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Gravitational-wave signatures of the hadron-quark phase transition in binary neutron star mergers

DPG-Frühjahrstagung

Fachverband: Physik der Hadronen und Kerne, Nukleare Astrophysik

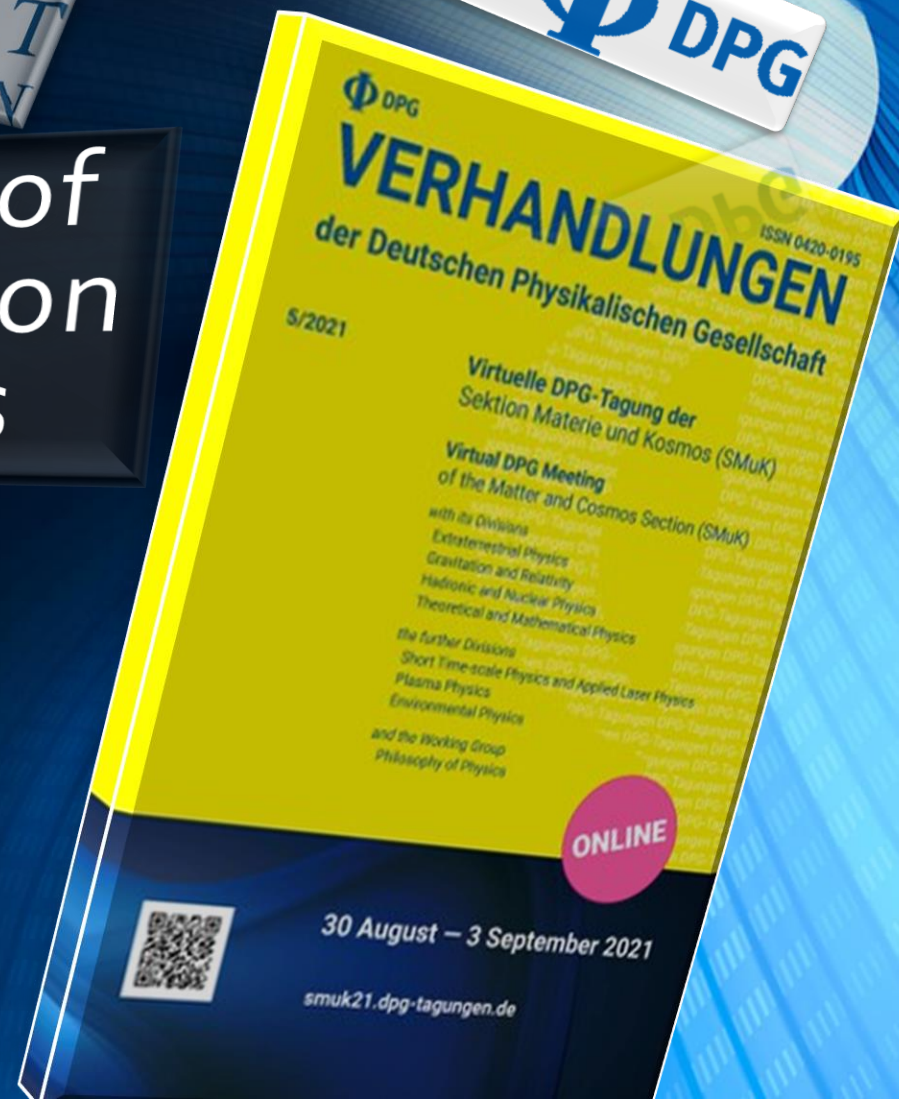
30.08.2021, 17:00

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

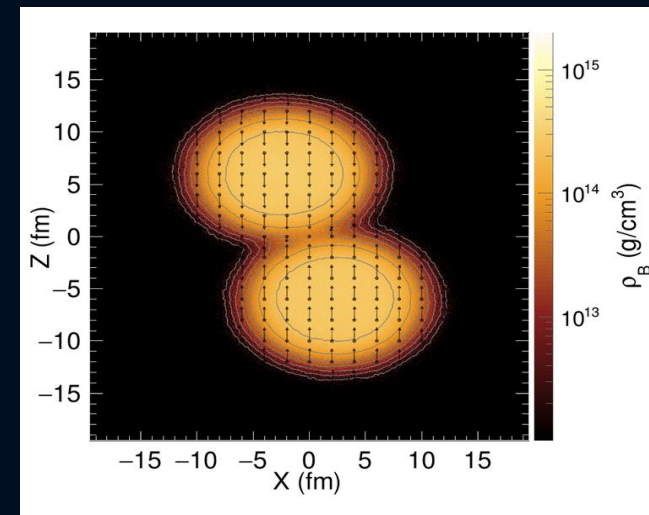


The Hadron-Quark Phase Transition and the QCD Phase Diagram

Past talk in HK1.3 by Szymon Harabasz

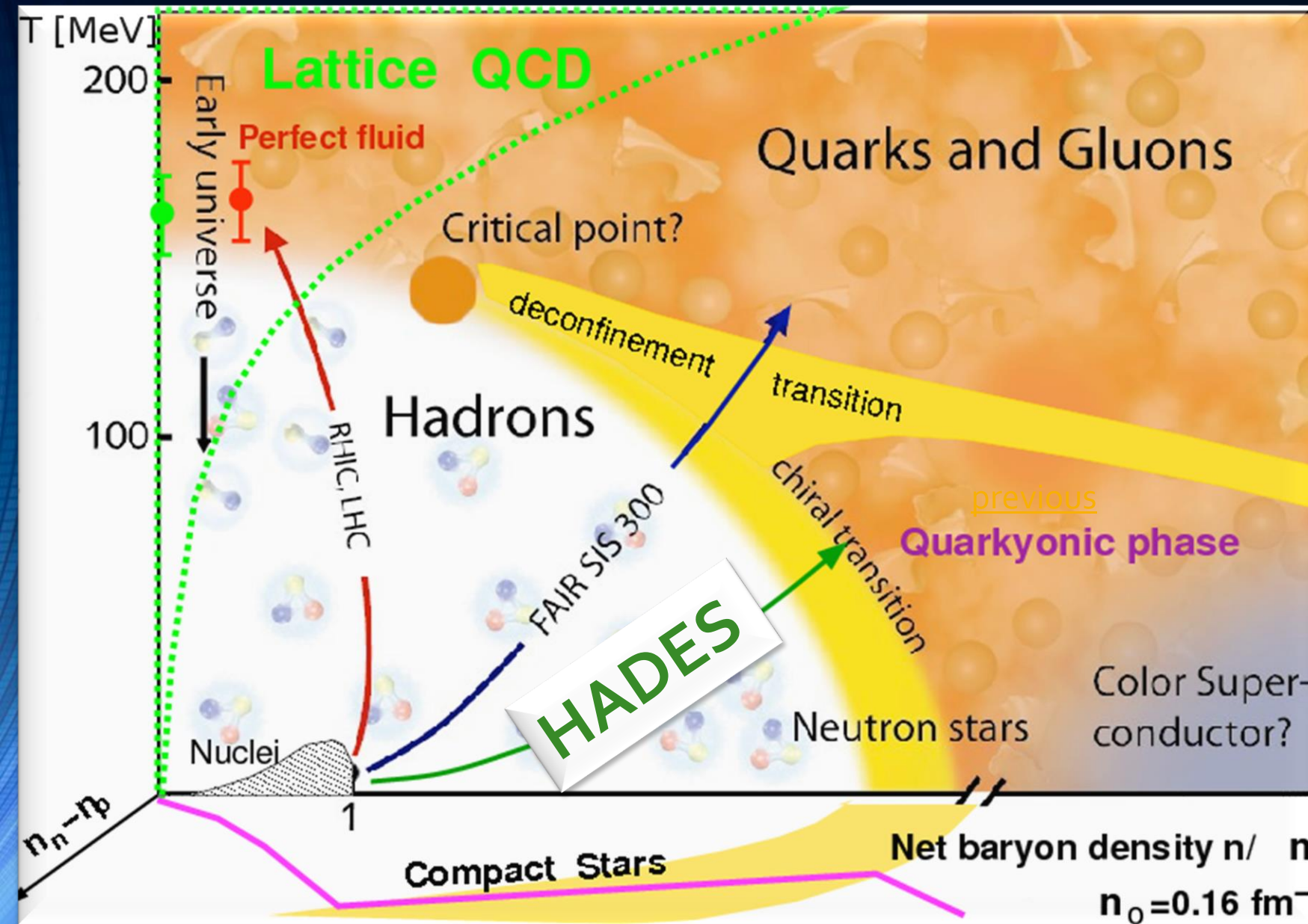
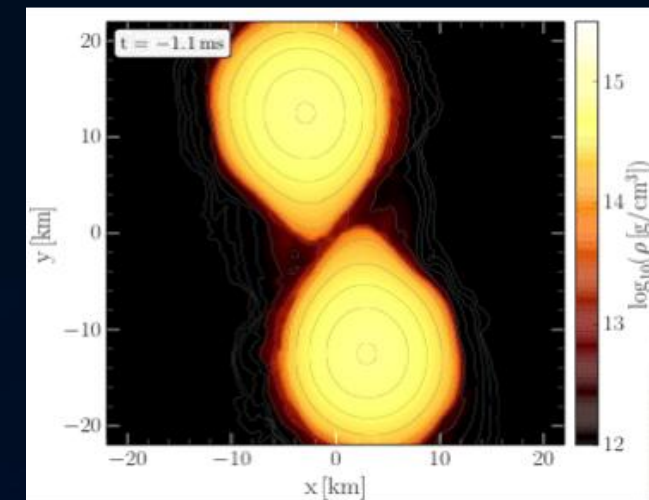
Characterizing baryon dominated matter with HADES measurements

