International Conference on Strangeness in Quark Matter

Gravitational Waves from Binary Compact Star Mergers in the Context of Strange Matter

New Project!
MAGIC

UNIVERSITY OF UTRECHT, THE NETHERLANDS
10.-15. JULY, 2017

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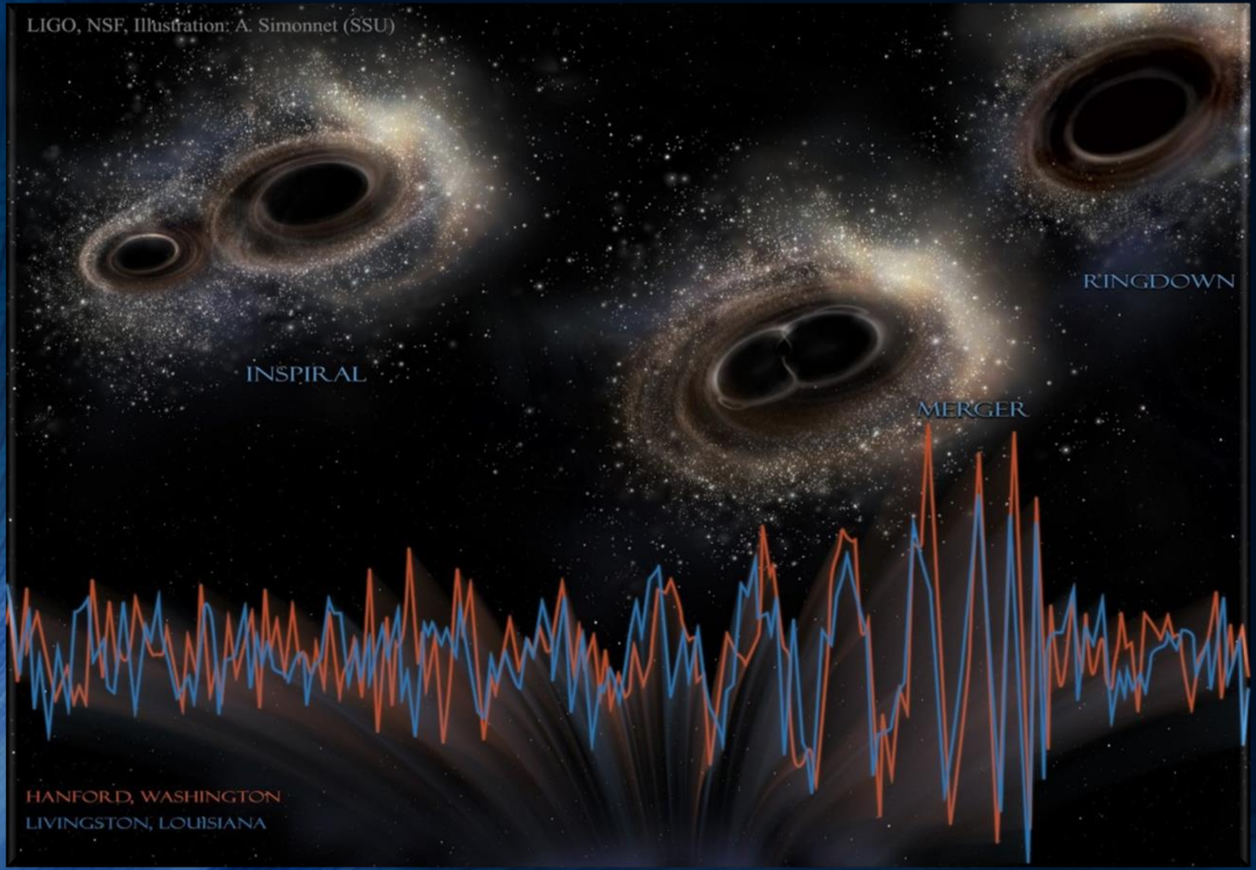
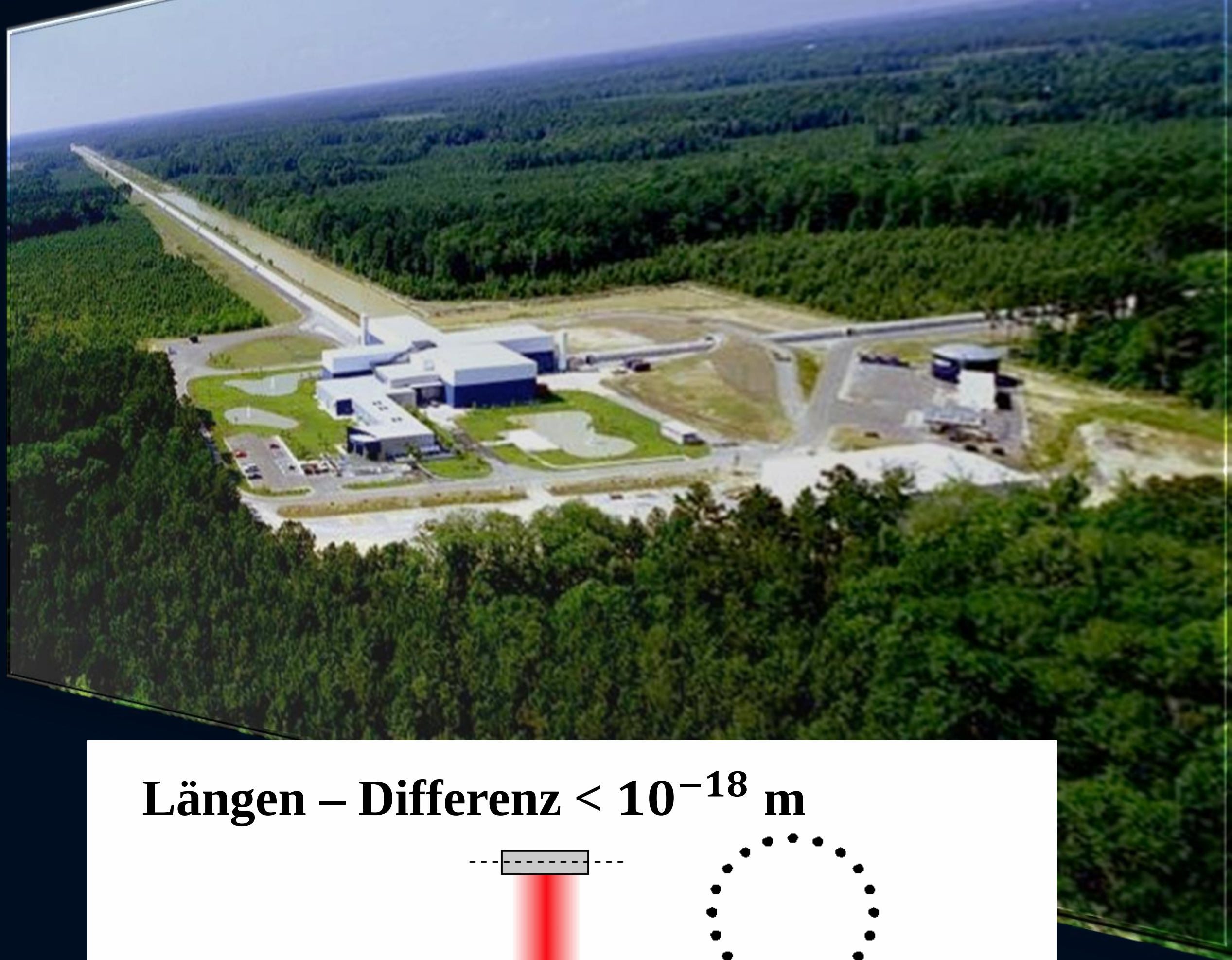
Gravitational Waves detected!!!

Several Collisions of two Black Holes
GW150914, GW151226 and GW170104

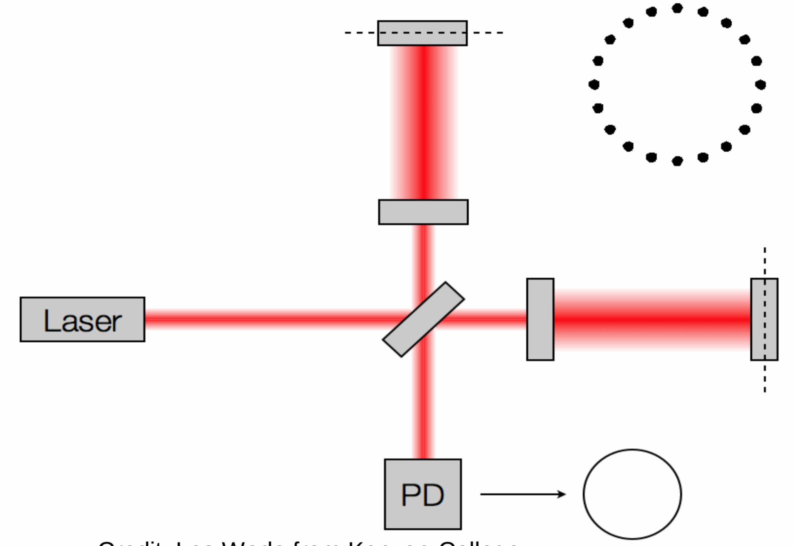
GW150914 :

Masses: 36 & 29 Sun masses
Distance to the earth 410 Mpc
(1.34 Billion Light Years)





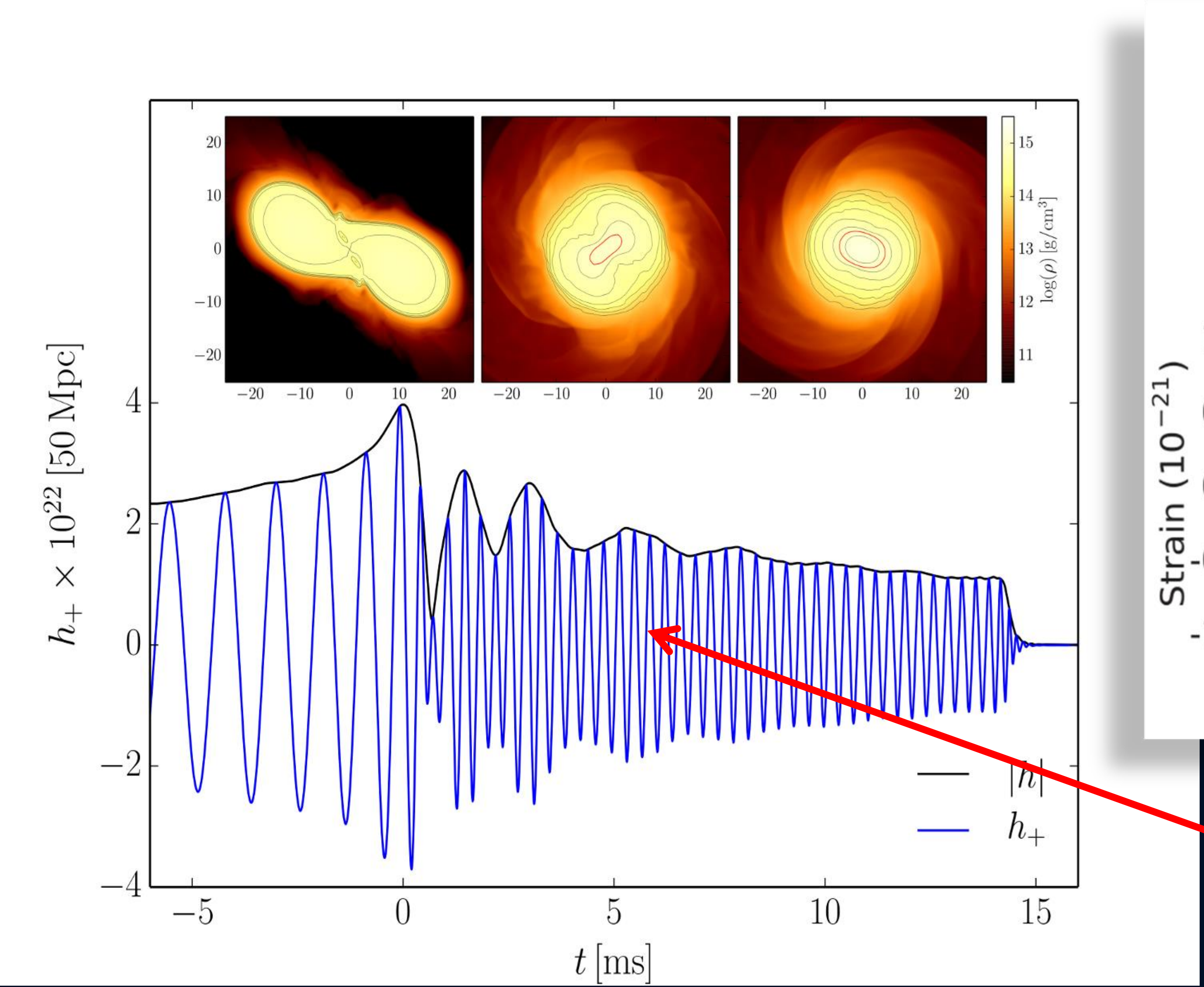
Längen – Differenz < 10^{-18} m



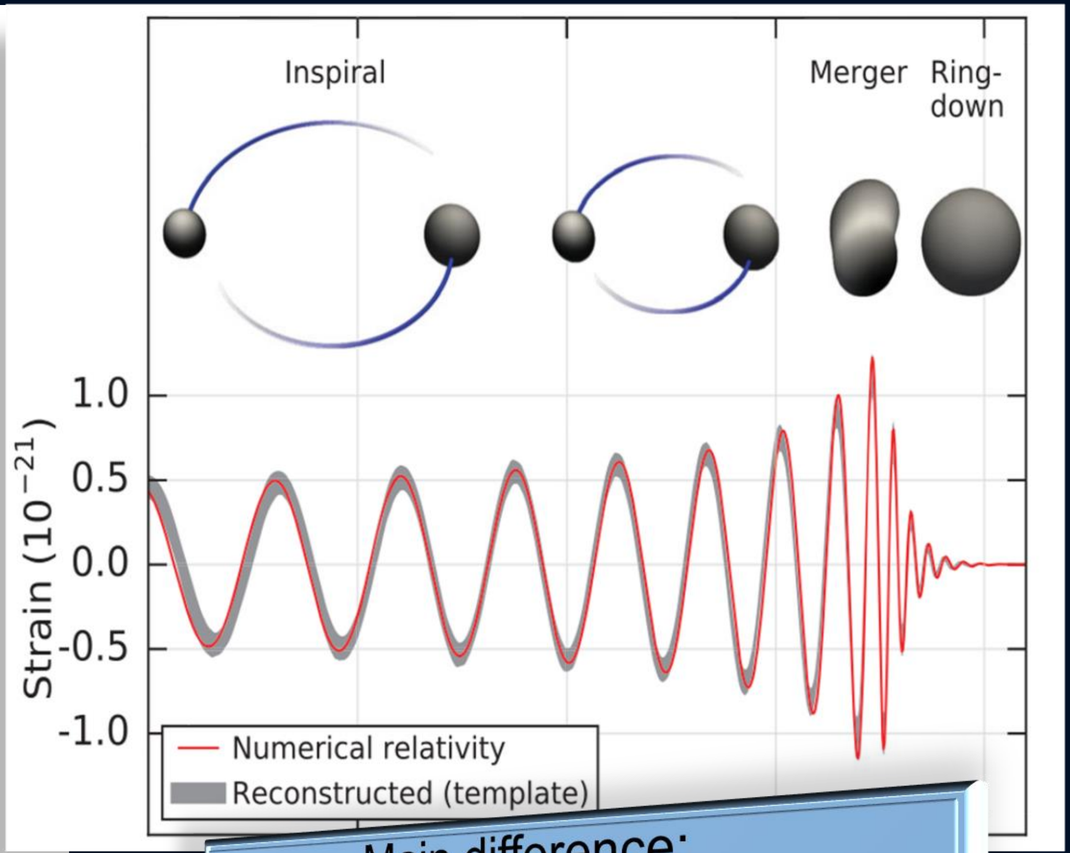
Credit: Les Wade from Kenyon College

Gravitational Waves from Neutron Star Mergers

Neutron Star Collision (Simulation)



Collision of two Black Holes



<u>Main difference:</u>
In binary neutron star mergers a **Post-Merger Phase** often exists

The Einstein Equation

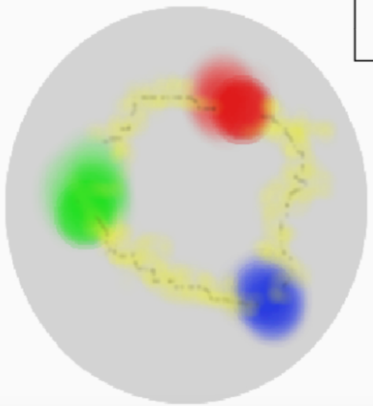
ART	Yang-Mills-Theories
$D_\beta v^\alpha = \partial_\beta\, v^\alpha + \Gamma^\alpha_{\sigma\beta}\, v^\sigma$	$D_{\beta a}{}^{b} = \partial_\beta\, 1_a{}^{b} + ig\, A_{\beta a}{}^{b}$
$R^\delta{}_{\mu\alpha\beta}\, v^\mu = [D_\alpha, D_\beta]\, v^\delta$ $R^\delta{}_{\mu\alpha\beta} = \Gamma^\delta_{\mu\alpha\|\beta}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

QuantumCromoDynamic:

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

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

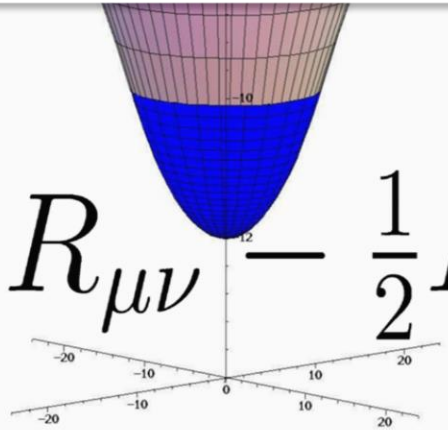
$_{A,}{}^{B}$ =red, green, blue



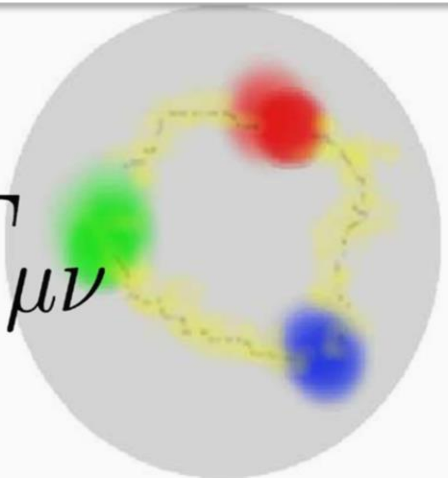
$$\psi^f_A = \begin{pmatrix} \psi^f_r \\ \psi^f_g \\ \psi^f_b \end{pmatrix}$$

Confinement

chiral symmetry, ...



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



Canonical transformation path to gauge theories of gravity, Phys. Rev. D 95, 124048

J. Struckmeier, J. Muench, D. Vasak, J. Kirsch, M. Hanauske, and H. Stoecker

The Hadron-Quark Phase Transition

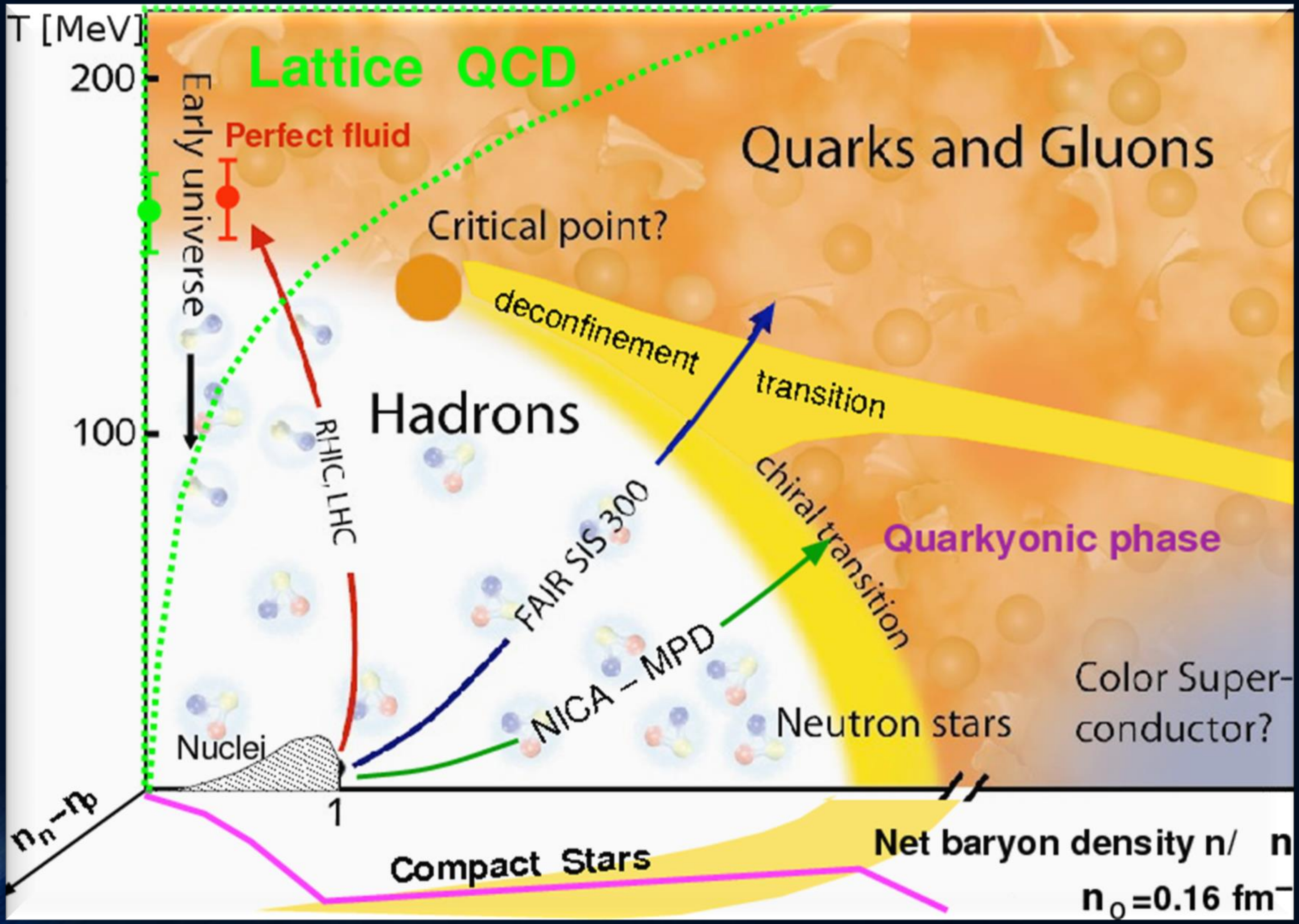
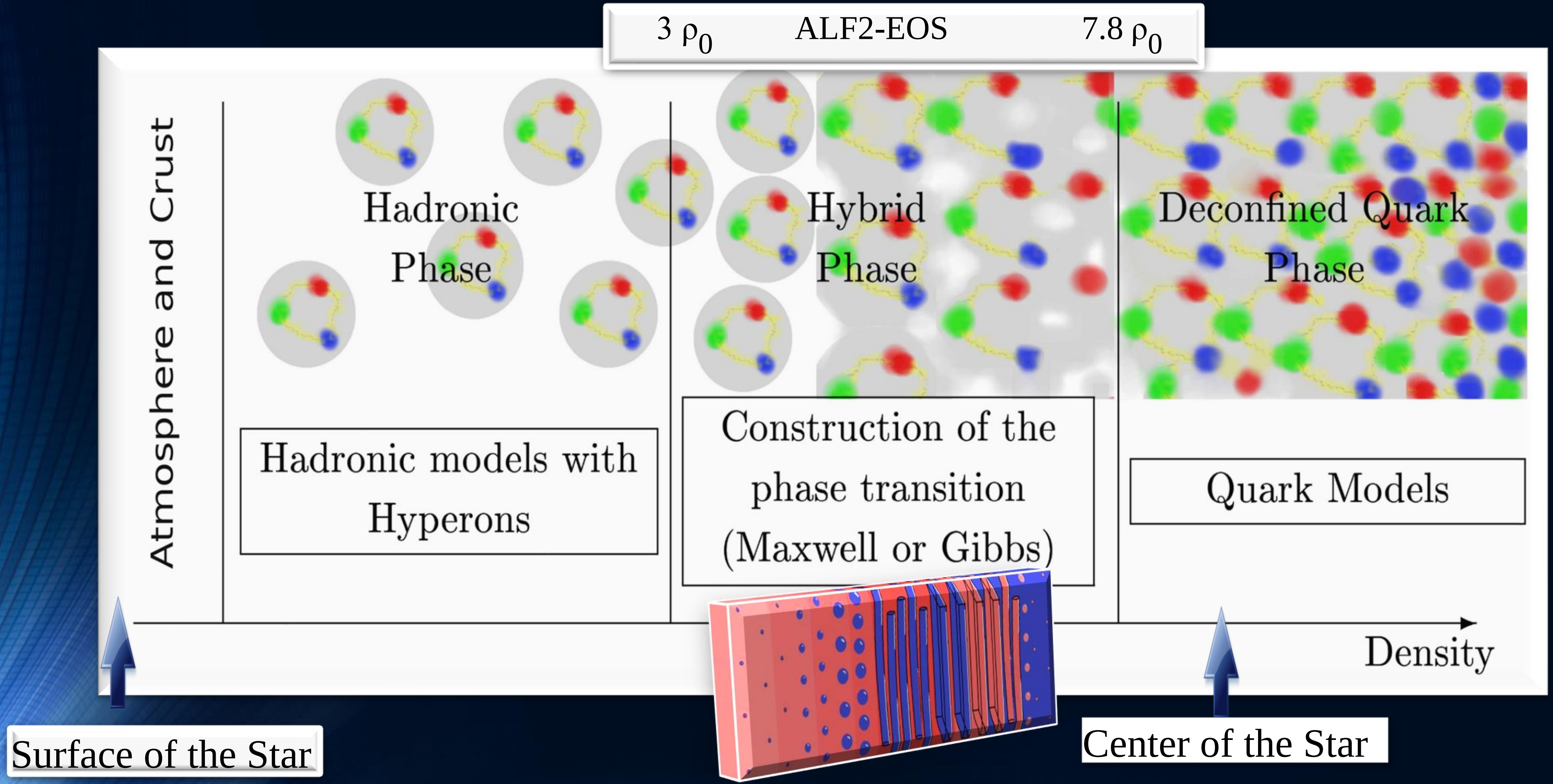


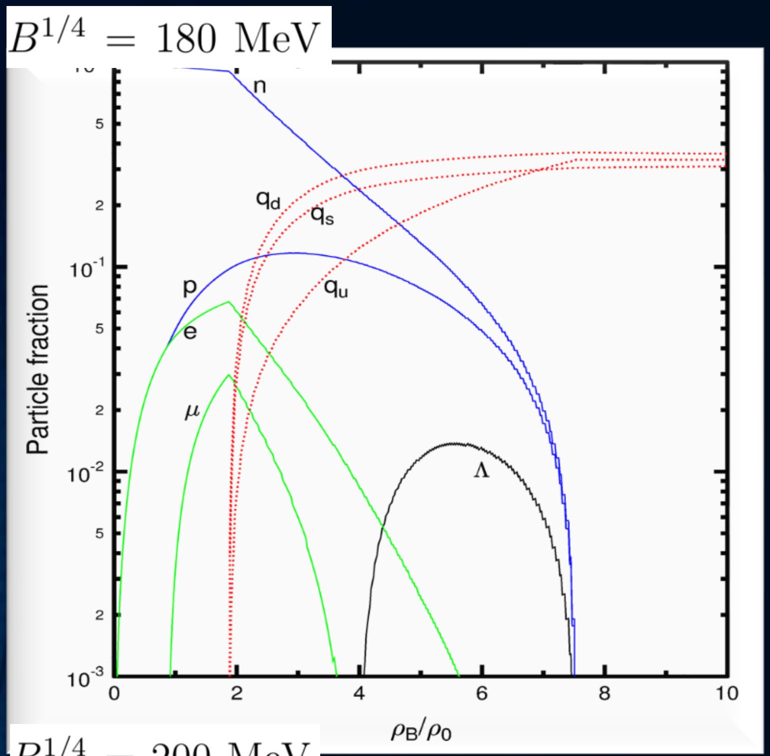
Image from http://inspirehep.net/record/823172/files/phd_qgp3D_quarkyonic2.png

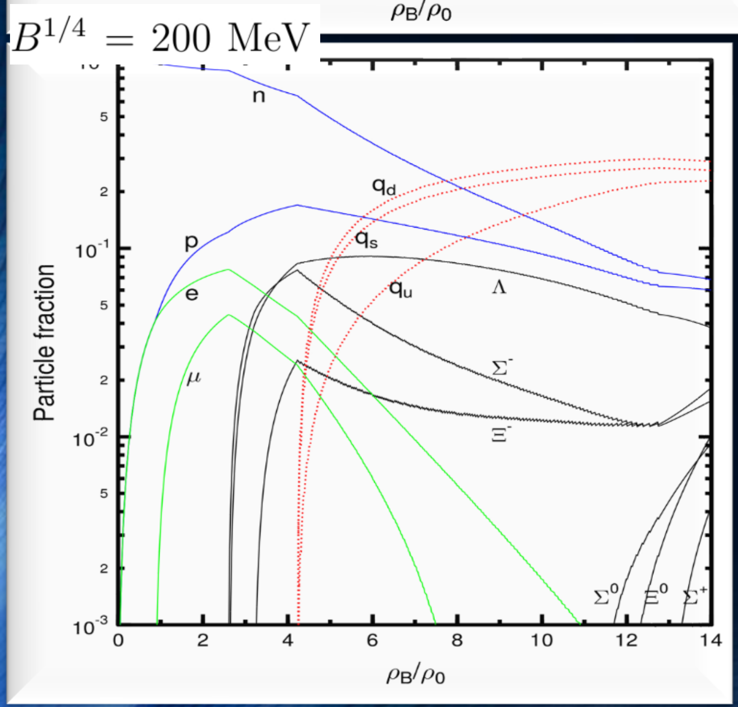
The QCD – Phase Transition and the Interior of a Hybrid Star

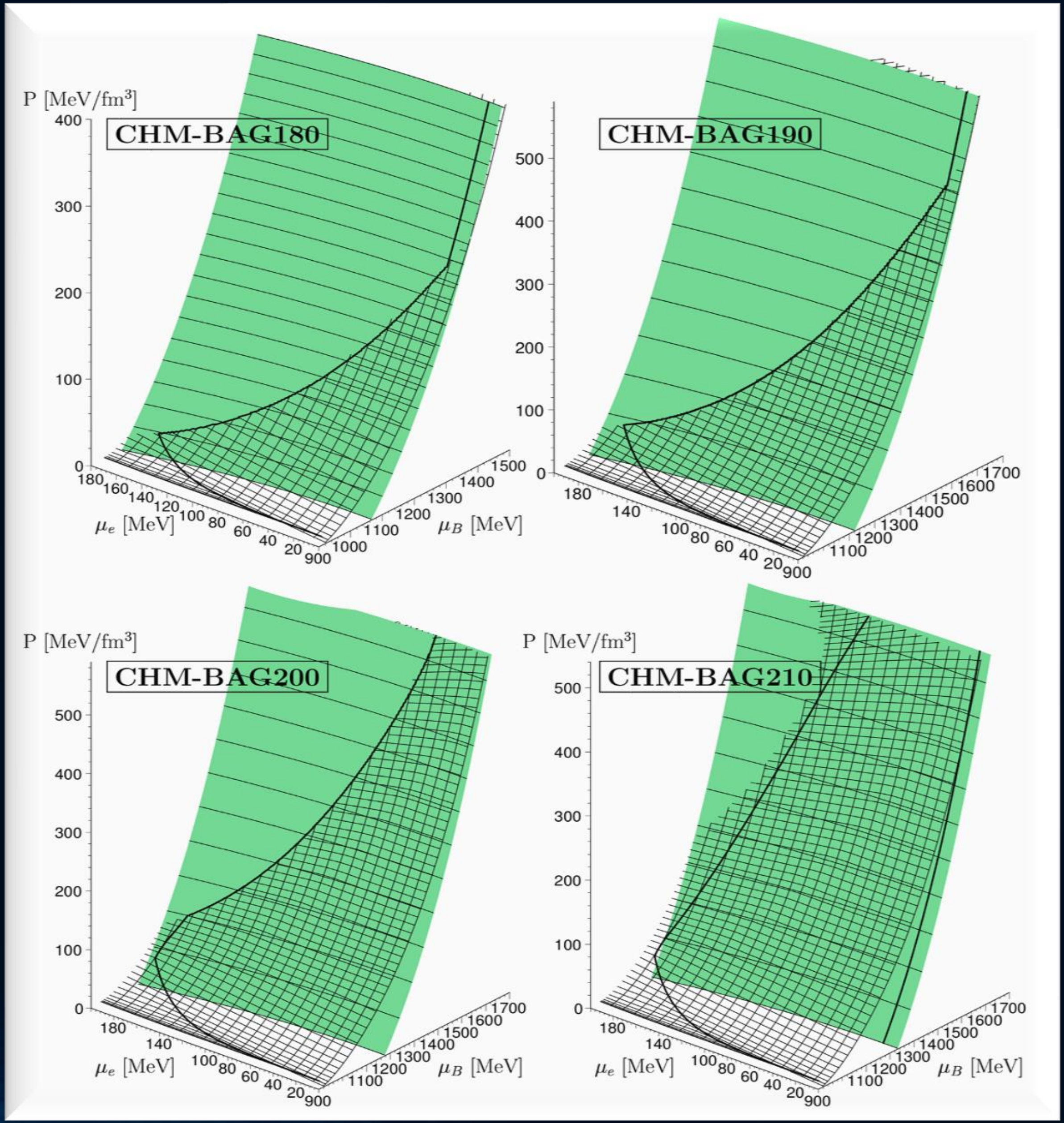


Properties of Compact Stars within QCD-motivated Models
M.Hanauske, PHD-Thesis (2004)

The Gibbs Construction







Numerical Relativity and Relativistic Hydrodynamics of Binary Neutron Star Mergers

A realistic numerical simulation of a twin star collapse, a merger of two compact stars or a collapse to a black hole needs to go beyond a static, spherically symmetric TOV-solution of the Einstein- and hydrodynamical equations.

