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INSTITUT FÜR THEORETISCHE PHYSIK
ARBEITSGRUPPE RELATIVISTISCHE ASTROPHYSIK
D-60438 FRANKFURT AM MAIN



Der Tanz der Neutronensterne

Themenreihe: Astronomie am Freitag

Veranstaltungsort:

Hörsaal im Physikalischer Verein,

Robert-Mayer-Straße 2,

60325 Frankfurt

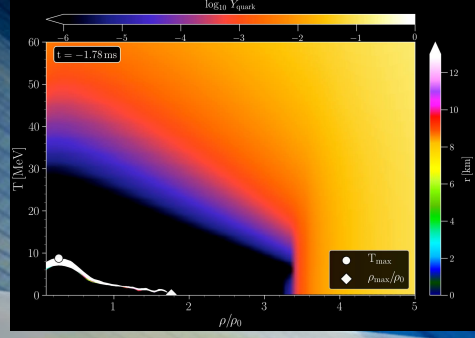
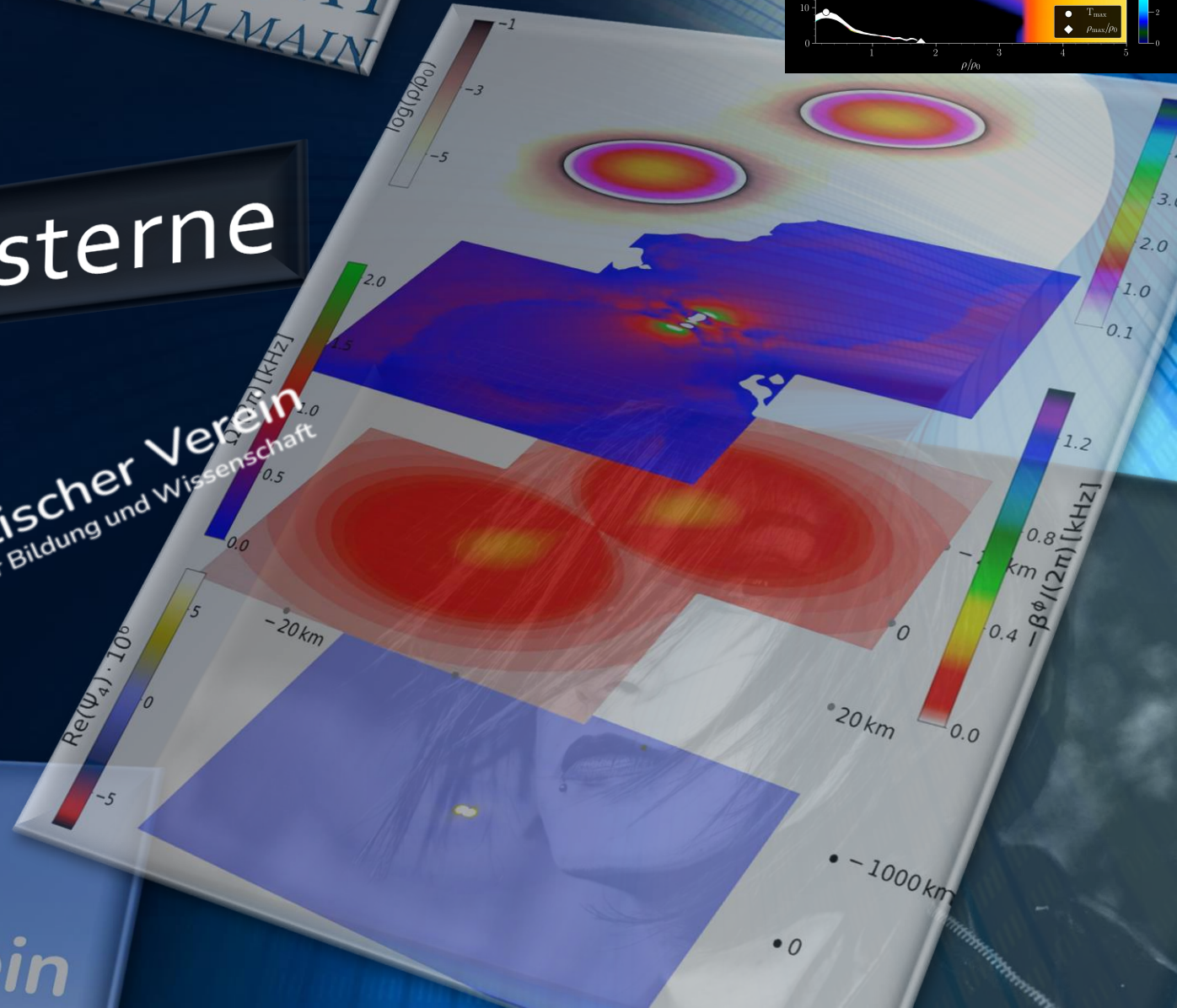
Fr, 21. Okt 2022 20:00 Uhr



Physikalischer Verein
Gesellschaft für Bildung und Wissenschaft



Herzlich Willkommen
beim Physikalischen Verein

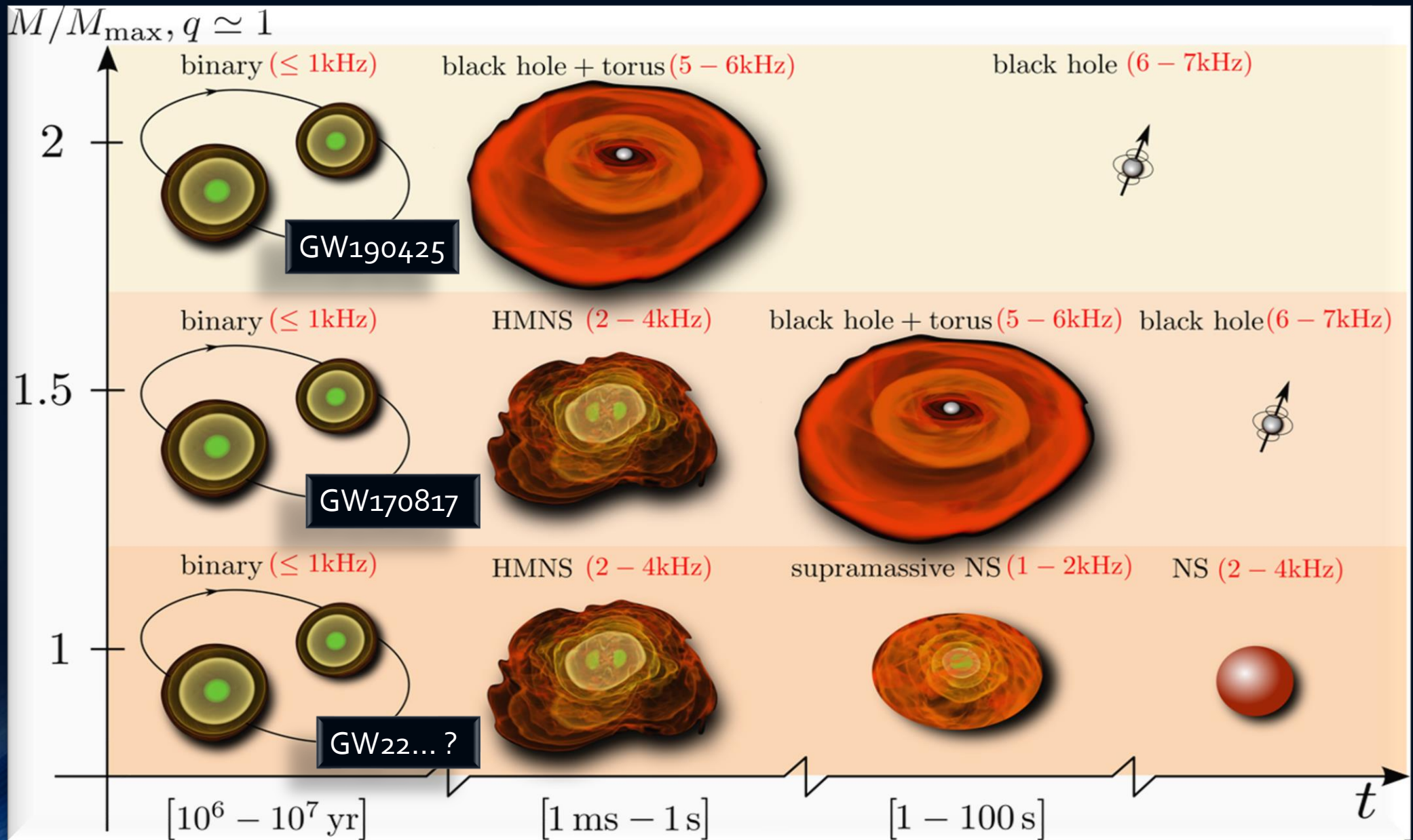


Was geschieht wenn zwei Neutronensterne miteinander kollidieren?

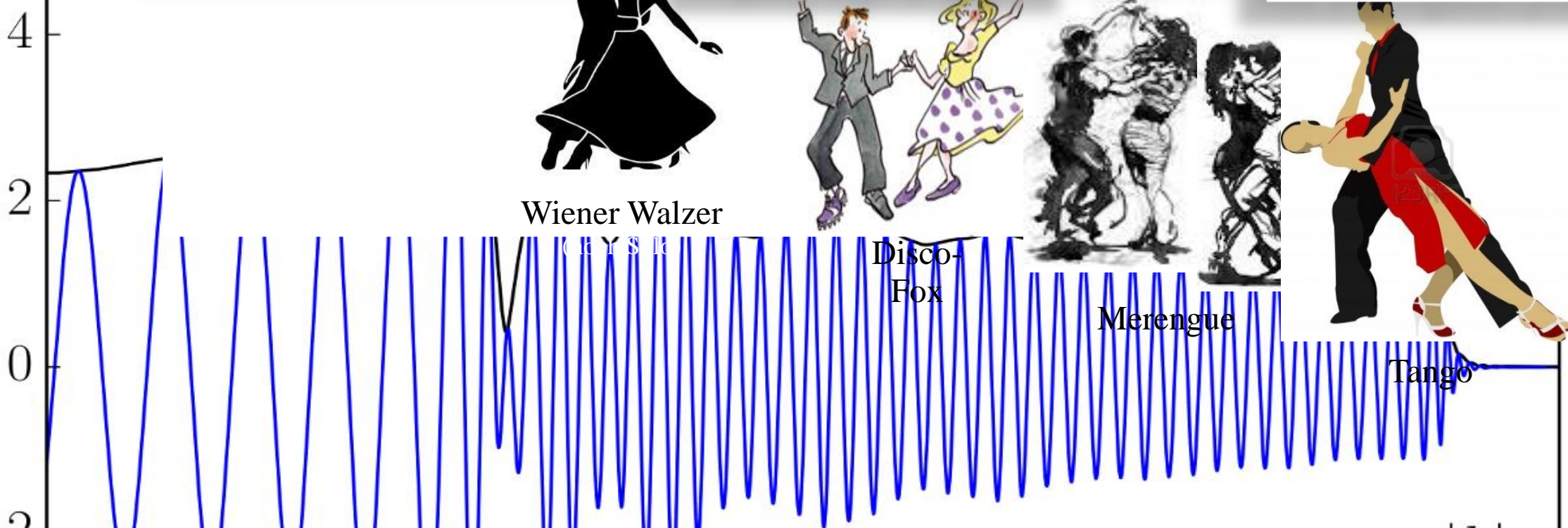
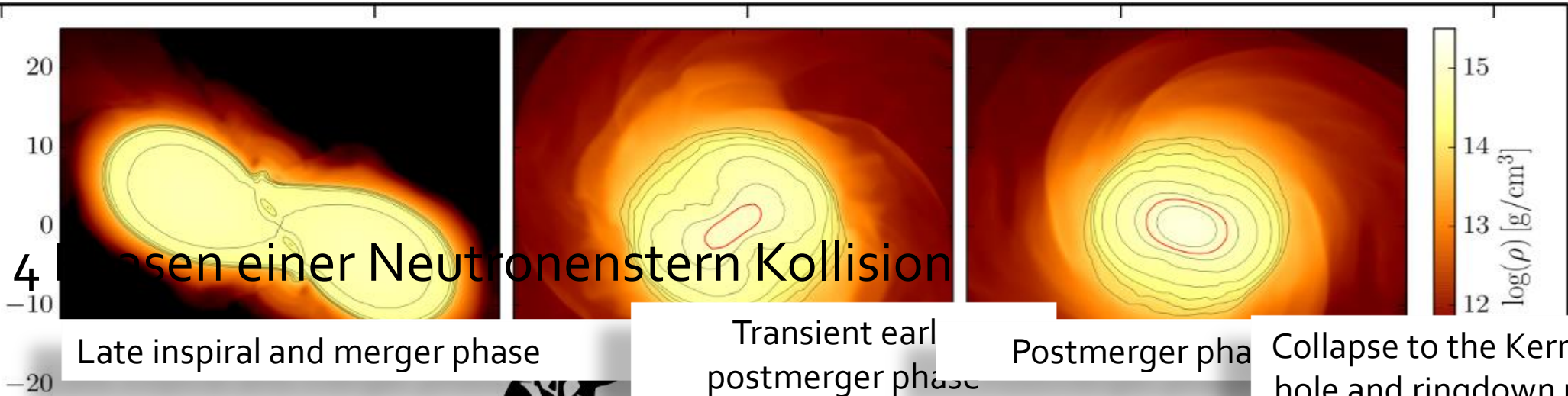
Zwei sehr massive Neutronensterne

Zwei mittelschwere Neutronensterne

Zwei leichte Neutronensterne



The Die 4 Phasen einer Neutronenstern Kollision





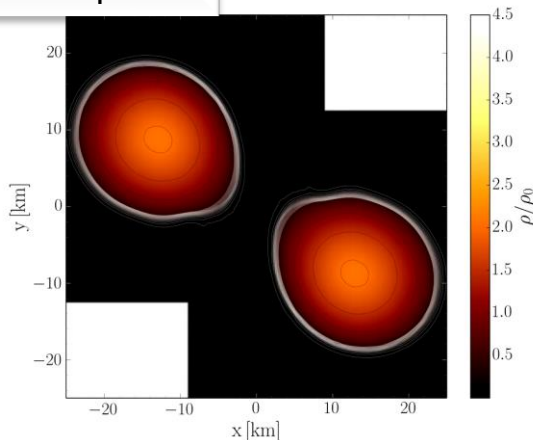
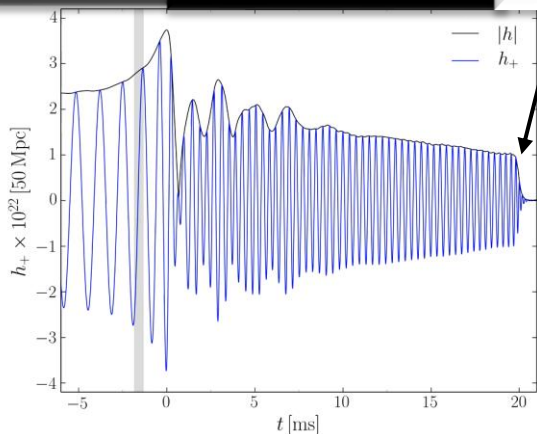
Das Musikstück „Opus“ von Eric Prydz verdeutlicht in exzellenter Weise die einzelnen Phasen einer Neutronenstern Kollision. Das gesamte Stück ist ca. 9 Minuten lang, wobei die erste Phase (inspiral phase) bei 3.4 min endet (der Kollisionszeitpunkt) und der Kollapse zum schneller rotierenden hybriden Quarkstern (delayed collapse) sich wohl bei 4.55 min ereignet.

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

Inspiral phase

Post-merger phase

Gravitational collapse



The two neutron stars will collide in 85 million years



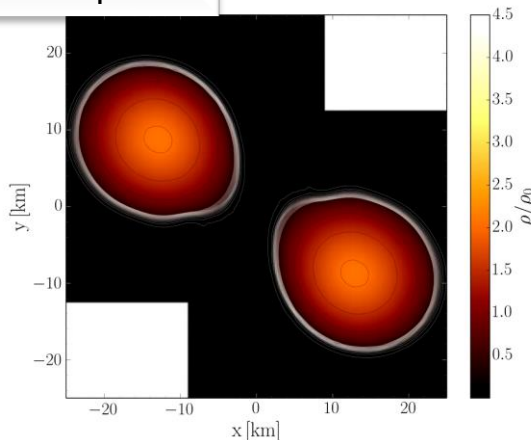
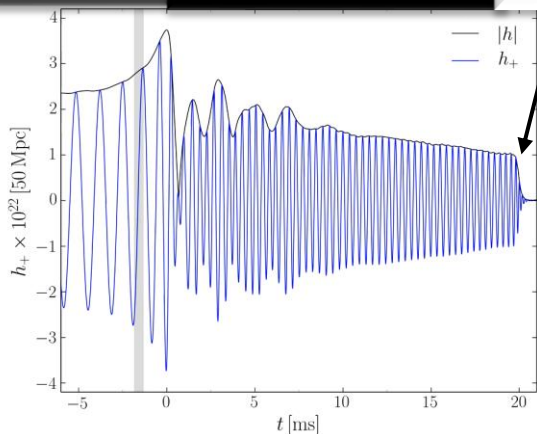
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Inspiral phase

Post-merger phase

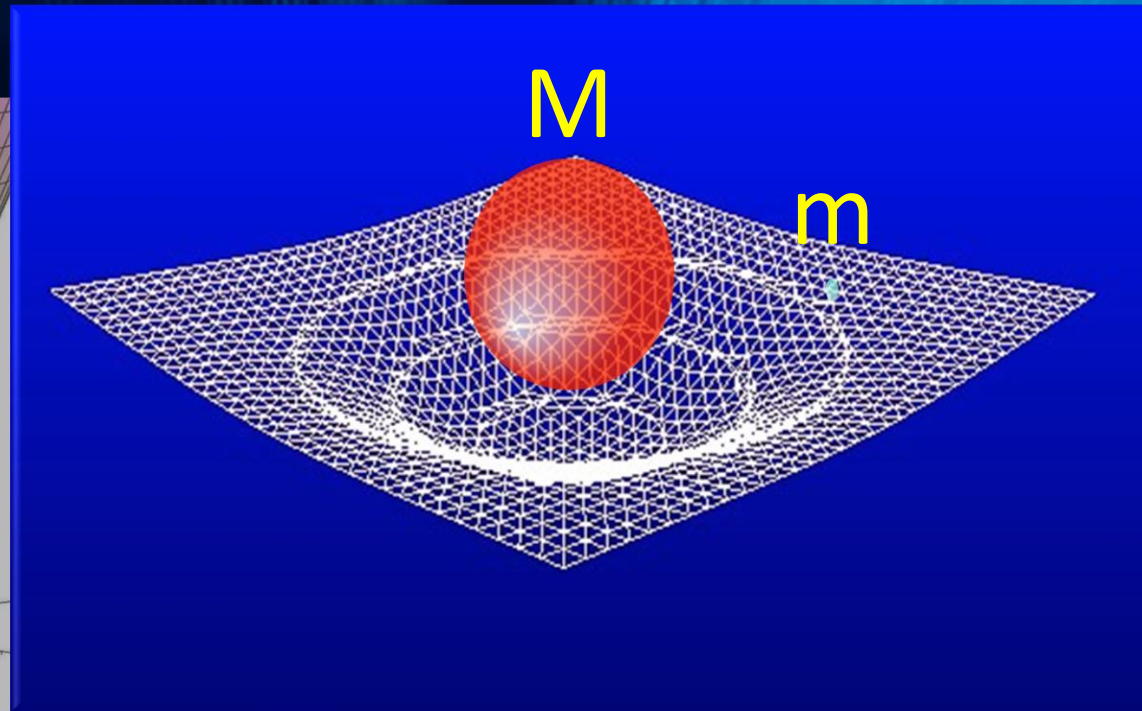
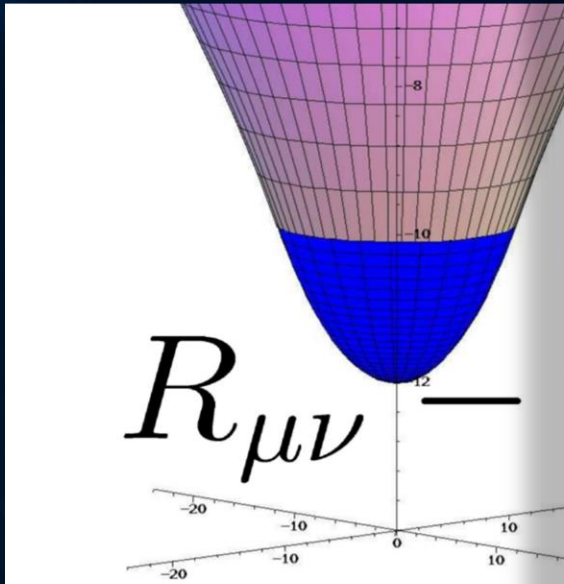
Gravitational collaps



The two neutron stars will collide in 85 million years

Allgemeinen Relativitätstheorie

Die Einsteingleichung



„Allgemeine Relativitätstheorie“ (ART) der

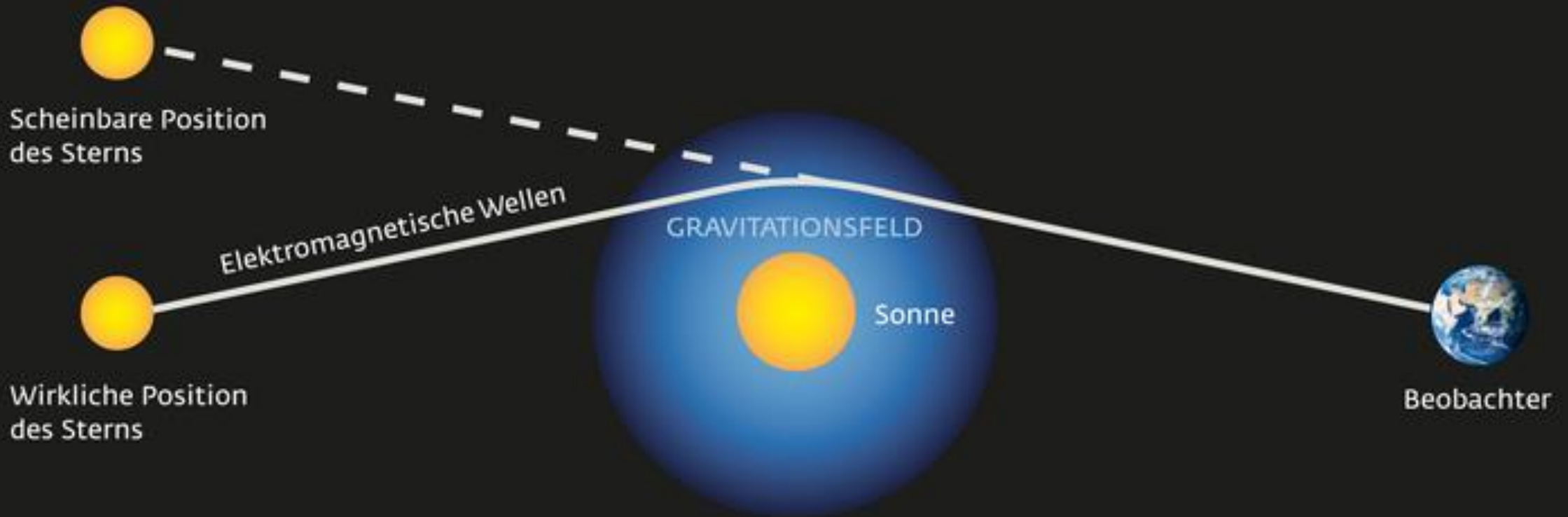
$$T_{\mu\nu}$$

Raumzeit-Krümmung = Energie

Die ART ist eine sehr revolutionäre Theorie. Sie besagt, dass jegliche Energieformen (z.B. Masse der Erde) die „Raumzeit“ verbiegen und durch diese Krümmung des Raumes und der Zeit resultiert die Gravitationskraft (Schwerkraft).

Erste Bestätigung der ART: Sonnenfinsternis 1919

Aufgrund des extrem revolutionären Charakters der ART glaubten viele Physiker zunächst nicht an Einsteins Theorie. Das änderte sich schlagartig im Jahre 1919:



Der Einstein-Ring



LRG 3-757: im Jahre 2007 mit dem Hubble Space Teleskop aufgenommen

Gravitative Zeitdilatation

Den Effekt der Zeitverbiegung kann man heutzutage sogar auf der Erde nachweisen -> Uhren ticken in den Bergen ein wenig schneller als im Tal.

News
12.02.2018
[Drucken](#)
[Teilen](#)

RELATIVITÄTSTHEORIE

Warum die Zeit im Gebirge schneller vergeht

Mit einem surrealen Effekt der Gravitationsphysik haben Wissenschaftler die Höhe eines Tunnels in den französischen Alpen bestimmt.

von Robert Gast



© ISTOCK / SKOUATROULIO (AUSSCHNITT)

2018 auf www.spektrum.de

Frankfurter Allgemeine

Physik & Mehr

WISSENSCHAFT GIZIN GENE KLIMA WELTRAUM GARTEN NETZRÄTSEL

ALLGEMEINE RELATIVITÄTSTHEORIE

Hurra, wir hier unten leben länger!

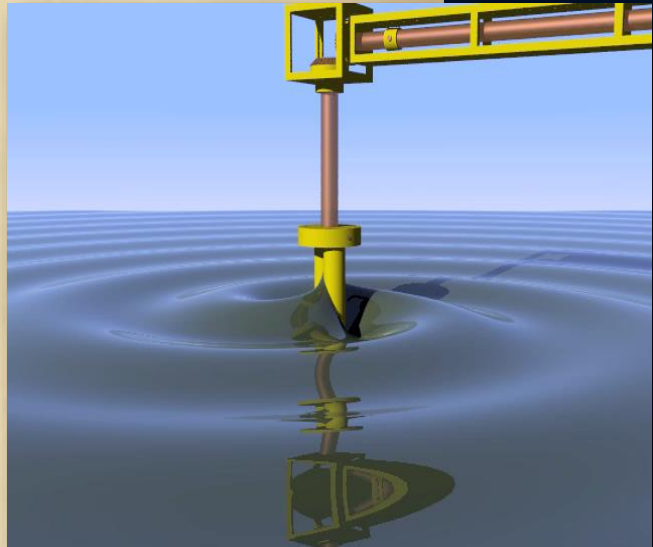
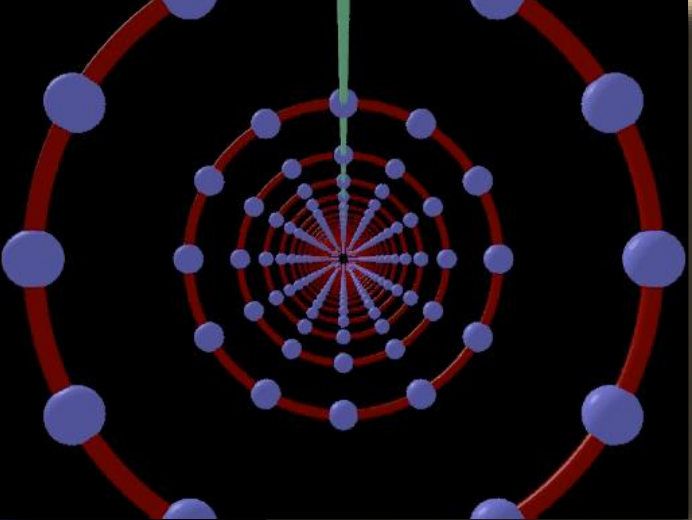
VON ANNE HARDY · AKTUALISIERT AM 19.10.2010 · 06:00



Über Gravitationswellen.

Von A. EINSTEIN.

(Vorgelegt am 31. Januar 1918 [s. oben S. 79].)

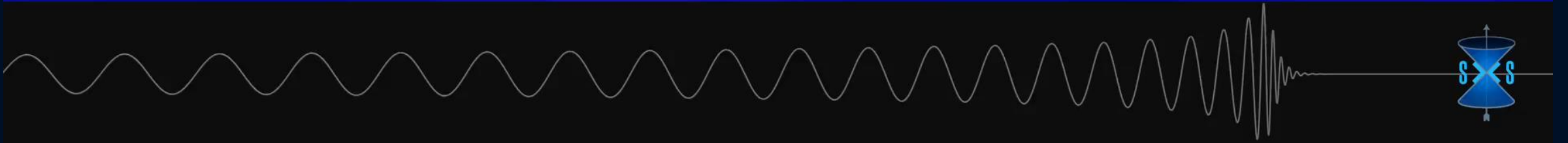
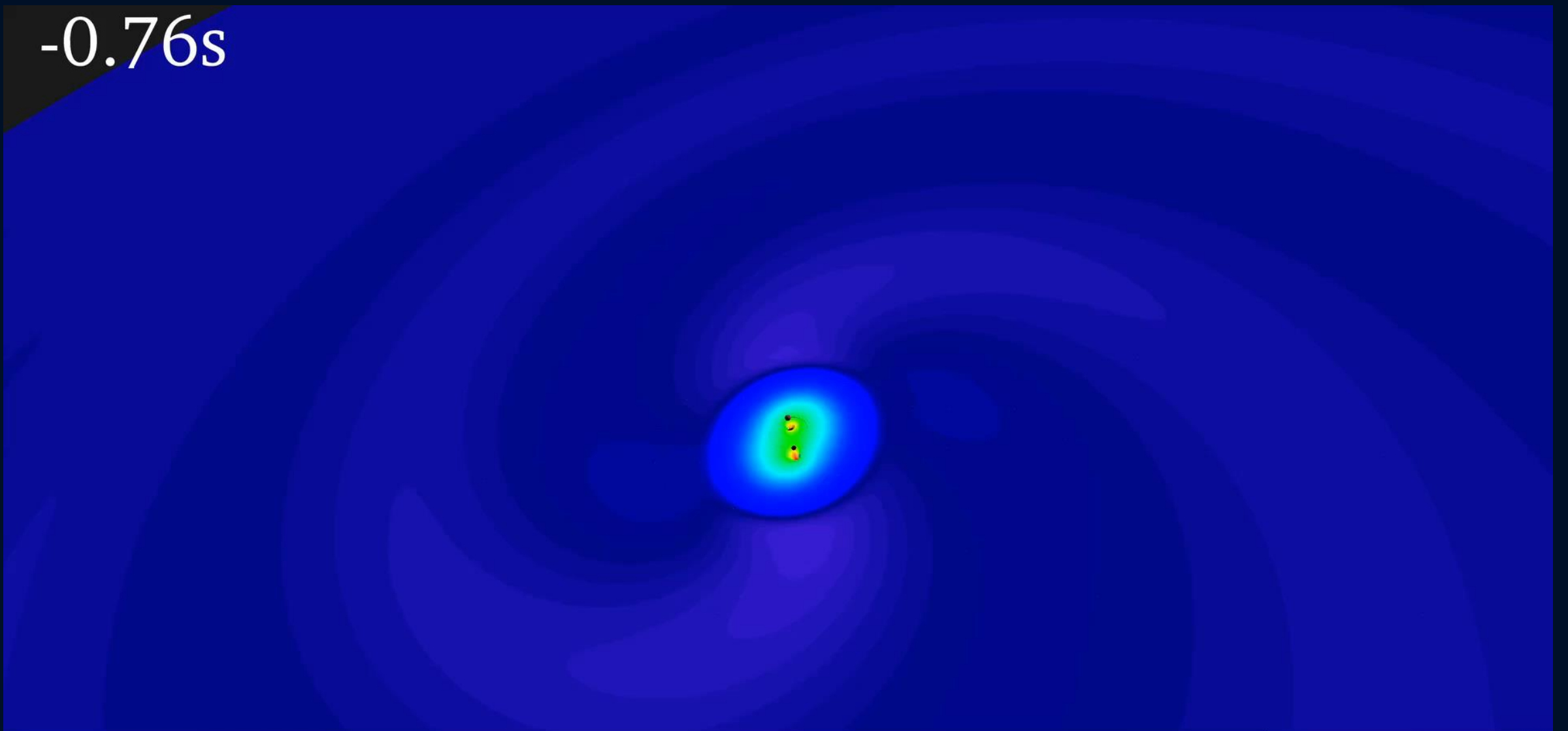


Die wichtige Frage, wie die Ausbreitung der Gravitationsfelder erfolgt, ist schon vor anderthalb Jahren in einer Akademiearbeit von mir behandelt worden¹. Da aber meine damalige Darstellung des Gegenstandes nicht genügend durchsichtig und außerdem durch einen bedauerlichen Rechenfehler verunstaltet ist, muß ich hier nochmals auf die Angelegenheit zurückkommen.

