Allgemeine Relativitätstheorie mit dem Computer

VORLESUNGSREIHE
JOHANN WOLFGANG GOETHE UNIVERSITÄT
29. JUNI, 2023

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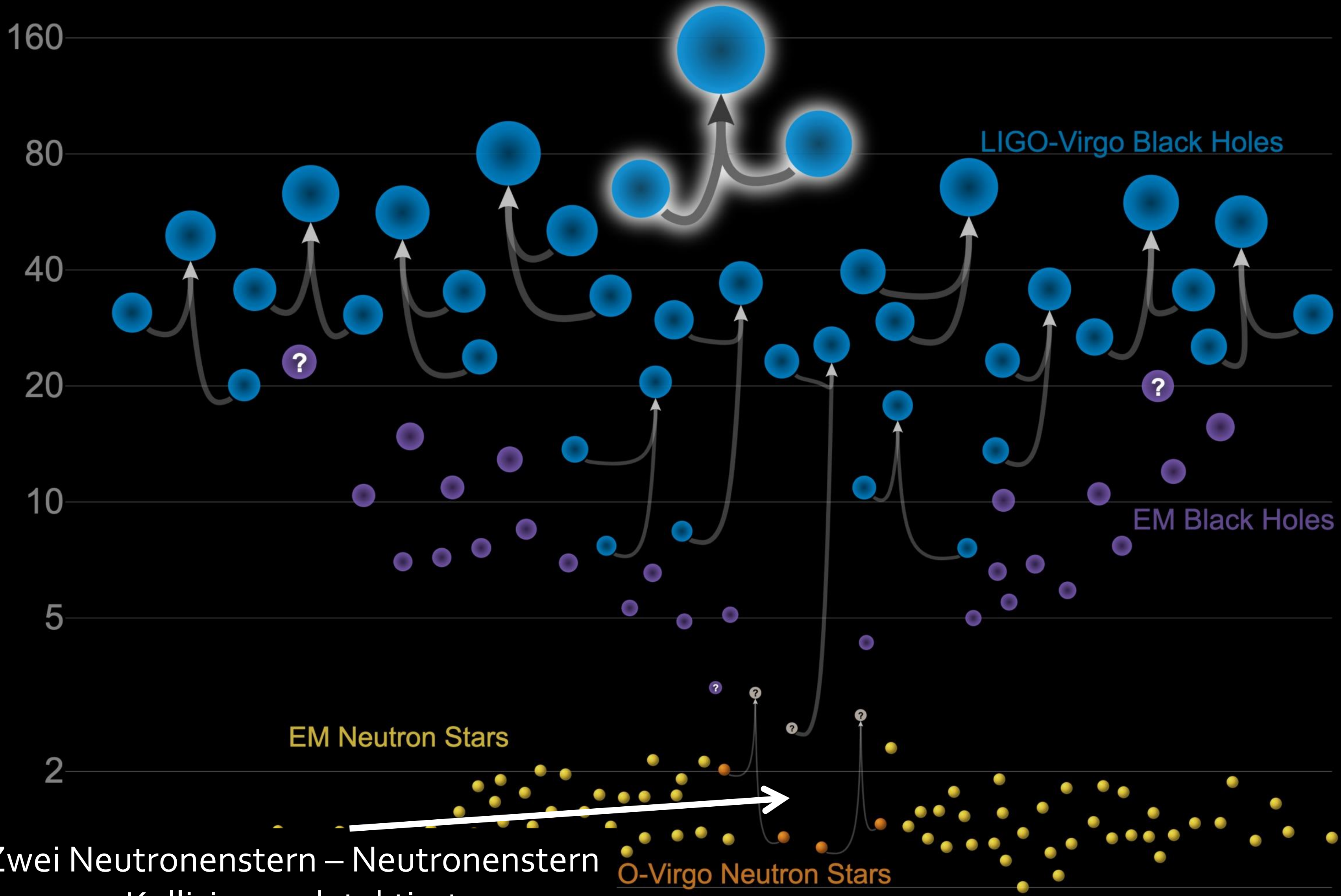
10. Vorlesung

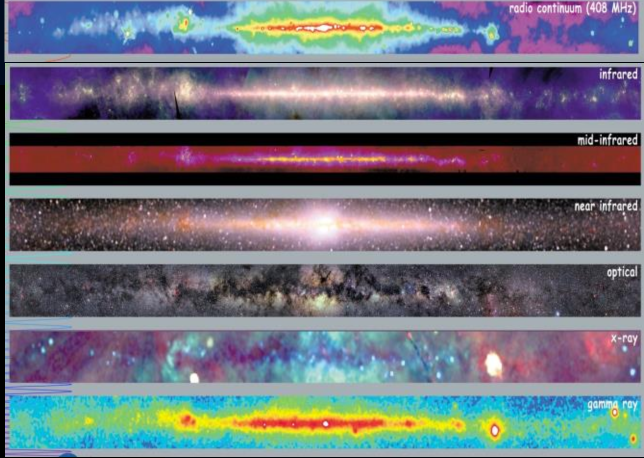
Gravitational Waves (GW): The new way of looking at our universe

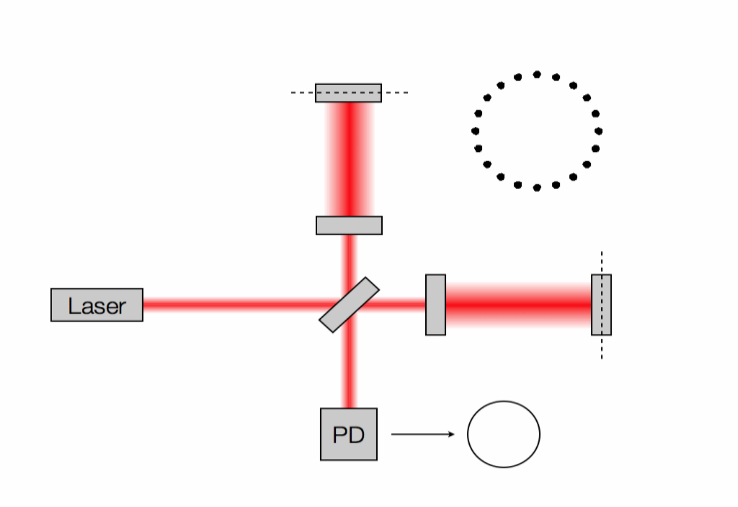
Es ist so als ob die Menschheit eine neue wundersame Brille hat, ein neues Sinnesorgan, mit denen sie zuvor unbeobachtbare Ereignisse in unserem Universum wahrnehmen kann.

Im Jahre 2015 gelang die erste Detektion einer Gravitationswelle

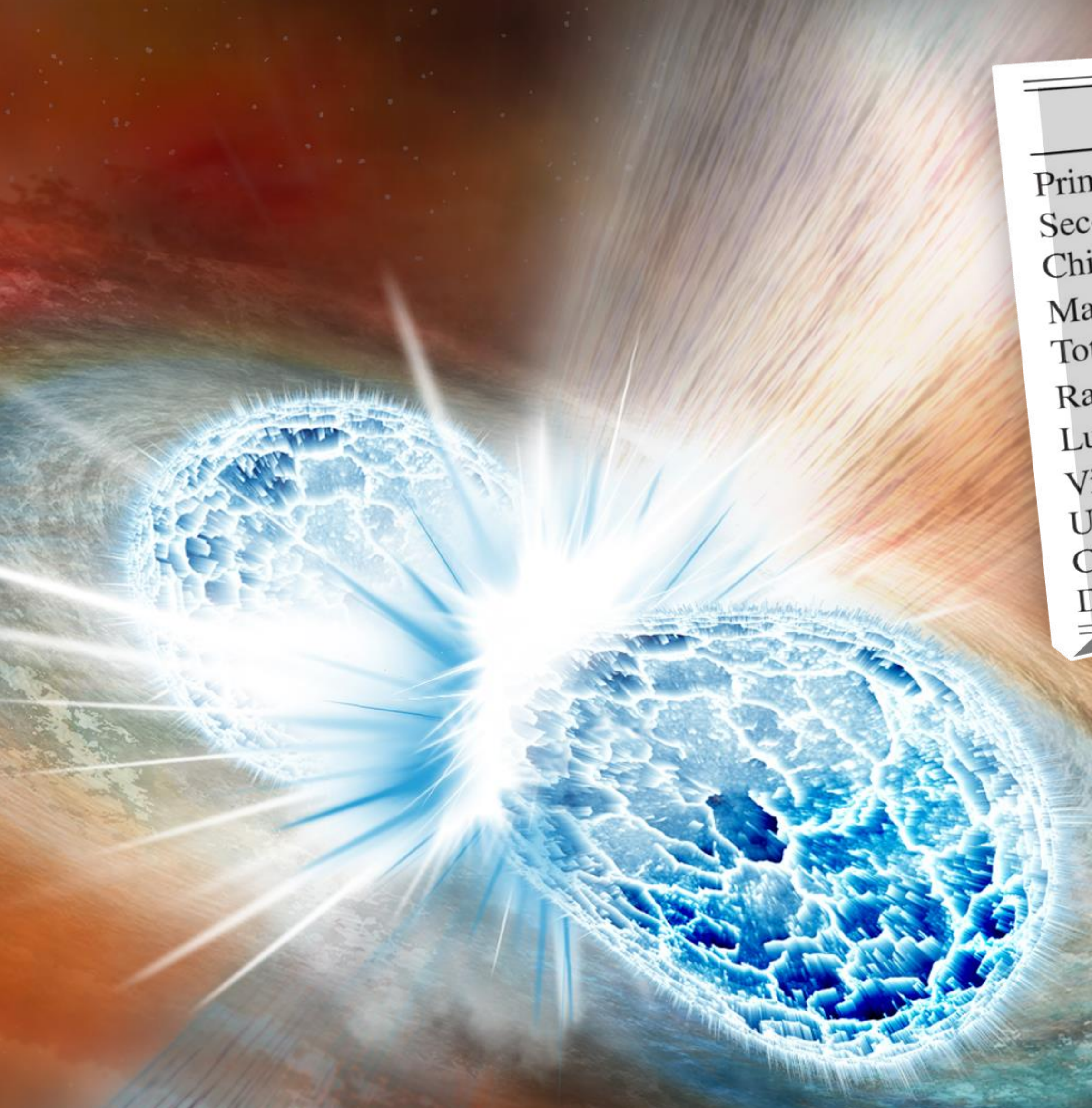


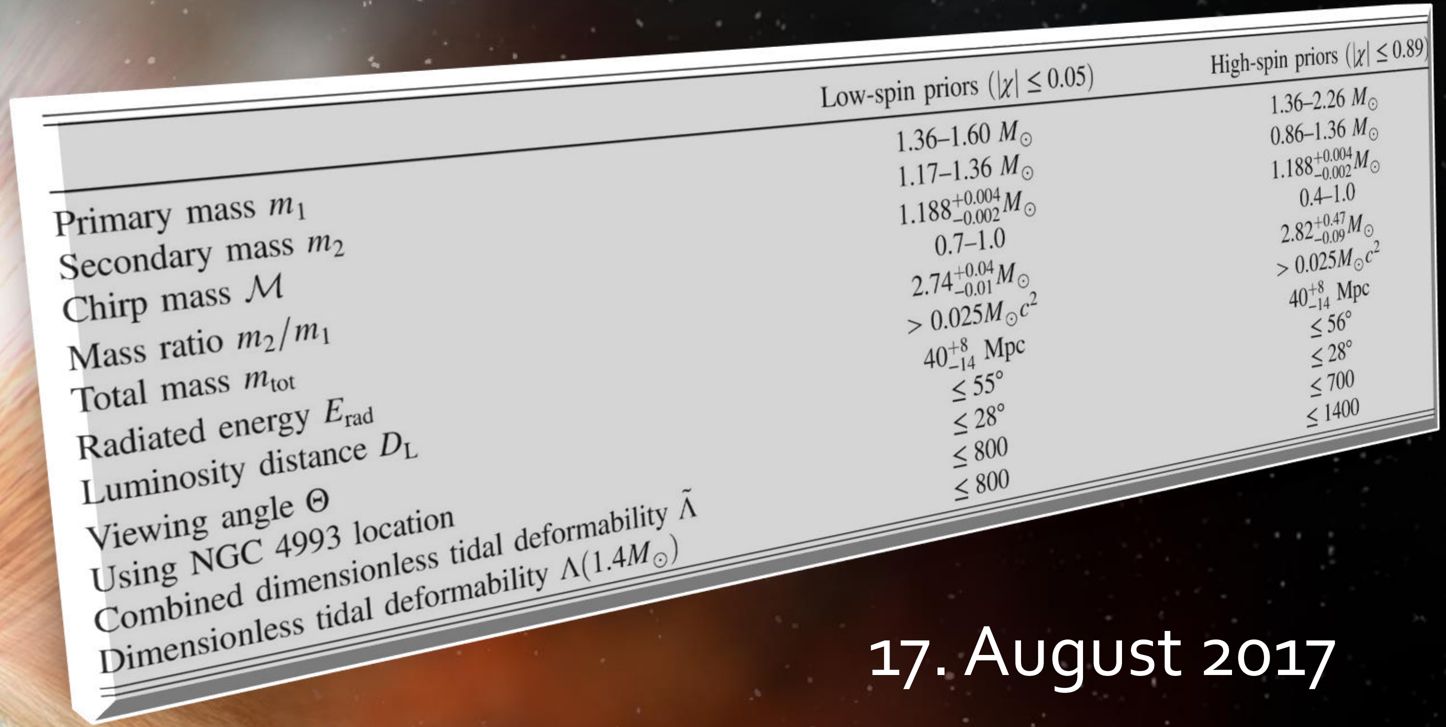
Zwei Neutronenstern – Neutronenstern Kollisionen detektiert





Das lang ersehnte Ereignis 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	$\leq 55°$	$\leq 56°$
Using NGC 4993 location	$\leq 28°$	$\leq 28°$
Combined dimensionless tidal deformability $\tilde{\Lambda}$	≤ 800	≤ 700
Dimensionless tidal deformability $\Lambda(1.4M_\odot)$	≤ 800	≤ 1400

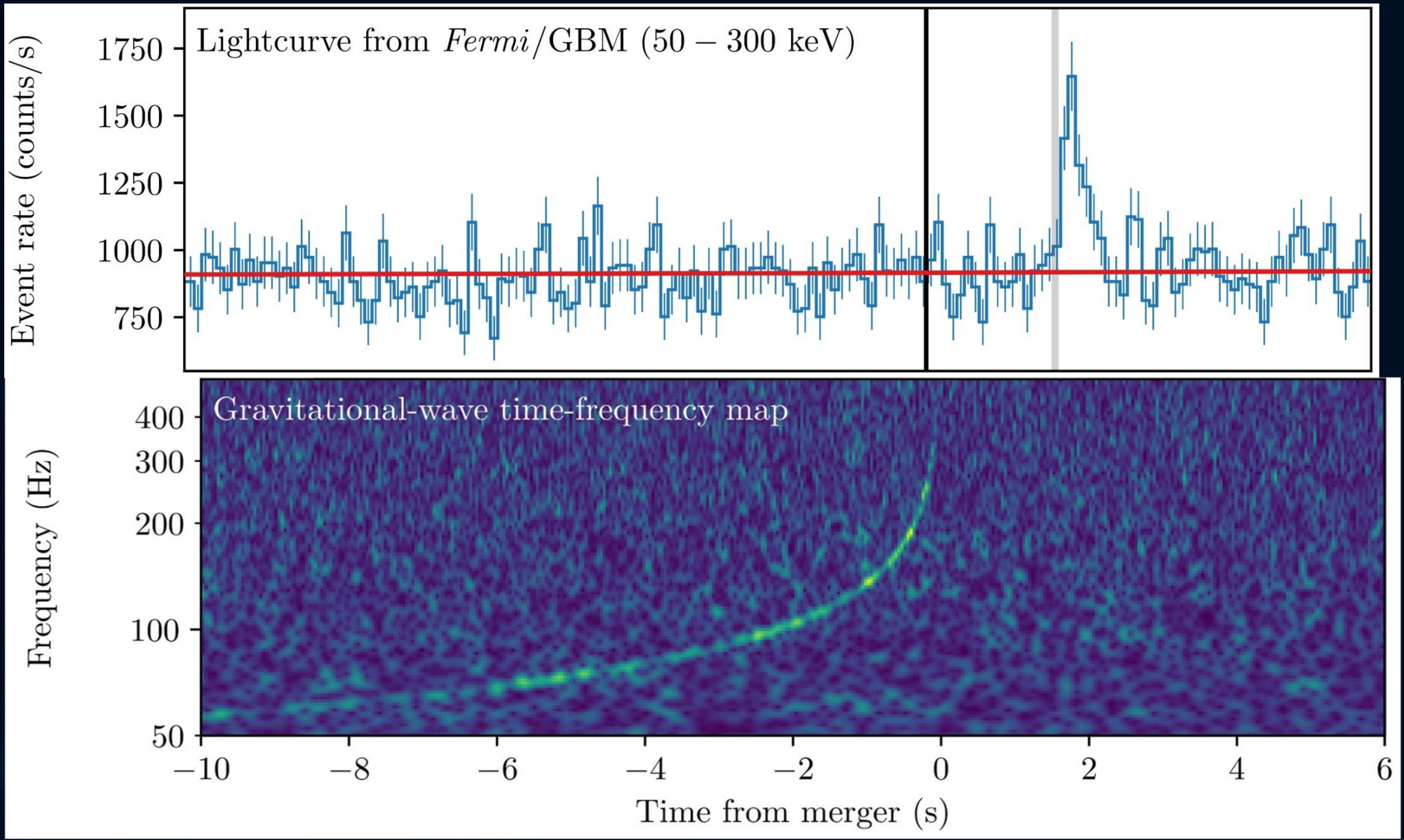
17. August 2017

Gravitationswelle einer
Neutronenstern Kollision gemessen!

Die gemessene Gravitationswelle und der darauf folgende hochenergetische Lichtblitz

Der von dem Gammastrahlen Detektor FERMI gemessene Gammastrahlen Ausbruch
(1.7 Sekunden später)

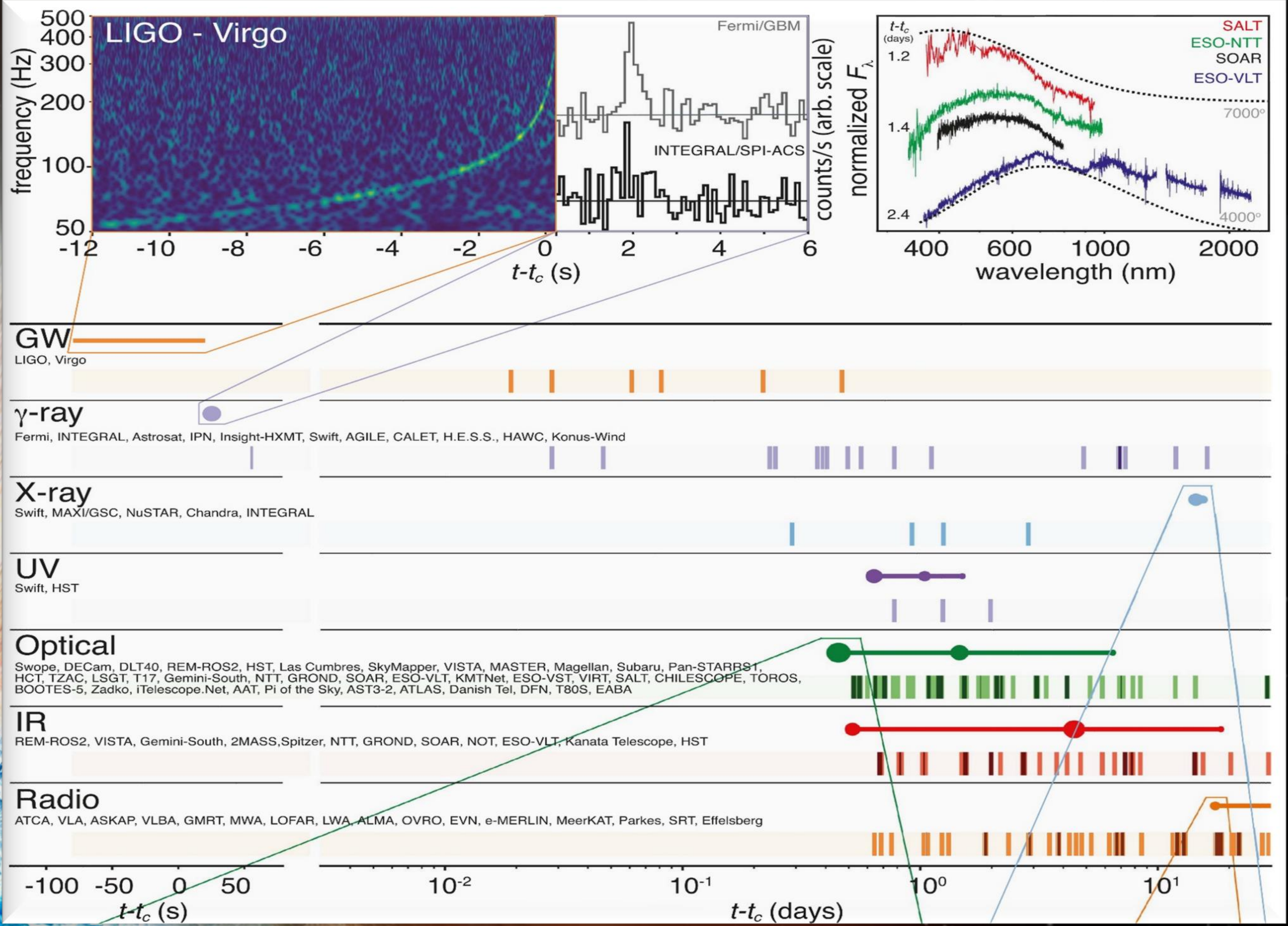
Die von dem Gravitationswellen Detektor LIGO detektierte Frequenz der Gravitationswelle



GW170817: Observation of Gravitational Waves from a Binary Neutron Star Inspiral, LIGO Scientific Collaboration and Virgo Collaboration, Phys. Rev. Lett. 119, 161101 (2017), Gravitational Waves and Gamma-Rays from a Binary Neutron Star Merger: GW170817 and GRB170817A, LIGO, Virgo, Fermi GBM, and INTEGRAL Collaborations, Astrophys. J. Lett. 848, L13 (2017)

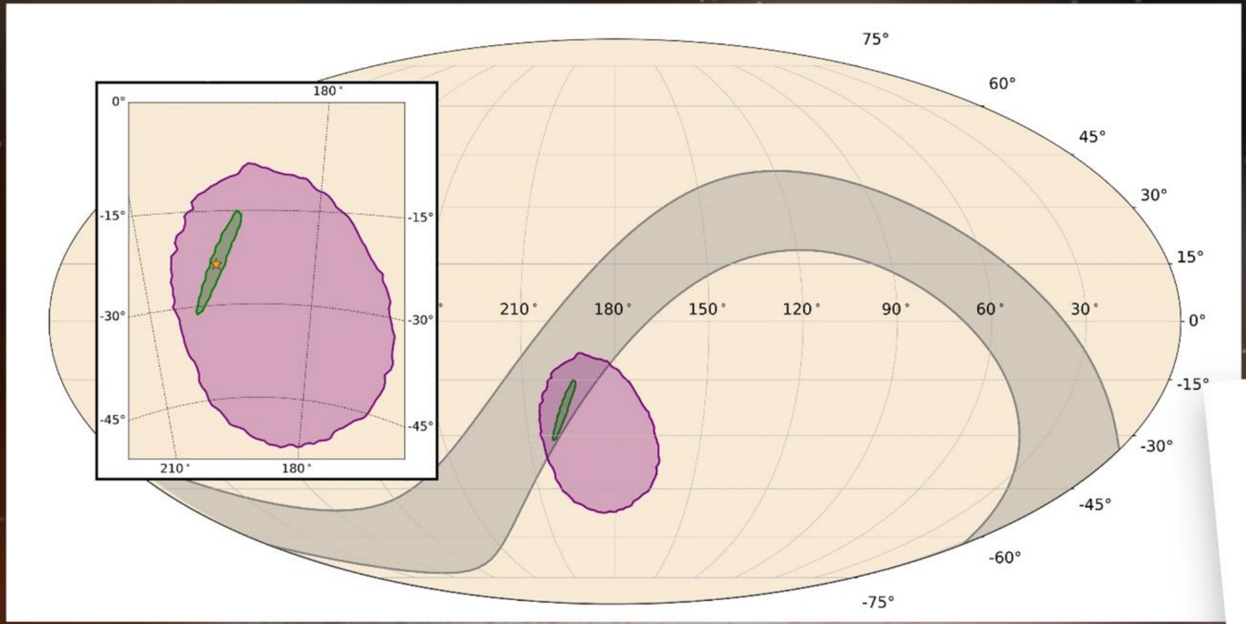
GW170817

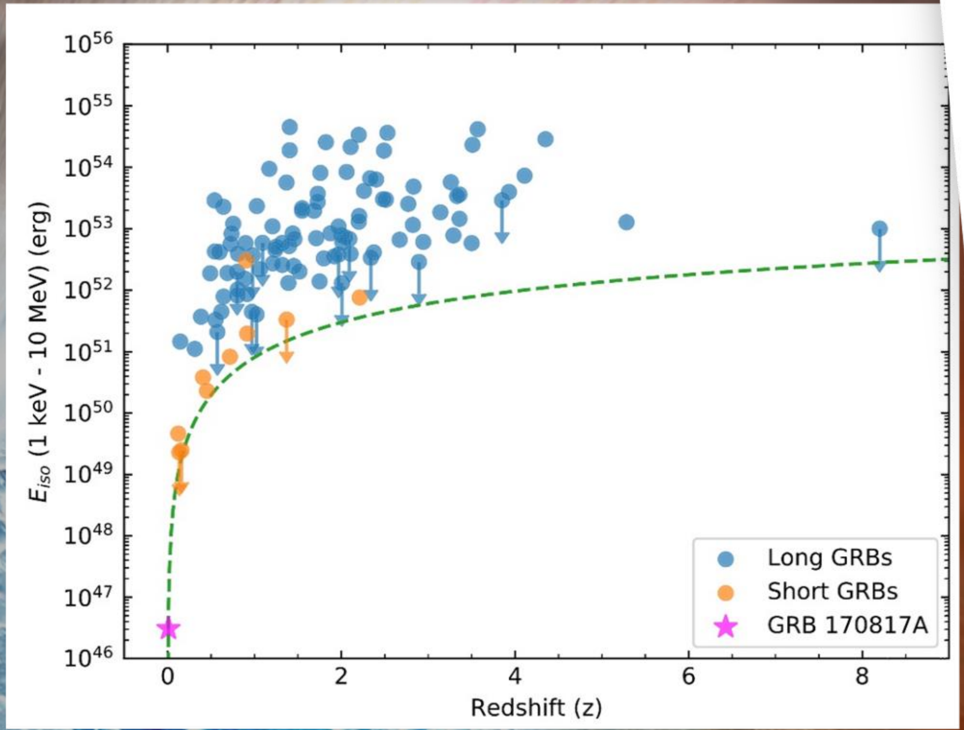
Tage, Wochen und Monate später detektierten weltweit unterschiedliche Teleskope (radio, infrarot, optische,…) eine Nachstrahlung dieser Neutronenstern Kollision (eine so genannte Kilonova)

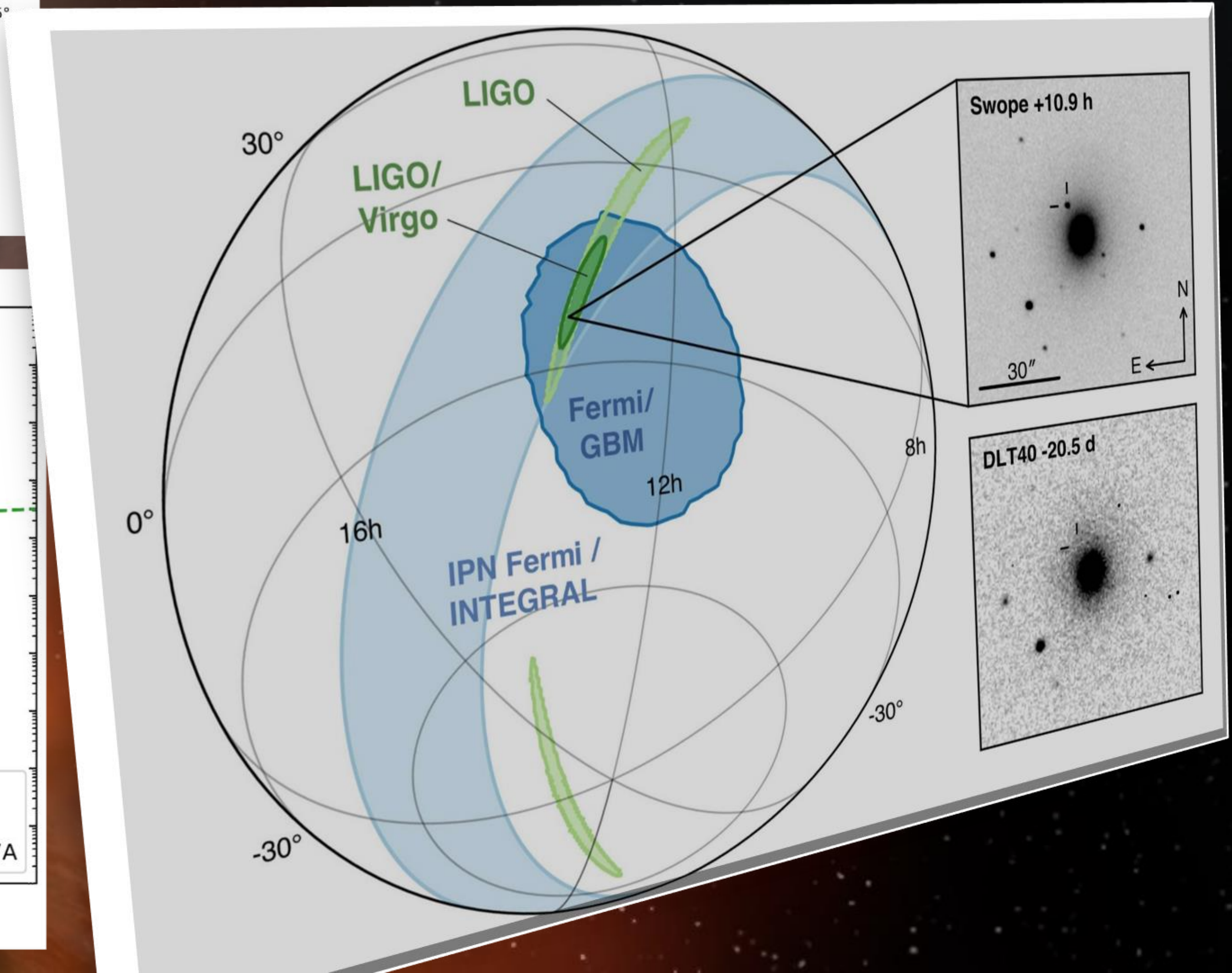


Multi-Messenger Observations of a Binary Neutron Star Merger, LIGO and Virgo Collaborations together with 50 teams of electromagnetic and neutrino astronomers, Astrophys. J. Lett. 848, L12 (2017)

