

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

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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

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

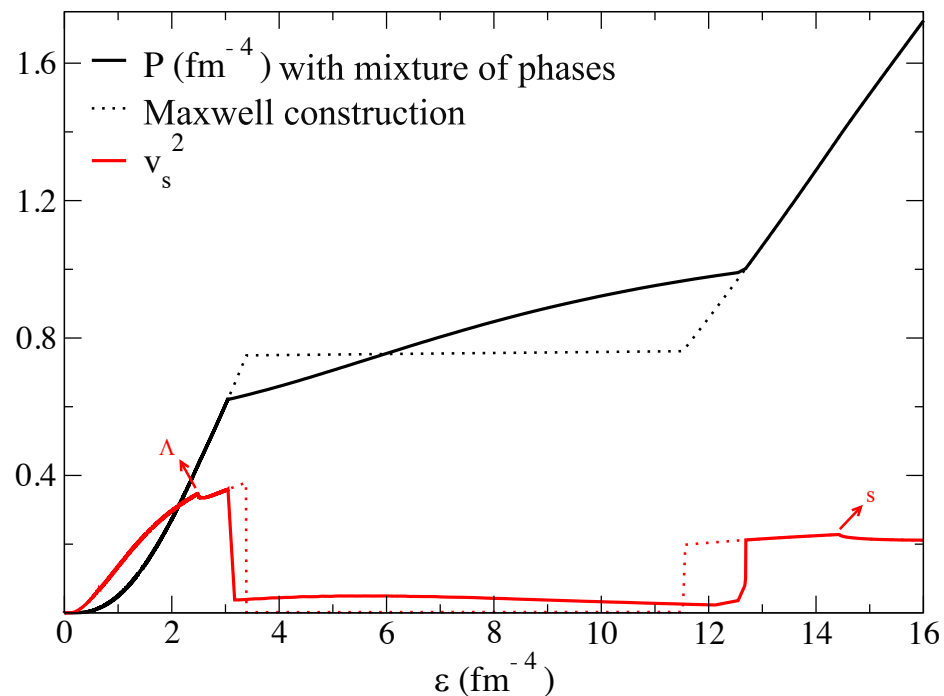
- 1st order phase transitions or crossovers

- potential for Φ
deconfinement
order parameter

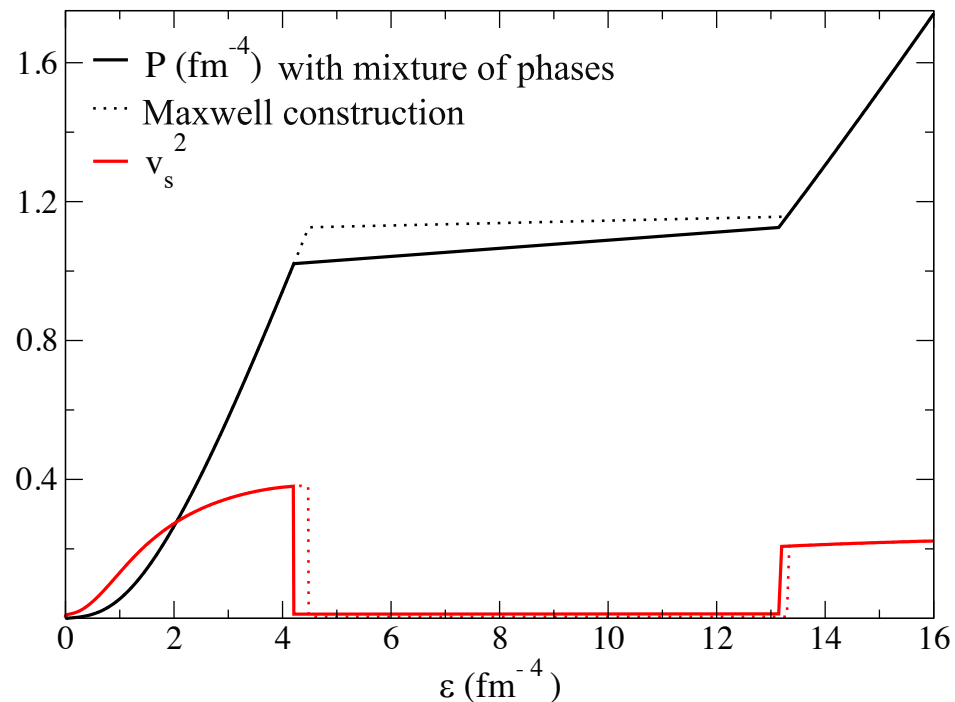
$$U = (a_0 T^4 + a_1 \mu_B^4 + a_2 T^2 \mu_B^2) \Phi^2 + a_3 T_o^4 \ln(1 - 6\Phi^2 + 8\Phi^3 - 3\Phi^4)$$

