Gravitational Waves and Rotational Properties of Hypermassive Neutron Stars from Binary Mergers

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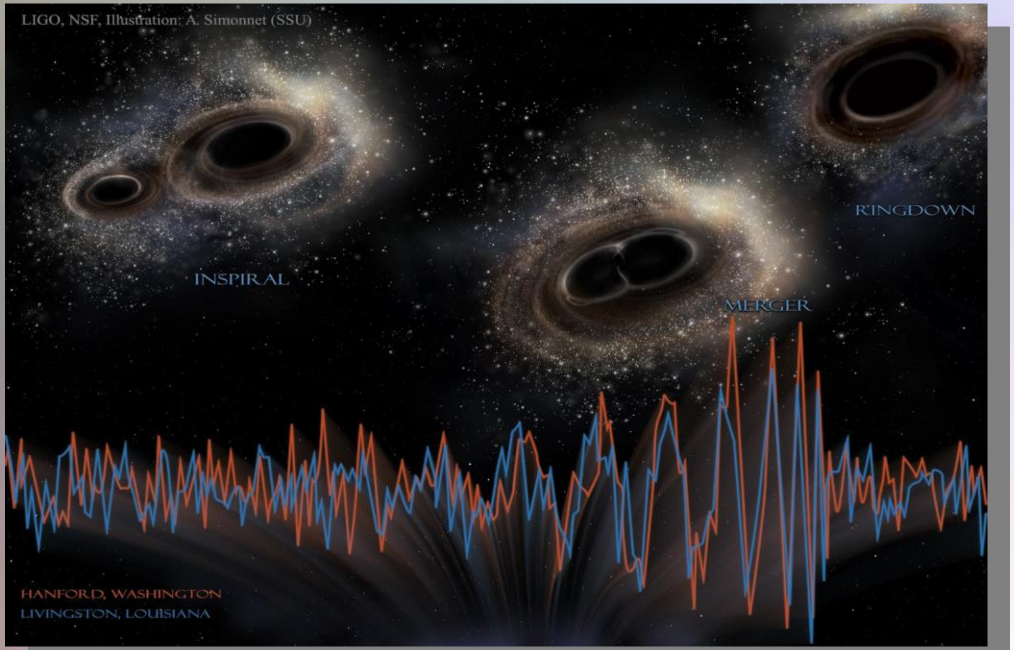
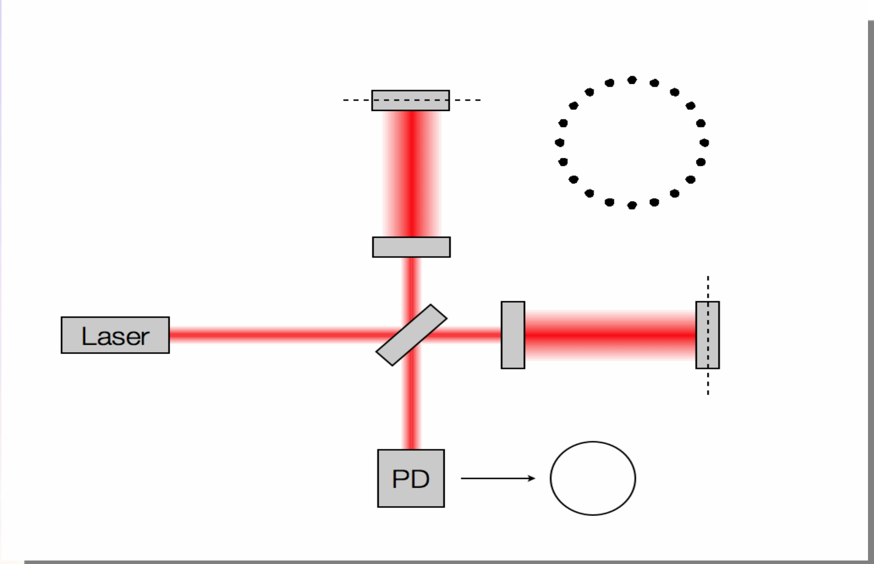
First observation gravitational waves from binary black hole merger by LIGO

GW150914

Merger of two black holes of around 36 and 29 solar masses

Distance: 410 Mpc (1340 million Ly)

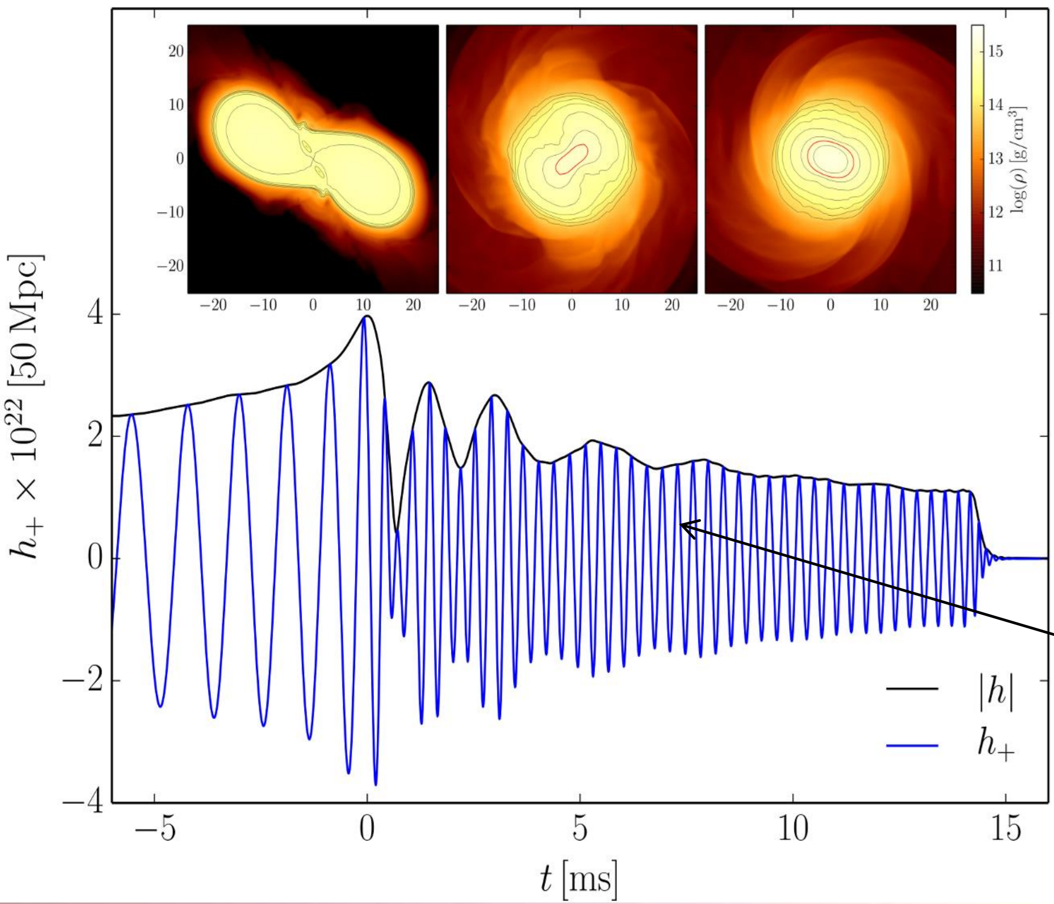




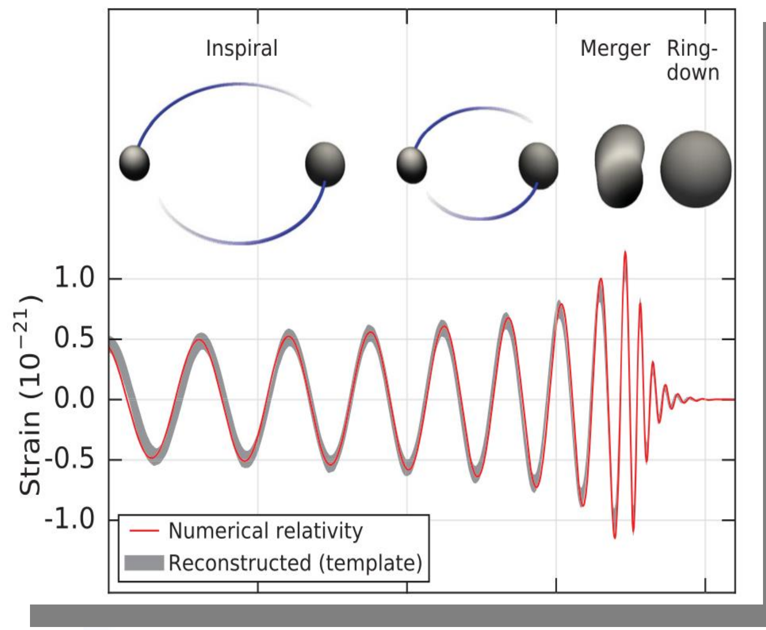
Credit: Les Wade from Kenyon College.