GW170817, GRB170817A Localisation and unusual dimness of GRB

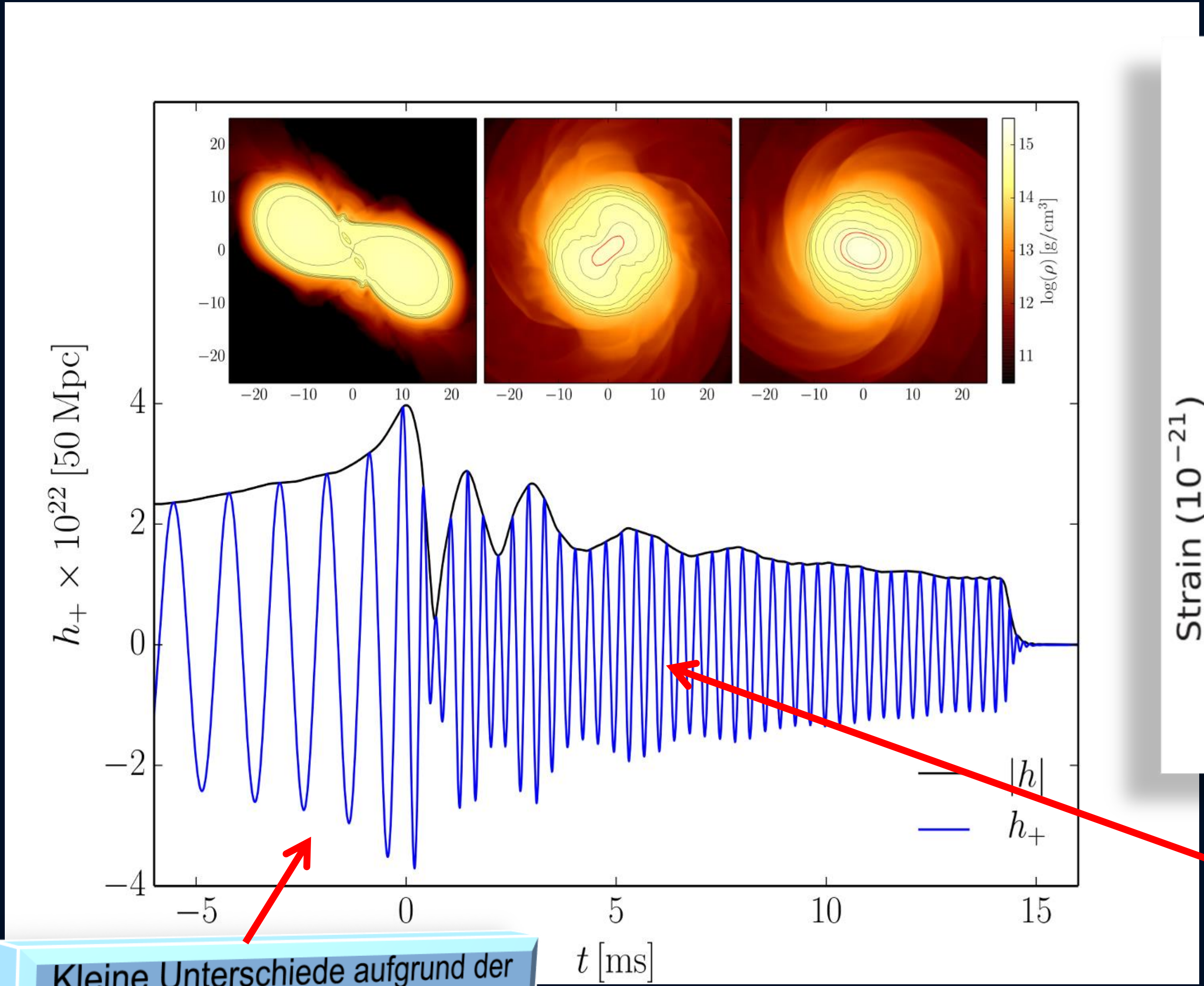






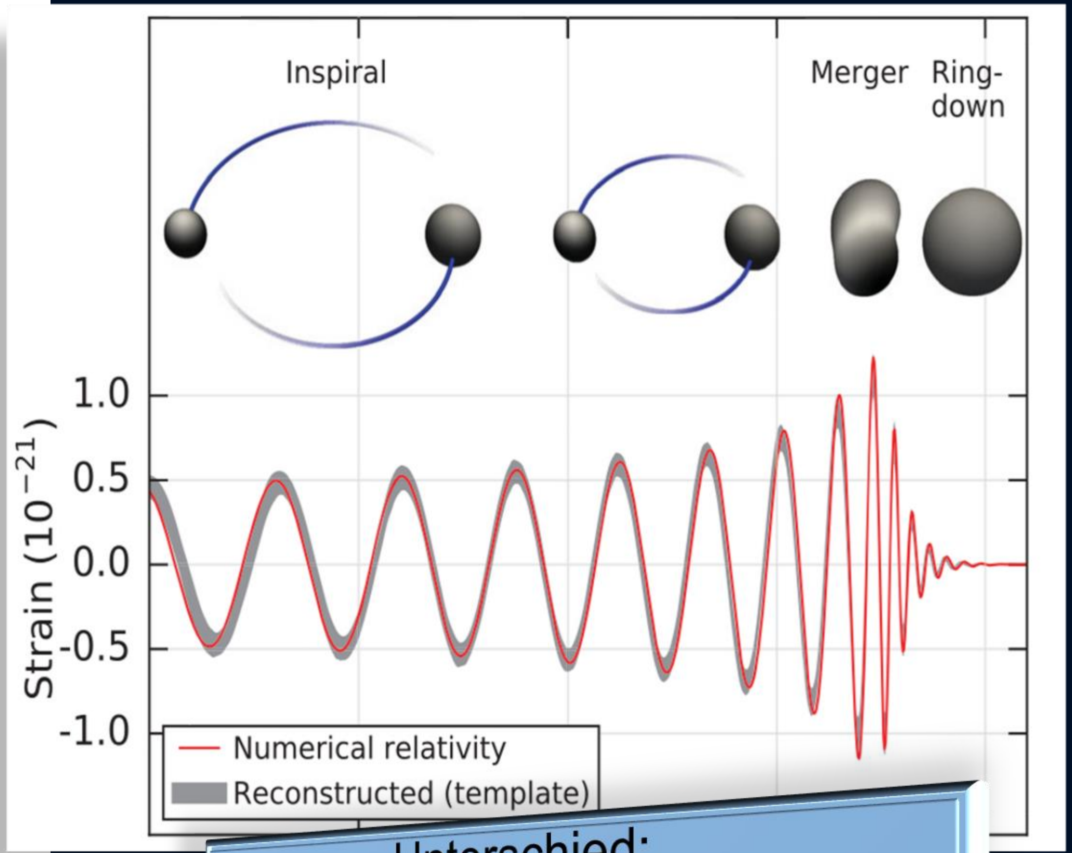
Gravitationswellen von Neutronenstern Kollisionen

Neutronenstern Kollision (Simulation)



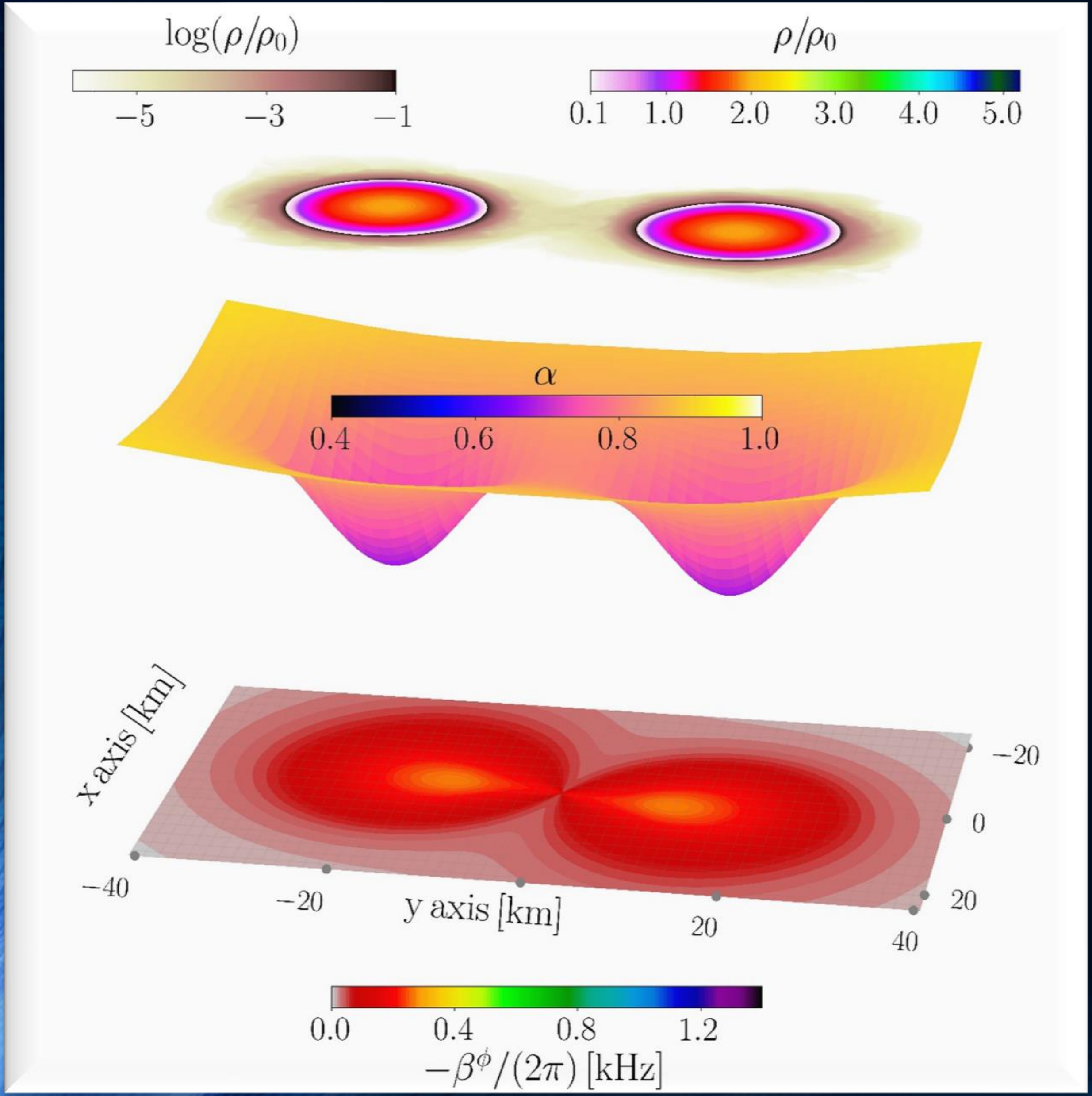
Kleine Unterschiede aufgrund der Verformbarkeit der Neutronensterne

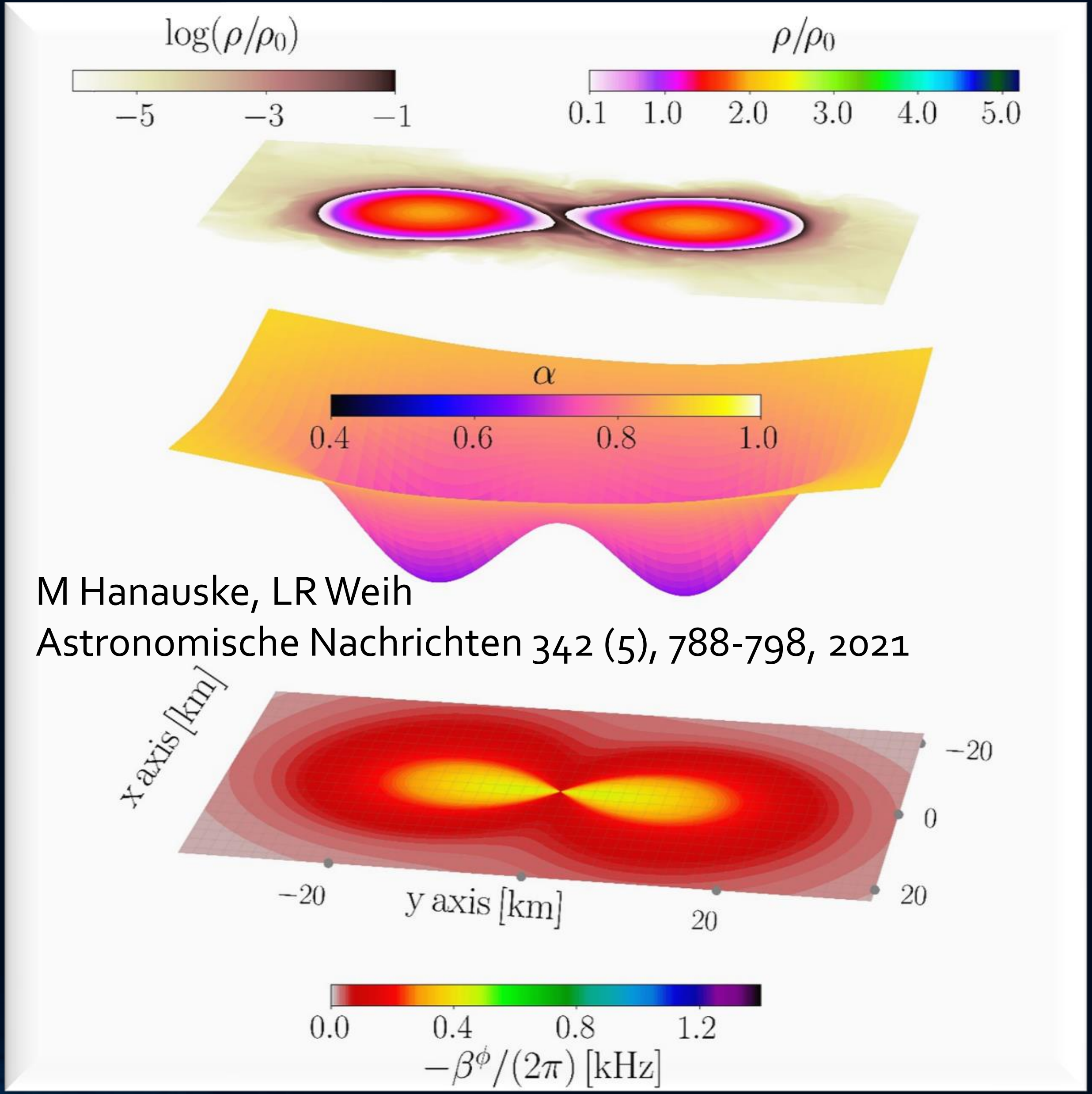
Kollision zweier schwarzer Löcher



Unterschied:
Bei Neutronenstern Kollisionen gibt es oft eine ***Post-Kollisionsphase***

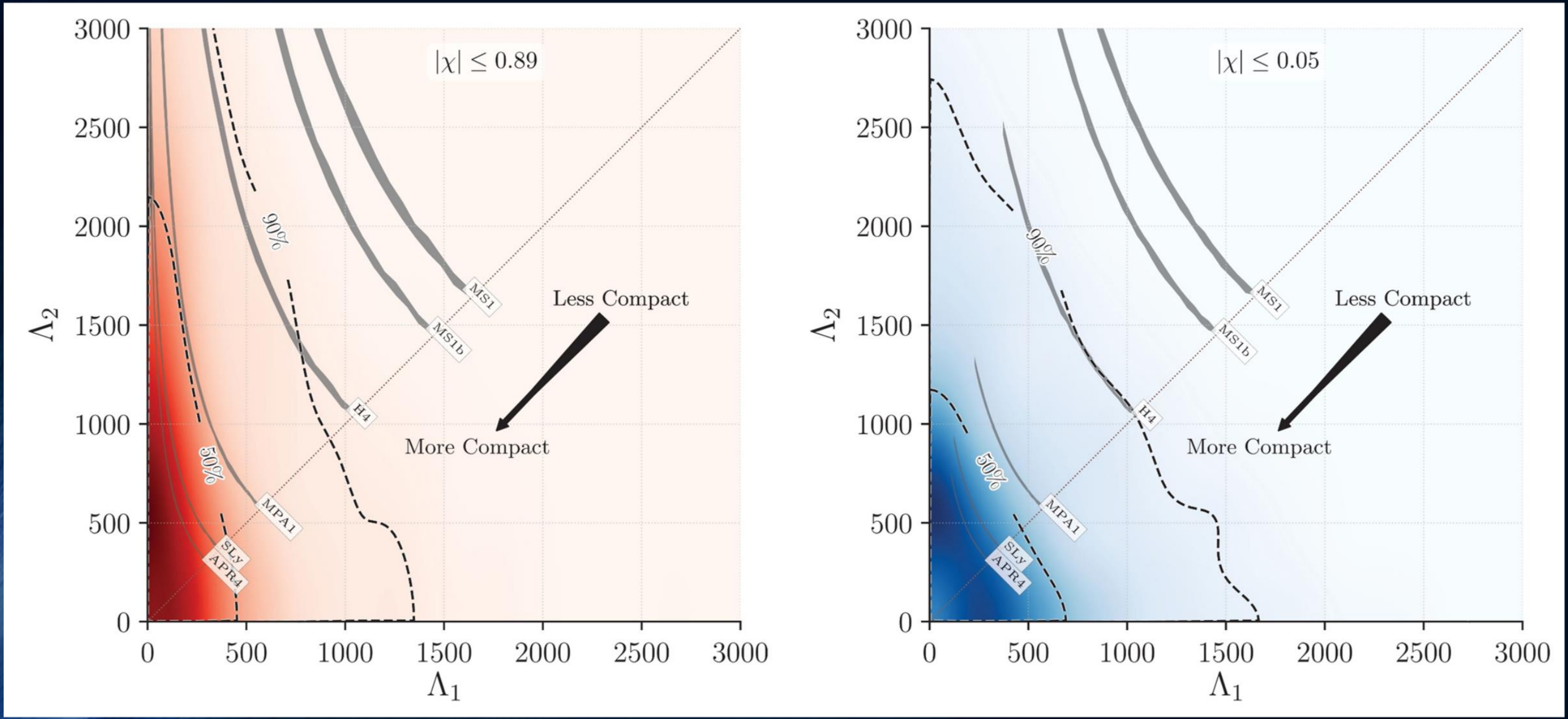
The late inspiral phase (density, lapse and shift)





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

GW170817: Tidal Deformability Restrictions on the Equation of State (EOS) (for high and low spin assumption)



Numerical Relativity and Relativistic Hydrodynamics of Binary Neutron Star Mergers

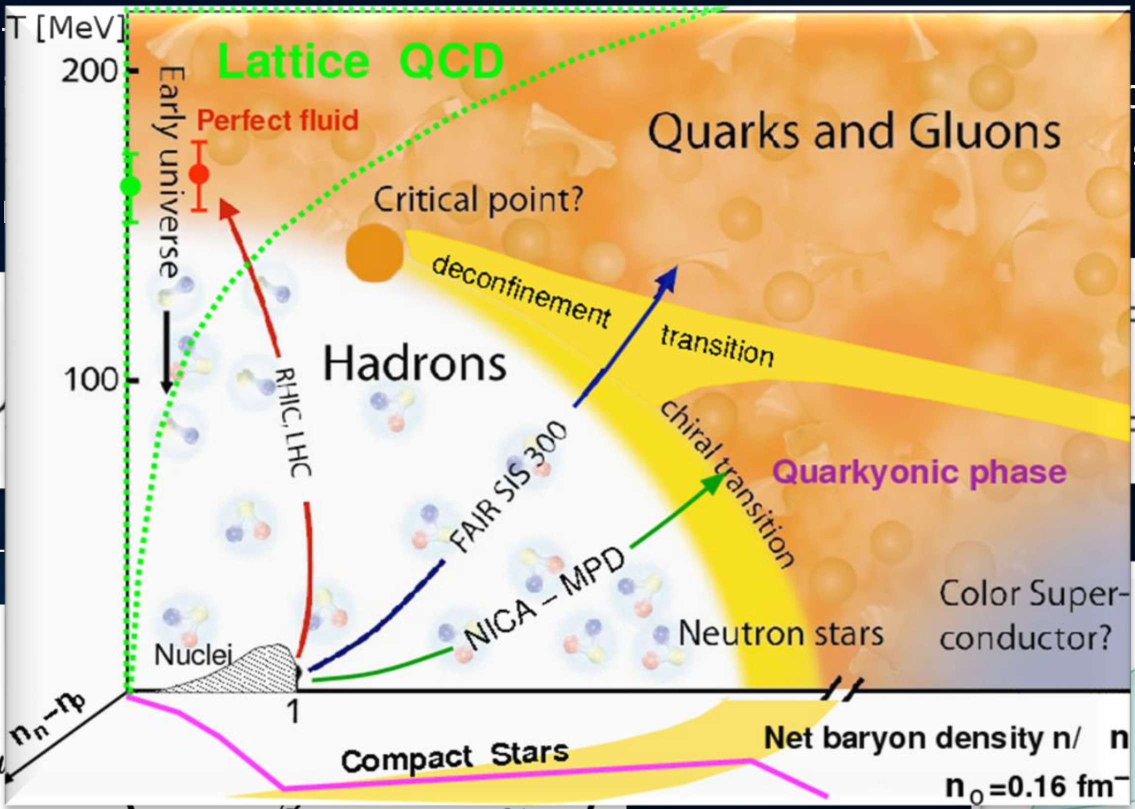
Eins… relat… with… neut… …l …ction …s of

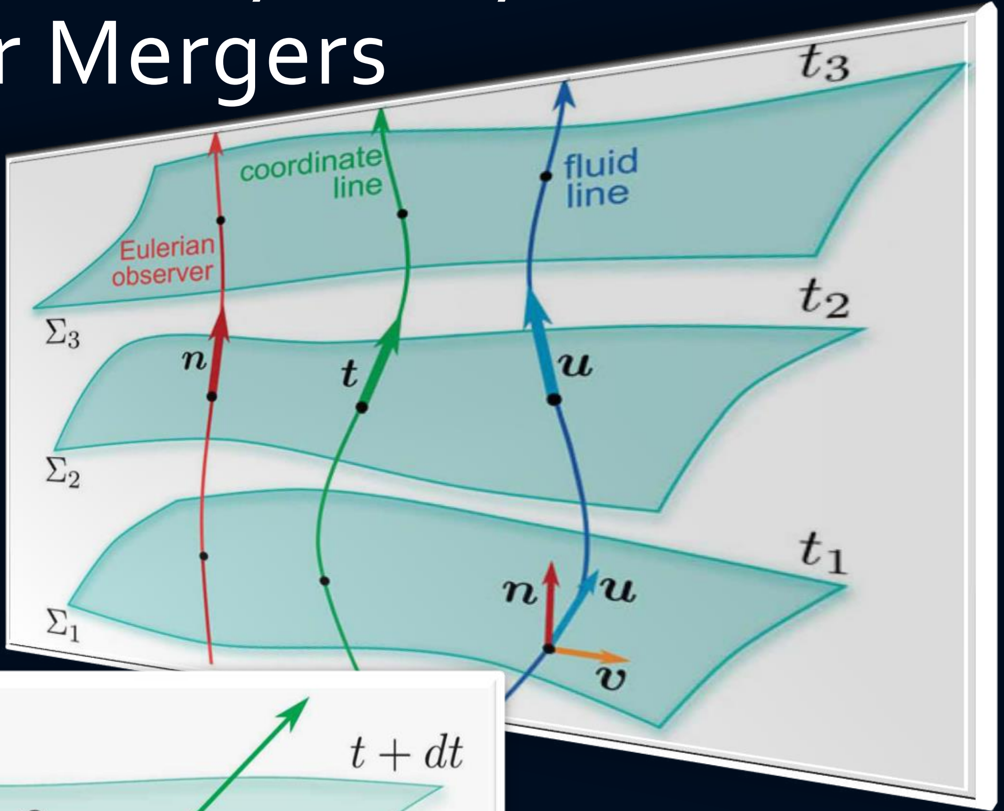
$R_{\mu\nu} \ldots = 0\,,$

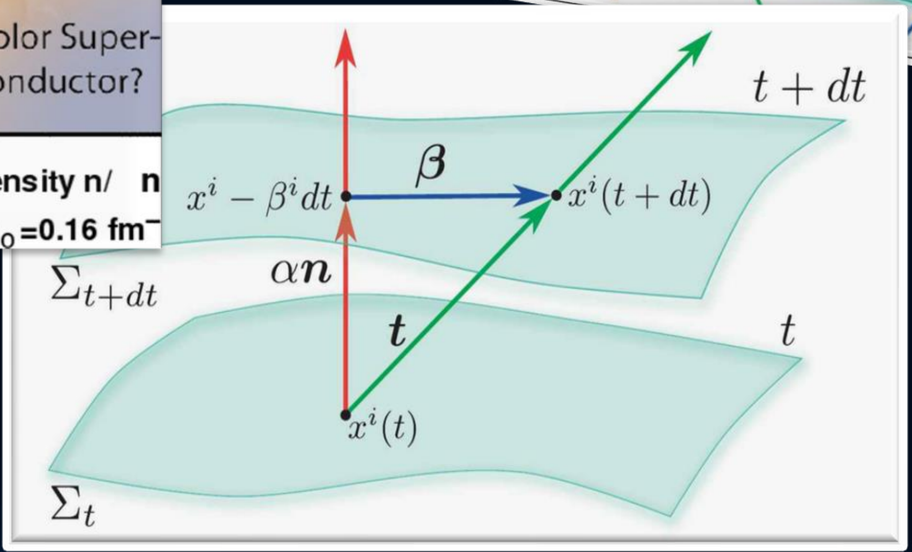
$\ldots = 0\,.$

(3+…

$g_{\mu\nu} \ldots \begin{pmatrix} \ldots & \beta_i & \gamma_{ij} \end{pmatrix}$





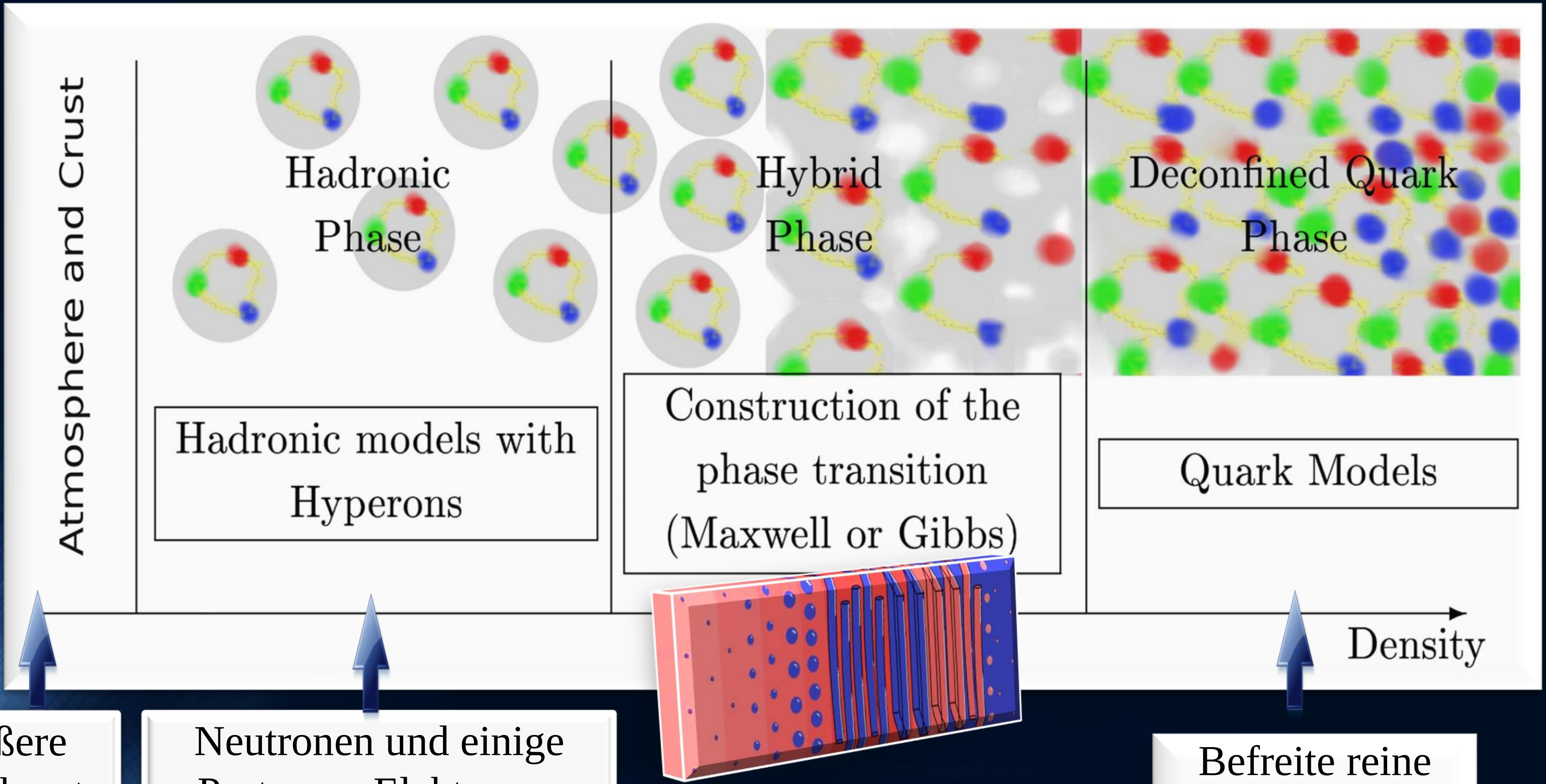


$$d\tau^2 = \alpha^2(t, x^j)dt^2$$

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

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

Das Innere von hybriden Sternen



Äußere Eisenkruste

Neutronen und einige Protonen, Elektronen vielleicht auch Hyperonen

Phasenübergang vielleicht Pasta-Struktur

Befreite reine Quarkphase

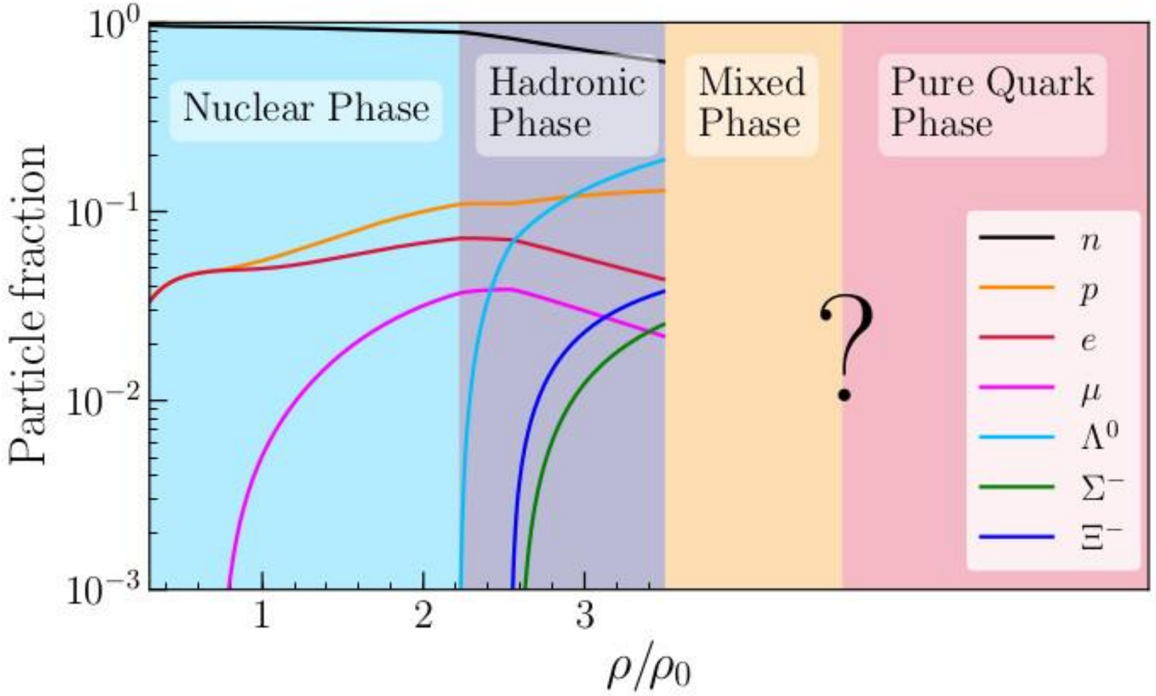
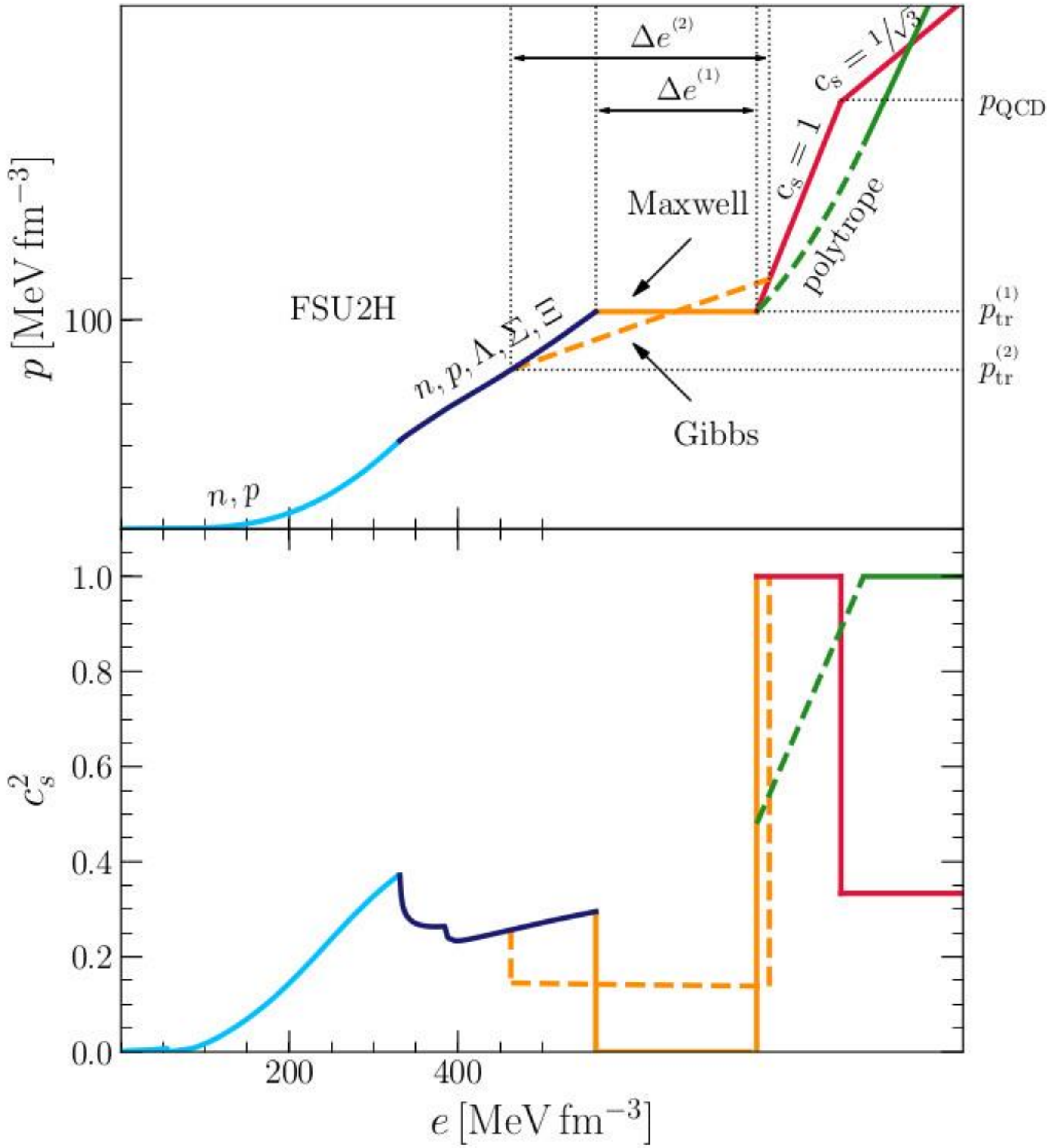


FIG. 1. Particle fractions as functions of the baryonic density for the FSU2H model [69, 70] up to the point where the HQPT is implemented, giving rise to a phase of deconfined quark matter which can be separated from the nuclear (or hadronic) phase by a mixed phase of hadrons and quarks. We note that the actual fractions of nucleons/hyperons and quarks u, d, s in the mixed and quark phases cannot be determined with the parametrizations used in this work.