Speed of sound for neutron-star matter

T=0

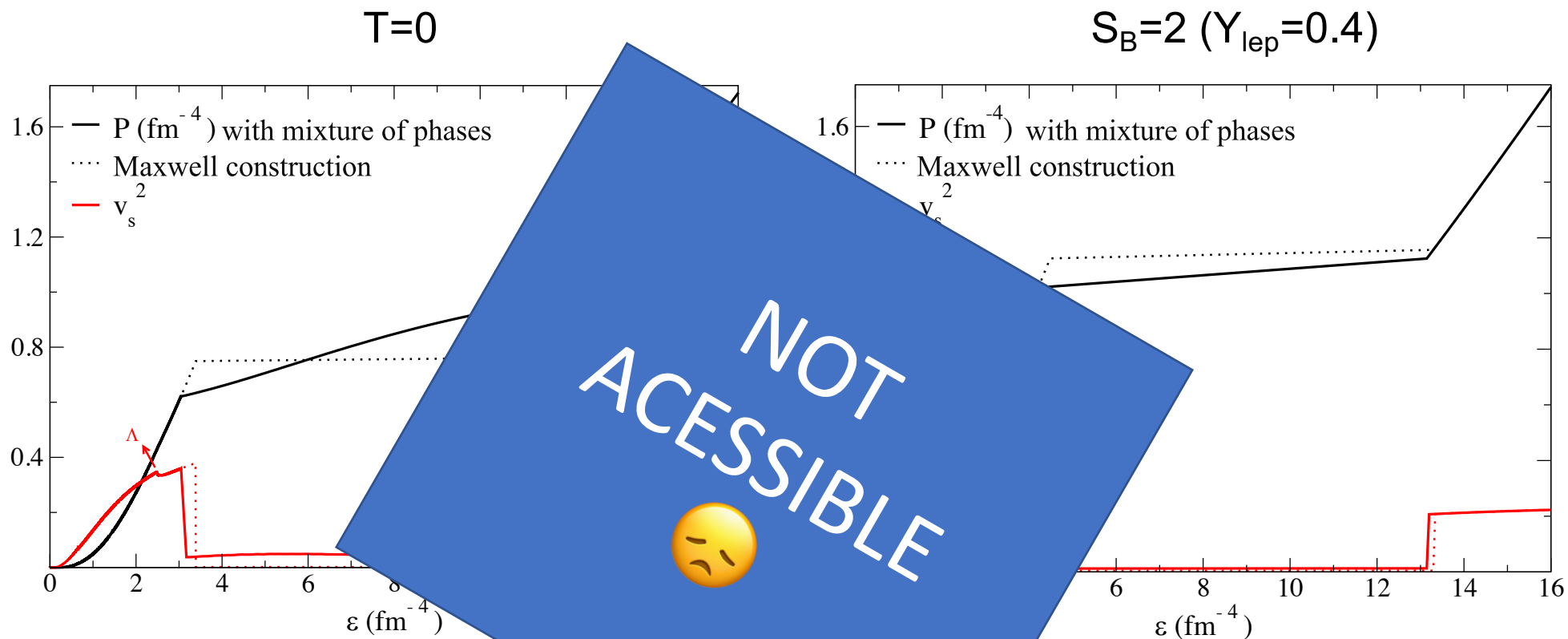


S_B=2 (Y_{lep}=0.4)



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

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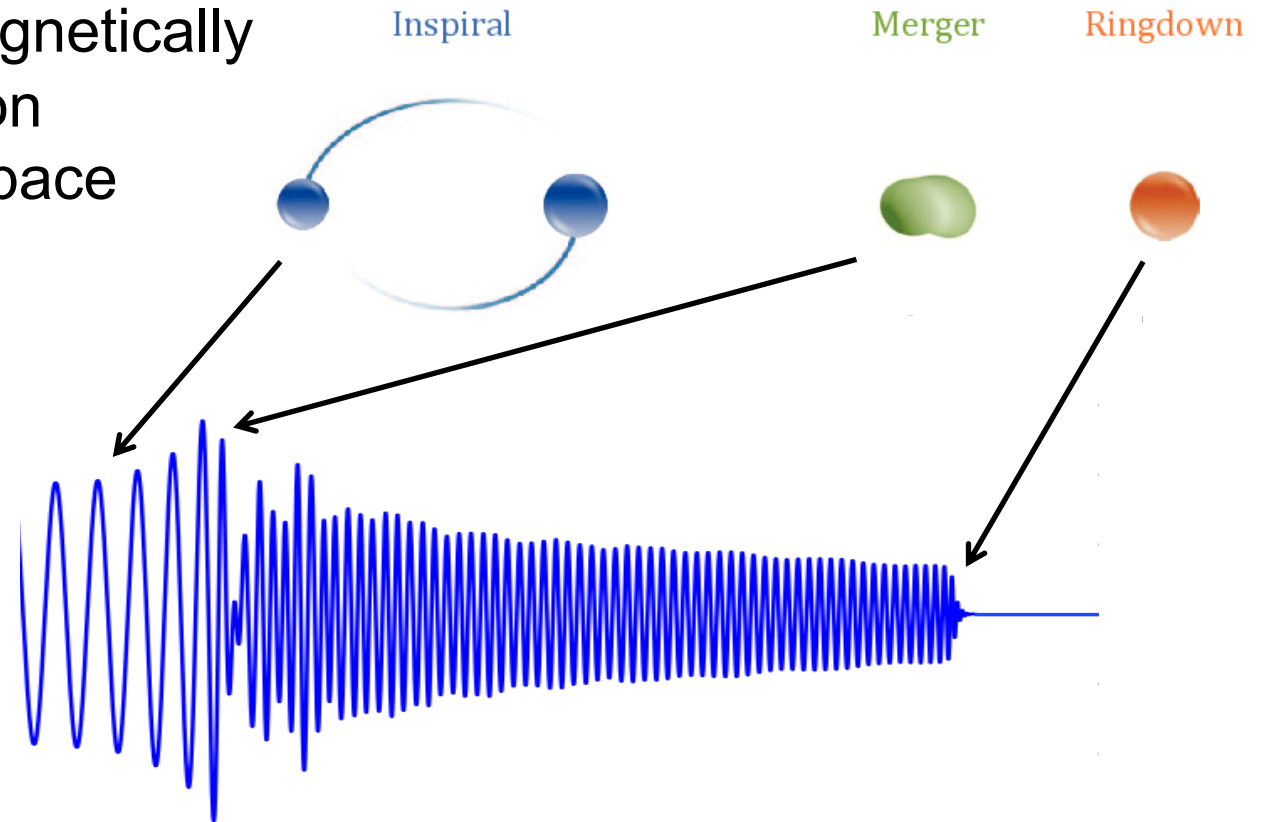


