SAHA INSTITUTE OF NUCLEAR PHYSICS
ONLINE-VIDEO SEMINAR

APC Division Seminar
Saha Institute of Nuclear Physics
Kolkata (India), 22. September, 2020

Hypermassive/Supramassive hybrid stars as neutron-star merger remnants

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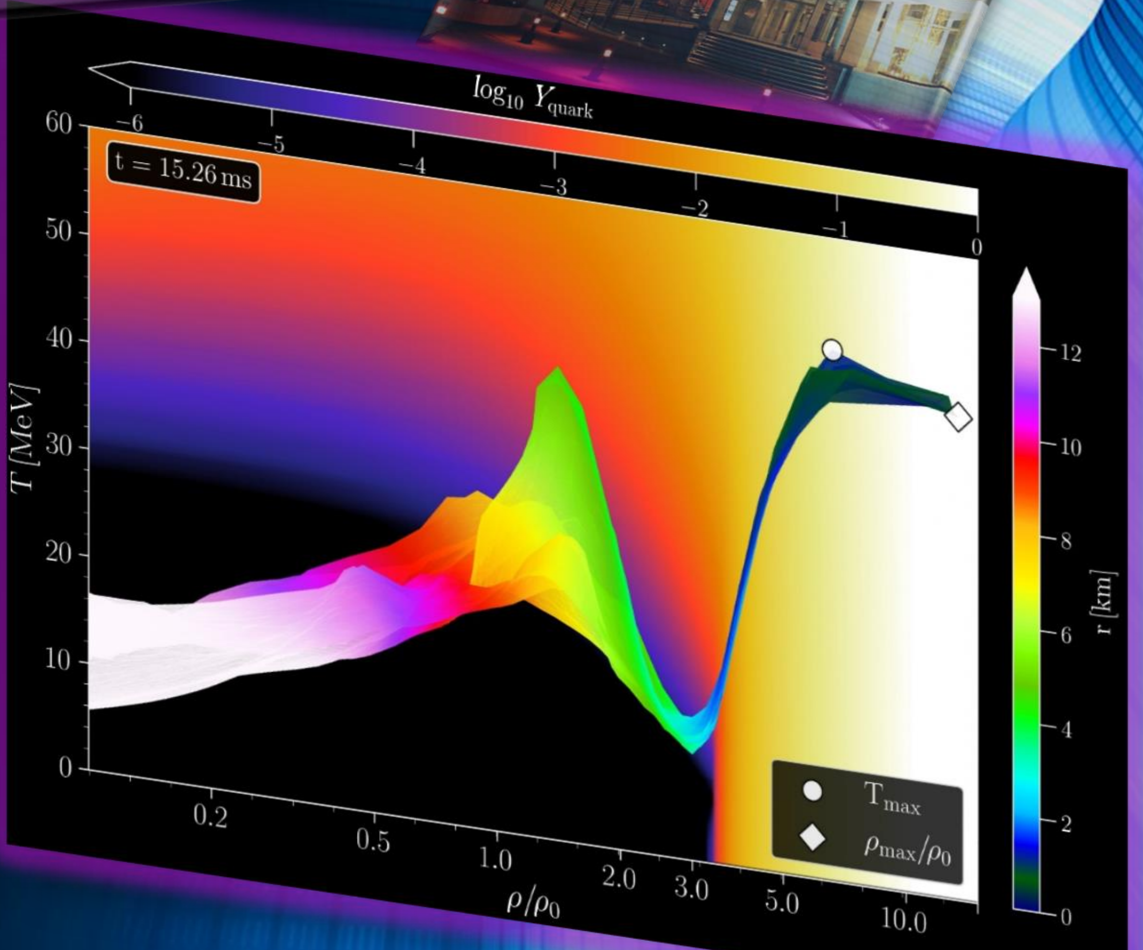
D-60438 FRANKFURT AM MAIN



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

First of all thanks to the Saha Institute and especially to Prof. Dr. Debades Bandyopadhyay

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
- Properties of hypermassive and supramassive compact stars
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- Summary and Outlook

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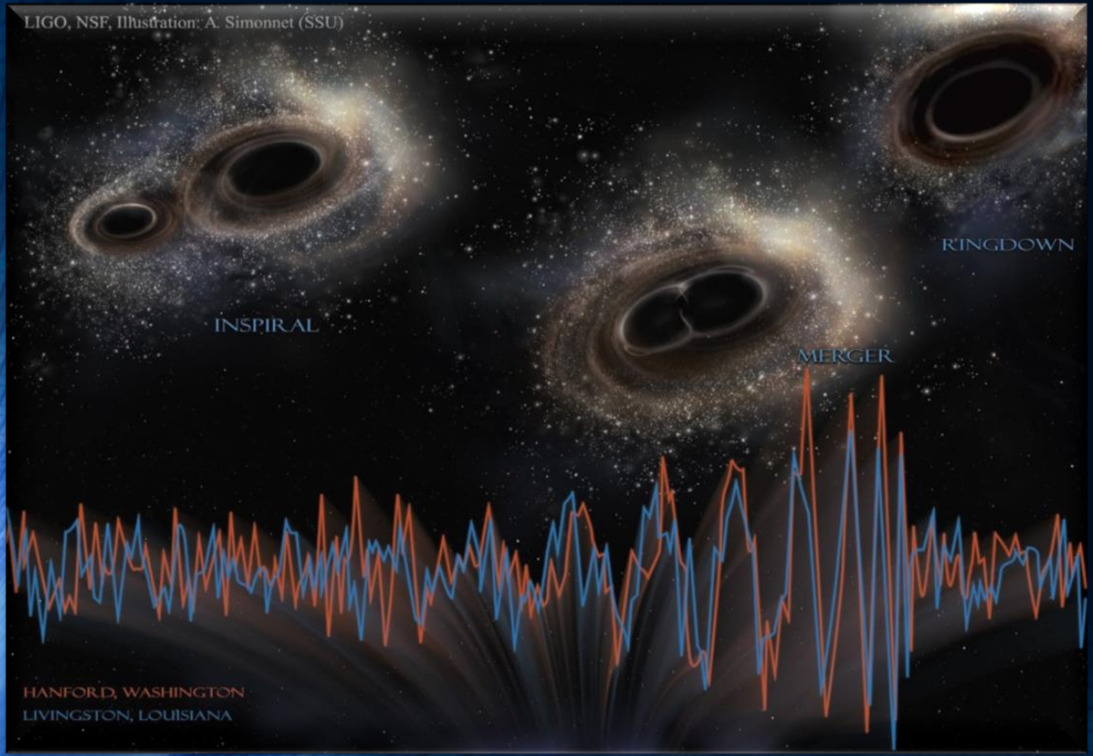
2015: Gravitational Waves observed by LIGO

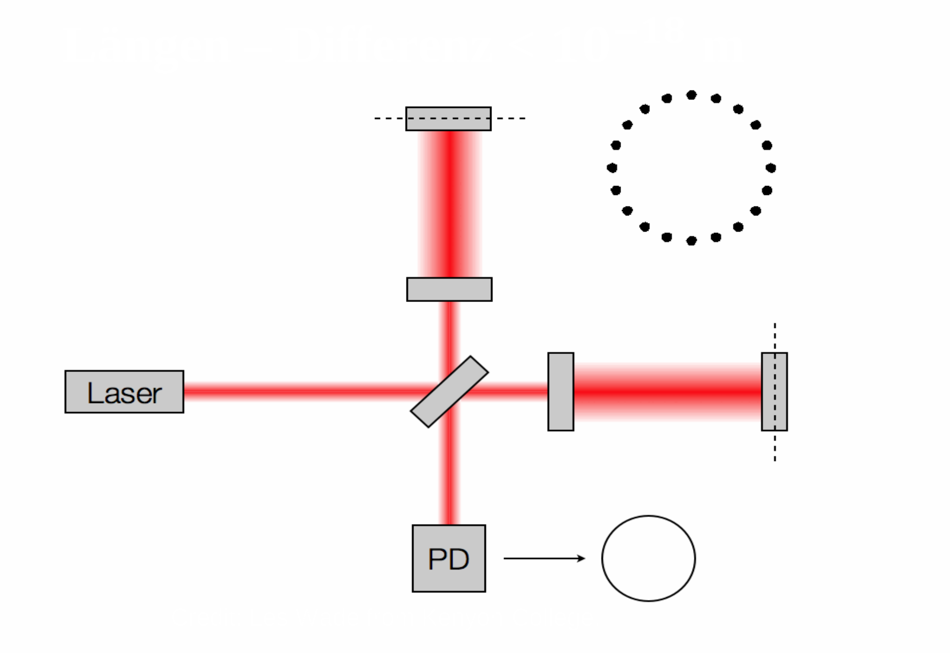
Collission of two Black Holes
GW150914

Masses: 36 & 29 Sunmasses

Distance to the Earth 410 Mpc
(1.34 Billion Lightyears)

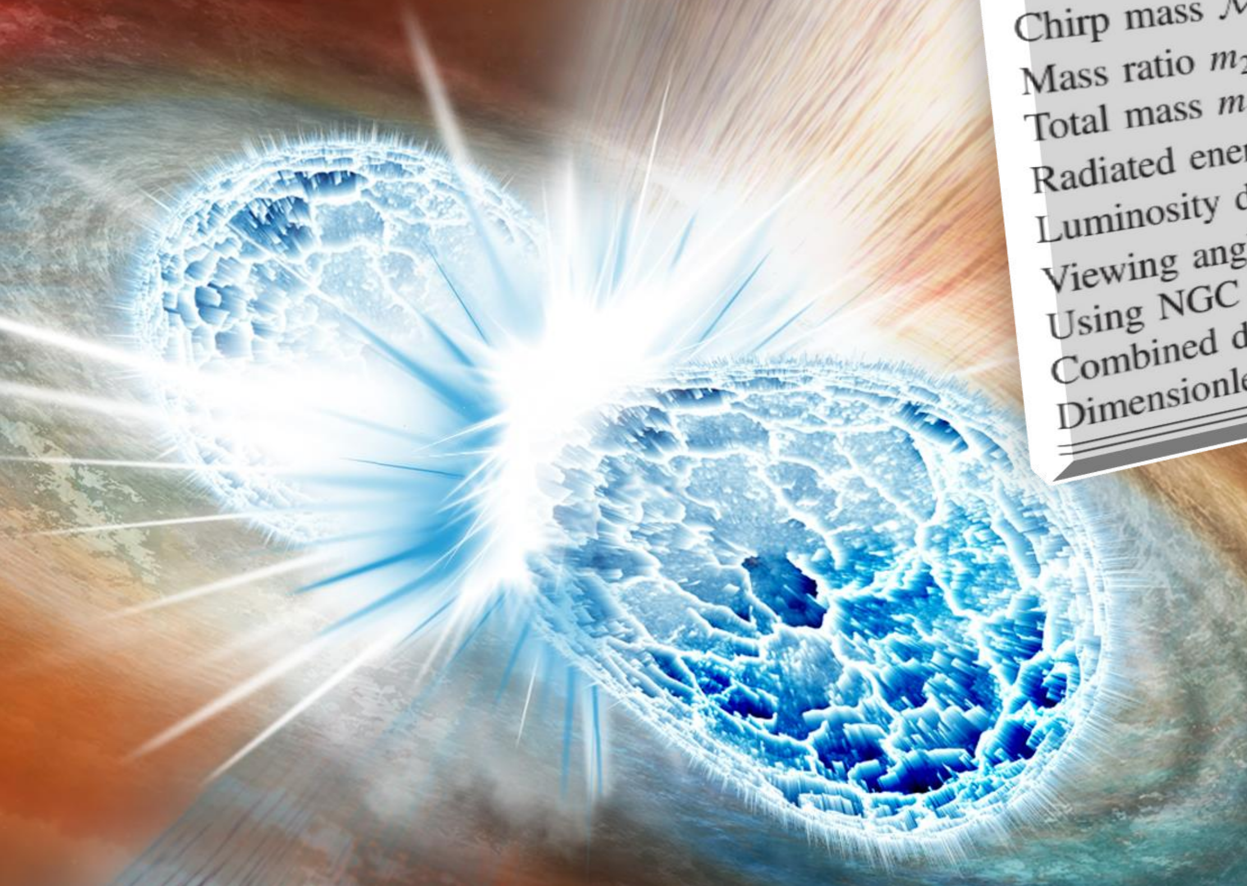


LIGO Gravitational Wave Detector



The long awaited event GW170817

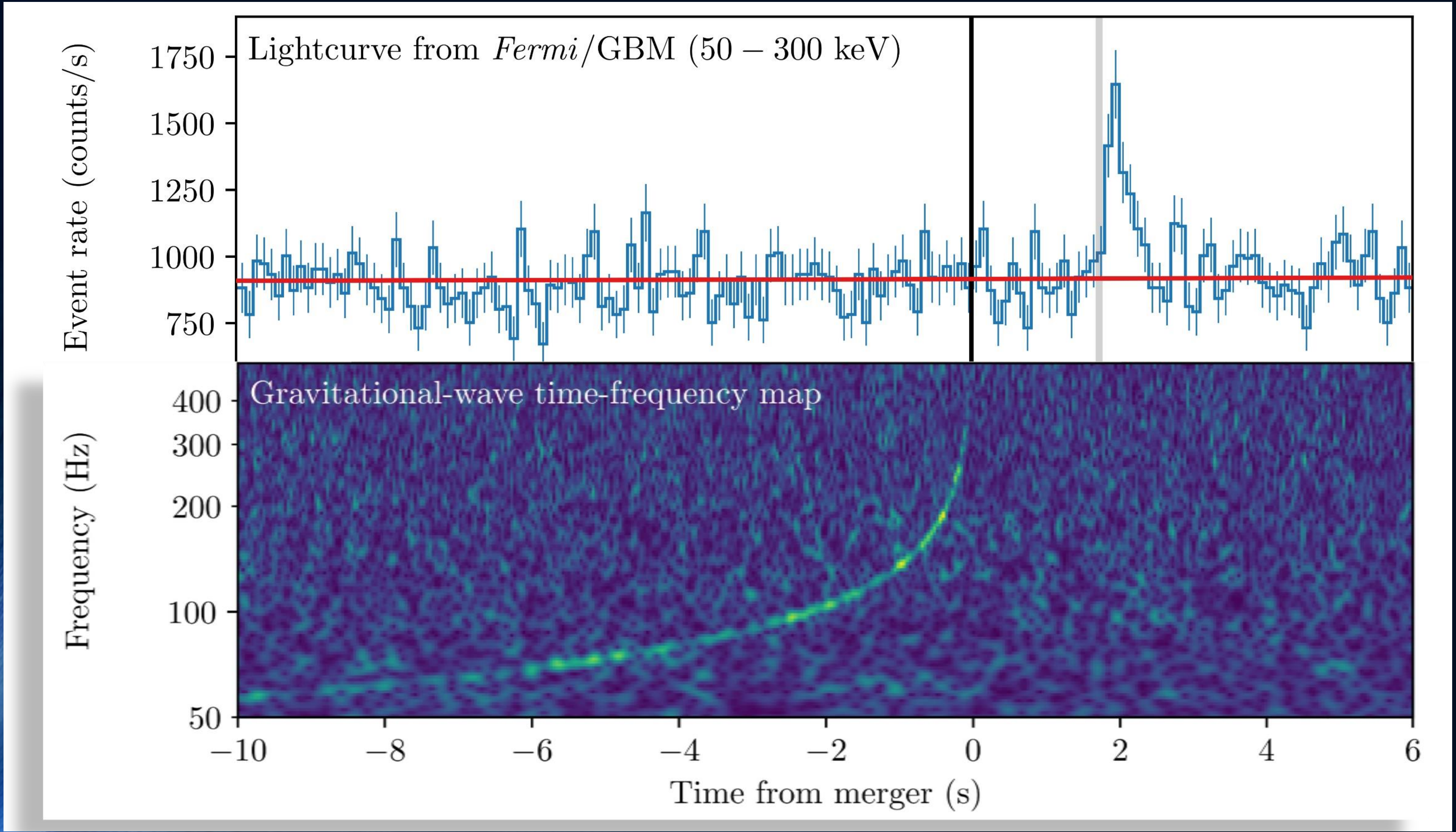
	Low-spin priors ($\|\chi\| \leq 0.05$)	High-spin priors ($\|\chi\| \leq 0.89$)
Primary mass m_1	$1.36–1.60\ M_\odot$	$1.36–2.26\ M_\odot$
Secondary mass m_2	$1.17–1.36\ M_\odot$	$0.86–1.36\ M_\odot$
Chirp mass $\mathcal{M}$	$1.188^{+0.004}_{-0.002} M_\odot$	$1.188^{+0.004}_{-0.002} M_\odot$
Mass ratio m_2/m_1	$0.7–1.0$	$0.4–1.0$
Total mass m_{tot}	$2.74^{+0.04}_{-0.01} M_\odot$	$2.82^{+0.47}_{-0.09} M_\odot$
Radiated energy E_{rad}	$> 0.025 M_\odot c^2$	$> 0.025 M_\odot c^2$
Luminosity distance D_L	40^{+8}_{-14} Mpc	40^{+8}_{-14} Mpc
Viewing angle Θ	$\lesssim 55°$	$\lesssim 56°$
Using NGC 4993 location	$\lesssim 28°$	$\lesssim 28°$
Combined dimensionless tidal deformability $\tilde{\Lambda}$	$\lesssim 800$	$\lesssim 700$
Dimensionless tidal deformability $\Lambda(1.4 M_\odot)$	$\lesssim 800$	$\lesssim 1400$



17. August 2017

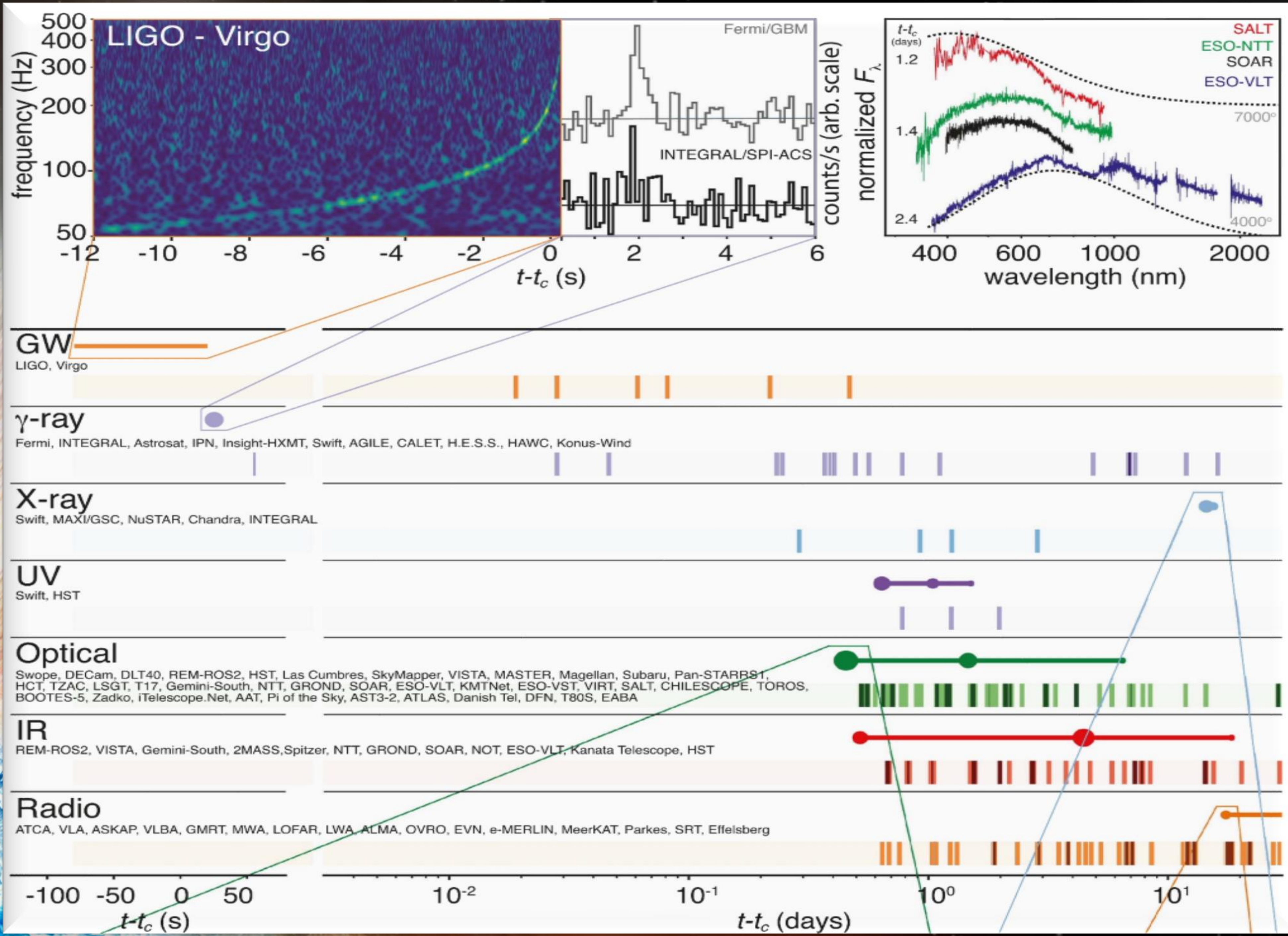
First detection of a gravitational wave from a binary neutron star merger event!

Gravitational Wave GW170817 and Gamma-Ray Emission GRB170817A

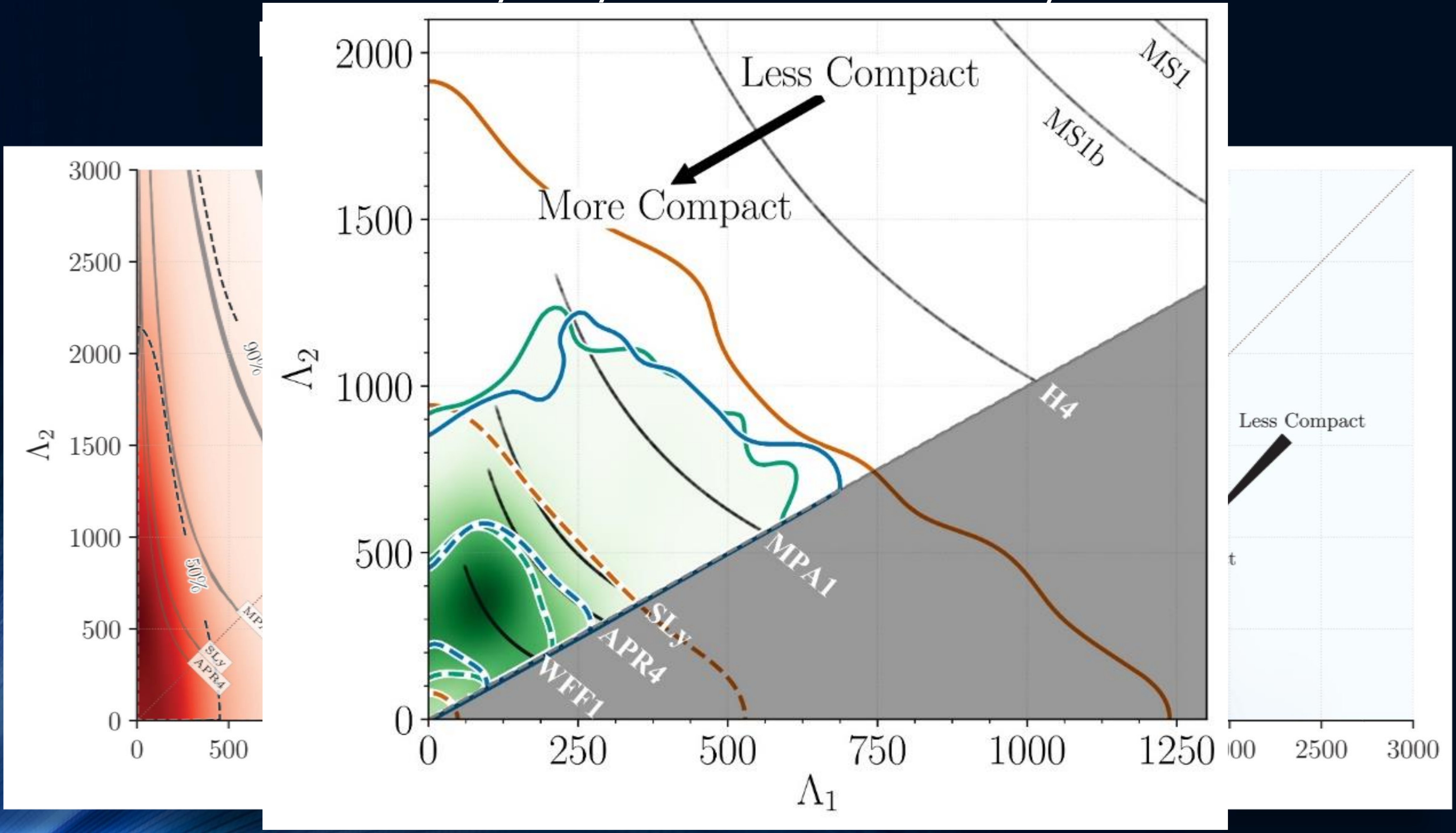


GW170817

Kilonova observed



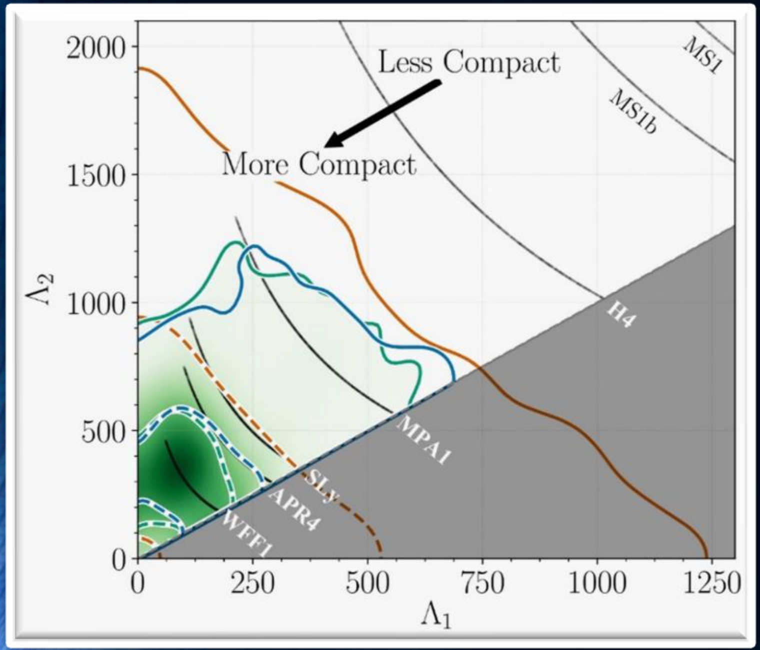
GW170817: Tidal Deformability

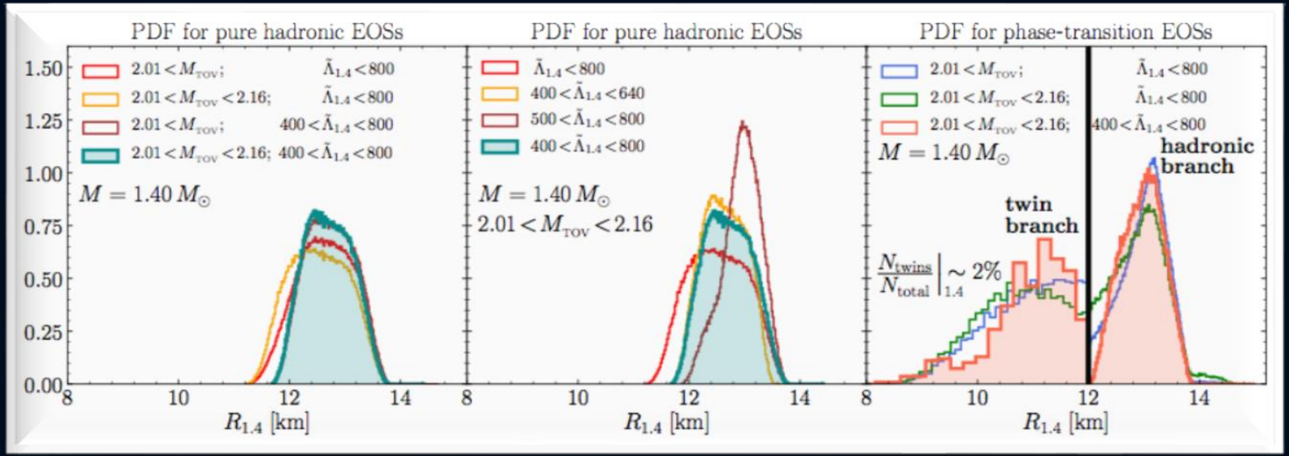


GW170817 (only the late inspiral GW was detected!)
Constraining the maximum mass and radius of neutron stars

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 +/-0.04 < M_{TOV} < 2.16 +/-0.17

Constraining M_{TOV} , 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)



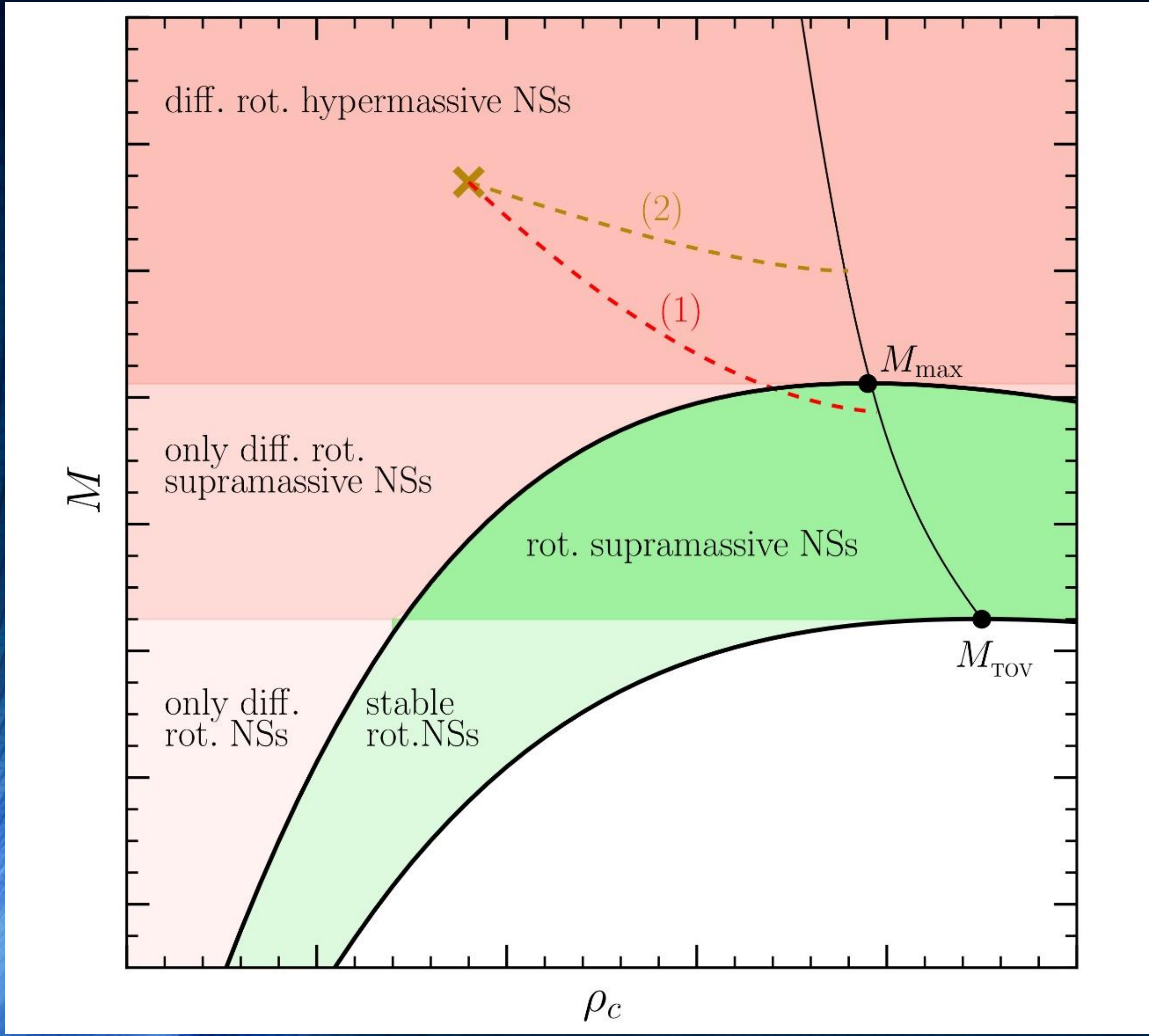


E.Most, L.Weih, L.Rezzolla, J. Schaffner-Bielich “New constraints on radii and tidal deformabilities of neutron stars from GW170817”, PRL 120, 261103 (2018)

GW170817: Measurements of neutron star radii and equation of state, *The LIGO /Virgo Collaboration*, arXiv:1805.11581v1

See also: De, Finstad, Lattimer, Brown, Berger, Biwer, (2018), arXiv:1804.08583 ; Bauswein, Just, Janka, N. Stergioulas, APJL 850, L34 (2017) ; Fattoyev, Piekarewicz, Horowitz, PRL 120, 172702 (2018) ; Nandi & Char, Astrophys. J. 857, 12 (2018) ; Paschalidis, Yagi, Alvarez-Castillo, Blaschke, Sedrakian, PRD 97, 084038 ; Ruiz, Shapiro, Tsokaros, PRD 97, 021501 (2018) ; Annala, Gorda, Kurkela, Vuorinen, PRL 120, 172703 (2018) ; Raithel, Özel, Psaltis, (2018) arXiv:1803.07687

