

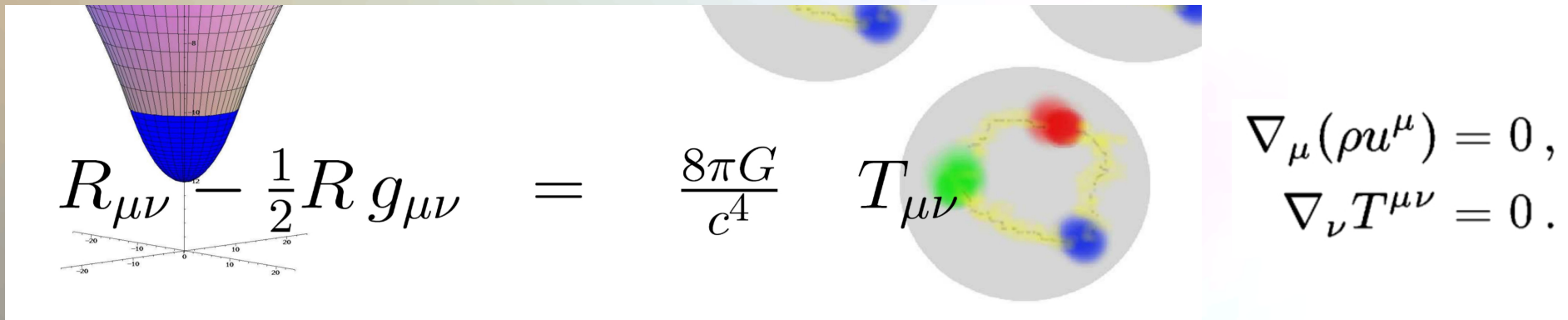
Relativistic Hydrodynamics in the Context of the Hadron-Quark Phase Transition in Compact Stars

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*Matthias Hanauske, Andreas Zacchi, Jürgen Schaffner-Bielich, Luciano
Rezzolla, and Horst Stöcker*

*Frankfurt Institute for Advanced Studies
Johann Wolfgang Goethe-University
Institute for Theoretical Physics
Department of Relativistic Astrophysics
Frankfurt am Main, Germany*

Relativistic Hydrodynamics and Numerical General Relativity

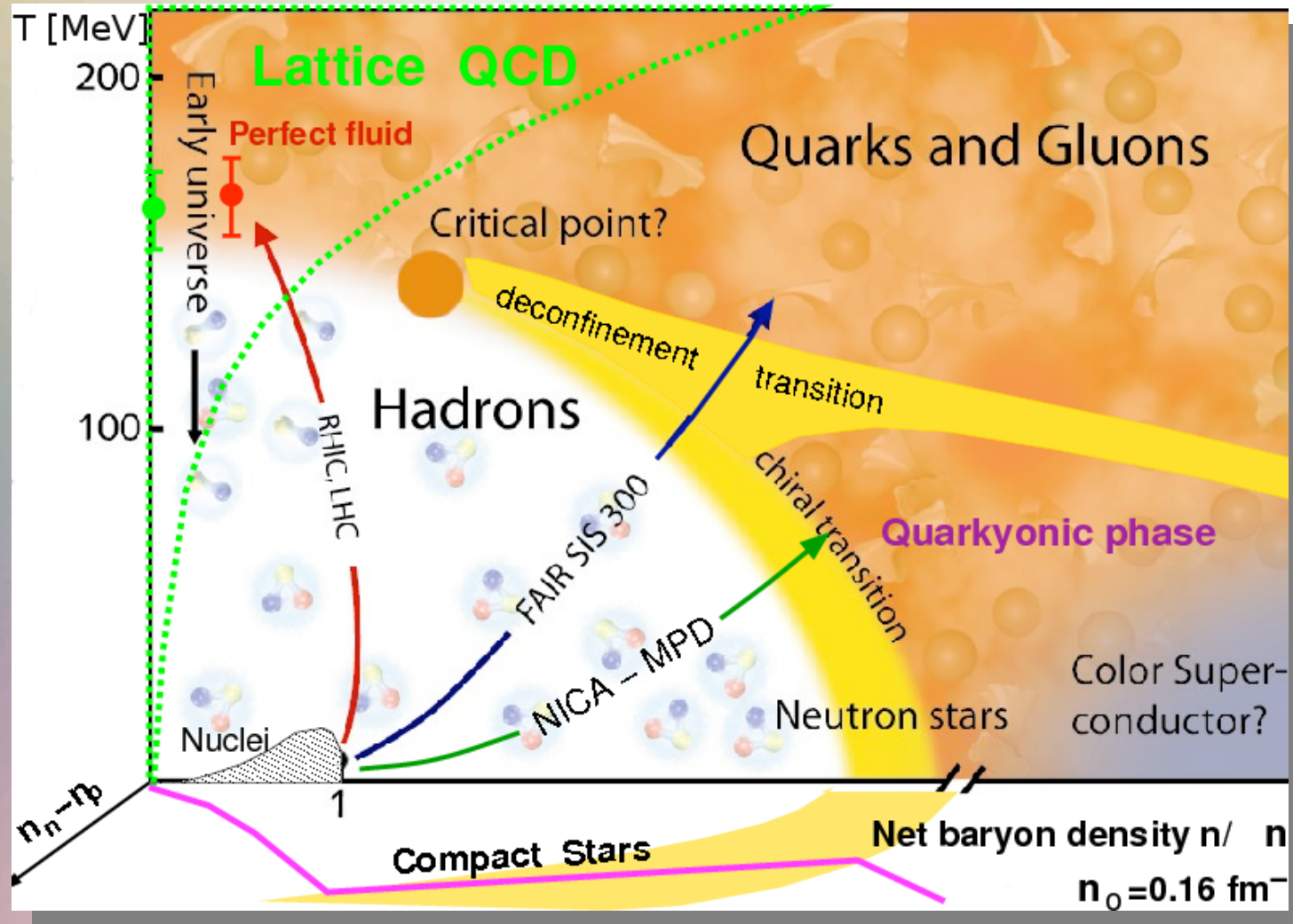

$$R_{\mu\nu} - \frac{1}{2}R g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$
$$\nabla_{\mu}(\rho u^{\mu}) = 0, \quad \nabla_{\nu} T^{\mu\nu} = 0.$$

Nonrotating Single Neutron Star: Tolmann-Openheimer-Volkoff equations

Rotating Single Neutron Star: Slow rotation Hartle-Thorne approximation
Computer Codes: RNS, Lorene, Cocal, ...