Gravitational Waves from Binary Neutron Star Mergers

Neutron star merger (Simulation)

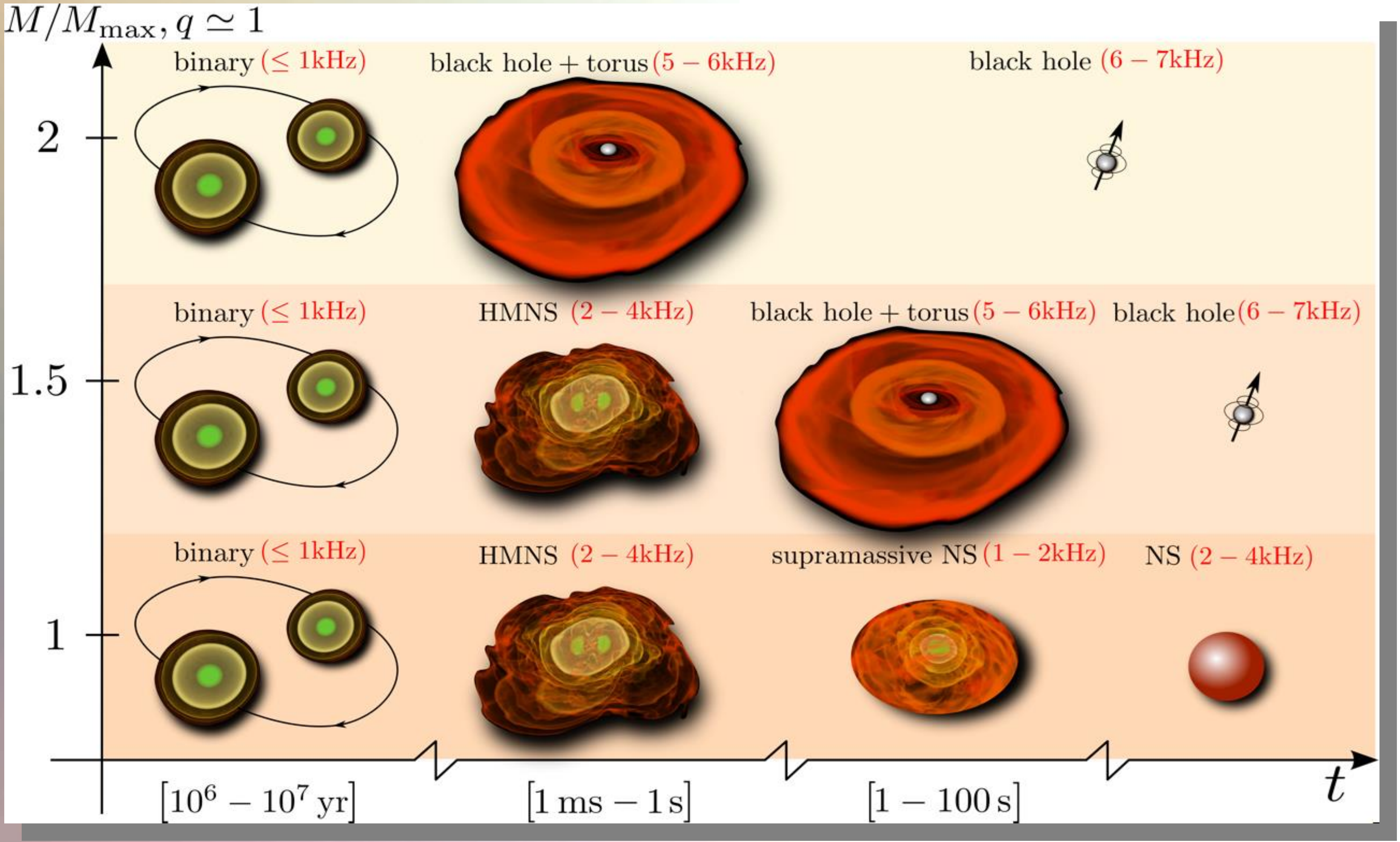


Merger of two Black Holes



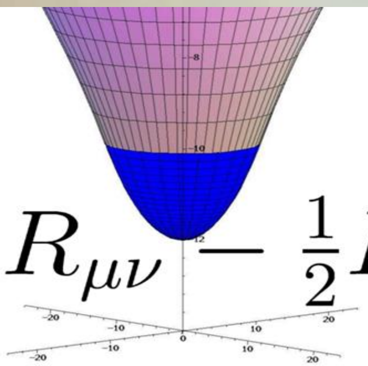
<u>Main Difference:</u>
Neutron star mergers could have a ***post-merger phase***

The Neutron Star Merger Product

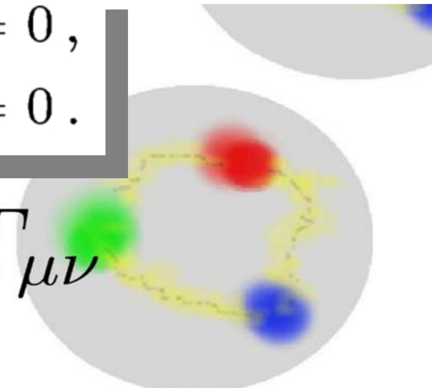


Relativistic Hydrodynamics and Numerical General Relativity

The time evolution of a merger scenario of a binary neutron star system requires the (3+1)-split of the Einstein- and hydrodynamic equations