Einsteins erste Arbeit über Gravitationswellen, Juni 1916, war leider falsch ...
Sitzungsberichte der Königlich-Preußischen Akademie der Wissenschaften

Kollidierende Schwarze Löcher

-0.76s



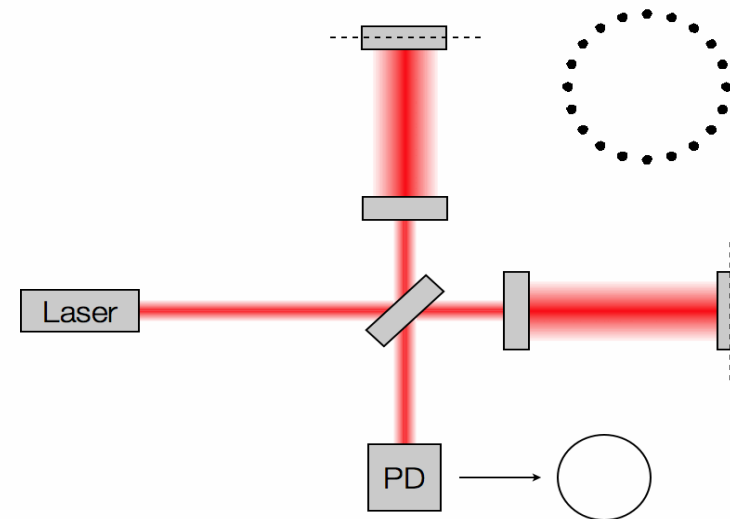
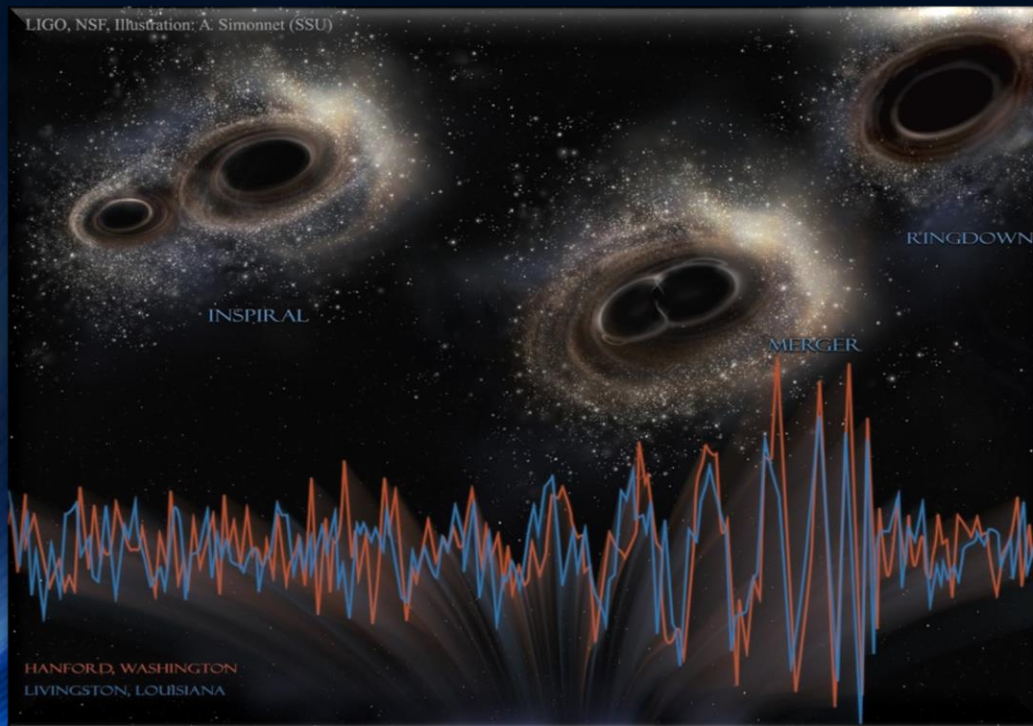
Im Jahre 2015

Erste Gravitationswellen gefunden: LIGO!!!

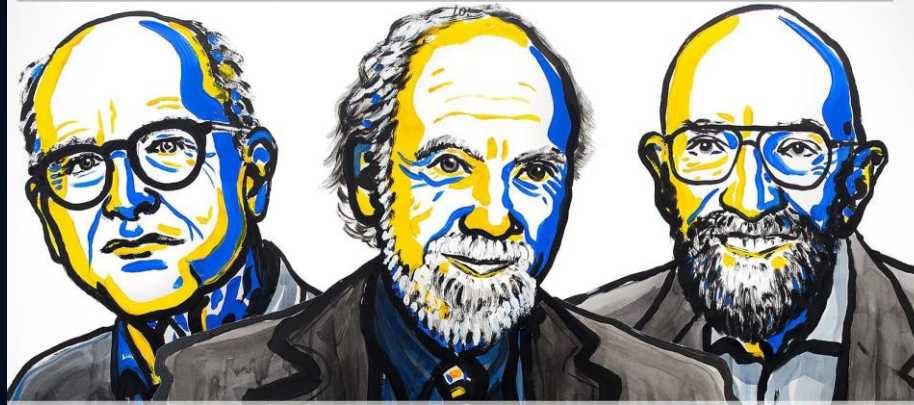
Kollision zweier Schwarzer Löcher GW150914

Massen: 36 & 29 Sonnenmassen

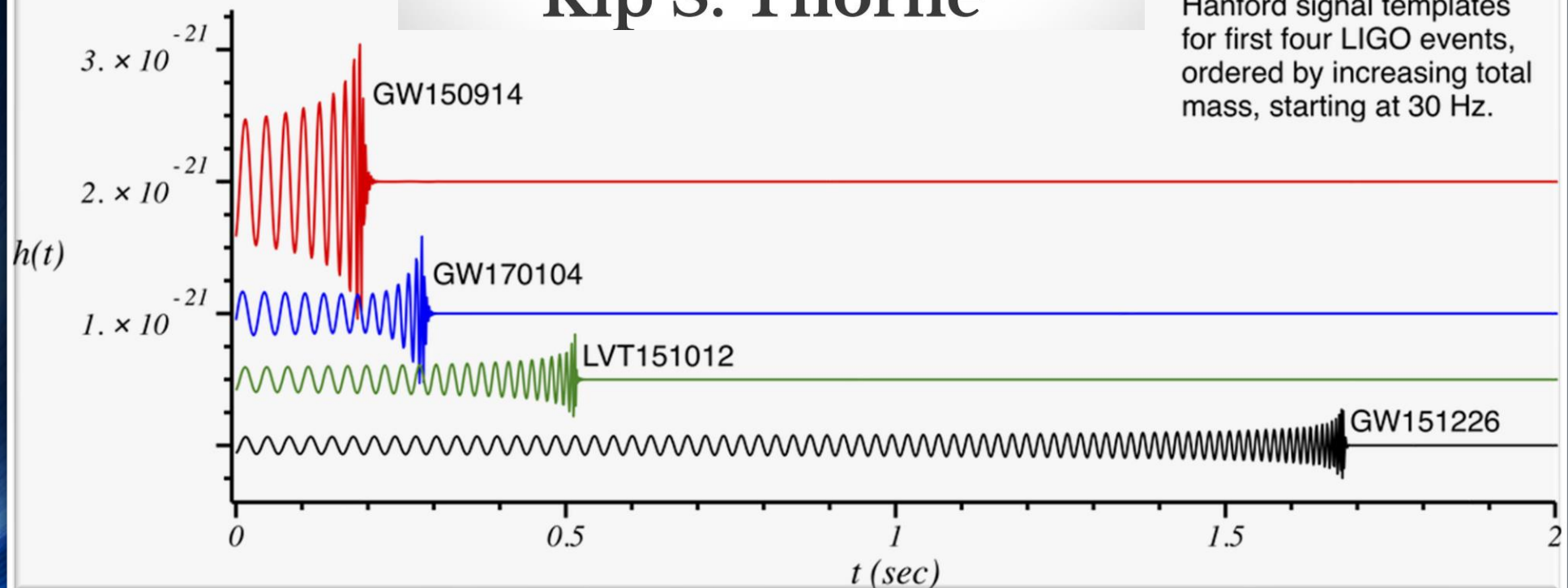
Abstand zur Erde 410 Mpc
(1.34 Milliarden Lichtjahre)



2017 NOBEL PRIZE IN PHYSICS

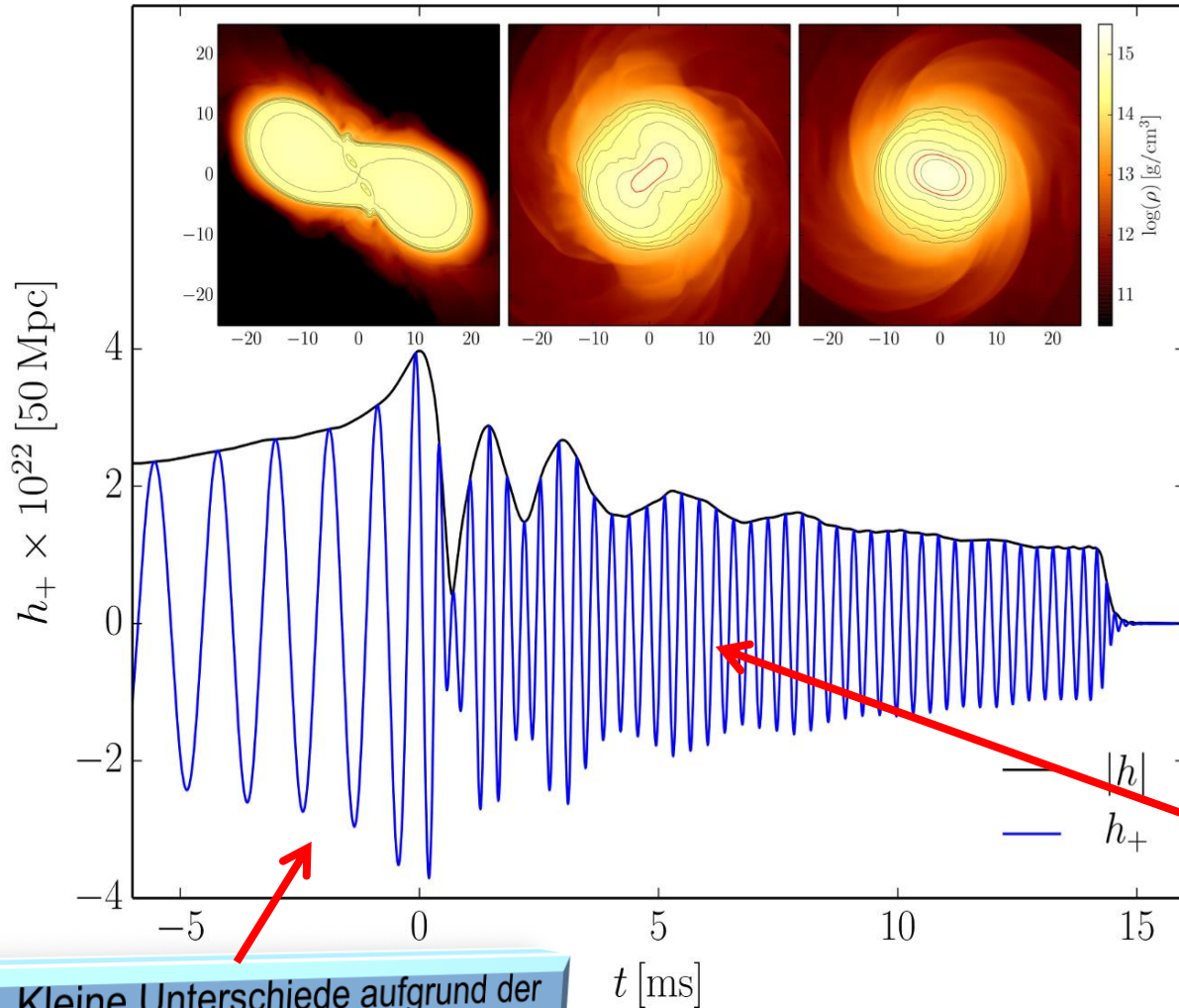


Rainer Weiss
Barry C. Barish
Kip S. Thorne

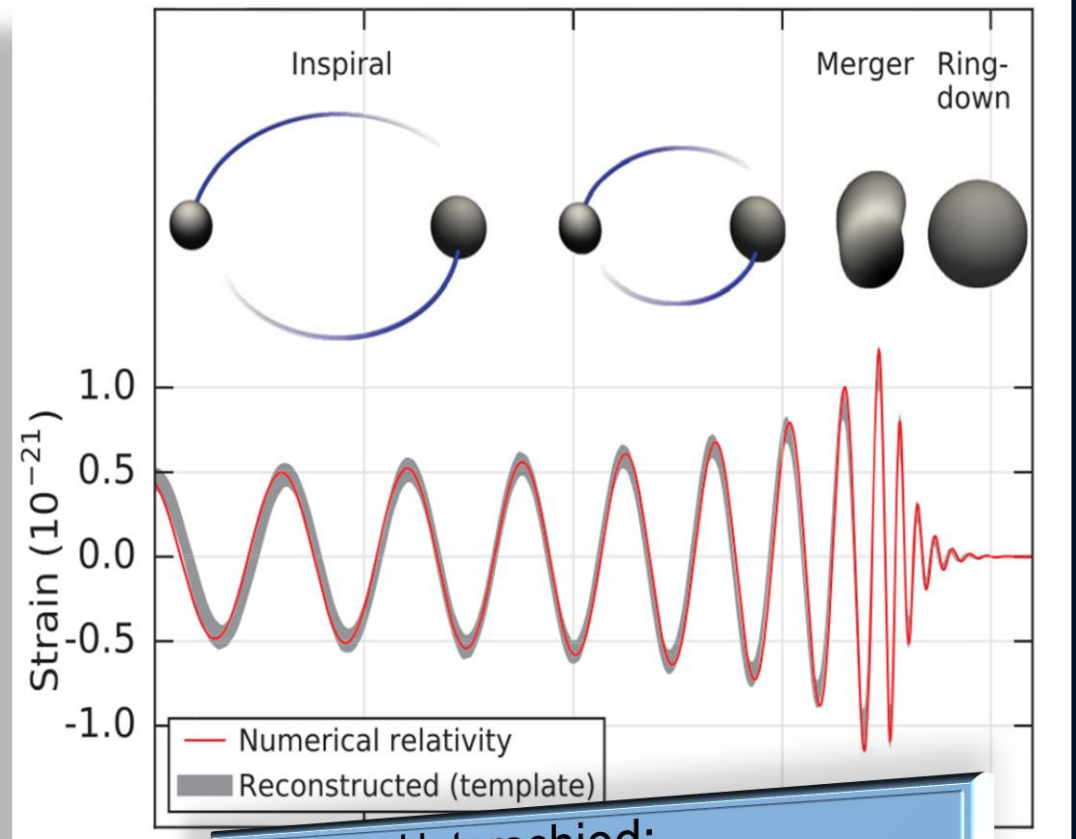


Gravitationswellen von Neutronenstern Kollisionen

Neutronenstern Kollision (Simulation)



Kollision zweier schwarzer Löcher



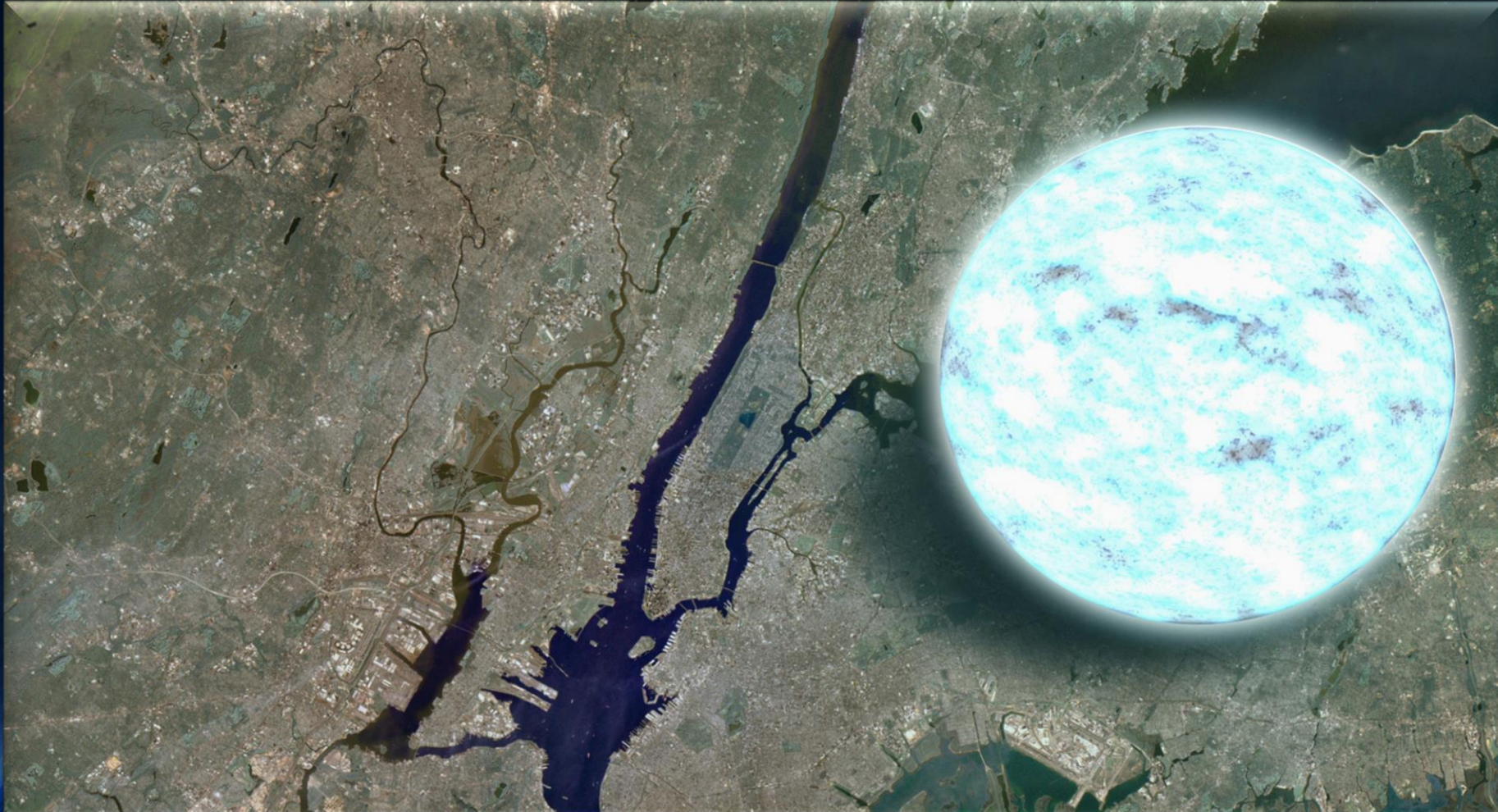
Unterschied:
Bei Neutronenstern Kollisionen
gibt es oft eine
Post-Kollisionsphase

Kleine Unterschiede aufgrund der
Verformbarkeit der Neutronensterne

Neutronensterne: Sehr klein und sehr schwer

Radius ~ 10 km, Masse ~ 1 -2 Sonnenmassen

Riesige Magnetfelder $\sim 10^{11}$ Tesla, schnell rotierend (bis zu 716 Hz)

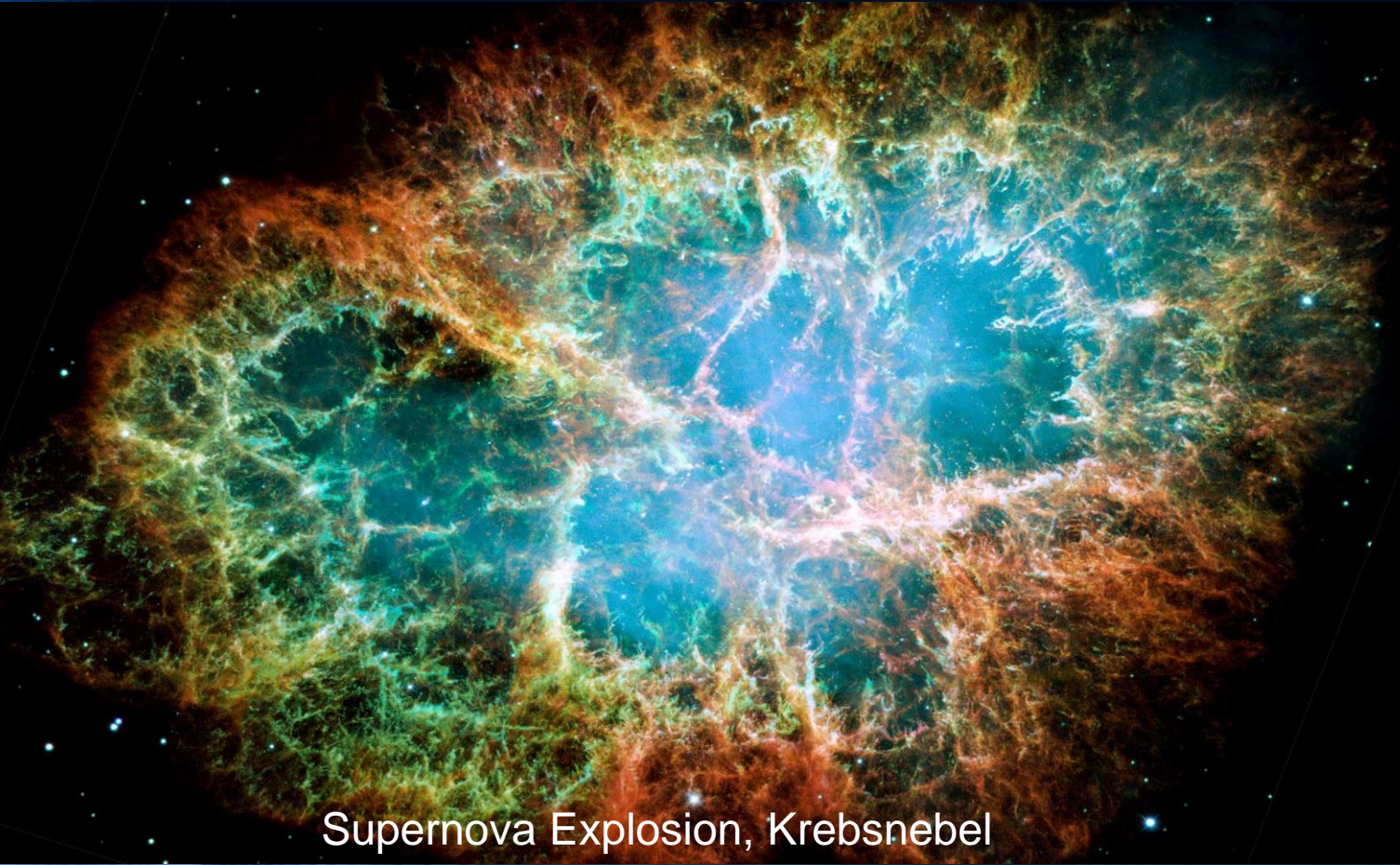


Wie entstehen Neutronensterne?

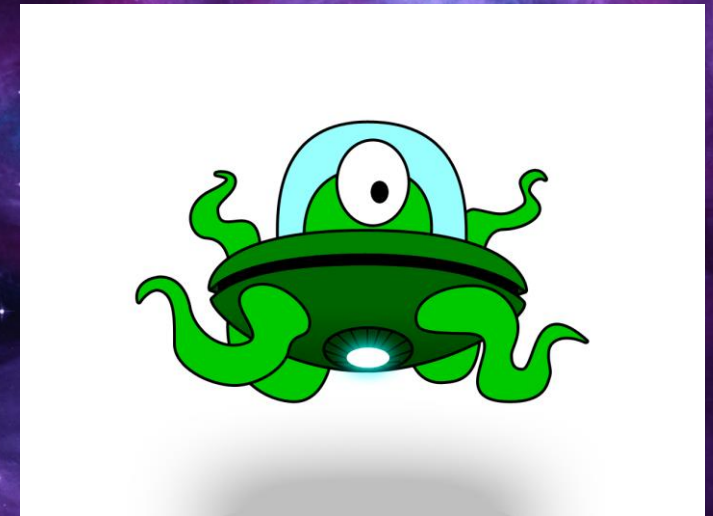
Neutronensterne entstehen in einer Supernova Explosion. Sonnen, die mindestens 8-mal schwerer als unsere Sonne sind explodieren am Ende ihrer Lebenszeit in einer Supernova Explosion – im Zentrum bleibt ein Neutronenstern oder ein schwarzes Loch zurück.



Im Zentrum des Nebels
ist ein Neutronenstern

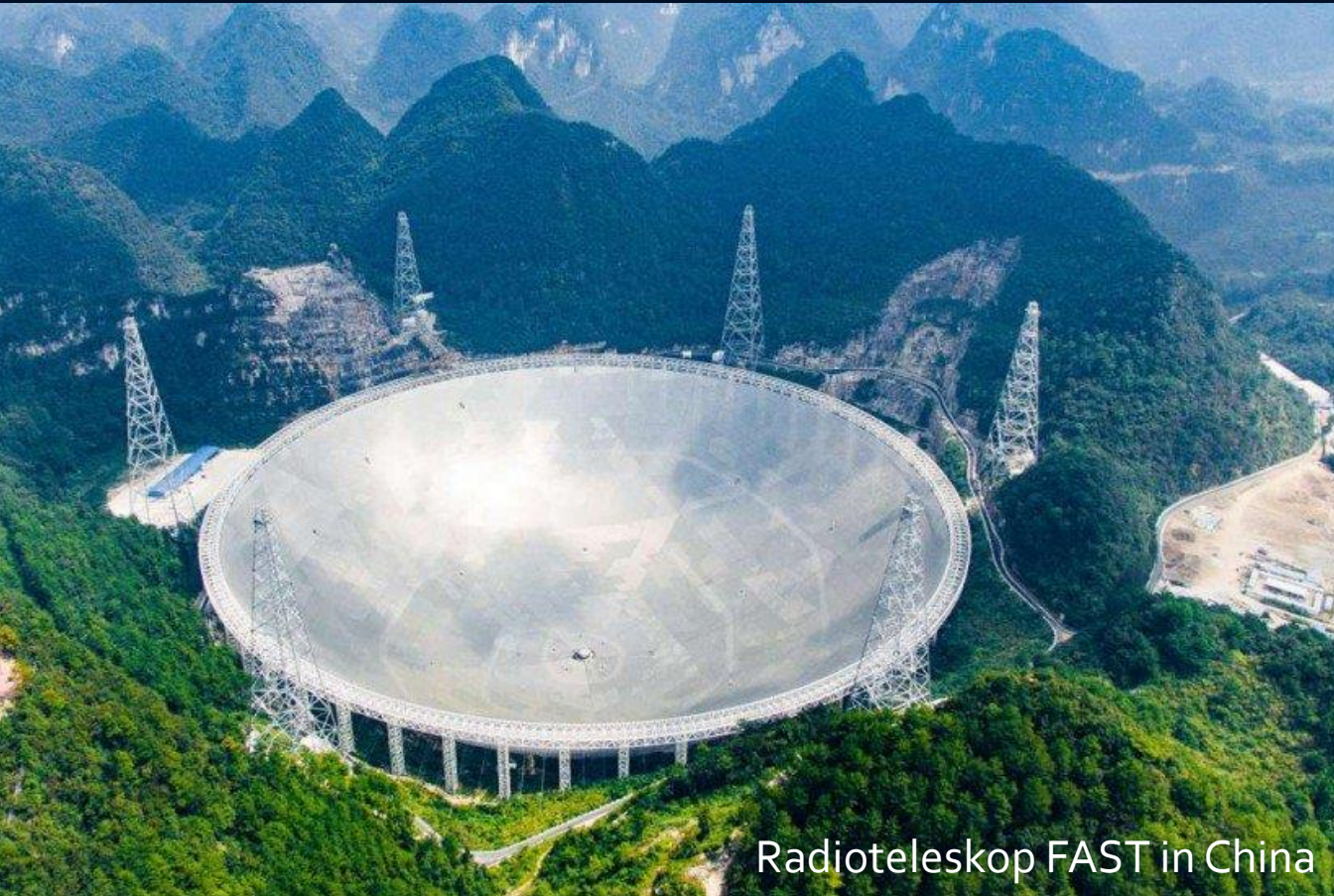


Supernova Explosion, Krebsnebel



Krebsnebel (Röntgenteleskop Chandra)

Pulsare sind Rotierende Neutronensterne mit starkem Magnetfeld



Radioteleskop FAST in China



Radioteleskop in Effelsberg

Der erste Pulsar wurde im Jahre 1967 entdeckt (PSR 1919+21, Jocelyn Bell) und wurde zunächst LGM-1 genannt

In den letzten 50 Jahren konnten mittels Radioteleskopen ca. 3000 rotierende Neutronensterne (Pulsare) gefunden werden.