The Hadron-Quark Phase Transition and the Third Family of Compact Stars (Twin Stars)

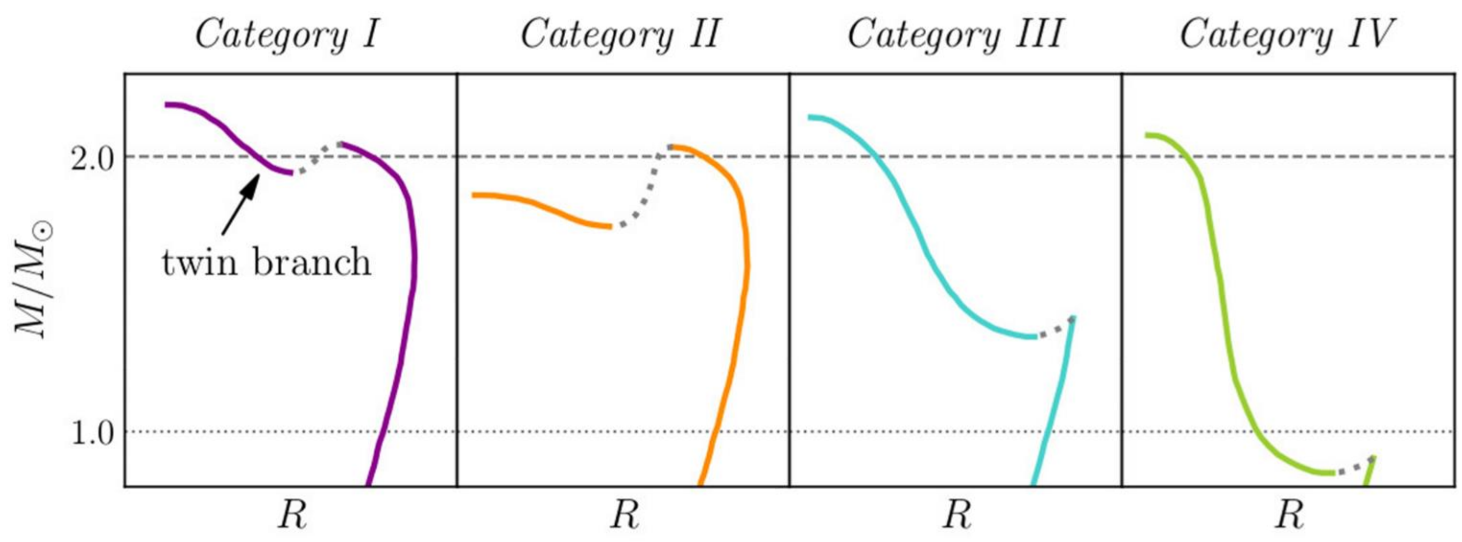
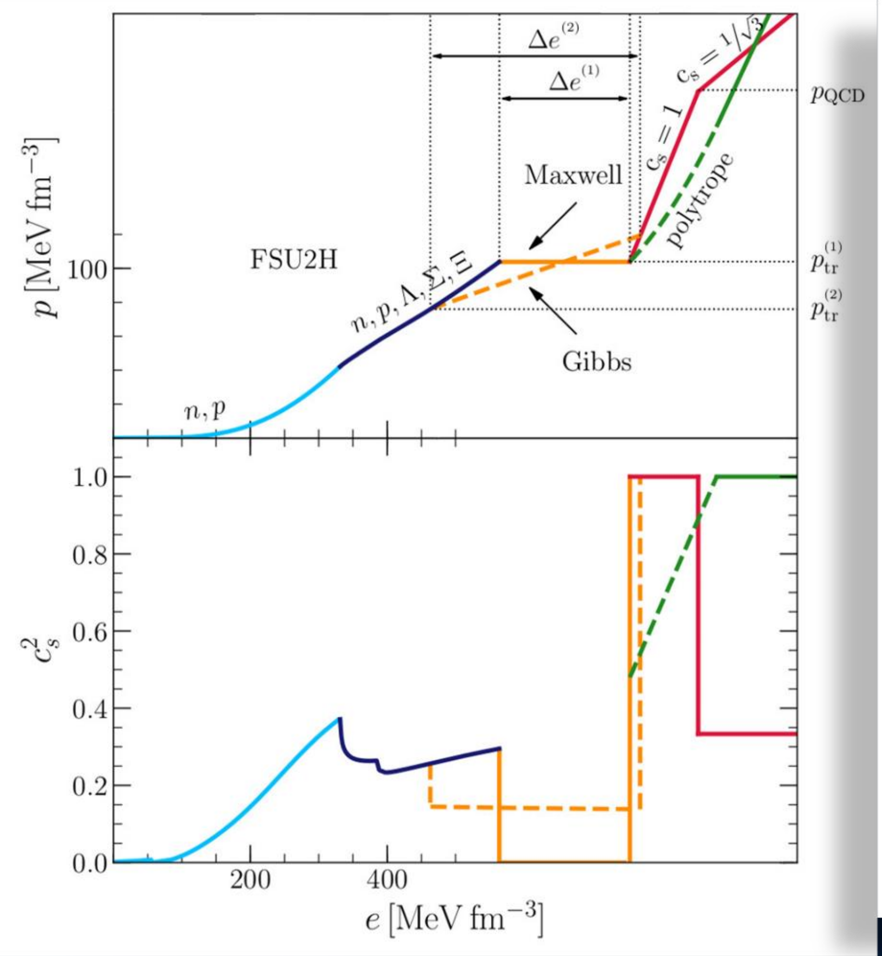


FIG. 3. Schematic behaviour of the mass–radius relation for the twin-star categories *I–IV* defined in the text. Note the appearance of a "twin" branch with a mixed or pure-quark phase; the twin branch has systematically smaller radii than the branch with a nuclear or hadronic phase. The colors used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

- Glendenning, N. K., & Kettner, C. (1998). Nonidentical neutron star twins. Astron. Astrophys., 353(LBL-42080), L9.
- Sarmistha Banik, Matthias Hanauske, Debades Bandyopadhyay and Walter Greiner, Rotating compact stars with exotic matter, Phys.Rev.D 70 (2004) p.12304
- I.N. Mishustin, M. Hanauske, A. Bhattacharyya, L.M. Satarov, H. Stöcker, and W. Greiner, Catastrophic rearrangement of a compact star due to quark core formation, Physics Letters B 552 (2003) p.1-8
- M.Alford and A. Sedrakian, Compact stars with sequential QCD phase transitions. Physical review letters, 119(16), 161104 (2017)..
- D.Alvarez-Castillo and D.Blaschke, High-mass twin stars with a multipolytrope equation of state. Physical Review C, 96(4), 045809 (2017) .
- A. Ayriyan, N.-U. Bastian, D. Blaschke, H. Grigorian, K. Maslov, D. N. Voskresensky, How robust is a third family of compact stars against pasta phase effects?, arXiv:1711.03926 [nucl-th]

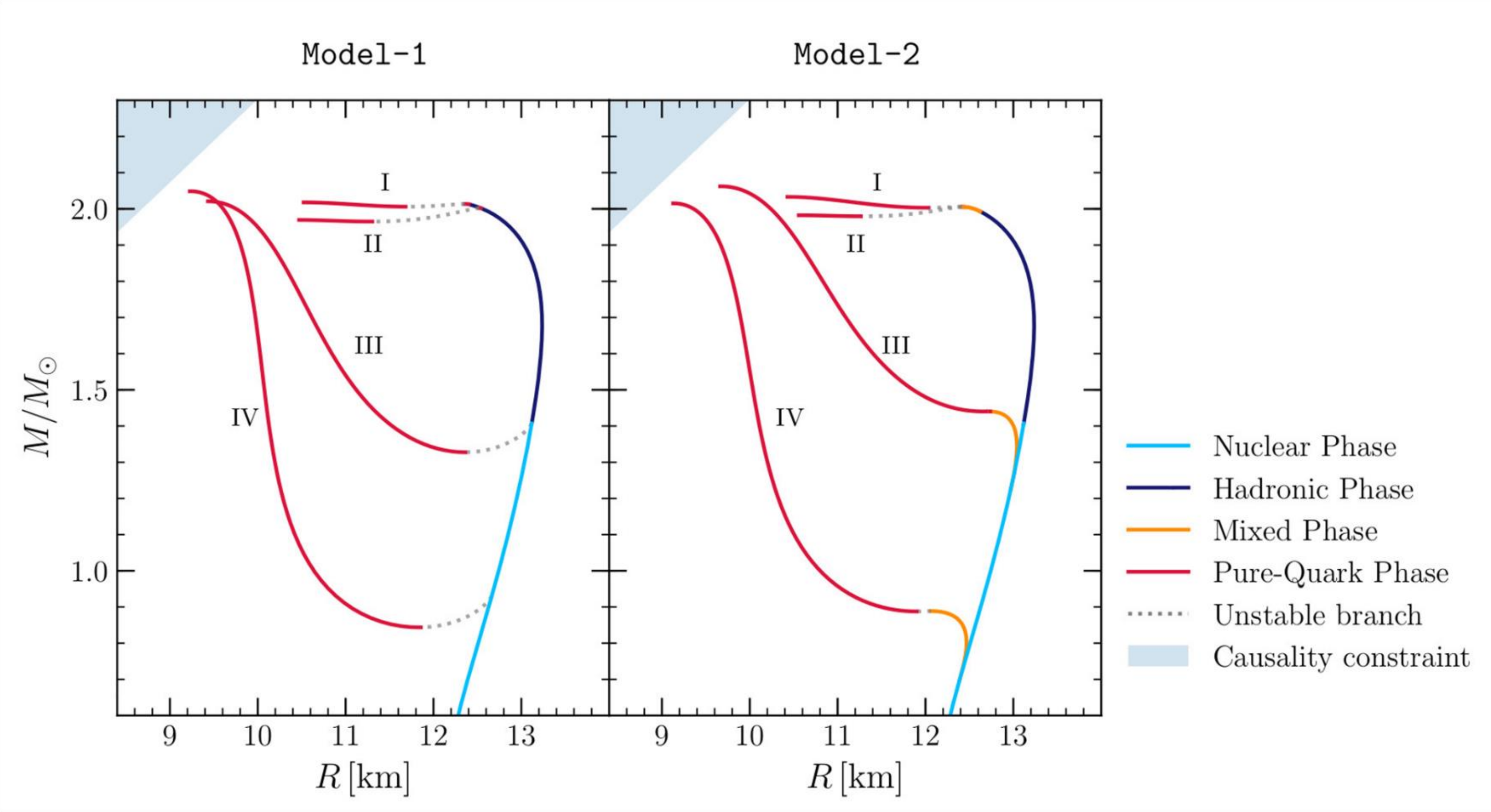
Binary Hybrid Star Mergers and the Twin Star Possibility

Construction of the EOS with a HadronQuarkPhaseTransition

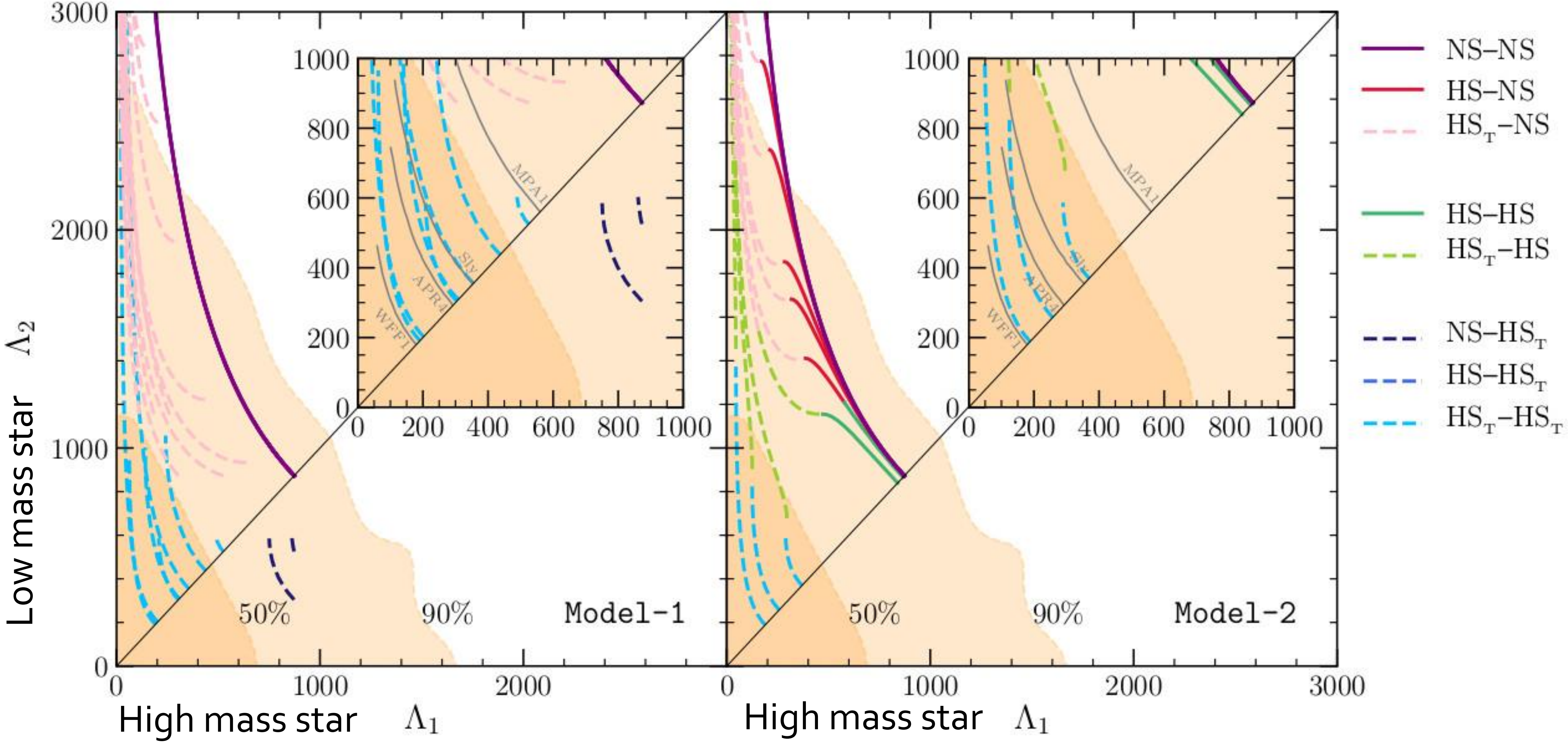


The Mass-Radius relation and the Twin Star property

Maxwell Construction Gibbs Construction

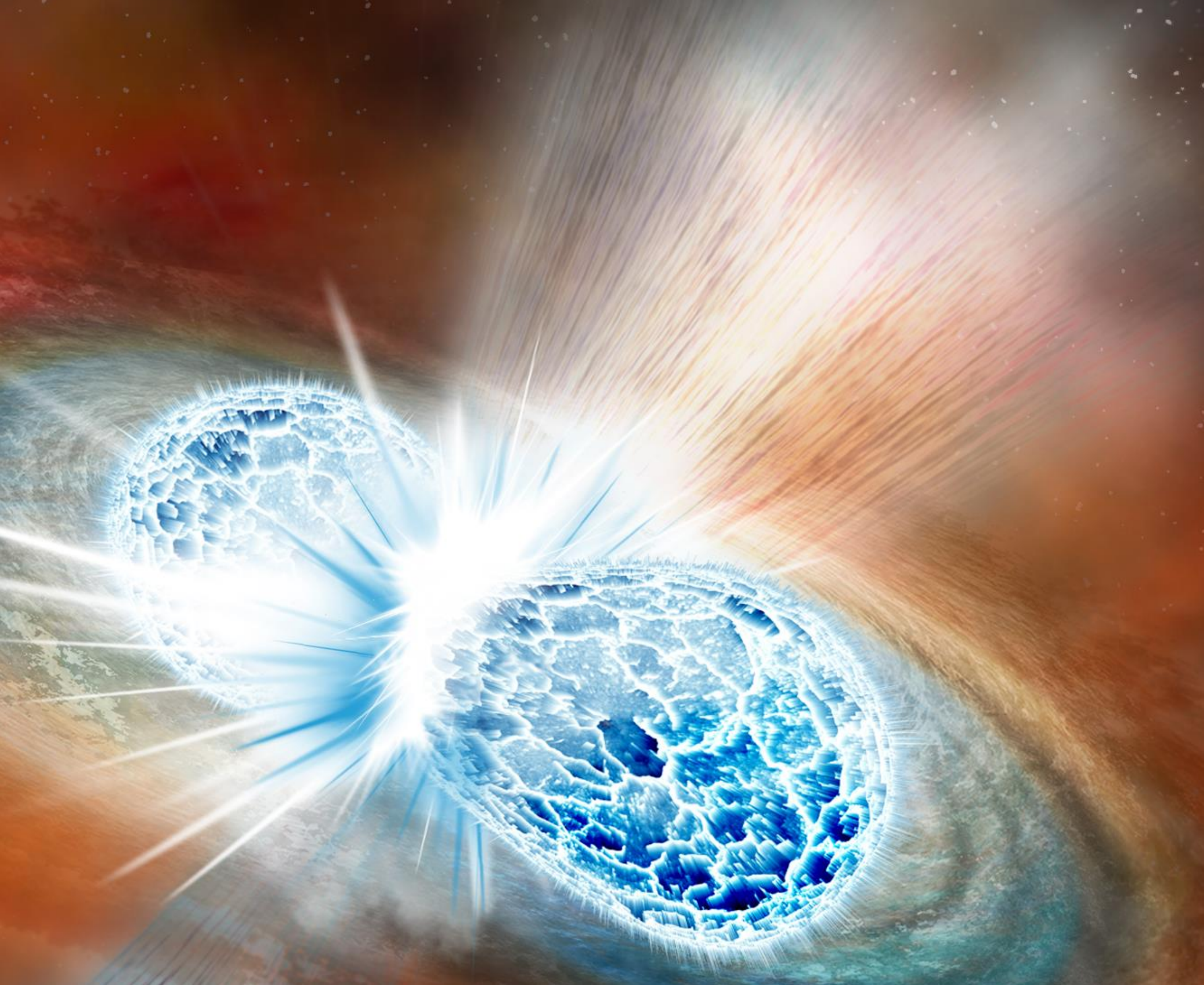


G. Montana, L.Tolos, M.Hanauske and L.Rezzolla „Constraining twin stars with GW170817, PRD 99(10), 2019



In a binary hybrid star merger the two masses of the individual stars can be different (q<1). As a result, the tidal deformability and the stars composition can be different. In this plot the total mass of the binary system has been fixed to the measured chirp mass of GW170817 (M=1.188 M_{solar}) and the different curve show results for EOSs of Category III.

The second event: GW190425



Total mass ~ 3.4 $M_{\odot}$

19. April 2019

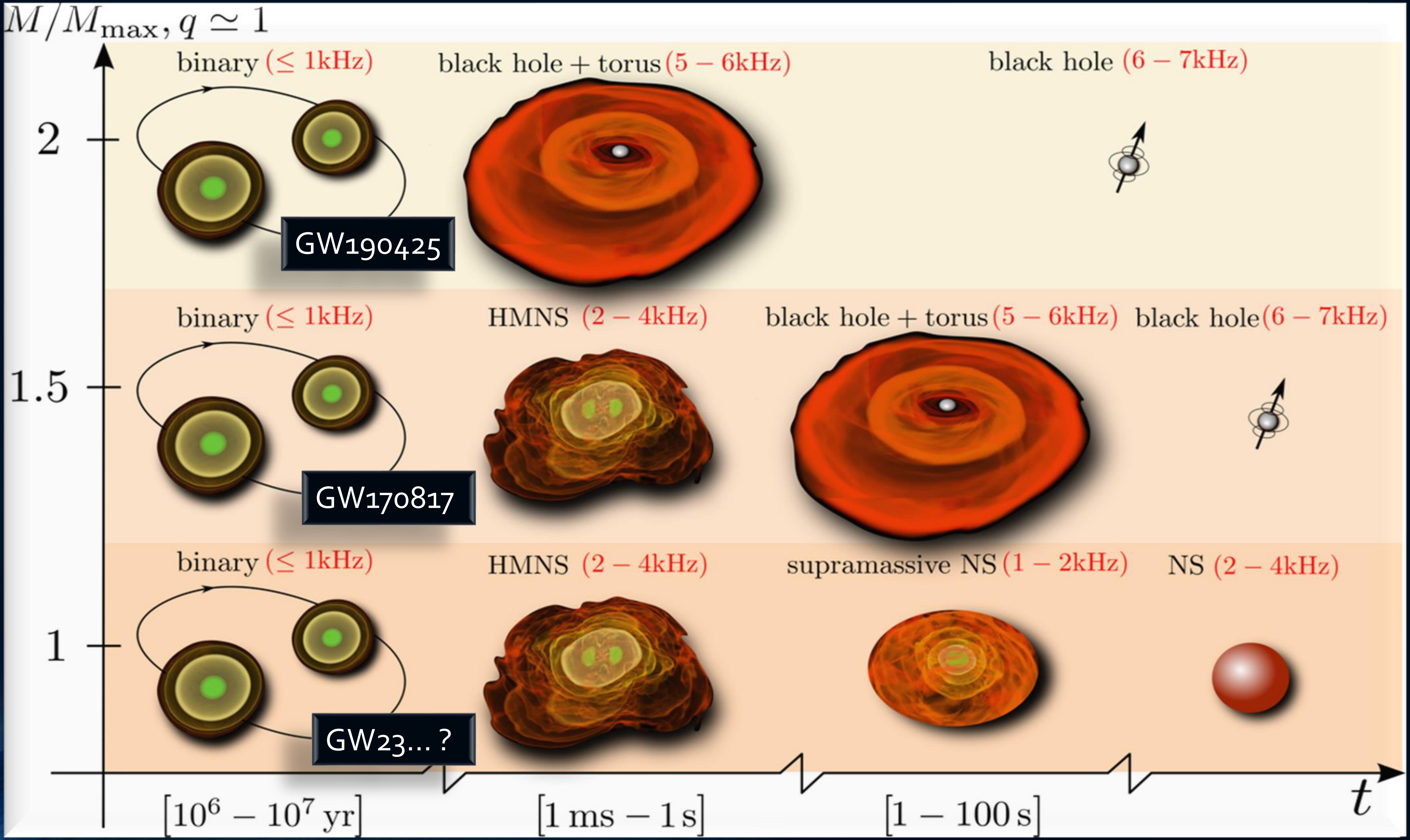
Second detection of a gravitational wave from a binary neutron star merger event!

Was geschieht wenn zwei Neutronensterne miteinander kollidieren?

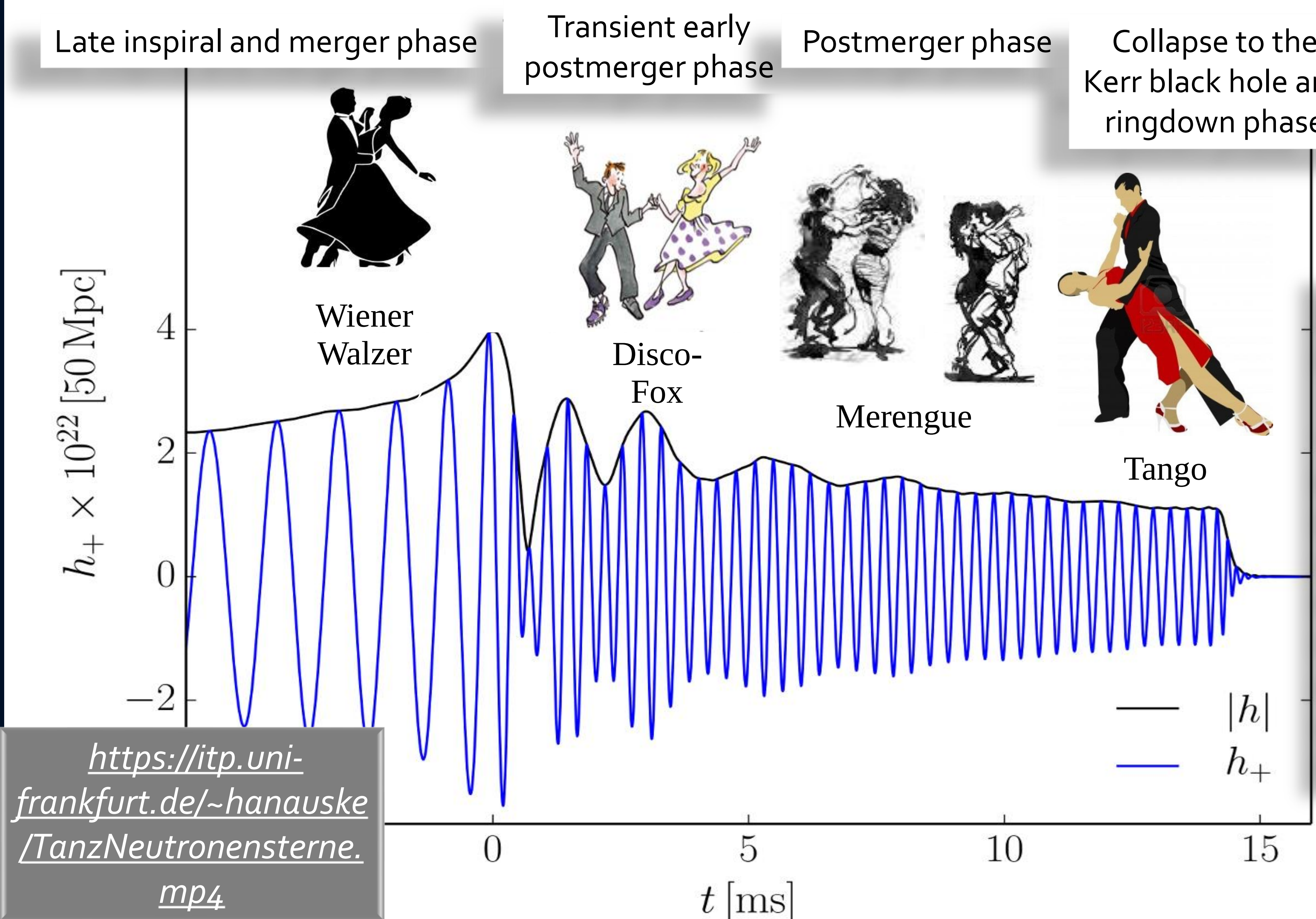
Zwei sehr massive Neutronensterne

Zwei mittelschwere Neutronensterne

Zwei leichte Neutronensterne



The different Phases of a Binary Compact Star Merger Event



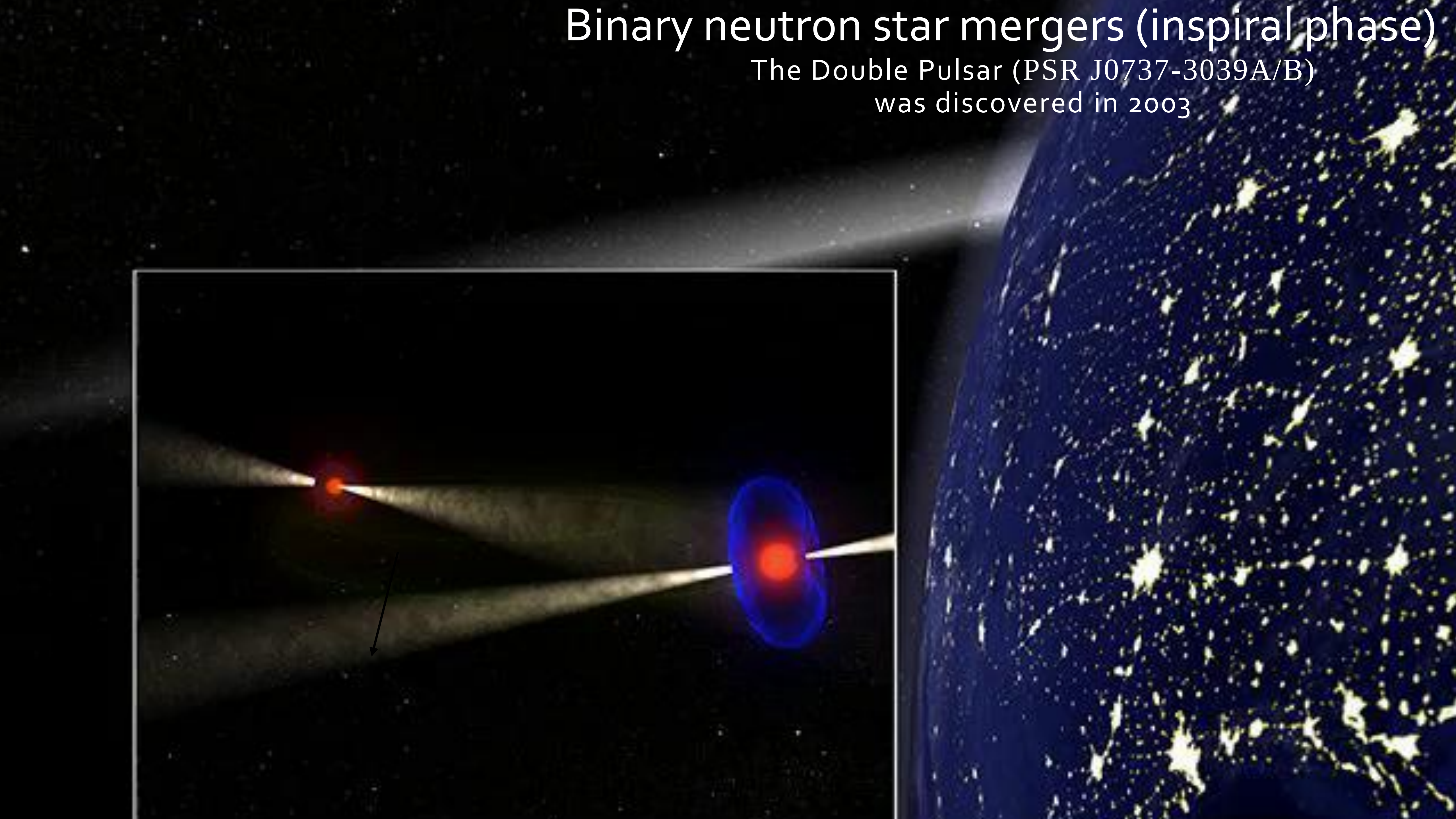
Wy exactly these dances? Details in

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

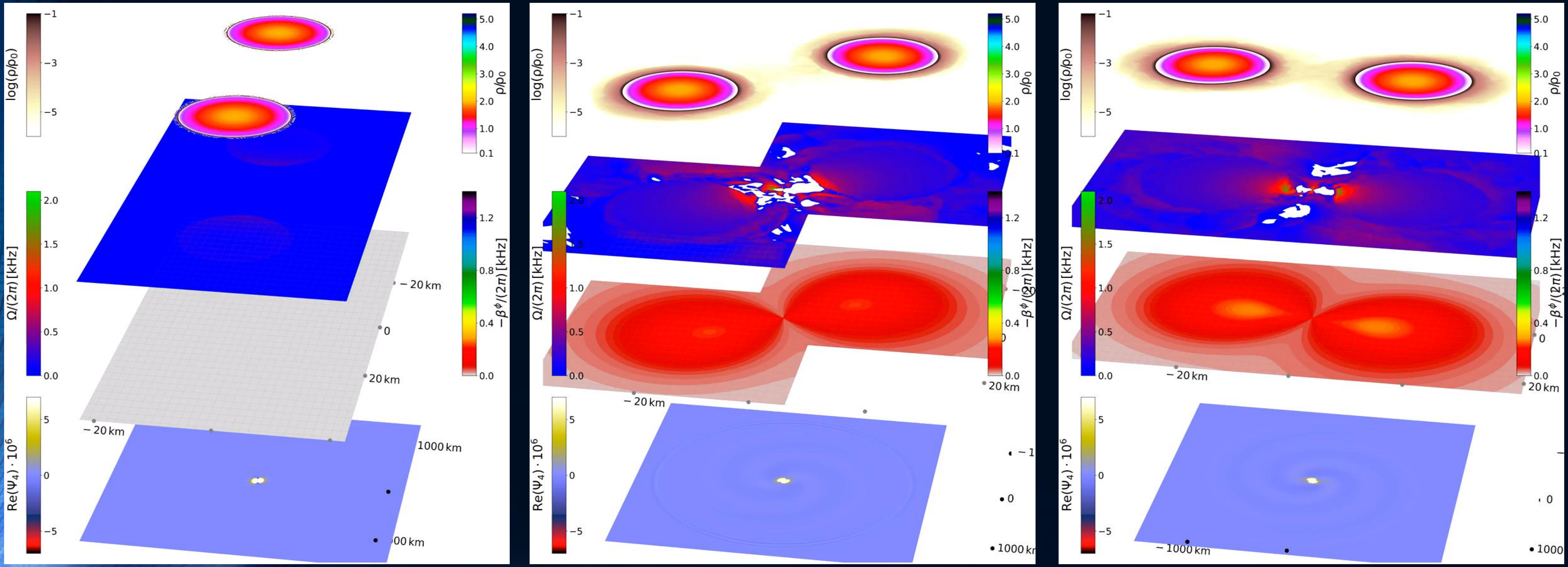
https://itp.uni-frankfurt.de/~hanauske/TanzNeutronensterne.mp4