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Neutron-star merger 170817

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

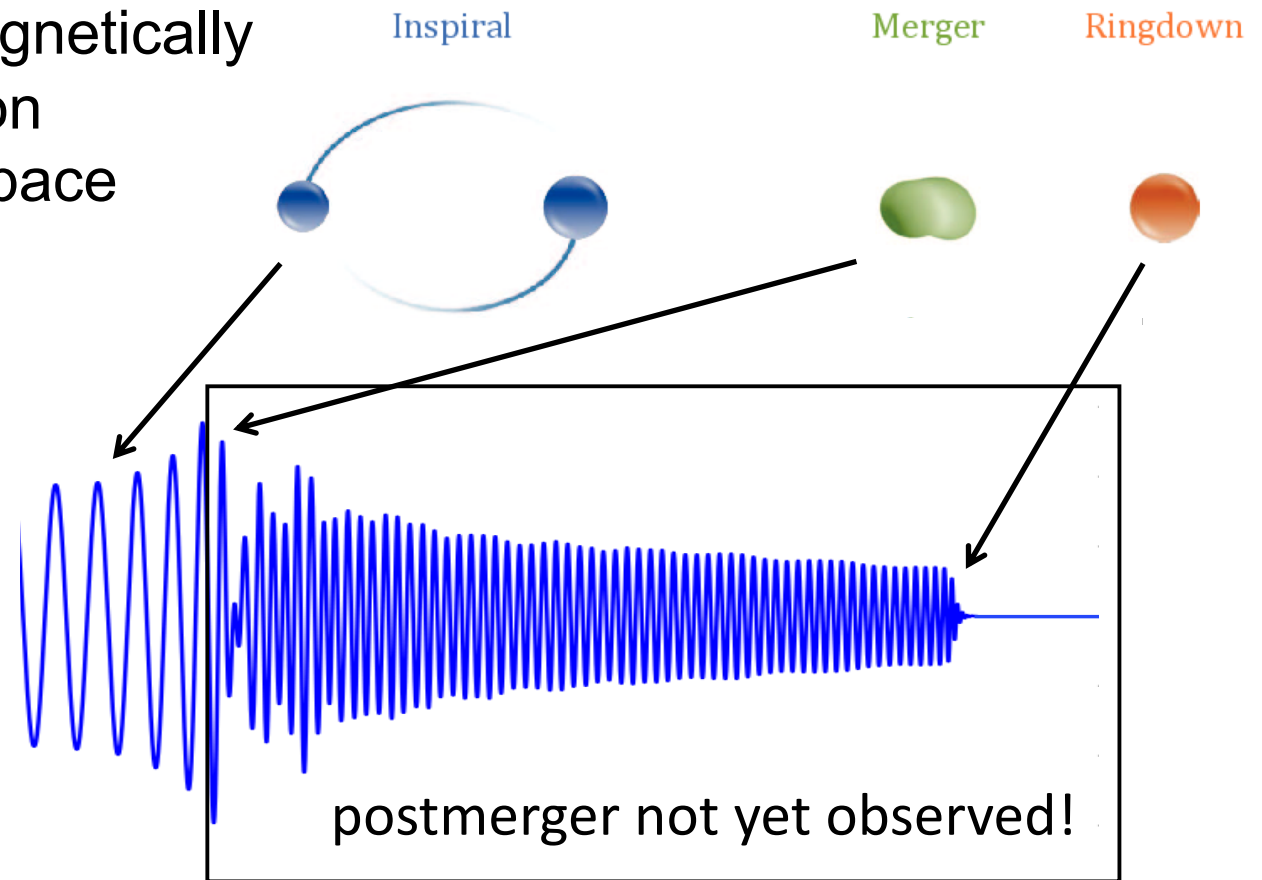
- observed electromagnetically by 70 observatories on 7 continents and in space