GW170817: Constraining the maximum mass of Neutron Stars

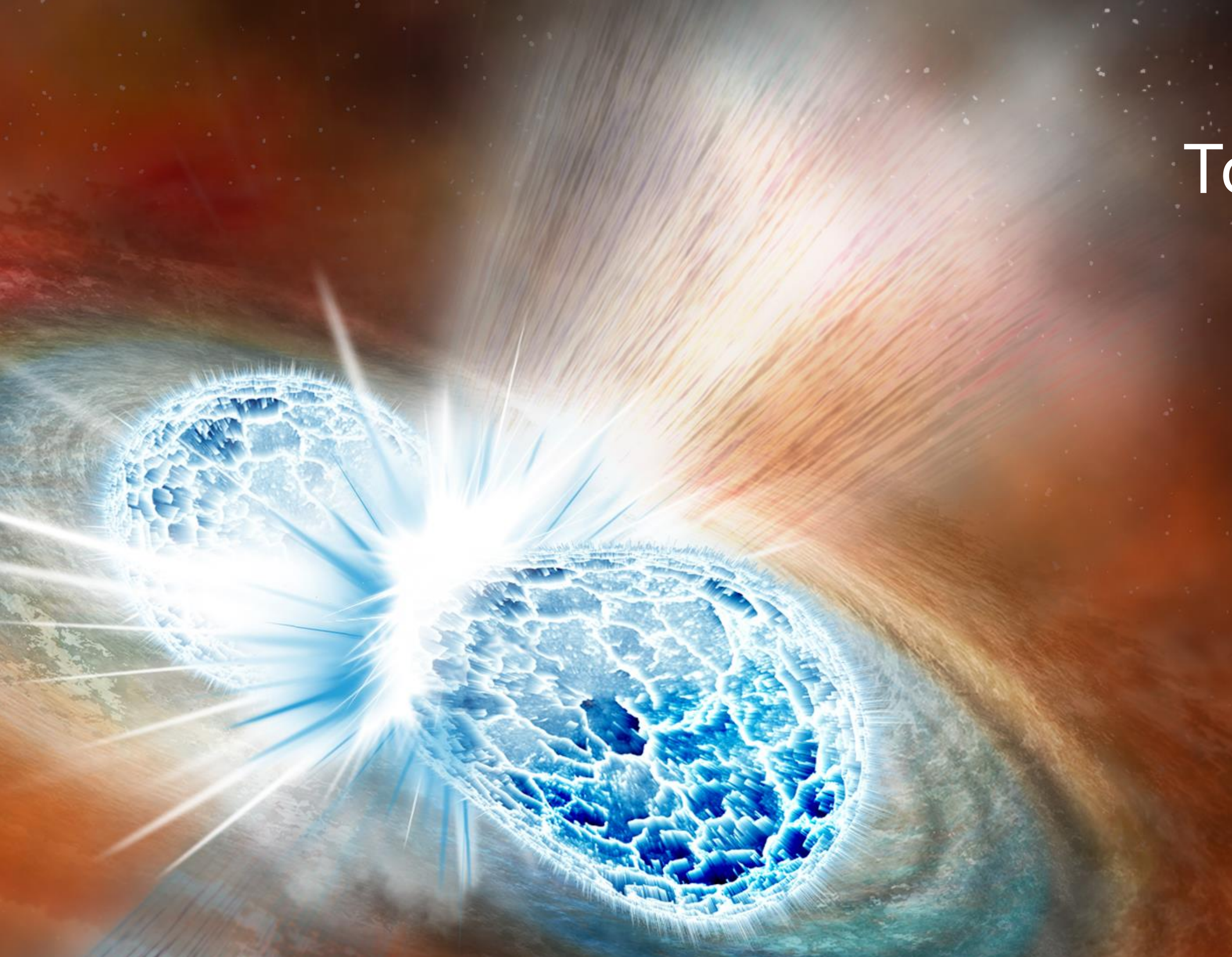


The highly differentially rotating hypermassive/supramassive neutron star will spin down and redistribute its angular momentum (e.g. due to viscosity effects, magnetic braking). After ~1 second it will cross the stability line as a uniformly rotating supramassive neutron star (close to M_{max}) and collapse 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 second event: GW190425

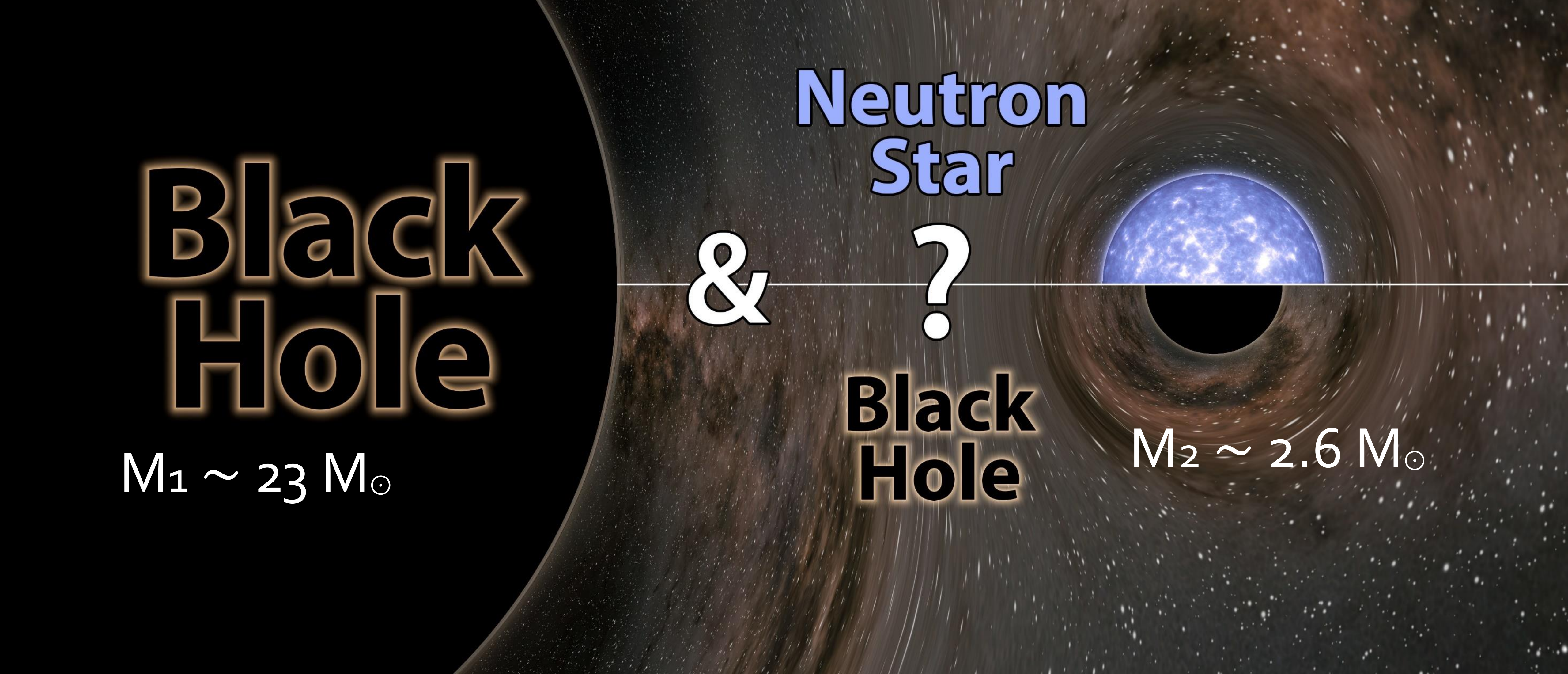


Total mass $\sim 3.4\ M_{\odot}$

19. April 2019

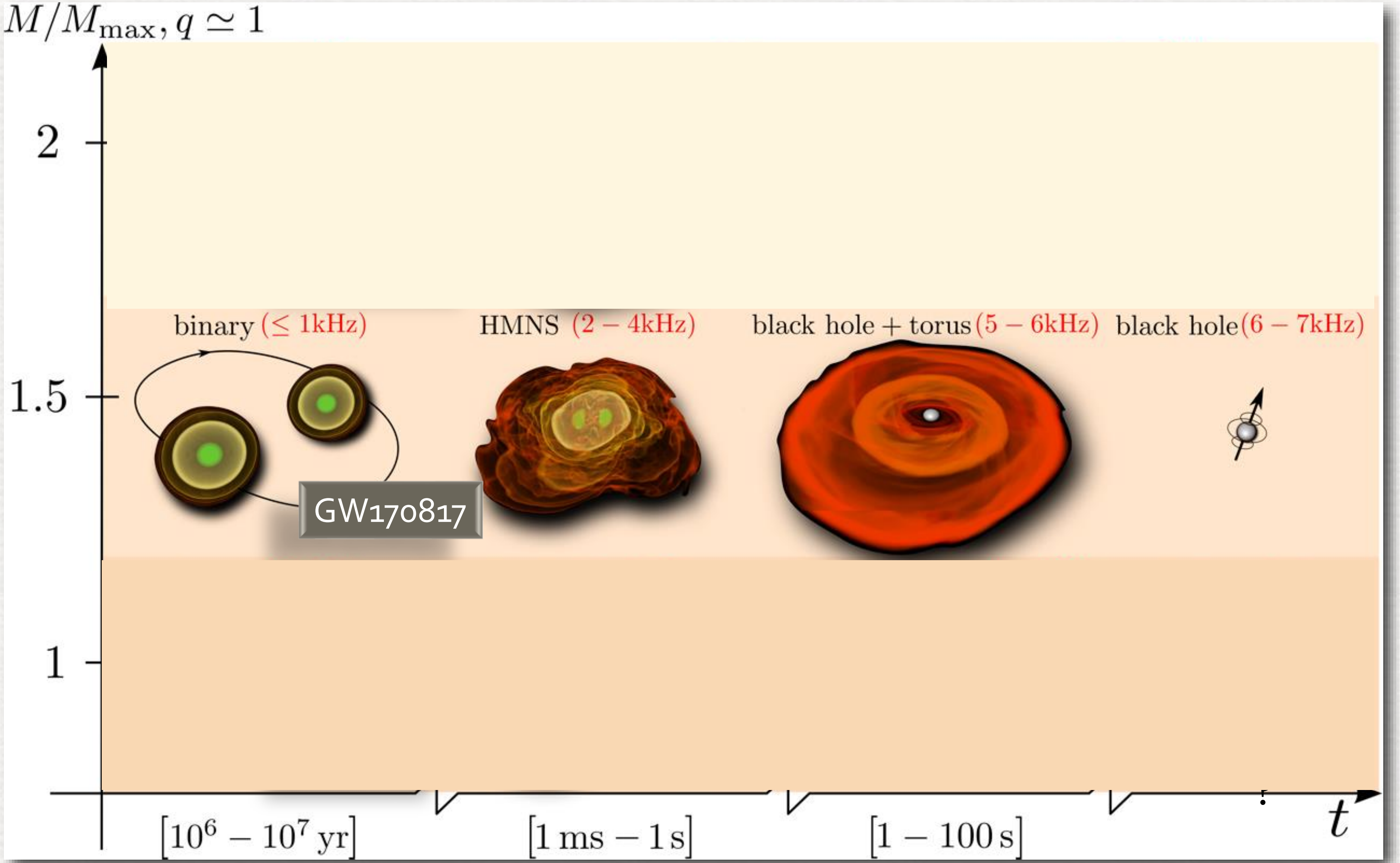
Second detection of a gravitational wave from a binary neutron star merger event!

GW190814 The third event ???



14. August 2019

Broadbrush picture



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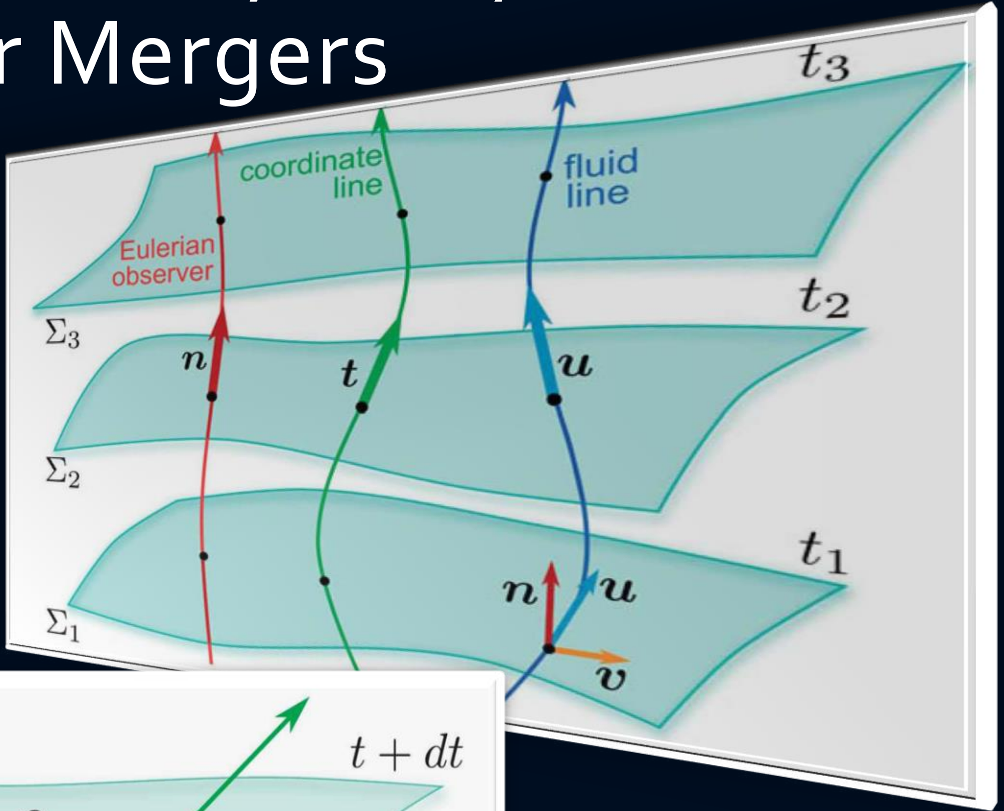
Numerical Relativity and Relativistic Hydrodynamics of Binary Neutron Star Mergers

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:

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

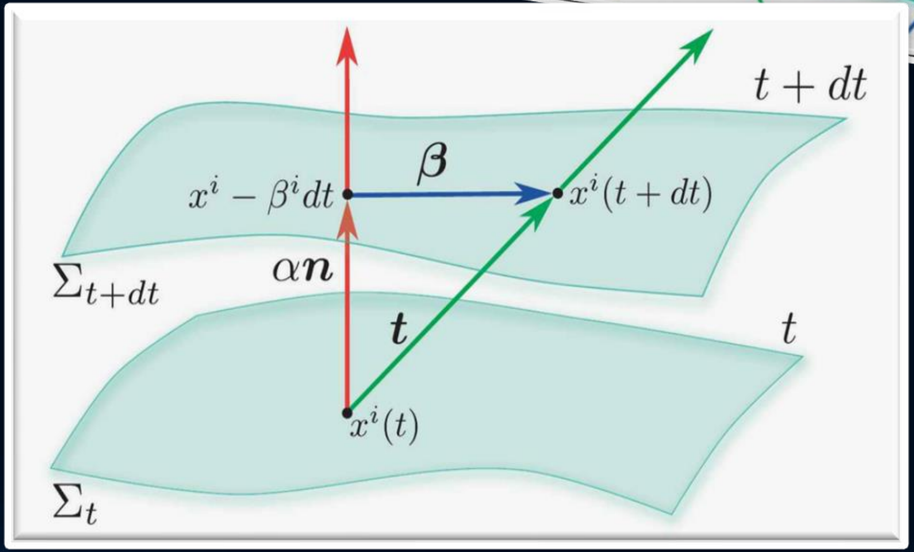
$$\nabla_\mu (\rho u^\mu) = 0 \,, \qquad \nabla_\nu T^{\mu\nu} = 0 \,.$$



(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)

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The Einstein Equation and the EOS of Compact Stars

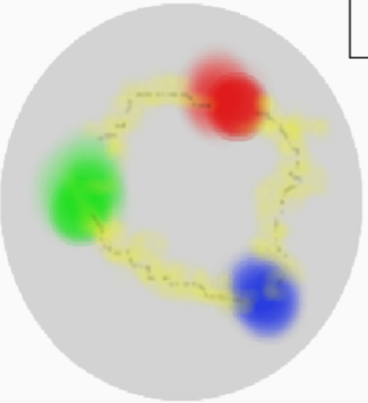
ART	Yang-Mills-Theories
$D_\beta v^\alpha = \partial_\beta v^\alpha + \Gamma^\alpha_{\sigma\beta} v^\sigma$	$D_{\beta a}{}^b = \partial_\beta 1_a{}^b + ig A_{\beta a}{}^b$
$R^\delta{}_{\mu\alpha\beta} v^\mu = [D_\alpha, D_\beta] v^\delta$ $R^\delta{}_{\mu\alpha\beta} = \Gamma^\delta_{\mu\alpha\|\beta}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

QuantumCromoDynamic:

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

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

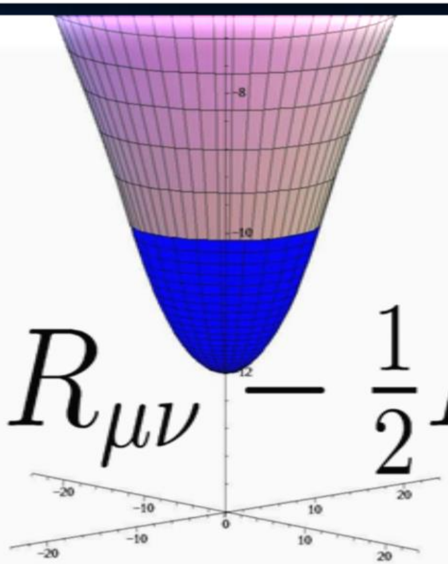
$_A,{}^B$ =red, green, blue



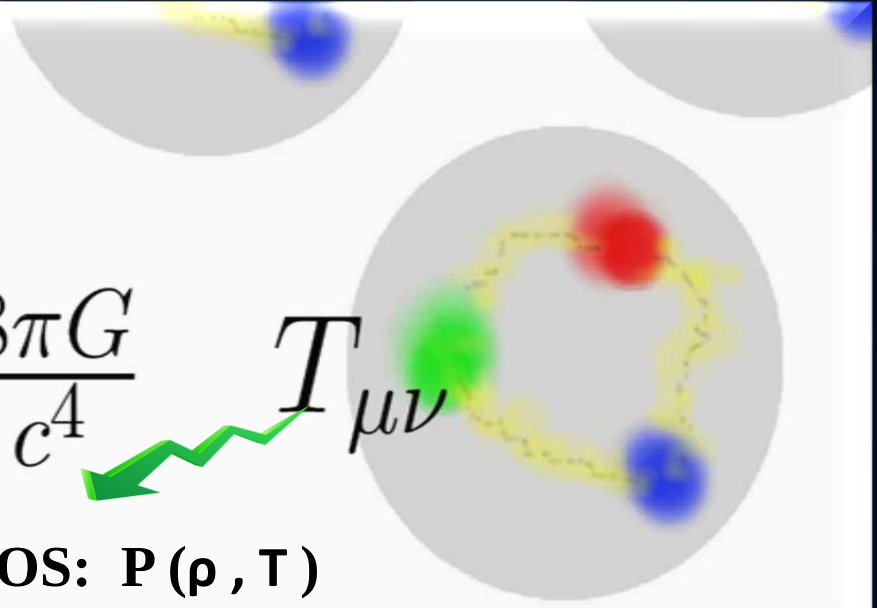
$$\psi^f_A = \begin{pmatrix} \psi^f_r \\ \psi^f_g \\ \psi^f_b \end{pmatrix}$$

Confinement

chiral symmetry, ...



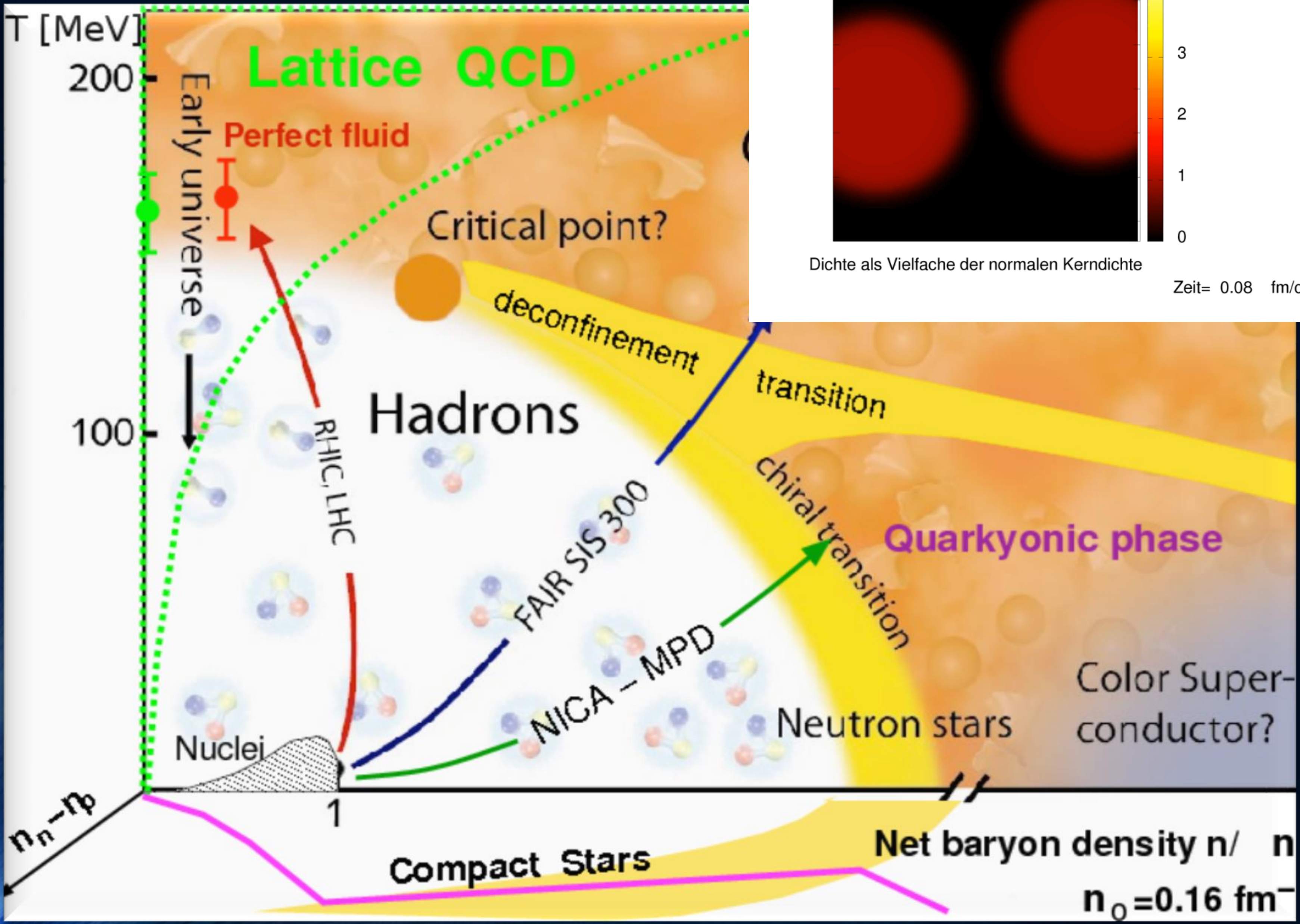
$$R_{\mu\nu} - \frac{1}{2} R\, g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

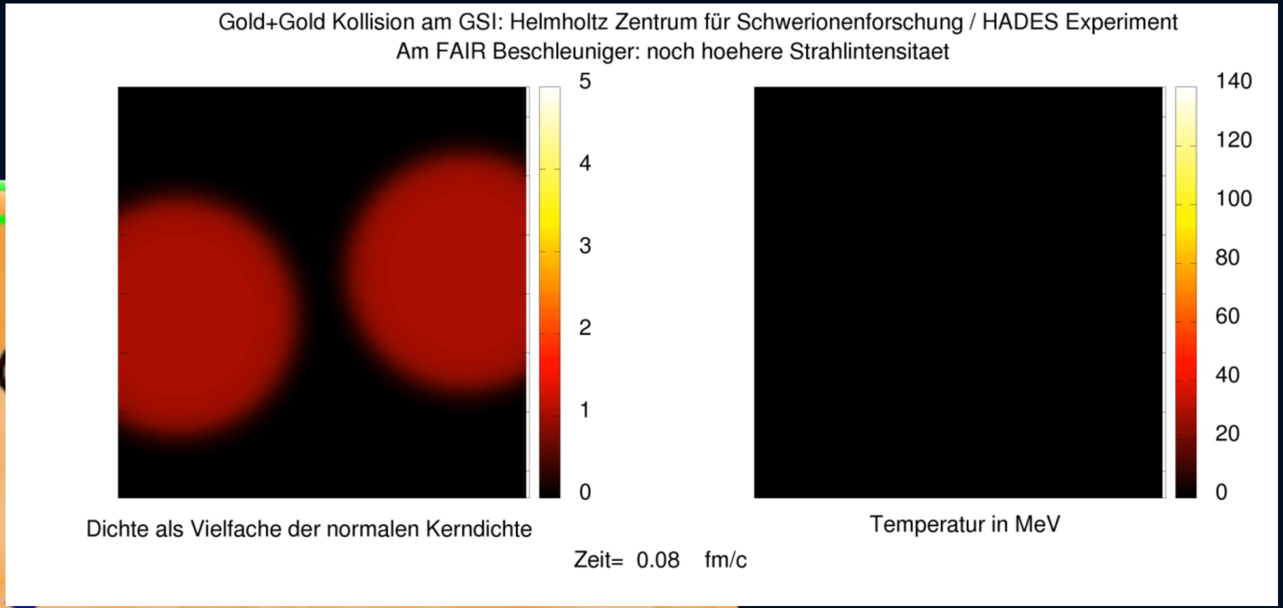


EOS: P (ρ , T)

The Hadron-Quark Phase Transition

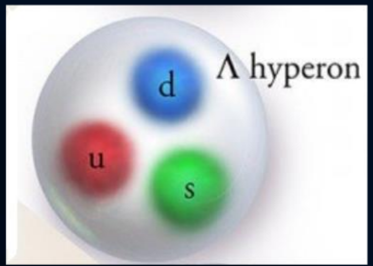
The QCD Phase Diagram



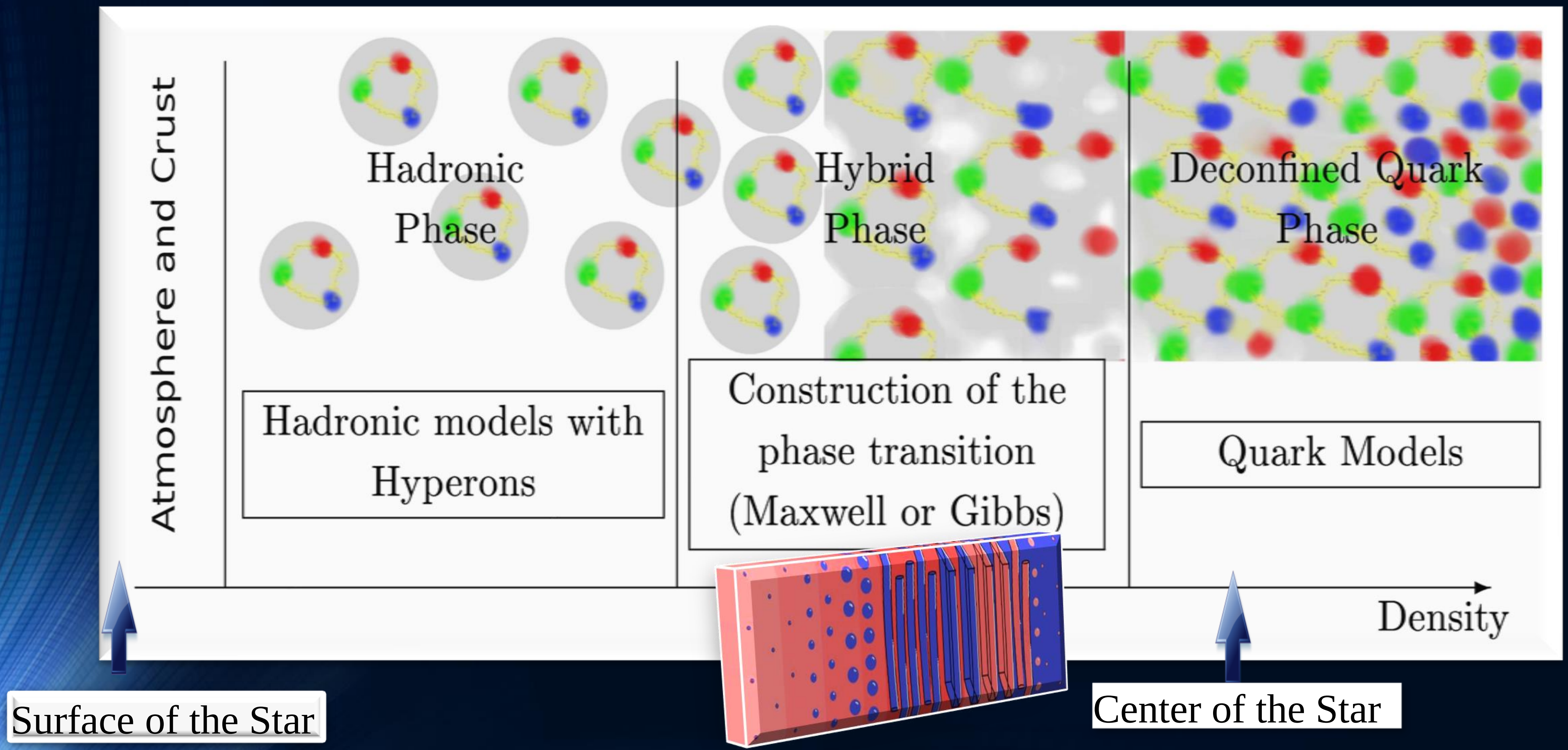


Credits:
Jan Steinheimer

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)

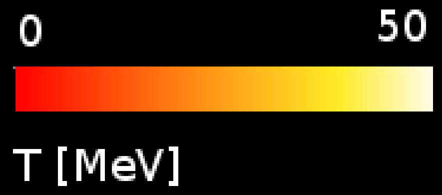
Hypermassive/Supramassive hybrid stars as neutron-star merger remnants

Computer Simulation of a Binary Neutron Star Merger

Credits: Cosima Breu, David Radice und Luciano Rezzolla

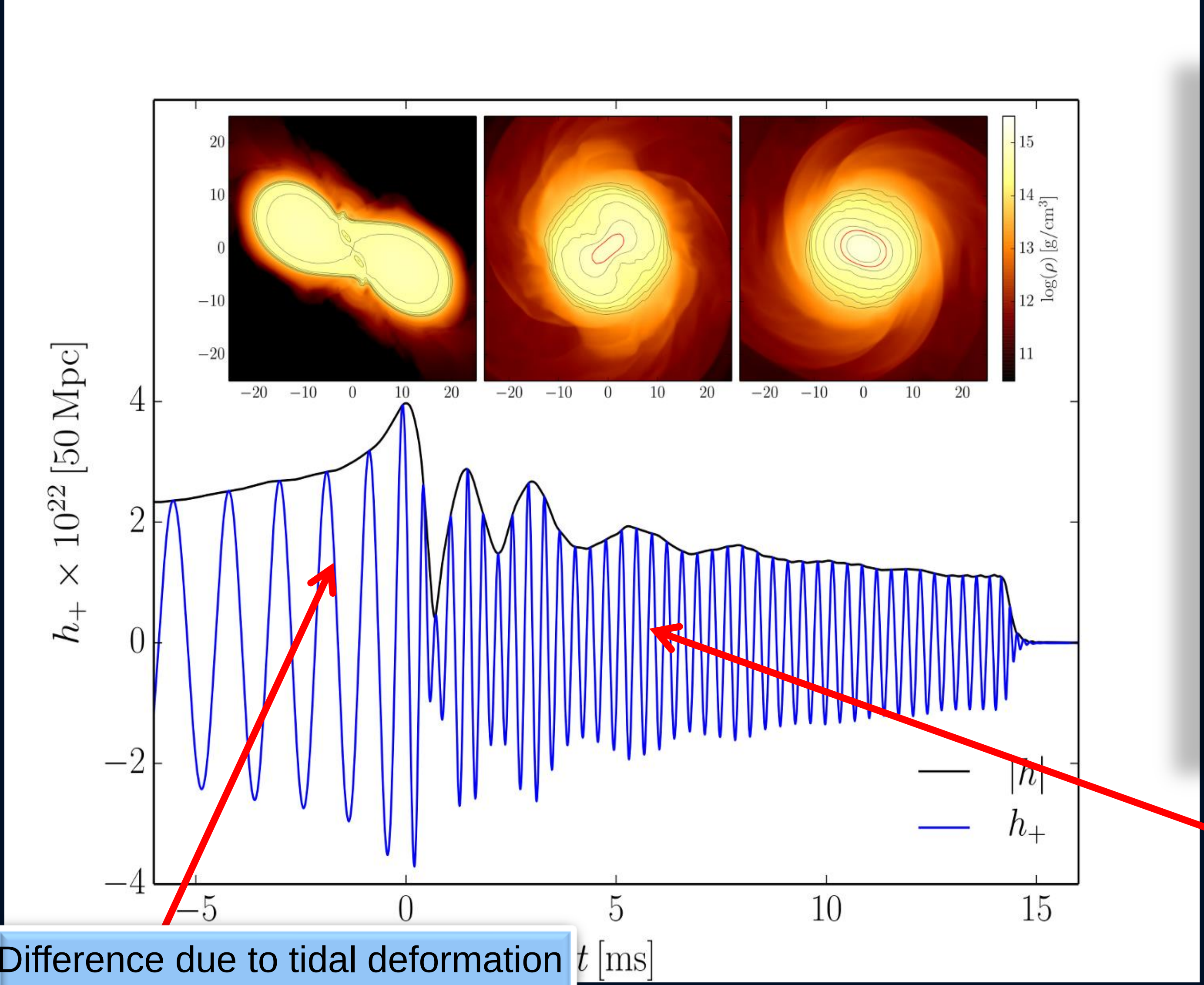
Density

Temperature



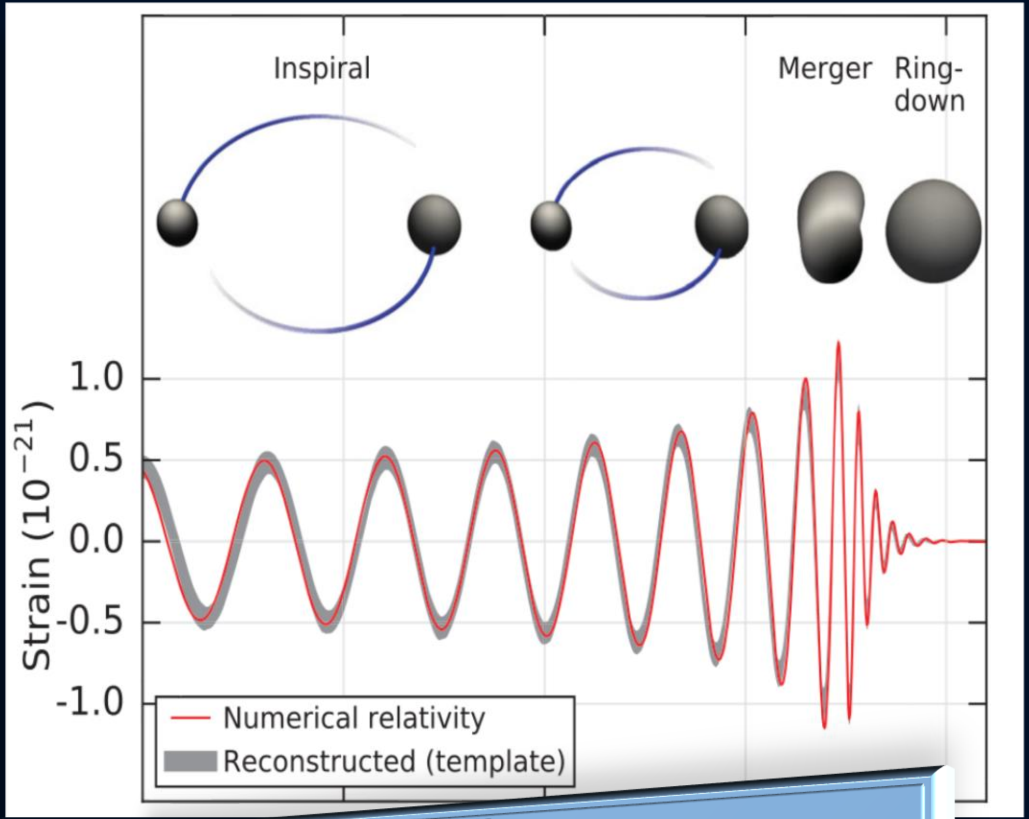
Gravitational Waves from Neutron Star Mergers