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

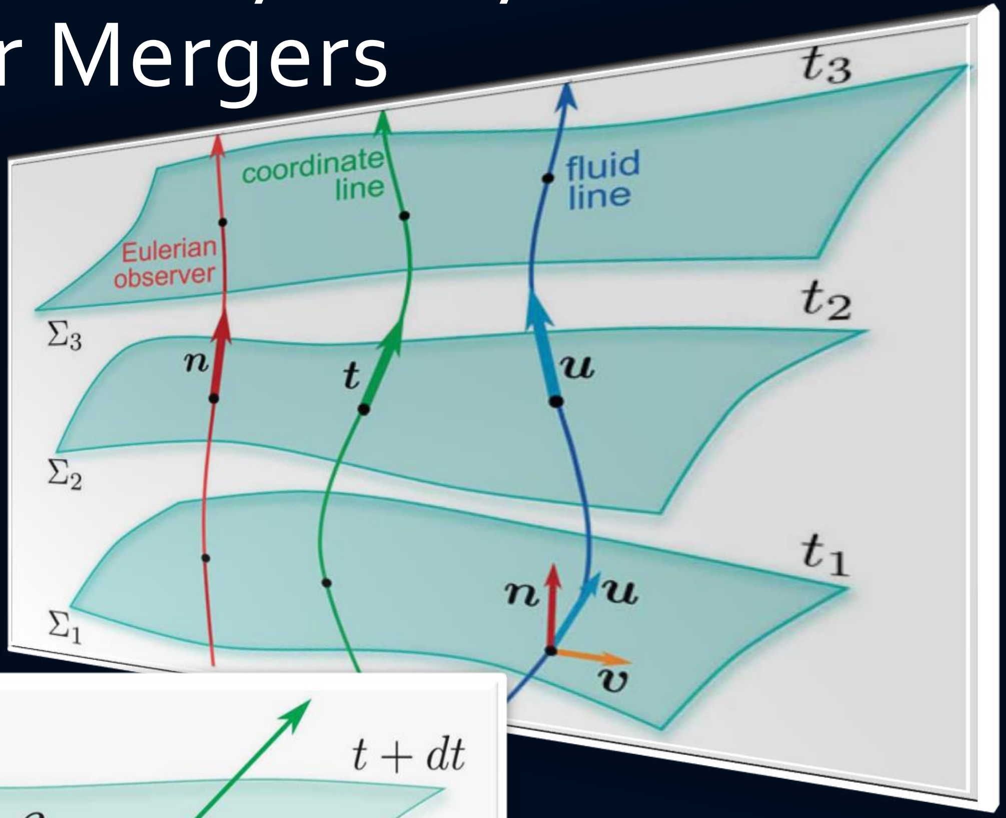
$$\nabla_\mu (\rho u^\mu) = 0\,, \qquad \nabla_\nu T^{\mu\nu} = 0\,.$$

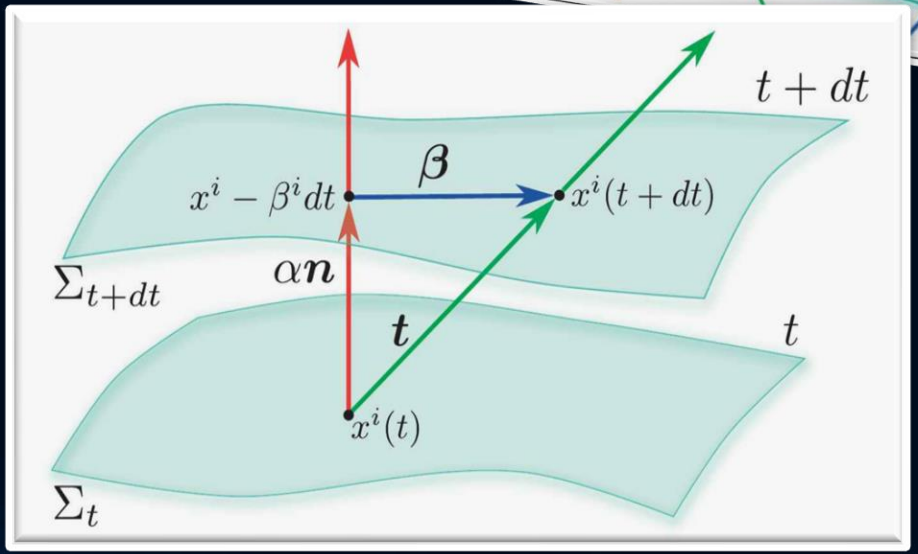
(3+1) decomposition of spacetime

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

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

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

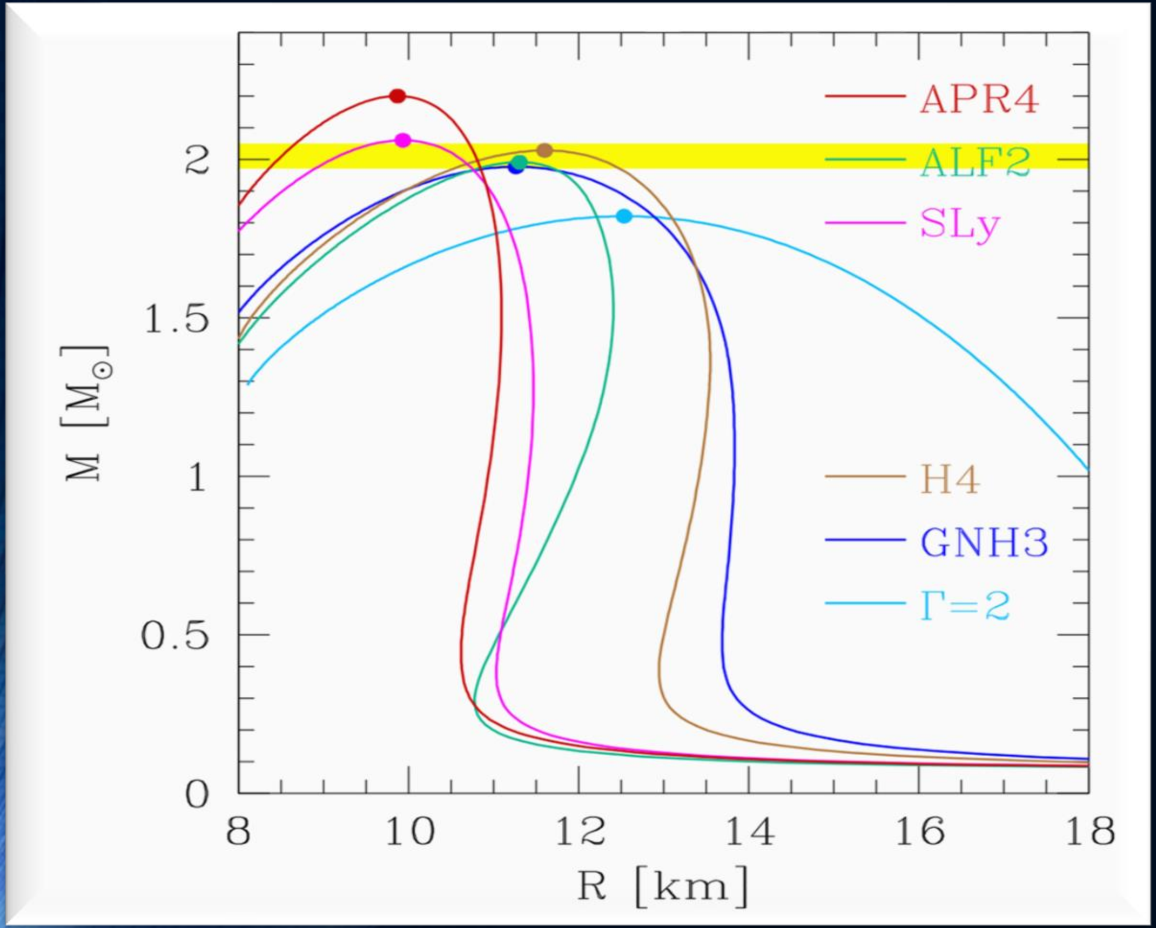




All figures and equations from: Luciano Rezzolla, Olindo Zanotti: Relativistic Hydrodynamics, Oxford Univ. Press, Oxford (2013)

Several different EOSs : ALF2, APR4, GNH3, H4 and Sly, approximated by piecewise polytopes. Thermal ideal fluid component (Γ=2) added to the nuclear-physics EOSs.

EOSs



composed of a "cold" nuclear-physics part and of a "thermal" ideal-fluid component[1] [56]

$$p = p_c + p_{th}\,, \qquad \epsilon = \epsilon_c + \epsilon_{th}\,, \tag{6}$$

where p and ϵ are the pressure and specific internal energy,

The "cold" nuclear-physics contribution to each EOS is obtained after expressing the pressure and specific internal energy ϵ_c in the rest-mass density range $\rho_{i-1} \le \rho < \rho_i$ as (for details see [36, 64–66])

$$p_c = K_i \rho^{\Gamma_i}\,, \qquad \epsilon_c = \epsilon_i + K_i \frac{\rho^{\Gamma_i - 1}}{\Gamma_i - 1}\,. \tag{7}$$

($\Gamma_1 = 4.070$ and $\Gamma_2 = 2.411$). Finally, the "thermal" part of the EOS is given by

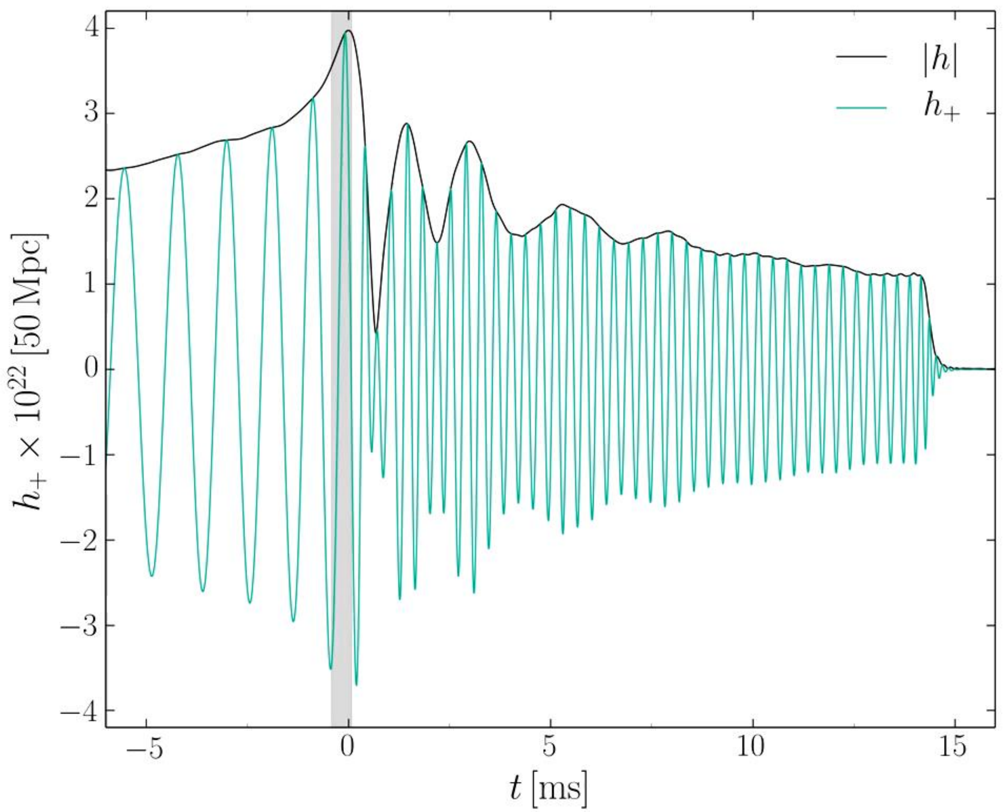
$$p_{th} = \rho \epsilon_{th} (\Gamma_{th} - 1)\,, \qquad \epsilon_{th} = \epsilon - \epsilon_c\,. \tag{8}$$

where the last equality in (8) is really a definition, since ϵ refers to the computed value of the specific internal energy. In all of the simulations reported hereafter we use $\Gamma_{th} = 2.0$

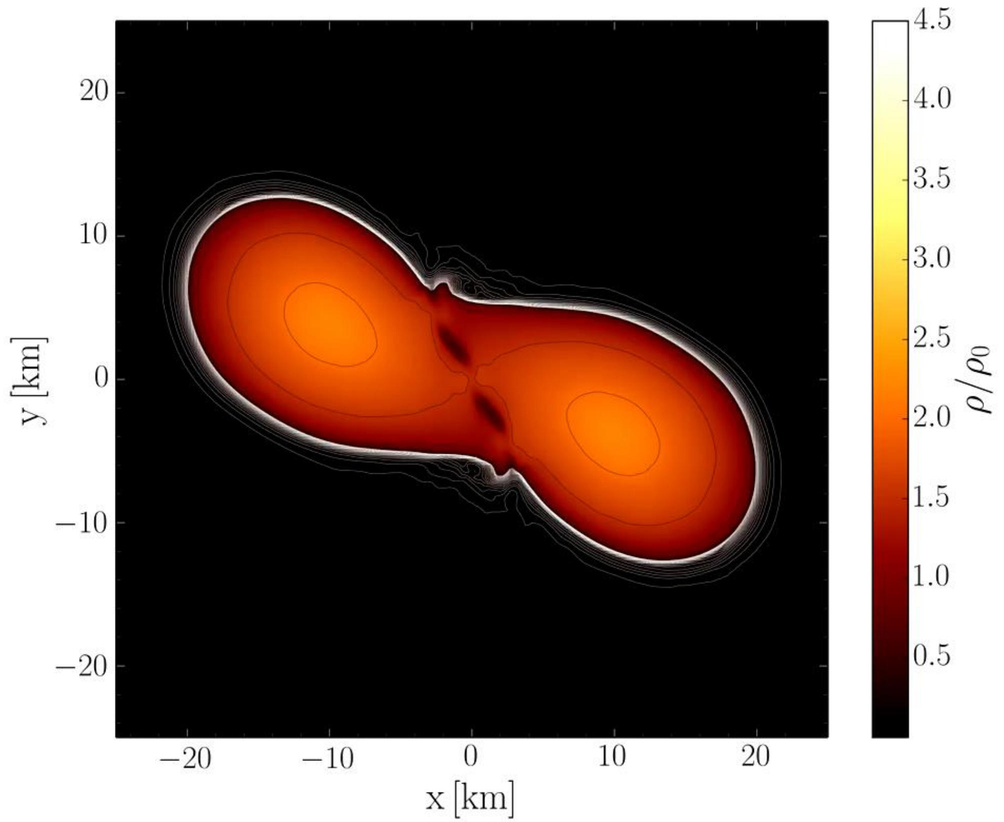
Additionally LS220-EOS used: Density and Temperature dependent EOS-table (Lattimer-Swesty)

Evolution of the rest-mass density distribution

ALF2, High mass model: Mixed phase region starts at $3\rho_0$,initial NS mass: 1.35 M_{solar}



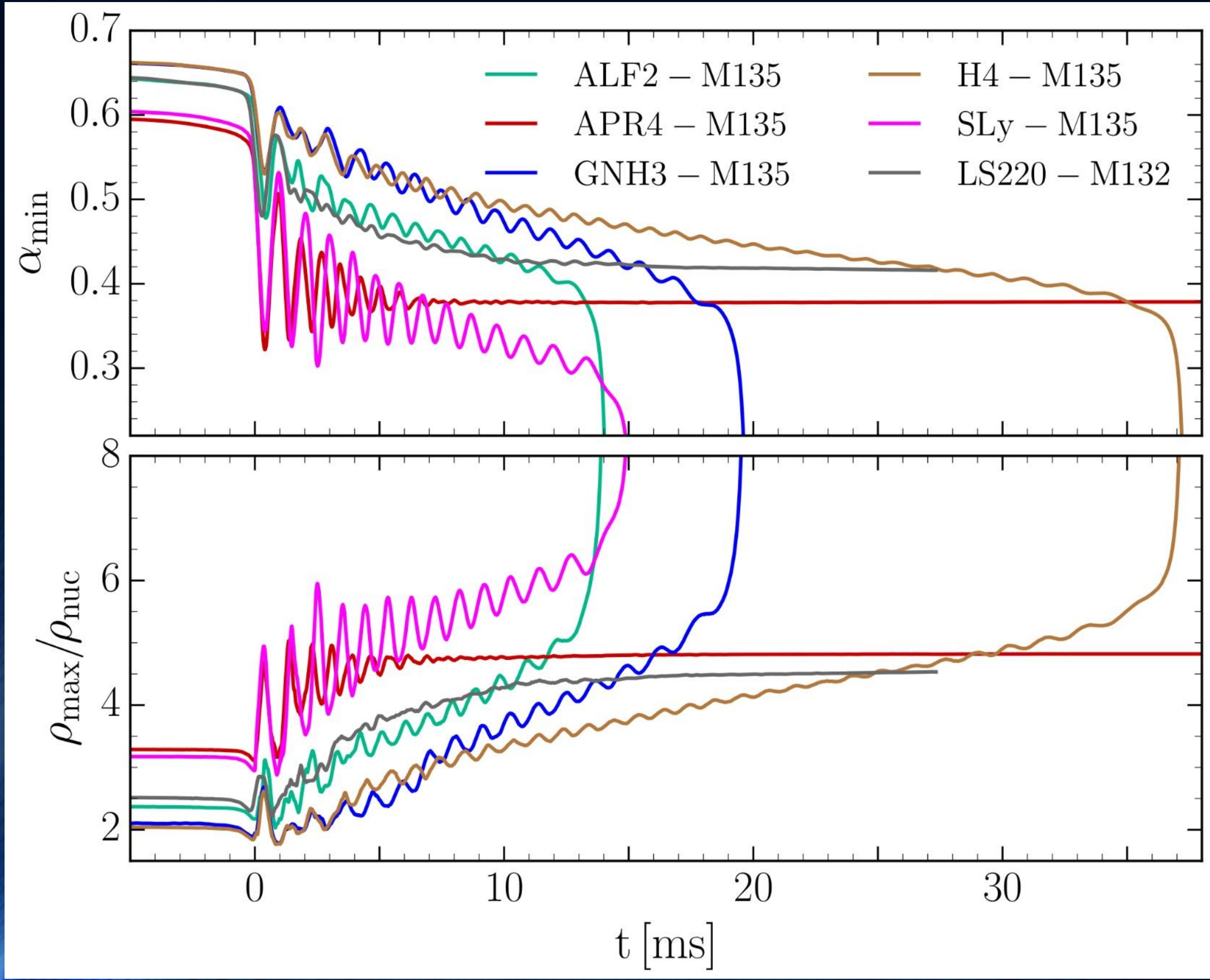
Gravitational wave amplitude
at a distance of 50 Mpc



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

HMNS Evolution for different EoSs

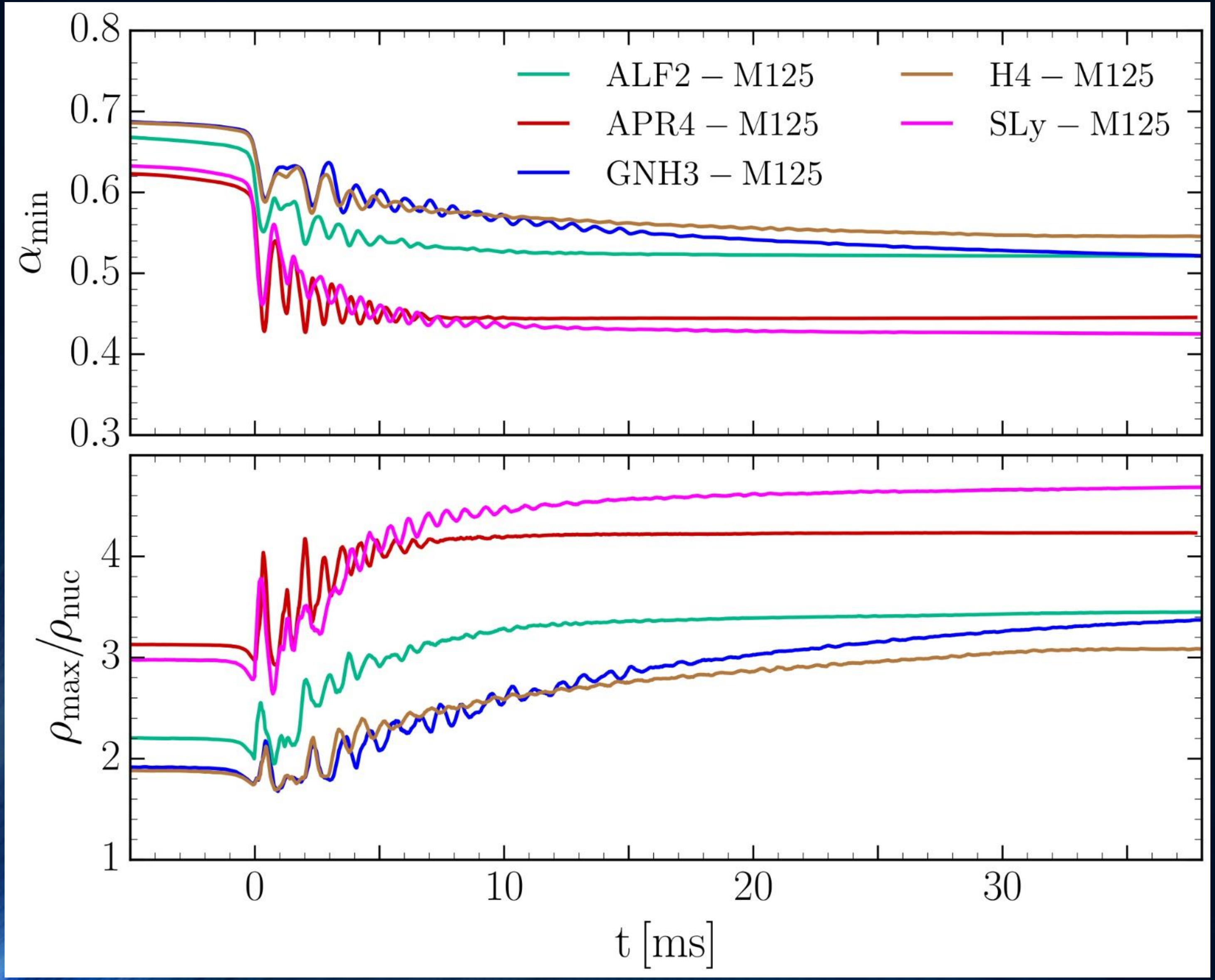
High mass simulations (M=1.35 Msolar)



Central value of the lapse function α_c (upper panel) and maximum of the rest mass density ρ_{max} in units of ρ_0 (lower panel) versus time for the high mass simulations.

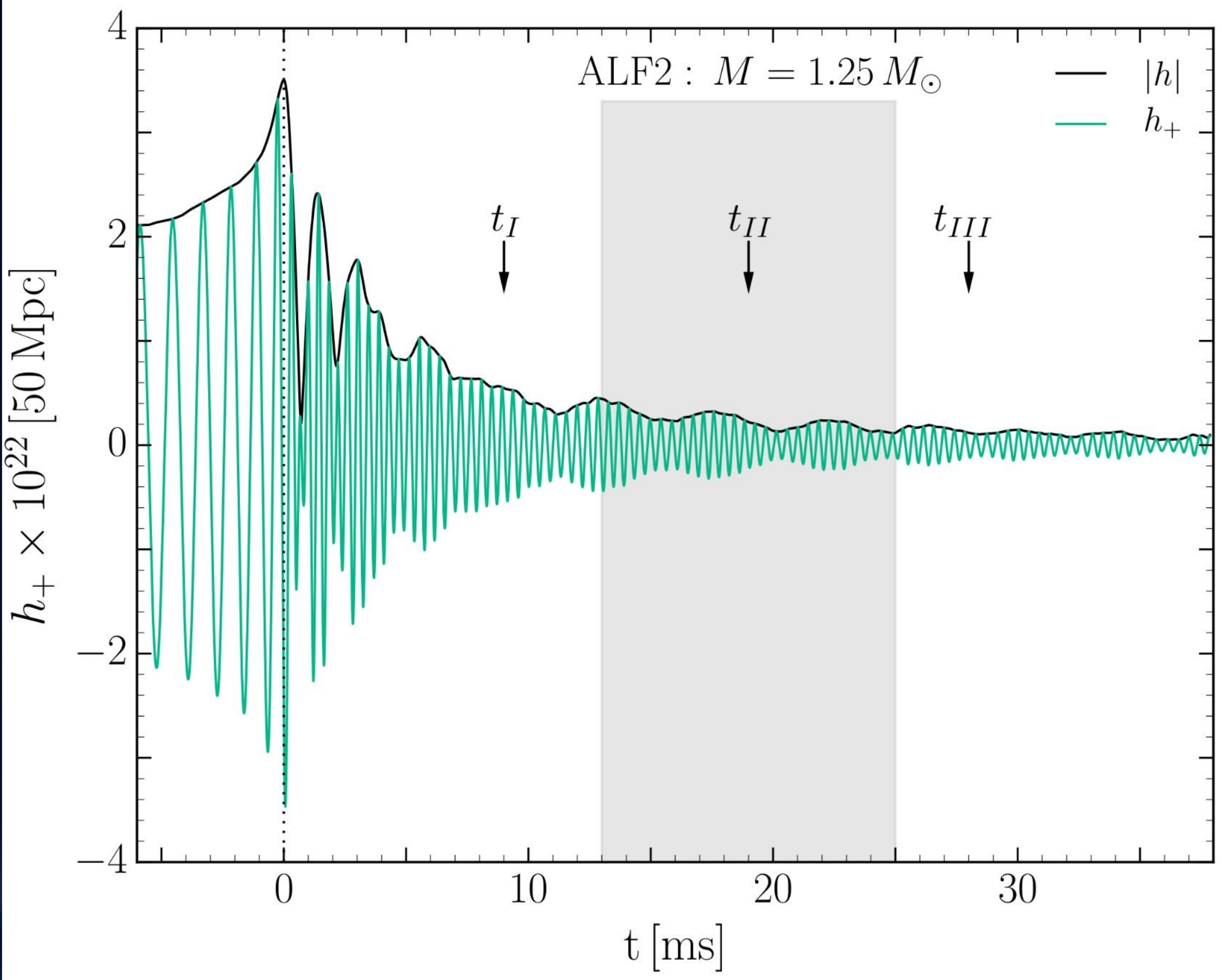
HMNS Evolution for different EoSs

Low mass simulations (M=1.32 Msolar)



Central value of the lapse function α_c (upper panel) and maximum of the rest mass density ρ_{max} in units of ρ_0 (lower panel) versus time for the low mass simulations.

