Quark formation and phenomenology in binary neutron-star mergers using V-QCD

Konrad Topolski, Goethe University

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S. Tootle, C. Ecker, K. Topolski, T. Demircik, M. Järvinen, L. Rezzolla

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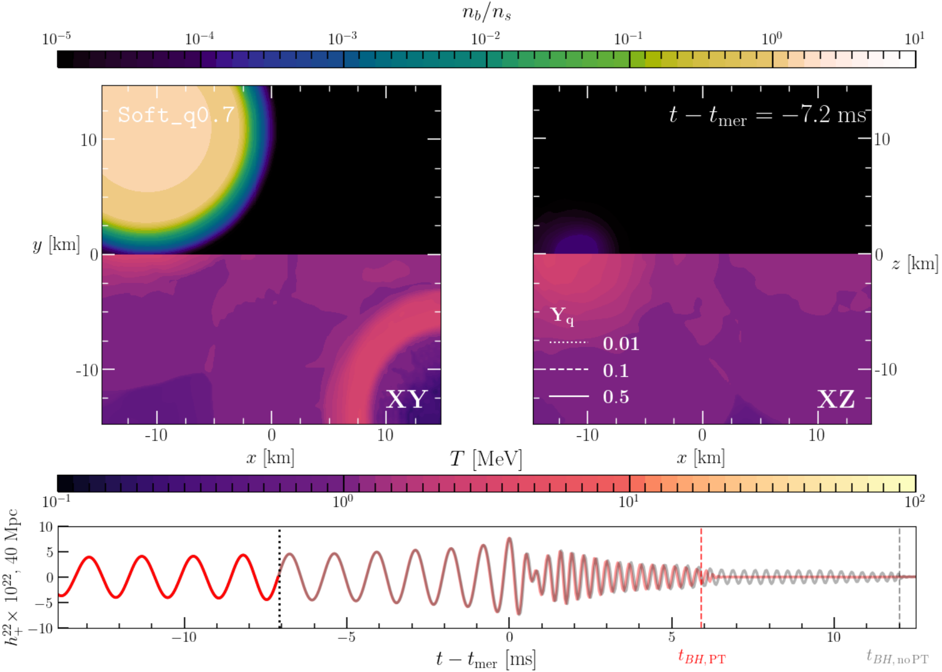
Outline

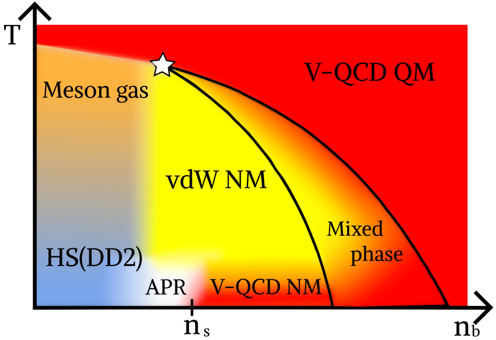
1. Introduce the EoS with a novel contribution from the V-QCD.
2. Describe the binary neutron star merger setup and configurations.
3. Technicalities and tools.
4. Quark formation stages in the post-merger phase.
5. Phase transition signatures in the gravitational wave signal (or lack thereof).
6. Future perspectives.


n_b/n_s
Soft_q0.7
$t - t_{\rm mer} = -7.2$ ms
y [km]
z [km]
$\mathrm{Y_q}$
0.01
0.1
0.5
XY
XZ
x [km]
x [km]
T [MeV]
$h_+^{22} \times 10^{22}$, 40 Mpc
$t - t_{\rm mer}$ [ms]
$t_{BH,\rm PT}$
$t_{BH,\rm noPT}$

(Very) Shortly about V-QCD

- V-QCD is a non-perturbative gauge-gravity duality model of of QCD; includes sectors both for quarks and for gluons
- based on a string theory setup in the Veneziano limit
- action of the model is tuned to agree with QCD data at finite number of colours and flavours
- remaining freedom - lattice data
- gauge/gravity duality provides a mapping between solutions in strongly coupled four dimensional field theory (various phases!) to classical five dimensional gravity

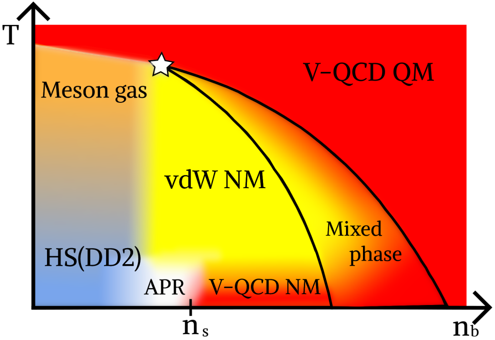
The equation of state



- low density nuclear matter: HS(DD2) EoS + APR model
- dense baryon and quark matter: V-QCD model of the gauge/gravity duality
- temperature dependence: van der Walls model & an effective potential
- electron fraction dependence: HS(DD2) for NM and free electron model for QM

