Phys. Lett. B 860 (2025) 139184

Contents lists available at ScienceDirect

Physics Letters B

journal homepage: www.elsevier.com/locate/physletb

Letter

Upper bound on the speed of sound in nuclear matter from transport

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ARTICLE INFO

Editor: B. Balantekin

ABSTRACT

We point out that there is an upper bound on the speed of sound squared given by $c_s^2 \leq 0.781$ valid for all known systems described by relativistic transient hydrodynamics where calculations of certain ratios of hydrodynamic transport coefficients can be performed from first principles. Assuming this bound is valid for ultradense matter implies that the maximum mass of isolated (non-rotating) neutron stars cannot be larger than 2.7 solar masses.

1. Introduction

The measurements of neutron stars with masses $\gtrsim 2\,M_\odot$ (where $M_\odot$ is the mass of the sun) [1–3] suggest that the cold neutron star equation of state (EoS) is stiff enough such that its speed of sound, c_s, surpasses its conformal limit, $c_s \leq 1/\sqrt{3}$, at a given density [4]. This is also supported by the binary neutron-star merger gravitational-wave event GW170817 [5–7], which further constrained the masses and effective tidal deformability of the inspiraling neutron stars [8–16]. Further support to a supraconformal speed of sound may come from the observation of gravitational waves from the merger of a black hole with a compact object of mass $2.6\,M_\odot$ [17], if the latter is a neutron star [18–23].

Due to asymptotic freedom [24,25], the speed of sound in QCD is expected to approach the conformal limit from below at sufficiently large densities [26,27]. This fact, combined with the knowledge about the nuclear physics equation of state at low densities [8,28–30] and the recent observation of large neutron star masses, implies that c_s in QCD is not monotonic as this quantity must display at least one peak as a function of density (when taking into account the region of asymptotically large density). Assuming there is only a single peak, essential questions are: (i) How large is c_s at the peak? (ii) At what density does c_s peak? (iii) What is the correct effective theory of ultradense matter that explains the answers to (i) and (ii)? Ultimately, future observations [31–34] will constrain the answer to (i) and (ii) [35–41] and provide useful guidance towards answering (iii).

Relativistic causality and covariant stability [42] impose that the speed of sound cannot surpass the speed of light, i.e., $c_s \leq 1$. At high temperatures and zero baryon chemical potential, lattice QCD calculations [43,44] and holographic models [45–48] find that the conformal limit for the speed of sound is respected, $c_s \leq 1/\sqrt{3}$. At nonzero baryon density, however, discussions concerning the (subluminal) upper bound to the speed of sound go back several decades [49–52]. It is now known that the speed of sound can surpass the conformal result in a variety of systems such as QCD at large isospin density [53], two-color QCD [54], holographic models [55–59], resummed perturbation theory [60,61], quarkyonic matter [62–66], and other models at high density [67–82]. However, despite recent progress [83,84], very little is known about the transport properties of ultradense matter when the speed of sound nears the speed of light.

In this work, we point out that ultradense matter with nearly luminal speed of sound must have very unusual transport properties. We discuss a scenario where fundamental properties of thermodynamics and transport in relativity can constrain the equation of state of ultradense matter. Assuming the validity of relativistic transient hydrodynamics in which dissipative stresses obey additional relaxation equations [85], we argue that causality and stability of matter imply that there is an upper bound on the speed of sound squared given by $c_s^2 \leq 0.781$ in all known systems[1] where calculations of certain ratios of first-order hydrodynamic

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[1] We only consider systems where the equilibrium state is unique and the correlation length is finite.

https://doi.org/10.1016/j.physletb.2024.139184
Received 22 July 2024; Received in revised form 30 September 2024; Accepted 6 December 2024

Available online 10 December 2024
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transport coefficients and their corresponding relaxation times can be performed from first principles. In this case, a violation of the bound implies that such systems either exhibit very unusual transport coefficients or cannot be consistently described by transient fluid dynamics,[2] signaling the presence of exotic transport behavior that simple relaxation dynamics cannot describe.[3] Given current astrophysical constraints, we show that imposing this bound on c_s implies that the maximum mass of an isolated neutron star is bound by $M < 2.7\, M_\odot$, assuming chiral effective theory is valid up to two times saturation density. Therefore, the new transport bound provides further support to the claim that the 2.6 $M_\odot$ compact object observed to merge with a 23 $M_\odot$ black hole causing the GW190814 event [17] can be a neutron star.