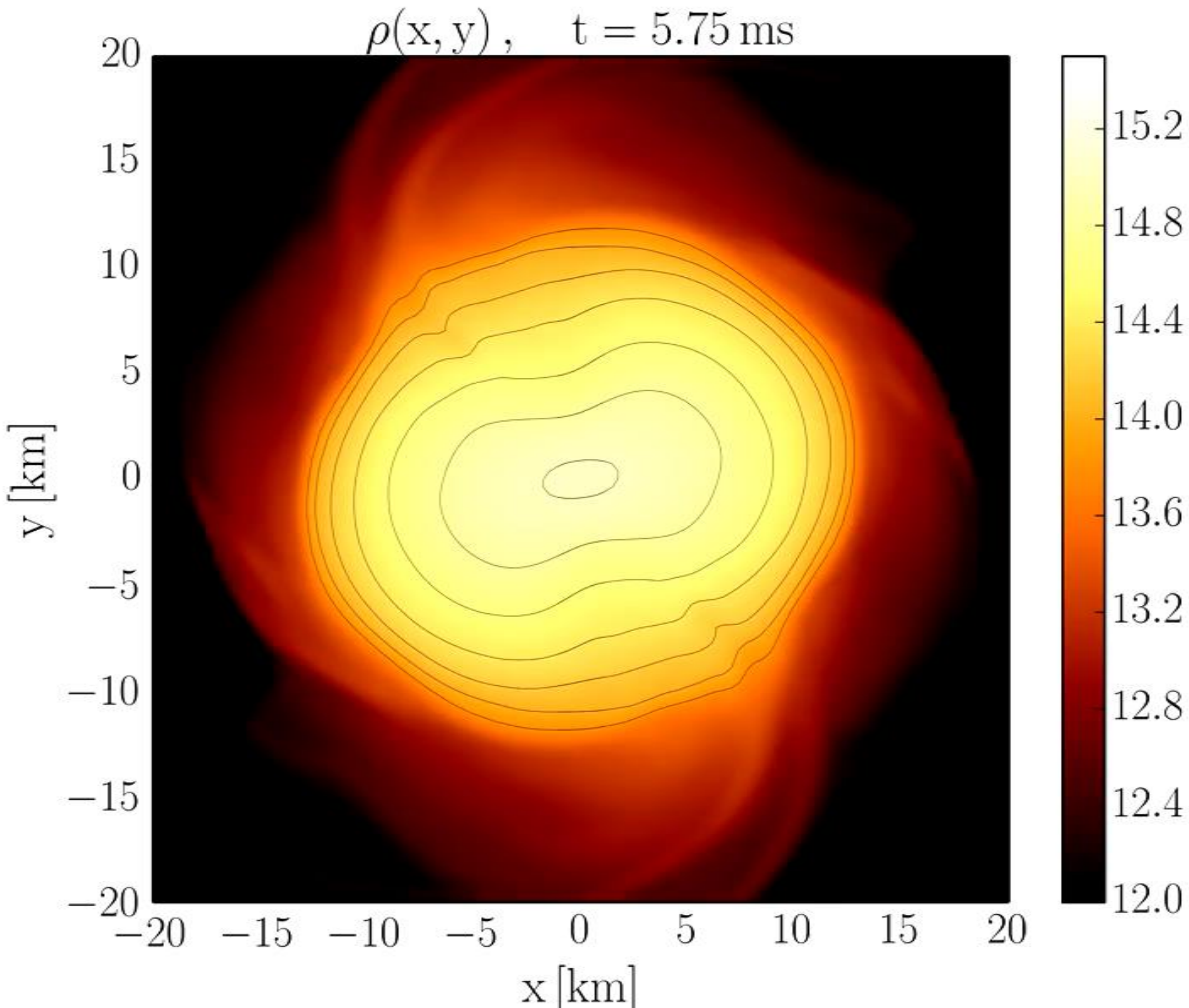
Gravitational Waves

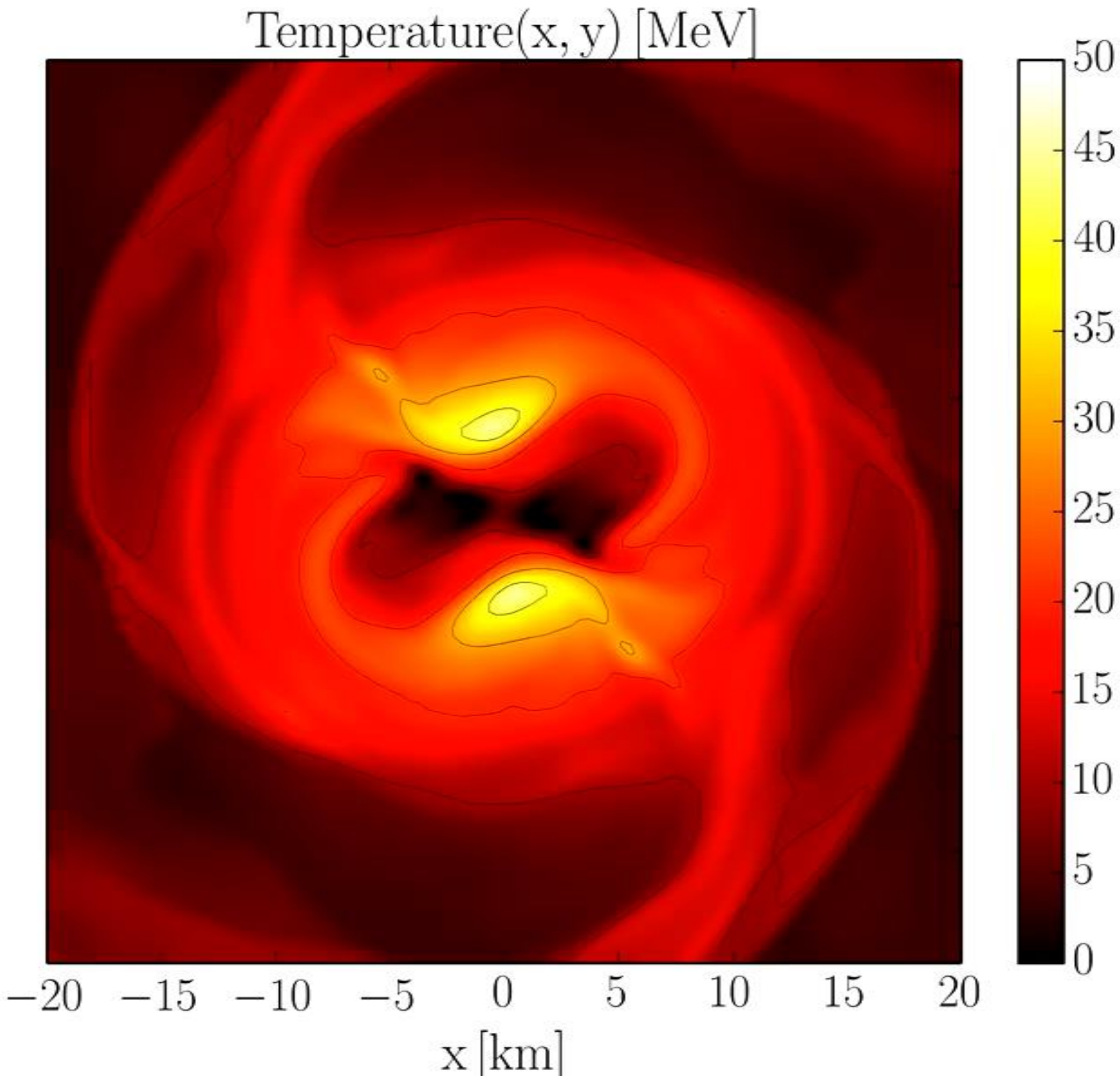


Gravitational-wave amplitude for the ALF2-M125 binary at a distance of 50 Mpc.

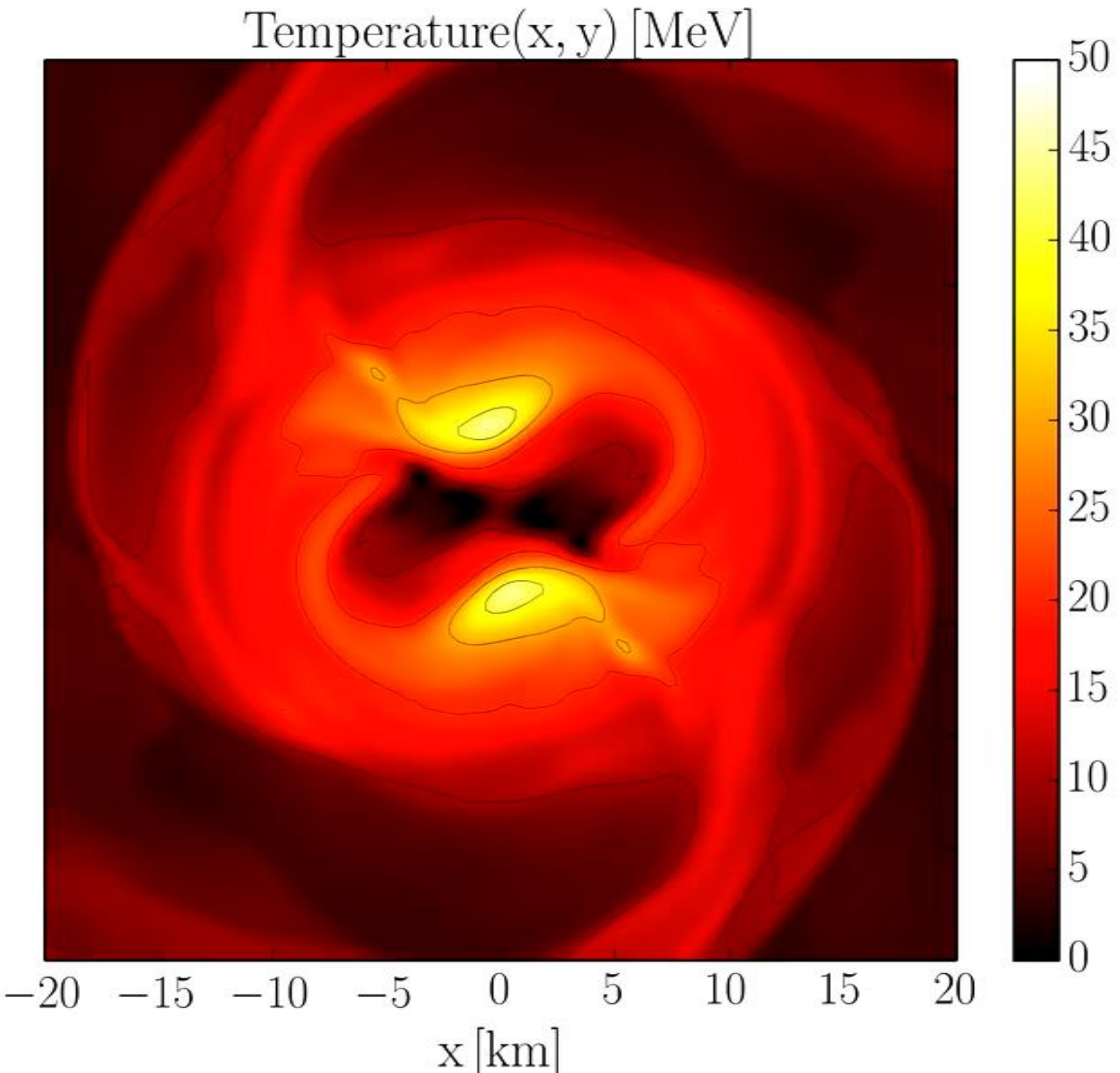
Logarithm of the density

Temperature

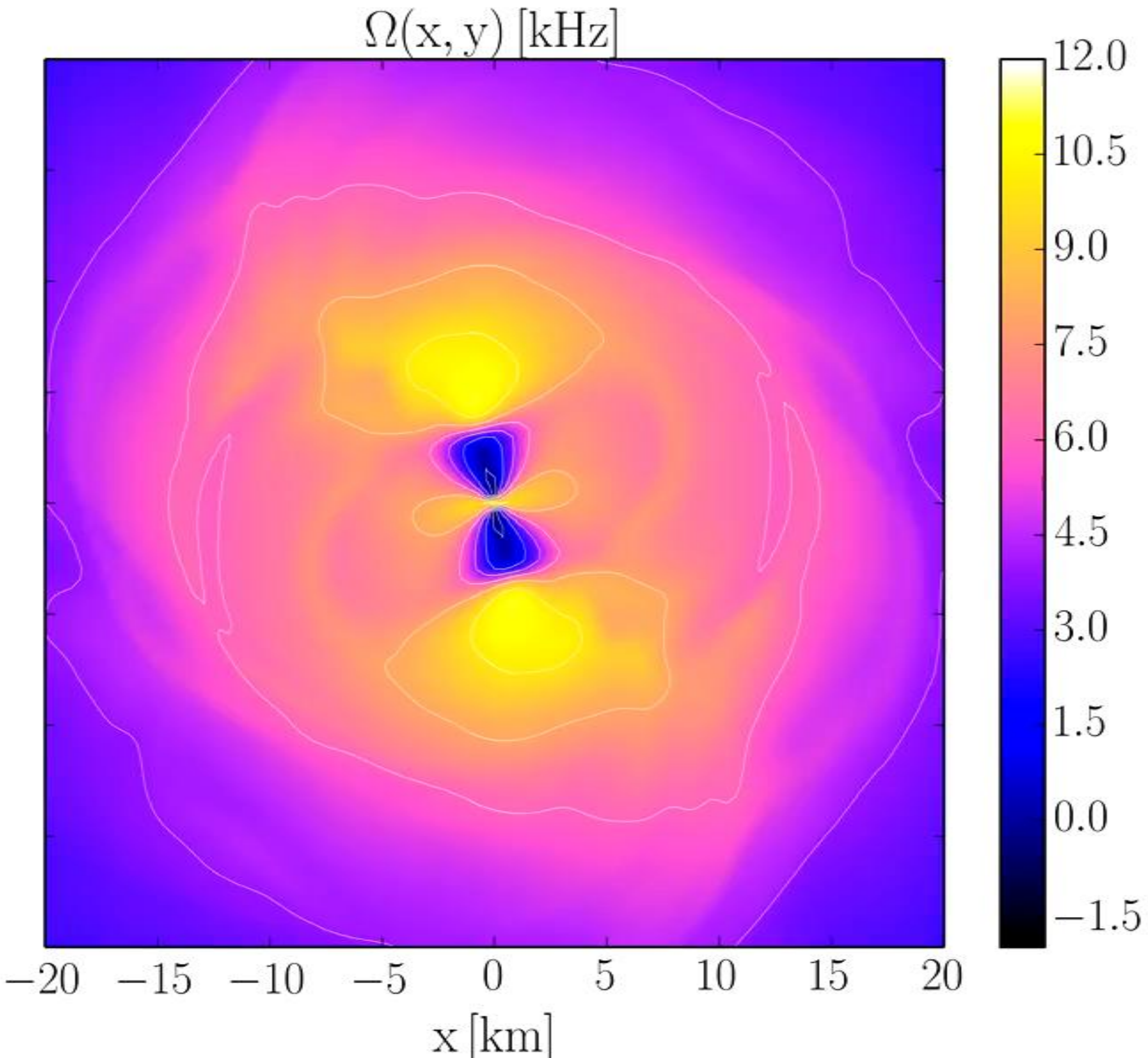




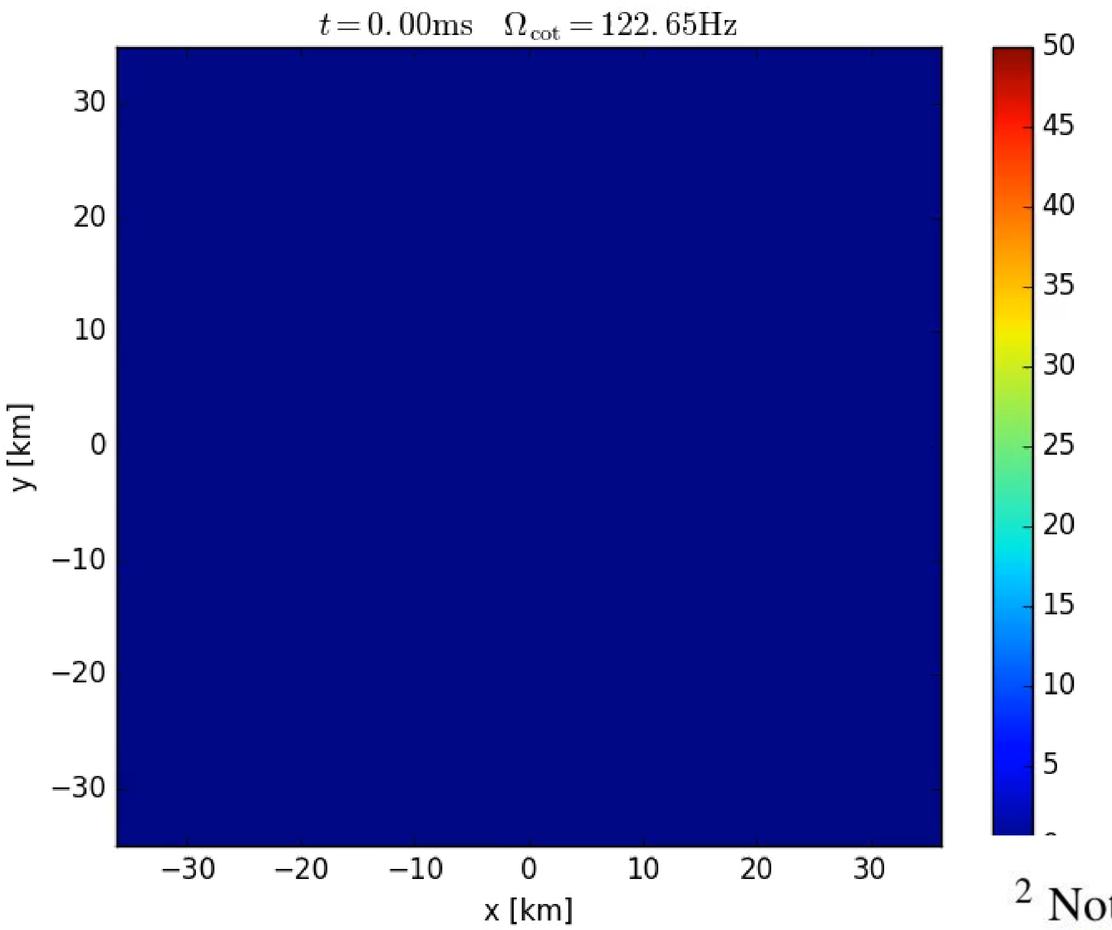
Temperature

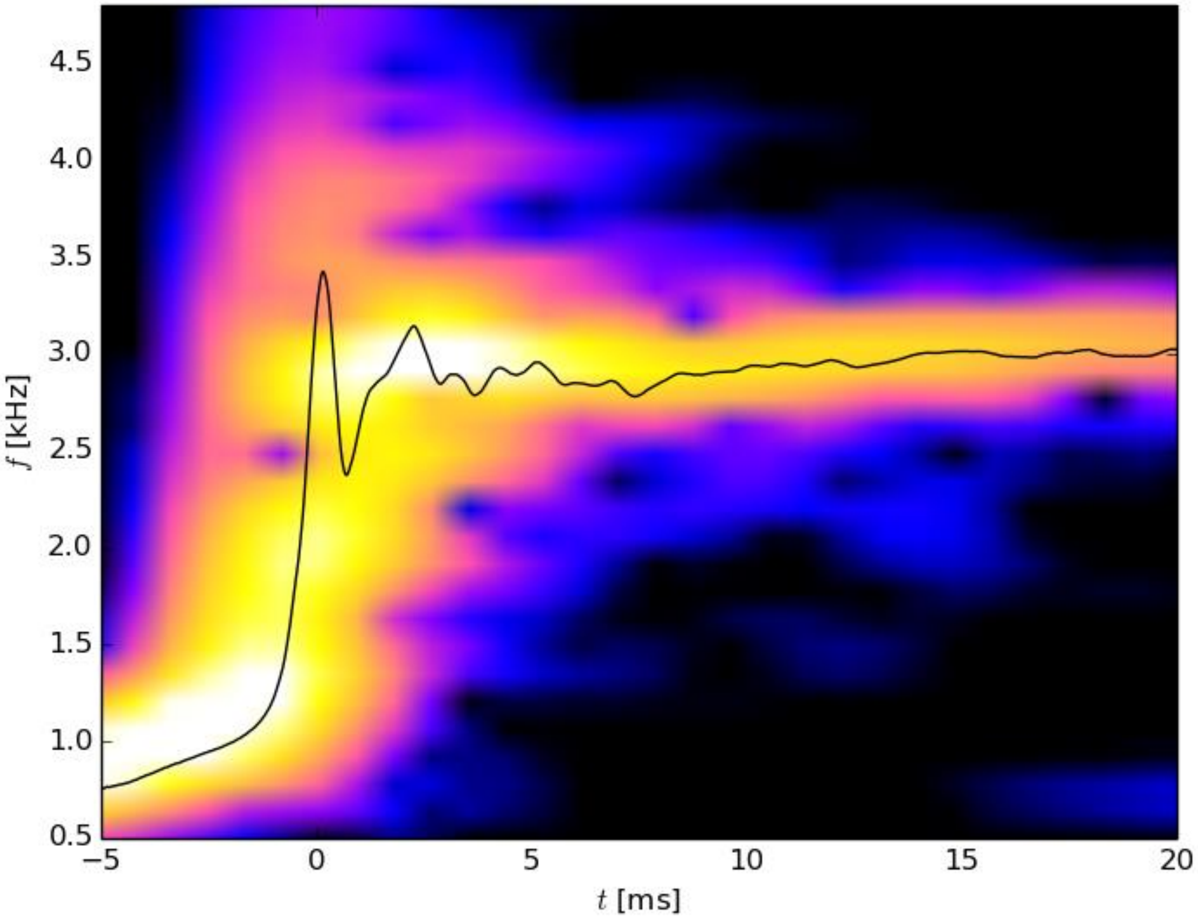


Angular Velocity



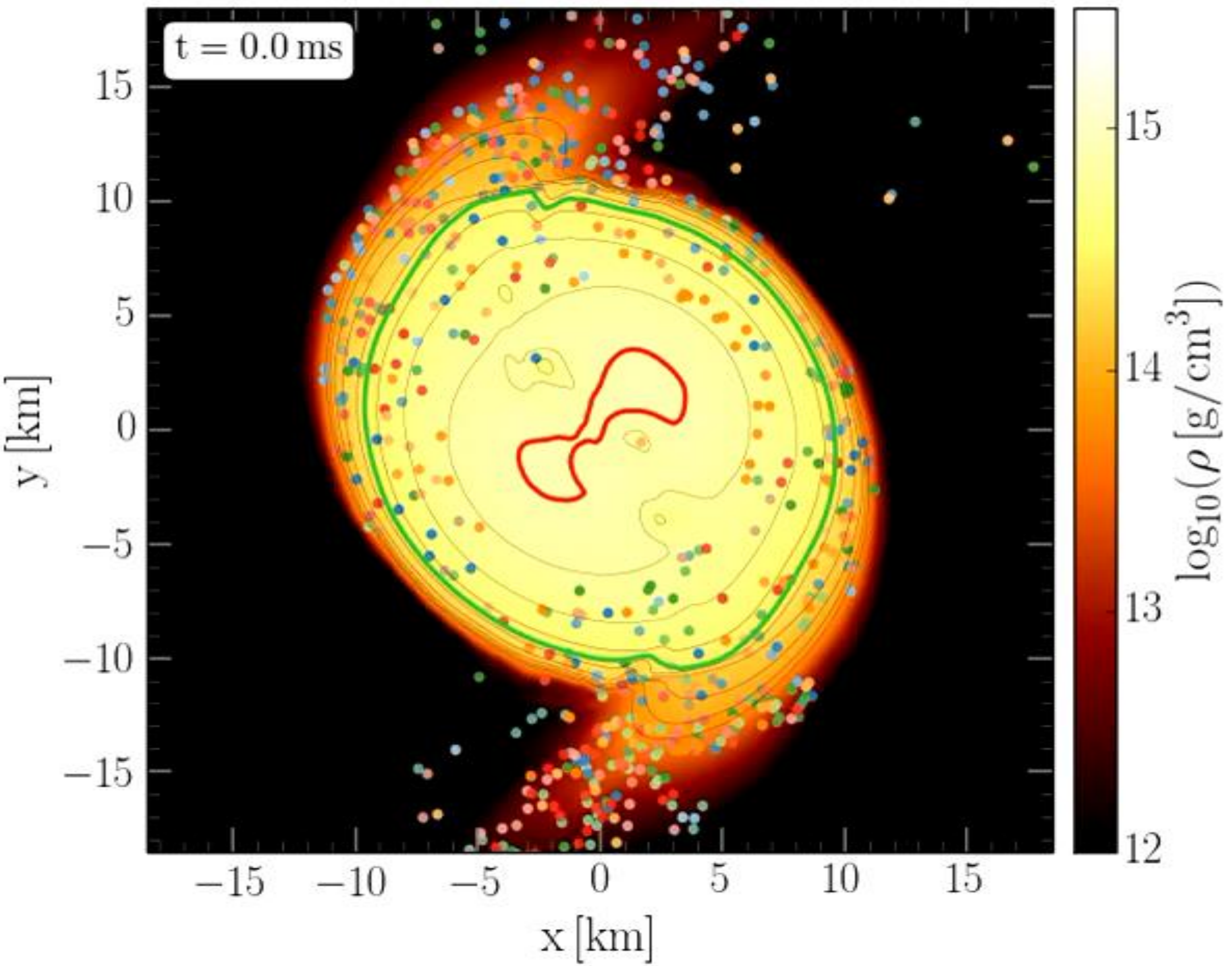
The Co-Rotating Frame



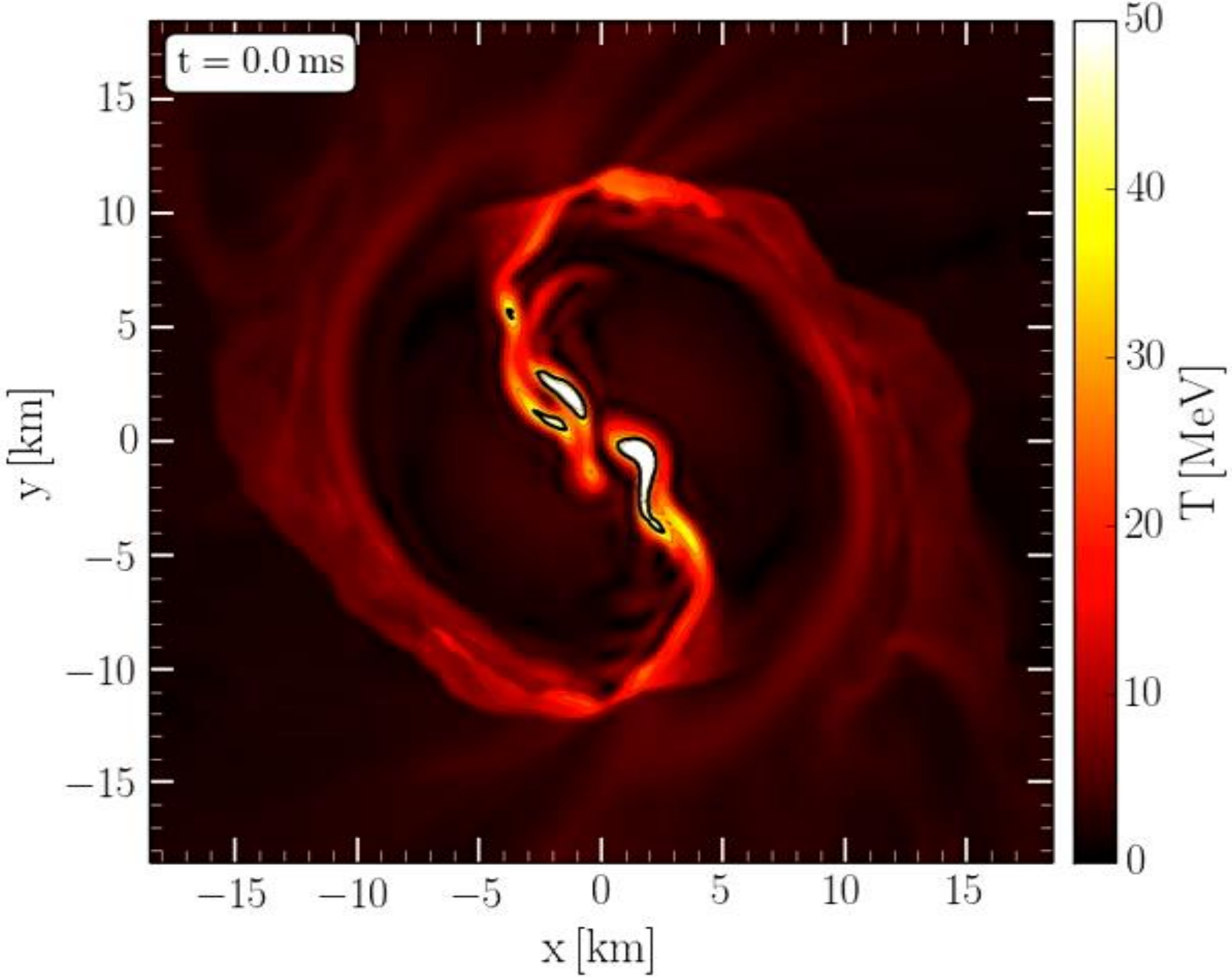


[2] Note that the angular-velocity distribution in the lower central panel of Fig. 10 refers to the corotating frame and that this frame is rotating at half the angular frequency of the emitted gravitational waves, Ω_{GW}. Because the maximum of the angular velocity Ω_{max} is of the order of $\Omega_{GW}/2$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



t = 0.0 ms
y [km]
x [km]
$\log_{10}(\rho\,[\mathrm{g/cm^3}])$
15
10
5
0
−5
−10
−15
12
13
14
15



t = 0.0 ms
y [km]
x [km]
T [MeV]