Demircik, Ecker, Järvinen arXiv:2112.12157

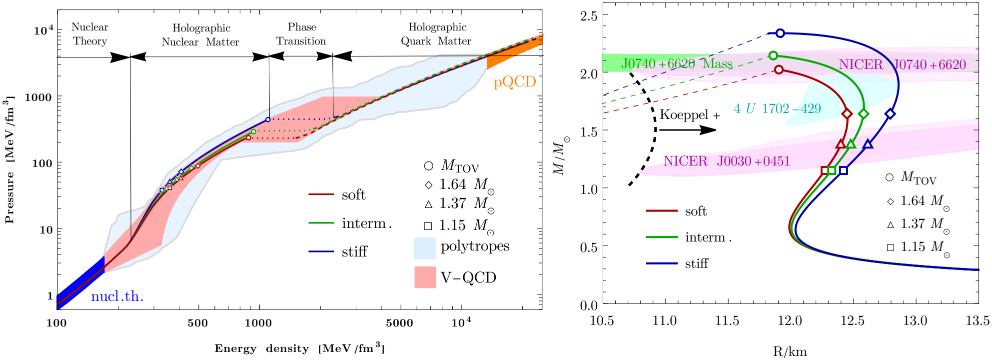
The equation of state - cd.



The construction provides, in a consistent manner:

- agreement with perturbative QCD at large densities
- an agreement with nuclear theory at low densities
- a strong first-order phase transition (mixed NM-QM phase) **within** the V-QCD framework, obtained via Gibbs construction

Cold slices & observational constraints

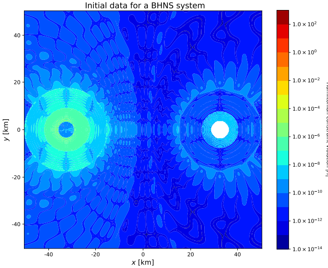


- p-QCD and nuclear theory constraints satisfied
- consistent with mass-radius observational data
- the upper bound on the binary tidal deformability $\tilde{\Lambda} < 720$ respected

Our tools (technical slide)

To simulate the BNS mergers, we have used:

- The public Einstein Toolkit computational infrastructure with our private *thorns* - ANTELOPE for spacetime evolution and FIL-GRMHD for (magneto-)hydrodynamics.
  - solving the 3+1 formulation of EFEs in a Z4c formulation,
  - 4-th order finite differencing,
  - handling of tabulated EoS, $P = P(\rho, T, Y_e)$
- An elliptic equations' solver FUKA for initial binary configurations
  - solve the constraint equations (for the initial spacetime slice) in the XCTS scheme + an assumption of a time-symmetry moment
  - low (realistic!) eccentricity of the orbit
- roughly $\sim$ 5M CPUh altogether, for all the $\sim$ 20 simulations, ran at the HAWK supercomputing centre



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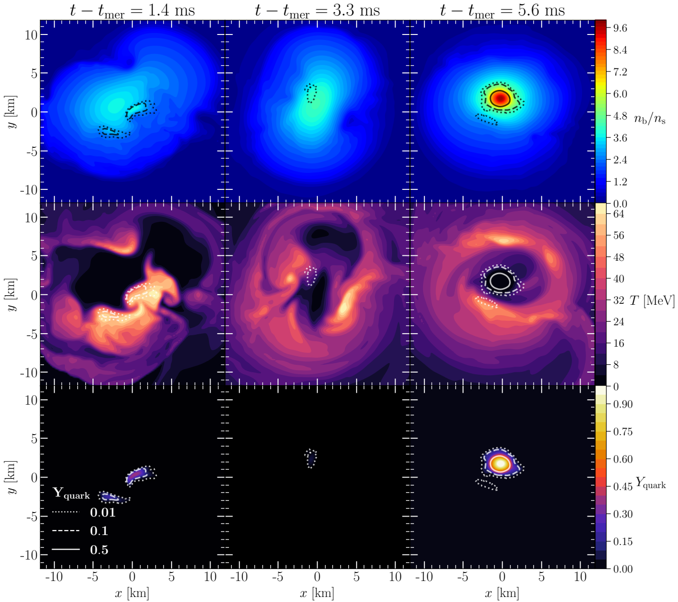
Binary systems' configurations