2. Speed of sound bound from transport

Fluid dynamics describes the long-time, long-wavelength dynamics of conserved quantities in many-body systems [91]. Ideal fluid dynamics describes the evolution of the energy density ϵ, number density n, and flow velocity in the absence of dissipation, with the information about the system's microscopic properties encoded in the equation of state, e.g., $P = P(\epsilon, n)$, where P is the pressure computed in thermodynamic equilibrium. In this limit, sound waves propagate with frequency $\omega = \pm c_s k$, where $c_s = \sqrt{dP/d\epsilon}$ denotes the isentropic speed of sound in the fluid, and $k = |\mathbf{k}|$ is the wavenumber.

Small dissipative corrections can be taken into account by expressing the dissipative fluxes in a systematic derivative expansion of the hydrodynamic fields [91], which introduces the well-known transport coefficients: the shear viscosity η, bulk viscosity ζ, and charge conductivity σ.

Constraining any transport coefficients in nuclear matter is challenging since it involves extracting near-equilibrium information at strong coupling from QCD. However, imposing causality can provide useful information about transport coefficients when the speed of sound nears the speed of light.

In causal and stable first-order theories [92–96], the long-wavelength behavior of the sound wave dispersion relation is given by[4] $\omega = \pm c_s k - i\Gamma k^2/2 + \mathcal{O}(k^3)$, where the damping coefficient is

$$\Gamma = \frac{\zeta + \frac{4}{3}\eta}{\epsilon + P} + \frac{\sigma}{(\epsilon + P)c_s^2}\left(\frac{\partial P}{\partial n}\right)_\epsilon^2 . \tag{1}$$

Causality [97] and the stability of the equilibrium state [42] impose that dispersion relations must obey the fundamental inequality $\mathrm{Im}\,\omega \leq |\mathrm{Im}\,k|$, $\omega, k \in \mathbb{C}$. Since the second law of thermodynamics imposes that η, ζ, σ are non-negative, $\Gamma \geq 0$, one can show[5] that $\Gamma \to 0$ when $c_s \to 1$ [42]. This statement was generalized in Ref. [98], where it was shown that the contribution from all the other terms also vanishes, making luminal sound waves exactly non-dispersive and described by the trivial dispersion relation, $\omega = k$. This implies that at densities where the speed of sound of ultradense matter approaches the speed of light, sound waves propagate without damping or dispersion.

In relativistic transient fluid dynamics [85], transport is further characterized by relaxation time coefficients that determine when the dissipative fluxes approach their first-order values. For instance, the shear relaxation time coefficient τ_π has been calculated for many theories (see, e.g., Tab. 2.1 in Ref. [99]). In all of these systems, it was found to be tightly constrained as

$$\tau_\pi = C_\pi \times \frac{\eta}{\epsilon + P} , \quad C_\pi \in [2(2 - \ln 2), 6.1] , \tag{2}$$

with the upper limit of C_π originating from theories evaluated at *weak coupling*[6] [101]. We, therefore, find the following bound

$$\frac{4\eta}{3\tau_\pi(\epsilon + P)} = \frac{4}{3C_\pi} \geq \frac{4}{3 \times 6.1} , \tag{3}$$

from relativistic transport in theories where calculations can be done from first principles.

By contrast, while the bulk relaxation time τ_Π has also been calculated in many theories, the corresponding bound on the ratio of $\frac{\zeta}{\tau_\Pi(\epsilon+P)}$, where ζ is the bulk viscosity, is much less constrained,

$$\frac{\zeta}{\tau_\Pi(\epsilon + P)} = \frac{1}{C_\Pi} > 0 , \tag{4}$$

because there are examples where $\zeta = 0, \tau_\Pi \neq 0$ [102]. Finally, not much is known from first principles about similar ratios involving the charge conductivity and the relaxation times, and thus, we shall not consider it further in this work.

Further general statements about transport can also be made in the context of transient fluid dynamics. By requiring that the entropy measured by all inertial observers is maximized in equilibrium in the presence of constraints (such as energy and/or particle number), one can derive a number of thermodynamic inequalities that ensure that the stability of the equilibrium state holds in all Lorentz reference frames [103]. These inequalities also imply causality in the linear regime around equilibrium [104]. In transient fluid dynamics, one can obtain such thermodynamic inequalities by computing the so-called information current E^μ [104], which must be a time-like future-directed 4-vector with non-positive divergence, $\nabla_\mu E^\mu \leq 0$, to satisfy the covariant version of the second law of thermodynamics. In the case of Israel-Stewart theory with shear and bulk viscosity, this implies the following thermodynamic inequality [105,106]

$$c_s^2 \leq 1 - \frac{4}{3C_\pi} - \frac{1}{C_\Pi} , \tag{5}$$

which constitutes an upper bound on the speed of sound[7] from relativistic thermodynamic principles[8] Furthermore, we see that matter in a state where the equilibrium speed of sound $c_s \to 1$ must have unusual transport behavior as not only η and ζ but also their corresponding ratios involving the relaxation times must vanish.

