1,M2, Λ1, Λ2) for different mass ratios q

In the next few years, further gravitational waves from binary neutron star collisions with different chirp masses and mass ratios will be detected and thus the equation of state will be further restricted.


Laser Interferometer Space Antenna
LISA (2034)
Cosmic Explorer (2035?)
Einstein Telescope (2035?)
LIGO Hanford
LIGO Livingston
GEO600
Virgo
KAGRA
LIGO India
Operational

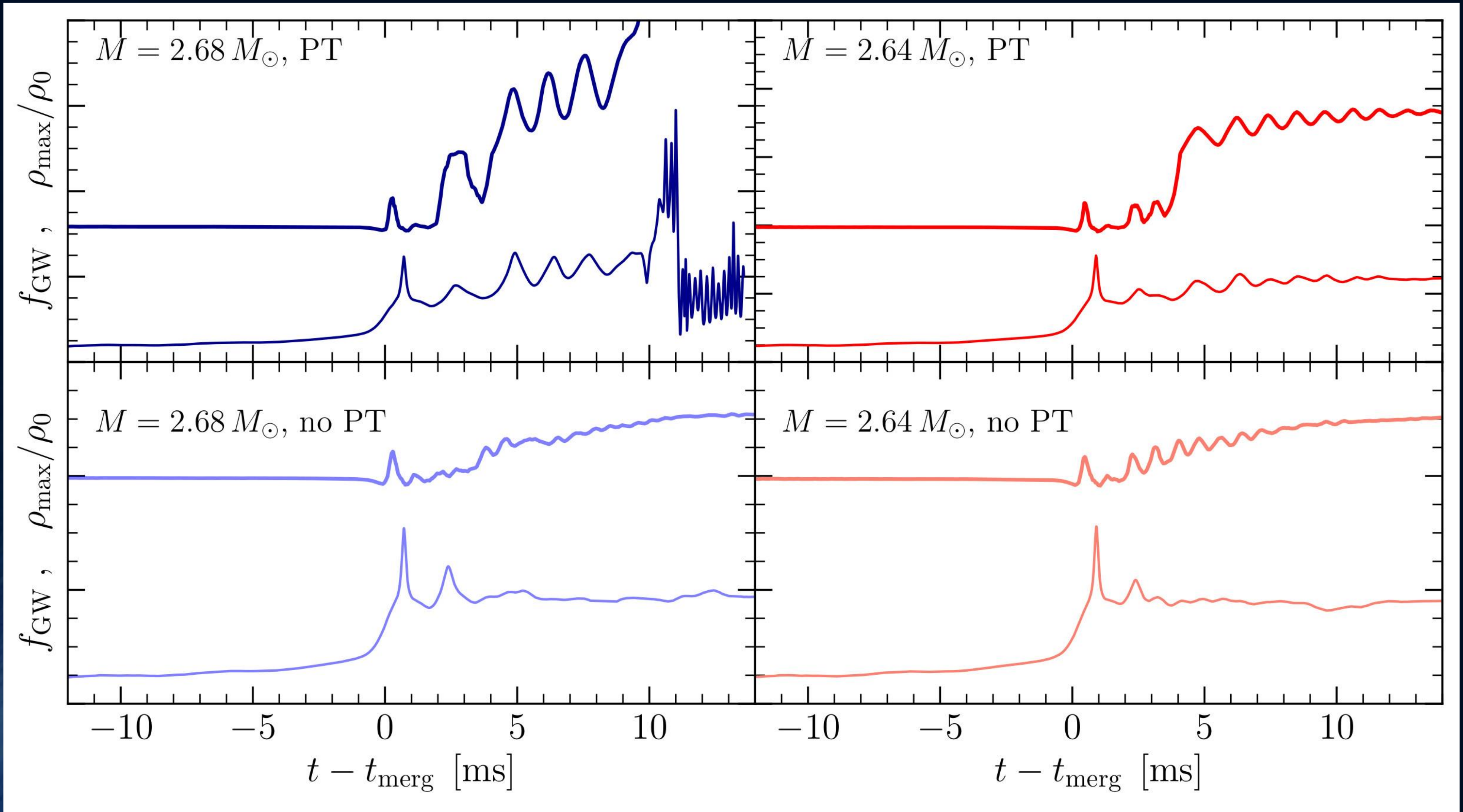
- Additional Slides


Masses in the Stellar Graveyard
in Solar Masses
160
80
40
20
10
5
2
1
LIGO-Virgo Black Holes
EM Black Holes
EM Neutron Stars
LIGO-Virgo Neutron Stars
Updated 2020-09-02
LIGO-Virgo | Frank Elavsky, Aaron Geller | Northwestern



The Neutronstar Merger Dance

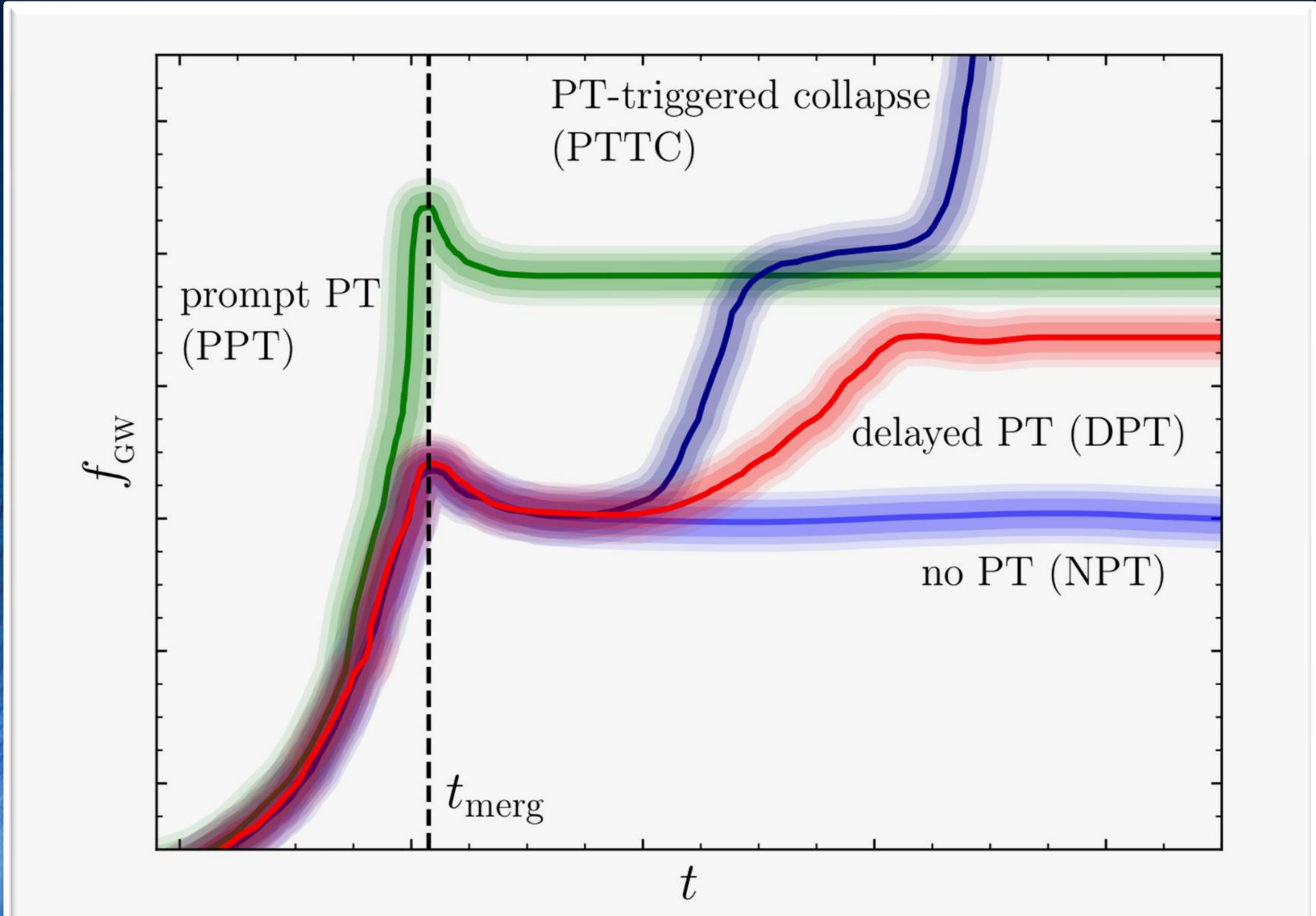
arXiv:1912.09340v1



Evolution of the central rest-mass density (top) and instantaneous gravitational wave frequency (bottom).

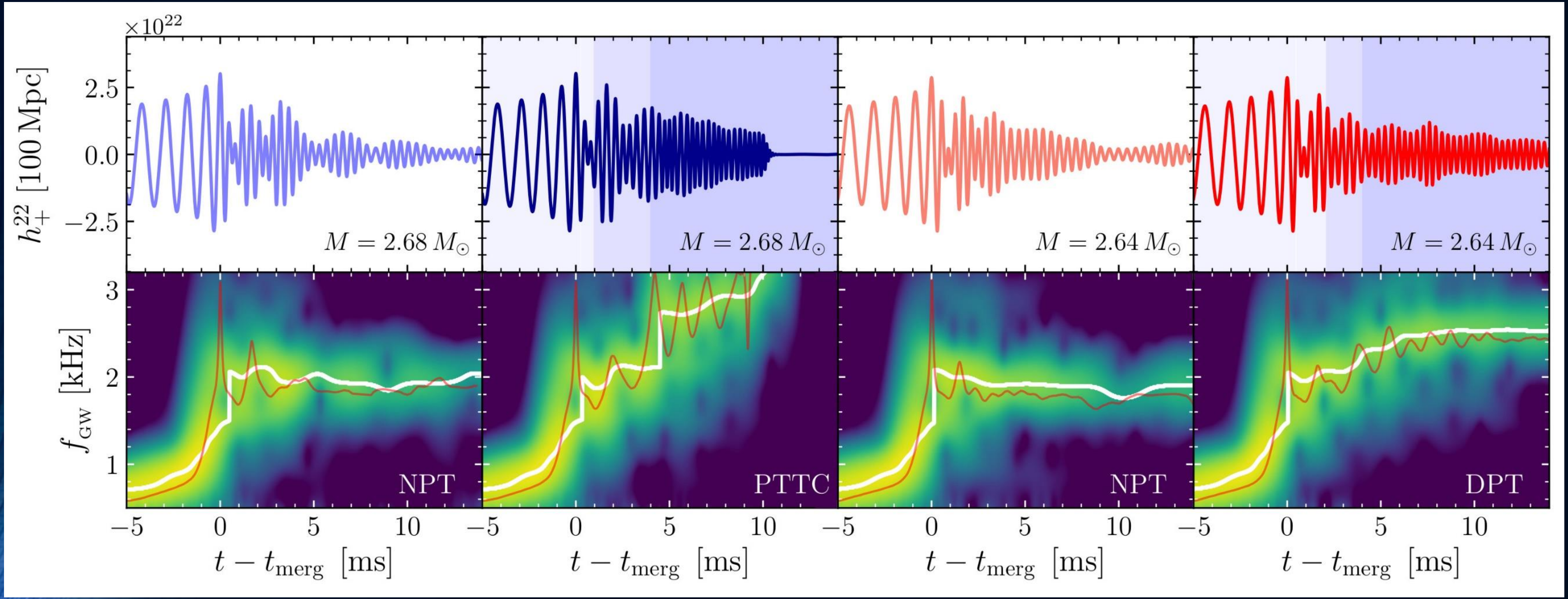
Post-merger gravitational-wave signatures of phase transitions in binary compact star mergers

PRL 124, 171103 (2020)



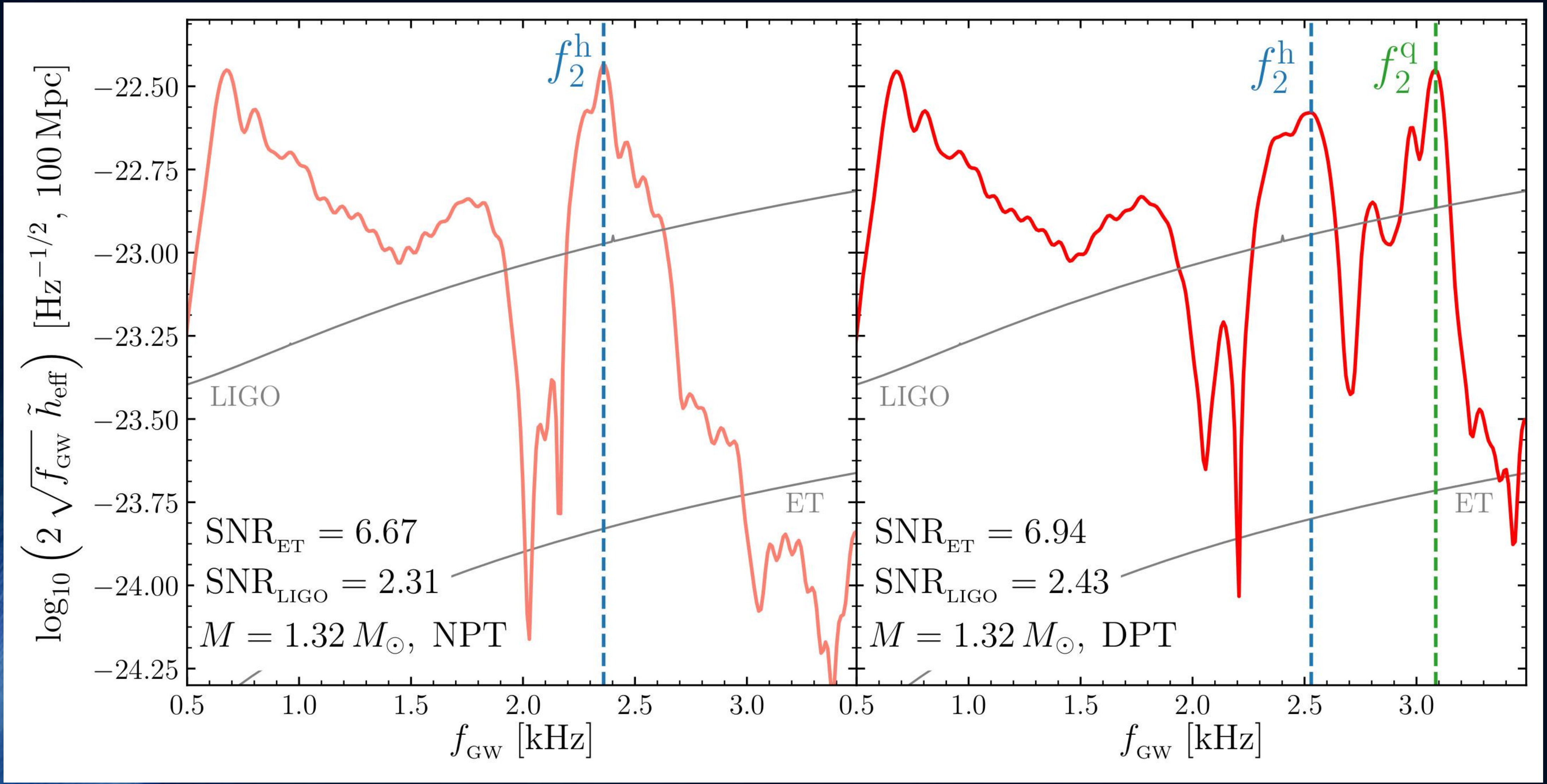
Schematic overview of the instantaneous gravitational wave frequency and how its evolution can be used to classify the different scenarios associated with a hadron-quark phase transition.

