Gravitational waves and rotational properties of hypermassive neutron stars from binary mergers

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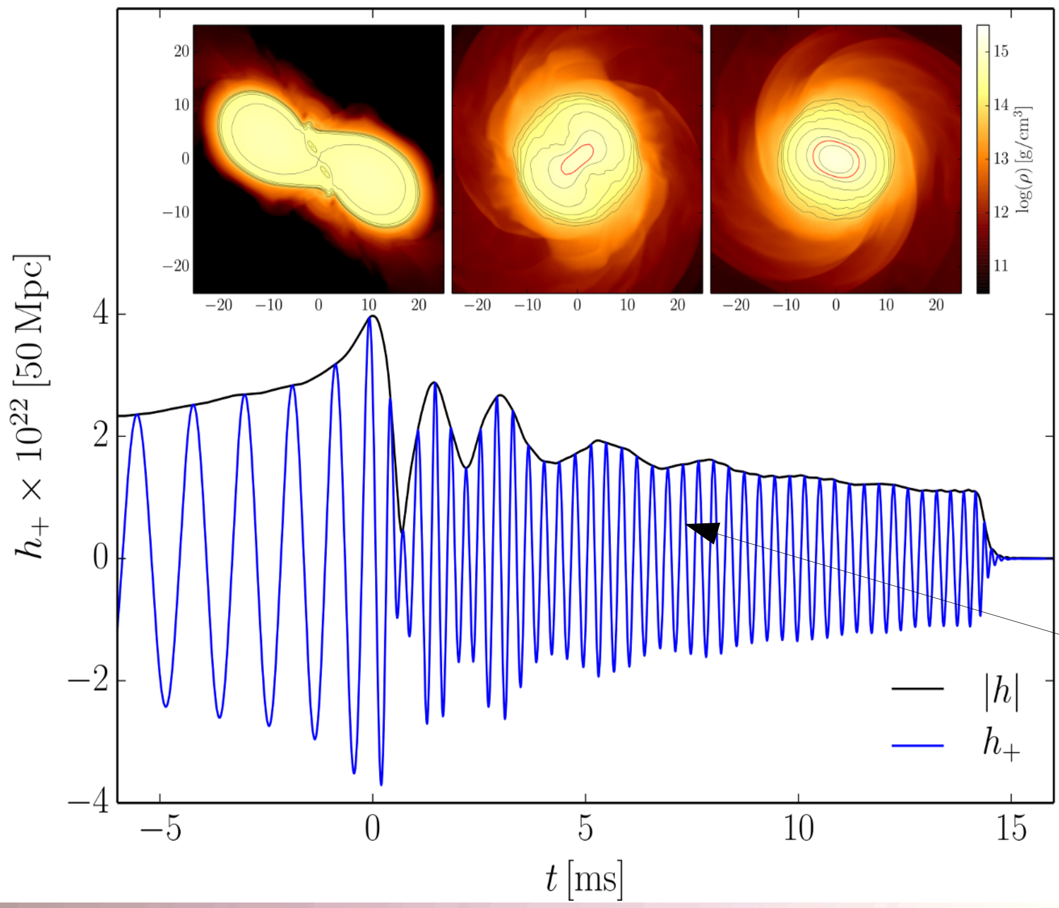
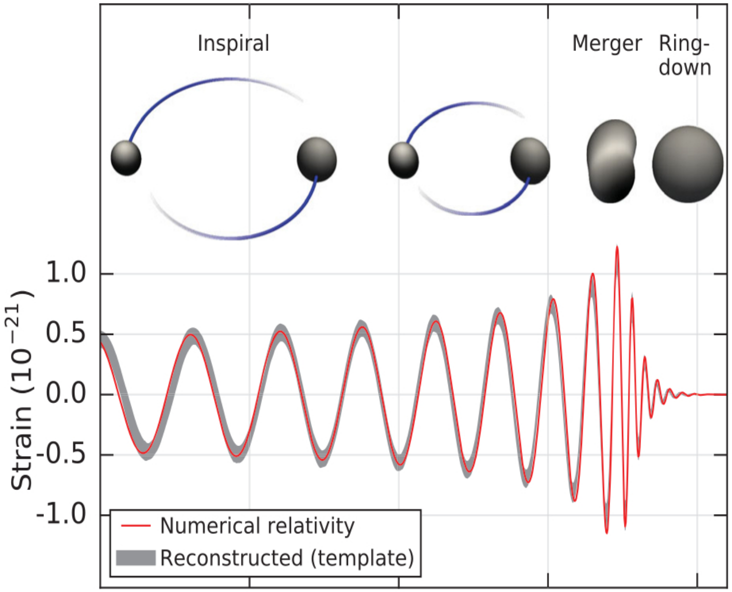
Gravitational Waves from Binary Neutron Star Mergers

Neutron star merger (Simulation)