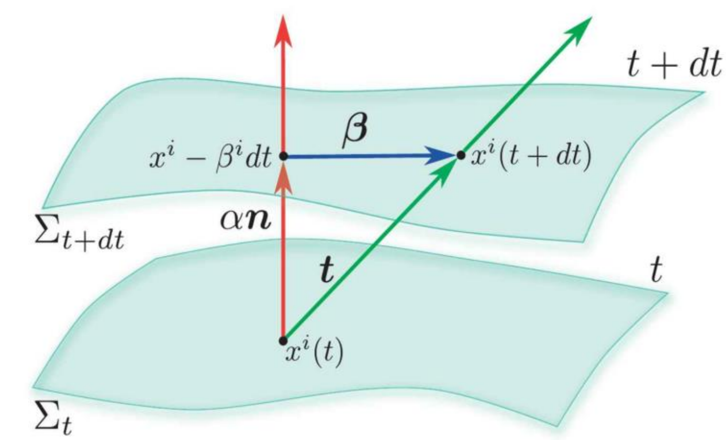


$$\nabla_\mu(\rho u^\mu) = 0\,,$$
$$\nabla_\nu T^{\mu\nu} = 0\,.$$



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

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



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

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

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

The Equation of State and the QCD Phase Diagram

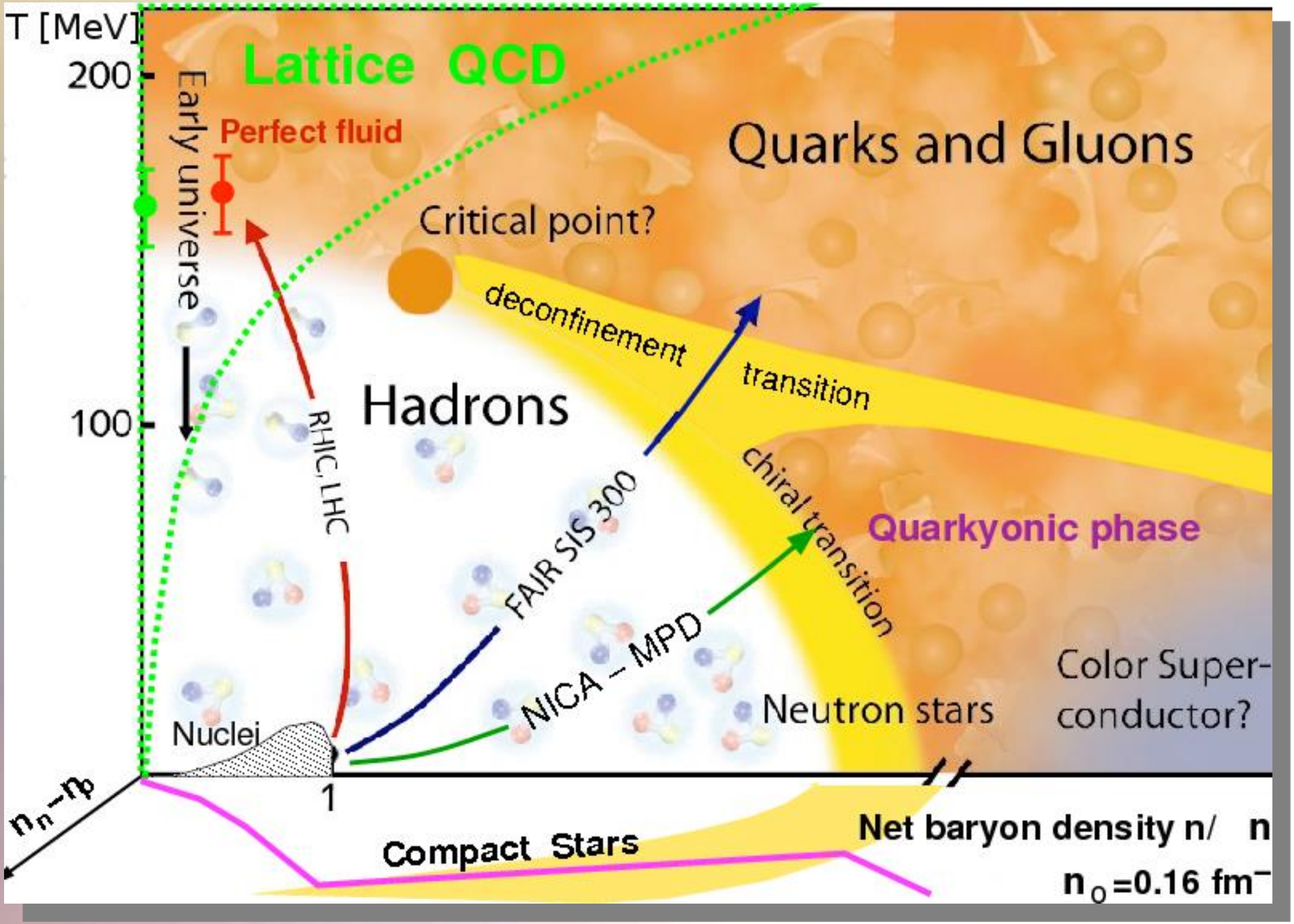
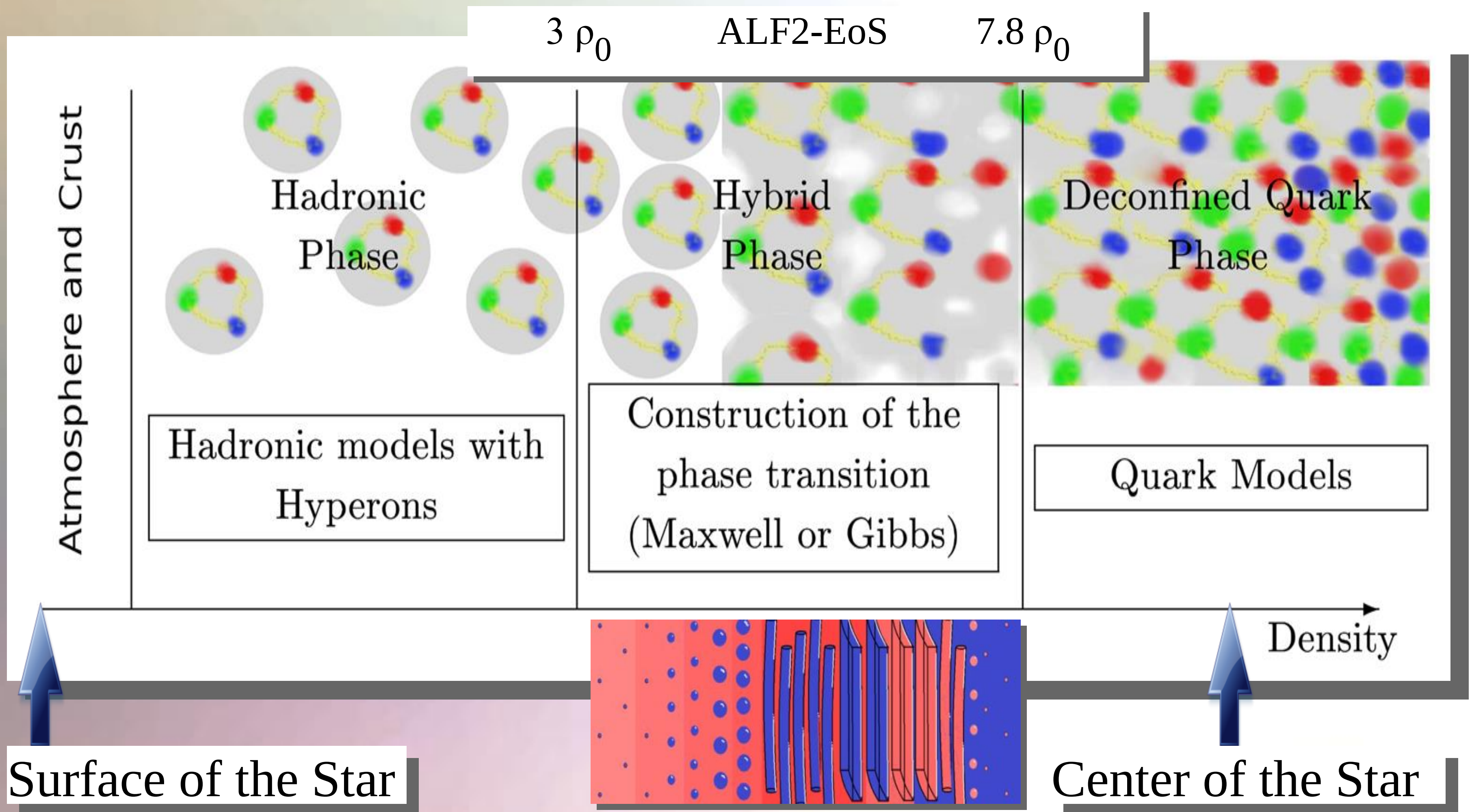


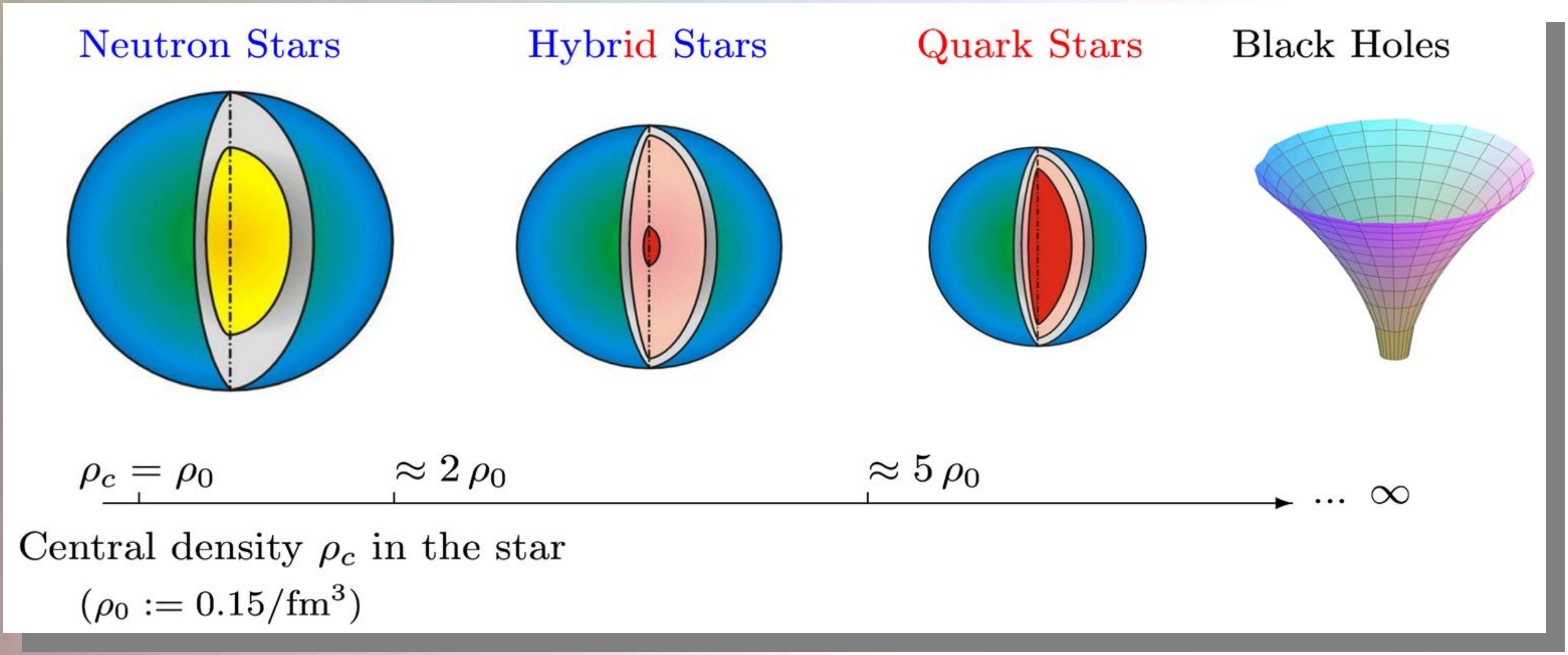
Image from http://inspirehep.net/record/823172/files/phd_qgp3D_quarkyonic2.png

