Neutron Star Mergers in the Context of the Hadron-Quark Phase Transition

ADVANCES IN ASTROPARTICLE PHYSICS AND COSMOLOGY
ON THE OCCASION OF THE 125TH BIRTH ANNIVERSARY OF PROF. MEGHNAD SAHA

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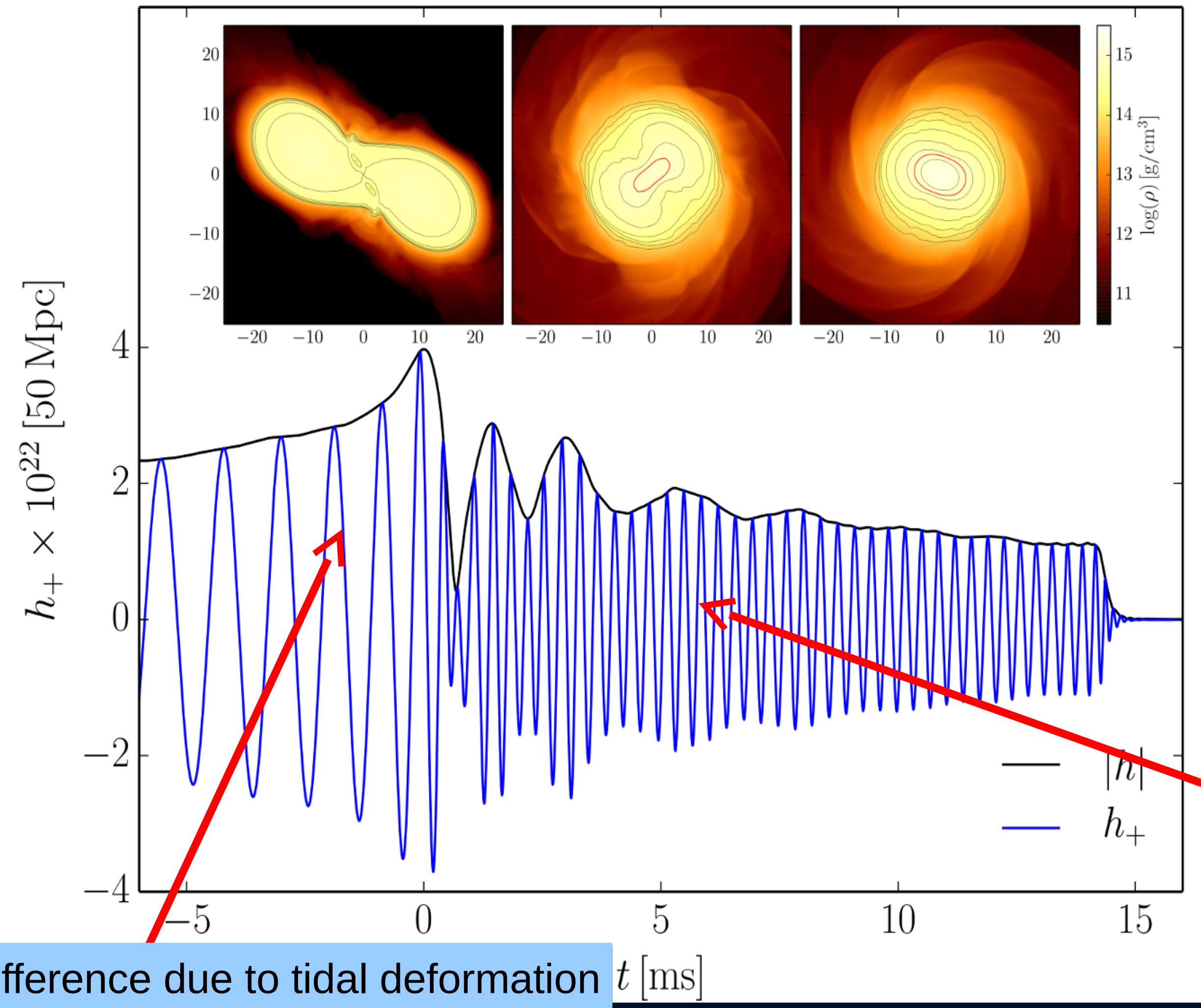
The long-awaited event GW170817

	Low-spin priors ($|\chi| \leq 0.05$)	High-spi
Primary mass m_1	1.36–1.60 $M_\odot$	1
Secondary mass m_2	1.17–1.36 $M_\odot$	0
Chirp mass $\mathcal{M}$	$1.188^{+0.004}_{-0.002} M_\odot$	1
Mass ratio m_2/m_1	0.7–1.0	
Total mass $m_{\rm tot}$	$2.74^{+0.04}_{-0.01} M_\odot$	
Radiated energy $E_{\rm rad}$	$> 0.025 M_\odot c^2$	>
Luminosity distance $D_{\rm L}$	40^{+8}_{-14} Mpc	
Viewing angle Θ	$\leq 55°$	
Using NGC 4993 location	$\leq 28°$	
Combined dimensionless tidal deformability $\tilde{\Lambda}$	≤ 800	
Dimensionless tidal deformability $\Lambda(1.4 M_\odot)$	≤ 800	

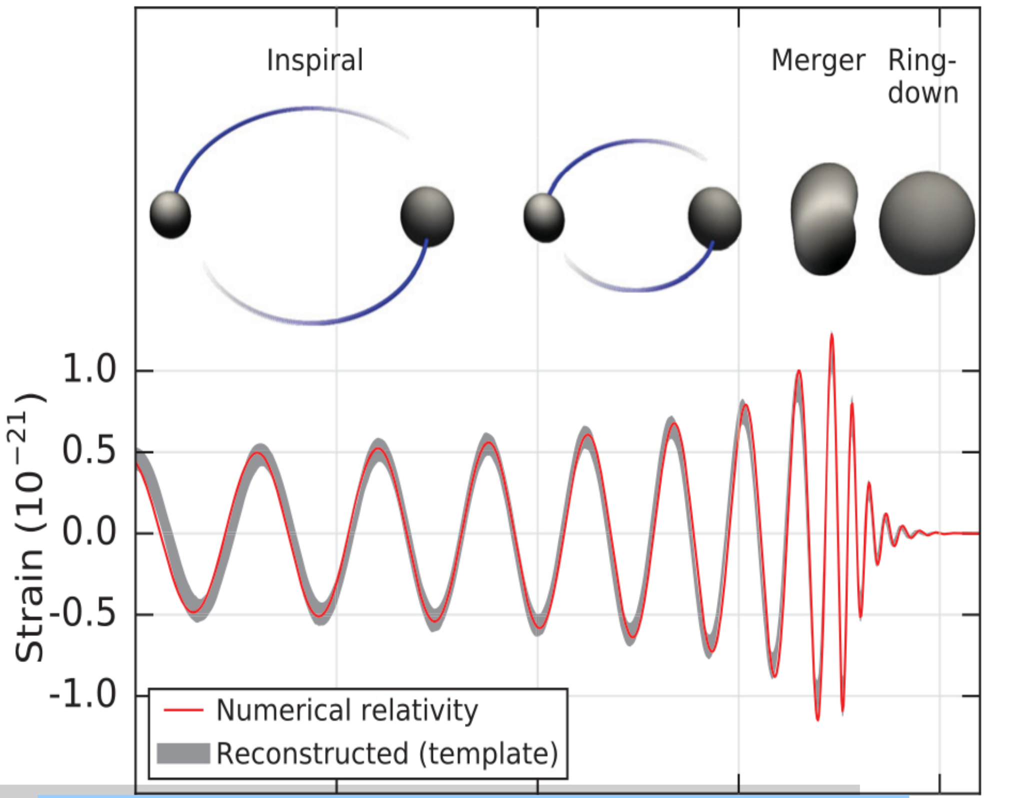
Gravitational Waves from Neutron Star Mergers

Neutron Star Collision (Simulation)



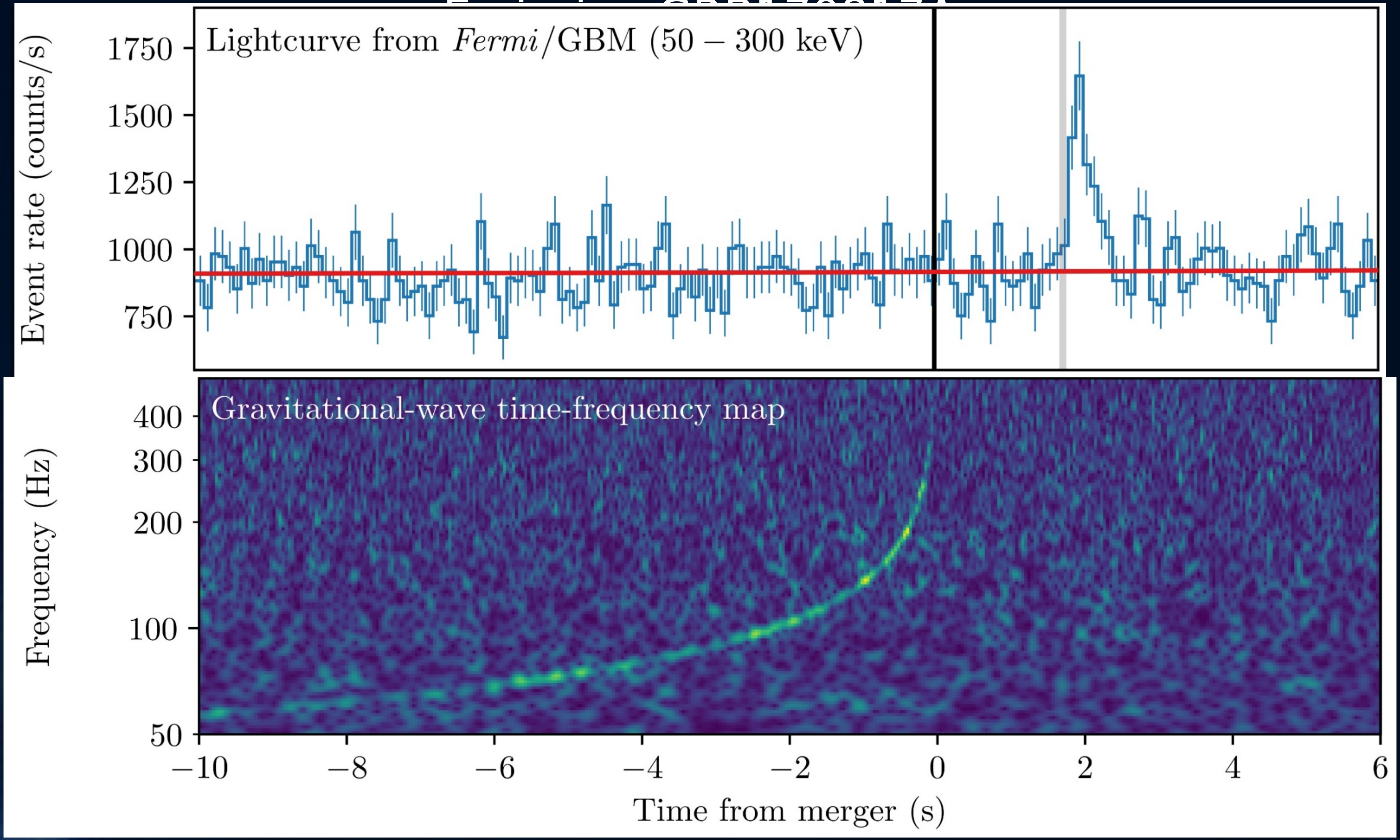
Difference due to tidal deformation in the late Inspiral phase

Collision of two Black Holes
GW150914



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

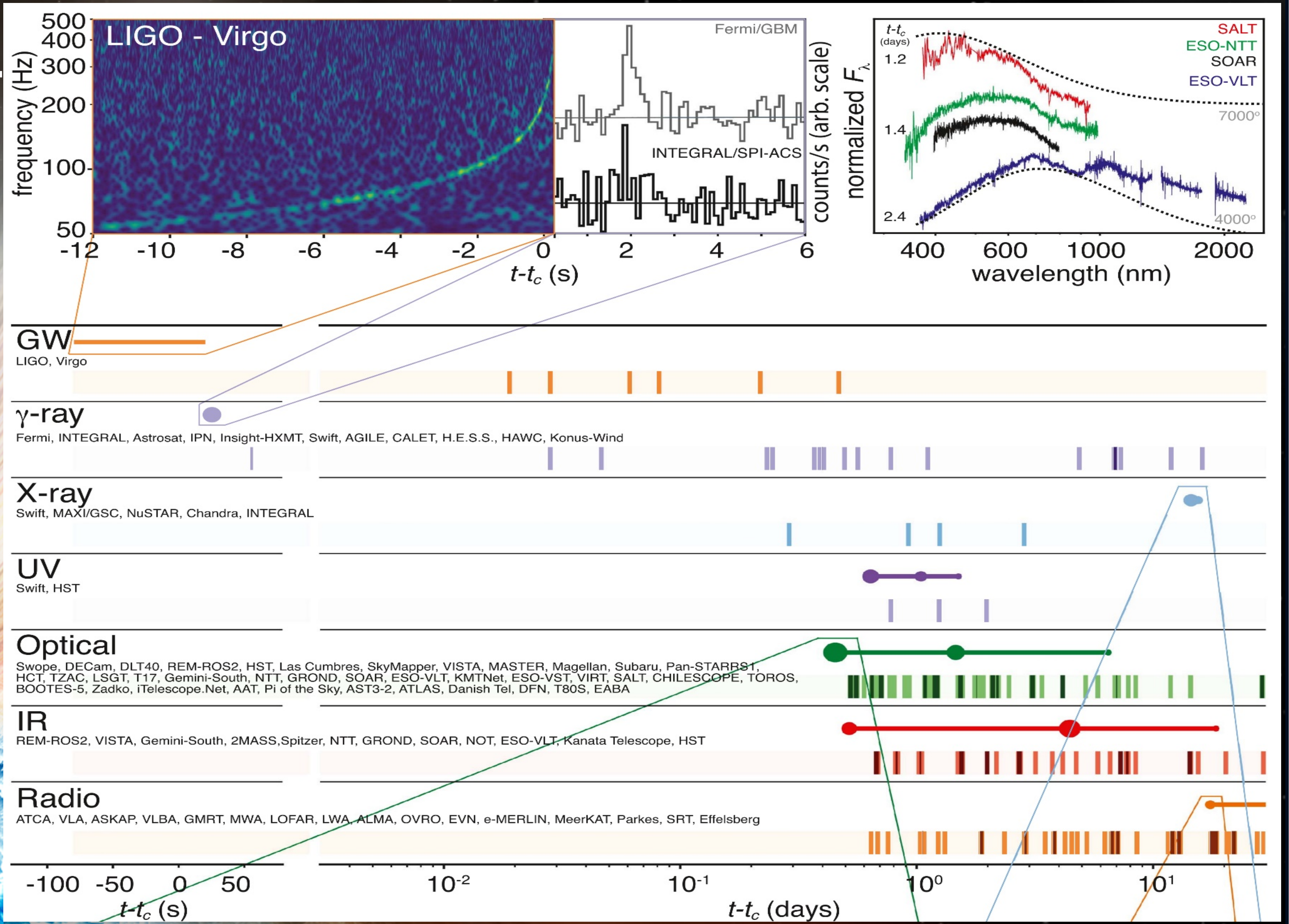
Gravitational Wave GW170817 and Gamma-Ray



GW170817: Observation of Gravitational Waves from a Binary Neutron Star Inspiral, LIGO Scientific Collaboration and Virgo Collaboration, Phys. Rev. Lett. 119, 161101 (2017), Gravitational Waves and Gamma-Rays from a Binary Neutron Star Merger: GW170817 and GRB170817A, LIGO, Virgo, Fermi GBM, and INTEGRAL Collaborations, Astrophys. J. Lett. 848, L13 (2017)

GW170817

Multi-Messenger Observations of a Binary Neutron Star Merger, LIGO and Virgo Collaborations together with 50 teams of electromagnetic and neutrino astronomers, Astrophys. J. Lett. 848, L12 (2017)

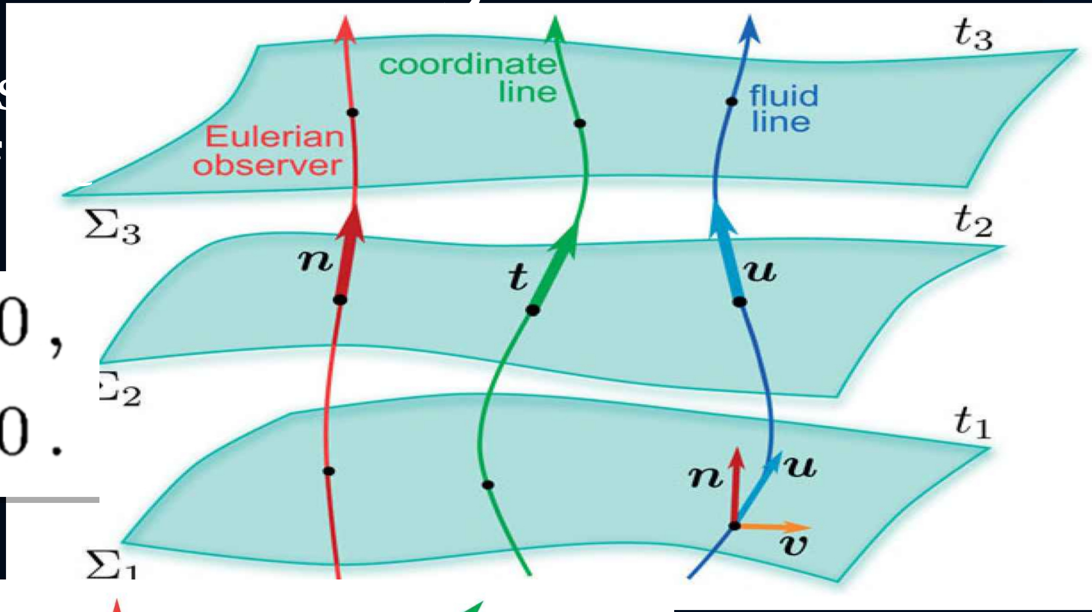


Numerical Relativity and Relativistic Hydrodynamics of Binary Neutron Star Mergers

Numerical simulations of a merger of two compact s
are based on a (3+1) decomposition of spacetime of
Einstein and hydrodynamic equations.