The Hadron-Quark Phase Transition

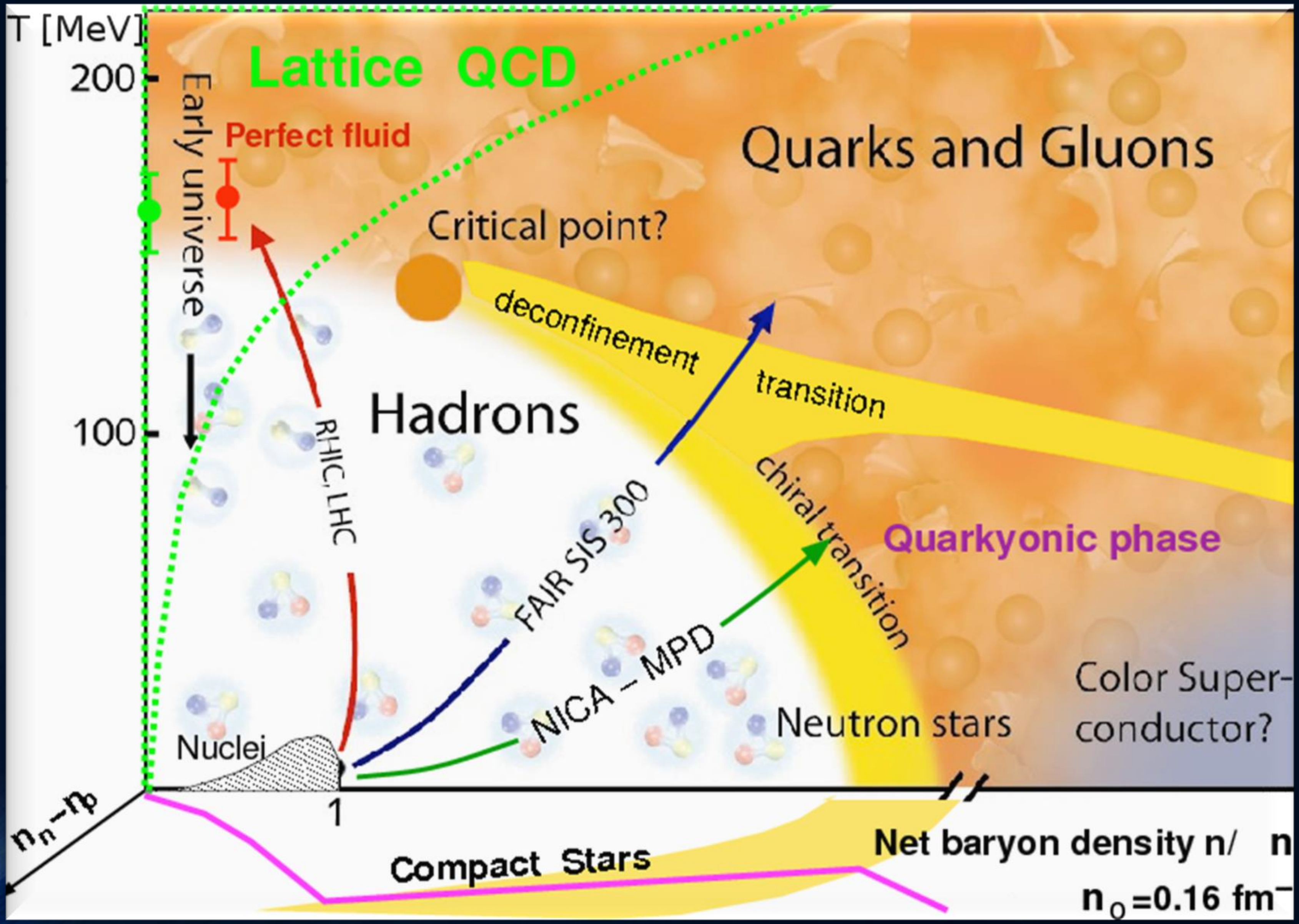
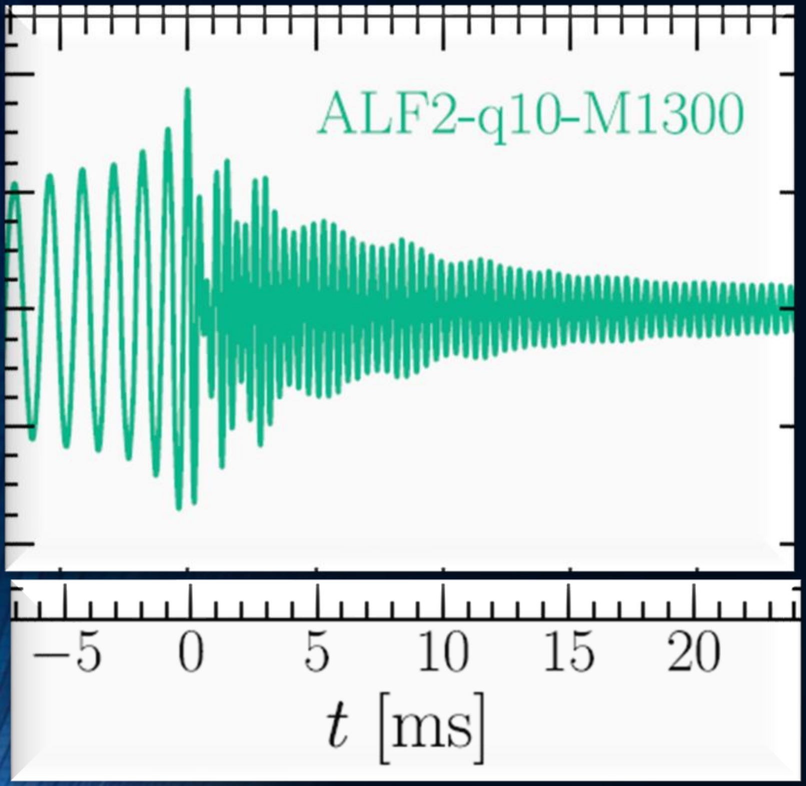
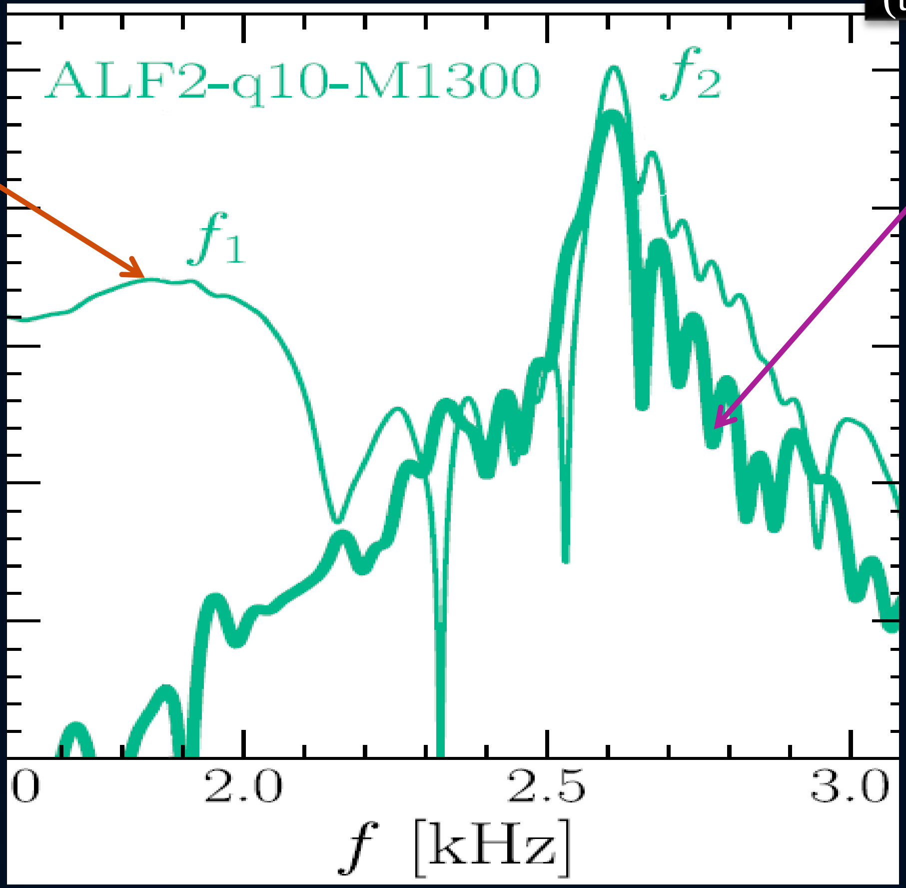


Image from http://inspirehep.net/record/823172/files/phd_qgp3D_quarkyonic2.png

Spectral Properties of GWs





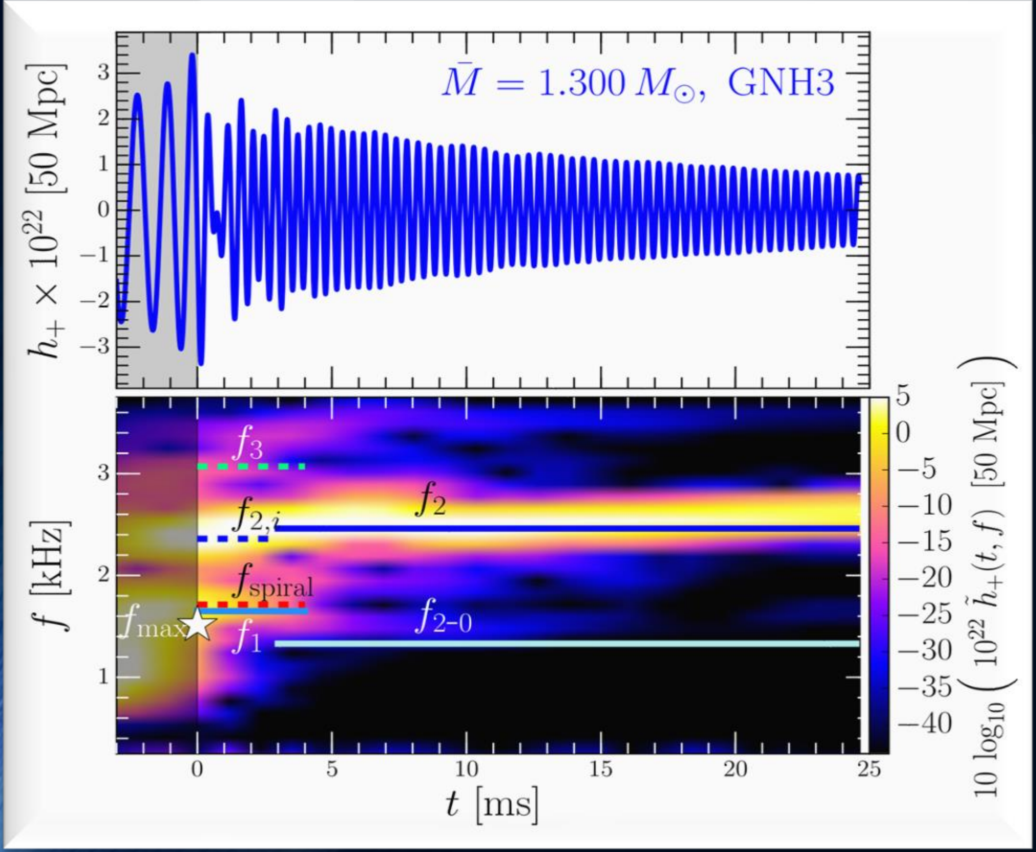
Two characteristic GW frequency peaks (f_1 and f_2);

the origin of f_1 comes from t<3 ms. By measuring M, f_1 and f_2 one can set high constraints on the EoS.

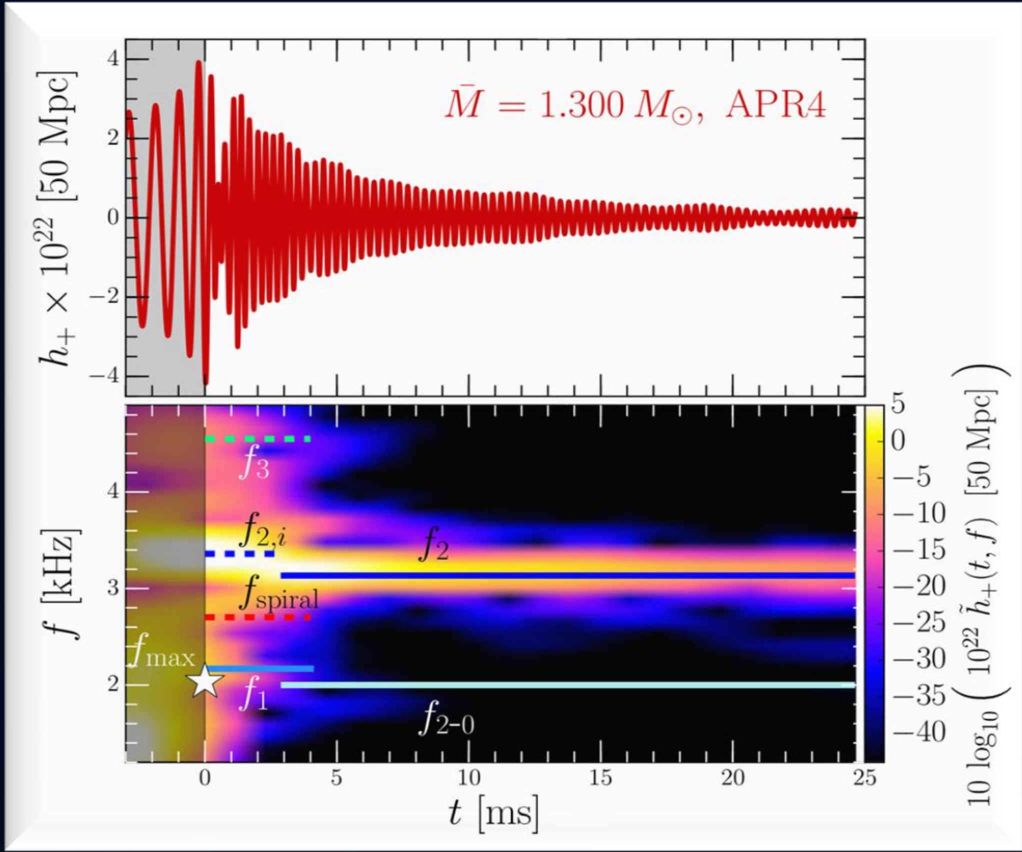
"Spectral properties of the post-merger gravitational-wave signal from binary neutron stars",
Kentaro Takami, Luciano Rezzolla, and Luca Baiotti, PHYSICAL REVIEW D 91, 064001 (2015)

Time Evolution of the GW-Spectrum

The power spectral density profile of the post-merger emission is characterized by several distinct frequencies f_{max}, f_1, f_2, f_3 and f_{2-0}. After approximately 5 ms after merger, the only remaining dominant frequency is the f_2-frequency (See L.Rezzolla and K.Takami, arXiv:1604.00246)



Stiff EOS

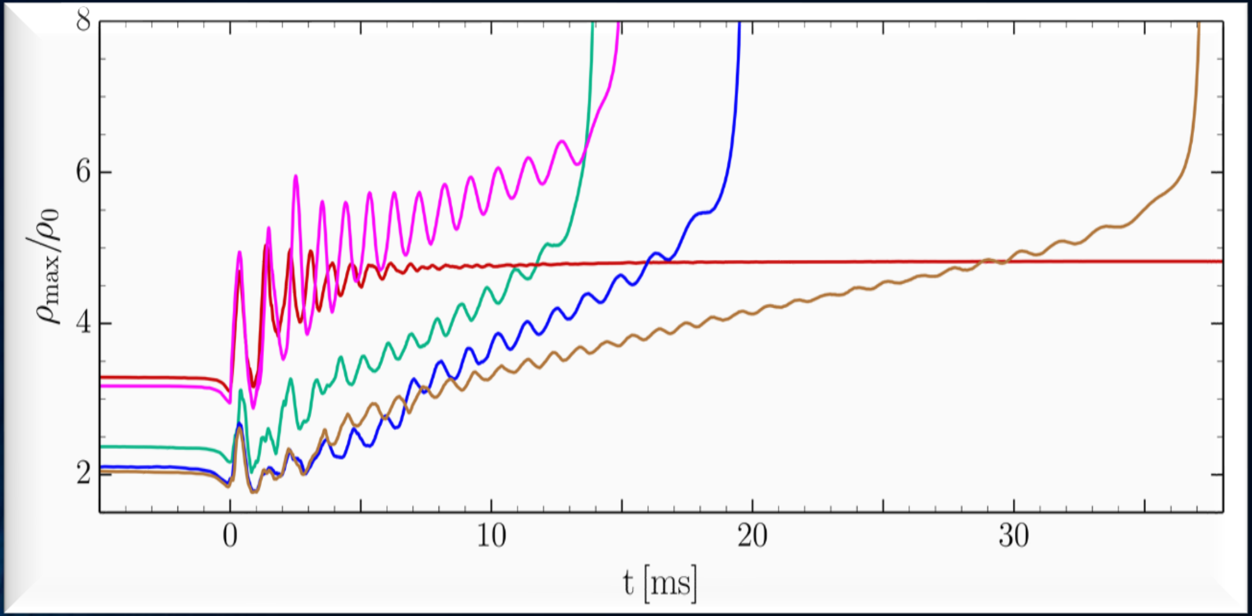


Soft EOS

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

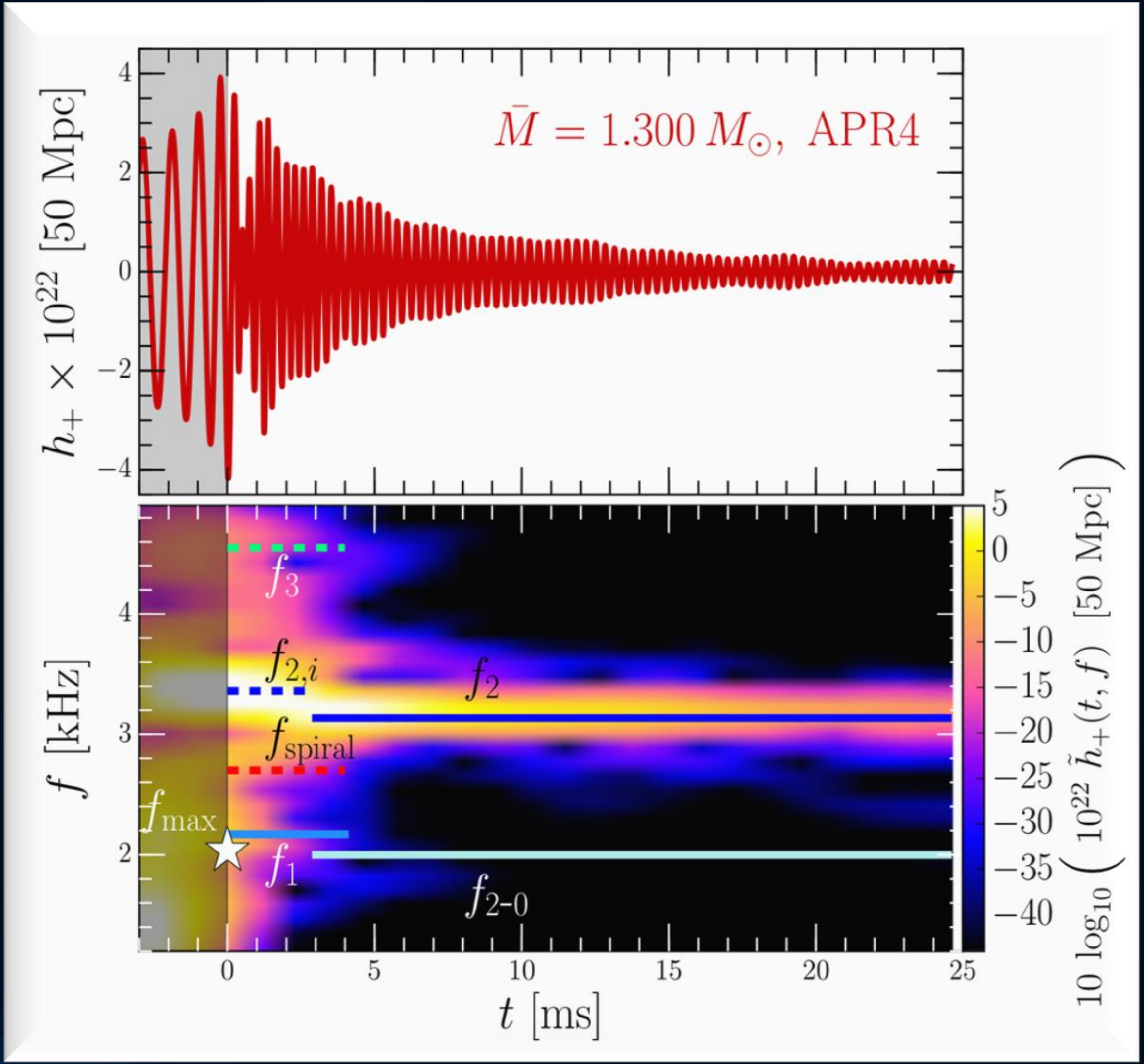
How to observe the QGP with gravitational waves from NS mergers?

Outlook

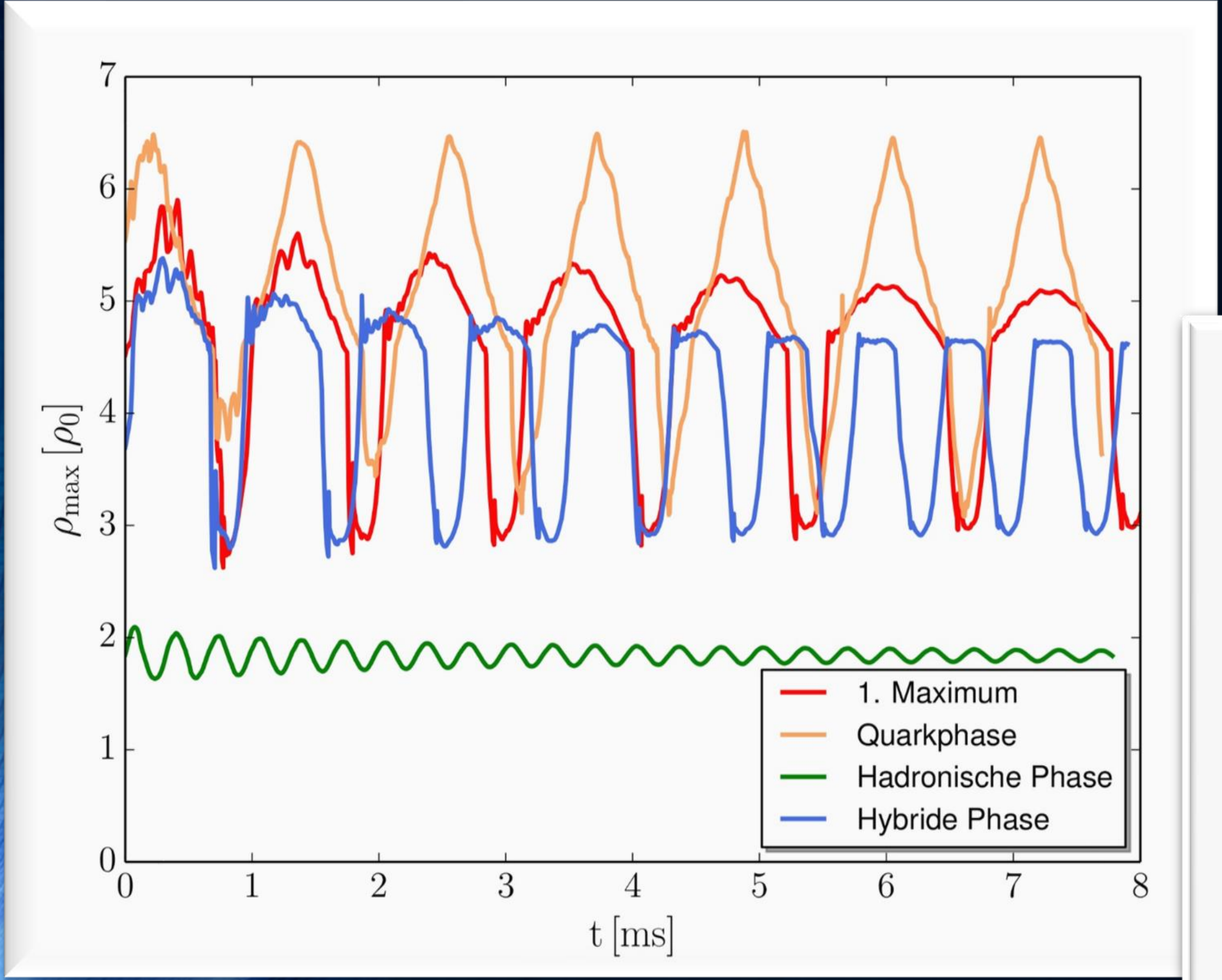


Maximum of the rest mass density ρ_{max} in units of ρ_0 versus time for the high mass simulations.