The Hadron-Quark Phase Transition and the Interior of a Hybrid Star



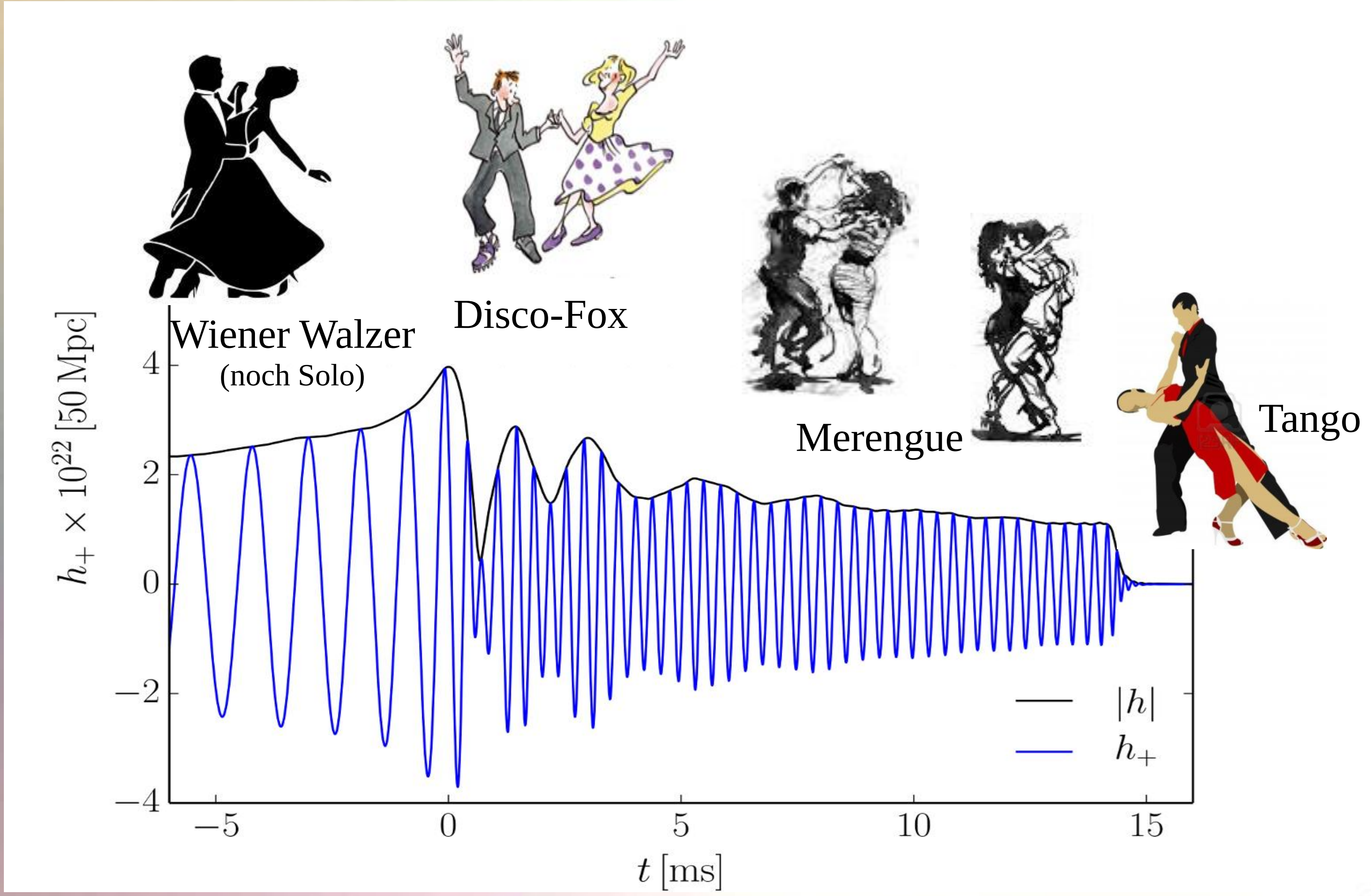
The Compact Star Zoo

Depending on the model used, the compact star zoo consists of different inhabitants: e.g. neutron stars with and without hyperons, quark stars and strange quark stars, hybrid stars with color superconducting quark matter, hybrid stars with Bose-Einstein condensates of antikaons.