Merger of two Black Holes



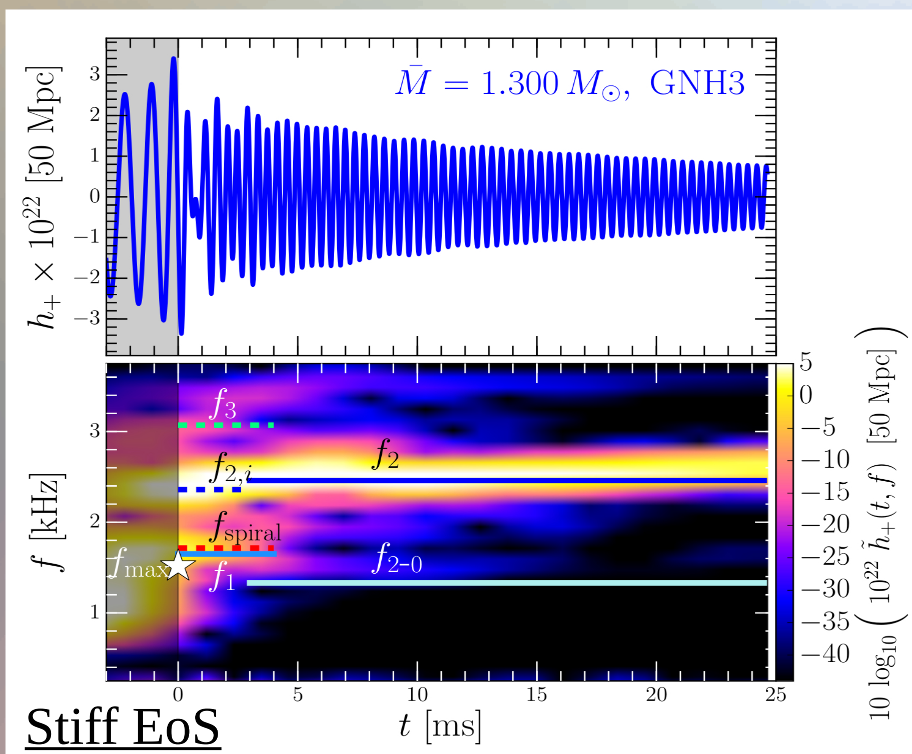
<u>Main Difference:</u>
Neutron star mergers could have a
post-merger phase

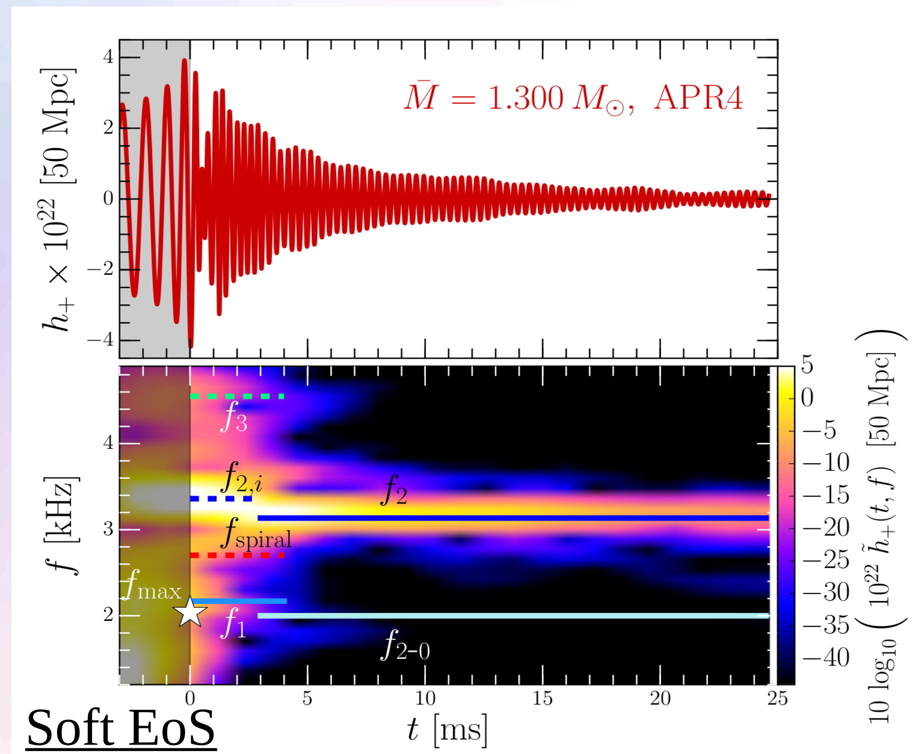
Time Evolution of the GW-Spectrum depends on the Equation of State

Early post-merger emission: frequencies f_{max}, f_1, f_2, f_3 and f_{2-0}

t > 5 ms after merger: dominant frequency is the f_2-frequency

See L.Rezzolla and K.Takami, arXiv:1604.00246





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

Numerical Setup

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.