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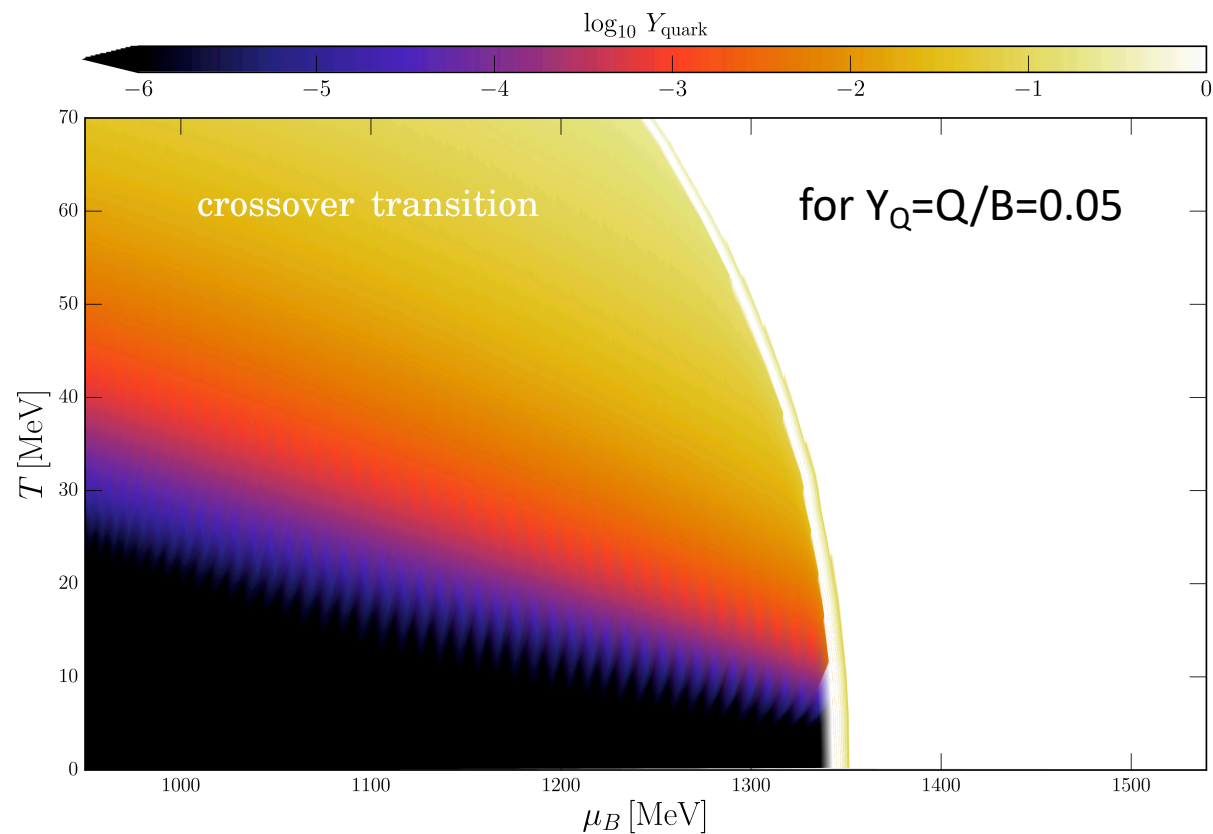
- dephasing due to deconfinement to quark matter (Luciano Rezzolla's plenary talk on Saturday)



NS-merger simulation with deconfinement

- 3D (T, n_B, Y_Q) CMF EoS with 1st order phase transition
- solve coupled Einstein-hydrodynamics system using Frankfurt/IllinoisGRMHD code (FIL)