Our simulations are characterized by:

- chirp mass fixed to $\mathcal{M}_{\mathrm{chirp}} = 1.186\, M_{\odot}$(GW170817)
- non-spinning components (GW170817 favours low-spin priors)
- equal mass ($q = 1$) and unequal-mass ($q = 0.7$) binaries
- 3 versions of the EoS (soft, intermediate & stiff), as well as a soft version without a phase transition
- resolutions of $\Delta_{\mathrm{L}} := 369\,\mathrm{m}$, $\Delta_{\mathrm{M}} := 295\,\mathrm{m}$ and $\Delta_{\mathrm{H}} := 221\,\mathrm{m}$

Merger dynamics and quark formation



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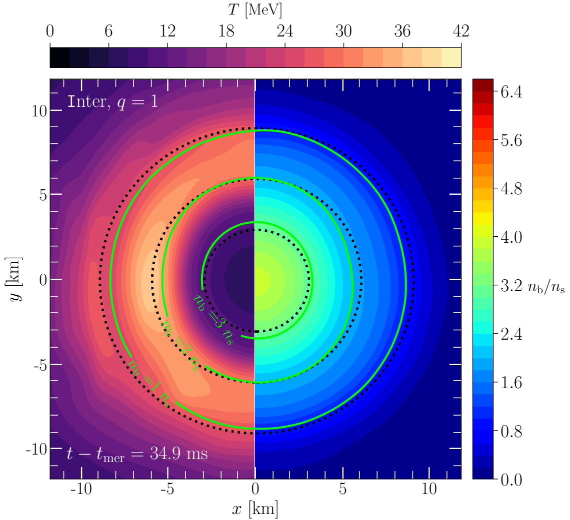
Characterizing quark production channels



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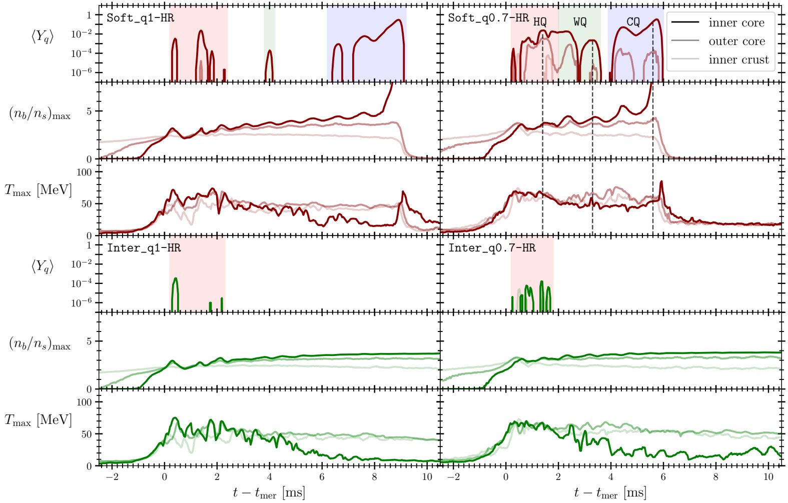
The impact of stiffness and mass ratio



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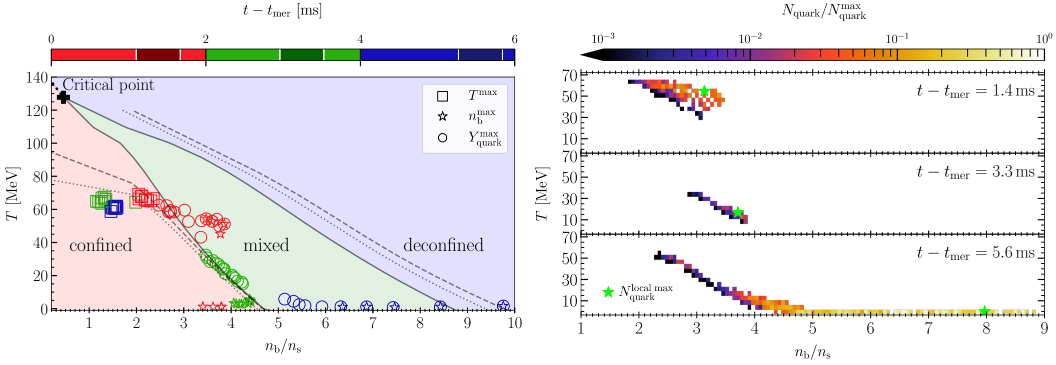
Quark abundance