Heavy-ion Collision



HADES: Au+Au, $\sqrt{s_{NN}} = 2.4$ GeV

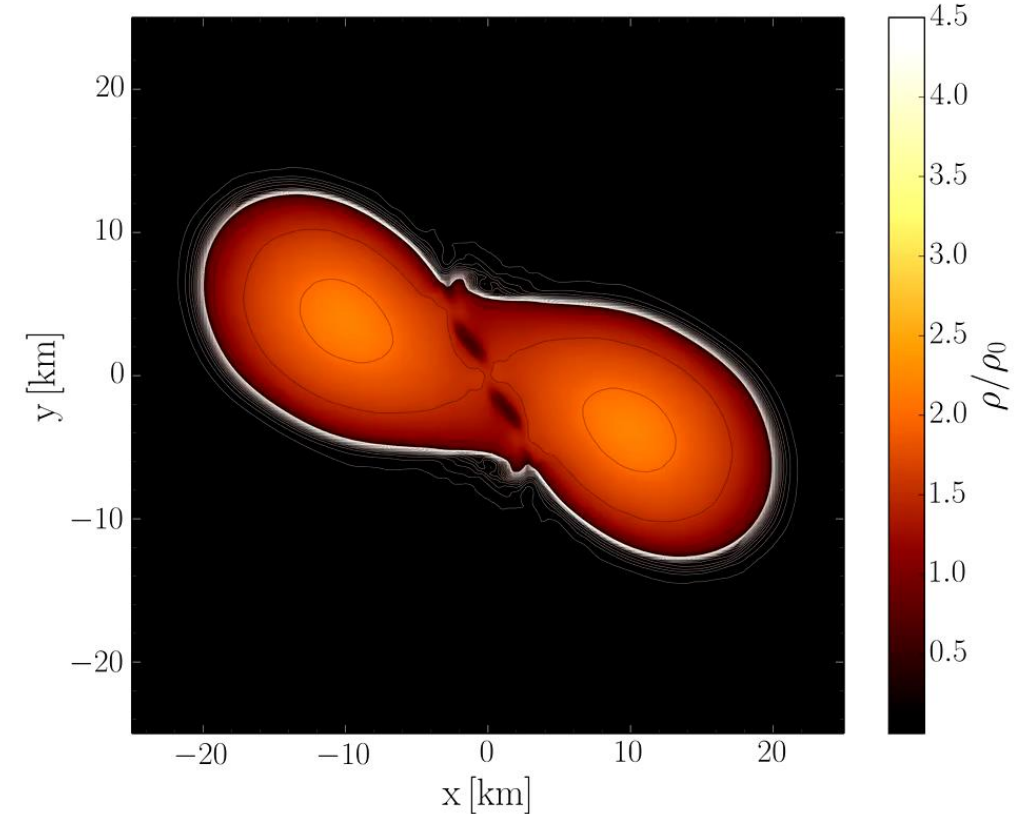
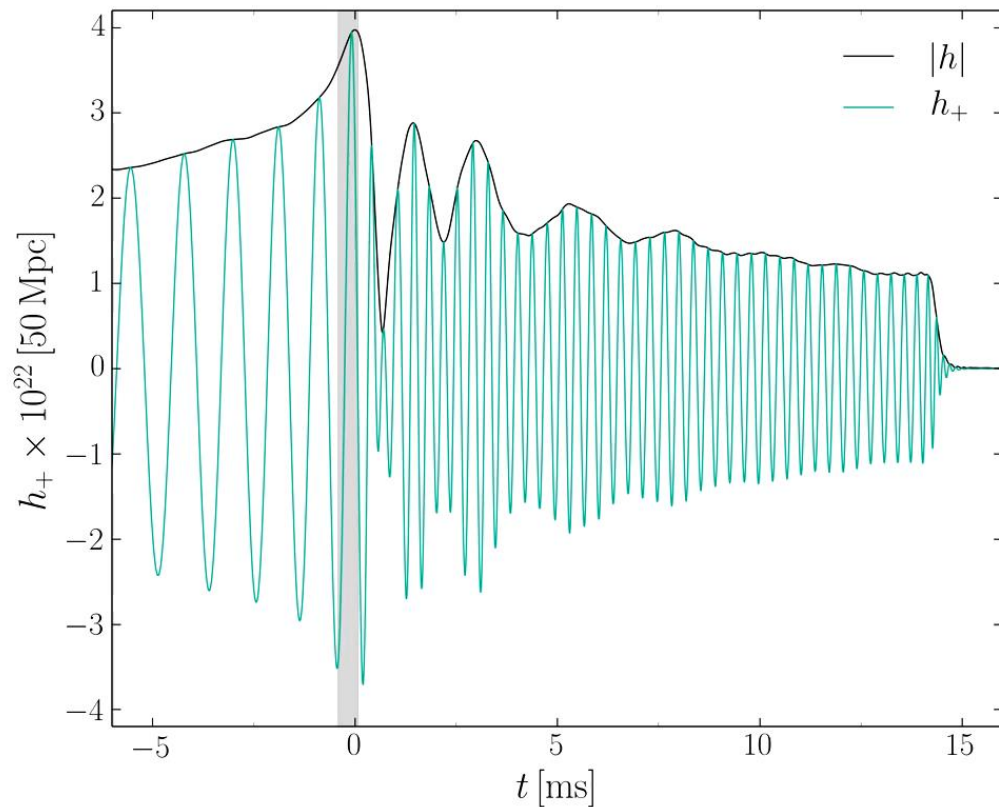
Neutron star mergers



Gravitational Waves and Hypermassive Hybrid Stars

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

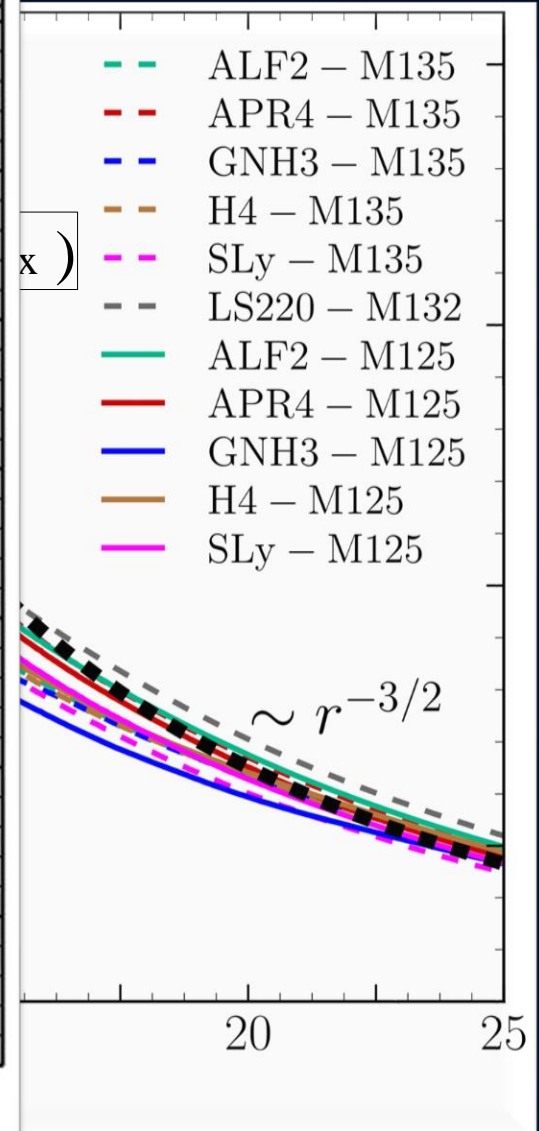
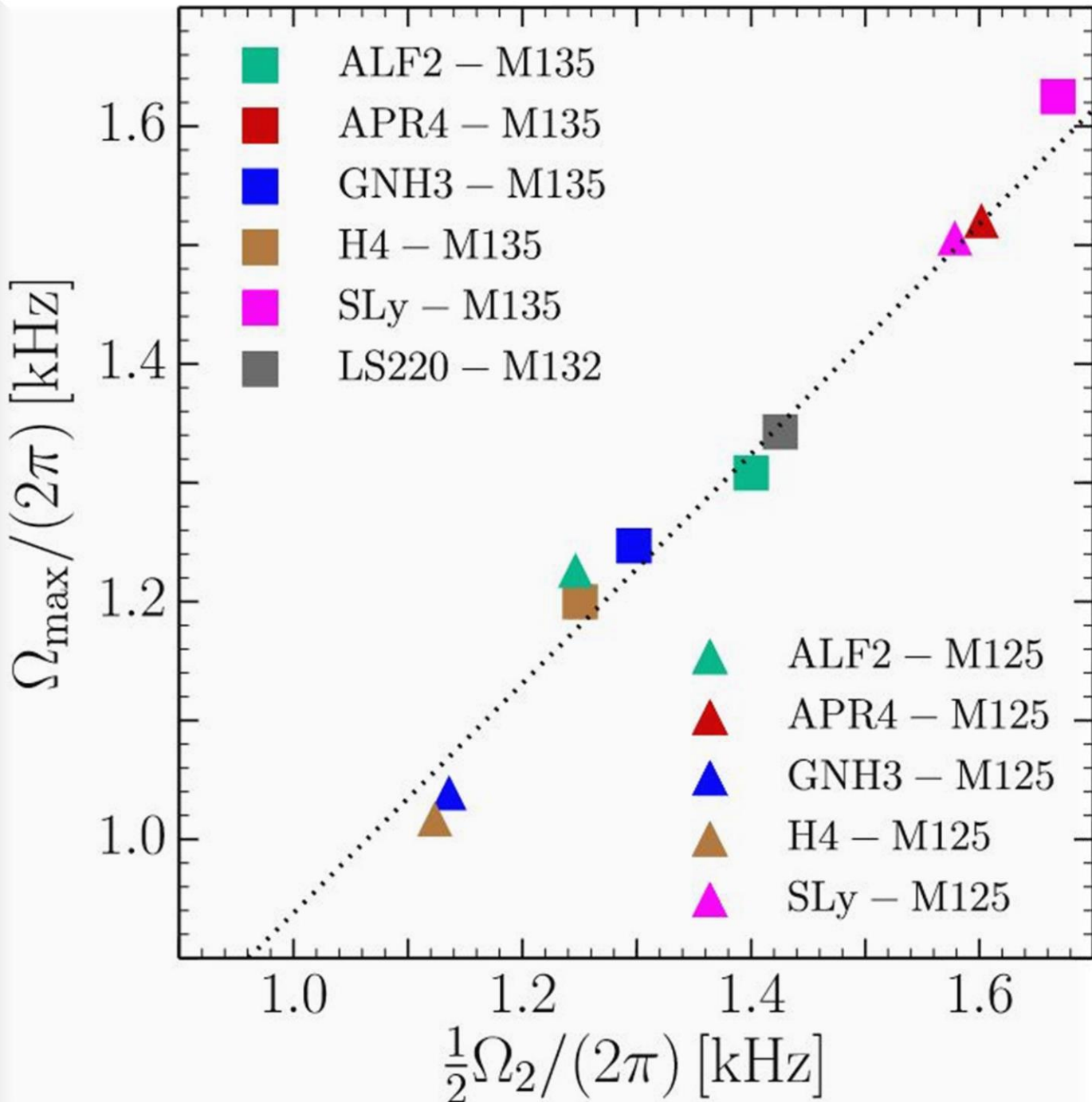
Hanauske, et.al. PRD, 96(4), 043004 (2017)



