Signatures of Quark-Hadron Phase Transitions in General-Relativistic Neutron-Star Mergers

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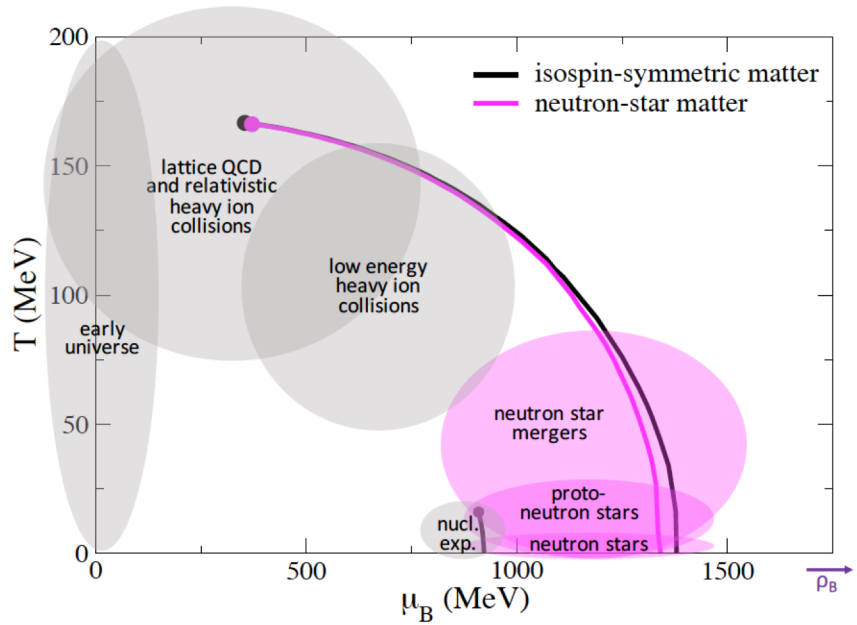
PHAROS
THE MULTI-MESSENGER PHYSICS AND ASTROPHYSICS OF NEUTRON STARS

NSF

EoS Ingredients for NS Mergers

(in addition to nuclear and astrophysical constraints)

- high density description
- quantum relativistic description
- finite/high temperature description
- provides particle population
- include hyperons and quarks
- include chiral symmetry restoration
- in agreement with lattice QCD
- in agreement with heavy-ion collision results
- in agreement with perturbative QCD results



CMF (Chiral Mean Field) Model

- non-linear realization of the linear sigma model
- includes baryons (+ leptons) and quarks
- fitted to reproduce nuclear, astrophysical, lattice QCD, and heavy ion, constraints
- baryon and quark effective masses

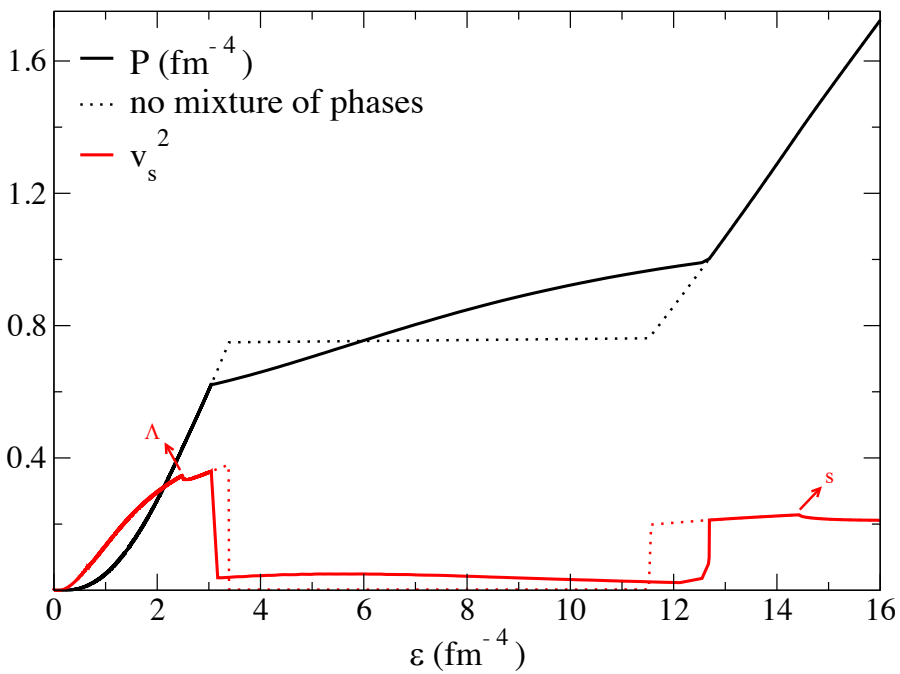
$$M_B^* = g_{B\sigma}\sigma + g_{B\delta}\tau_3\delta + g_{B\zeta}\zeta + M_{0_B} + g_{B\Phi}\Phi^2$$
$$M_q^* = g_{q\sigma}\sigma + g_{q\delta}\tau_3\delta + g_{q\zeta}\zeta + M_{0_q} + g_{q\Phi}(1-\Phi)$$