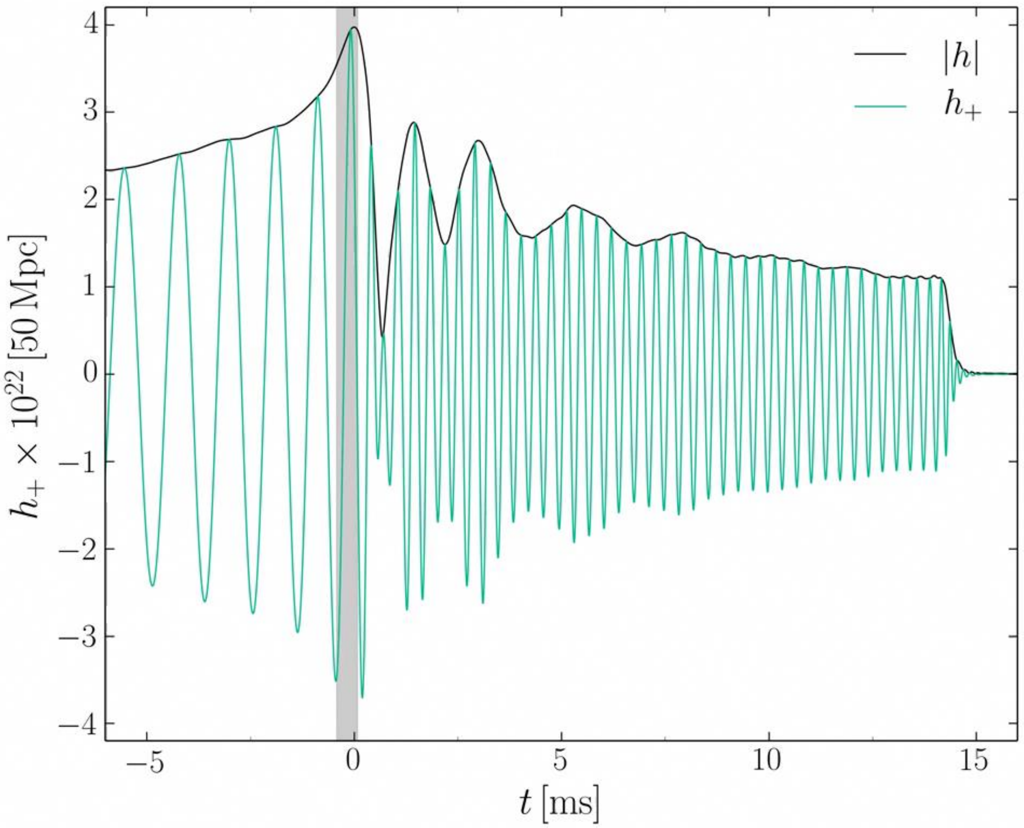

8.5
Density
14
lg(rho) [g/cm^3]
Credits:
Cosima Breu, David Radice and Luciano Rezzolla
0
Temperature
50
T [MeV]

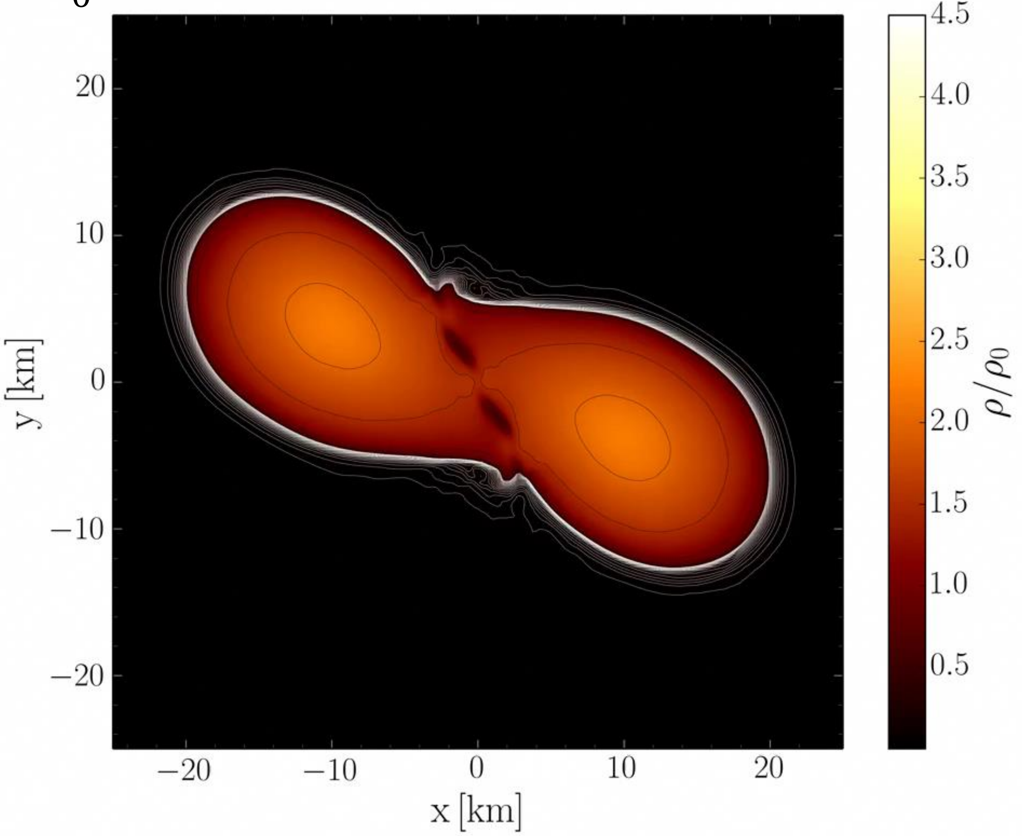
The Phases of a Binary Neutron Star Merger as a Mixture of different Ballroom Dances



Evolution of the Density Distribution

ALF2-EOS; mixed phase region starts at $3\rho_0$ (indicated with a read contour line)

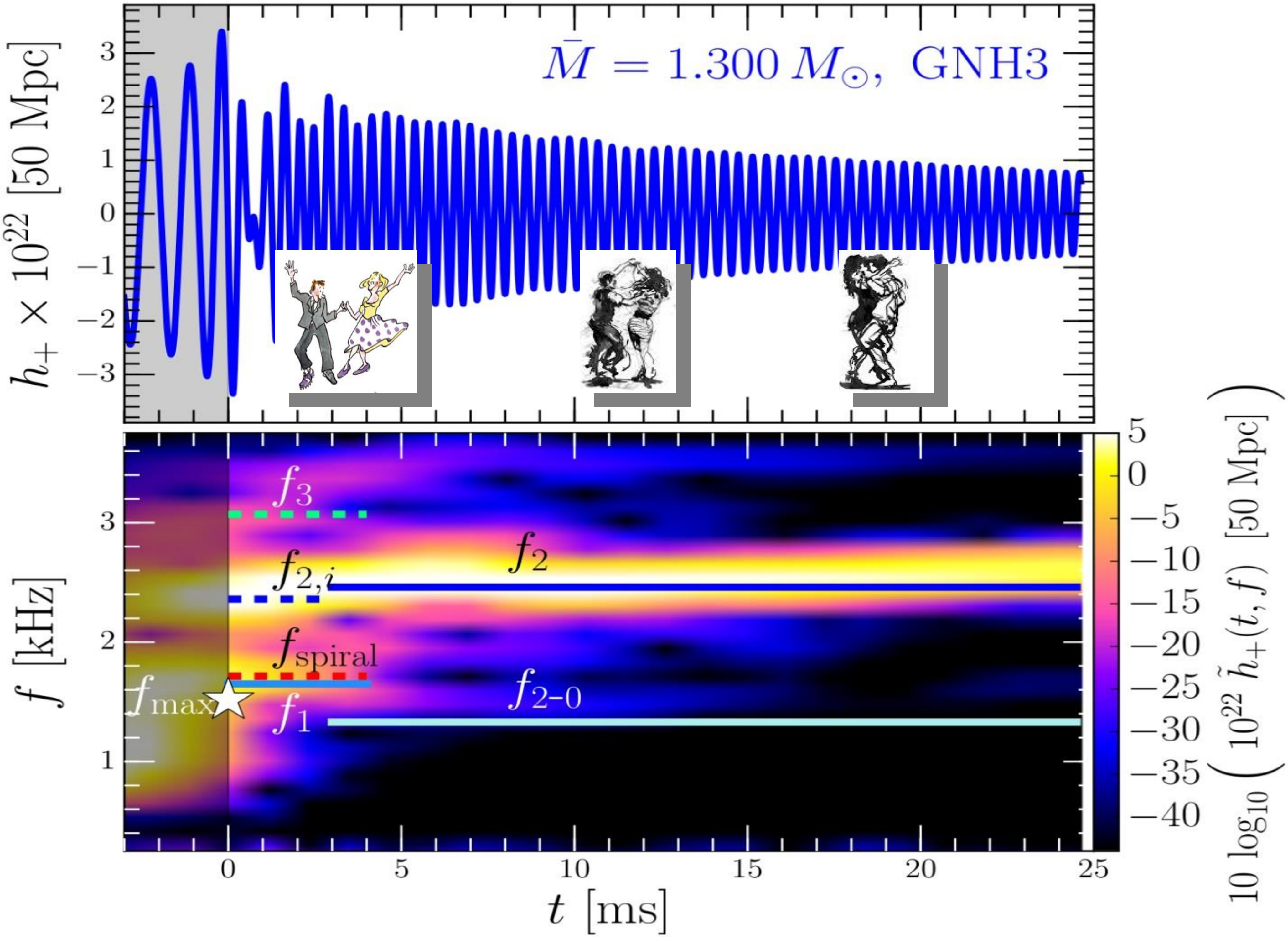




Gravitational wave amplitude
at a distance of 50 Mpc

Rest mass density distribution ρ(x,y)
in the equatorial plane

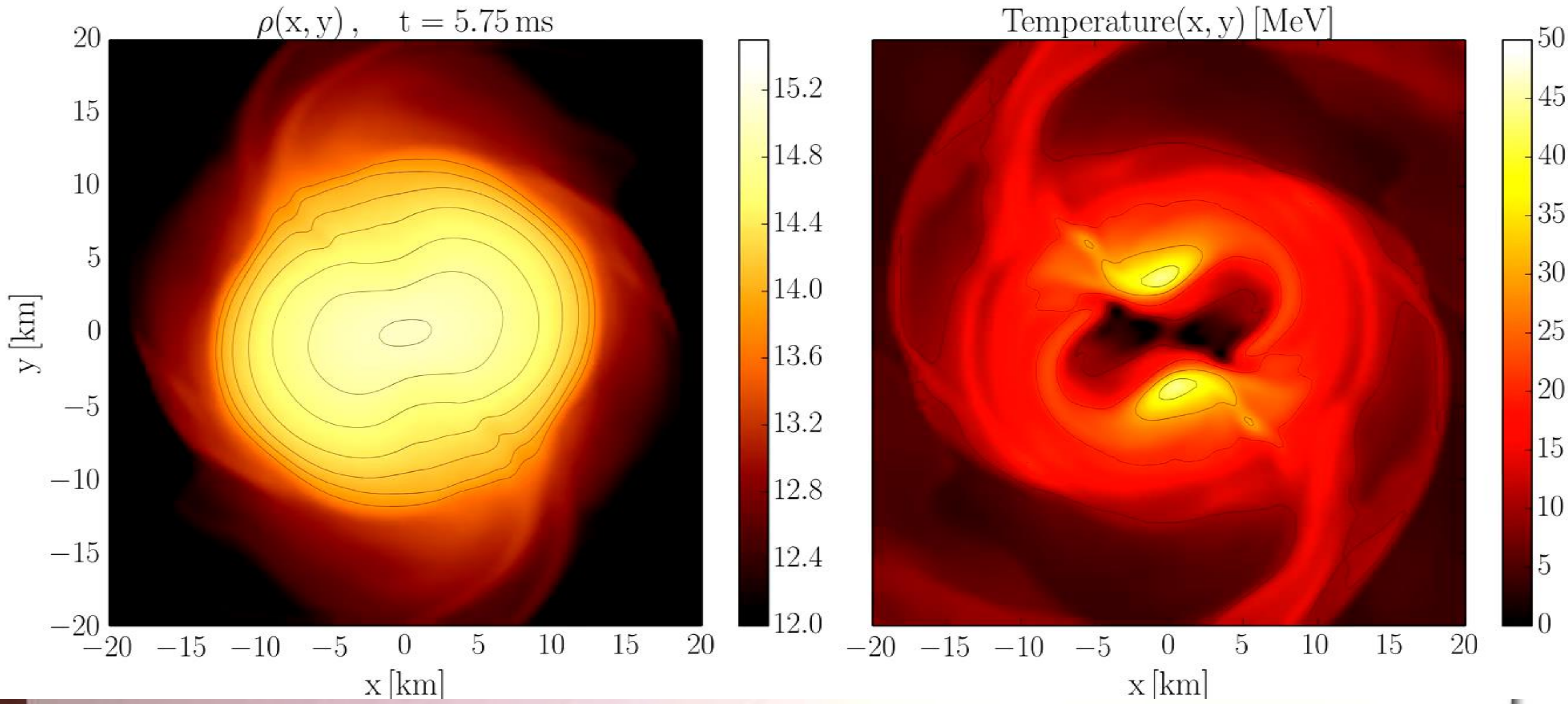
in units of the nuclear matter density ρ_0