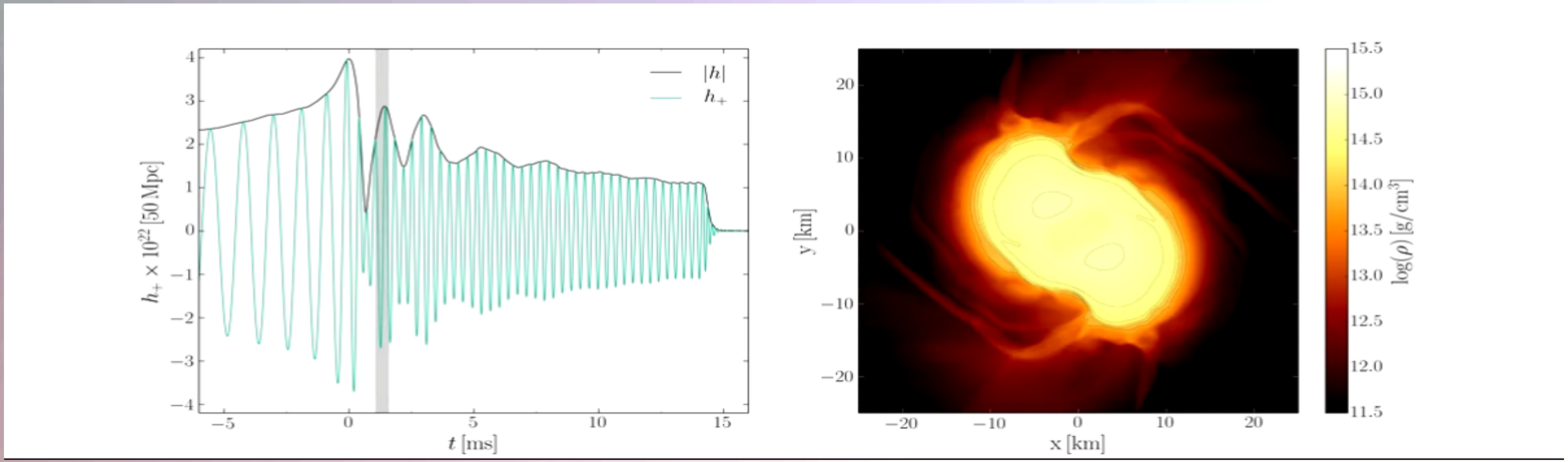
Grid Structure:

Adaptive mesh refinement (six ref. levels)

Grid resolution: (from 221 m to 7.1 km)

Initial separation of stellar cores: 45 km

BSSNOK conformal traceless formulation of the ADM equations. 3+1 Valencia formulation and high resolution shock capturing methods for the hydrodynamic evolution. Full general relativity using the **Einstein-Toolkit** and the **WHISKY/WhiskyTHC code** for the general-relativistic hydrodynamic equations.



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

The angular velocity Ω in the (3+1)-Split is a combination of the lapse function α , the φ-component of the shift vector β^{φ} and the 3-velocity v^{φ} of the fluid (spatial projection of the 4-velocity **u**):

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

Angular velocity Ω

Lapse function α

Φ-component of 3-velocity v^{φ}

Frame-dragging β^{φ}

(3+1)-decomposition of spacetime:

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

Focus: Inner core of the differentially rotating HMNS

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)

Rotation Profiles (ALF2-1.35 Model)