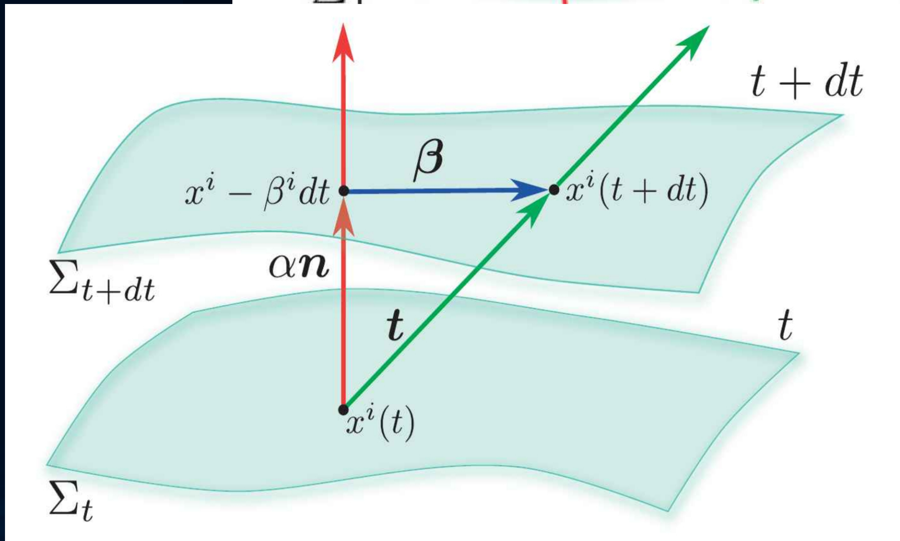
$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = 8\pi T_{\mu\nu}$$

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



(3+1) decomposition of spacetime

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



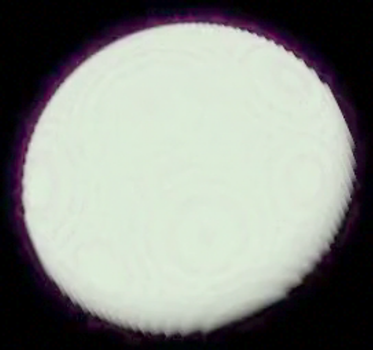
$$d\tau^2 = \alpha^2(t, x^j) dt^2$$

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

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

Computersimulation of a Neutron Star Merger in full General Relativity

Credits: Cosima Breu, David Radice and Luciano Rezzolla



Density

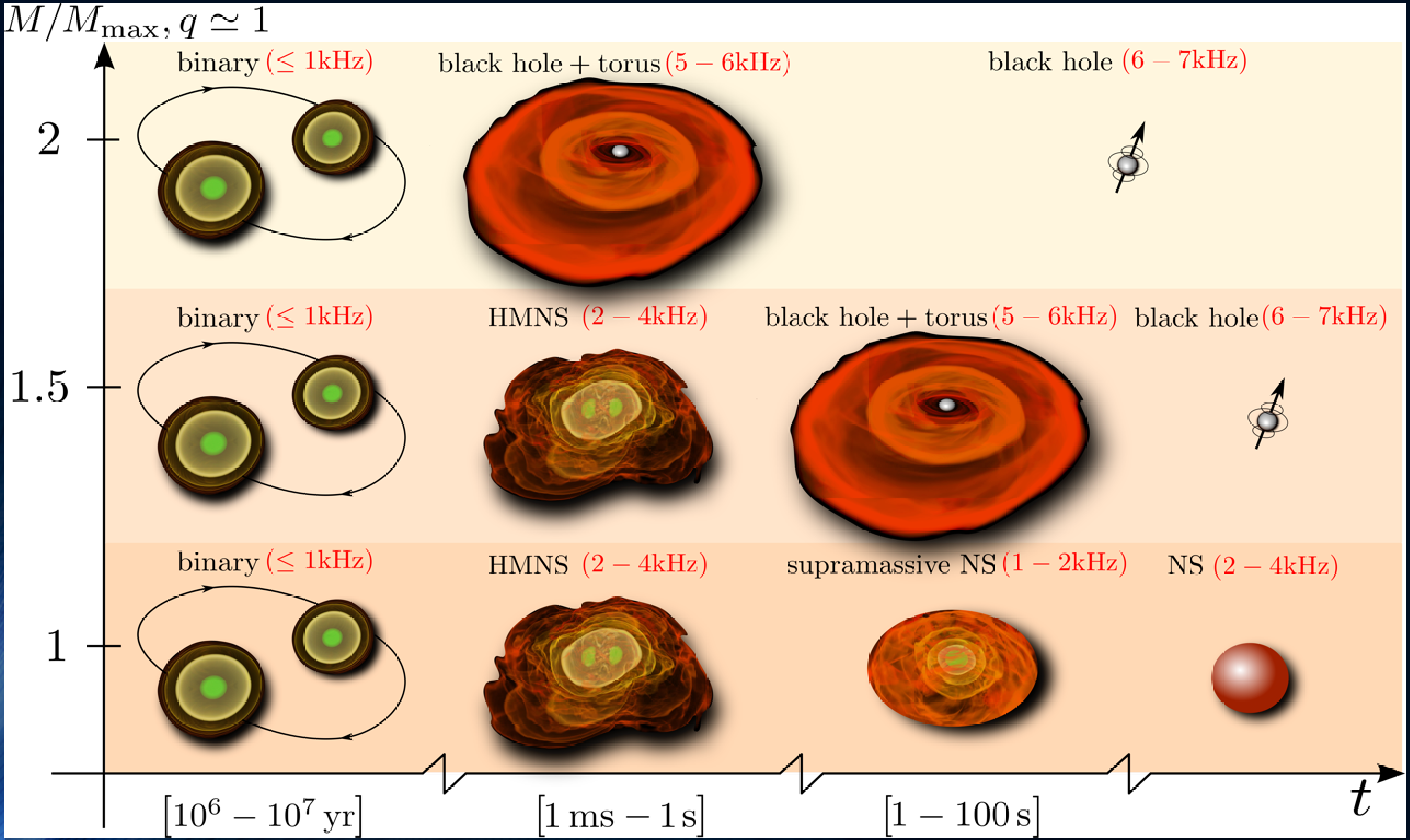
8.5 14

lg(rho) [g/cm^3]

Temperature

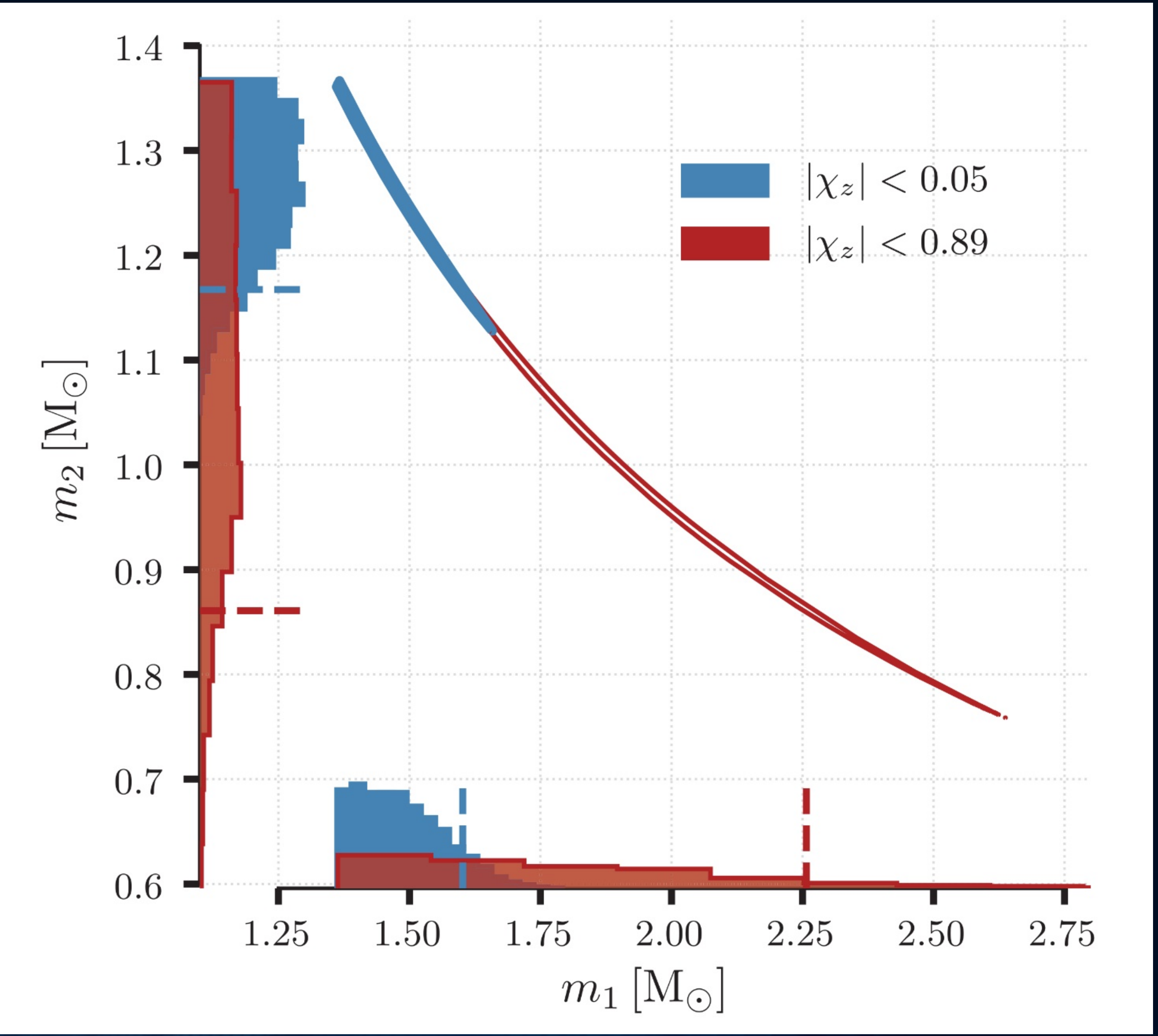
0 50

T [MeV]



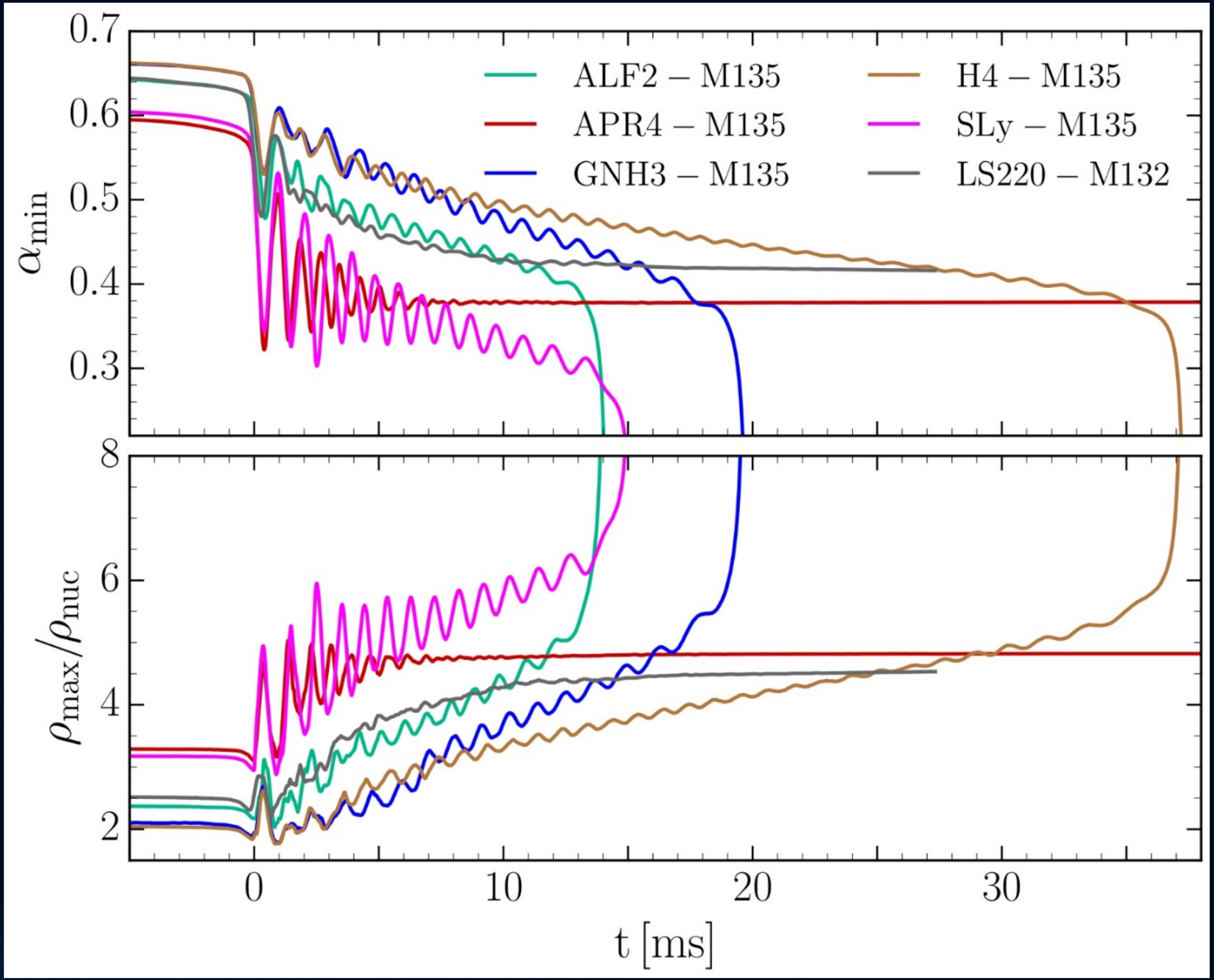
$M/M_{\max}, q \simeq 1$
binary ($\leq$ 1kHz)
black hole + torus (5 – 6kHz)
black hole (6 – 7kHz)
2
binary ($\leq$ 1kHz)
HMNS (2 – 4kHz)
black hole + torus (5 – 6kHz)
black hole (6 – 7kHz)
1.5
binary ($\leq$ 1kHz)
HMNS (2 – 4kHz)
supramassive NS (1 – 2kHz)
NS (2 – 4kHz)
1
$[10^6 - 10^7\,\mathrm{yr}]$
$[1\,\mathrm{ms} - 1\,\mathrm{s}]$
$[1 - 100\,\mathrm{s}]$
t

Measured Mass Ratio of GW170817 (for high and low spin assumption)



Binary Merger of two Neutron Stars for different EoSs

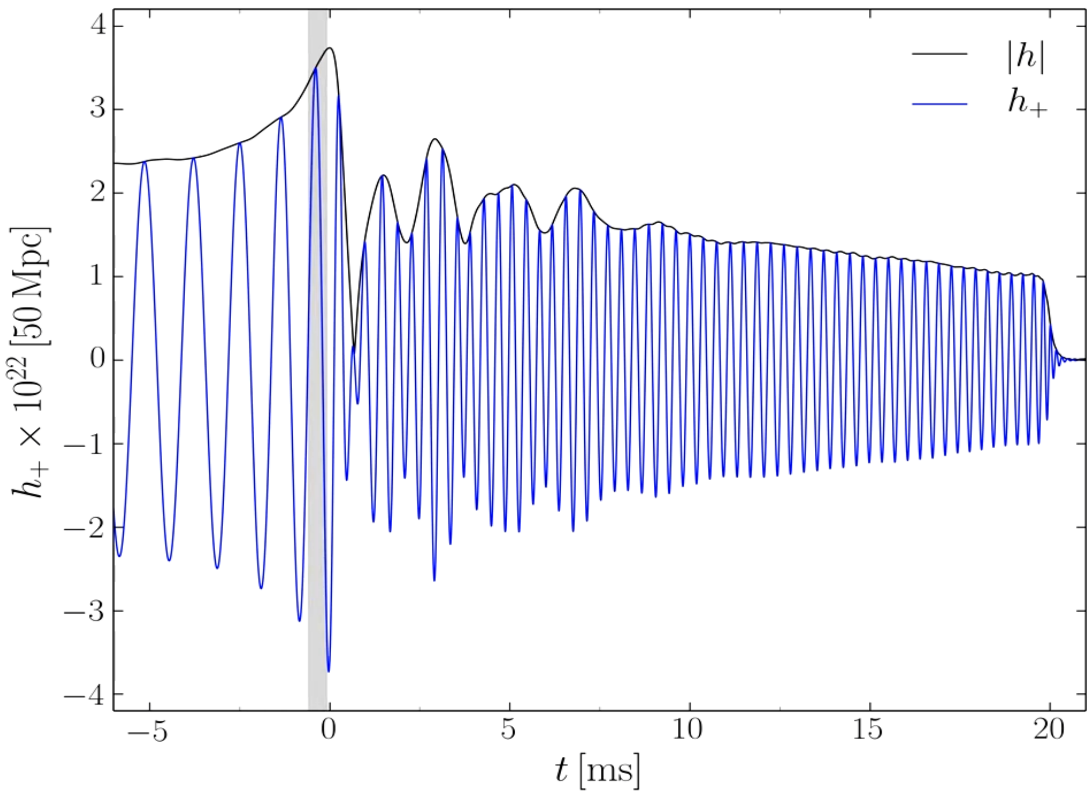
M=1.35 Msolar
for details see Hanauske, et.al. PRD, 96(4), 043004 (2017)



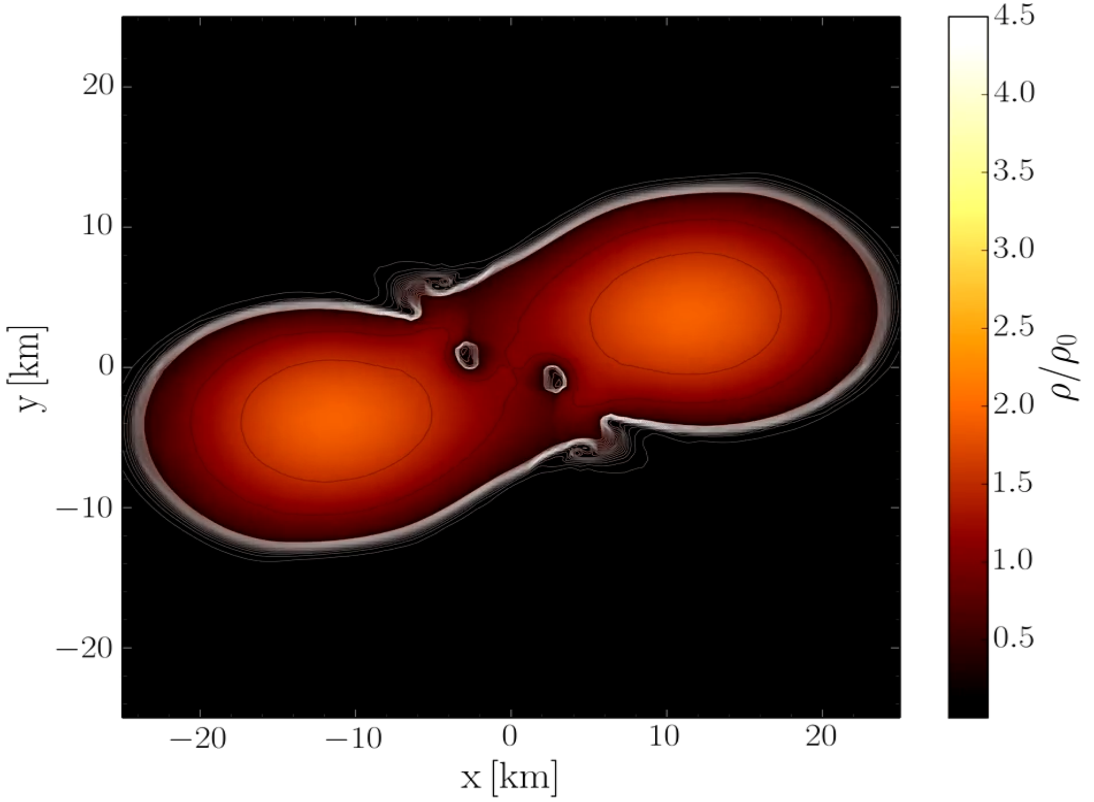
Central value of the lapse function α_c (upper panel) and maximum of the rest mass density ρ_{max} in units of ρ_0 (lower panel) versus time for the high mass simulations.

