Exploring the Phase Diagram of V-QCD with Neutron Star Mergers

Christian Ecker

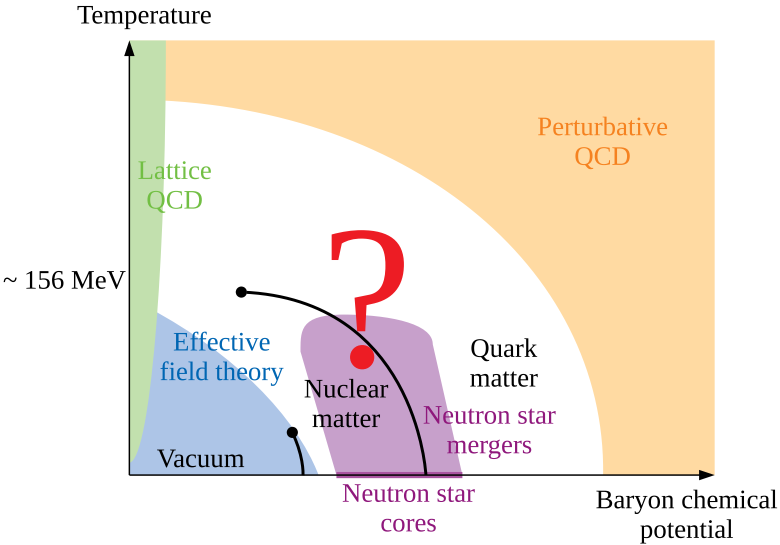
ELEMENTS Conference
11 July 2023

Based on
2009.10731 (ApJL), 2112.12157 (PRX) and 2205.05691 (SciPost) with
Tuna Demircik, Matti Järvinen, Luciano Rezzolla, Samuel Tootle and Konrad Topolski

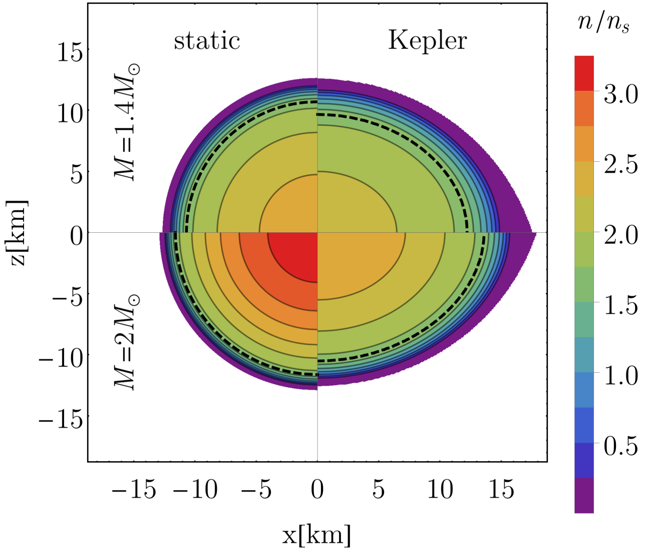
and

2203.14974 (ApJL), 2207.04417 (ApJL), 2209.08101 (MNRAS) and 2307.03225 with
Sinan Altiparmak, Carlo Musolino and Luciano Rezzolla

What we (don't) know about QCD



Density Profile



Demircik, CE, Järvinen 2009.10731 (ApJL)

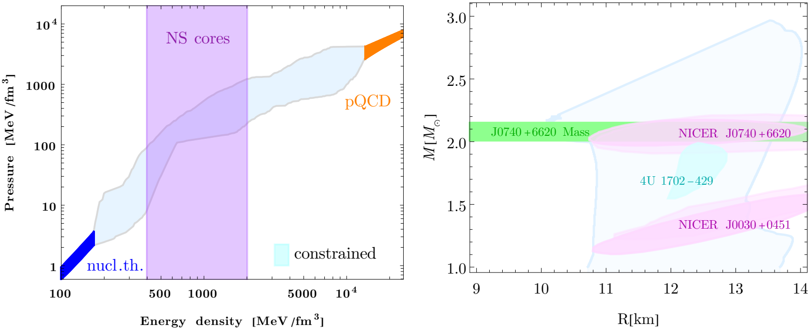
Equation of State

Relates properties of dense matter to properties of neutron stars.

$$p = p(e, \dots) \xrightarrow{\text{Einstein Eq.}} M(R)$$

Constrained by theory and neutron star observations:

- Causality & thermodynamic stability: $0 < c_s^2 = \frac{\mathrm{d}p}{\mathrm{d}e} < 1$
- Direct mass and radius measurements: $M_{\mathrm{TOV}} \gtrsim 2\,M_\odot$, $11\,\mathrm{km} \lesssim R \lesssim 14\,\mathrm{km}$
- First GW detection from a BNS merger GW170817: $\tilde{\Lambda} \lesssim 720$



Model Independent Approach

Impose boundary conditions from nuclear theory and perturbative QCD.

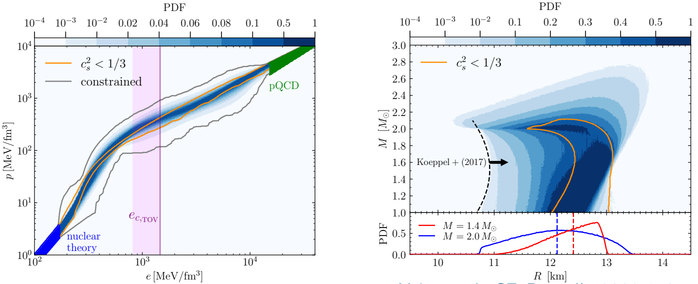
Hebeler, Lattimer, Pethick, Schwenk 1303.4662(ApJ); Fraga,Kurkela,Vuorinen 1311.5154(ApJL)

Connect with random, but causal and thermodynamically consistent EOS.