Neutron Star Merger Simulations: (3+1)-Split, ADM- and BSSNOK equations,
Valencia Formulation
Computer Codes: ET, BAM, ...

The Equation of State and the QCD Phase Diagram



The Maxwell Construction

No Mixed Phase Region

Pressure and baryon chemical potential stays constant, while the density and the charge chemical potential jump discontinuously during the phase transition.

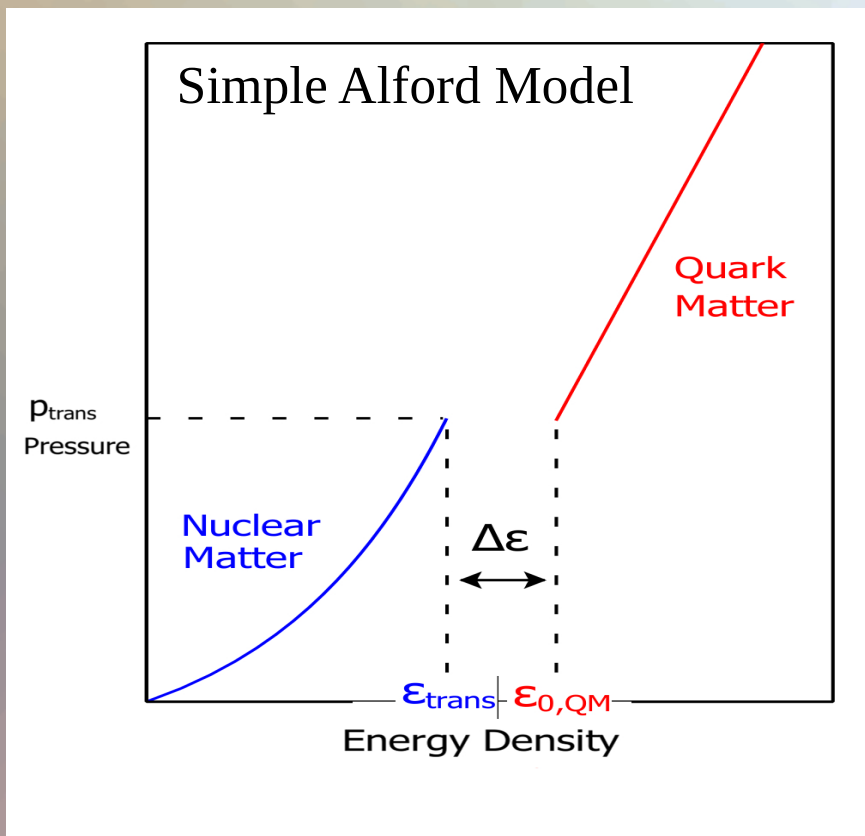
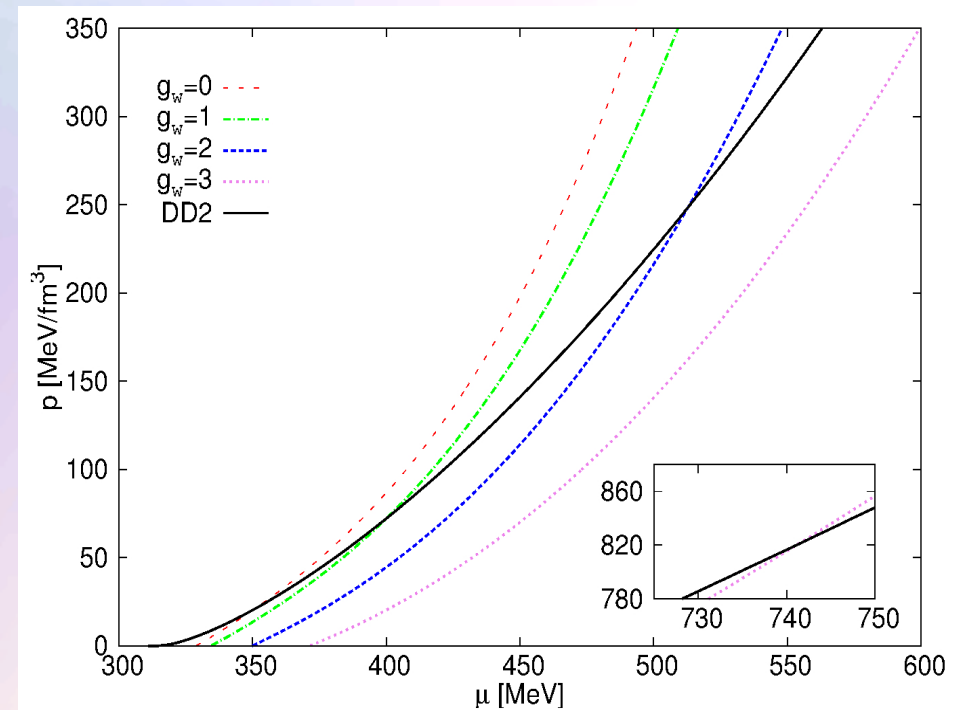


Image from M.G. Alford, S. Han, and M. Prakash, Phys. Rev. D 88, 083013 (2013)

Hadronic Phase: DD2-Model

Quark Phase: Chiral Quark Meson Model



A.Zacchi, M.Hanuske and Schaffner-Bielich, Phys. Rev. D 93, 065011 (2016)