Evolution of the density in the post merger phase

GNH3-EOS, initial NS mass: 1.35 M_{solar}



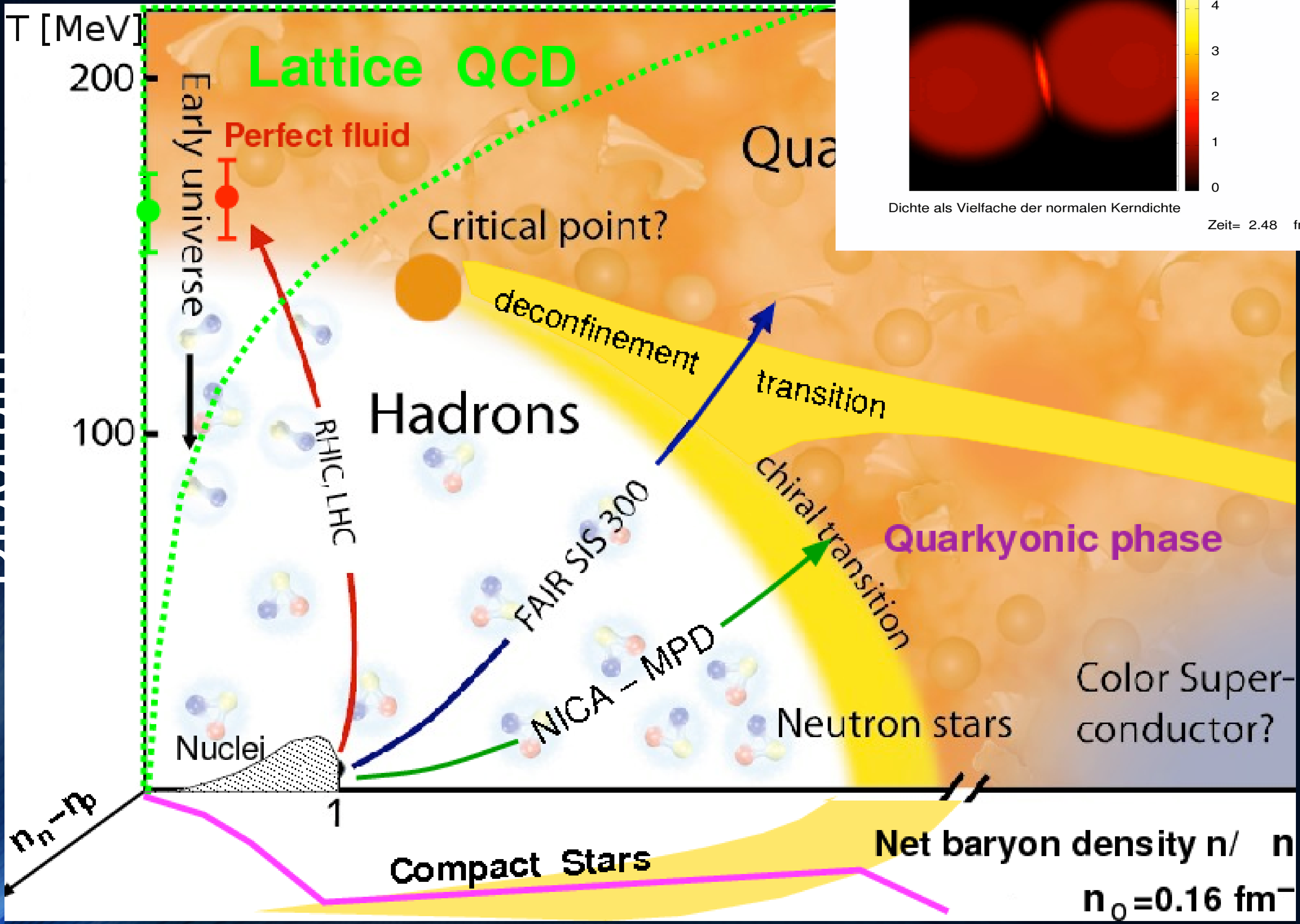
Gravitational wave amplitude at a distance of 50 Mpc

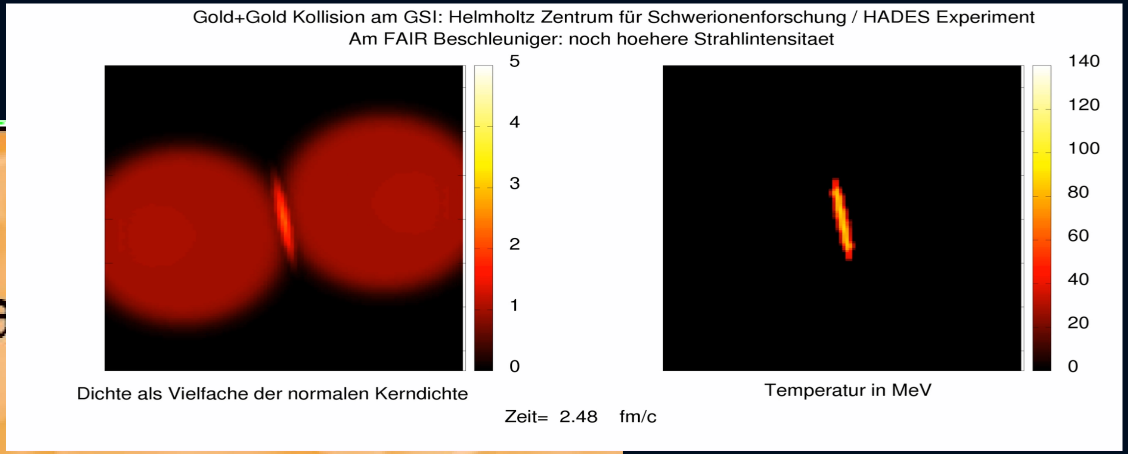


Rest mass density distribution $\rho(x,y)$ in the equatorial plane in units of the nuclear matter density ρ_0

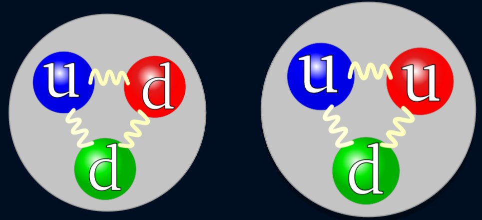
The Hadron-Quark Phase Transition

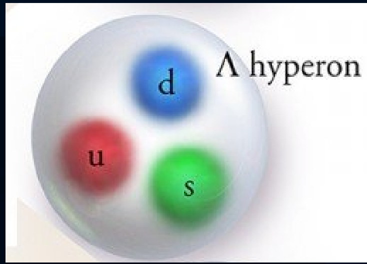
The QCD Phase Diagram



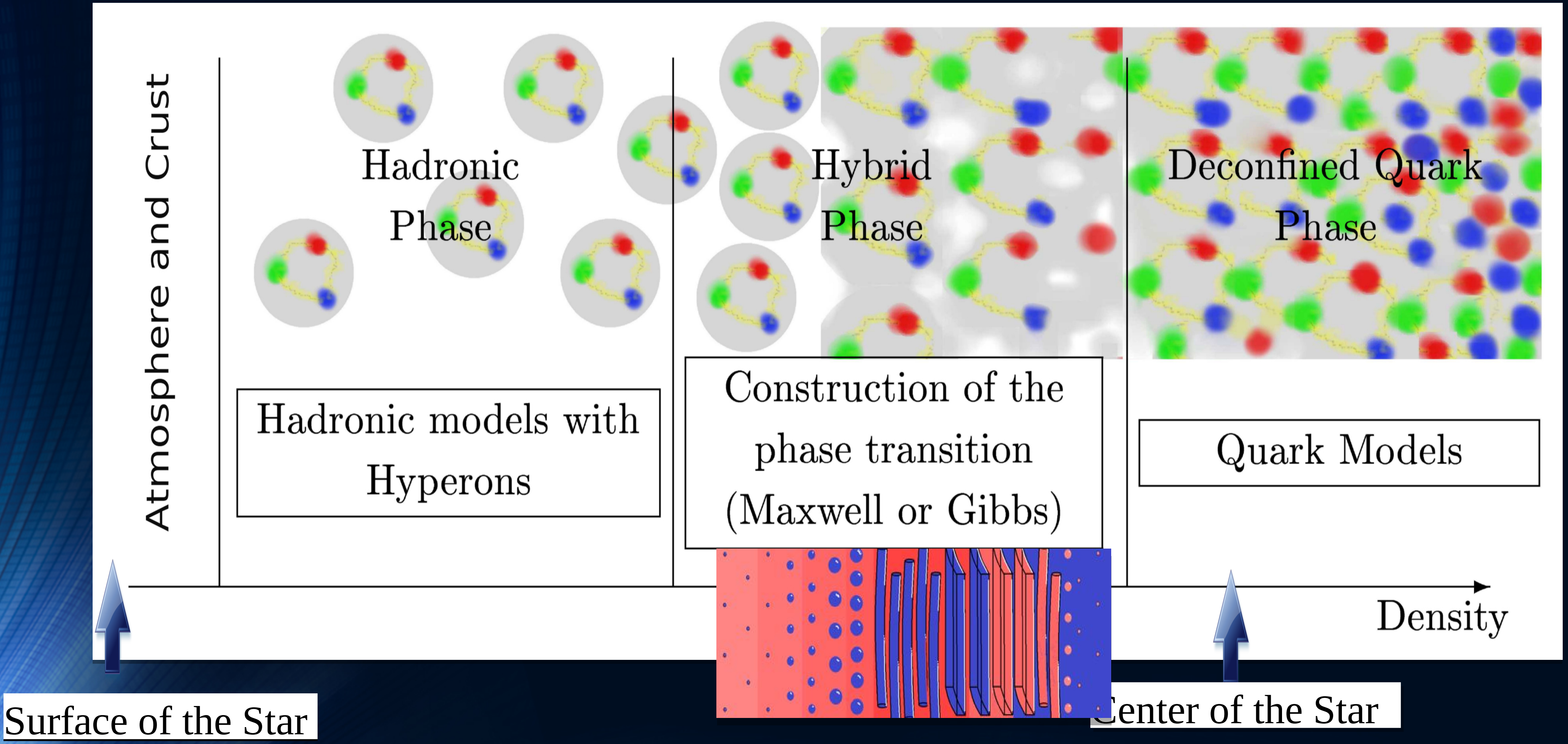


Credits:
Jan
Steinheimer
Neutron Proton



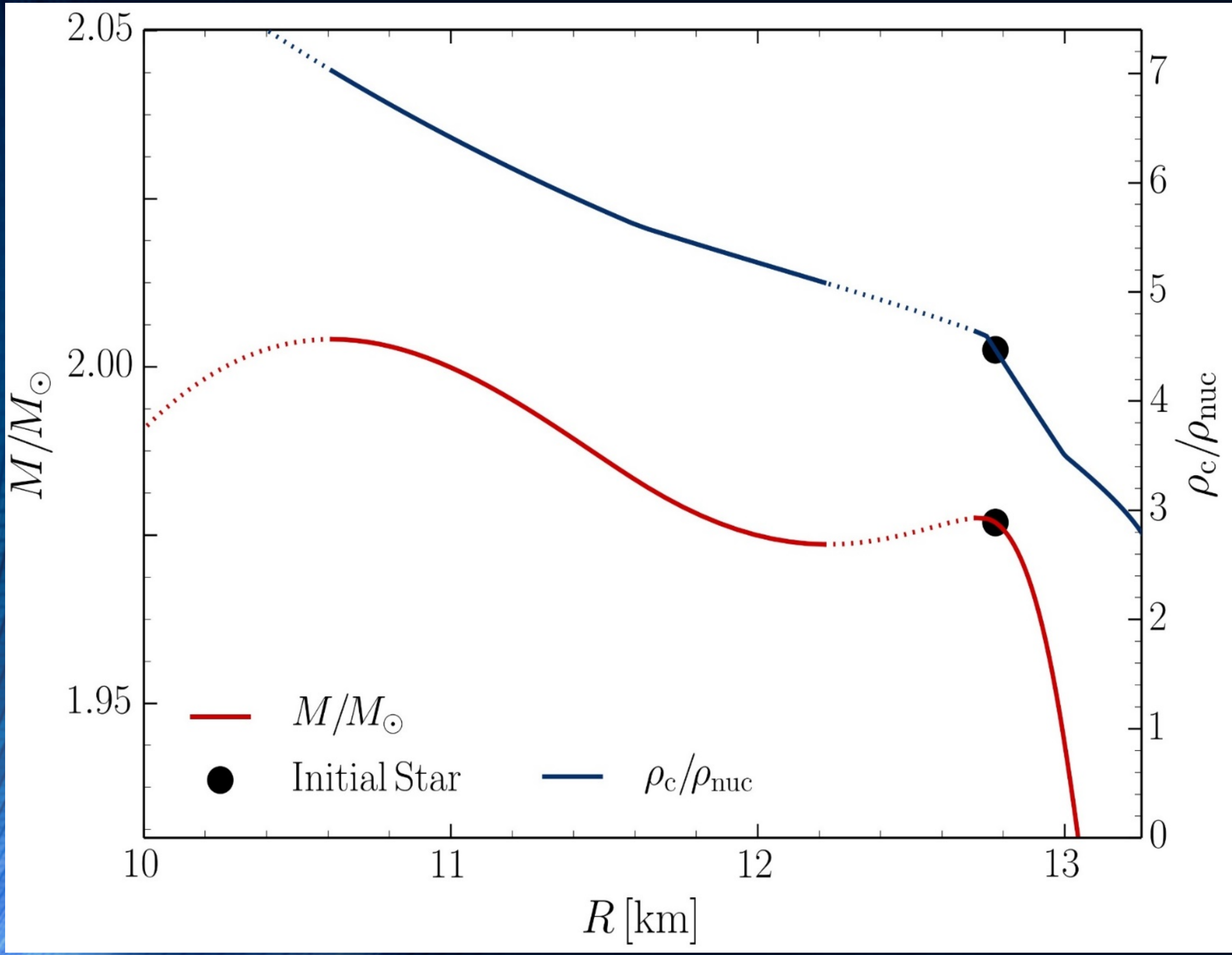


The QCD – Phase Transition and the Interior of a Hybrid Star



Matthias Hanauske; Doctoral Thesis:
Properties of Compact Stars within QCD-motivated Models; University Library Publication Frankfurt (2004)

The Hadron-Quark Phase Transition and
the Third Family of Compact Stars (Twin Stars)



Sarmistha Banik, Matthias Hanauske, Debades Bandyopadhyay and Walter Greiner, Rotating compact stars with exotic matter, Phys.Rev.D 70 (2004) p.12304

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

M.Alford and A. Sedrakian, Compact stars with sequential QCD phase transitions. Physical review letters, 119(16), 161104 (2017)..

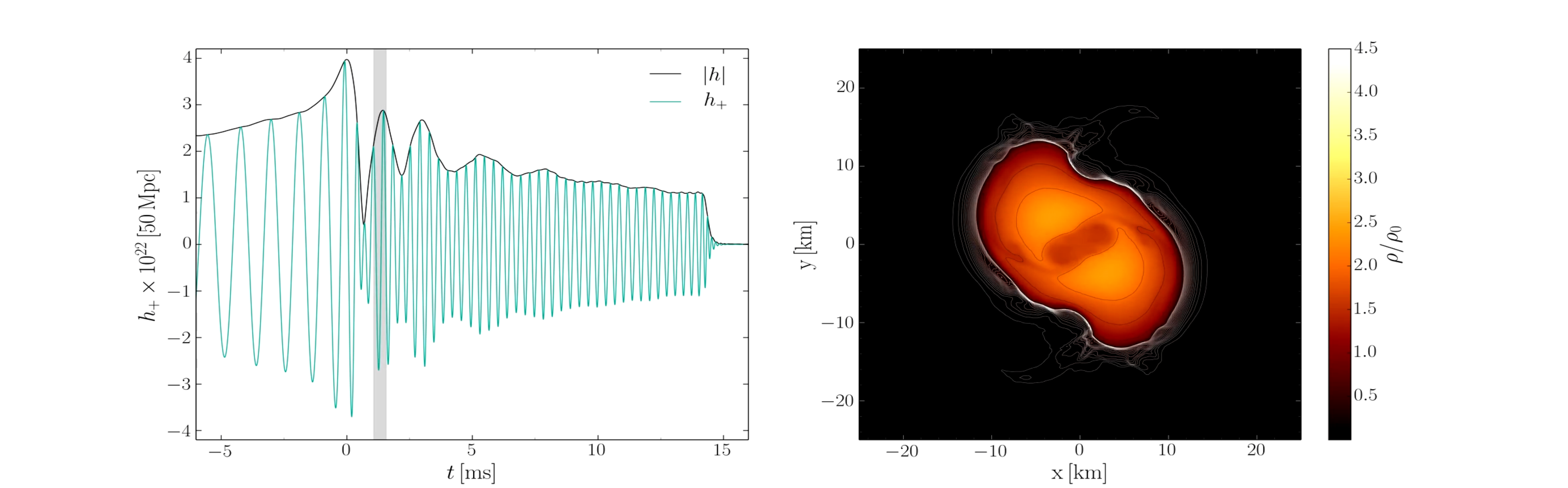
D.Alvarez-Castillo and D.Blaschke, High-mass twin stars with a multipolytrope equation of state. Physical Review C, 96(4), 045809 (2017) .

A. Ayriyan, N.-U. Bastian, D. Blaschke, H. Grigorian, K. Maslov, D. N. Voskresensky, How

Glendenning, N. K., & Kettner, C. (1998). Nonidentical neutron star twins. Astron. Astrophys., 353(LBL-42080), L9.

Evolution of the density in the post merger phase

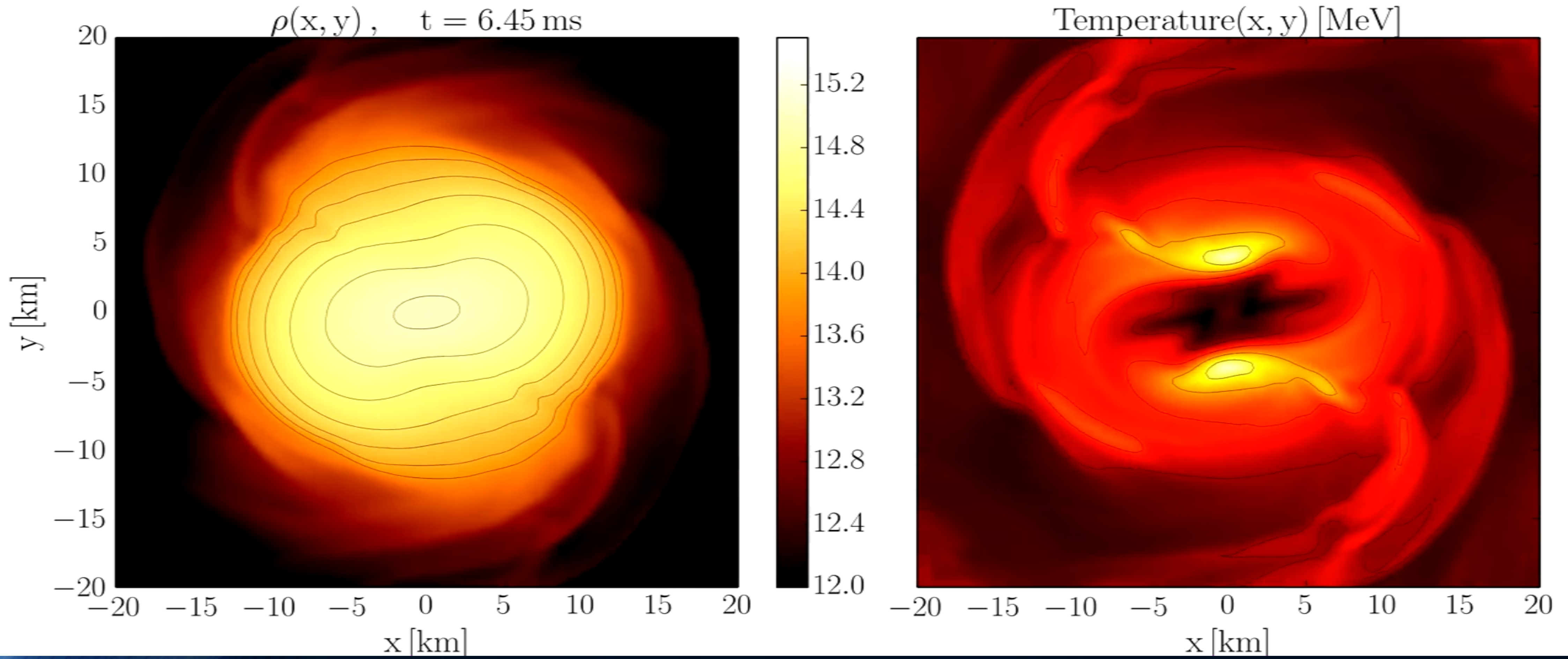
ALF2-EOS: Mixed phase region starts at $3\rho_0$ (see red curve), initial NS mass: 1.35 M_{solar}



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

Density   Temperature



EOS: LS200 , Mass: 1.32 M_{Solar}

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

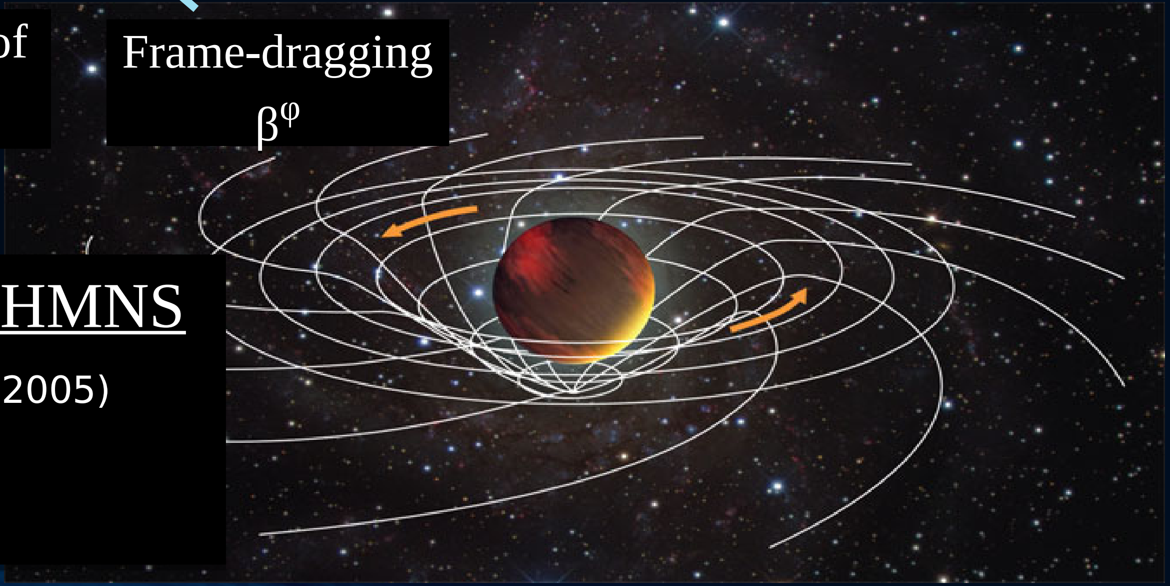
Lapse function α

Φ-component of 3-velocity v^φ

Frame-dragging β^φ

(3+1)-decomposition of spacetime:

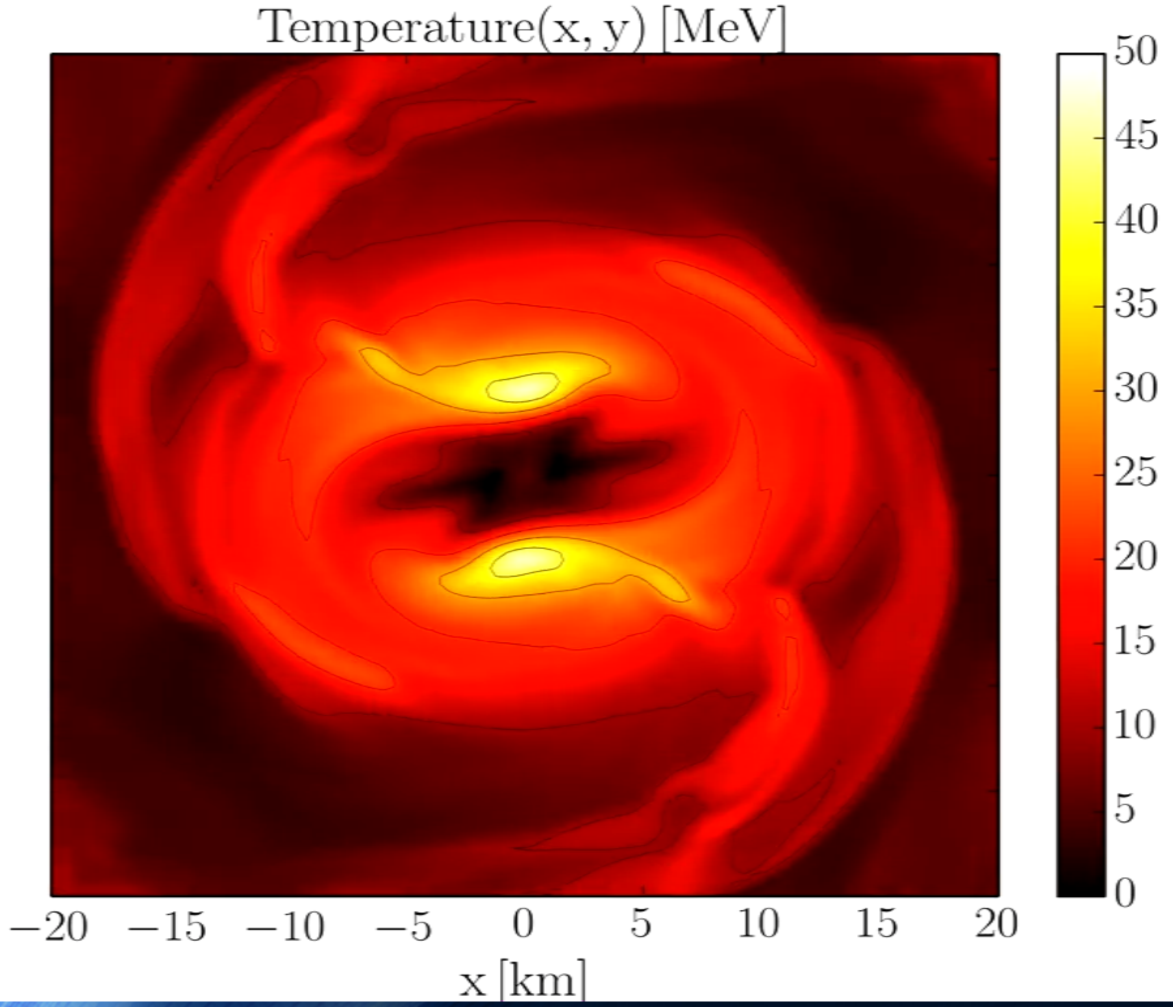
$$g_{\mu\nu} = \begin{pmatrix} -\alpha^2 + \beta_i\beta^i & \beta_i \\ \beta_i & \gamma_{ij} \end{pmatrix}$$

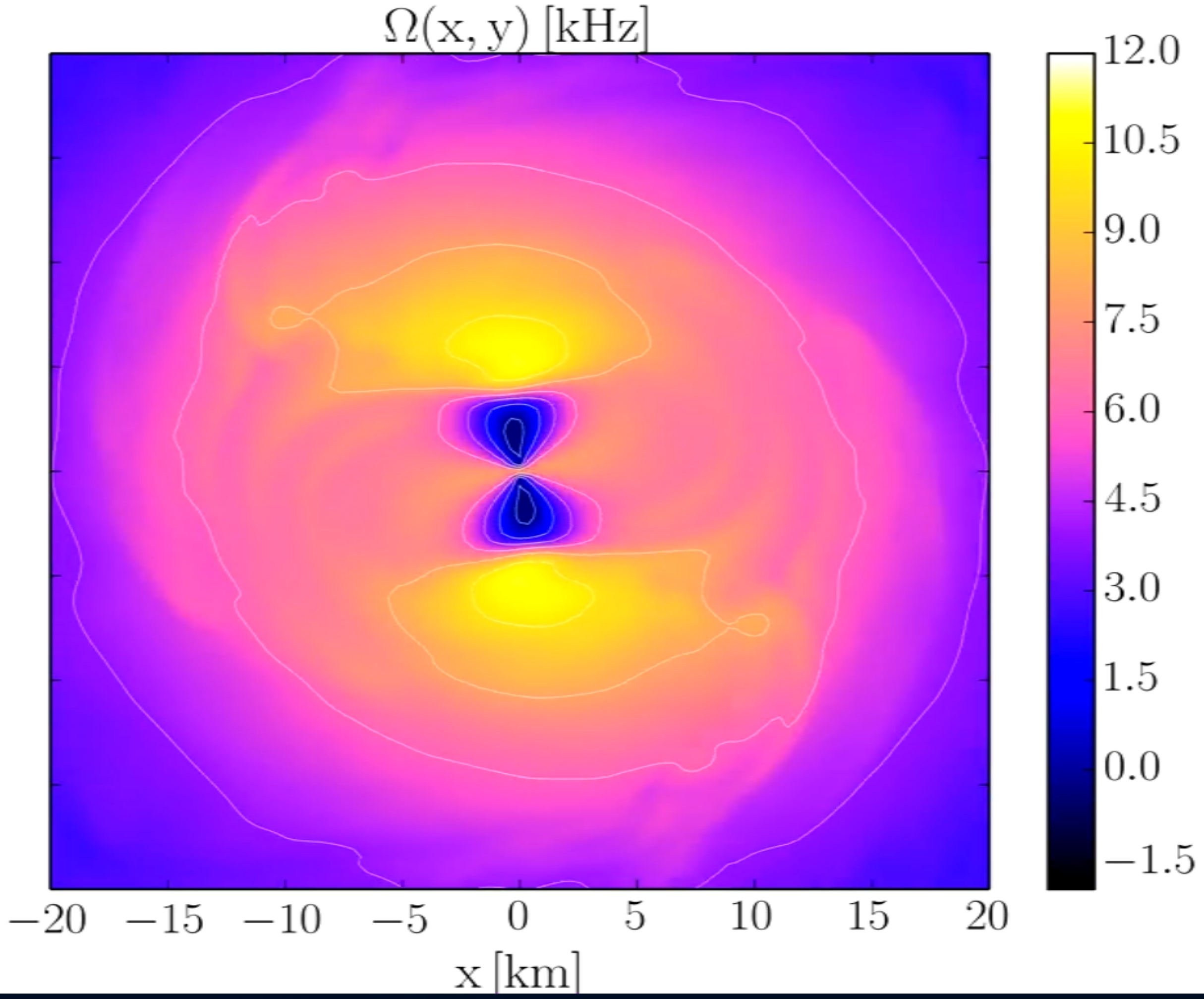


Focus: Inner core of the differentially rotating HMNS

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)

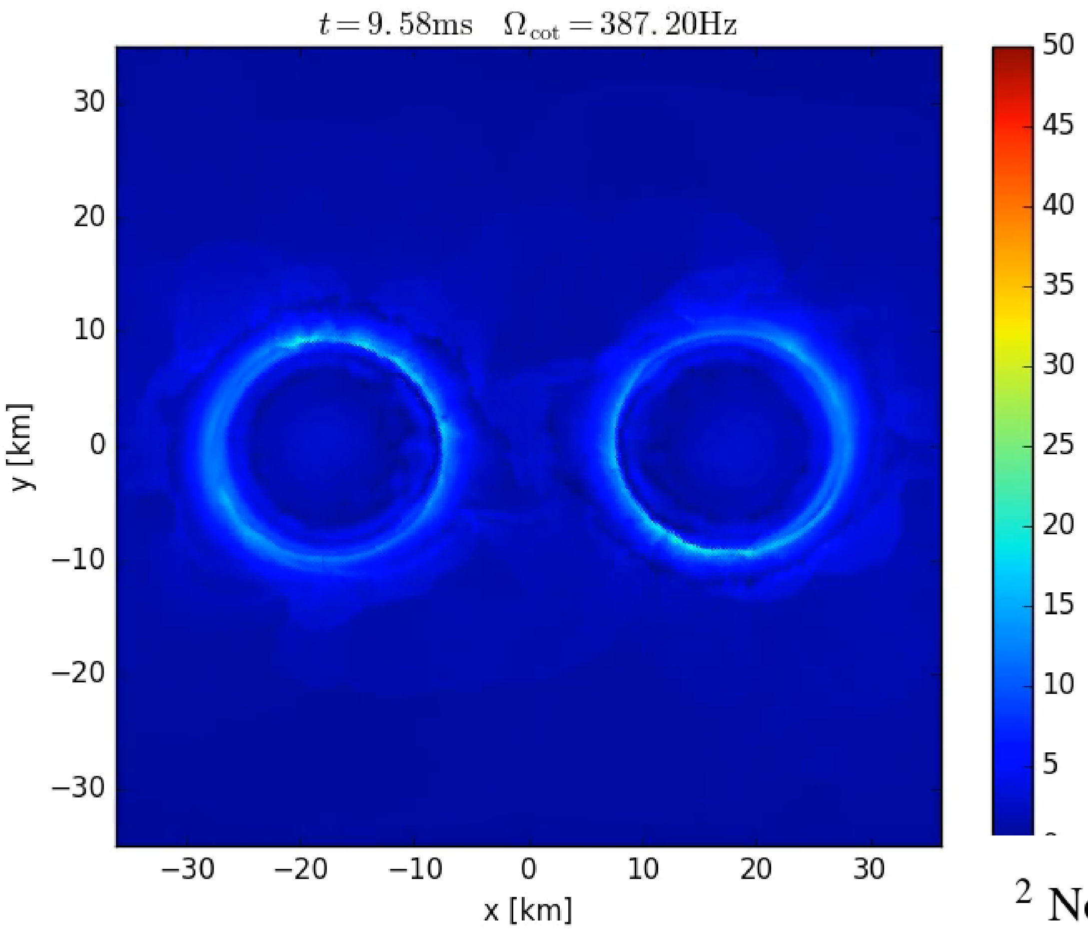
Temperature Angular Velocity

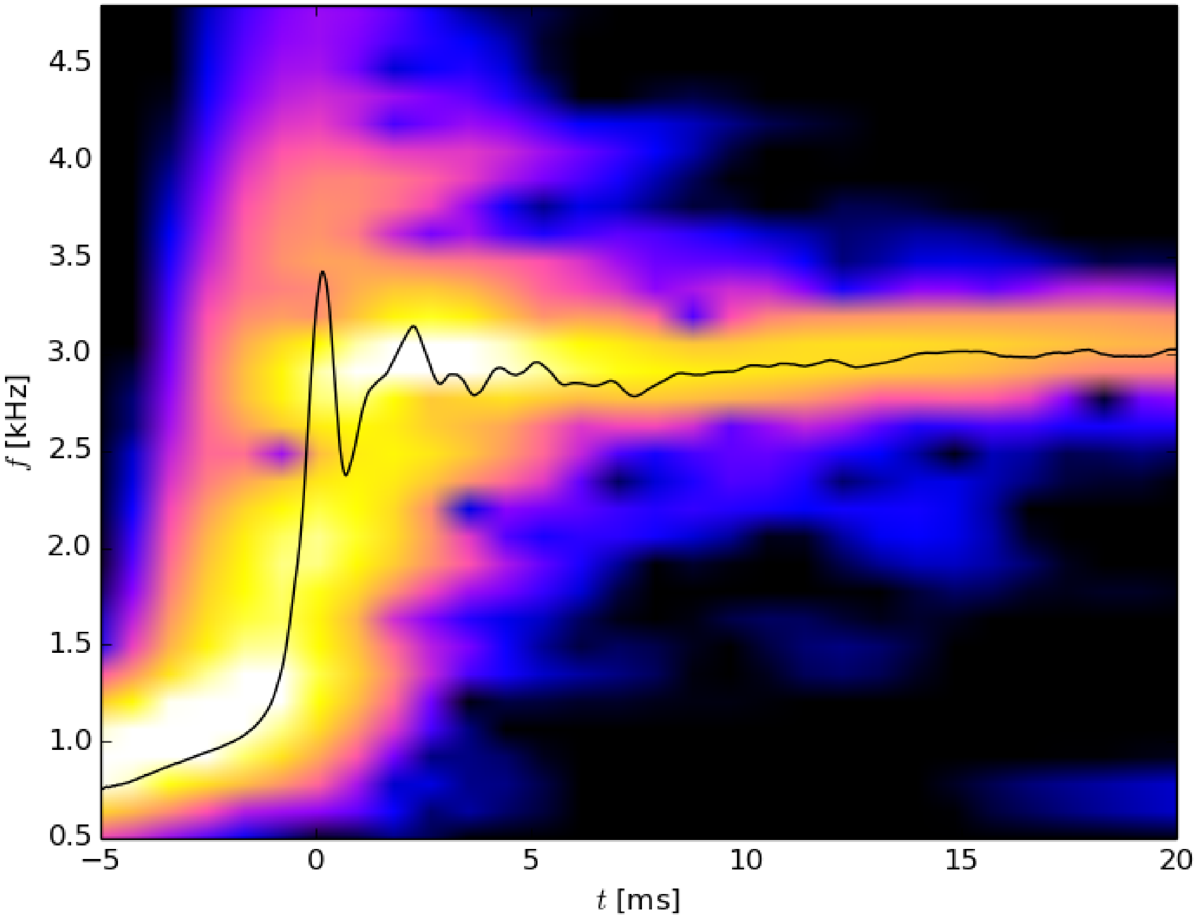




EOS: LS200 , Mass: 1.32 M_{Solar}

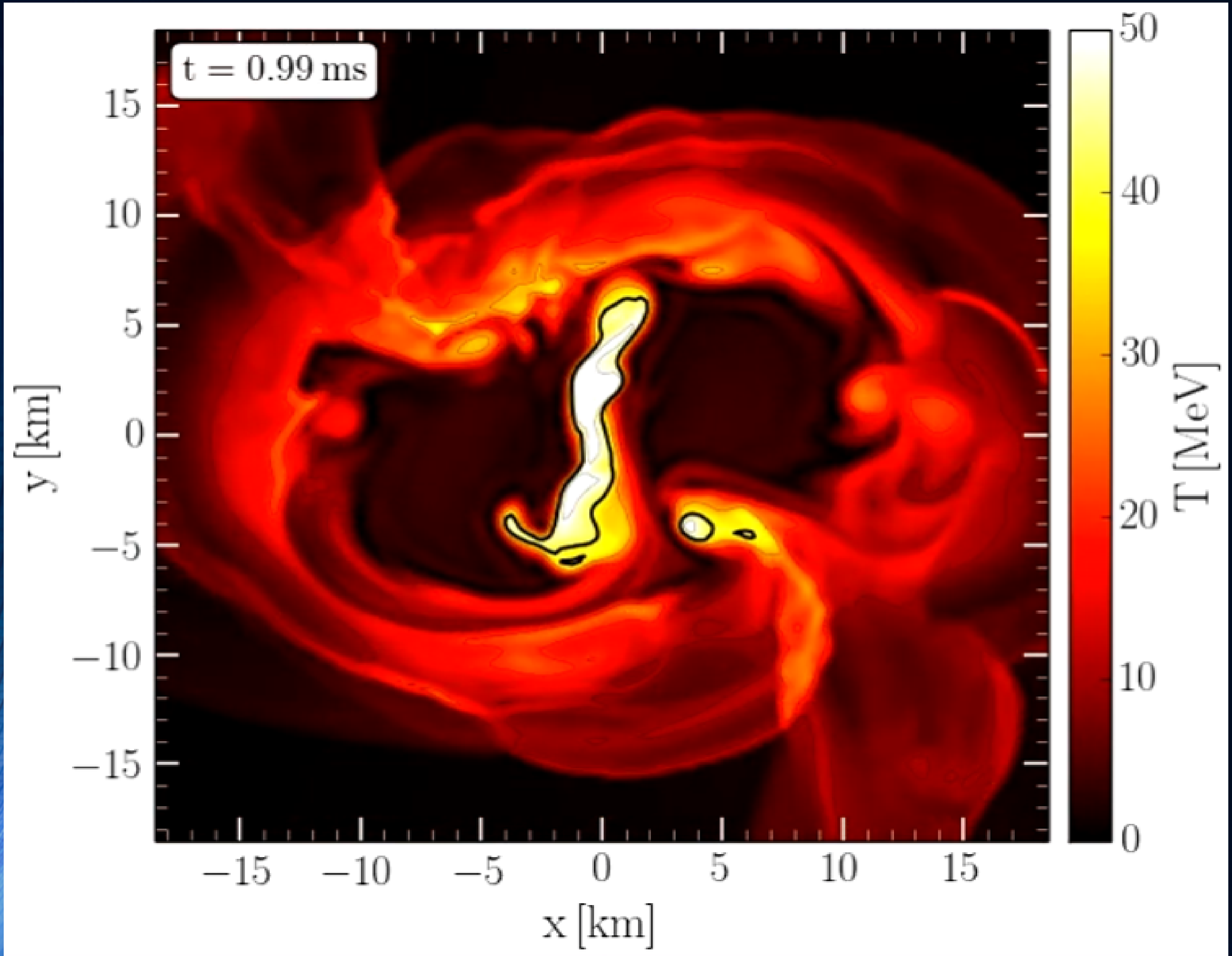
The Co-Rotating Frame





Simulation and movie has been produced by Luke Bovard

[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.