Gravitational wave amplitude
at a distance of 50 Mpc

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

files of the HMNSs

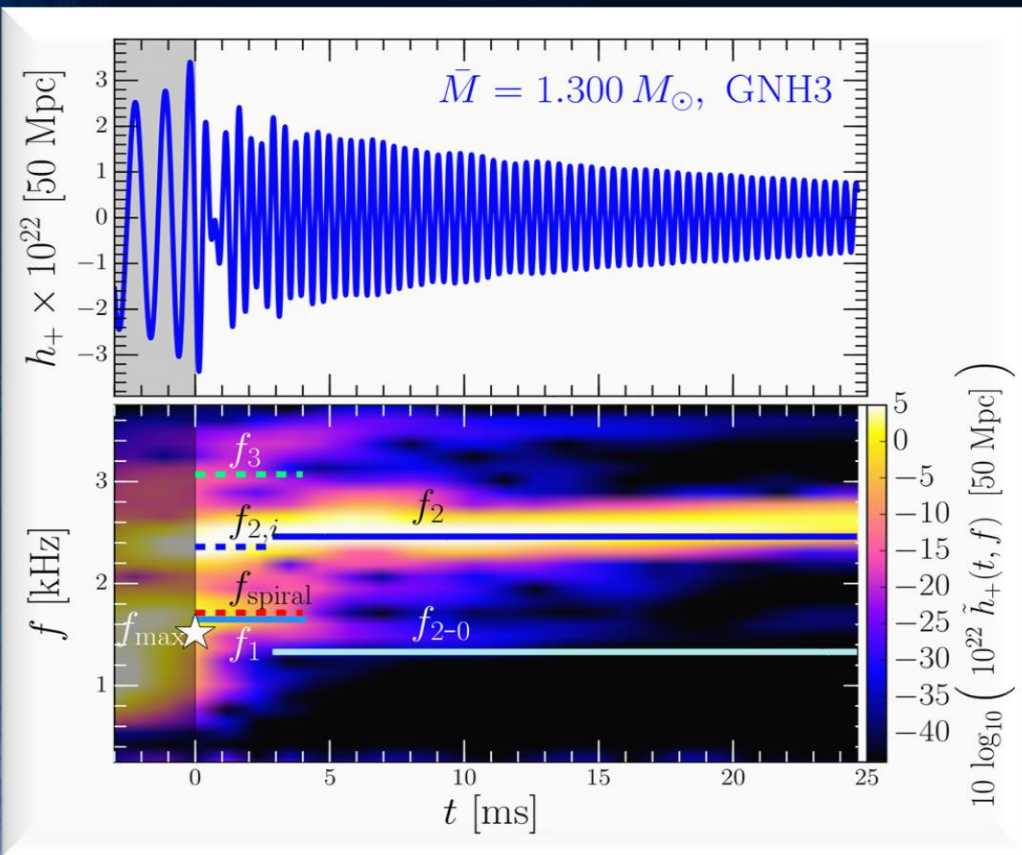


Soft EoSs:
Sly
APR4

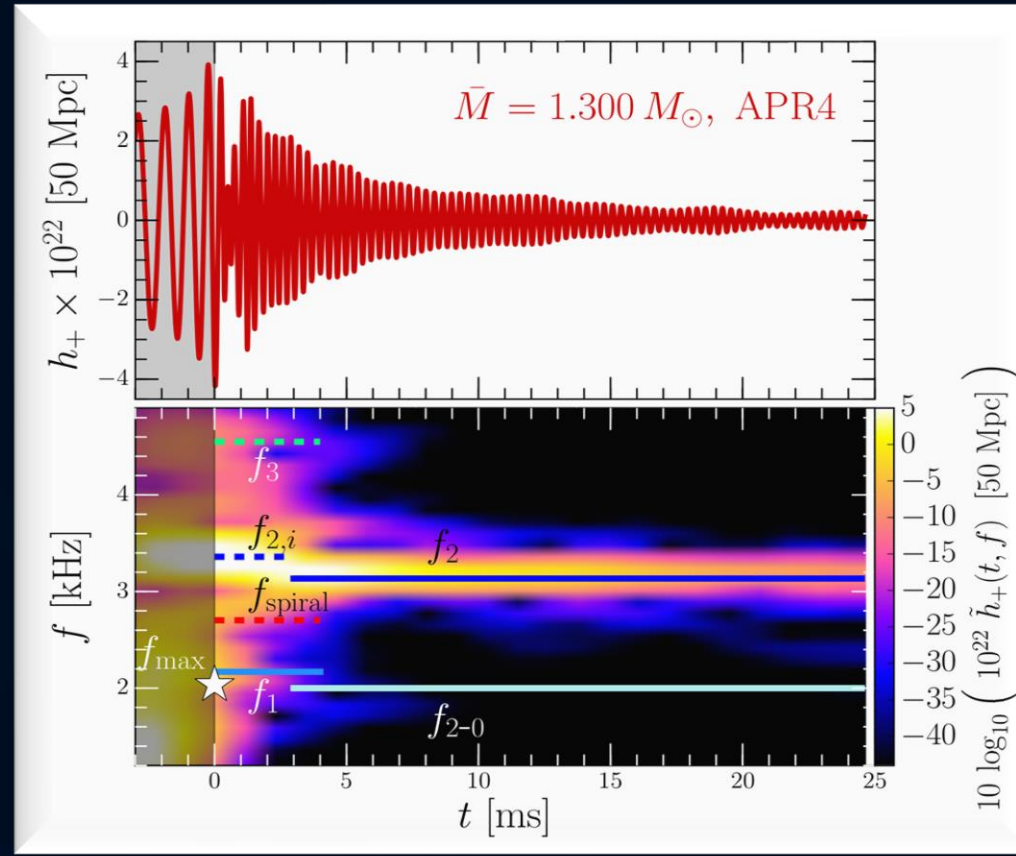
Stiff EoSs:
GNH3
H4

Time Evolution of the GW-Spectrum

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



Stiff EOS



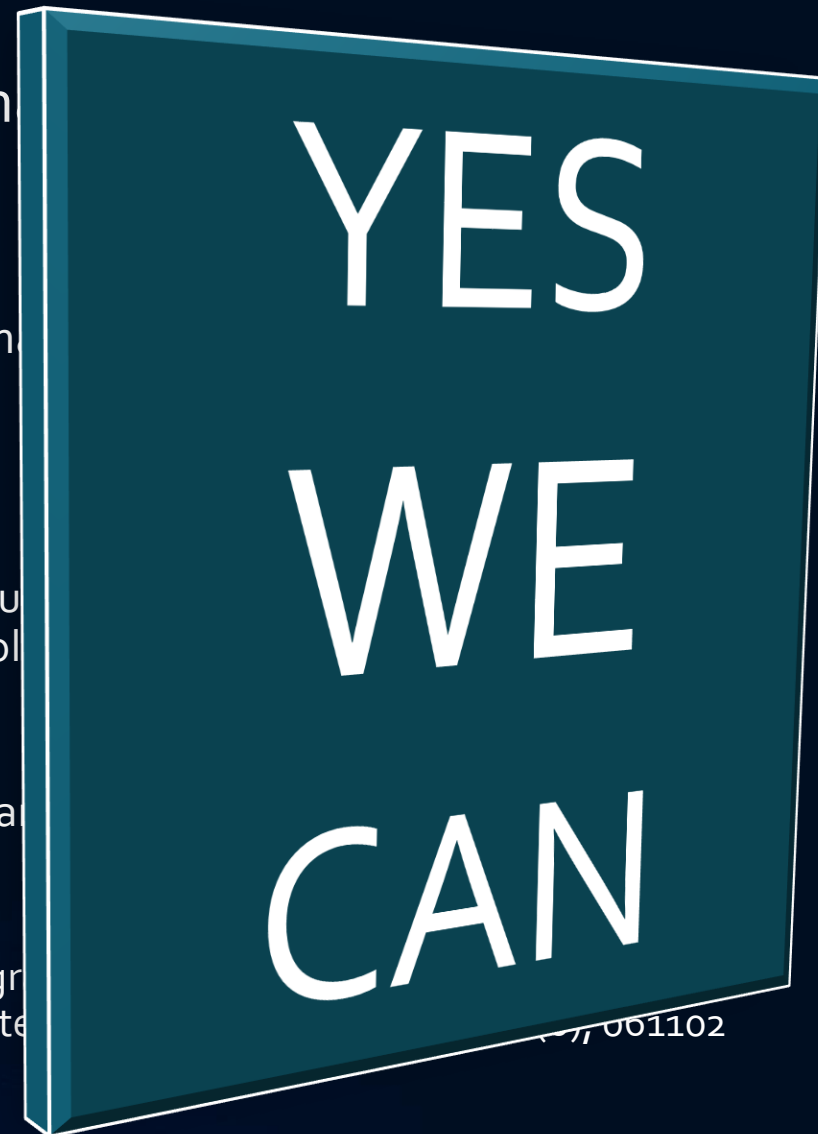
Soft EOS

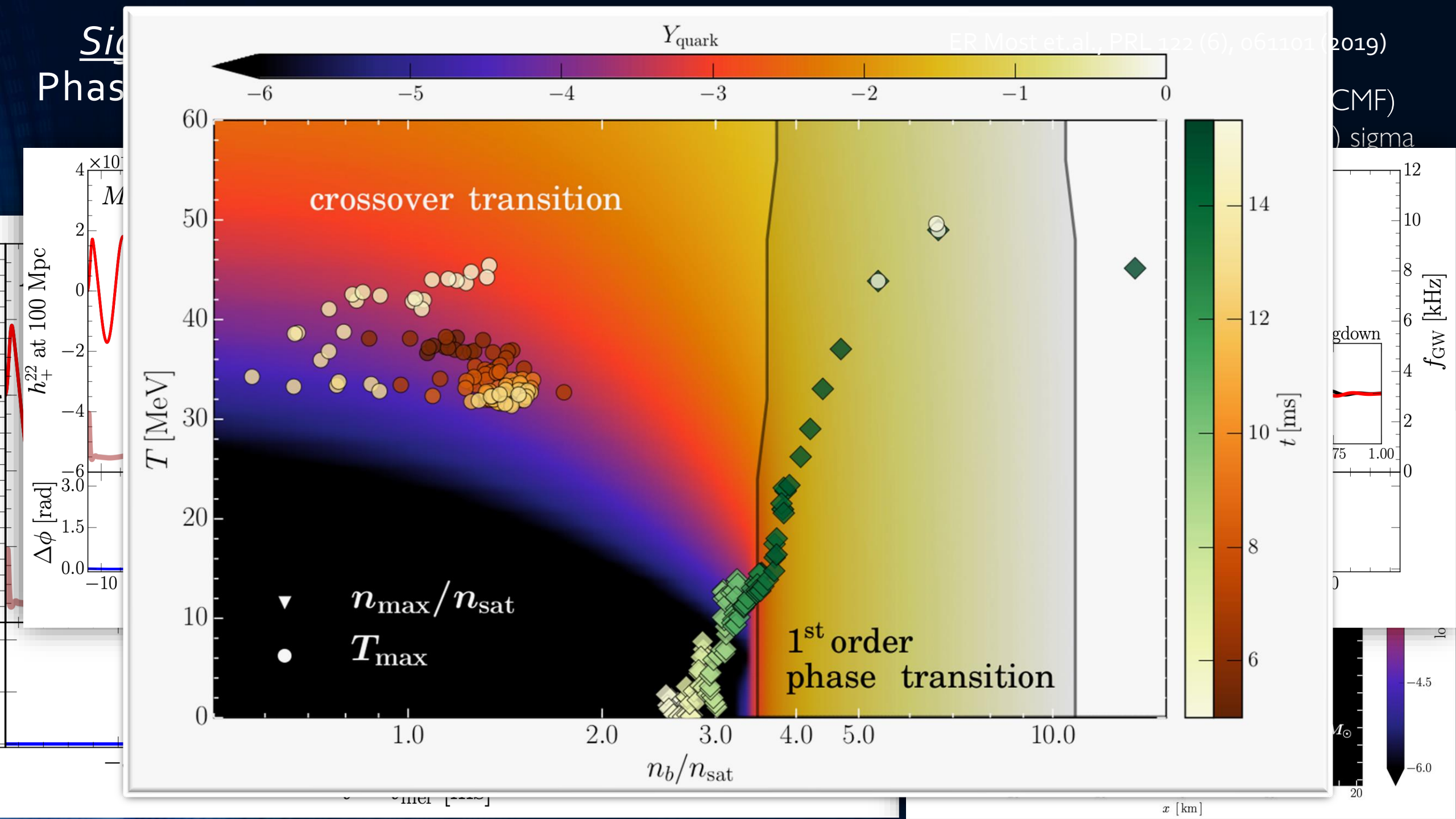
Unfortunately, due to the low sensitivity at high gravitational wave frequencies, no post-merger signal has been found in GW170817.