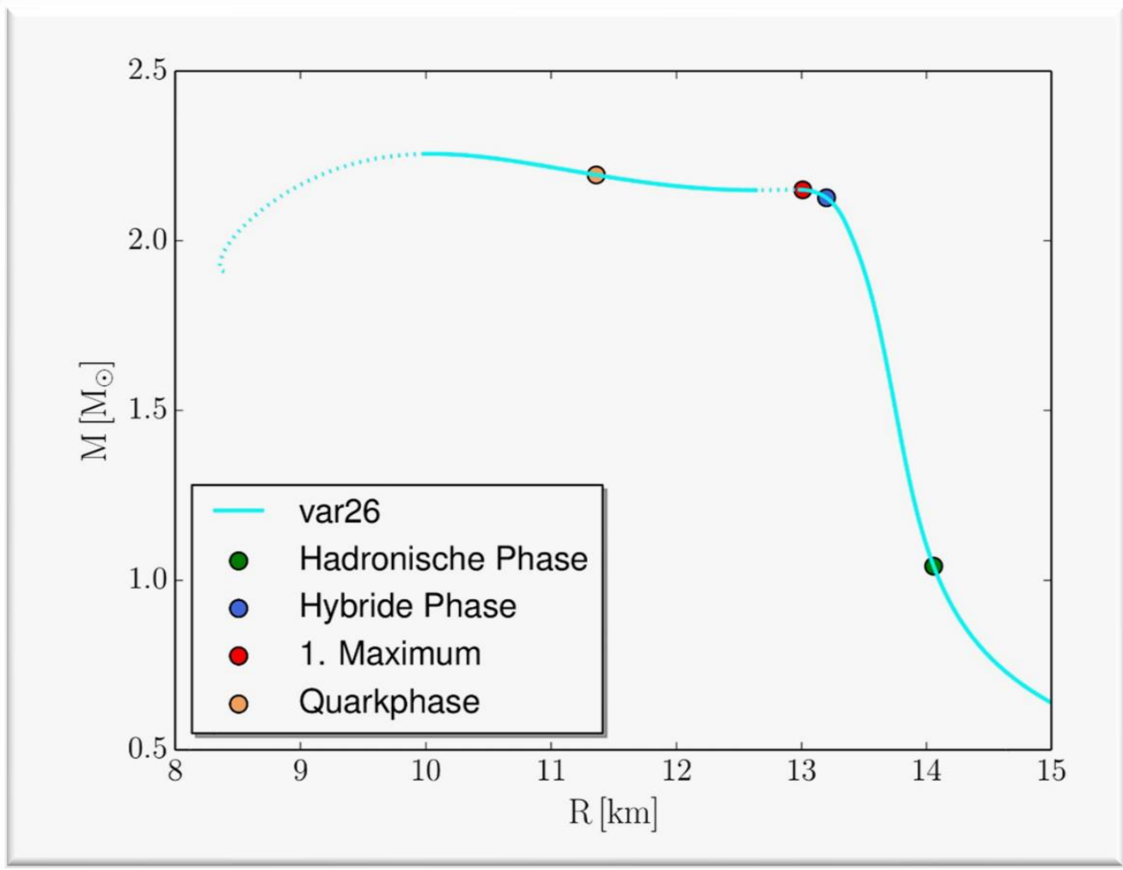
The power spectral density profile of the post-merger emission is characterized by several distinct frequencies f_{max} , f_1 , f_2 , …, $f_{2\text{-PT}}$



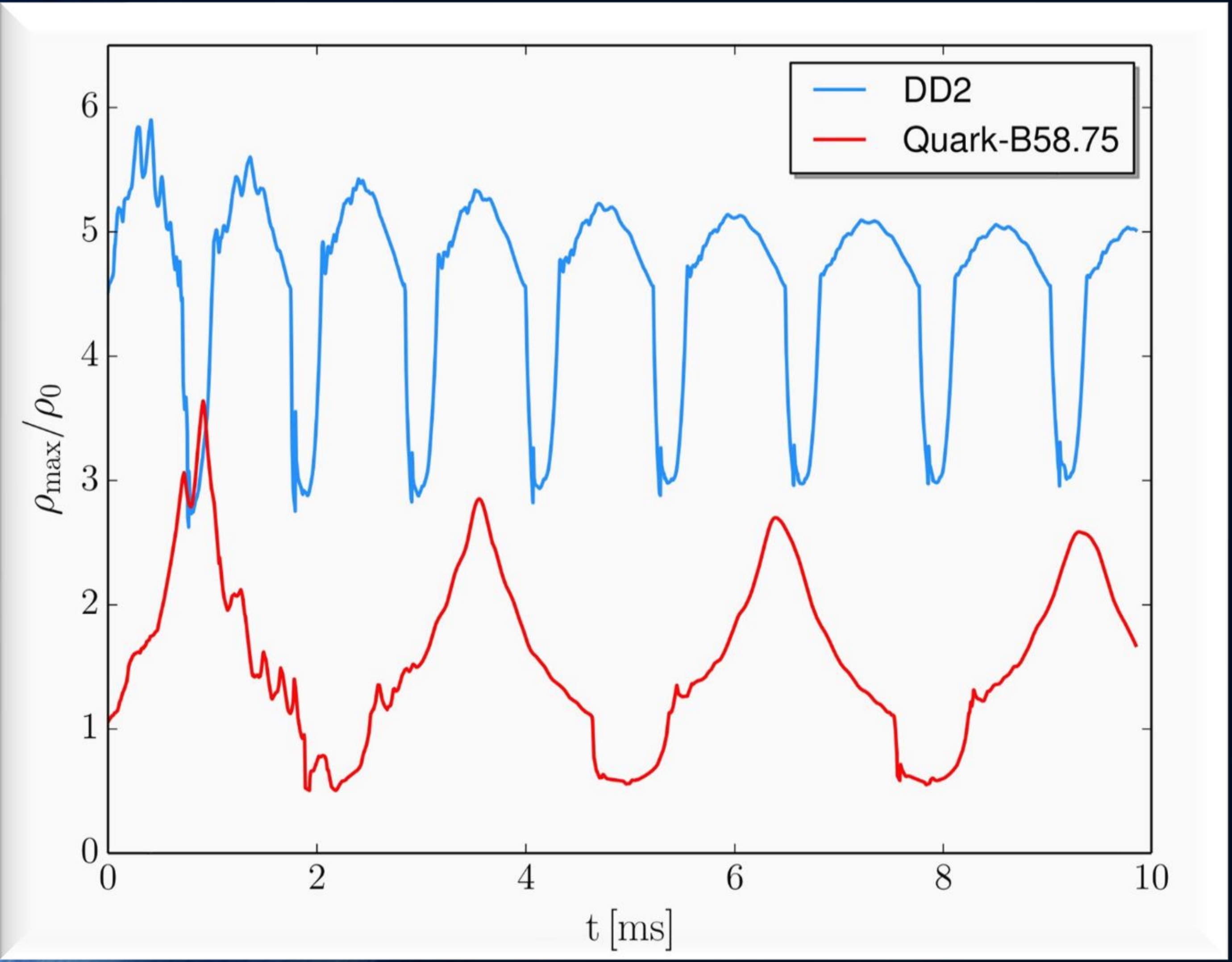
Twin Star EOSs and the prompt splitting of the f_2-Peak



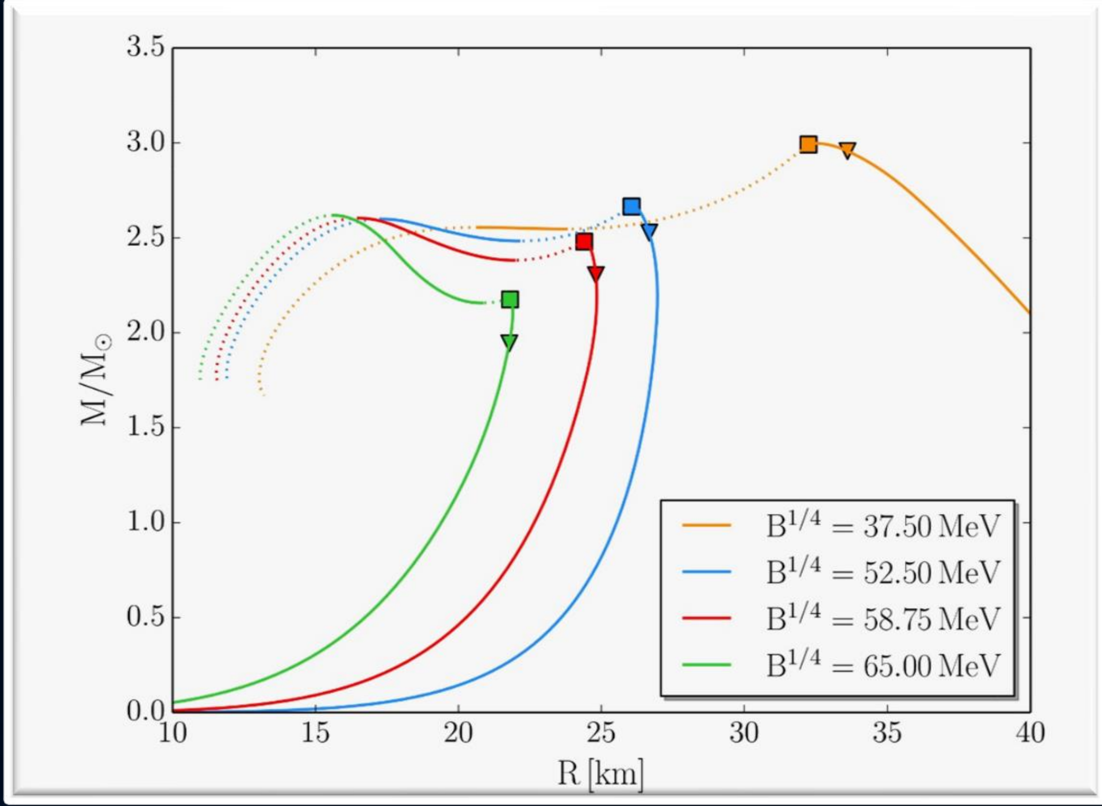
Master Thesis:
"From Neutron Stars
to Hybrid Stars"
by Ms Zekiye Simay Yilmaz



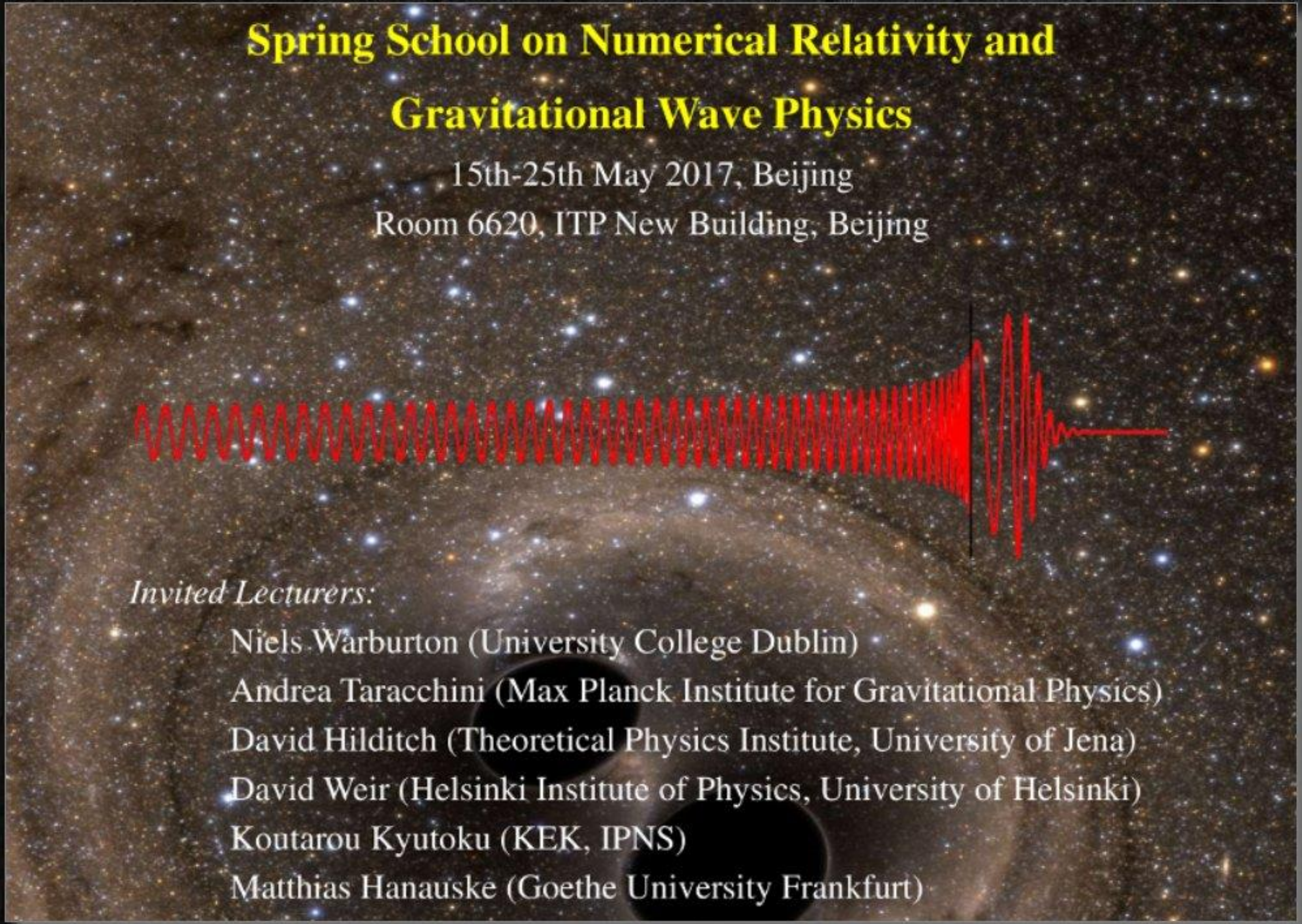
Twin Star EOSs and the prompt splitting of the f_2-Peak



Master Thesis:
Ms Christina Mitropoulos



See: *Stable hybrid stars within a SU(3) Quark-Meson-Model*,
A.Zacchi, M.Hanauske, J.Schaffner-Bielich, PRD 93, 065011 (2016)



(Spring School on Numerical Relativity and Gravitational Wave Physics)

Vorlesungsreihe (6 Vorlesungen) über
Gravitationswellen von kollidierenden kompakten Sternen und die Eigenschaften seltsamer Materie
(Gravitational waves from colliding compact star binaries in the context of strange/exotic matter)
致密星碰撞引起的引力波和奇异物质的性质
Beijing, China, 15.-25. May 2017

Die im Jahre 2017 gehaltene Vorlesungsreihe führt einerseits in die Allgemeine Relativitätstheorie ein, andererseits fokussiert sie sich auf den speziellen Teilaspekt der relativistischen Astrophysik kollidierender hybrider Neutronensterne, in deren innerem Bereich es zur Bildung seltsamer und exotischer Materie kommen kann. Kollabiert ein instabiler Neutronenstern zu einem schwarzen Loch oder zu einem Quark Stern? Wie kann man anhand des ausgesandten Gravitationswellen-Signals zweier kollidierender kompakter Sterne die Eigenschaften der Nuklearen- und Quark-Materie entschlüsseln?

(The series of lectures held in 2017. Topics: theory of general relativity theory, relativistic astrophysics of colliding hybrid neutron stars, strange and exotic matter in the interior of compact stars. Questions: Does an unstable neutron star collapse to a black hole or quark star? How can we extract the strange properties of high density nuclear and quark matter by means of the emitted gravitational wave signal of two colliding compact stars?)

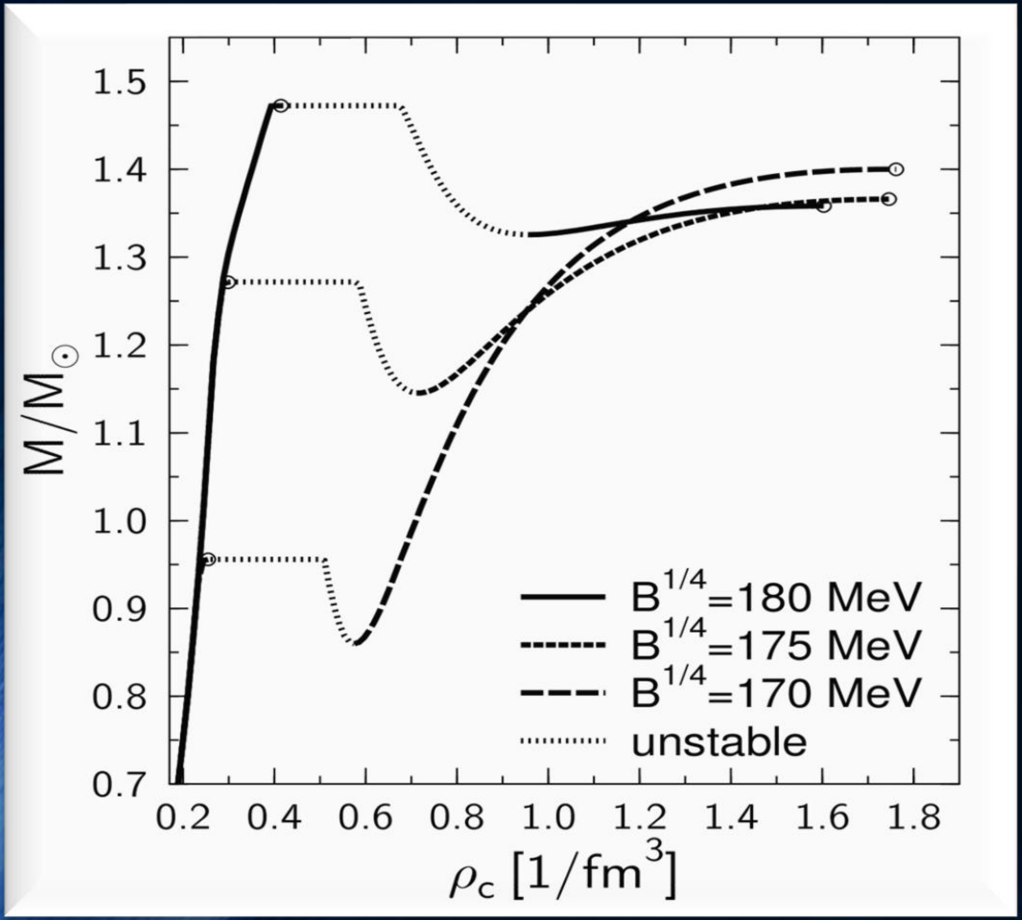
在2017年开设的课程，一方面介绍广义相对论理论，另一方面聚焦于相对论天体物理中的一个特殊部分：混合致密星碰撞,以及在其内部可能生成的奇异和异常物质。一个不稳定的中子星是会坍缩成黑洞还是夸克星？如何根据两个致密星碰撞发射的引力波信号来解码核物质和夸克物质的奇异特性？

www.fias.uni-frankfurt/~hanauske/VARTC/ssnr2017

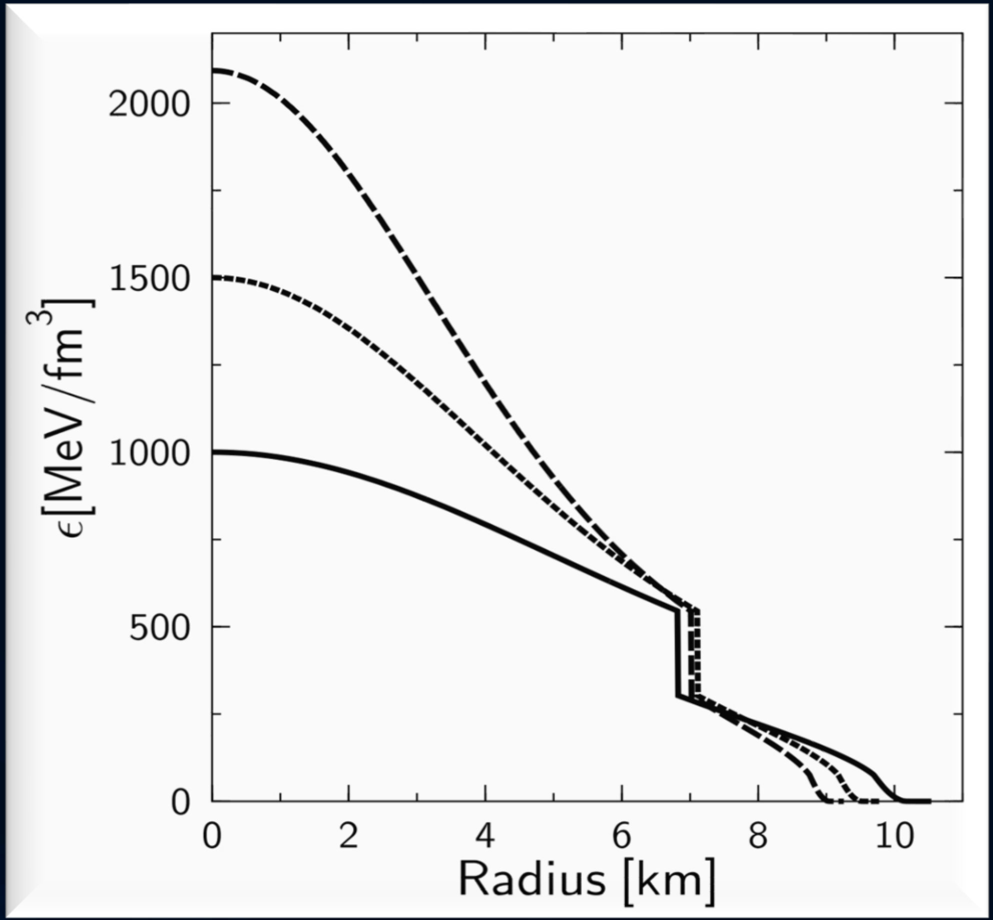
Hybrid Star Properties

In contrast to the Gibbs construction, the star's density profile within the Maxwell construction (see right figure) will have a huge density jump at the phase transition boundary. Twin star properties can be found more easily when using a Maxwell construction.

Mass-Density relation



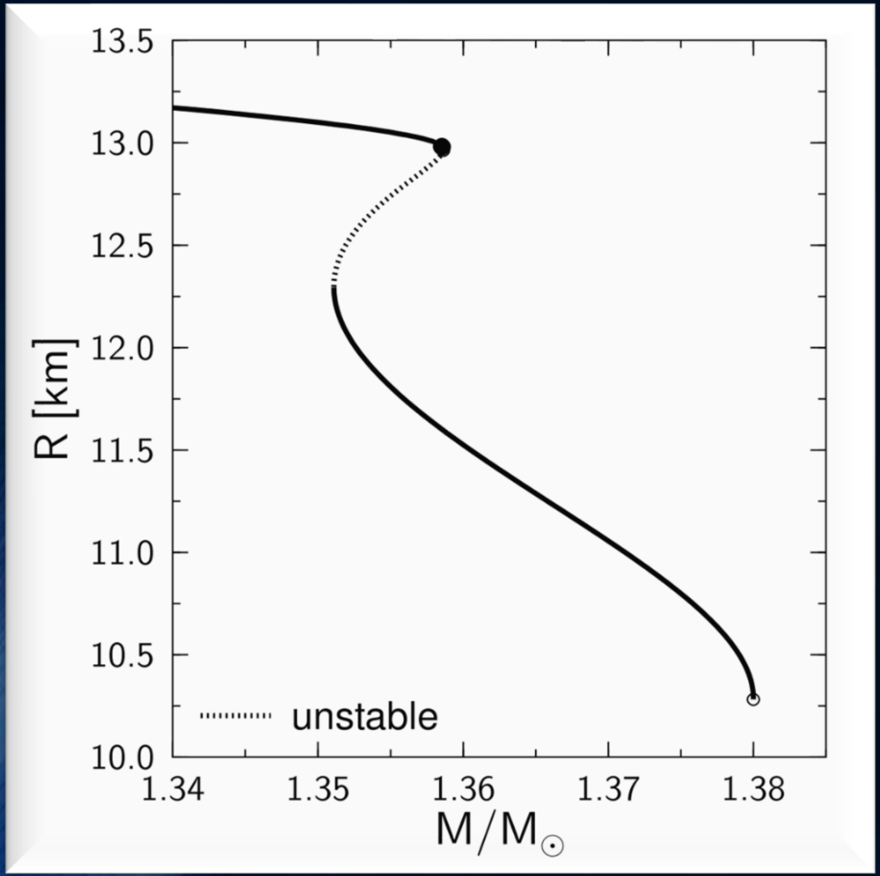
Energy-density profiles

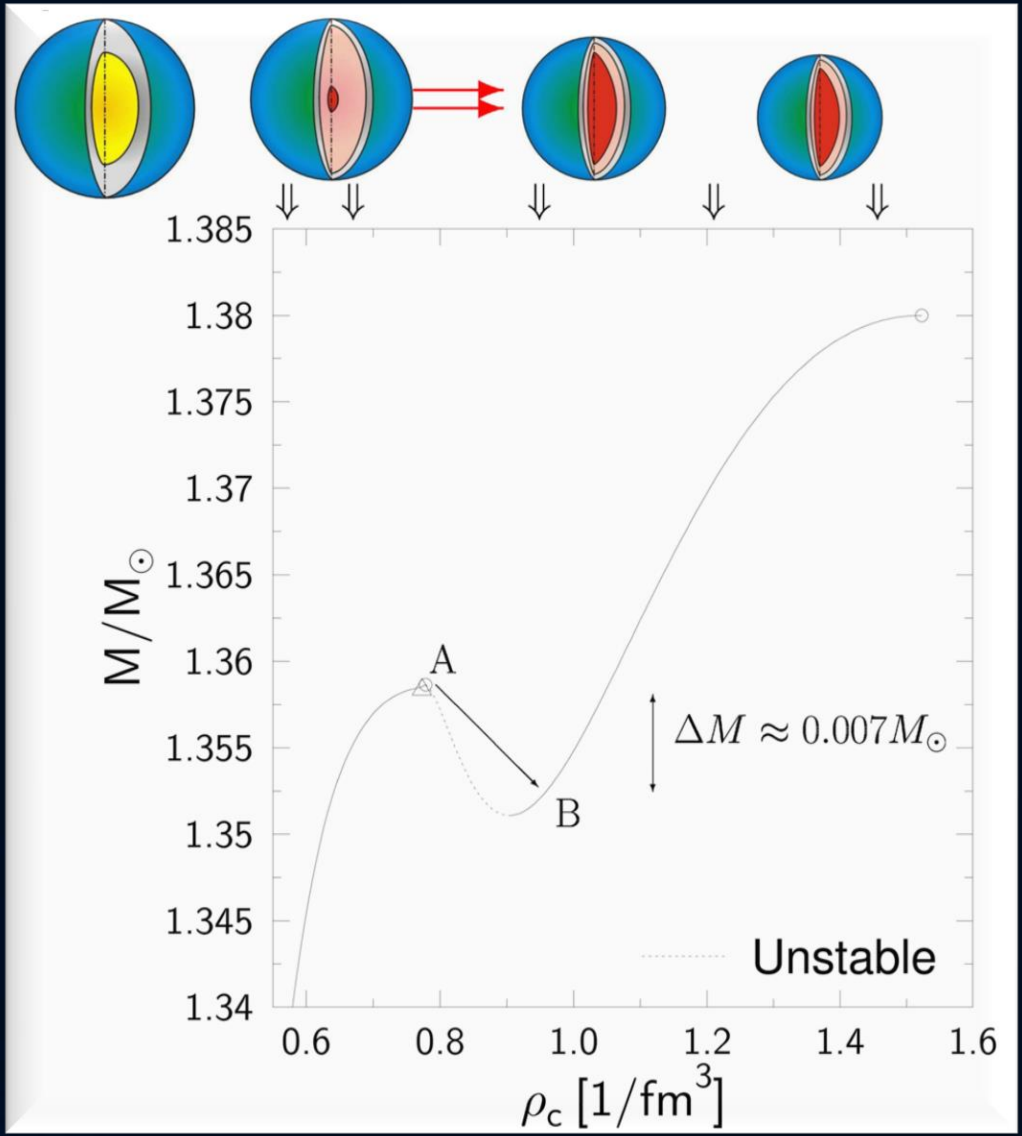


Matthias Hanauske: "How to detect the QGP with telescopes", GSI Annual Report 2003, p.96

Twin Stars

Usually it is assumed that this loss of stability leads to the collapse into a black hole. However, realistic calculations open another possibility: the collapse into the twin star on the second sequence.

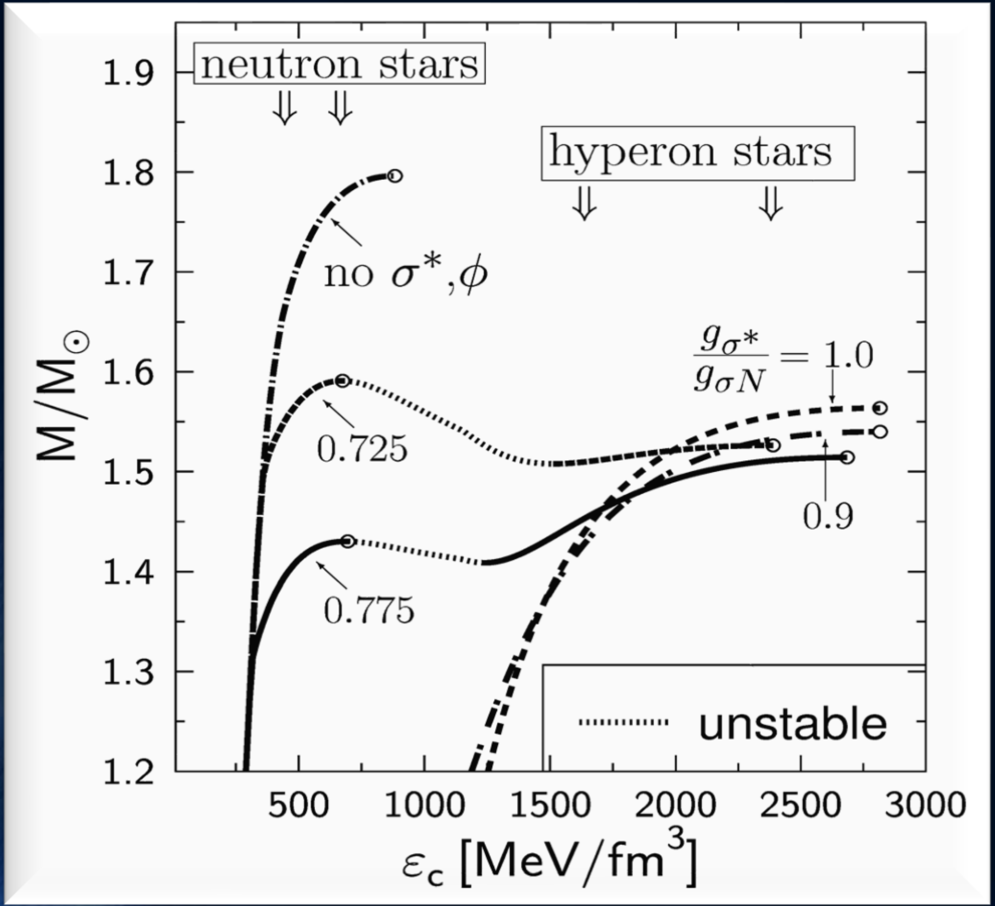


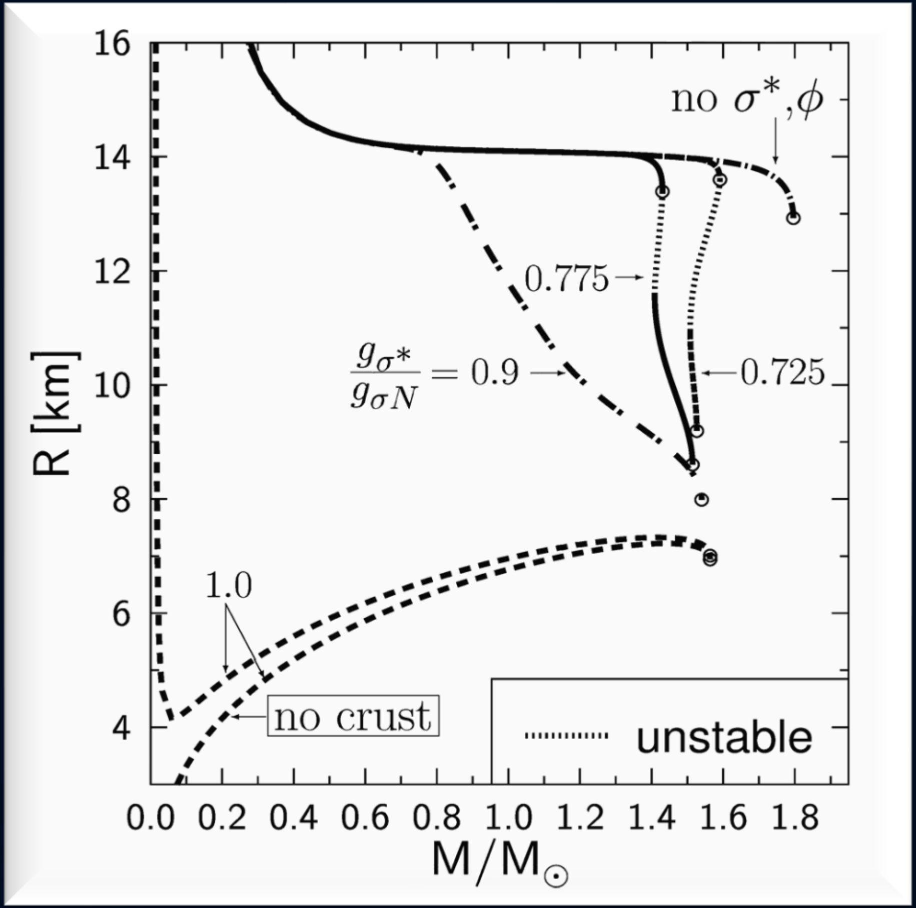


I.N. Mishustin, M. Hanauske, A. Bhattacharyya, L.M. Satarov, H. Stöcker, and W. Greiner, "Catastrophic rearrangement of a compact star due to quark core formation", Physics Letters B 552 (2003) p.1-8

Exotic Stars

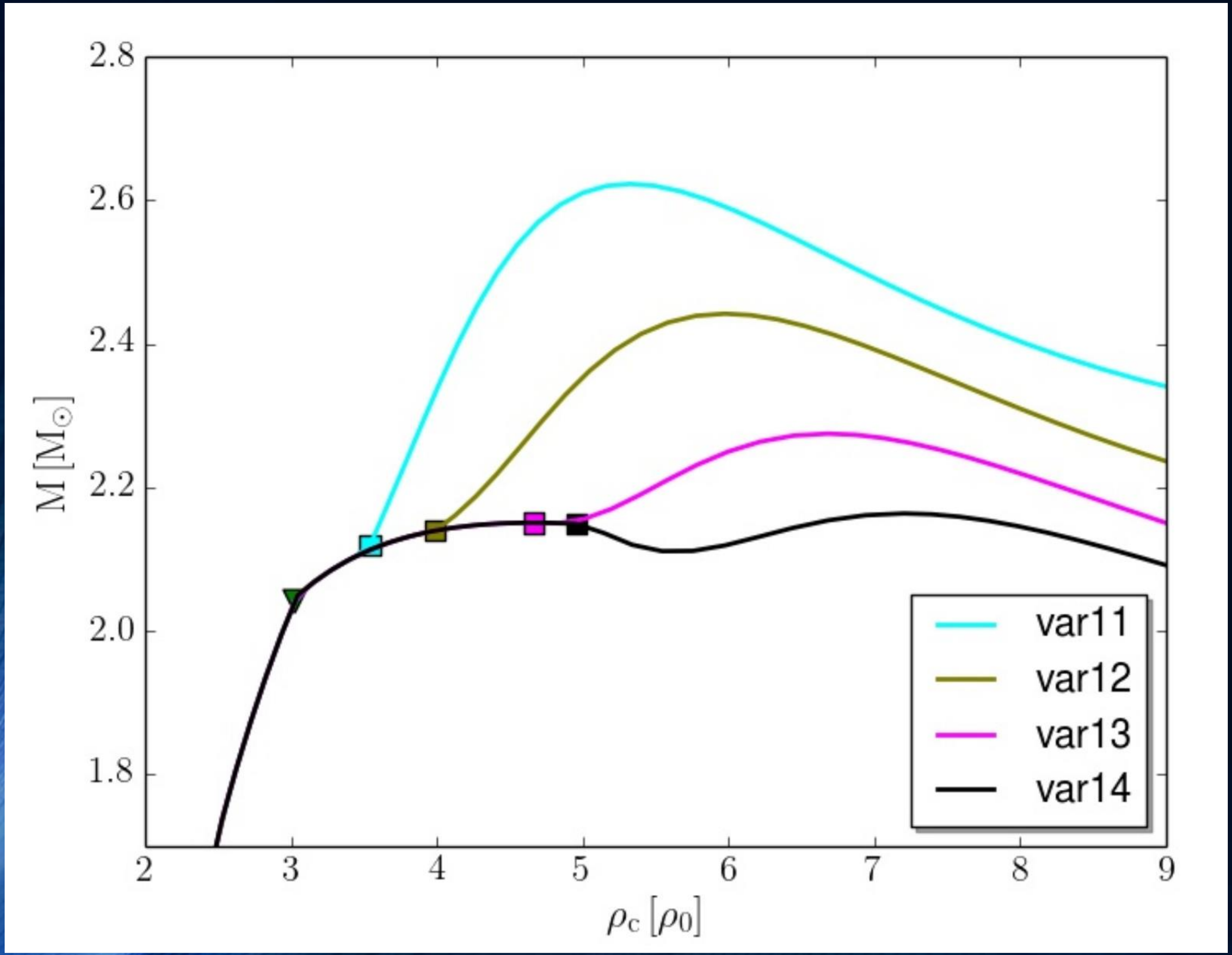
But, unfortunately, twin stars can not be created solely by a Hadron-Quark phase transition. Extremely bound hyperon mater, or kaon condensation could also form a twin star behaviour.