- 1st order phase transitions or crossovers
- potential for **Φ** deconfinement order parameter

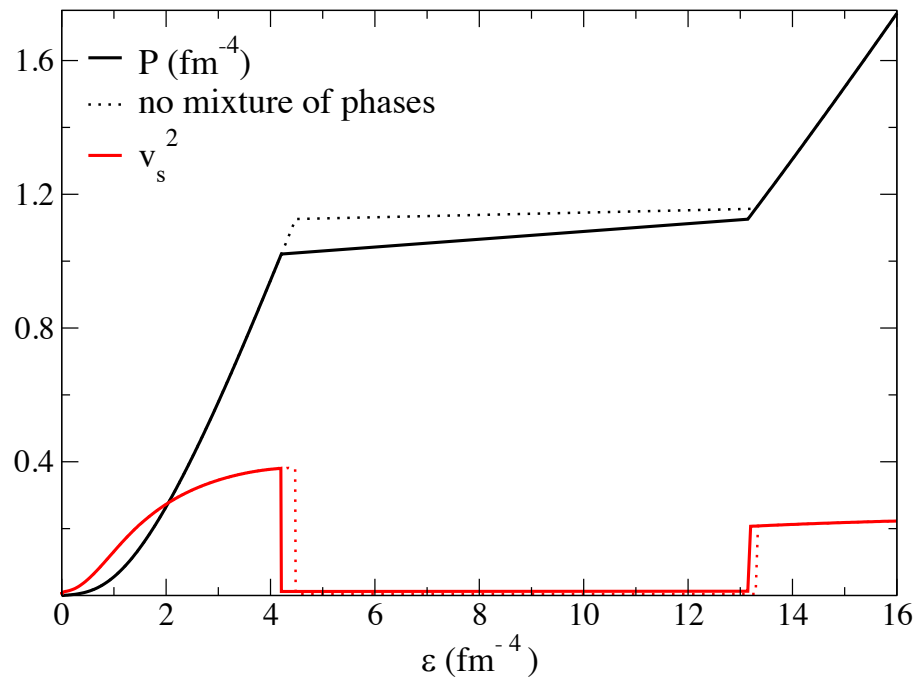
$$U = (a_o T^4 + a_1\mu_B^4 + a_2 T^2\mu_B^2)\Phi^2 + a_3 T_o^4 \ \ln(1 - 6\Phi^2 + 8\Phi^3 - 3\Phi^4)$$

Speed of sound for neutron-star matter

T=0



S_B=2 (Y_l=2)