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



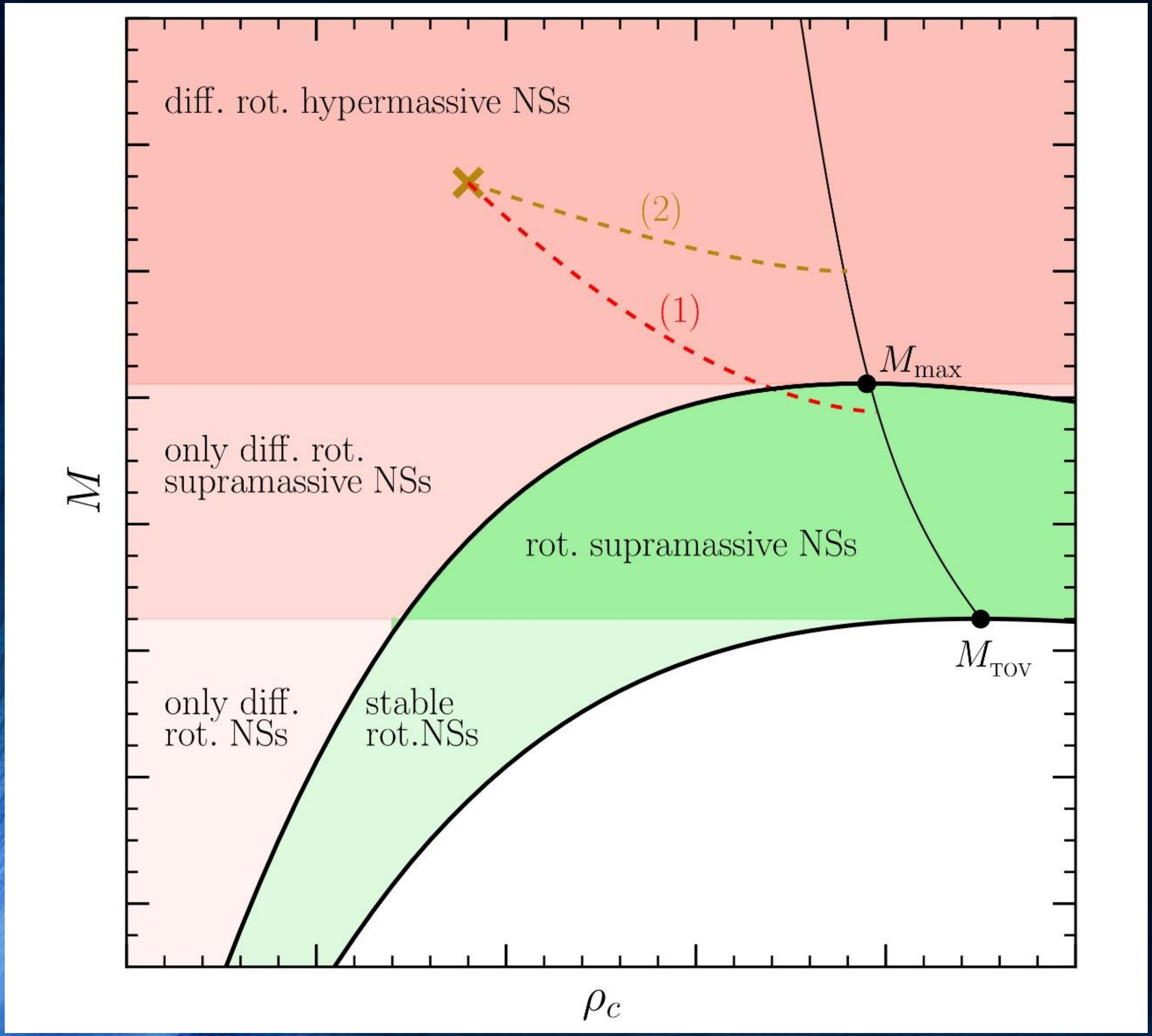
Strain h+ (top) and its spectrogram (bottom) for the four BNSs considered. In the top panels the different shadings mark the times when the HMNS core enters the mixed and quark phases the NPT models are always purely hadronic. In the bottom panels, the white lines trace the maximum of the spectrograms,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

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



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

GW170817: Constraining the maximum mass of Neutron Stars



The highly differentially rotating hypermassive/supramassive neutron star will spin down and redistribute its angular momentum (e.g. due to viscosity effects, magnetic braking). After ~1 second it will cross the stability line as a uniformly rotating supramassive neutron star (close to M_{max}) and collapse to a black hole. Parts of the ejected matter will fall back into the black hole producing the gamma-ray burst.

L.Rezzolla, E.Most, L.Weih, "Using Gravitational Wave Observations and Quasi-Universal Relations to constrain the maximum Mass of Neutron Stars",The Astrophysical Journal Letters 852, L25 (2018): $2.01 \pm 0.04 < M_{TOV} < 2.16 \pm 0.17$

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

The Einstein Equation and the EOS of Compact Stars

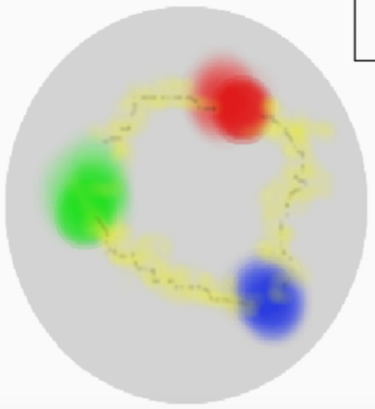
ART	Yang-Mills-Theories
$D_\beta v^\alpha = \partial_\beta v^\alpha + \Gamma^\alpha_{\sigma\beta} v^\sigma$	$D_{\beta a}{}^{b} = \partial_\beta 1_a{}^{b} + ig A_{\beta a}{}^{b}$
$R^\delta{}_{\mu\alpha\beta} v^\mu = [D_\alpha, D_\beta] v^\delta$ $R^\delta{}_{\mu\alpha\beta} = \Gamma^\delta_{\mu\alpha\|\beta} - \Gamma^\delta_{\mu\beta\|\alpha} + \Gamma^\delta_{\nu\beta}\Gamma^\nu_{\mu\alpha} + \Gamma^\delta_{\nu\alpha}\Gamma^\nu_{\mu\beta}$	$F_{\alpha\beta a}{}^{b} = \frac{1}{ig}\left[D_{\alpha a}{}^{c}, D_{\beta c}{}^{b}\right] = A_{\beta a}{}^{b}{}_{\|\alpha} - A_{\alpha a}{}^{b}{}_{\|\beta} + \frac{1}{ig}\left[A_{\alpha a}{}^{c}, A_{\beta c}{}^{b}\right]$
$\mathcal{L}_G = R + \underbrace{(c_1 R_{\mu\nu} R^{\mu\nu} + \dots)}_{\equiv 0 \text{ for ART}}$	$\mathcal{L}_{YM} = \frac{1}{4} F_{\mu\nu a}{}^{b} F^{\mu\nu}{}_{a}{}^{b}$

QuantumCromoDynamic:

$(SU(3)_{(c)}$- Color Yang-Mills-Gauge Theory)

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

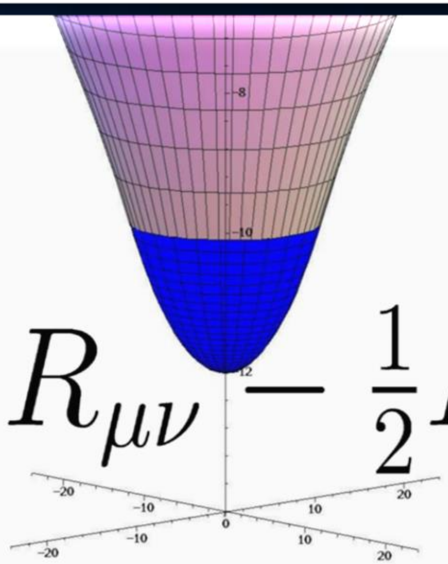
$_{A,}{}^{B}$ =red, green, blue

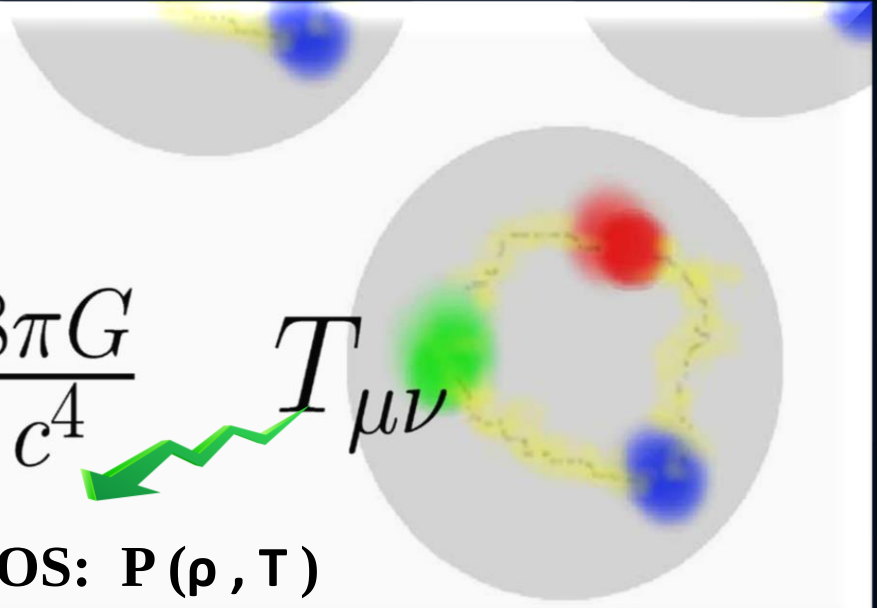


$$\psi^f_A = \begin{pmatrix} \psi^f_r \\ \psi^f_g \\ \psi^f_b \end{pmatrix}$$

Confinement

chiral symmetry, ...





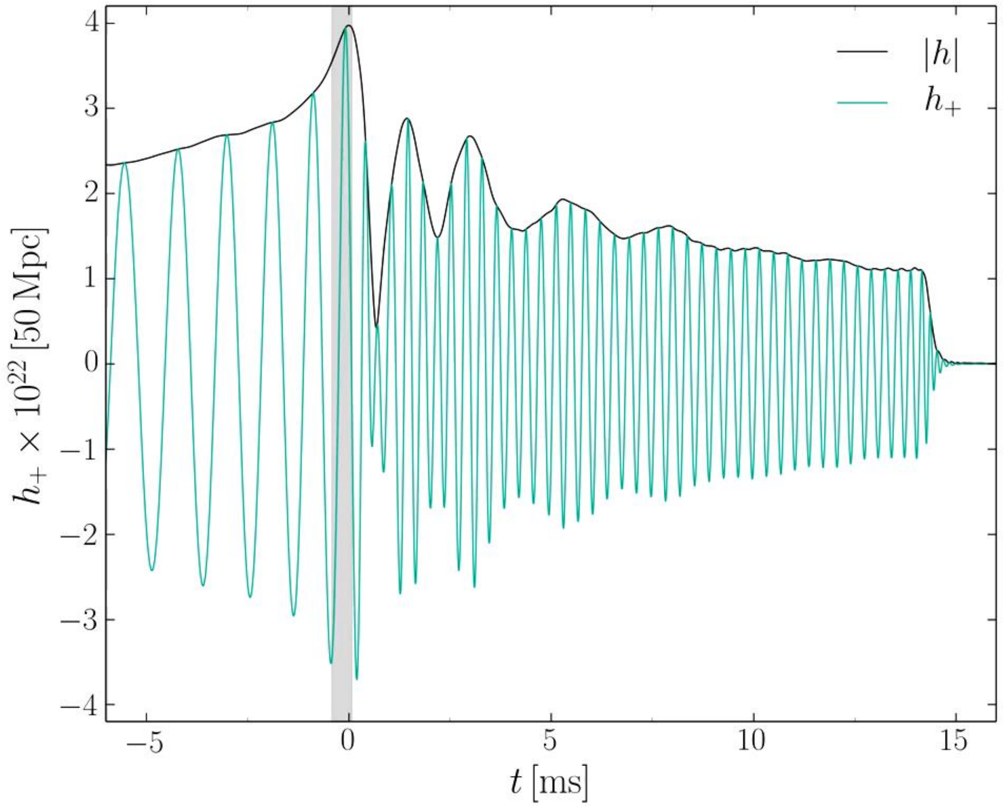
$$R_{\mu\nu} - \frac{1}{2} R\, g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

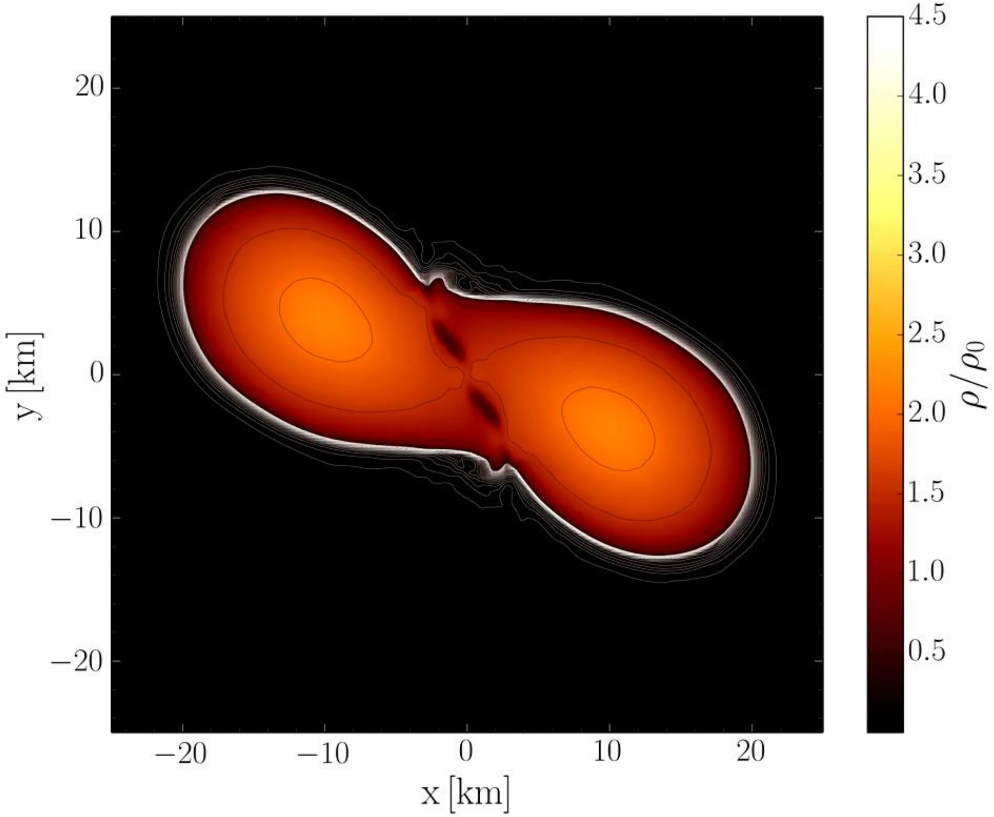
EOS: P (ρ , T)

Evolution of the density in the post merger phase

ALF2-EOS: Mixed phase region starts at $3\rho_0$ (see red curve), initial NS mass: 1.35 $M_\odot$