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

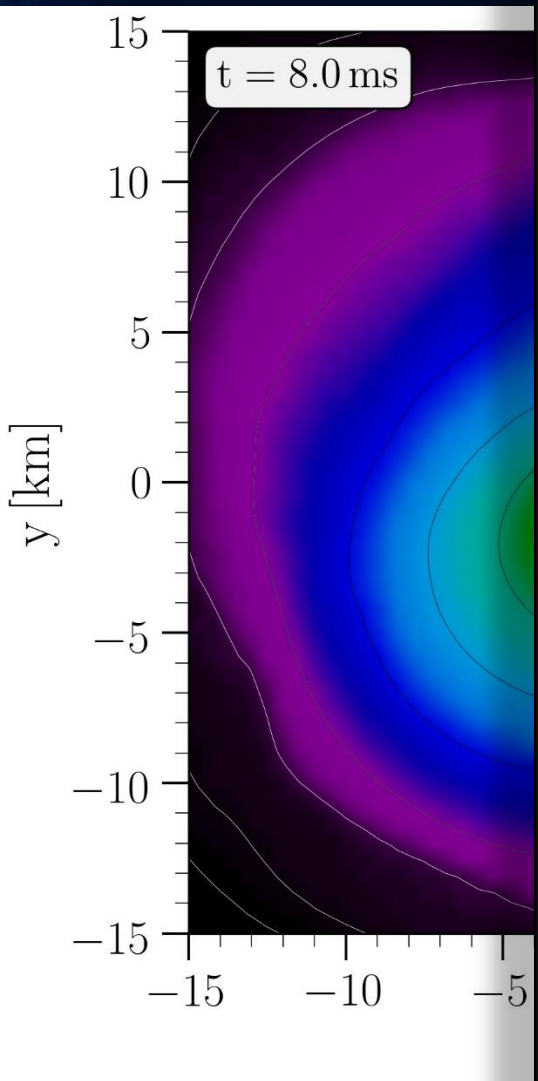
Can we detect the quark-gluon plasma with gravitational waves?

- 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; P. Papenfort, 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; M. 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. Rezzolla, M. C. Miller, M. Hanauske, M. H. P. M. van Kesteren, M. O. Ruffert, M. C. Miller, M. Hanauske, M. O. Ruffert, M. C. Miller, M. Hanauske, M. O. Ruffert; Physical Review Letters 123 (10), 101101 (2019)