Man unterscheidet
Sekundenpulsare
und
Millisekunden-Pulsare



PSR B0329+54 (0.715 s)



PSR B0531+21 (33.5 ms)



PSR B1937+21 (1.56 ms)

Binäre Neutronenstern Systeme

Zurzeit kennt man ca. 25
binäre Neutronenstern Systeme

Beispiel:

Der **Double Pulsar**

(PSR J0737-3039A/B):

Entdeckt im Jahre 2003

Eccentricity: 0.088

Pulsar A: $P=23$ ms, $M=1.3381(7)$

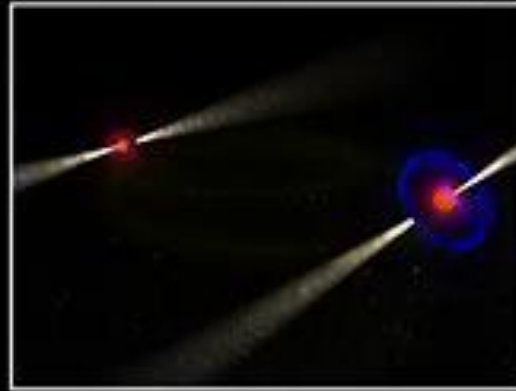
Pulsar B: $P=2.7$ s, $M=1.2489(7)$

Abstand zwischen den Sternen nur
800,000 km

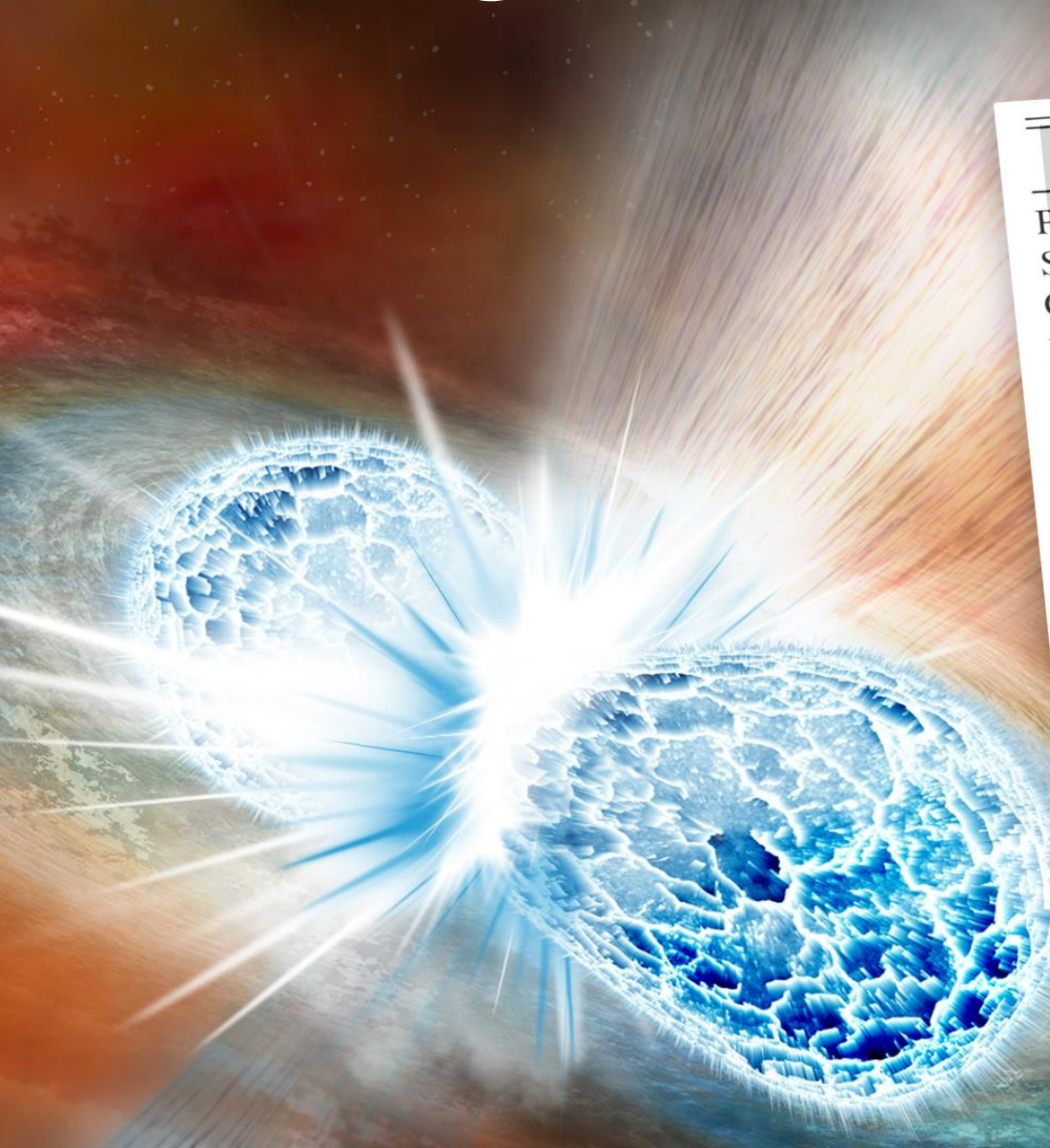
Orbitale Periode: 147 Minuten

Abstand verkleinert sich langsam
aufgrund der Abstrahlung von
Gravitationswellen

Die beiden Neutronensterne
werden erst in 85 Millionen
Jahren kollidieren



Das lang ersehnte Ereignis GW170817



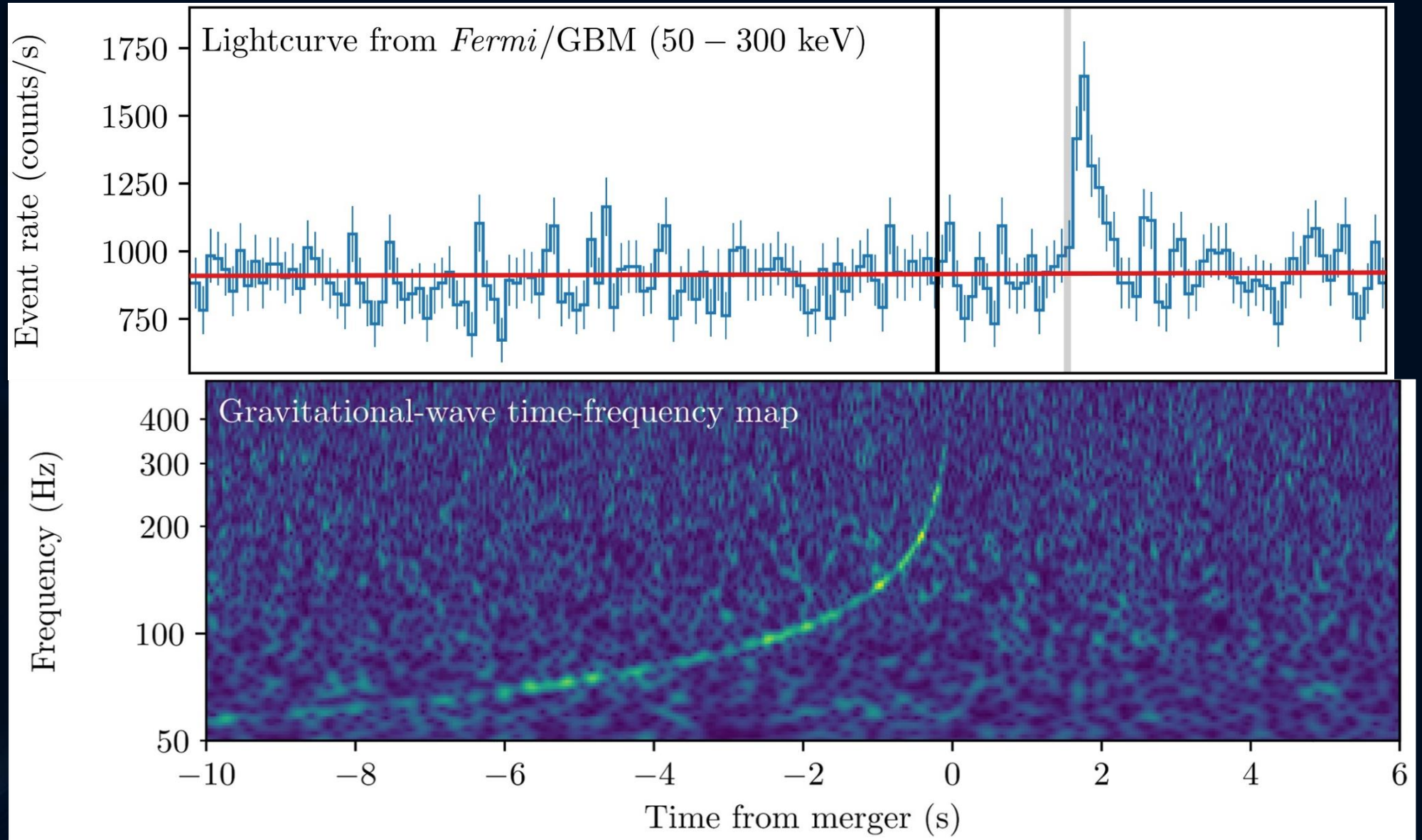
	Low-spin priors ($ \chi \leq 0.05$)	High-spin priors ($ \chi \leq 0.89$)
Primary mass m_1	1.36–1.60 M_\odot	1.36–2.26 M_\odot
Secondary mass m_2	1.17–1.36 M_\odot	0.86–1.36 M_\odot
Chirp mass \mathcal{M}	$1.188^{+0.004}_{-0.002} M_\odot$	$1.188^{+0.004}_{-0.002} M_\odot$
Mass ratio m_2/m_1	0.7–1.0	0.4–1.0
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	$\leq 55^\circ$	$\leq 56^\circ$
Using NGC 4993 location	$\leq 28^\circ$	$\leq 28^\circ$
Combined dimensionless tidal deformability $\tilde{\Lambda}$	≤ 700	≤ 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)



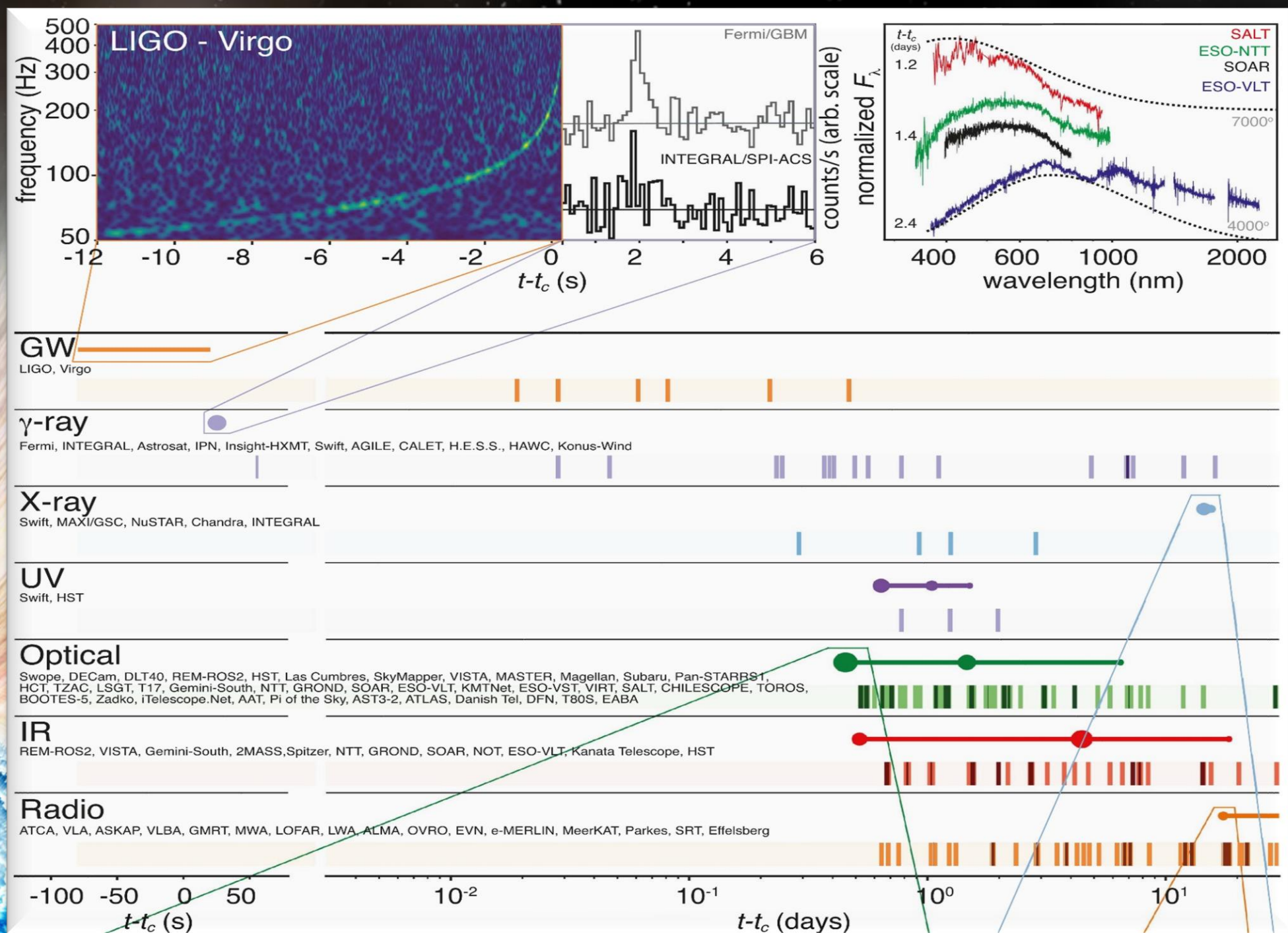
Die von dem
Gravitationswellen
Detektor LIGO
detektierte
Frequenz der
Gravitationswelle



GW170817

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)



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 ???

**Black
Hole**

$M_1 \sim 23 M_\odot$

**Neutron
Star**

& ?

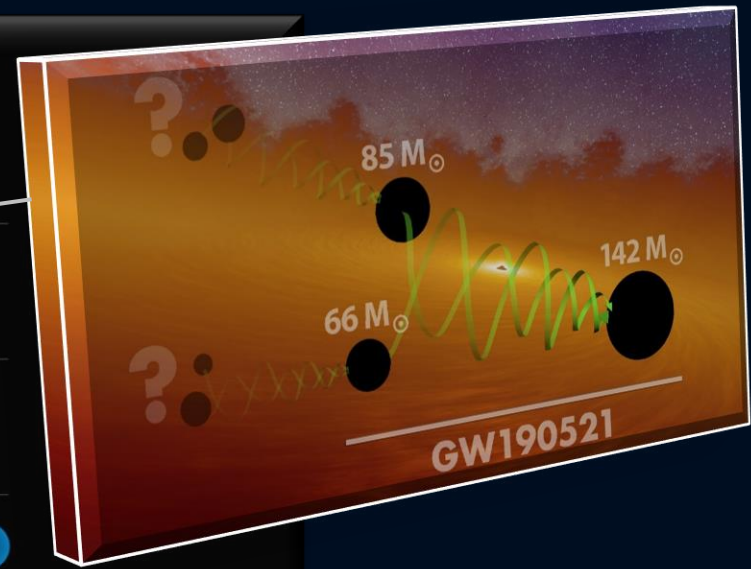
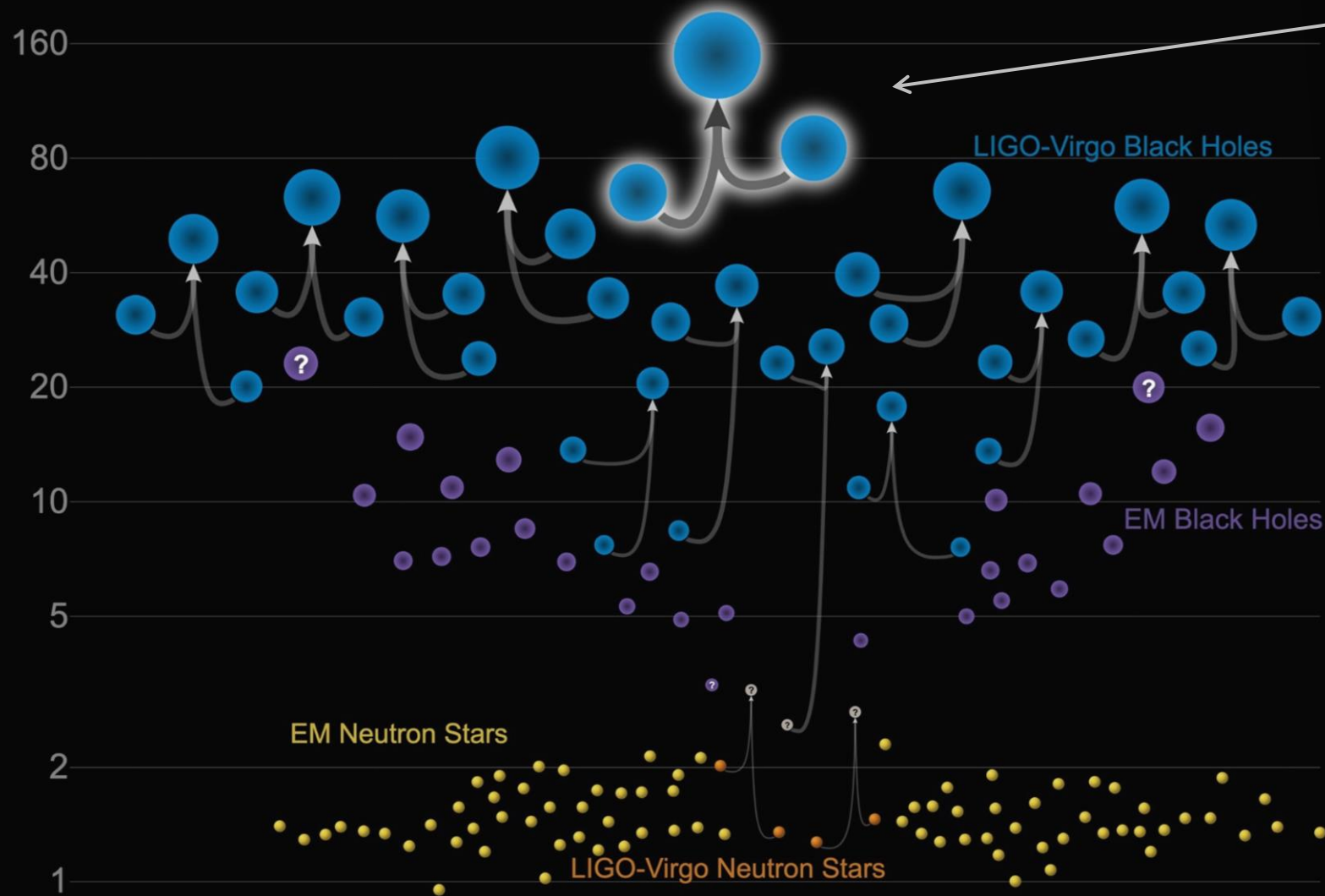
**Black
Hole**

$M_2 \sim 2.6 M_\odot$

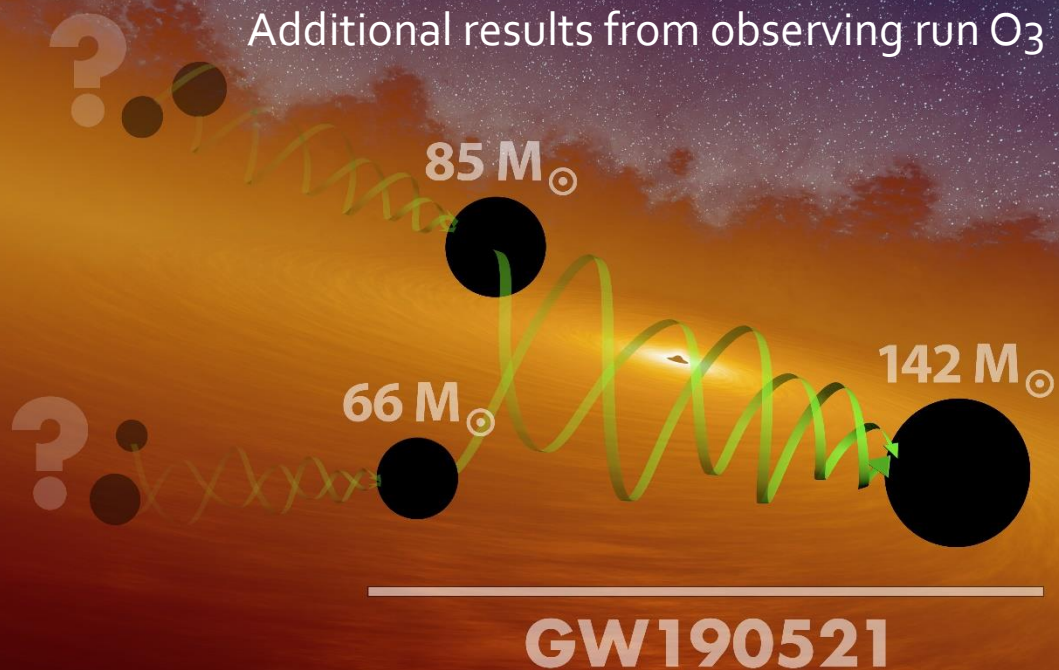
14. August 2019

Masses in the Stellar Graveyard

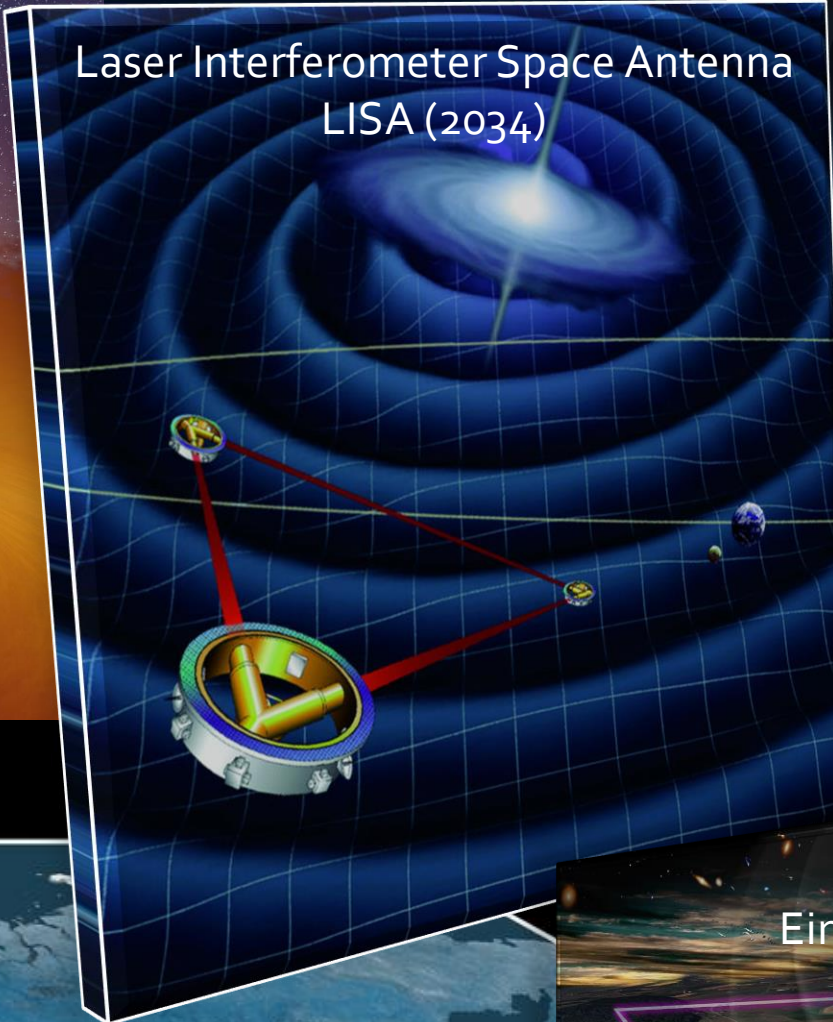
in Solar Masses



Additional results from observing run O₃



Laser Interferometer Space Antenna
LISA (2034)



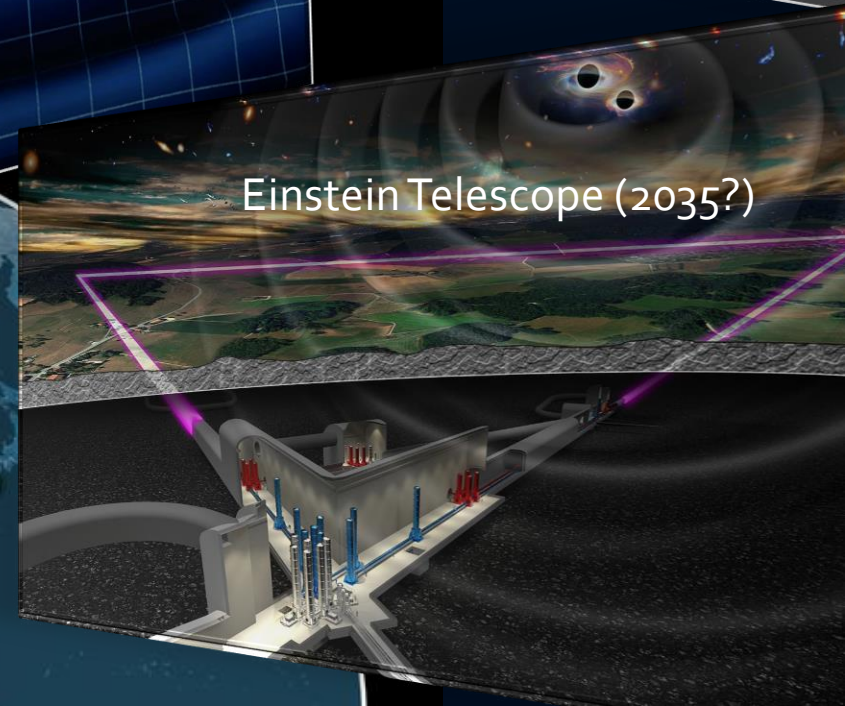
Cosmic Explorer (2035?)



The next observing runs (O₄, O₅, ..)

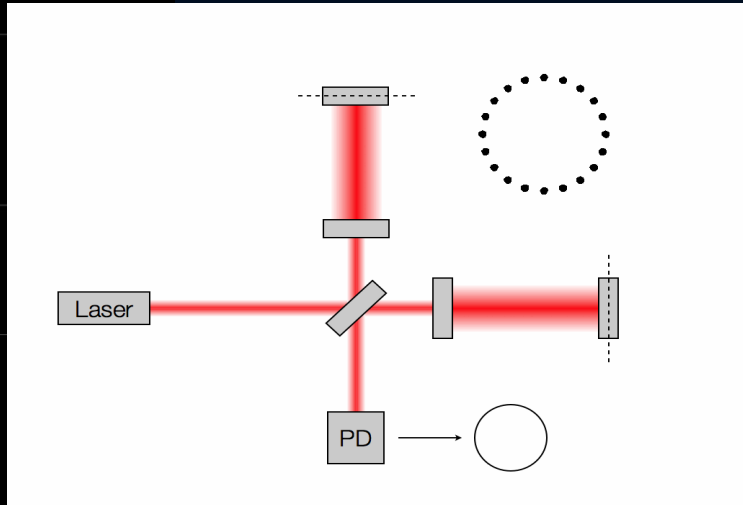
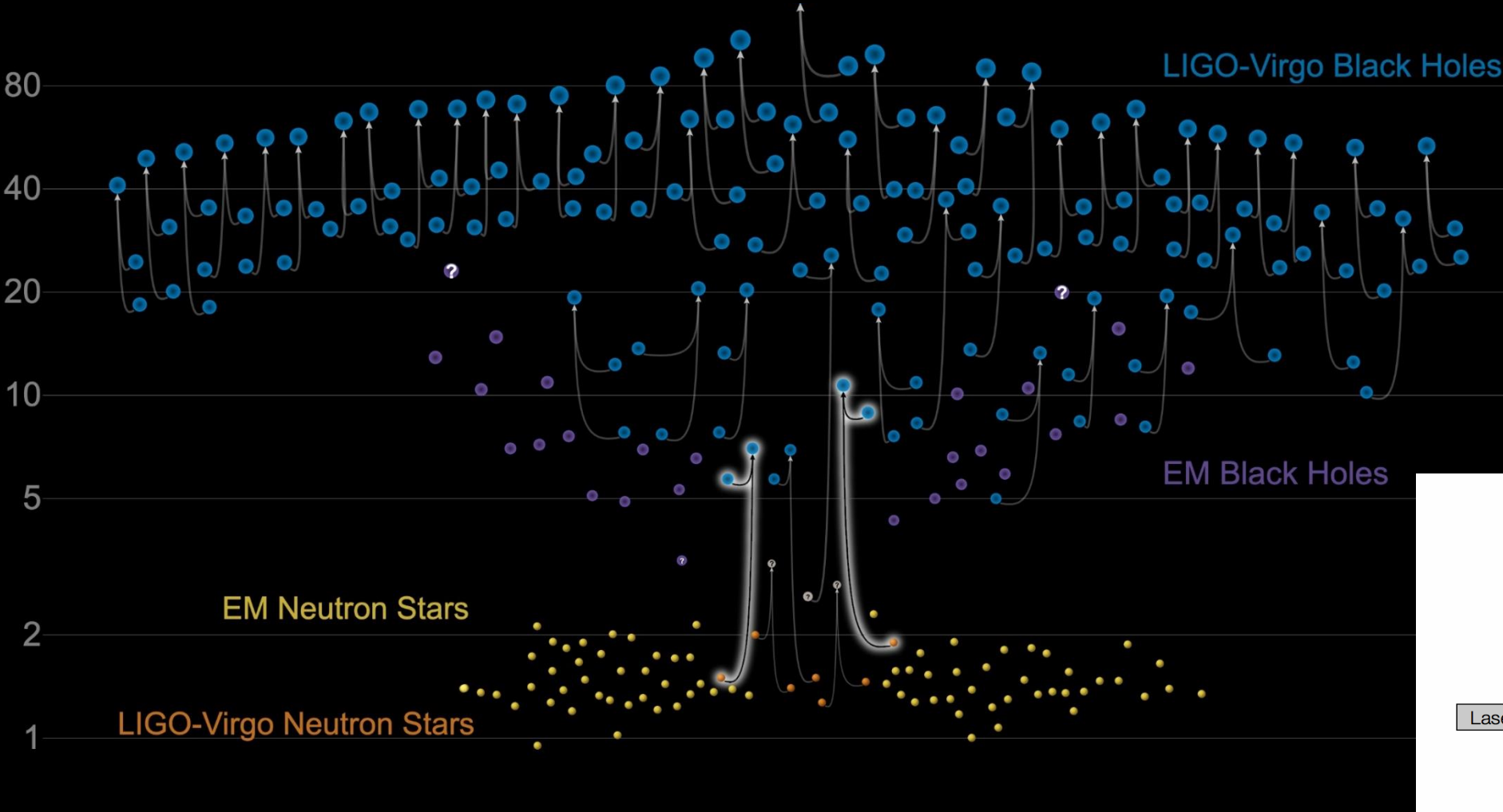
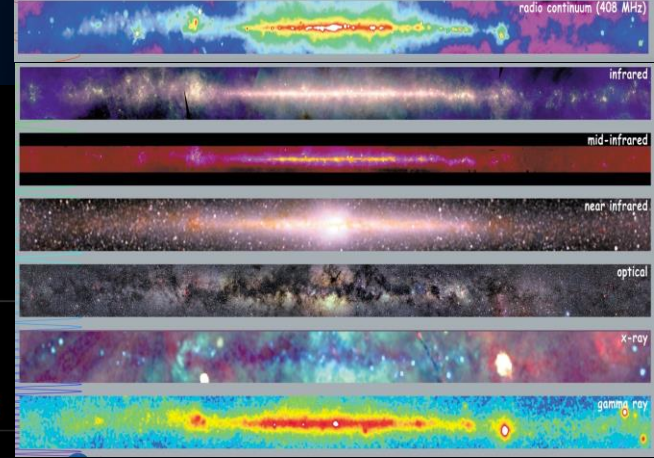


Einstein Telescope (2035?)