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





Gravitational wave amplitude
at a distance of 50 Mpc

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

Hypermassive/Supramassive hybrid stars as neutron-star merger remnants

- Introduction
- Numerical general relativity of compact star mergers
- The equation of state of compact star matter and the hadron-quark phase transition
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- Gravitational-wave signatures of the hadron-quark phase transition in binary compact star mergers
  - Hypermassive hybrid stars (HMHS) within the phase transition triggered collapse scenario (PTTC)
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  - SMHS and HMHS within the prompt phase transition scenario (PPT)
  - The inspiral and merger phase (premerger signals)
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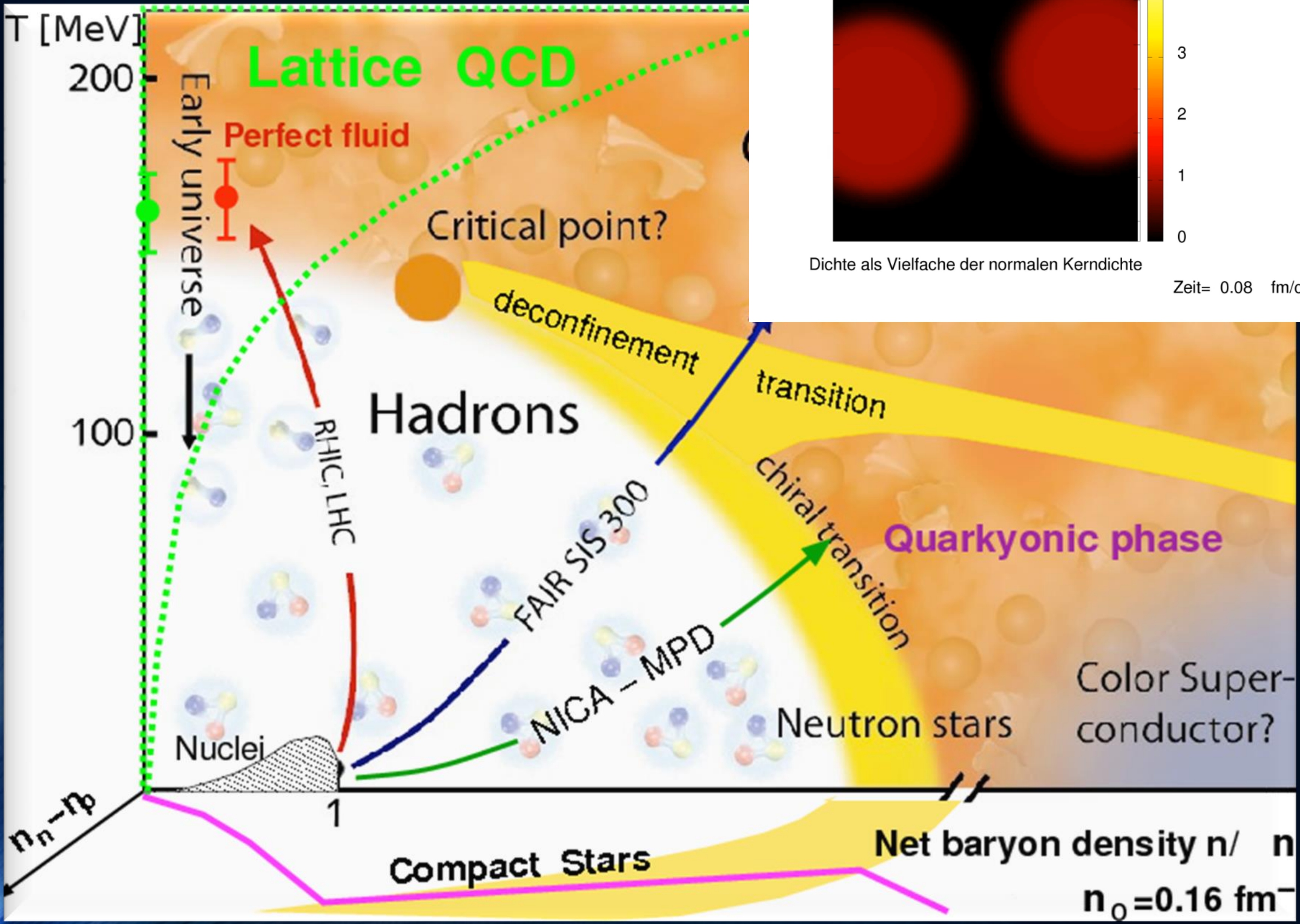
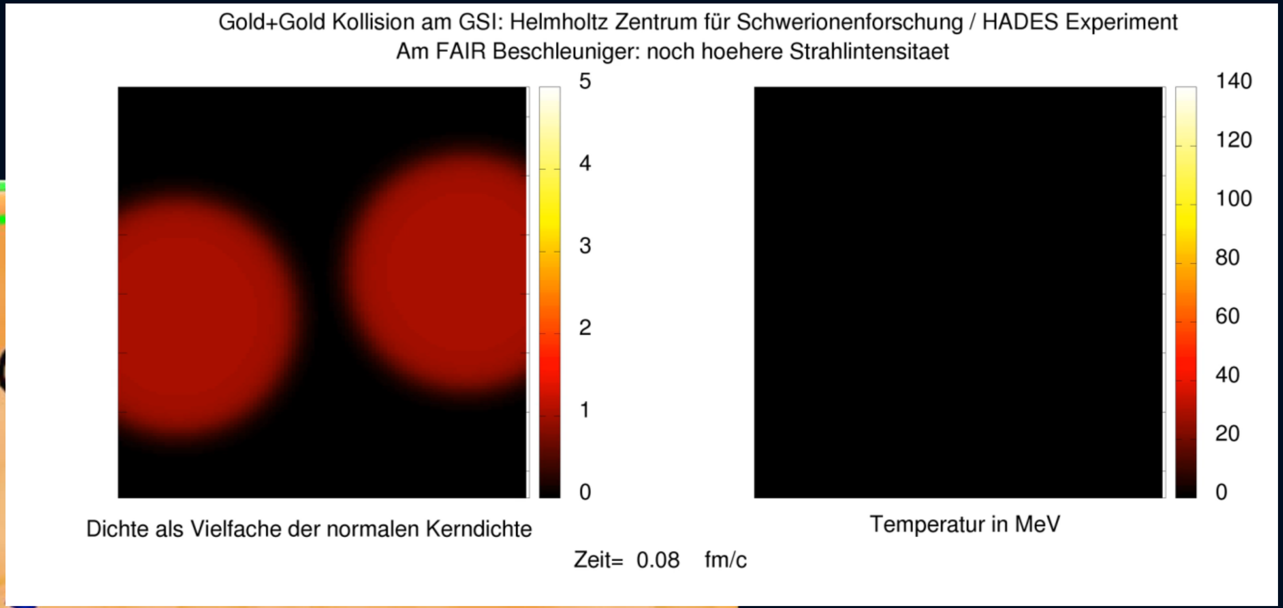
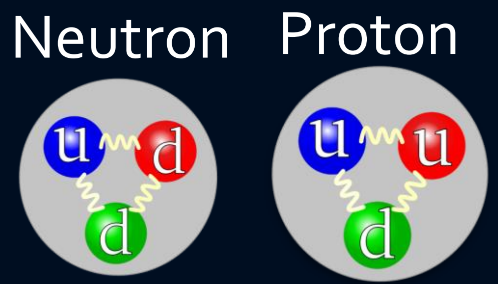
The Hadron-Quark Phase Transition

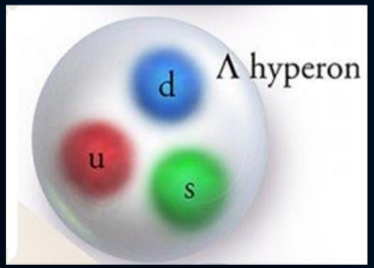
The QCD Phase Diagram



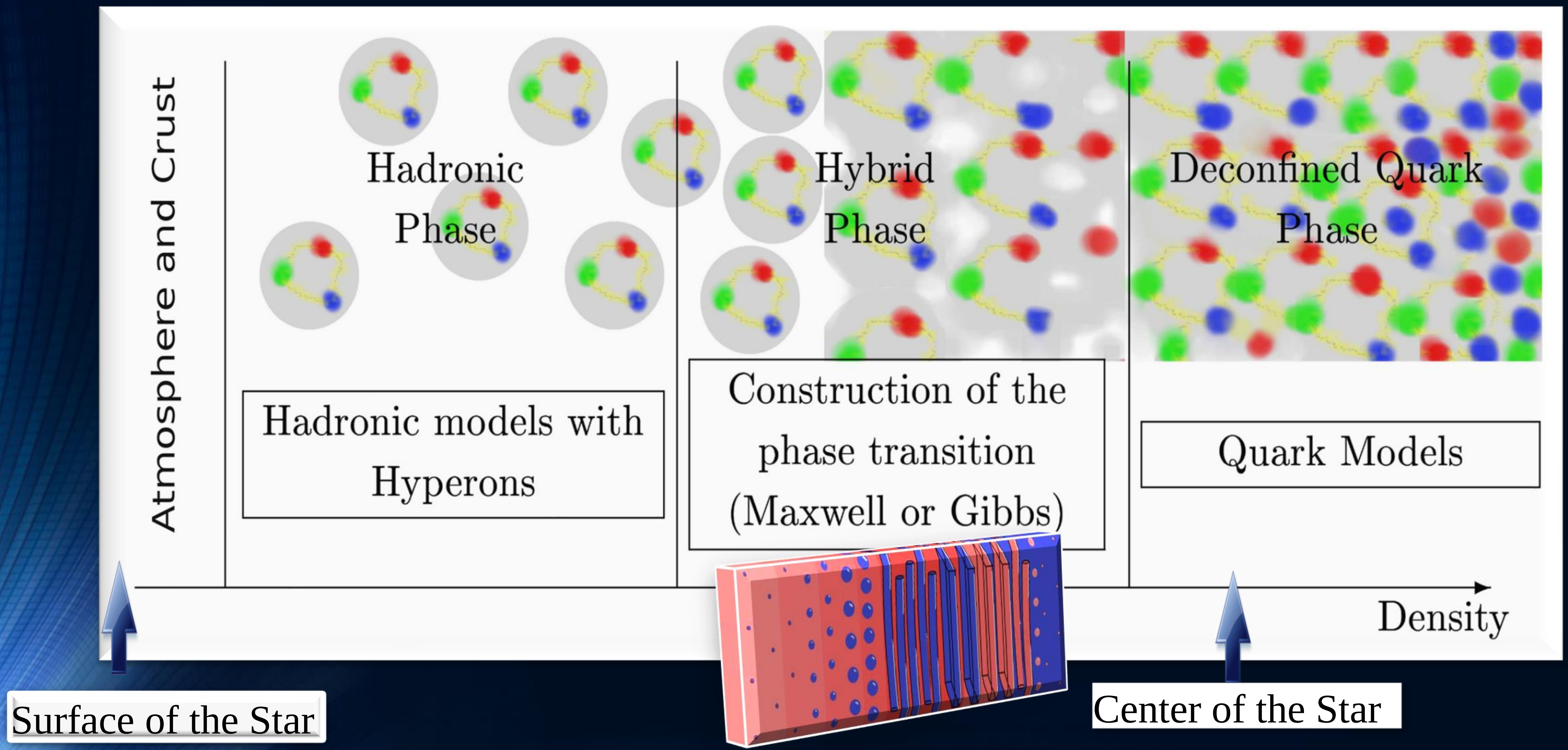


Credits:
Jan Steinheimer





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)

Hypermassive/Supramassive hybrid stars as neutron-star merger remnants

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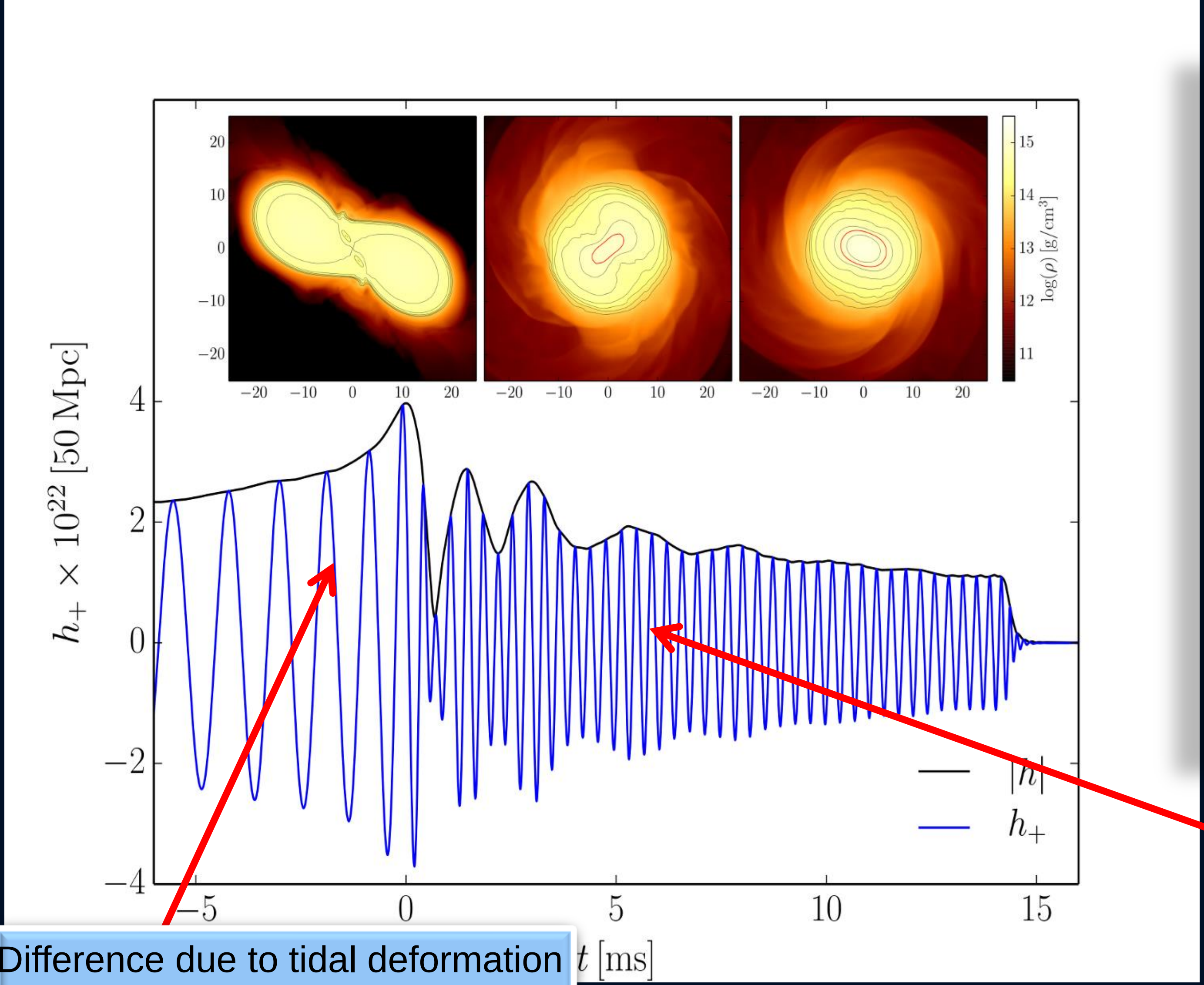
Computer Simulation of a Binary Neutron Star Merger