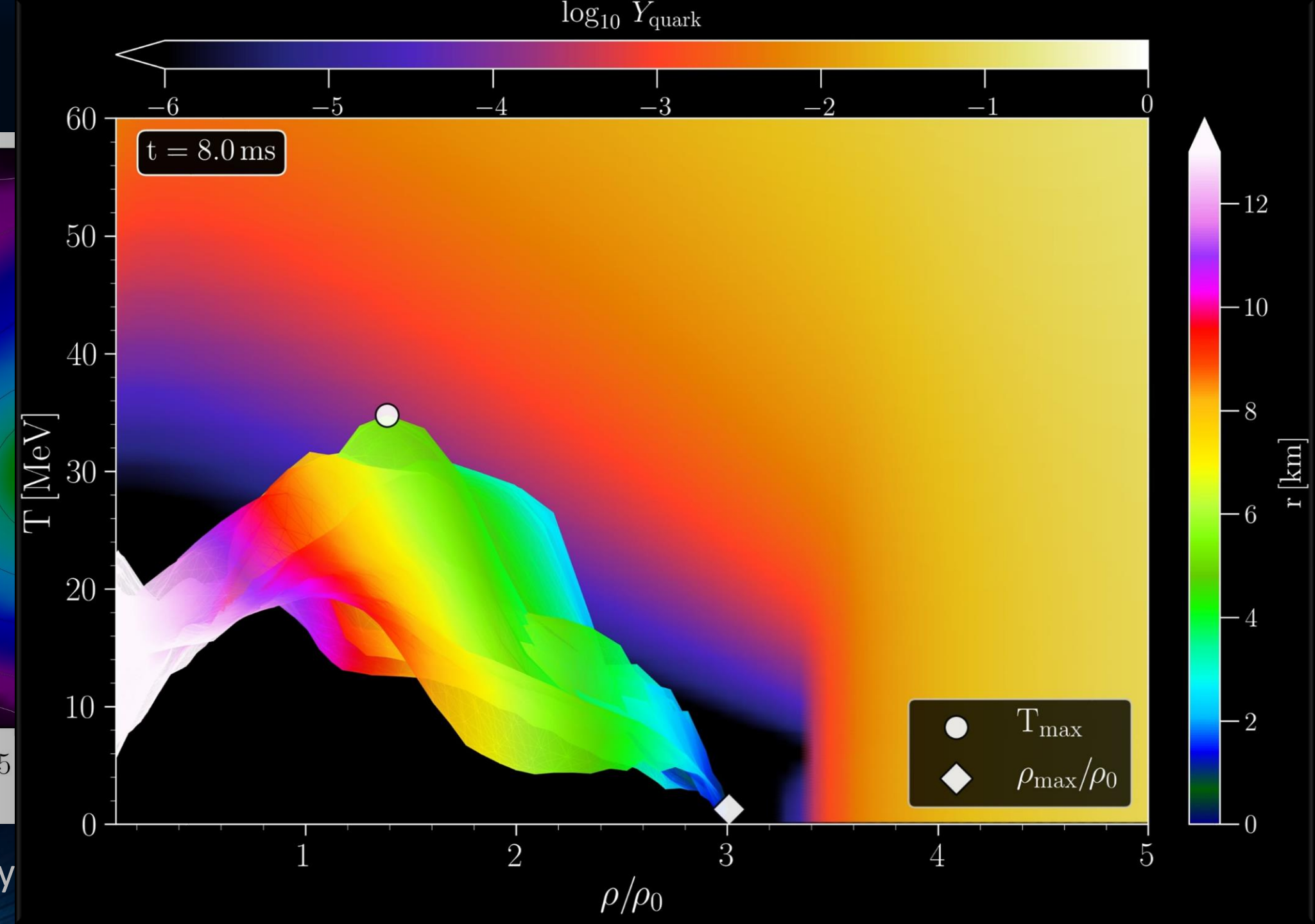




Postmerger phase



Rest mass density



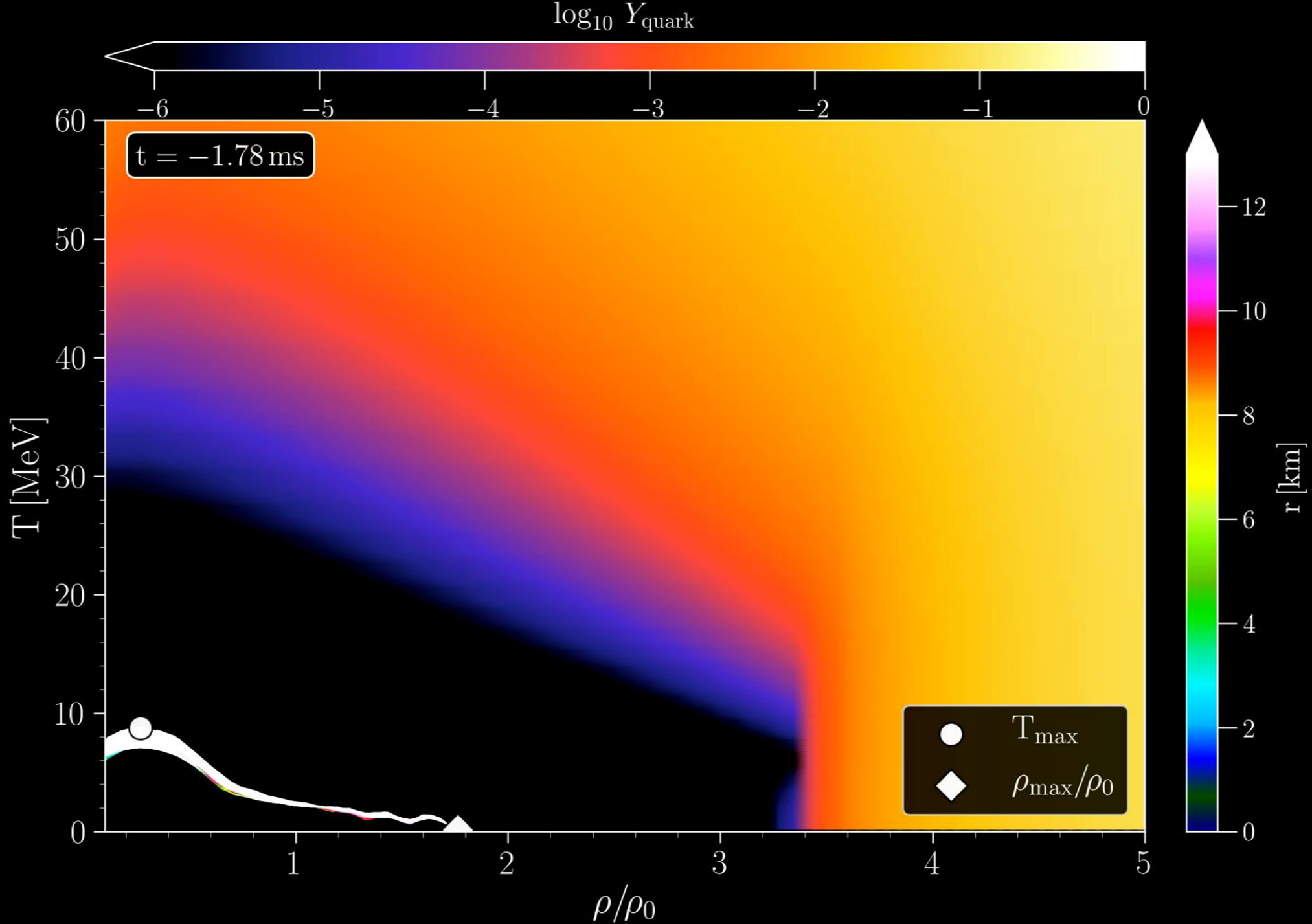
Phase-transition triggered collapse scenario

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 CMF₀ model. Simulation of total mass $M=2.8 M_{\text{solar}}$

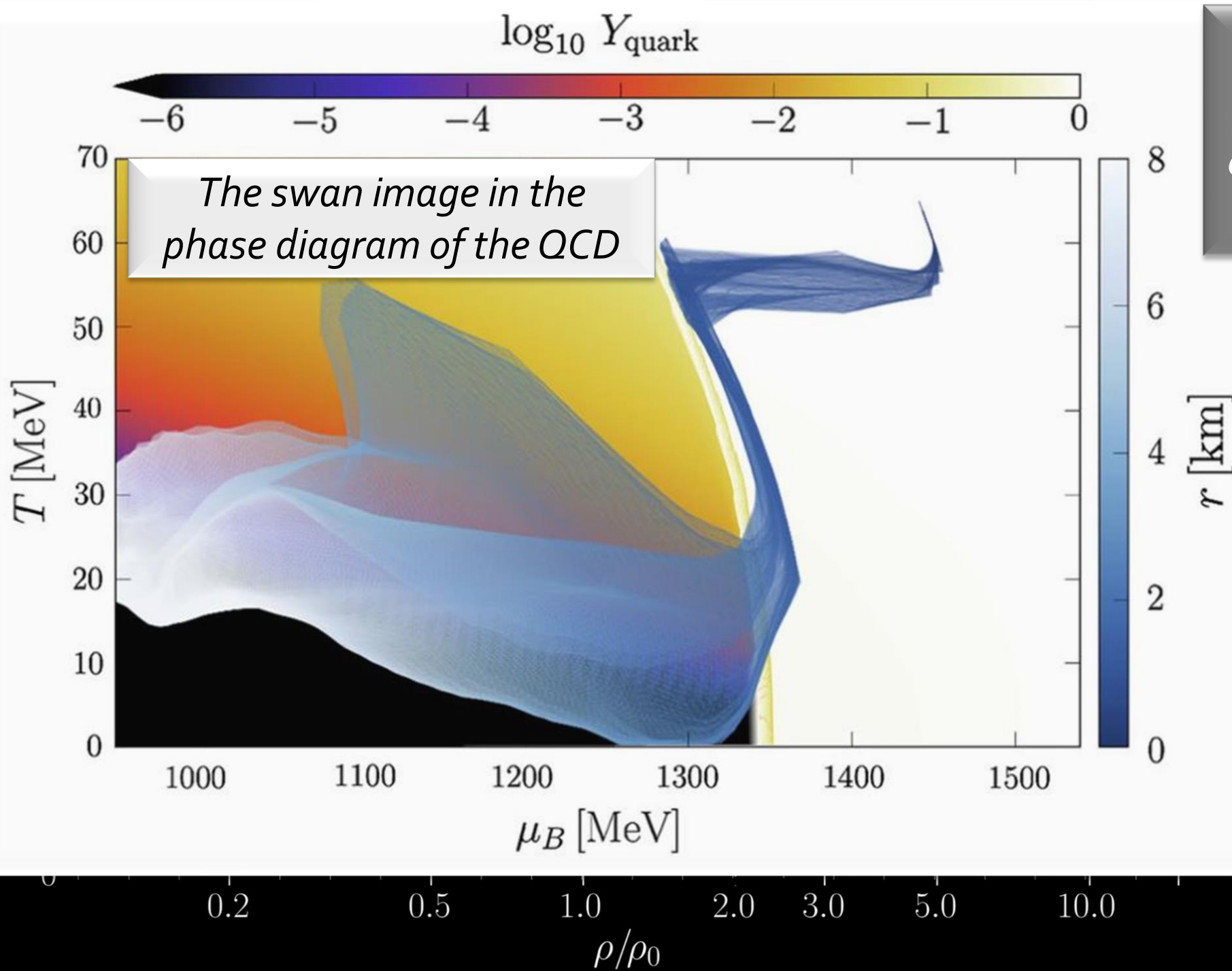


Talk on Tuesday

DPG division Gravitation and Relativity

3.00 PM in GR 3.5

On the properties of metastable
hypermassive hybrid stars



The formation of the event horizon of the accreting black hole macroscopically confines the free strange quark matter present in the head of the swan.