$$c_s^2(\mu) = \frac{\left(\mu_{i+1}-\mu\right)c_{s,i}^2 + (\mu-\mu_i)c_{s,i+1}^2}{\mu_{i+1}-\mu_i}\ ,\ n(\mu) = n_1\, e^{\int_{\mu_1}^{\mu} \frac{\mathrm{d}\mu'}{\mu' c_s^2(\mu')}}\ ,\ p(\mu) = p_1 + \int_{\mu_1}^{\mu} \mathrm{d}\mu'\, n(\mu')\ .$$

Annala, Gorda, Kurkela, Nättilä, Vuorinen 1903.09121 (Nature Physics)

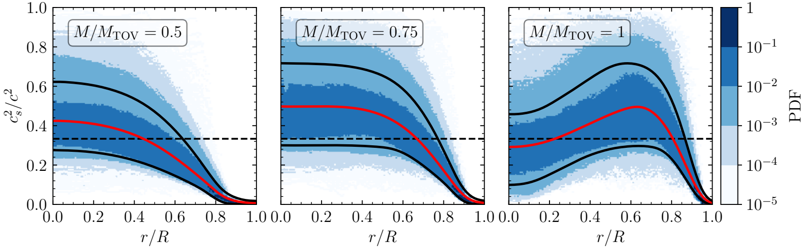
Constrain with pulsar and binary neutron star observations.



Altiparmak, CE, Rezzolla 2203.14974 (ApJL)

Lots of recent work:
...; Annala, Gorda, Kurkela, Nättilä, Vuorinen 2105.05132 (PRX);
Komoltsev, Kurkela 2111.05350 (PRL); Altiparmak, CE, Rezzolla (ApJL) 2203.14974;
Gorda, Komoltsev, Kurkela 2204.11877; CE, Rezzolla 2207.04417 (ApJL); ...

Sound Speed Inside Neutron Stars



- **Light Stars:** stiff core, soft outer layer.
- **Typical Stars:** large stiff core.
- **Massive Stars:** soft core, stiff outer layer.

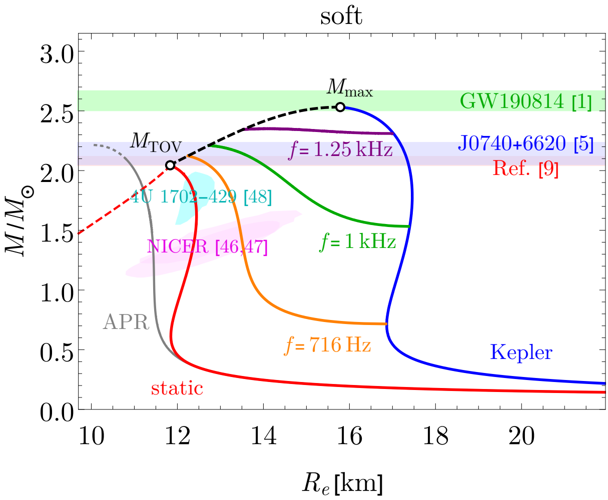
CE, Rezzolla 2207.04417 (ApJL);

Outreach: 3rd place idw award for science communication for Phyllis Mania.

Mass-Radius Relation of Rotating Stars

Universal Ratio: $\frac{M_{\max}}{M_{\mathrm{TOV}}} \approx 1.2$

Breu, Rezzolla arXiv:1601.06083 (MNRAS)



Demircik, CE, Järvinen arXiv:2009.10731 (ApJL)

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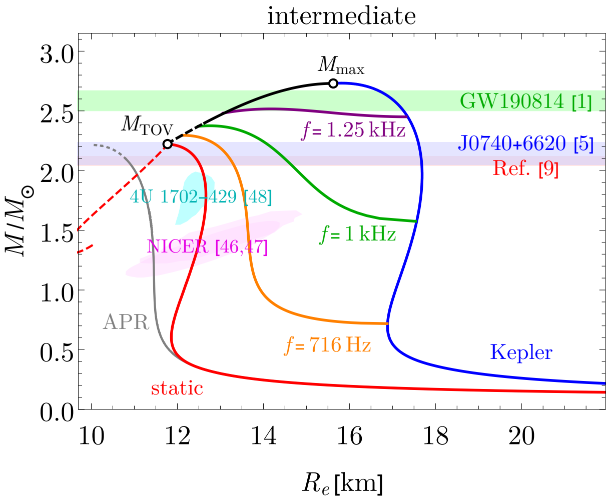

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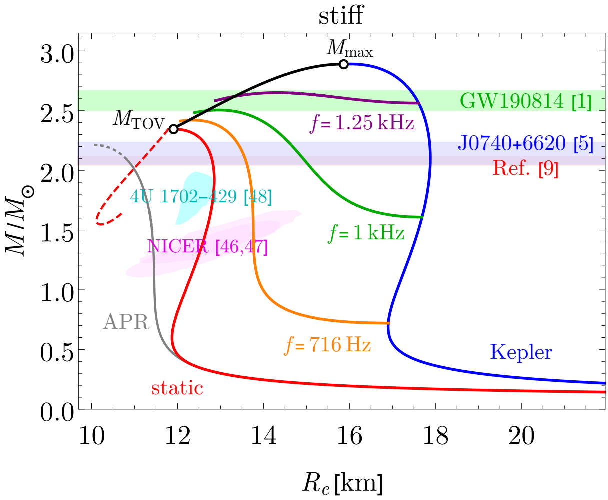
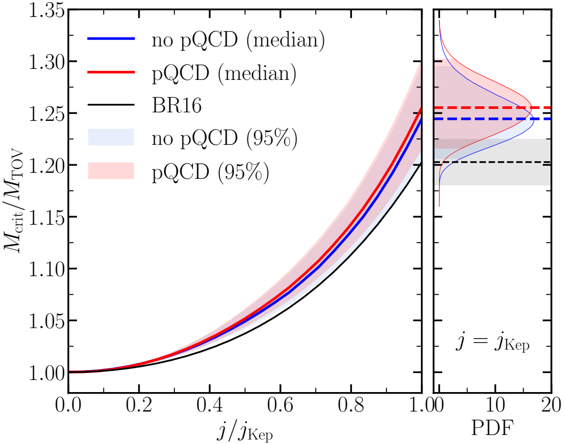