J. Schaffner-Bielich, M. Hanauske, H. Stöcker, and W. Greiner, Phys. Rev. Lett. 89, 171101 (2002)

Possibility of Twin Stars in Hybrid Star Models



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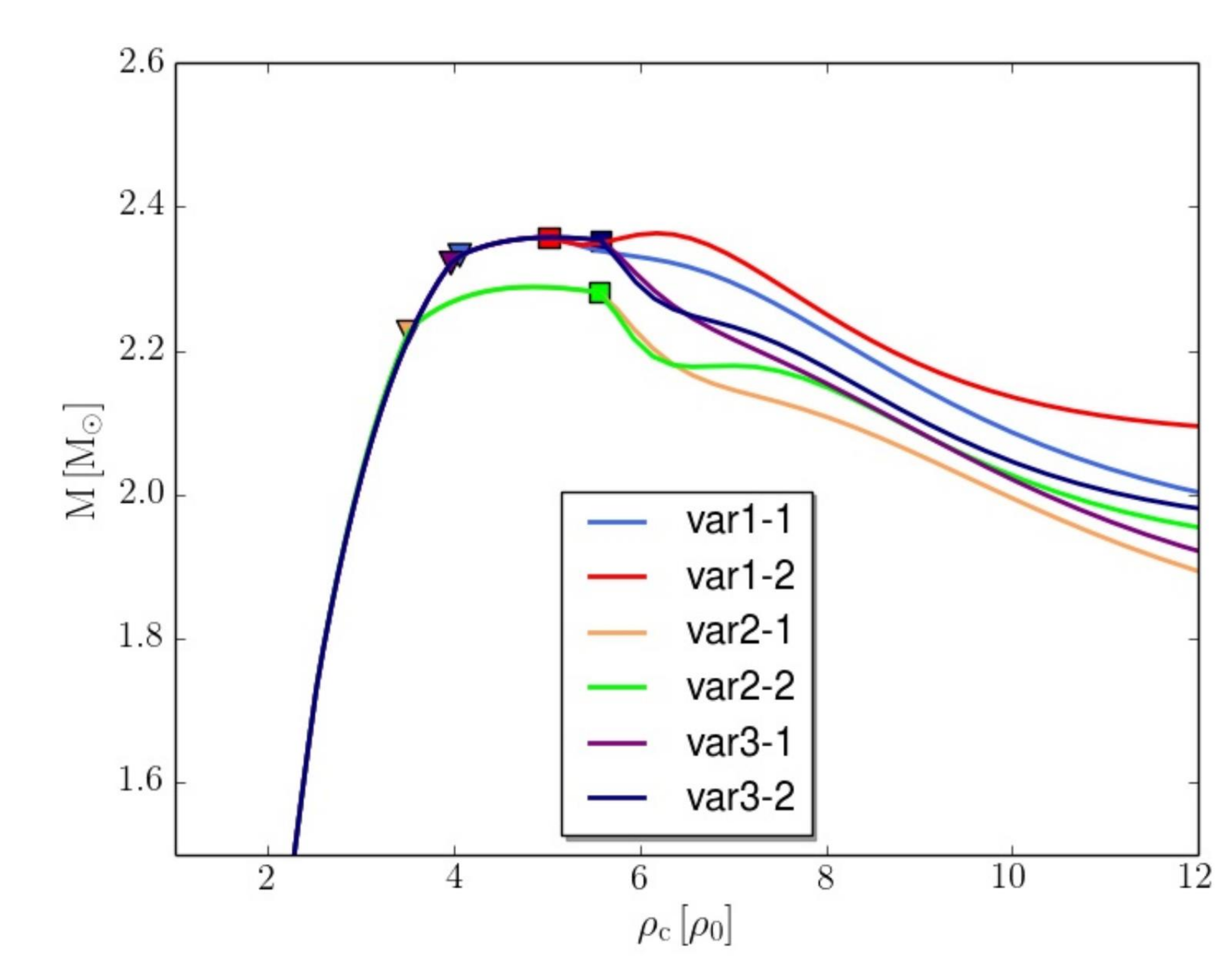
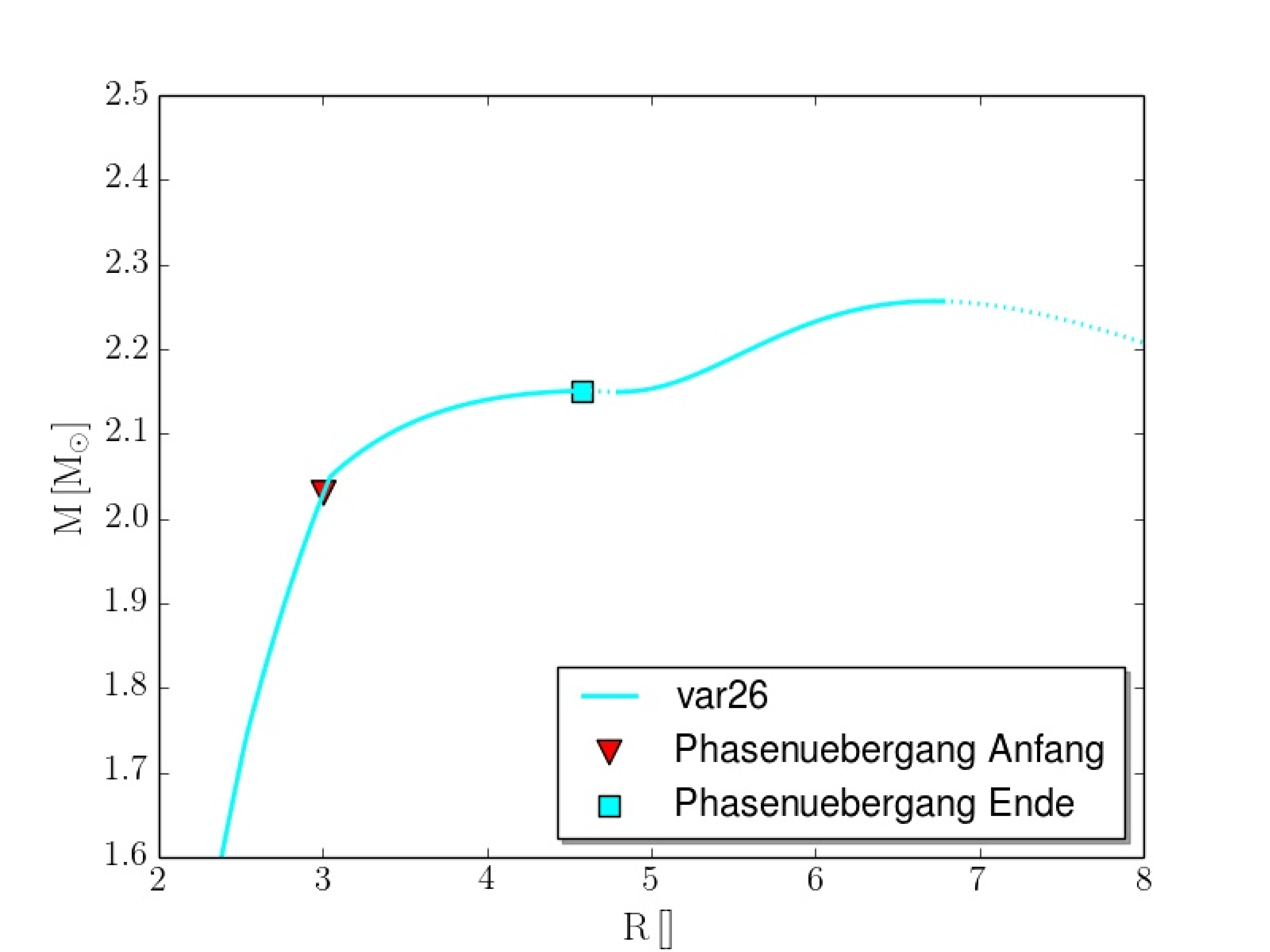
"From Neutron Stars to Hybrid Stars"
by Ms Zekiye Simay Yilmaz

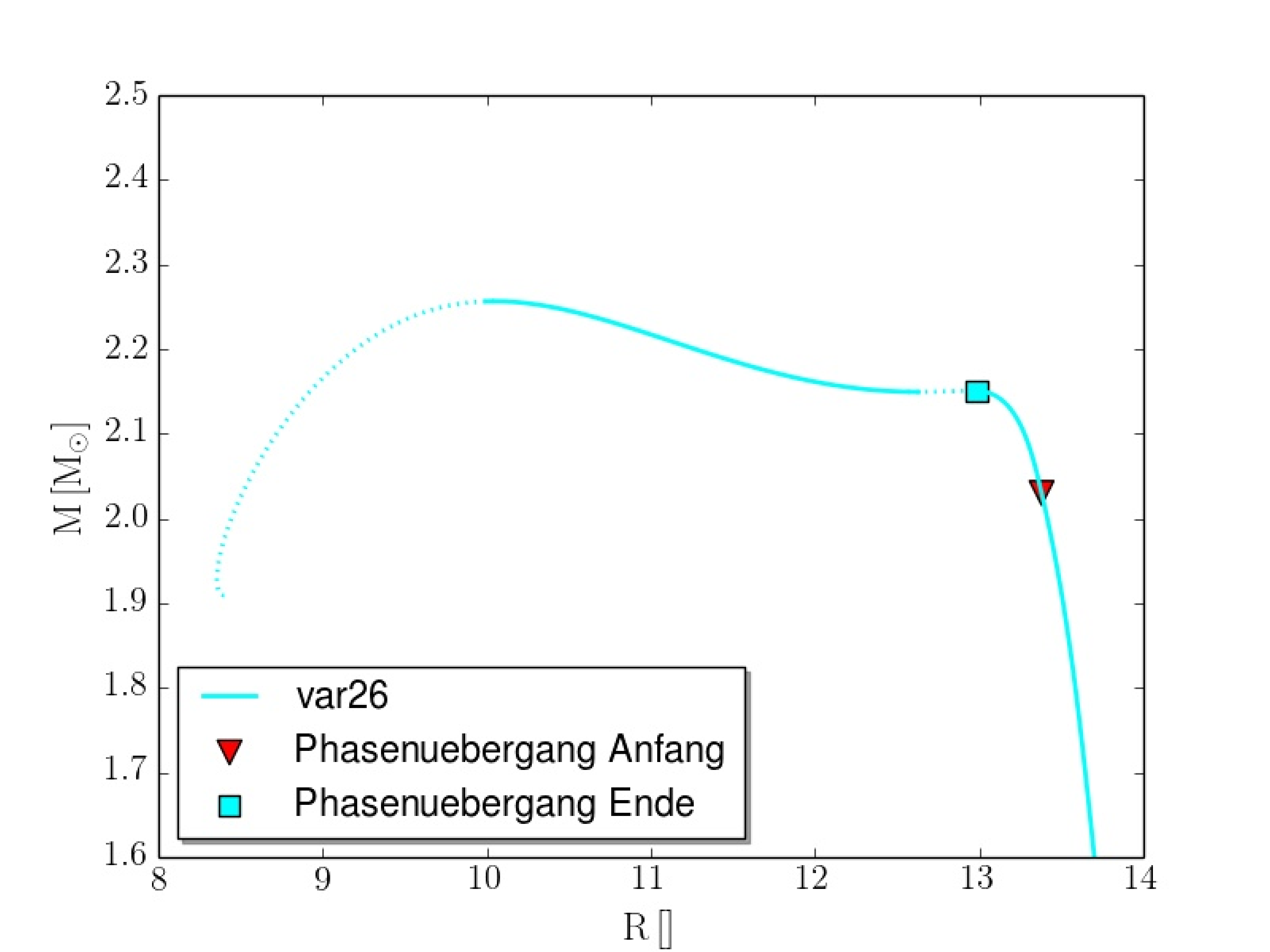
Possibility of Twin Stars in Hybrid Star Models



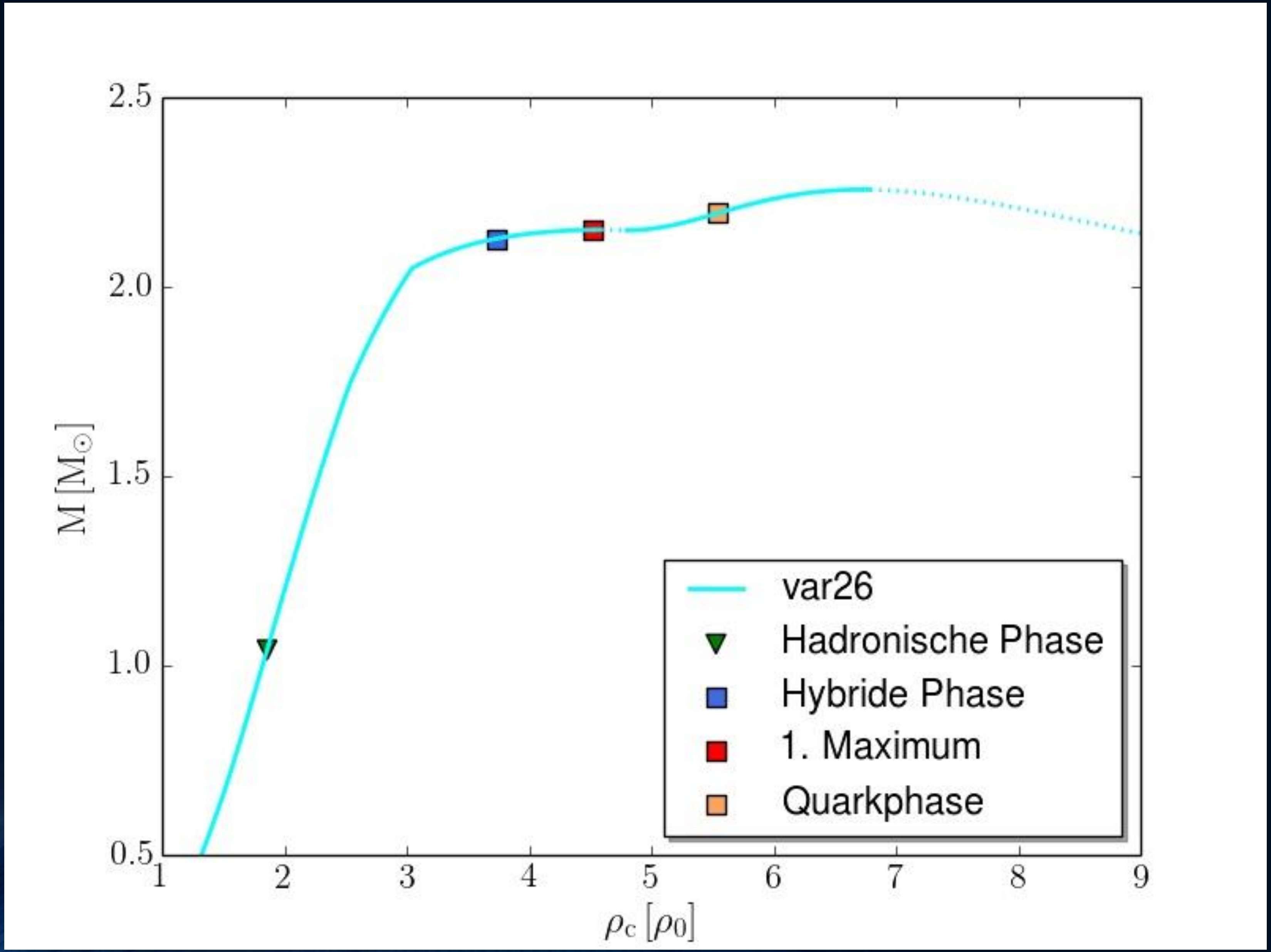
Twin Stars within a Hybrid Model (Gibbs Construction)



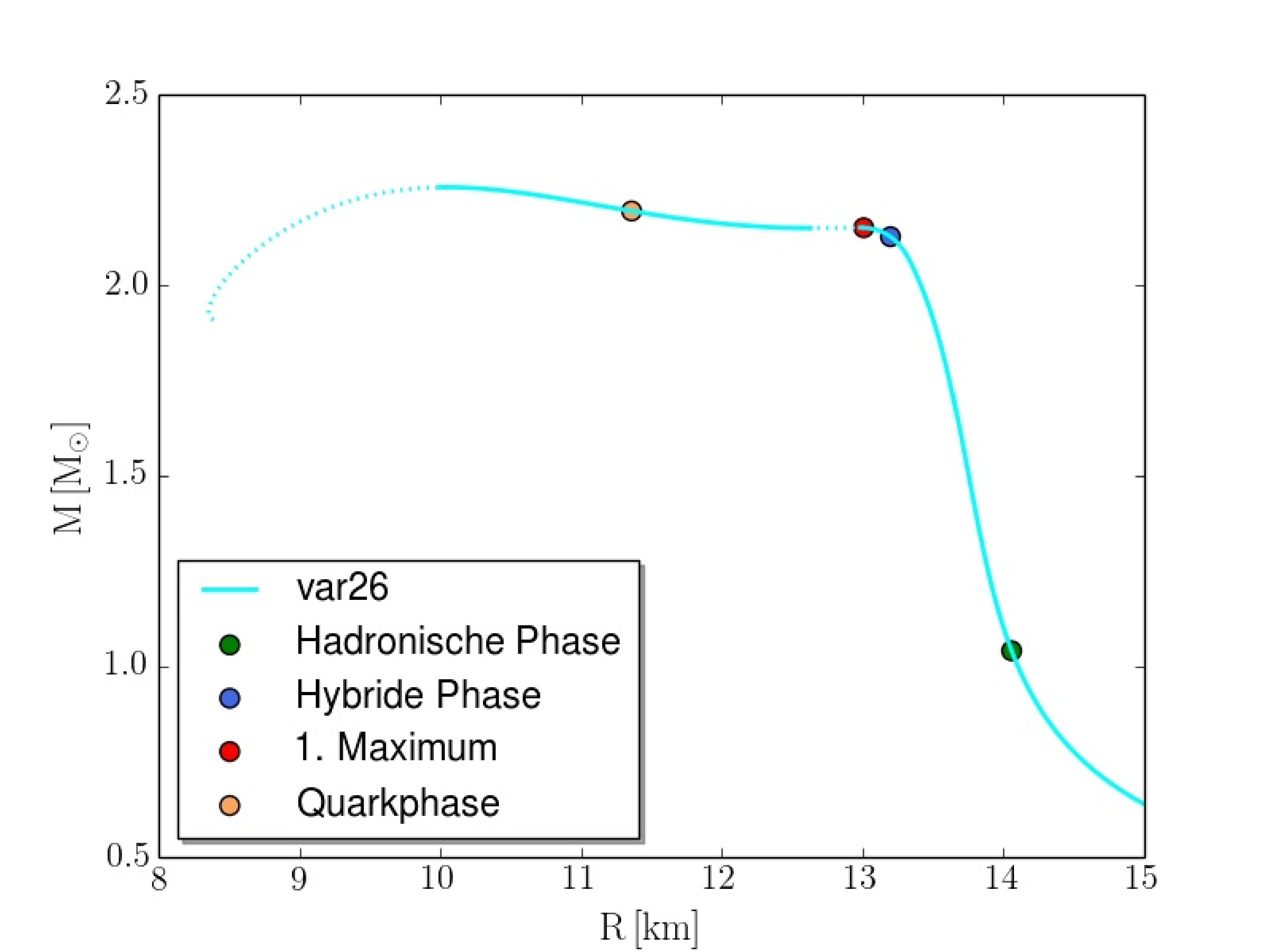
Twin Stars within a Hybrid Model (Gibbs Construction)



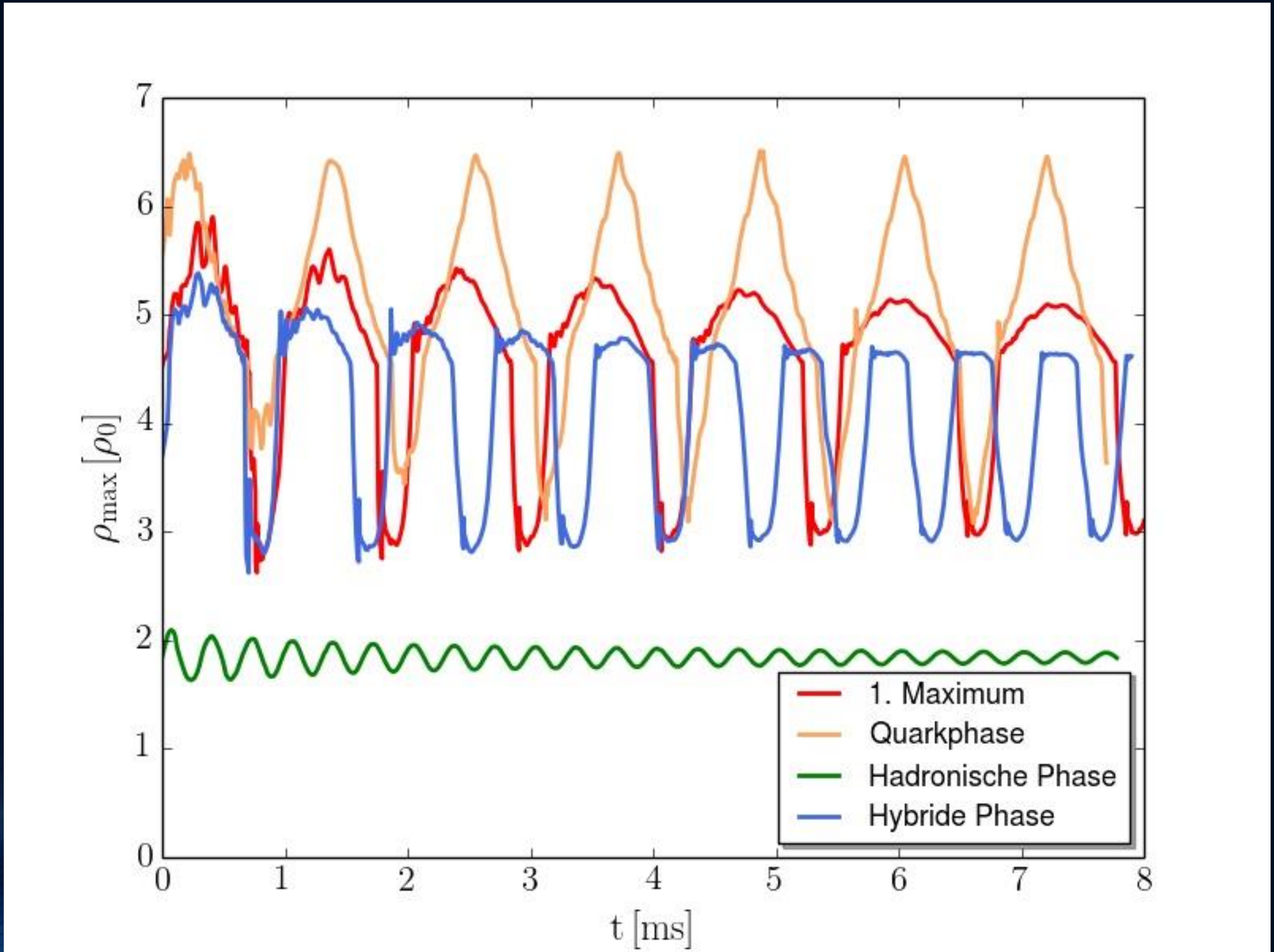
Initial Configuration of the Neutron and Hybrid Stars



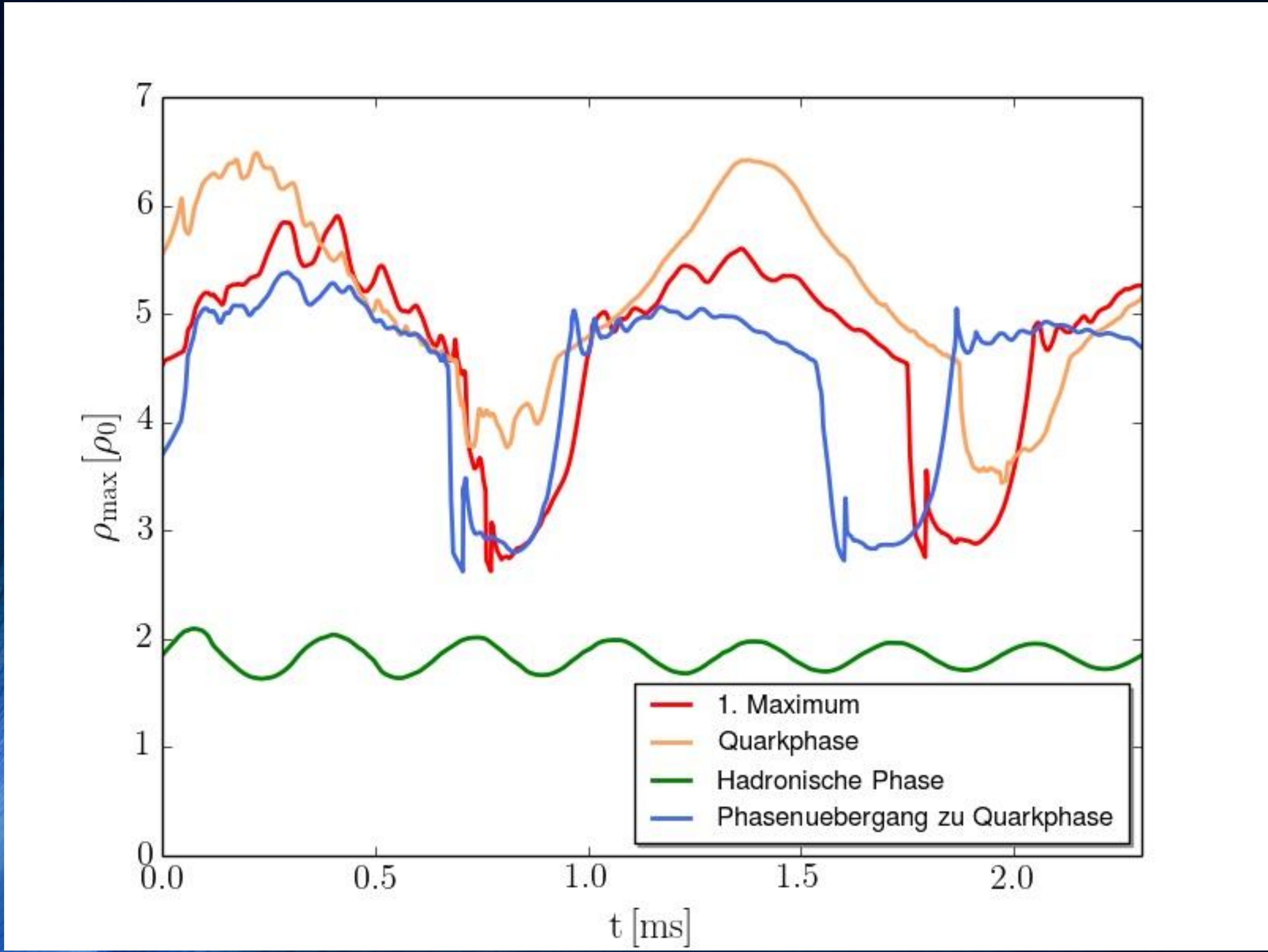
Initial Configuration of the Neutron and Hybrid Stars