Binary neutron star mergers (inspiral phase)

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



Binary neutron star mergers
(the late inspiral phase)



Computer Simulation of a neutron star merger

Credits: Cosima Breu, David Radice und Luciano Rezzolla

Log of density

8.5 14

lg(rho) [g/cm^3]

Temperature

0 50

T [MeV]

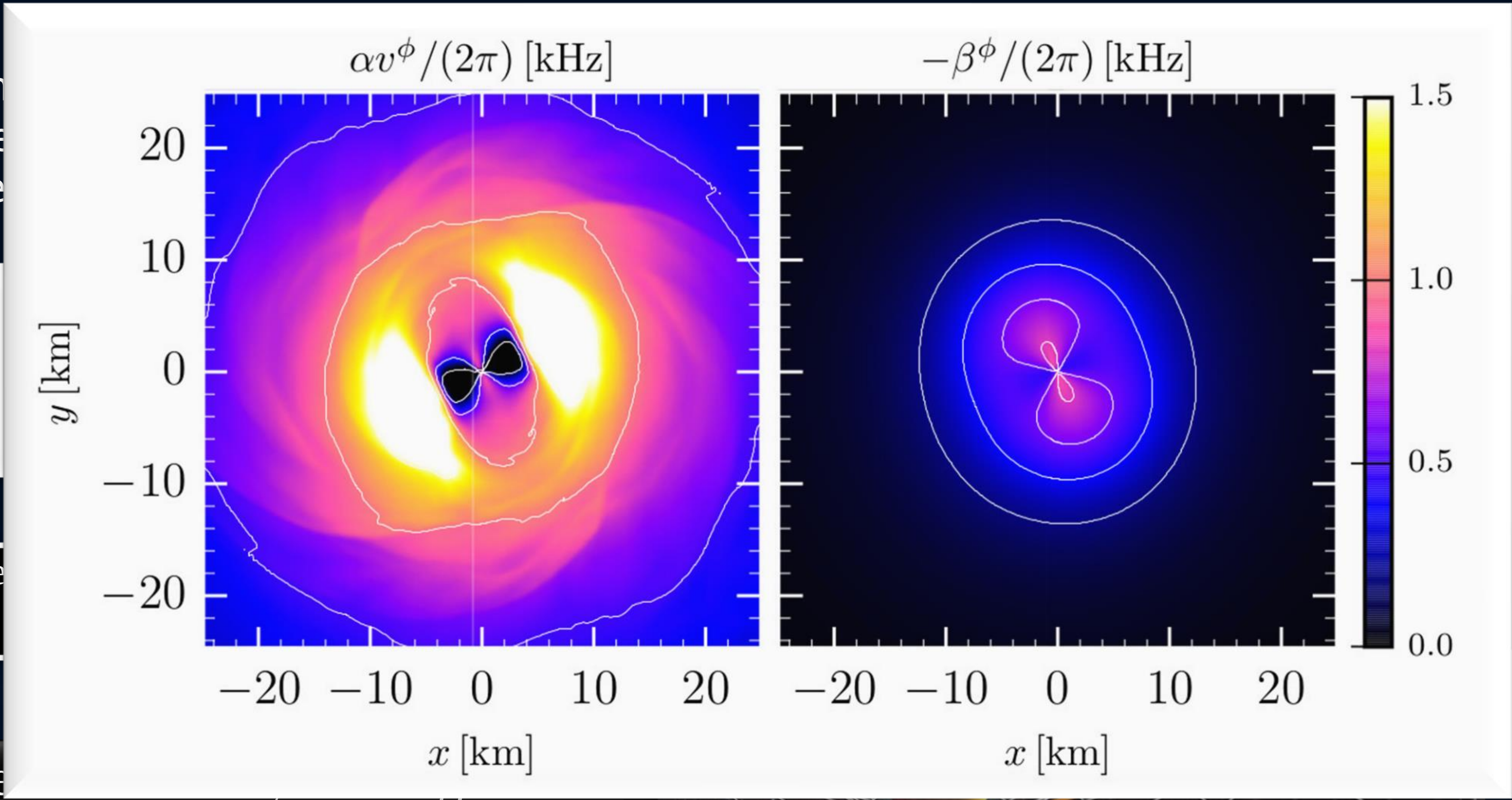
The Angular Velocity in the (3+1)-Split

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

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

Angular velocity
Ω

Lapse

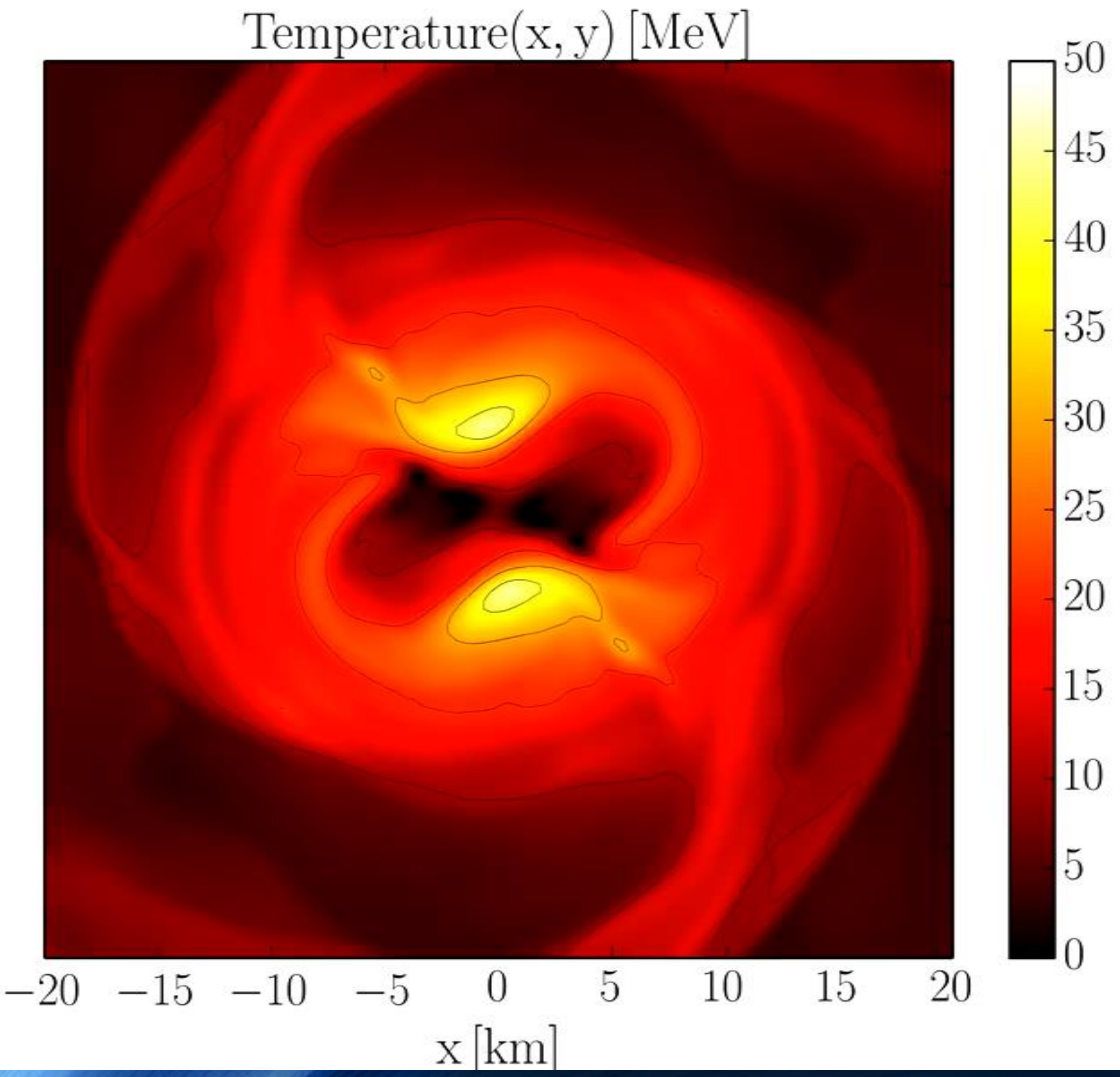


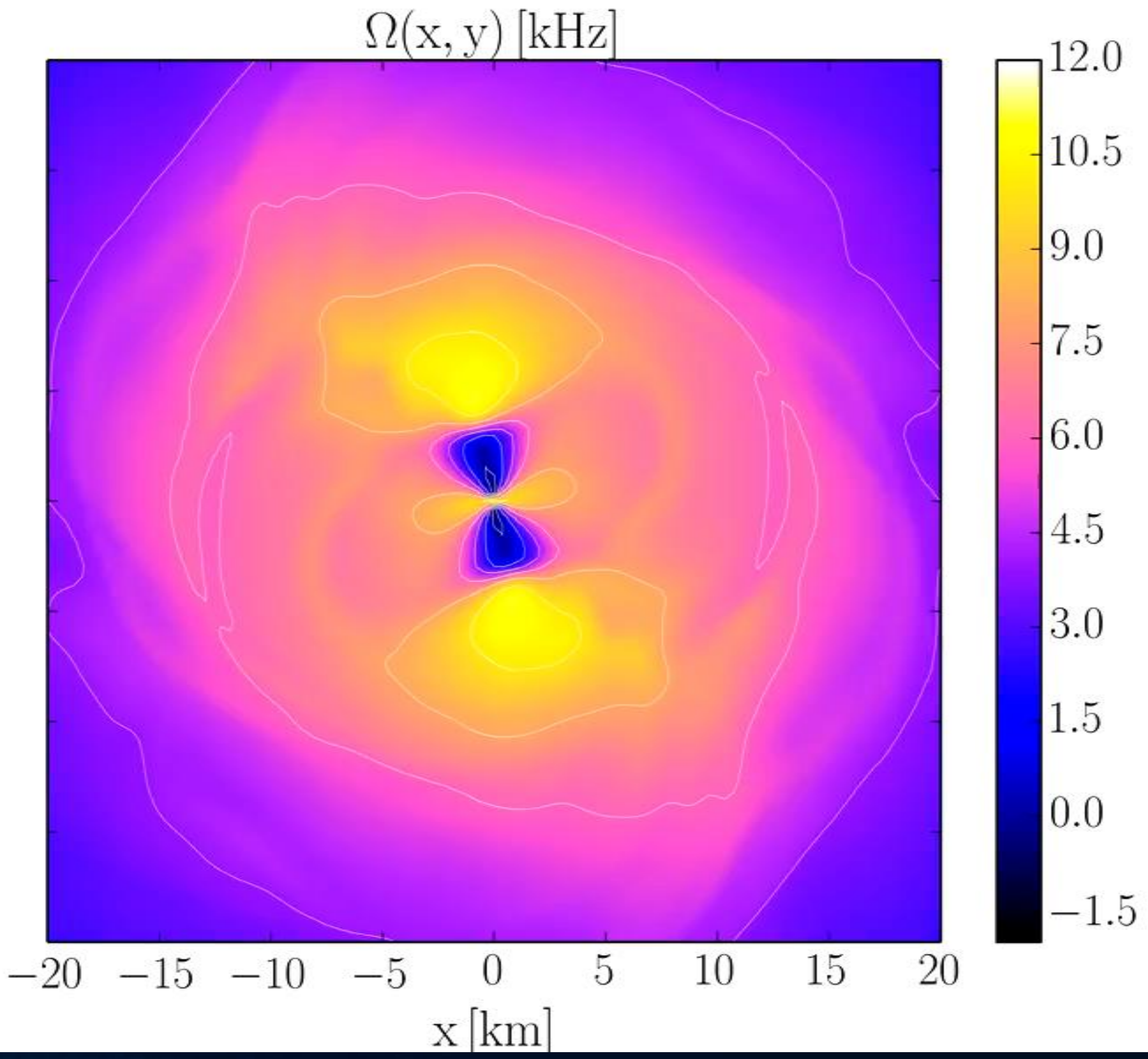
Focus: Inner core of the

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

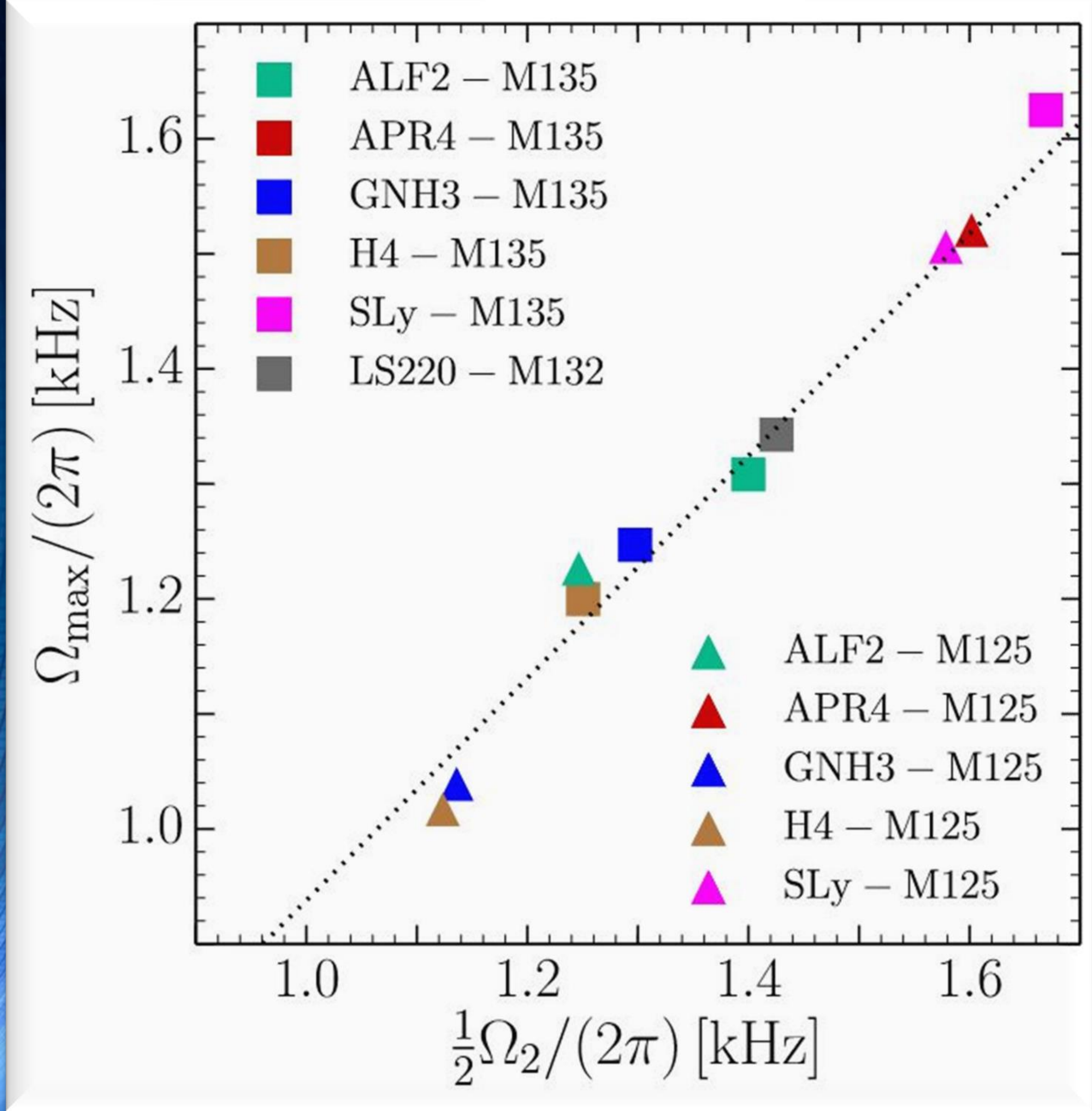
Temperature

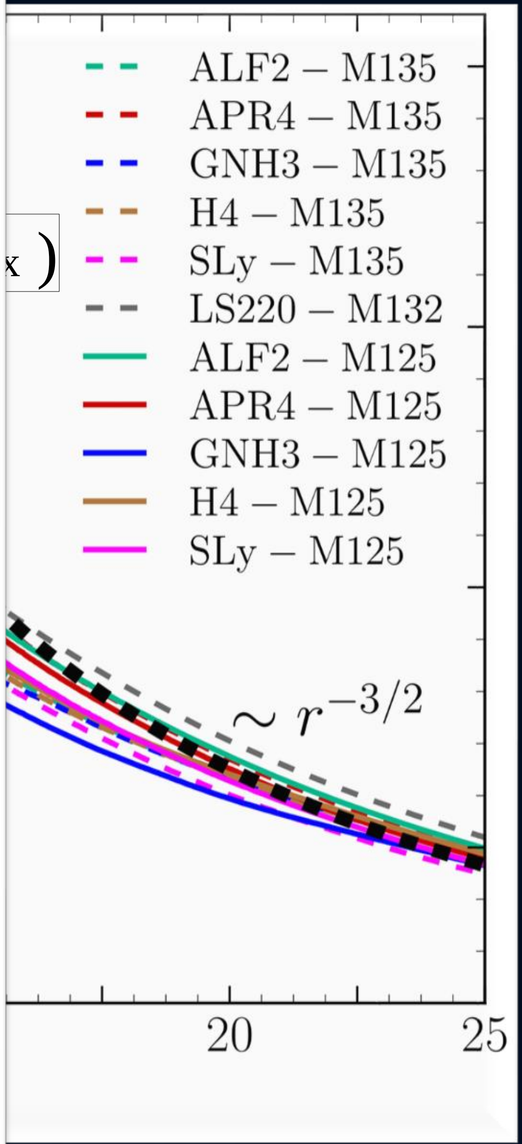
Angular Velocity





EOS: LS200 , Mass: 1.32 M_{solar} , simulation with Pi-symmetry files of the HMNSs





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

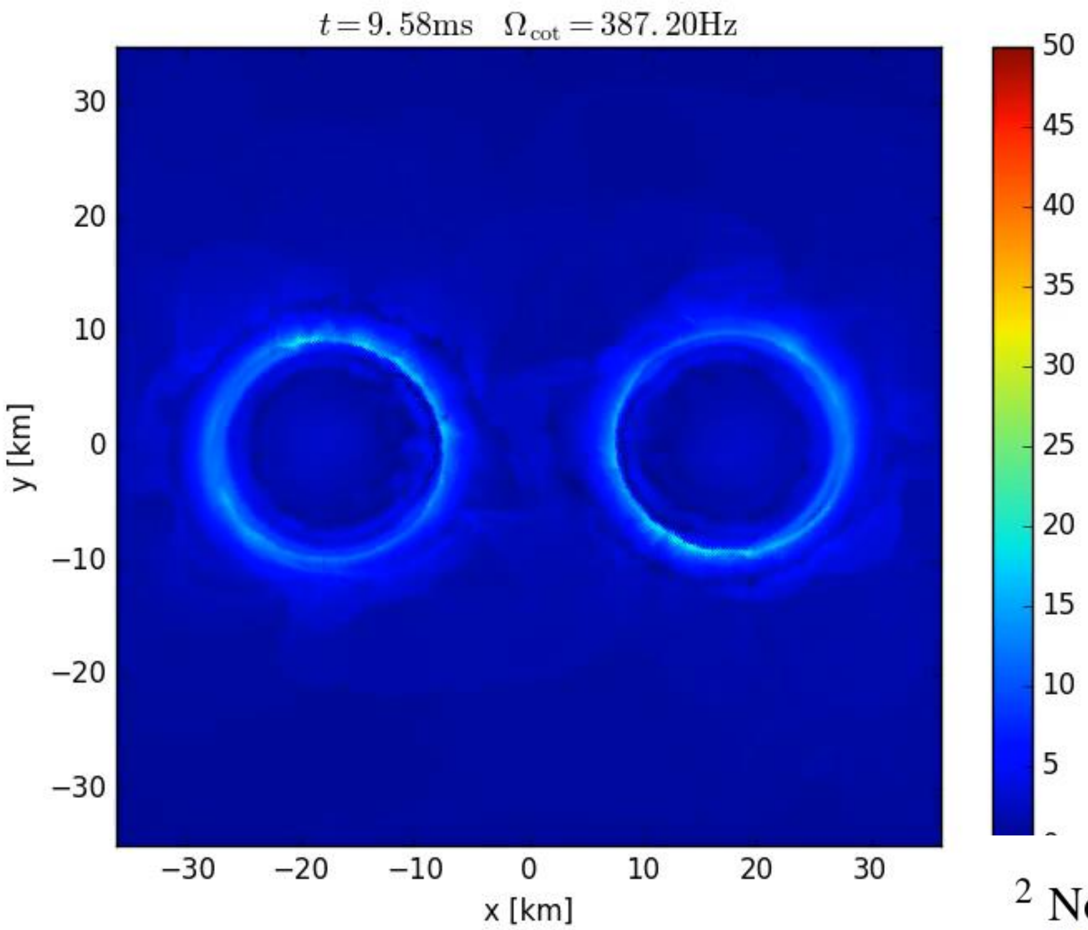
<u>Stiff EoSs</u>:
GNH3
H4

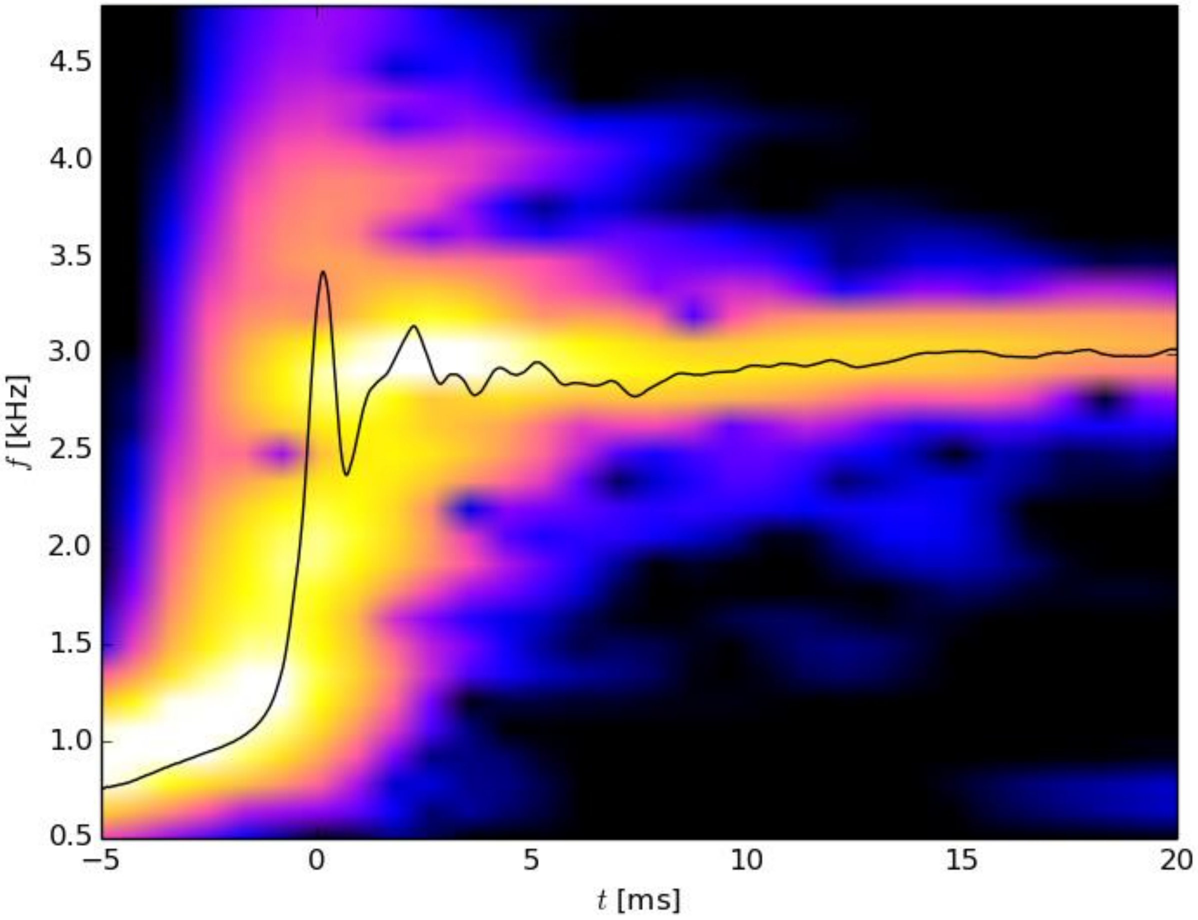
S

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

ashed curves).

The Co-Rotating Frame

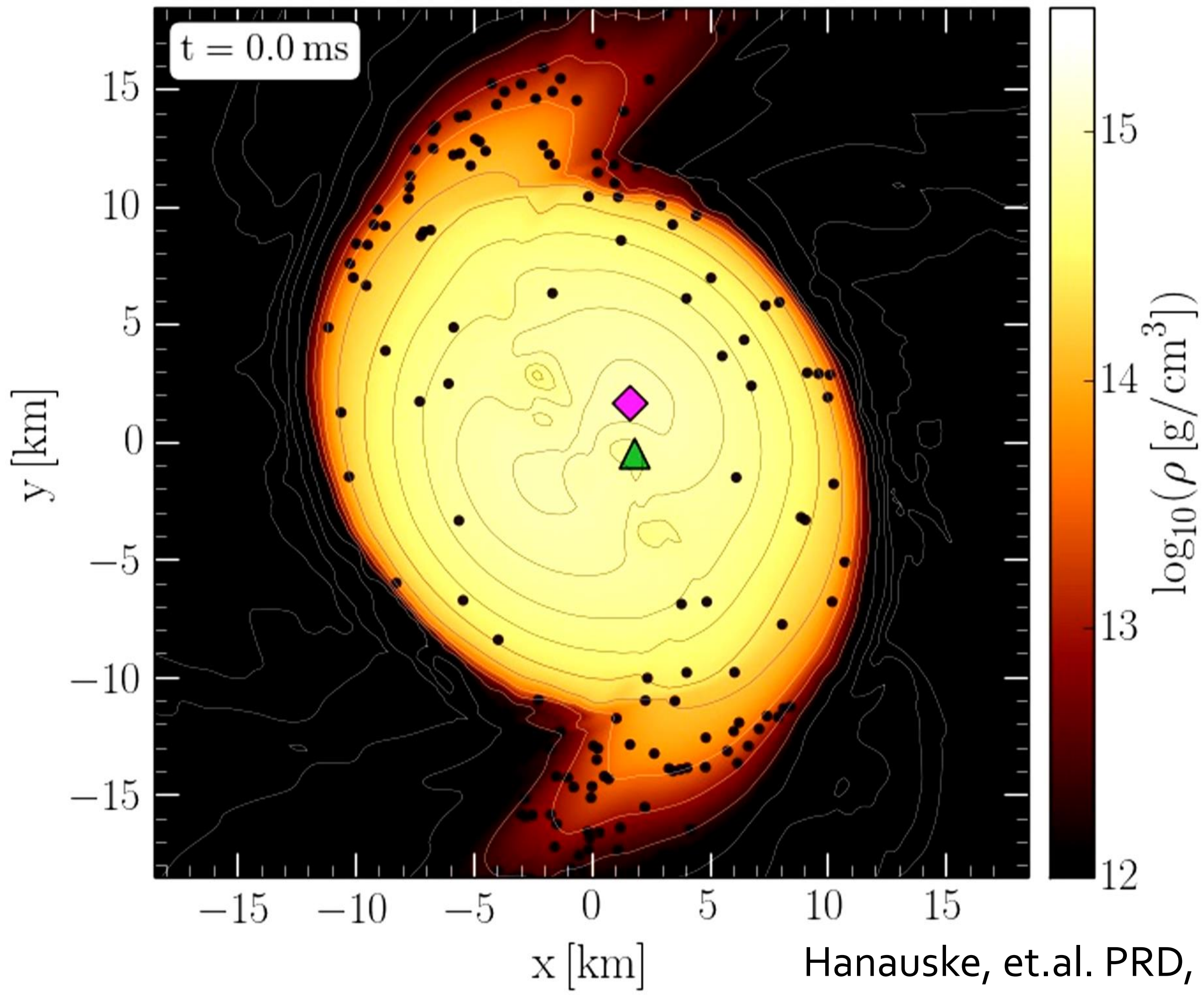


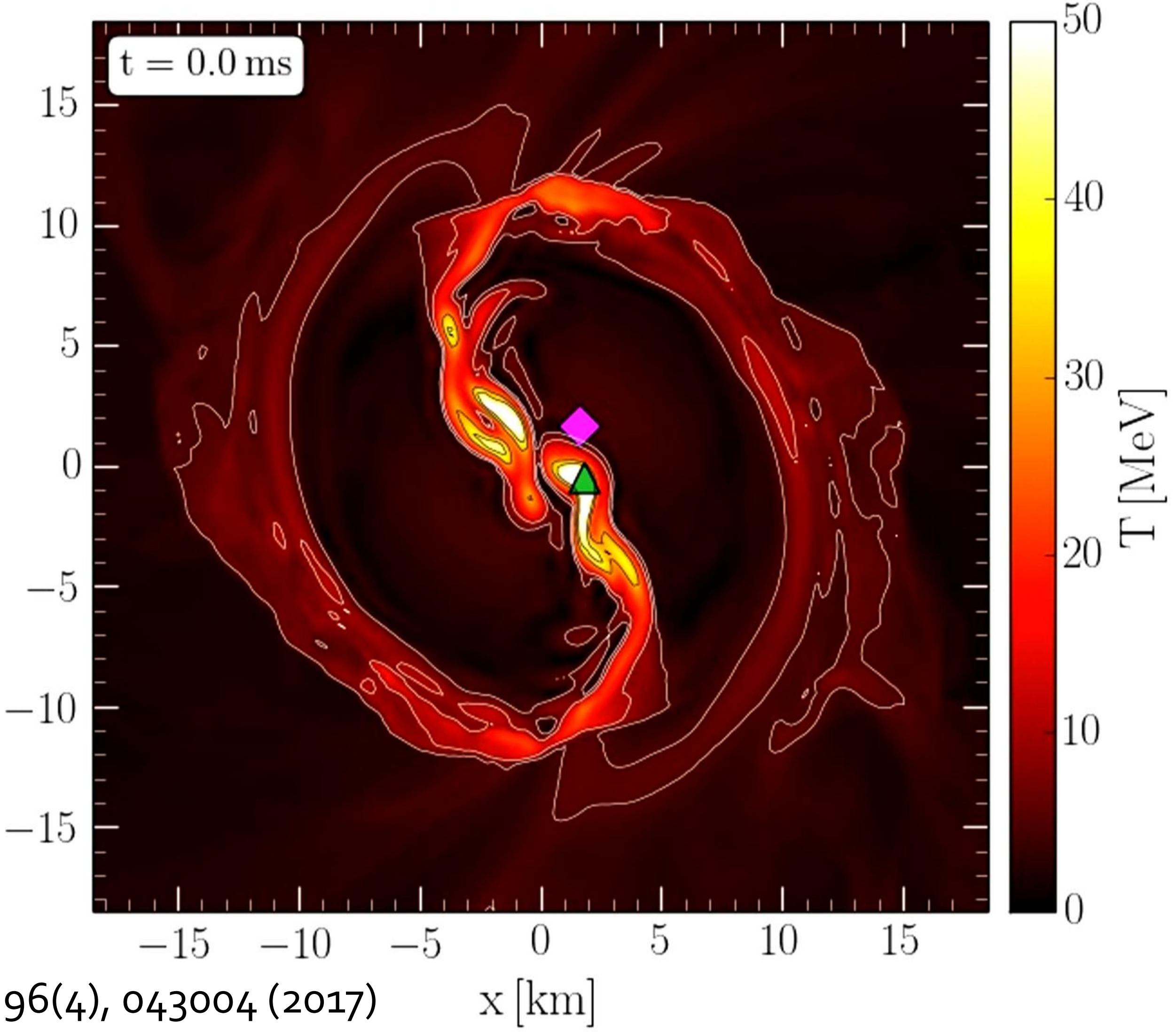


[2] Note that the angular-velocity distribution in the lower central panel of Fig. 10 refers to the corotating frame and that this frame is rotating at half the angular frequency of the emitted gravitational waves, Ω_{GW}. Because the maximum of the angular velocity Ω_{max} is of the order of $\Omega_{GW}/2$ (cf. left panel of Fig. 12), the ring structure in this panel is approximately at zero angular velocity.