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

It is as if humanity has wondrous new glasses, a new sensory organ, with which to perceive previously unobservable events in our universe
first GW- detection 2015

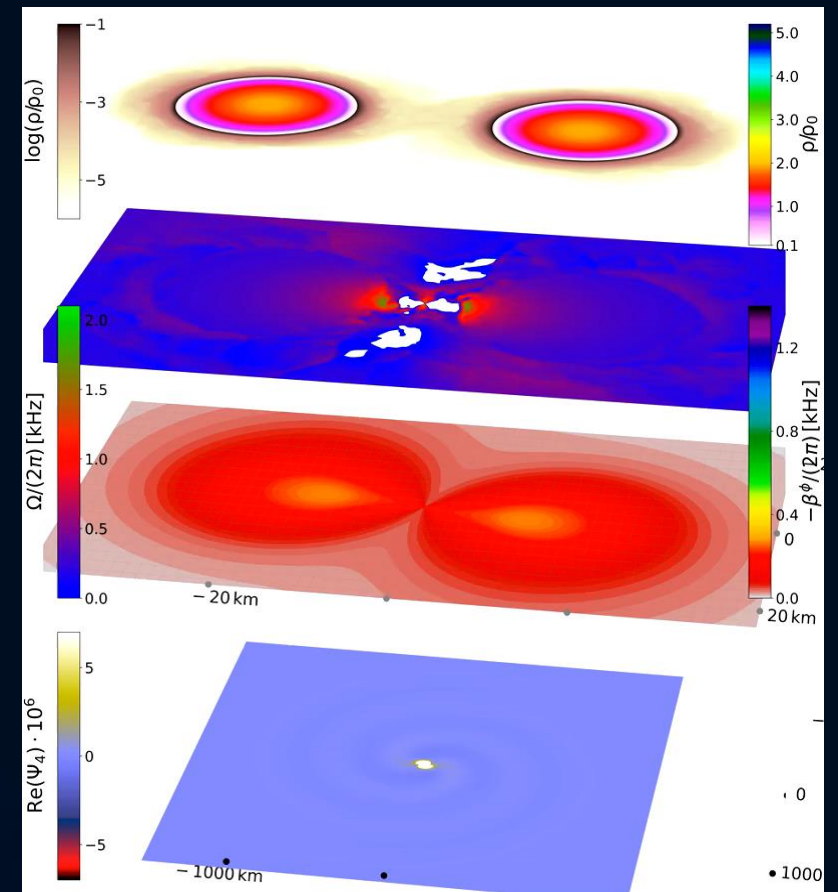
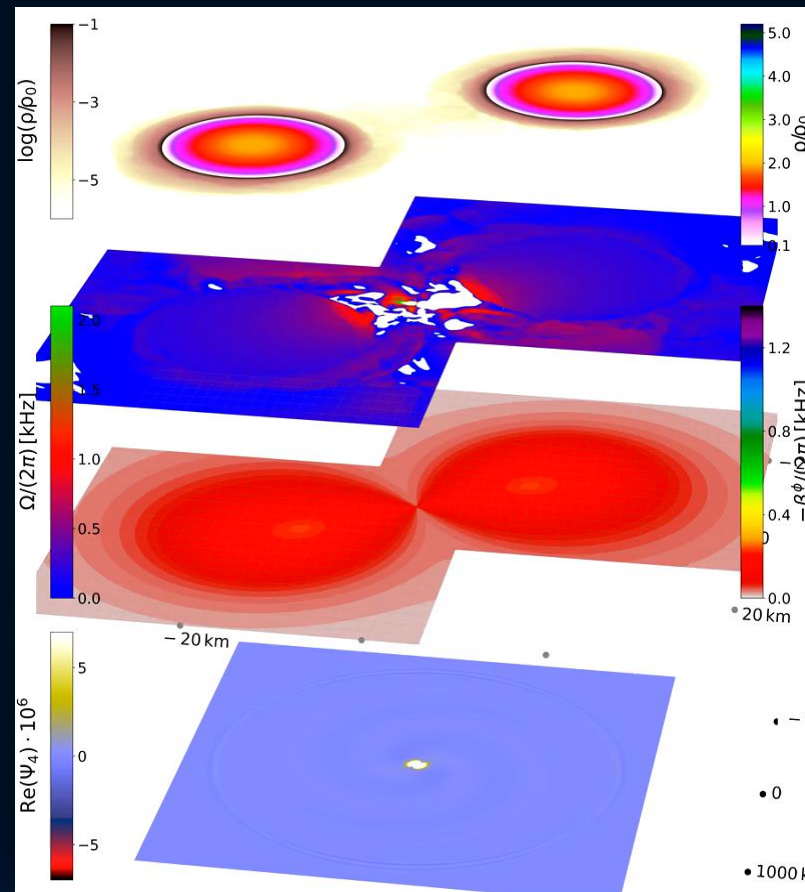
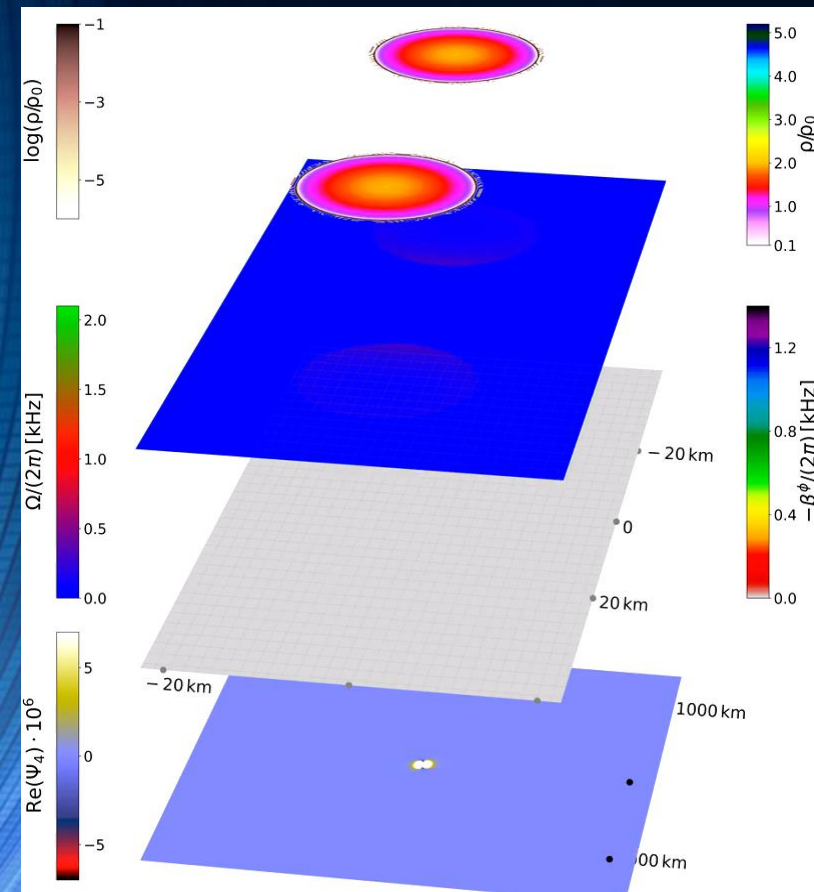


Music by
Eric Prydz
Opus
(9 min, inspiral phase ~1/3)

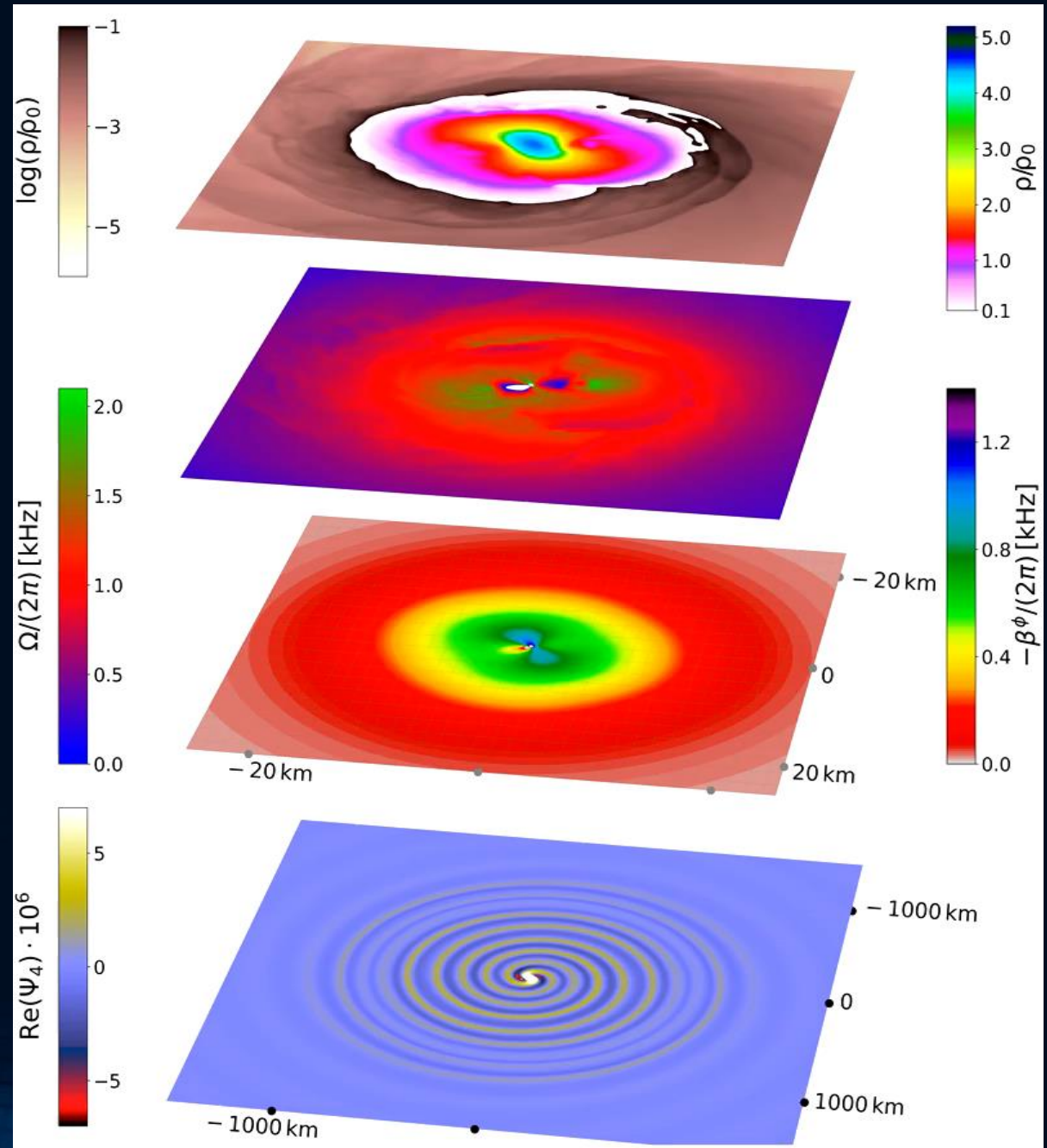
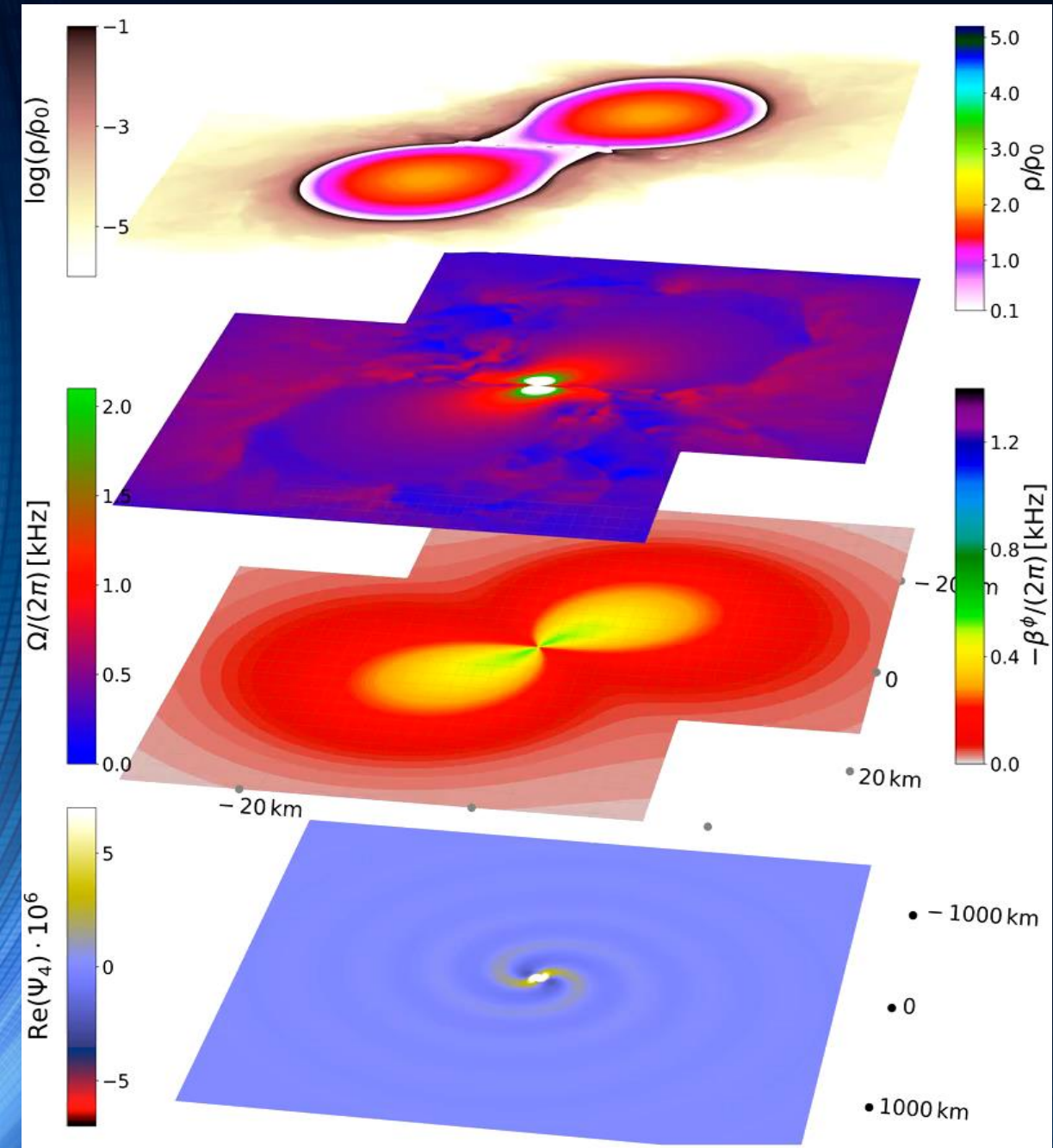


Binary neutron star systems and gravitational waves

Inspiral Phase



Post-Merger Phase

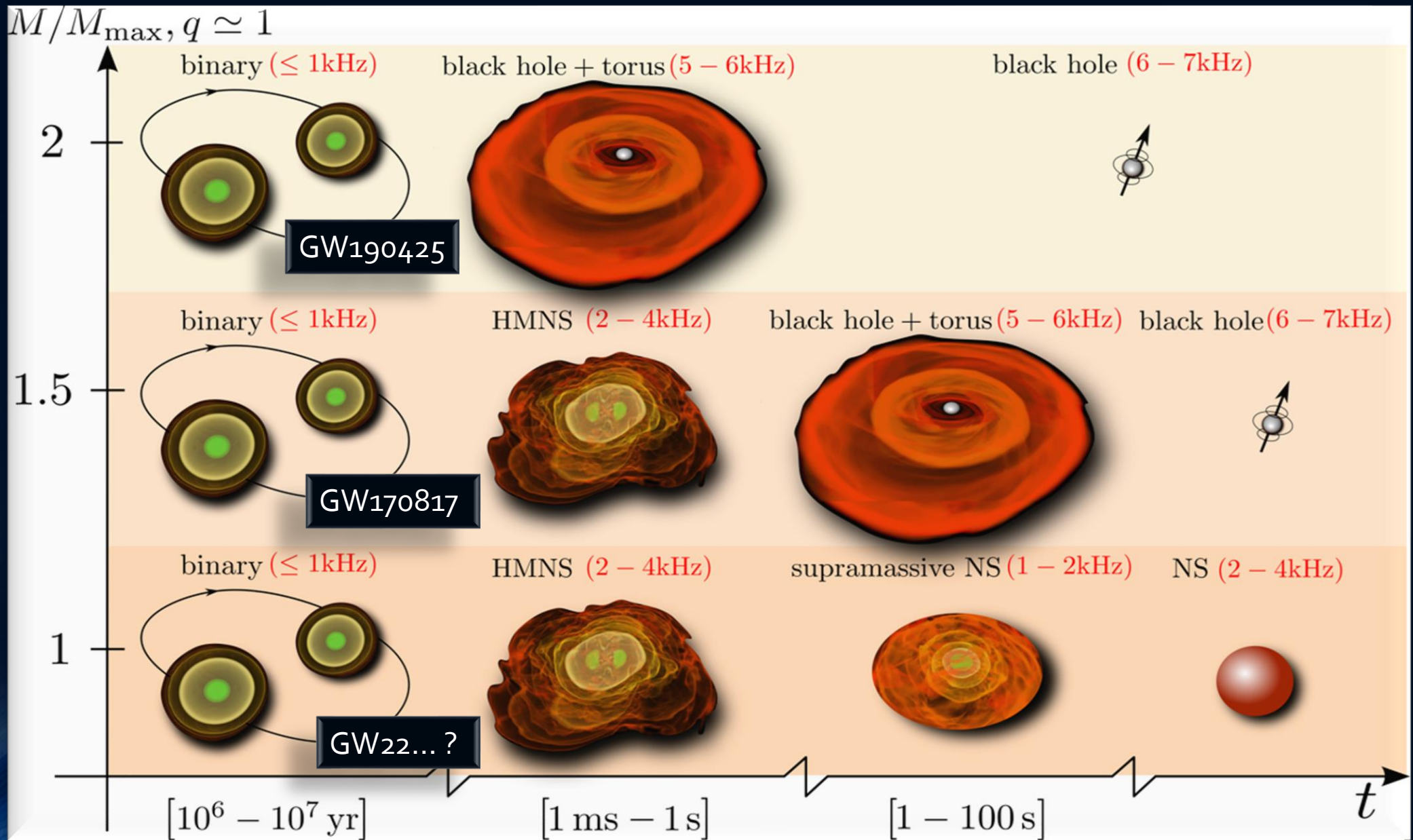


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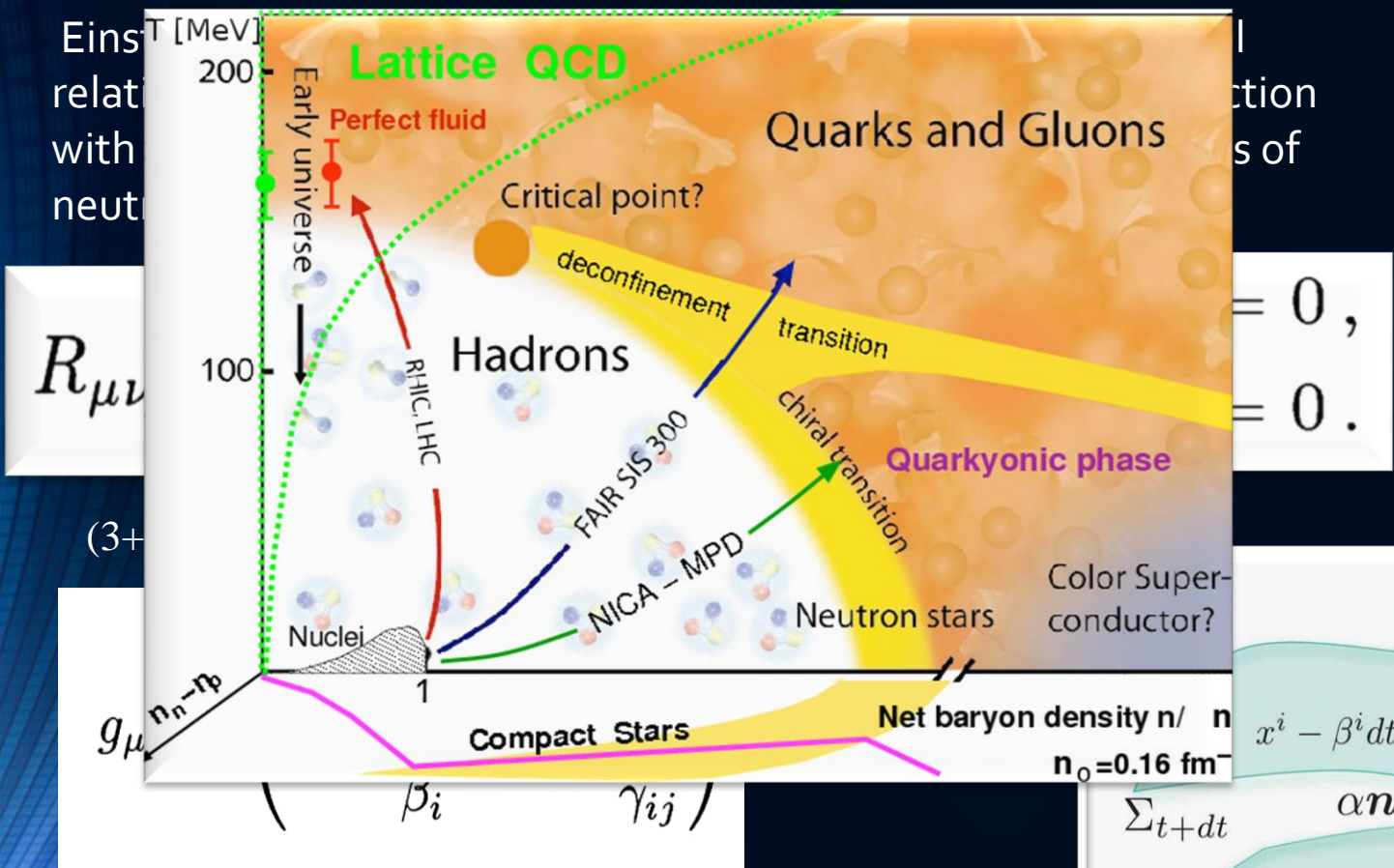
Zwei sehr massive Neutronensterne

Zwei mittelschwere Neutronensterne

Zwei leichte Neutronensterne



Numerical Relativity and Relativistic Hydrodynamics of Binary Neutron Star Mergers

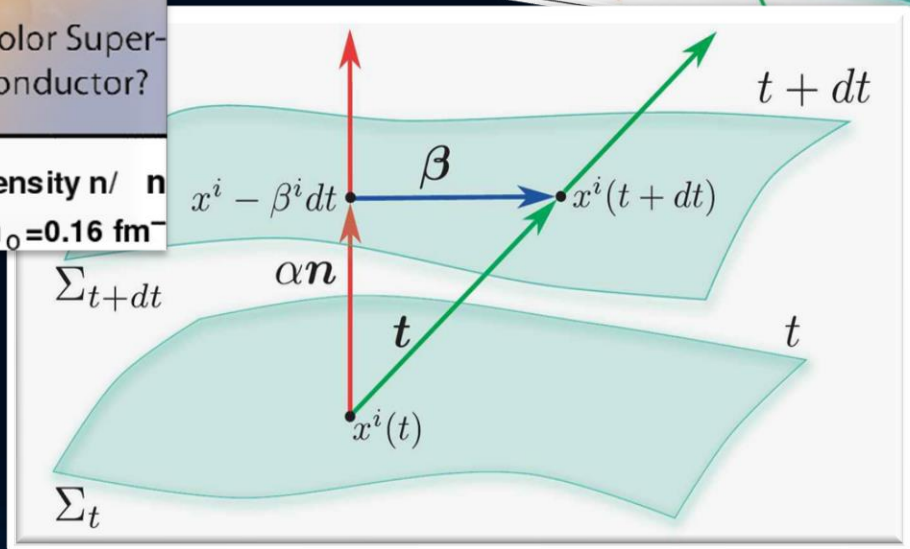
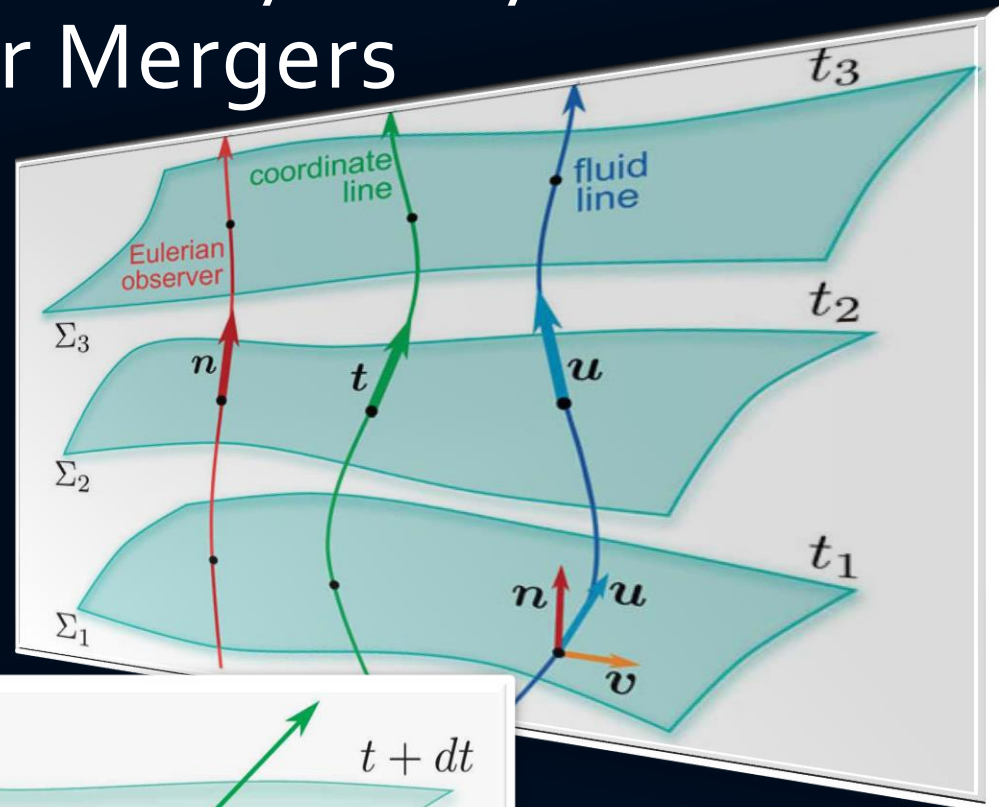


$$d\tau^2 = \alpha^2(t, x^j) dt^2$$

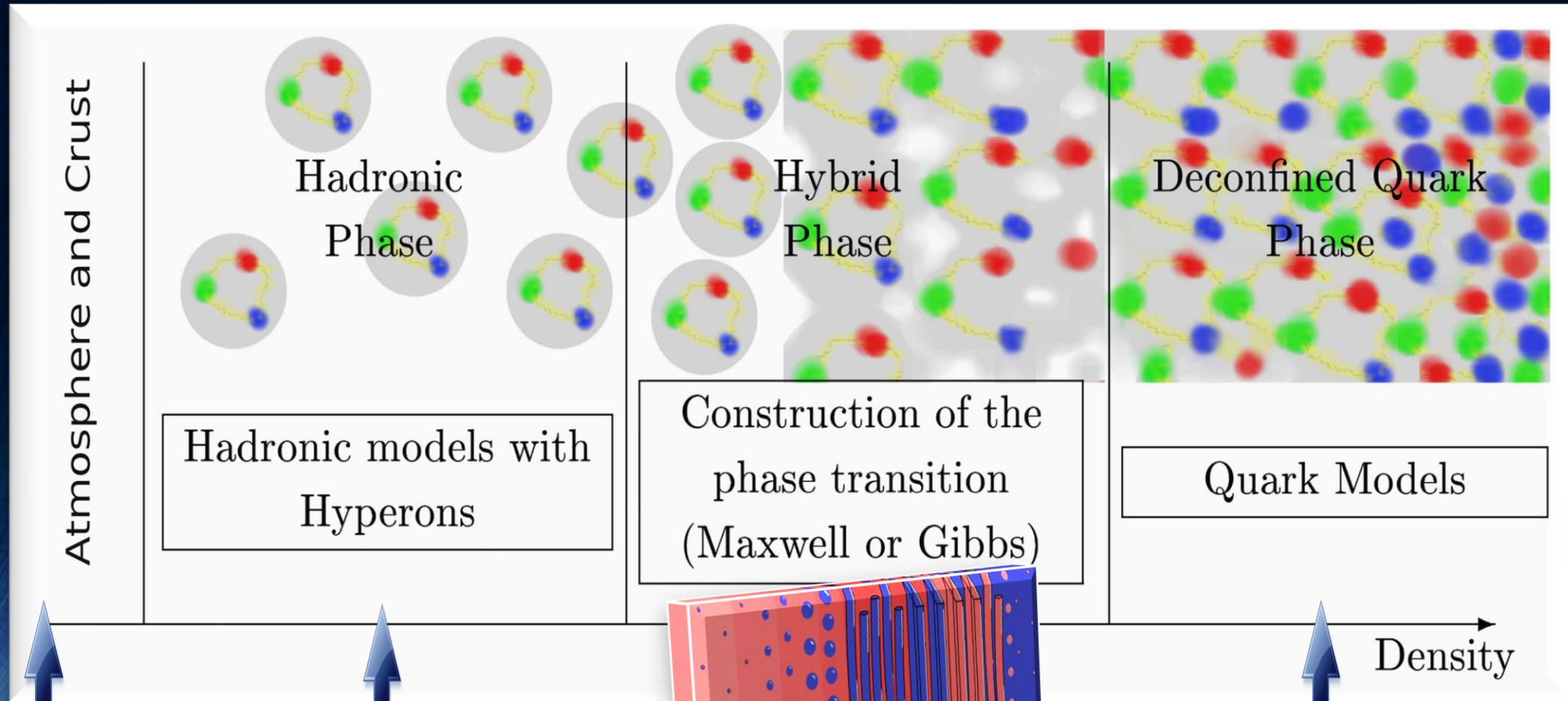
$$x^i_{t+dt} = x^i_t - \beta^i(t, x^j) dt$$