Demircik, CE, Järvinen arXiv:2009.10731 (ApJL)

Quasi-Universal Relations for Rotating Stars

$$\frac{M_{\rm max}}{M_{\rm TOV}} = 1.255^{+0.047}_{-0.040}, \quad \left(1.244^{+0.050}_{-0.039},\ 1.203^{+0.022}_{-0.022}\right) \tag{1}$$



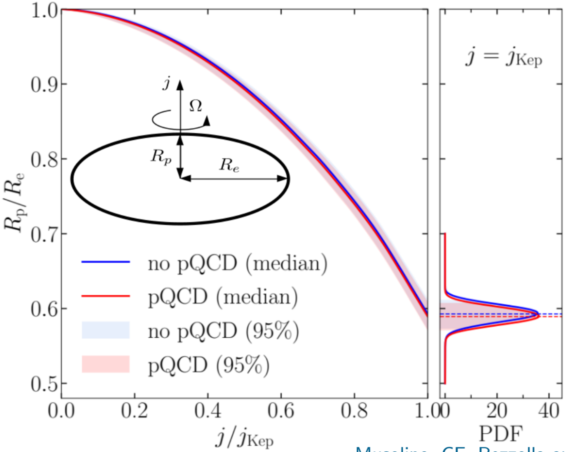
Musolino, CE, Rezzolla arXiv:2307.03225

Quasi-Universality of Neutron Star Oblateness

Oblateness: ratio of polar radius (R_p) and equatorial radius (R_e).

$$\frac{R_p}{R_e} = 1 - b_2 \left(j/j_{\rm Kep}\right)^2 \ , \ b_2 = 0.41^{+0.02}_{-0.02} \ \left(0.40^{+0.02}_{-0.02}\right) \ . \qquad (2)$$

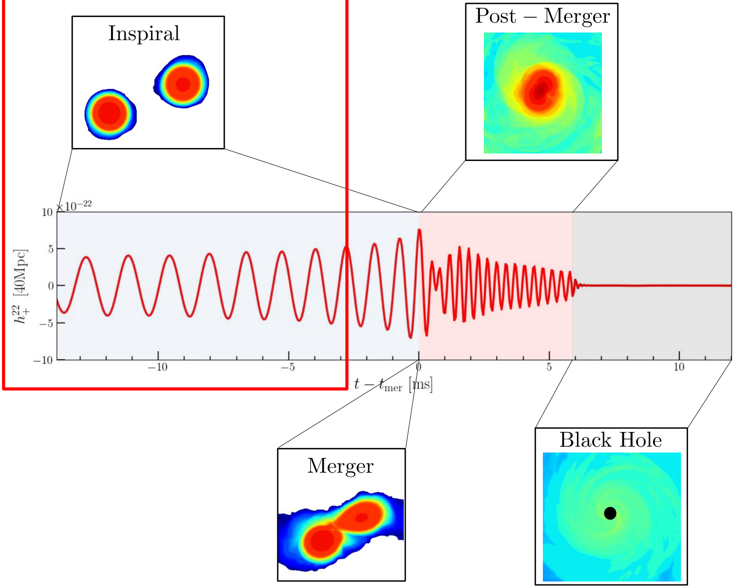
Lower bound depends only (mildly) on crust: $0.6 \lesssim \frac{R_p}{R_e} \leqslant 1$.



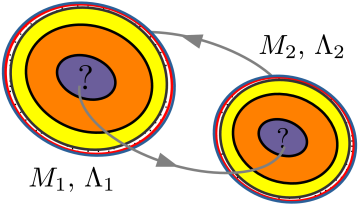
Musolino, CE, Rezzolla arXiv:2307.03225

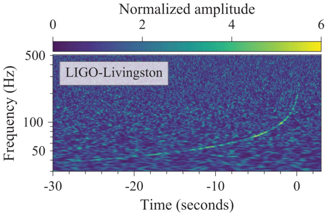
$\mathrm{GW}: f \approx 100s\ \mathrm{Hz} \rightarrow \mathcal{M}_{\mathrm{chirp}}$

$\mathrm{EOS}: \ T \approx 0 \rightarrow \tilde{\Lambda}$



Chirp Mass and Binary Tidal Deformability





- Chirp mass can be extracted accurately from inspiral GW strain frequency

$$\frac{\mathrm{d}f_{GW}}{\mathrm{d}t} = \frac{96}{5}\pi^{8/3}\mathcal{M}_{chirp}^{5/3} f_{GW}^{11/3}\,, \quad \mathcal{M}_{chirp} = \frac{(M_1 M_2)^{3/5}}{(M_1 + M_2)^{1/5}}\,.$$

Cutler, Flanagan arXiv:gr-qc/9402014 (PRD)

- Binary tidal deformability encodes EOS properties via Λ_i

$$\tilde{\Lambda} = \frac{16}{13}\frac{(12M_2 + M_1)\,M_1^4\Lambda_1 + (12M_1 + M_2)\,M_2^4\Lambda_2}{(M_1 + M_2)^5}\,, \quad \Lambda_i = \tfrac{2}{3}k_2\,(R_i/M_i)^5\,.$$

- GW170817 "best" event so far:

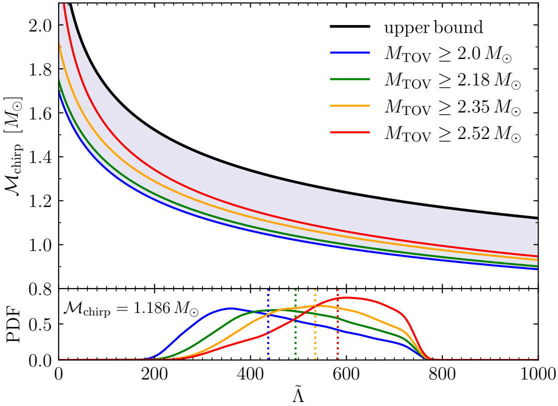
$$\mathcal{M}_{chirp} = 1.188^{+0.004}_{-0.002} M_\odot, \quad q = M_2/M_1 > 0.7, \quad \tilde{\Lambda} \lesssim 720\,.$$