- quark formation highly correlated with shock heating shortly after merger,
- once the remnant stabilizes, quark formation correlates with the density
- the greatest abundance of deconfined matter overall is in the cold and dense region of the phase diagram and leads to collapse

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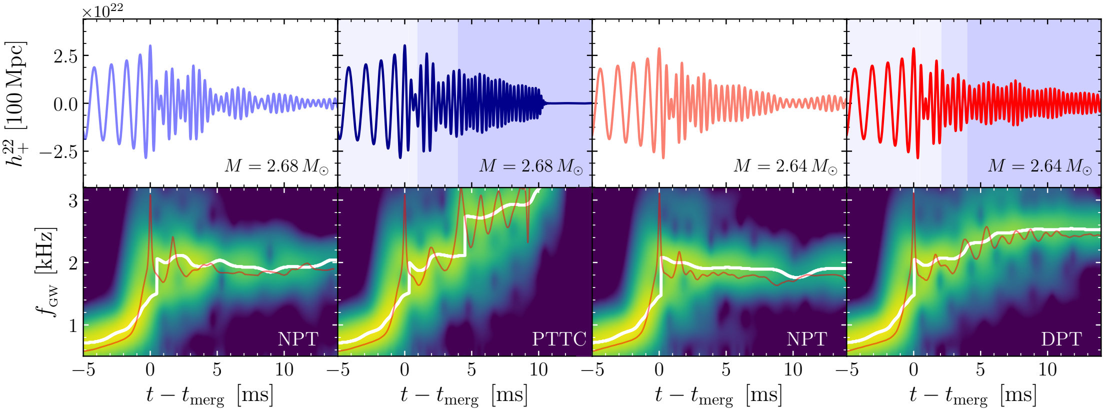
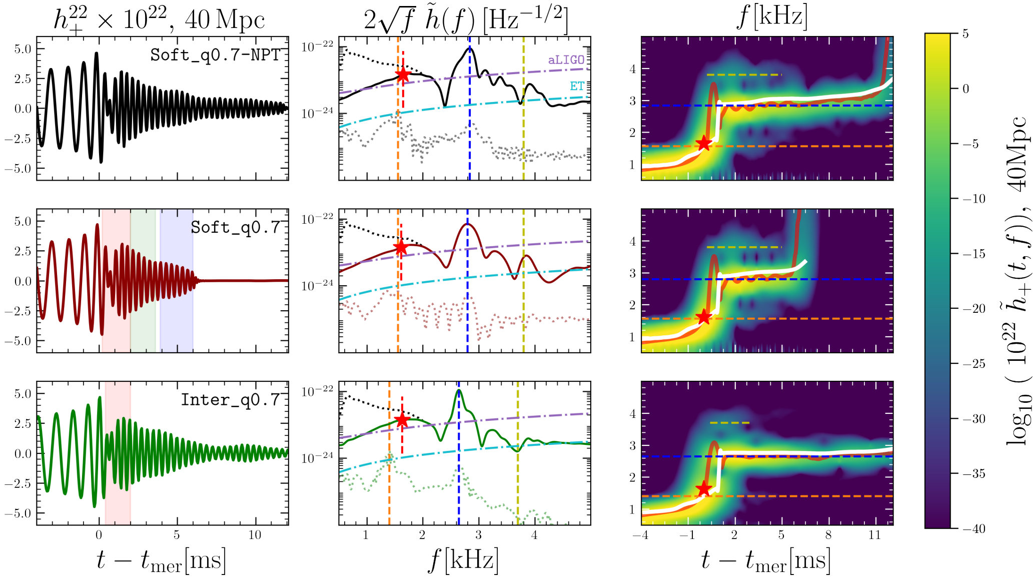
Impact on the GW signal - general PT classification



[1] arXiv:1912.09340, Weih, Hanauske, Rezzolla

Impact on the GW signal - V-QCD runs



In summary:

- three main quark production channels identified in the context of GW170817-like mergers
- possible constraining of the V-QCD critical point (admissible stiffness of the EOS) - delicate point!
- no smoking-gun signatures of phase transition apart from an earlier collapse time

Avenues to explore:

- prolong the intermediate and stiff EoS runs to $\mathcal{O}(1\mathrm{s})$ - e.g. in BHAC
- explore the 3D distribution of quark matter
- add magnetic fields & a neutrino cooling scheme
- analyze with greater accuracy the waveforms at quark-formation induced collapse for possible signatures - in particular beyond the $(2,2)$ mode