Credits: Cosima Breu, David Radice und Luciano Rezzolla

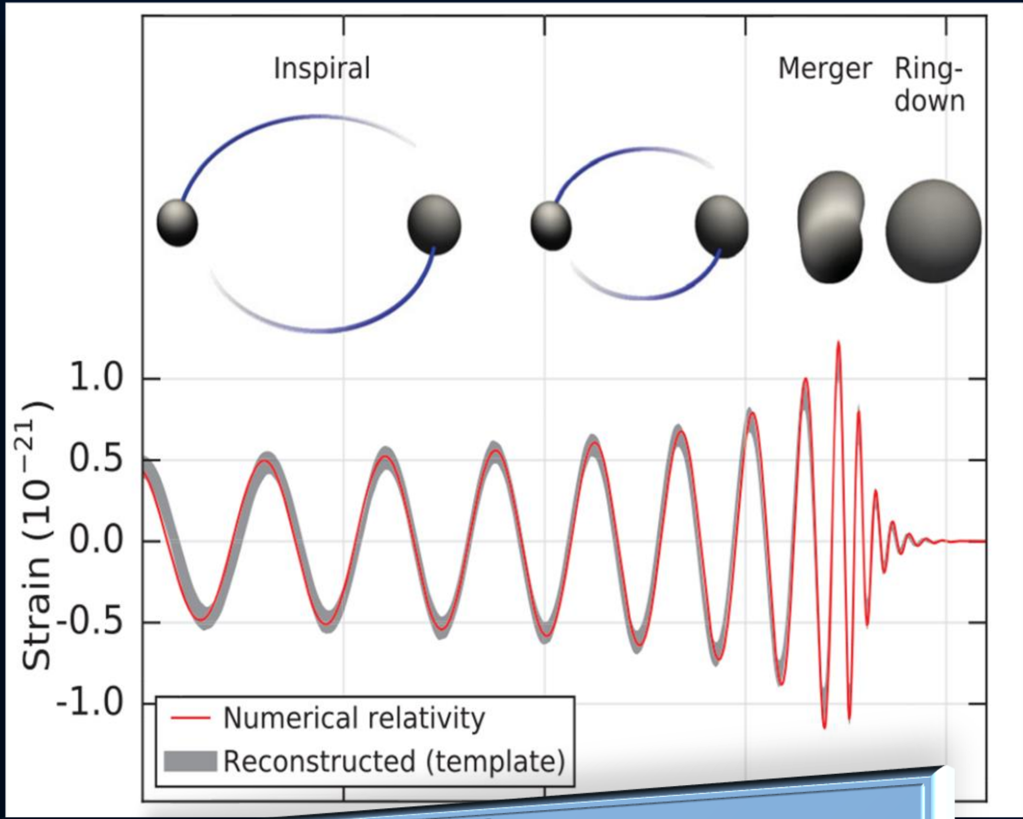
Gravitational Waves from Neutron Star Mergers

Neutron Star Collision (Simulation)



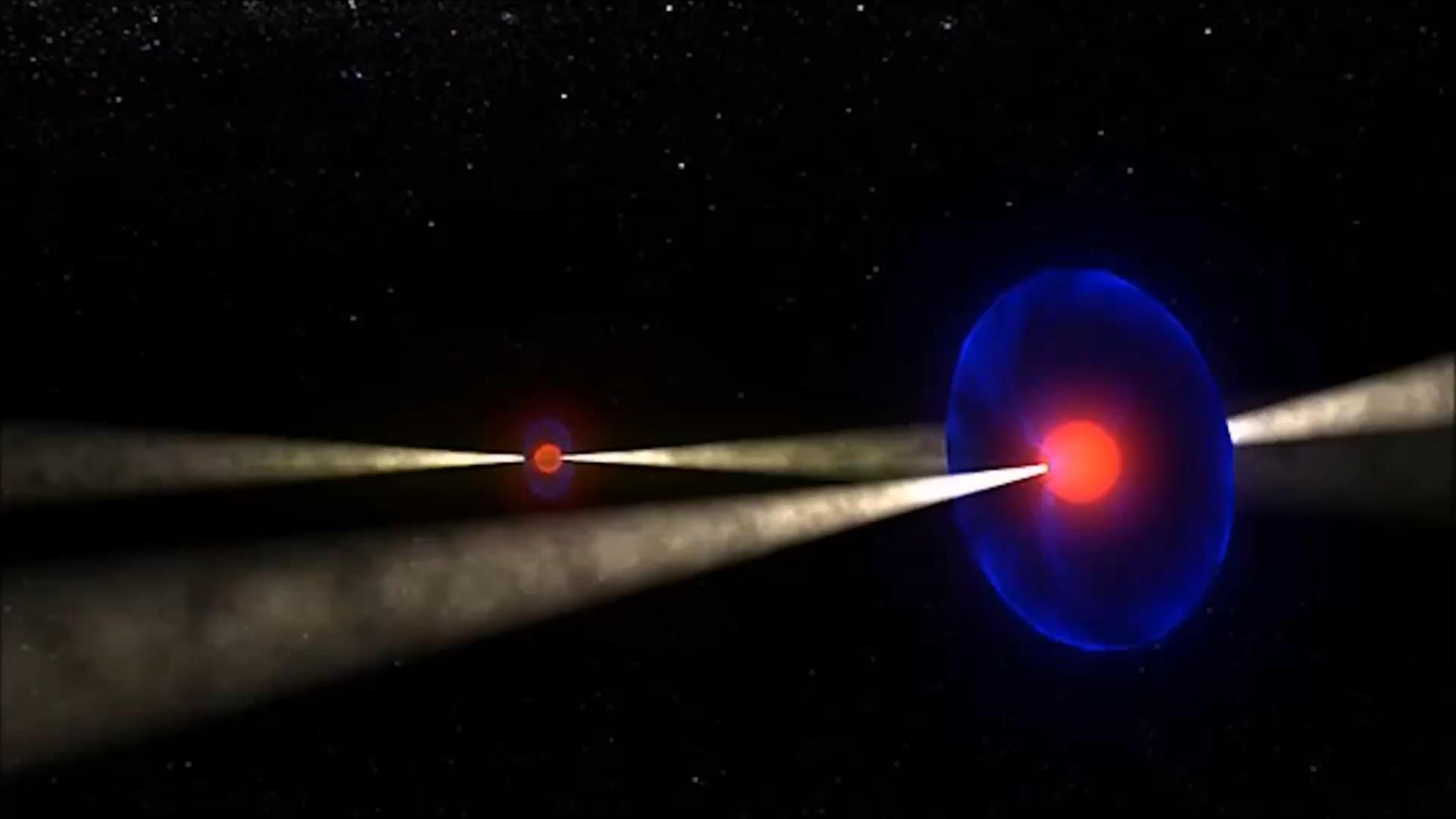
Difference due to tidal deformation in the late inspiral phase

Collision of two Black Holes
GW150914

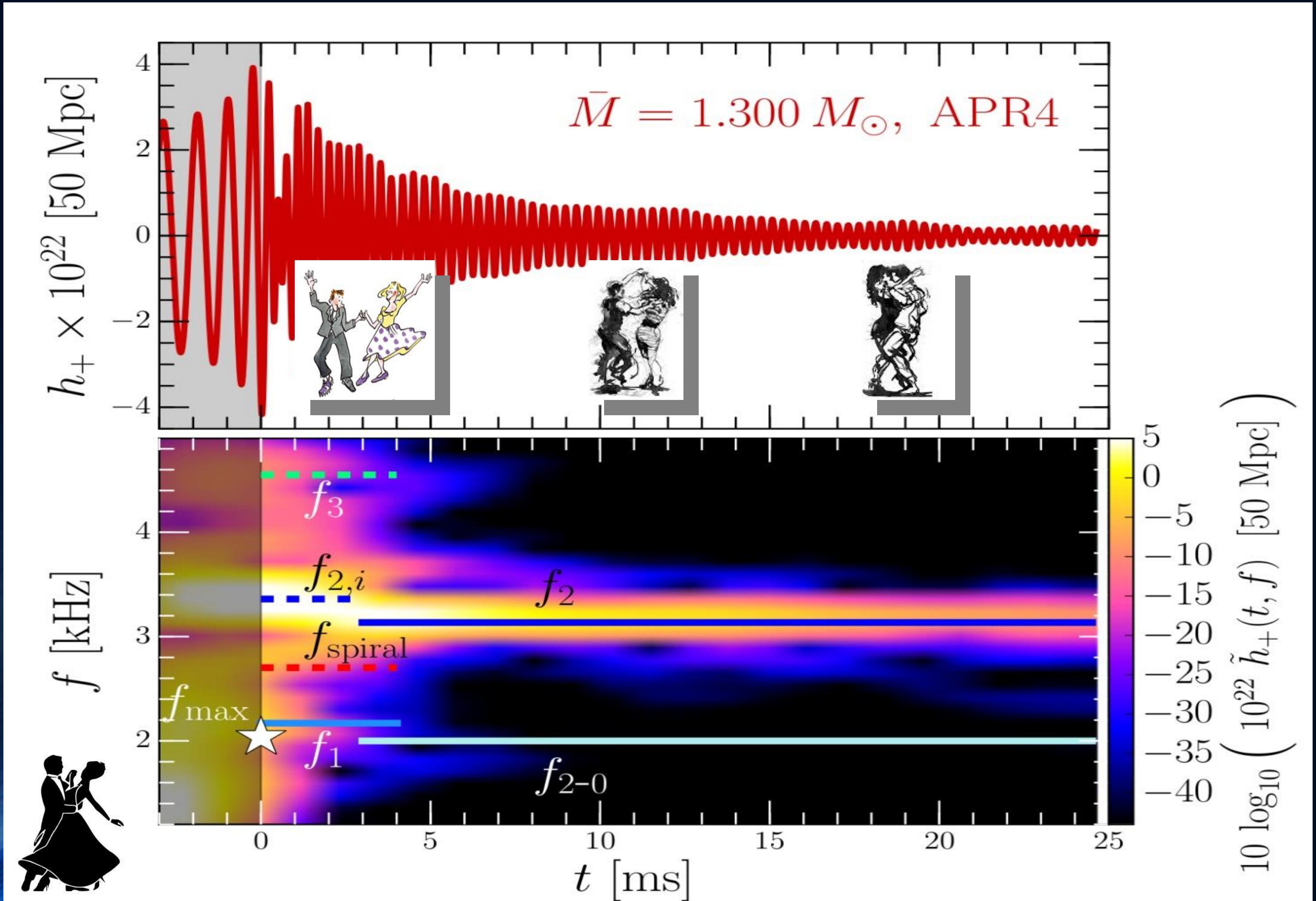


Main difference:

In binary neutron star mergers a **Post-Merger Phase** often exists



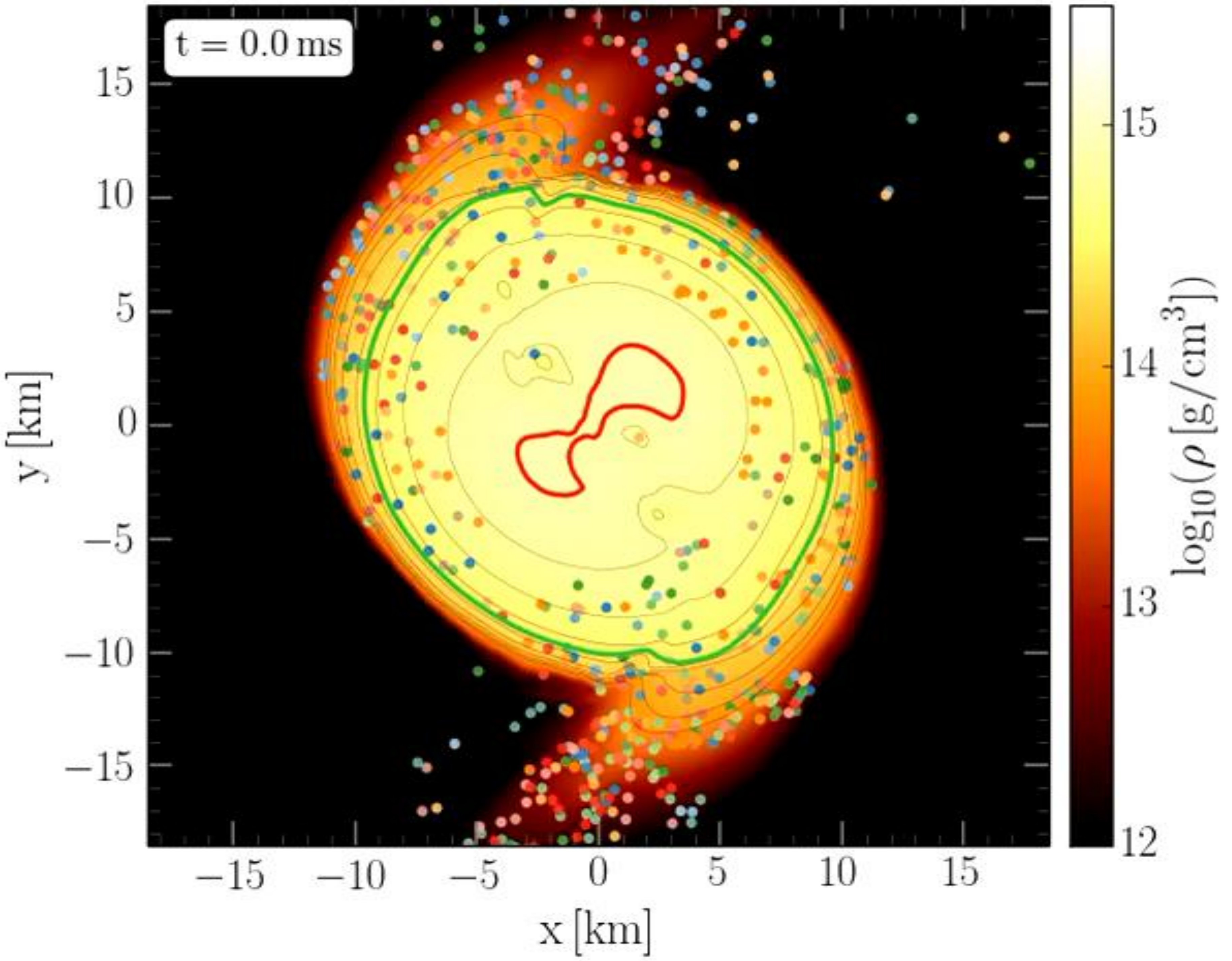
The different Phases during the Postmergerphase of the HMNS