LIGO/Virgo: arXiv:1805.11579

Binary Tidal Deformability

More than 10^8 binary configurations with $M_{1,2} \in [0.5M_\odot, M_{\rm TOV}]$.

$$\tilde{\Lambda}_{min(max)} = a + b\,\mathcal{M}_{chirp}^{c} \longrightarrow \tilde{\Lambda}^{\rm min}_{1.186} \in [236, 301]\,,\ M_{\rm TOV} > [2.18, 2.52]\ M_\odot\,.$$

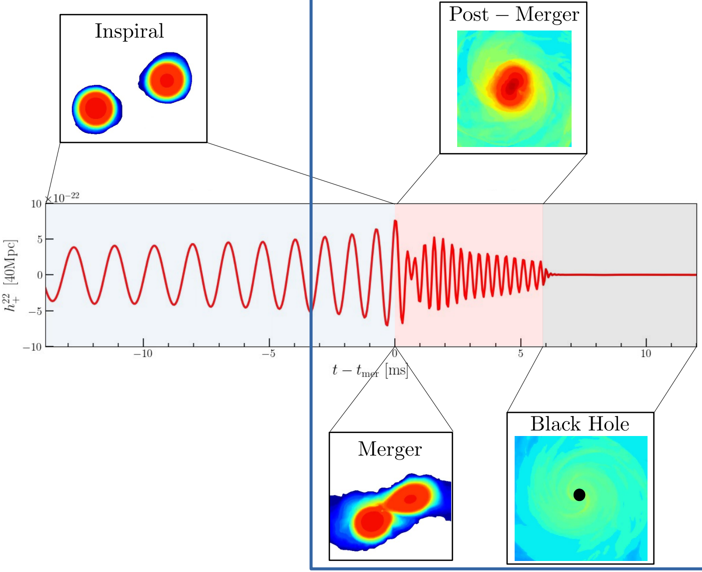


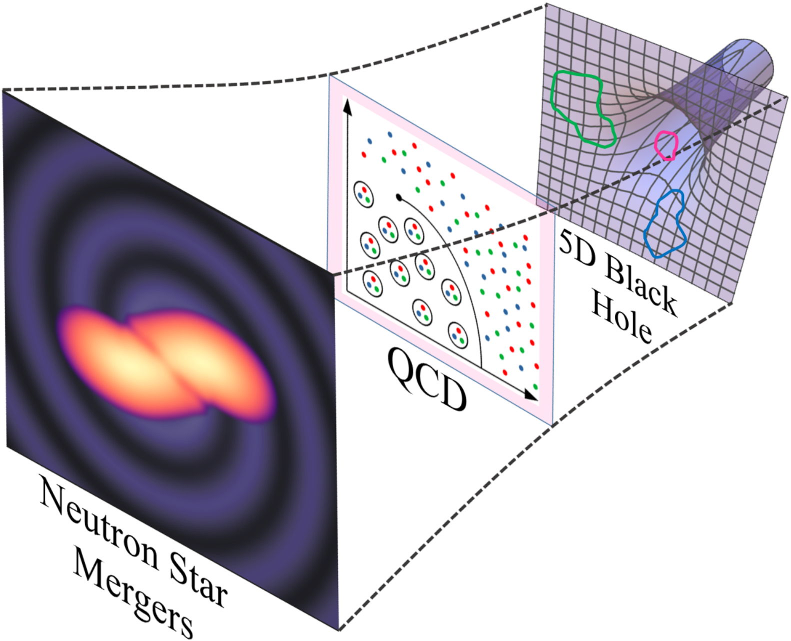
CE, Rezzolla 2209.08101 (MNRAS), see also Altiparmak, CE, Rezzolla 2203.14974 (ApJL)

GW : $f \approx \mathrm{kHz} \rightarrow f_1, f_2, f_3, \ldots$

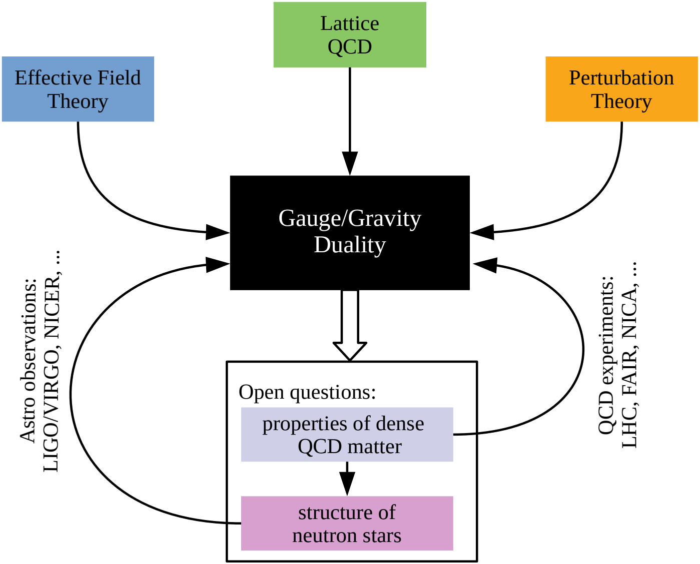
EOS : $T \gg 0$

lifetime?, composition?, ejecta?, . . .