Neutron Star Collision (Simulation)



Difference due to tidal deformation in the late inspiral phase

Collision of two Black Holes
GW150914



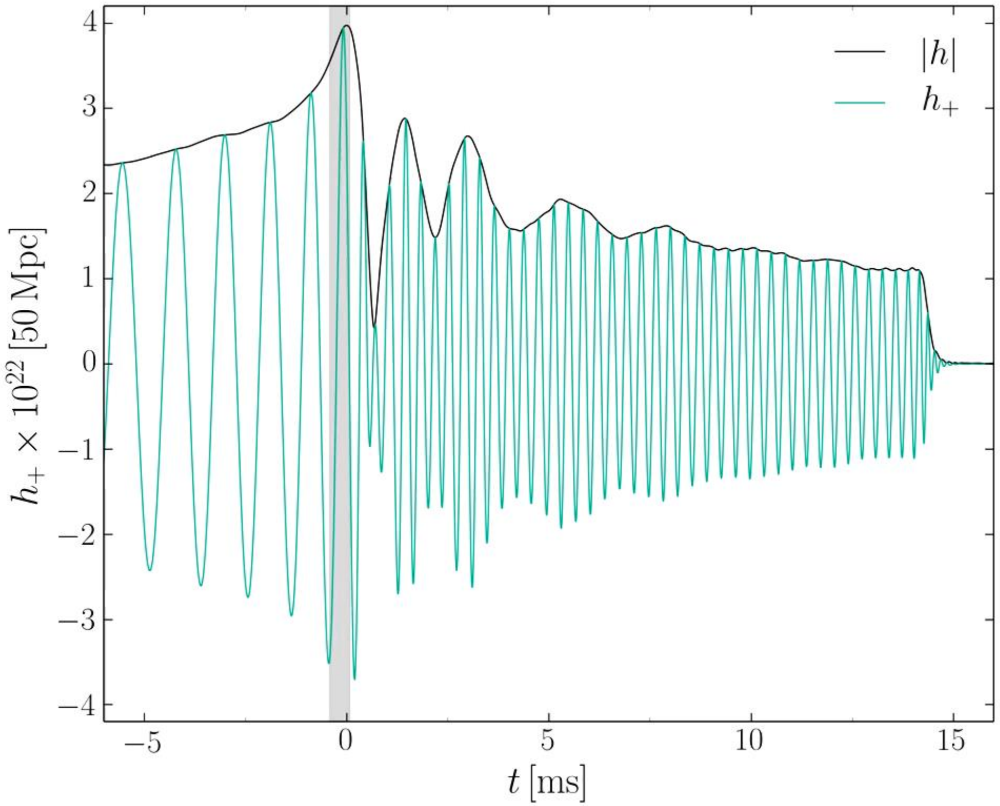
Main difference:

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

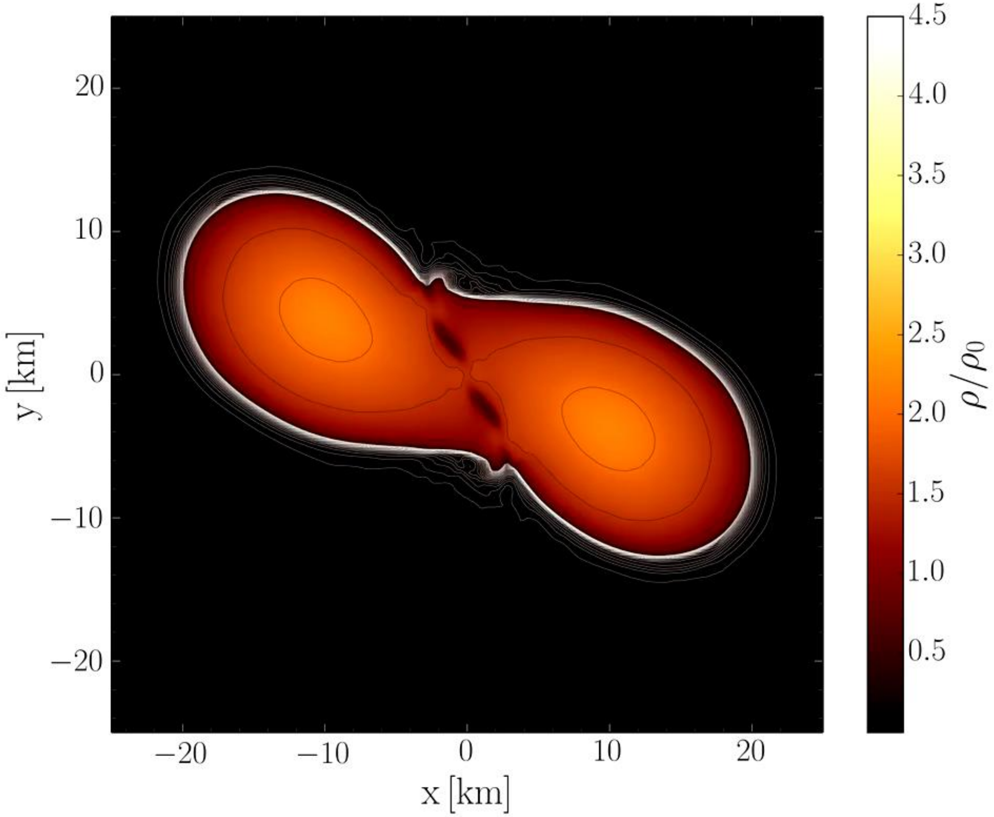
Evolution of the density in the post merger phase

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)

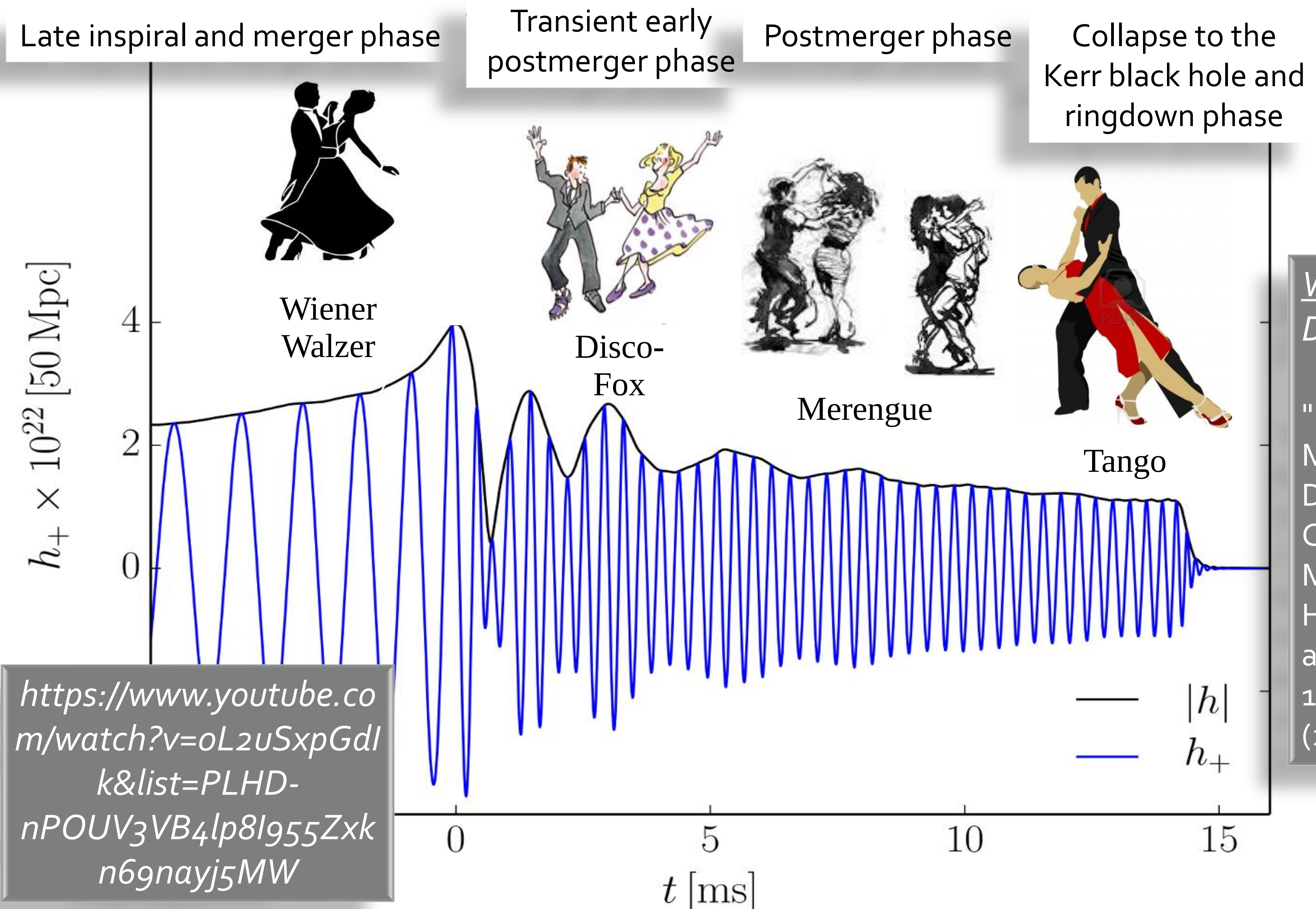


Gravitational wave amplitude
at a distance of 50 Mpc



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

The different Phases of a Binary Compact Star Merger Event

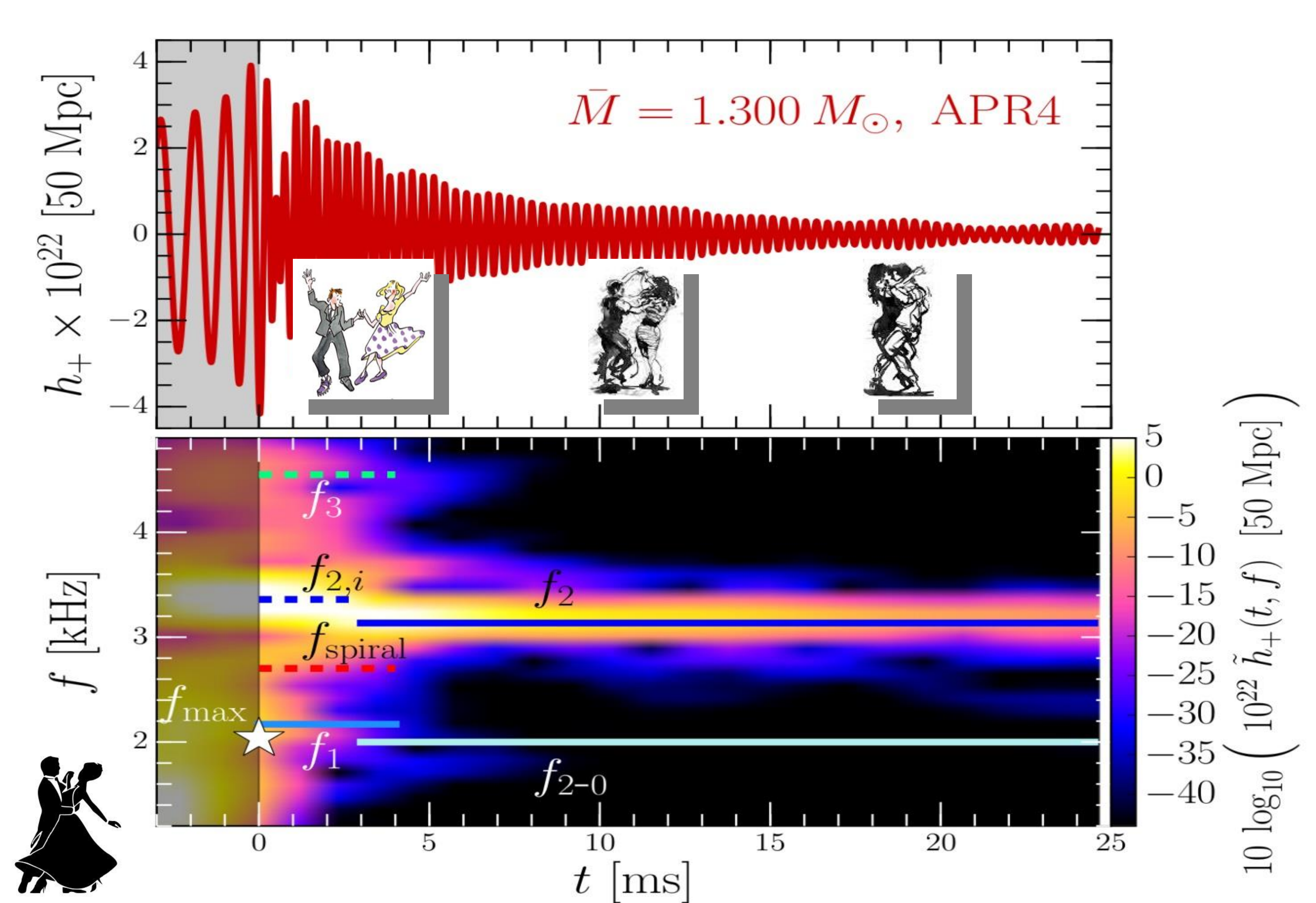


https://www.youtube.com/watch?v=oL2uSxpGdIk&list=PLHD-nPOUV3VB4lp8I955Zxkn69nayj5MW

Wy exactly these dances? Details in

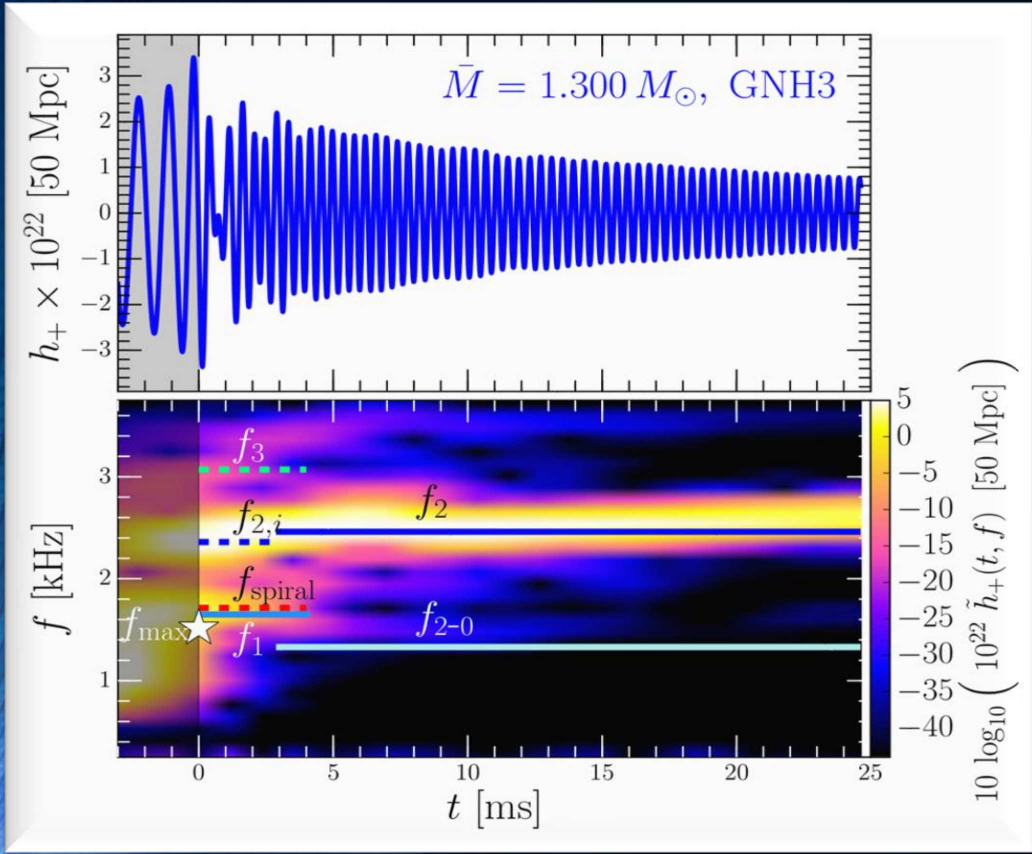
"Binary Compact Star Mergers and the Phase Diagram of Quantum Chromodynamics", Matthias Hanauske and Horst Stöcker, Discoveries at the Frontiers of Science, 107-132; Springer, Cham (2020)

The different Phases during the Postmergerphase of the HMNS

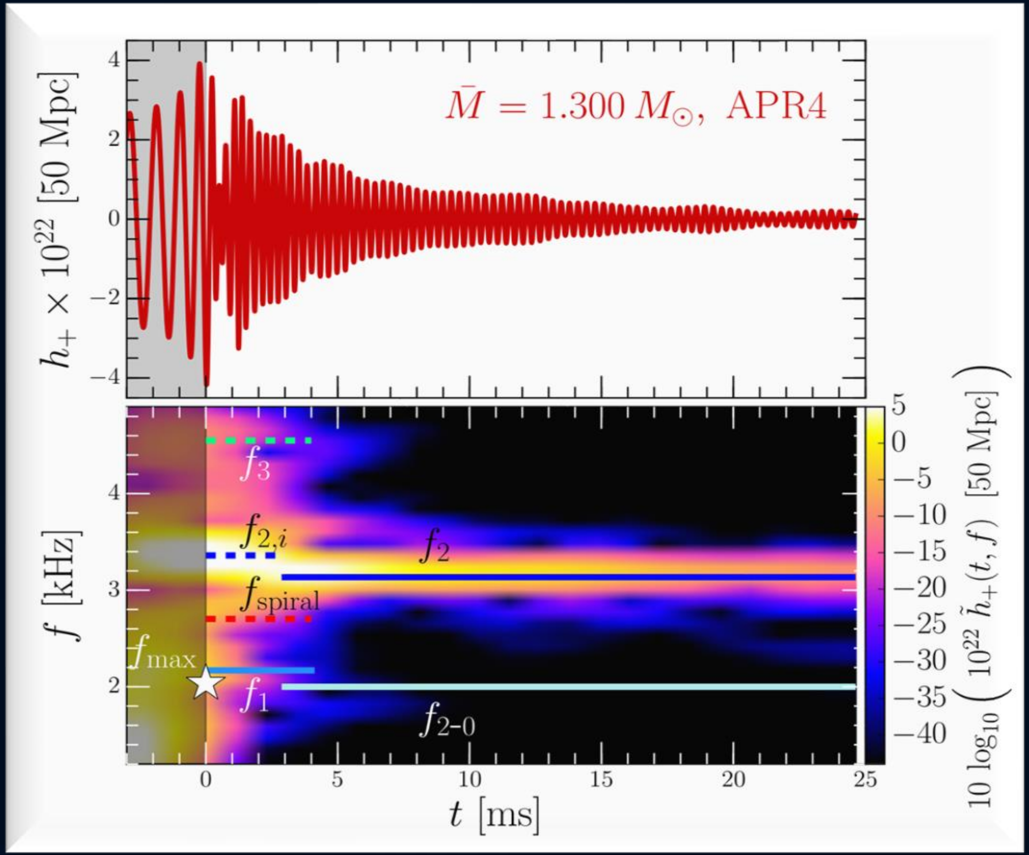


Time Evolution of the GW-Spectrum

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



<u>Stiff EOS</u>



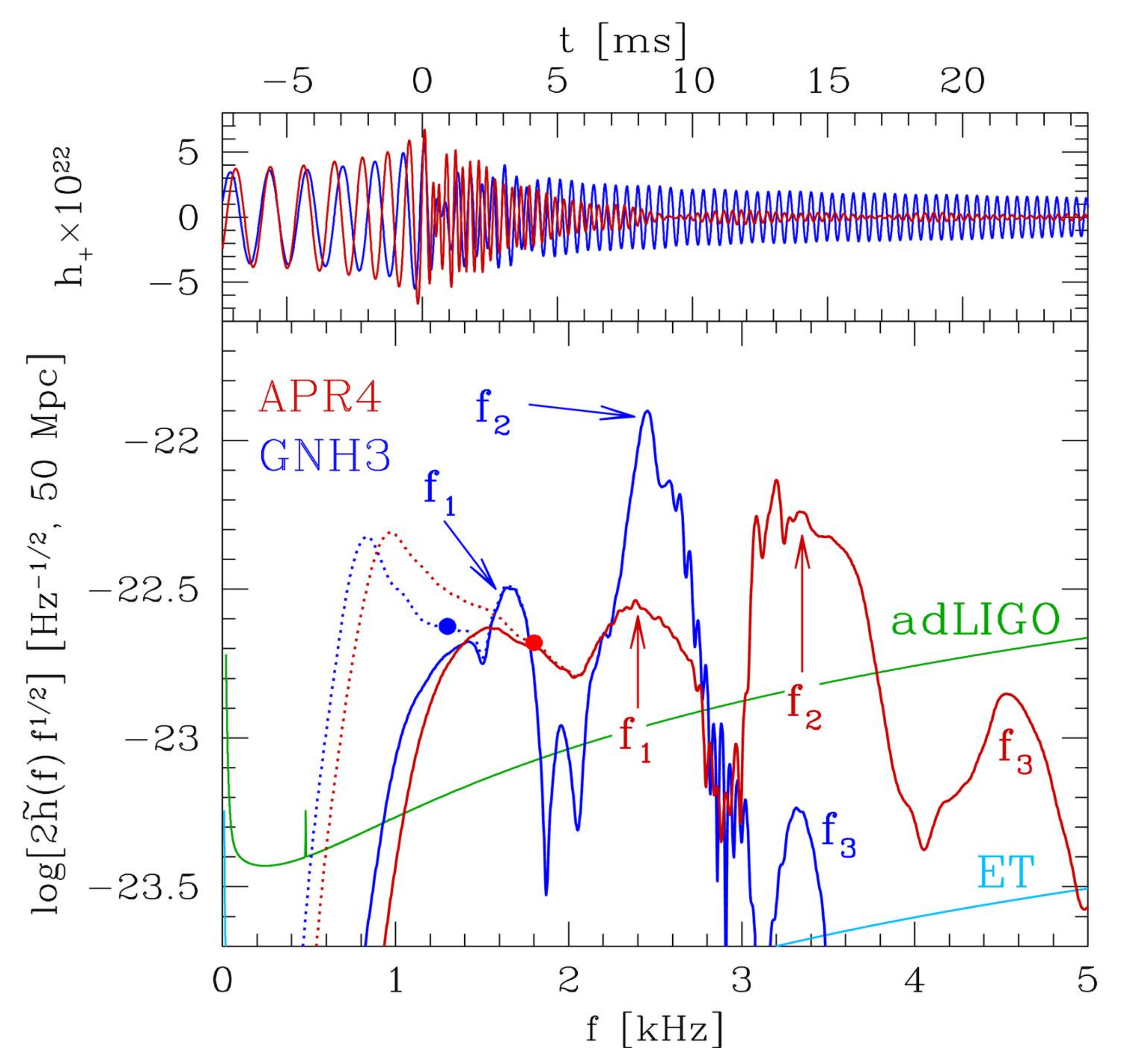
<u>Soft EOS</u>

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

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

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

A new approach to constrain the EOS



Kentaro Takami, Luciano Rezzolla, and Luca Baiotti, Physical Review D 91, 064001 (2015)

Hotokezaka, K., Kiuchi, K., Kyutoku, K., Muranushi, T., Sekiguchi, Y. I., Shibata, M., & Taniguchi, K. (2013). Physical Review D, 88(4), 044026.

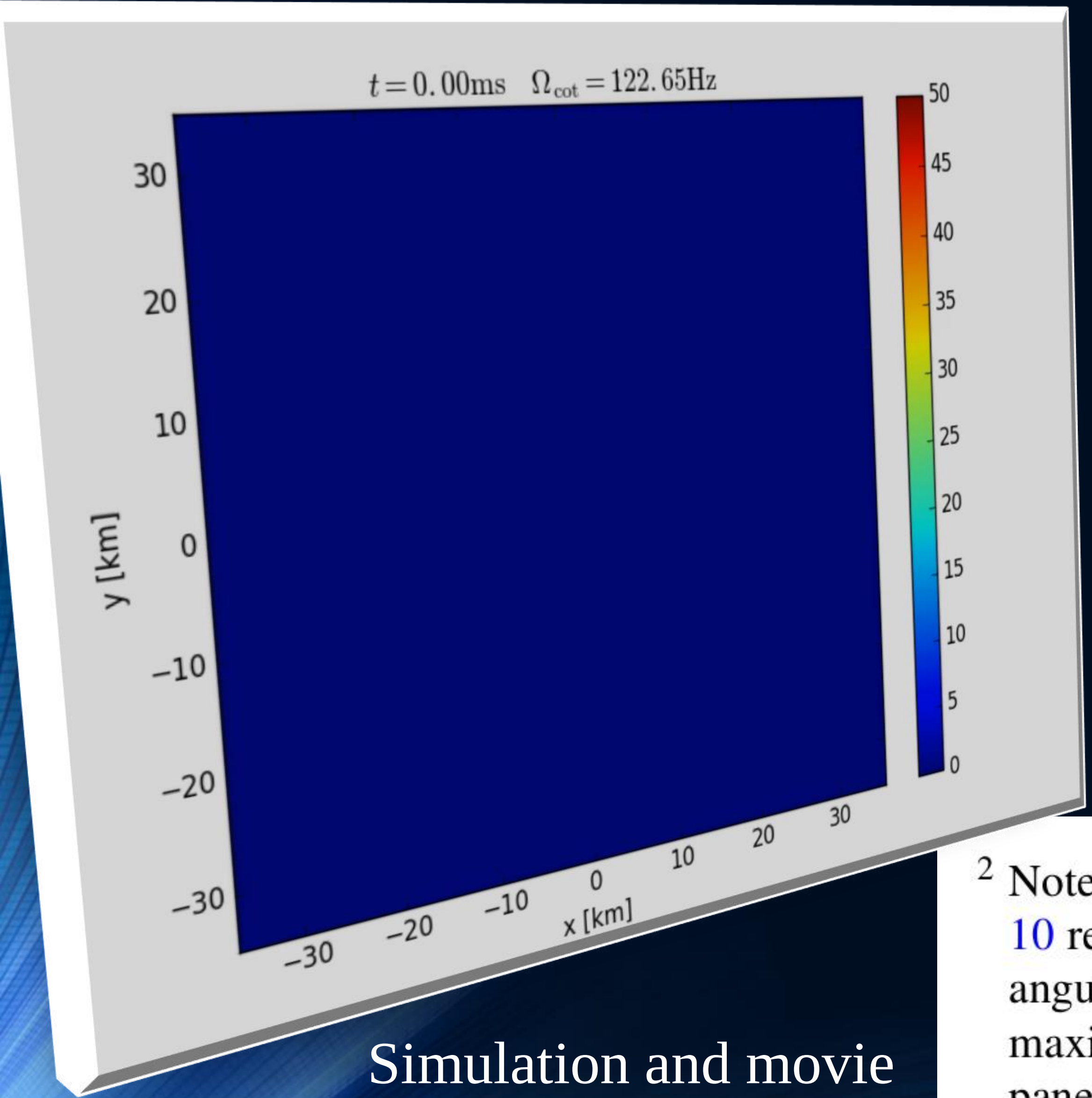
Bauswein, A., & Janka, H. T. (2012). Physical review letters, 108(1), 011101.

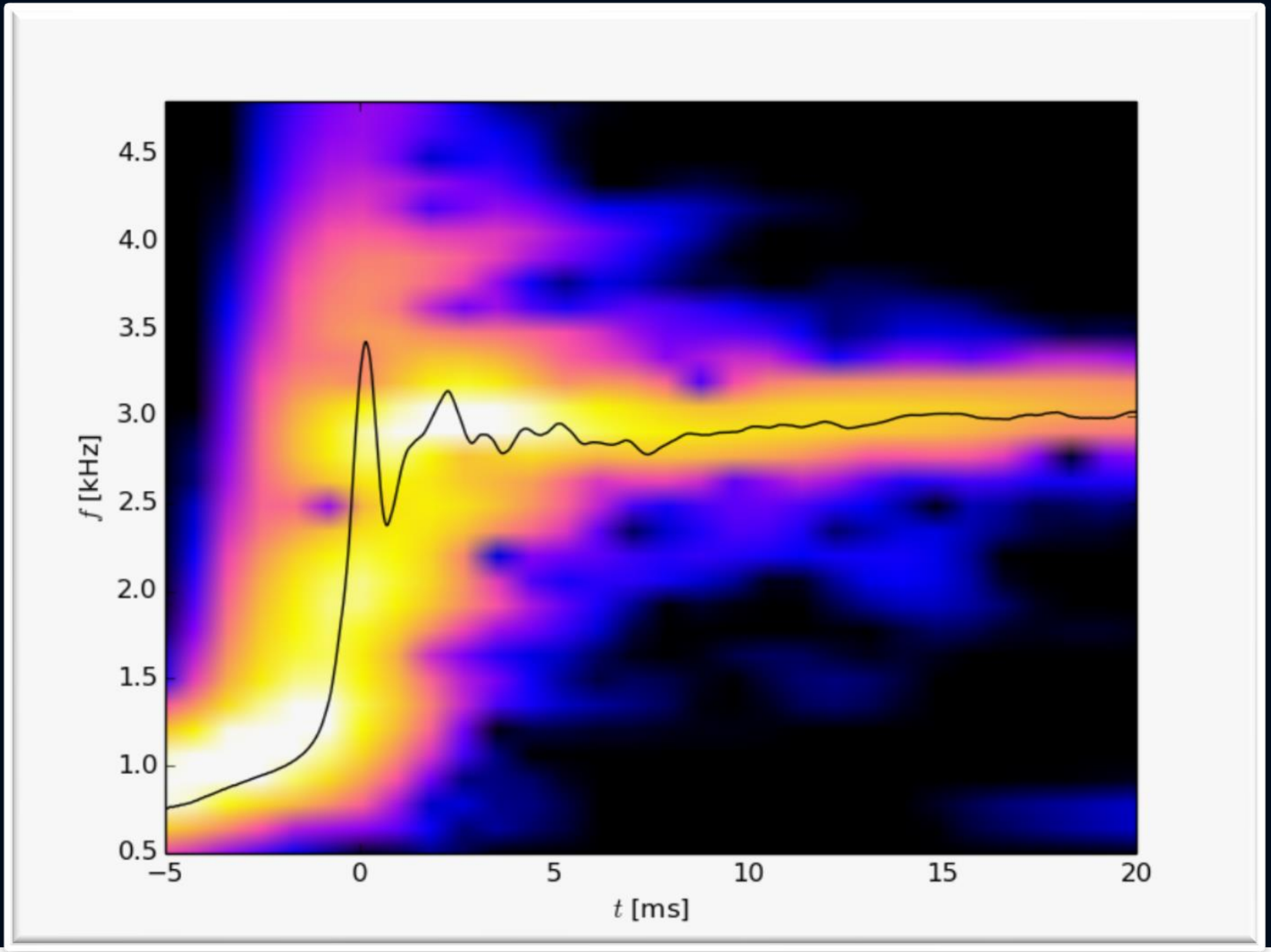
Clark, J. A., Bauswein, A., Stergioulas, N., & Shoemaker, D. (2015). arXiv:1509.08522.

Bernuzzi, S., Dietrich, T., & Nagar, A. (2015). Physical review letters, 115(9), 091101.