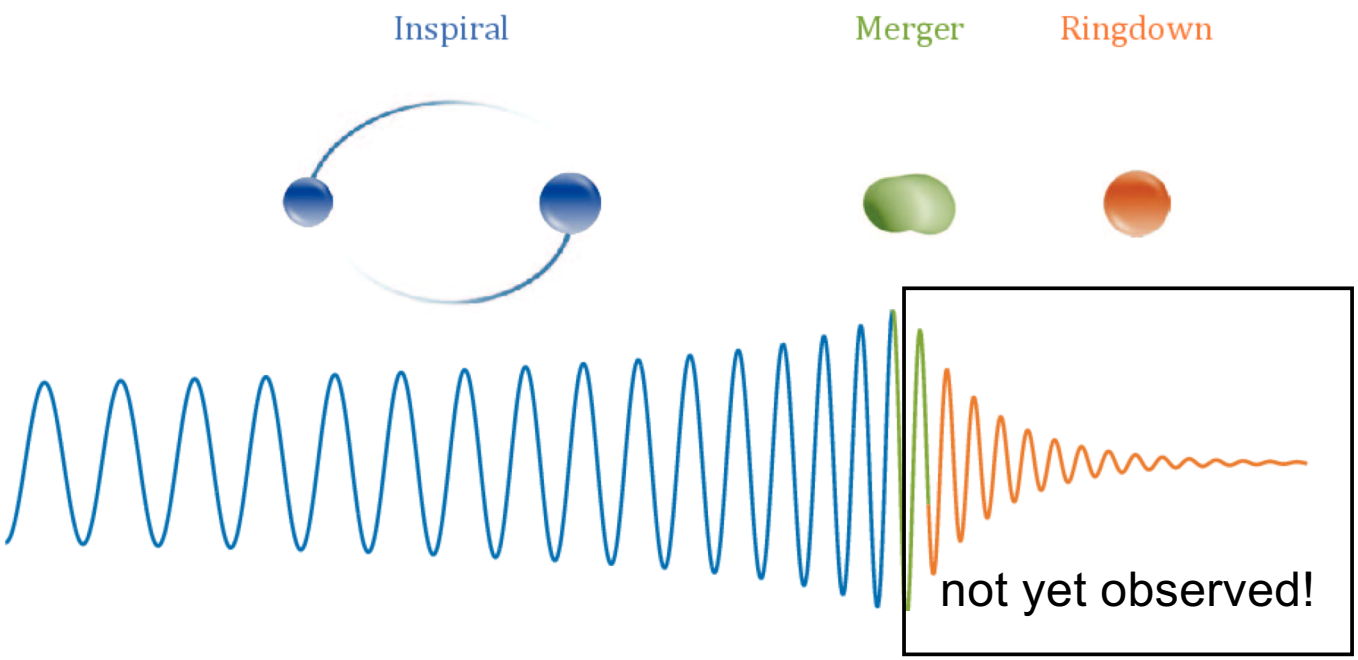


- $v_s^2 \sim 1/3$ at very large energies
- tested against PQCD results at zero/finite temperature