Evolution of the Temperature in the post merger phase

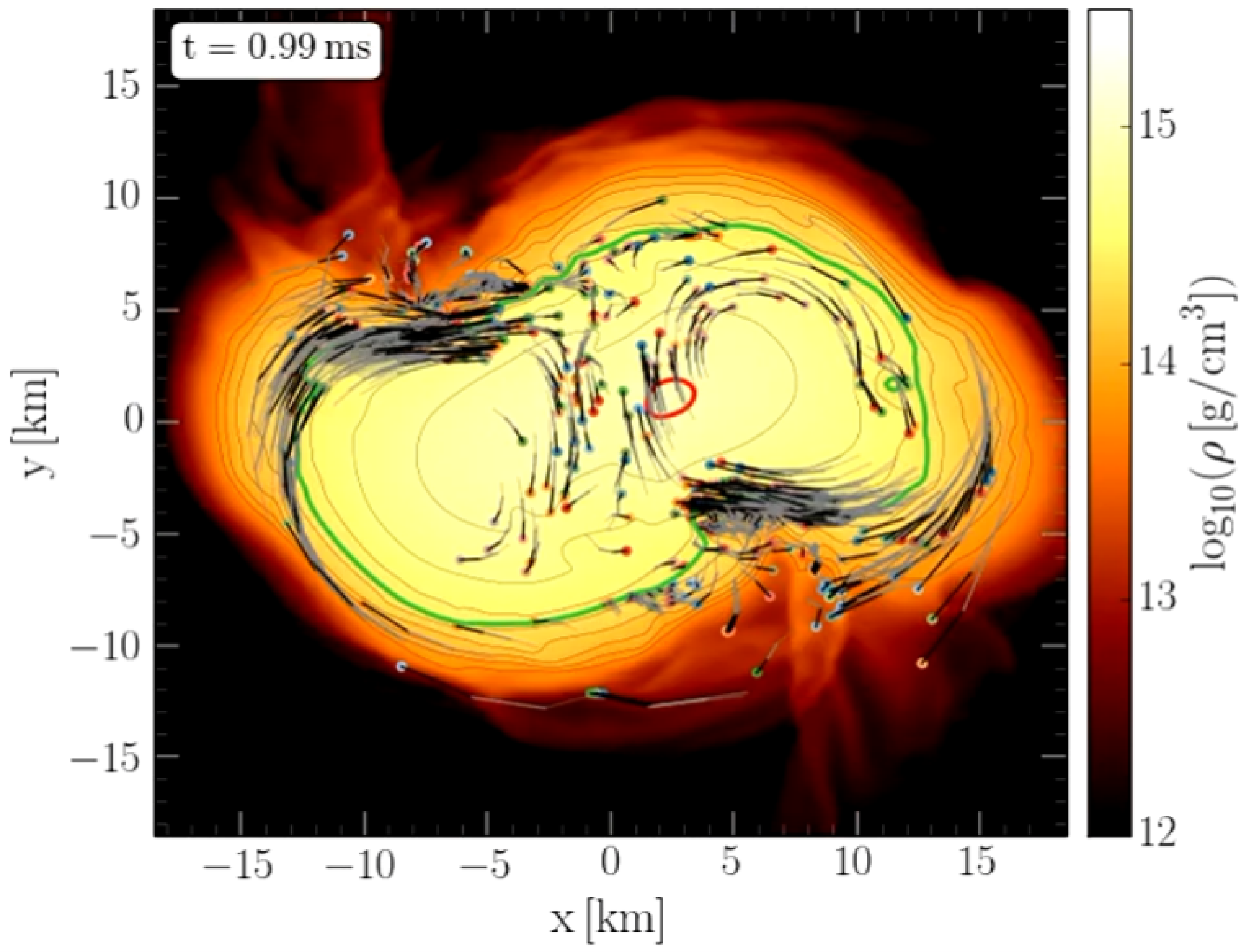
Hanauske, M., Takami, K., Bovard, L., Rezzolla, L., Font, J. A., Galeazzi, F., & Stöcker, H. (2017). Rotational properties of hypermassive neutron stars from binary mergers. Physical Review D, 96(4), 043004

Kastaun, W., Ciolfi, R., Endrizzi, A., & Giacomazzo, B. (2017). Structure of stable binary neutron star merger remnants: Role of initial spin. Physical Review D, 96(4), 043019

M. Hanauske, et.al., Connecting Relativistic Heavy Ion Collisions and Neutron Star Mergers by the Equation of State of Dense Hadron-and Quark Matter as signalled by Gravitational particles tracking individual fluid elements in the equatorial plane of the HMNS at post-merger times

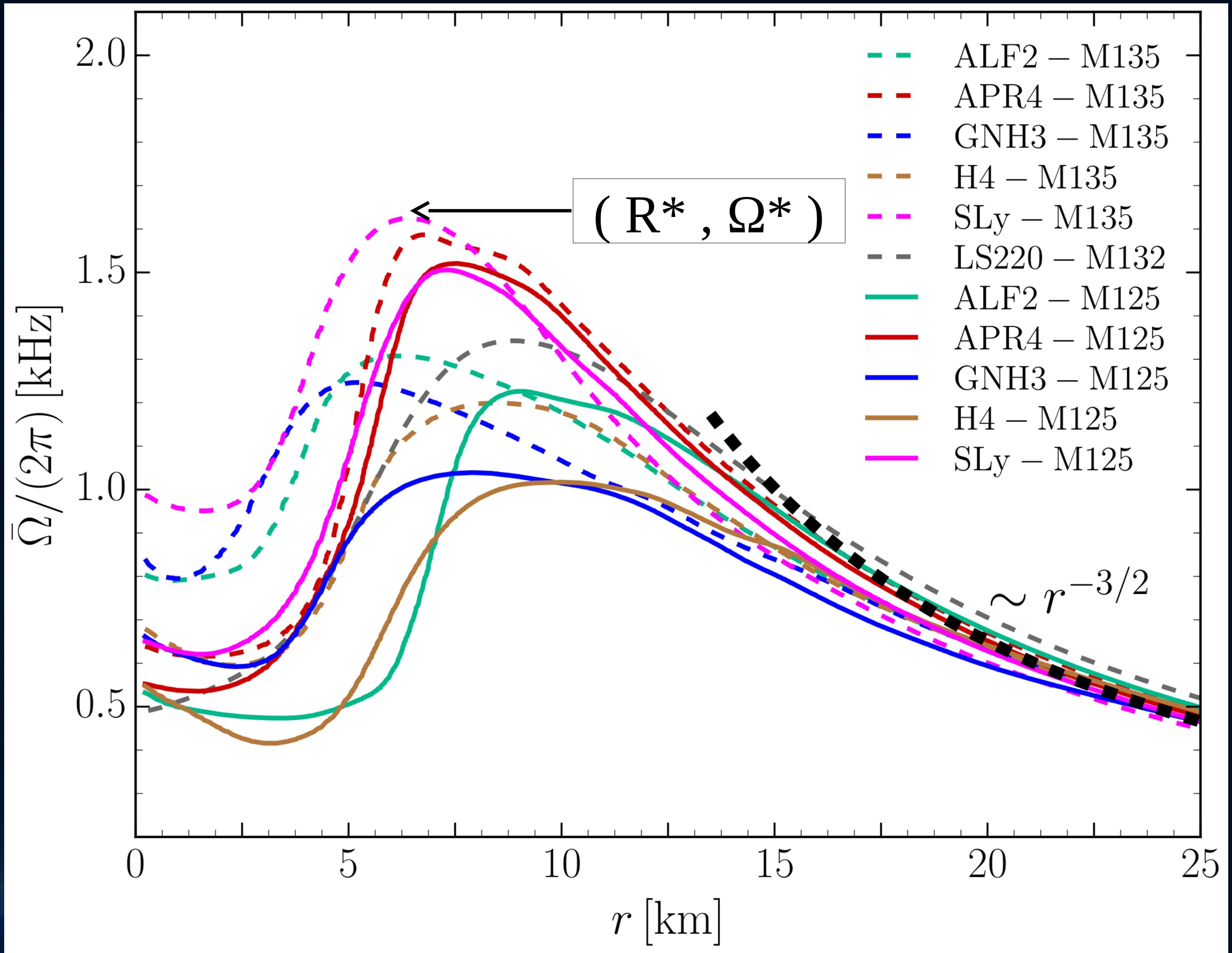
Mark G. Alford, Luke Bovard, Matthias Hanauske, Luciano Rezzolla, and Kai Schwenzer (2018)
Viscous Dissipation and Heat Conduction in Binary Neutron-Star Mergers. Phys. Rev. Lett. 120, 041101

Different rotational behaviour of the quark-gluon-plasma produced in non-central ultra-relativistic heavy ion collisions L. Adamczyk et.al., “Global Lambda-hyperon polarization in nuclear collisions: evidence for the most vortical fluid”, Nature 548, 2017



Central value

Time-averaged Rotation Profiles of the HMNSs

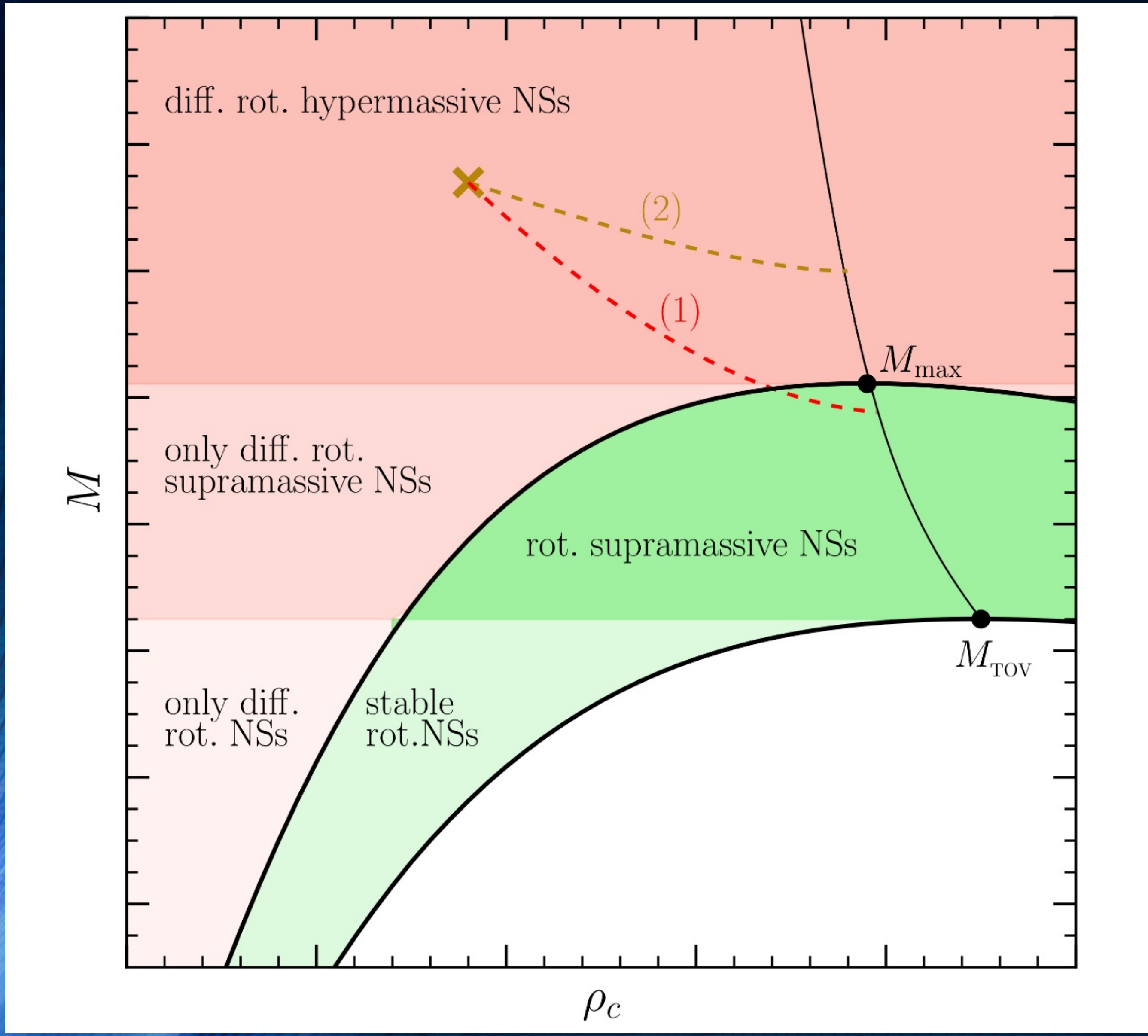


Time-averaged rotation profiles for different EoS
Low mass runs (solid curves), high mass runs (dashed curves).

Soft EoSs:
Sly
APR4

Stiff EoSs:
GNH3
H4

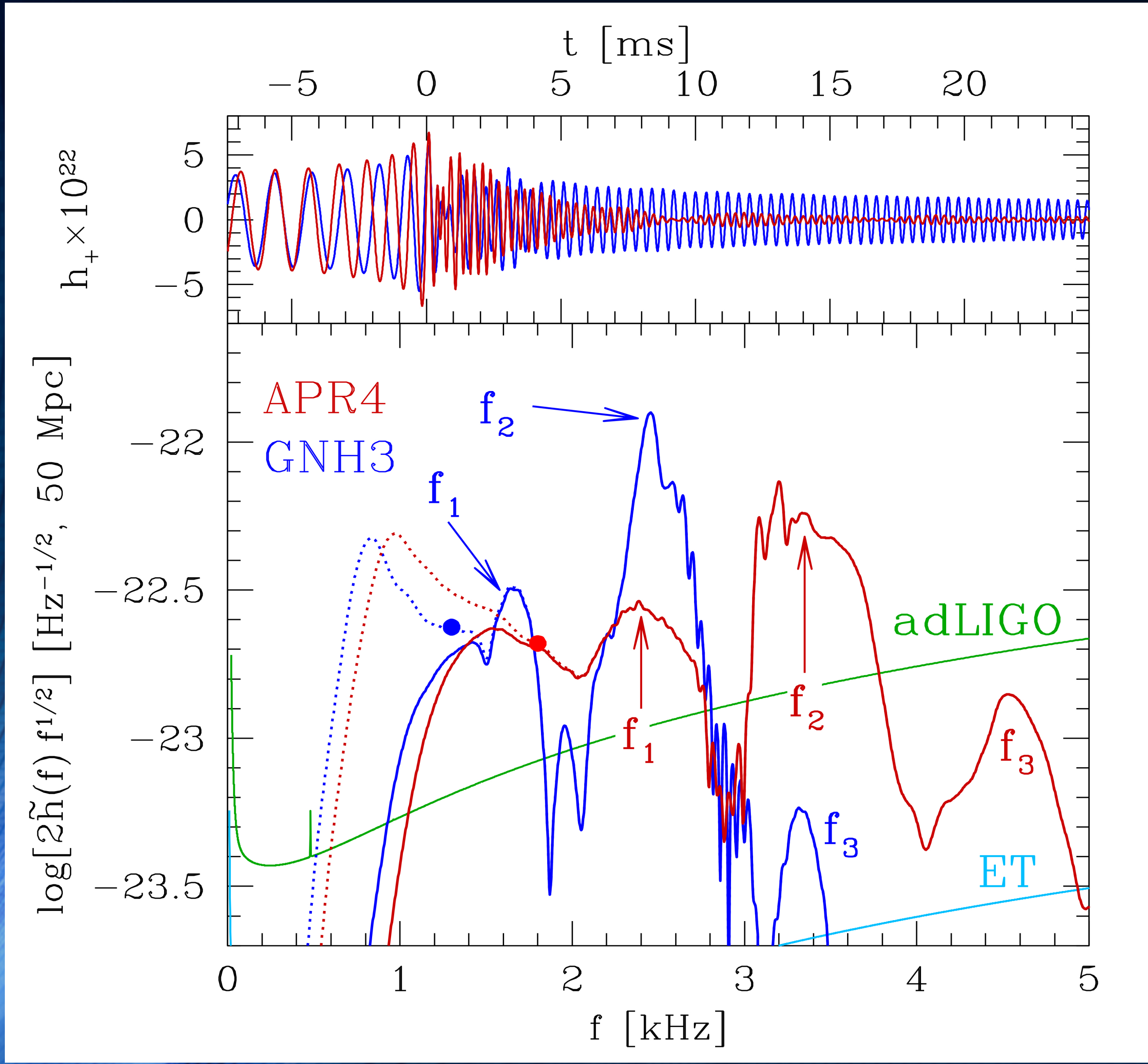
GW170817: Evolution of the HMNS until BH formation



The highly differentially rotating hypermassive/supramassive neutron star will spin down and redistribute its angular momentum (e.g. due to magnetic braking). After ~1 second it will cross the stability line as a uniformly rotating supramassive neutron star (close to M_{max}) and collapse to a black hole. Parts of the ejected matter will fall back into the black hole producing the gamma-ray burst.

L.Rezzolla, E.Most, L.Weih, “Using Gravitational Wave Observations and Quasi-Universal Relations to constrain the maximum Mass of Neutron Stars”, arXiv:1711.00314 (accepted in ApJL)
$2.01 \pm 0.04 < M_{max} < 2.16 \pm 0.17$
E.Most, L.Weih, L.Rezzolla, J. Schaffner-Bielich “New constraints on radii and tidal deformabilities of neutron stars from GW170817”, arXiv:1803.00549
$12\,km < R_{1.4} < 13.45\,km$, $\Lambda_{1.4} > 375$

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.

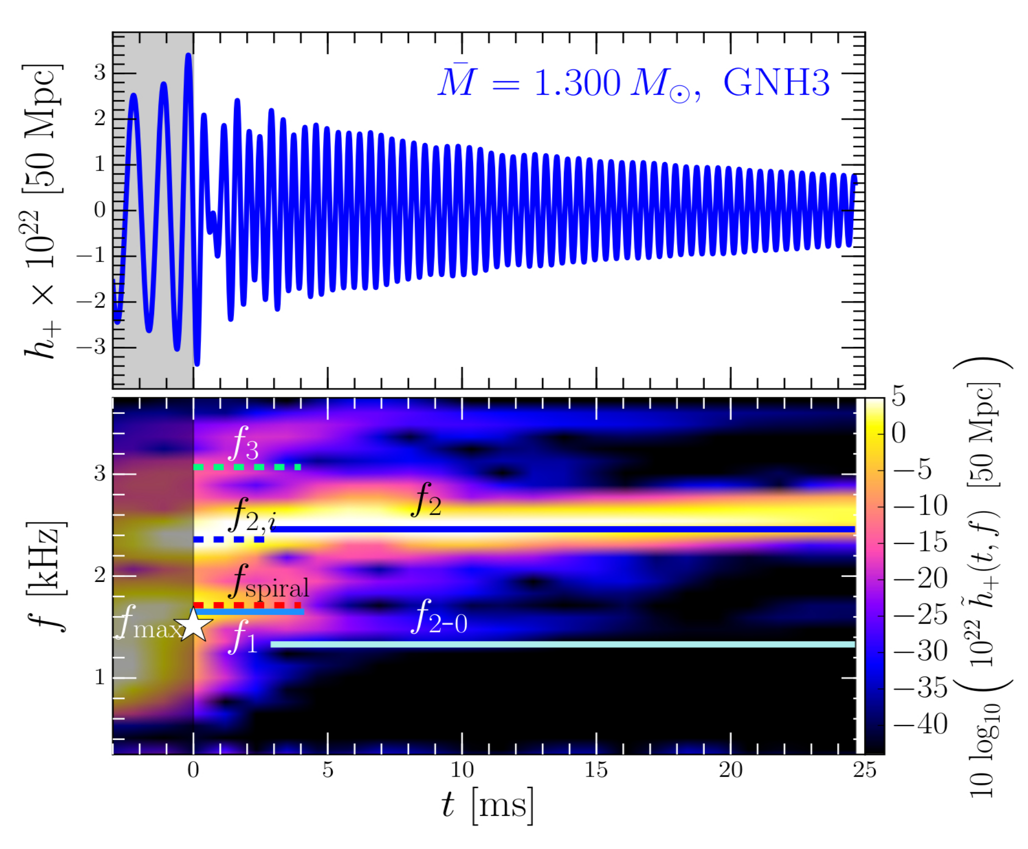
Bauswein, A., & Janka, H. T. (2012). Physical review letters, 108(1), 011101.

Clark, J. A., Bauswein, A., Stergioulas, N., & Shoemaker, D. (2015). arXiv:1509.08522.

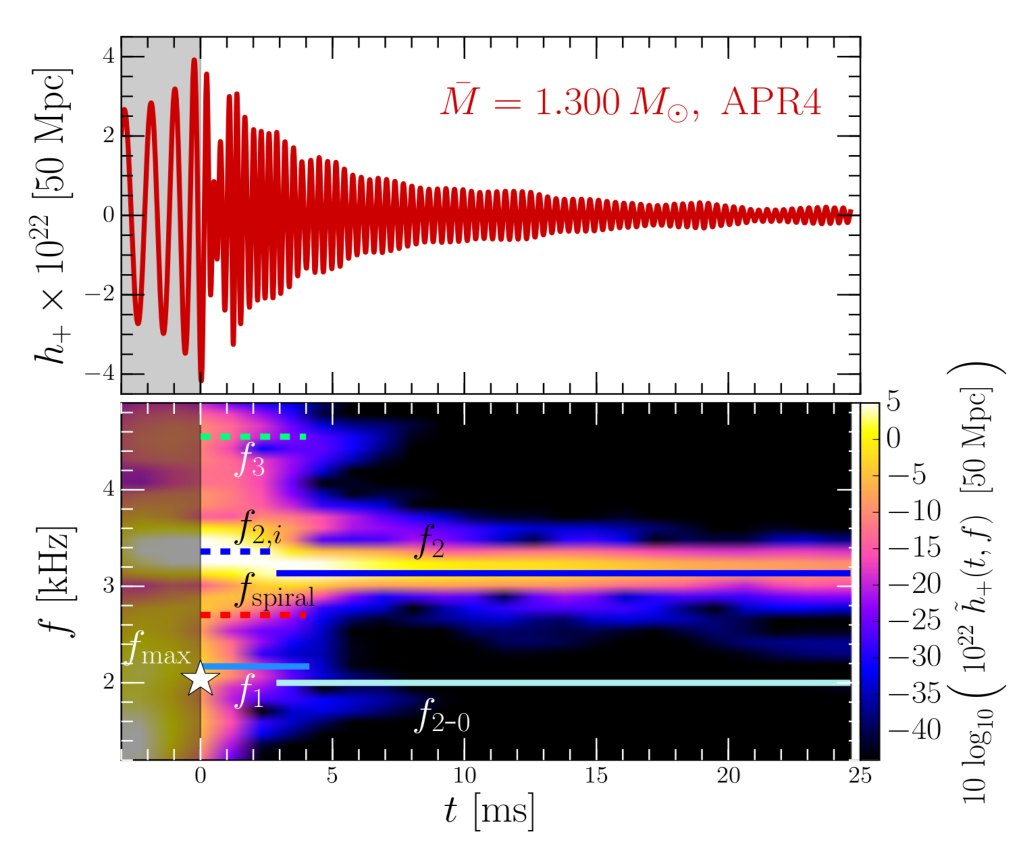
Bernuzzi, S., Dietrich, T., & Nagar, A. (2015). Physical review letters, 115(9), 091101.