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

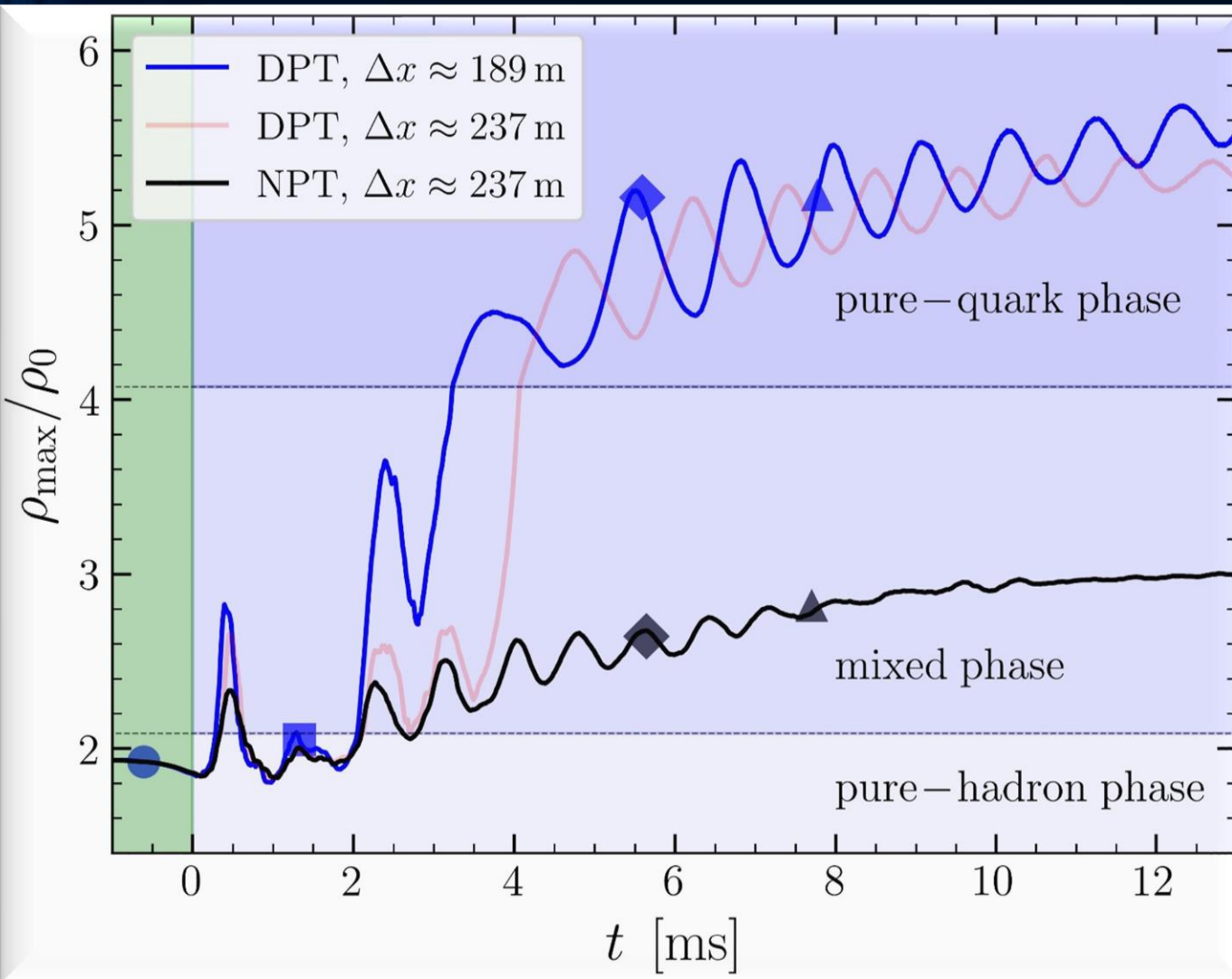
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Signatures within the post-merger phase evolution

DPT: Delayed phase transition scenario

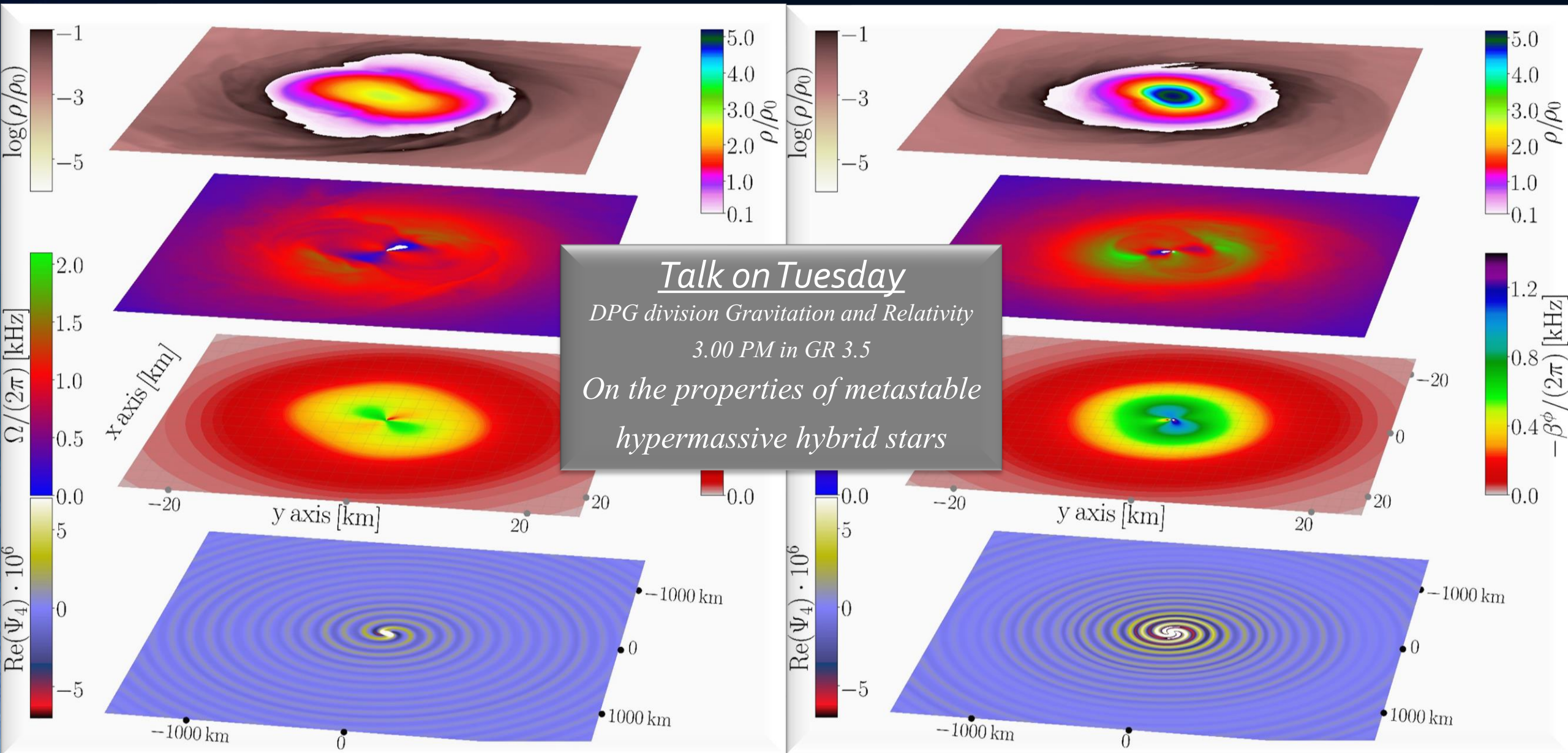
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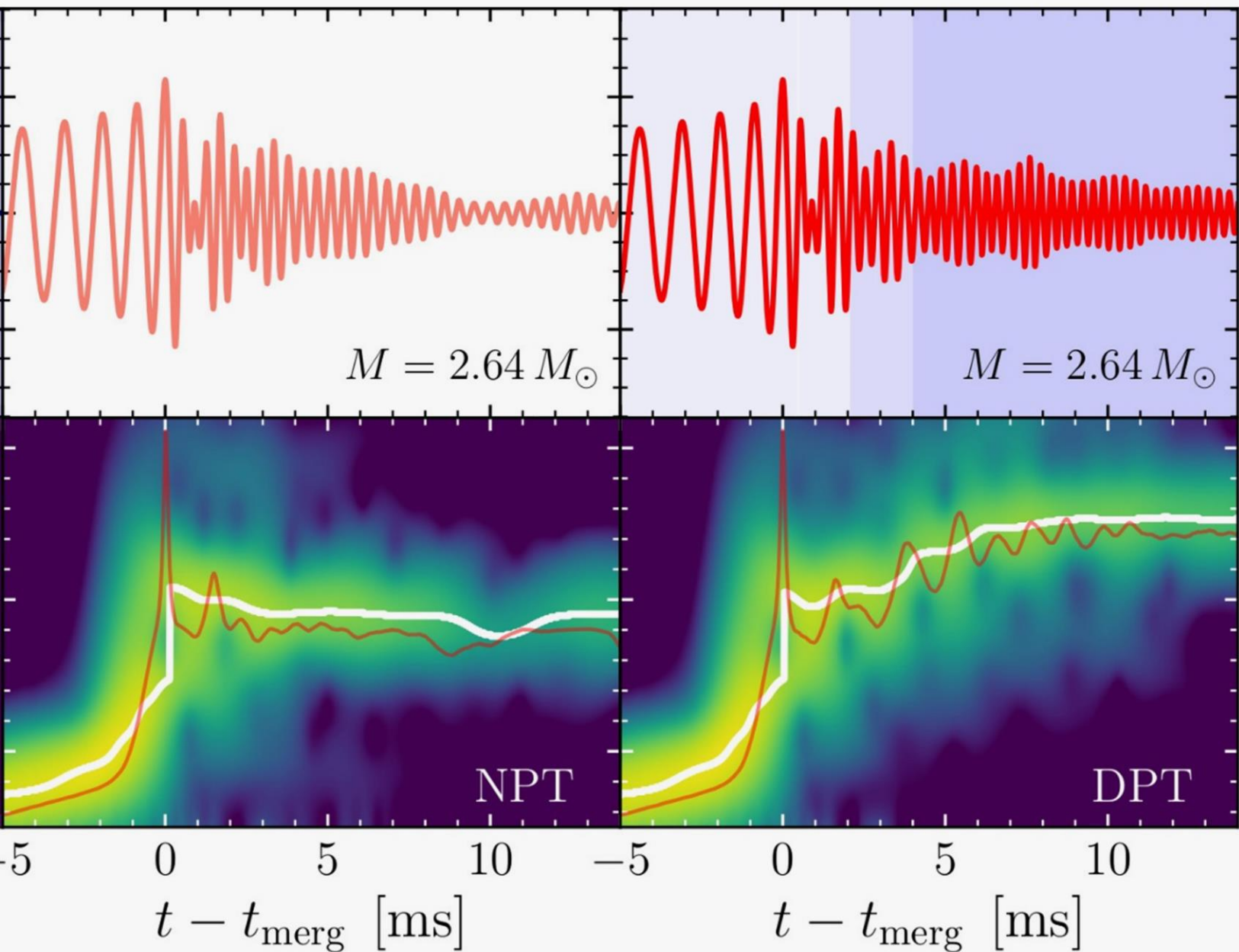