Oechslin+2007, Baiotti+2008, Bauswein+ 2011, 2012, Stergioulas+ 2011, Hotokezaka+ 2013, Takami 2014, 2015, Bernuzzi 2014, 2015, Bauswein+ 2015, Clark+ 2016, Rezzolla+2016, de Pietri+ 2016, Feo+ 2017, Bose+ 2017 …

The Co-Rotating Frame

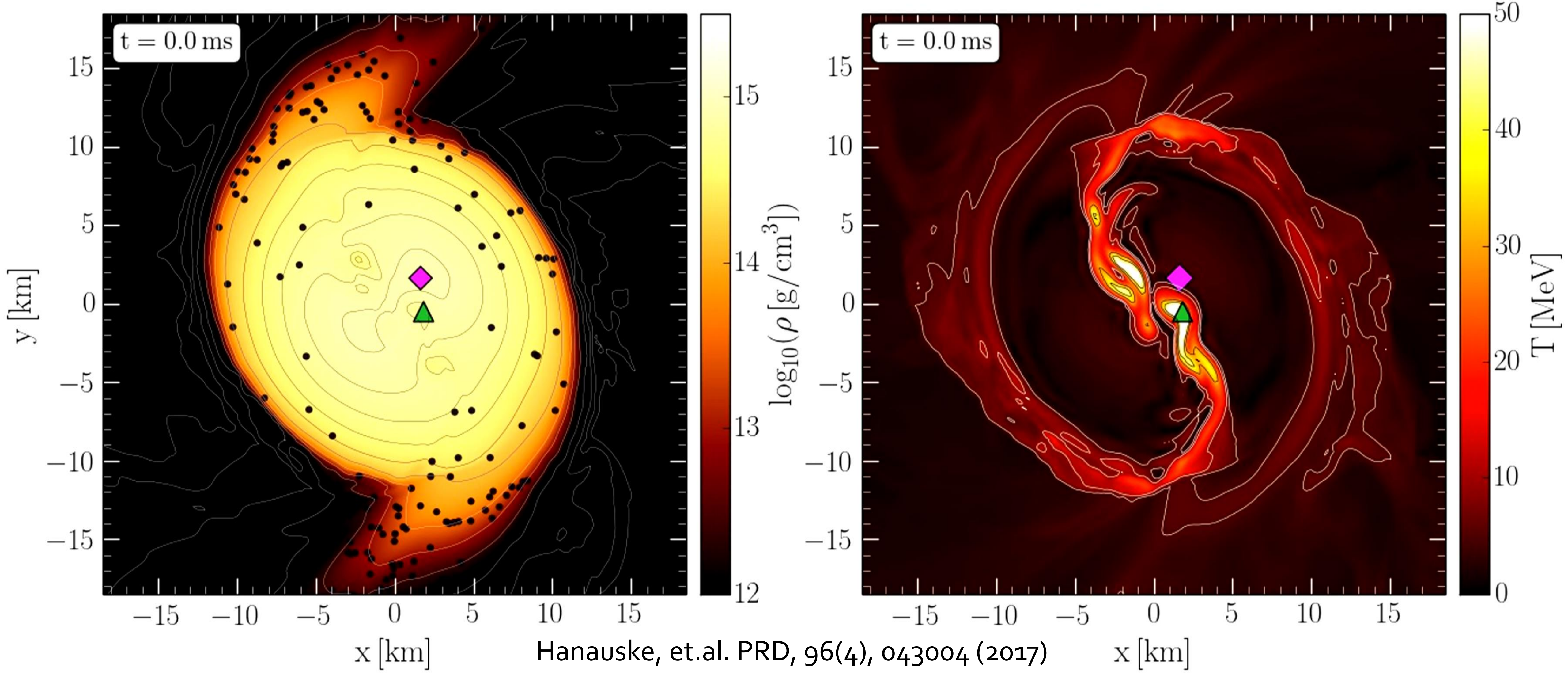




Simulation and movie
has been produced by Luke Bovard

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

Density and Temperature Evolution inside the HMNS

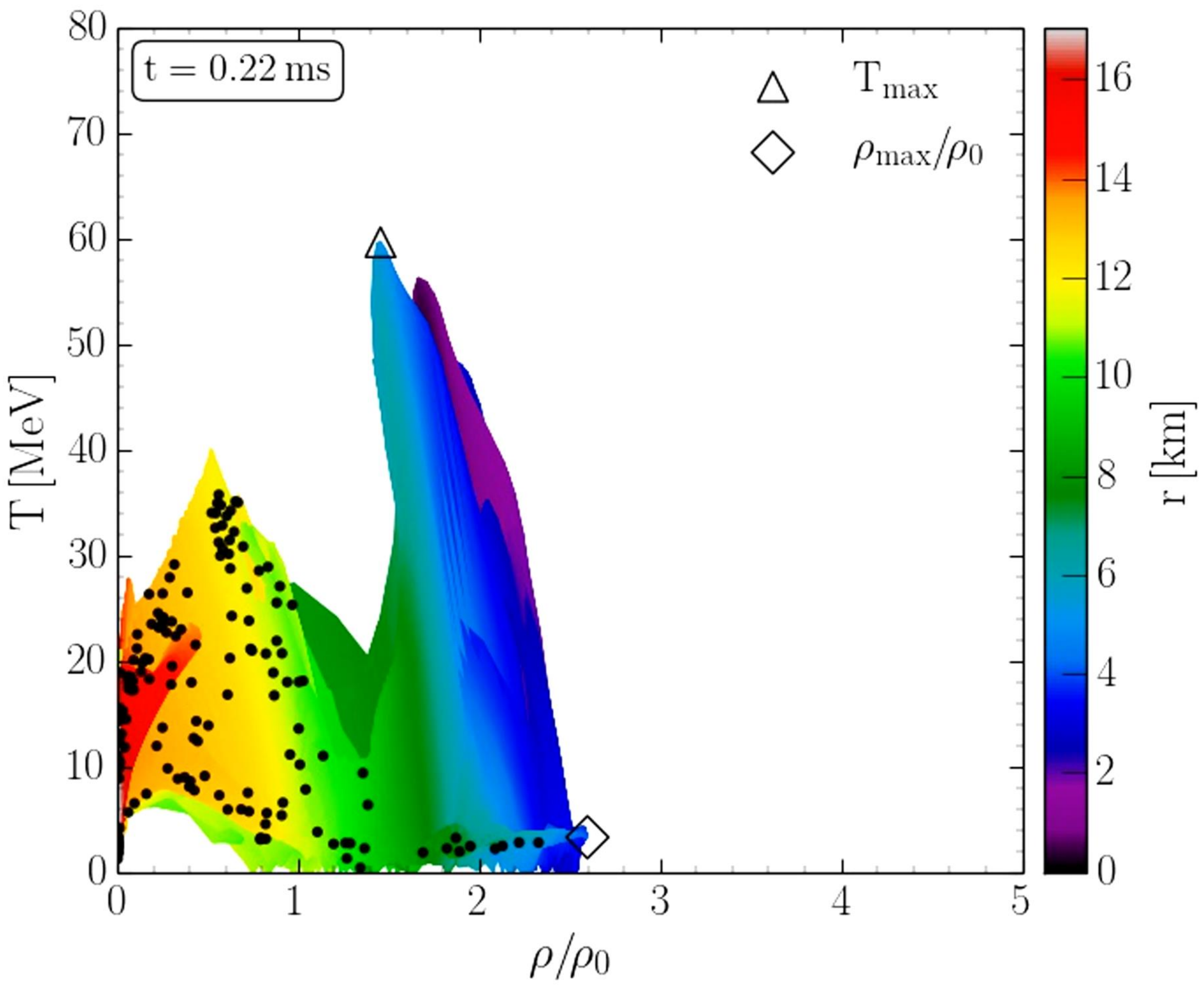


Hanauske, et.al. PRD, 96(4), 043004 (2017)

Rest mass density on the equatorial plane

Temperature on the equatorial plane

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

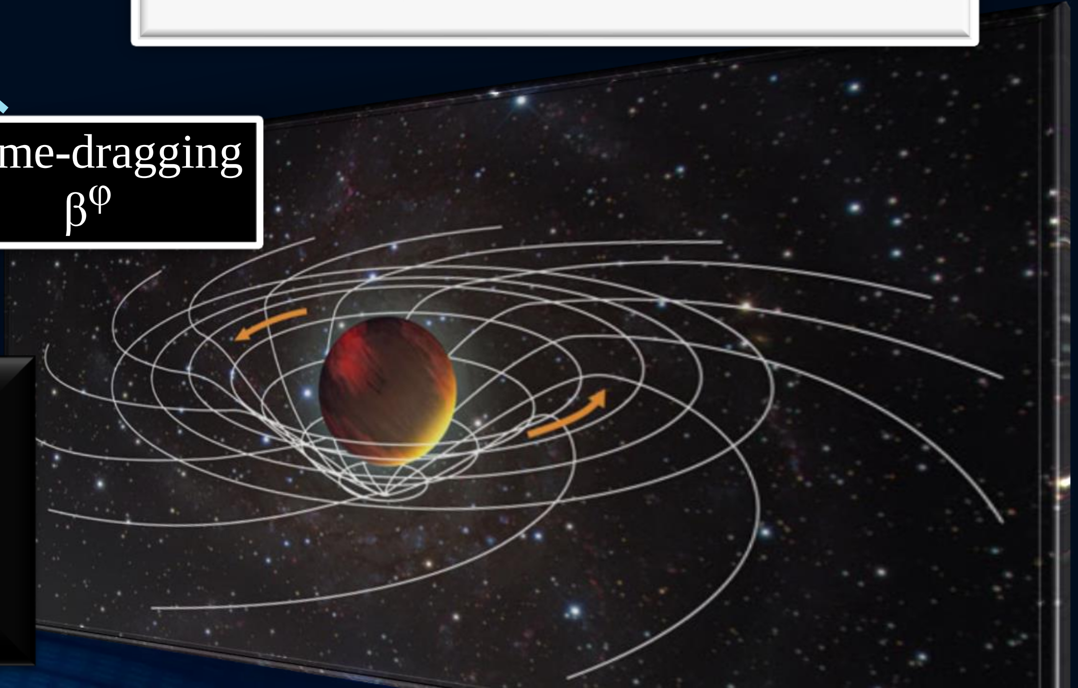
Lapse function α

Φ-component of 3-velocity v^{φ}

Frame-dragging β^{φ}

(3+1)-decomposition of spacetime:

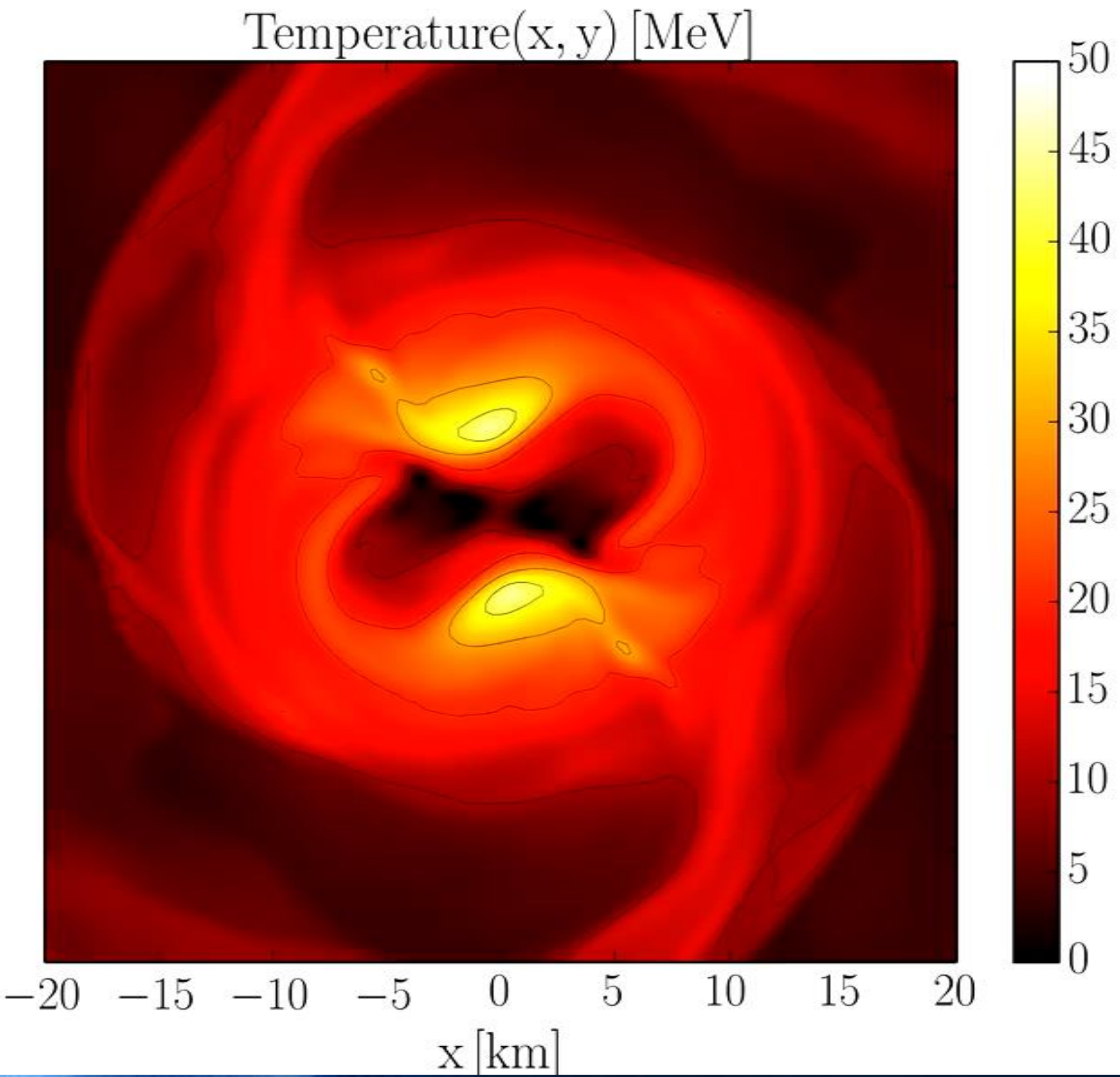
$$g_{\mu\nu} = \begin{pmatrix} -\alpha^2 + \beta_i \beta^i & \beta_i \\ \beta_i & \gamma_{ij} \end{pmatrix}$$



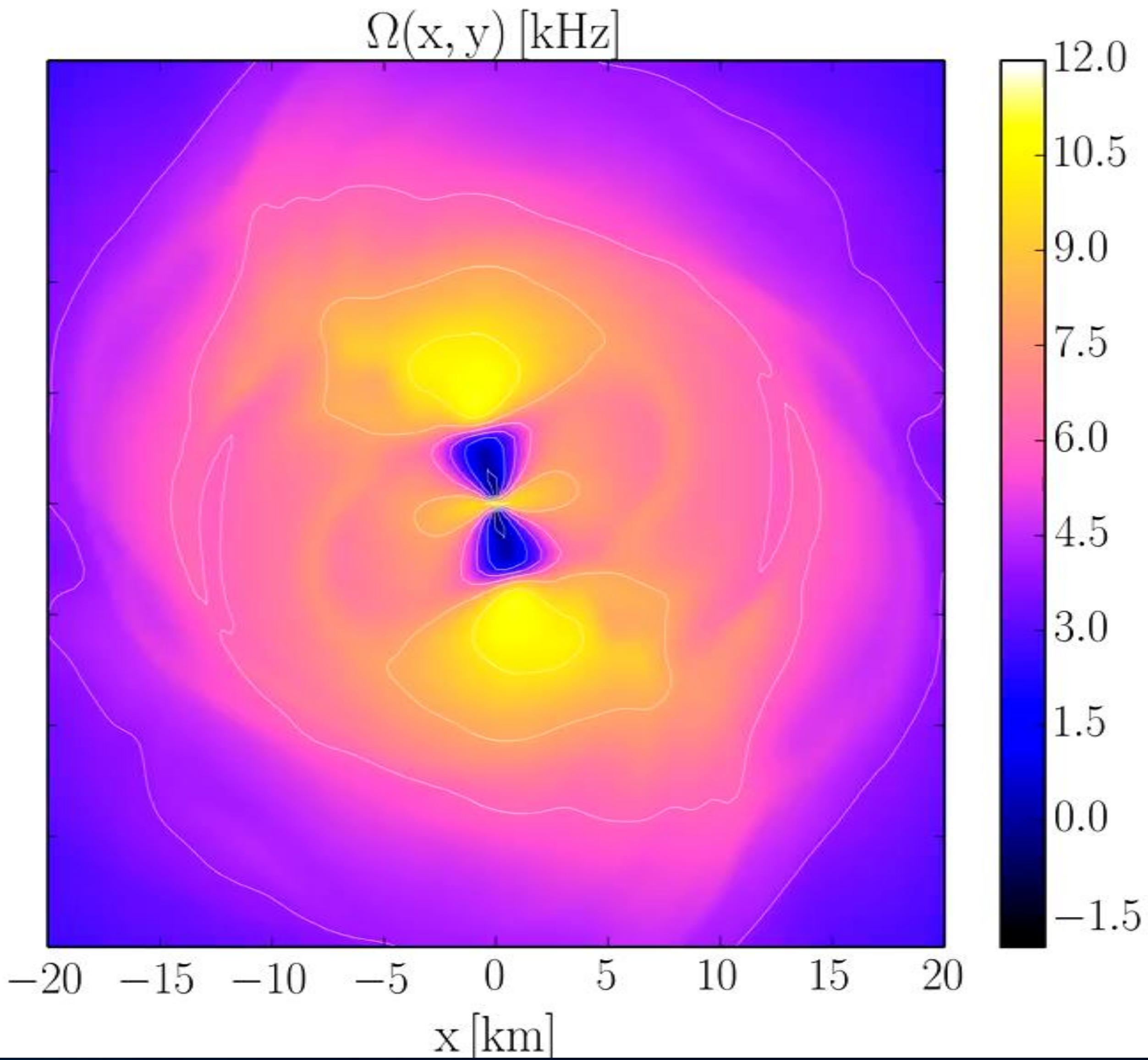
Focus: Inner core of the differentially rotating HMNS

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)

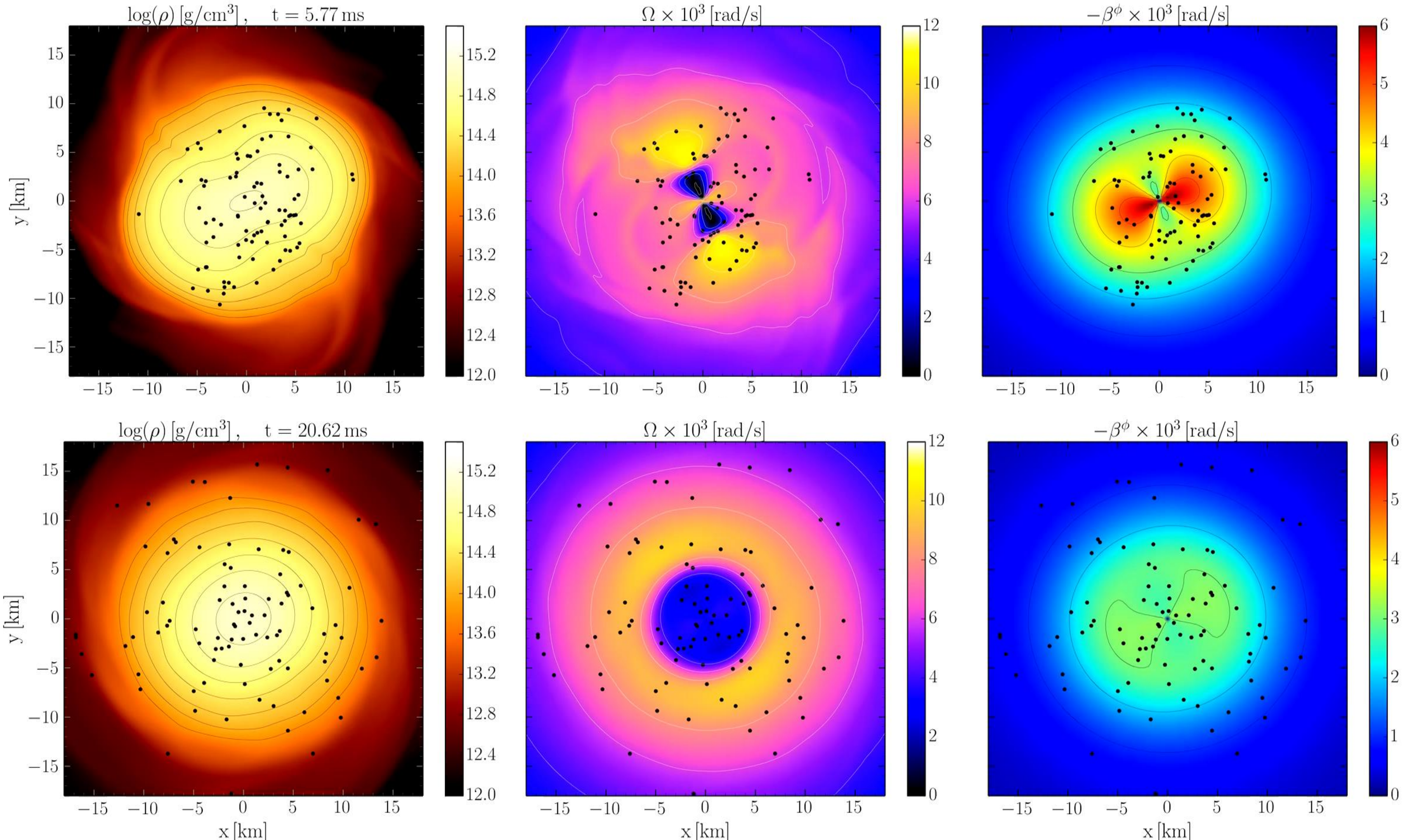
Temperature



Angular Velocity

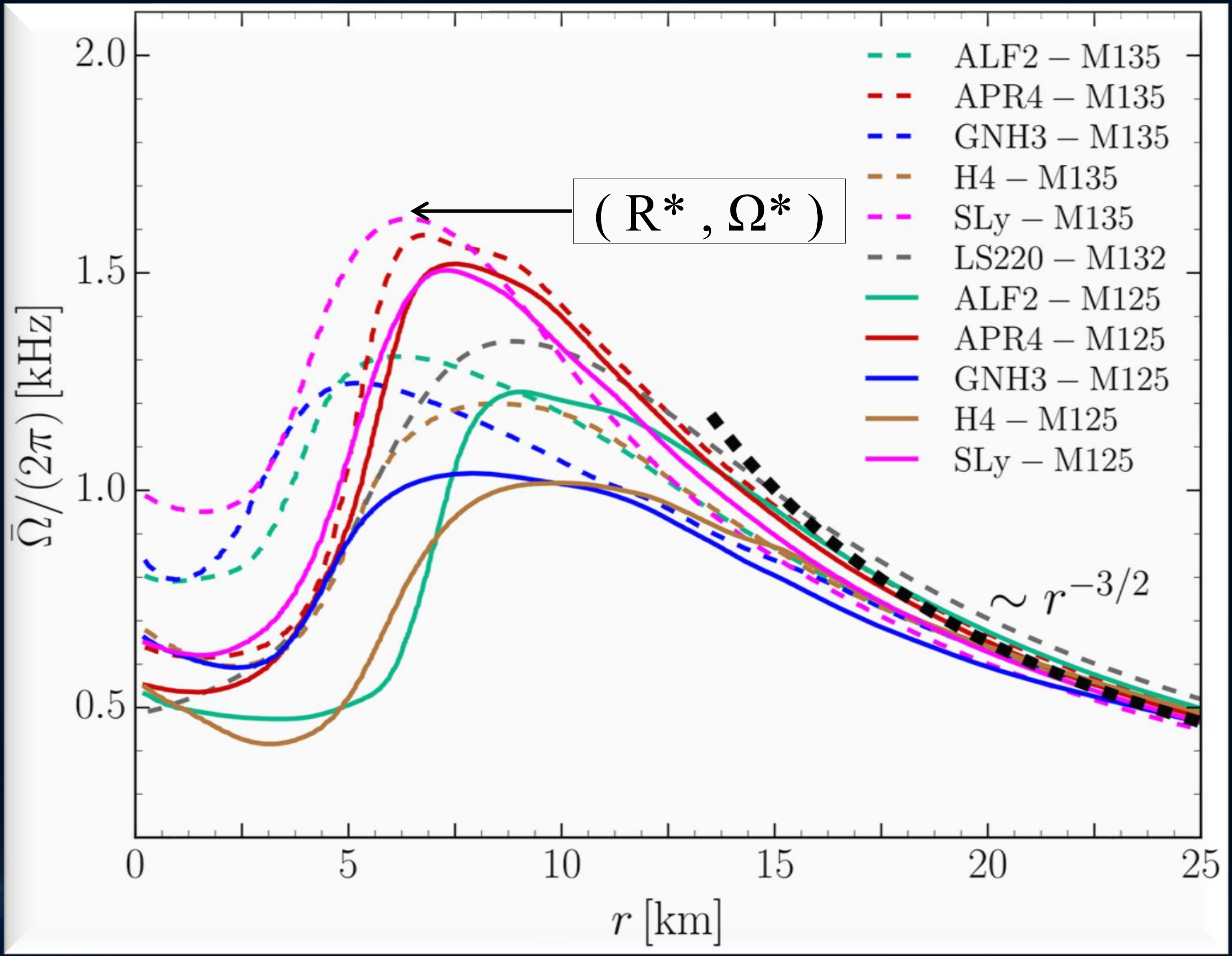


EOS: LS200 , Mass: 1.32 M_{solar} , simulation with Pi-symmetry



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]

Time-averaged Rotation Profiles of the HMNSs



Soft EoSs:
Sly
APR4

Stiff EoSs:
GNH3
H4

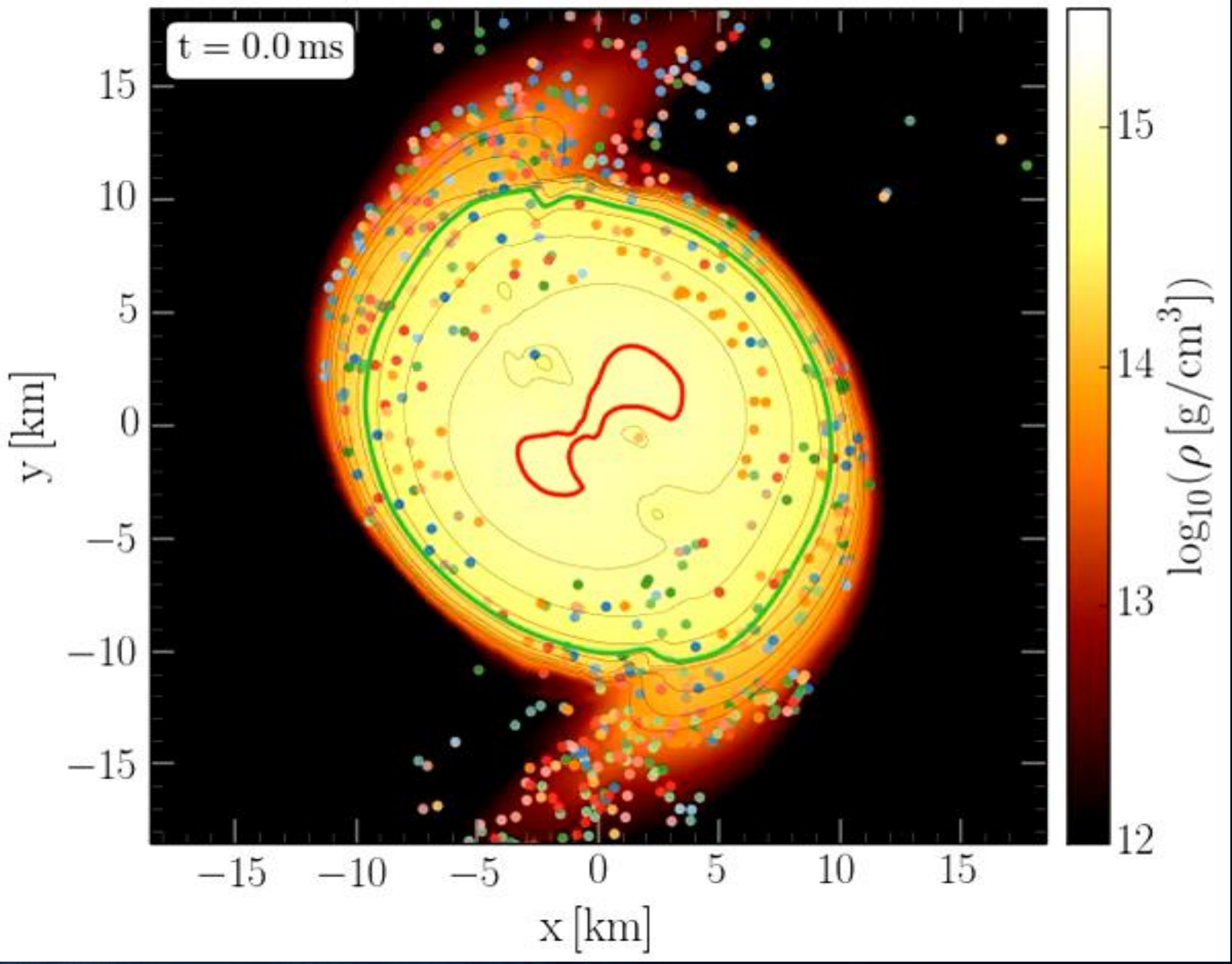
Time-averaged rotation profiles for different EoS
Low mass runs (solid curves), high mass runs (dashed curves).

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

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



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)

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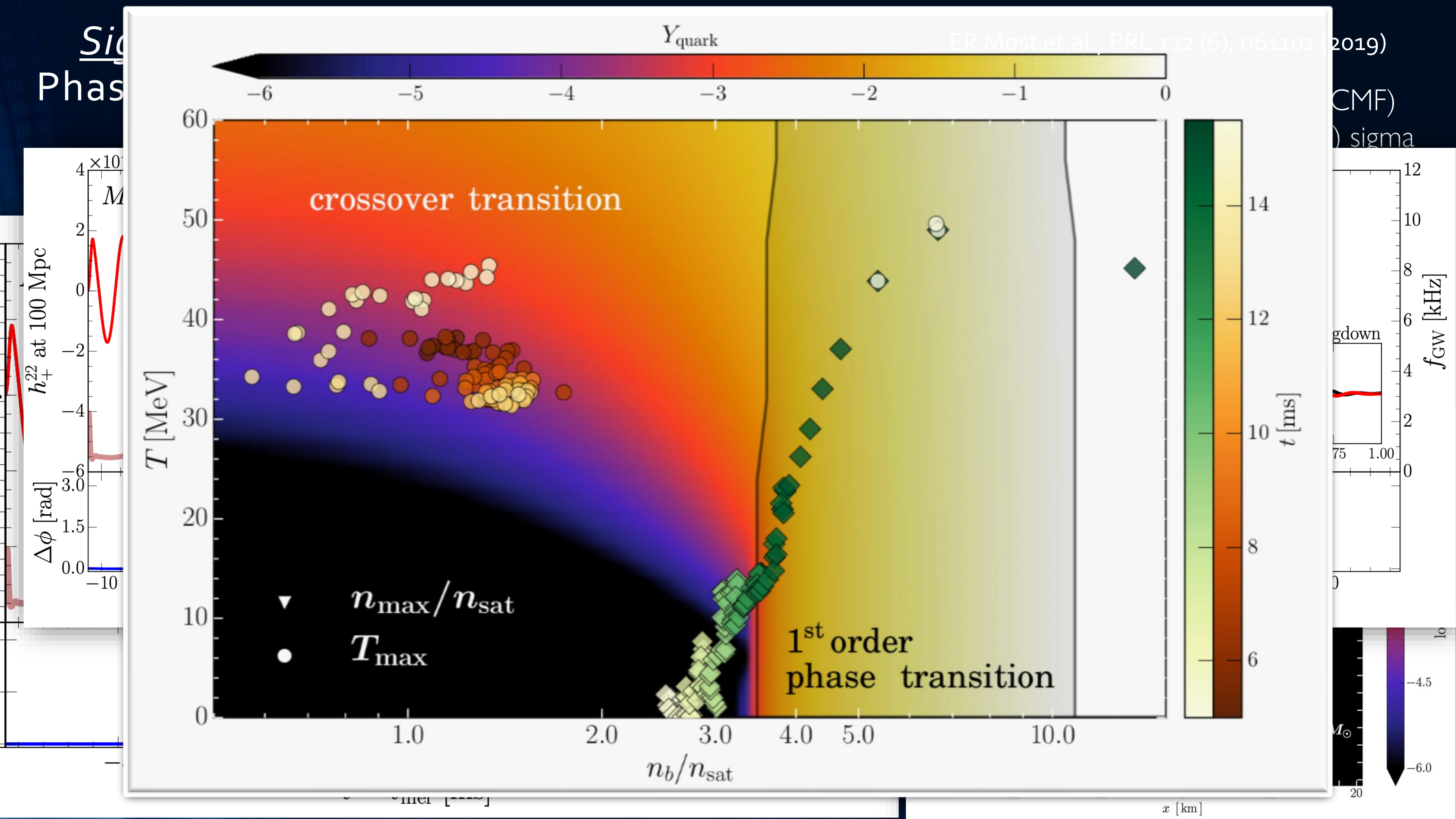


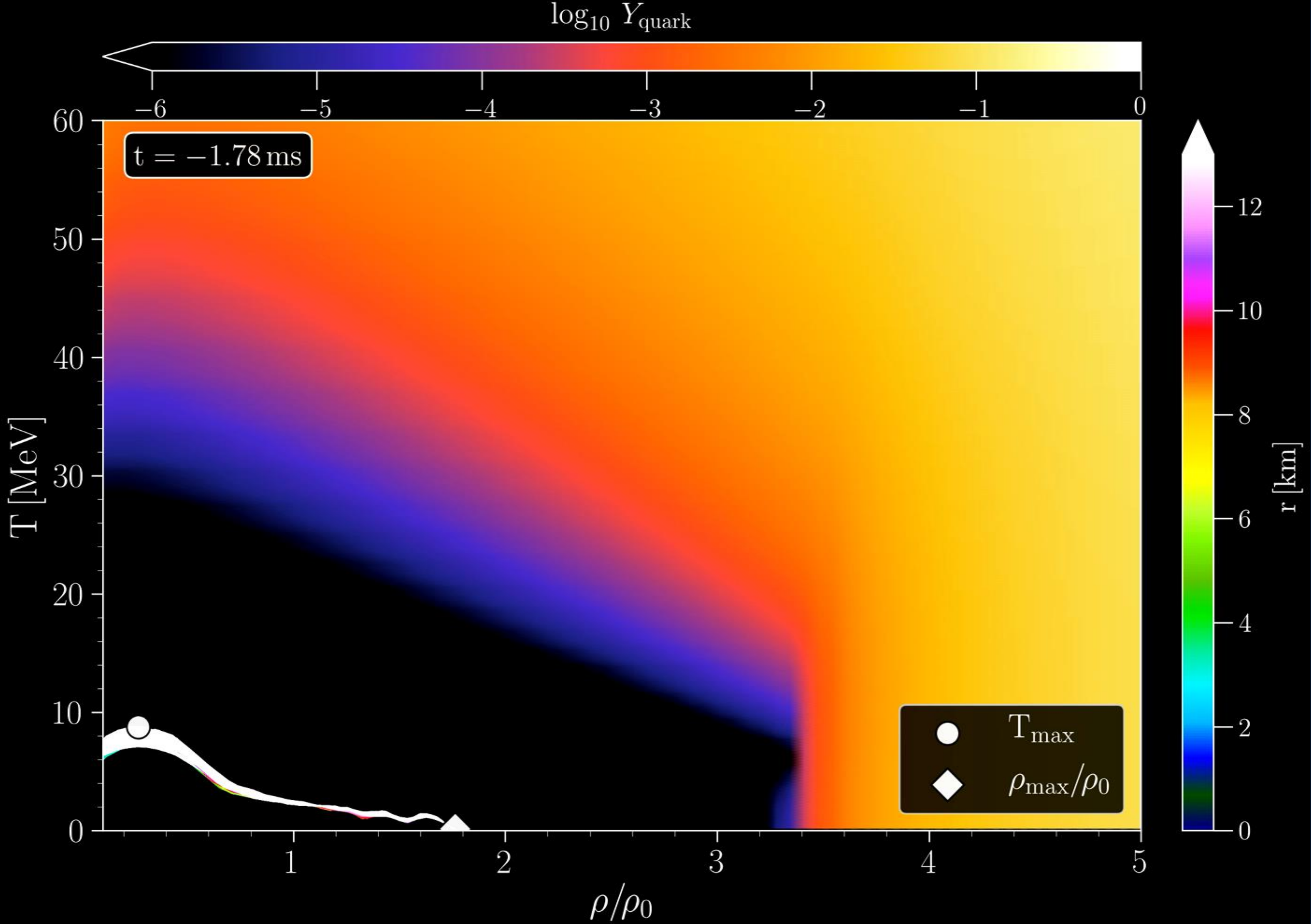
Sig
Phas
ER Most et al., PRL 122 (6), 061101 (2019)
CMF)
) sigma
$Y_{\rm quark}$
−6
−5
−4
−3
−2
−1
0
crossover transition
1st order phase transition
$n_{\max}/n_{\rm sat}$
$T_{\max}$
T [MeV]
$n_b/n_{\rm sat}$
1.0
2.0
3.0
4.0
5.0
10.0
t [ms]
h_+^{22} at 100 Mpc
$\Delta\phi$ [rad]
$f_{\rm GW}$ [kHz]
gdown
x [km]

Phase-transition triggered collapse scenario

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

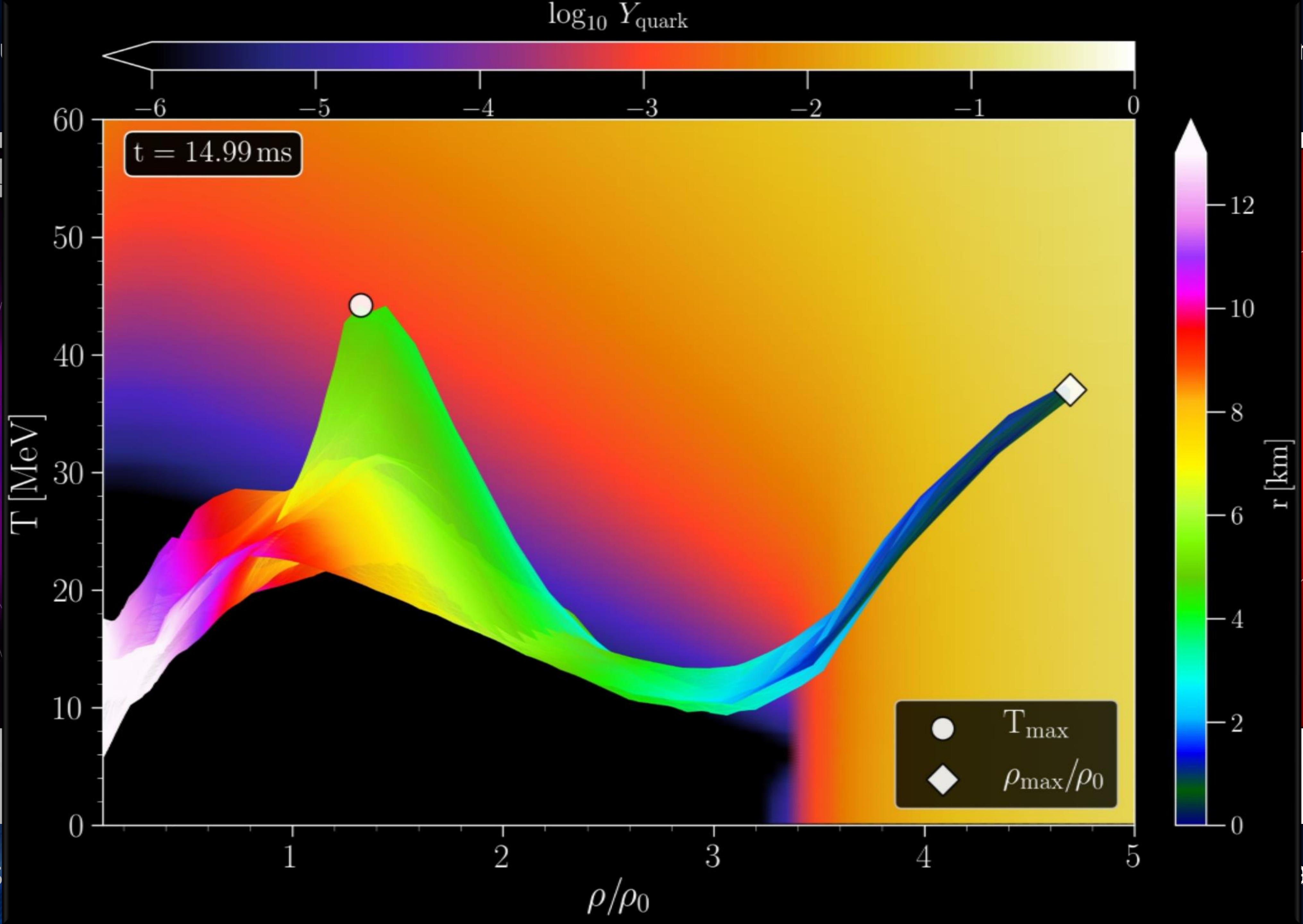
ER Most, LJ Papenfort, V Dexheimer, M Hanauske, S Schramm, H Stöcker and L. Rezzolla

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



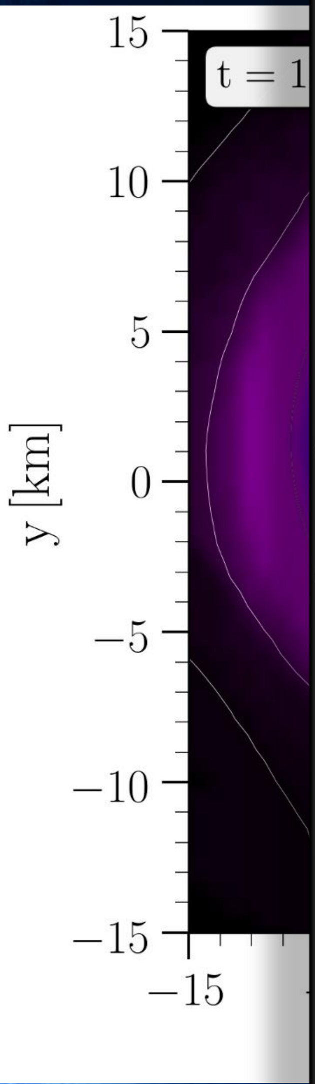
Density-Temperature-Composition dependent EOS within the CMFQ model.