Neutron Star Mergers
QCD
5D Black Hole

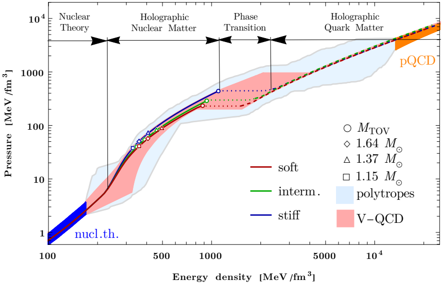
A Holographic Approach to Dense QCD Matter

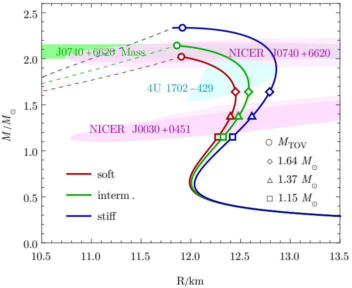


V-QCD Hybrid Equation of State

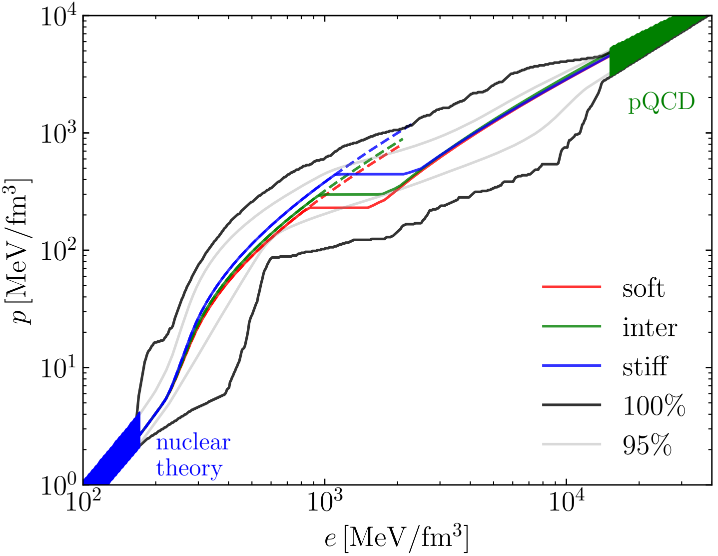
- Hybrid EOSs: nuclear theory model at lowest densities + V-QCD model for dense baryonic and quark matter at large densities.
- Van der Waals construction to extend cold V-QCD baryons to finite-T.
  Vovchenko, Motornenko, Alba, Gorenstein, Satarov, Stoecker 1707.09215 (PRC)
- Mixed baryon and quark matter phase from mech. and chem. equilibrium:

$$X_{NM}(T, n_b^{(1)}, Y_q^{(1)}) = X_{QM}(T, n_b^{(2)}, Y_q^{(2)}) , \quad X = \{p, \mu_b, \mu_{le}\} .$$





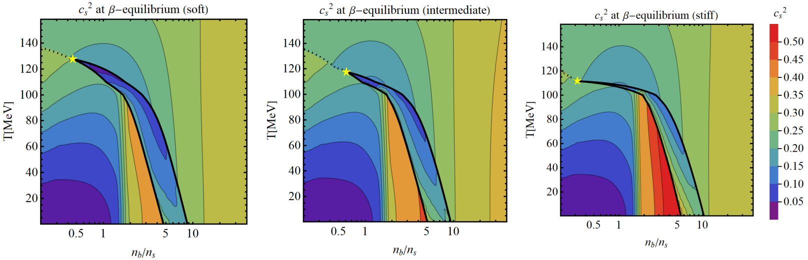
Demircik, CE, Järvinen 2112.12157 (PRX);
see also CE, Järvinen, Nijs, van der Schee 1908.03213 (PRD);
Jokela, Järvinen, Nijs, Remes 2006.01141 (JHEP);



EOSs: Demircik, CE, Järvinen 2112.12157 (PRX);

Grey band ($M_{\mathrm{TOV}} > 2.2\ M_\odot$): CE, Rezzolla 2209.08101 (MNRAS)

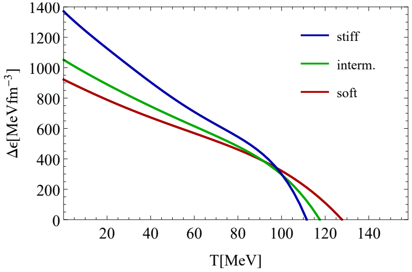
V-QCD Critical Point



Estimates for the critical point:

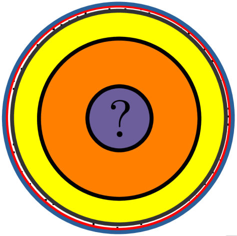
$$110\ \mathrm{MeV} \lesssim T_c \lesssim 130\ \mathrm{MeV}$$
$$0.3\ n_s \lesssim n_c \lesssim 0.6\ n_s$$

model	$\frac{n_{bc}}{n_s}$	$\frac{\mu_{bc}}{\mathrm{MeV}}$	$\frac{T_c}{\mathrm{MeV}}$
soft	0.46	485	128
interm.	0.62	575	118
stiff	0.32	565	112

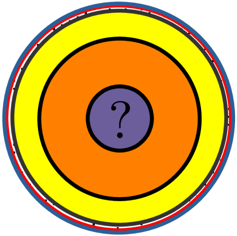


(Same ballpark as seen in Nicolas talk.)