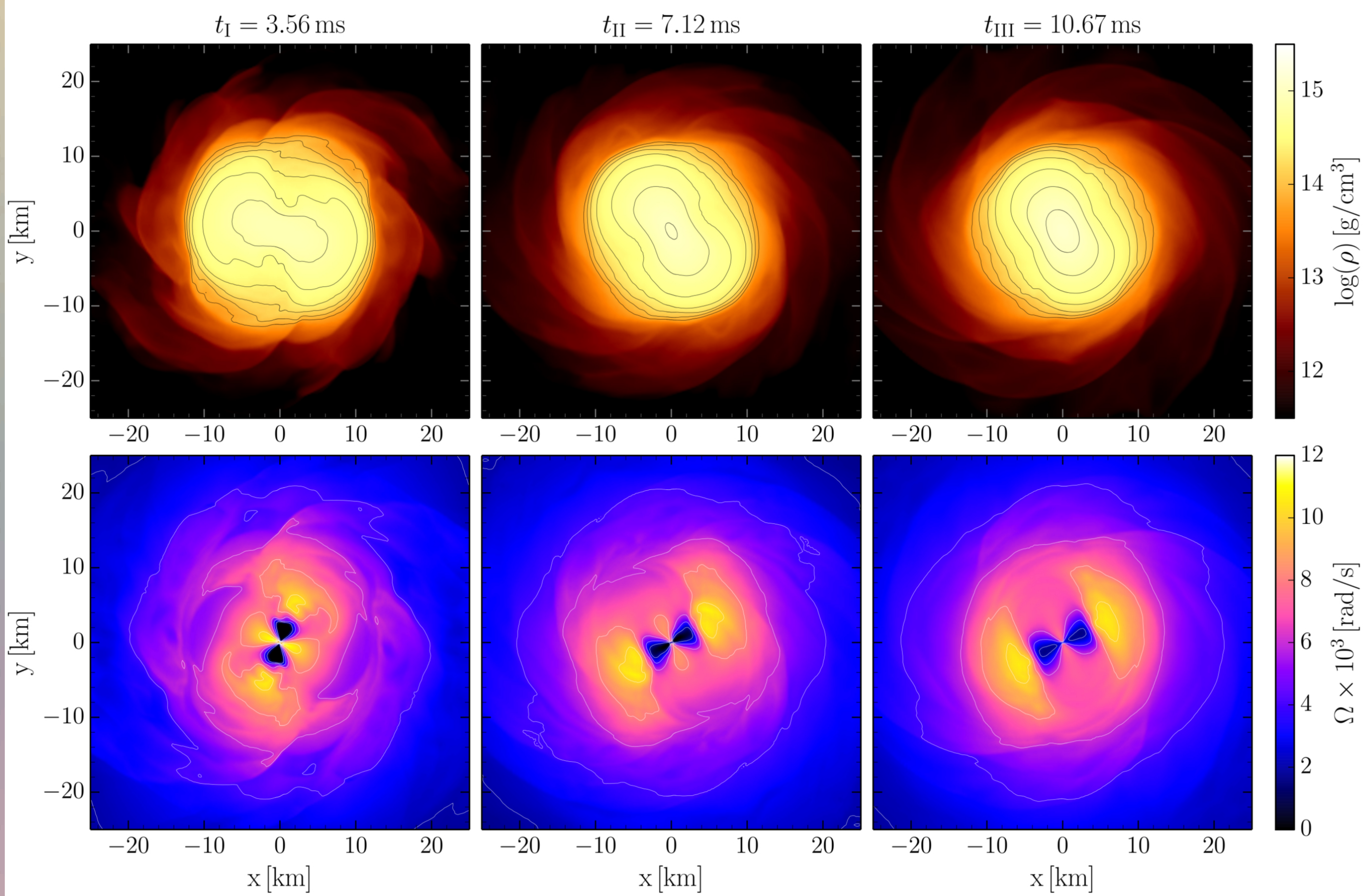


FIG. 3. Logarithm of the rest mass density Log(ρ) [g/cm^3] (upper row) and fluid angular velocity $\Omega \times 10^3$[rad/s] (lower row) in the xy-plane for the ALF2-M135 model at three different post-merger times. The iso-contour curves have been drawn at $13.8 + 0.2n$ (upper row) and $2n$ (lower row), $n \in \mathbb{N}$.

Rotation Profiles (ALF2-1.25 Model)

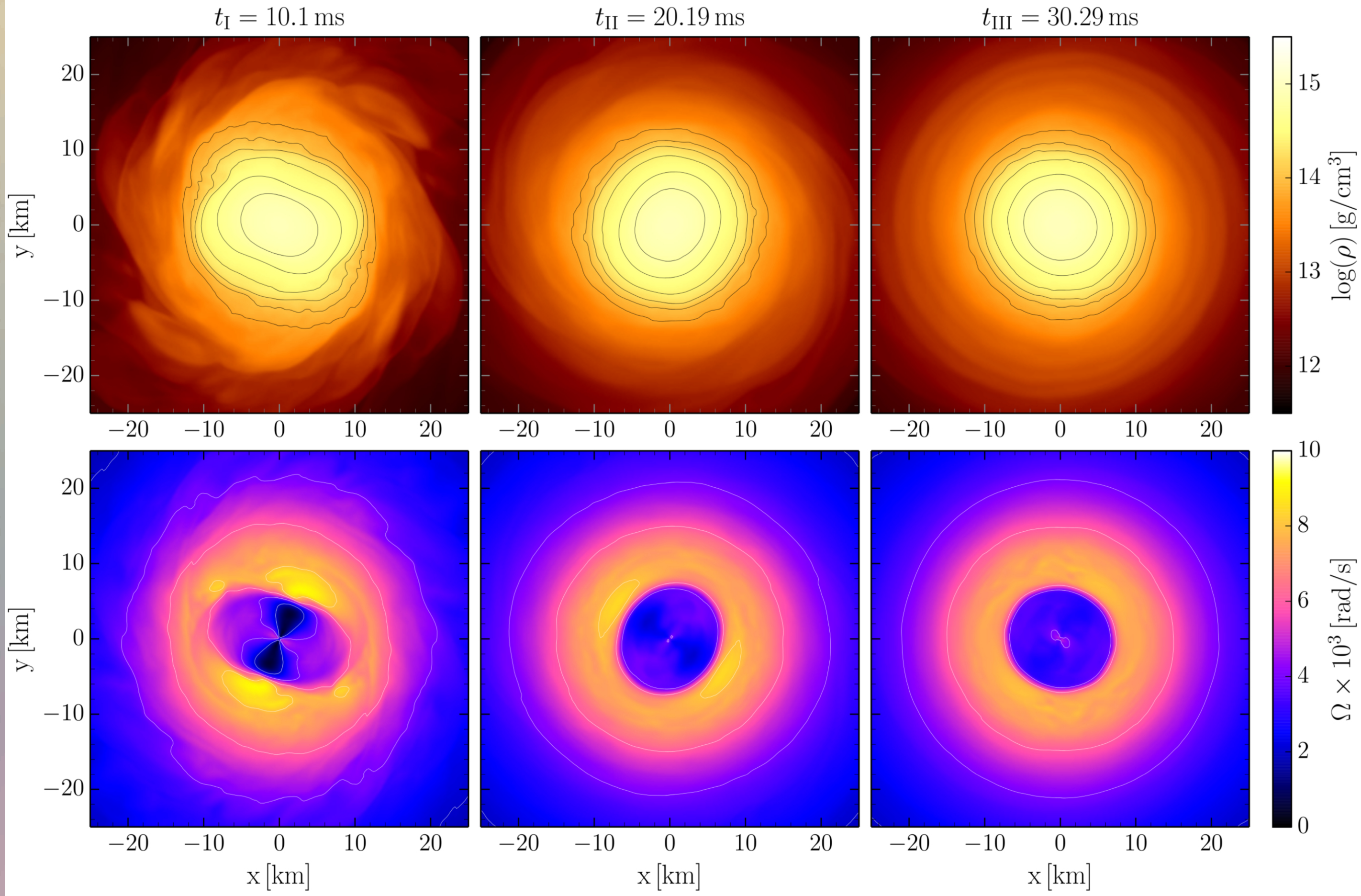


FIG. 11. Logarithm of the rest mass density Log(ρ) [g/cm^3] (upper row) and fluid angular velocity $\Omega \times 10^3$[rad/s] (lower row) in the xy-plane for the ALF2-M125 model at three different post-merger times. The iso-contour curves have been drawn at $13.8 + 0.2n$ (upper row) and $2n$ (lower row), $n \in \mathbb{N}$