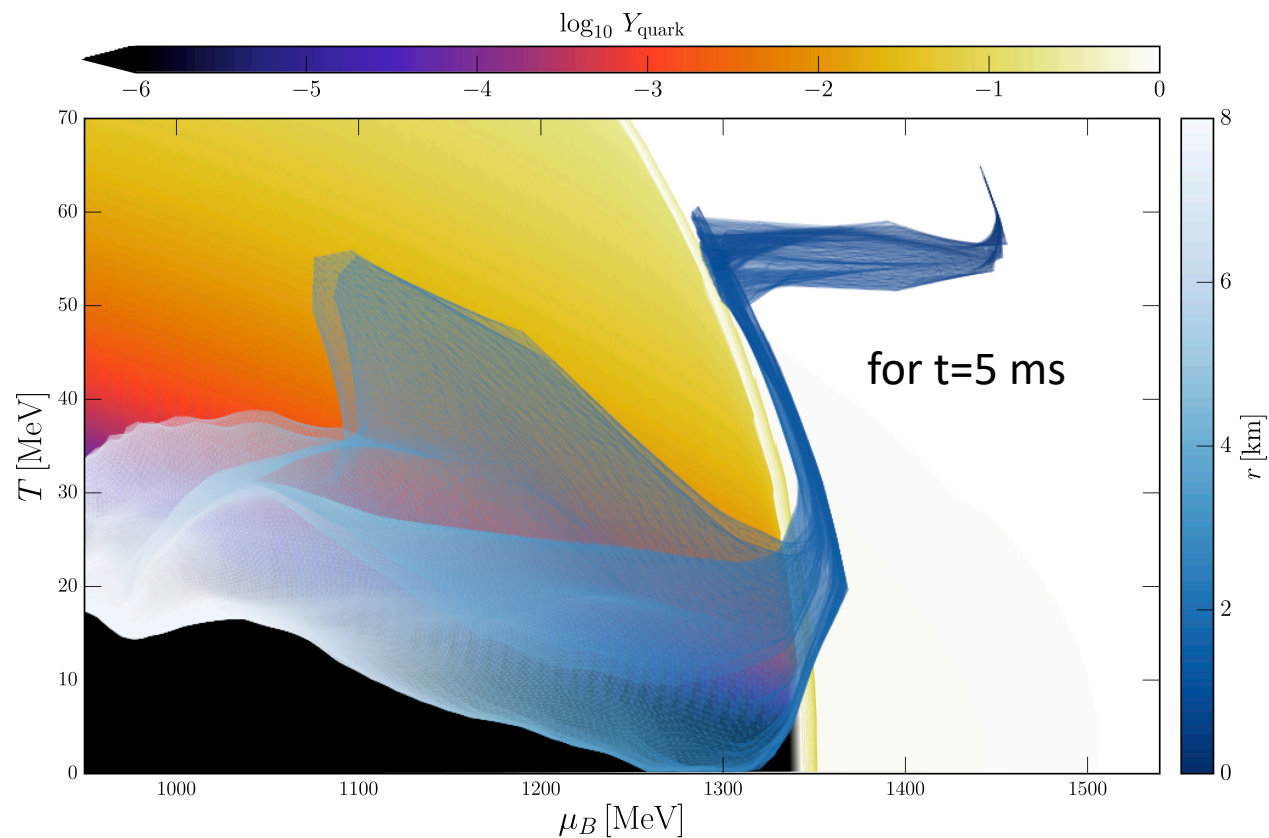
- interesting results for binaries with final masses of 2.8 and **2.9 M_{Sun}** after deconfinement but before collapse to black hole