Twin Stars in the simple Alford Model

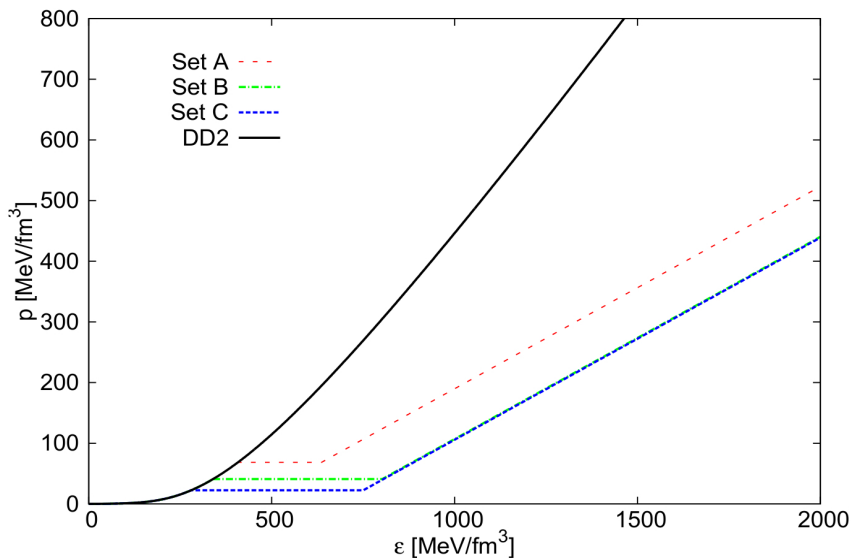
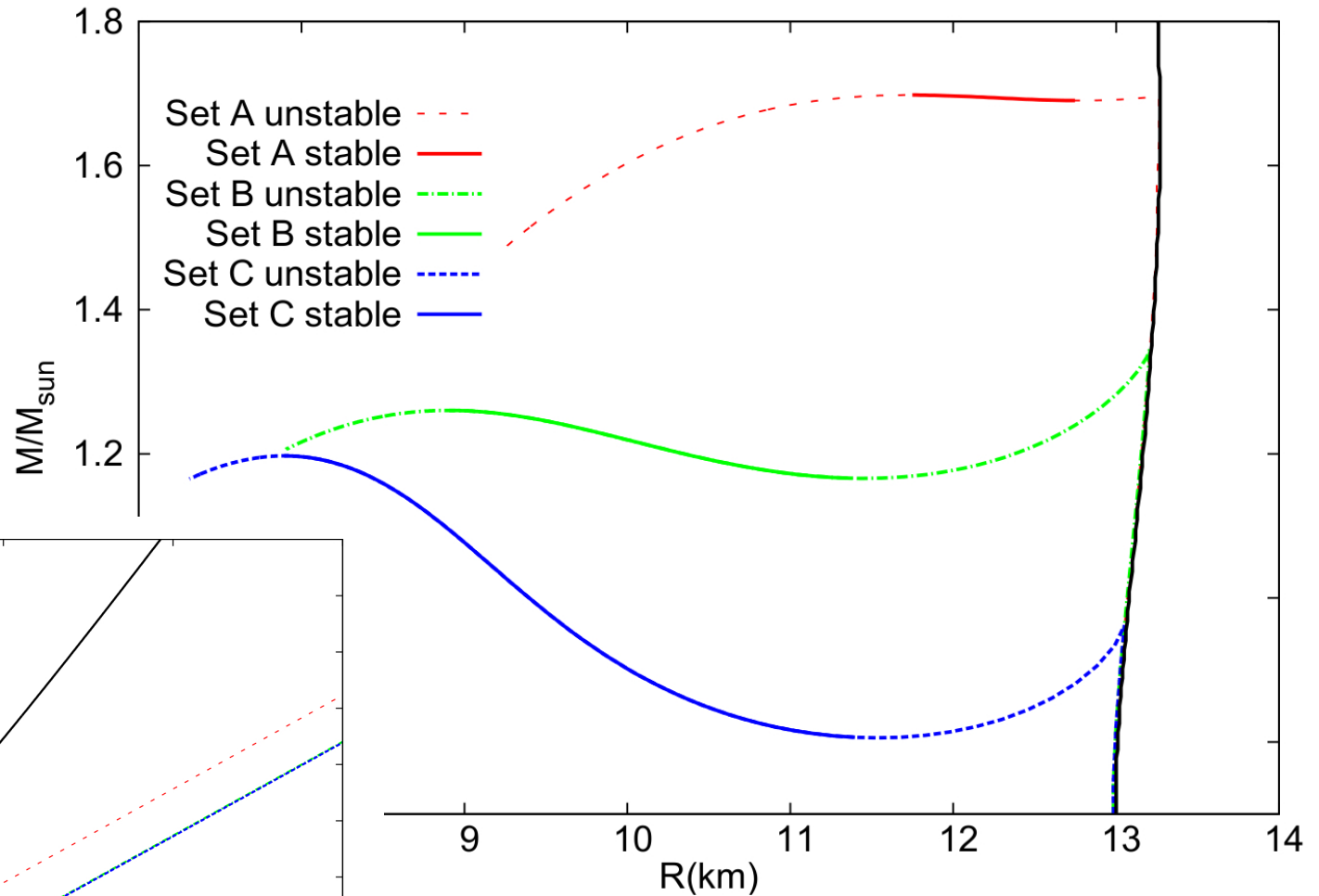
Hadronic Phase:

DD2-Model

Quark Phase:

Simple Alford
Model

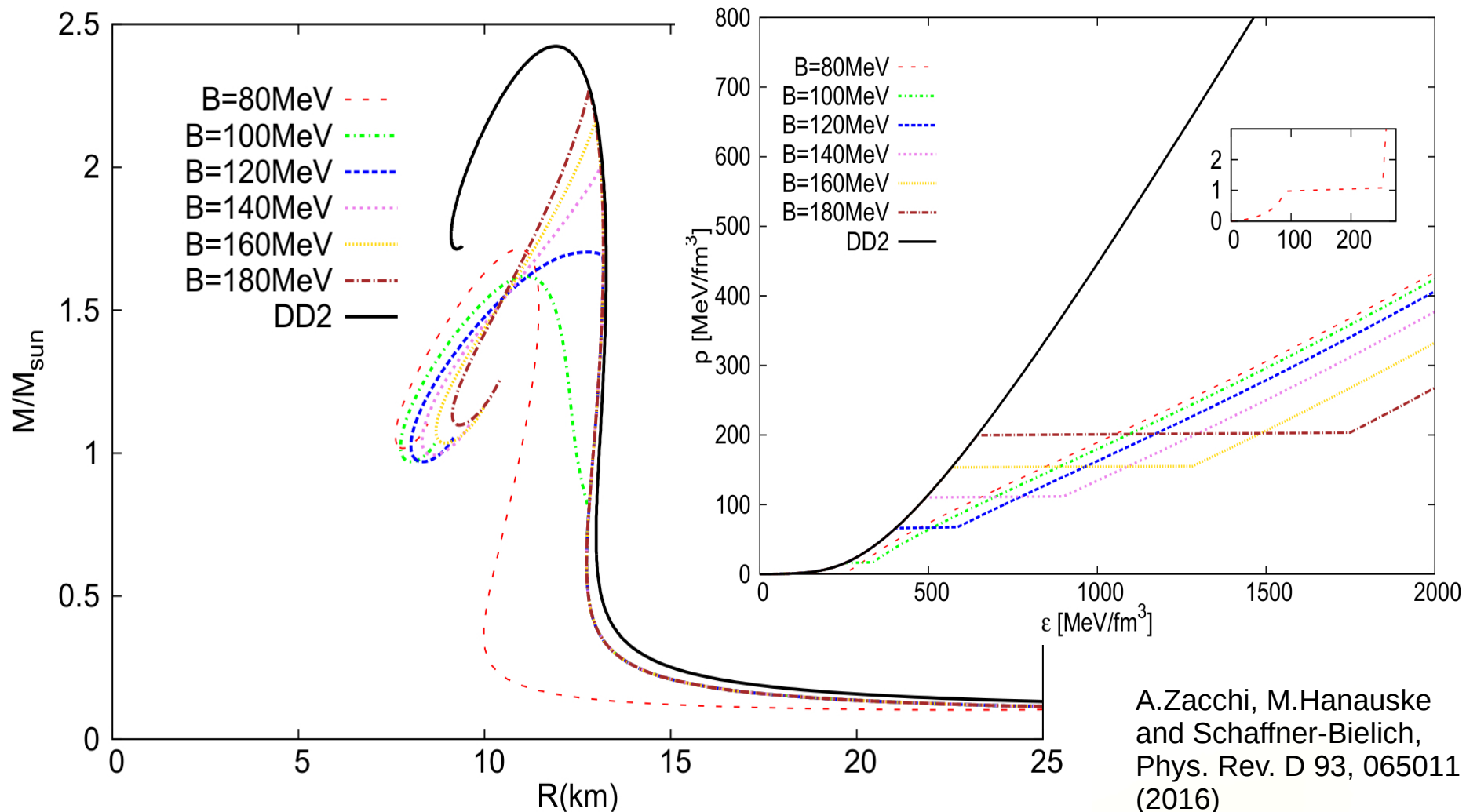
$p=1/3 (e - e_*)$



A.Zacchi, M.Hanuske and Schaffner-Bielich,
Phys. Rev. D 93, 065011 (2016)

No Twin Stars found

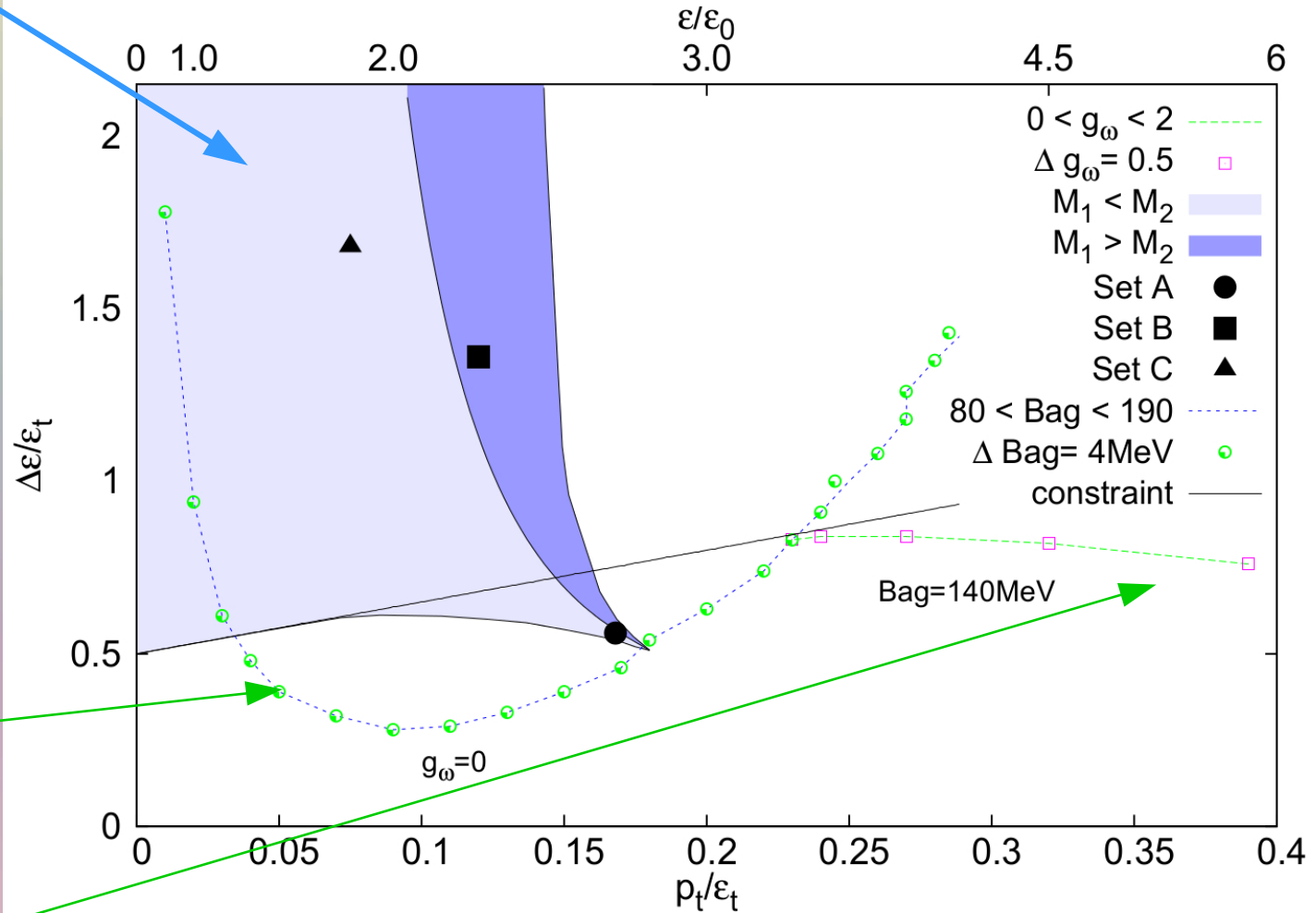
Hybrid Star properties (left) and the EOS (right) by varying the Bag constant B .