Simulation and movie has been produced by Luke Bovard

Density and Temperature Evolution inside the HMNS

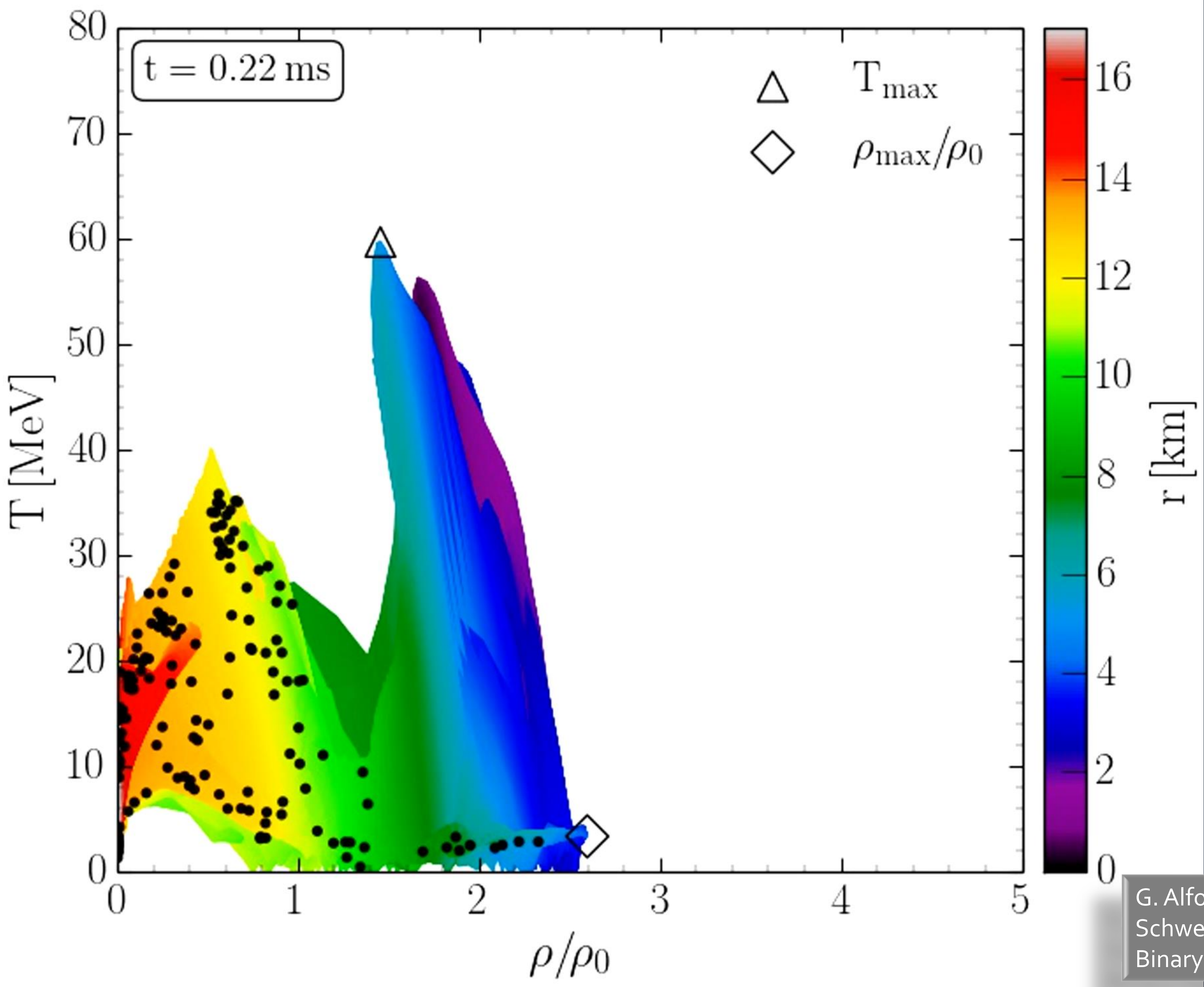




Hanauske, et.al. PRD, 96(4), 043004 (2017)

Rest mass density on the equatorial plane

Temperature on the equatorial plane



Binary Neutron Star Mergers in the QCD Phase Diagram

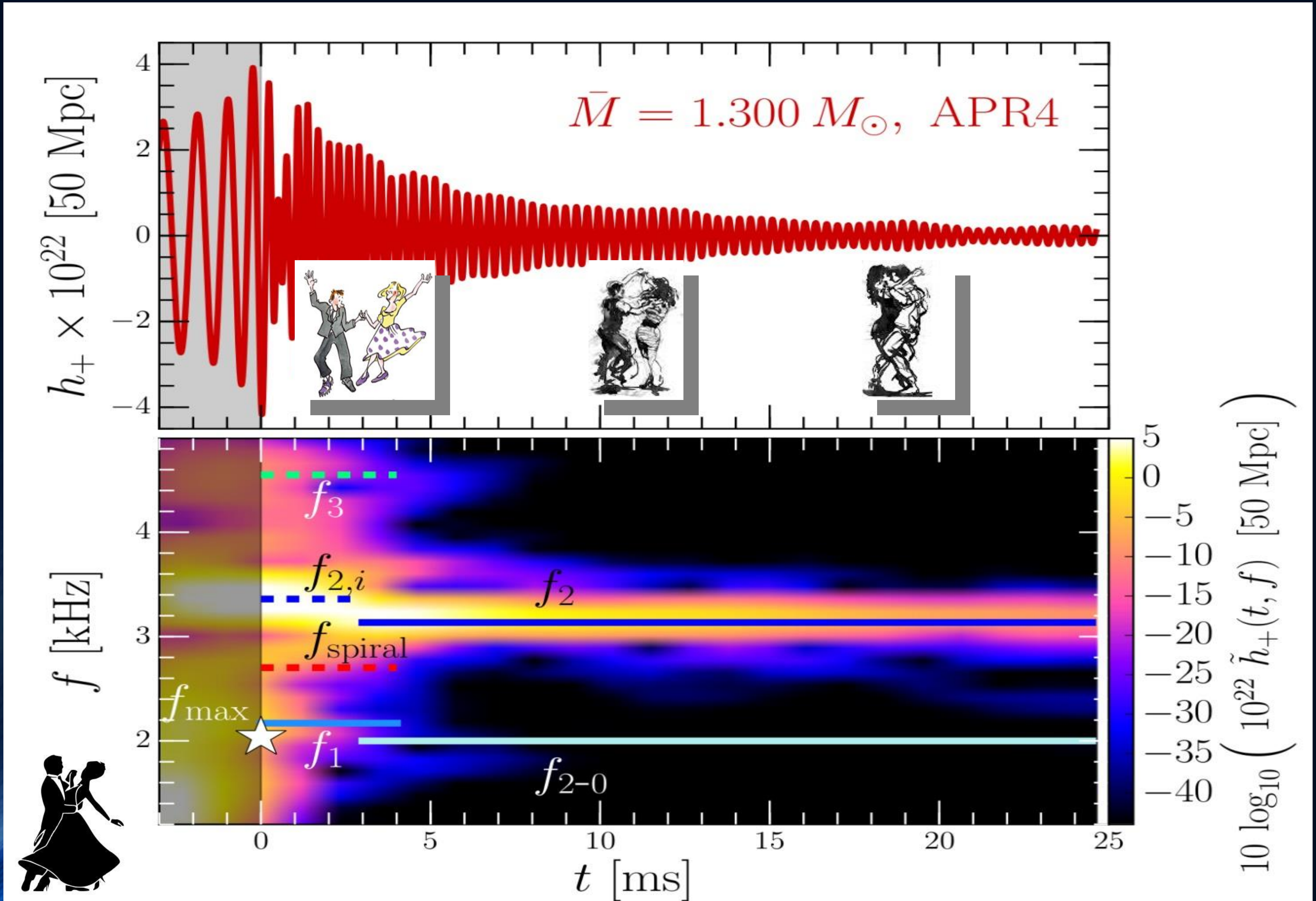
Evolution of hot and dense matter inside the inner area of a hypermassive neutron star simulated within the LS220 EOS with a total mass of $M_{total}=2.7\ M_{\odot}$ in the style of a (T- ρ) QCD phase diagram plot

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

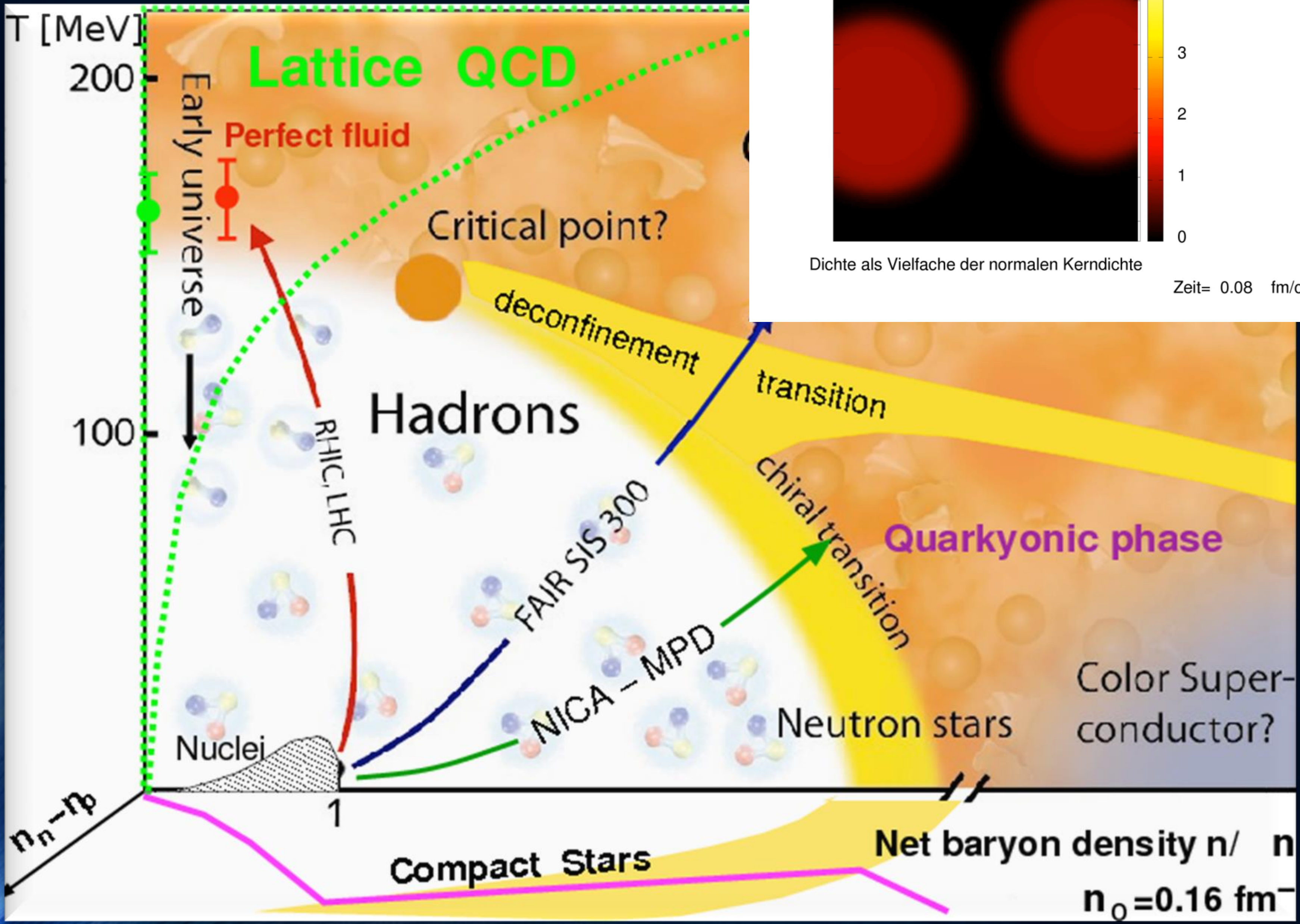
G. Alford, L. Bovard, M. Hanauske, L. Rezzolla, and K. Schwenzer „Viscous Dissipation and Heat Conduction in Binary Neutron-Star Mergers" PRL. 120, 041101 (2018)

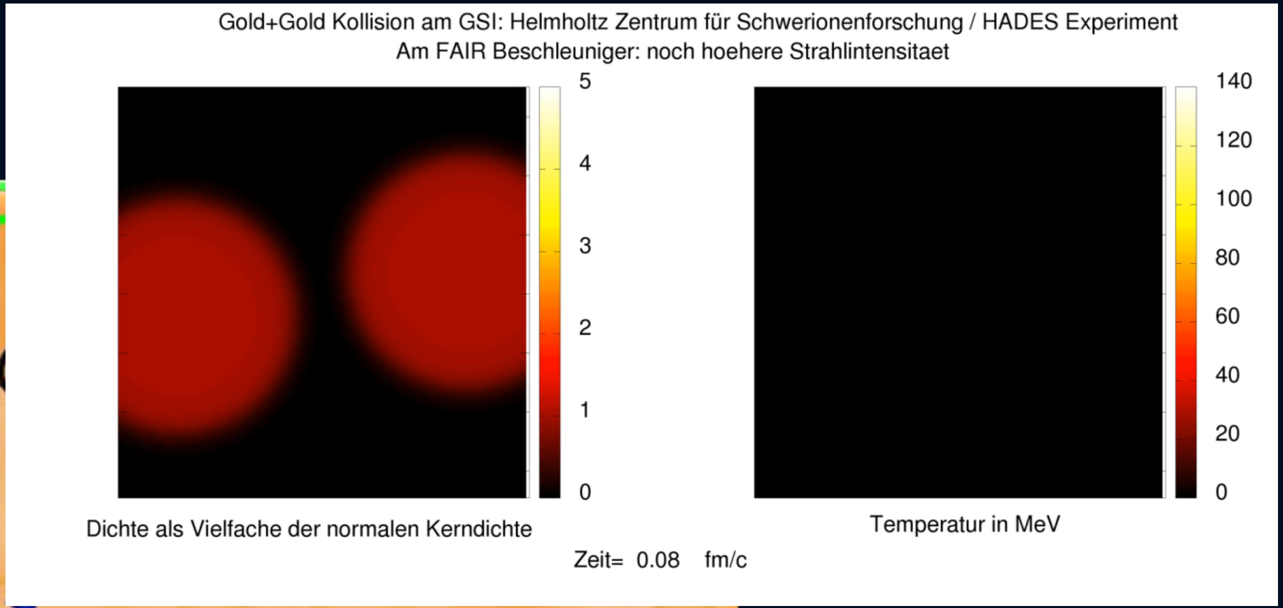
The different Phases during the Postmergerphase of the HMNS



The Hadron-Quark Phase Transition

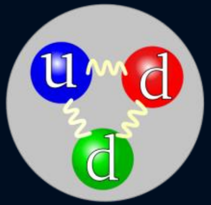
The QCD Phase Diagram



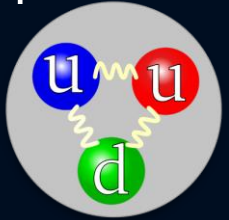


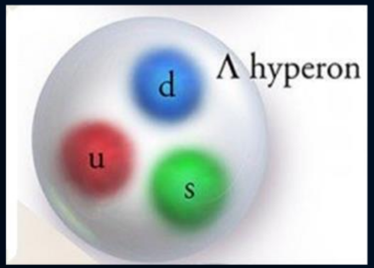
Credits:
Jan Steinheimer

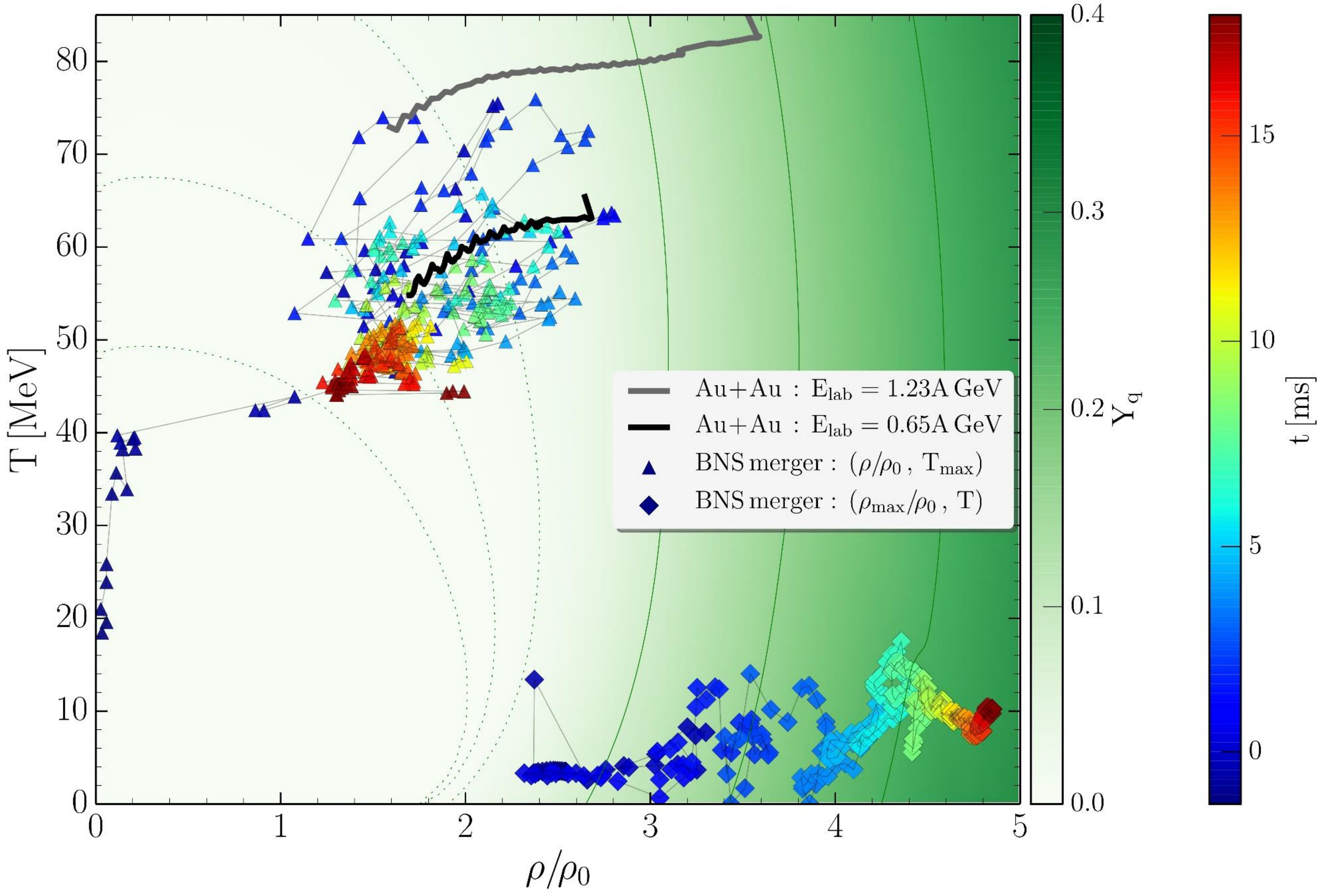
neutron



proton







Evolution of the maximum value of the temperature (triangles) and rest mass density (diamonds) at the equatorial plane in the interior of a HMNS using the simulation results of the LS220-M135 run

Color coding of triangles/diamonds: time of the simulation after merger in milliseconds

Grey and black curve: two heavy ion collision simulations within the quark-hadron chiral parity-doublet model

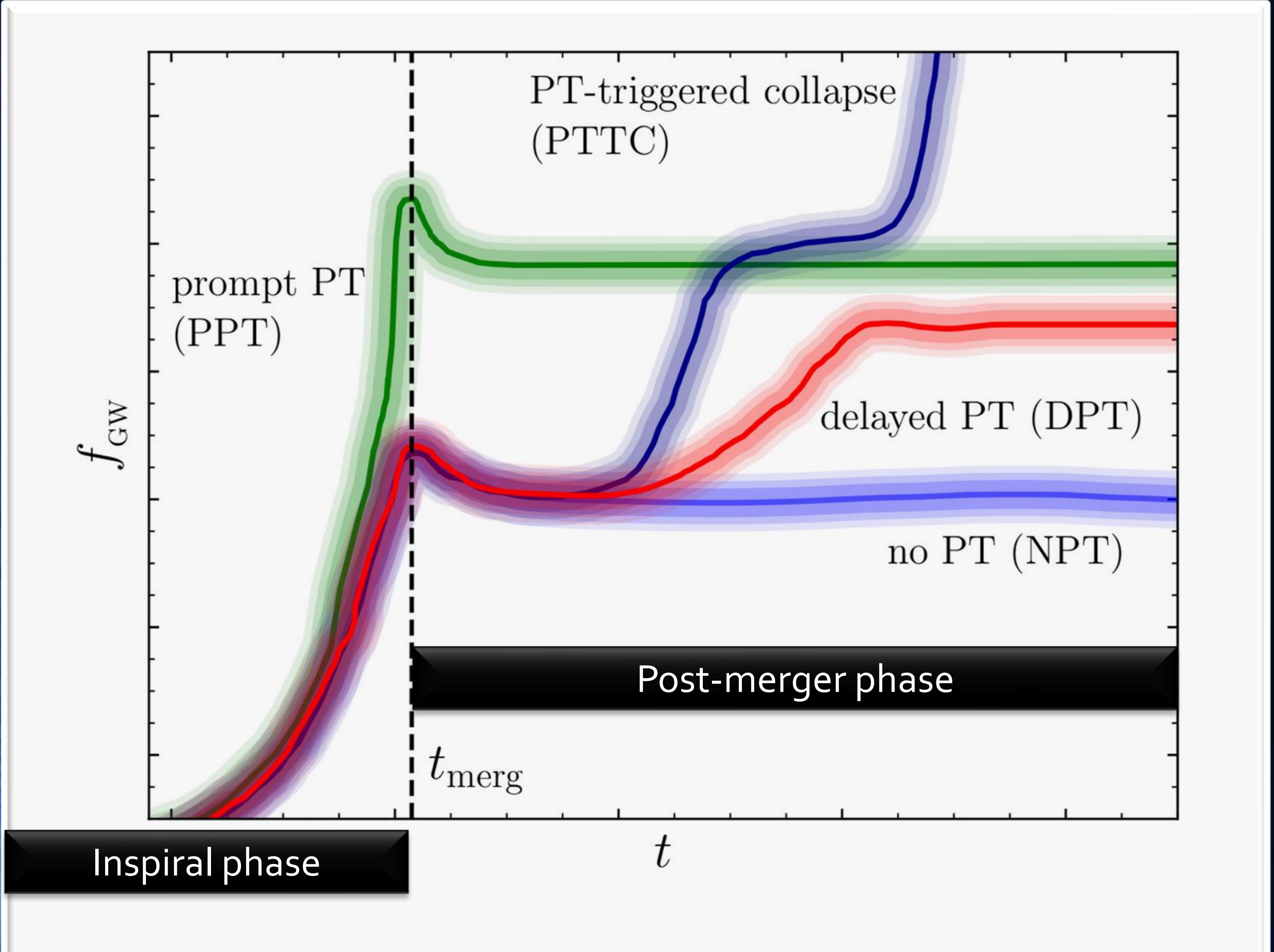
Y_q = Quark fraction

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

- Gravitational-wave signatures of the hadron-quark pha
compact star mergers
  - *Signatures within the late inspiral phase (premerger signals)*
    - Constraining twin stars with GW170817; G Montana, L Tolós, M Hanau
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 neutr
Papenfort, V Dexheimer, M Hanauske, S Schramm, H Stöcker, L. Rezzolla
(2019)
    - **Delayed phase transition scenario**
Postmerger Gravitational-Wave Signatures of Phase Transitions in Binary
Rezzolla; Physical Review Letters 124 (17), 171103 (2020)
    - **Prompt phase transition scenario**
Identifying a first-order phase transition in neutron-star mergers through grav
Bastian, DB Blaschke, K Chatziioannou, JA Clark, JA Clark, T Fischer, M Oertel;
(2019)

YES
WE
CAN

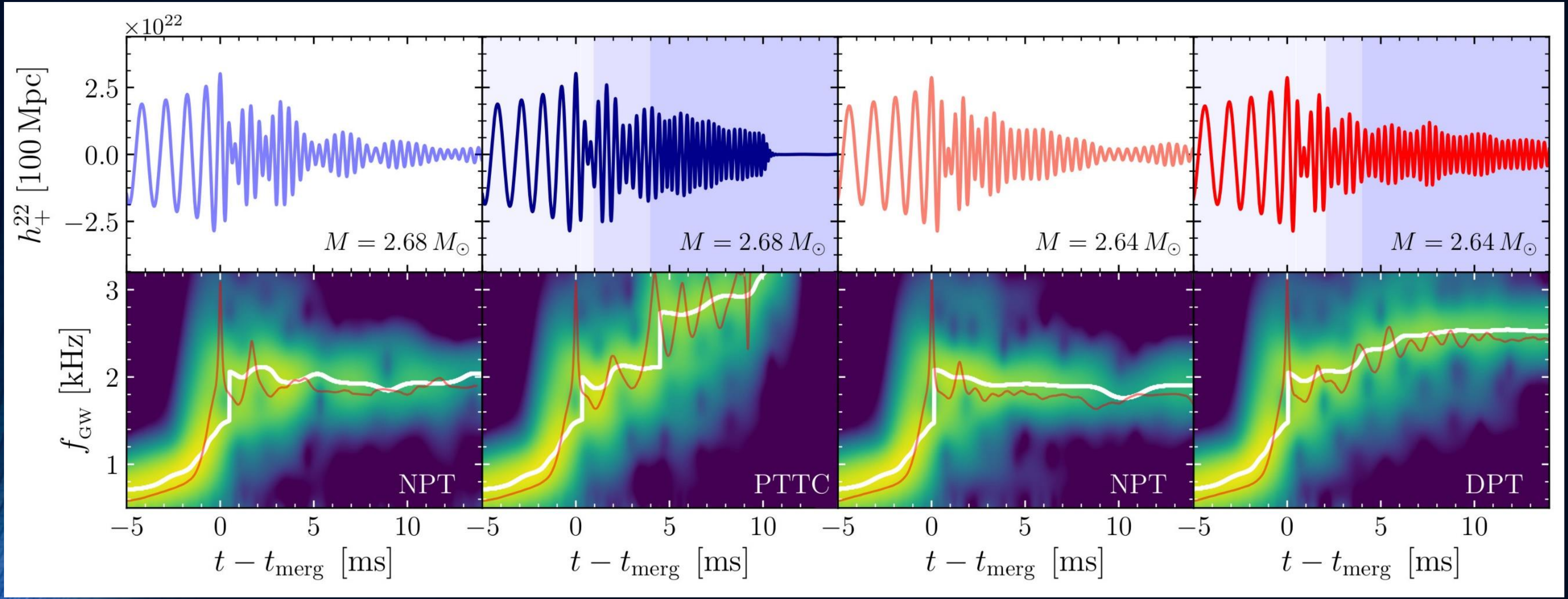
Post-merger gravitational-wave signatures of phase transitions in binary compact star mergers



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

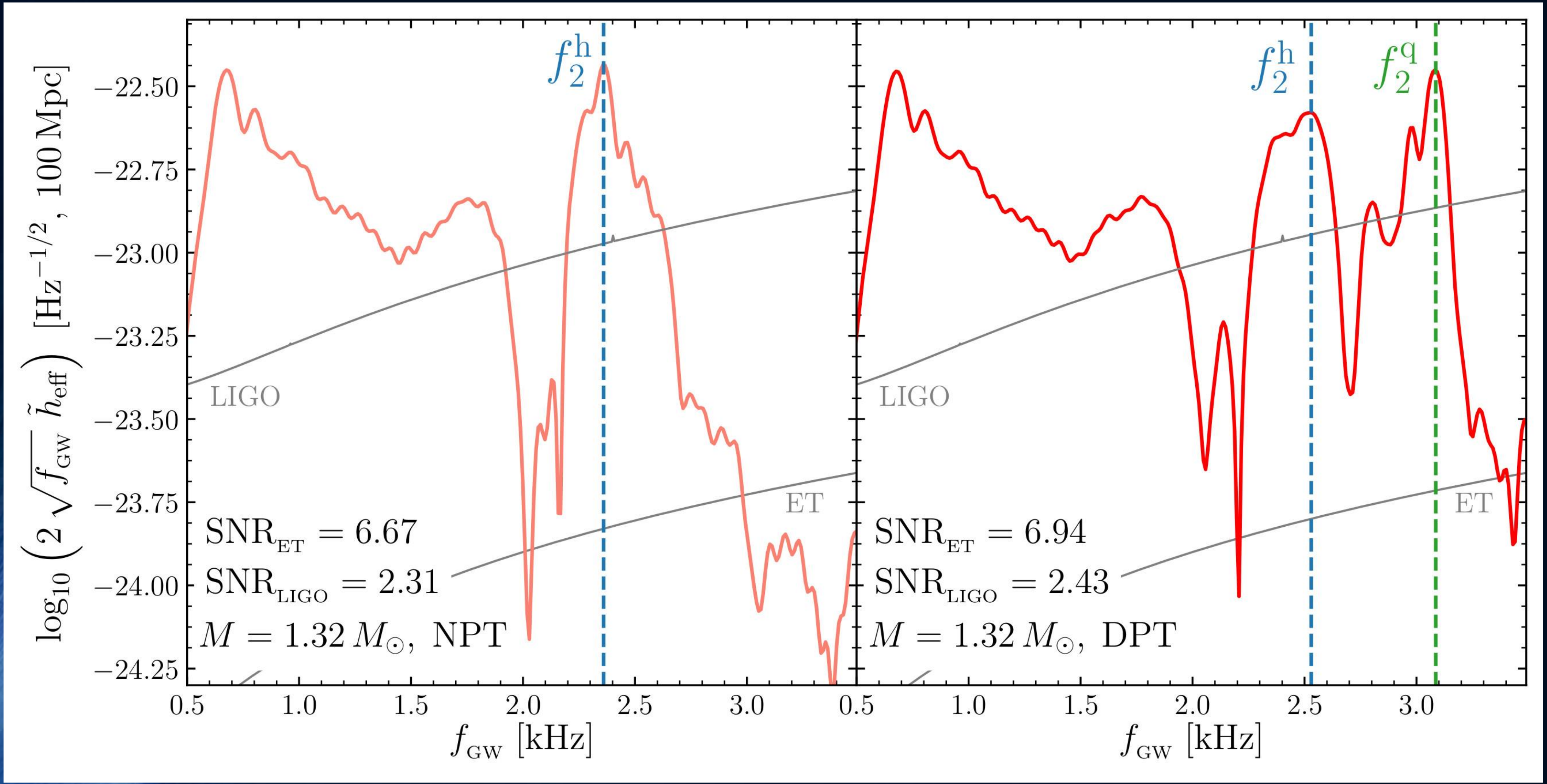
Schematic overview of the instantaneous gravitational wave frequency and how its evolution can be used to classify the different scenarios associated with a hadron-quark phase transition.

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.