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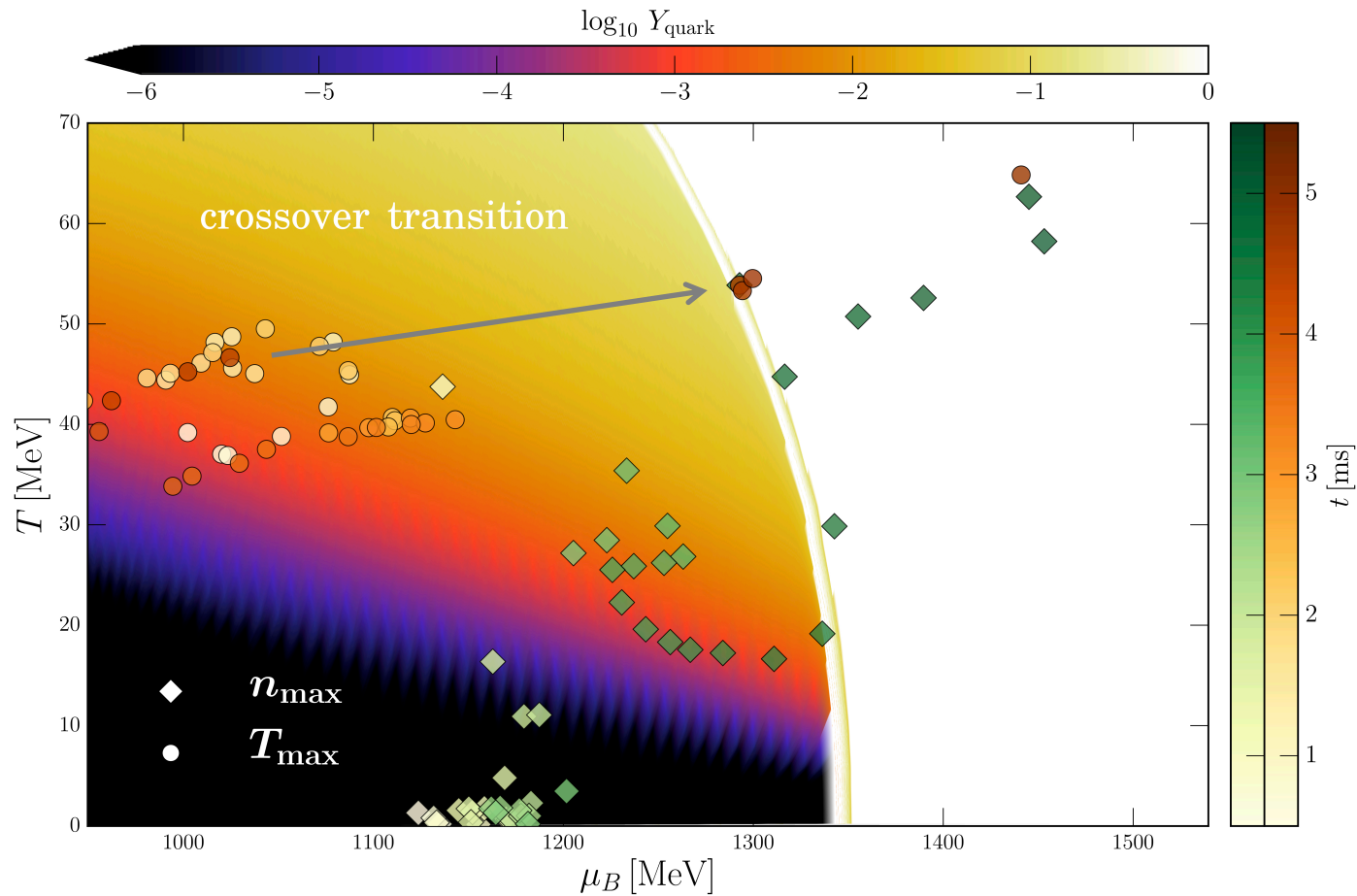
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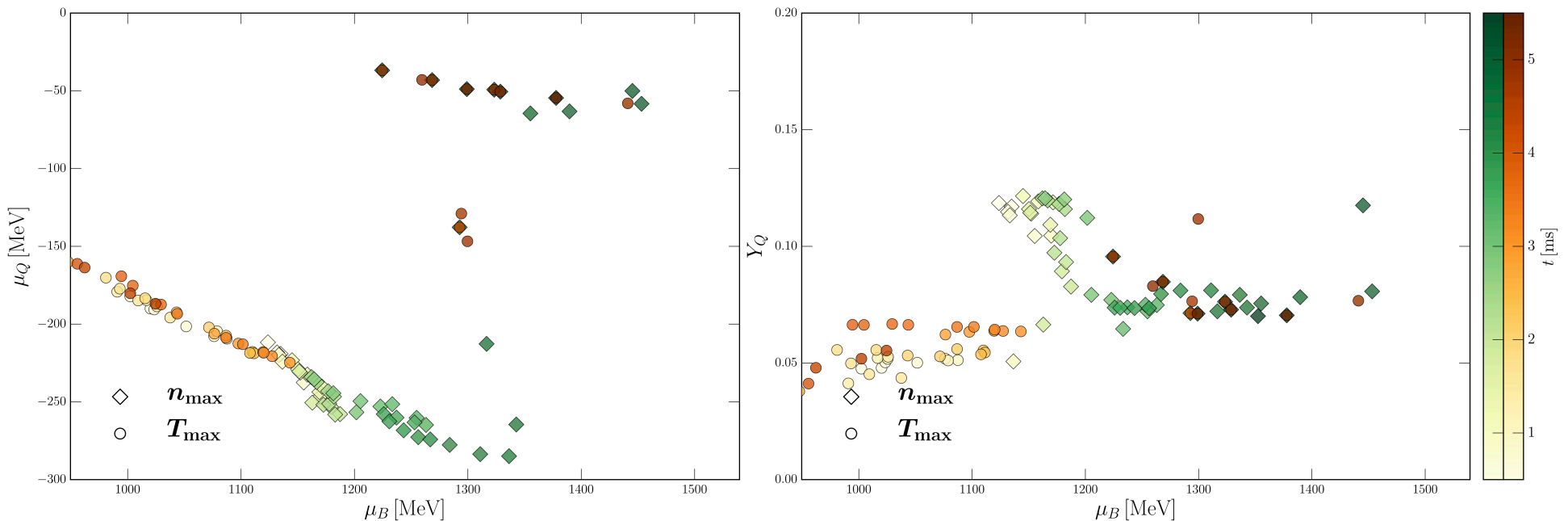
NS-merger in the QCD phase diagram