A.Zacchi, M.Hanuske
and Schaffner-Bielich,
Phys. Rev. D 93, 065011
(2016)

The Twin Star Region

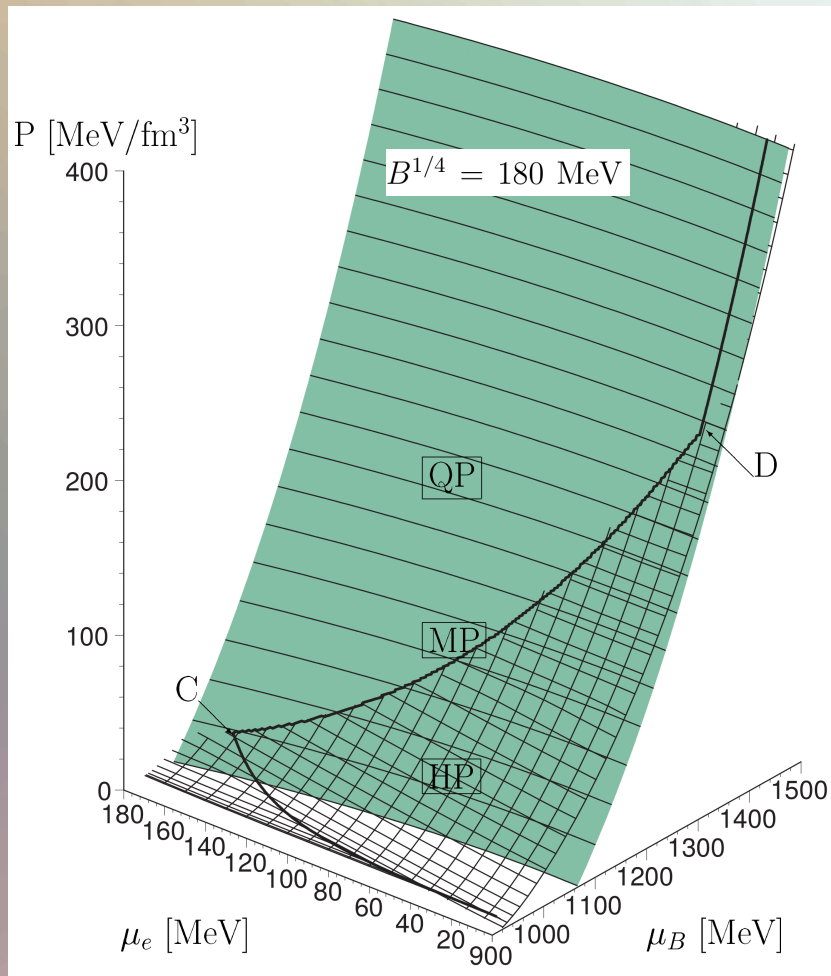
Twin star region within the simple Alford Model



No twin stars within the DD2 - Chiral Quark Meson Model

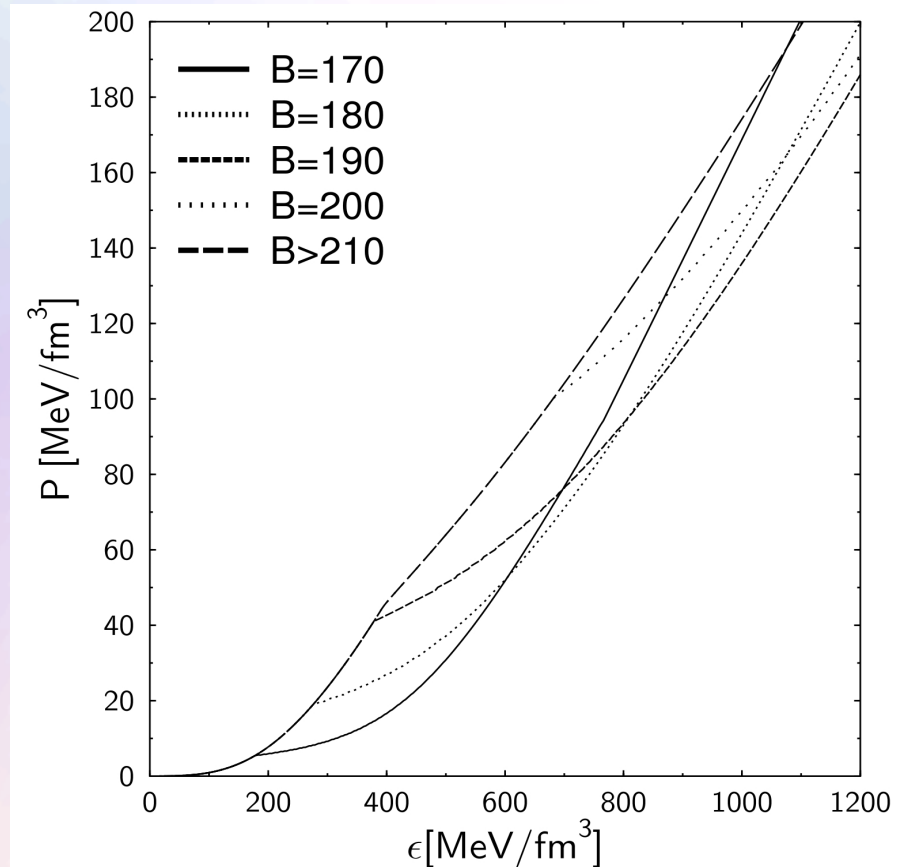
The Gibbs Construction

Hadronic and quark surface:

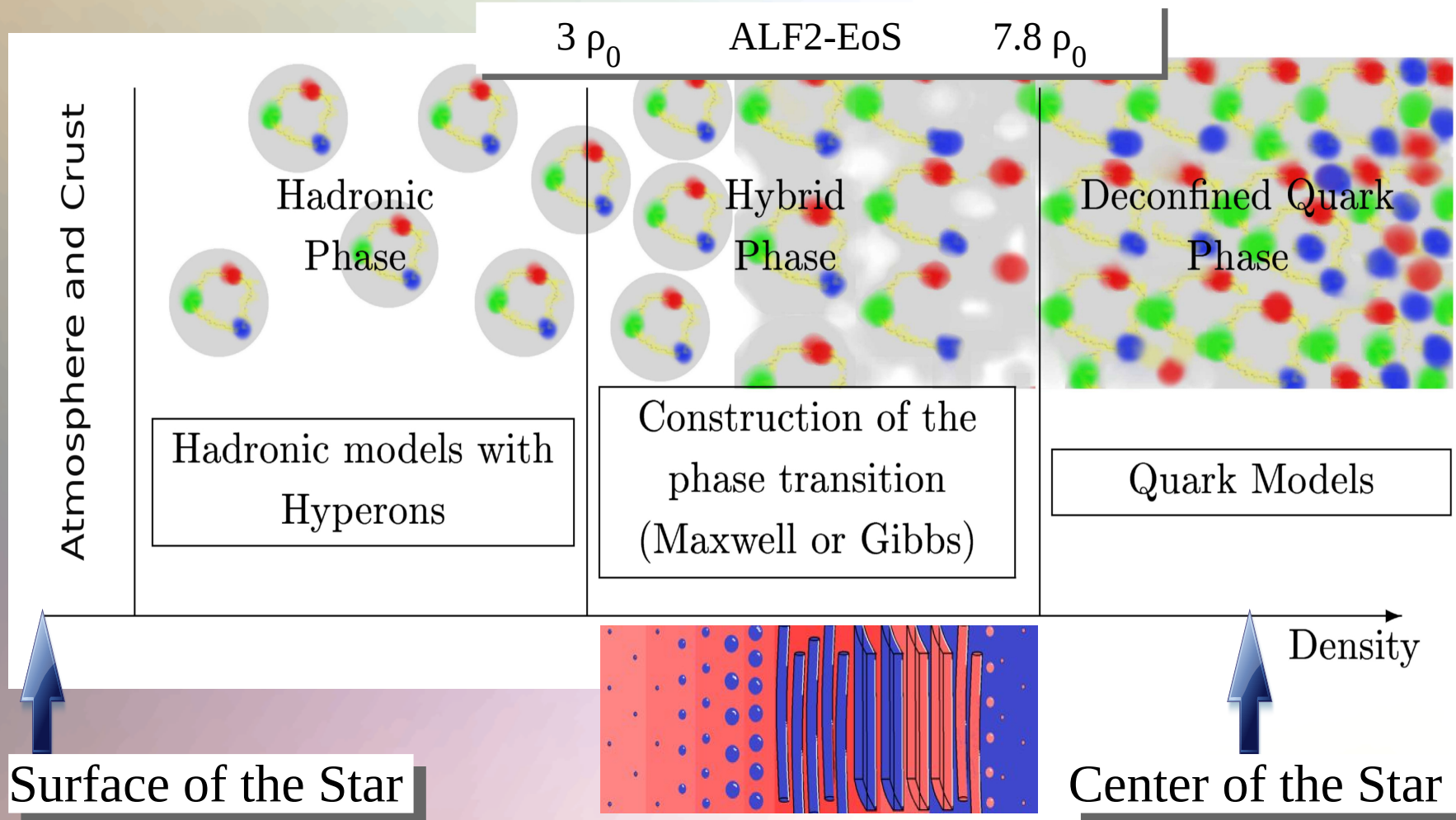


Charge neutrality condition is only globally realized

$$\rho_e := (1 - \chi)\rho_e^H(\mu_B, \mu_e) + \chi\rho_e^Q(\mu_B, \mu_e) = 0.$$

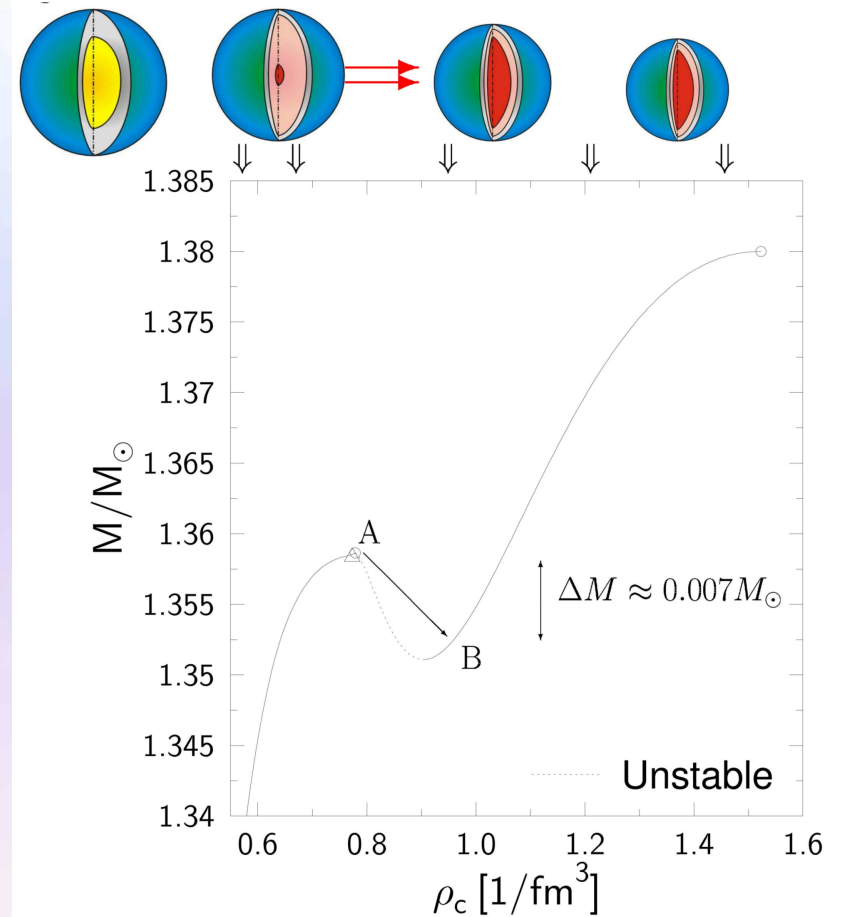
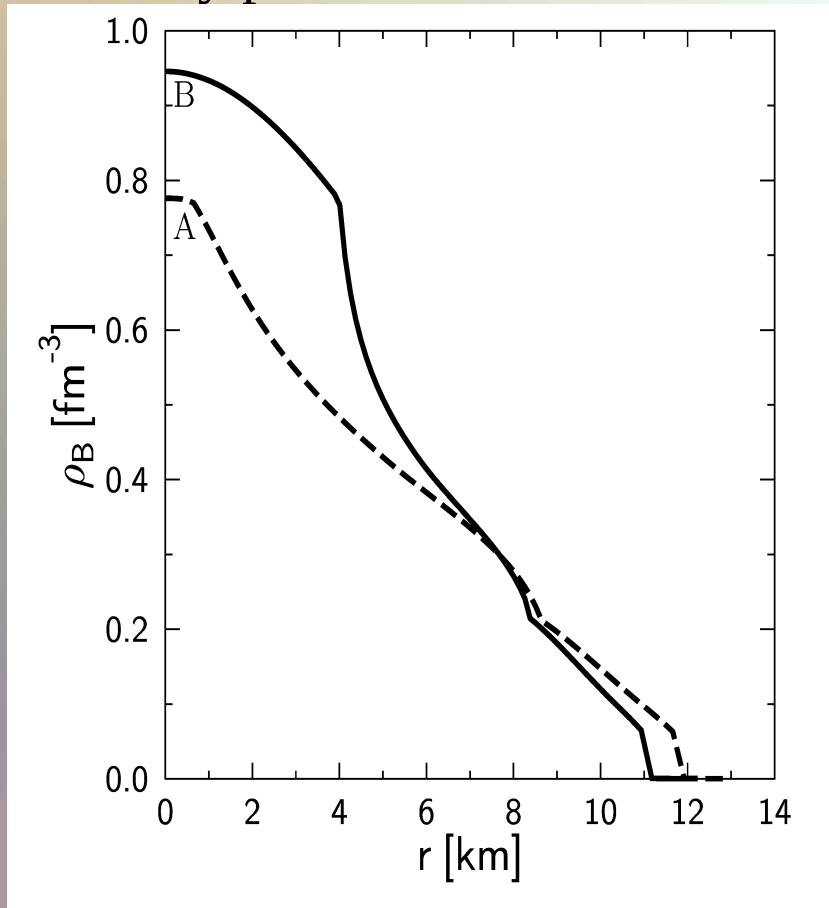