It should be stressed that the bound (5) relies on the assumption that transient fluid dynamics, where additional degrees of freedom (such as the shear and bulk stresses) are included as independent variables characterizing an extended quasi-equilibrium thermodynamic state [109], faithfully represent the thermodynamic properties of nuclear matter. This nontrivial assumption implies that the near-equilibrium properties of ultradense matter display not only typical fluid behavior but also visco-elastic properties, which are commonly found in liquids [110–112].

Using the additional information (3, 4) on C_π, C_Π, one can make the bound (5) sharp:

$$c_s^2 \leq 0.781 . \tag{6}$$

[2] This is not connected to the non-analytic behavior induced by the backreaction of sound waves [86].

[3] While unusual transport coefficients can be expected from superfluid phases, the onset of superfluidity leads to multiple sound modes [87], which makes causality and stability analyses considerably more convoluted [88]. Therefore, we leave the exploration of superfluid states to future work. However, we note that our bound holds even in the case of a pion condensate, where a global $U(1)$ symmetry is spontaneously broken [53,89,90] (see Fig. 1).

[4] The $\mathcal{O}(k^3)$ terms are determined by the UV regulators parameterizing the choice of hydrodynamic frame.

[5] Take $k = i\alpha$ (with $0 < \alpha \ll 1$) and impose the inequality $\mathrm{Im}\,\omega \leq |\mathrm{Im}\,k|$.

[6] A strict bound $C_\pi \geq 5$ has been proved in Ref. [100] for all weakly coupled theories, along with a pioneering calculation of τ_π to NLO in perturbative QCD.

[7] We only consider the equilibrium speed of sound; for a definition of a far-from-equilibrium speed of sound, see [107].

[8] We note that (5) also follows from applying the inequality $\mathrm{Im}\,\omega \leq |\mathrm{Im}\,k|$, or by simply computing the maximum propagation speeds in linearized Israel-Stewart-like theories [108, Eq. (49)].

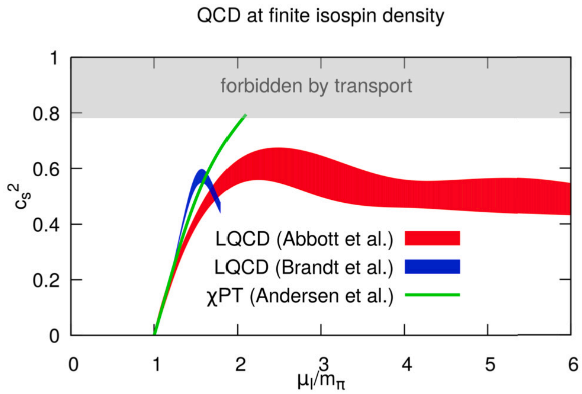

Fig. 1. Speed of sound squared at $T = 0$ in QCD as a function of isospin chemical potential μ_I. Shown are results from lattice QCD (LQCD) for $N_f = 2+1$ from Refs. [114,115] with $m_\pi \simeq 170$ MeV; LQCD for $N_f = 2+1$ from Refs. [116,117] with $m_\pi \simeq 135$ MeV; and chiral perturbation theory (χPT) results for $N_f = 2$ to NLO with $m_\pi \simeq 135$ MeV [118]. The transport bound (6) is indicated by the grey region marked as “forbidden by transport”.

If the bound above is violated, this indicates either that the shear viscous coefficients evade Eq. (3) somehow, or that transport cannot be studied using the framework of transient hydrodynamics without violating fundamental thermodynamic principles. This, per se, indicates the presence of nontrivial transport dynamics in ultradense matter that cannot be captured within well-known relativistic hydrodynamic formulations [113] where simple relaxation equations govern the evolution of the dissipative fluxes.

In the next section, we compare this bound to results in theories where c_s^2 can be calculated (or estimated) from first principles.

3. Speed of sound in nuclear matter

Results for the speed of sound squared for cold nuclear matter are available from first-principles QCD calculations such as lattice QCD, effective field theory, and perturbative QCD. In particular, results for c_s^2 are shown in Figs. 1, 2, 3 for QCD at finite isospin chemical potential, QCD at finite baryon chemical potential, and two-color QCD at finite chemical potential, respectively. In addition to the results shown, results on thermodynamics at finite-density for QCD in the strong coupling limit from Ref. [119] and various model calculation results for c_s^2 are available [120,121].