- tracking maximum temperature ● and density ◆ in merger



More phase diagrams

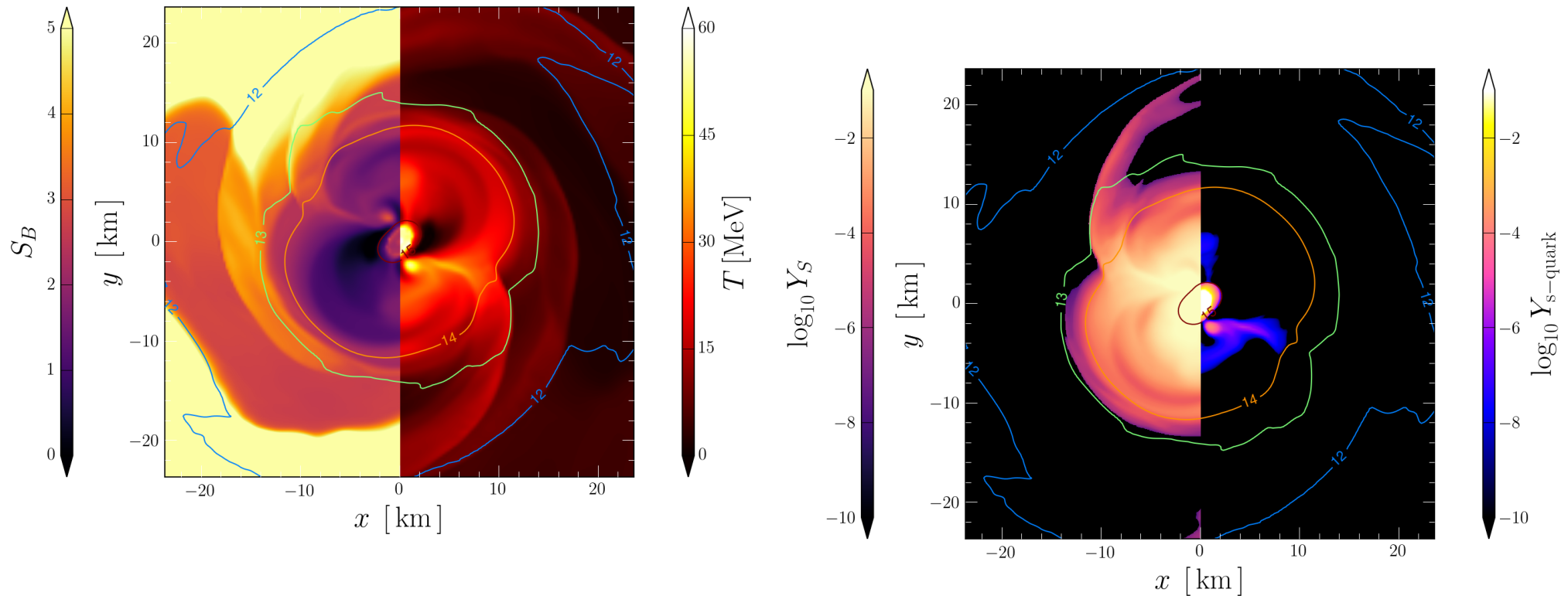
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- increase in abs. value of charged chemical potential until phase transition, when it drops
- decrease in charge fraction of core after when quarks appear

Inside 1 hypermassive neutron star

- total mass $2.9 M_{\text{Sun}}$ 5 ms after merger



- increase of temperature, entropy per baryon, and s-quark fraction at phase transition

- total strangeness (hyperons \rightarrow s-quarks) remains the same

Tidal deformability

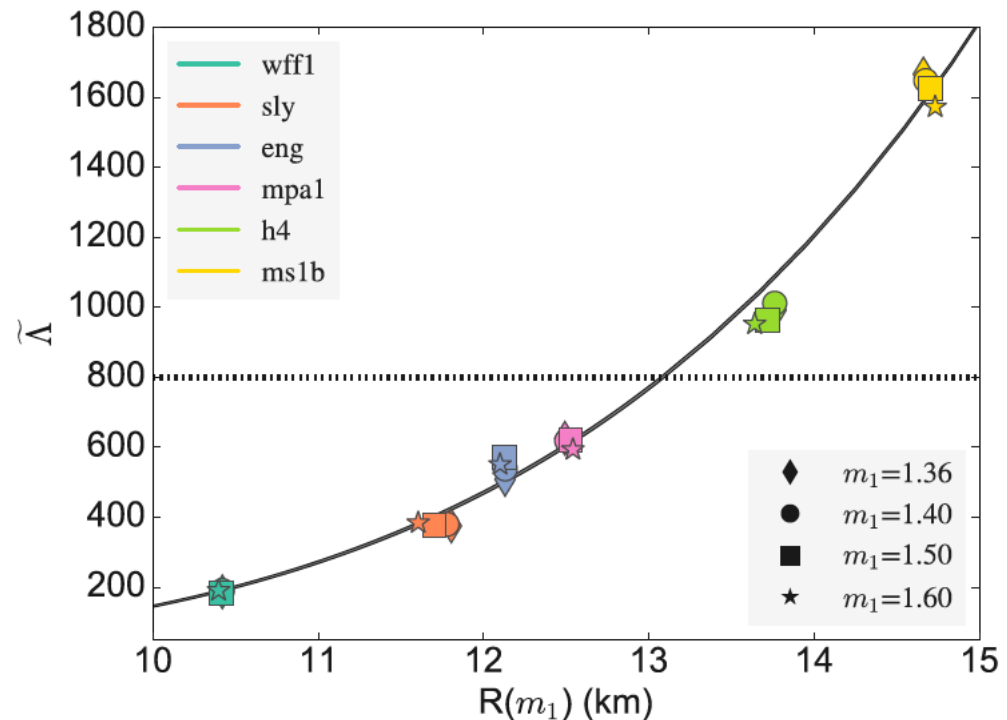
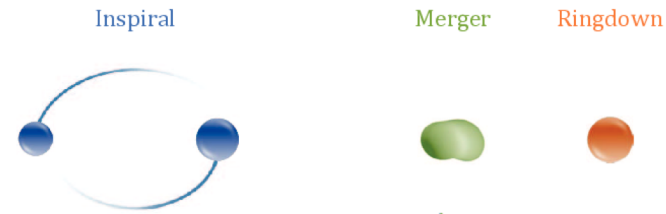
- normalized stellar quadrupole deformation by companion