$$= 0,$$

$$= 0.$$

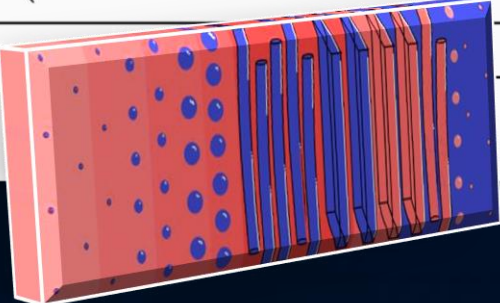


Das Innere von hybriden Sternen



Äußere Eisenkruste

Neutronen und einige Protonen, Elektronen vielleicht auch Hyperonen

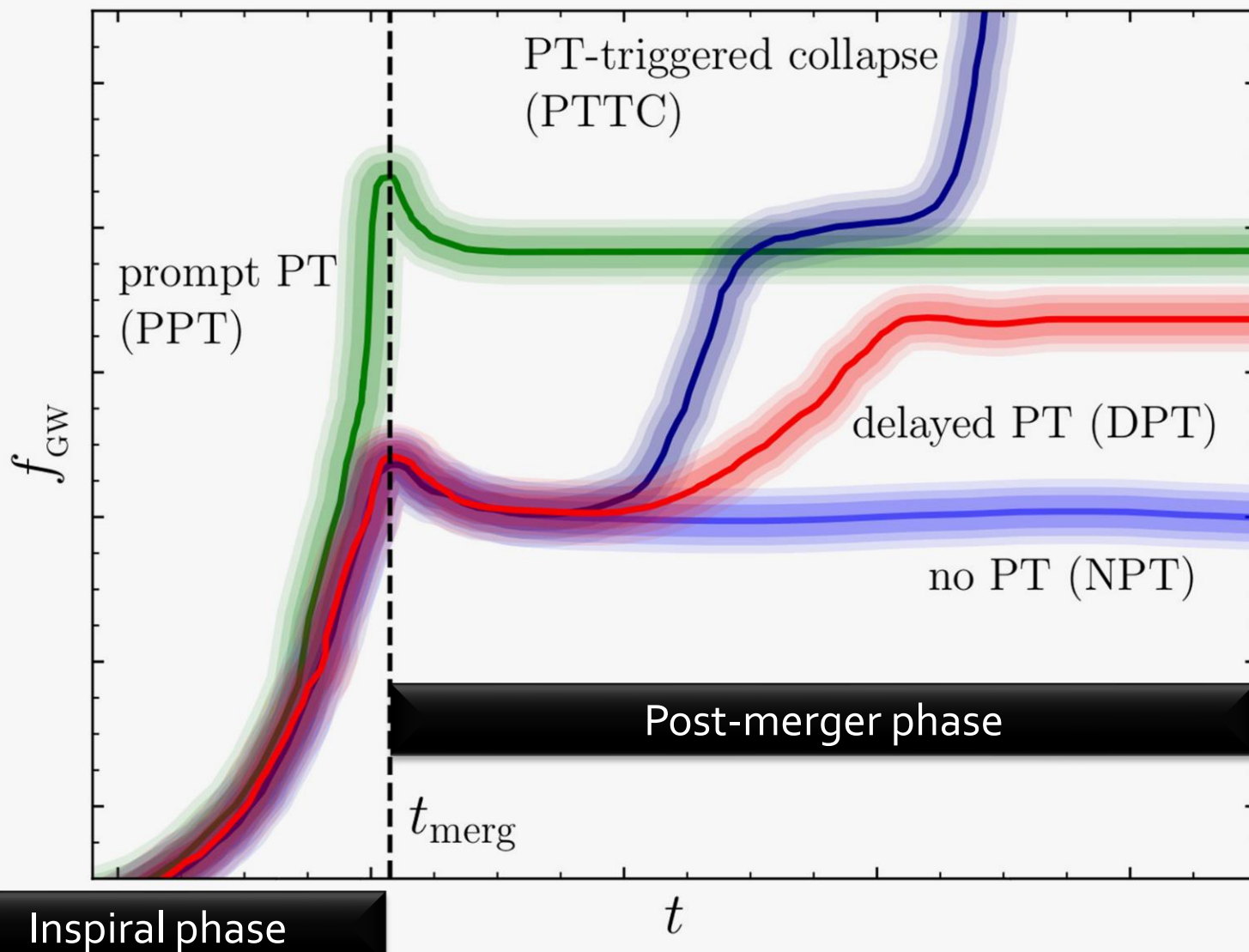


Phasenübergang vielleicht Pasta-Struktur

Befreite reine Quarkphase

Density

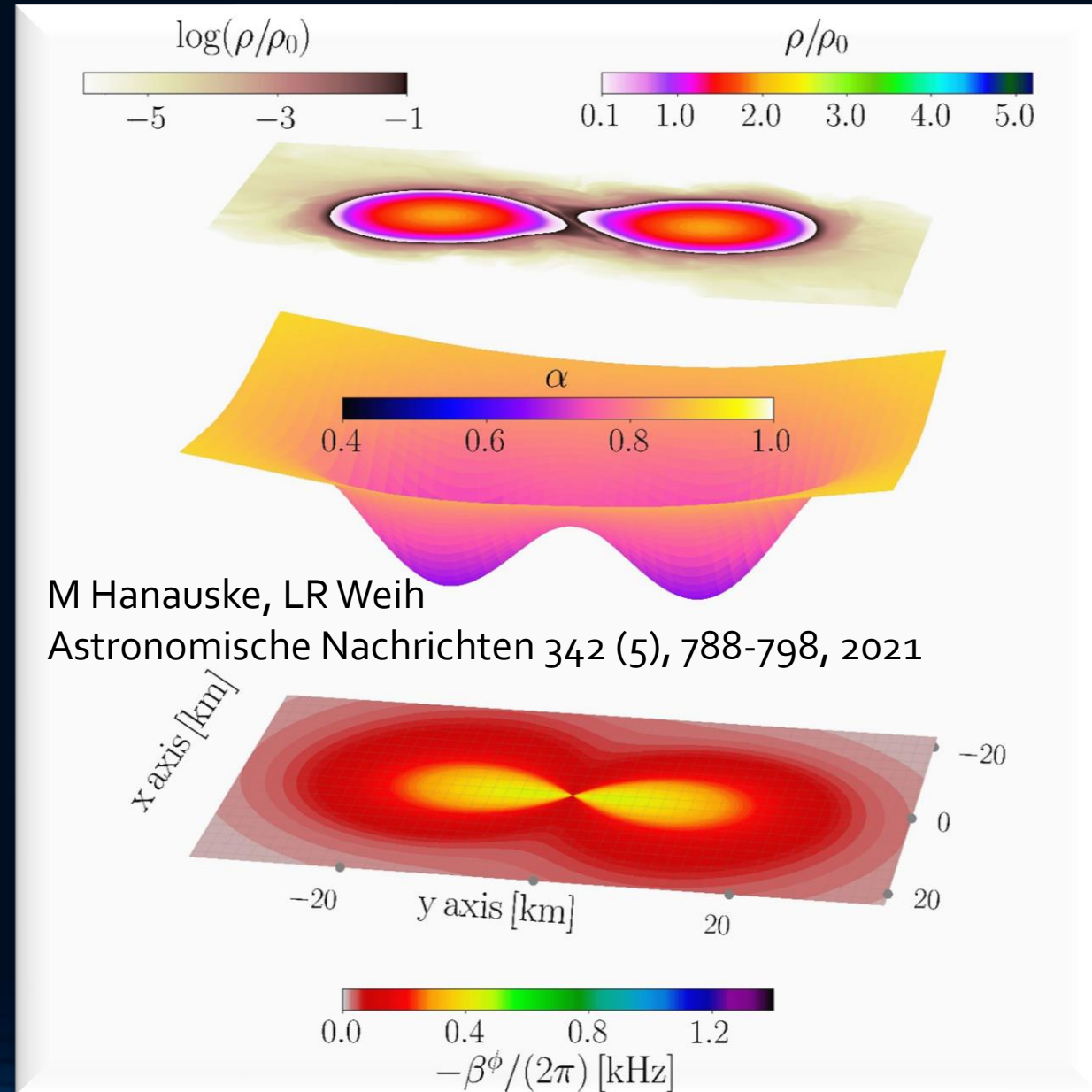
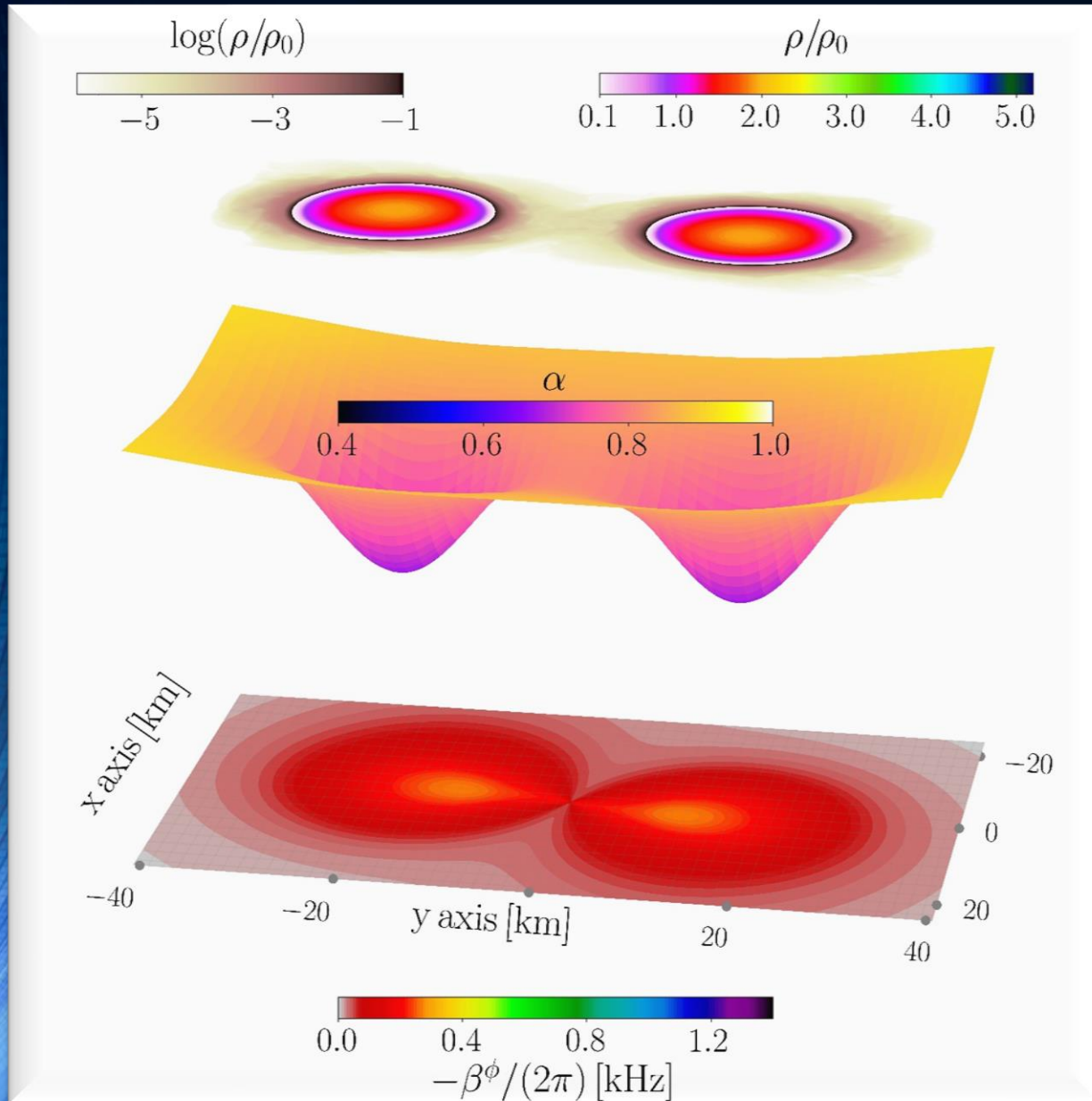
Post-merger gravitational-wave signatures of phase transitions in binary compact star mergers



PRL 124, 171103 (2020)

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

The late inspiral phase (density, lapse and shift)



Computer Simulation of a neutron star merger

Credits: Cosima Breu, David Radice und Luciano Rezzolla

„Opus“ von Eric Prydz
Das Ende der ‚inspiral phase‘ : Der Kollisionszeitpunkt



Log of density

8.5 14



$\lg(\rho)$ [g/cm³]

Temperature

0 50



T [MeV]

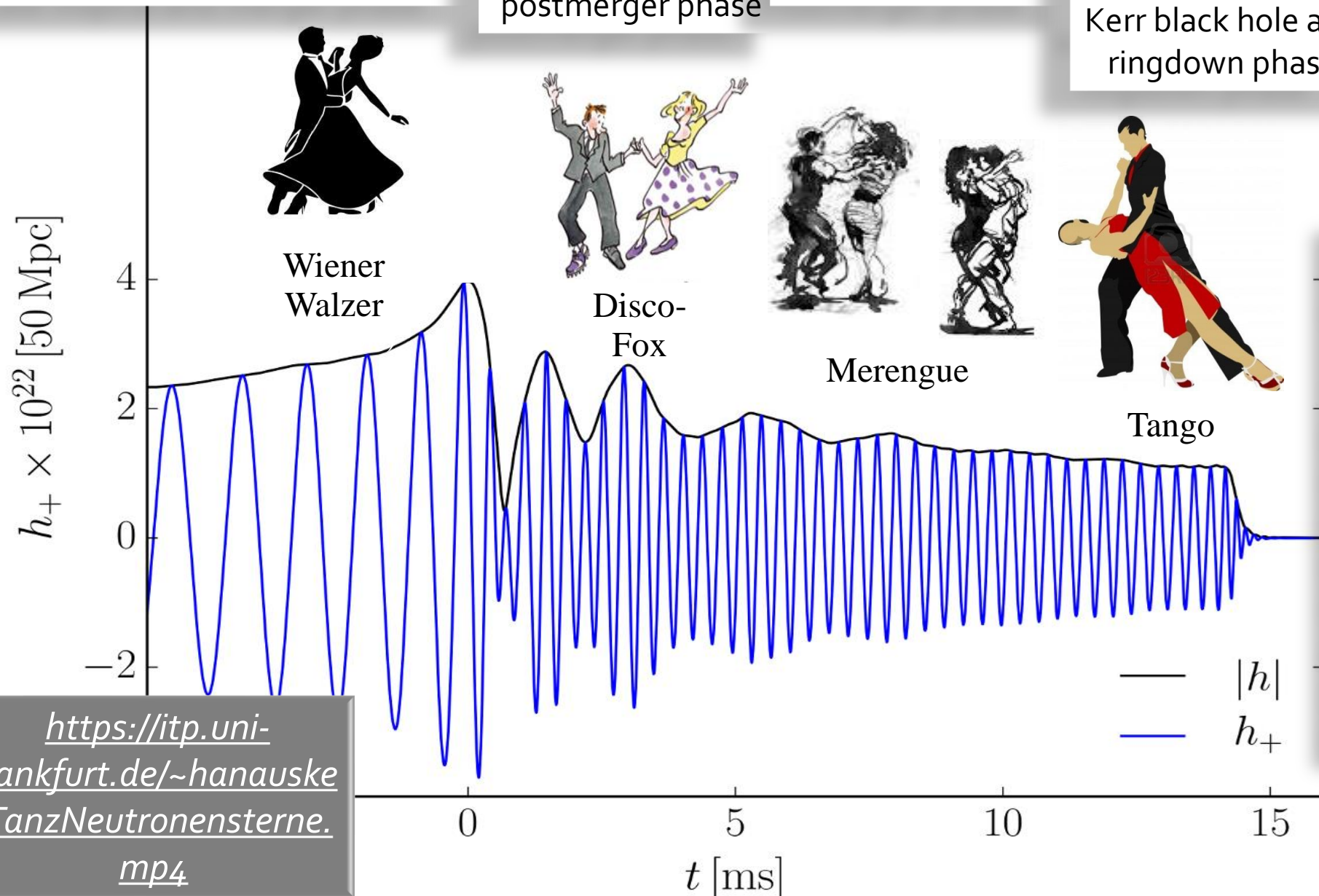
The different Phases of a Binary Compact Star Merger Event

Late inspiral and merger phase

Transient early postmerger phase

Postmerger phase

Collapse to the Kerr black hole and ringdown phase

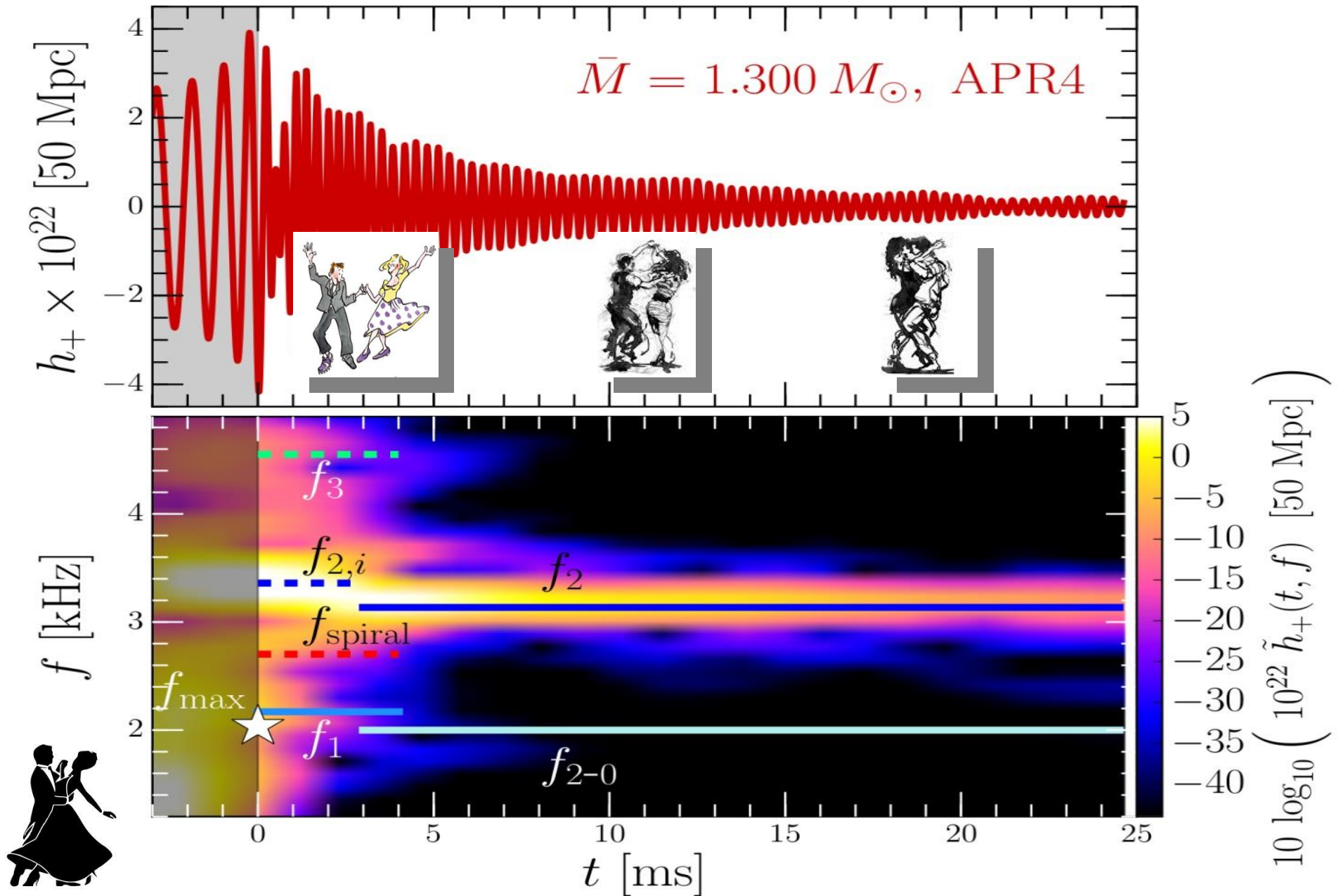


*Why exactly these dances?
Details in*

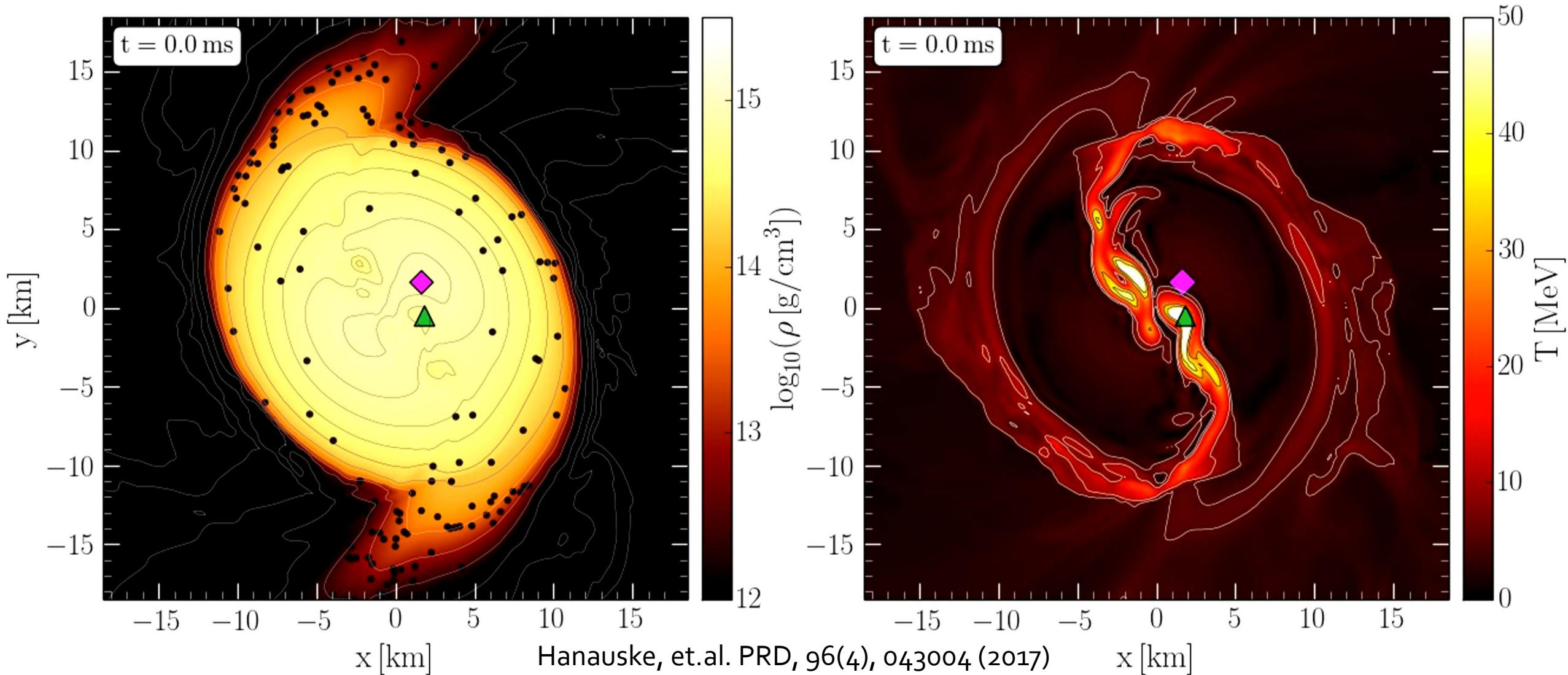
"Binary Compact Star Mergers and the Phase Diagram of Quantum Chromodynamics", Matthias Hanauske and Horst Stöcker, Discoveries at the Frontiers of Science, 107-132; Springer, Cham (2020)

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

The different Phases during the Postmergerphase of the HMNS



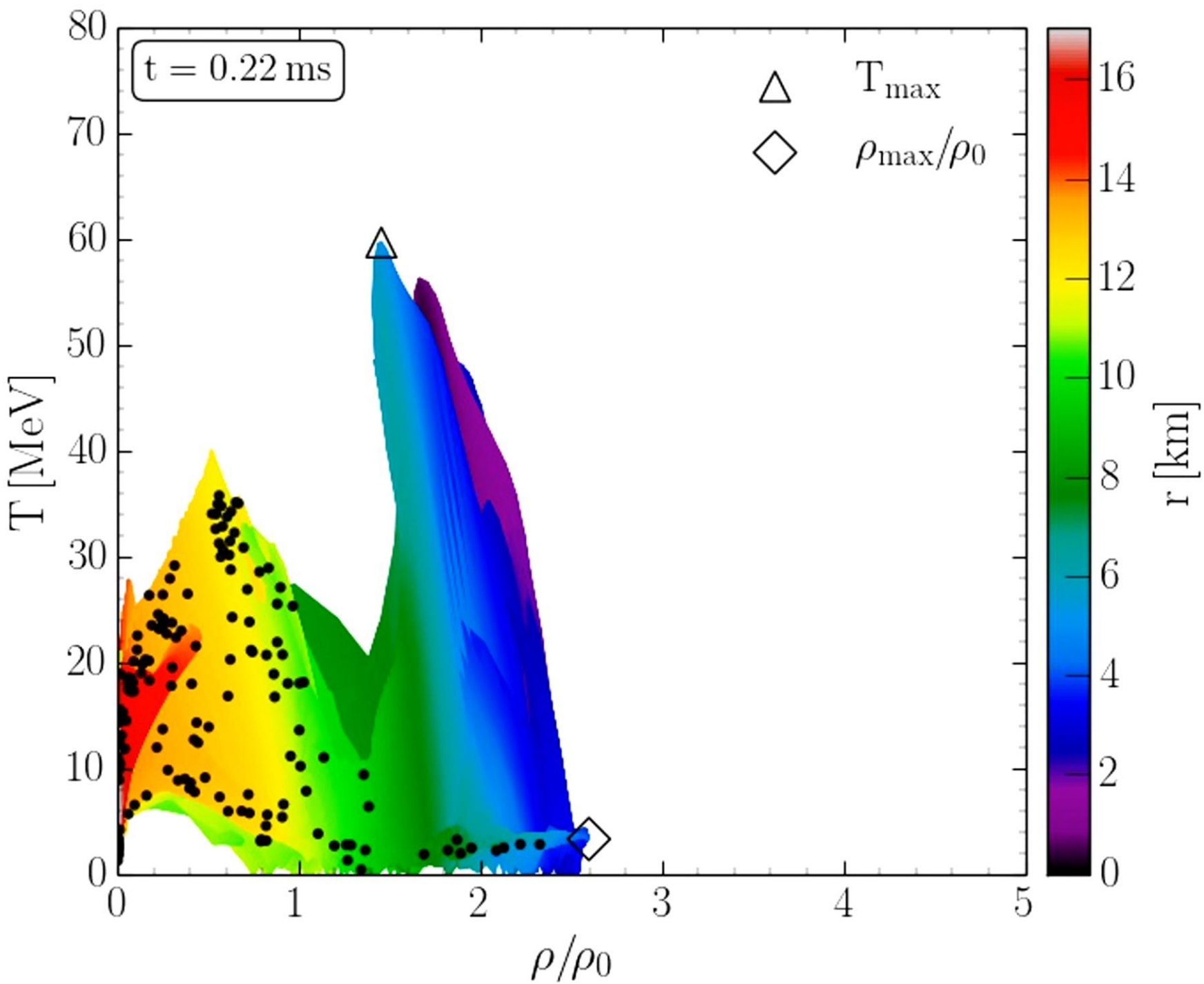
Density and Temperature Evolution inside the HMNS



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 $M_{\text{total}} = 2.7 M_{\odot}$ in the style of a $(T-\rho)$ QCD phase diagram plot

The color-coding indicates the radial position r of the corresponding $(T-\rho)$ 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.

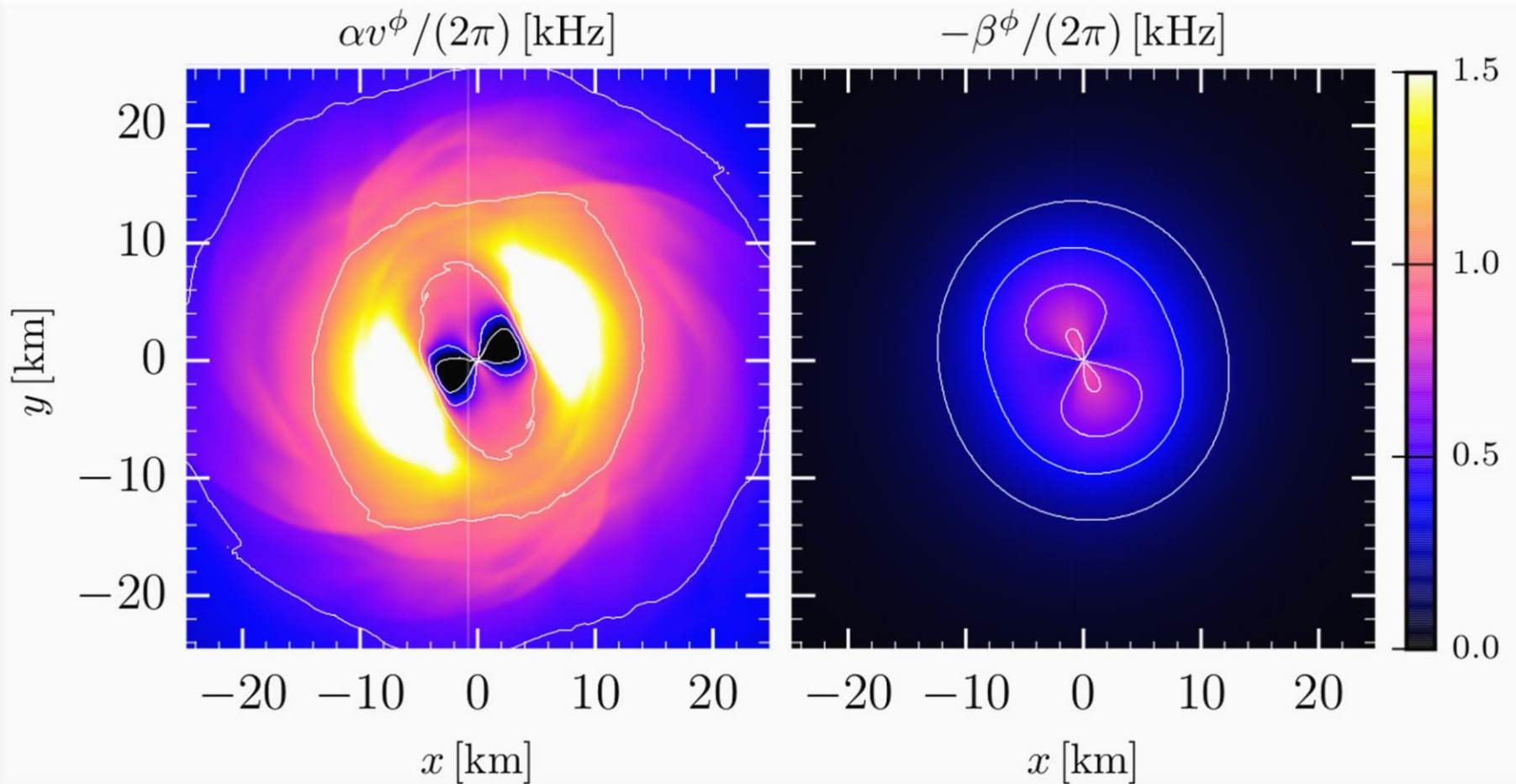
The Angular Velocity in the (3+1)-Split

The angular velocity Ω in the (3+1)-split is defined as a function of the lapse α , the ϕ -component of the fluid velocity v^ϕ of the fluid (spatial projection of the fluid velocity), and the lapse β^ϕ of the shift vector.

$$\Omega(x, y, z, t) = \frac{\alpha v^\phi - \beta^\phi}{2\pi r^2}$$

Angular velocity
 Ω

Lapse



Focus: Inner core of the black hole

M. Shibata, K. Taniguchi, and K. Uryu, Phys. Rev. D 71, 084021 (2005)

M. Shibata and K. Taniguchi, Phys. Rev. D 73, 064027 (2006)

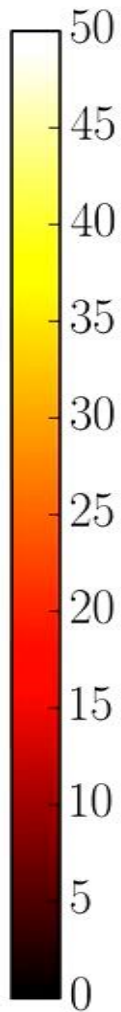
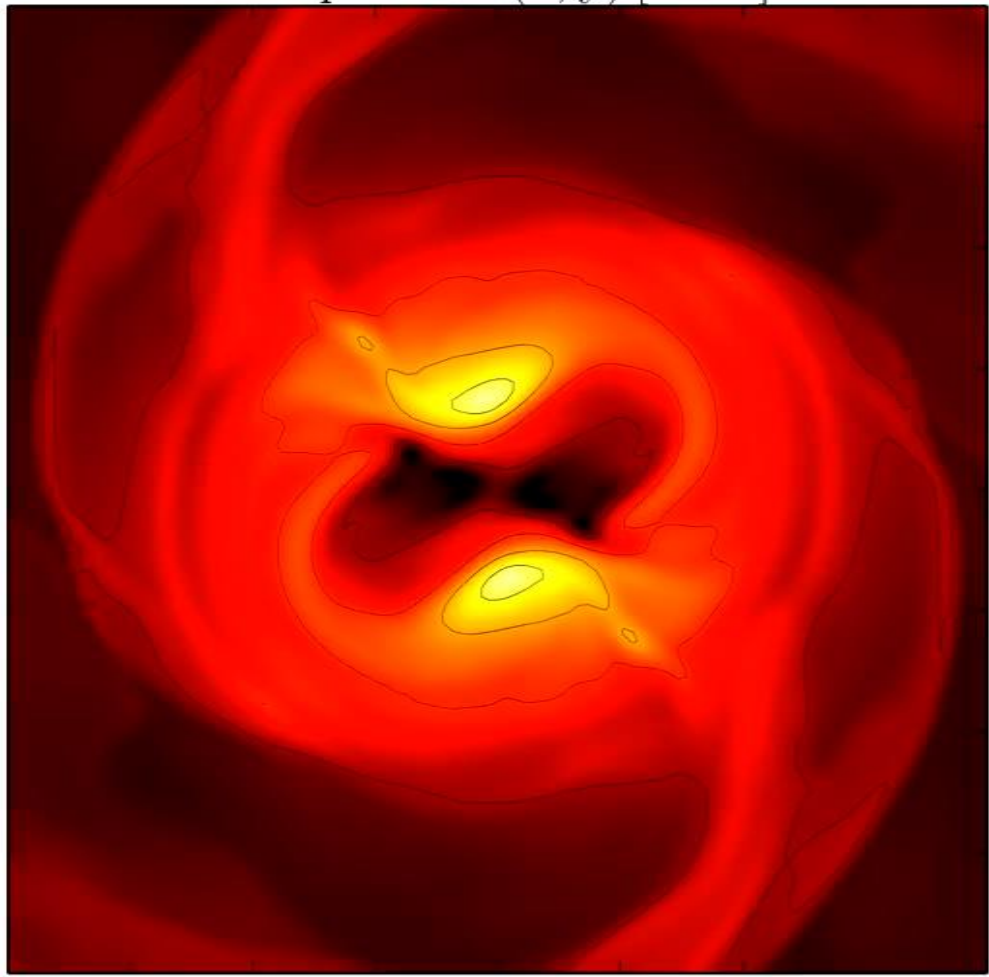
F. Galeazzi, S. Yoshida and Y. Eriguchi, A&A 541, p. A156 (2012)