Comparing the results for c_s^2 from first principles calculations shown in Figs. 1, 2, and 3 to the transport bound (6), one finds that the transport bound on the speed of sound is obeyed in all cases.

It is worth noticing that the bound in Eq. (6) is respected even for low temperature where superfluidity occurs, [53,89,90,122], as can be seen in Figs. 1, 2.

4. Implications for the neutron star mass – radius relation

The speed of sound of ultradense matter plays a crucial role in the structure of neutron stars. A larger c_s^2 allows for larger values of the stellar mass — as larger pressure gradients can counterbalance a larger gravitational force — but also gives rise to larger stars — as matter becomes harder to compress. Observations of “small” neutron star radii of $R \sim 13$ km [127–130], as well as tidal deformability constraints from GW170817 [5–7], require speeds of sound well below the conformal value of $c_s^2 \leq 1/3$ at low densities, while very massive stars of $M \sim 2\, M_\odot$ [1–3] require much larger values of c_s^2 at high density, most likely above $c_s^2 = 1/3$ [4,8,131–134].

We thus investigate the implications of the transport bound $c_s^2 \leq 0.781$ for the neutron star mass–radius relation. To find the most massive configurations allowed by this bound, we employ EoSs that saturate

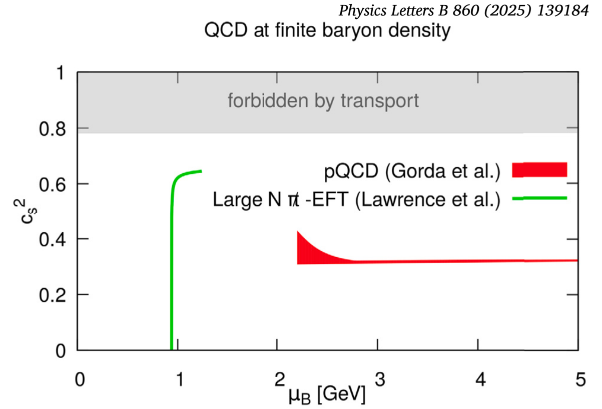

Fig. 2. Speed of sound squared at $T = 0$ in QCD as a function of baryon chemical potential μ_B. Shown are results from perturbative QCD (pQCD) for $N_f = 3$ to partial N3LO Refs. [123–125] and large N_f $\not\pi$ EFT results to LO from Ref. [122]. The transport bound (6) is indicated by the grey region marked as “forbidden by transport”.

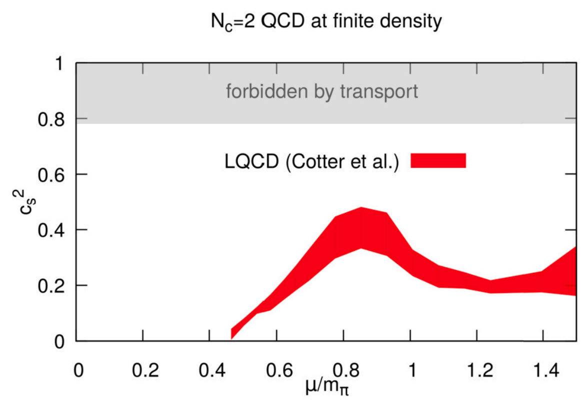

Fig. 3. Speed of sound squared at $T \simeq 50$ MeV in two-color QCD as a function of chemical potential μ. Shown are results for c_s^2 extracted from data provided in Ref. [126] with $m_\pi \simeq 700$ MeV. The transport bound (6) is indicated by the grey region marked as “forbidden by transport”.

this bound above a threshold $n > n_{\rm stiff}$ for the baryon density. At densities $n < n_{\rm stiff}$ below this threshold, we generate ~ 200 low-density EoSs consistent with uncertainty bands from chiral effective theory (χEFT) results [8], combined with a GPPVA(TM1e) crust EoS [135–139] (we refer the reader to the supplementary material for details). Most recent constraints from multiple sources on the symmetry energy in Ref. [140] suggest that the χEFT uncertainty does not cover the full range of posterior values reported in [140]. In particular, the authors of Ref. [140] find that considerably larger symmetry energy values are allowed, which would lead to higher neutron star masses than when considering χEFT. Reconciling the uncertainty bands between χEFT and Ref. [140] is beyond the scope of this work, so we choose to use the χEFT results in the following. We match each of these EoSs $\epsilon^{(i)}_{\rm soft}(P)$, where superscript i specifies which EoS, to a high-density EoS $\epsilon^{(i)}_{\rm stiff}(P)$ with constant speed of sound $c_s^2 = c^2_{s\,(\rm bound)} = 0.781$, while keeping ϵ a continuous function of P:

$$\epsilon^{(i)}_{\rm stiff}(P) = \epsilon^{(i)}_{\rm soft}(P_{\rm stiff}) + \frac{P - P_{\rm stiff}}{c^2_{s\,(\rm bound)}}, \tag{7}$$

where $P_{\rm stiff}$ is the value of the pressure as $n \to n^-_{\rm stiff}$ from the left.