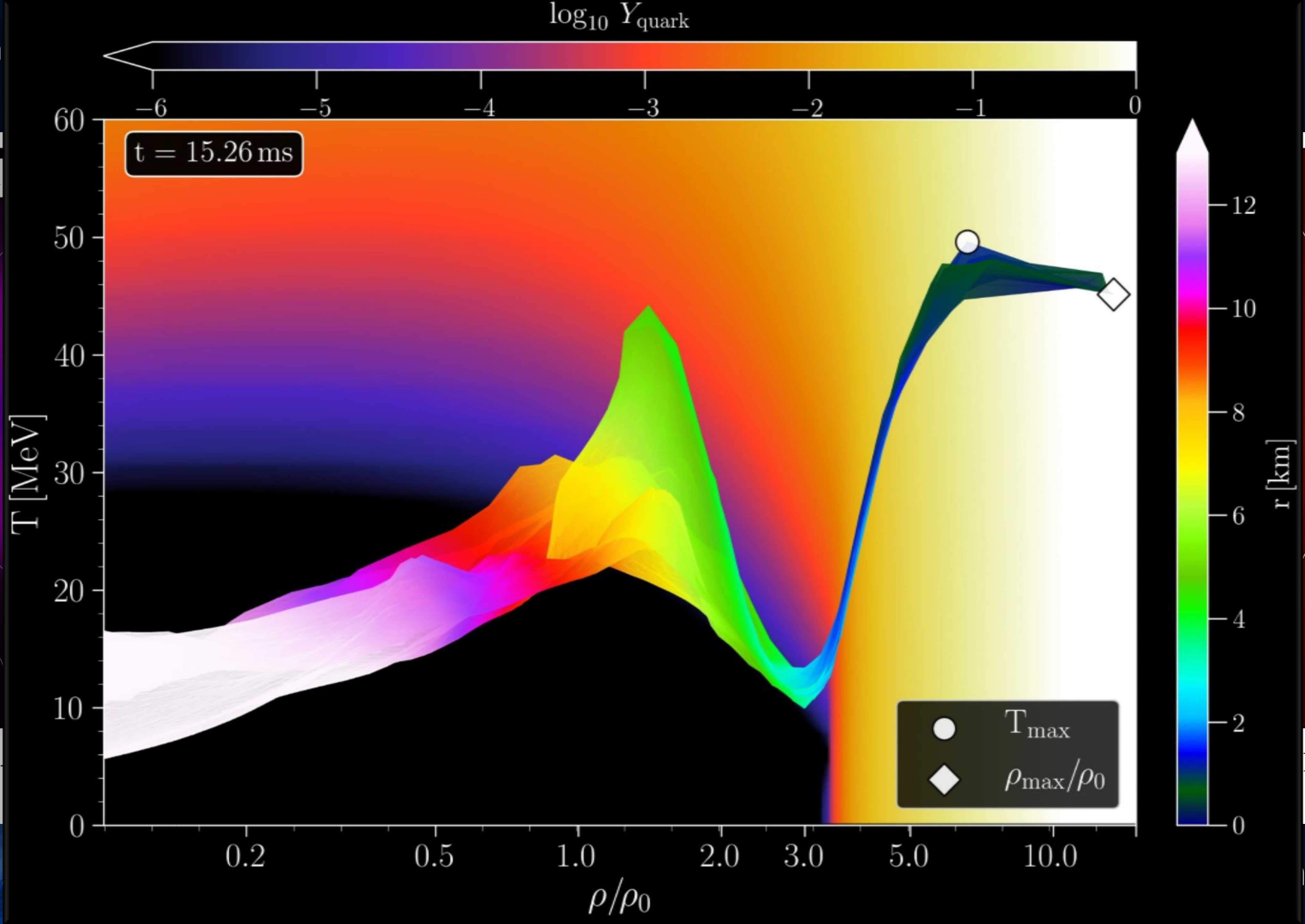
The last sim… r (HMHS)

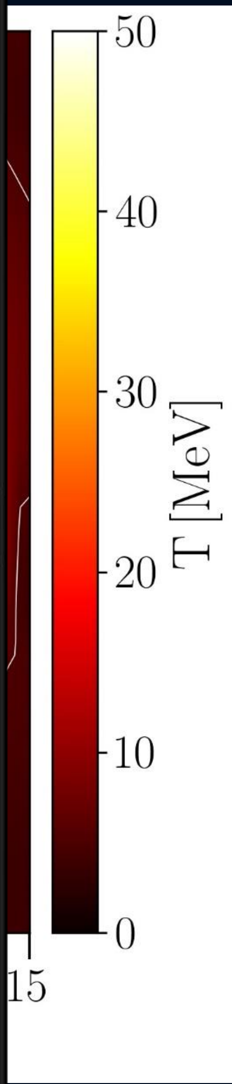


Rest mas… ane

The last sim … (HMHS)

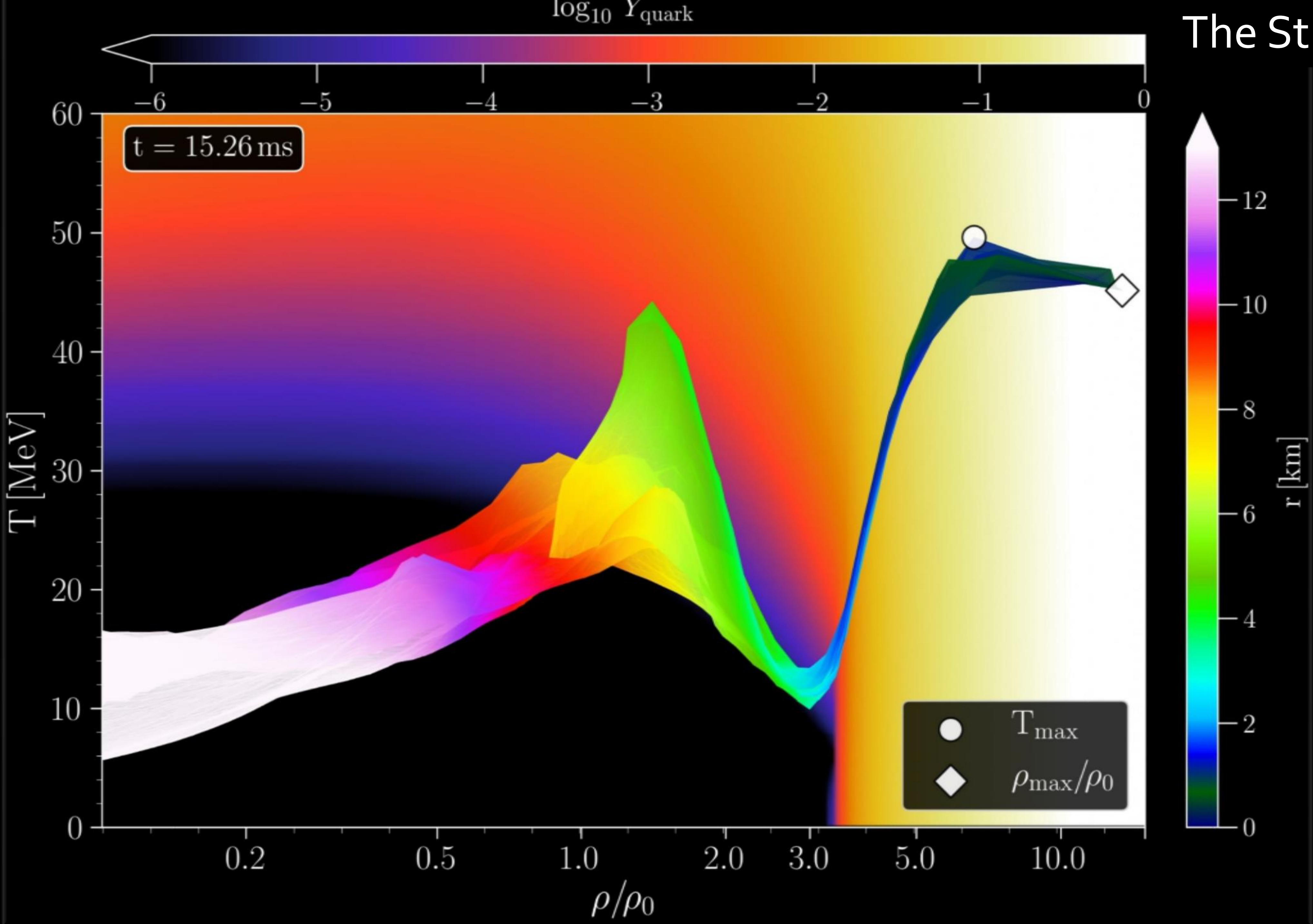






Rest mas … ne

The Strange Bird Plot



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

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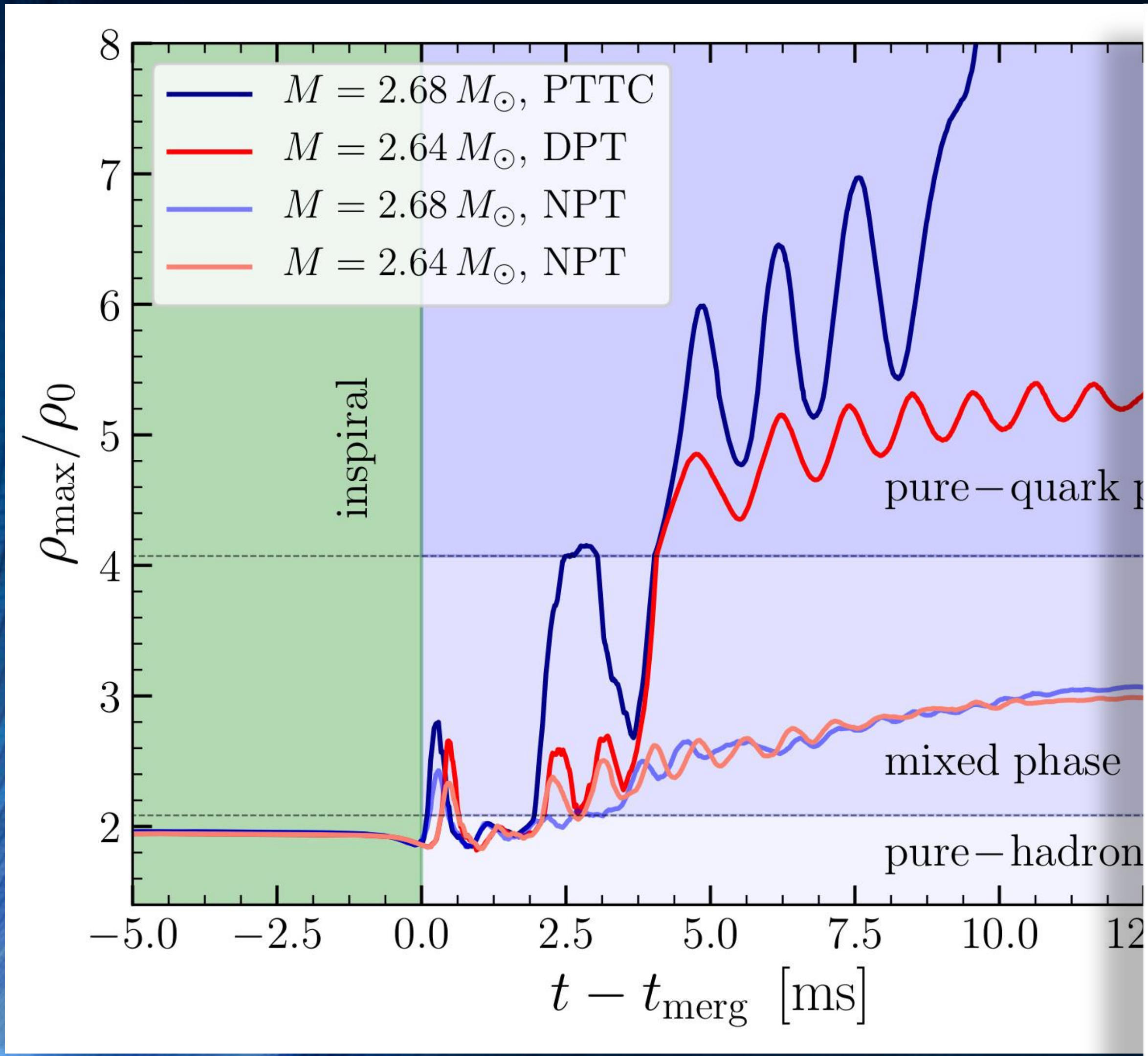
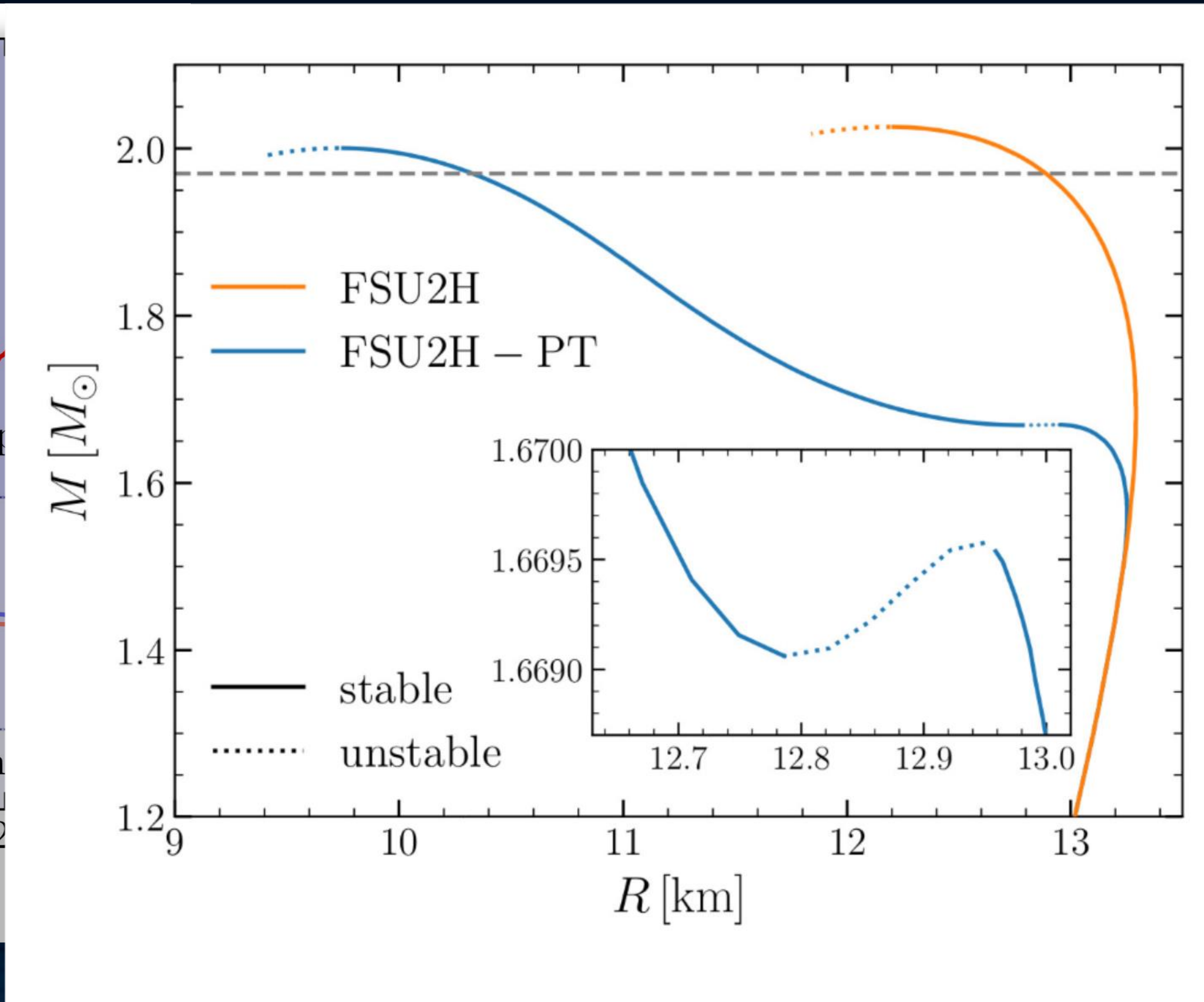
Signatures within the post-merger phase evolution

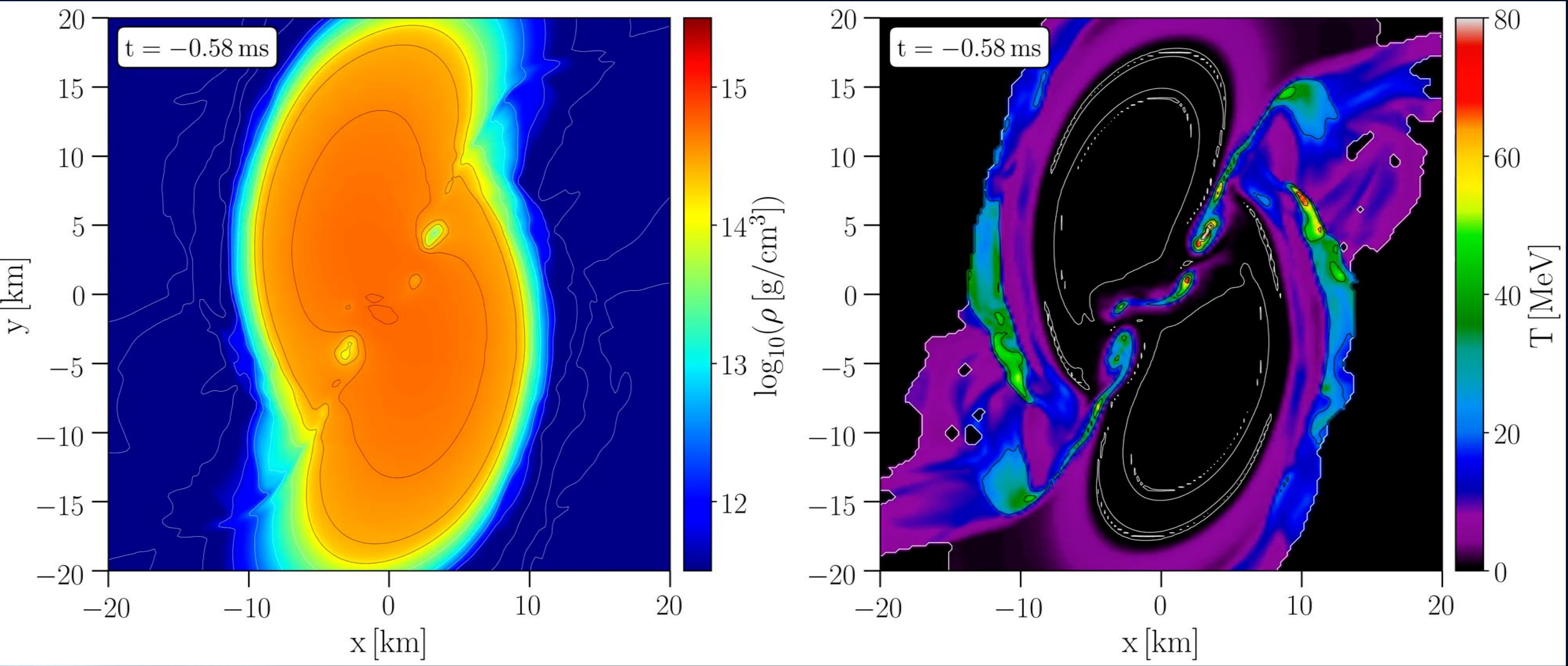
Delayed phase transition scenario

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



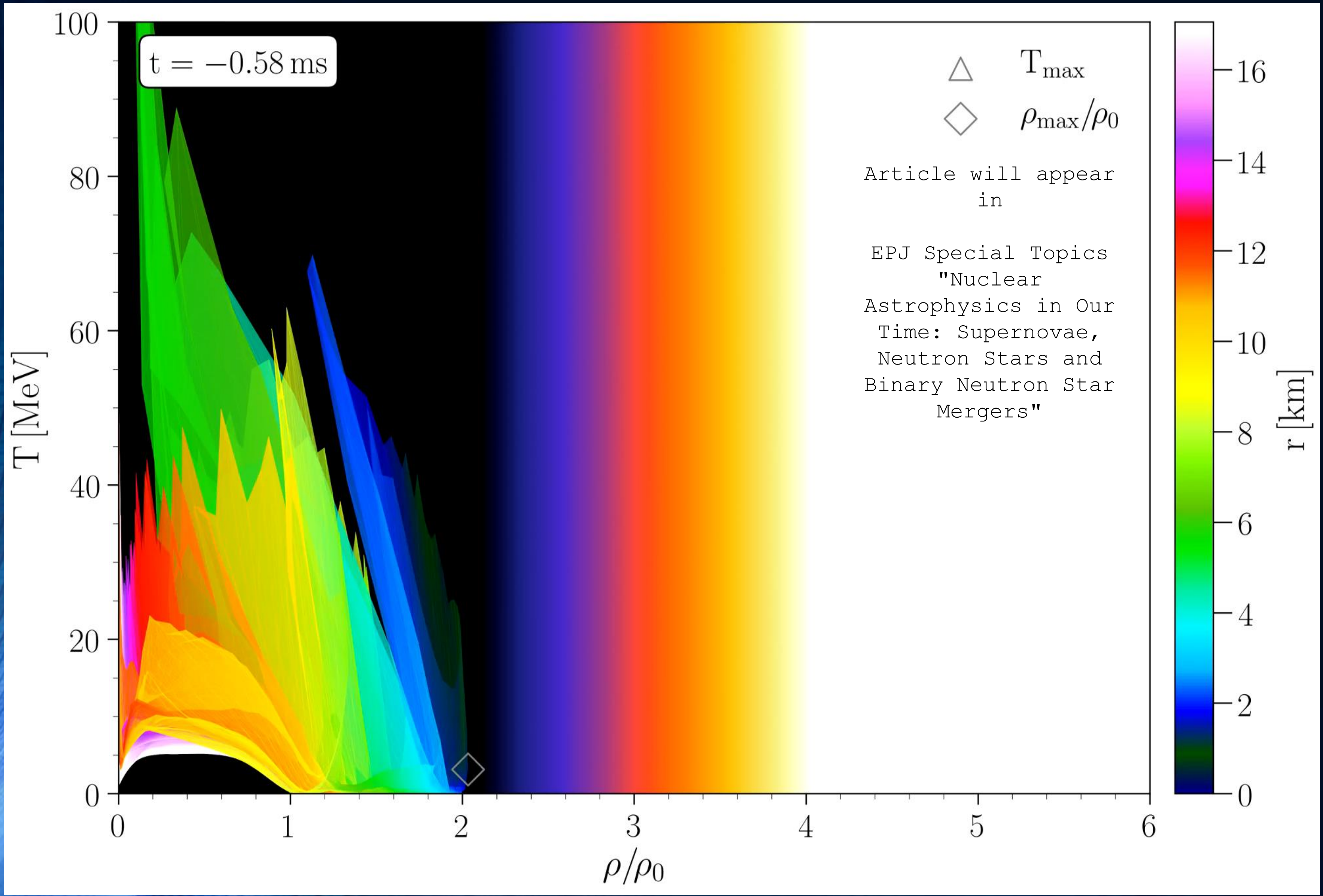


Density and temperature evolution inside the HMHS



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

Binary Neutron Star Mergers in the QCD Phase Diagram

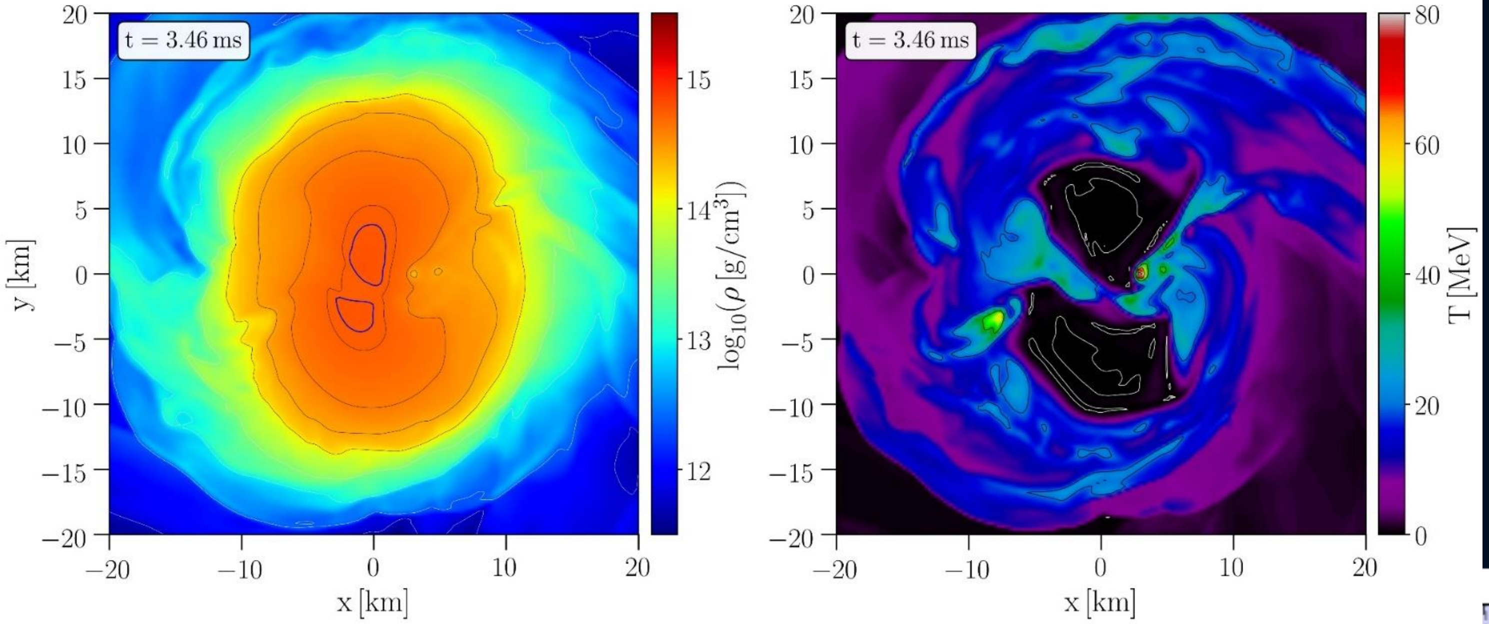


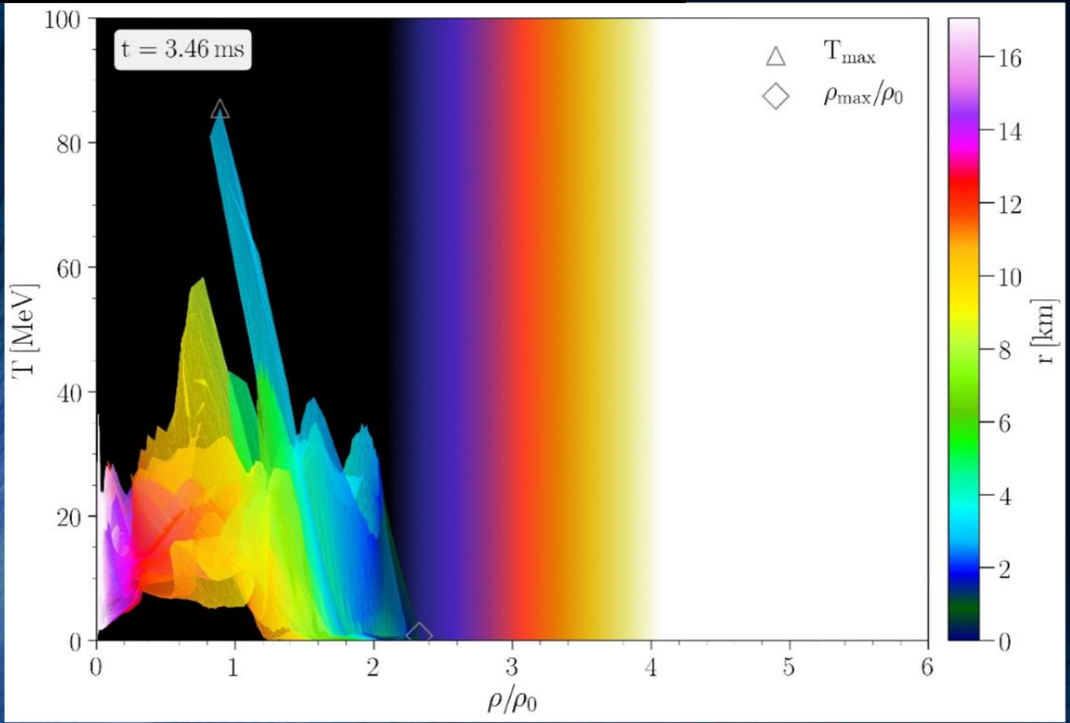
Evolution of hot and dense matter inside the inner area of a hypermassive hybrid star simulated within the (FSU2H-PT + thermal ideal fluid) EOS with a total mass of $M_{total}=2.64\ M_\odot$ in the style of a (T- ρ) QCD phase diagram plot

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.

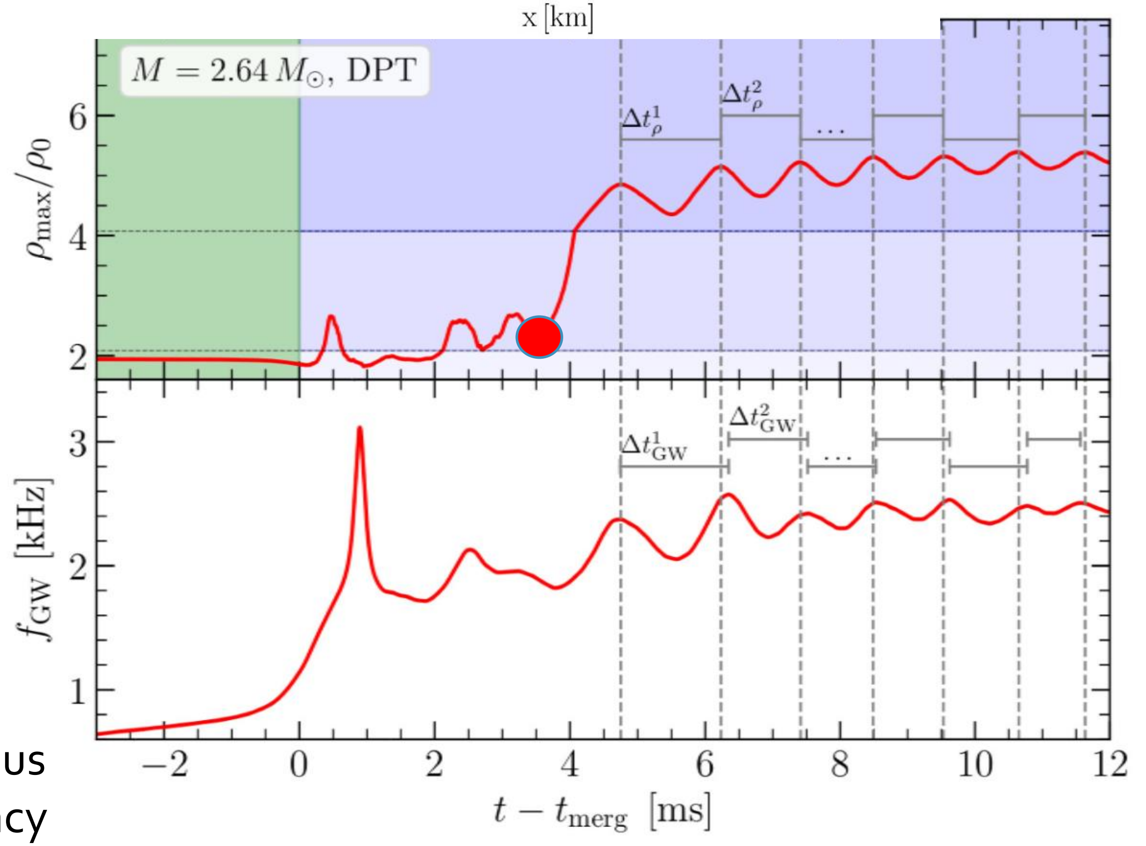
The open triangle marks the maximum value of the temperature while the open diamond indicates the maximum of the density.