W. Kastaun and F. Galeazzi, Phys. Rev. D 91, p. 064027 (2015)



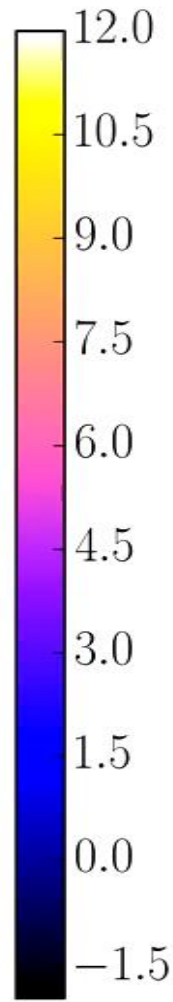
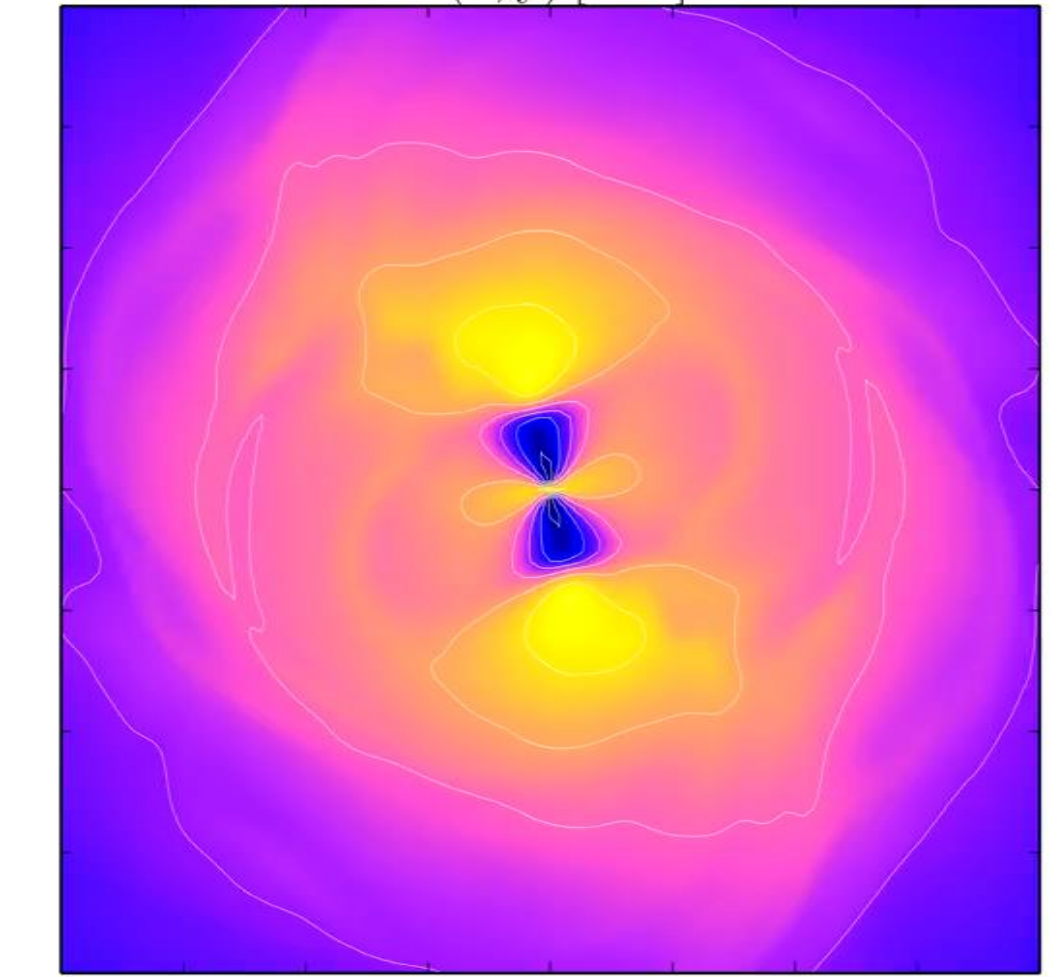
Temperature

Temperature(x, y) [MeV]



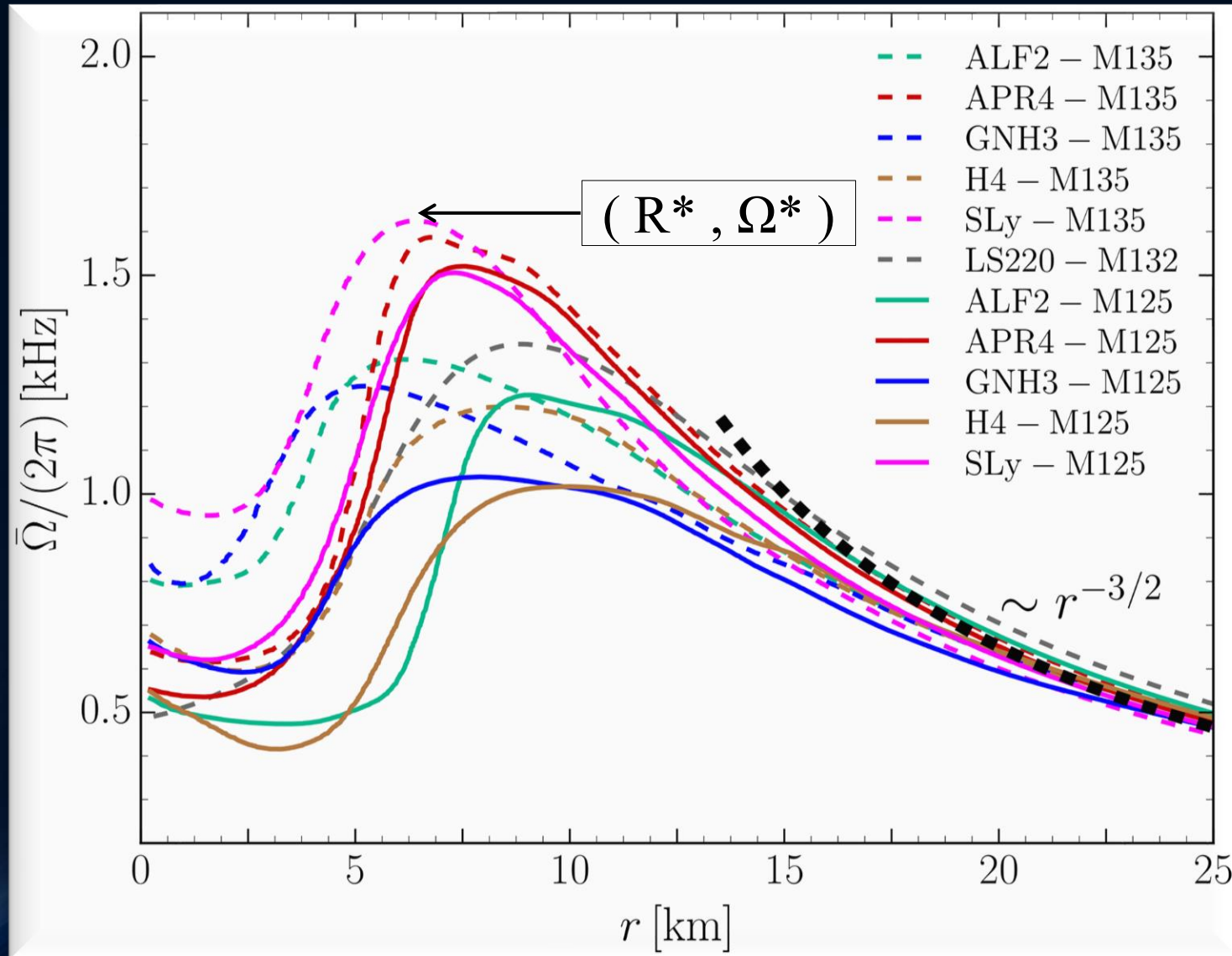
Angular Velocity

$\Omega(x, y)$ [kHz]



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

Time-averaged Rotation Profiles of the HMNSs



Soft EoSs:

Sly
APR4

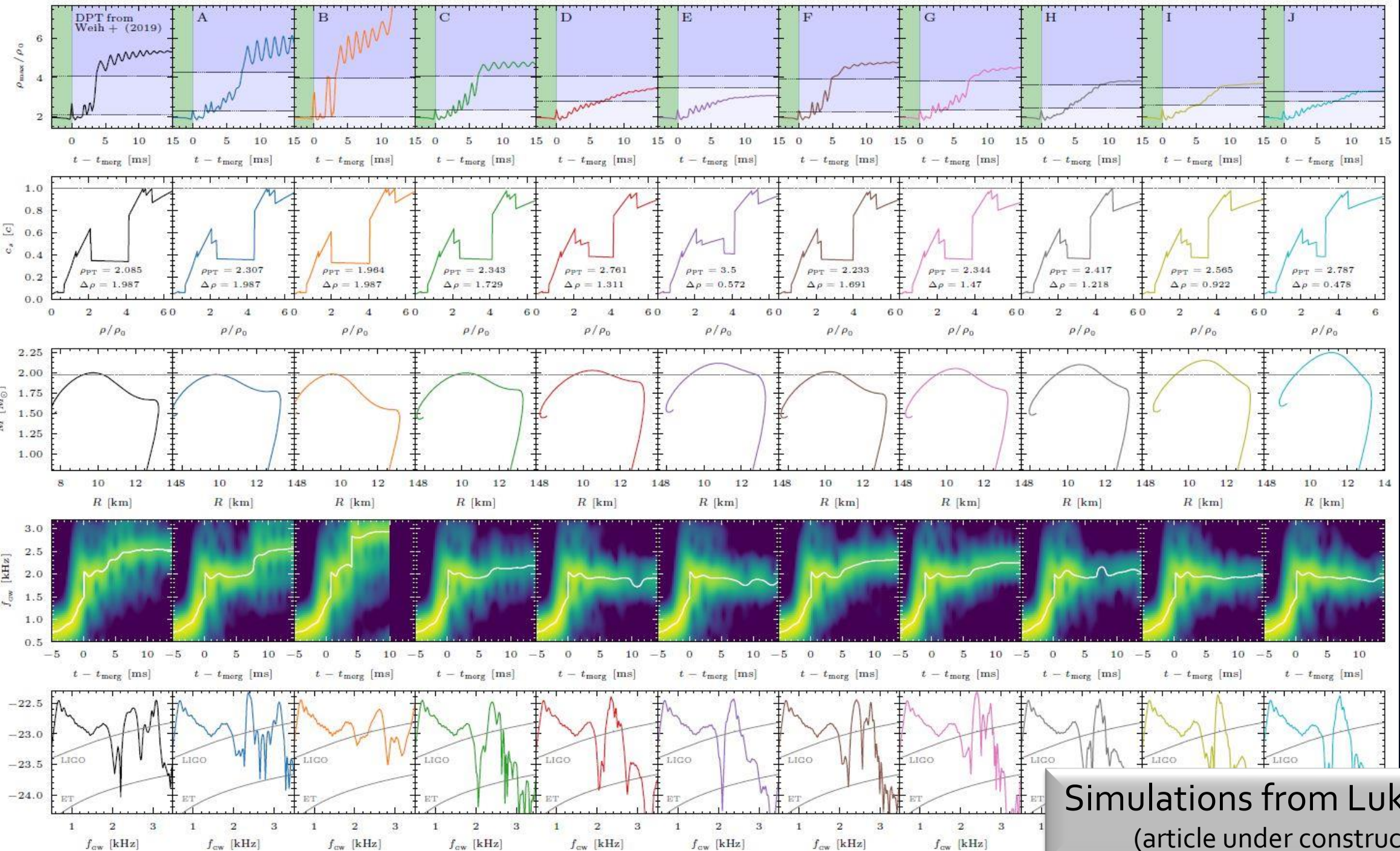
Stiff EoSs:

GNH3
H4

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

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

Analysis of phase transitions of impact

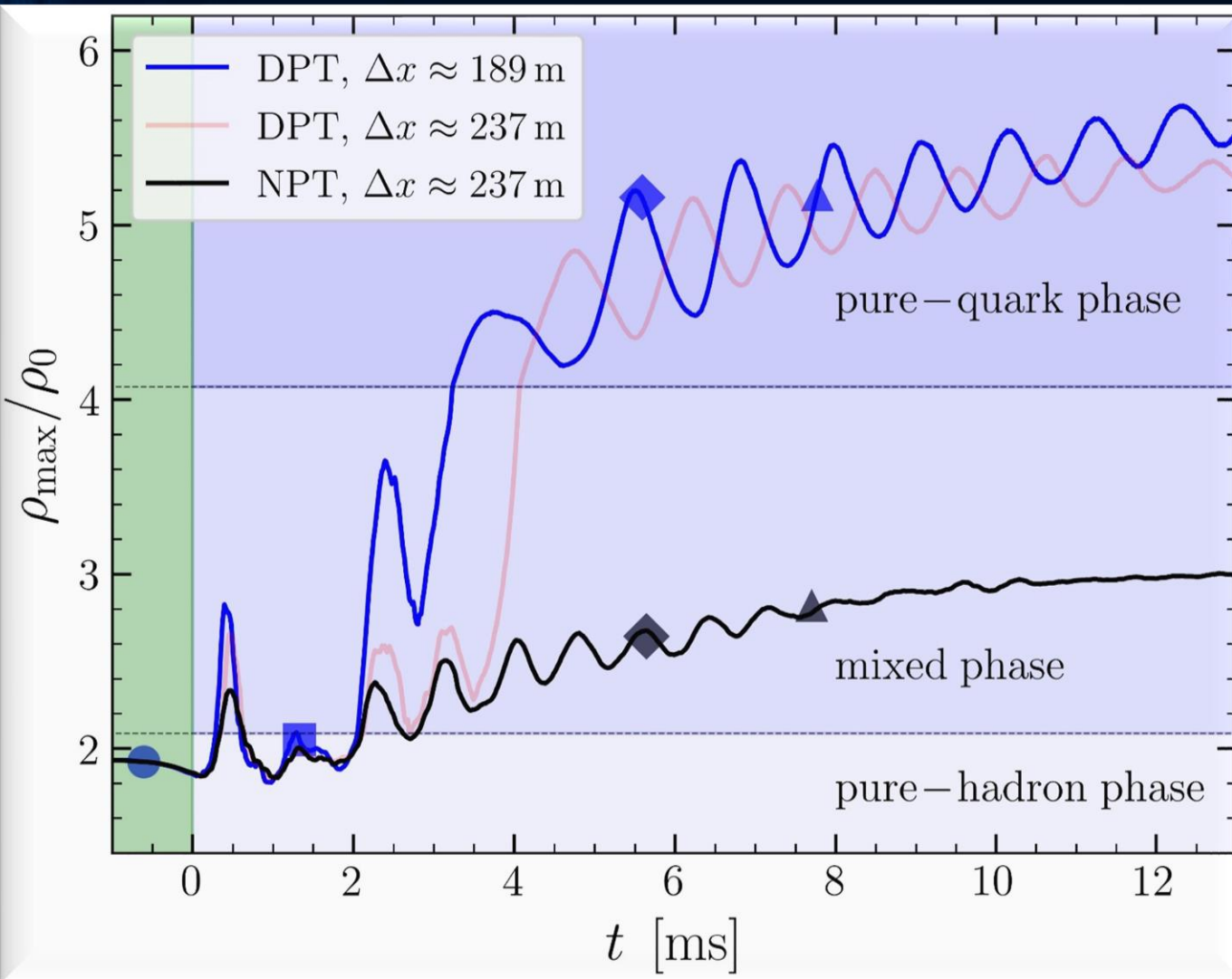


Simulations from Lukas Weih
(article under construction)

Signatures within the post-merger phase evolution

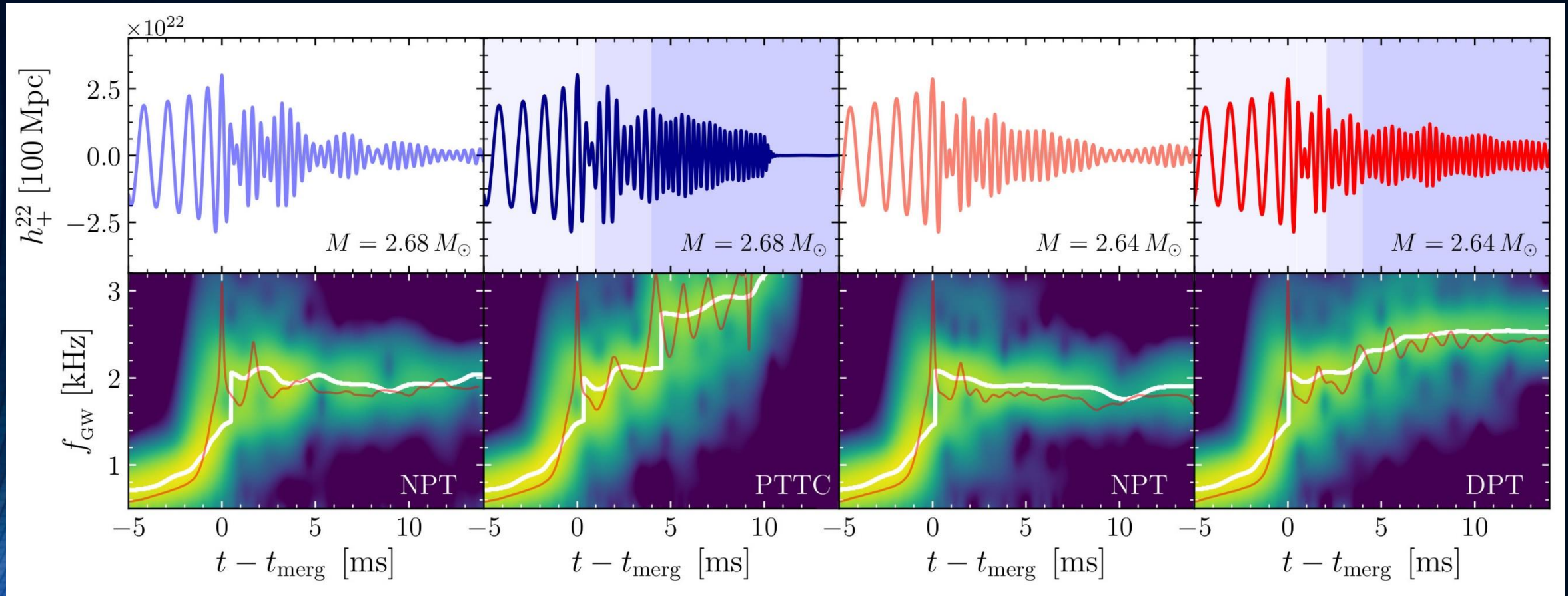
DPT: Delayed phase transition scenario

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



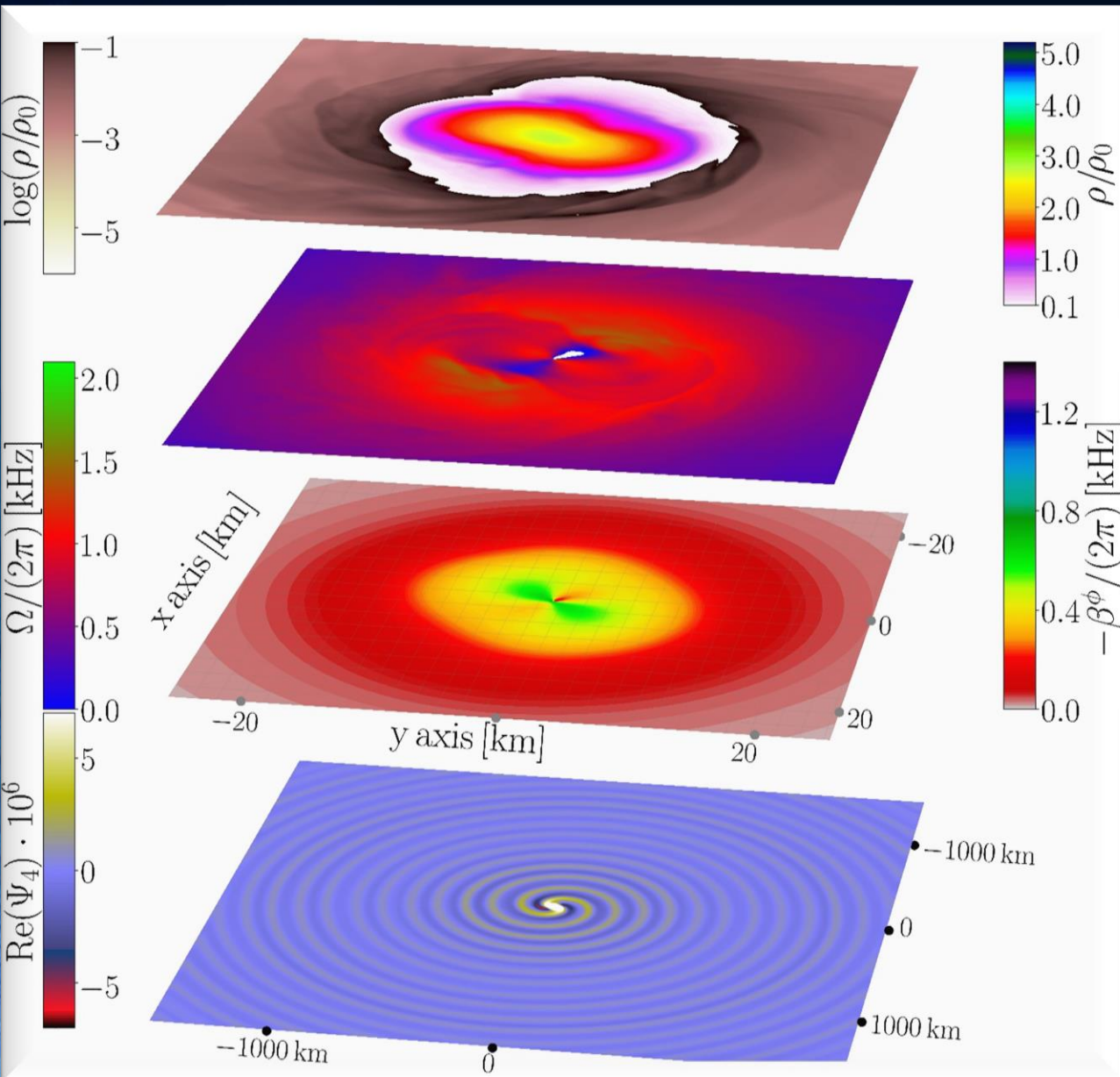
Maximum value of the rest-mass density vs time for three binary neutron star simulations. Black curve without a phase transition (NPT) and blue/red with a Gibbs-like hadron-quark phase transition (DPT: standard/low resolution). Blue-shaded regions mark the different phases of the EOS (mixed phase and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

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

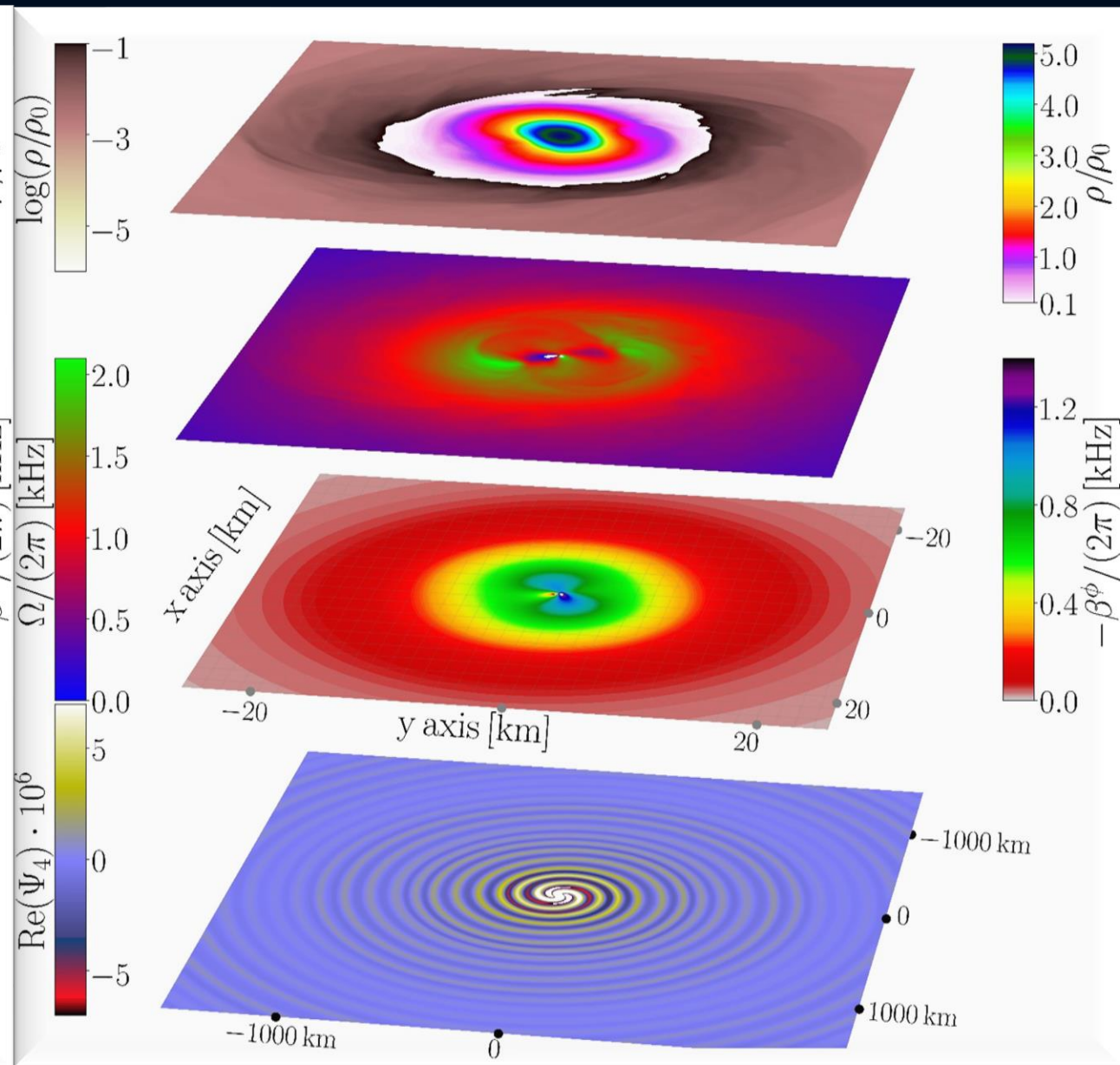


Strain h_+ (top) and its spectrogram (bottom) for the four BNSs considered. In the top panels the different shadings mark the times when the HMNS core enters the mixed and quark phases the NPT models are always purely hadronic. In the bottom panels, the white lines trace the maximum of the spectrograms,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