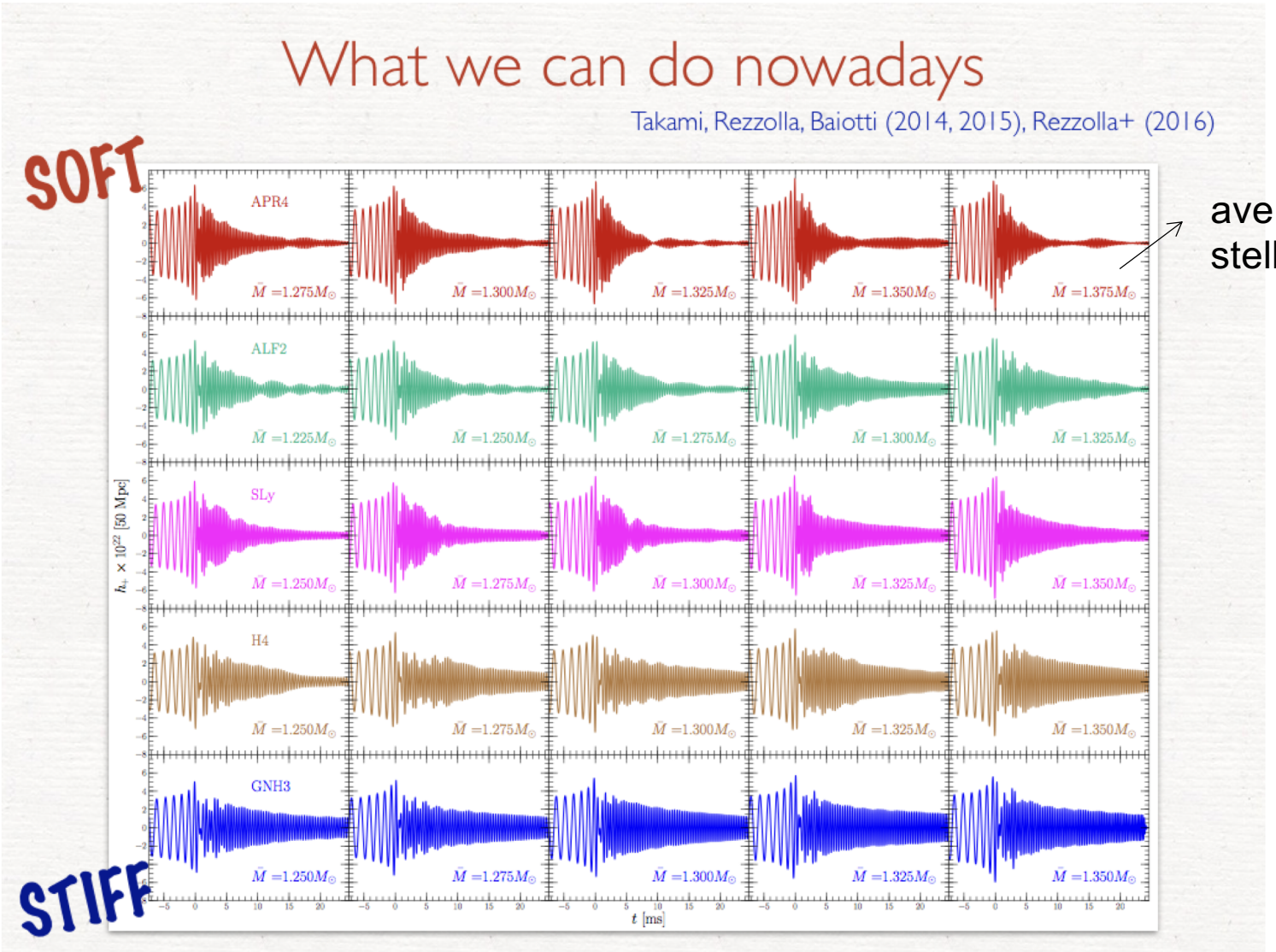
Neutron Star Merger 170817

- gravitational waves observed by LIGO/VIRGO in 17 August 2017 from galaxy NGC 4993 140 million light-years away