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.



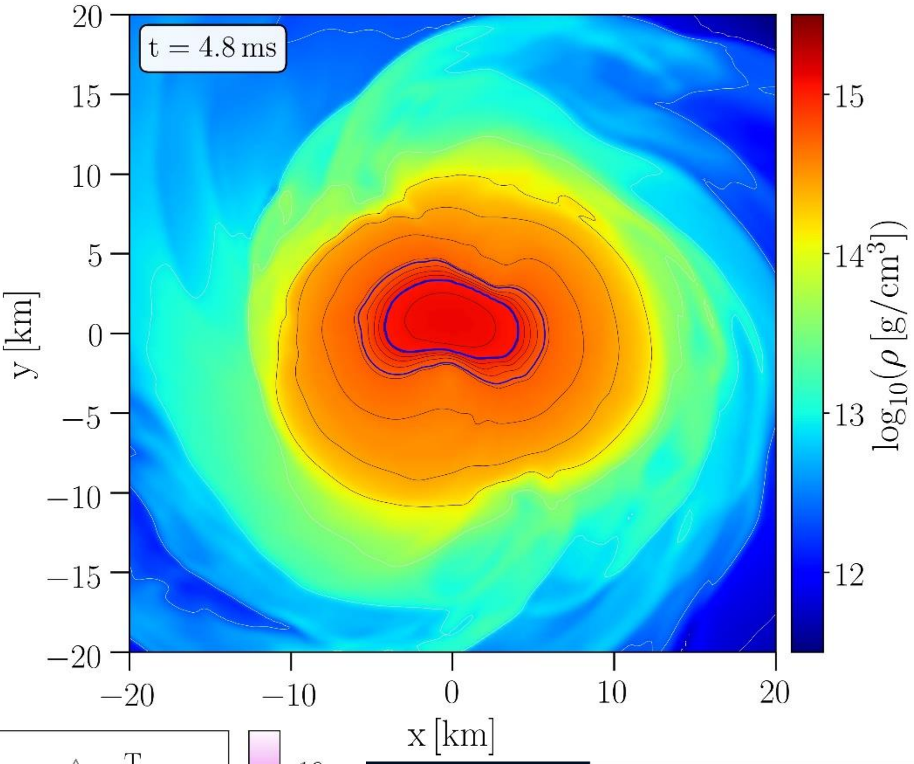


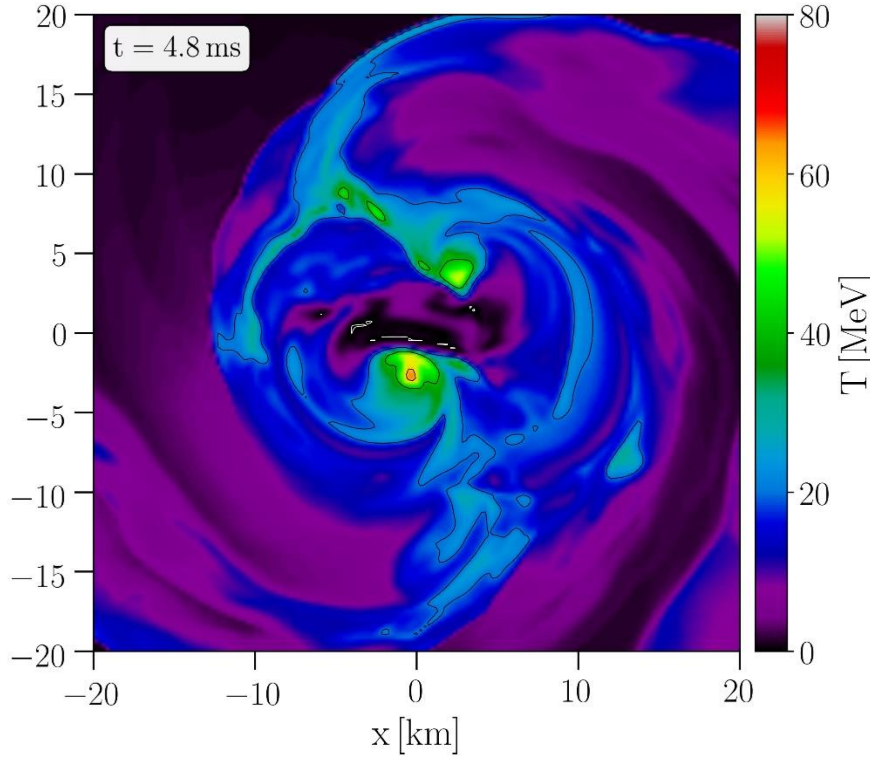
Density maximum

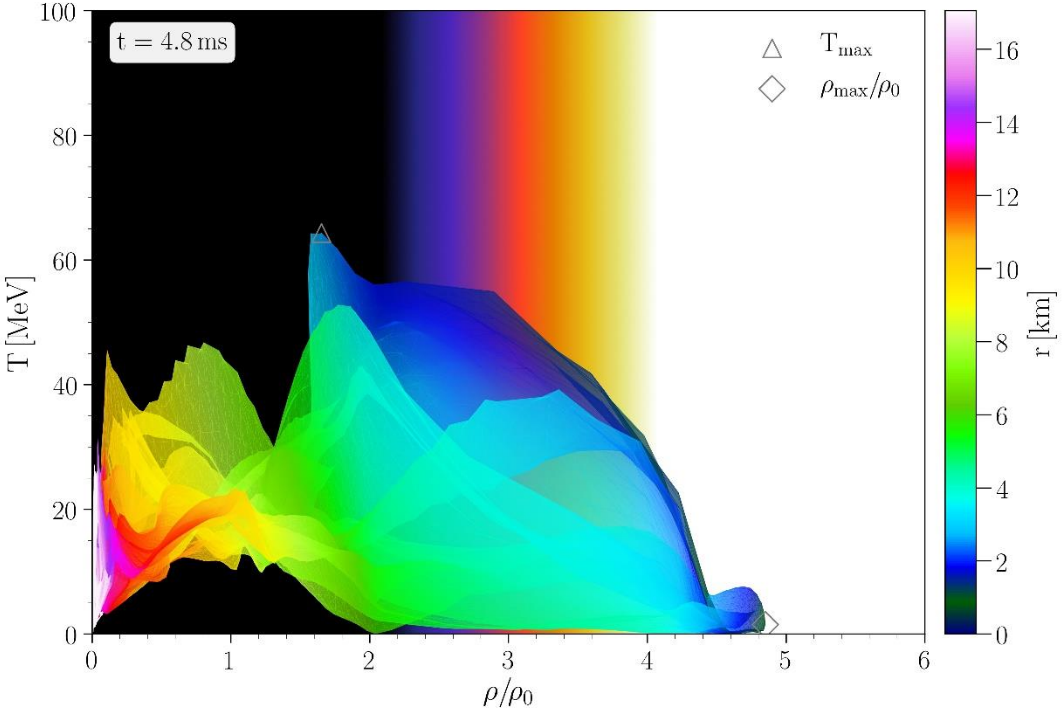


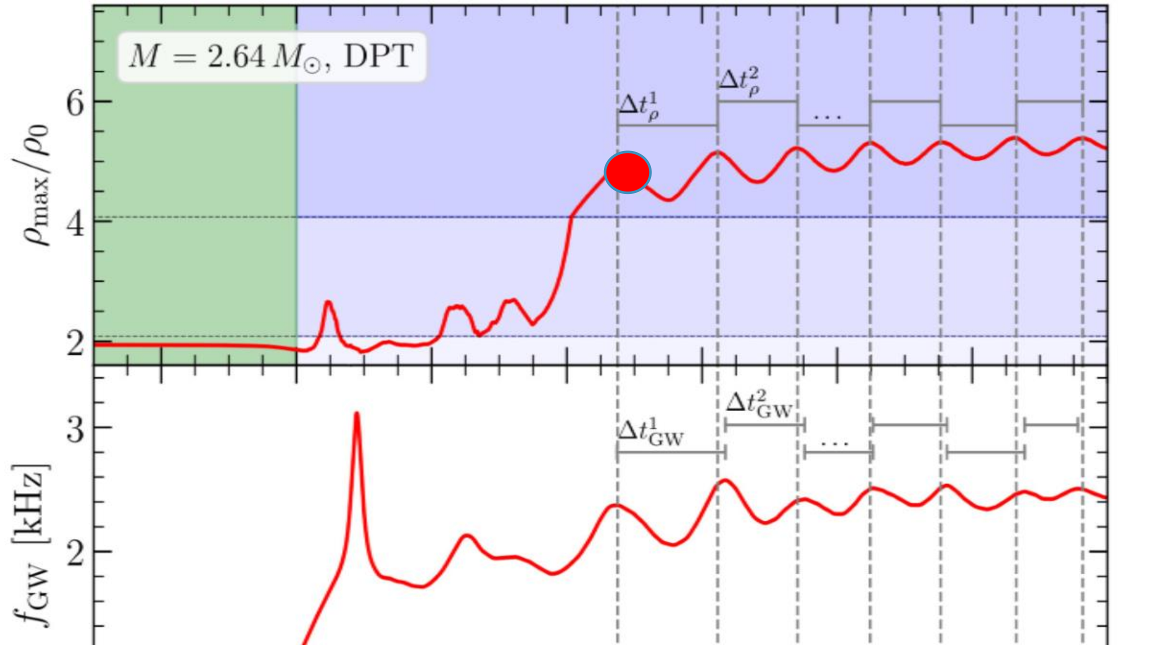
Instantaneous GW frequency

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.

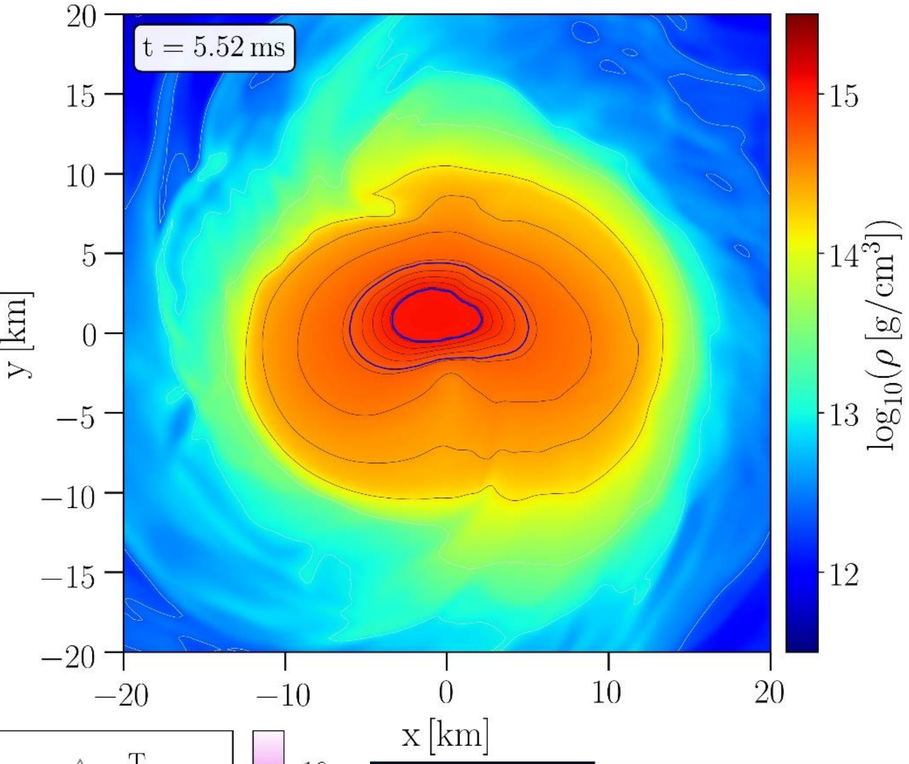


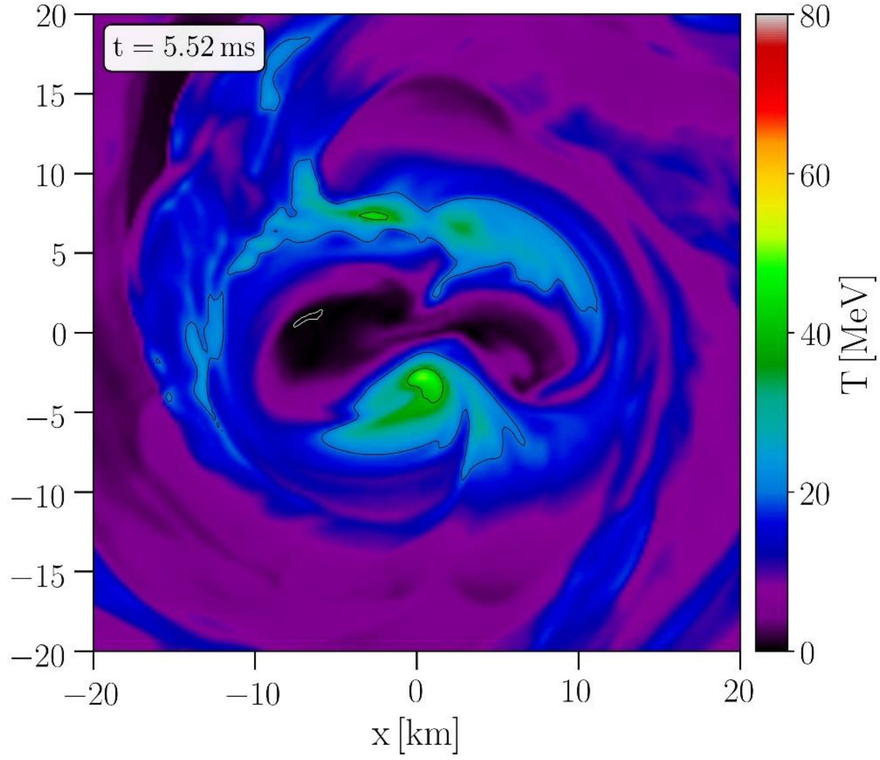


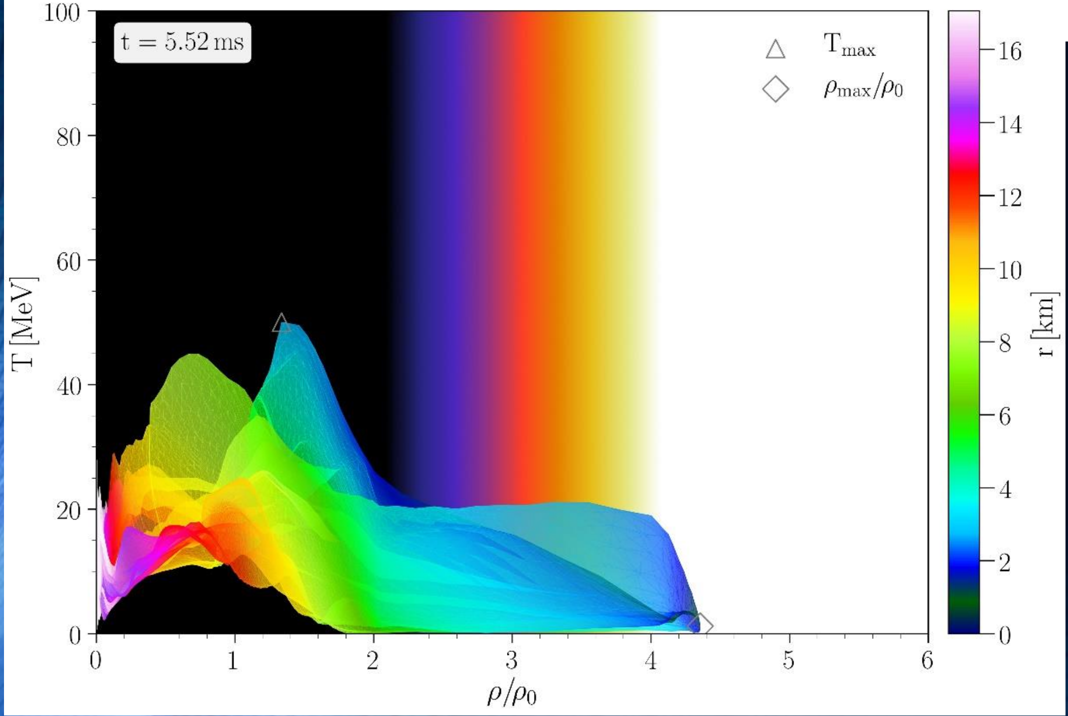


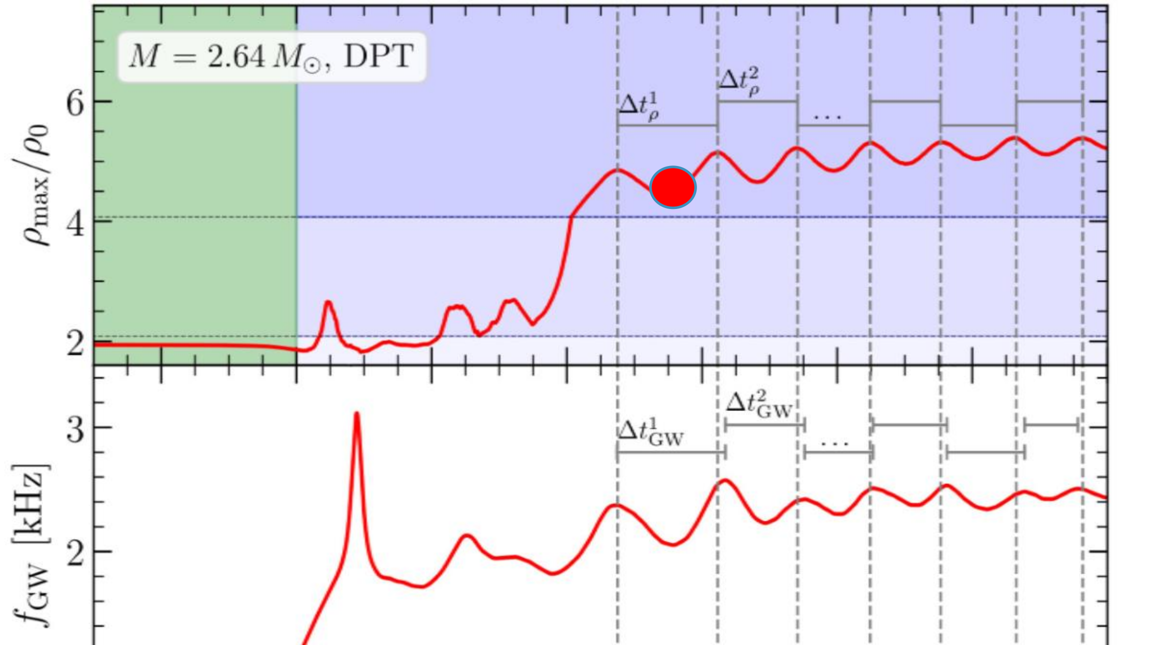


The figures correspond to a time near the first density minimum at t = 5.52ms (see red marker). The large m = 1 contribution can be seen by looking at the asymmetry of the spatial location of the quark core, which is marked with the second blue contour line. As a result of this asymmetry, the location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

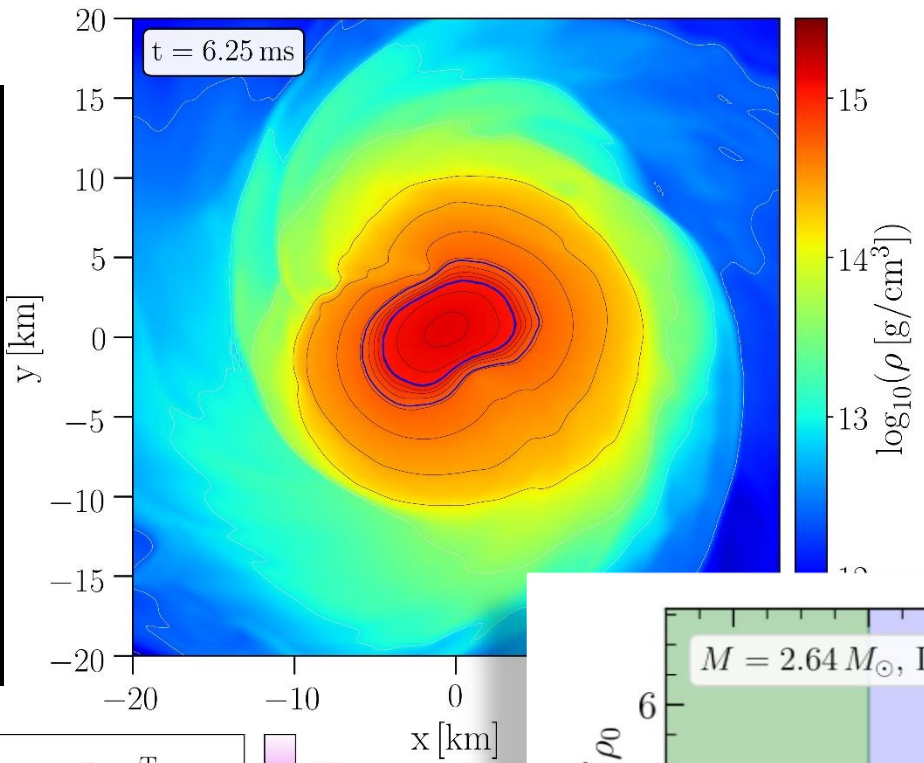


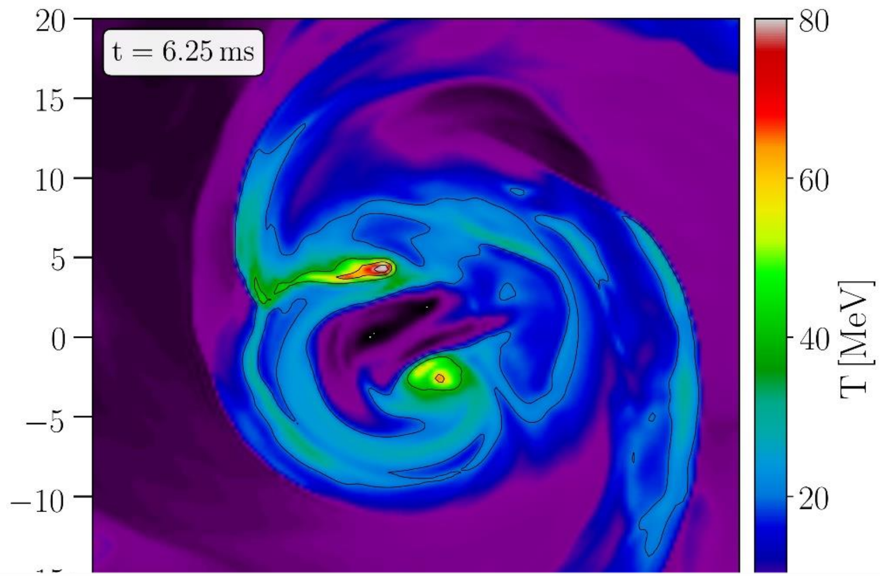


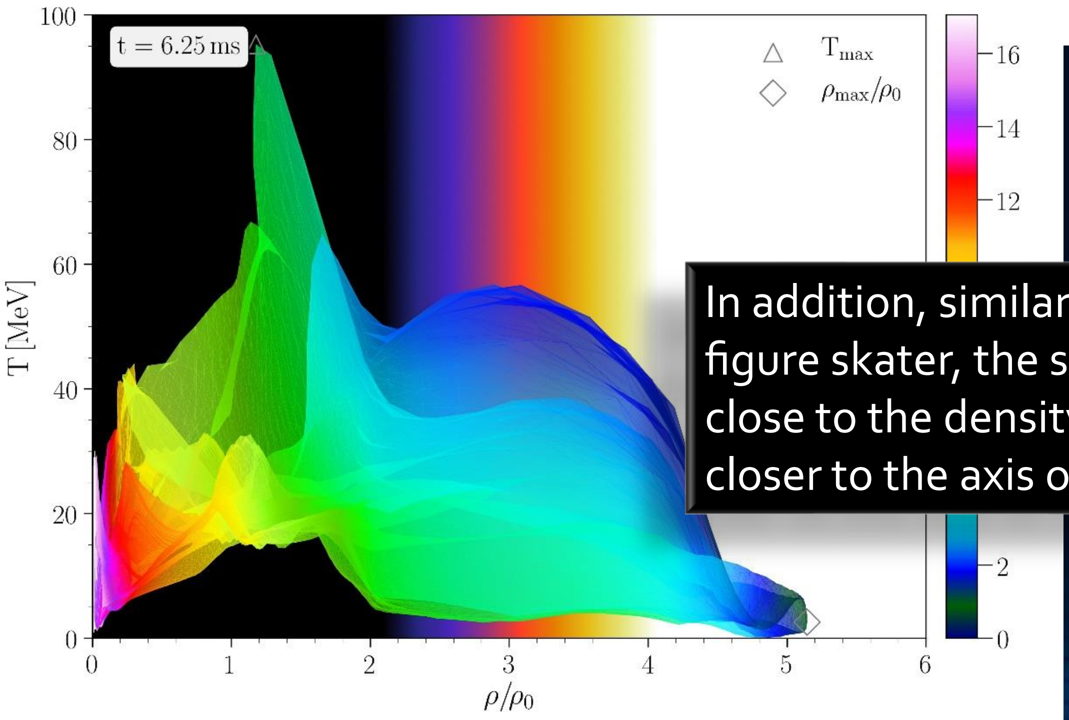


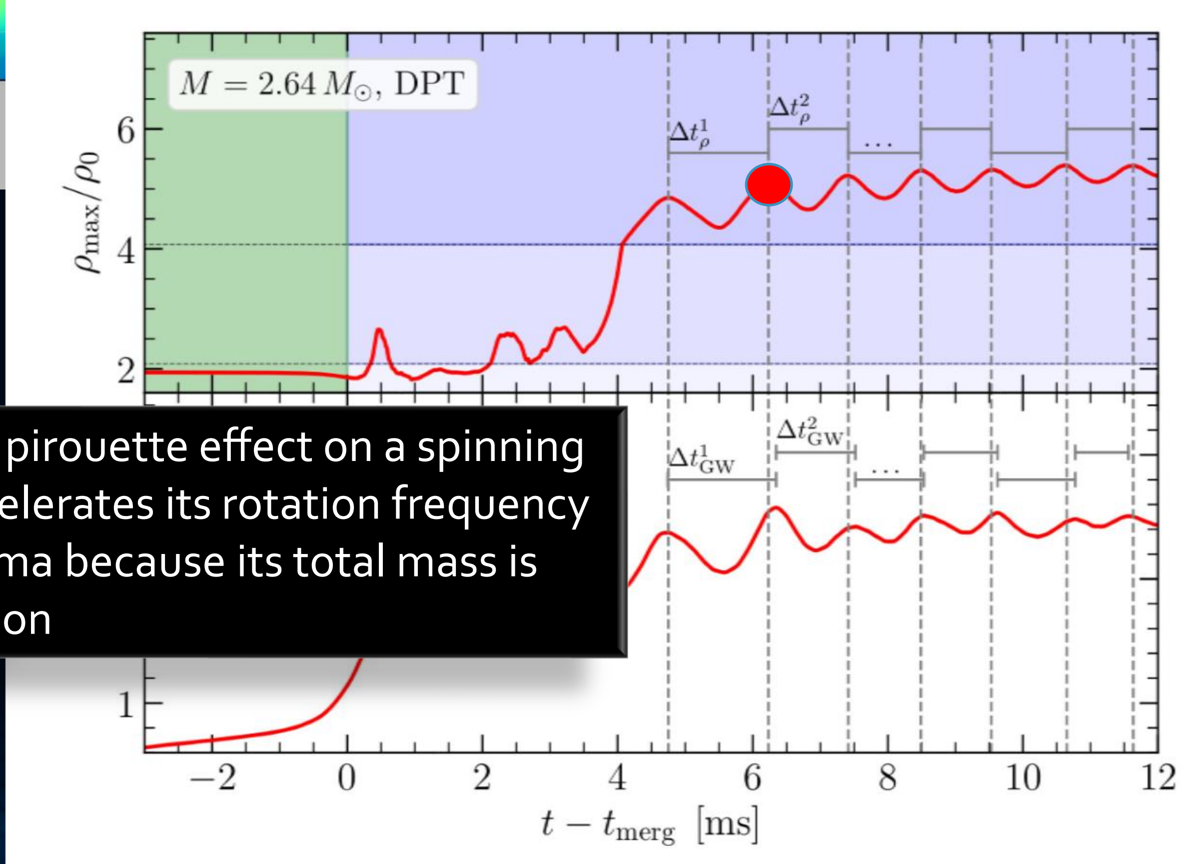


The collapse of the HMNS to the HMHS causes the system to vibrate. At the times when the maximum of the central density is reached, the pure quark core with its stiffer equation of state presses violently against the gravitational pressure and the star expands again and, as a result, its central density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



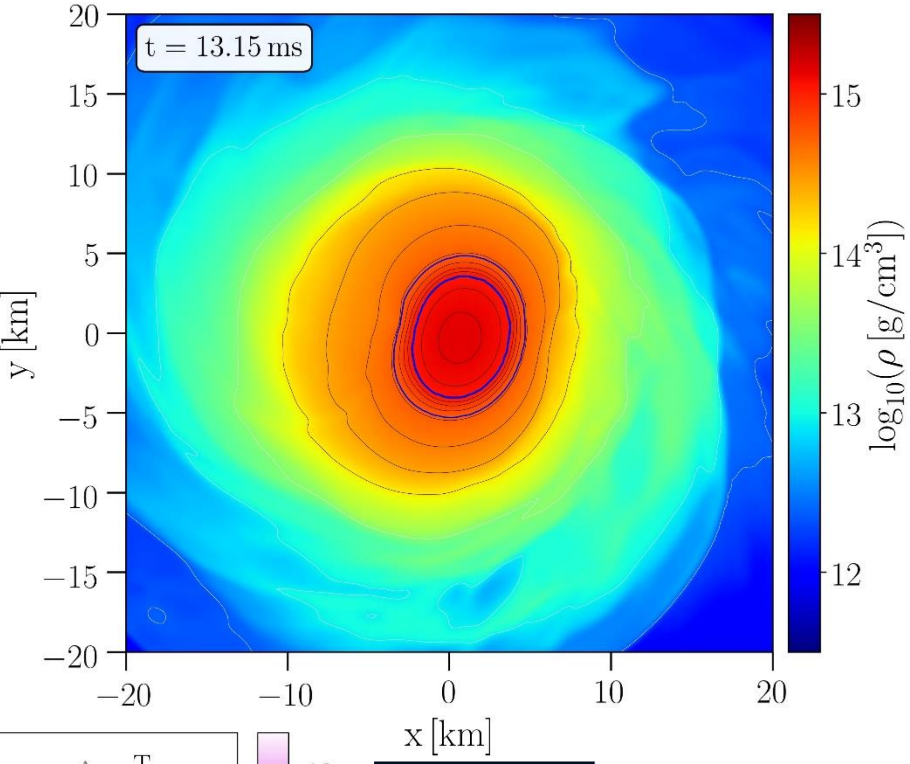


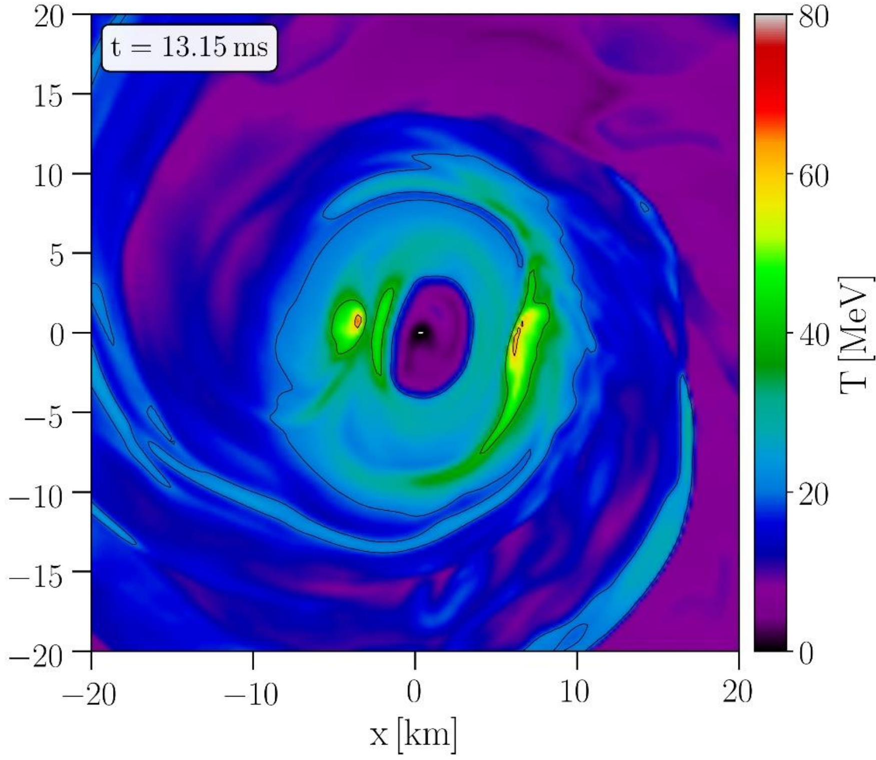


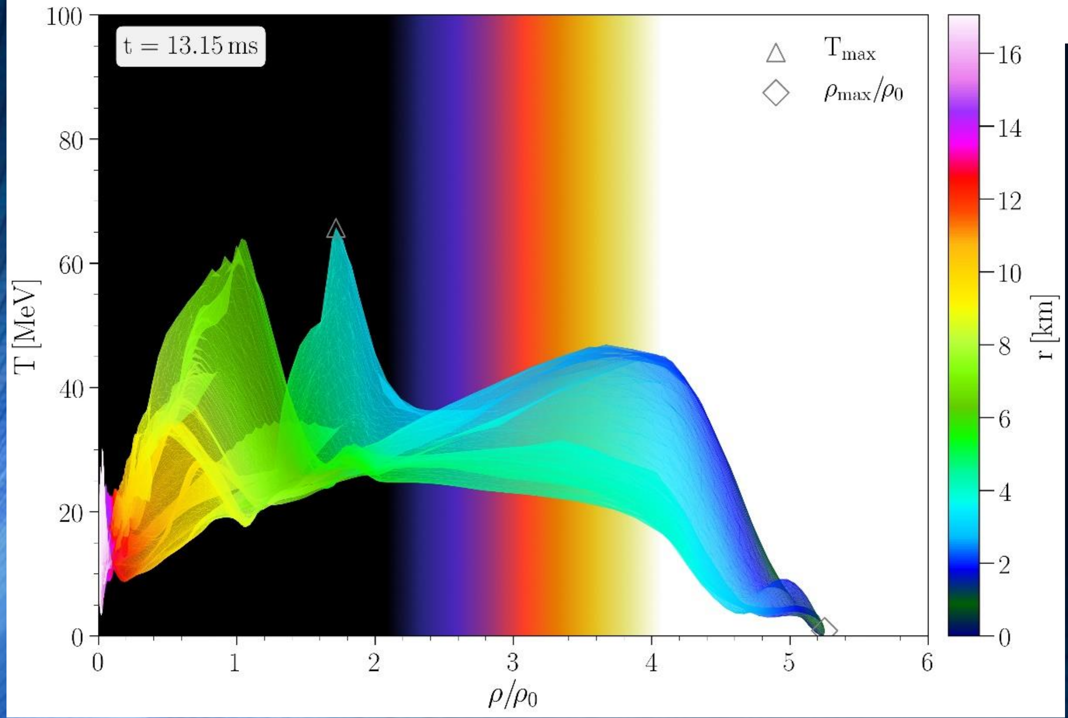


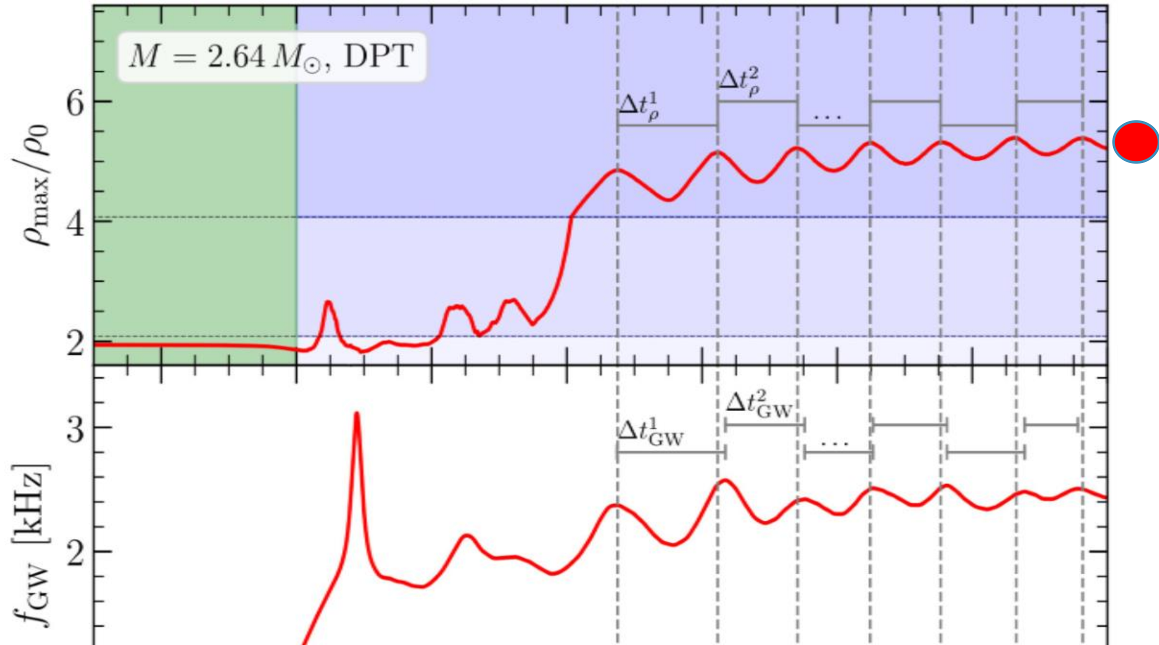
In addition, similar to the pirouette effect on a spinning figure skater, the star accelerates its rotation frequency close to the density maxima because its total mass is closer to the axis of rotation