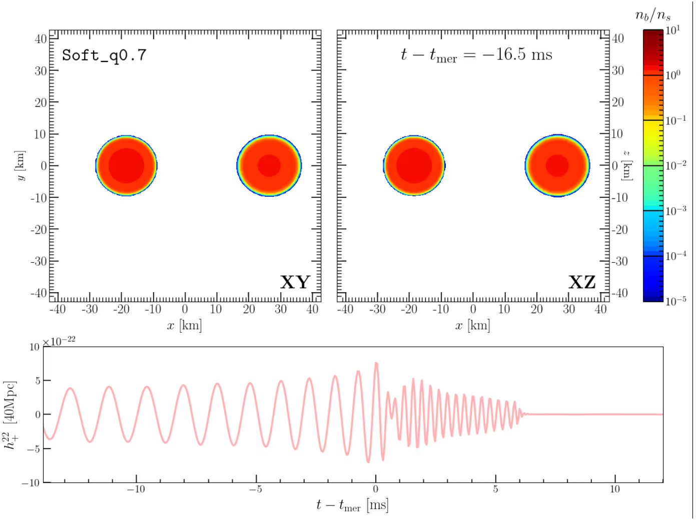
Demircik, CE, Järvinen 2112.12157 (PRX)



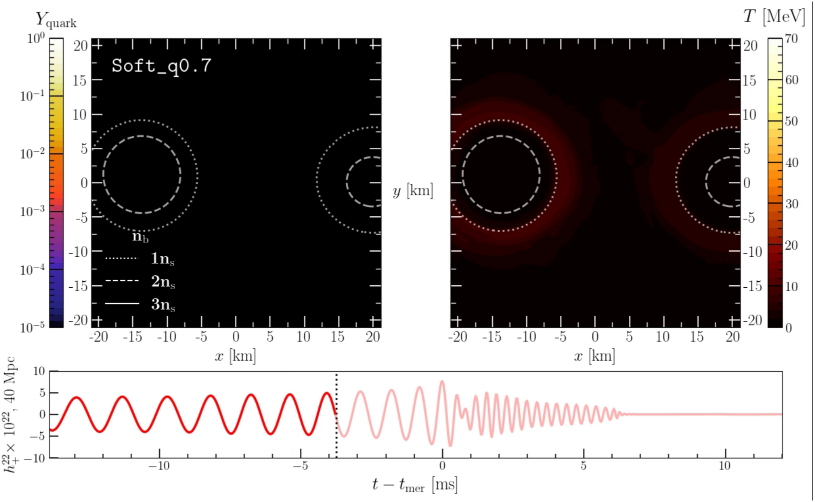
$+$



$= ?$

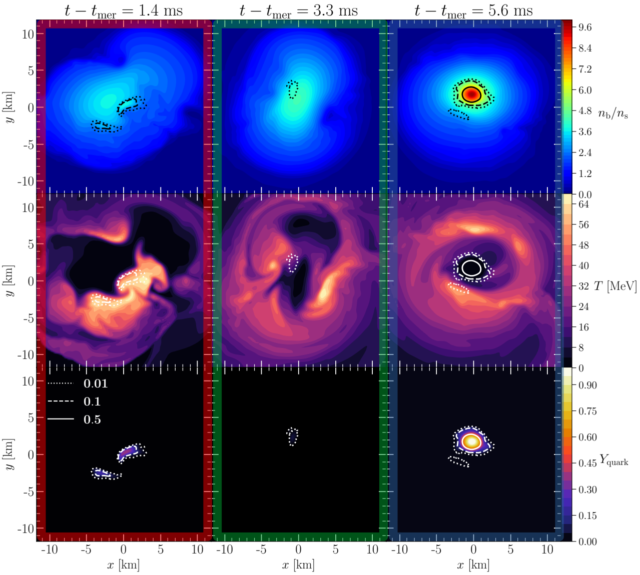


Movie by Konrad Topolski with data from 2205.05691 (SciPost).



Movie by Konrad Topolski with data from 2205.05691 (SciPost).

Hot, Warm and Cold Quarks



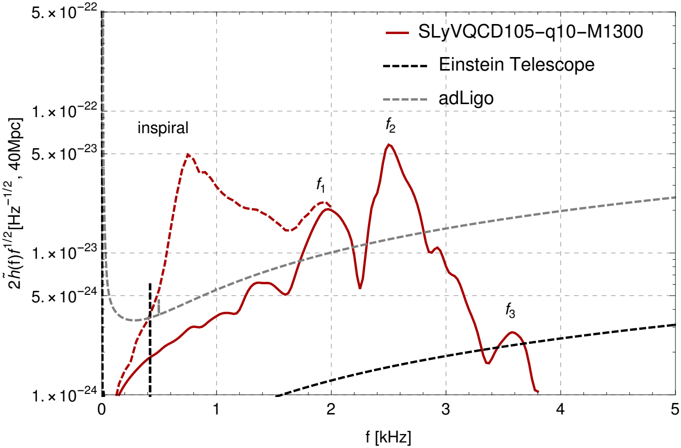
Tootle, CE, Topolski, Demircik, Järvinen, Rezzolla 2205.05691 (SciPost)

Power Spectral Density

Post-merger power spectral density (PSD) has typical three peak structure

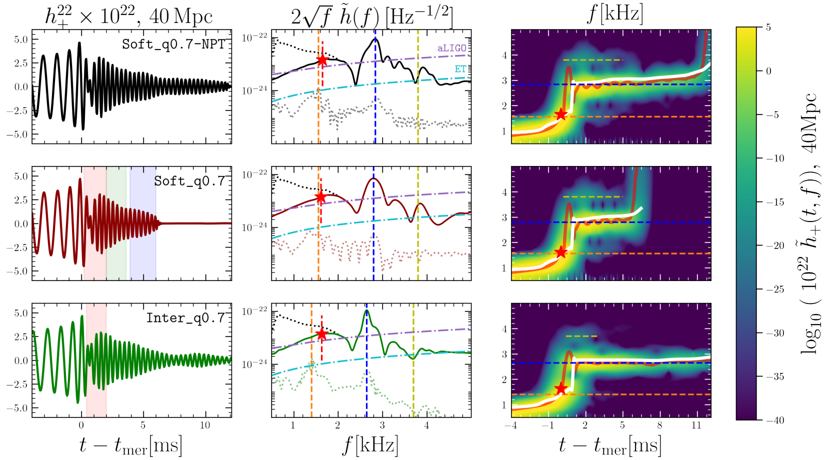
$$\tilde{h}(f) \equiv \sqrt{\frac{|\tilde{h}_+(f)|^2 + |\tilde{h}_\times(f)|^2}{2}}\,, \quad \tilde{h}_{+,\times}(f) \equiv \int h_{+,\times}(t) e^{-i2\pi f t} dt\,.$$

Characteristic frequencies f_1, f_2, f_3 encode information about EOS.