- observed electromagnetically by 70 observatories on 7 continents and in space



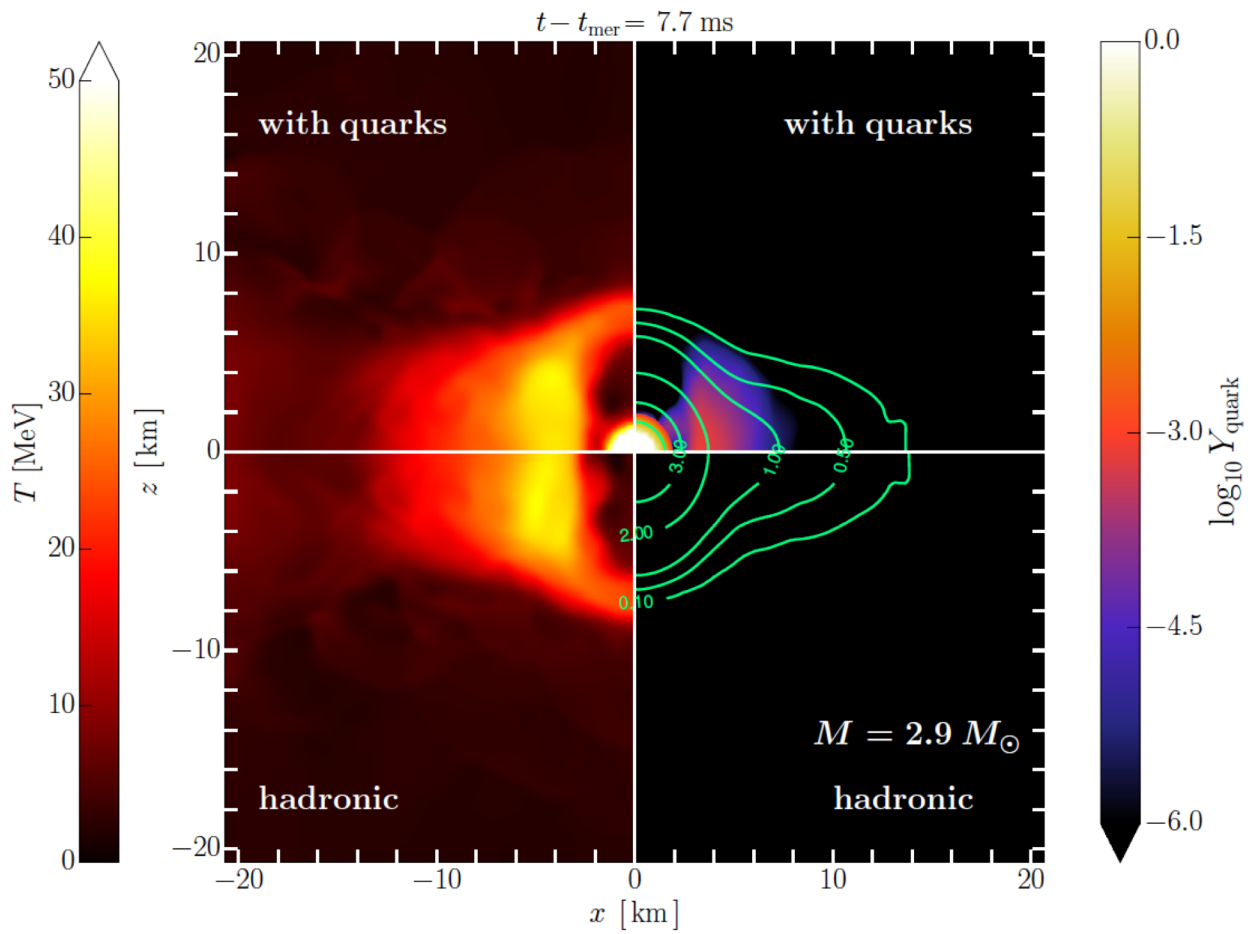
Hadronic NS Merger Simulations



average stellar mass

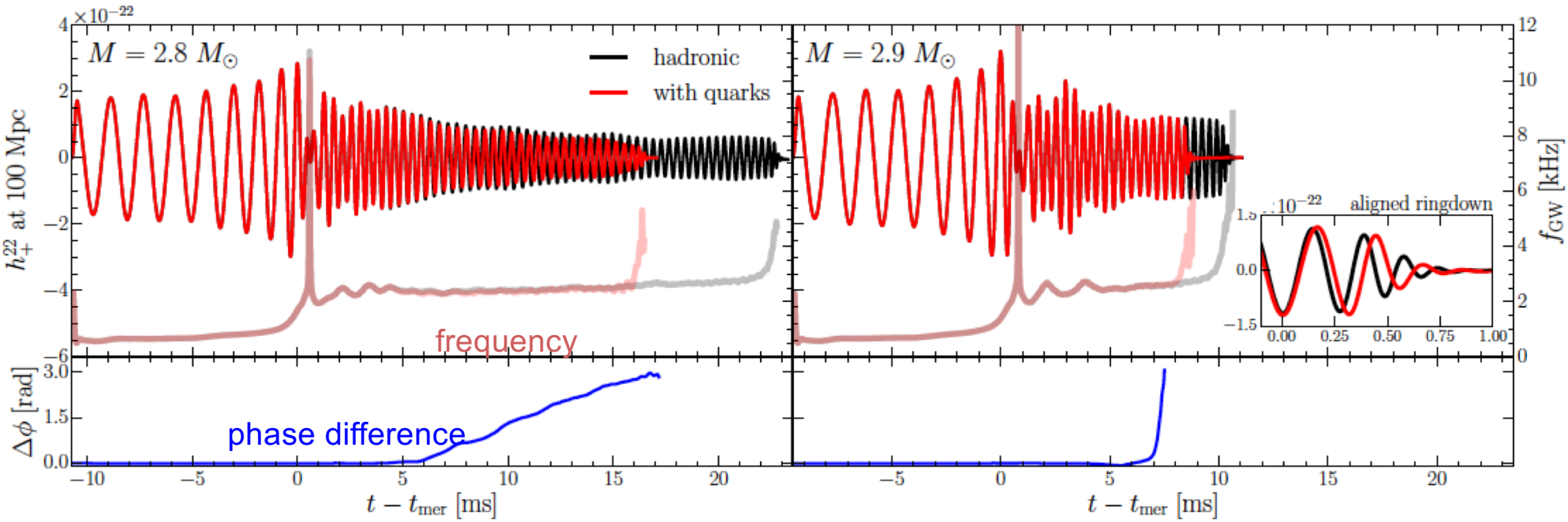
NS Merger Simulation with Deconfinement

- 3D (T, n_B,Y_c) CMF EoS with/without quarks
- solve coupled Einstein-hydrodynamics system using Frankfurt/IllinoisGRMHD code (FIL)
- interesting results for binaries with final masses of 2.8 and 2.9 M_{Sun} after deconfinement but before collapse to black hole