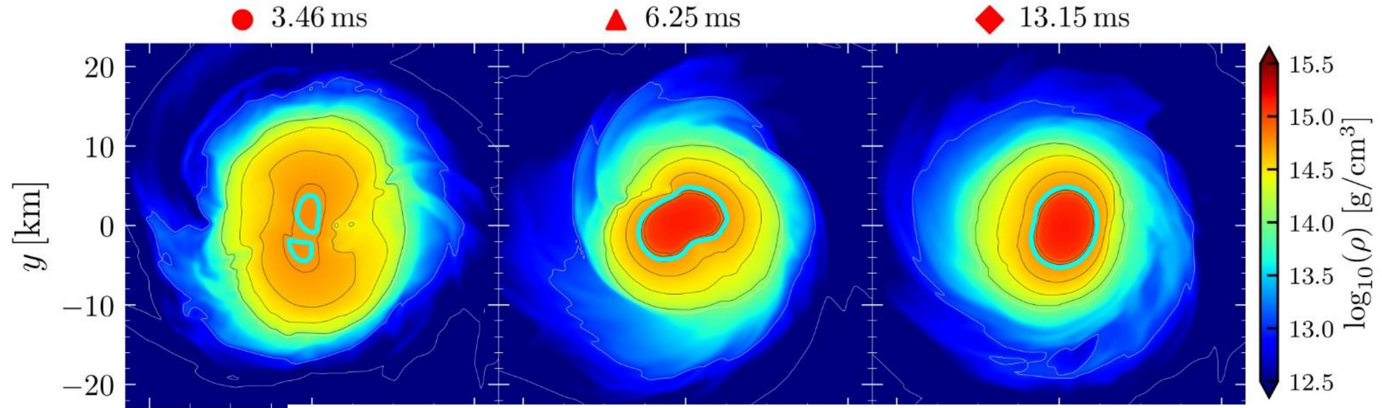
These figures report the HMHS properties at t = 13.15 ms and shows that in addition to the two temperature hot-spots, a new high temperature shell surrounding a cold core appears within the mixed phase region of the remnant . For subsequent post-merger times, the two temperature hot-spots will be smeared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





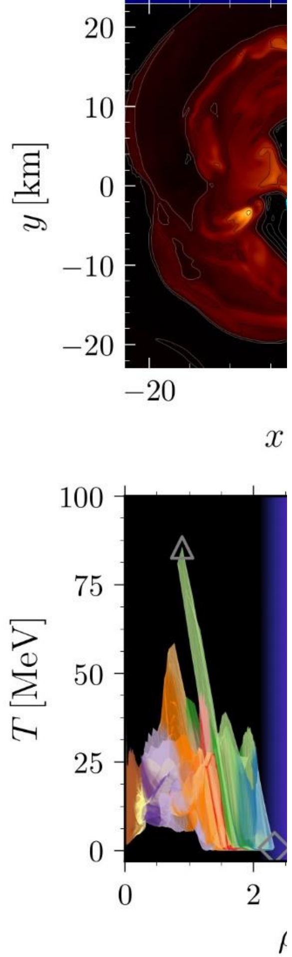


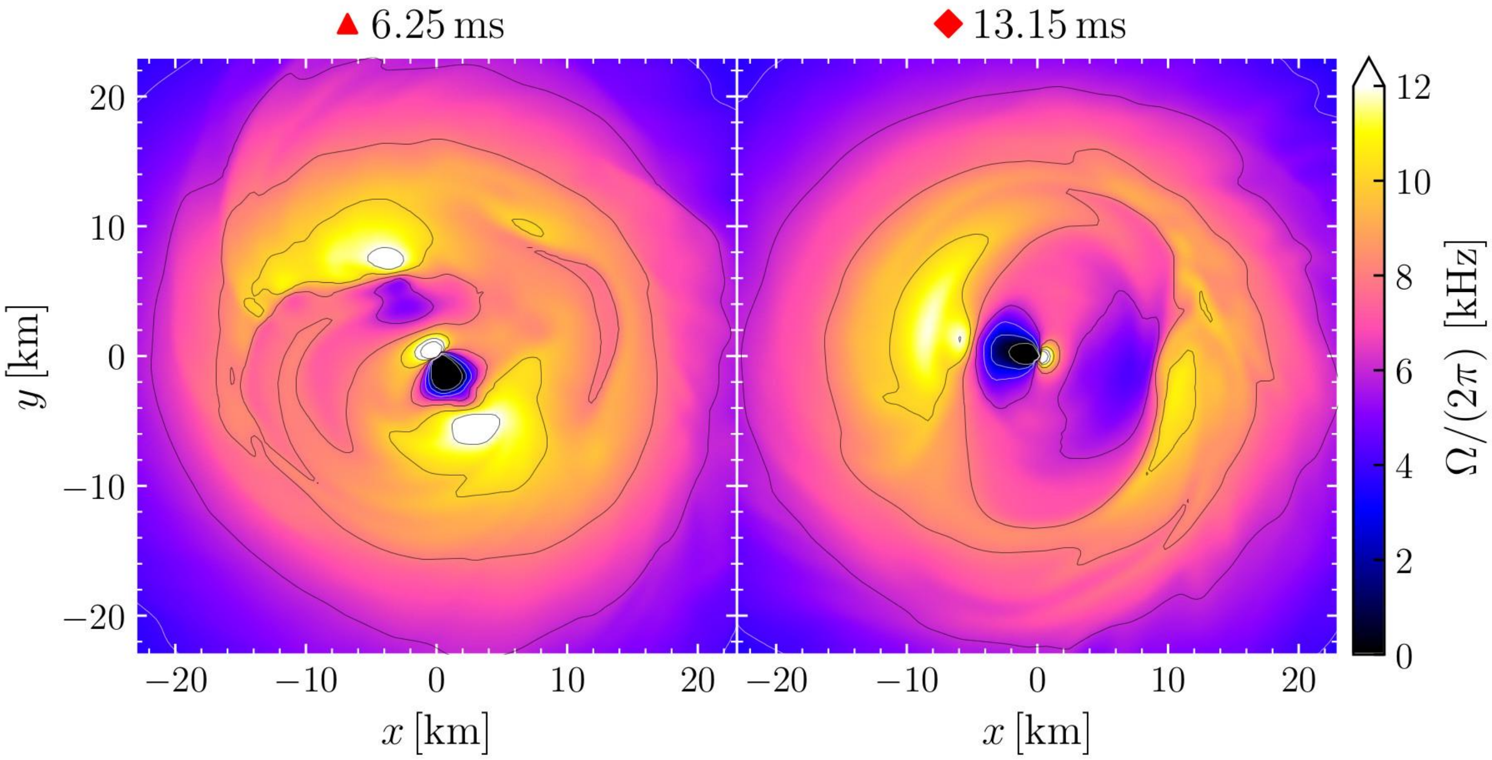




Article will appear in

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





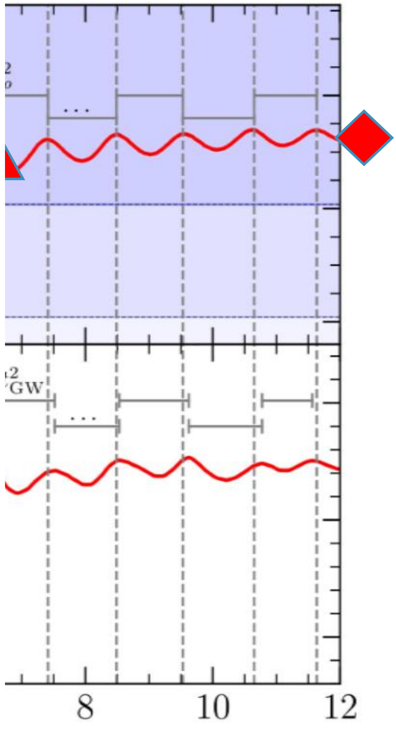
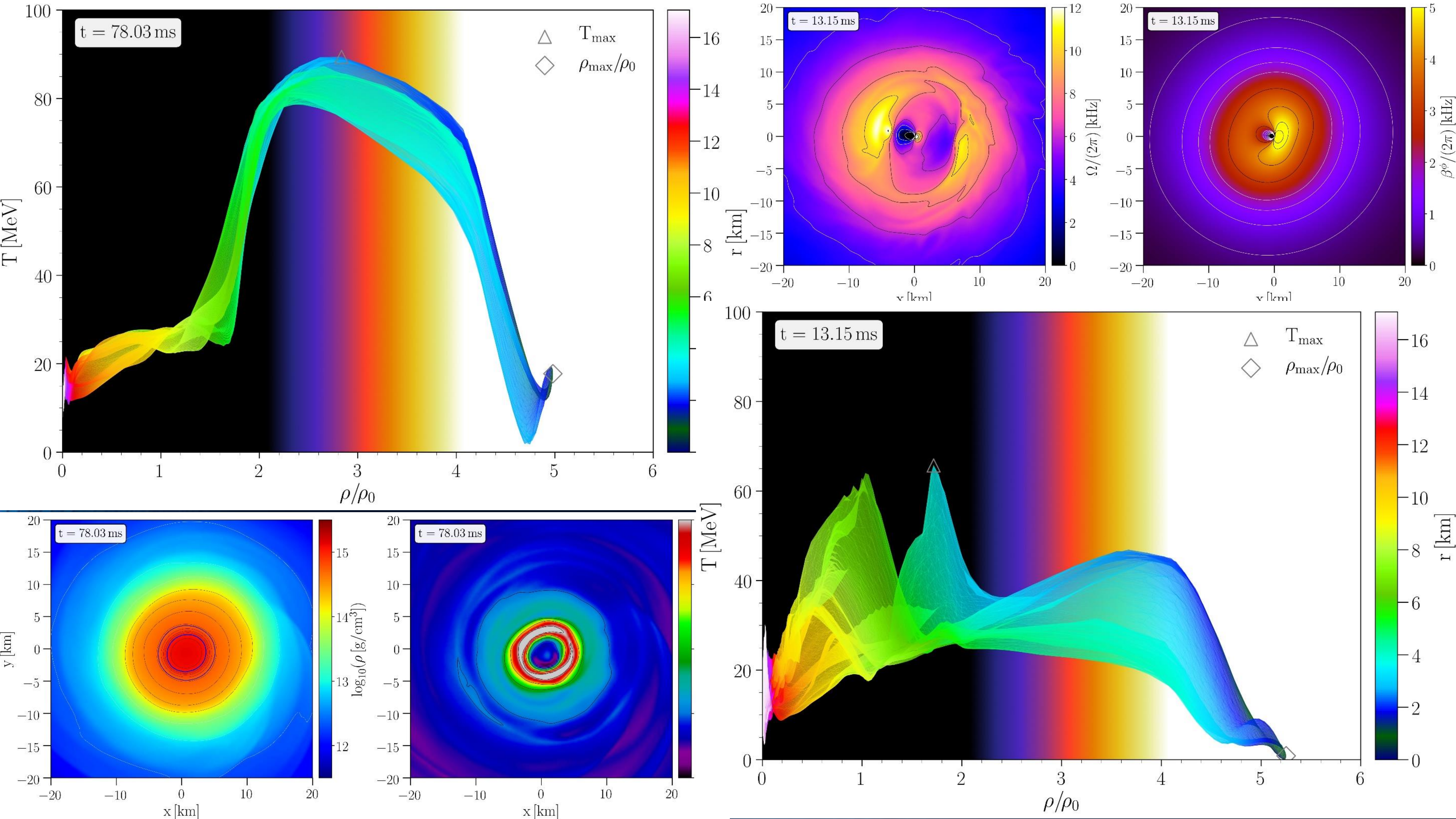
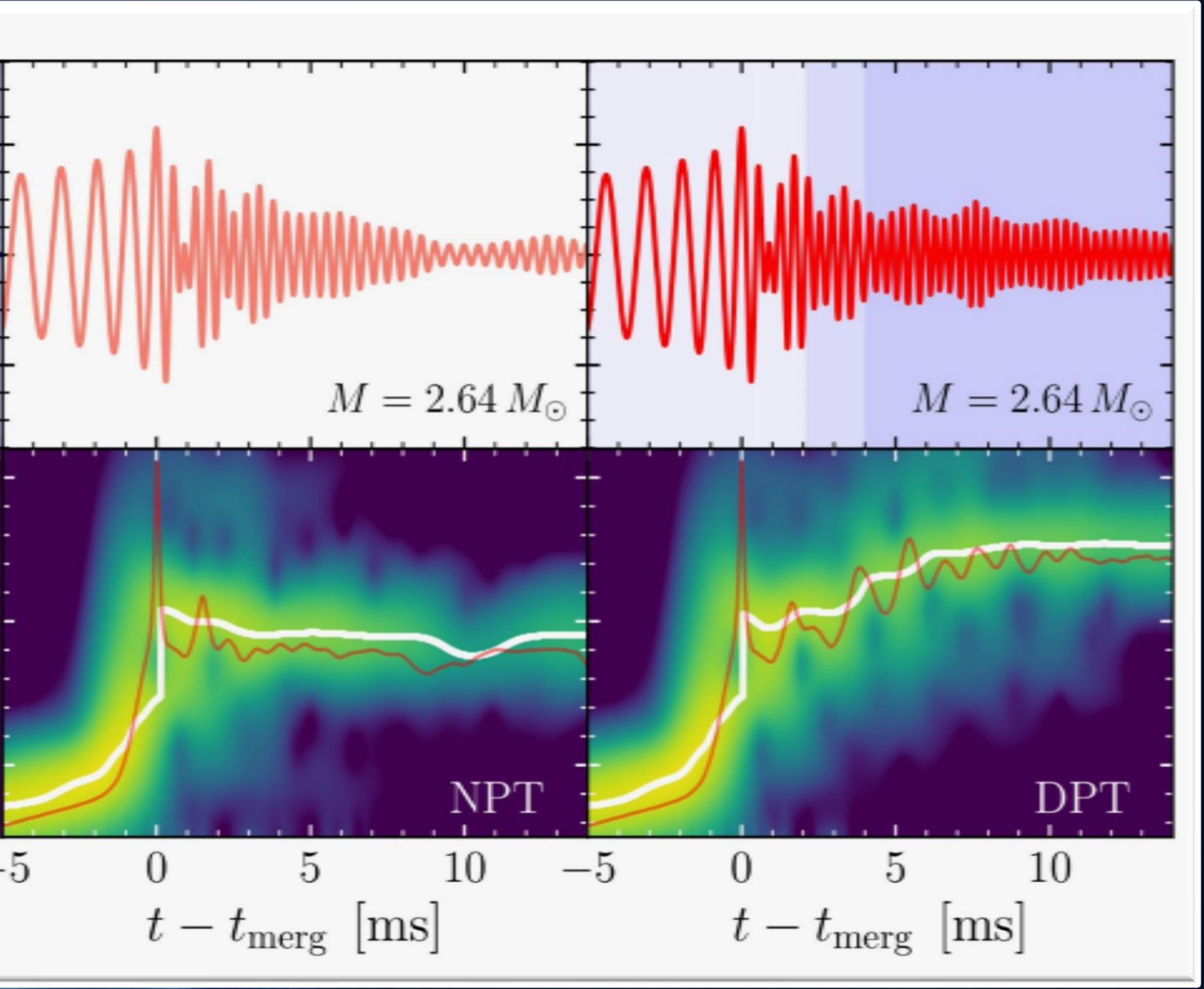


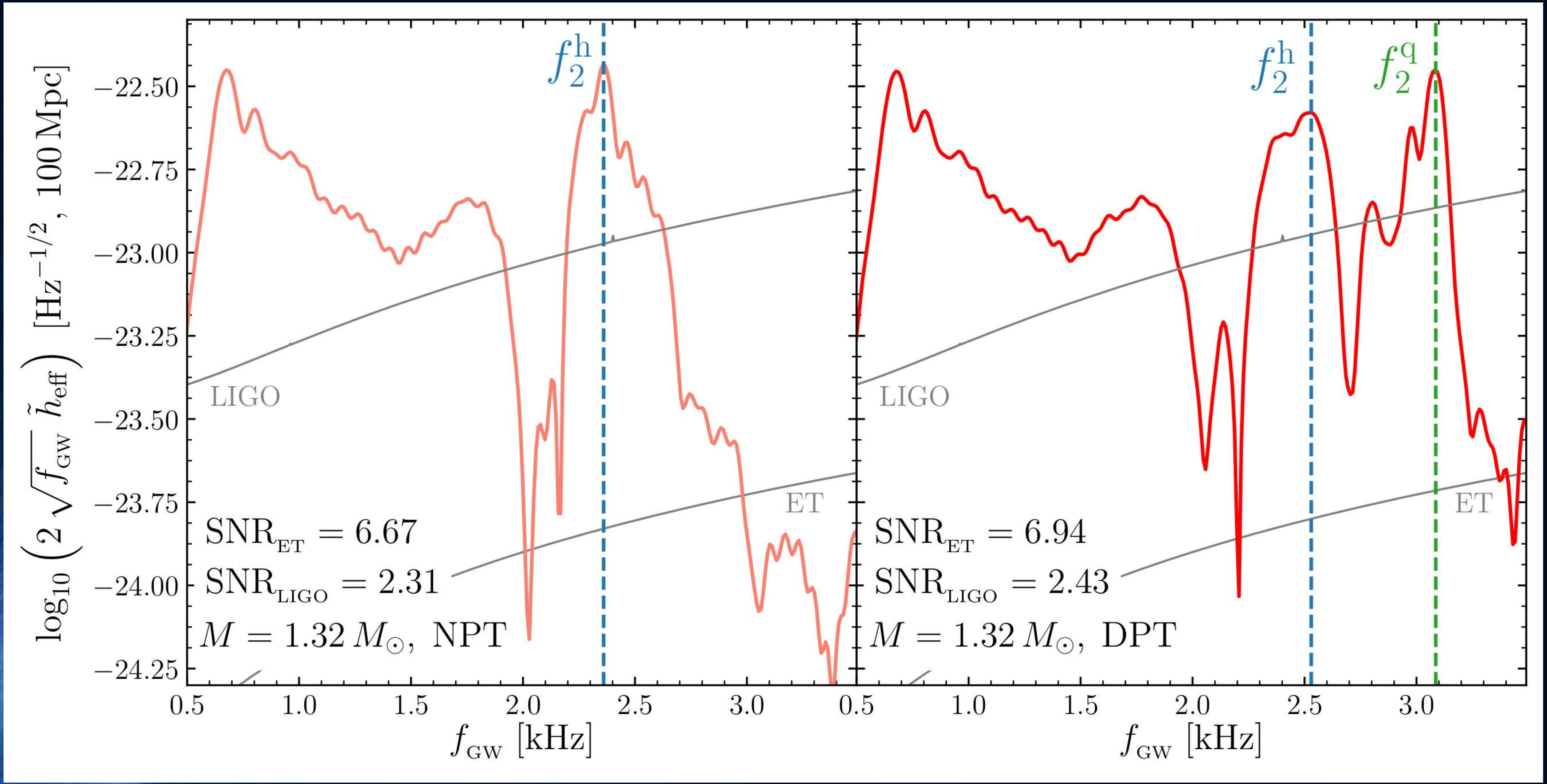
Fig. 4. Angular velocity for two representative times. Contours are drawn for $\Omega \in [0, 2, 4]$ kHz (white) and $\Omega \in [6, 8, 10, 12, 14]$ kHz (black).


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]
x [km]
y [km]
r [km]
$\log_{10}(\rho\,[\mathrm{g/cm^3}])$



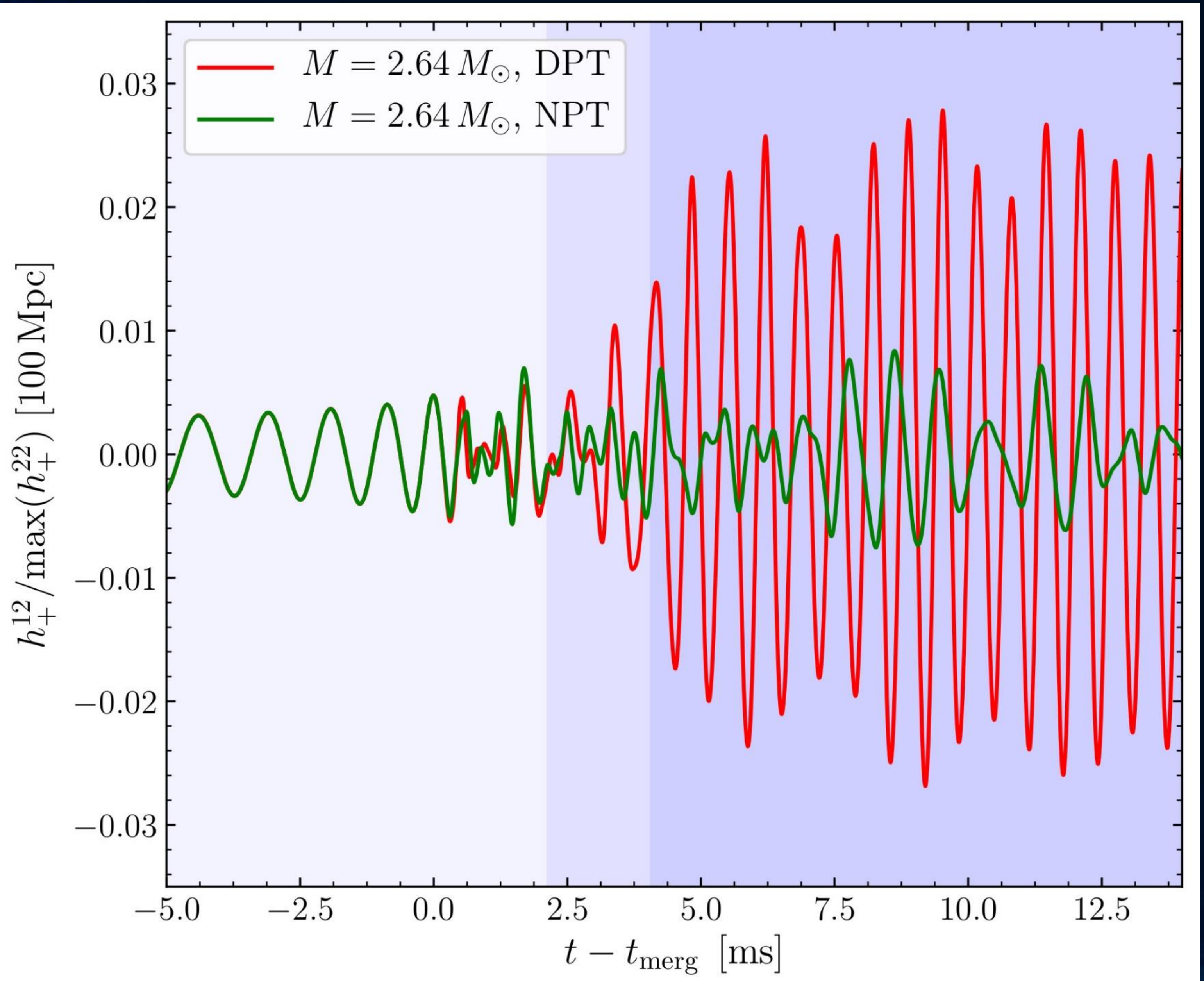
Strain h+ (top) and its spectrogram (bottom) for the binary neutron star simulation of the delayed phase transition scenario. In the top panel the different shadings mark the times when the HMNS core enters the mixed and pure quark phases.. In the bottom panels, the white lines trace the maximum of the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

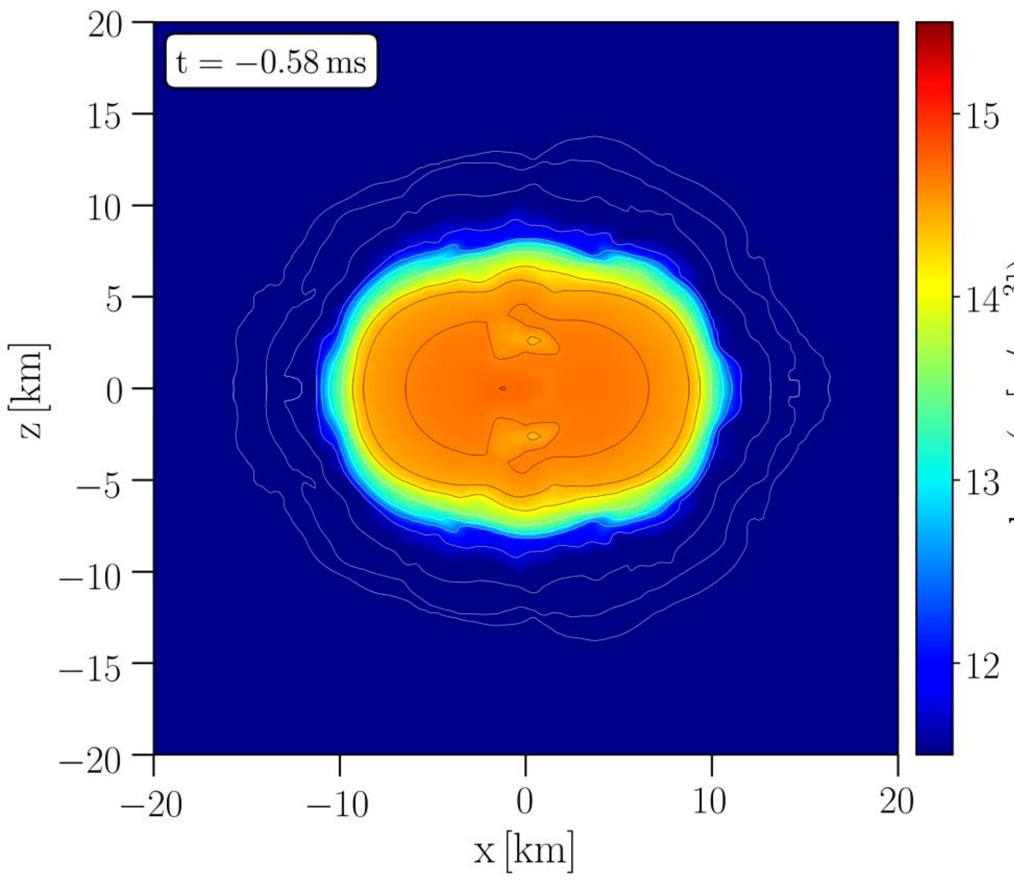
How to detect the hadron-quark phase transition with gravitational waves



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

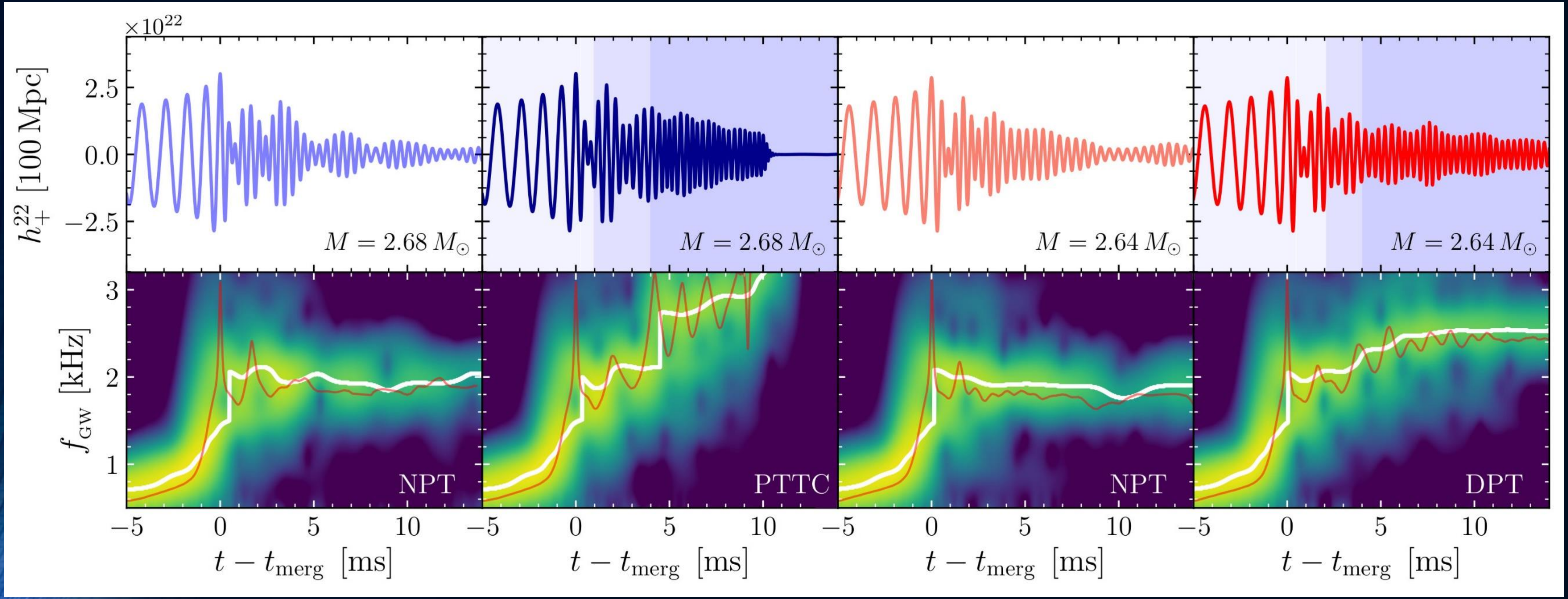
Differnce in the h_+^{12} − gravitational wave mode





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

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.