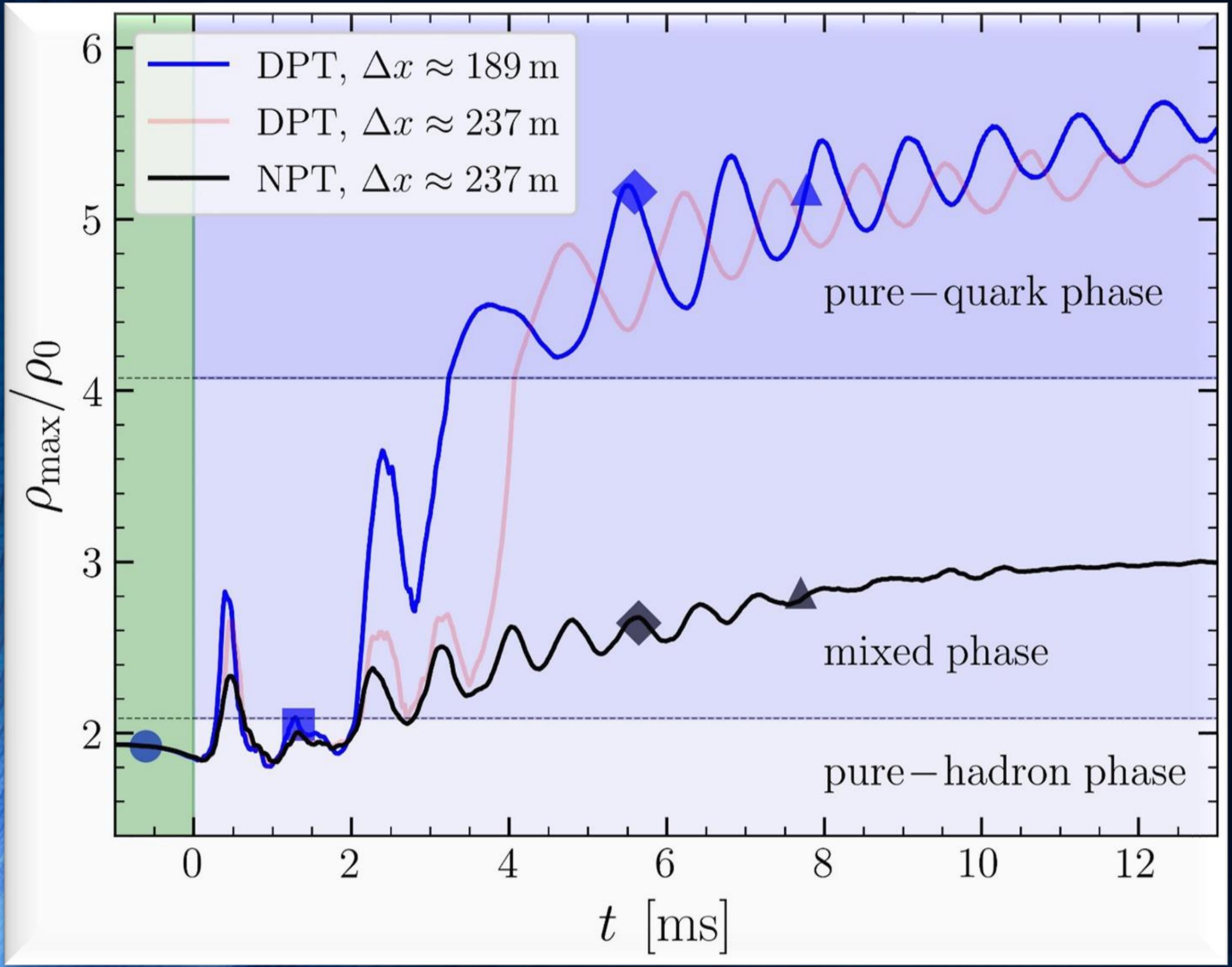
How to detect the hadron-quark phase transition with gravitational waves



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

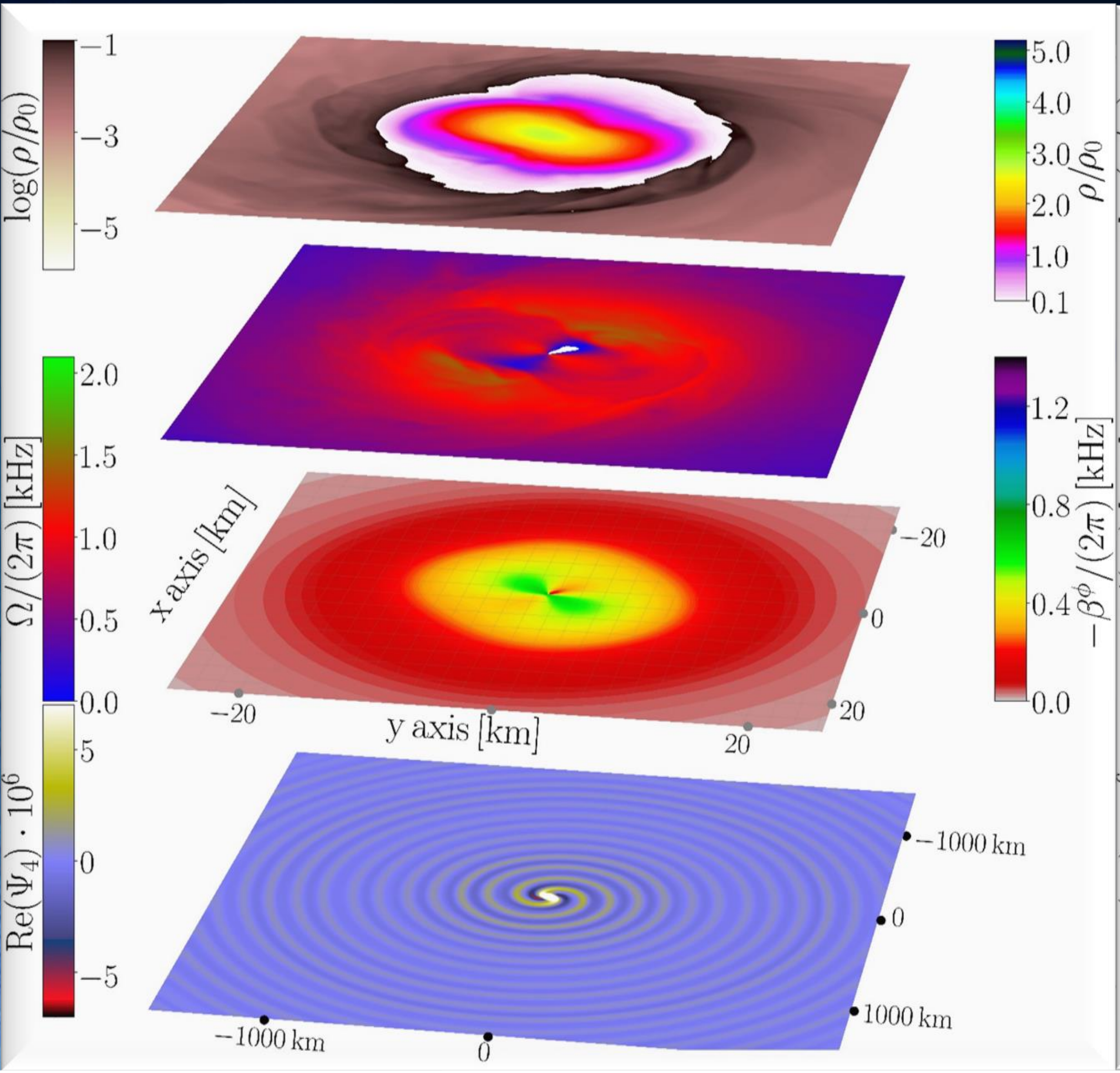
Signatures within the post-merger phase evolution

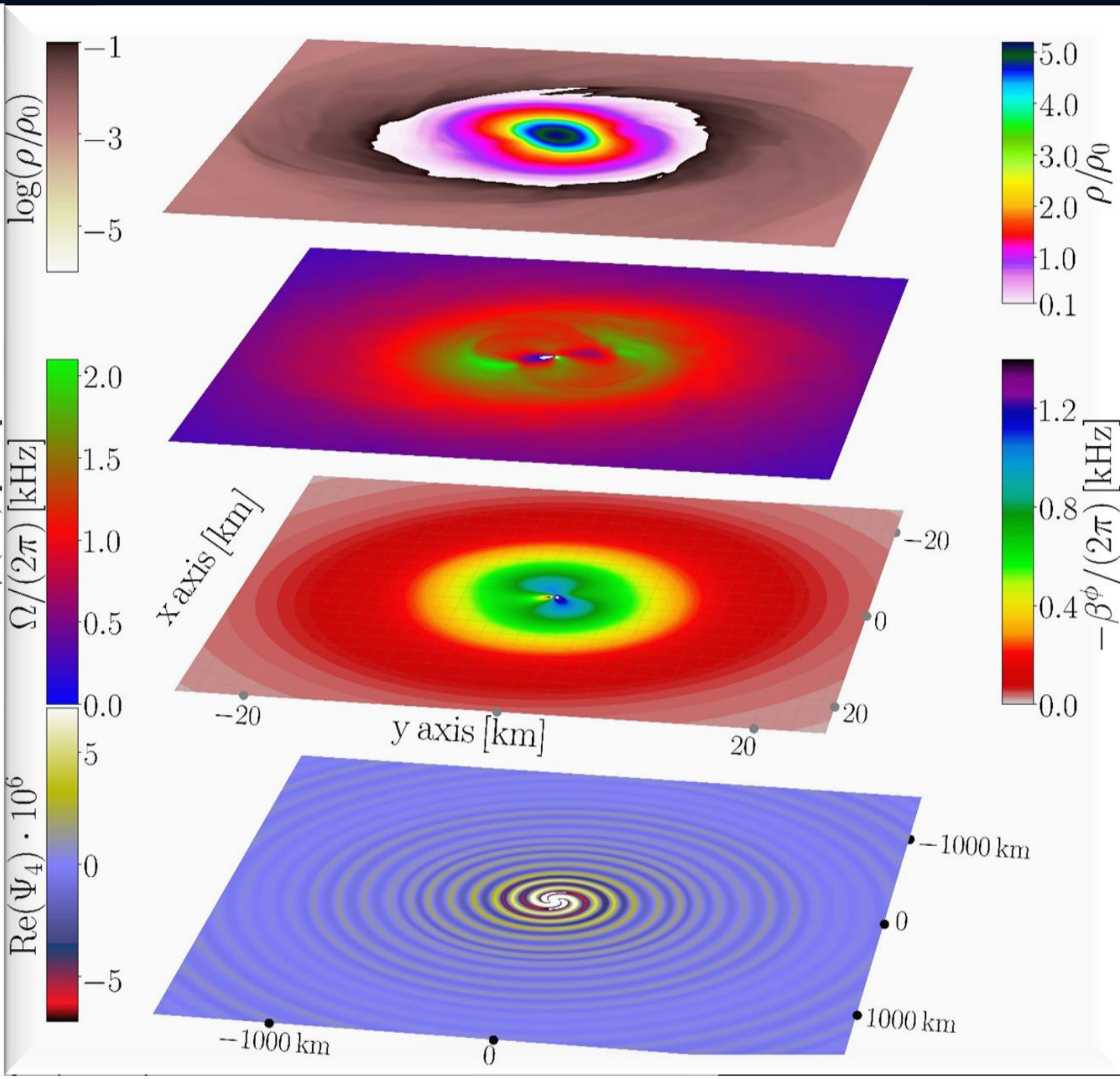
DPT: Delayed phase transition scenario



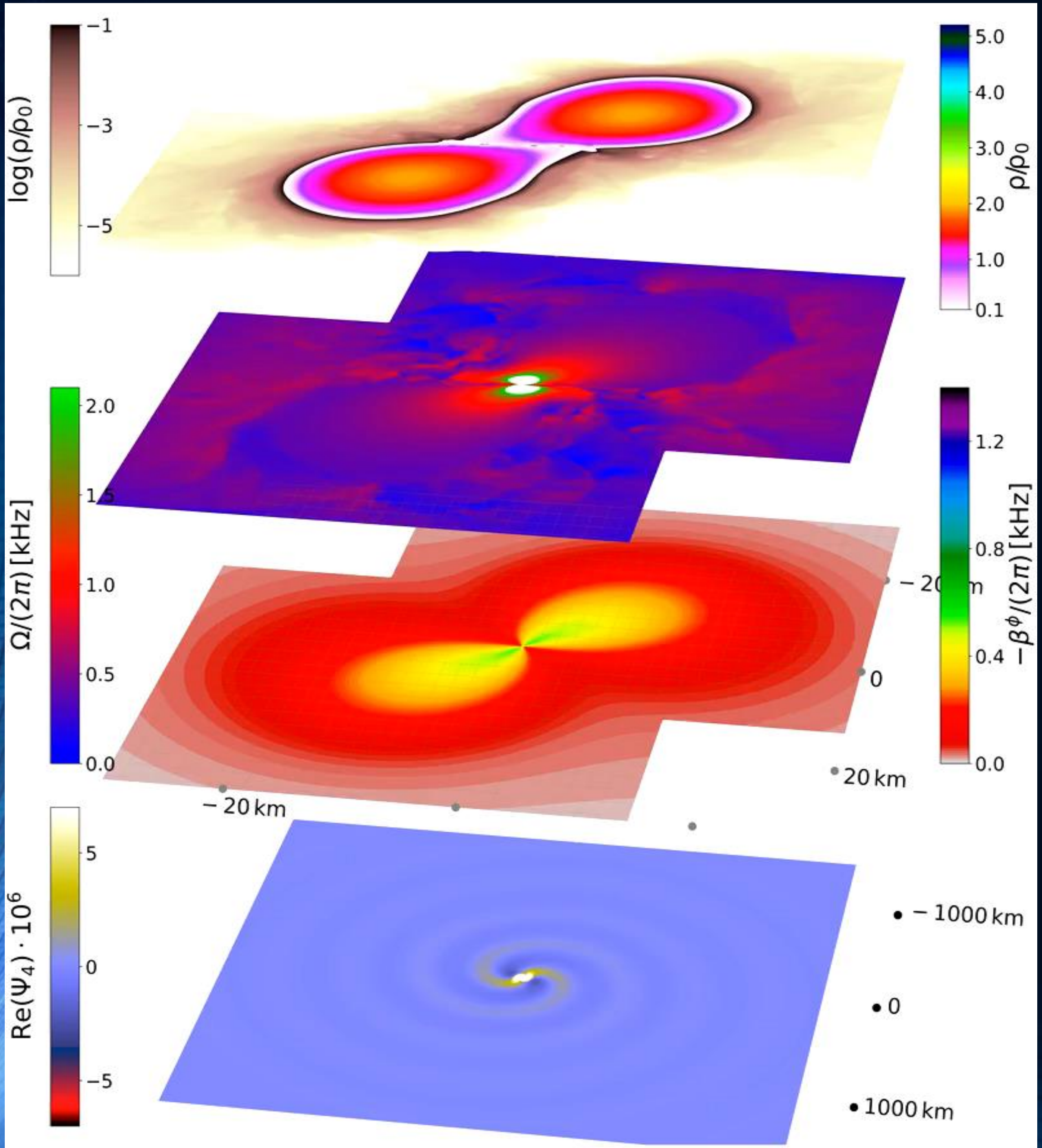
Maximum value of the rest-mass density vs time for three binary neutron star simulations. Black curve without a phase transition (NPT) and blue/red with a Gibbs-like hadron-quark phase transition (DPT: standard/low resolution). Blue-shaded regions mark the different phases of the EOS (mixed phase and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

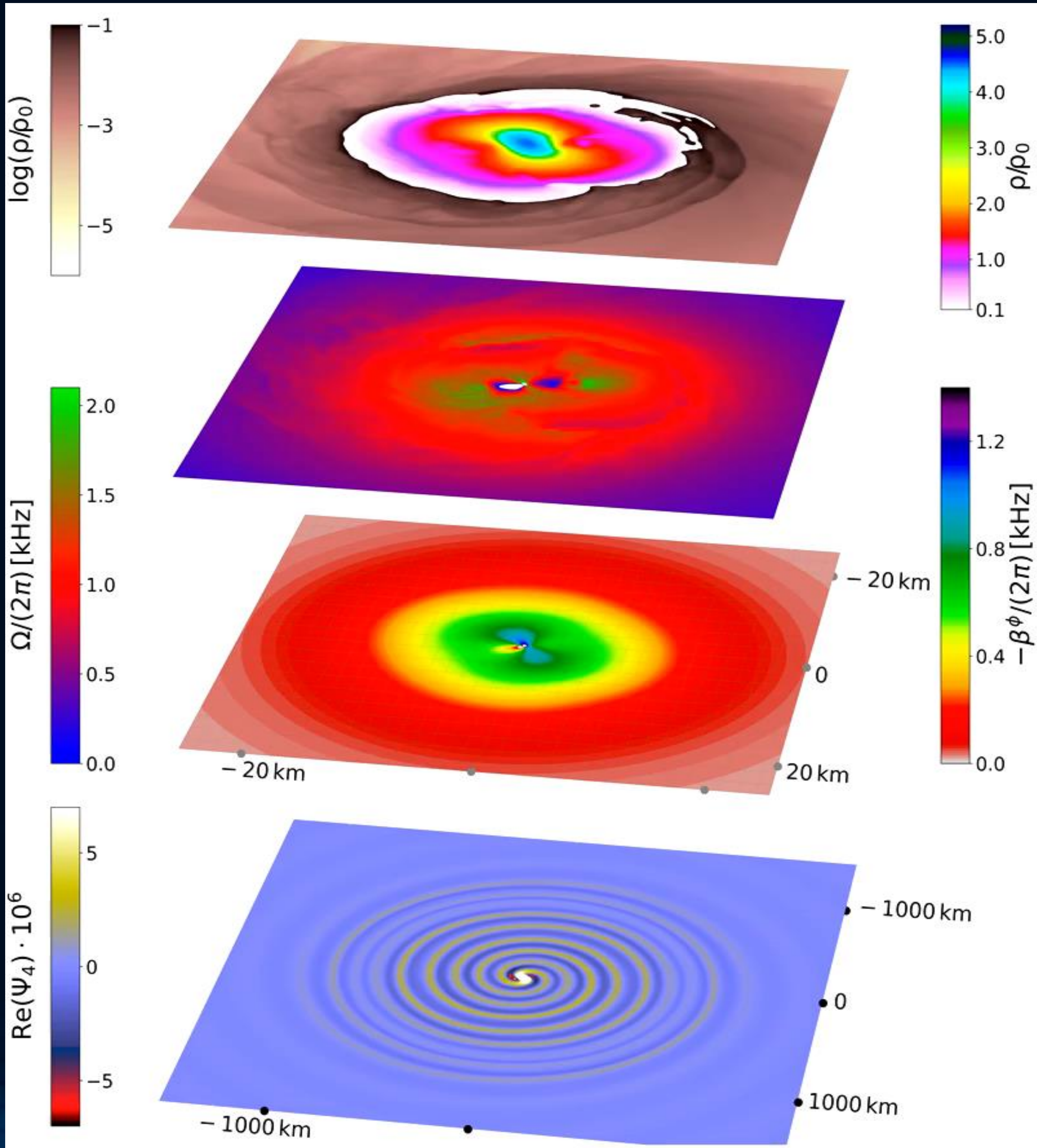
Without Phase Transition | With Phase Transition





Matthias Hanauske and Lukas Weih. "Neutron star collisions and gravitational waves." *Astronomische Nachrichten* (2021) t=0 .. 2 ms Post-Merger Phase t=2 ... 7 ms





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)

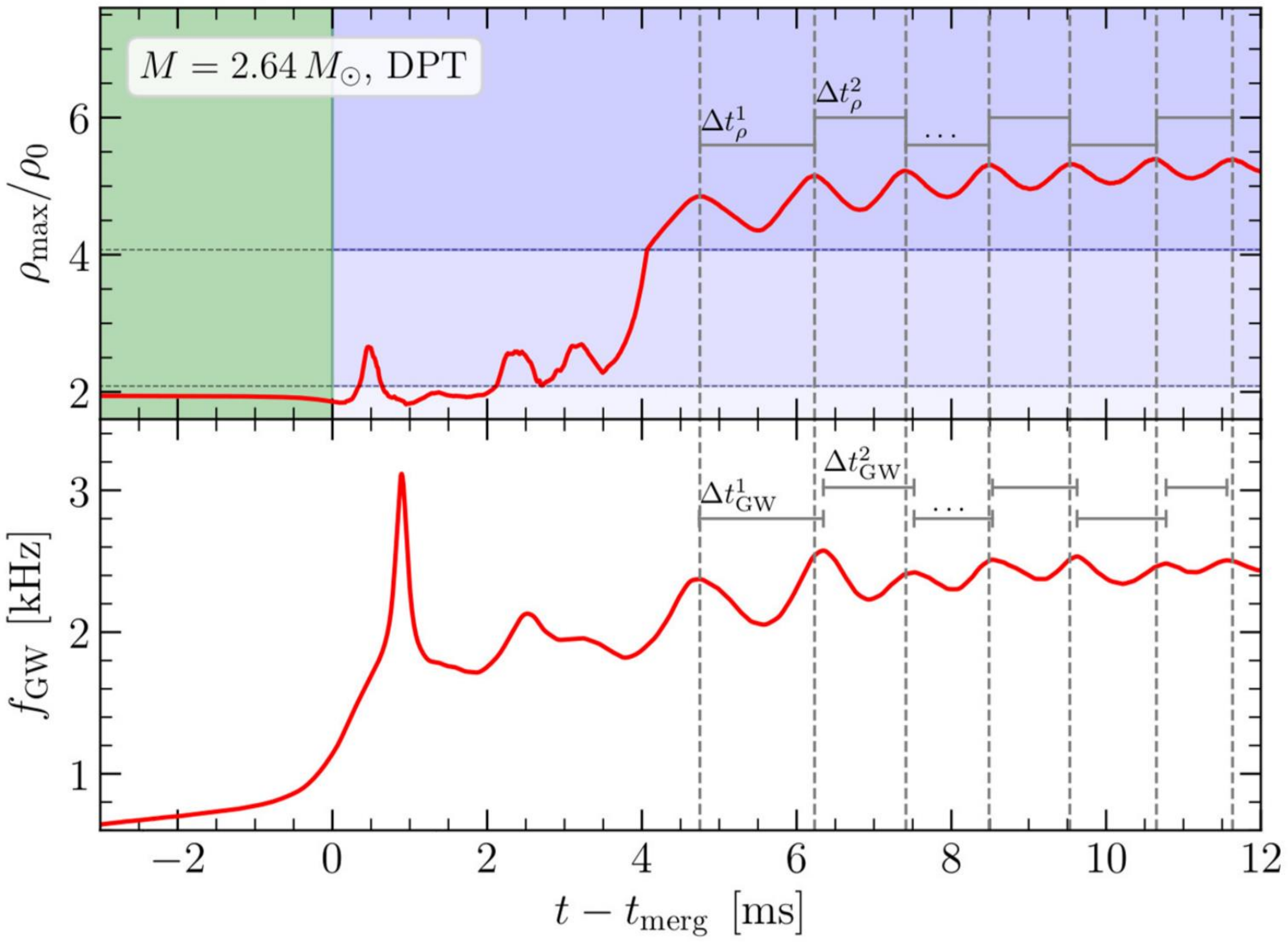
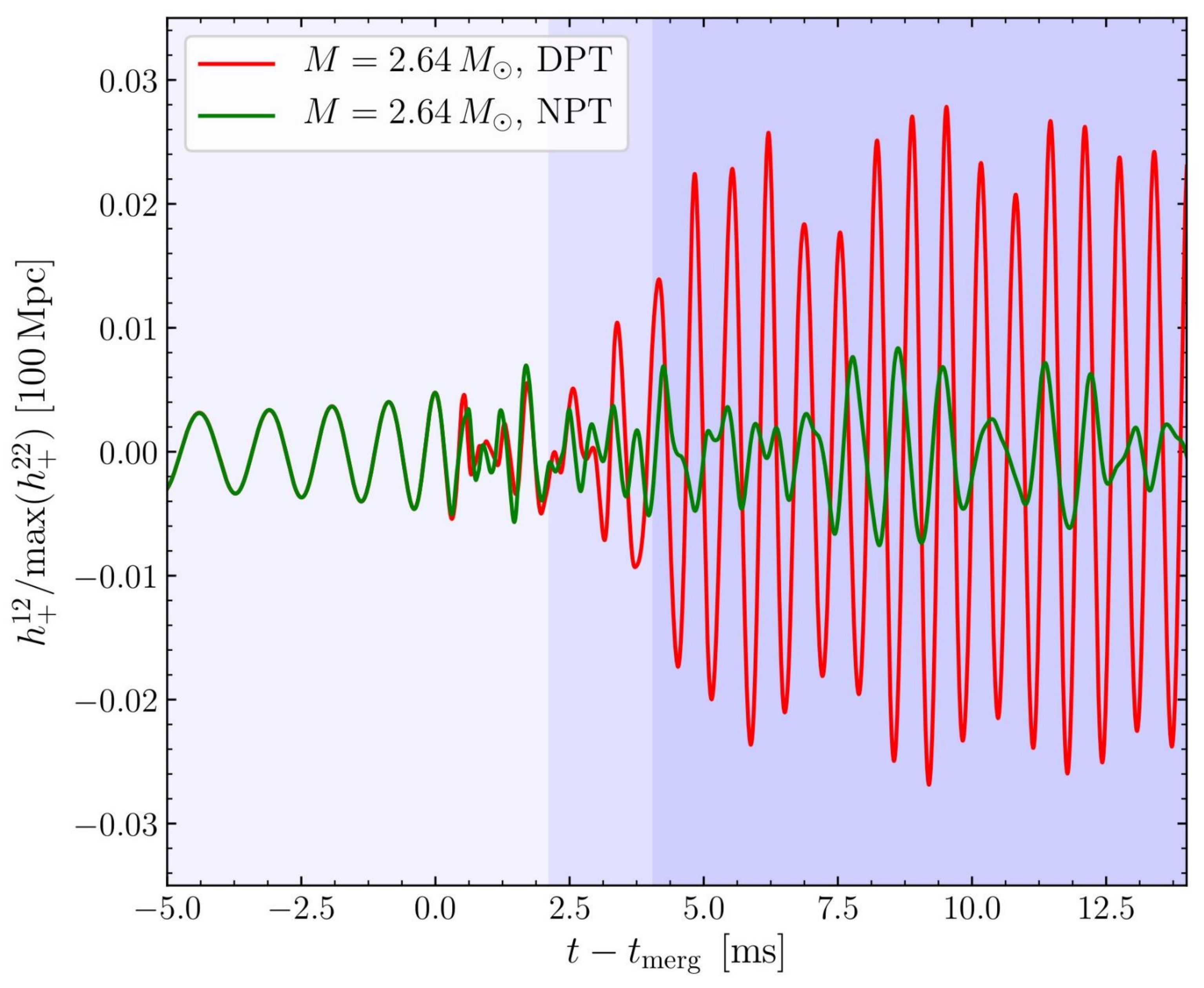
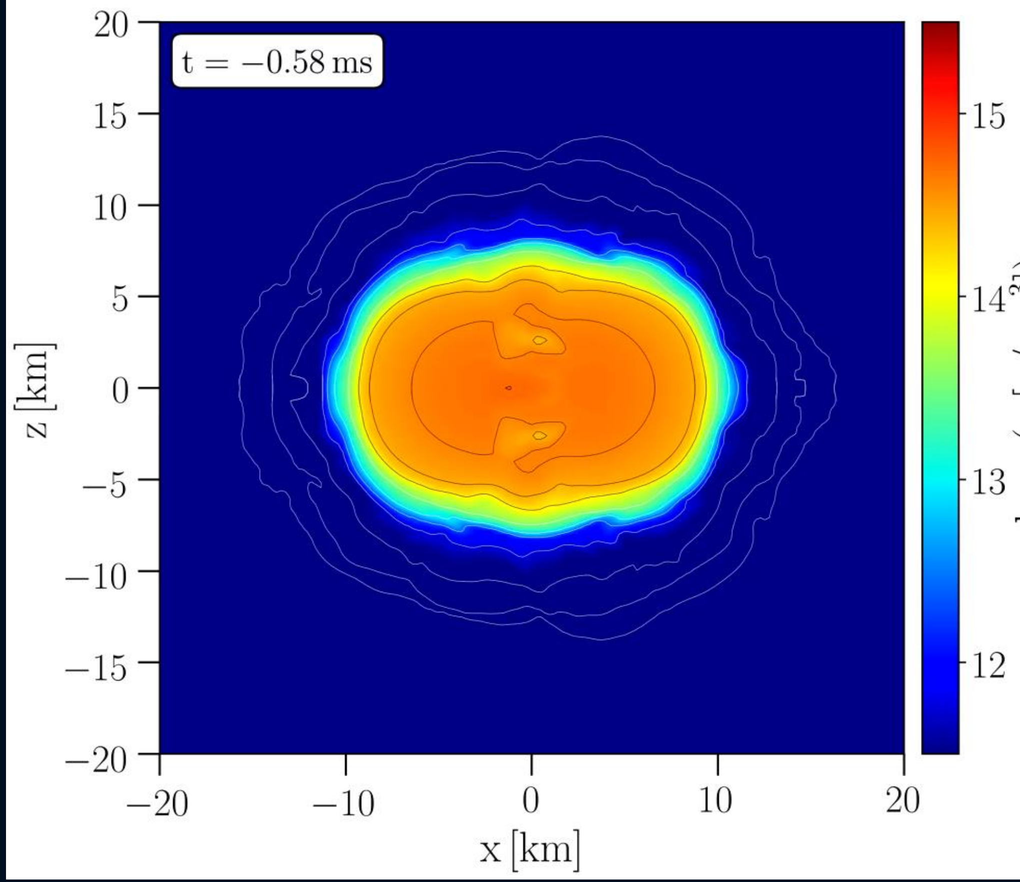


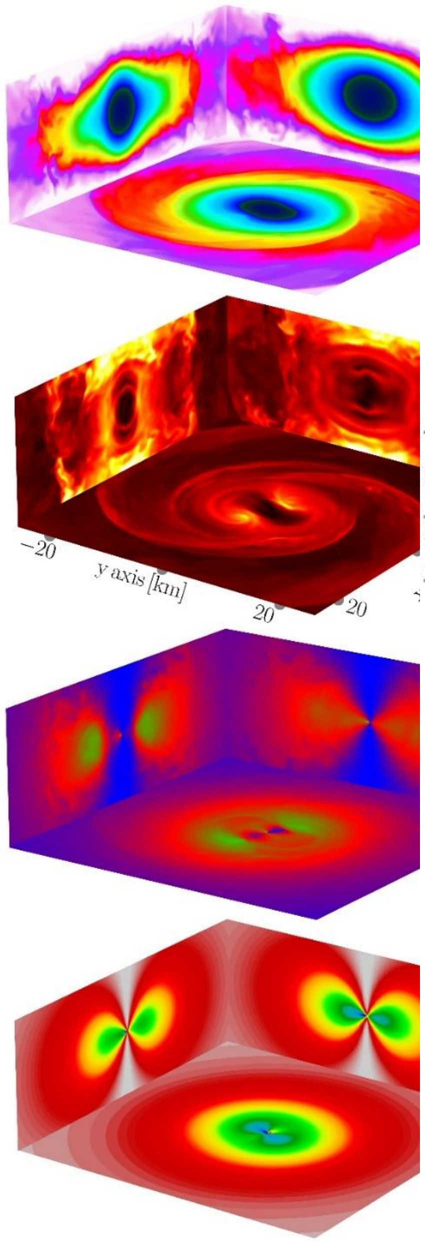
Fig. 3. *Top:* Same as Fig. 1. *Bottom:* Instantaneous GW frequency. The time intervals Δt_ρ^i and Δt_{GW}^i between consecutive peaks in the top and bottom panel, respectively, are marked by horizontal grey lines. The average difference between the two different types of peaks is less than 5%.

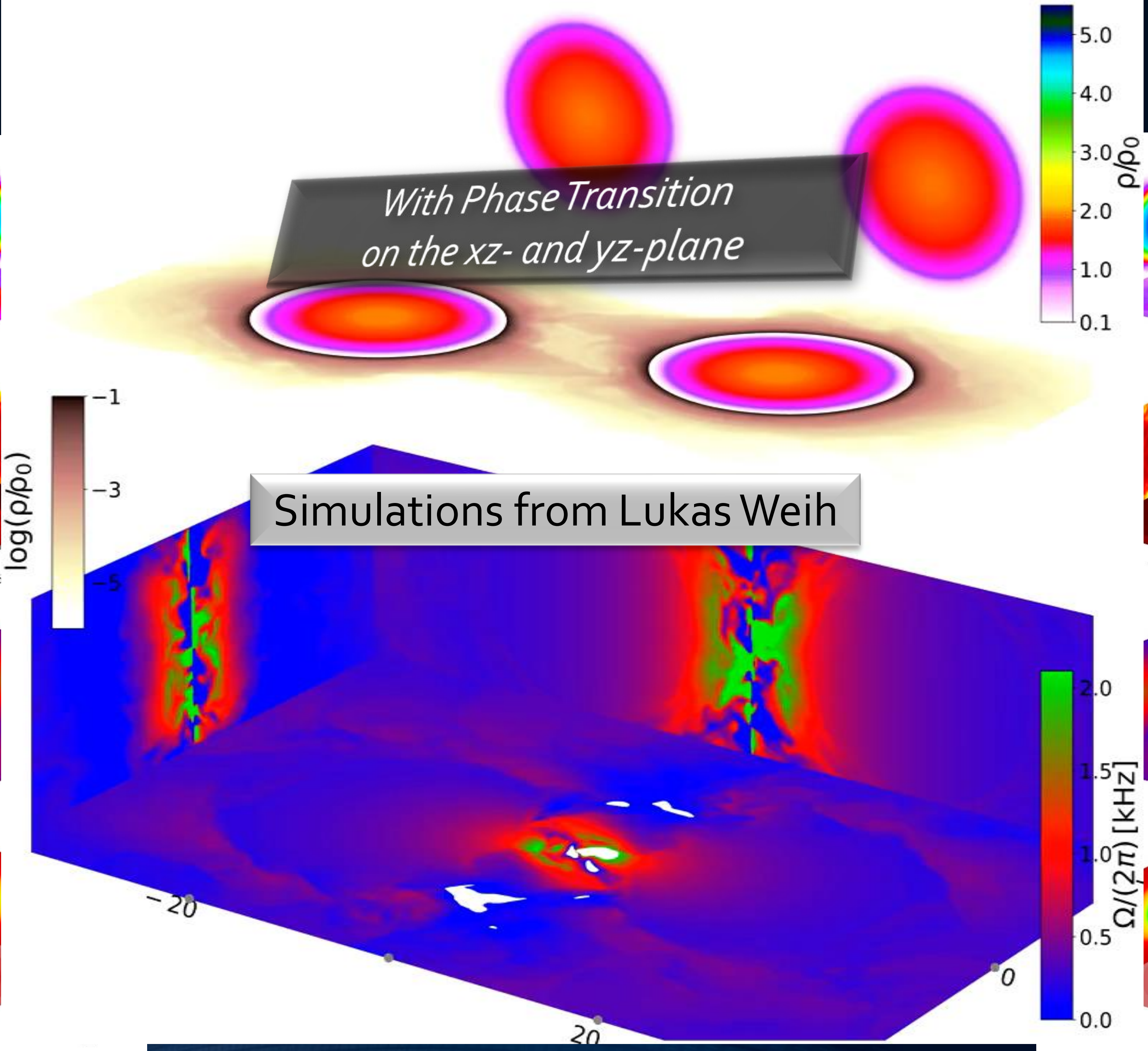
Difference in the h_+^{12} – gravitational wave mode

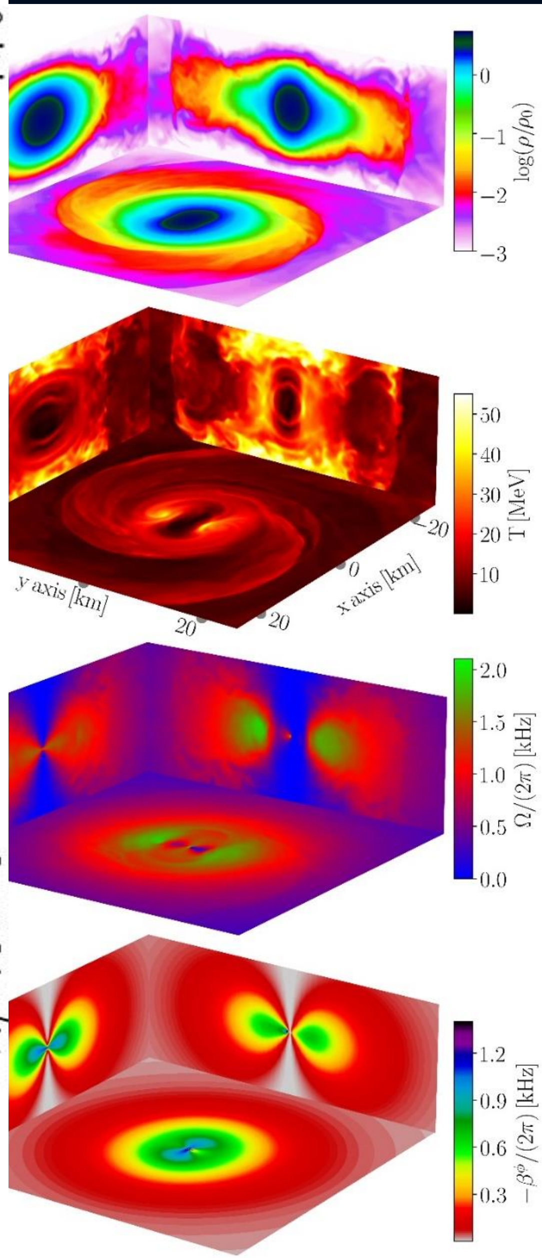




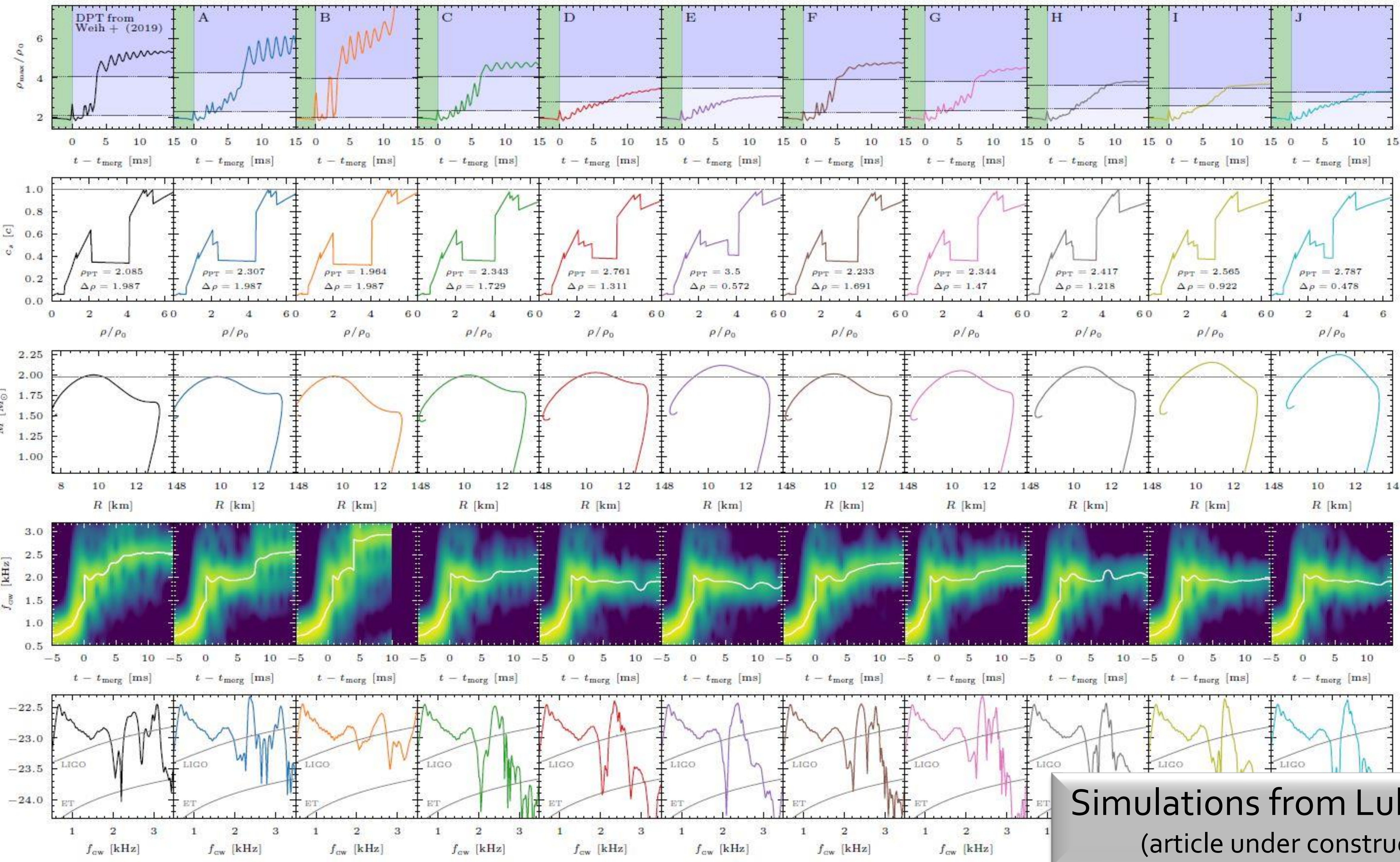
Due to the large m=1 mode of the emitted gravitational wave in the DPT case, a qualitative difference to the NPT scenario might be observable in future by focusing on the h_+^{12} – gravitational wave mode during the post-merger evolution.