Maximum value of the rest-mass density vs time for three binary neutron star simulations. Black curve without a phase transition (NPT) and blue/red with a Gibbs-like hadron-quark phase transition (DPT: standard/low resolution). Blue-shaded regions mark the different phases of the EOS (mixed phase and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

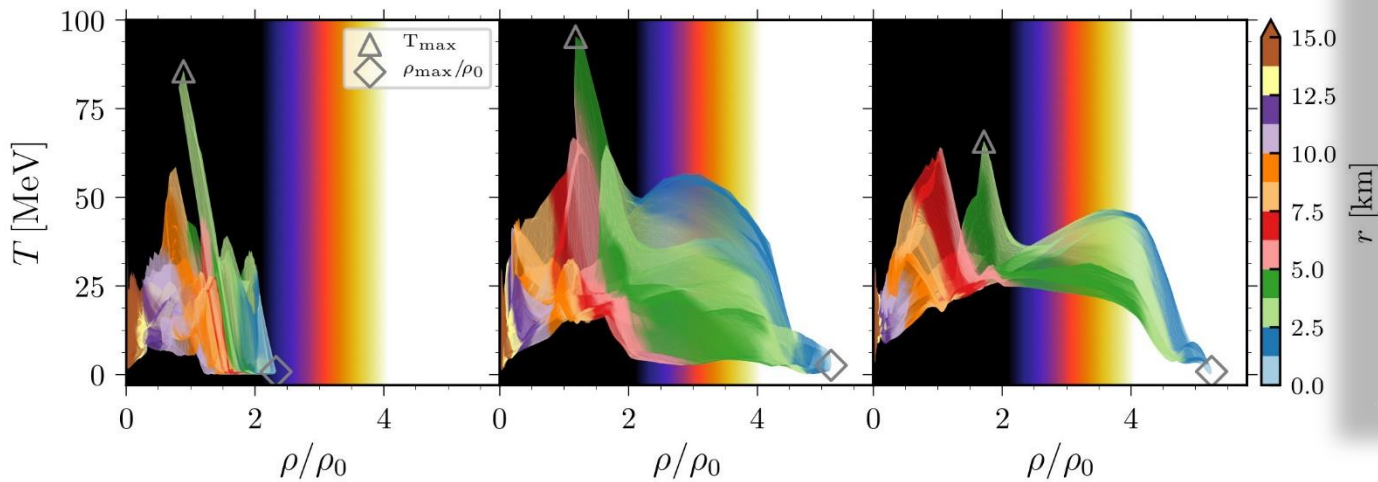
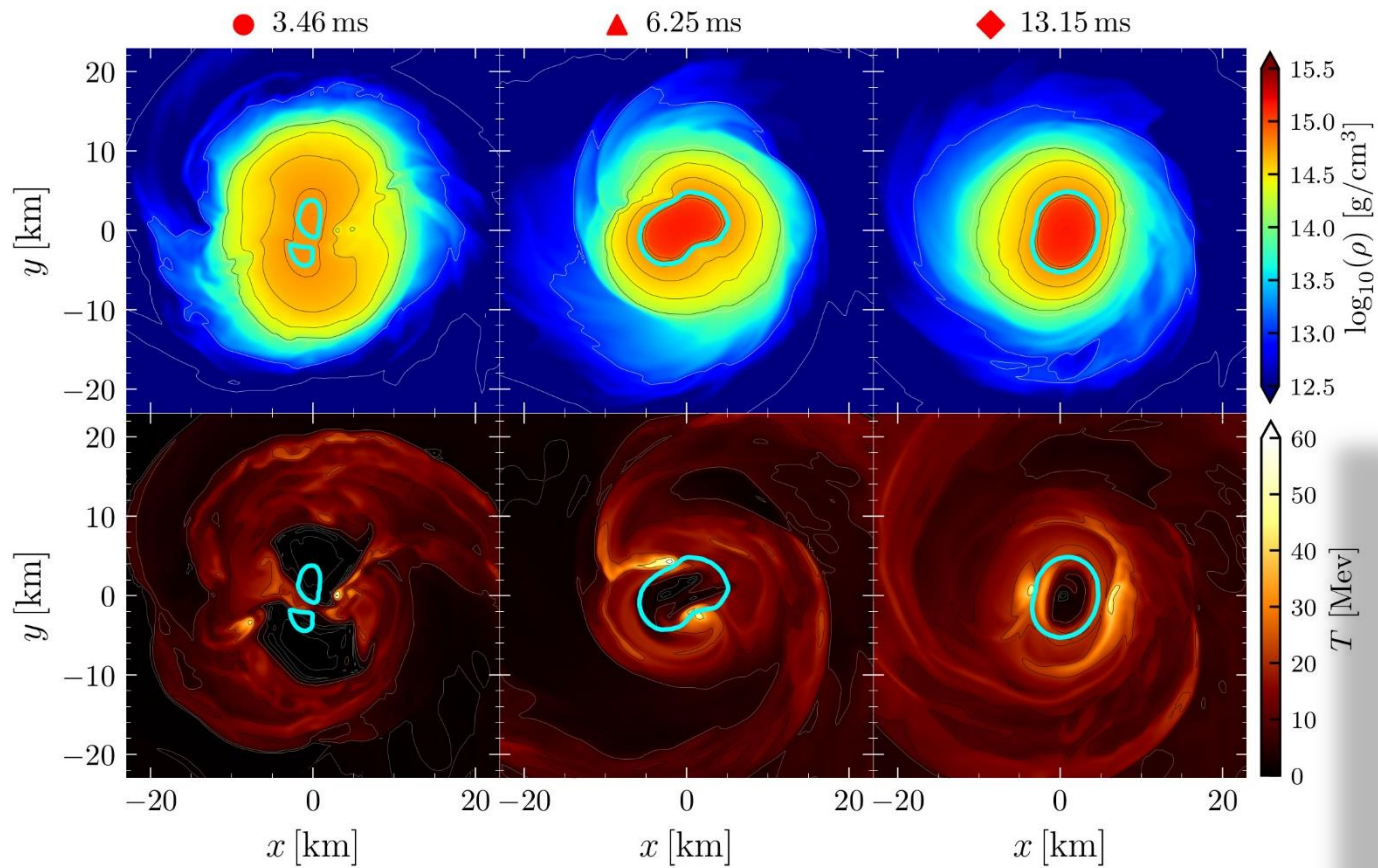
Without Phase Transition

With Phase Transition

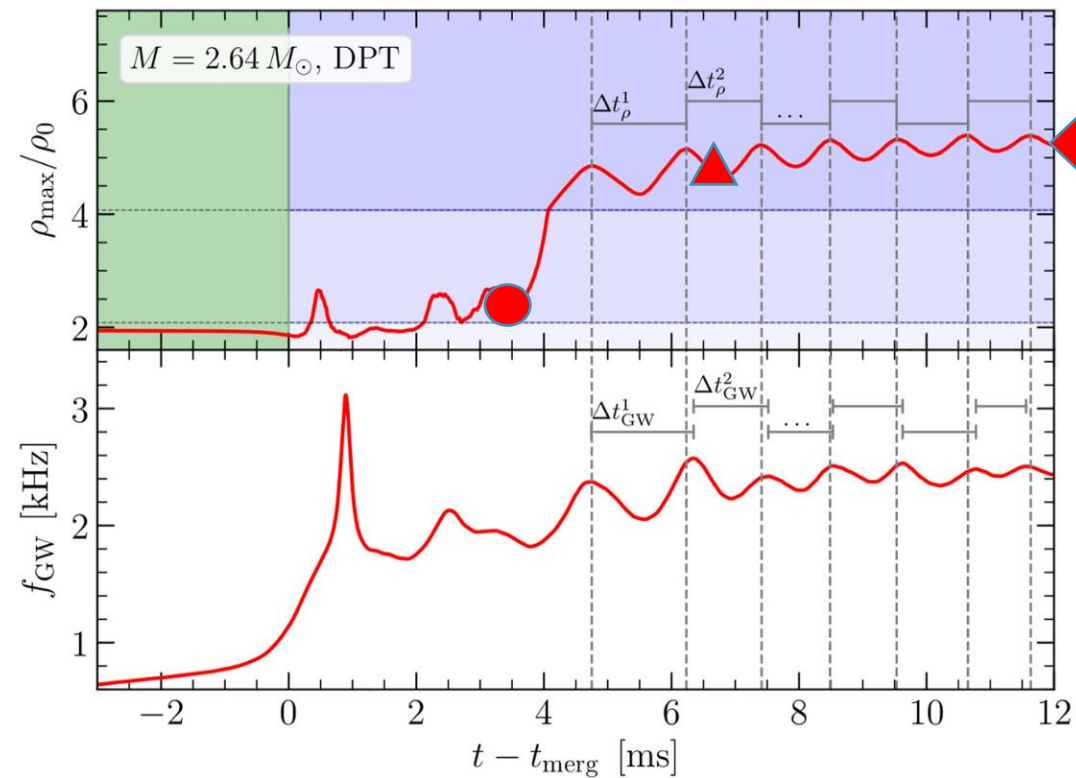




Strain h_+ (top) and its spectrogram (bottom) for the binary neutron star simulation of the delayed phase transition scenario. In the top panel the different shadings mark the times when the HMHS core enters the mixed and pure quark phases. In the bottom panels, the white lines trace the maximum of the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



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)