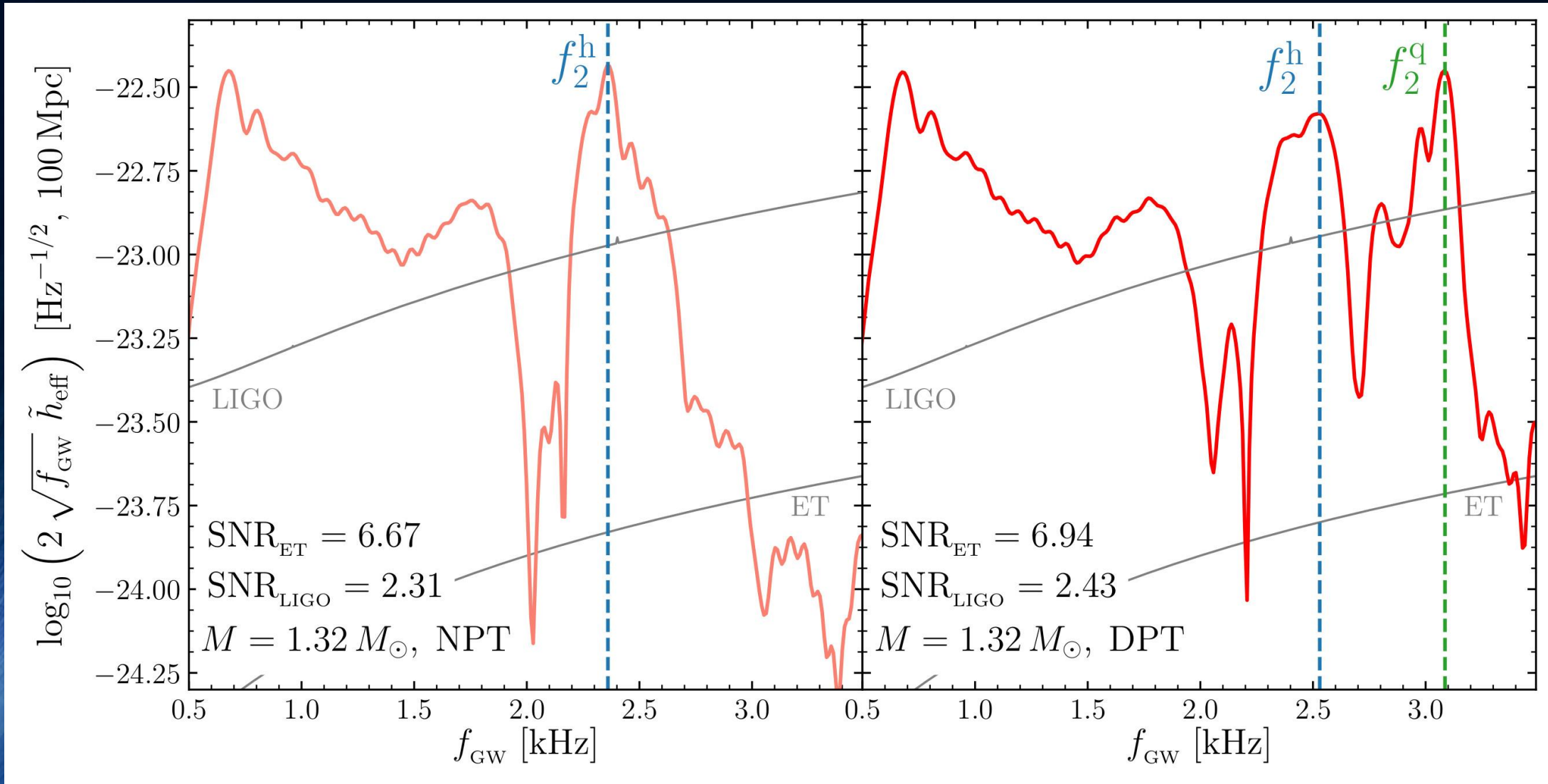
Without Phase Transition



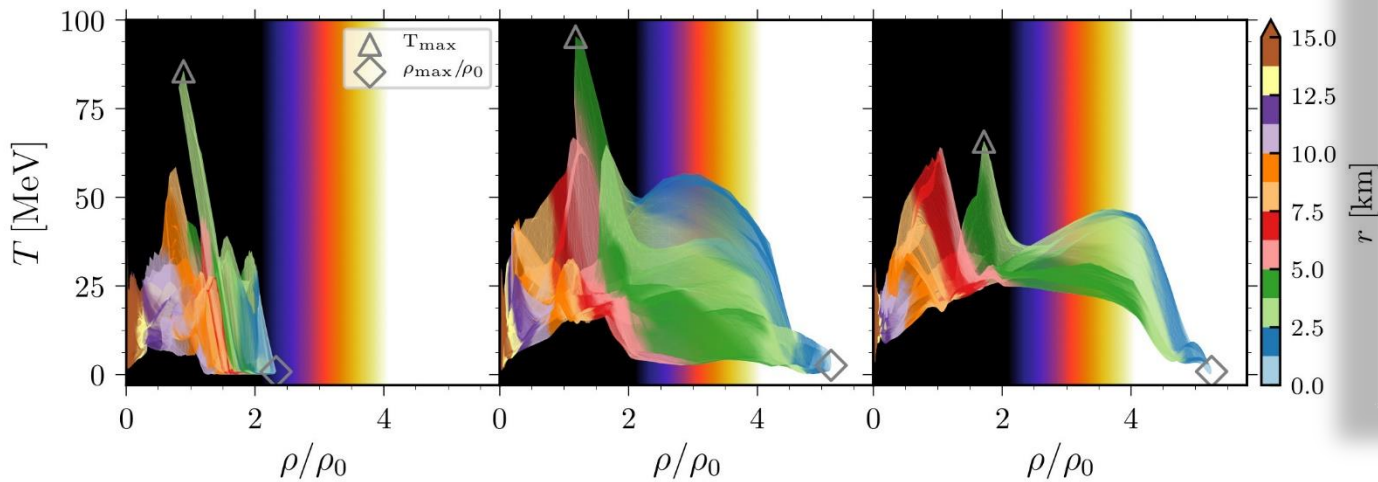
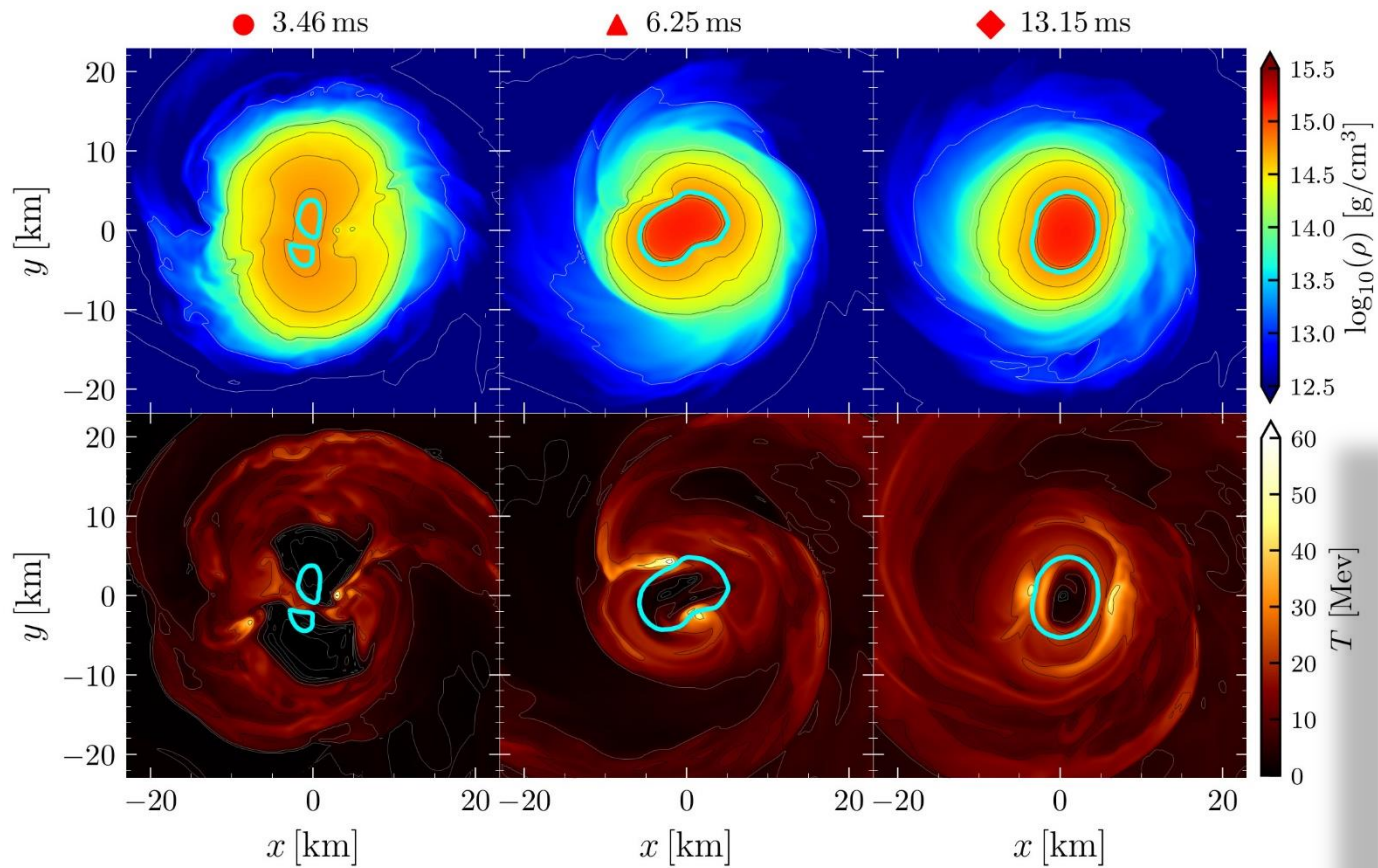
With Phase Transition



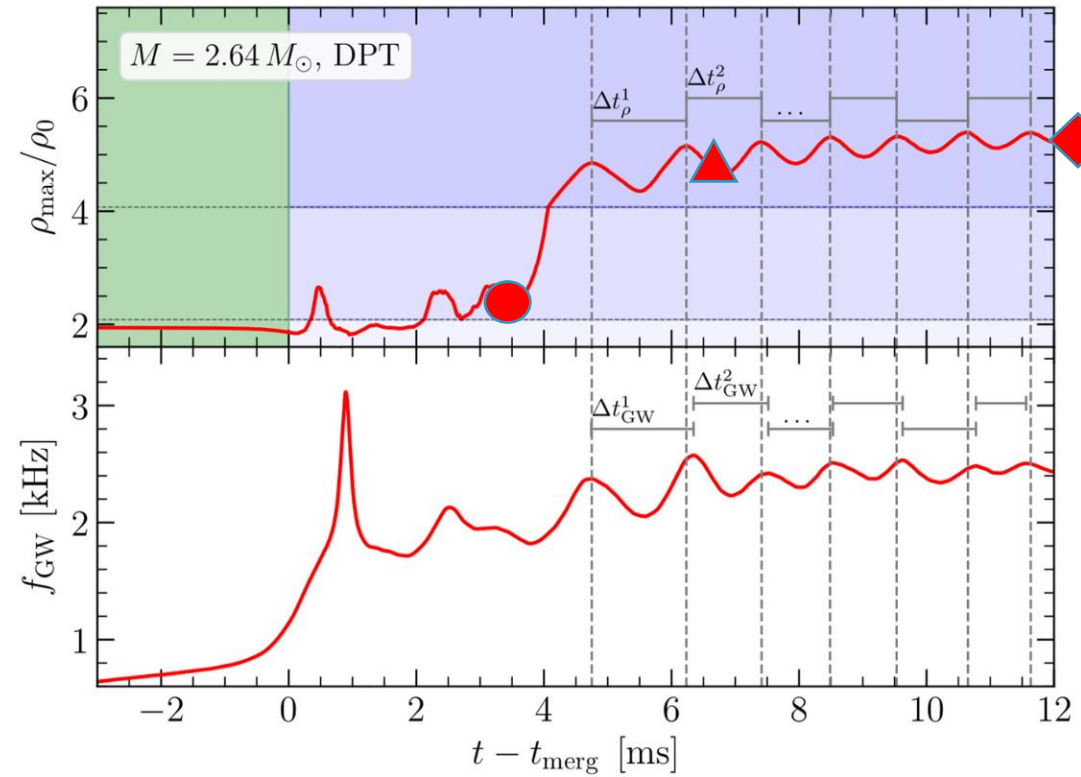
How to detect the hadron-quark phase transition with gravitational waves



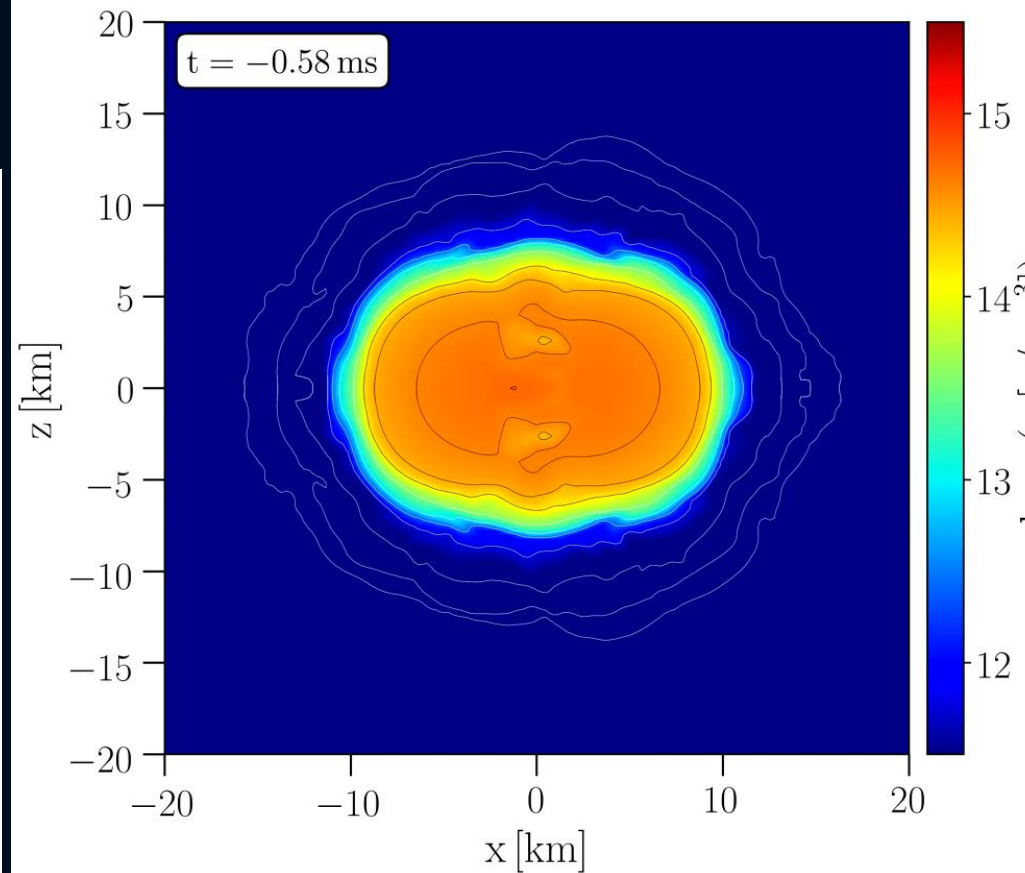
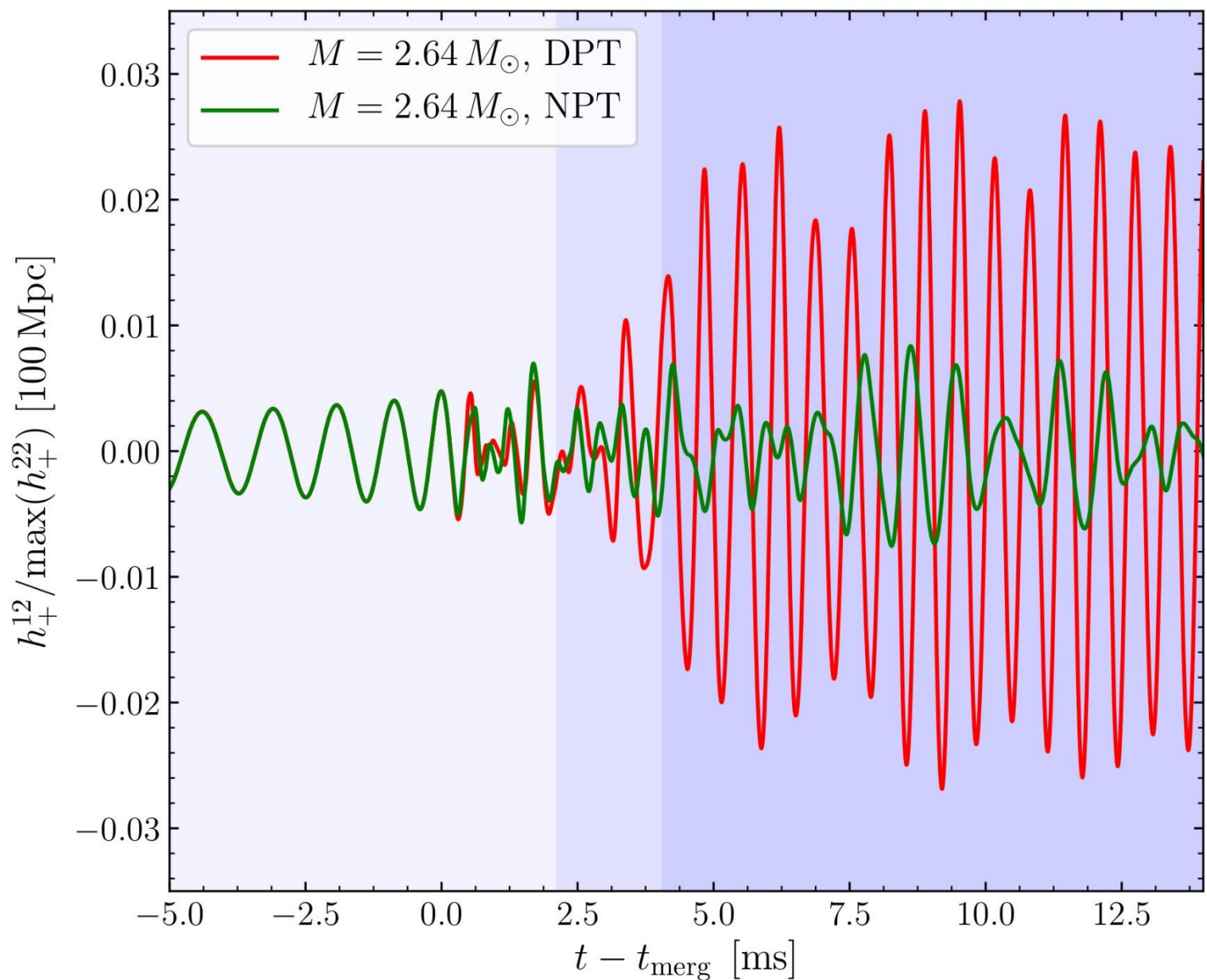
Total gravitational wave spectrum (left NPT, right DPT), PRL 124, 171103 (2020)



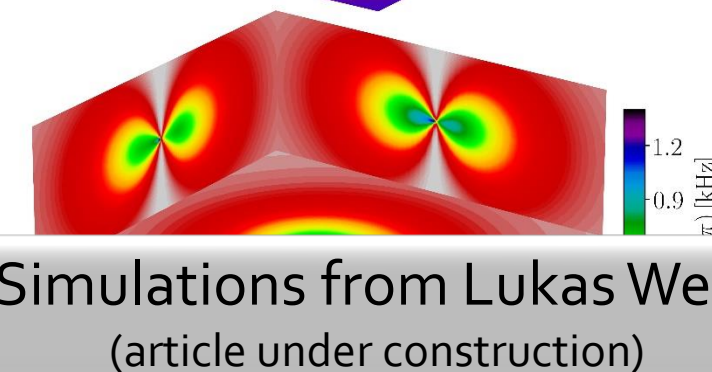
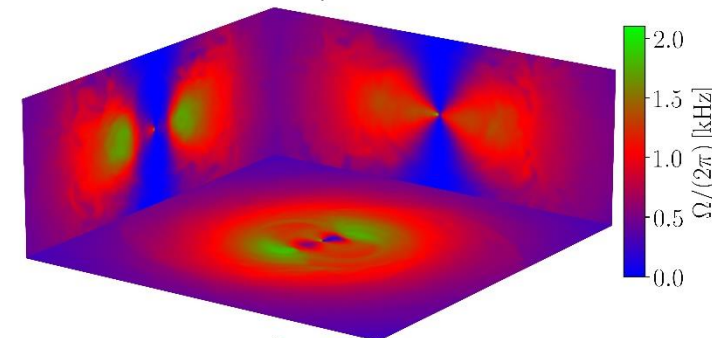
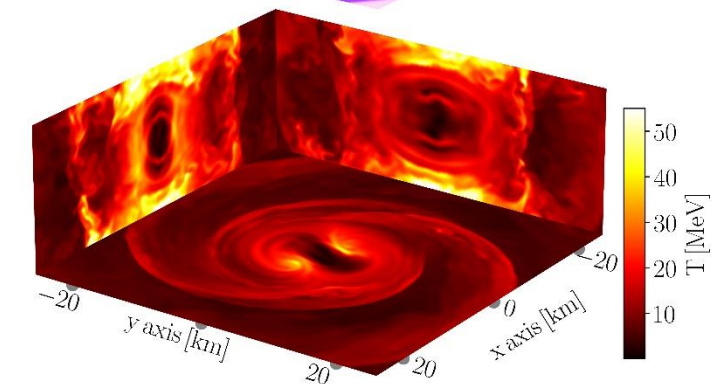
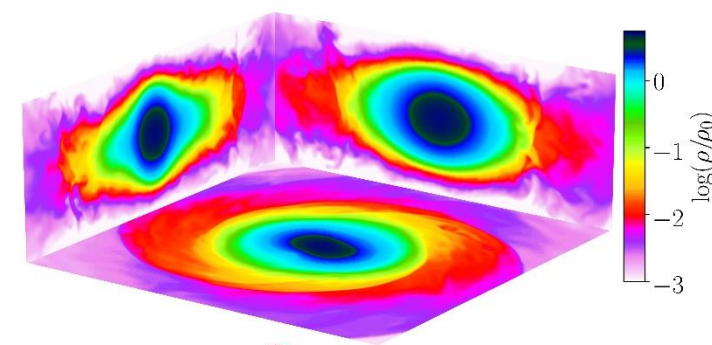
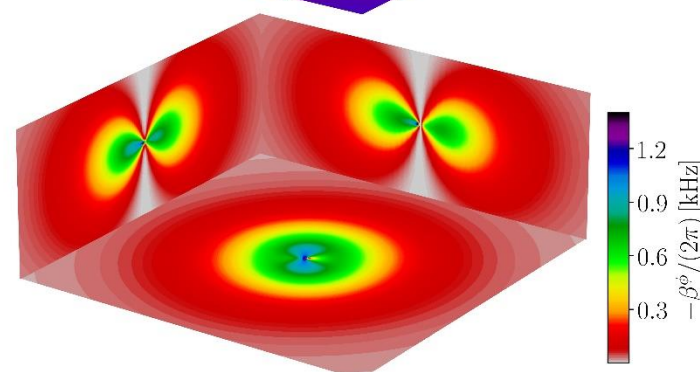
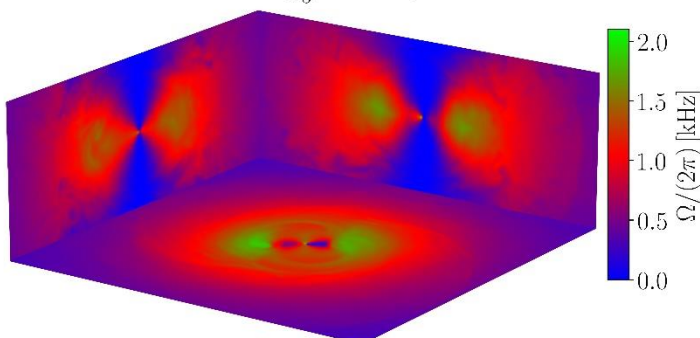
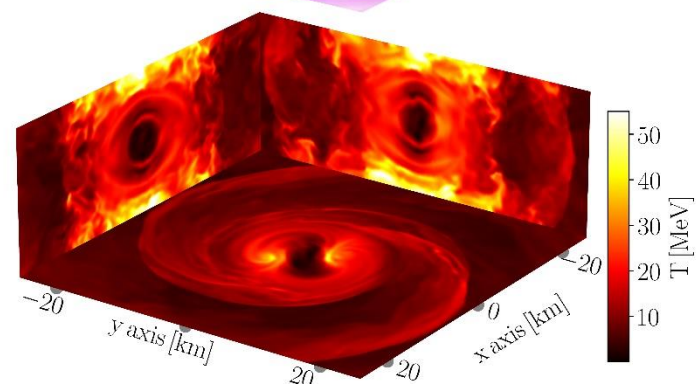
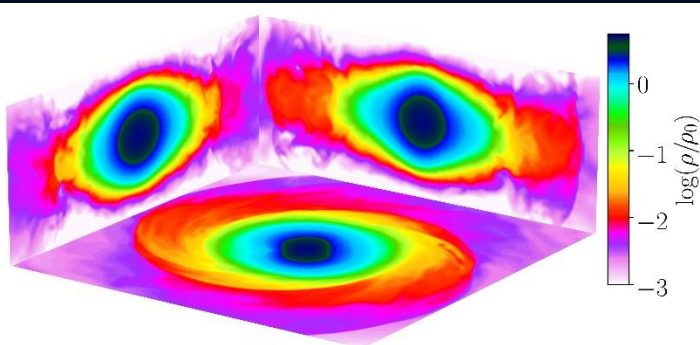
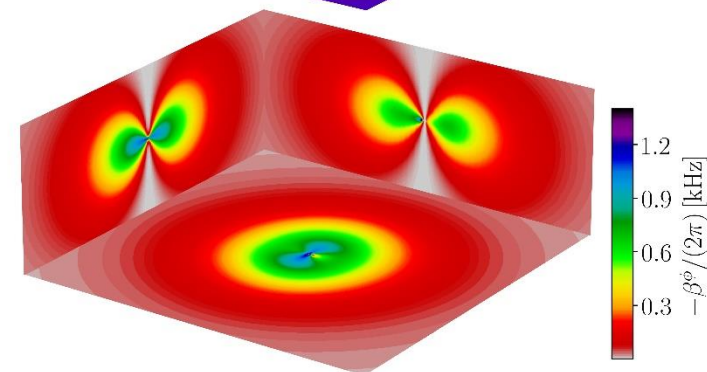
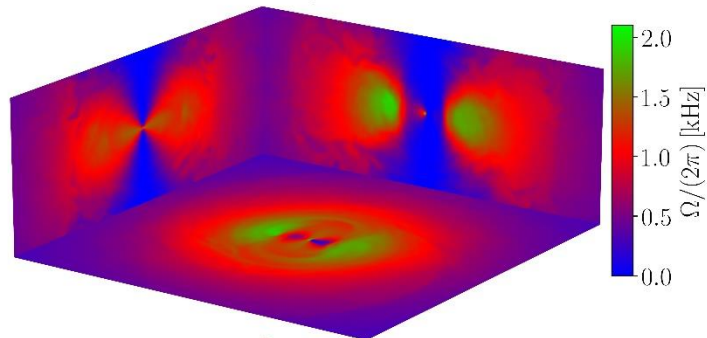
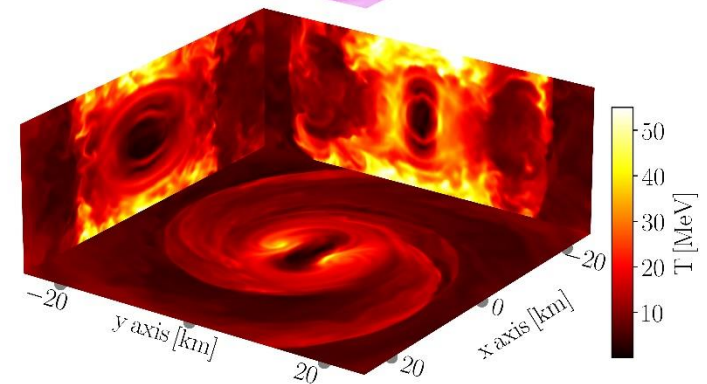
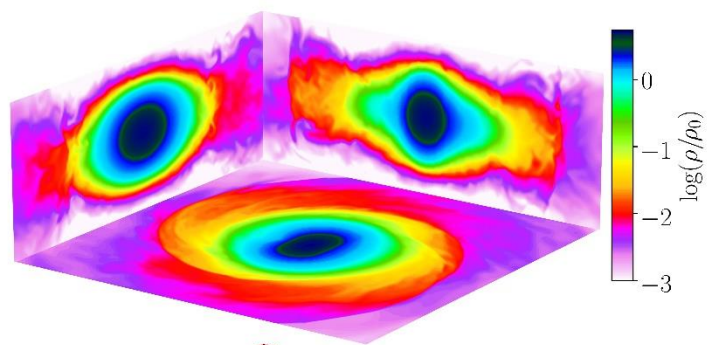
M. Hanauske, L. Weih, H. Stöcker
and L. Rezzolla
*Metastable hypermassive hybrid stars as
neutron-star merger remnants*
The European Physical Journal Special
Topics: 1-8 (2021)



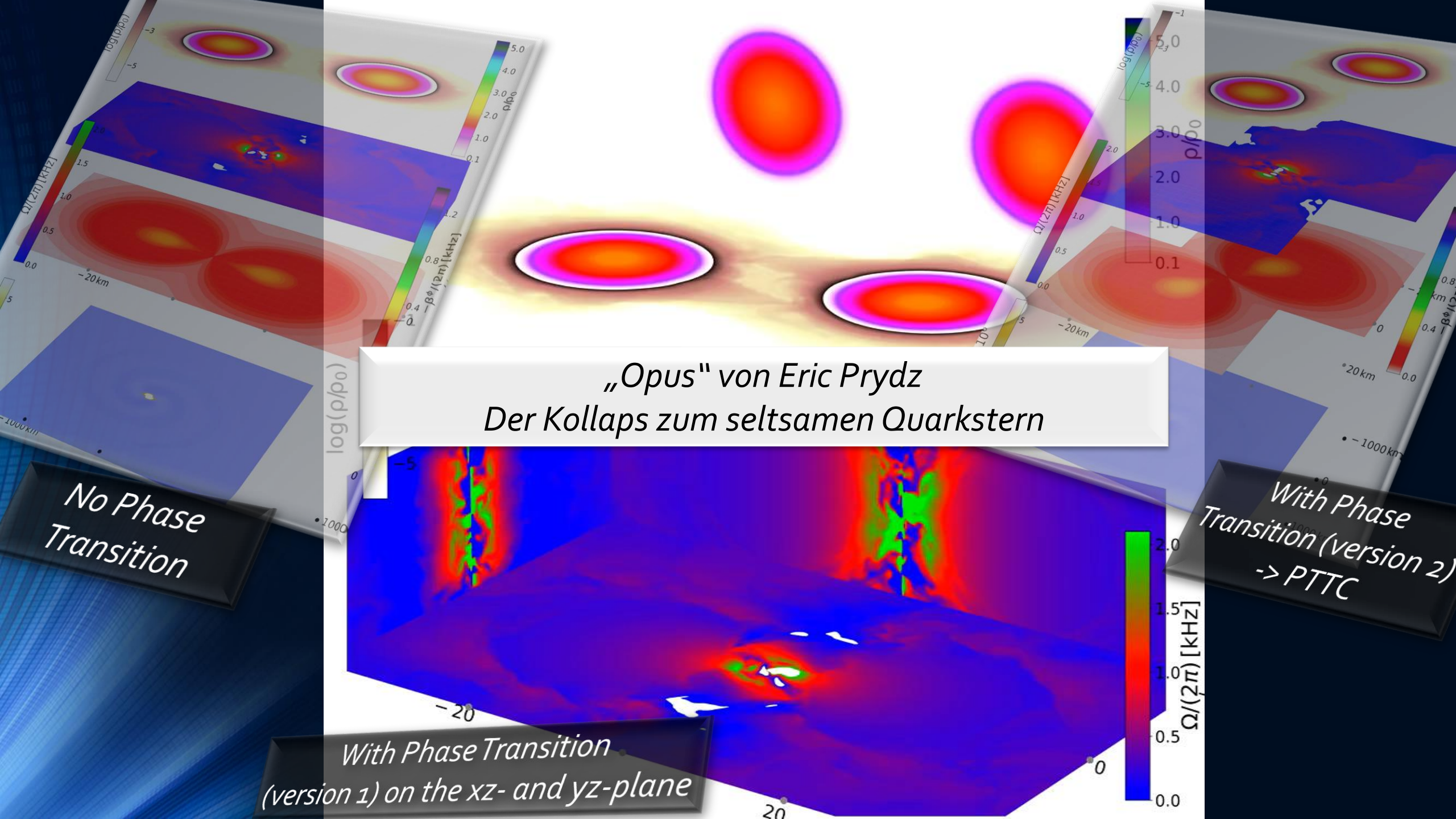
Difference in the h_+^{12} – gravitational wave mode



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



Simulations from Lukas Weih
(article under construction)



*„Opus“ von Eric Prydz
Der Kollaps zum seltsamen Quarkstern*

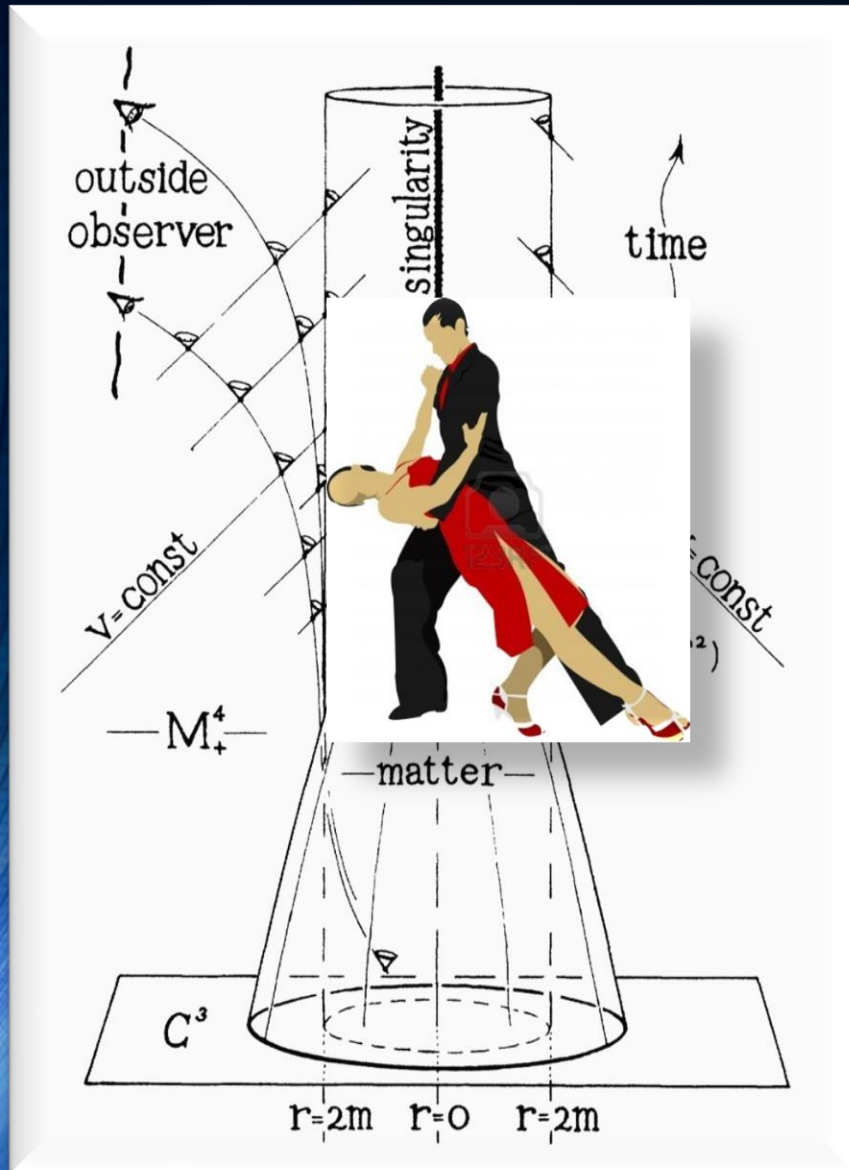
No Phase Transition

*With Phase Transition (version 2)
-> PTTC*

With Phase Transition (version 1) on the xz- and yz-plane

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)

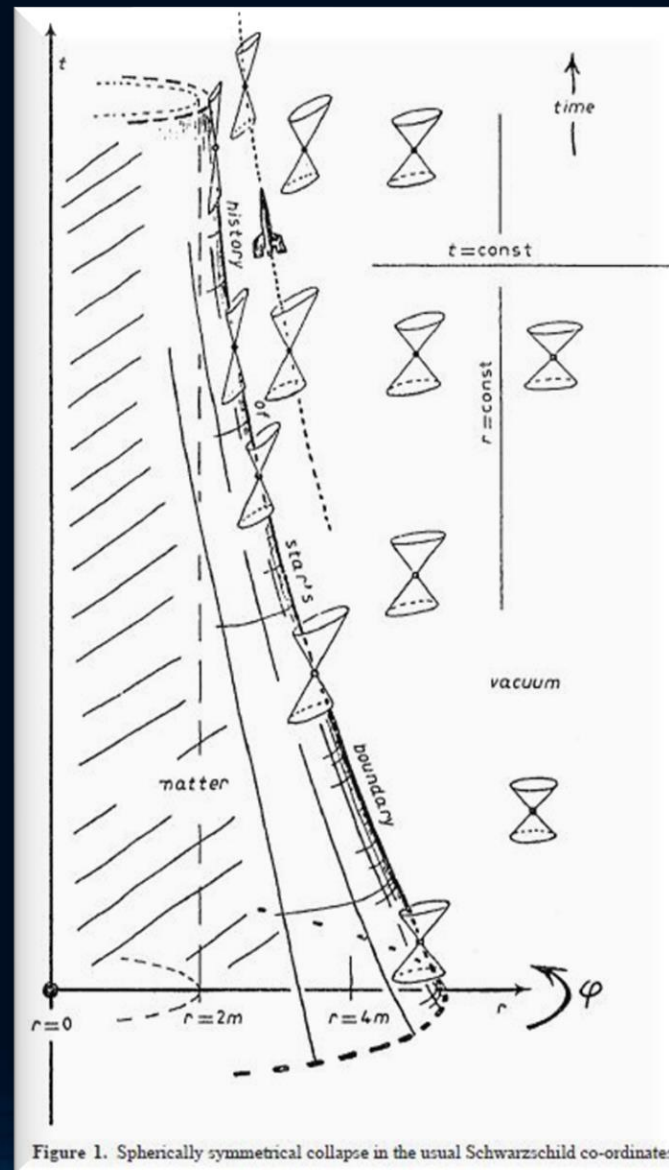


Figure 1. Spherically symmetrical collapse in the usual Schwarzschild co-ordinates.