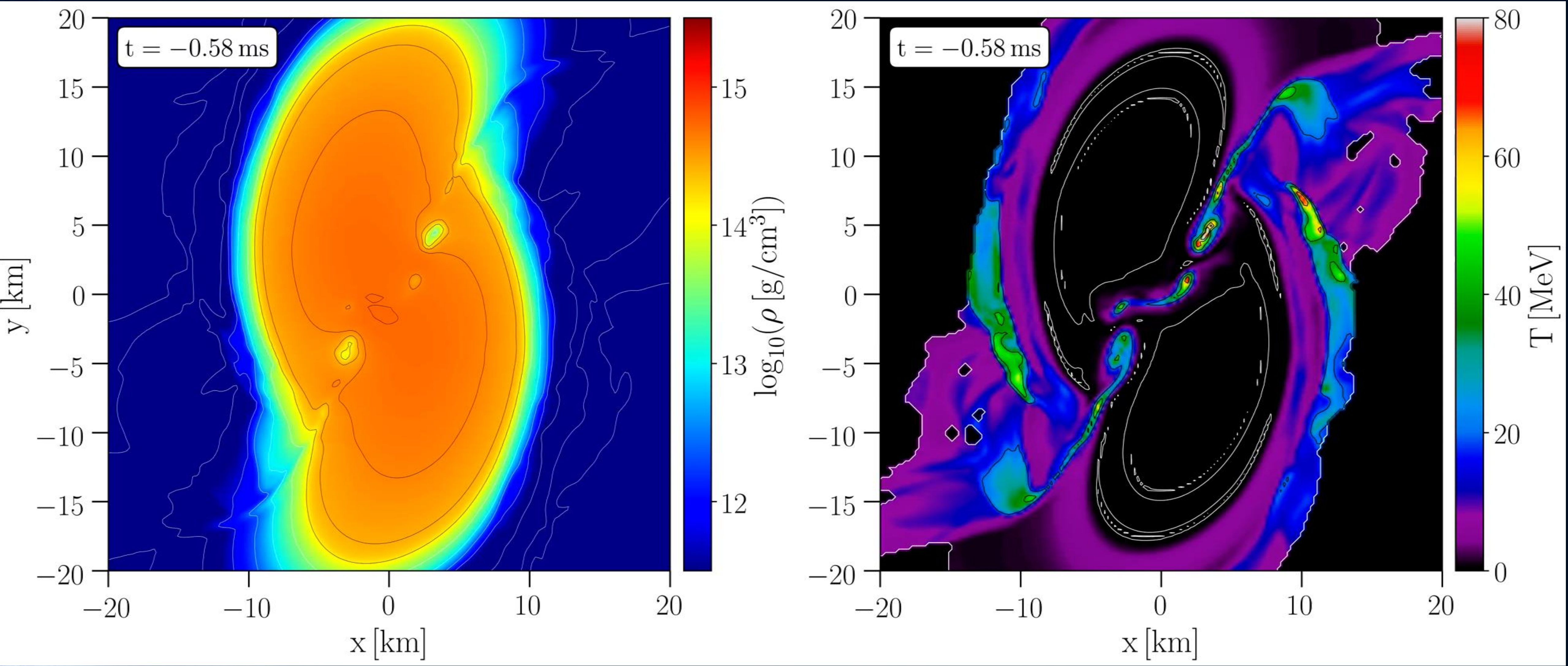
Evolution of Tracer-particles tracking individual fluid elements in the equatorial plane of the HMNS at post-merger times

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

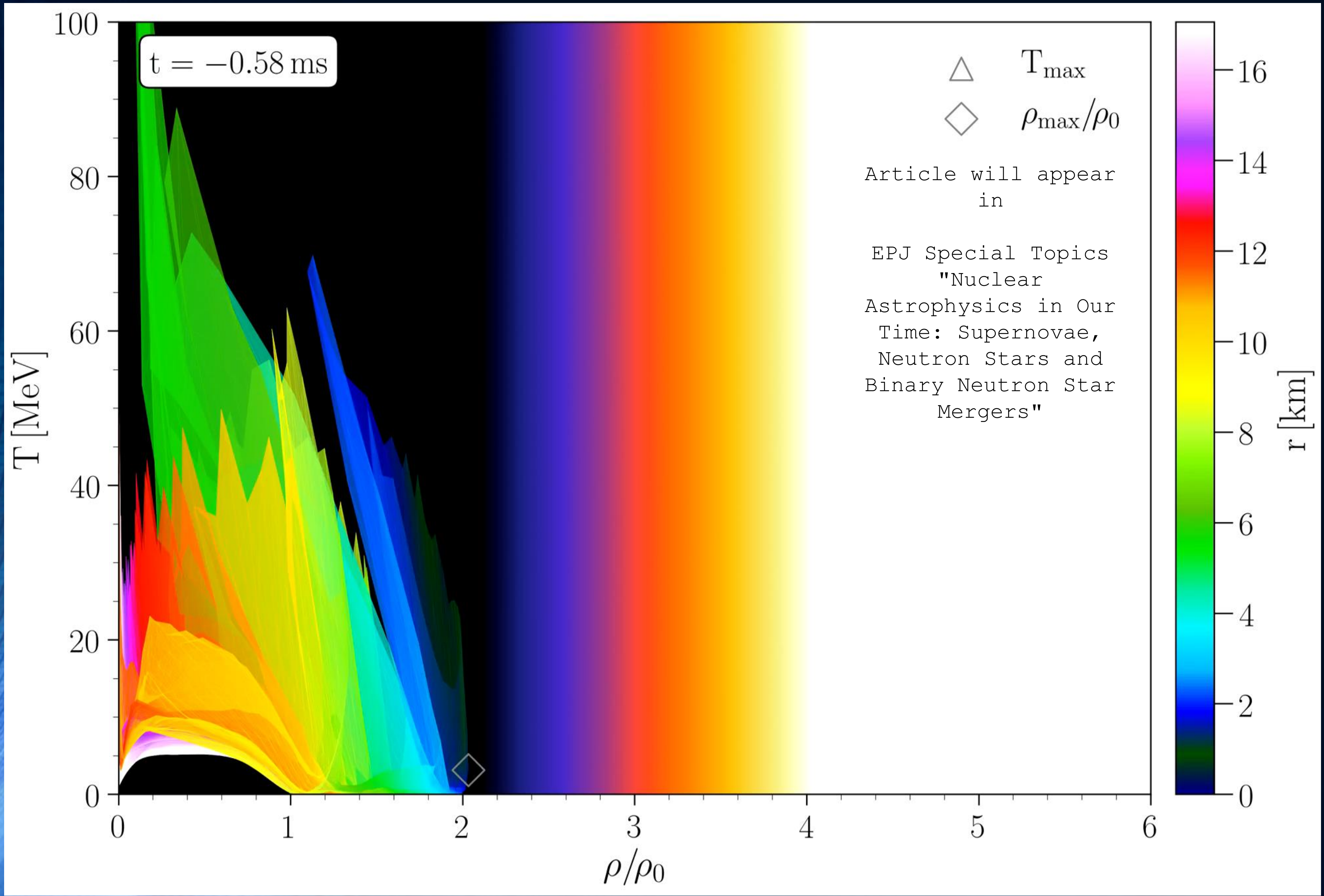


Density and temperature evolution inside the HMHS



EOS: FSU2H-PT + thermal ideal fluid, Mass: 1.32 $M_\odot$

Binary Neutron Star Mergers in the QCD Phase Diagram

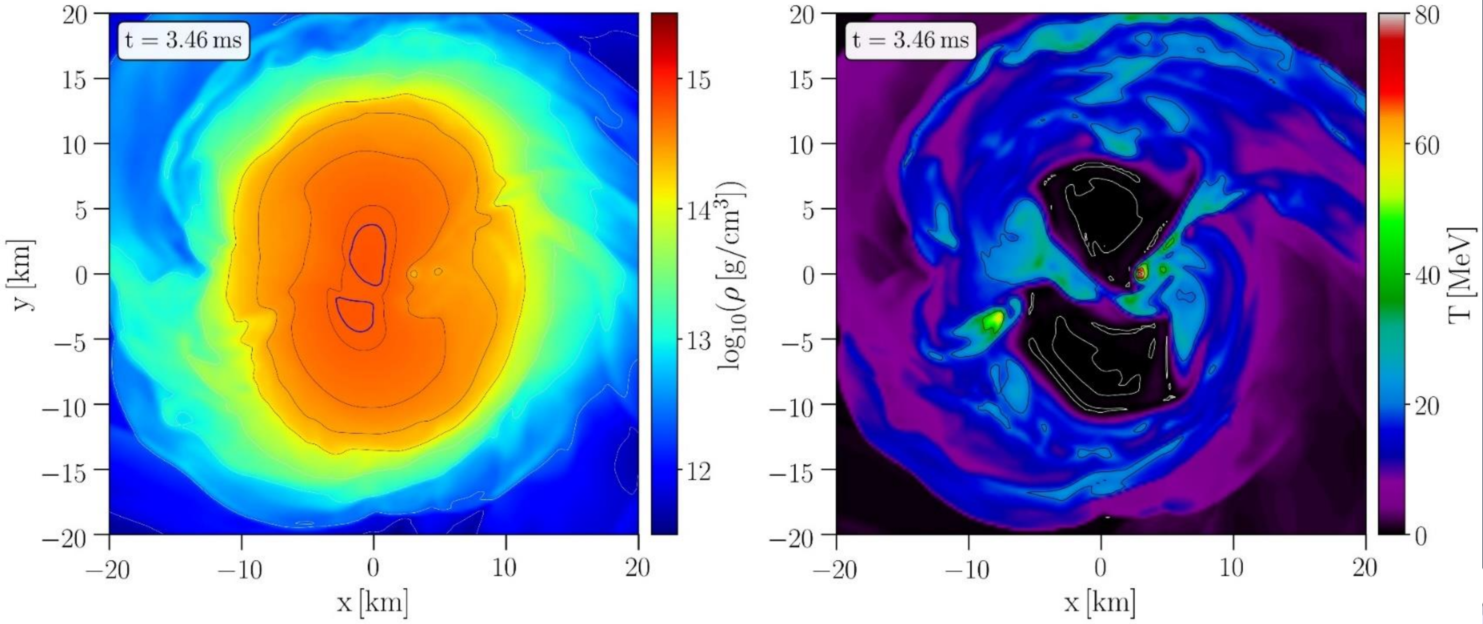


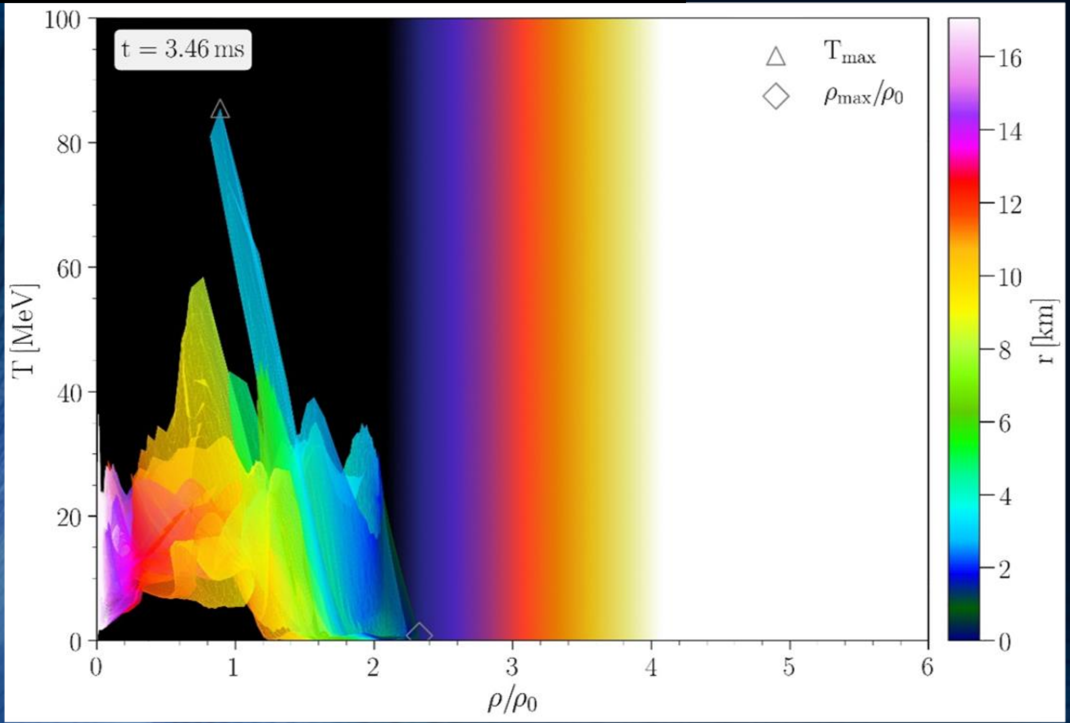
Evolution of hot and dense matter inside the inner area of a hypermassive hybrid star simulated within the (FSU2H-PT + thermal ideal fluid) EOS with a total mass of M_{total}=2.64 $M_\odot$ in the style of a (T- ρ) QCD phase diagram plot

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.

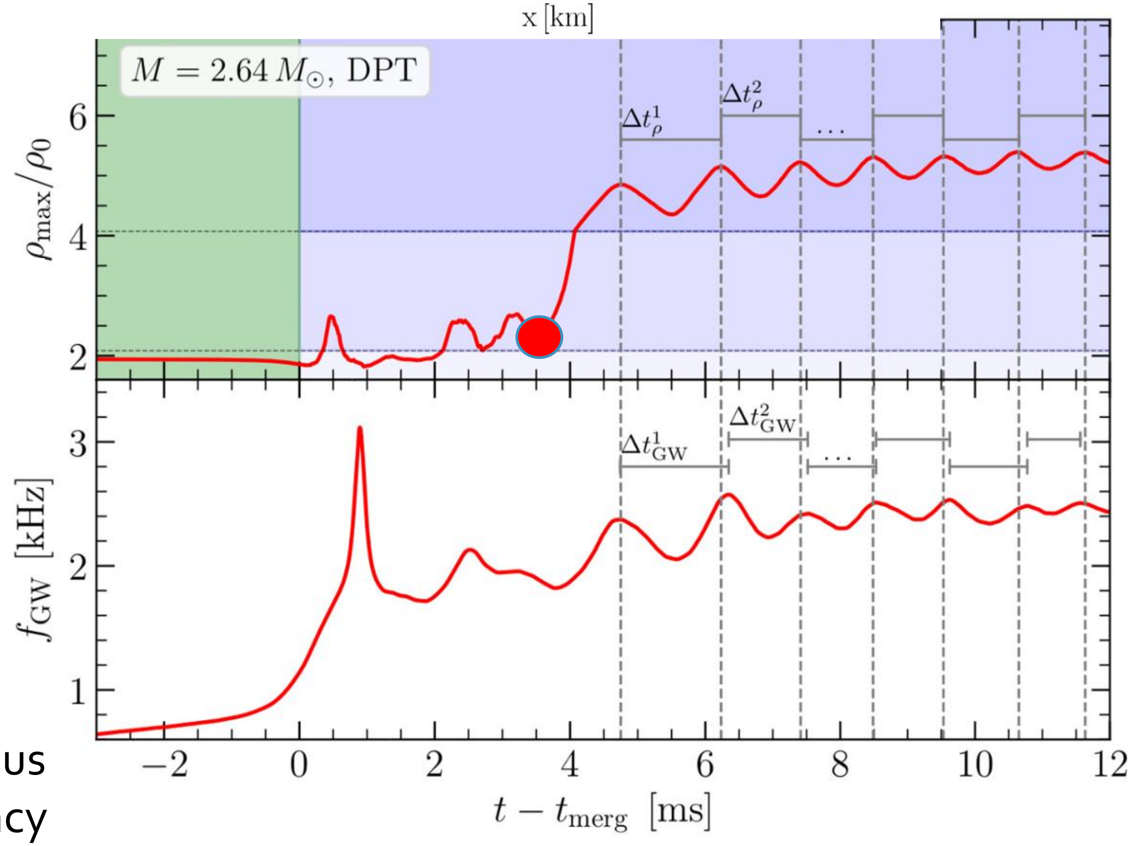
These figures show the configuration of the HMHS at a time right before the collapse to the more compact star. The small asymmetry in the density profile and especially the double-core structure is amplified by the collapse resulting in a large one-sided asymmetry (i.e., an m = 1 asymmetry in a spherical-harmonics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