Frame-Dragging and Gravitomagnetism

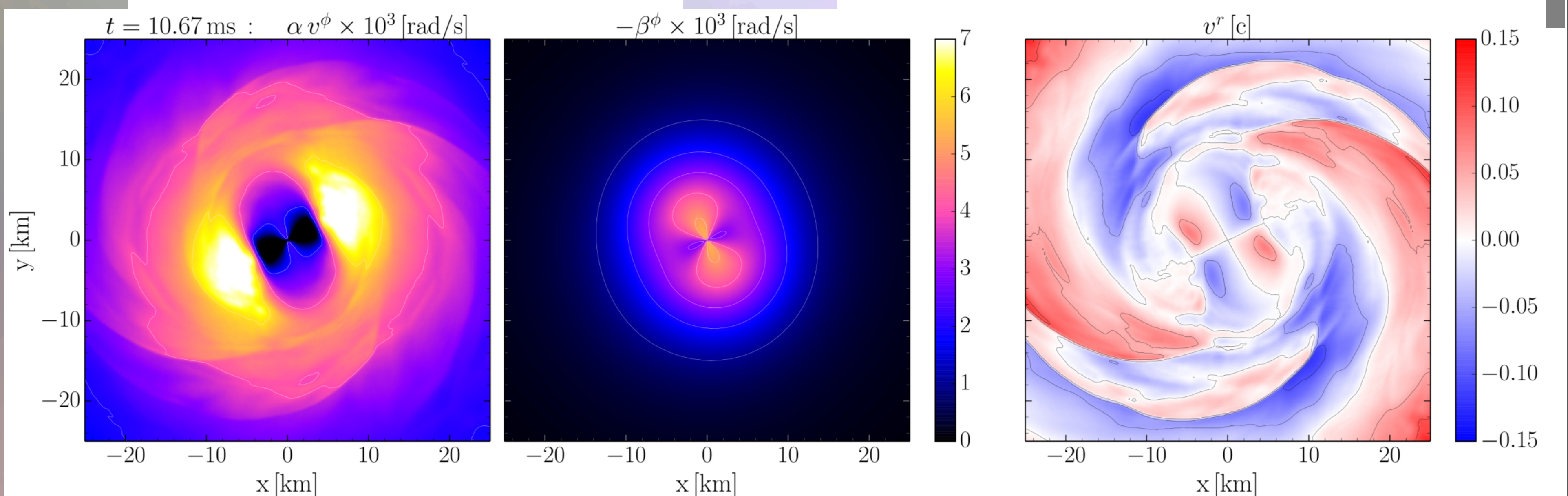
The dragging of local inertial frames is quite large in the interior of the HMNS and therefore an additional gravitomagnetic force is present. Like the Lorentz-force in electromagnetism, it acts orthogonal to the fluids velocity and the frame dragging.

Ingredients of the angular velocity:

(strong time and φ-dependence !)

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

$$\frac{d\mathbf{v}}{d\tau} = -\mathrm{grad}\,\Phi(\mathbf{r}) + 2\,\mathbf{\Omega}^F(\mathbf{r}) \times \mathbf{v} \;+ \mathcal{O}(v^2/c^2)\,, \qquad (11)$$



The Gravitomagnetic Effect in the Interior of the HMNS at Medium Post-Merger Times (4 ms < t < 15 ms)