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

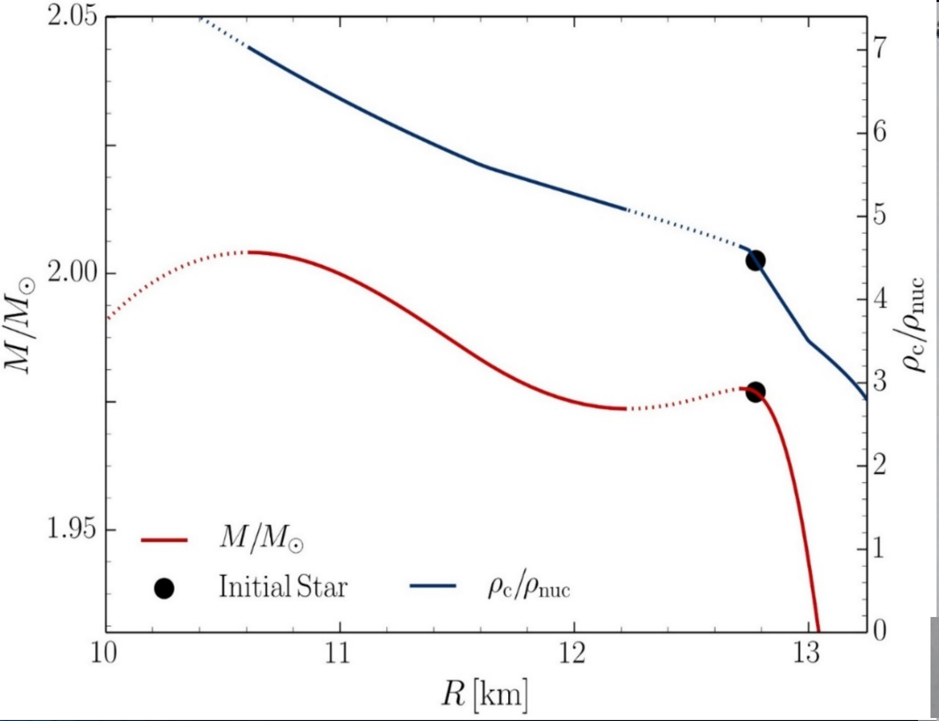


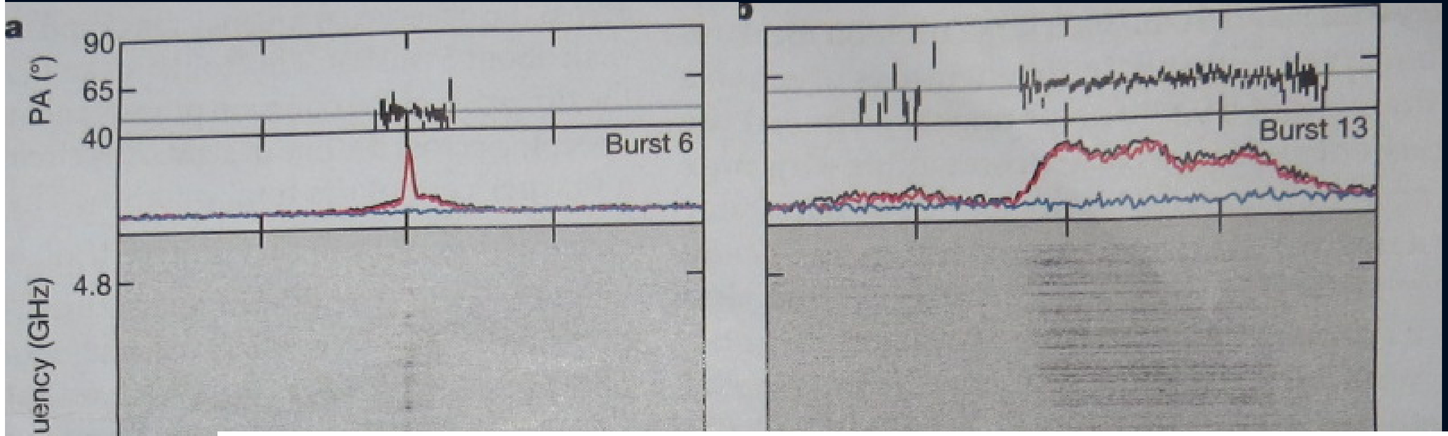
Soft EOS

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!!!

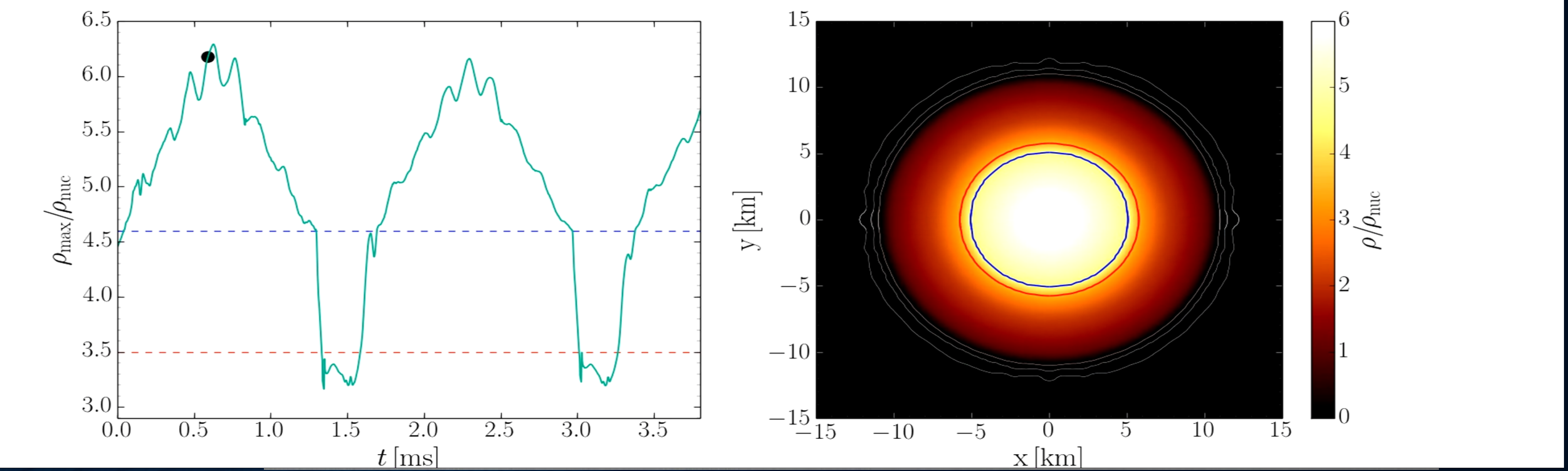
Evolution of the frequency spectrum of the emitted gravitational waves for the stiff GNH3 (left) and soft APR4 (right) EOS.

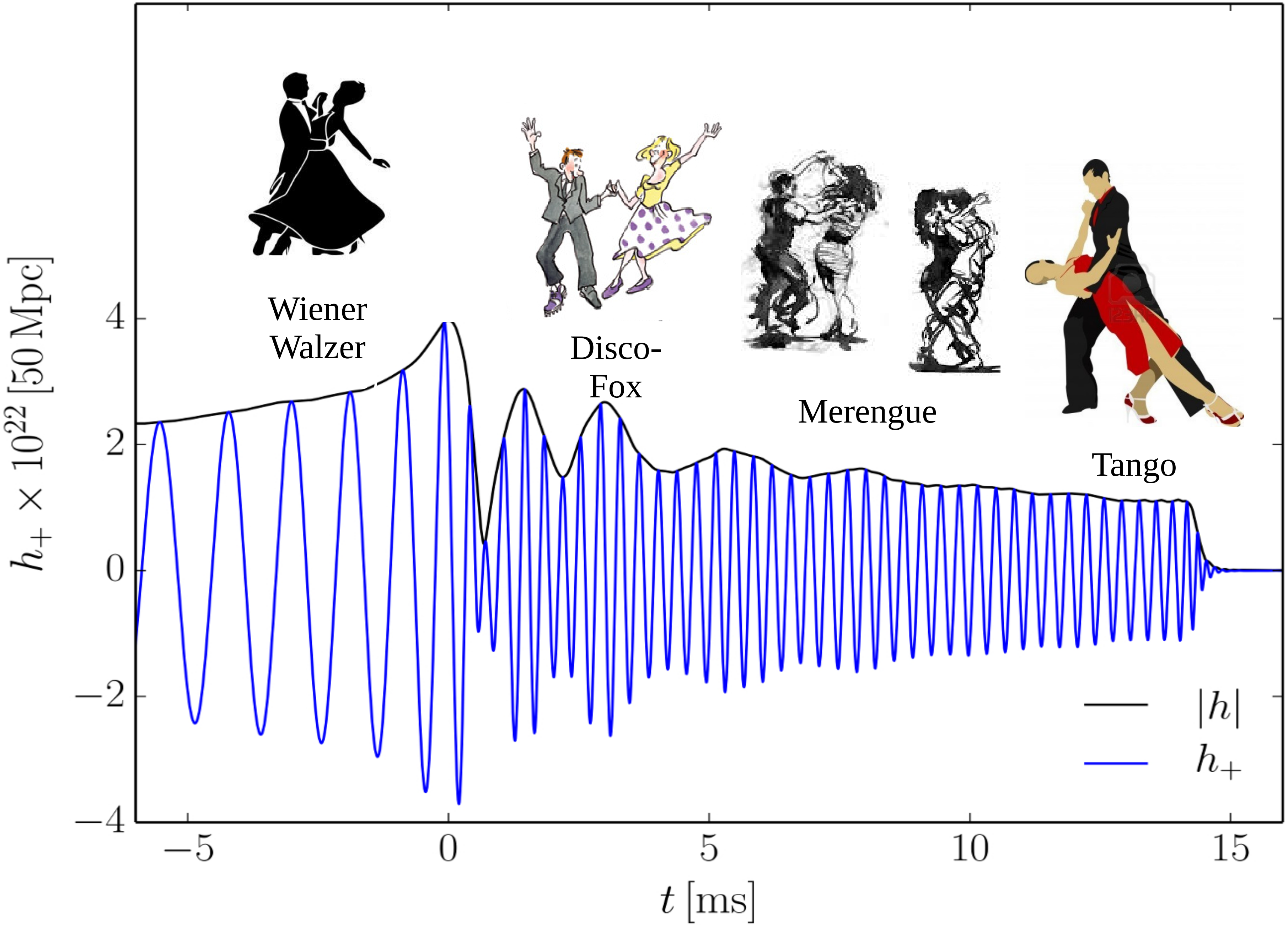




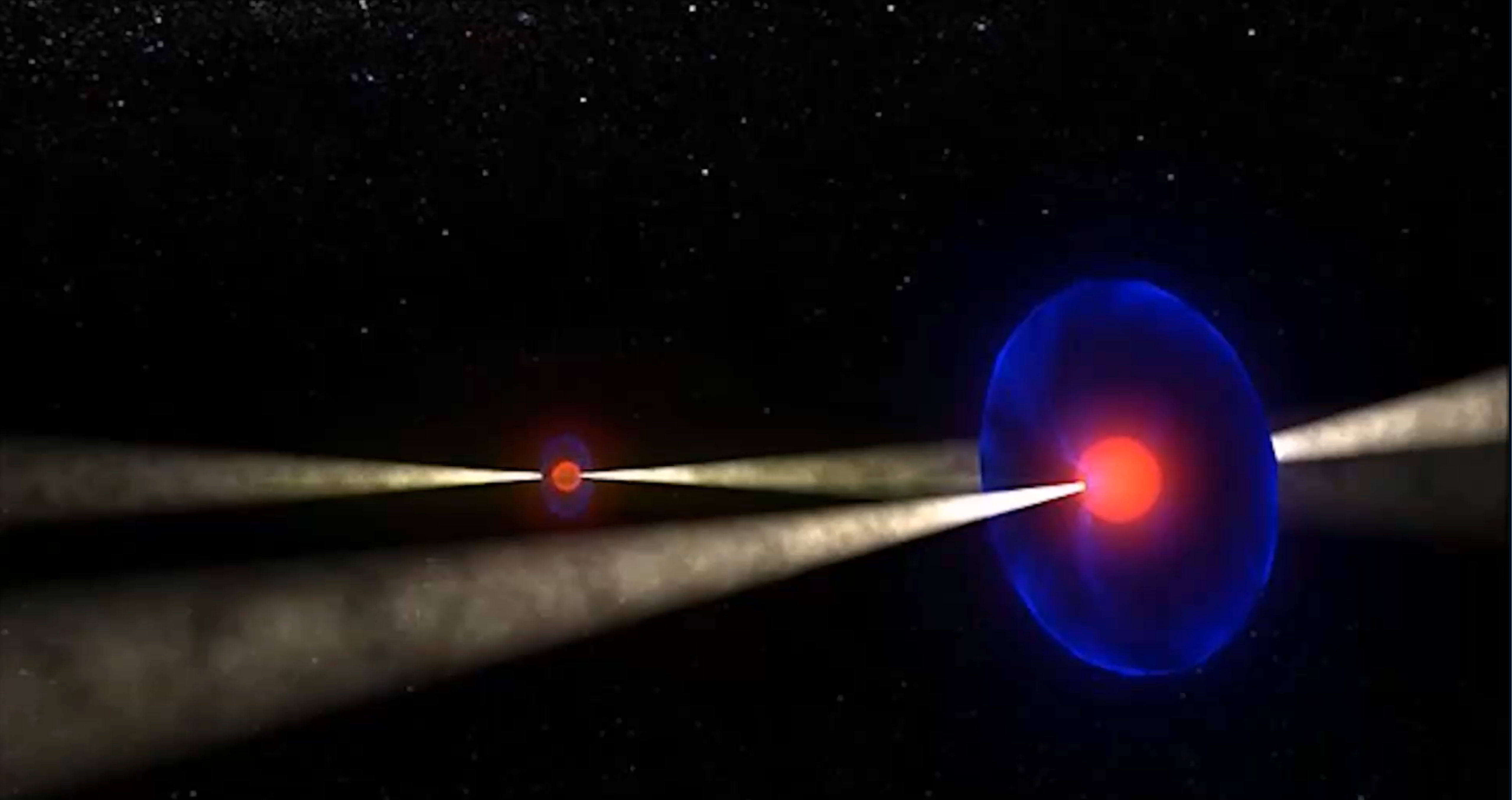
<u>Report of 16 detected bursts from FRB 121102:</u>
D.Michilli, et.al., “An extreme magneto-ionic environment associated with the fast radio burst source FRB 121102”, Nature 553, p.182 (2018)

M.Hanauske, et.al., “Twin Star Oscillations” (in preparation)

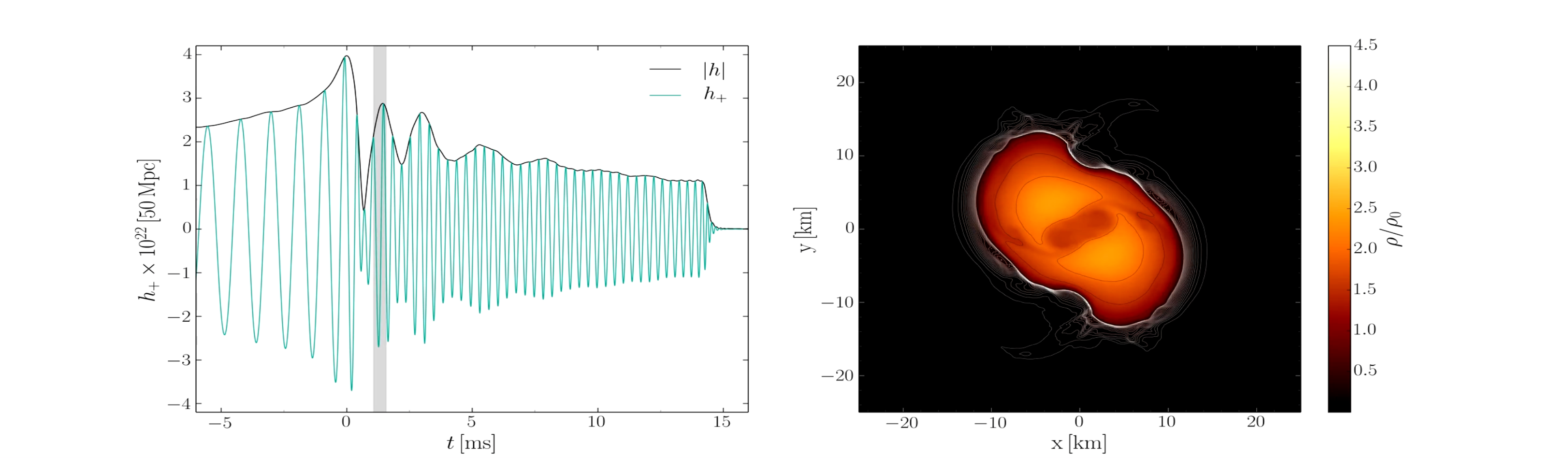




Wiener Walzer
Disco-Fox
Merengue
Tango
$h_+ \times 10^{22}\,[50\,\mathrm{Mpc}]$
$t\,[\mathrm{ms}]$
$|h|$
h_+
4
2
0
−2
−4
−5
0
5
10
15



The Neutronstar Merger Danc



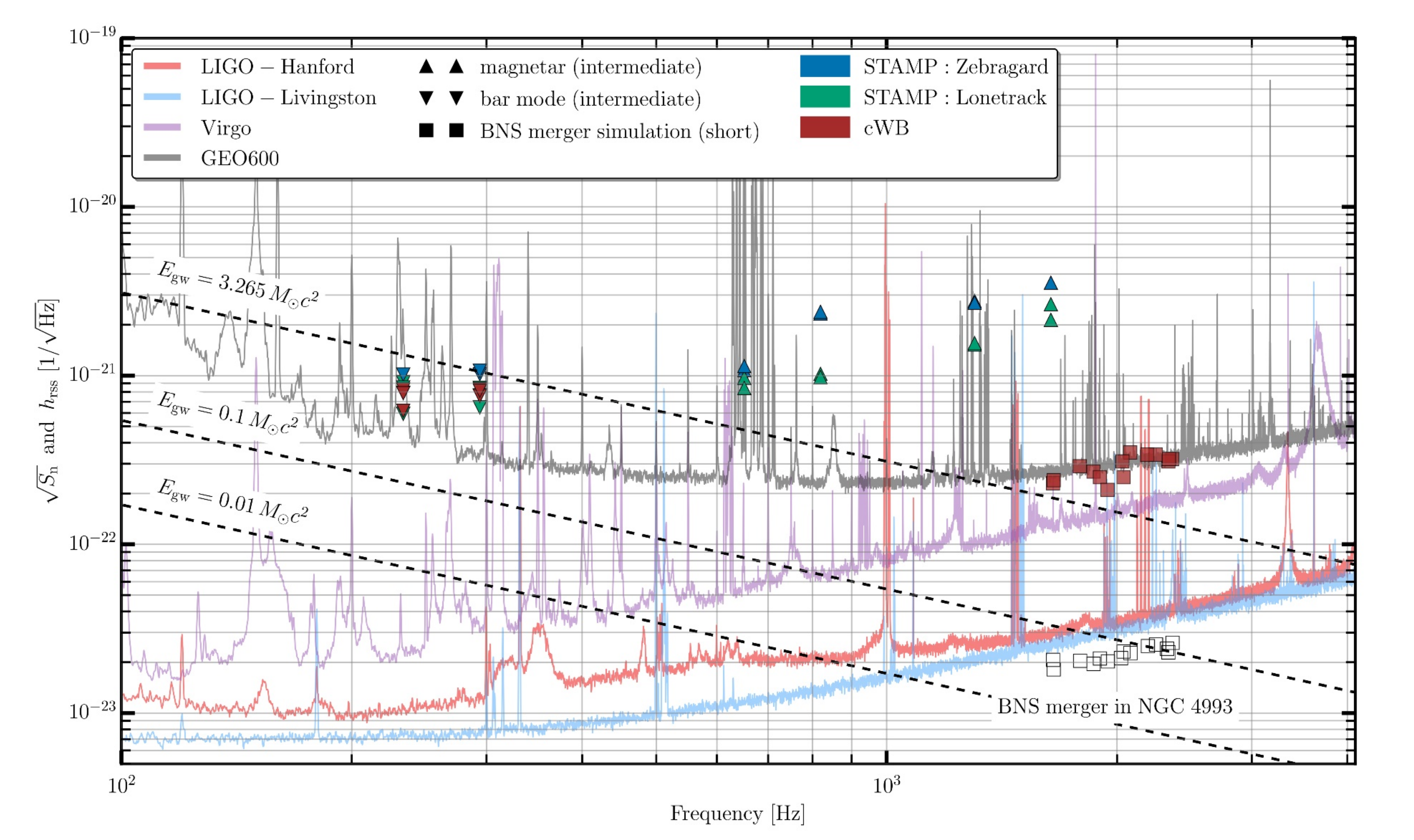
Summary and Discussions

ALF2-EOS: Mixed phase region starts at $3\rho_0$ (see red curve)