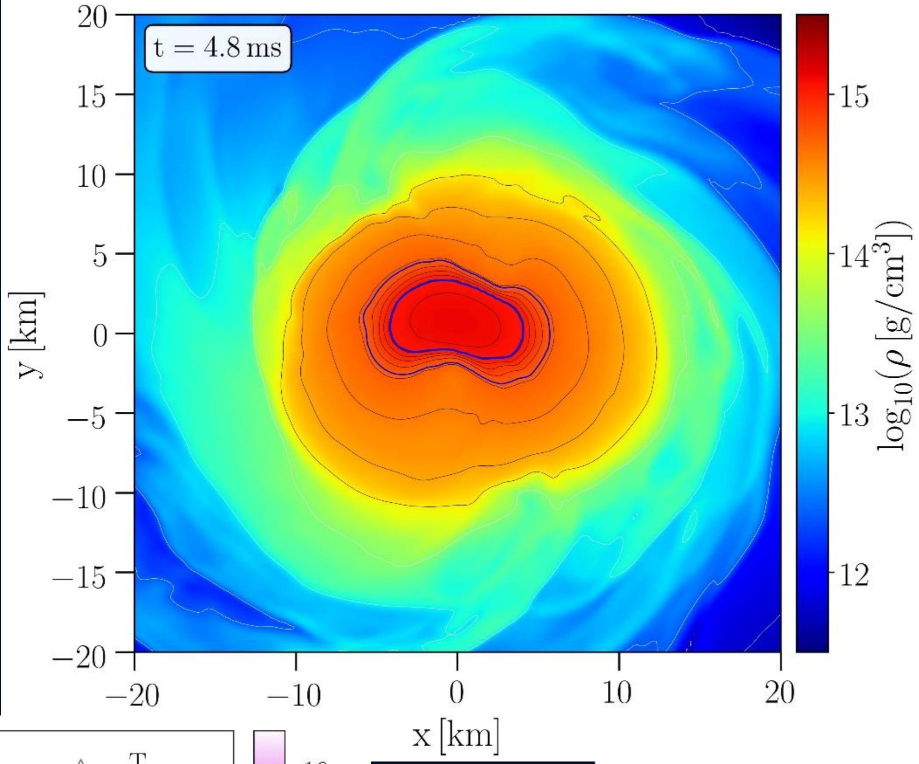


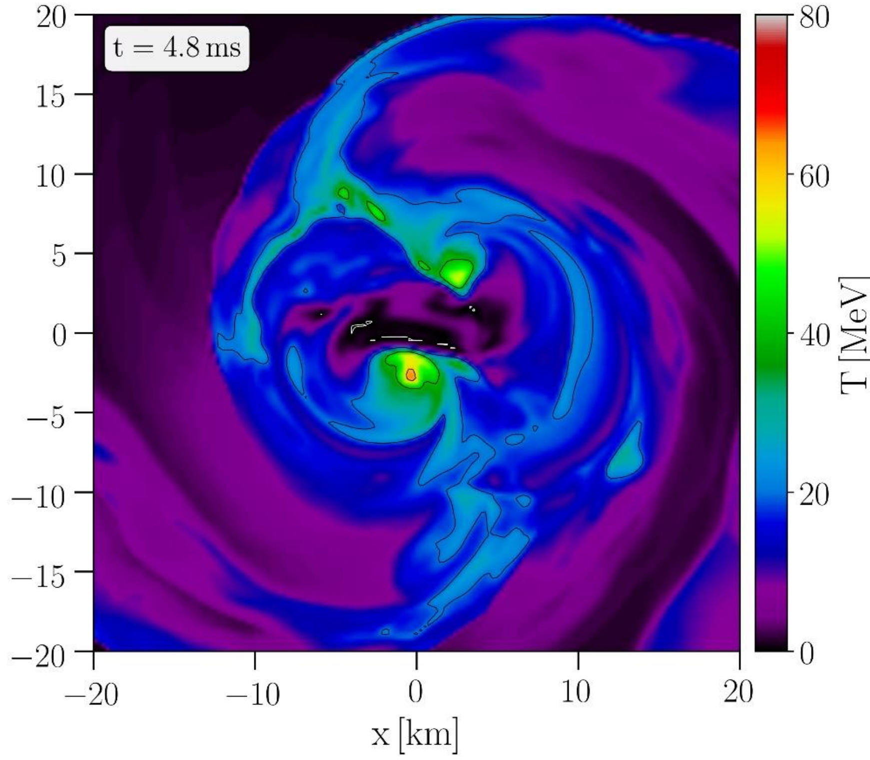
Density maximum

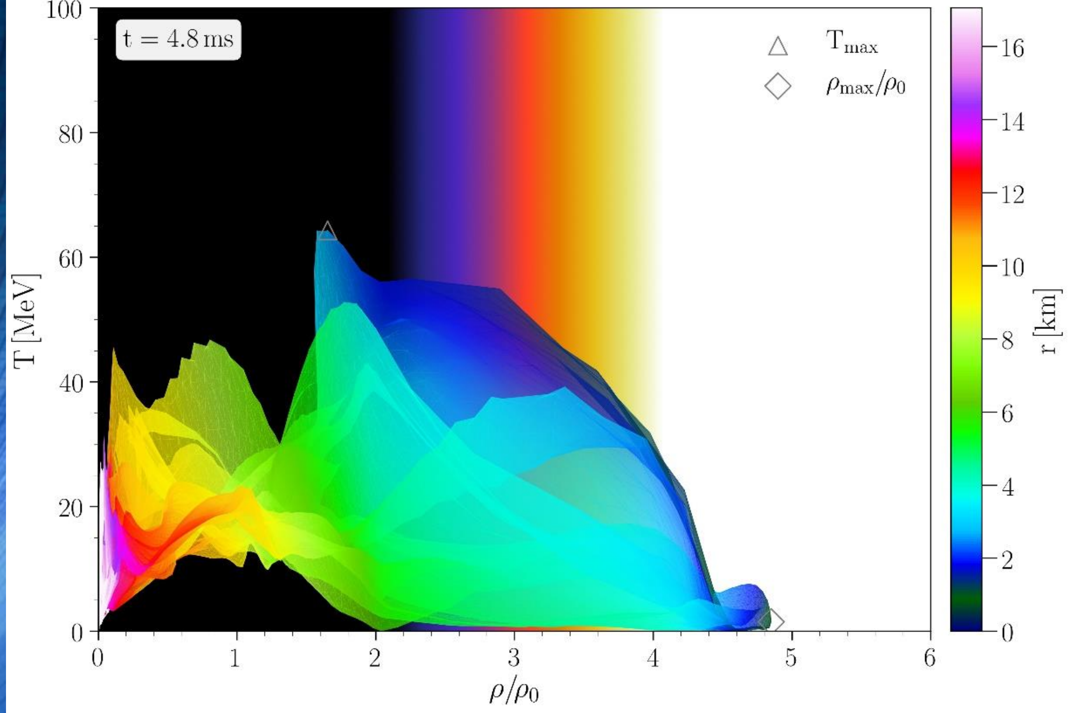
Instantaneous GW frequency

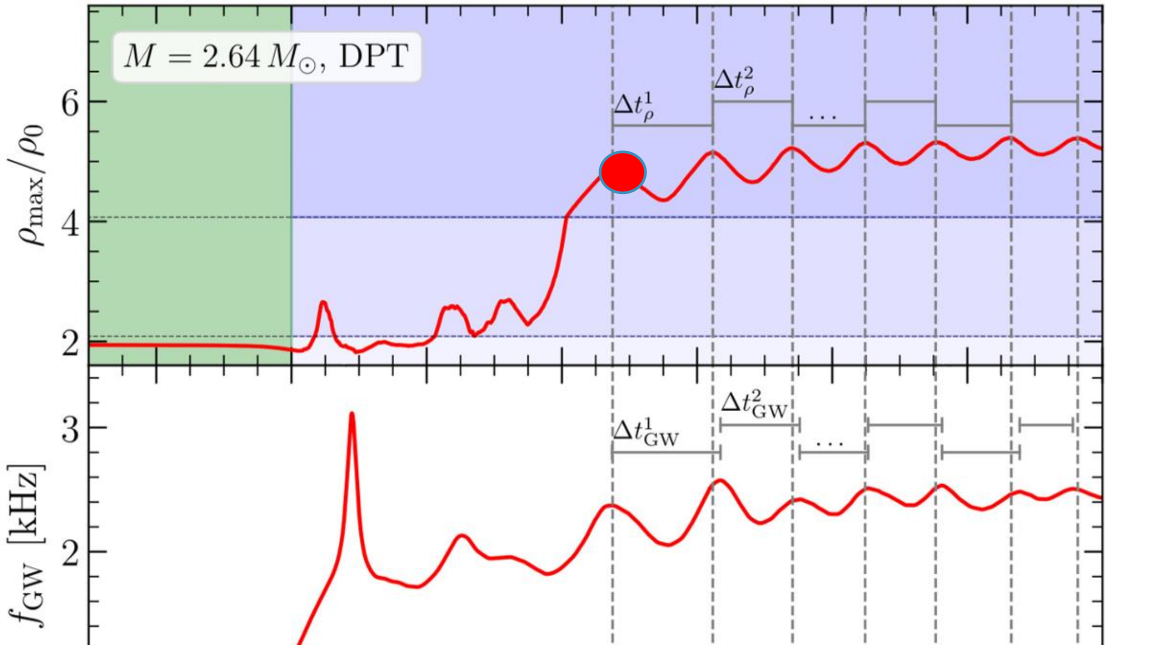


The figures correspond to a time near the first density maximum at t = 4.8ms (see red marker). The large m = 1 contribution can be seen by looking at the asymmetry of the spatial location of the quark core, which is marked with the second blue contour line. As a result of this asymmetry, the location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