We then employ the Tolman-Oppenheimer-Volkoff (TOV) equation to obtain mass–radius relations for each of these piecewise equations of state. Similar procedures have been extensively employed in the liter-

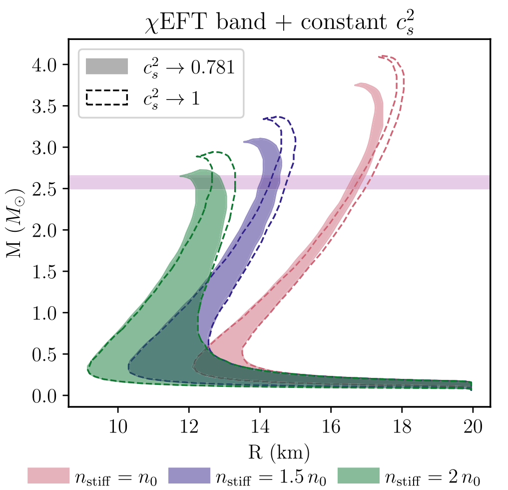

Fig. 4. Mass–radius relations for EoSs that are in agreement with χEFT results at baryon densities $n < n_{\rm stiff}$ and saturate the new bound $c_s^2 \leq 0.781$ at densities $n > n_{\rm stiff}$. Different shaded bands represent results for switching densities $n_{\rm stiff}$ of 1 (pink), 1.5 (purple), and 2 (green) times the baryon density at nuclear saturation, with the band thickness reflecting uncertainties in χEFT results. Dashed lines represent results in the case where $c_s^2 = 1$ saturates the causal bound for $n > n_{\rm stiff}$, with the same color scheme. The horizontal magenta band indicates the uncertainty in the mass of the compact object of unknown nature observed in GW190814 [17].

ature to investigate the evidence in favor of supraconformal speeds of sound [4,8,10,13,141]. The region in the mass–radius diagram obtained via this process is shown in Fig. 4 as shaded bands. We show results for different values of $n_{\rm stiff}$, of 1, 1.5 and 2 times the baryon density at nuclear saturation $n_0 \approx 0.16$ fm^{-3}.

Note that our constructed EoS are not meant to be realistic models of the nuclear EoS behavior, but instead are meant to check if χEFT plus transport bounds are relevant for astrophysics.

To gauge the significance of the new c_s^2 bound, we compare the maximum allowed mass for $c^2_{s\,({\rm bound})} = 0.781$ to the maximum mass when the less restrictive bound $c_s^2 \leq 1$ — from relativistic causality [49] — is saturated, which can be found by replacing $c^2_{s\,({\rm bound})} = 1$ in Eq. (7). Contours for the obtained regions in the mass–radius diagram, for each different value of $n_{\rm stiff}$, are represented as dashed lines in Fig. 4.

We find that the transport bound $c_s^2 \leq 0.781$ decreases the maximum mass by $\sim 8\%$ with respect to the maximum value allowed by the causal bound. This is the case for all the different soft EoSs, regardless of the density $n_{\rm stiff}$ at which the EoS becomes stiff, with an uncertainty of 0.2%. The new bound also tends to decrease the radius of the maximally massive configuration by $3.6 \pm 0.3\%$. Effects of the same bound become small for lighter stellar masses, below $\sim 2\, M_\odot$.

5. Discussion

Relativistic causality and covariant stability impose strong constraints on transport quantities and the speed of sound in relativistic fluids. Combining these constraints with bounds on transport coefficients observed in a wide range of systems, we have found that, for all of these systems, assuming the validity of transient relativistic fluid dynamics implies that the speed of sound squared is bounded from above by $c_s^2 \leq 0.781$. We investigated the applicability of this bound in first-principles calculations of the speed of sound in QCD and two-color QCD. All of the known first-principles calculations obey the new bound. This bound can be sharpened by further constraining the ratios C_π, C_Π from shear and bulk viscosity (and performing a similar analysis including effects from charge conductivity), especially in systems at finite baryon density.

Not much is known about transport properties beyond first order at low temperature and finite density, the exception being calculations of so-called thermodynamic transport coefficients [122,142–144]. Nonetheless, in Sec. 3, we have checked that our new bound on the speed of sound is respected in first-principles results both for QCD at zero temperature and for two-color QCD at a temperature around 50 MeV. The results discussed in this work can lead to a renewed interest in calculating transport coefficients, particularly the shear and bulk relaxation times, in order to assess to what extent the bounds in Eq. (3) and (4) apply in the cold and dense regime.