Waveforms and Frequency Spectra

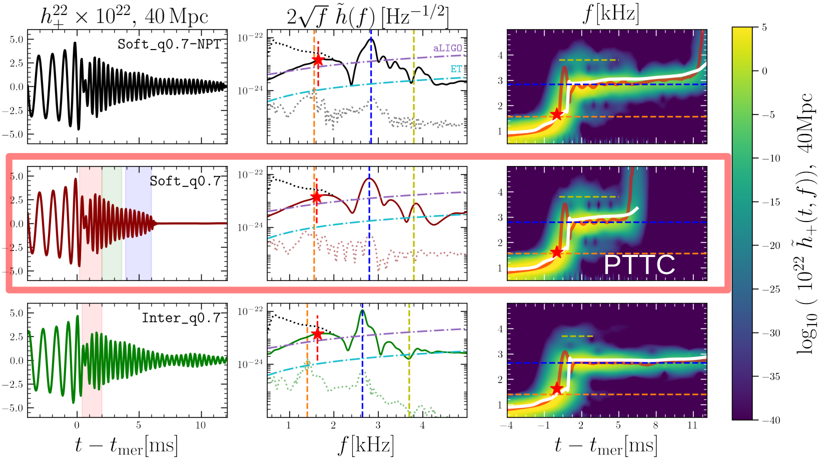
- Small impact of quark matter on post-merger frequencies.



Tootle, CE, Topolski, Demircik, Järvinen, Rezzolla 2205.05691 (SciPost)

Waveforms and Frequency Spectra

- Small impact of quark matter on post-merger frequencies.
- Phase transition triggered collapse (PTTC) leads to shorter lifetime of the hyper massive neutron star (HMNS).



Tootle, CE, Topolski, Demircik, Järvinen, Rezzolla 2205.05691 (SciPost)

Summary

- Basic properties of the cold EOS and neutron stars can be estimated from constraint sampling: $p(e)\,, M(R)\,, c_s^2\,, \tilde{\Lambda}(\mathcal{M}_{\rm chirp})\,, \ldots$

  CE, Rezzolla arXiv:2209.08101 (MNRAS), arXiv:2207.04417 (ApJL);

  Altiparmak, CE, Rezzolla arXiv:2203.14974 (ApJL)

- Improved value for $M_{\rm max}/M_{\rm TOV} = 1.255^{+0.047}_{-0.040}$ and quasi-universal relation of neutron star oblateness R_e/R_p.

  Musolino, CE, Rezzolla arXiv:2307.XXXX

- In binary mergers finite temperature effects are important!
- Hot V-QCD hybrid EOS with deconfinement phase transition, three tabulated versions on CompOSE database: DEJ(DD2-VQCD).

  https://compose.obspm.fr/

- Predictions for the QCD critical point:

$$110\ \mathrm{MeV} \lesssim T_c \lesssim 130\ \mathrm{MeV}\,, \quad 0.3\ n_s \lesssim n_c \lesssim 0.6\ n_s\,.$$

Demircik, CE, Järvinen 2112.12157 (PRX)

- Neutron star merger simulations with V-QCD EOS.
- Identified 3 different stages in HMNSs: hot, warm, cold quark matter.
- Small impact on frequencies, but PTTC shortens HMNS lifetime.

Tootle, CE, Topolski, Demircik, Järvinen, Rezzolla 2205.05691 (SciPost)

Holographic Veneziano QCD

Holographic bottom-up model for QCD with many parameters that are tuned to mimic QCD and that are constrained by lattice QCD data.

Järvinen, Kiritsis 1112.1261 (JHEP)

Gluons: Improved holographic QCD (Einstein-dilaton gravity)

$$S_{\rm g} = N_c^2 M^3 \int d^5x \sqrt{-g} \left[R - \frac{4}{3}\frac{(\partial\lambda)^2}{\lambda^2} + V_g(\lambda) \right]$$

$\lambda \equiv e^{\phi} \leftrightarrow \mathrm{Tr} F^2$ sources the 't Hooft coupling in YM theory

Gürsoy, Kiritsis 0707.1324 (JHEP); Gürsoy, Kiritsis, Nitti 0707.1349 (JHEP)

Quarks: Tachyonic Dirac-Born-Infeld (DBI) action

$$S_{\rm f} = -N_f N_c M^3 \int d^5x V_{f0}(\lambda) e^{-\tau^2} \sqrt{-\det\left[g_{ab} + \kappa(\lambda)\partial_a\tau\partial_b\tau + w(\lambda)F_{ab}\right]}$$

$$F_{rt} = \Phi'(r)\,, \quad \Phi(0) = \mu\,,$$

tachyon $\tau \leftrightarrow \bar{q}q$ controls chiral symmetry breaking.

Bigazzi et al. 0505140 (JHEP); Casero et al. 0702155 (Nucl.Phys.B)

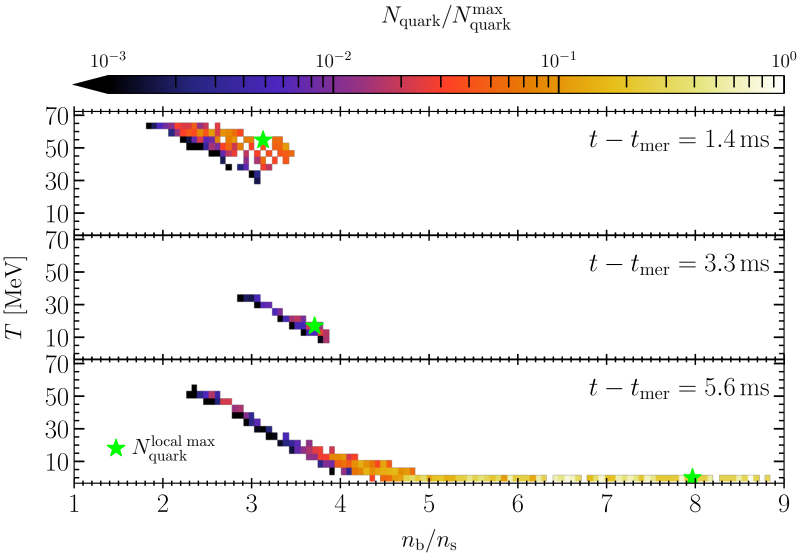
Baryons: homogeneous solution of non-Abelian DBI + Cern–Simons action.