The QCD – Phase Transition and the Interior of a Hybrid Star



The Twin Star Collapse

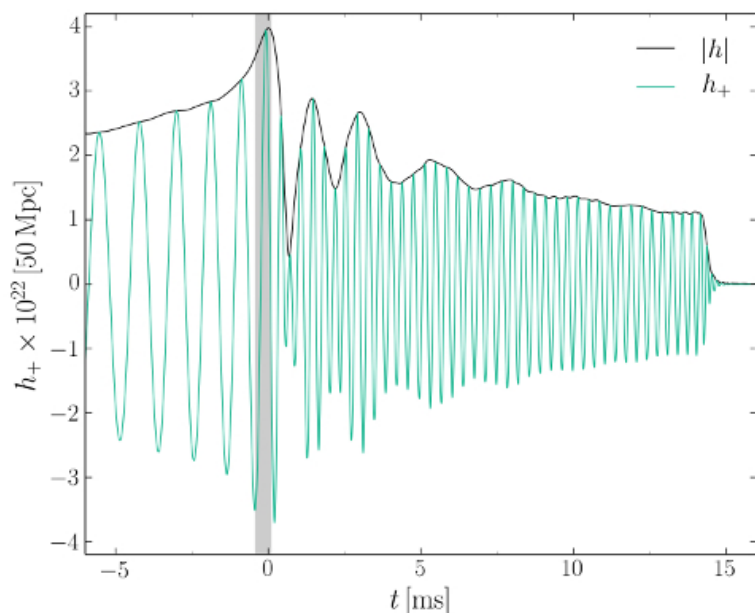
Density profiles of the two twins



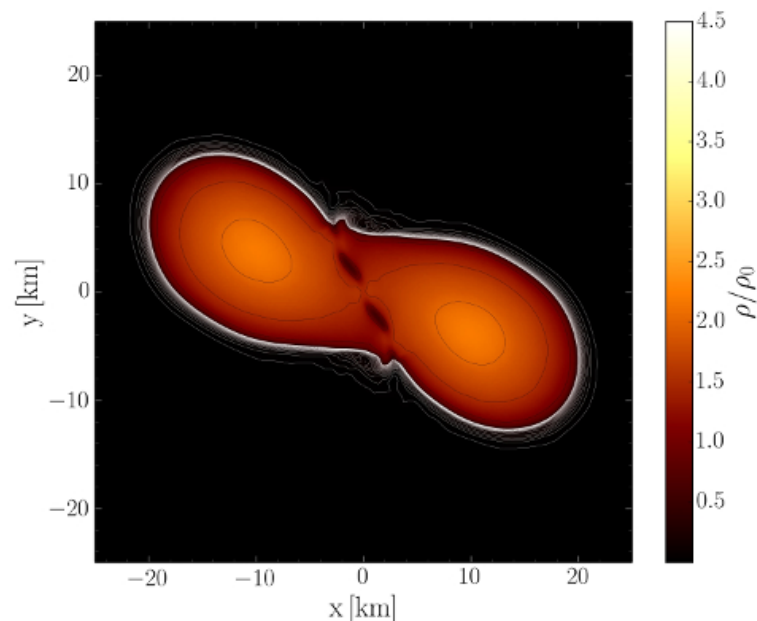
I.N. Mishustin, M. Hanauske, A. Bhattacharyya, L.M. Satarov, H. Stöcker, and W. Greiner, "Catastrophic rearrangement of a compact star due to quark core formation", Physics Letters B 552 (2003) p.1-8

Gravitational Waves and the Hadron Quark Phase Transition

Merger of two neutron stars: Hybrid ALF2 model,
initial neutron star masses where 1.35 solar masses

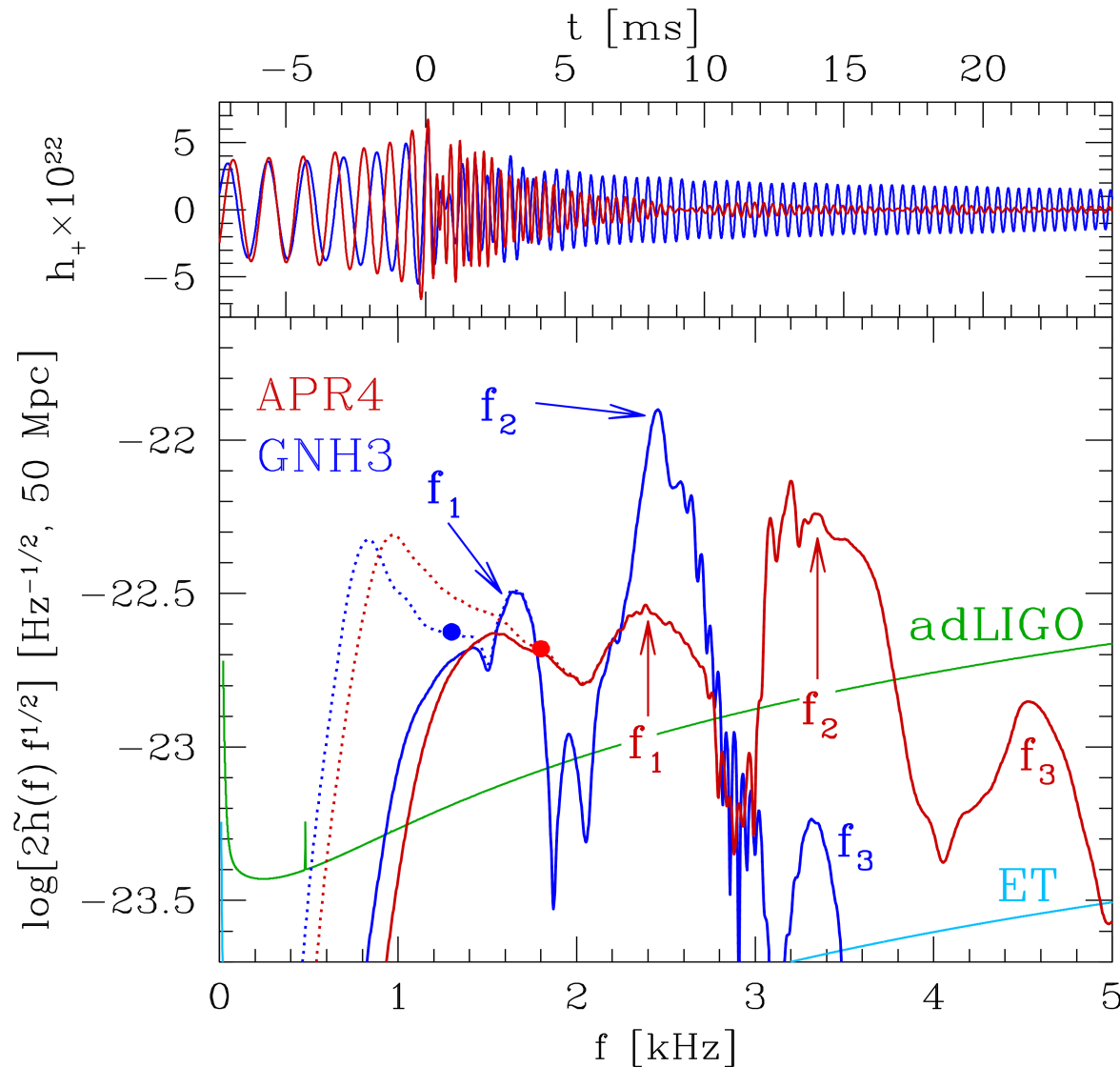


Gravitational wave amplitude at a distance of 50
Mpc for the ALF2-M135 model



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

GW-Spectrum for different EoSs



See:

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.

Collapse Scenario of a Hybrid Star

The gravitational collapse of a hybrid star to a black hole is visualized on the right side within a space-time diagram of the Schwarzschild metric in advanced Eddington-Finkelstein coordinates.

The formation of the apparent and event horizon of the black hole confines the quark star macroscopically. Finally the colour charge of the deconfined free quarks cannot be observed from outside.