The Twin Star Collapse



The Twin Star Collapse



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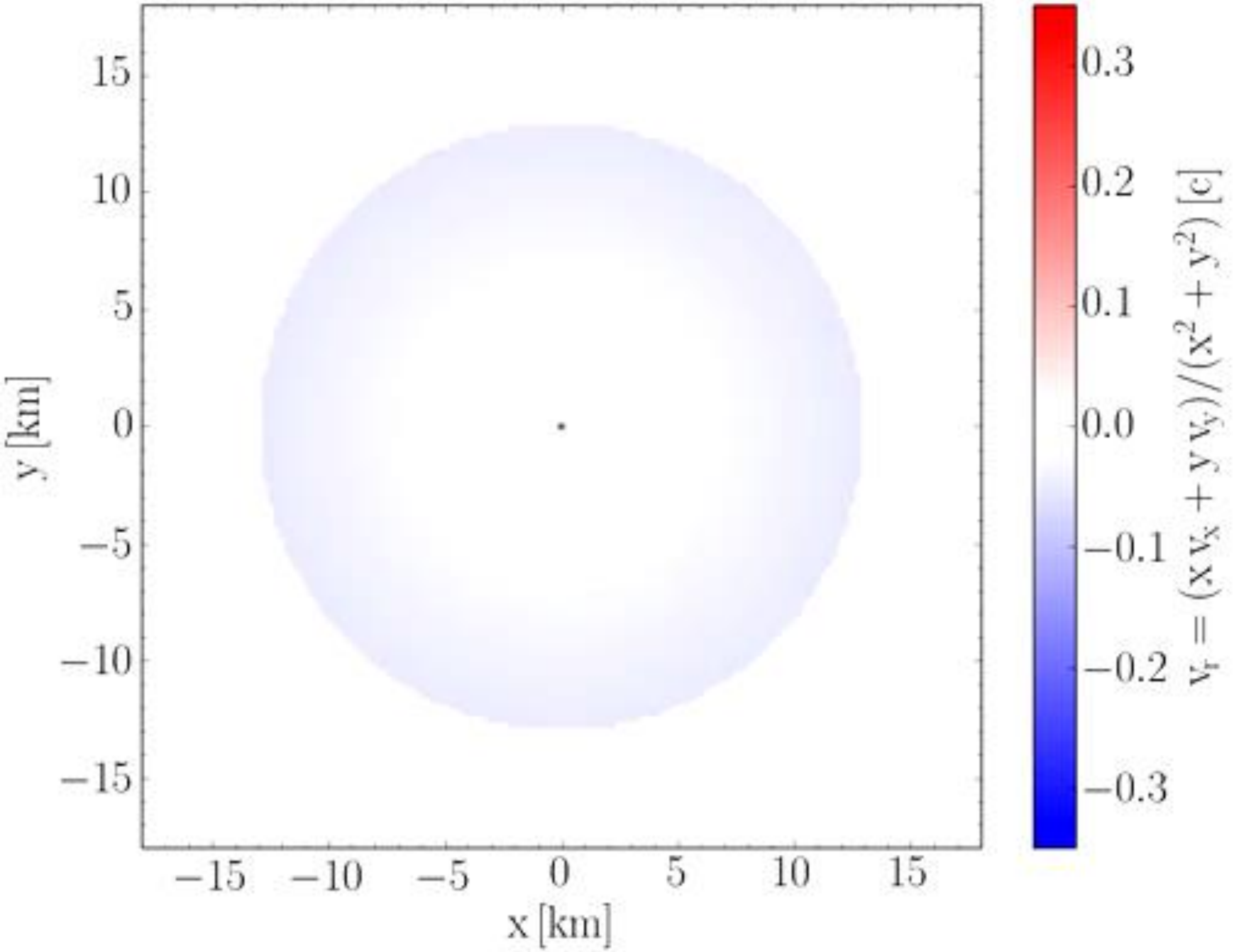
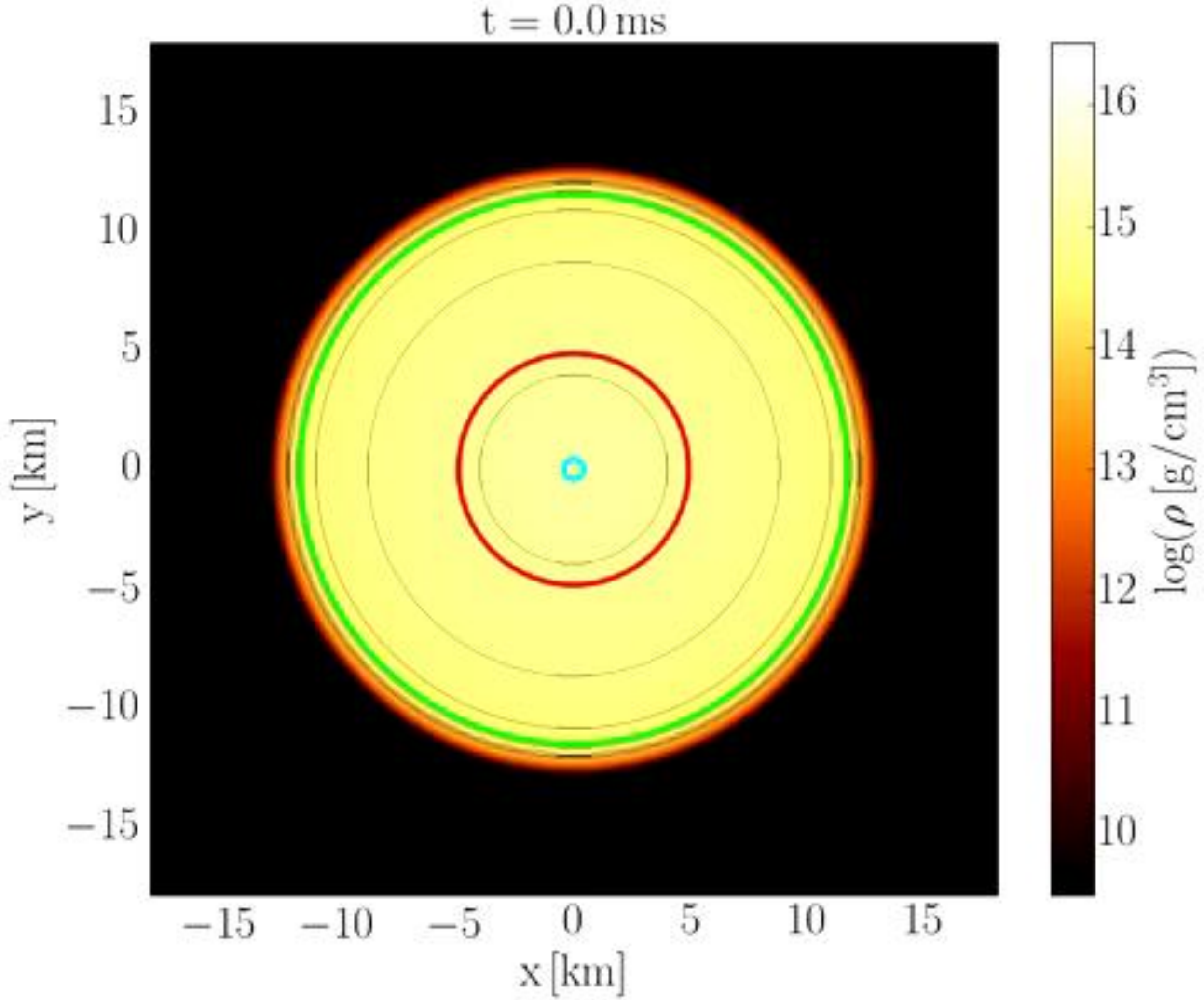
The Twin Star Collapse (red)

Green contour line: Nuclear Matter density
Red contour line: Beginning of PT
Cyan contour line: End of PT

Radial velocity



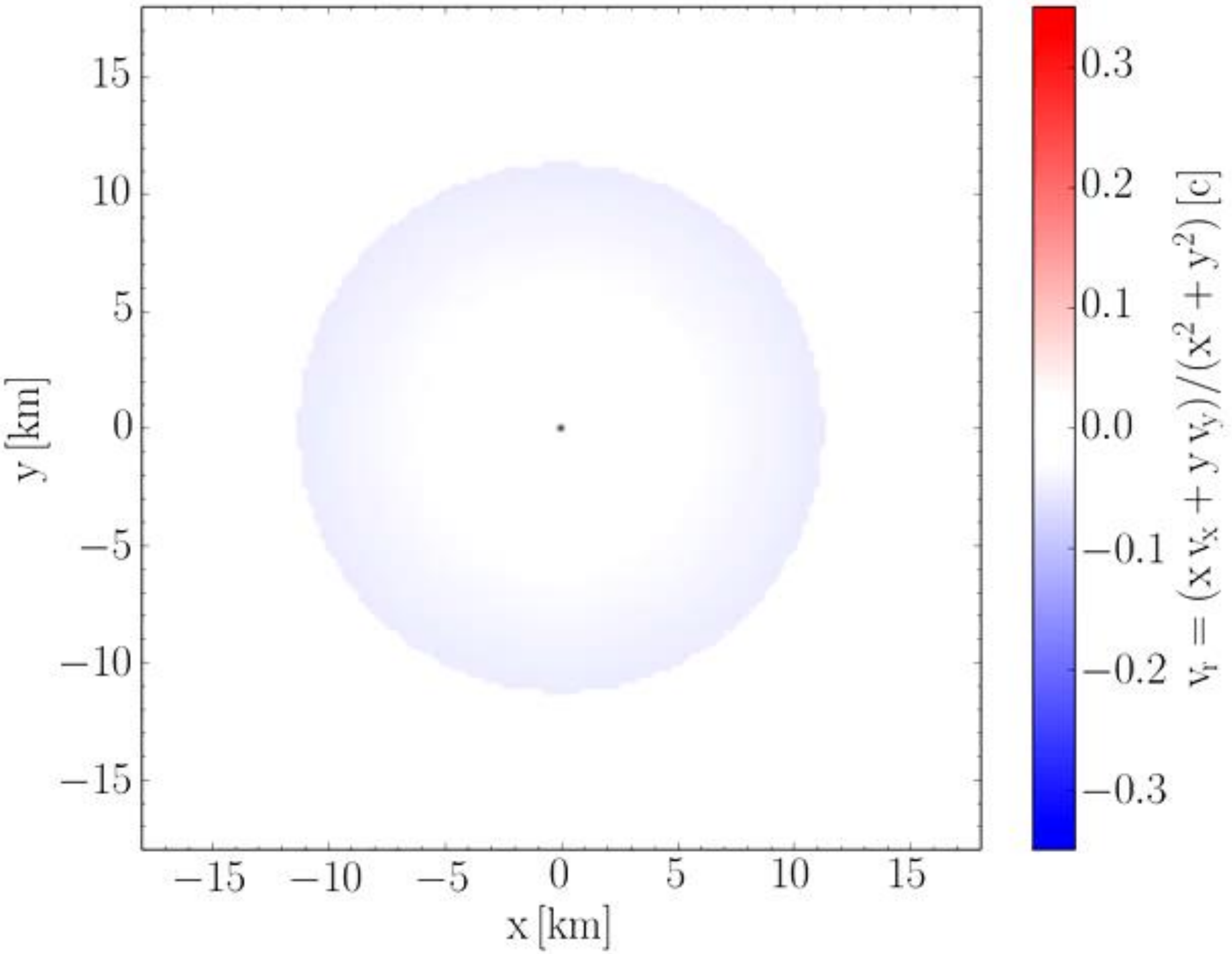
Density



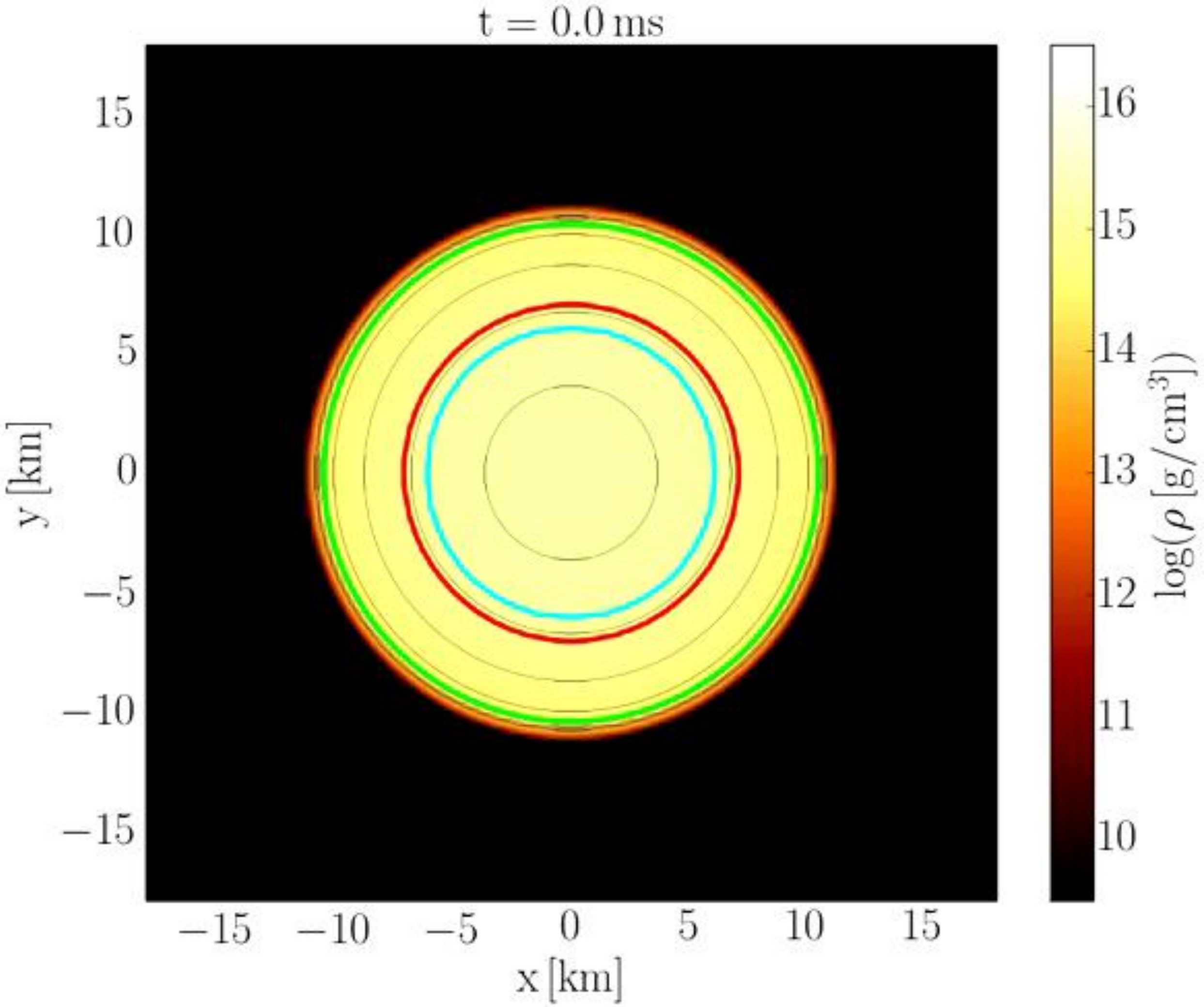
The Twin Star Collapse (brown)

Green contour line: Nuclear Matter density
Red contour line: Beginning of PT
Cyan contour line: End of PT

Radial velocity



Density



Pure Quark Stars including a Chiral Phase Transition

Twin Stars within the SU(3) Chiral Quark-Meson Model

Andreas Zacchi,[1,*] Laura Tolos,[2,3,†] and Jürgen Schaffner-Bielich[1,‡]

[1] *Institut für Theoretische Physik, Goethe Universität Frankfurt, Max von Laue Strasse 1, D-60438 Frankfurt, Germany*

[2] *Institut de Ciencies de l' Espai (IEEC/CSIC), Campus Universitat Autonoma de Barcelona, Carrer de Can Magrans, s/n, E-08193 Bellaterra, Spain*

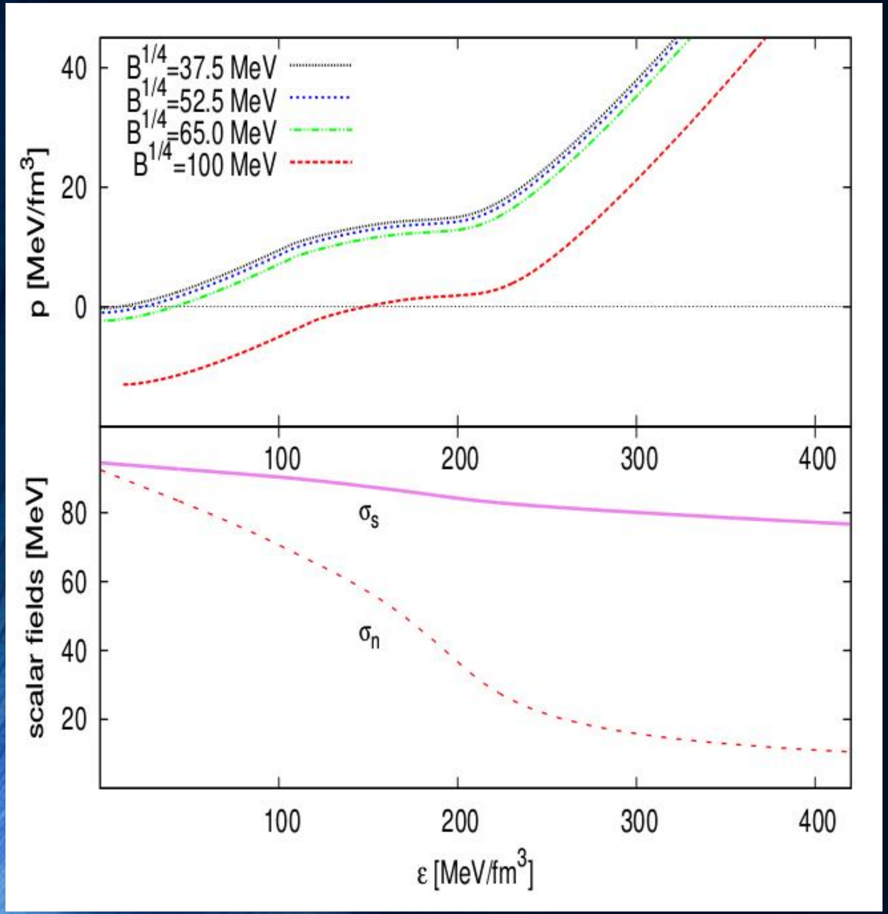
[3] *Frankfurt Institute for Advanced Studies, Goethe Universität Frankfurt, Ruth-Moufang-Str. 1, 60438, Frankfurt am Main, Germany*

(Dated: April 27, 2017)

We present new stable solutions of the Tolman Oppenheimer Volkoff equations for quark stars using a quark matter equation of state based on the SU(3) Quark-Meson model that exhibits the onset of the chiral phase transition. These new solutions appear as two stable branches in the mass-radius relation allowing for so called twin stars, i.e. two stable quark star solutions with the same mass, but distinctly different radii. We find solutions which are compatible with causality, the stability conditions of dense matter, the astrophysical constraints of the rotation of the millisecond pulsar PSR J1748-2446ad and the $2M_\odot$ pulsar mass constraint.

EOS fitted with Piecewise Polytropes

EOSs for different values of the vacuum Pressure (Bag Constant B)



The phase transition to a chirally restored phase

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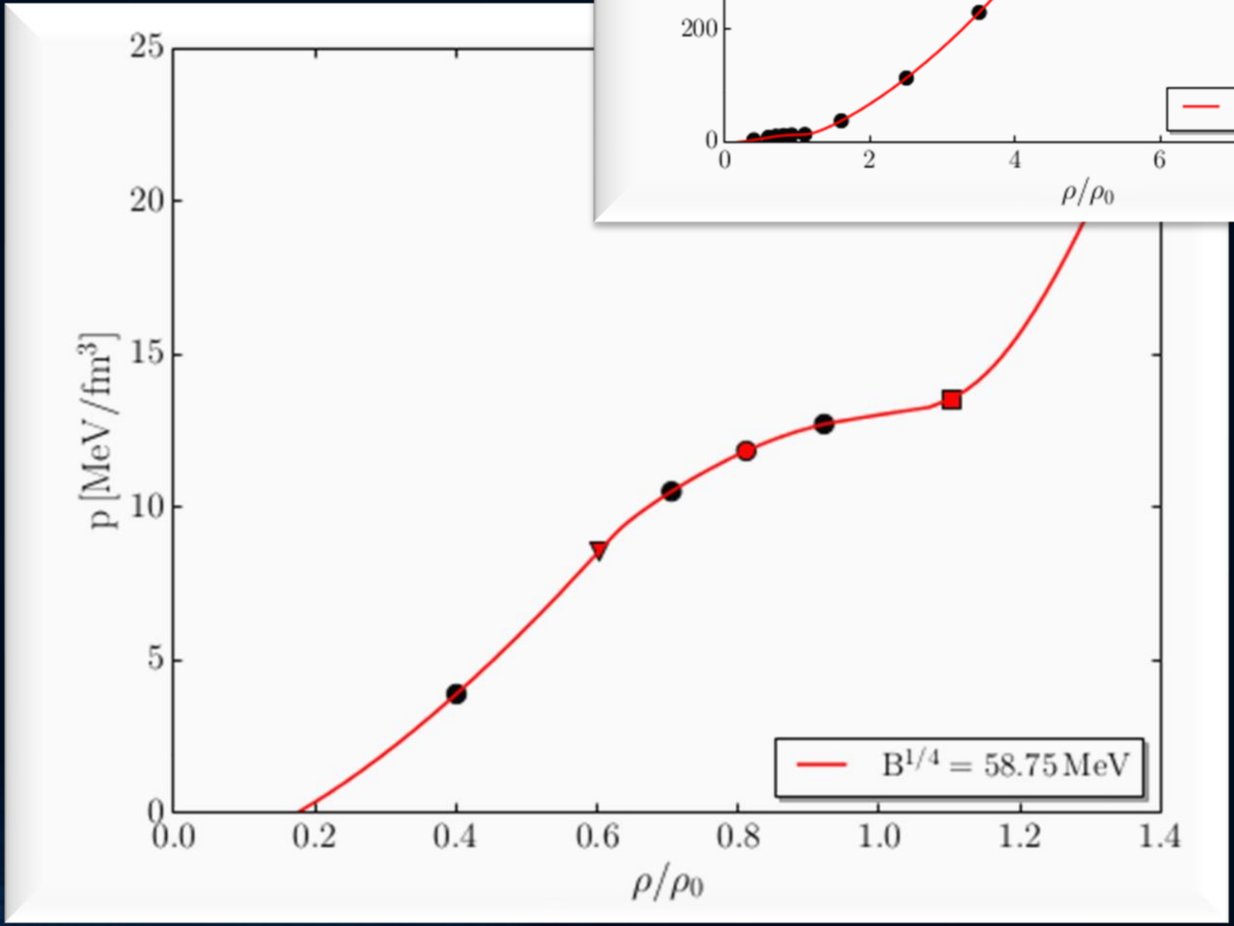
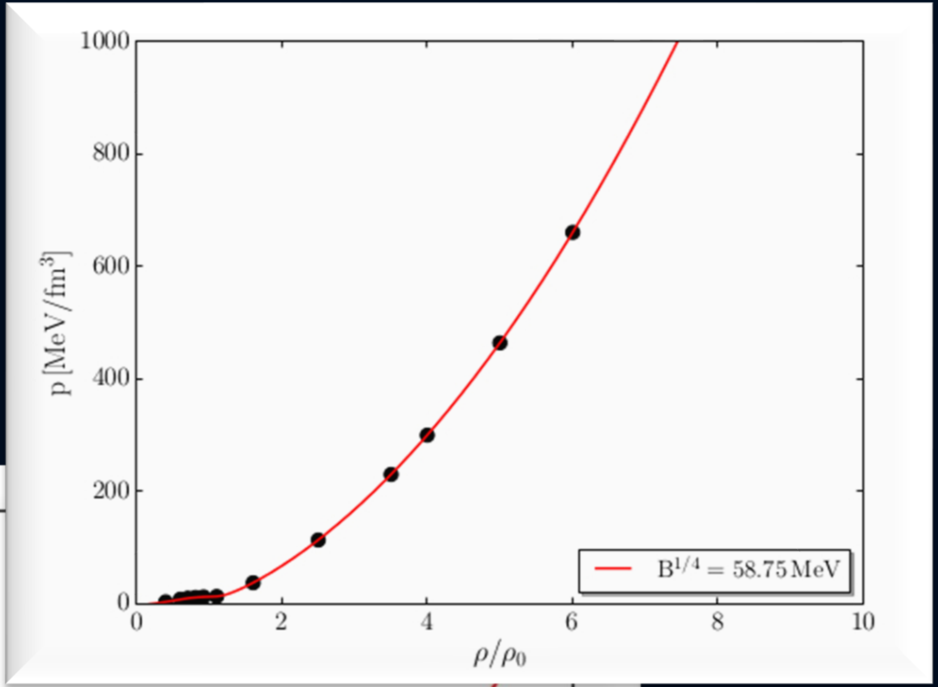
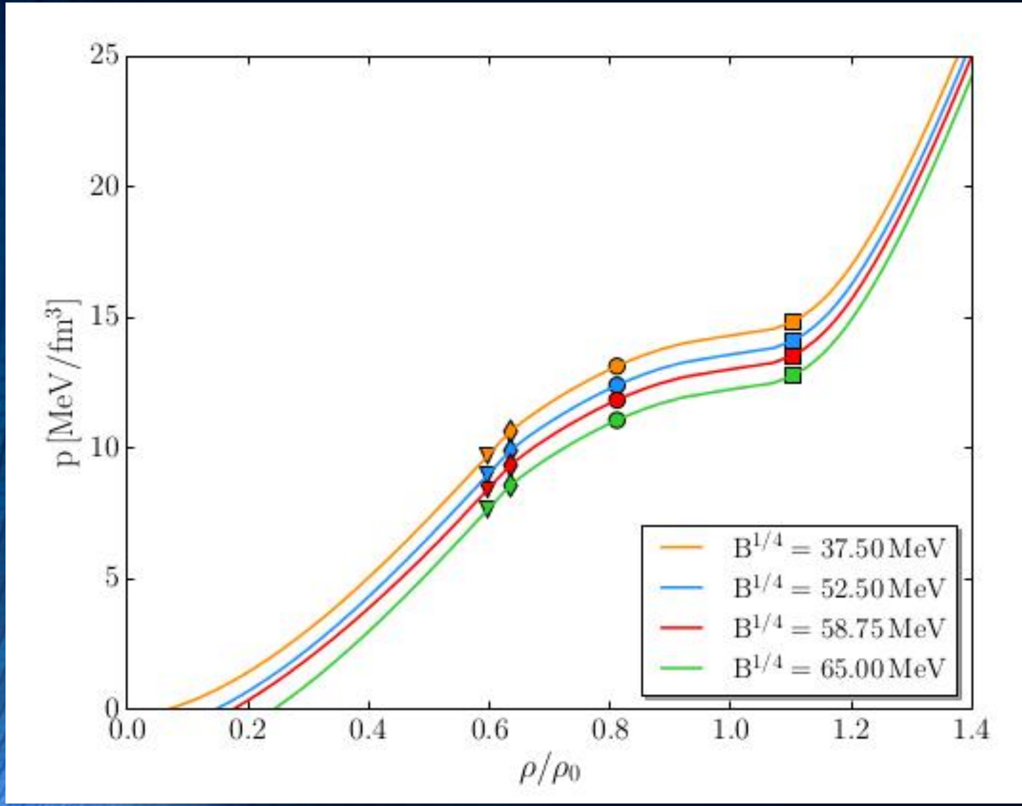
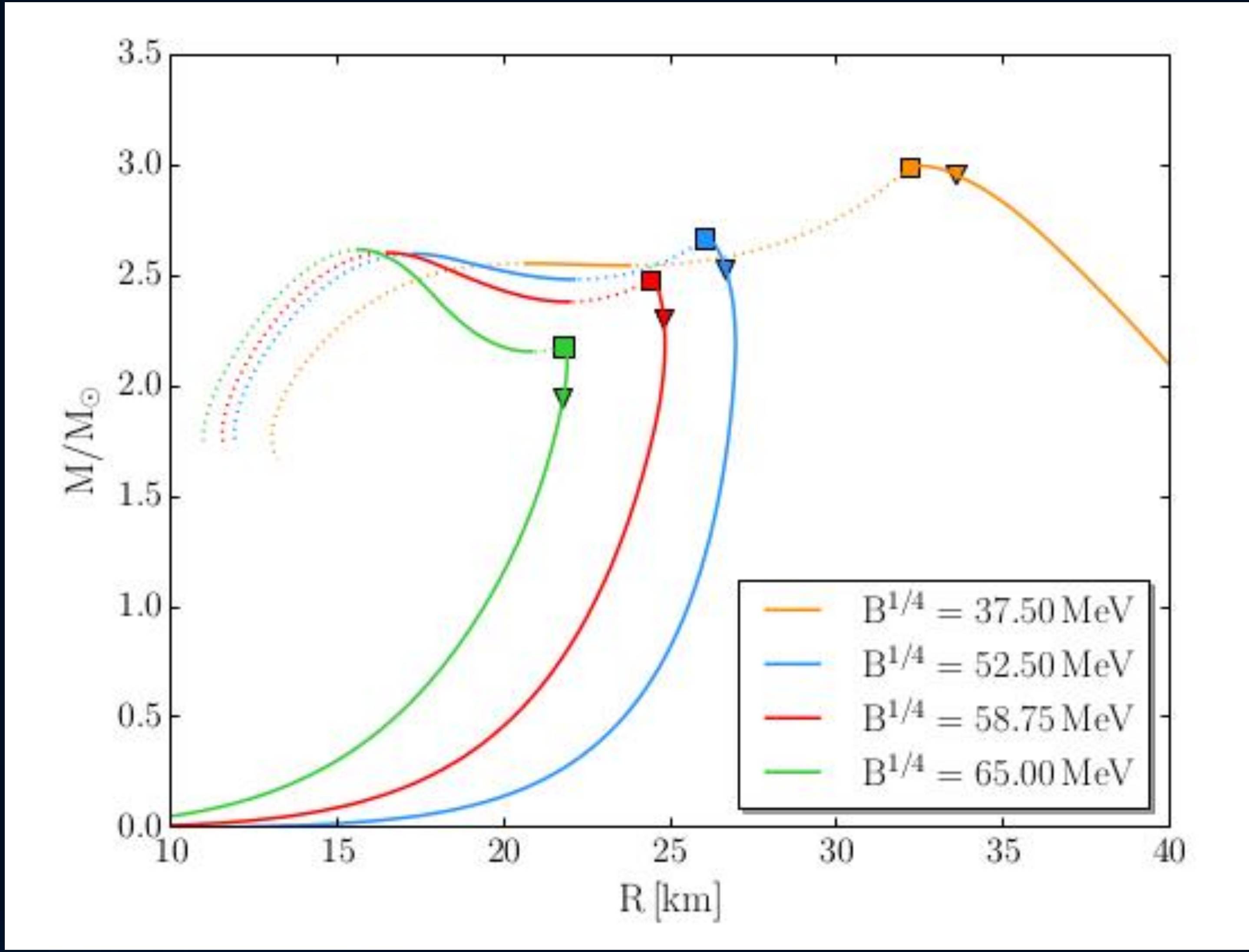