Ishii, Järvinen, Nijs 1903.06169 (JHEP)

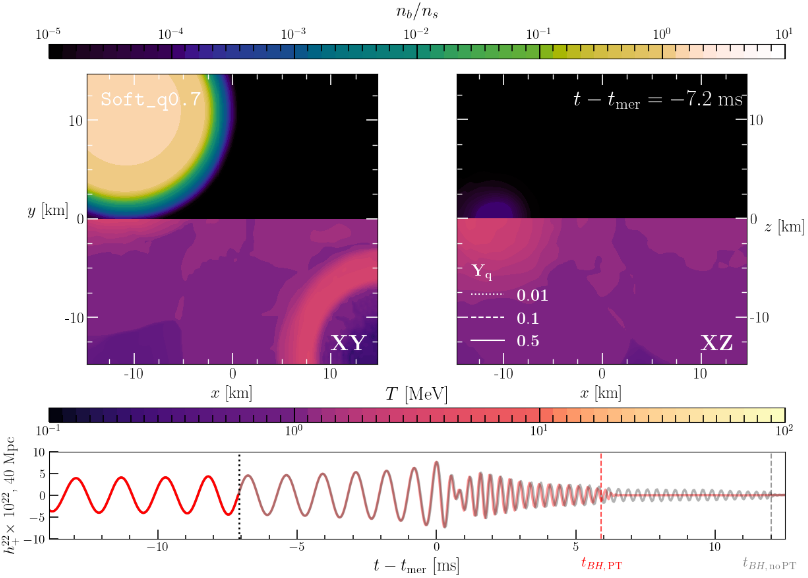
Veneziano limit: $N_c \to \infty$ and $N_f \to \infty$ with $N_f/N_c = \mathcal{O}(1)$ fixed

Järvinen, Kiritsis 1112.1261 (JHEP)

Quark Abundance

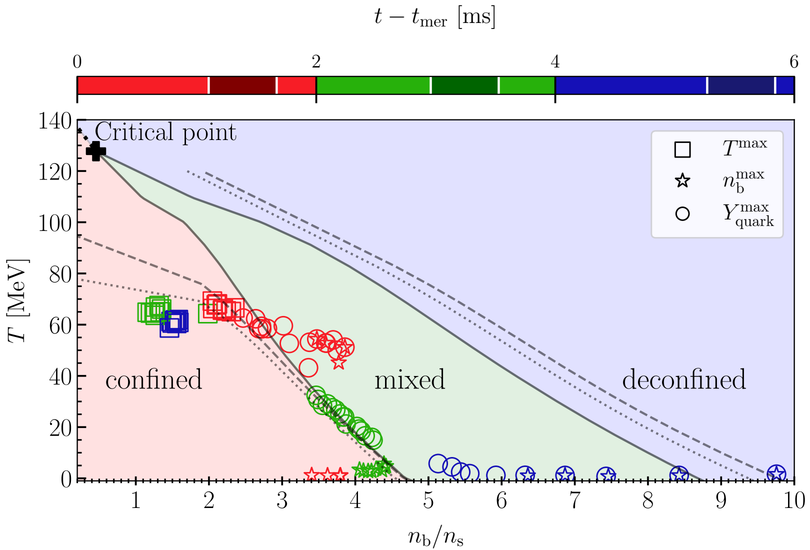


Tootle, CE, Topolski, Demircik, Järvinen, Rezzolla 2205.05691 (SciPost)



Movie by Konrad Topolski with data from 2205.05691 (SciPost).

Phase Diagram

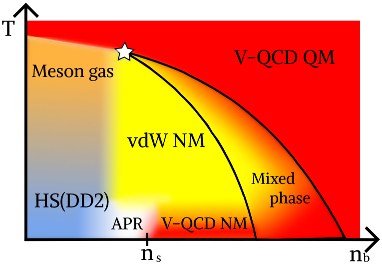


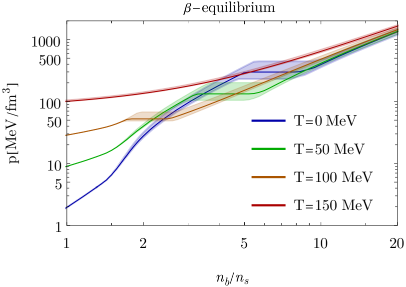
Tootle, CE, Topolski, Demircik, Järvinen, Rezzolla 2205.05691 (SciPost)

Hot V-QCD Hybrid Equation of State

- Low density part: Hemple-Schaffner-Bielich model (HS)DD2 + Particle Data Group (PDG) mesons. Hempel, Schaffner-Bielich 0911.4073 (Nucl.Phys.A); Zyla et al. (Particle Data Group 2020)
- (HS)DD2 too stiff around n_s, replace with APR model. Akmal, Pandharipande, Ravenhall 9804027 (PRC)
- Van der Waals construction to extend cold V-QCD baryons to finite-T. Vovchenko, Motornenko, Alba, Gorenstein, Satarov, Stoecker 1707.09215 (PRC)
- Mixed baryon and quark matter phase from mech. and chem. equilibrium:

$$X_{NM}(T, n_b^{(1)}, Y_q^{(1)}) = X_{QM}(T, n_b^{(2)}, Y_q^{(2)}), \quad X = \{p, \mu_b, \mu_{le}\}.$$





Demircik, CE, Järvinen 2112.12157 (PRX)