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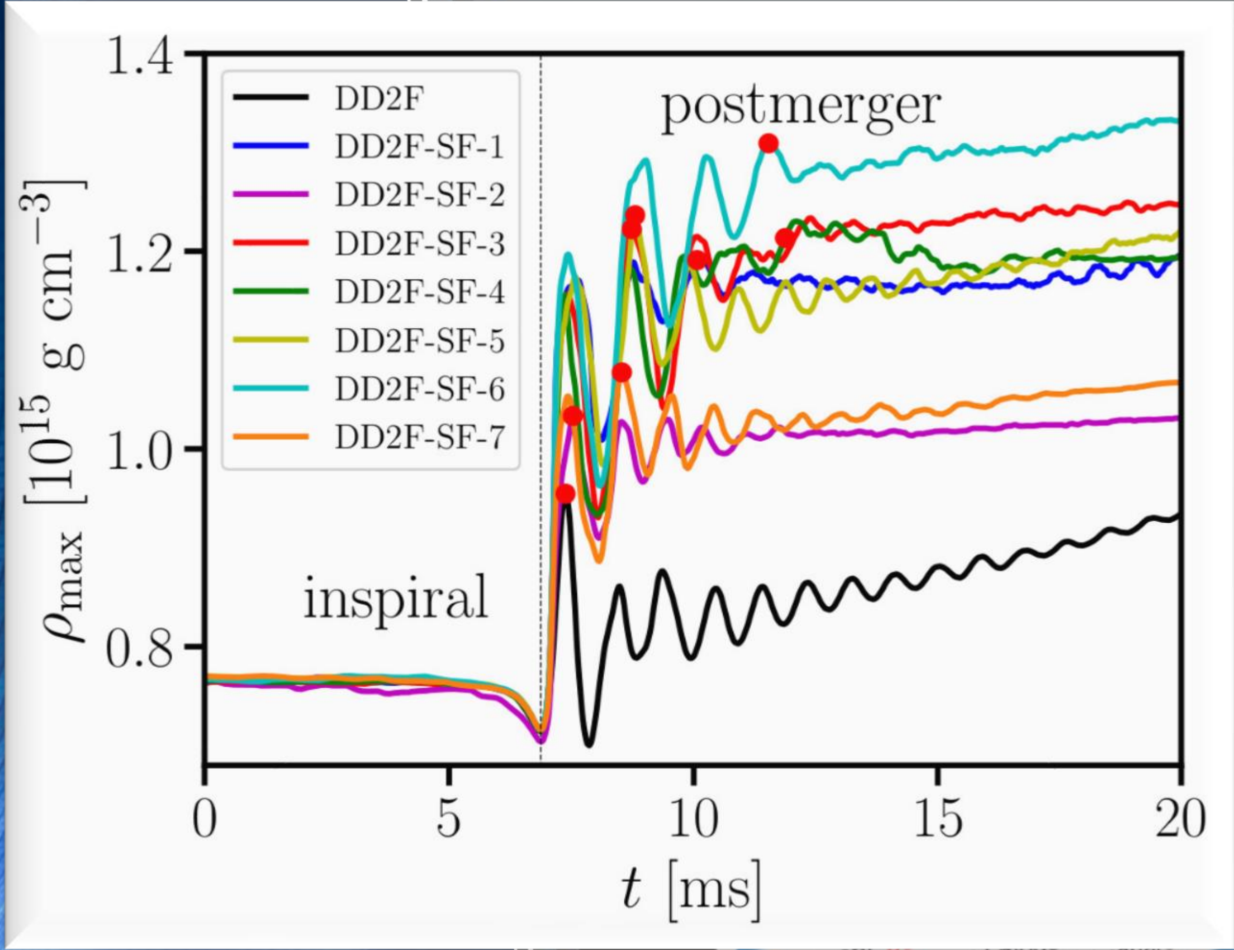
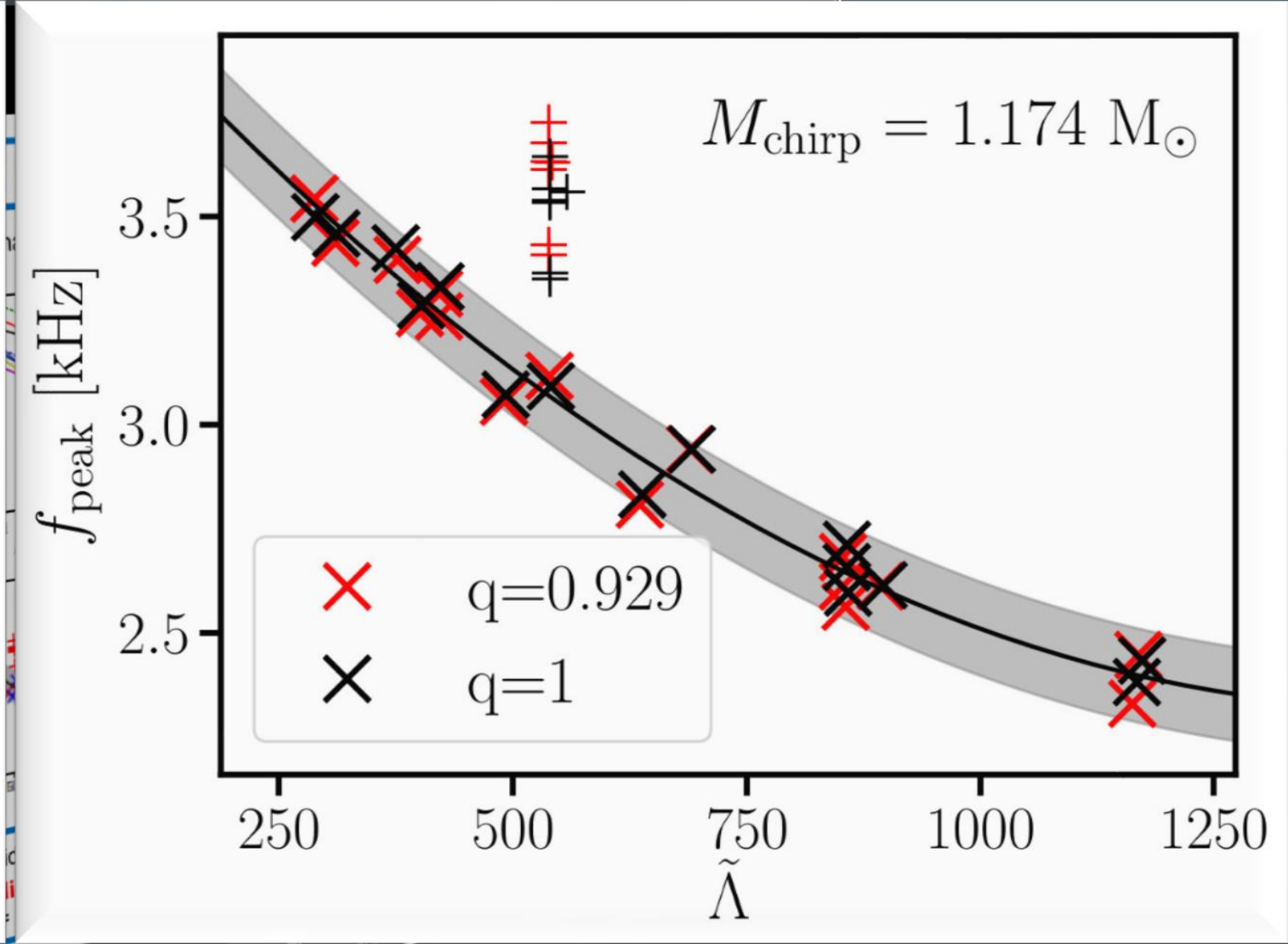
Prompt phase transition scenario

IWARA Conference
Talk by David Blaschke

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)



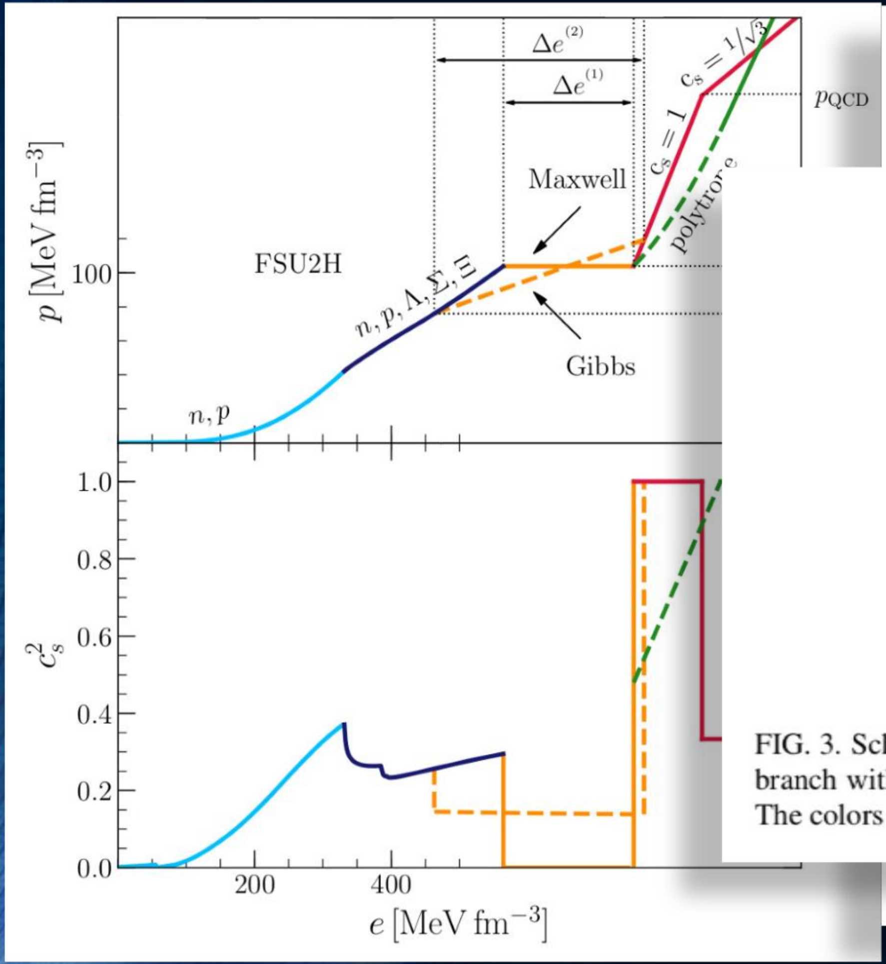


Hypermassive/Supramassive hybrid stars as neutron-star merger remnants

- Introduction
- Numerical general relativity of compact star mergers
- The equation of state of compact star matter and the hadron-quark phase transition
- Properties of hypermassive and supramassive compact stars
- **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)
  - Supramassive hybrid stars (SMHS) and HMHS within the delayed phase transition scenario (DPT)
  - SMHS and HMHS within the prompt phase transition scenario (PPT)
  - **The inspiral and merger phase (premerger signals)**
- Summary and Outlook

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

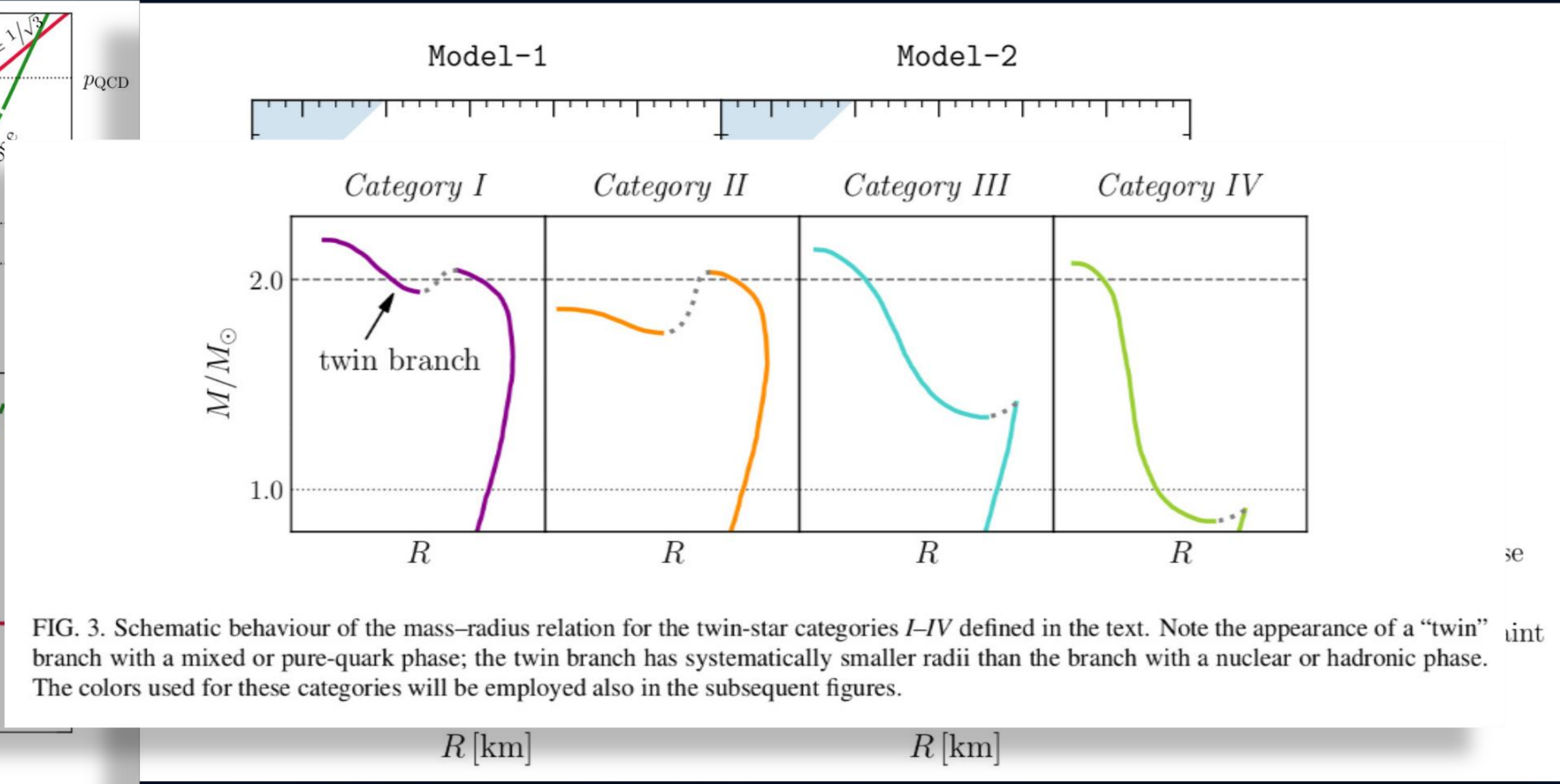
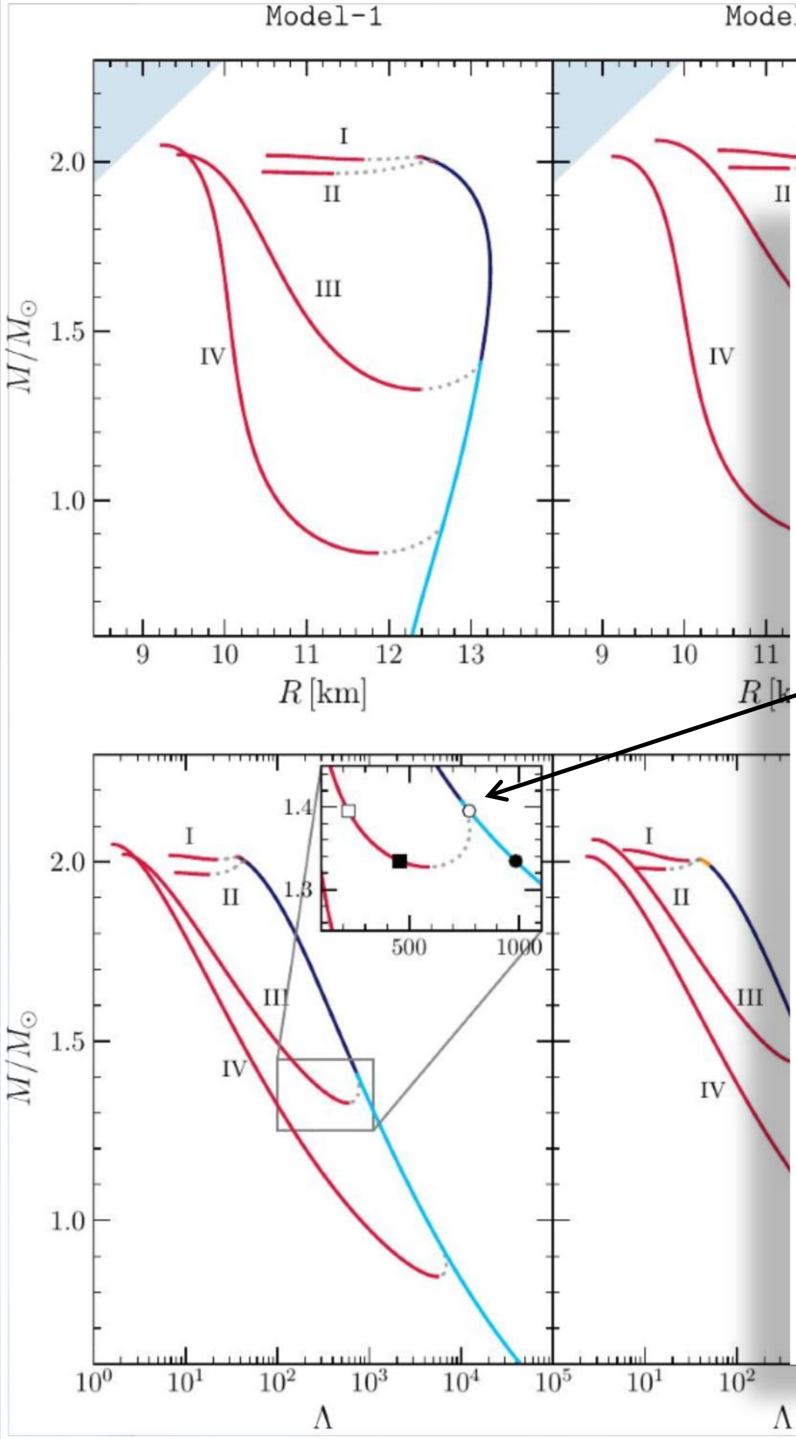


FIG. 3. Schematic behaviour of the mass–radius relation for the twin-star categories *I–IV* defined in the text. Note the appearance of a “twin” branch with a mixed or pure-quark phase; the twin branch has systematically smaller radii than the branch with a nuclear or hadronic phase. The colors used for these categories will be employed also in the subsequent figures.

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



G. Montana, L.Tolos, M.Hanauske

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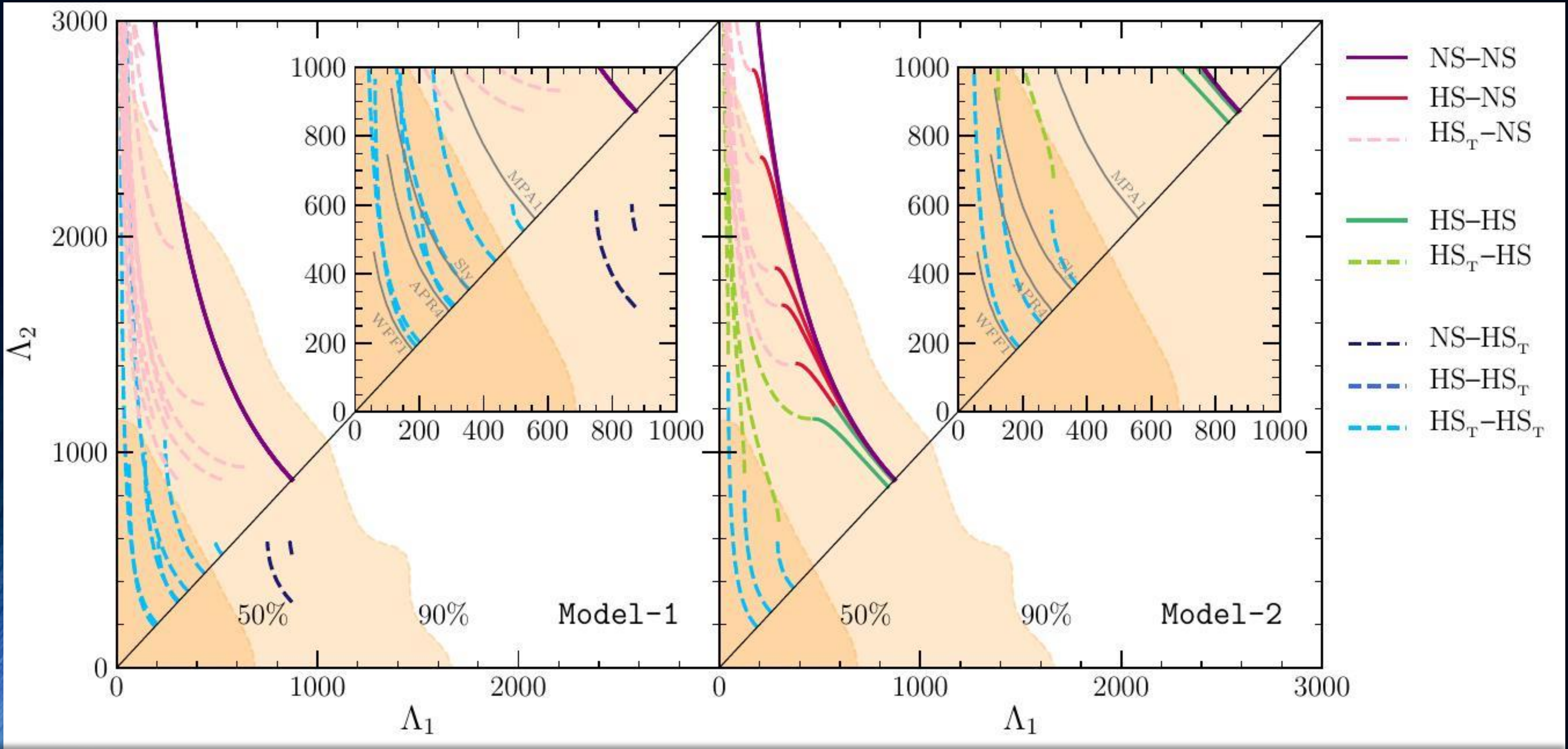
Twin star effect in the tidal deformability

GW170817:
Chirp mass set to M_{ch} = 1.188 $M_\odot$

4 possible merger scenarios:

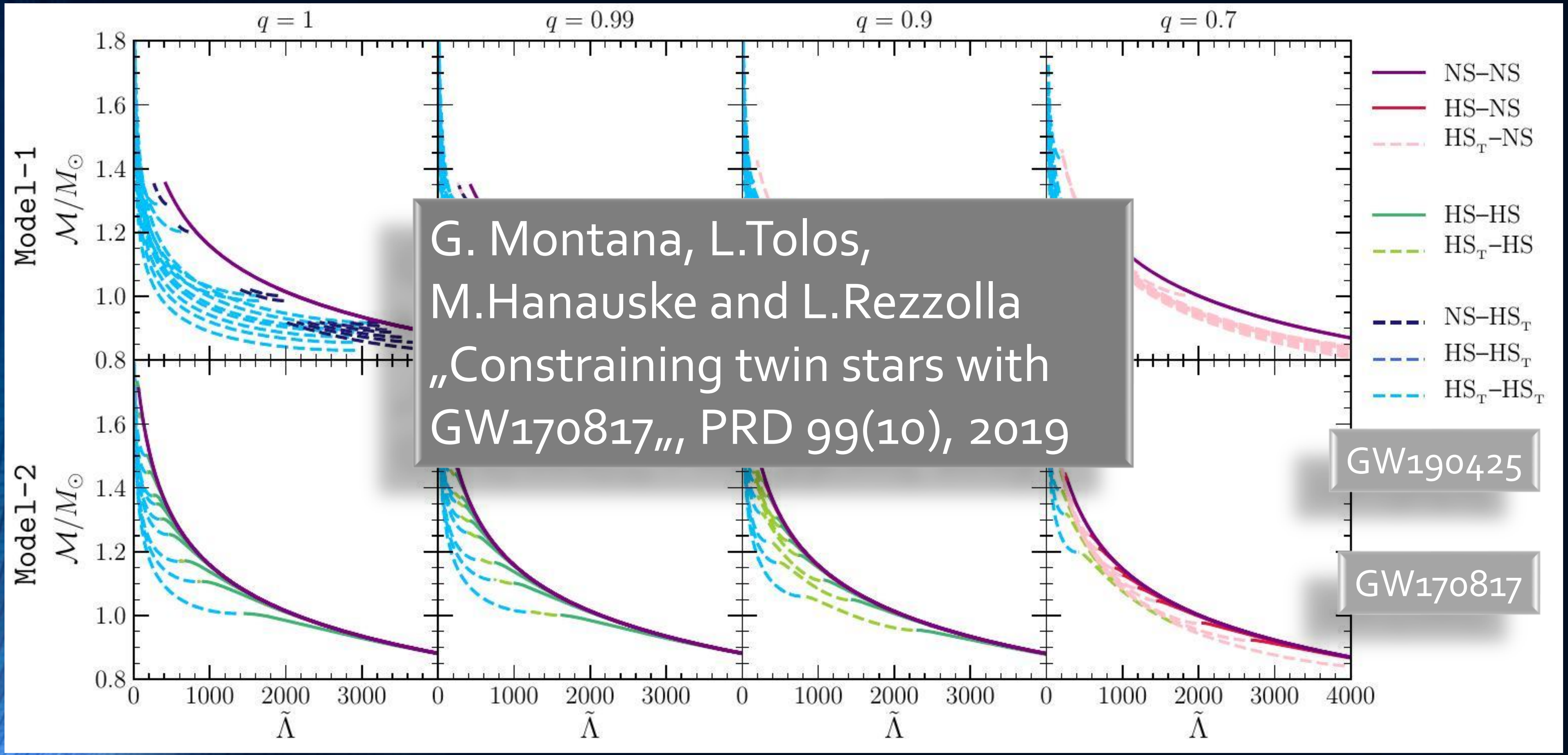
- □ ■ HS_T – HS_T : Hybrid star – Hybrid Star
- □ ● HS_T – NS : Hybrid star – Neutron Star
- ○ ■ NS – HS_T : Neutron star – Hybrid Star
- ○ ● NS – NS : Neutron star – Neutron Star

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 $\tilde{\Lambda} = \tilde{\Lambda}(M_1, M_2, \Lambda_1, \Lambda_2)$ 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.

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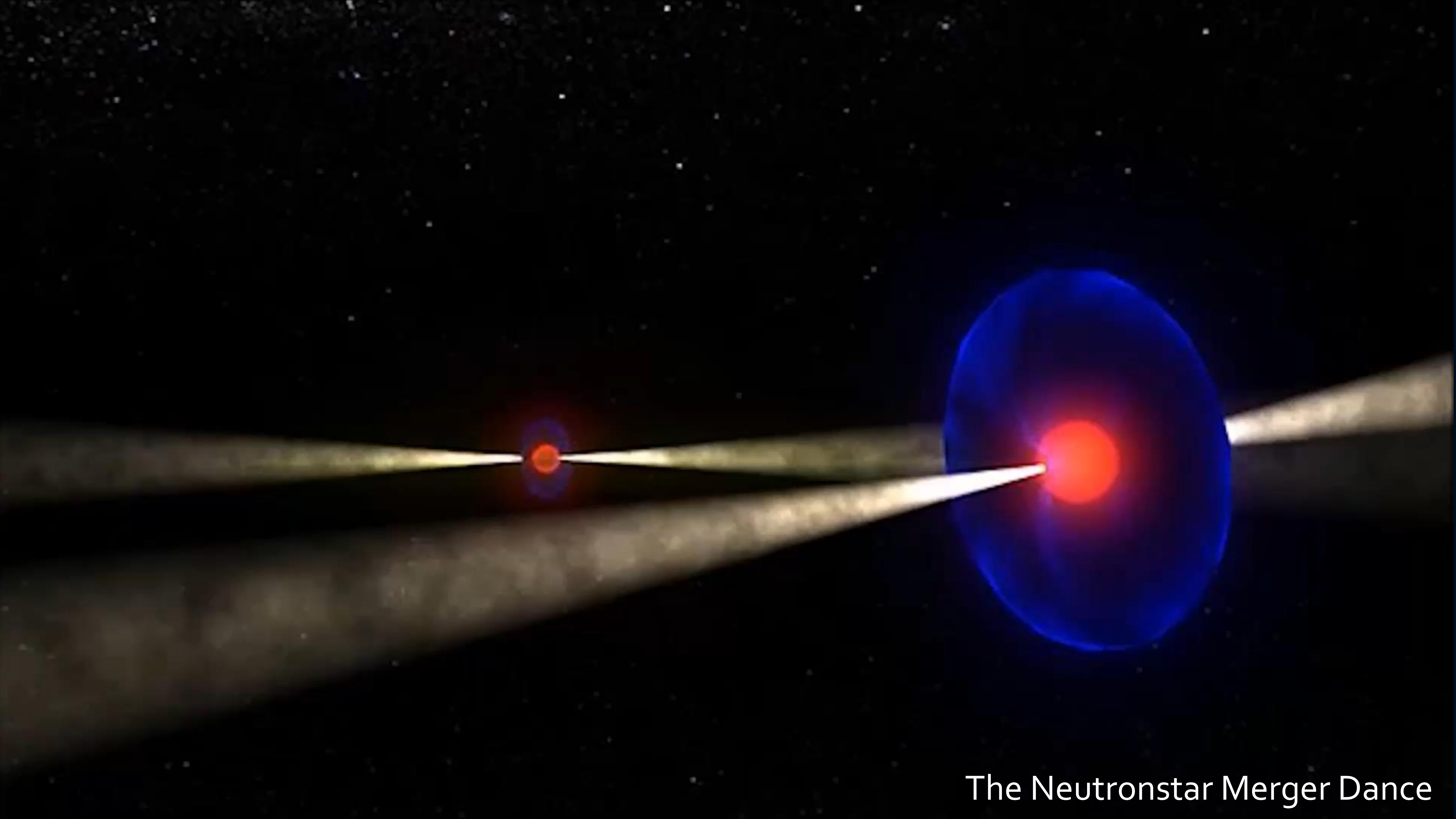
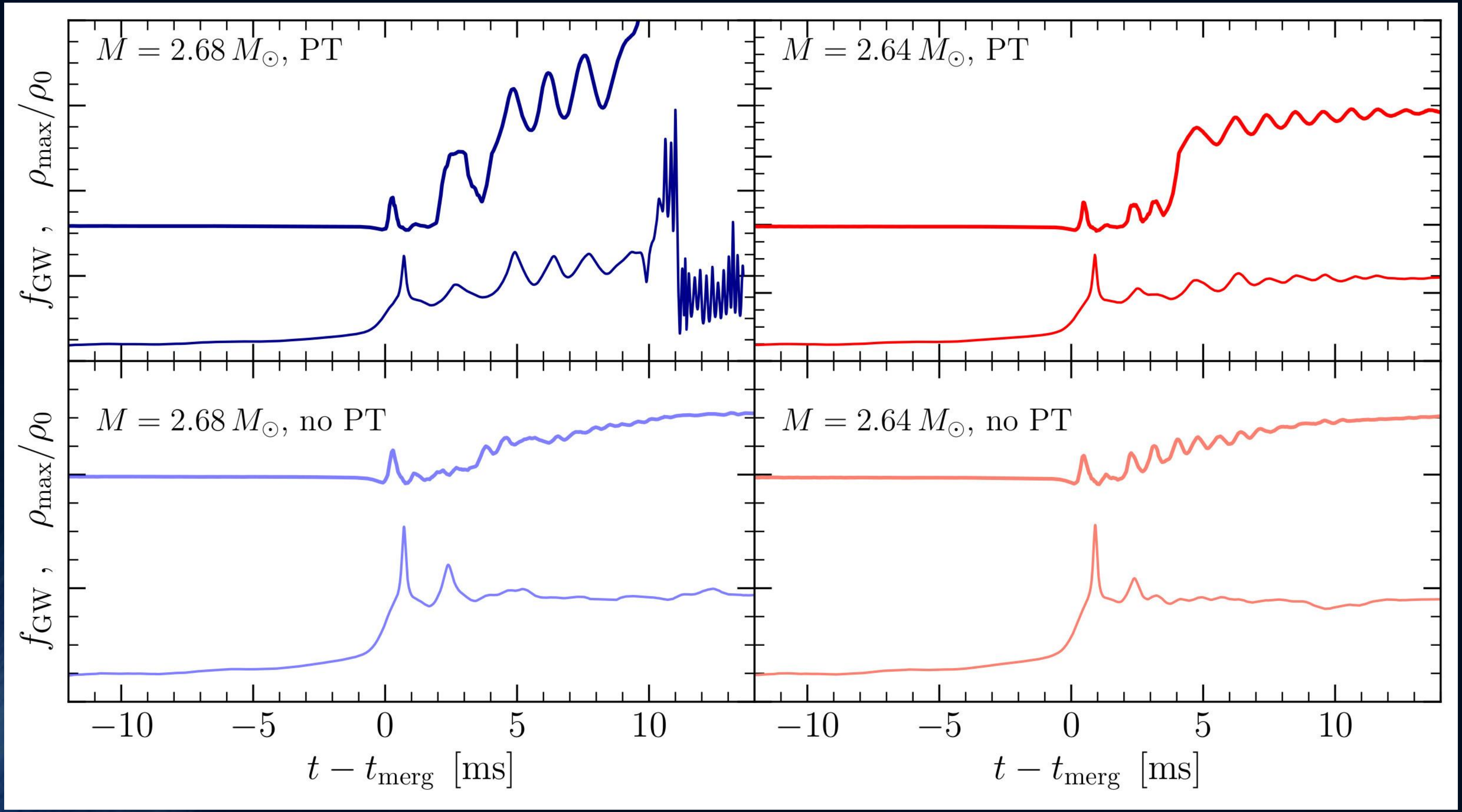
- Additional Slides



The Neutronstar Merger Dance

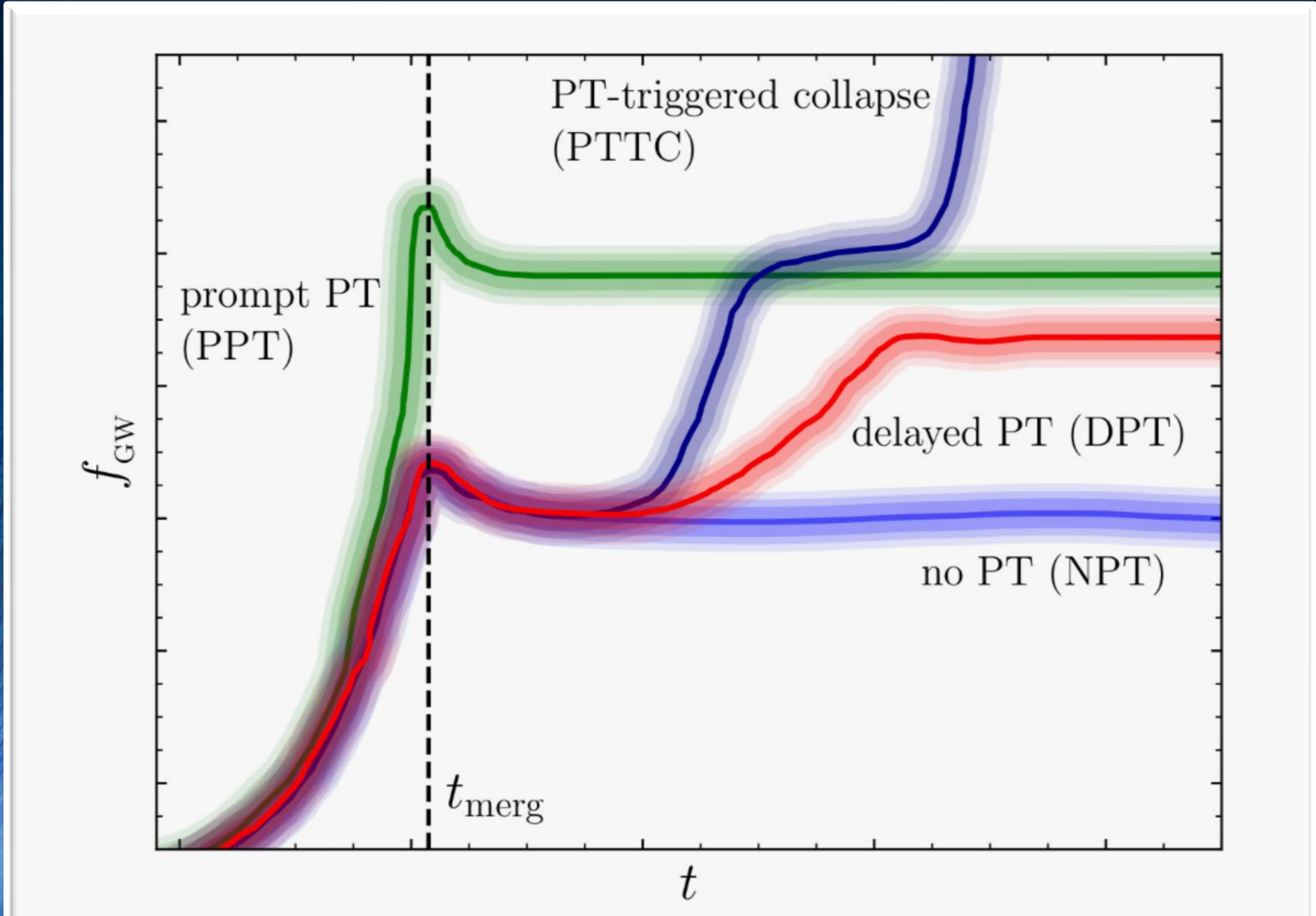
arXiv:1912.09340v1



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.