−20
y axis [km]
20
20


With Phase Transition
on the xz- and yz-plane
Simulations from Lukas Weih
5.0
4.0
3.0
2.0
1.0
0.1
ρ/ρ_0
−1
−3
−5
$\log(\rho/\rho_0)$
2.0
1.5
1.0
0.5
0.0
$\Omega/(2\pi)$ [kHz]
−20
0
20


0
−1
−2
−3
$\log(\rho/\rho_0)$
50
40
30
20
10
T [MeV]
y axis [km]
x axis [km]
−20
0
20
20
2.0
1.5
1.0
0.5
0.0
$\Omega/(2\pi)$ [kHz]
1.2
0.9
0.6
0.3
$-\beta^\phi/(2\pi)$ [kHz]

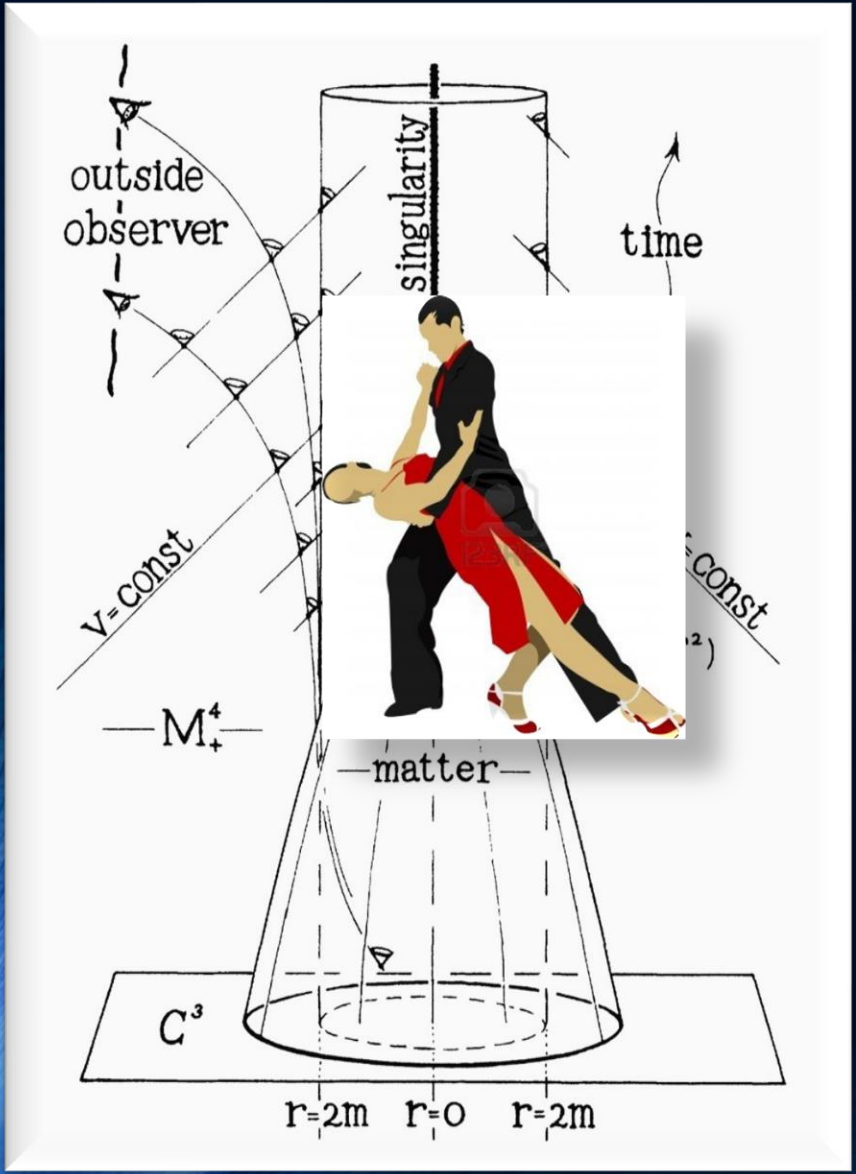
Analysis of the impact of phase transitions



Simulations from Lukas Weih
(article under construction)

GRAVITATIONAL COLLAPSE AND SPACE- TIME SINGULARITIES

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



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

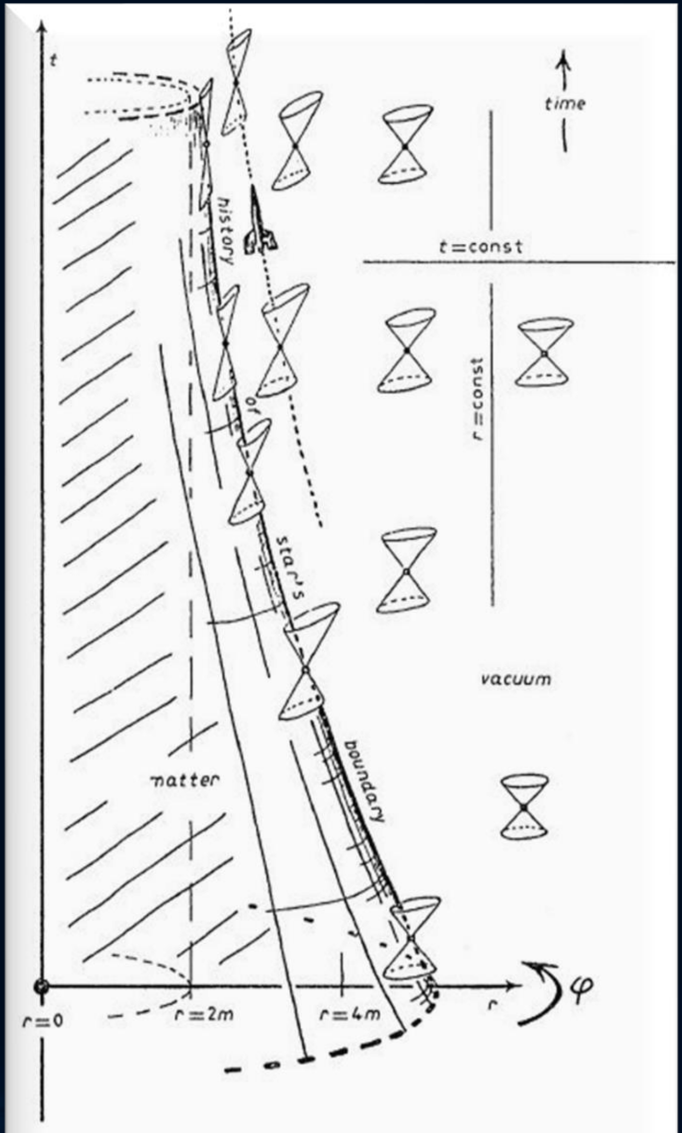


Figure 1. Spherically symmetrical collapse in the usual Schwarzschild co-ordinates.

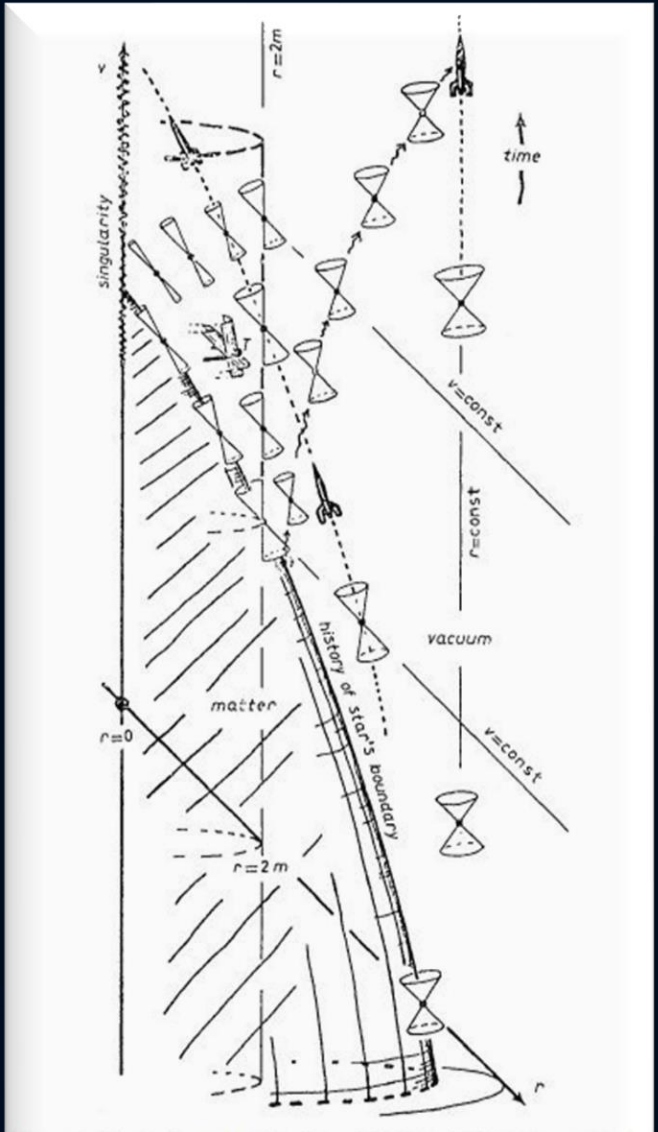
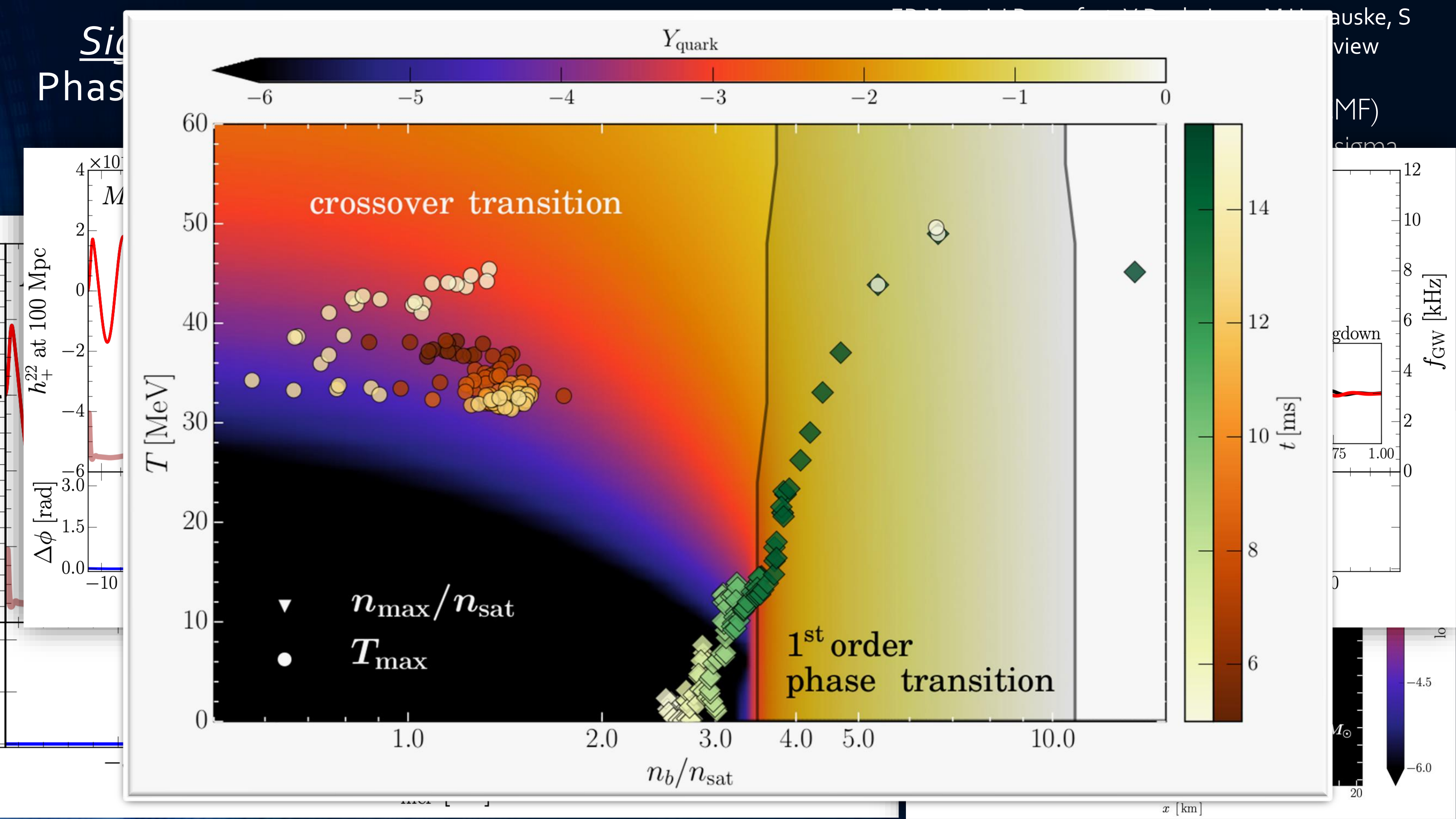


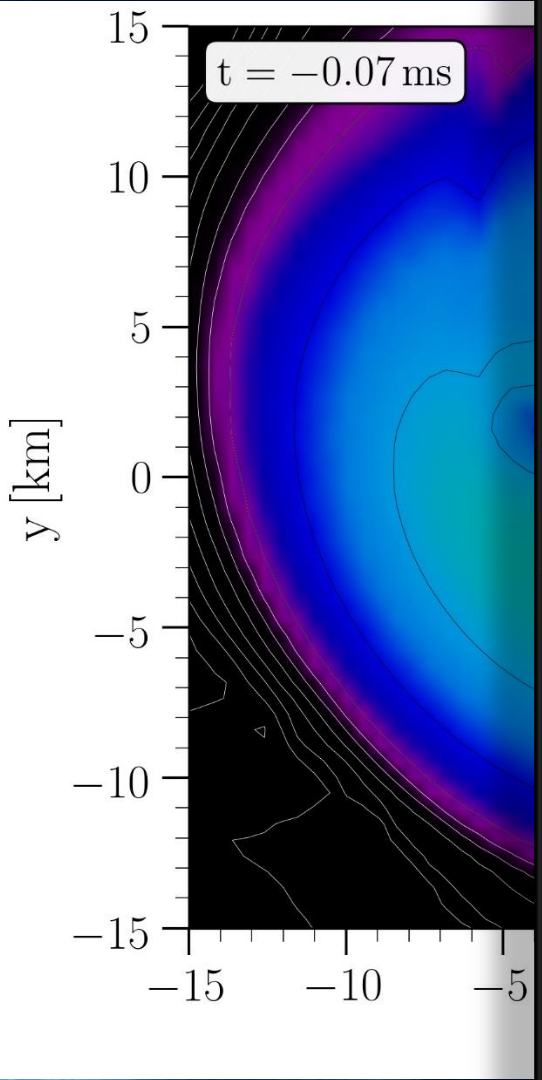
Figure 2. Spherically symmetrical collapse in Eddington-Finkelstein co-ordinates.

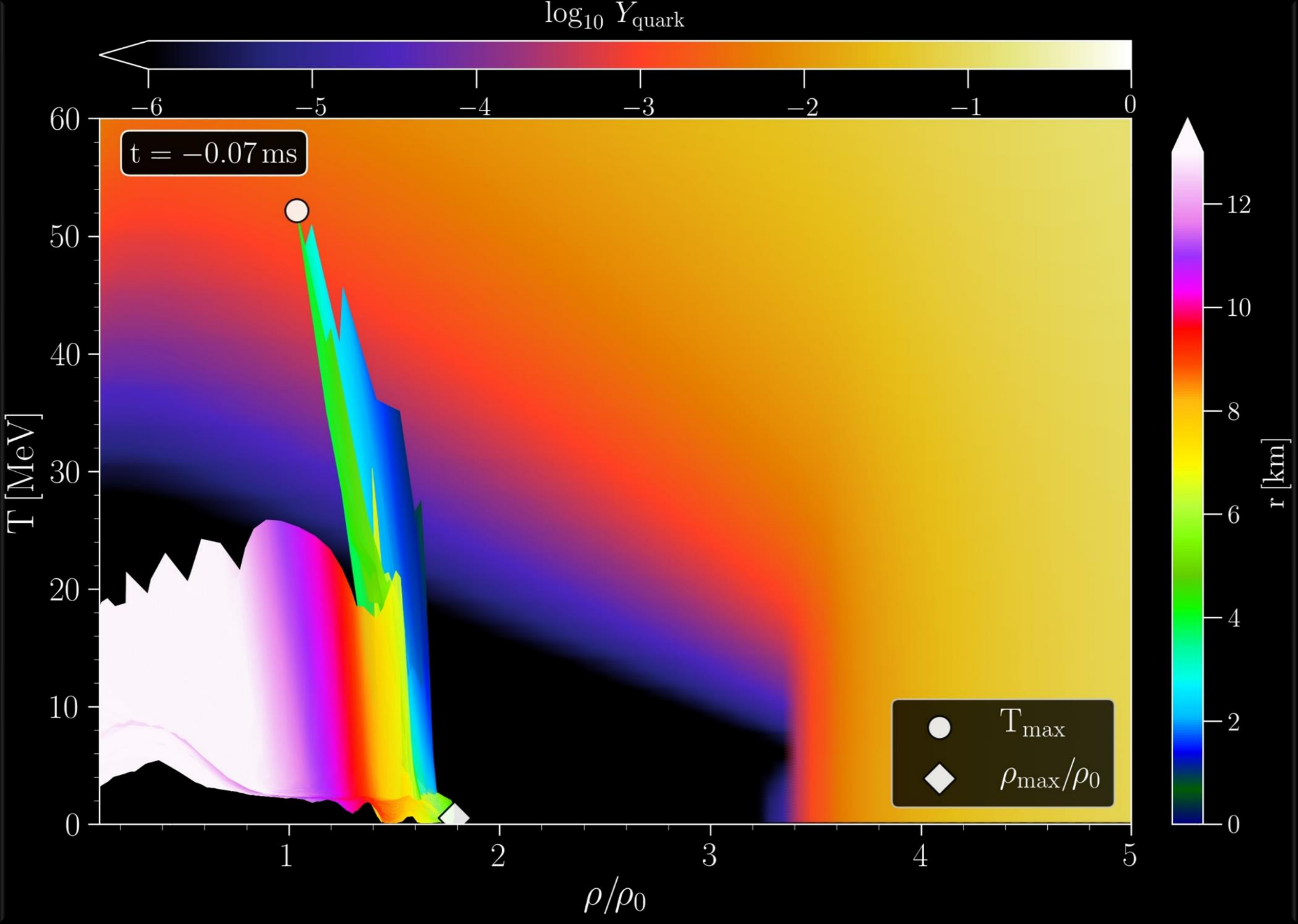
R.Penrose in Rivista del Nuovo Cimento, Num.Spez. I, 257 (1969)



Y_{quark}
−6
−5
−4
−3
−2
−1
0
crossover transition
1st order phase transition
n_{max}/n_{sat}
T_{max}
T [MeV]
n_b/n_{sat}
t [ms]