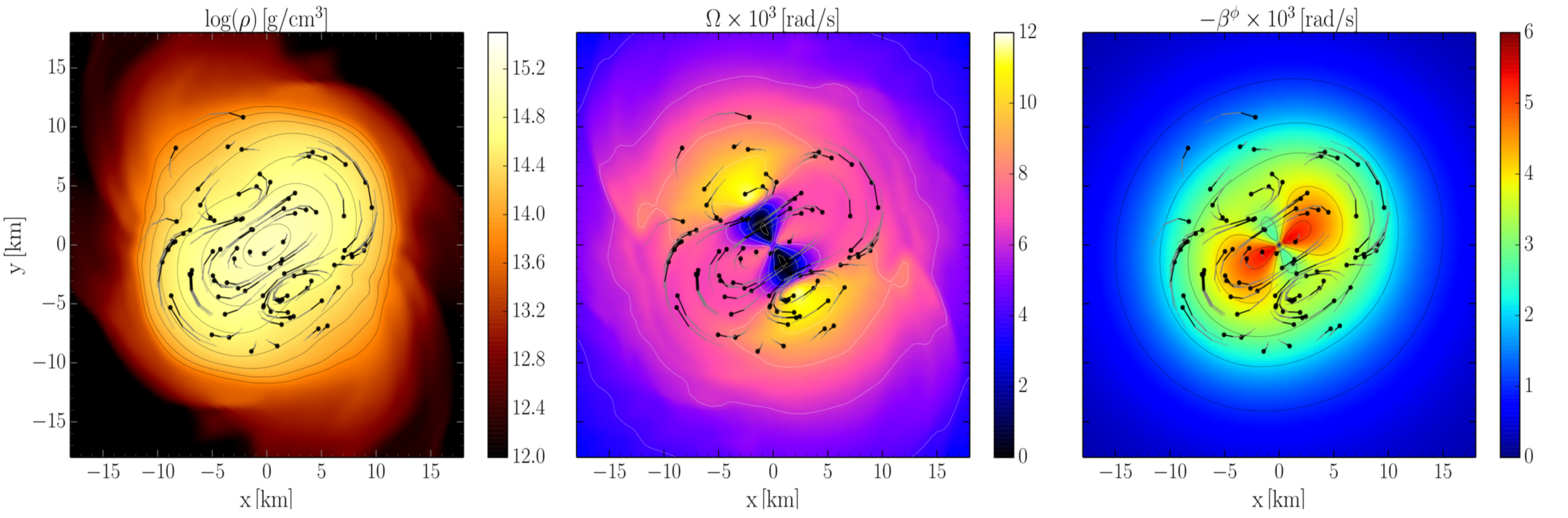


FIG. 7. Logarithm of the rest mass density Log(ρ) [g/cm^3] (left picture), the fluid angular velocity $\Omega \times 10^3$[rad/s] (middle) and $-\beta^\phi \times 10^3$[rad/s] (right picture) in the xy-plane for the SLY-M132 model at $t = 6.71$ ms. The trajectories of several tracer-cells are additionally mapped for two previous times (separation Δt_{Tr} =0.095 ms).

The Interior of the HMNS at Late Post-Merger Times (t > 15 ms)

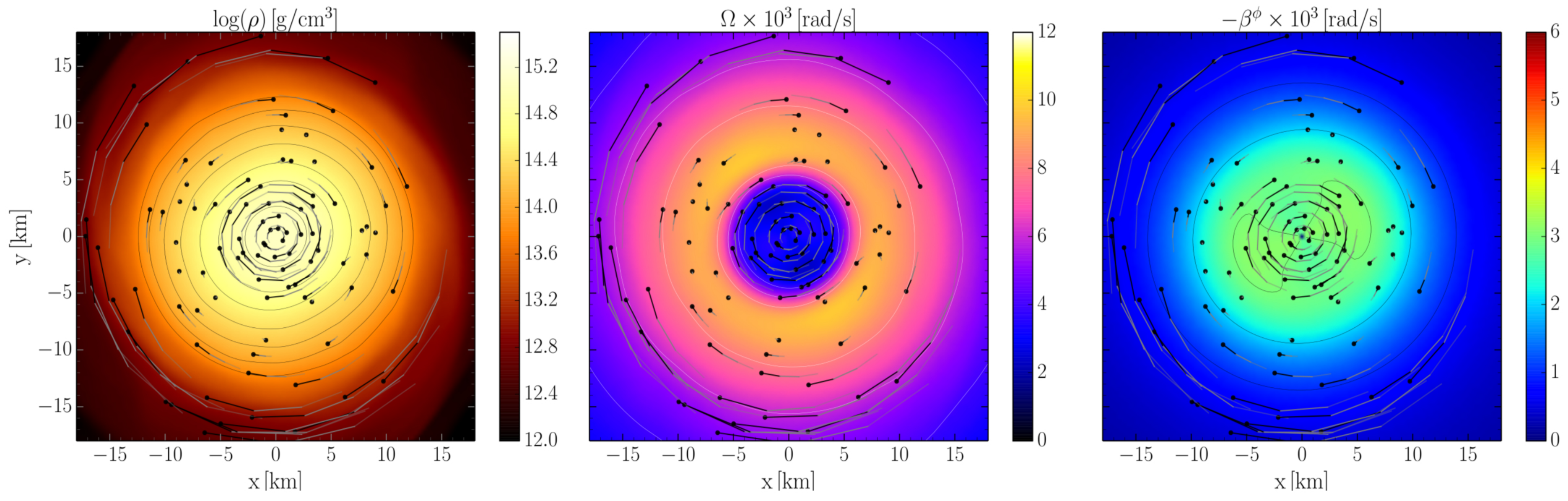
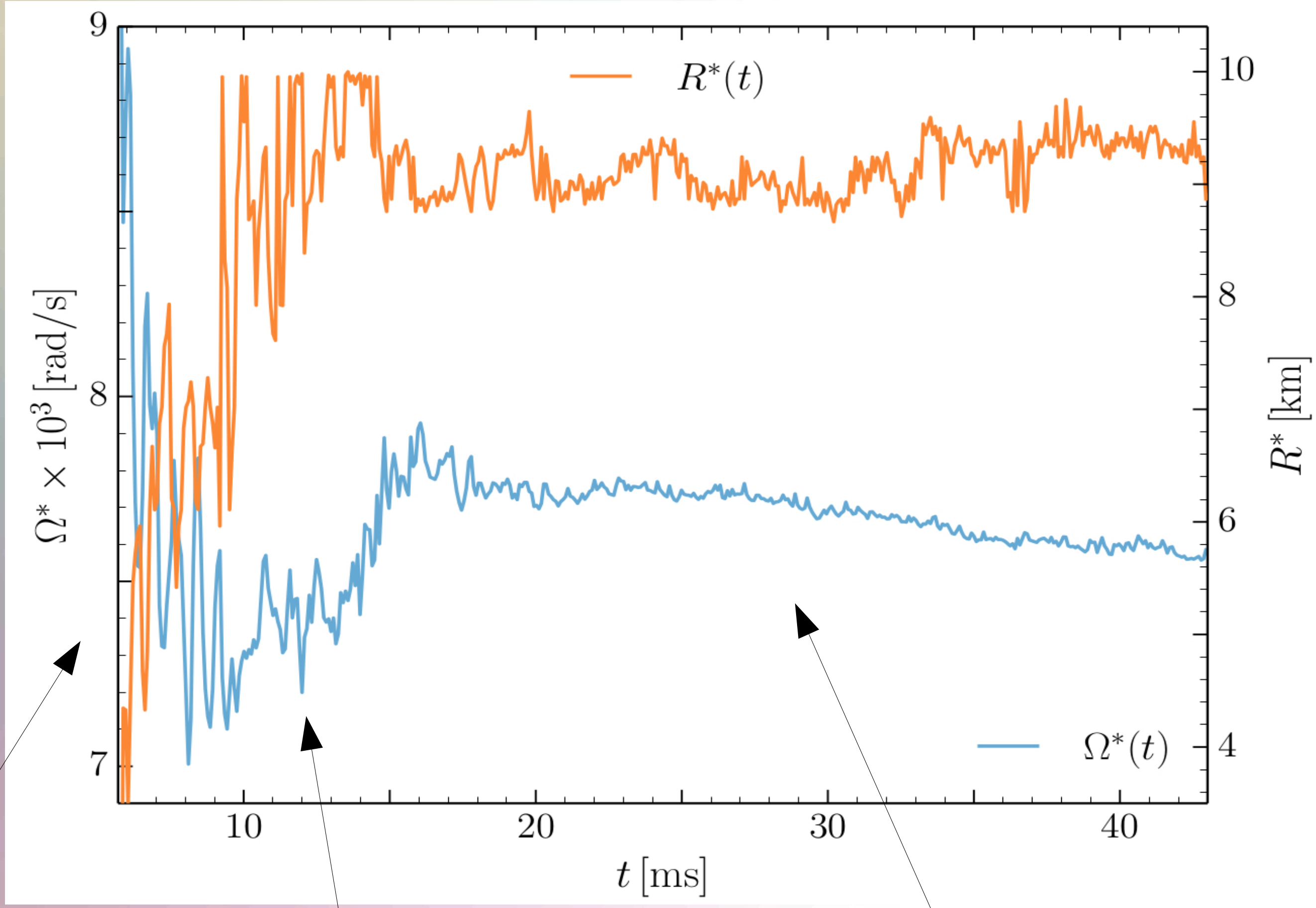