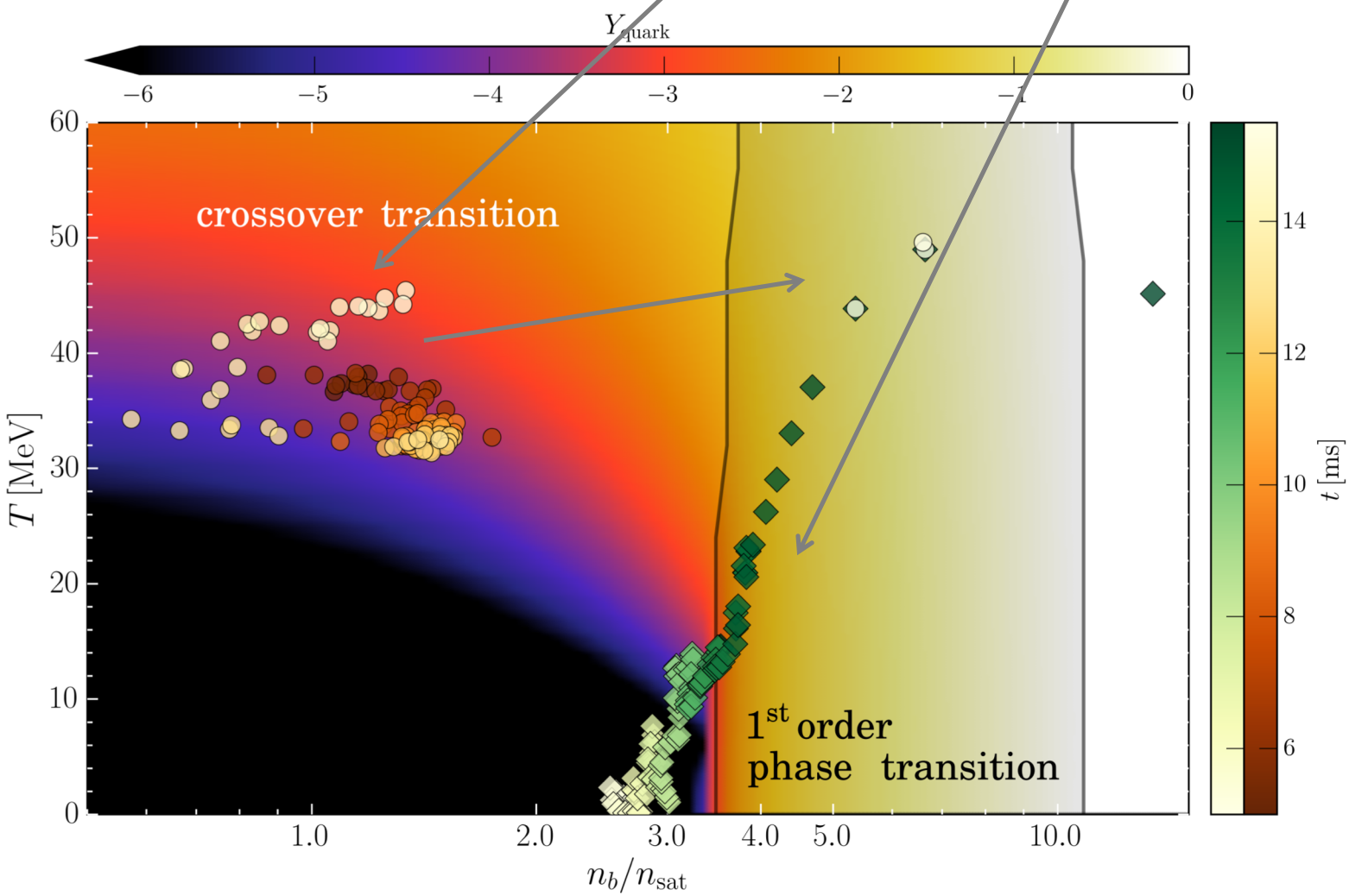
NS Merger Simulation with Deconfinement

- effects from quarks only after the merger
- change in frequency, strain, and time for collapse to blackhole
- collapse is faster in more massive case