- In the post-merger phase of a binary neutron star merger, the density and temperature will reach extreme values and it is expected that a hadron-quark phase transition will be present in the interior region of the supramassive or hypermassive neutron star.
- Astrophysical observables of the hadron-quark phase transition:
  - If such a twin star collapse would happen during the postmerger phase it will be imprinted in the GW-signal
  - If the unstable twin star region is reached during the "post-transient" phase, the f2-frequency peak of the GW signal will change rapidly due to the sudden speed up of the differentially rotating HMNS

Additional Slides

SEARCH FOR POST-MERGER GRAVITATIONAL WAVES FROM THE REMNANT OF THE BINARYNEUTRON STAR MERGER GW170817 (see arXiv:1710.09320v1)

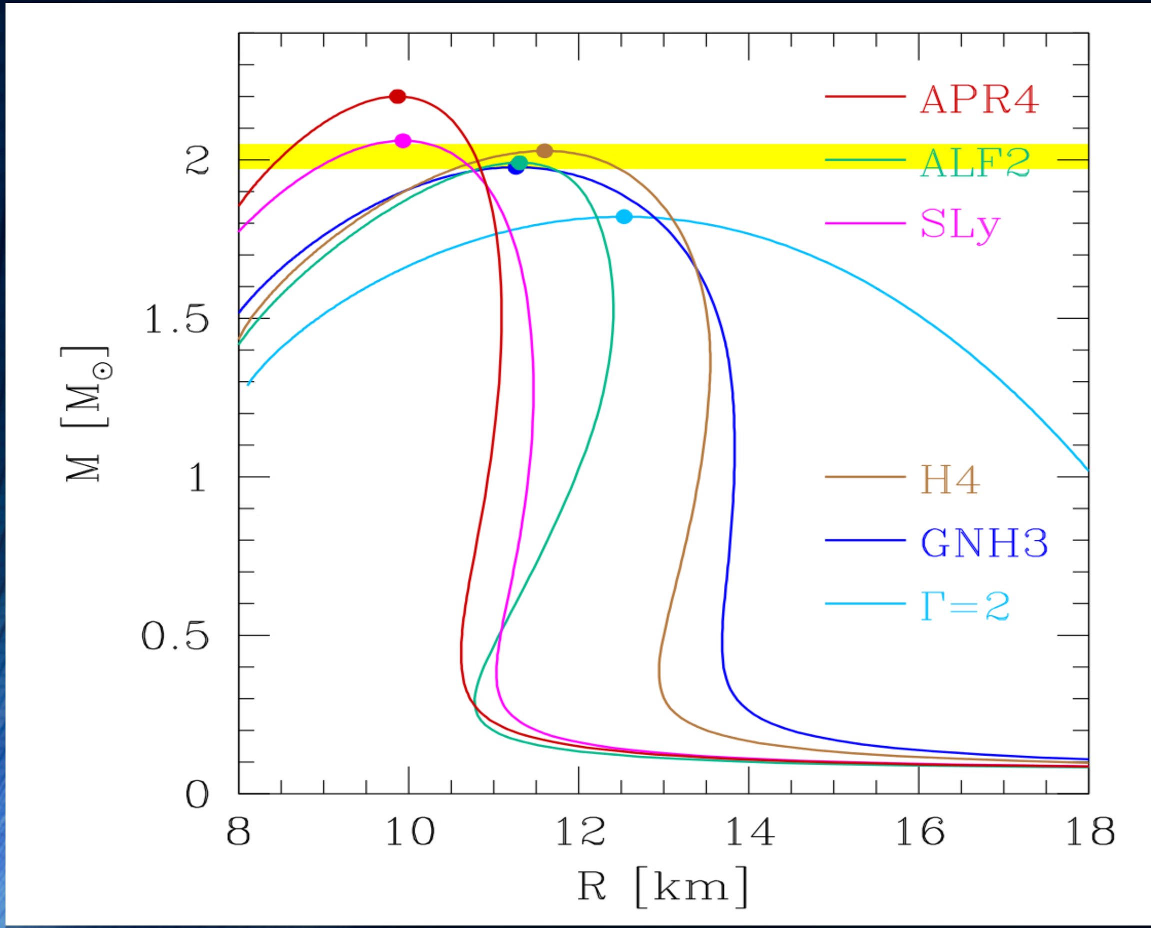


Unfortunately, due to the low sensitivity at high gravitational wave frequencies, no post-merger signal has been found in GW170817.

But, the results indicate that post-merger emission from a similar event may be detectable when advanced detectors reach design sensitivity or with next-generation detectors.

EOSs

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.



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

$$p = p_{\rm c} + p_{\rm th}\,, \qquad \epsilon = \epsilon_{\rm c} + \epsilon_{\rm th}\,, \tag{6}$$

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 $\epsilon_{\rm c}$ in the rest-mass density range $\rho_{i-1} \le \rho < \rho_i$ as (for details see [36, 64–66])

$$p_{\rm c} = K_i \rho^{\Gamma_i}\,, \qquad \epsilon_{\rm c} = \epsilon_i + K_i \frac{\rho^{\Gamma_i - 1}}{\Gamma_i - 1}\,. \tag{7}$$

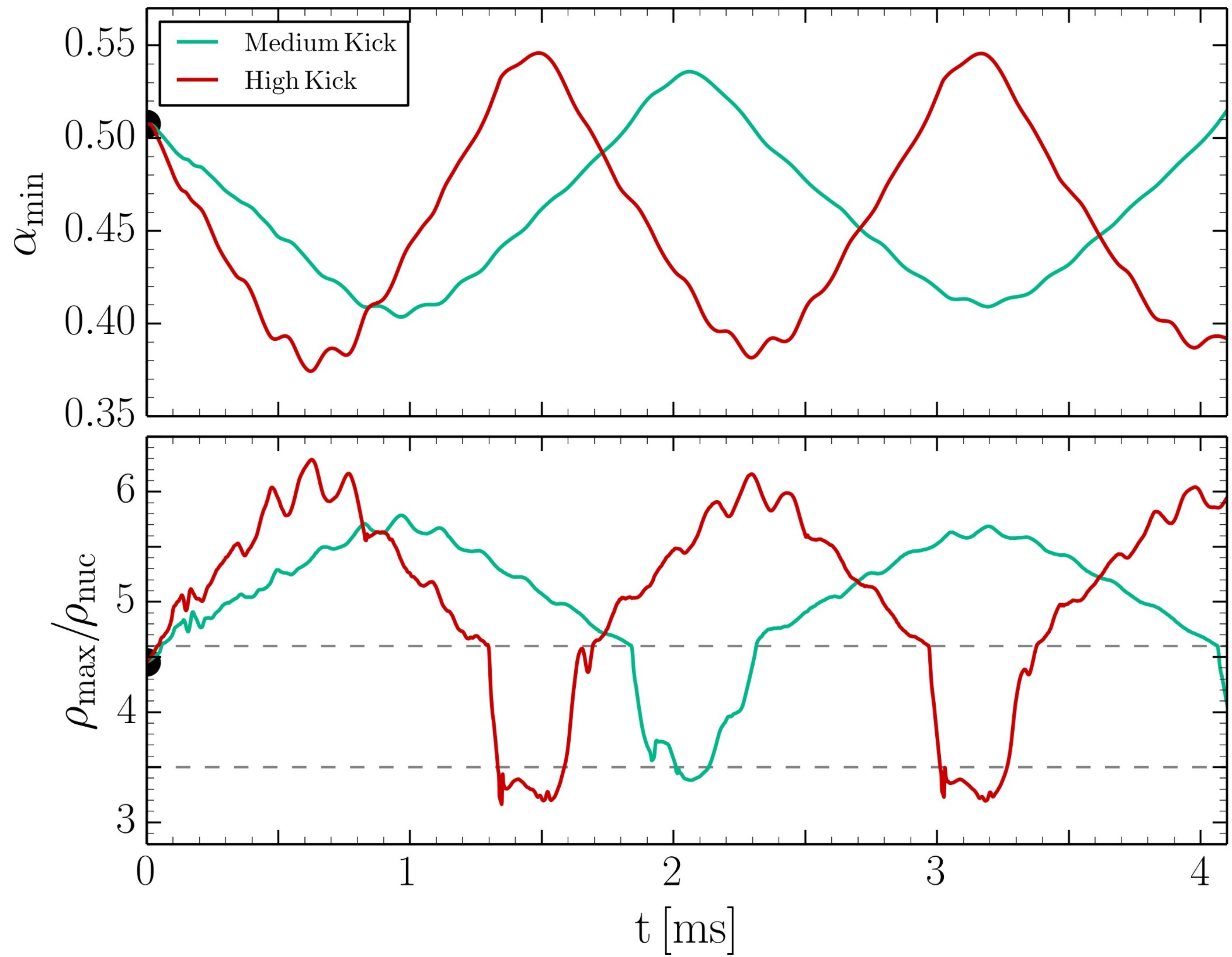
($\Gamma_1 = 4.070$ and $\Gamma_2 = 2.411$). Finally, the "thermal" part of the EOS is given by

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

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 $\Gamma_{\rm th} = 2.0$

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

Twin Star Oscillations

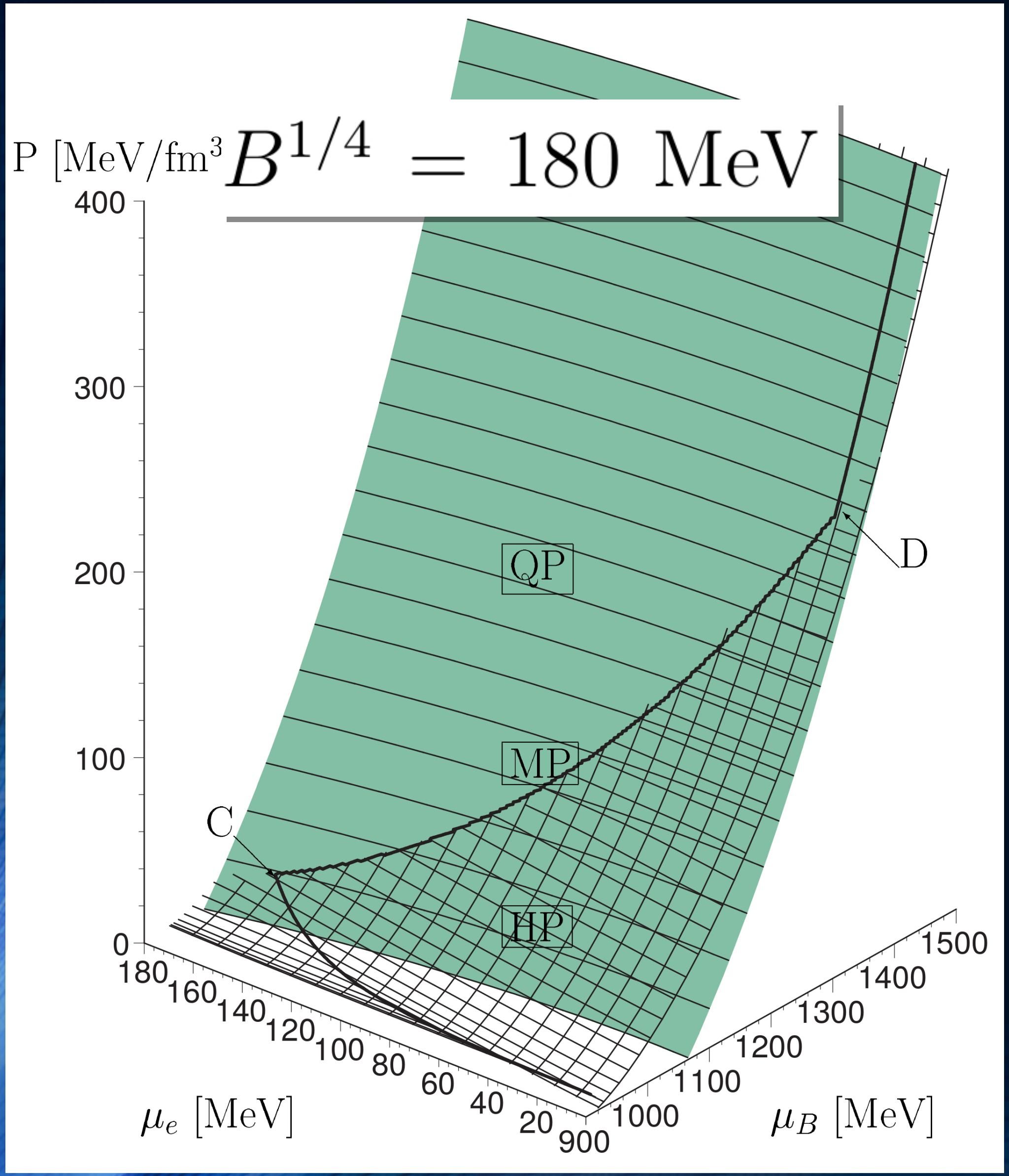


Yamasaki, S., Totani, T., & Kiuchi, K. (2017). Repeating and Non-repeating Fast Radio Bursts from Binary Neutron Star Mergers. arXiv preprint arXiv:1710.02302.

Michilli, D, et.al. (2018). An extreme magneto-ionic environment associated

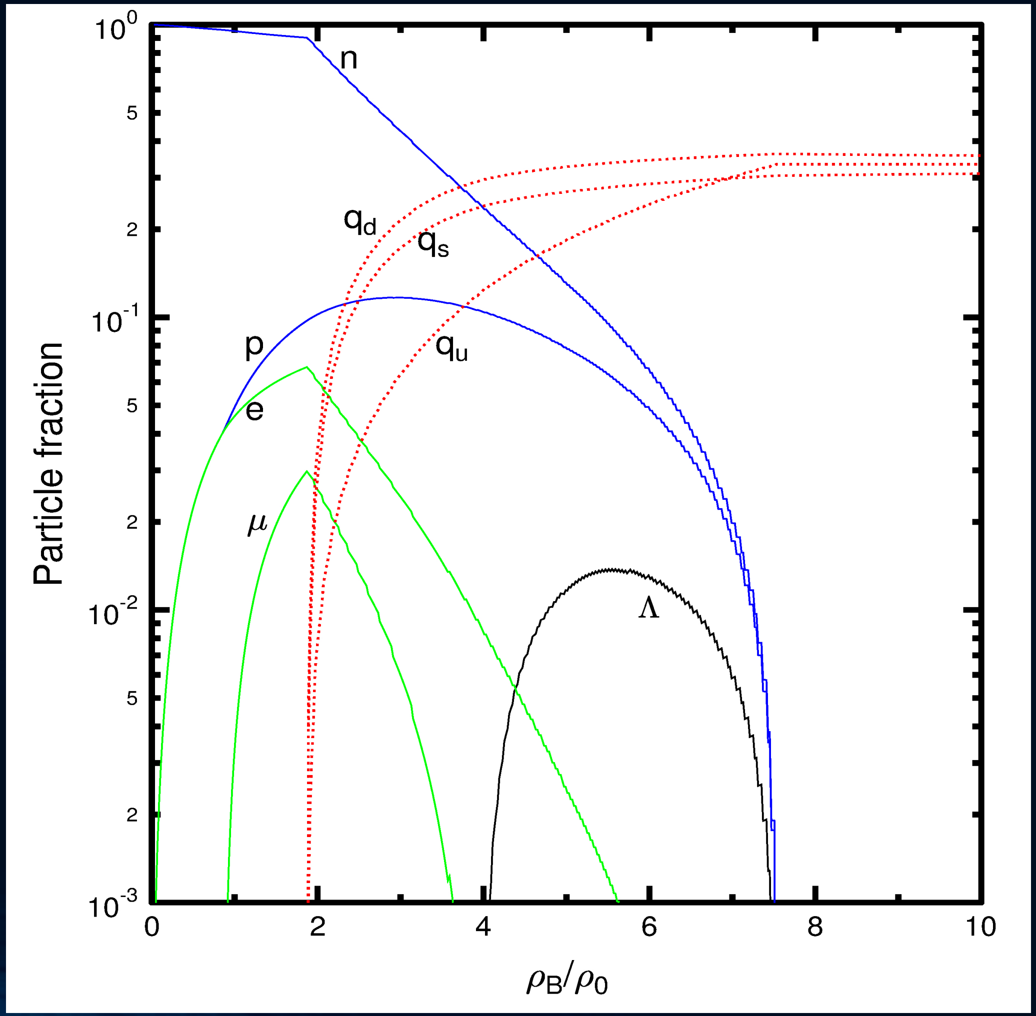
The Gibbs Construction

Hadronic and quark surface:



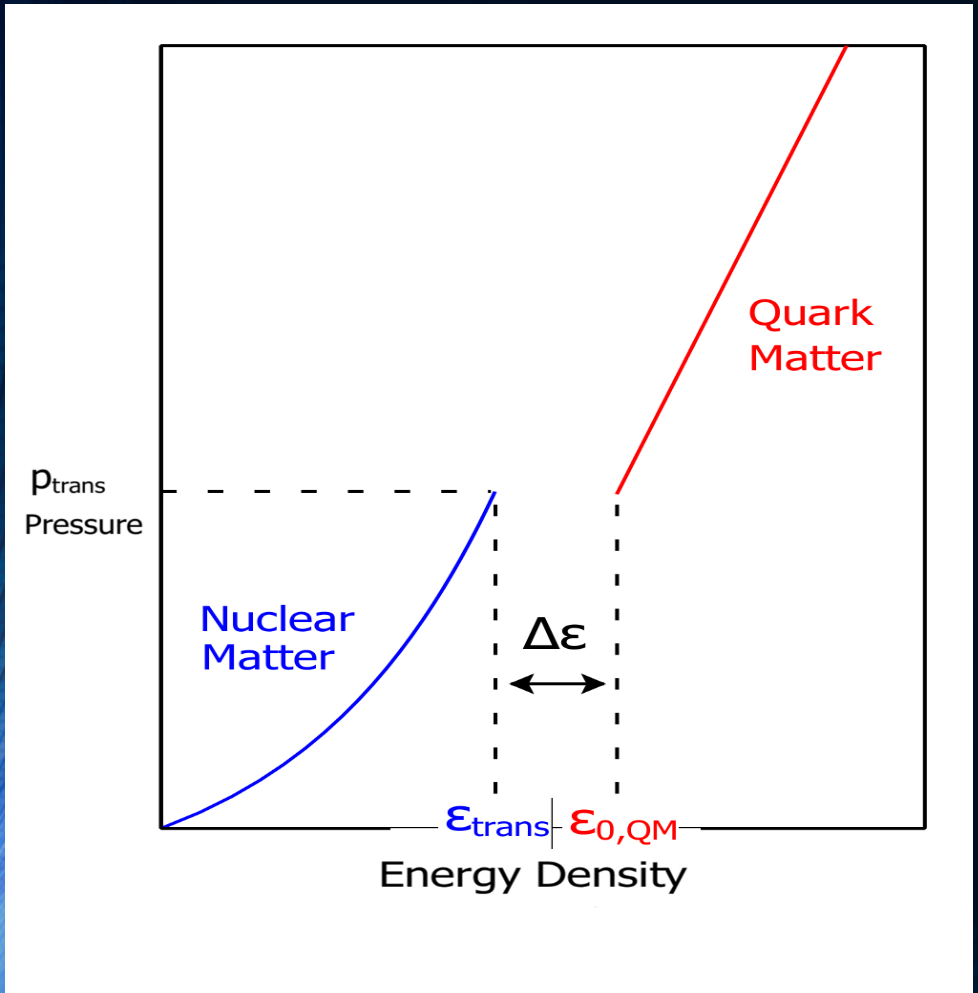
Charge neutrality condition is only globally realized

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



The Maxwell Construction

If the surface tension between the hadron and quark phase is large, the mixed phase could completely disappear -> sharp boundary between hadronic and quark. The Hadron-quark phase transition is then described using a Maxwell construction.