It would be interesting to extend our analysis to the case where superfluids may be present, which we leave for future work. While our analysis is not directly applicable in this case, we have seen that our bound on c_s^2 is not violated in first-principles results for QCD at high isospin density, where a superfluid pion condensate is expected [53,89,90], and non-relativistic chiral QCD where the analogues of Cooper pairs form [122].[9]

We also investigated the consequences of this bound for the neutron star mass–radius relation. Our results show that, if χEFT is taken to be a good description of nuclear matter up to two times saturation density ($n_{\rm stiff} = 2\, n_0$), then a single neutron star mass above $2.7\, M_\odot$ (and below $\sim 2.9\, M_\odot$) would provide strong evidence for the breaking of the $c_s^2 \leq 0.781$ bound, indicating that ultradense matter must exhibit exotic transport properties. On the other hand, our new bound is fully compatible with the possibility that the $\sim 2.6\, M_\odot$ compact object observed via gravitational wave event GW190814 could be a neutron star.

It is worth noting that our proposed bound to the speed of sound seems to be compatible with observation-driven analyses of the neutron-star equations of state, e.g., [41,146–148], which suggest that values of $c_s^2 \gtrsim 0.781$ are statistically disfavored.

A potential follow-up direction to this work is provided by extending our modeling analysis for neutron stars in light of the constraints on the nuclear matter EoS up to three times n_0 given in Ref. [140].

Future Bayesian analyses of neutron star and gravitational wave observations could be employed to more systematically assess the implications of our new bound on c_s^2 for the cold and dense nuclear matter EoS and for the neutron star mass–radius relation. Such analyses could also estimate the probability that this new bound is violated inside neutron stars and, therefore, help establish how likely it is that the matter in the core of massive neutron stars displays unusual transport properties.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

We want to thank Ryan Abbot, Bastian Brandt, Tyler Gorda, Jon-Ivar Skullerud, Ingo Tews, and Qing Yu for providing tabulated data for the equations of state in Refs. [115,117,118,125,126]. M.H. and J.N. thank J. Noronha-Hostler, D. Mroczek, and G. S. Denicol for helpful discussions. J.N especially thanks L. Gavassino for a number of insightful and clarifying comments about thermodynamic stability and causality in relativistic fluids. M.H. and J.N. were supported in part by the National Science Foundation (NSF) within the framework of the MUSES Collaboration, under grant number OAC-2103680. M.H. was supported in part by Universidade Estadual do Rio de Janeiro, within the Programa de Apoio à Docência (PAPD). J.N. was partially supported by the U.S. Department of Energy, Office of Science, Office of Nuclear Physics under Award No. DE-SC0023861. P.R. was supported by the Department of Energy, DOE award No DE-SC0017905.

[9] A superfluid state may also be present in two-color QCD [145], where the bound $c_s^2 \leq 0.781$ also seems to hold.

Appendix A. Supplementary material

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.physletb.2024.139184.

Data availability

Data will be made available on request.

References

[1] Paul Demorest, Tim Pennucci, Scott Ransom, Mallory Roberts, Jason Hessels, Shapiro delay measurement of a two solar mass neutron star, Nature 467 (2010) 1081–1083, arXiv:1010.5788 [astro-ph.HE].

[2] John Antoniadis, et al., A massive pulsar in a compact relativistic binary, Science 340 (2013) 6131, arXiv:1304.6875 [astro-ph.HE].

[3] H.T. Cromartie, et al., NANOGrav, Relativistic Shapiro delay measurements of an extremely massive millisecond pulsar, Nat. Astron. 4 (2019) 72–76, arXiv:1904.06759 [astro-ph.HE].

[4] Paulo Bedaque, Andrew W. Steiner, Sound velocity bound and neutron stars, Phys. Rev. Lett. 114 (2015) 031103, arXiv:1408.5116 [nucl-th].

[5] B.P. Abbott, et al., LIGO Scientific, Virgo, GW170817: observation of gravitational waves from a binary neutron star inspiral, Phys. Rev. Lett. 119 (2017) 161101, arXiv:1710.05832 [gr-qc].

[6] B.P. Abbott, et al., LIGO Scientific, Virgo, GW170817: measurements of neutron star radii and equation of state, Phys. Rev. Lett. 121 (2018) 161101, arXiv:1805.11581 [gr-qc].