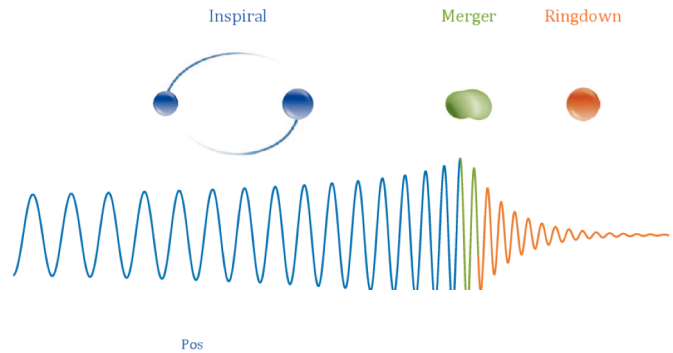
Merger in the QCD phase diagram:

- Tracking maximum temperature ● and density ◆ in merger



Tidal Deformability

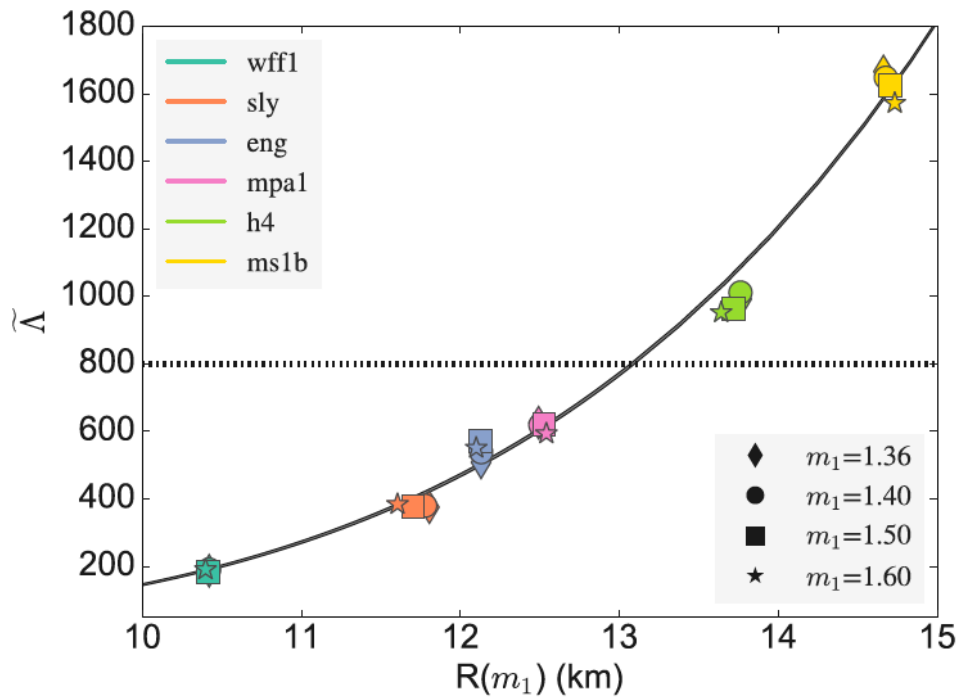
- normalized stellar quadripole deformation by companion



- calculated from finite-size effects in end of inspiral: 76 $\rightarrow$ 1045 with 90% confidence (De et. al 2018)

- related to NS radius of M=1.4 M_{sun} (Raithel et. al 2018)