$\bar{M} = 1.300\ M_\odot$, GNH3
$h_+ \times 10^{22}$ [50 Mpc]
f_3
$f_{2,i}$
f_2
$f_{\rm spiral}$
$f_{\rm max}$
$f_{2\text{-}0}$
f_1
f [kHz]
t [ms]
$10\log_{10}\left(10^{22}\,\tilde{h}_+(t,f)\right)$ [50 Mpc]

Evolution of the Temperature Distribution

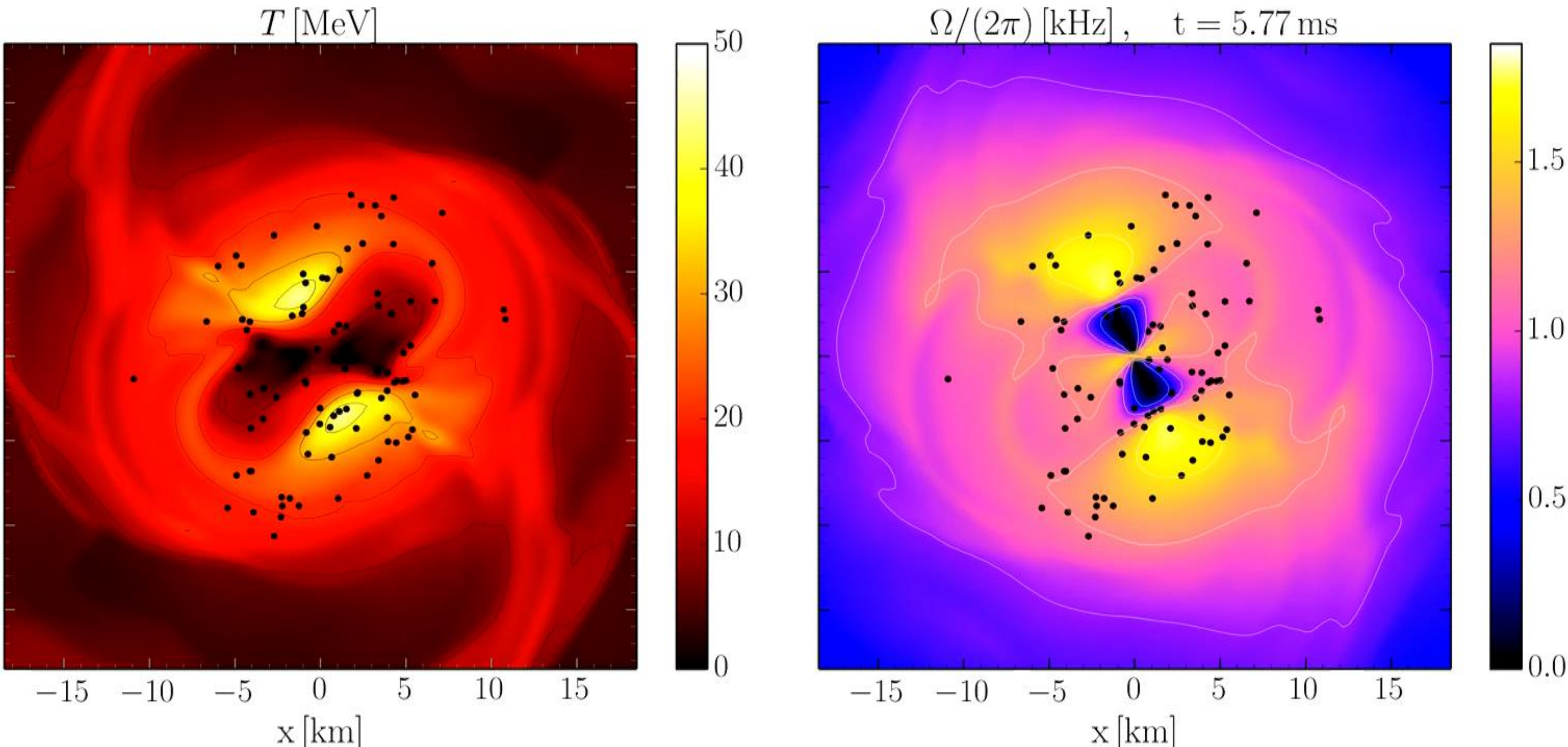
LS220-EOS:
Density and temperature dependent EOS
No hadron-quark phase transition implemented (only n, p, e)



Temperature Distribution and HMNS Rotation Profile

Visualisation in a frame which is corotating with the HMNS
Tracer particles: Trajectories of fluid cells advected in the flow