FIG. 8. Same as in Fig. 7, but at $t = 23.83$ ms.

Maximum Value of Ω and its Radial Position



t < 5 ms
Violent early phase

5 ms < t < 15 ms
Gravitomagnetism

t > 15 ms:
Quasi equilibrated and φ-symmetric HMNS

Averaging Procedure for Ω

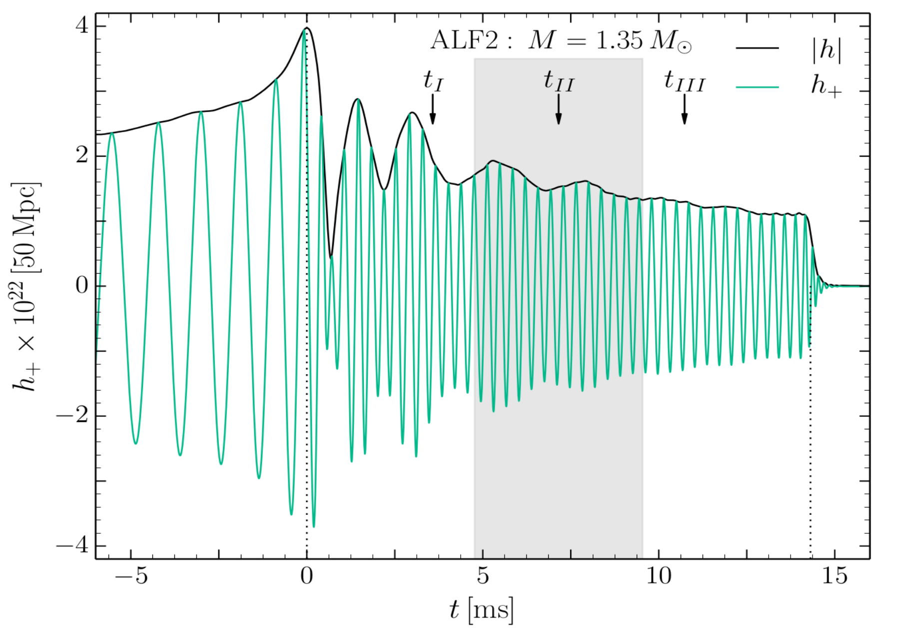


FIG. 2. Gravitational wave amplitude $|h|$ and h_+ at a distance of 50 Mpc for the ALF2-M135 model.