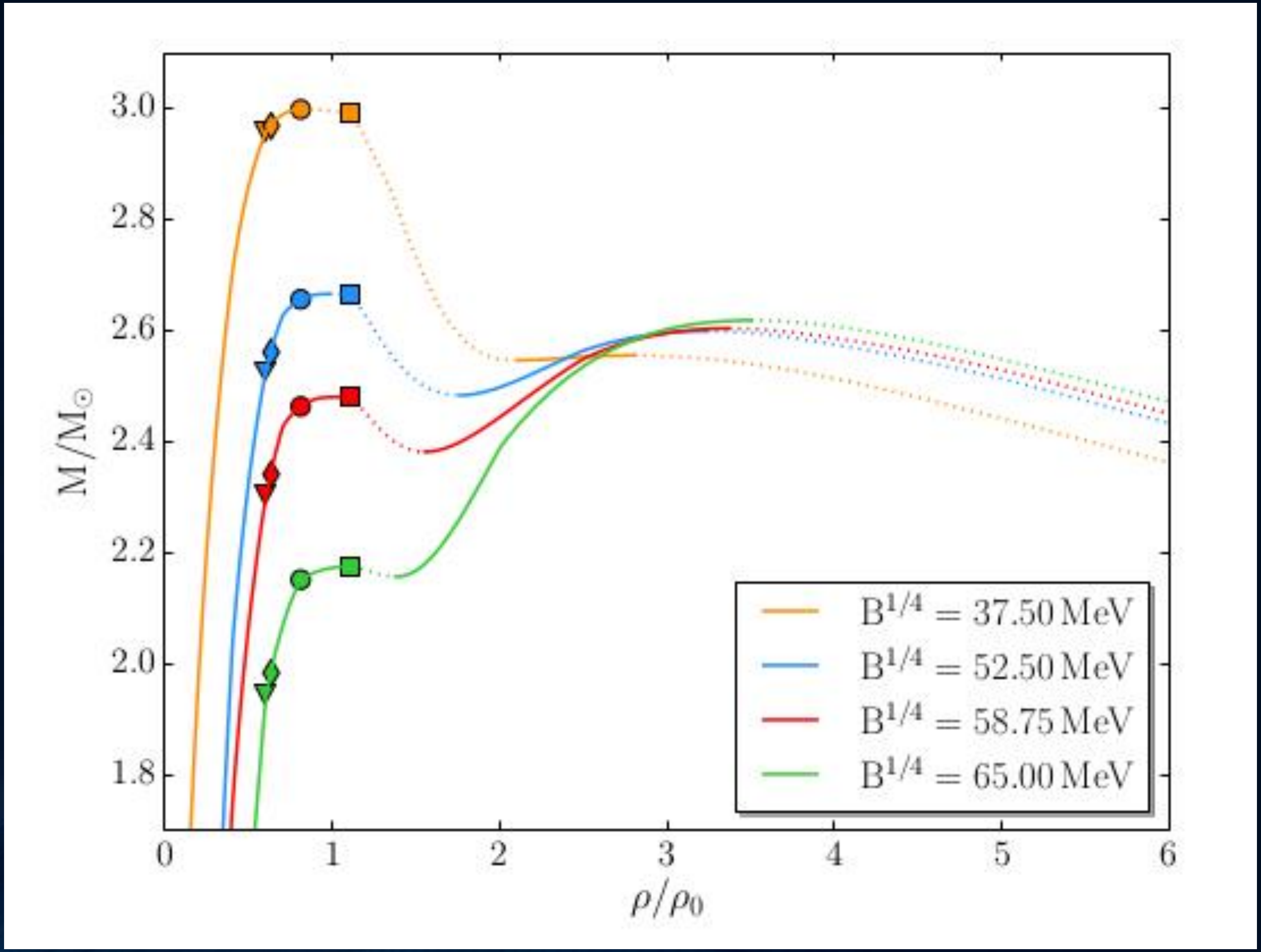


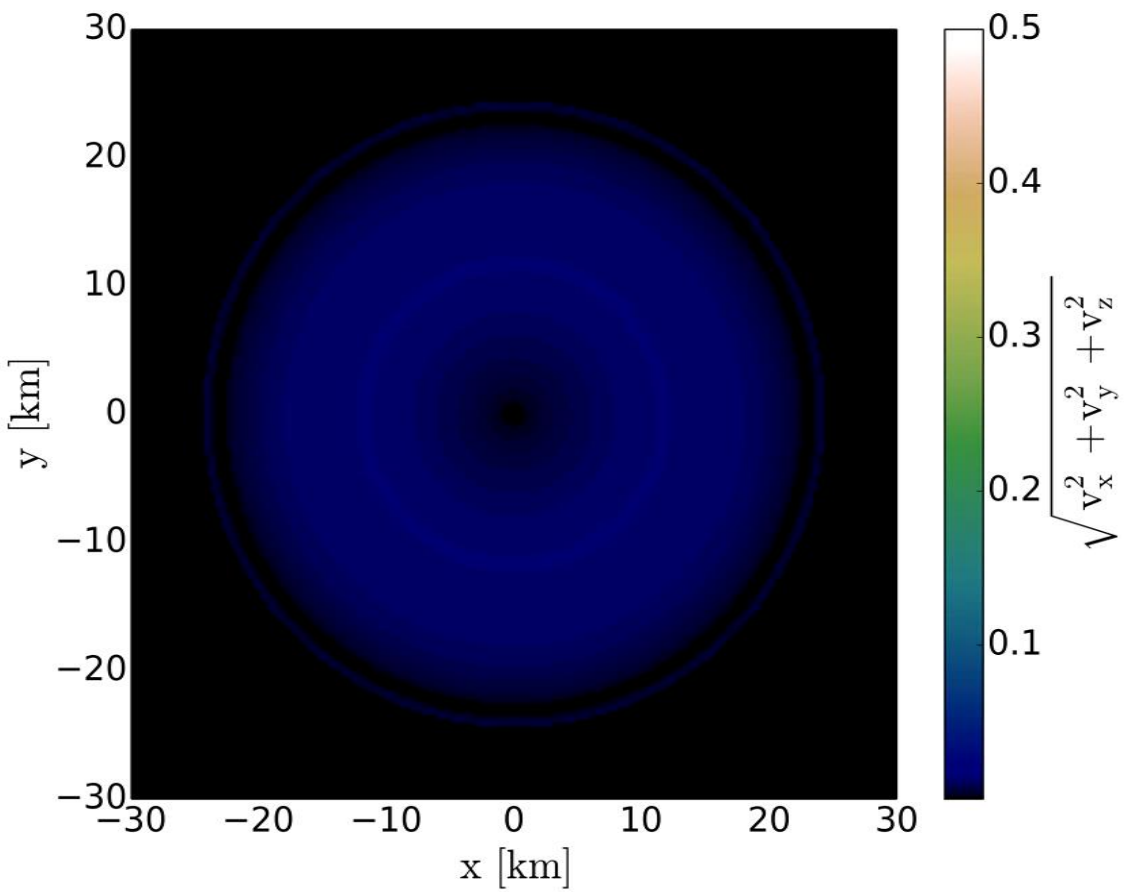
Mass-Radius Relation of TOV Stars

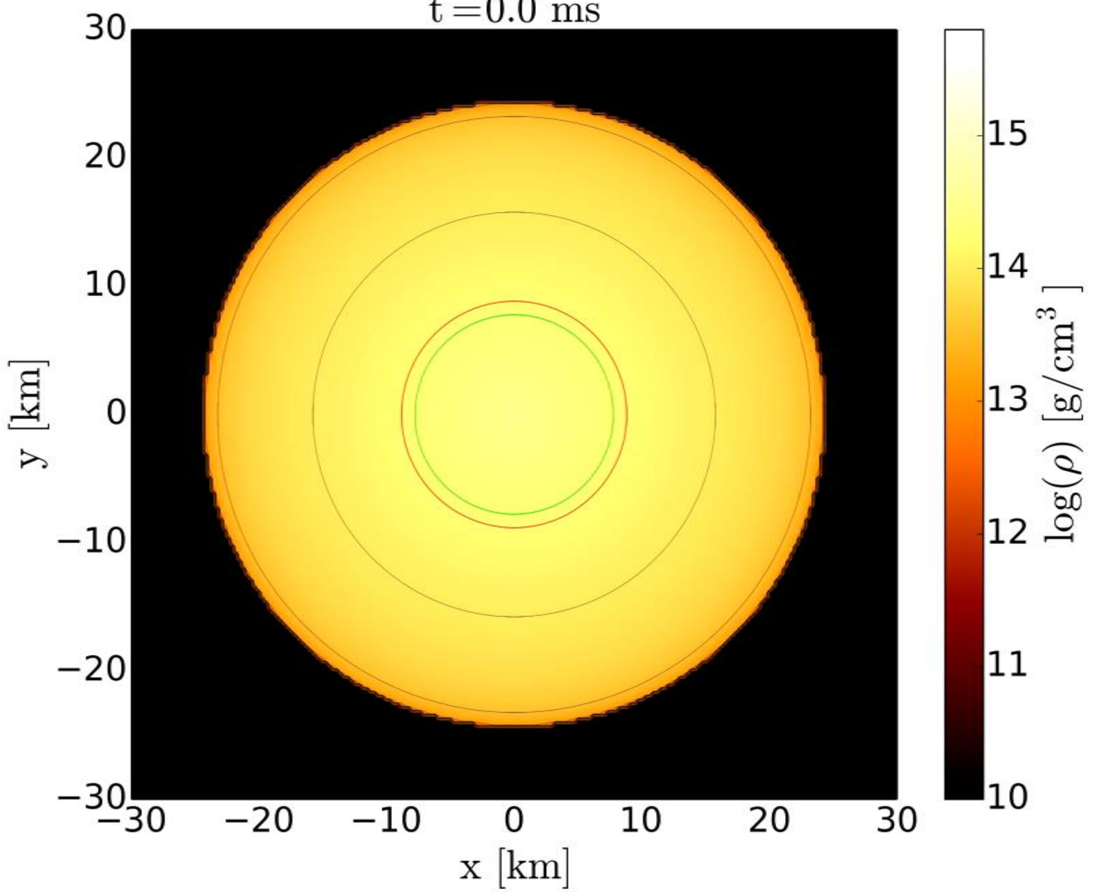




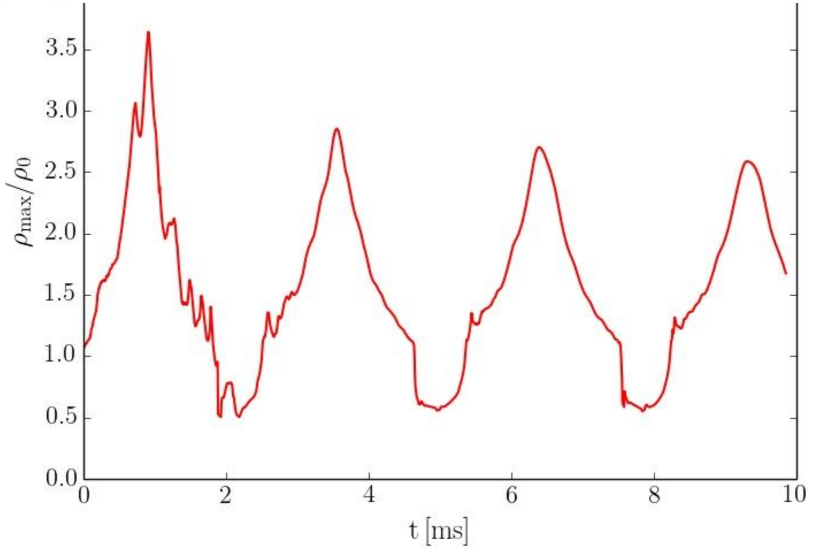
Possibility of Twin Stars in a certain Range of Bag Constant







Twin Star Collapse



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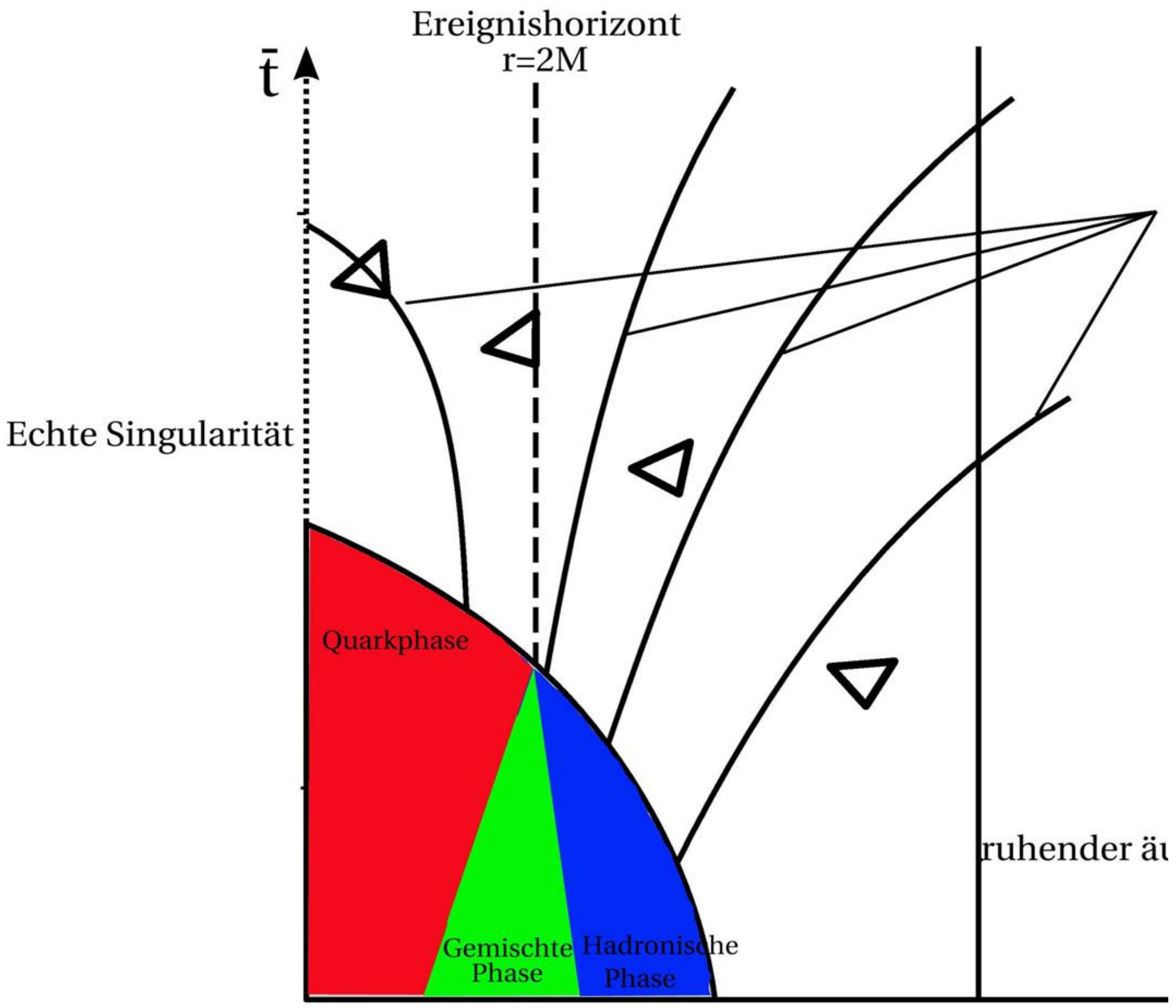
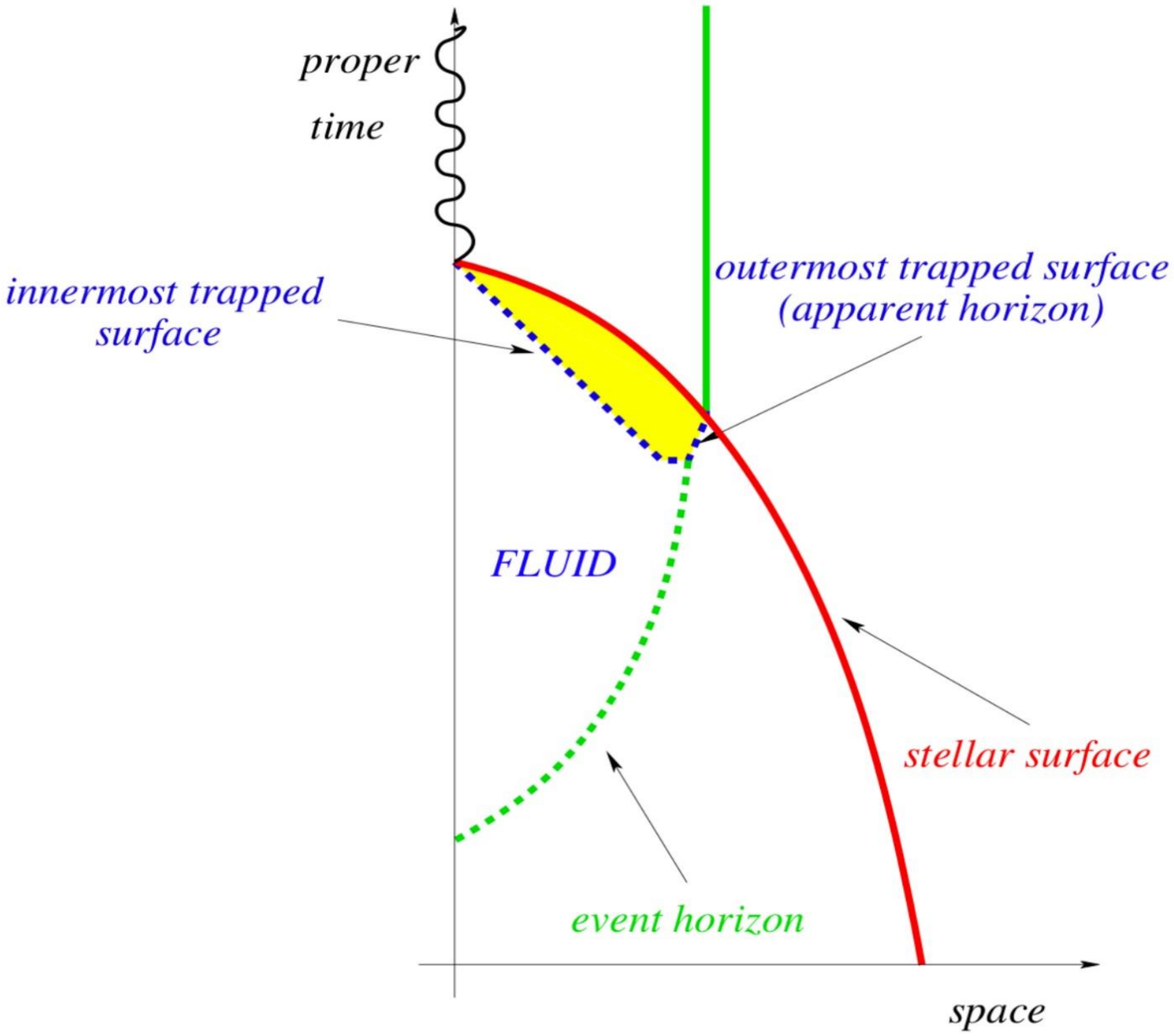
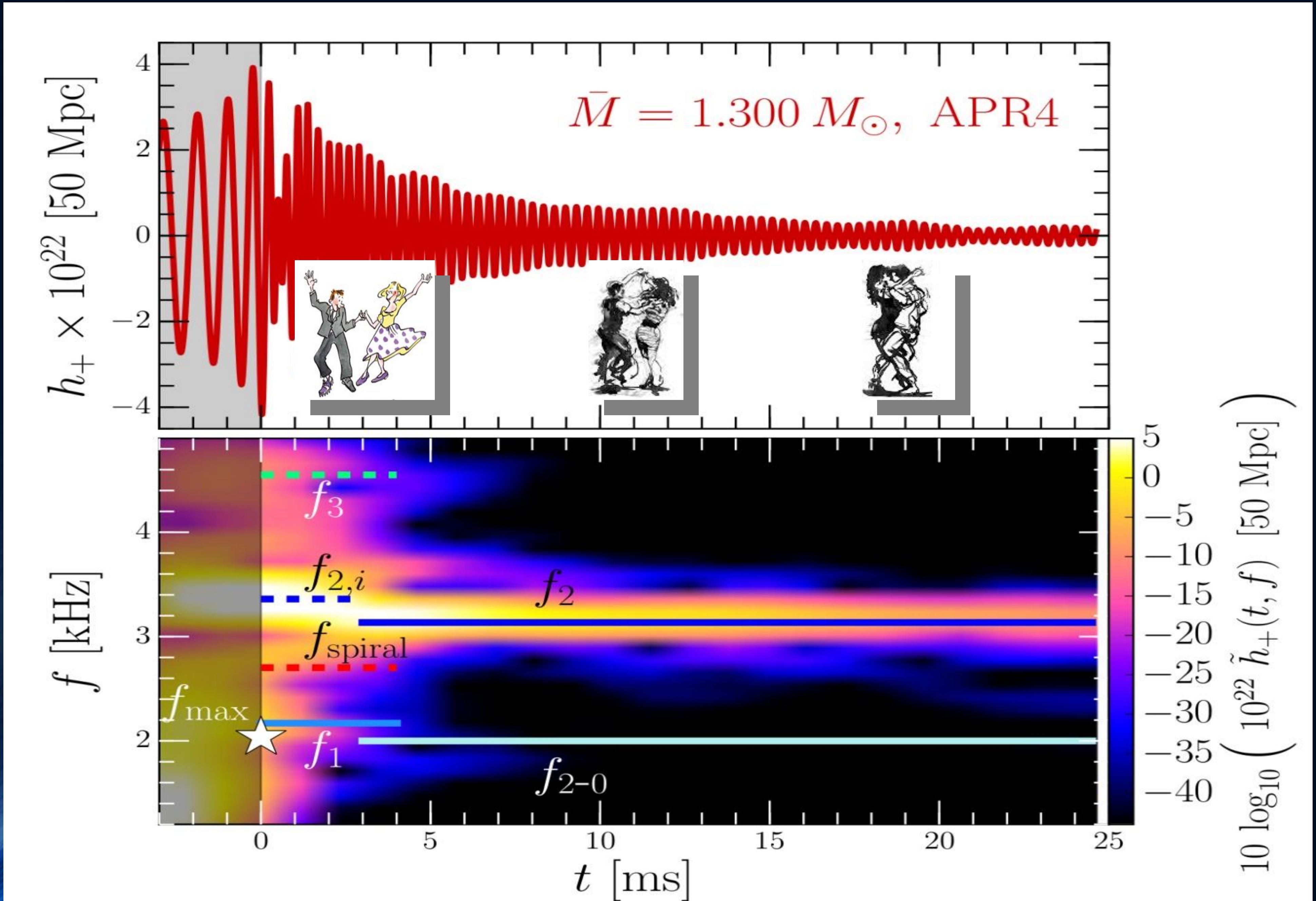
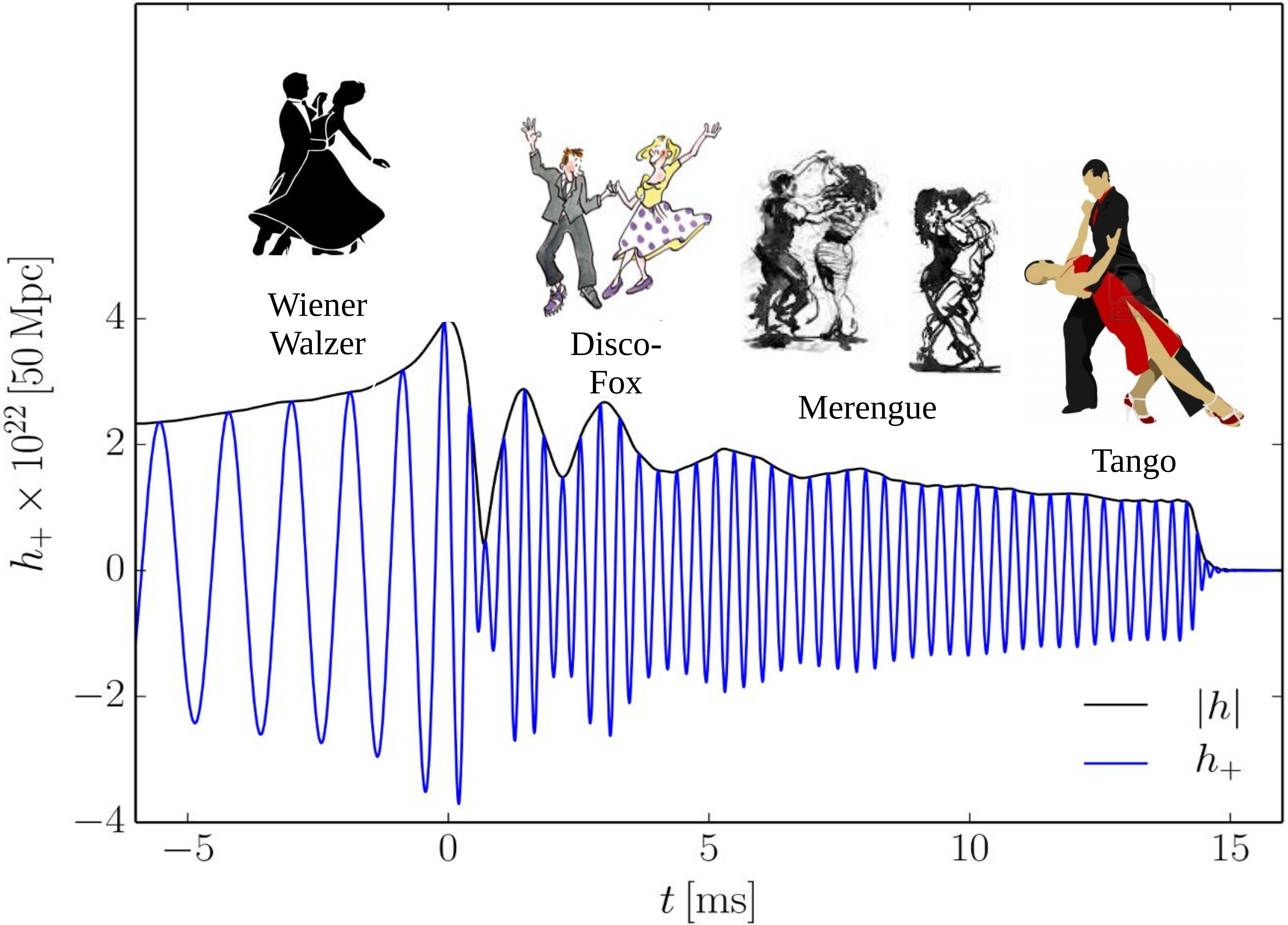
The deconfiened Quark Matter will be Macroscopically Confient by the Event Horizon





The different Phases during the Postmergerphase of the HMNS





Wiener
Walzer
Disco-
Fox
Merengue
Tango
$|h|$
h_+
$h_+ \times 10^{22}\,[50\,\mathrm{Mpc}]$
4
2
0
−2
−4
−5
0
5
10
15
$t\,[\mathrm{ms}]$

Many Thanks to the following Persons

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Mr. Federico Guercilena

Mr. Jens Papenfort

Ms. Natascha Wechselberger

Mr. Elias Most

Prof. Kentaro Takami

and
Ms Zekiye Simay Yilmaz
Ms Christina Mitropoulos