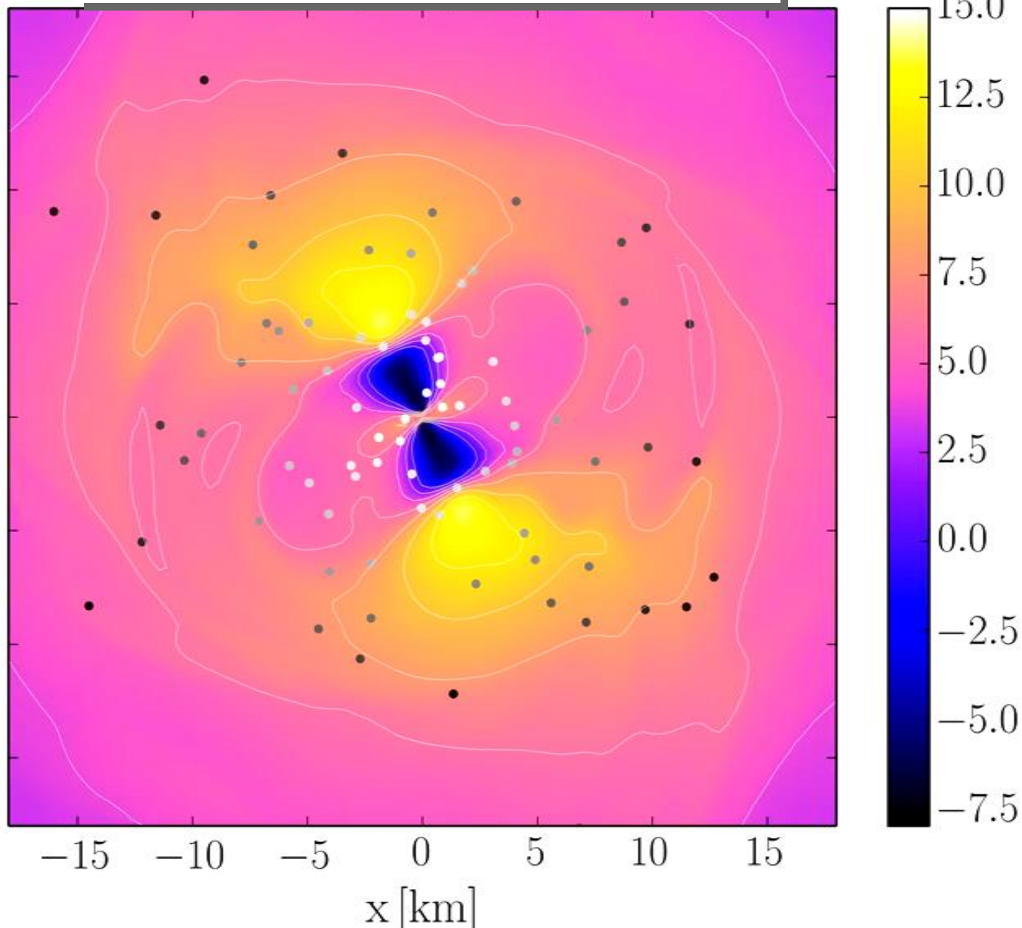
Temperature | Angular velocity



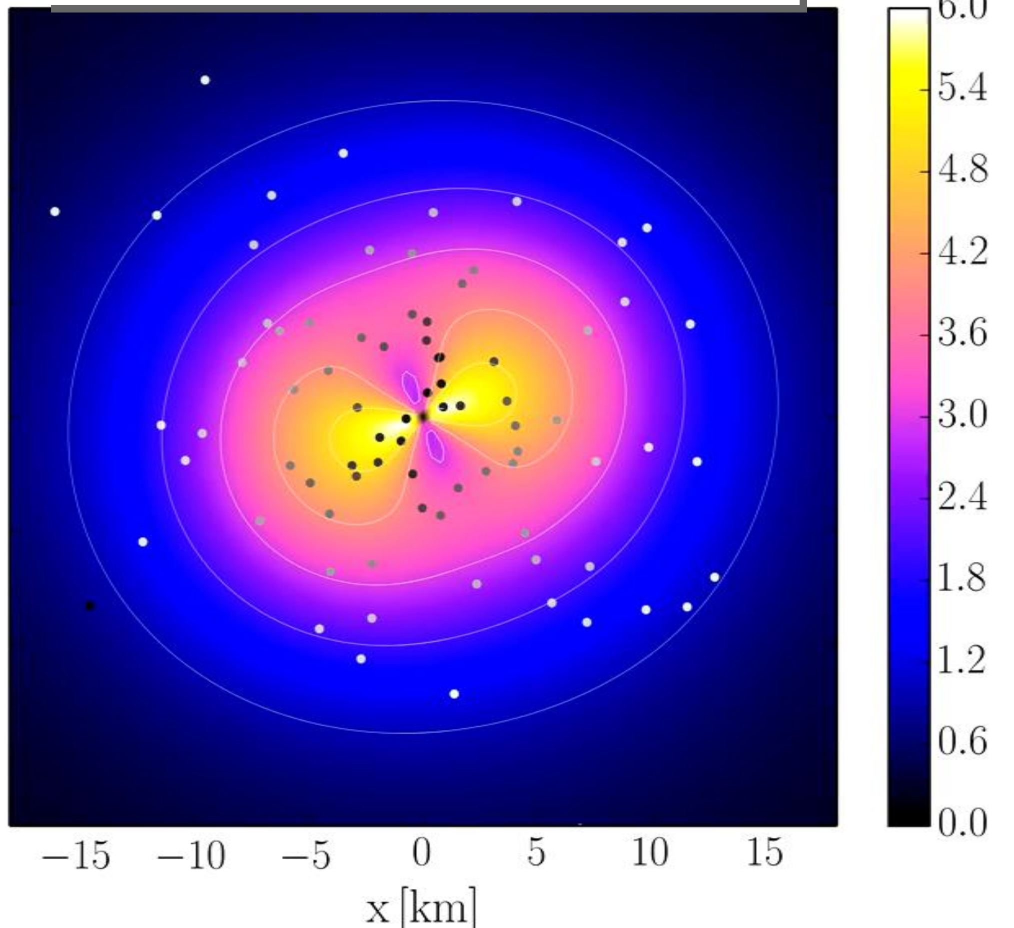
Constituents of the Angular Velocity

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

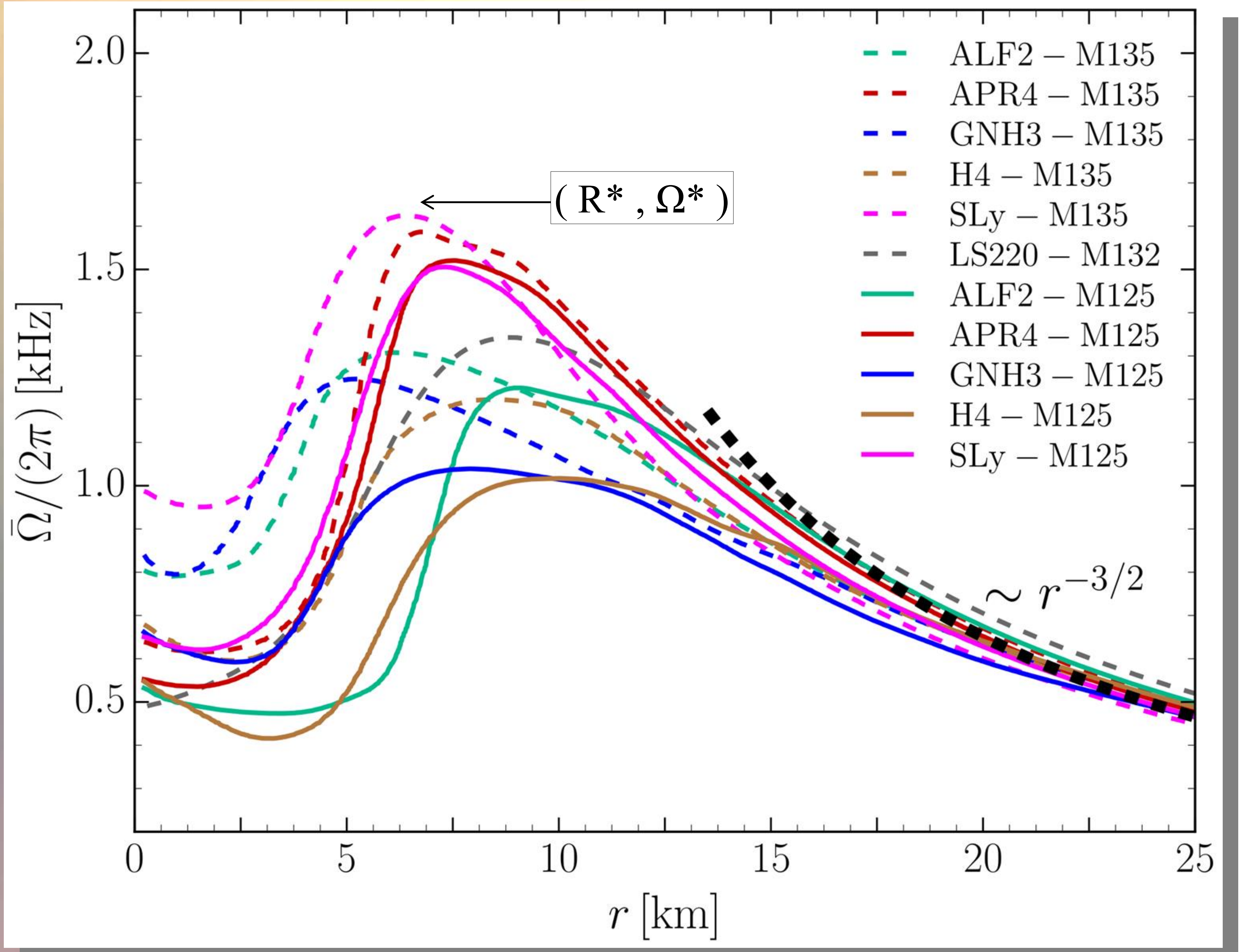
Φ-component of 3-velocity v^{φ}



Frame-dragging β^{φ}



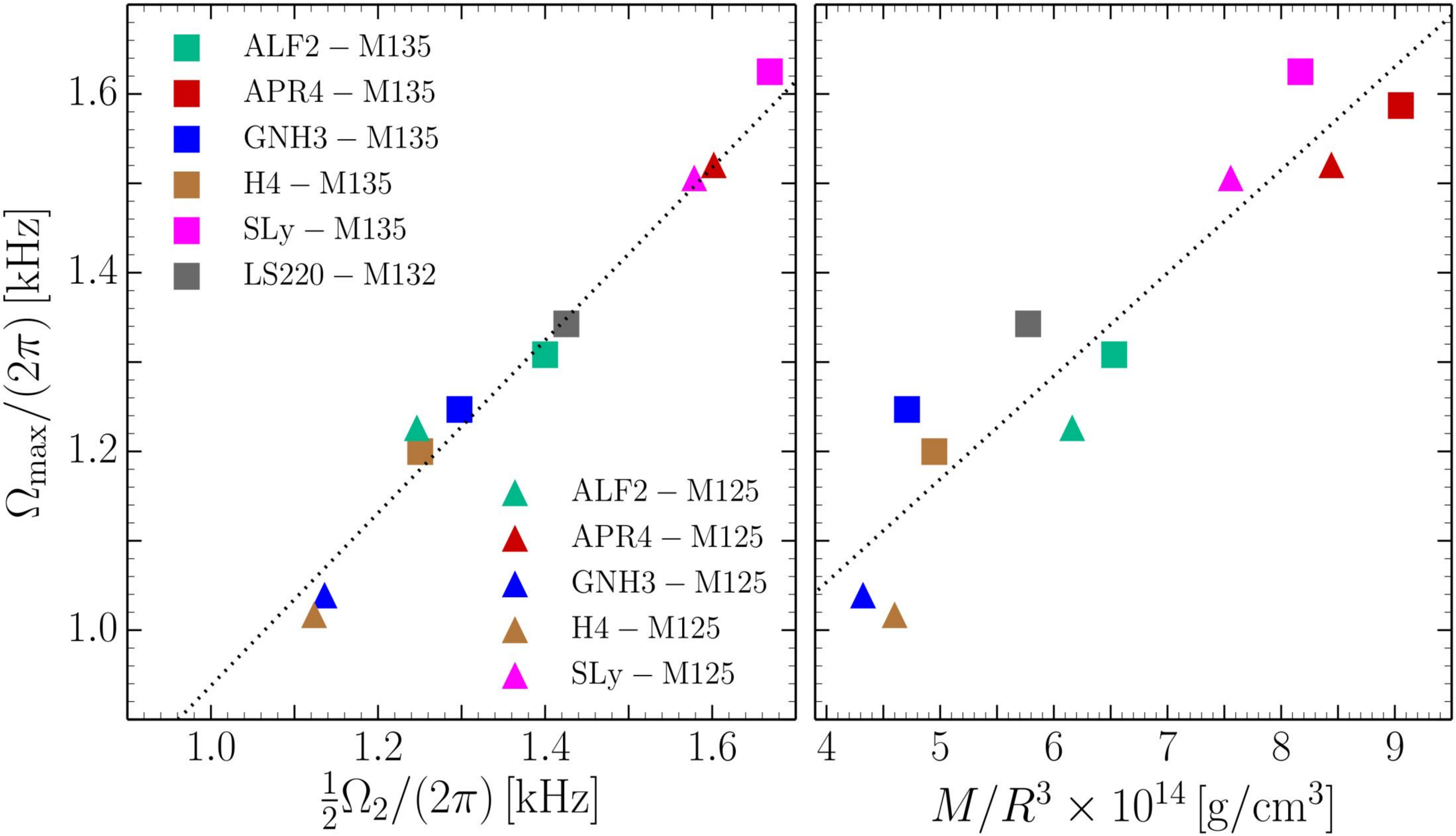
Time-averaged Rotation Profiles



Rotation Profiles and Gravitational Waves

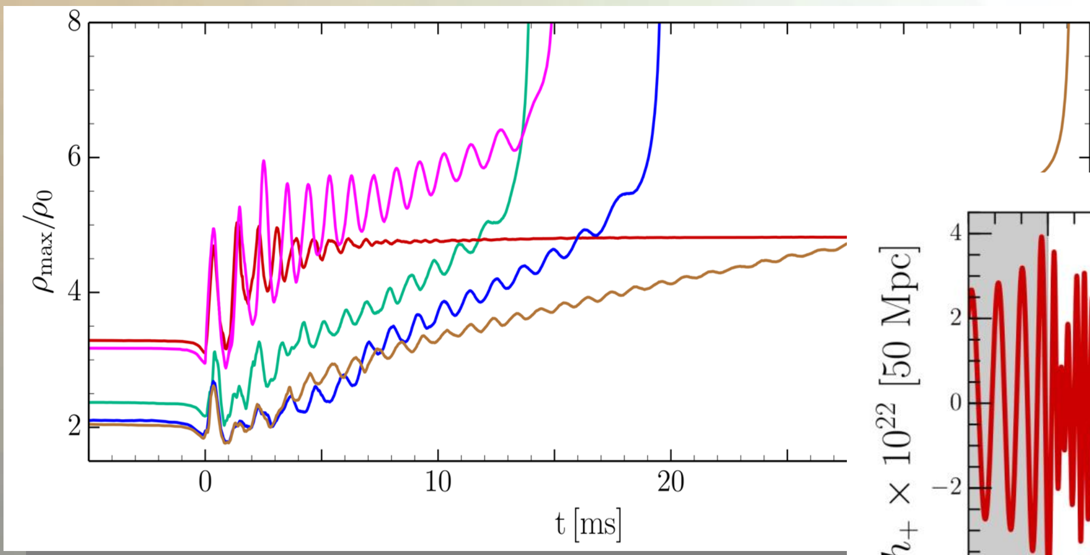
Maximum of the rotation profile vs. gravitational wave frequency peak f_2

Maximum of the rotation profile vs. average density of the M_{max} star



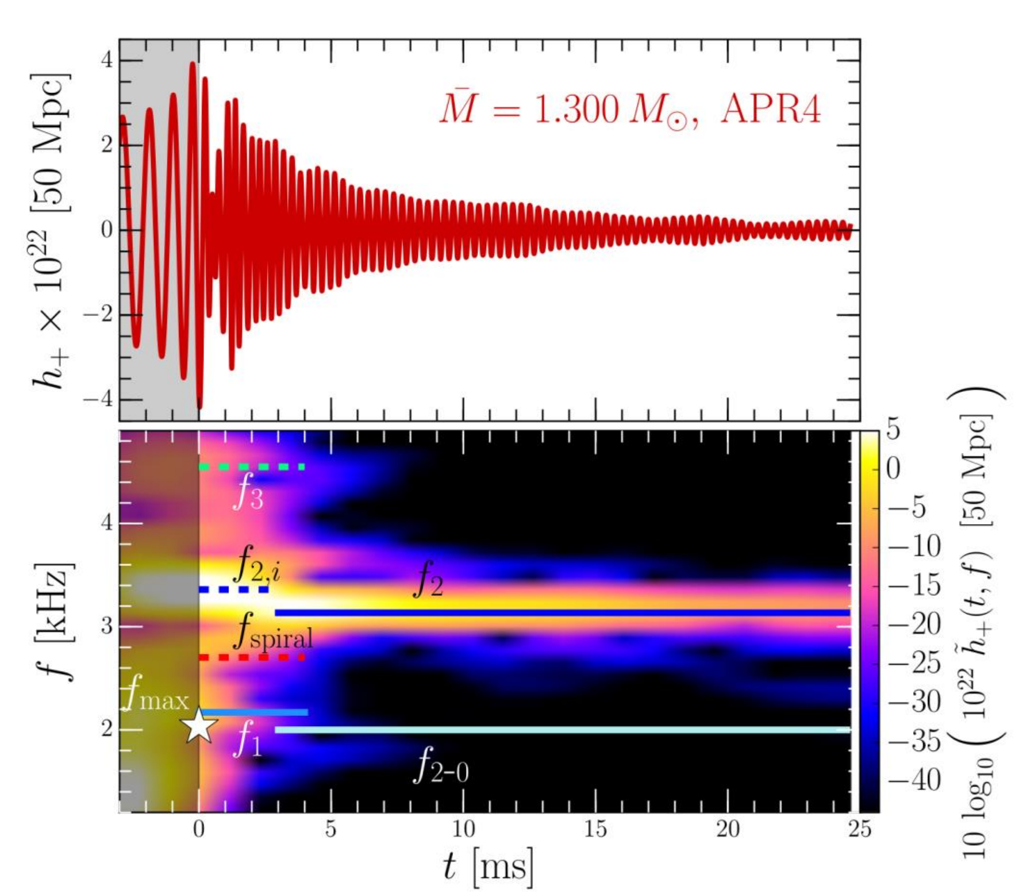
How to Observe the Hadron-Quark Phase Transition with Gravitational Waves from NS Mergers?

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, …, $f_{2\text{-}PT}$



M.Hanauske, K.Takami, L.Bovard, L.Rezzolla, J.A.Font, F.Galeazzi and H.Stöcker : arXiv:1611.07152

Rotational properties of hypermassive neutron stars from binary mergers

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Determining the differential-rotation law of compact stellar objects produced in binary neutron stars mergers or core-collapse supernovae is an old problem in relativistic astrophysics. Addressing this problem is important because it impacts directly on the maximum mass these objects can attain and hence on the threshold to black-hole formation under realistic conditions. Using the results from a large number of numerical simulations in full general relativity of binary neutron star mergers described with various equations of state and masses, we study the rotational properties of the resulting hypermassive neutron stars. We find that the angular-velocity distribution shows only a modest dependence on the equation of state, thus exhibiting the traits of "quasi-universality" found in other aspects of compact stars, both isolated and in binary systems. The distributions are characterized by an almost uniformly rotating core and a quasi-Keplerian "disk". Such a configuration is significantly different from the $j-$ constant differential-rotation law that is commonly adopted in equilibrium models of differentially rotating stars. Furthermore, the rest-mass contained in such a disk can be quite large, ranging from $\simeq 0.03\,M_{\odot}$ in the case of high-mass binaries with stiff equations of state, up to $\simeq 0.2\,M_{\odot}$ for low-mass binaries with soft equations of state. We comment on the astrophysical implications of our findings and on the long-term evolutionary scenarios that can be conjectured on the basis of our simulations.