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

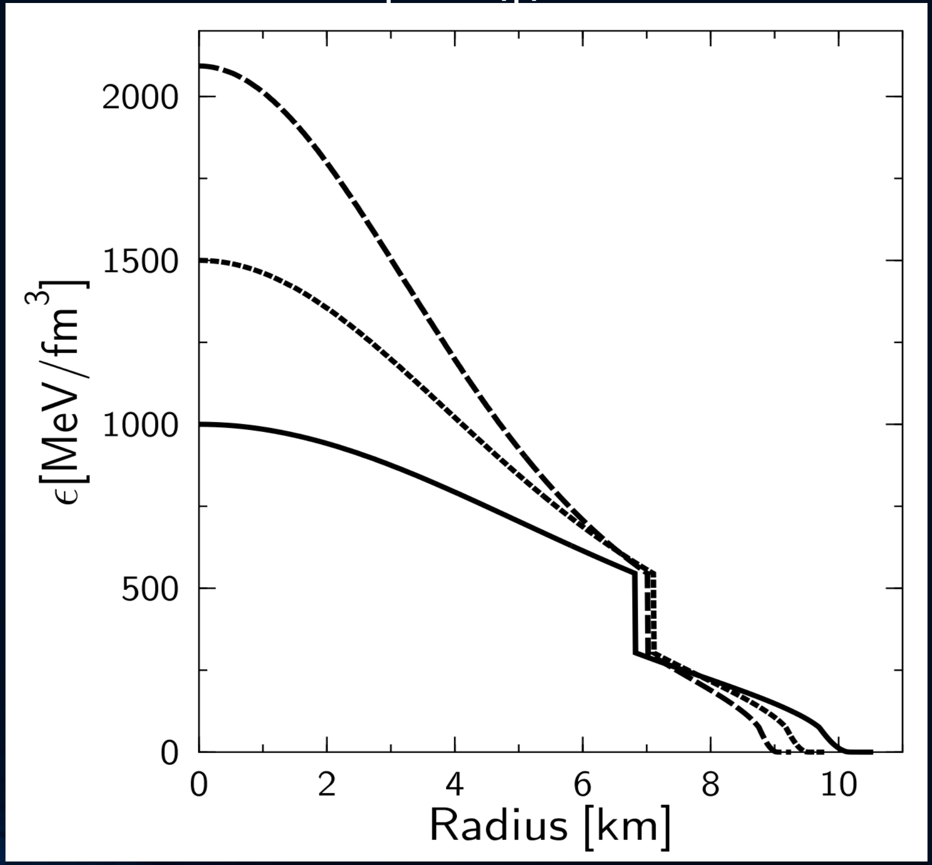
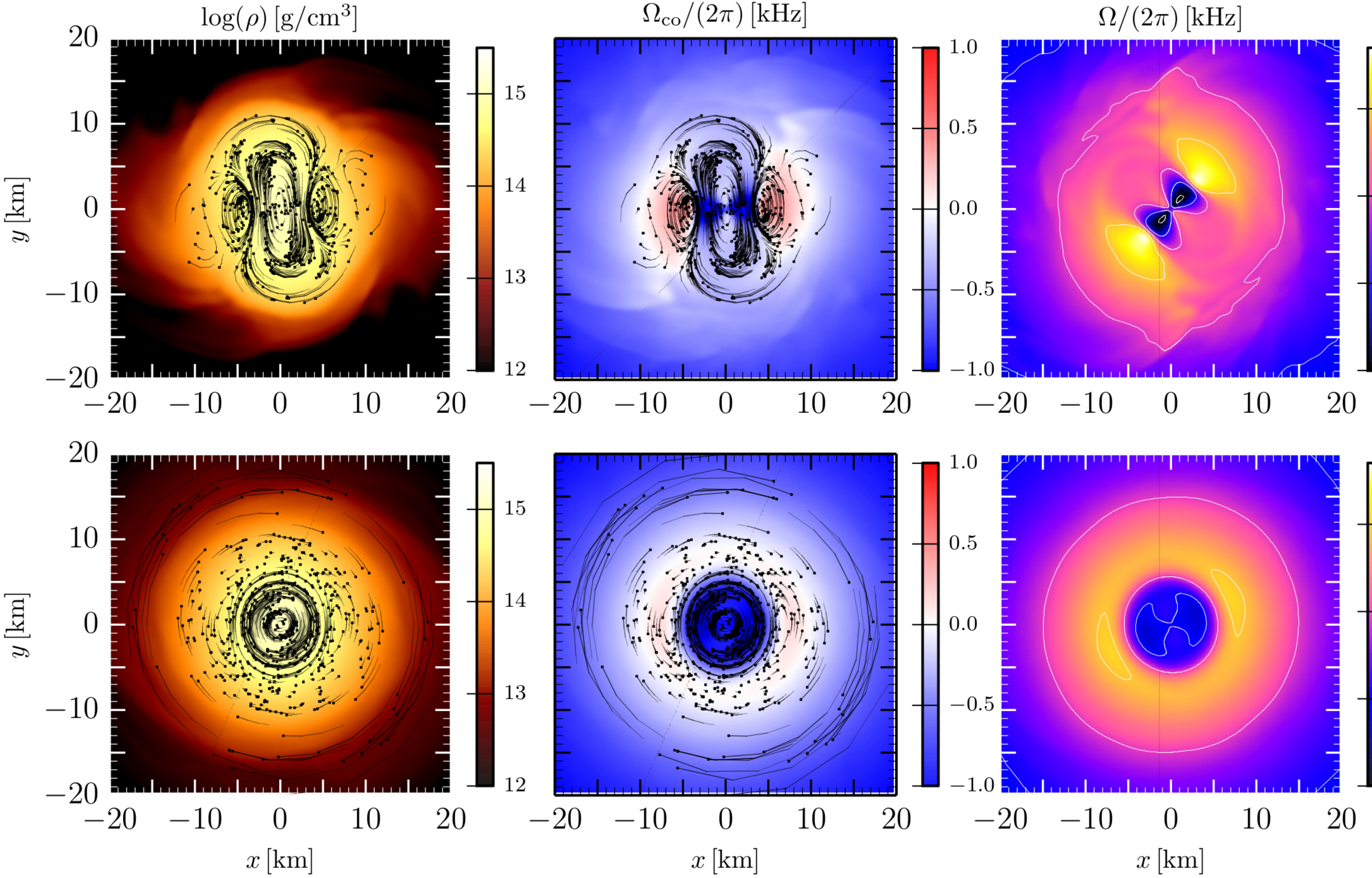
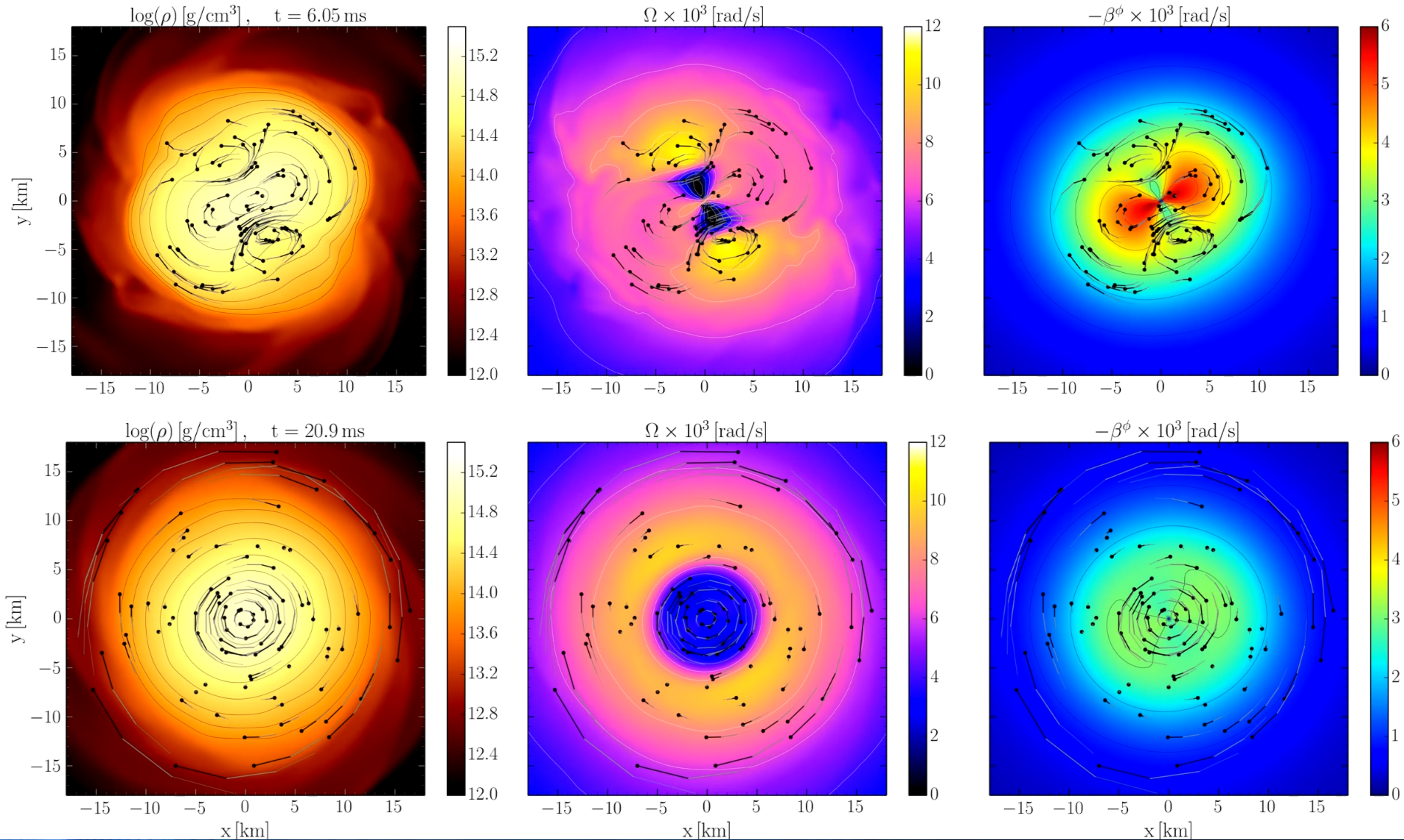


Image from M.G. Alford, S. Han, and M. Prakash, Phys. Rev. D 88, 083013 (2013)



$\log(\rho)$ [g/cm^3]
$\Omega_{co}/(2\pi)$ [kHz]
$\Omega/(2\pi)$ [kHz]
y [km]
x [km]

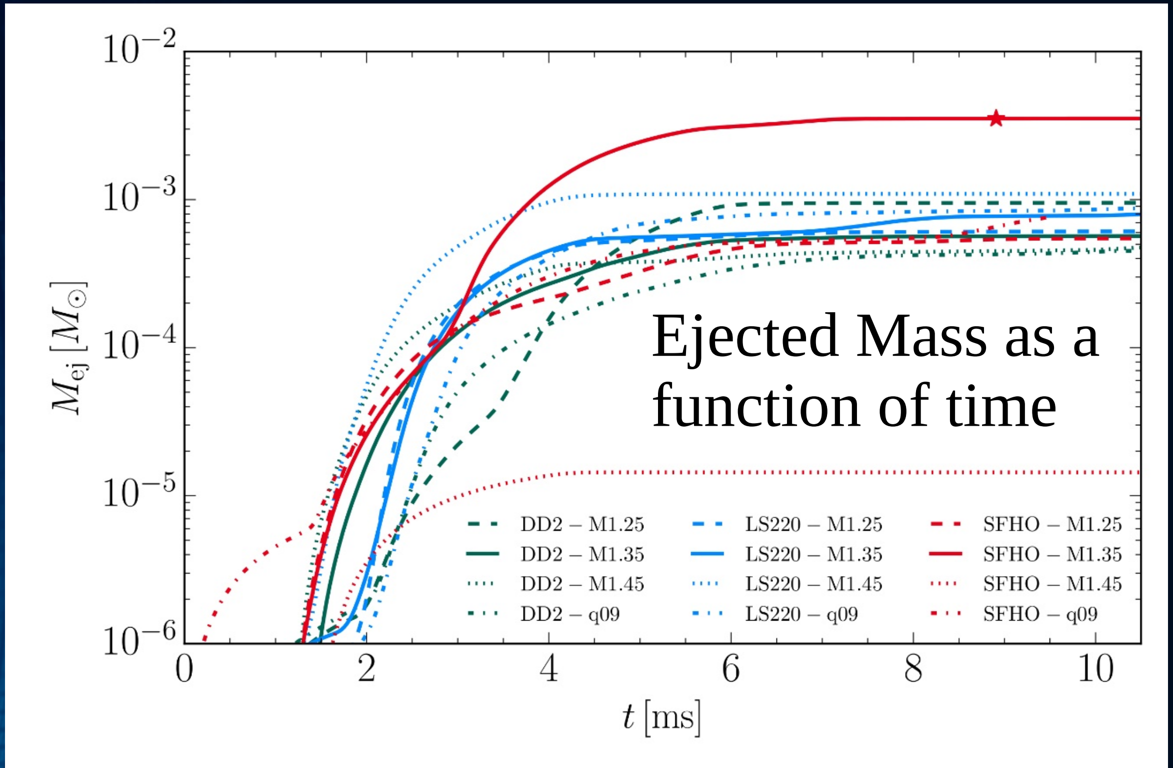


log(ρ) [g/cm³] , t = 6.05 ms
Ω × 10³ [rad/s]
−β^φ × 10³ [rad/s]
log(ρ) [g/cm³] , t = 20.9 ms
Ω × 10³ [rad/s]
−β^φ × 10³ [rad/s]
y [km]
x [km]

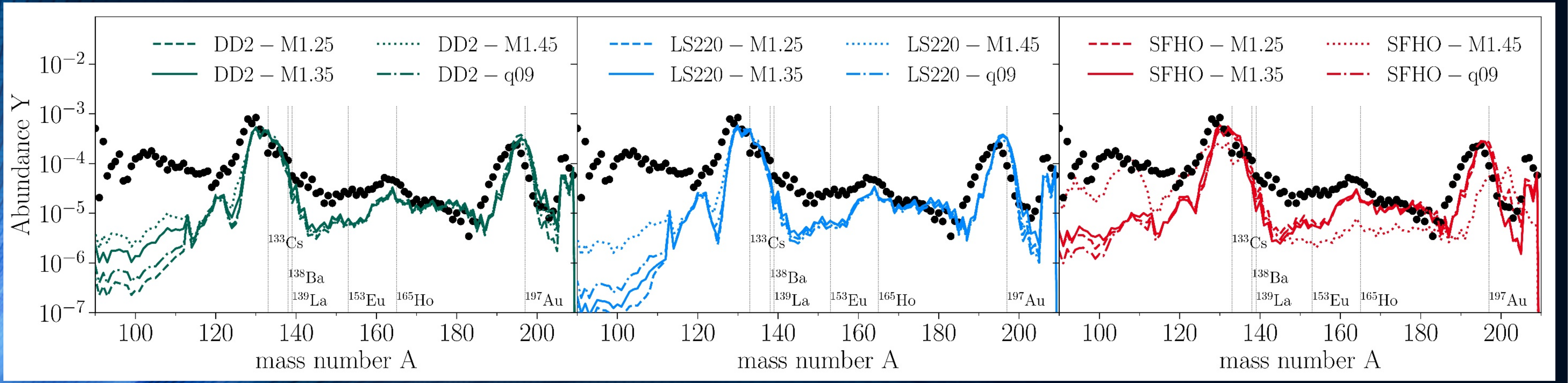
r-process nucleosynthesis in binary neutron star mergers

Luke Bovard, Dirk Martin, Federico Guercilena, Almudena Arcones, Luciano Rezzolla and Oleg Korobkin

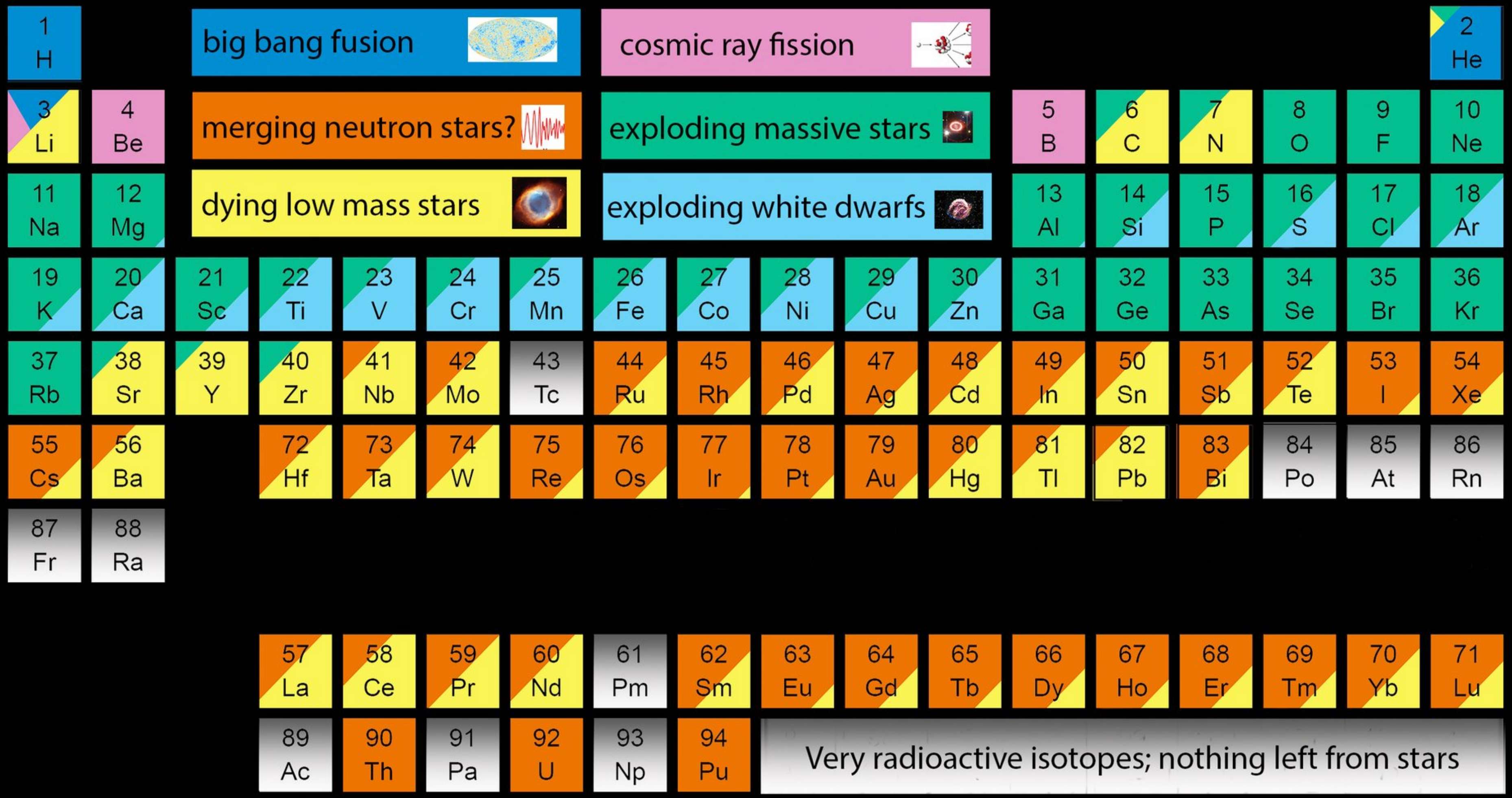
arXiv:1709.09630v1 [gr-qc] 27 Sep 2017



Simulation of the relative abundances of heavy elements produced in a binary neutron star merger.



The Origin of the Solar System Elements



Graphic created by Jennifer Johnson
http://www.astronomy.ohio-state.edu/~jaj/nucleo/

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Merger Product from an eccentric colliding Neutron Star Binaries