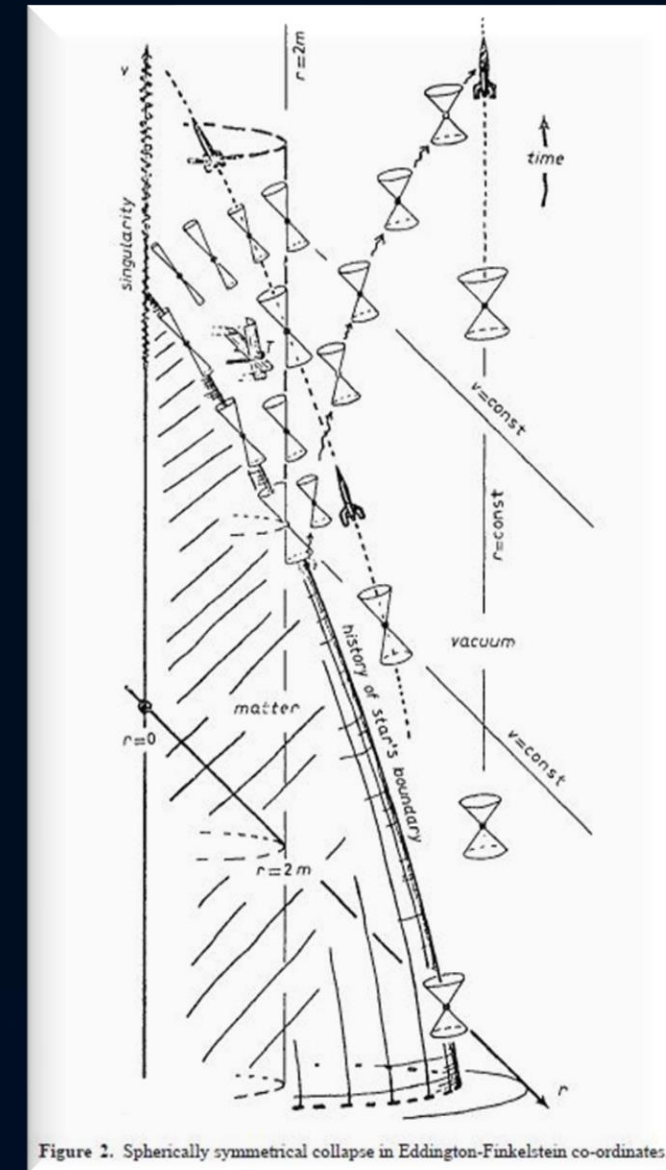
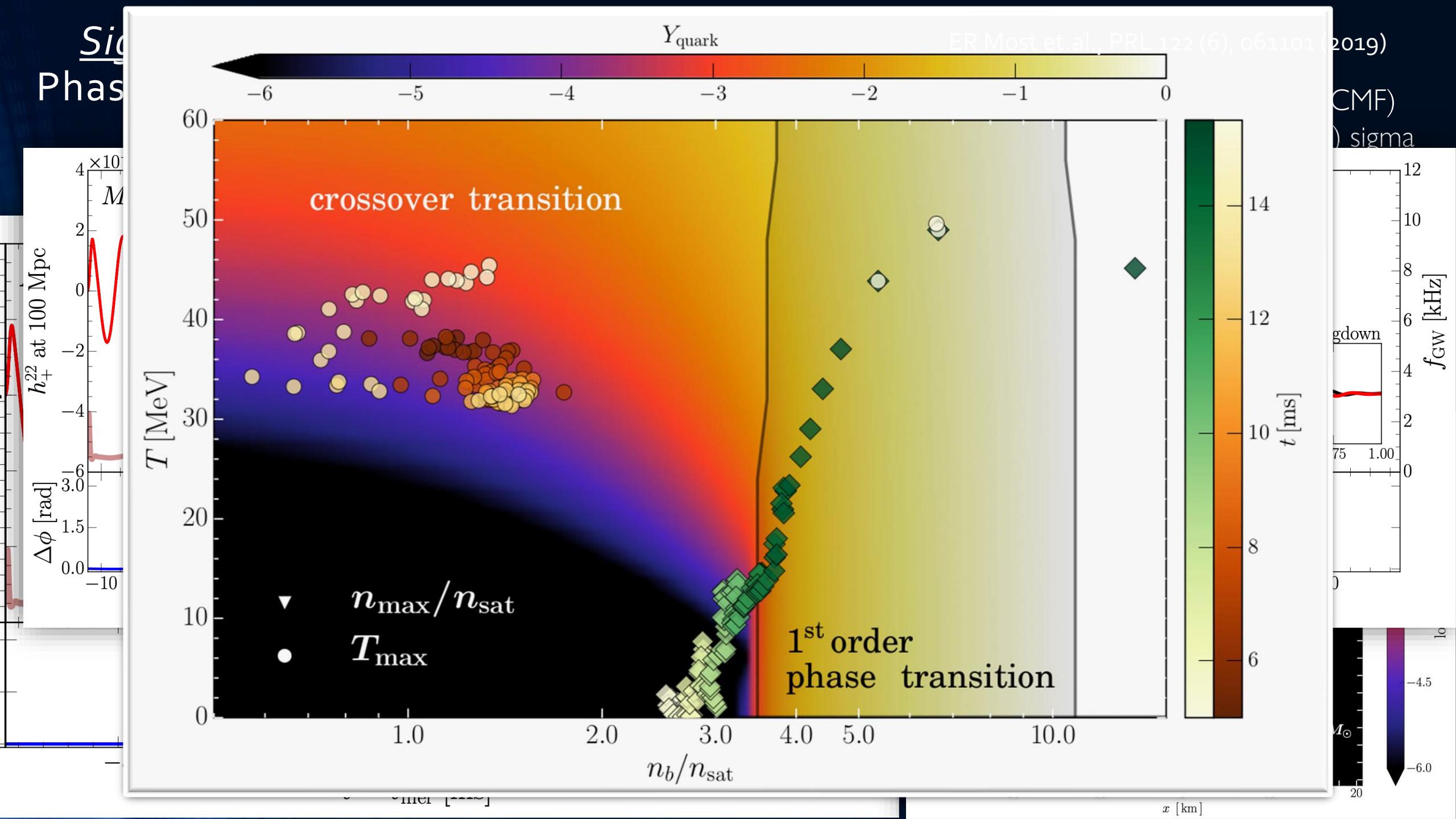


Figure 2. Spherically symmetrical collapse in Eddington-Finkelstein co-ordinates.



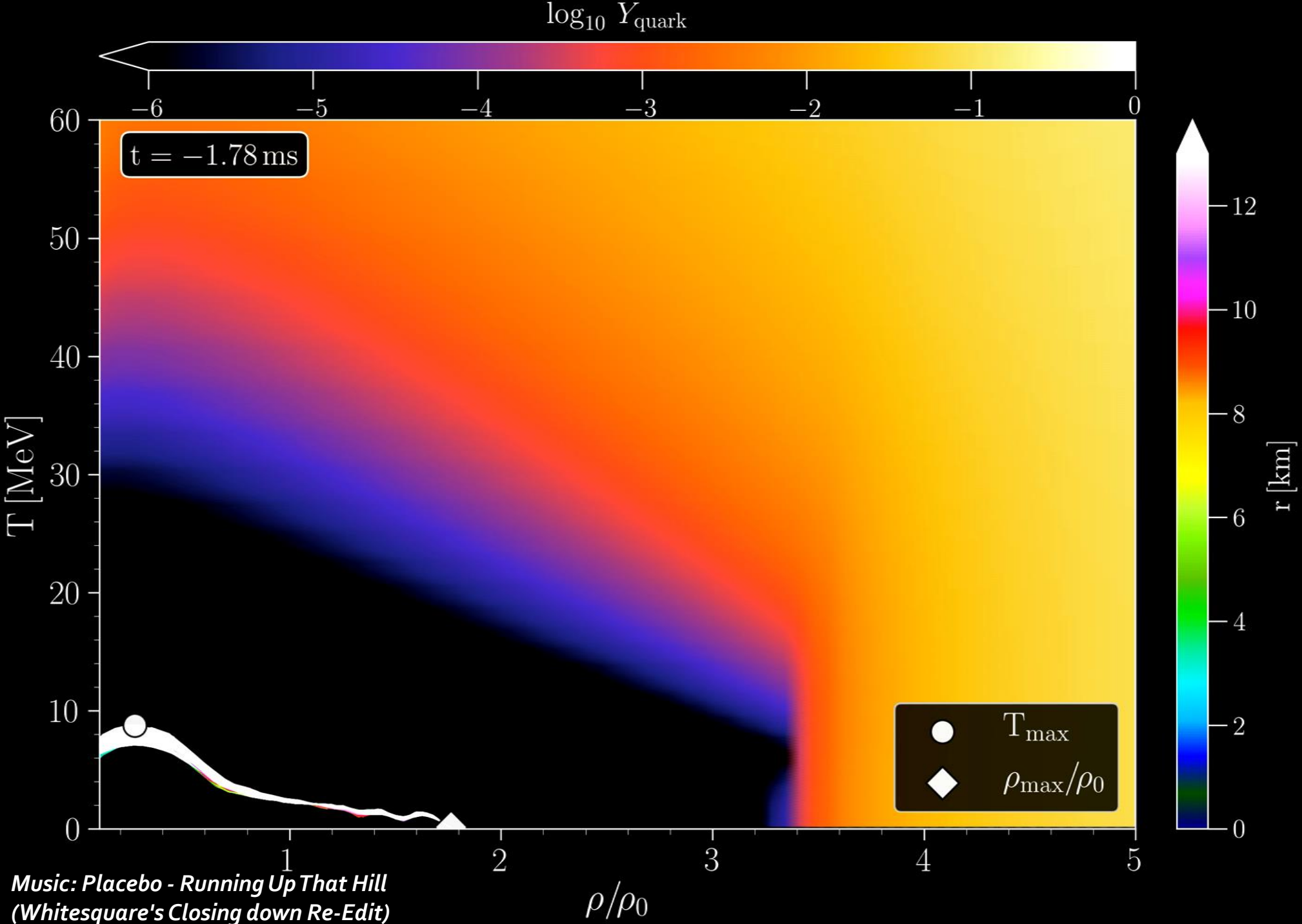
Phase-transition triggered collapse scenario

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

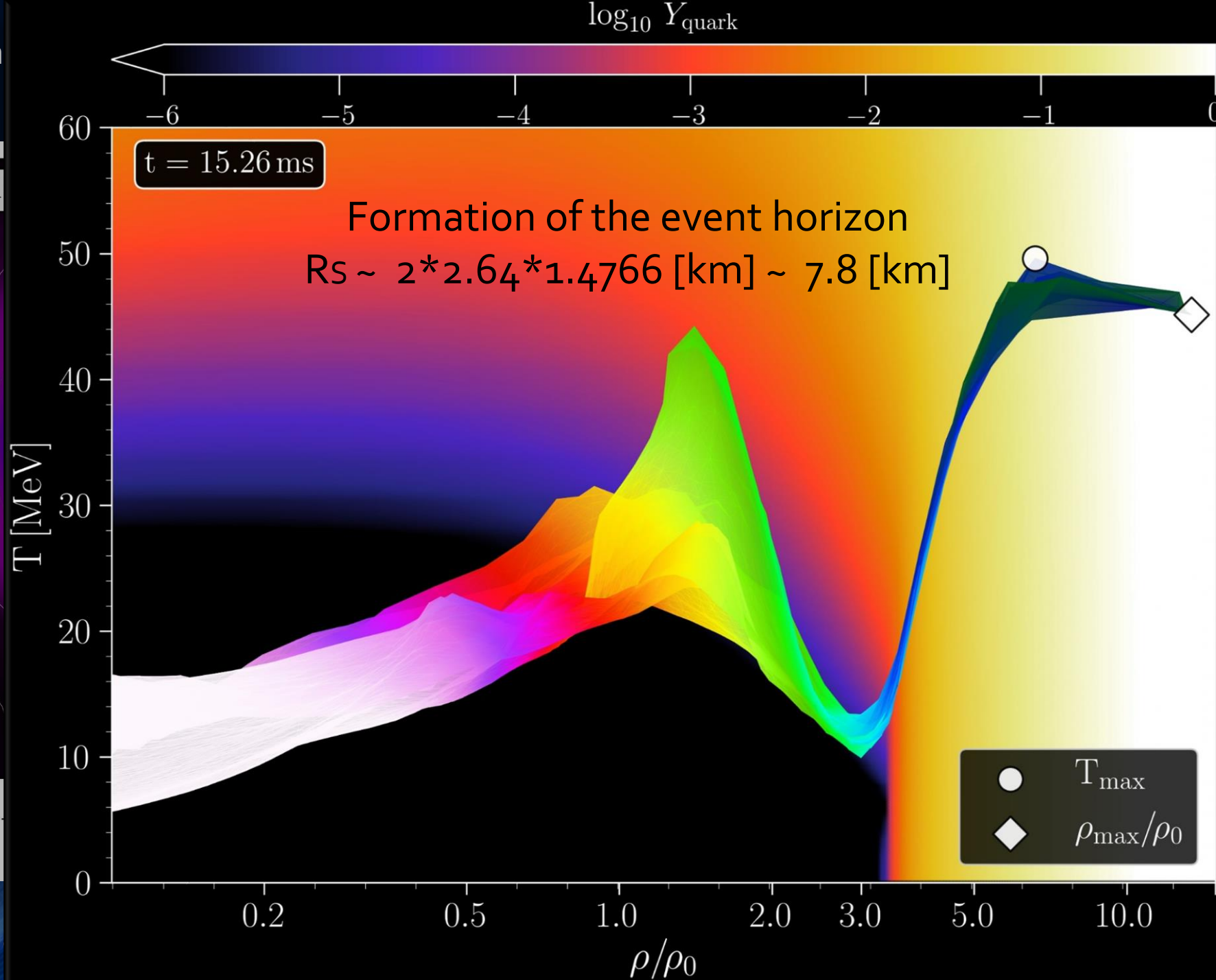
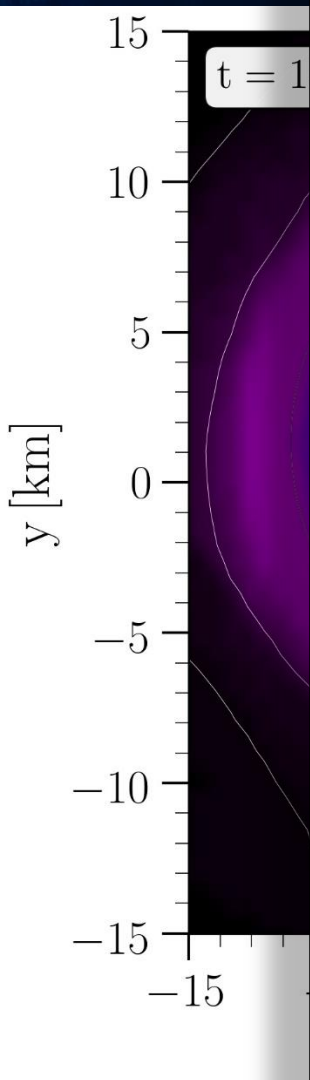
ER Most, LJ Papenfort, V Dexheimer, M Hanauske, S Schramm, H Stöcker and L. Rezzolla

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

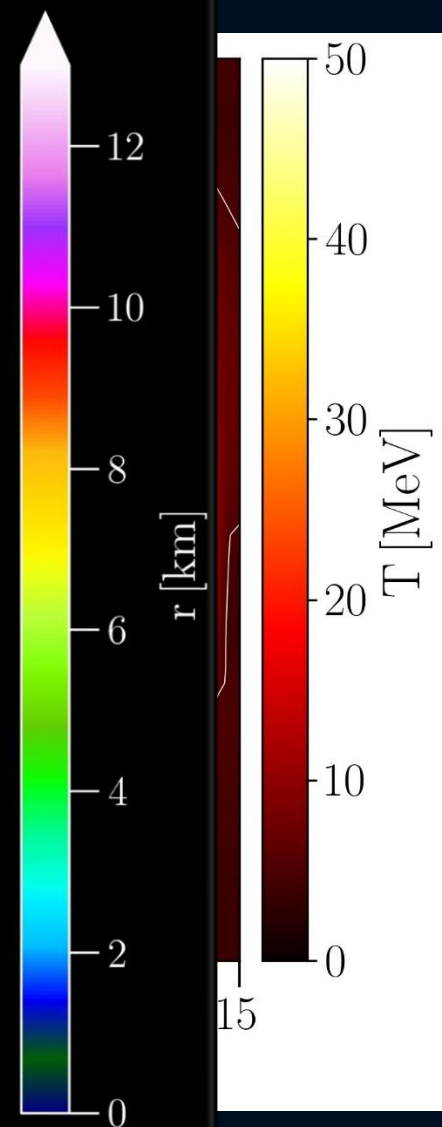
Density-Temperature-Composition dependent EOS within the CMFo model.



The last sim

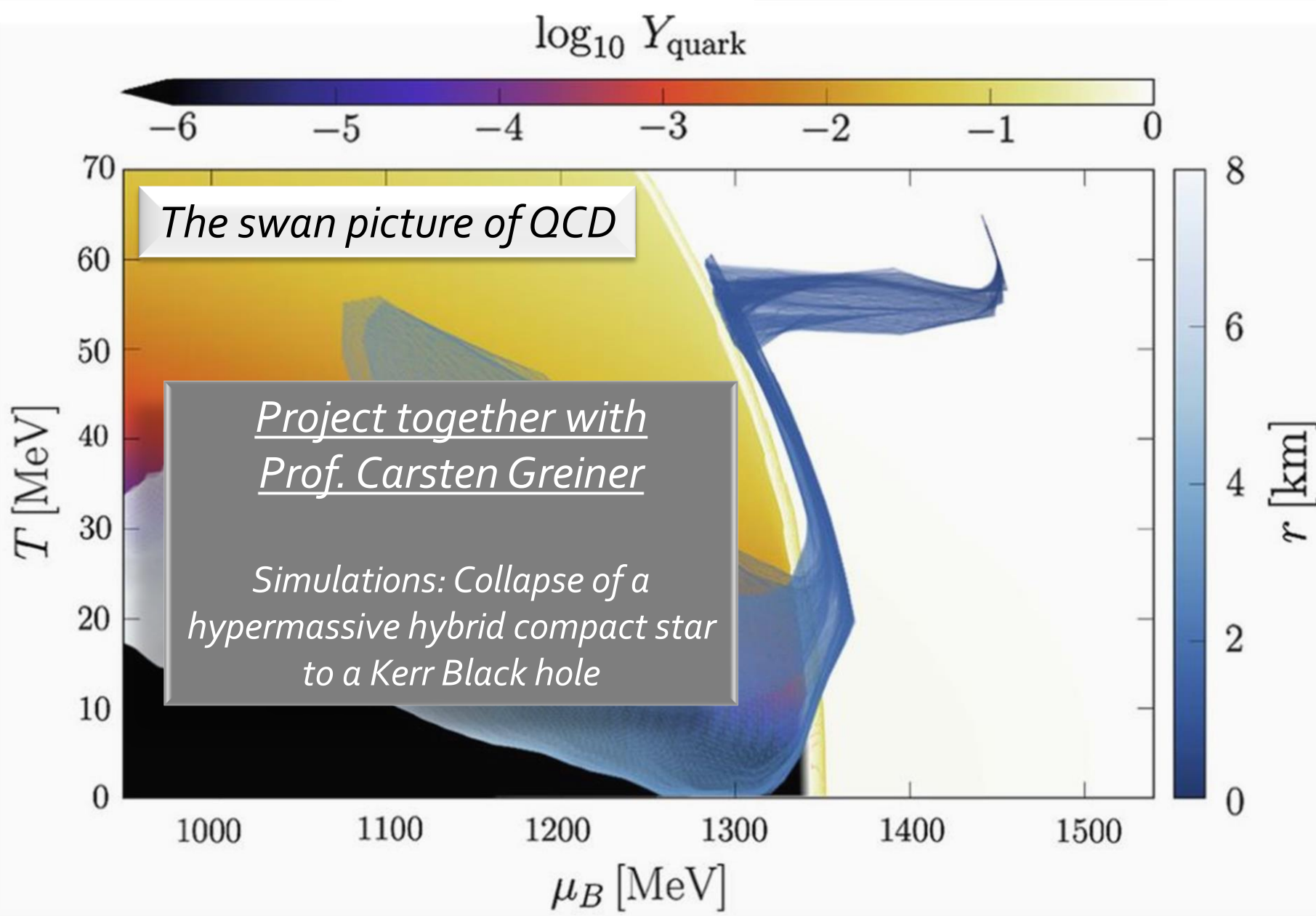


(HMHS)



Rest mas

ne



The swan picture of QCD

*Project together with
Prof. Carsten Greiner*

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

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

$r=2m$ $r=0$ $r=2m$

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

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

R. Penrose in Rivista del Nuovo Ci

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

- Gravitational-wave signatures of the hadron-quark phase transition in compact star mergers
 - Signatures within the late inspiral phase (premerger signals)
 - Constraining twin stars with GW170817; G Montana, L Tolós, M Hanauske; *Physical Review Letters* 123 (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; V Dexheimer, M Hanauske, S Schramm, H Stöcker, L. Rezzolla; *Physical Review Letters* 123 (10), 101101 (2019)
 - **Delayed phase transition scenario**
Postmerger Gravitational-Wave Signatures of Phase Transitions in Binary Neutron Star Mergers; 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; M. Oertel, M. C. Miller, M. Hanauske, K. Chatziioannou, J. A. Clark, J. A. Clark, T. Fischer, M. Oertel; *Physical Review Letters* 123 (10), 101101 (2019)



Lateral Thoughts, Popular Science Articles:

<http://itp.uni-frankfurt.de/~hanauske/new/etc/pdf/LateralThoughts.pdf>

<http://itp.uni-frankfurt.de/~hanauske/new/etc/pdf/MG16-Hanauske.pdf>

The neutronstar merger dance:

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

<https://www.physikalischer-verein.de/veranstaltung/der-tanz-der-neutronensterne.html>

Recent scientific articles:

<https://onlinelibrary.wiley.com/doi/full/10.1002/asna.202113994>

<https://inspirehep.net/files/1bd749e8d48a948b39aa6498a63doecd>

<https://link.springer.com/article/10.1140/epjs/s11734-021-00003-5>

<https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.124.171103>

<https://journals.aps.org/prd/abstract/10.1103/PhysRevD.99.103009>

<https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.122.061101>

<https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.120.041101>

<https://journals.aps.org/prd/abstract/10.1103/PhysRevD.96.043004>

<https://arxiv.org/pdf/2201.13150.pdf>

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

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

¹Princeton Center for Theoretical Science, Princeton University, Princeton, NJ 08544, USA

²Princeton Gravity Initiative, Princeton University, Princeton, NJ 08544, USA

³School of Natural Sciences, Institute for Advanced Study, Princeton, NJ 08540, USA

⁴Institut für Theoretische Physik, Goethe Universität, D-60438 Frankfurt am Main, Germany

⁵Frankfurt Institute for Advanced Studies, Giersch Science Center, D-60438 Frankfurt am Main, Germany

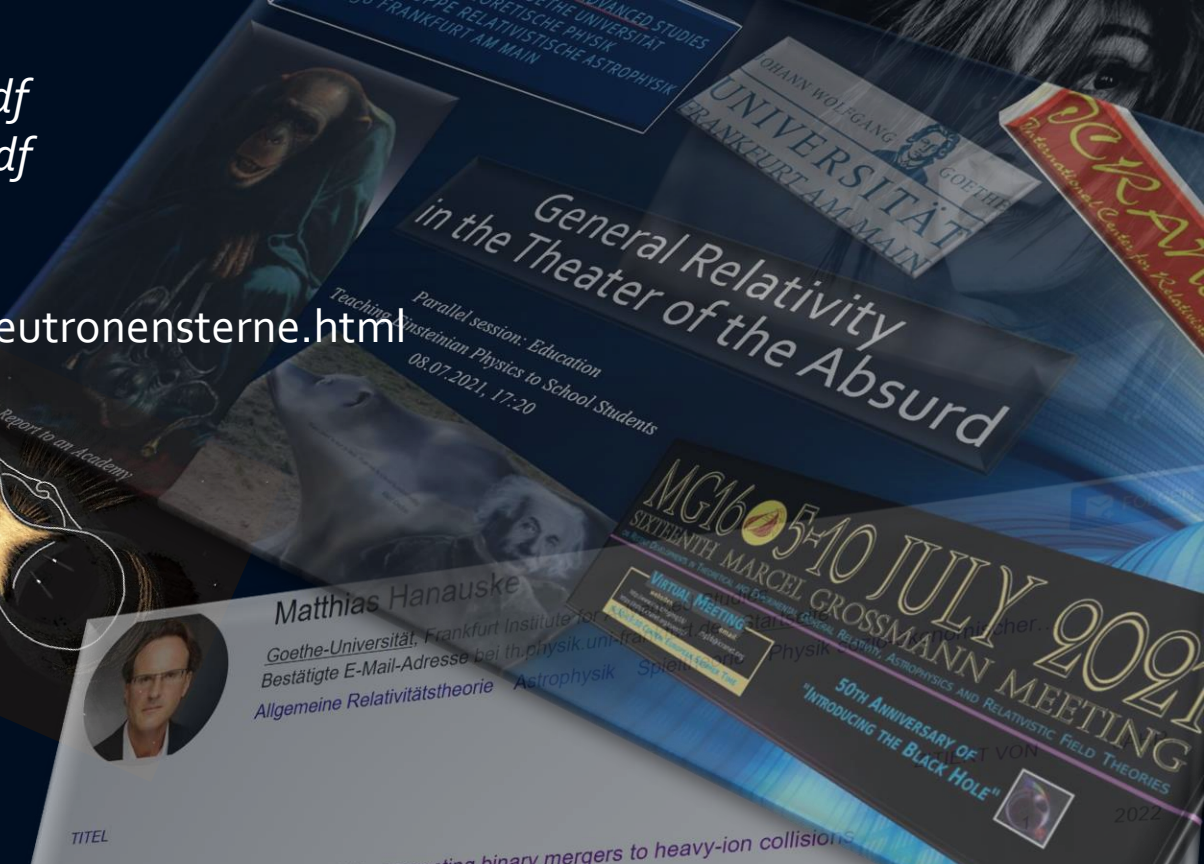
⁶Department of Physics, Kent State University, Kent, OH 44243, USA

⁷School of Mathematics, Trinity College, Dublin 2, Ireland

⁸GSI Helmholtzzentrum für Schwerionenforschung GmbH, D-64291 Darmstadt, Germany

(Dated: February 1, 2022)

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



TITEL	Year
Probing neutron-star matter in the lab: connecting binary mergers to heavy-ion collisions ER Most, A Motornenko, J Steinheimer, V Dexheimer, M Hanauske, ... arXiv preprint arXiv:2201.13150	2021
Neutron star collisions and gravitational waves M Hanauske, LR Weih Astronomische Nachrichten 342 (5), 788-798	2021
Metastable hypermassive hybrid stars as neutron-star merger remnants M Hanauske, LR Weih, H Stöcker, L Rezzolla The European Physical Journal Special Topics 230 (2), 543-550	2020
体物理, 引力波及重离子碰撞中的物质 Anton, H Matthias, W Lukas, S Jan, S Horst 核物理评论 37 (3), 272-282	2020
IC: matter in astrophysics, gravitational waves, and ion collisions Motornenko, M Hanauske, L Weih, J Steinheimer, H Stöcker 核物理评论 37 (3)	2020
nger gravitational-wave signatures of phase transitions in binary mergers M Hanauske, L Rezzolla View Letters 124 (17), 171103	2020



in 2022



Einen Dank an Eric Prydz und das Ushuiaia Hotel