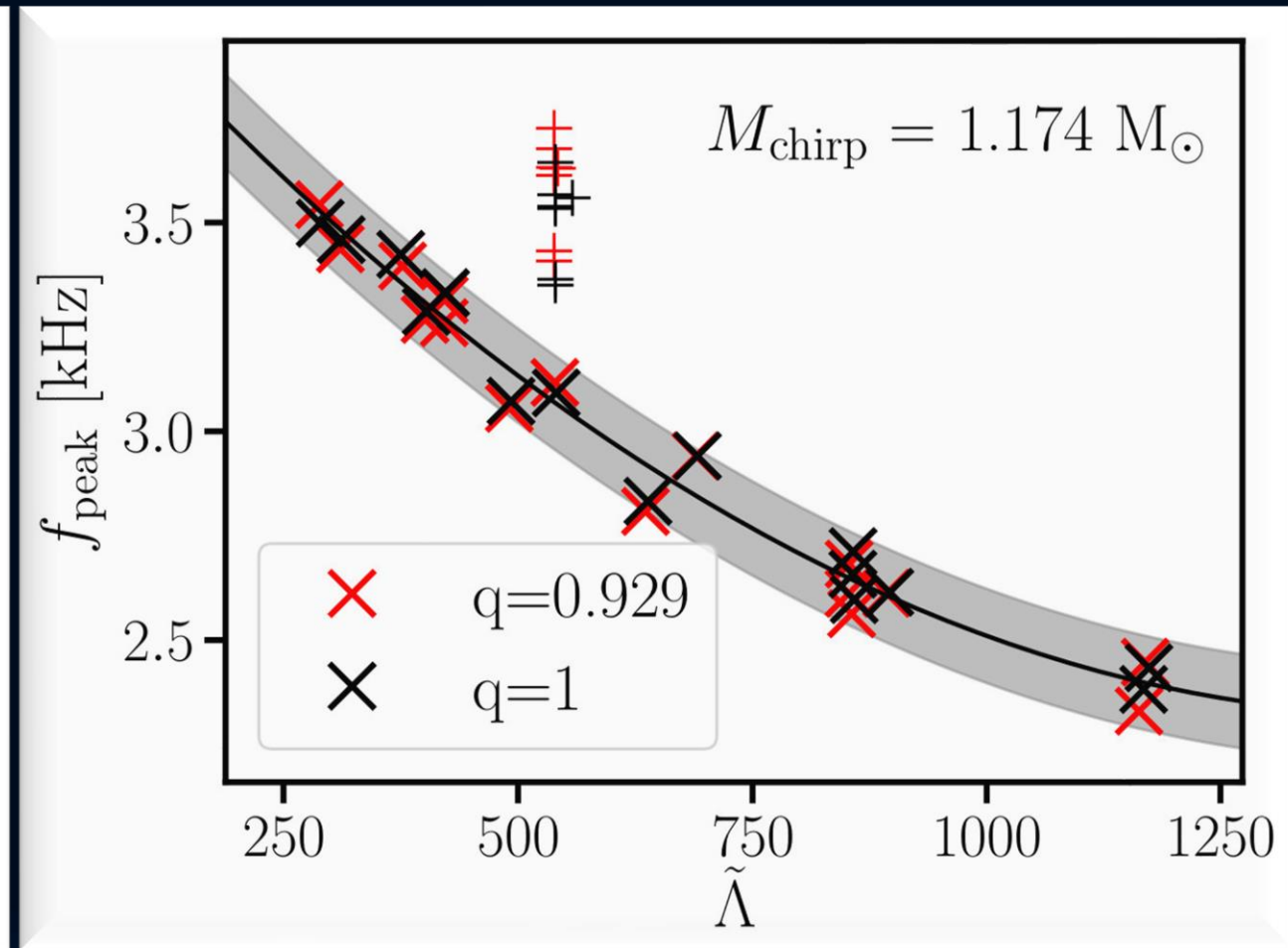
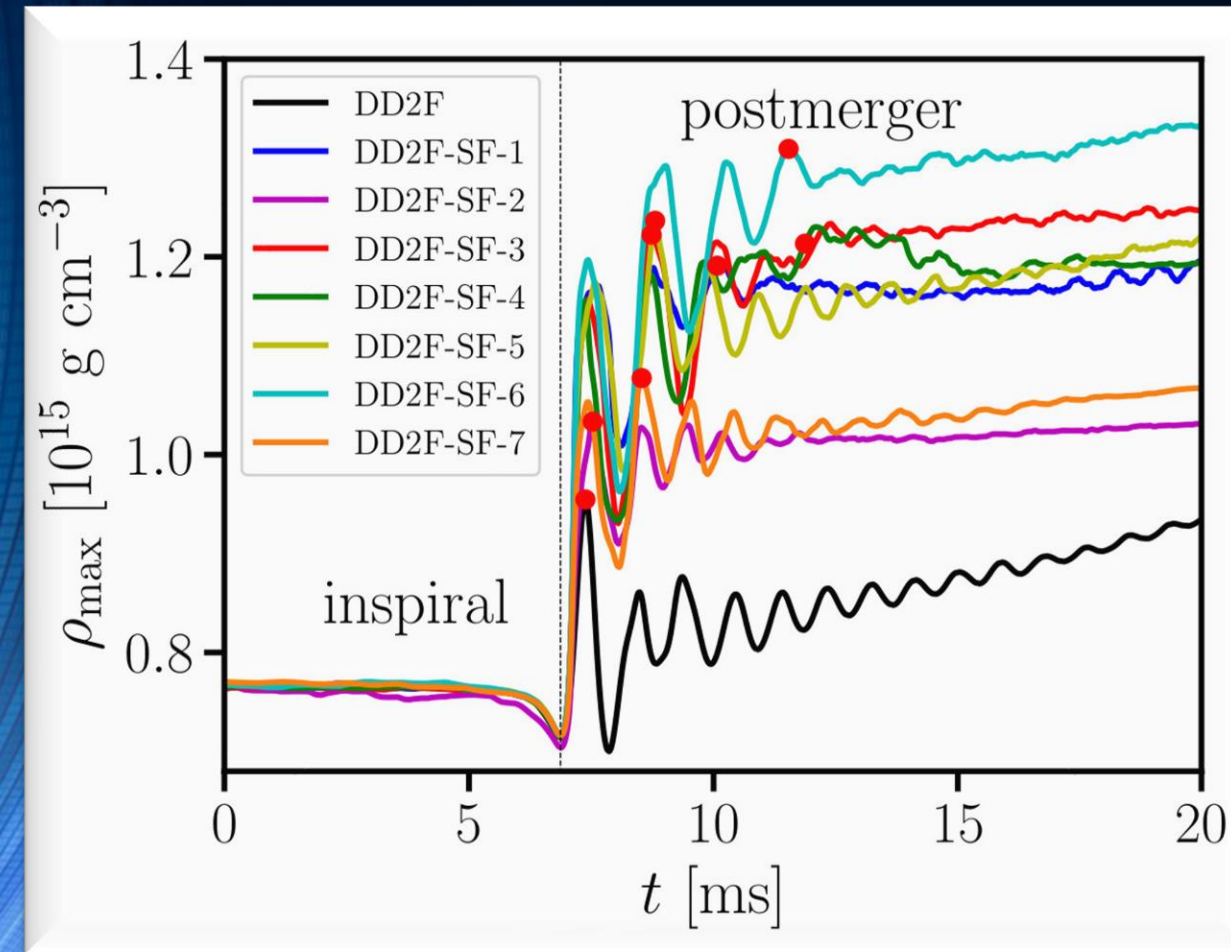
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Prompt phase transition scenario

Identifying a first-order phase transition in neutron-star mergers through gravitational waves; A Bauswein, NUF Bastian, DB Blaschke, K Chatziioannou, JA Clark, JA Clark, T Fischer, M Oertel; Physical review letters 122 (6), o61102 (2019)



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

Two new articles from other groups

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

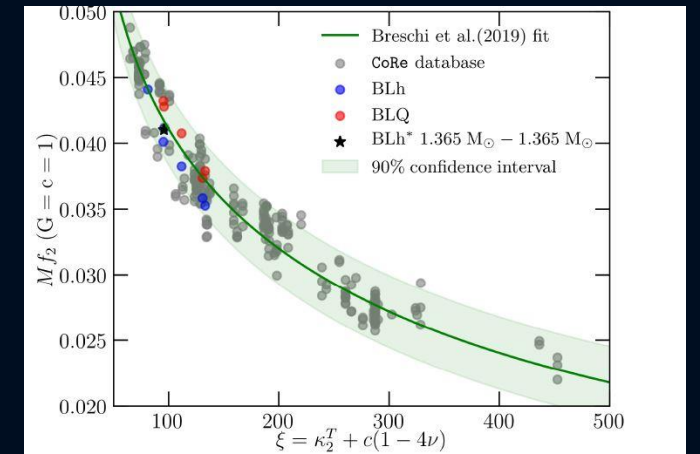
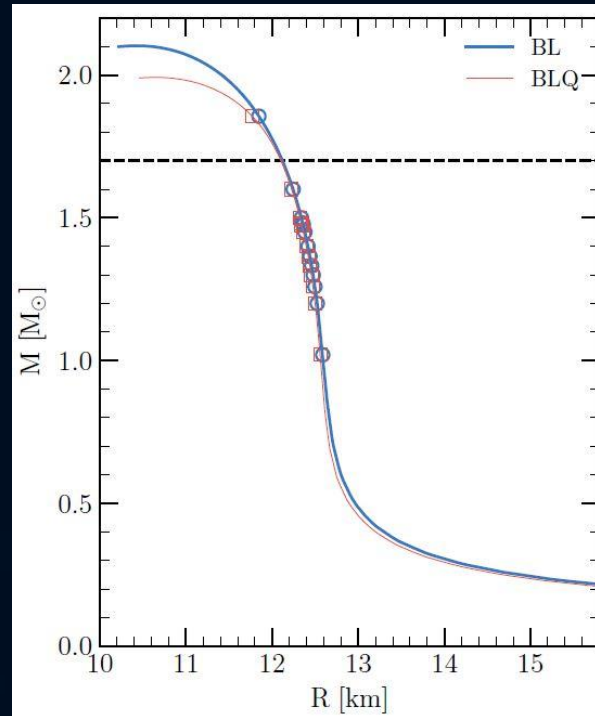


FIG. 10. Correlations between the total mass-scaled post-merger peak frequency $M f_2$ and the tidal parameter ξ . Also shown is the fit from the quasi universal relation presented in [25] along with its 90% confidence interval. The grey points correspond to simulations catalogued in the CoRe database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

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

- Additional Slides