[7] B.P. Abbott, et al., LIGO Scientific, Virgo, Properties of the binary neutron star merger GW170817, Phys. Rev. X 9 (2019) 011001, arXiv:1805.11579 [gr-qc].

[8] Ingo Tews, Joseph Carlson, Stefano Gandolfi, Sanjay Reddy, Constraining the speed of sound inside neutron stars with chiral effective field theory interactions and observations, Astrophys. J. 860 (2018) 149, arXiv:1801.01923 [nucl-th].

[9] I. Tews, J. Margueron, S. Reddy, Confronting gravitational-wave observations with modern nuclear physics constraints, Eur. Phys. J. A 55 (2019) 97, arXiv:1901.09874 [nucl-th].

[10] Brendan Reed, C.J. Horowitz, Large sound speed in dense matter and the deformability of neutron stars, Phys. Rev. C 101 (2020) 045803, arXiv:1910.05463 [astro-ph.HE].

[11] Collin D. Capano, Ingo Tews, Stephanie M. Brown, Ben Margalit, Soumi De, Sumit Kumar, Duncan A. Brown, Badri Krishnan, Sanjay Reddy, Stringent constraints on neutron-star radii from multimessenger observations and nuclear theory, Nat. Astron. 4 (2020) 625–632, arXiv:1908.10352 [astro-ph.HE].

[12] Eemeli Annala, Tyler Gorda, Aleksi Kurkela, Joonas Nättilä, Aleksi Vuorinen, Evidence for quark-matter cores in massive neutron stars, Nat. Phys. 16 (2020) 907–910, arXiv:1903.09121 [astro-ph.HE].

[13] A. Kanakis-Pegios, P.S. Koliogiannis, Ch.C. Moustakidis, Speed of sound constraints from tidal deformability of neutron stars, Phys. Rev. C 102 (2020) 055801, arXiv:2007.13399 [nucl-th].

[14] S. Huth, C. Wellenhofer, A. Schwenk, New equations of state constrained by nuclear physics, observations, and QCD calculations of high-density nuclear matter, Phys. Rev. C 103 (2021) 025803, arXiv:2009.08885 [nucl-th].

[15] Ming-Zhe Han, Jin-Liang Jiang, Shao-Peng Tang, Yi-Zhong Fan, Bayesian nonparametric inference of the neutron star equation of state via a neural network, Astrophys. J. 919 (2021) 11, arXiv:2103.05408 [hep-ph].

[16] Hung Tan, Travis Dore, Veronica Dexheimer, Jacquelyn Noronha-Hostler, Nicolás Yunes, Extreme matter meets extreme gravity: ultraheavy neutron stars with phase transitions, Phys. Rev. D 105 (2022) 023018, arXiv:2106.03890 [astro-ph.HE].

[17] R. Abbott, et al., LIGO Scientific, Virgo, GW190814: gravitational waves from the coalescence of a 23 solar mass black hole with a 2.6 solar mass compact object, Astrophys. J. Lett. 896 (2020) L44, arXiv:2006.12611 [astro-ph.HE].

[18] Hung Tan, Jacquelyn Noronha-Hostler, Nico Yunes, Neutron star equation of state in light of GW190814, Phys. Rev. Lett. 125 (2020) 261104, arXiv:2006.16296 [astro-ph.HE].

[19] Antonios Tsokaros, Milton Ruiz, Stuart L. Shapiro, GW190814: spin and equation of state of a neutron star companion, Astrophys. J. 905 (2020) 48, arXiv:2007.05526 [astro-ph.HE].

[20] Ingo Tews, Peter T.H. Pang, Tim Dietrich, Michael W. Coughlin, Sarah Antier, Mattia Bulla, Jack Heinzel, Lina Issa, On the nature of GW190814 and its impact on the understanding of supranuclear matter, Astrophys. J. Lett. 908 (2021) L1, arXiv:2007.06057 [astro-ph.HE].

[21] Daniel A. Godzieba, David Radice, Sebastiano Bernuzzi, On the maximum mass of neutron stars and GW190814, Astrophys. J. 908 (2021) 122, arXiv:2007.10999 [astro-ph.HE].

[22] Kaixuan Huang, Jinniu Hu, Ying Zhang, Hong Shen, The possibility of the secondary object in GW190814 as a neutron star, Astrophys. J. 904 (2020) 39, arXiv:2008.04491 [nucl-th].

[23] Bhaskar Biswas, Rana Nandi, Prasanta Char, Sukanta Bose, Nikolaos Stergioulas, GW190814: on the properties of the secondary component of the binary, Mon. Not. R. Astron. Soc. 505 (2021) 1600–1606, arXiv:2010.02090 [astro-ph.HE].