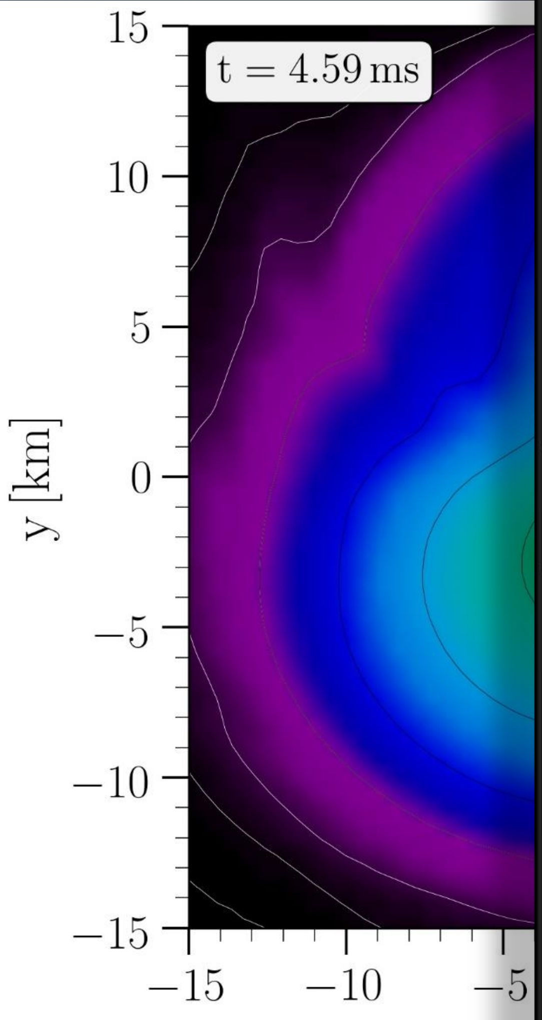
Merger Phase



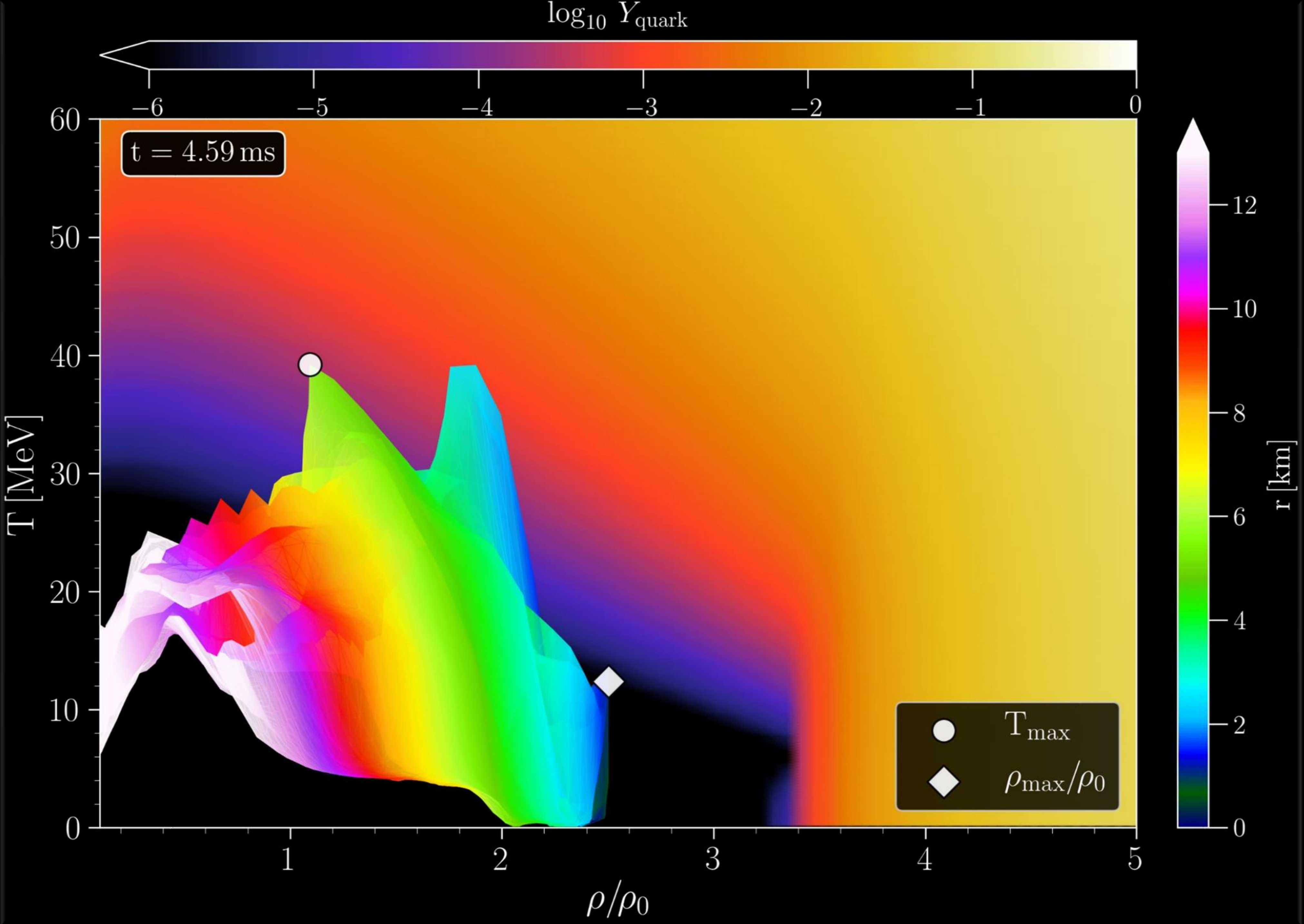


Rest mass density

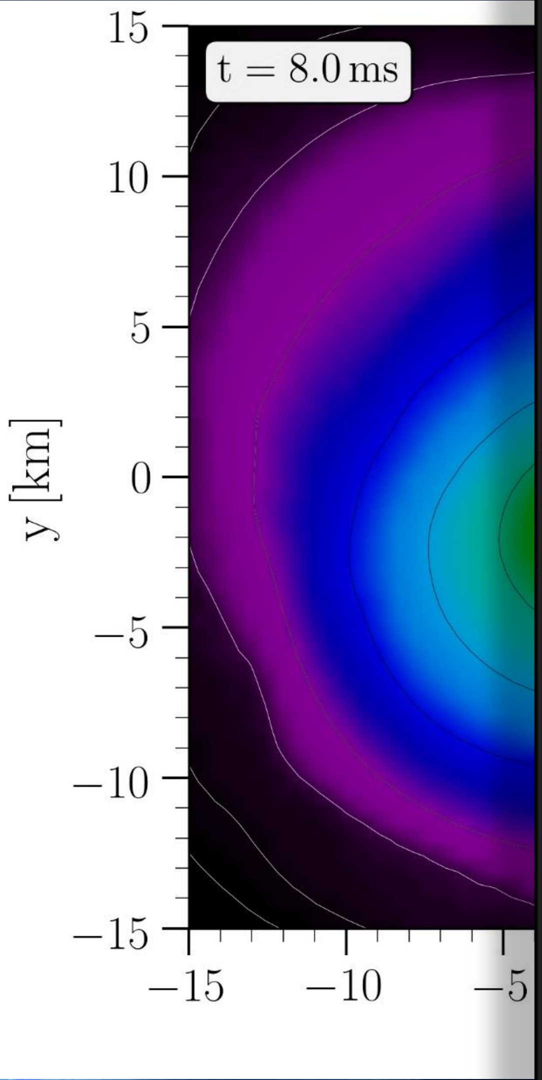
Post Merger Phase



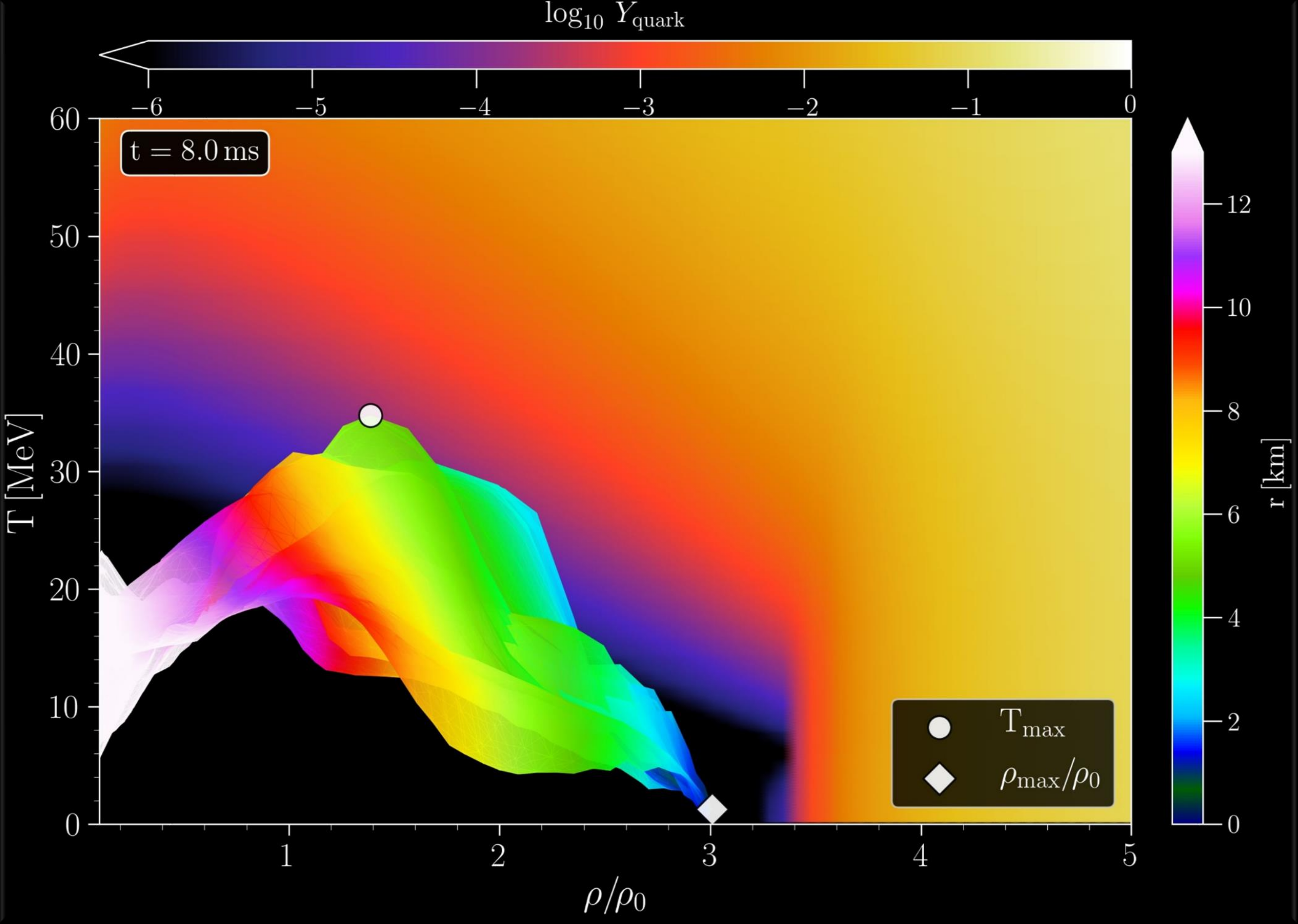
Rest mass density



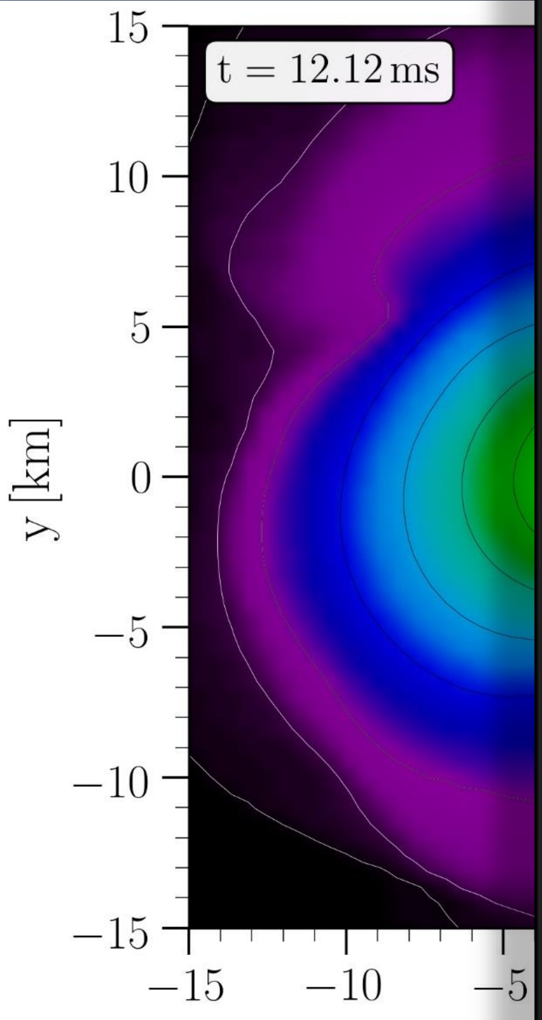
Merger Phase

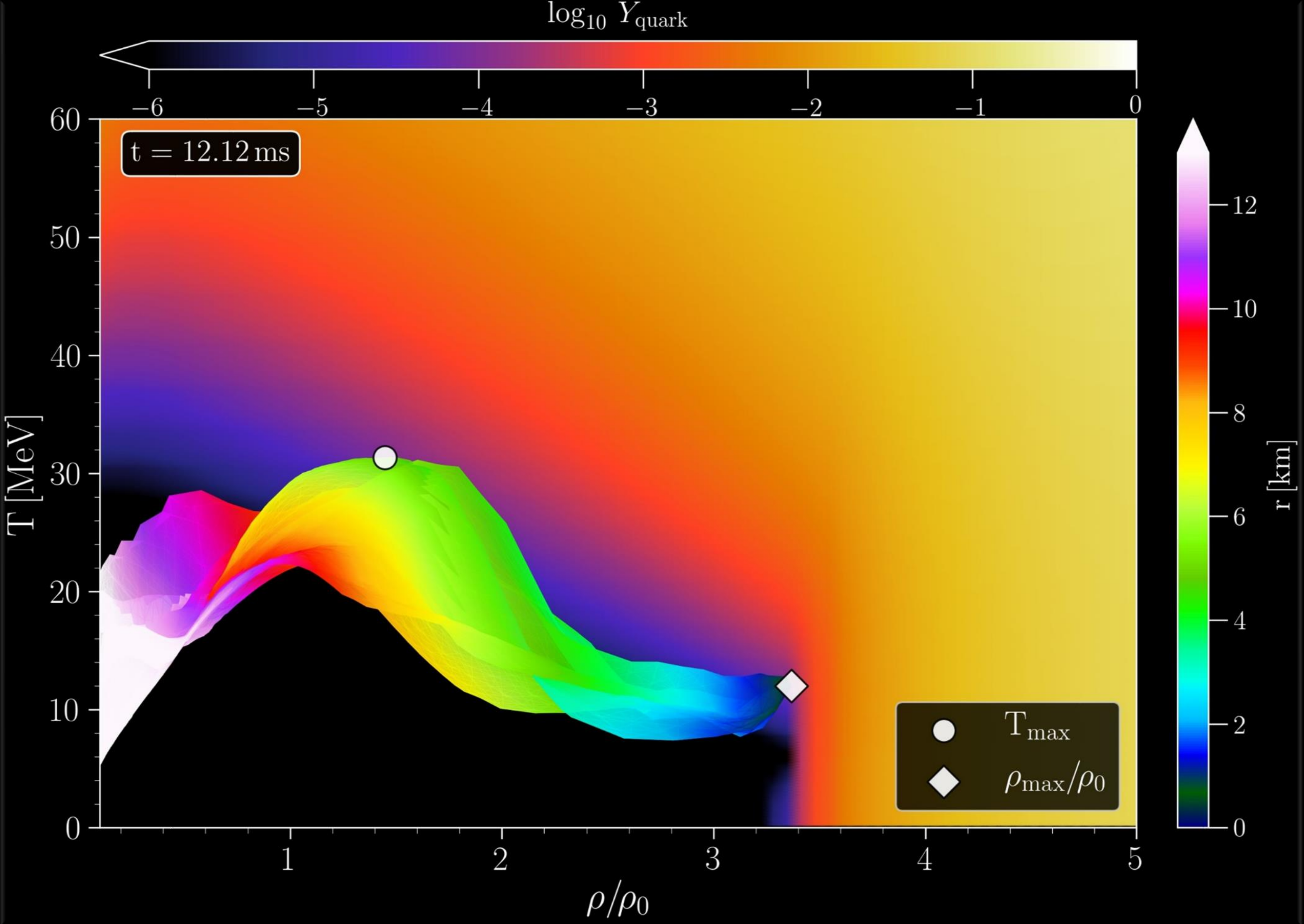


Rest mass density



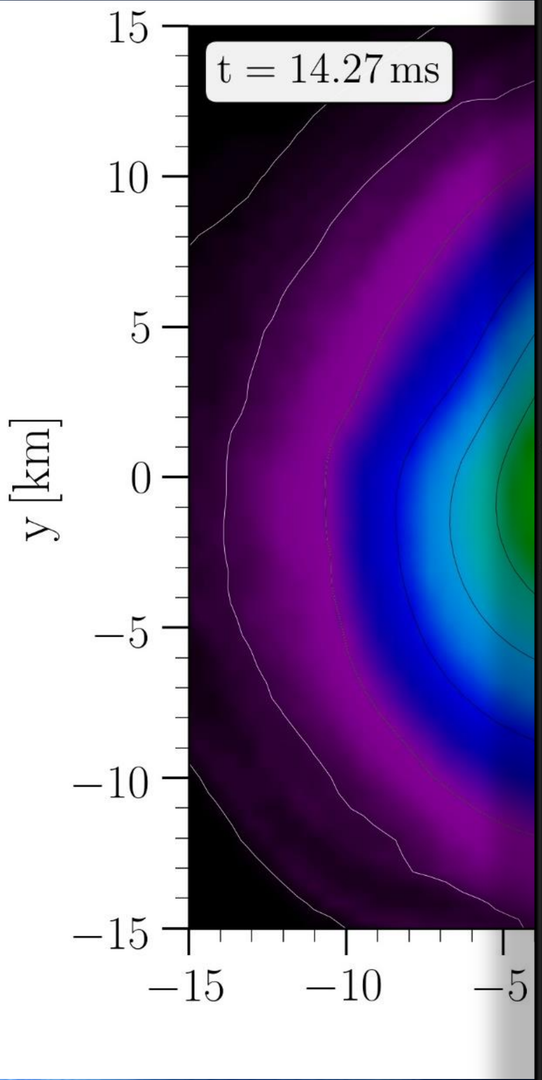
Merger Phase

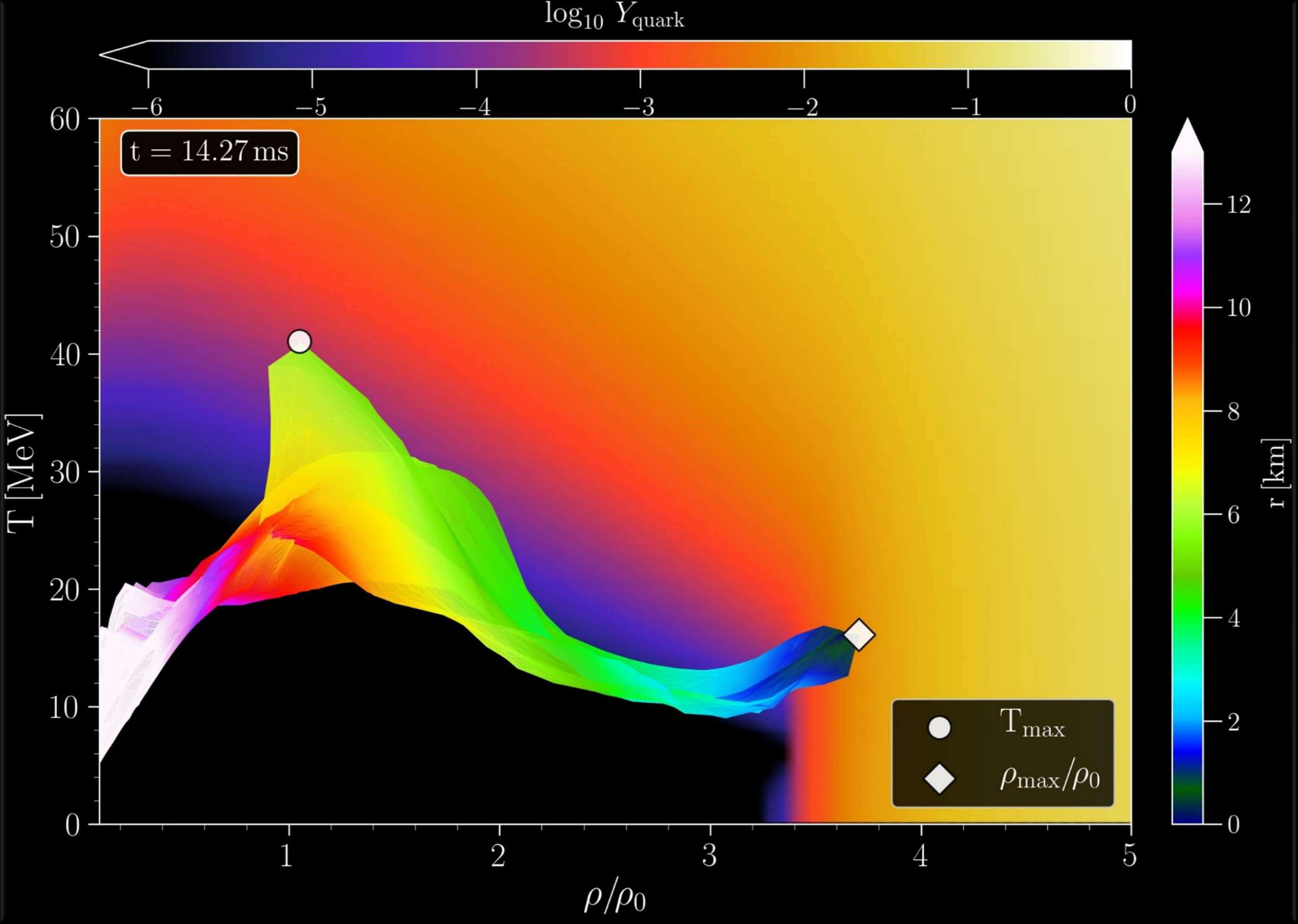




Rest mass density

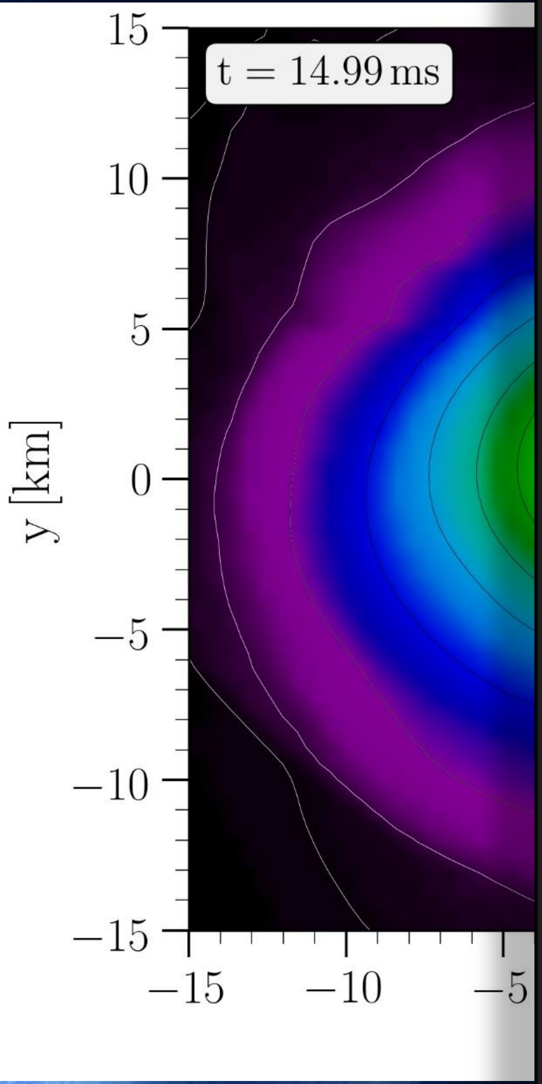
Merger Phase

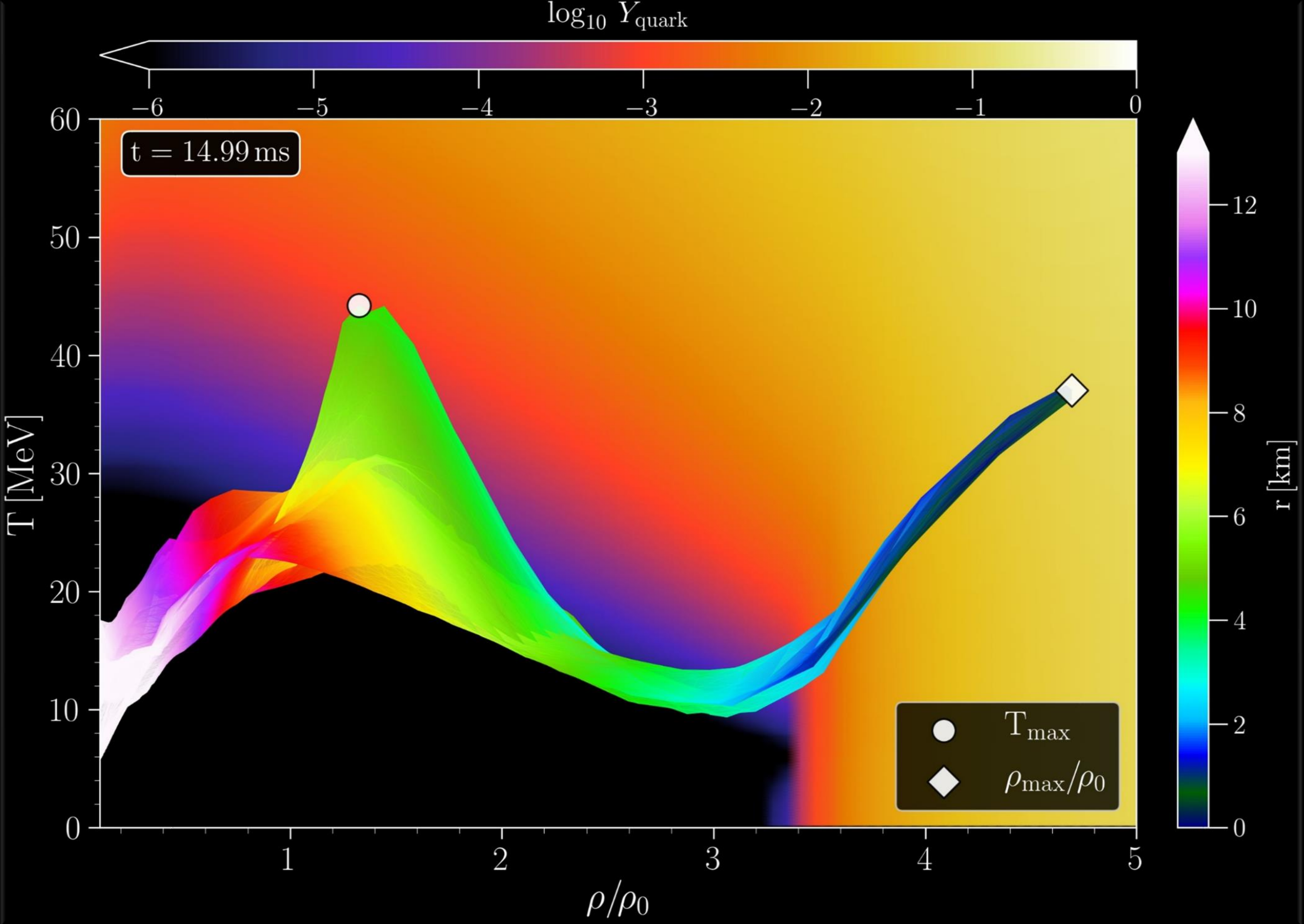




Rest mass density

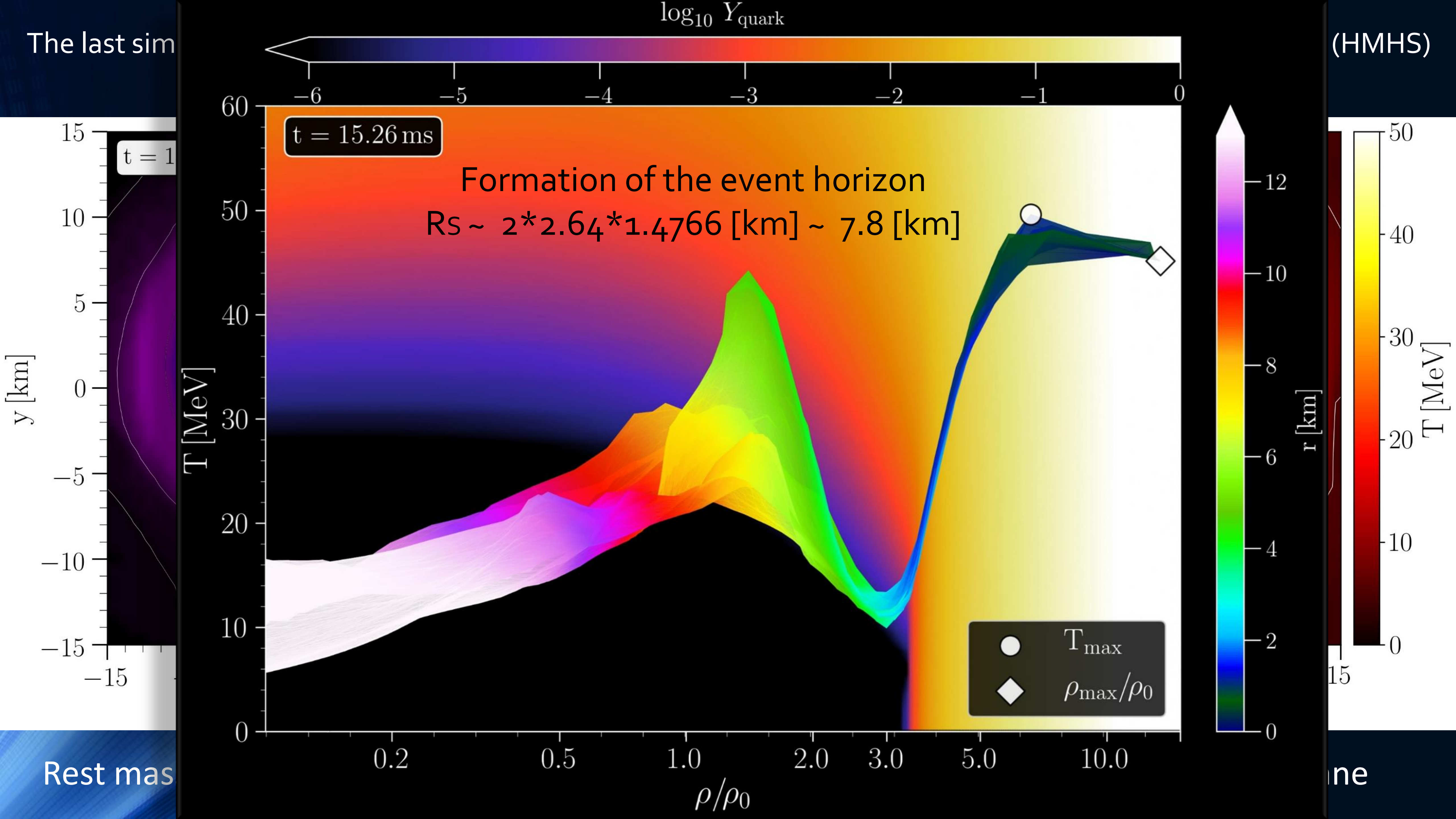
Merger Phase





Rest mass density

The last sim (HMHS)



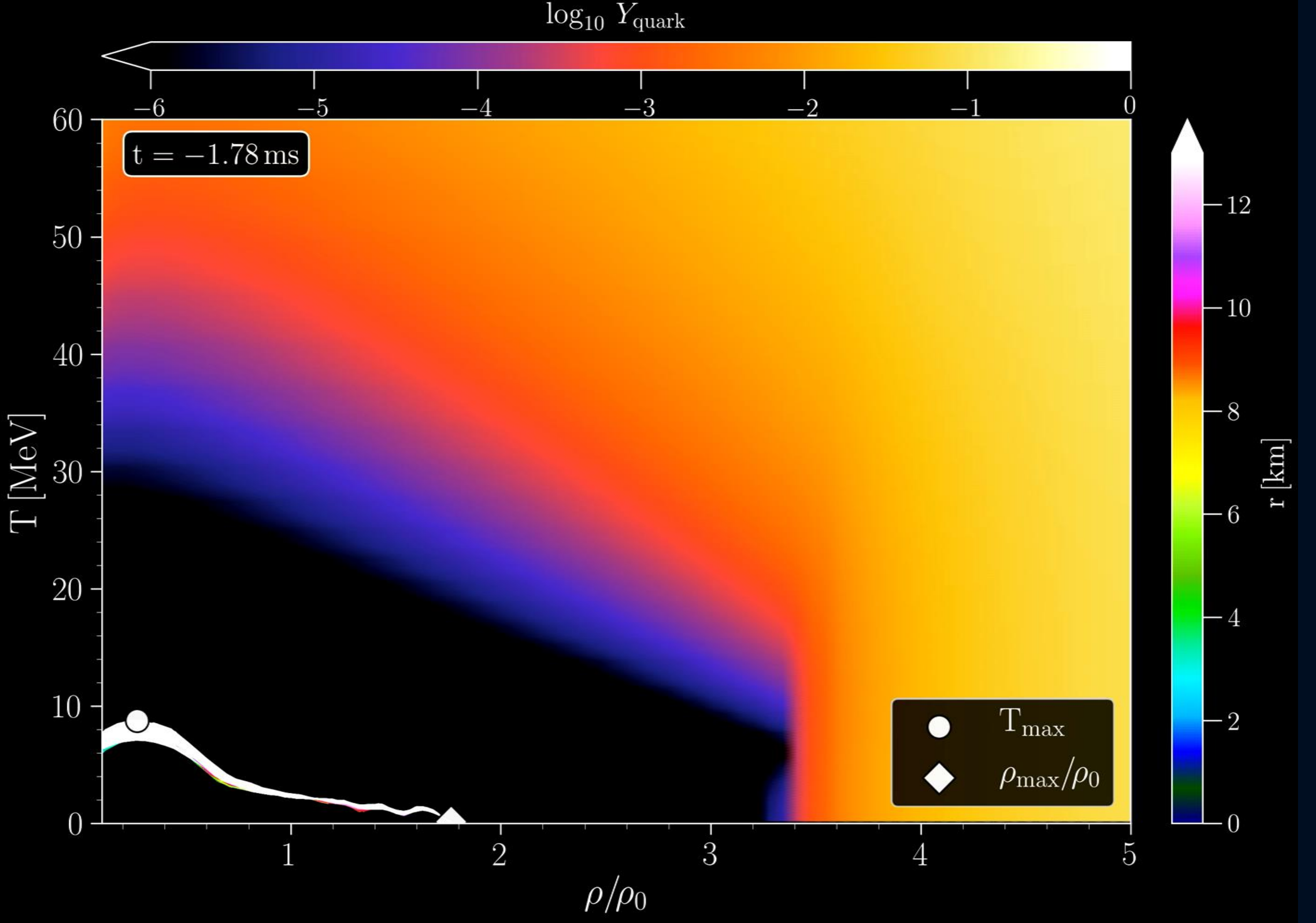
Rest mas ne

Phase-transition triggered collapse scenario

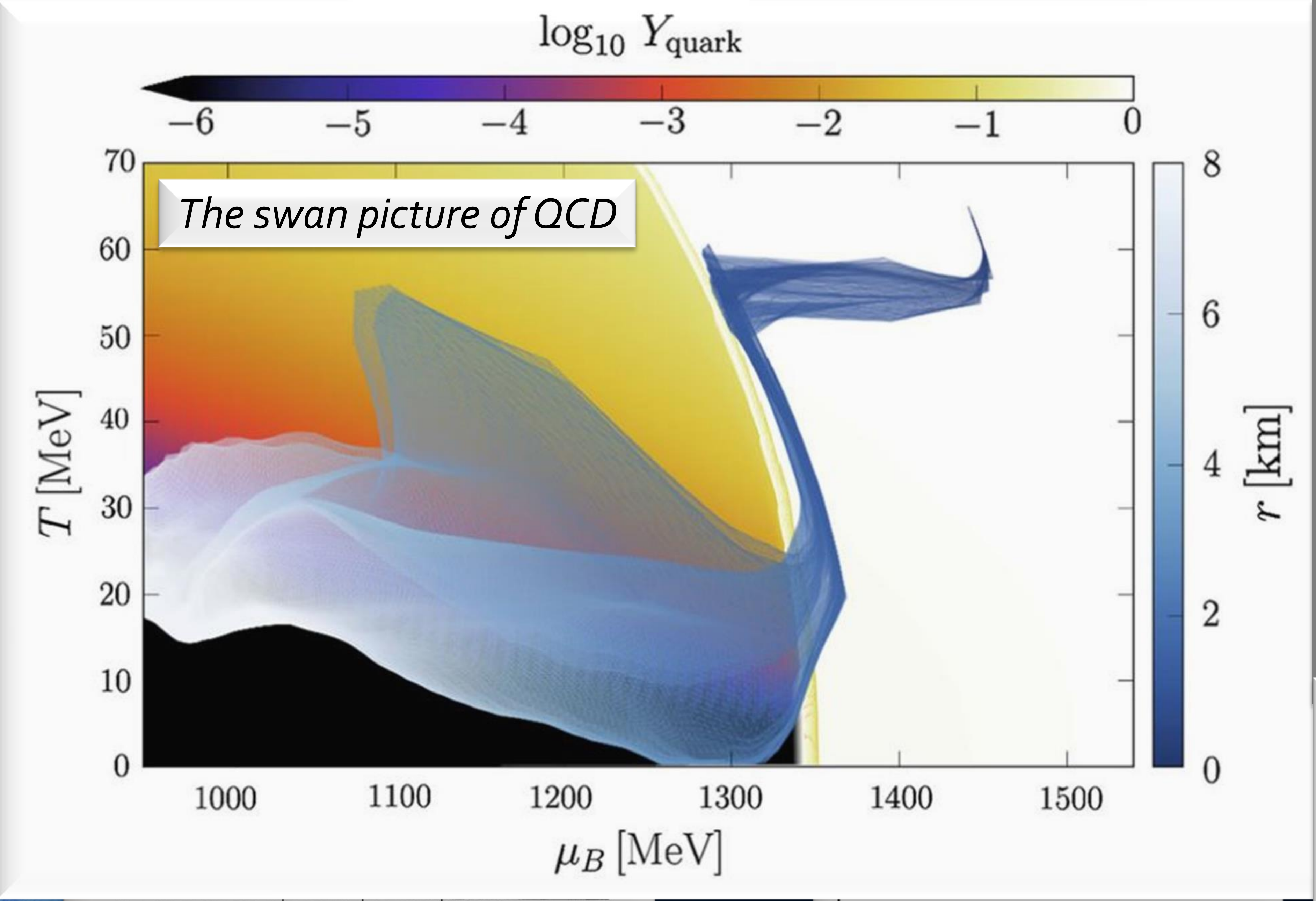
Signatures of quark-hadron phase transitions in general-relativistic neutron-star mergers

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

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



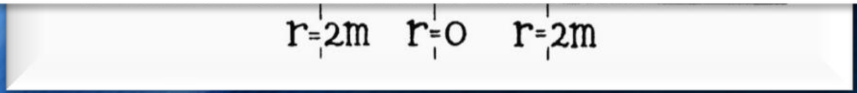
Density-Temperature-Composition dependent EOS within the CMFQ model.



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

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

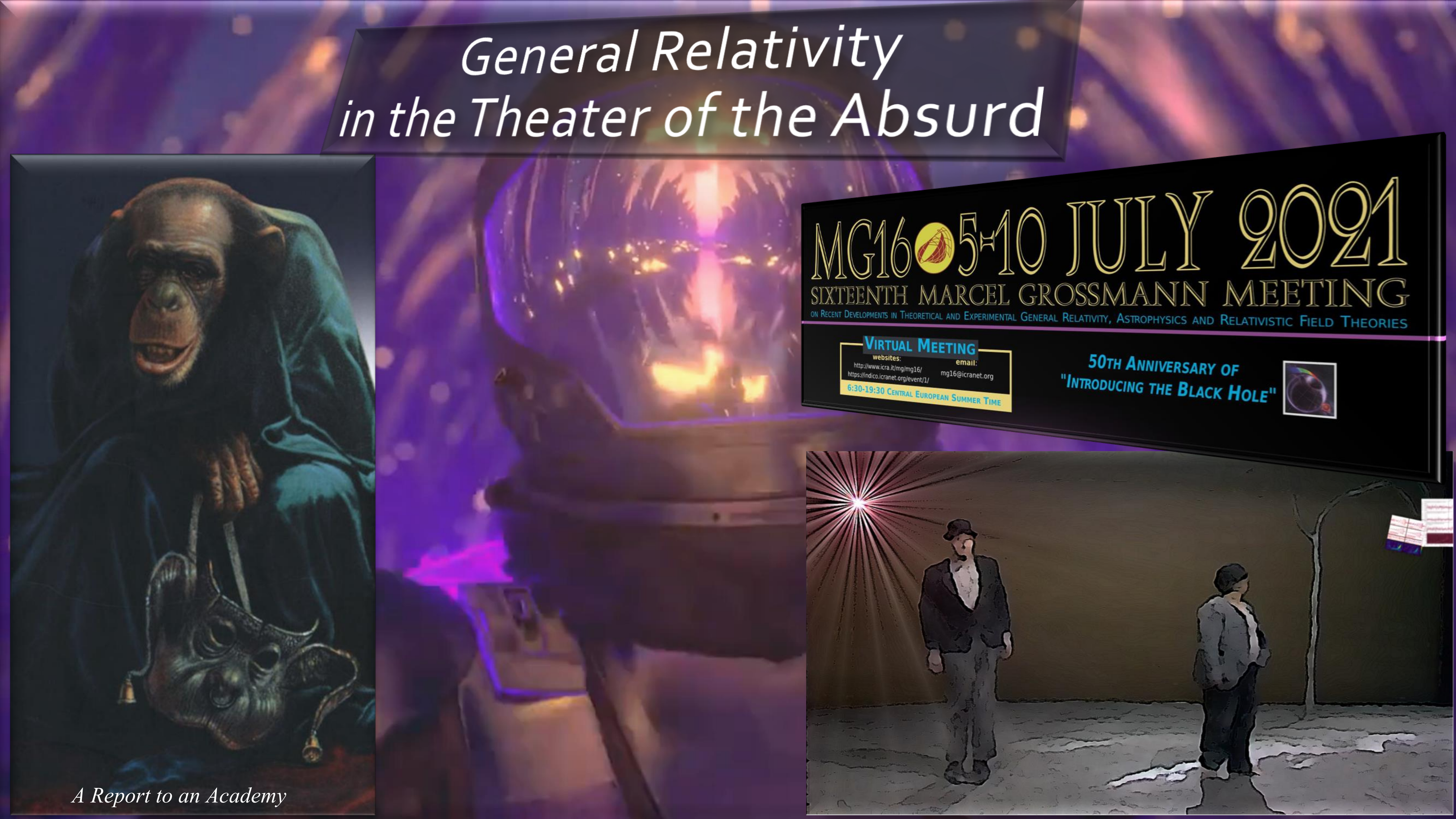
The last picture what an outside observer sees is the frozen picture of a dying swan



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

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

R.Penrose in Rivista del Nuovo Ci



General Relativity
in the Theater of the Absurd
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"
A Report to an Academy