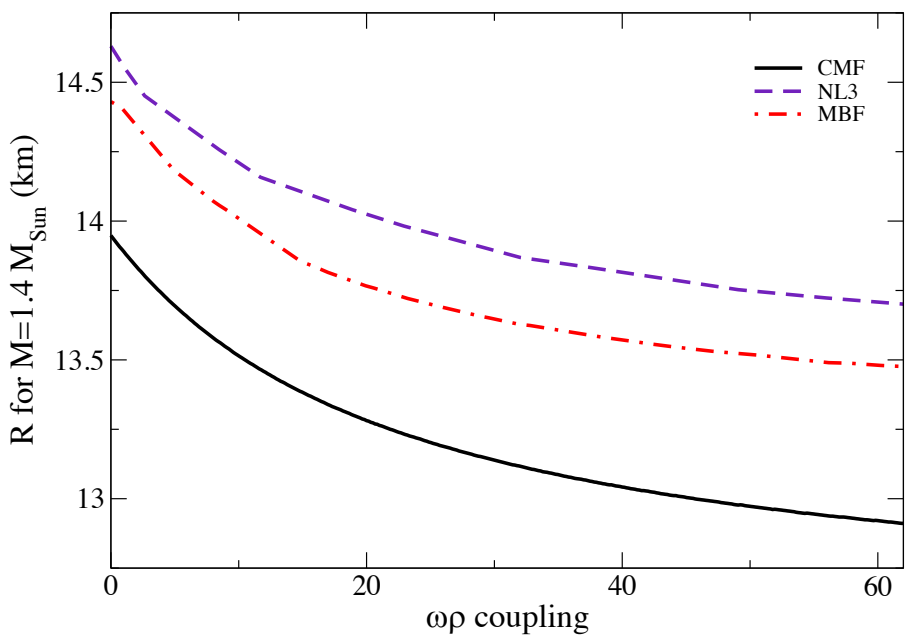
- universal relation?

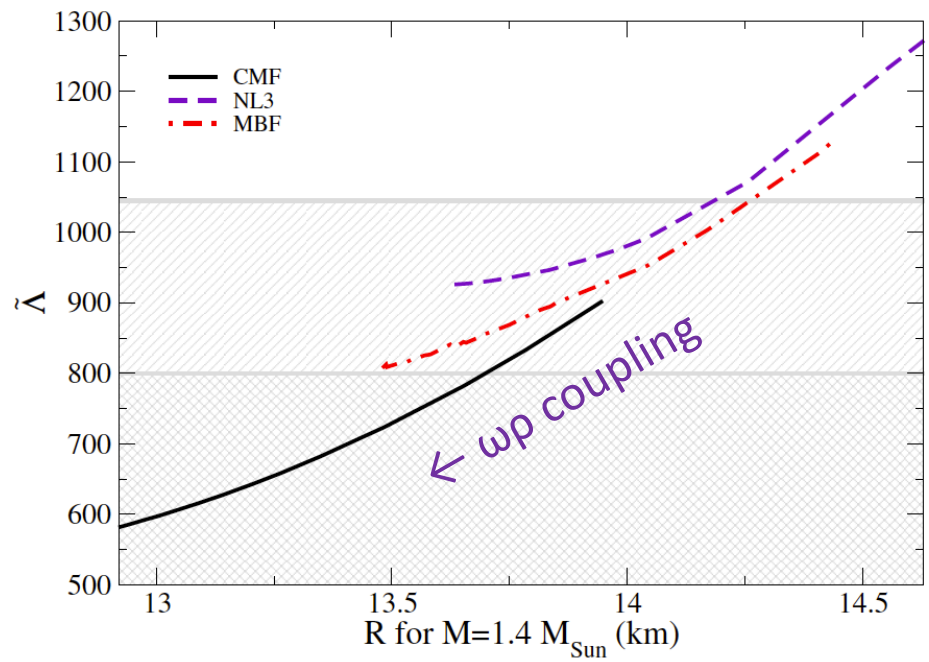


Exploring hadronic isovector coupling

- using 3 relativistic EoS's that fulfil standard nuclear and astrophysical constraints: NL3, MBF, and CMF

- new repulsive vector-isovector channel $L_{\omega\rho} = g_{\omega\rho} g_\omega^2 g_\rho^2 \omega_\mu \omega^\mu \boldsymbol{\rho_\mu \rho^\mu}$ suggested by Horowitz and Piekarewicz (2002) ωρ coupling





- non-trivial relation between $\tilde{\Lambda}$ and $R_{1.4M_{Sun}}$

Outlook

- GW170817 provided us a new way to study dense and hot matter

- more quantum relativistic models with temperature/exotic degrees of freedom needed to study

    - relation between tidal deformability and nuclear physics
    - realistic neutron-star merger simulations

- more merger data coming soon …so, maybe, a clear first signature for quark deconfinement phase transition will come from astrophysics?