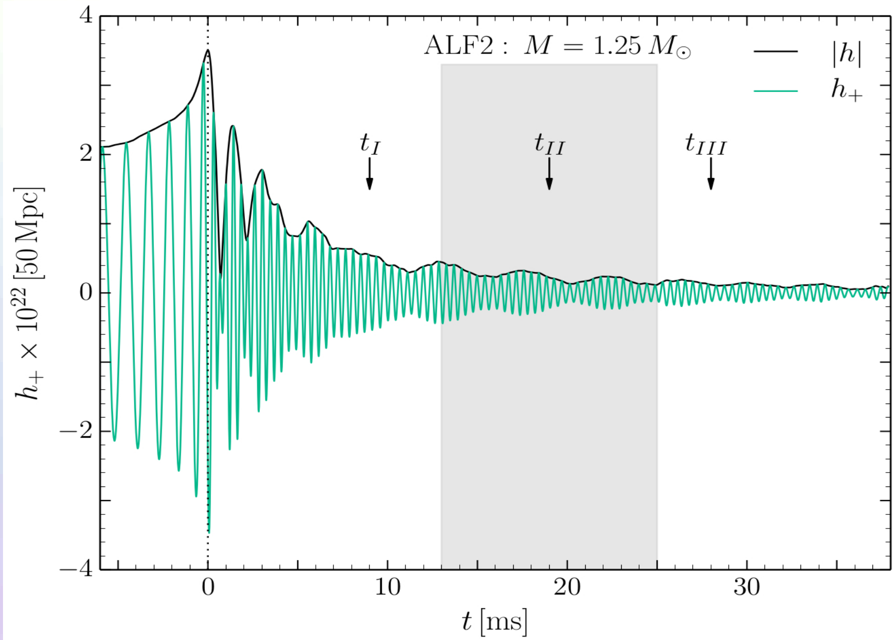
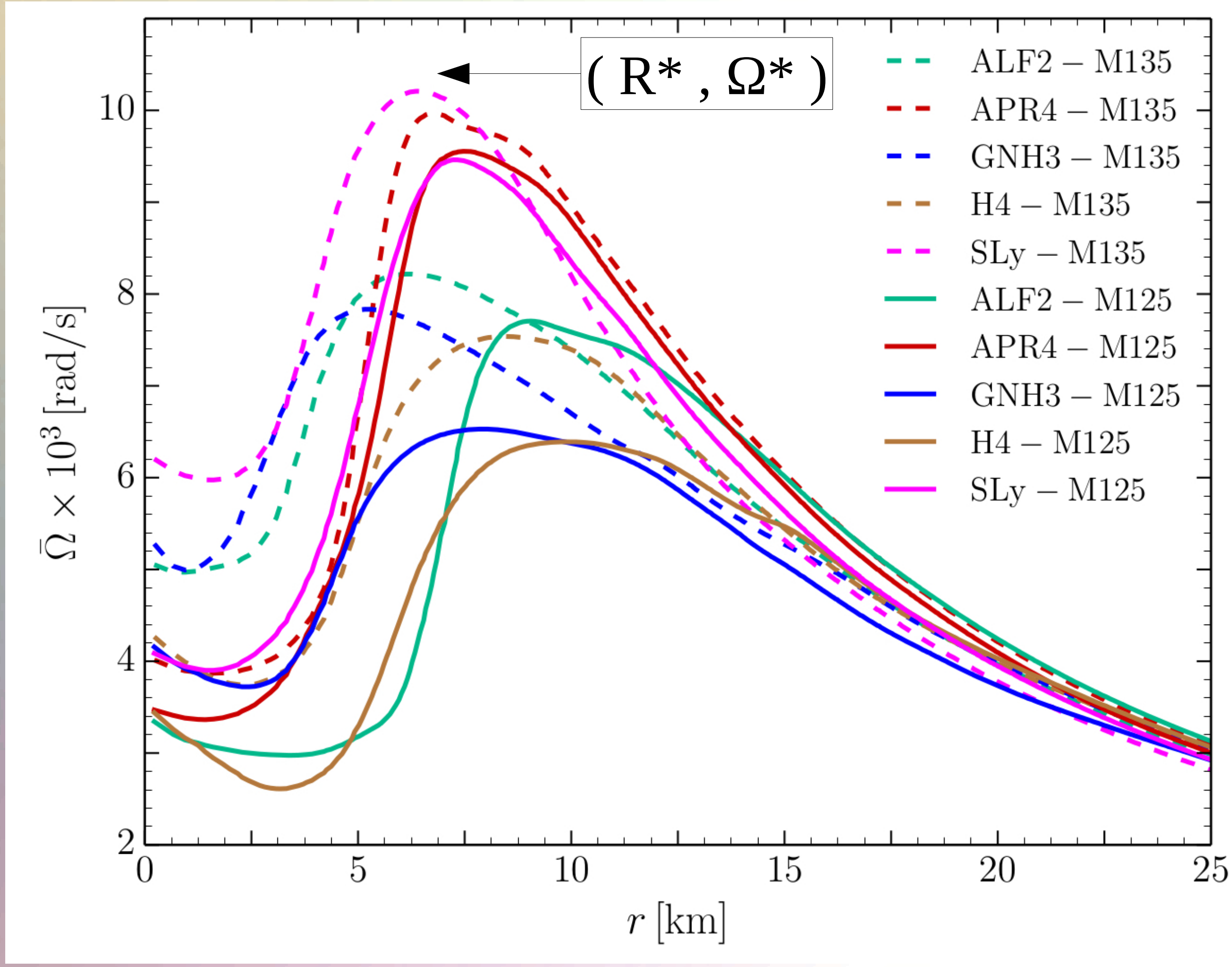


FIG. 10. Gravitational wave amplitude h_+ and $|h|$ at a distance of 50 Mpc for the ALF2-M125 model.

In order to compare the structure of the rotation profiles between the different EOSs, a certain time averaging procedure has been used:

$$\bar{\Omega}(r, t_c) = \int_{t_c-\Delta t/2}^{t_c+\Delta t/2} \int_{-\pi}^{\pi} \Omega(r, \phi, t')\; d\phi\, dt'$$

Time-averaged Rotation Profiles



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).

Gravitational Waves and the maximum of the Rotation Curve