- calculated from finite-size effects in end of inspiral:

76 \rightarrow 1045 with 90% confidence (De et. al 2018)

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

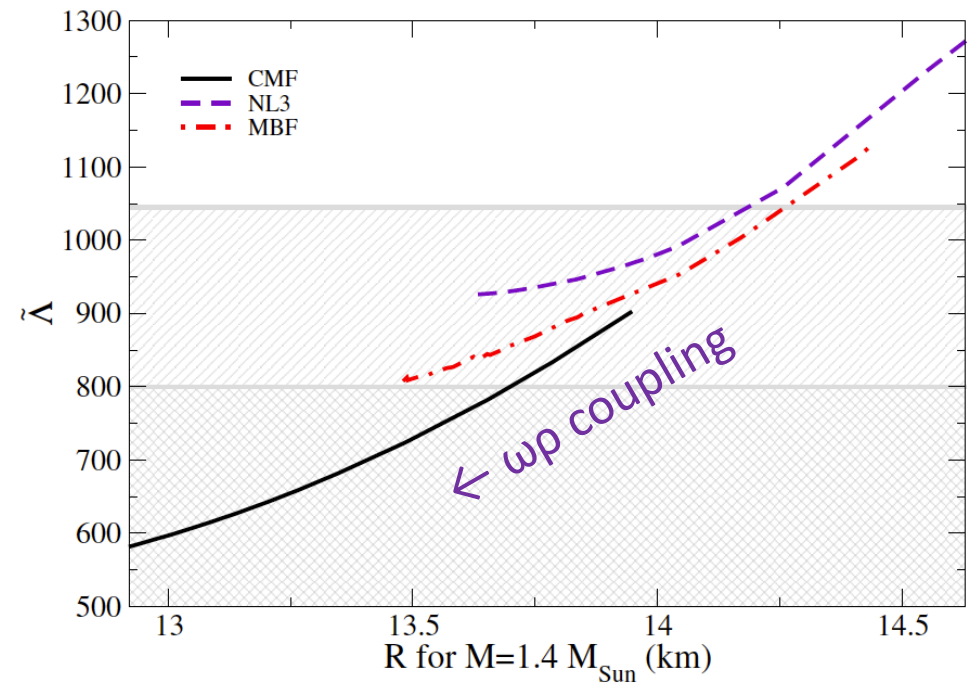
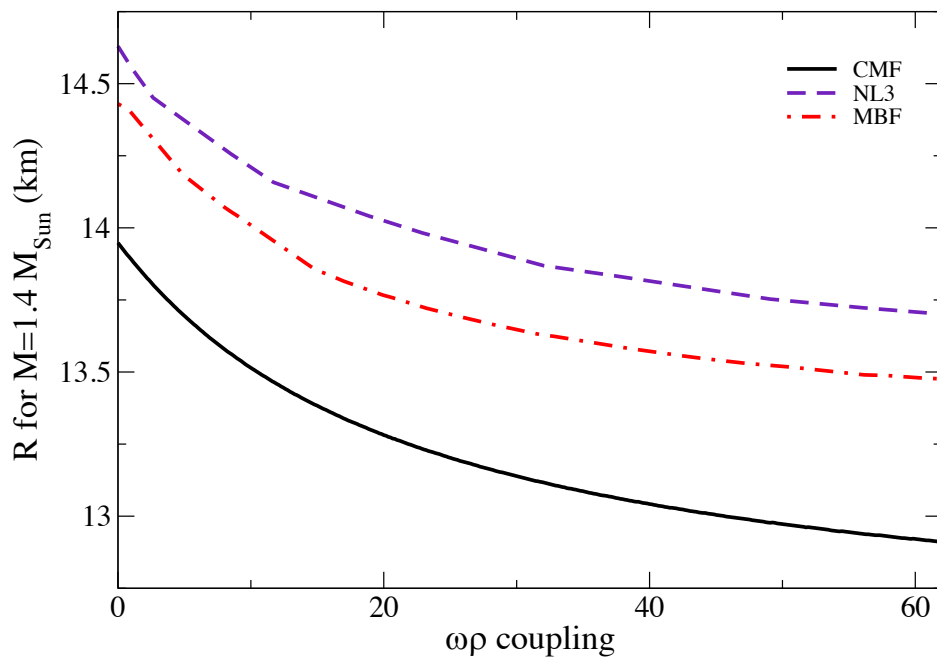
- universal relation?



Exploring hadronic isovector coupling

- using 3 relativistic EoS's that fulfill standard nuclear and astrophysical constraints

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



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

Outlook

- GW170817 provided us a new way to study dense and hot matter in an environment not quite the same as heavy-ion or supernova ones
- 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 LIGO/VIRGO merger data coming soon ...so, maybe, there will be a clear signature for deconfinement from astrophysics!