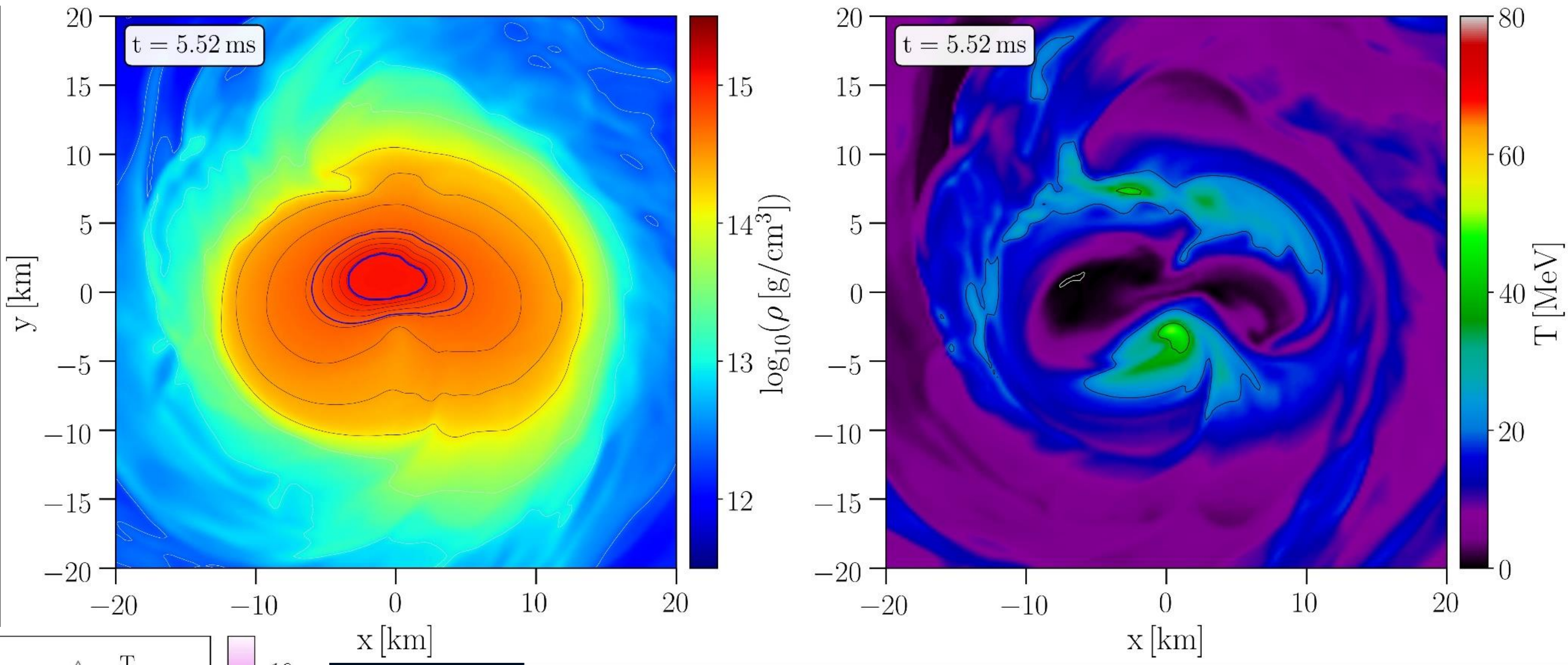


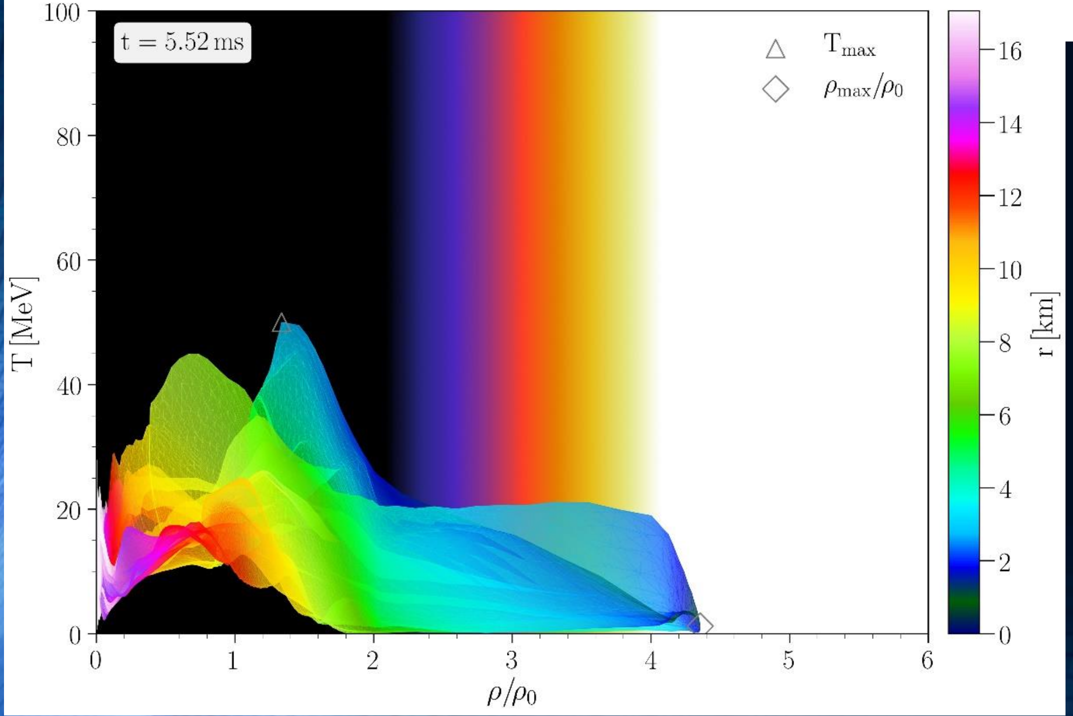


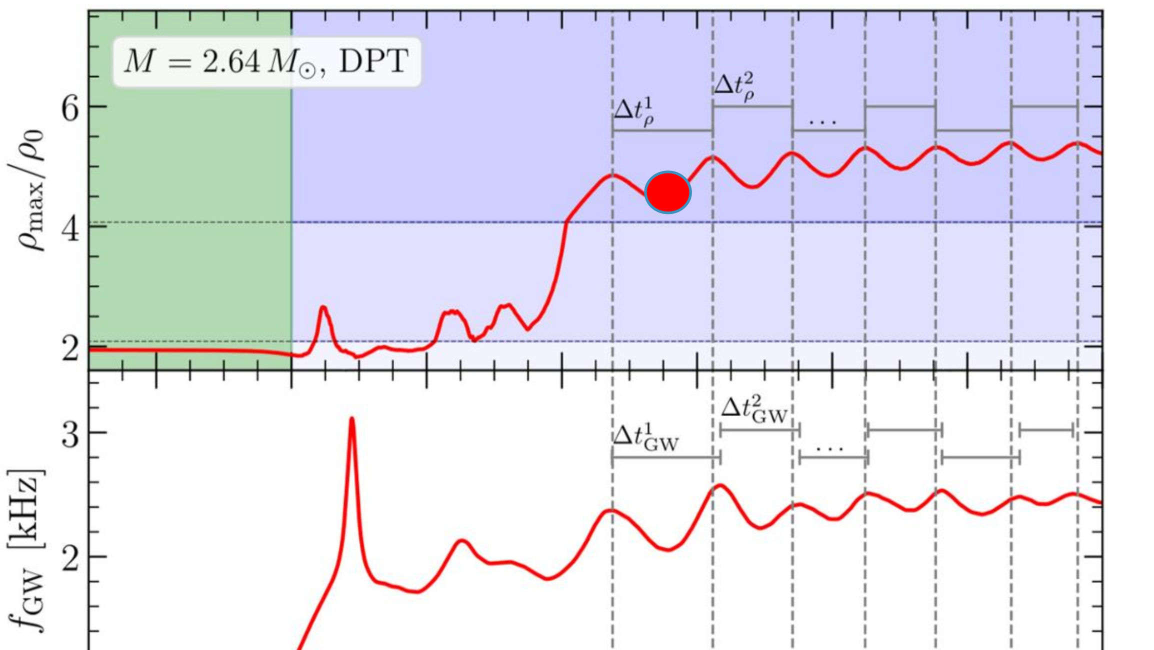




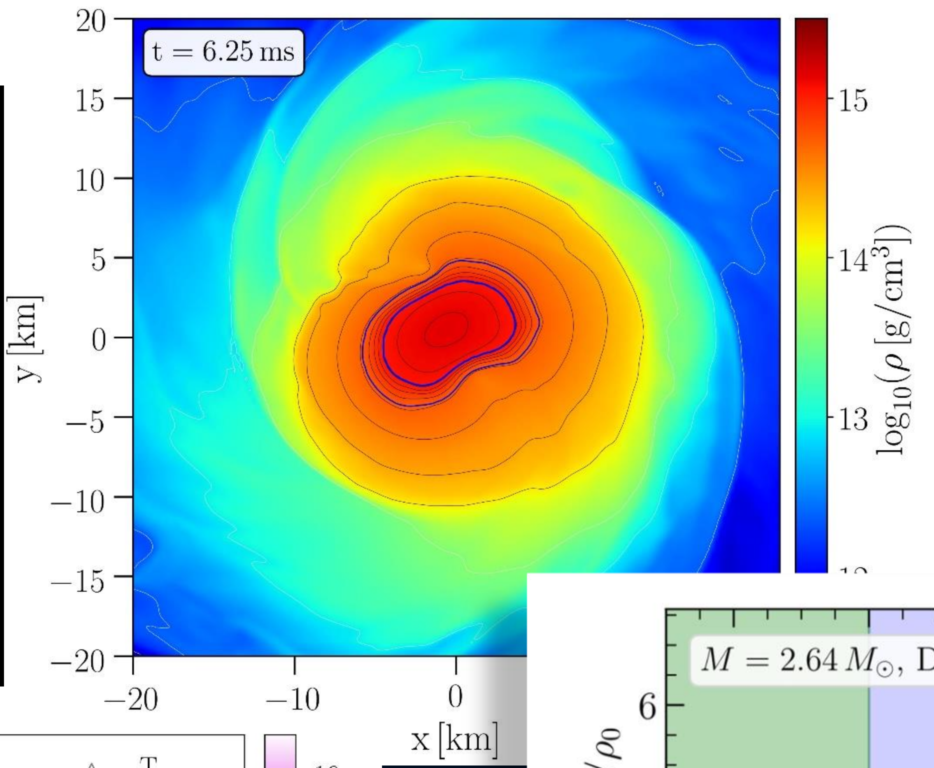
The figures correspond to a time near the first density minimum at t = 5.52ms (see red marker). The large m = 1 contribution can be seen by looking at the asymmetry of the spatial location of the quark core, which is marked with the second blue contour line. As a result of this asymmetry, the location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

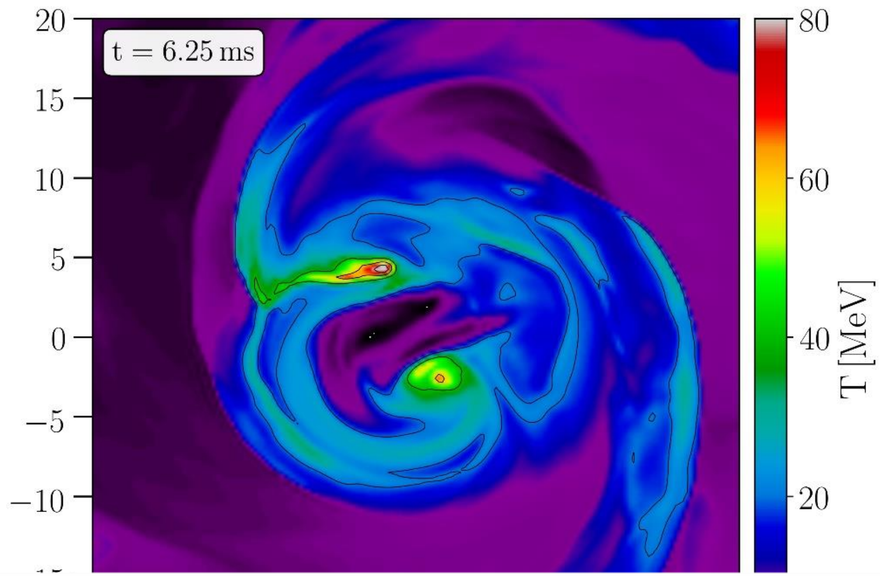


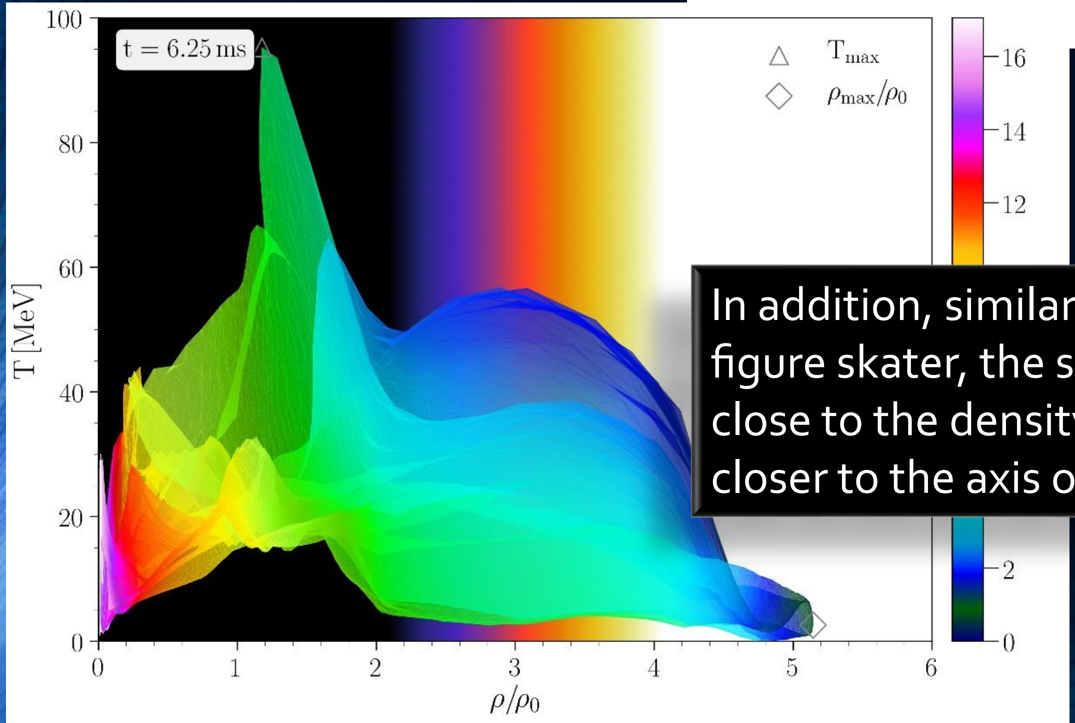


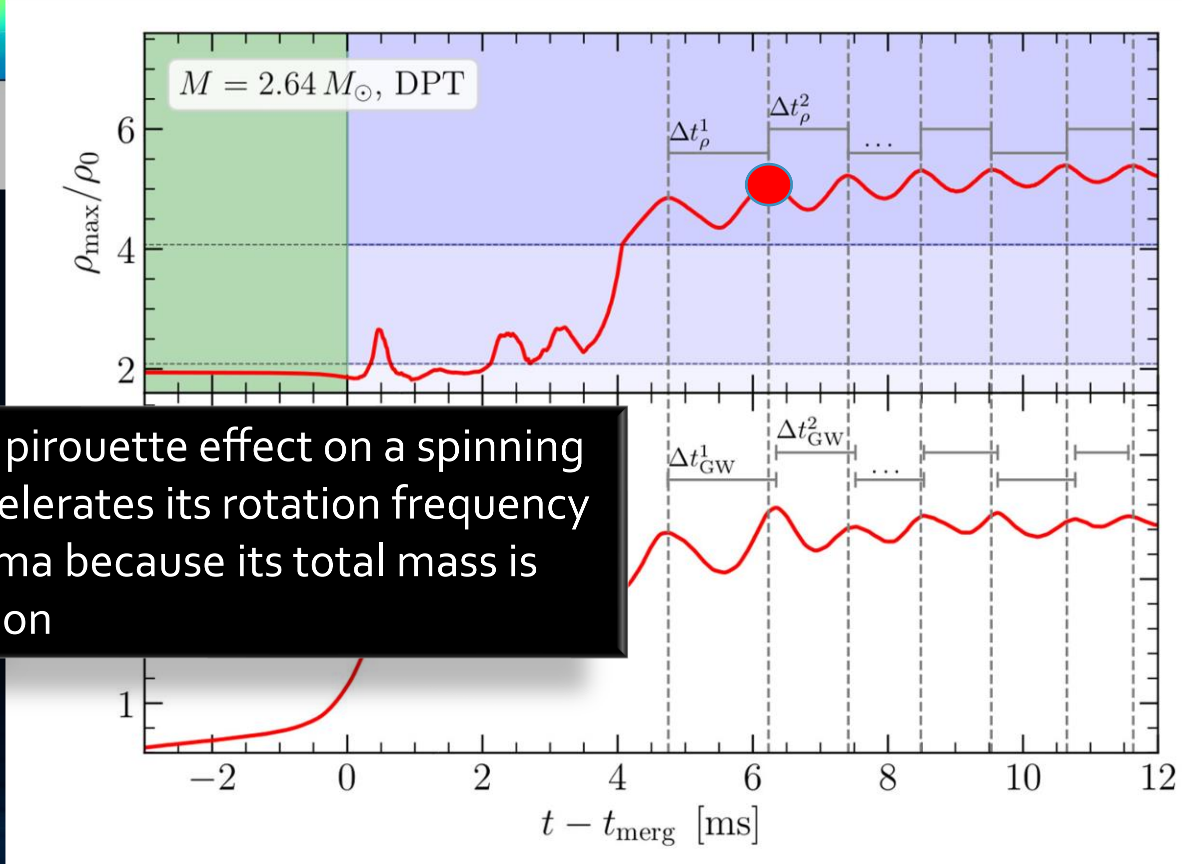


The collapse of the HMNS to the HMHS causes the system to vibrate. At the times when the maximum of the central density is reached, the pure quark core with its stiffer equation of state presses violently against the gravitational pressure and the star expands again and, as a result, its central density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



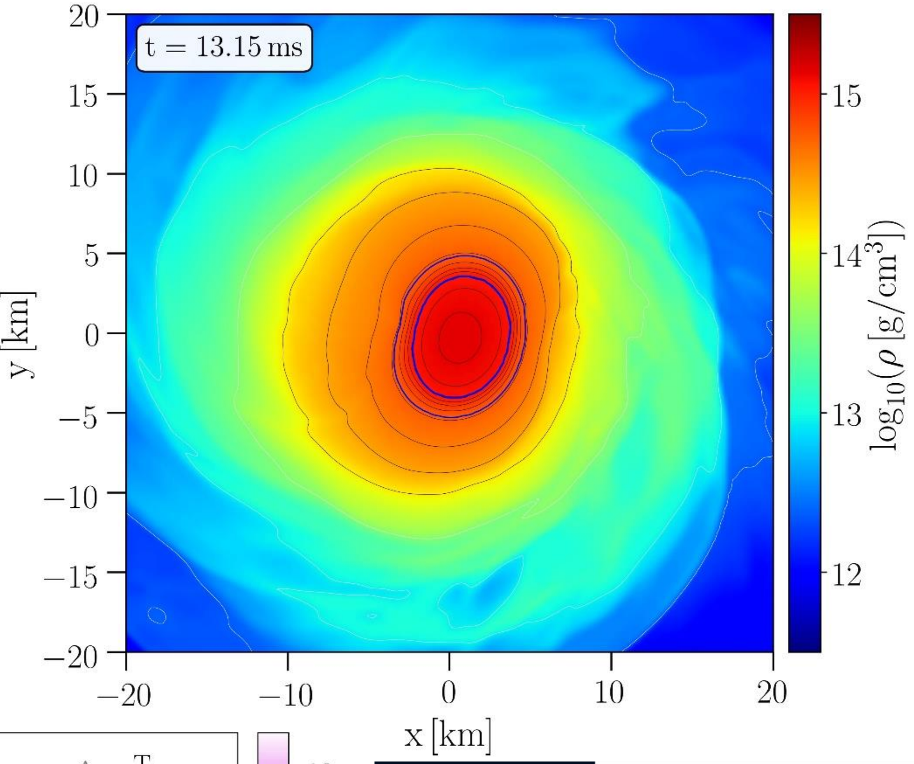


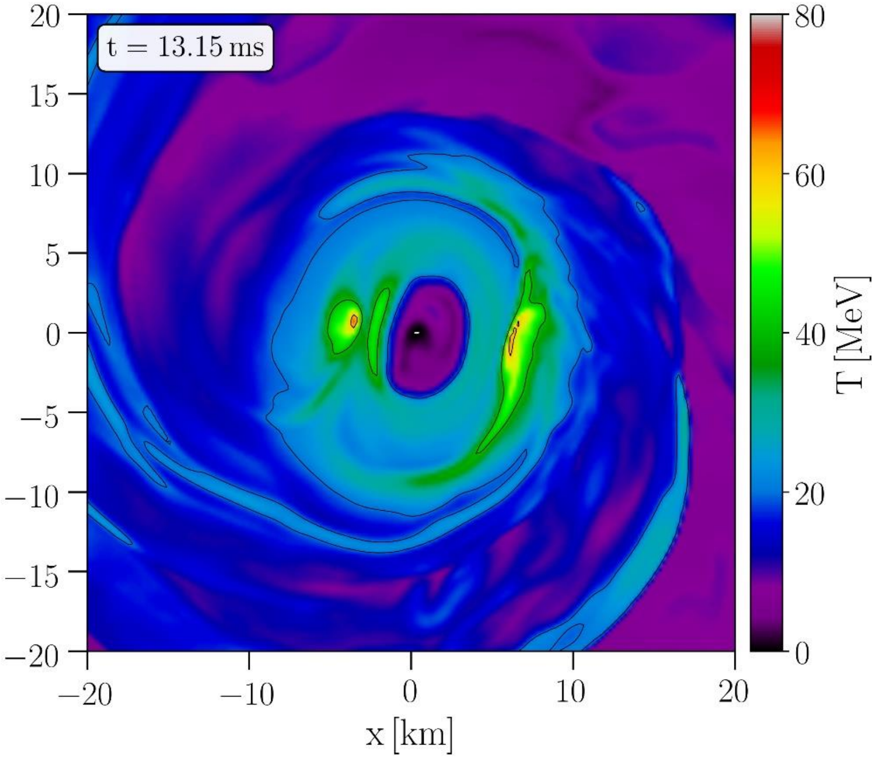


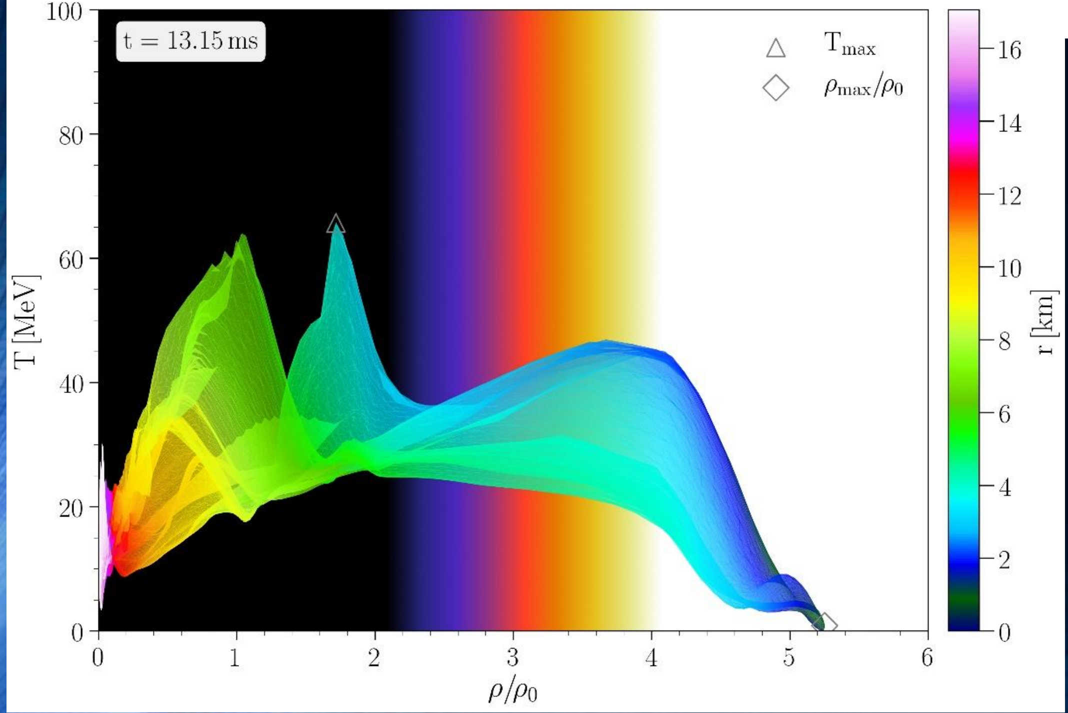


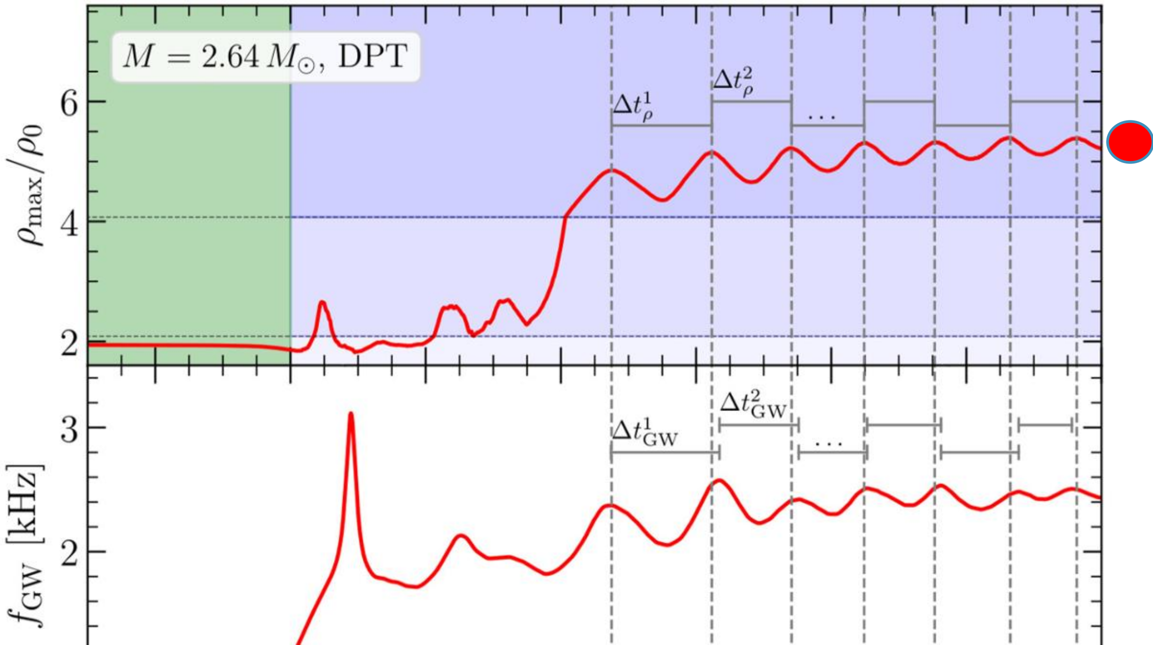
In addition, similar to the pirouette effect on a spinning figure skater, the star accelerates its rotation frequency close to the density maxima because its total mass is closer to the axis of rotation

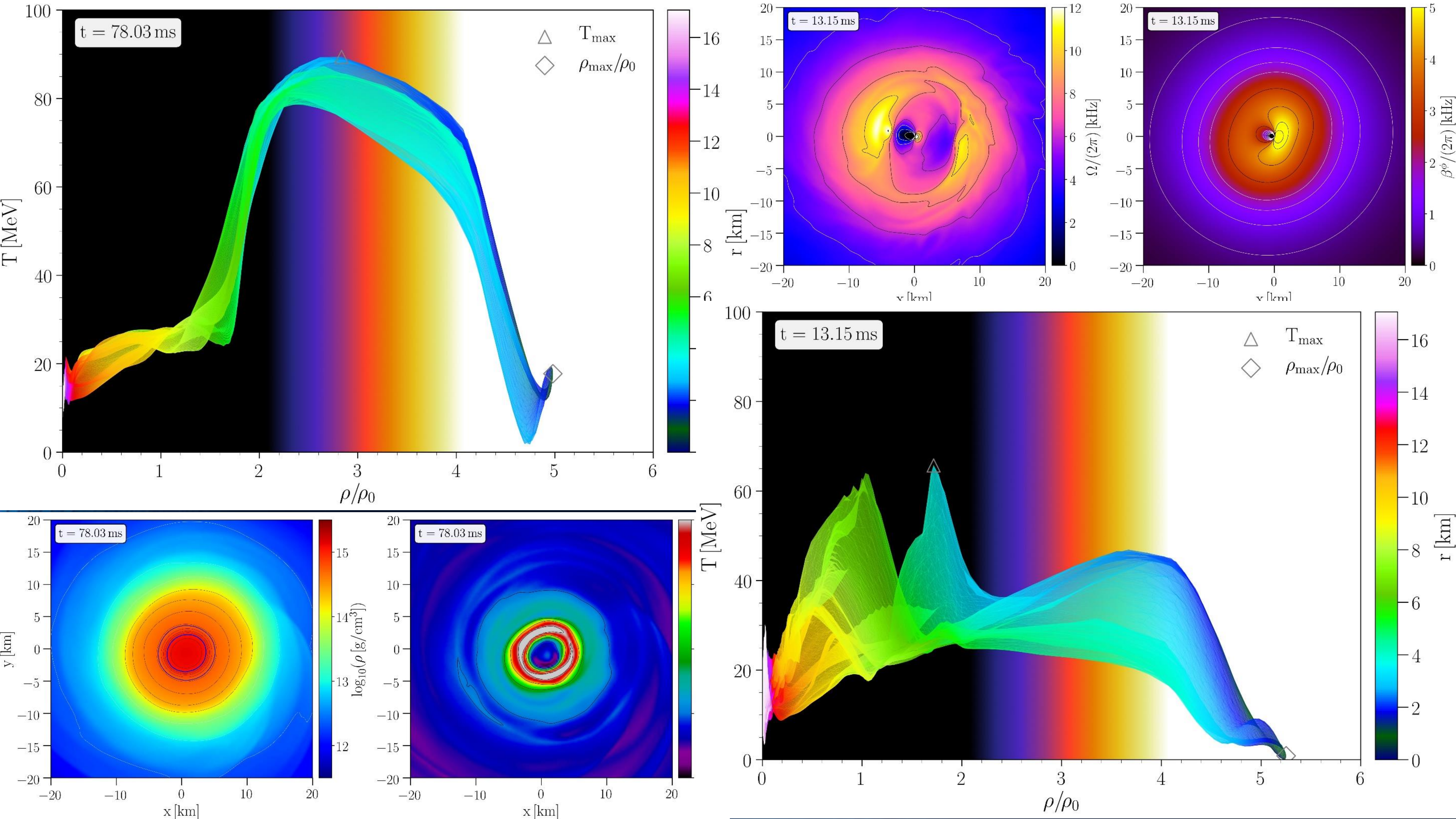
These figures report the HMHS properties at t = 13.15 ms and shows that in addition to the two temperature hot-spots, a new high temperature shell surrounding a cold core appears within the mixed phase region of the remnant . For subsequent post-merger times, the two temperature hot-spots will be smeared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










t = 78.03 ms
T_{max}
ρ_{max}/ρ_0
T [MeV]
ρ/ρ_0
t = 13.15 ms
$\Omega/(2\pi)$ [kHz]
$\beta^\phi/(2\pi)$ [kHz]
r [km]
x [km]
y [km]
$\log_{10}(\rho\,[g/cm^3])$
r [km]

G. Montana, L.Tolos, M.Hanauske

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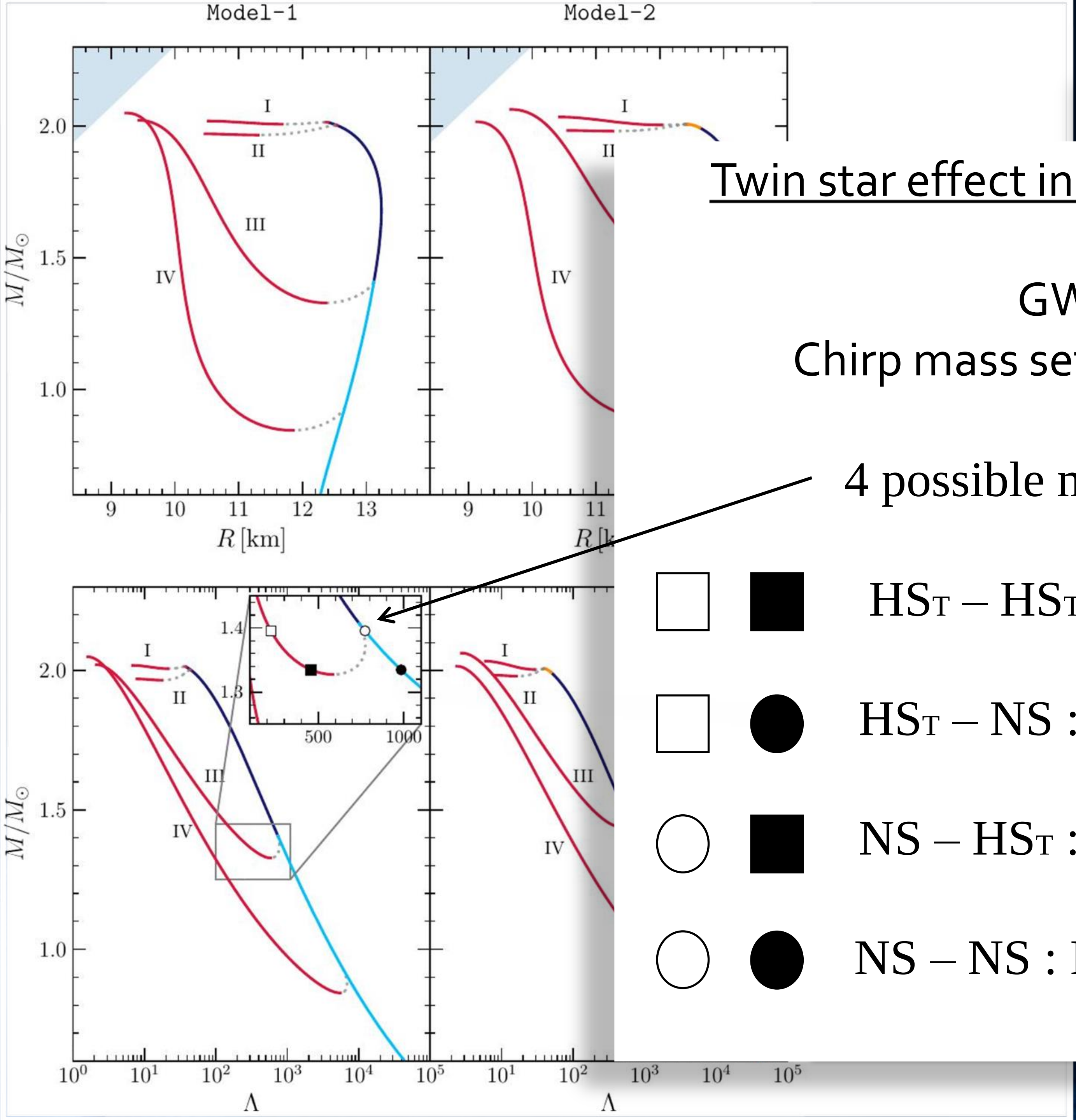

Twin star effect in the tidal deformability

GW170817:

Chirp mass set to $M_{ch} = 1.188\ M_\odot$

4 possible merger scenarios:

- □ ■ HS_T – HS_T : Hybrid star – Hybrid Star
- □ ● HS_T – NS : Hybrid star – Neutron Star
- ○ ■ NS – HS_T : Neutron star – Hybrid Star
- ○ ● NS – NS : Neutron star – Neutron Star