[24] David J. Gross, Frank Wilczek, Ultraviolet behavior of nonabelian gauge theories, Phys. Rev. Lett. 30 (1973) 1343–1346.

[25] H. David Politzer, Reliable perturbative results for strong interactions?, Phys. Rev. Lett. 30 (1973) 1346–1349.

[26] Aleksi Kurkela, Paul Romatschke, Aleksi Vuorinen, Cold quark matter, Phys. Rev. D 81 (2010) 105021, arXiv:0912.1856 [hep-ph].

[27] Thorben Graf, Juergen Schaffner-Bielich, Eduardo S. Fraga, The impact of quark masses on pQCD thermodynamics, Eur. Phys. J. A 52 (2016) 208, arXiv:1507.08941 [hep-ph].

[28] Evgeny Epelbaum, Hans-Werner Hammer, Ulf-G. Meissner, Modern theory of nuclear forces, Rev. Mod. Phys. 81 (2009) 1773–1825, arXiv:0811.1338 [nucl-th].

[29] C. Drischler, K. Hebeler, A. Schwenk, Chiral interactions up to next-to-next-to-next-to-leading order and nuclear saturation, Phys. Rev. Lett. 122 (2019) 042501, arXiv:1710.08220 [nucl-th].

[30] Bing-Nan Lu, Ning Li, Serdar Elhatisari, Dean Lee, Evgeny Epelbaum, Ulf-G. Meißner, Essential elements for nuclear binding, Phys. Lett. B 797 (2019) 134863, arXiv:1812.10928 [nucl-th].

[31] Michele Maggiore, et al., Science case for the Einstein telescope, J. Cosmol. Astropart. Phys. 03 (2020) 050, arXiv:1912.02622 [astro-ph.CO].

[32] Stefan W. Ballmer, et al., Snowmass2021 cosmic frontier white paper: future gravitational-wave detector facilities, in: Snowmass 2021, 2022, arXiv:2203.08228 [gr-qc].

[33] Slavko Bogdanov, et al., Snowmass 2021 cosmic frontier white paper: the dense matter equation of state and QCD phase transitions, in: Snowmass 2021, 2022, arXiv:2209.07412 [astro-ph.HE].

[34] Barbara Patricelli, Maria Grazia Bernardini, Michela Mapelli, Paolo D'Avanzo, Filippo Santoliquido, Giancarlo Cella, Massimiliano Razzano, Elena Cuoco, Prospects for multimessenger detection of binary neutron star mergers in the fourth LIGO–Virgo–KAGRA observing run, Mon. Not. R. Astron. Soc. 513 (2022) 4159–4168, arXiv:2204.12504 [astro-ph.HE], Erratum: Mon. Not. R. Astron. Soc. 514 (2022) 3395.

[35] Philippe Landry, Reed Essick, Nonparametric inference of the neutron star equation of state from gravitational wave observations, Phys. Rev. D 99 (2019) 084049, arXiv:1811.12529 [gr-qc].

[36] Philippe Landry, Reed Essick, Katerina Chatziioannou, Nonparametric constraints on neutron star matter with existing and upcoming gravitational wave and pulsar observations, Phys. Rev. D 101 (2020) 123007, arXiv:2003.04880 [astro-ph.HE].

[37] Eemeli Annala, Tyler Gorda, Evangelia Katerini, Aleksi Kurkela, Joonas Nättilä, Vasileios Paschalidis, Aleksi Vuorinen, Multimessenger constraints for ultradense matter, Phys. Rev. X 12 (2022) 011058, arXiv:2105.05132 [astro-ph.HE].

[38] S. Huth, et al., Constraining neutron-star matter with microscopic and macroscopic collisions, Nature 606 (2022) 276–280, arXiv:2107.06229 [nucl-th].

[39] Isaac Legred, Katerina Chatziioannou, Reed Essick, Sophia Han, Philippe Landry, Impact of the PSR J0740+6620 radius constraint on the properties of high-density matter, Phys. Rev. D 104 (2021) 063003, arXiv:2106.05313 [astro-ph.HE].

[40] Rajesh Kumar, et al., MUSES, Theoretical and experimental constraints for the equation of state of dense and hot matter, Living Rev. Relativ. 27 (2024) 3, arXiv:2303.17021 [nucl-th].

[41] Debora Mroczek, M. Coleman Miller, Jacquelyn Noronha-Hostler, Nicolas Yunes, Nontrivial features in the speed of sound inside neutron stars, arXiv:2309.02345 [astro-ph.HE], 2023.

[42] L. Gavassino, Bounds on transport from hydrodynamic stability, Phys. Lett. B 840 (2023) 137854, arXiv:2301.06651 [hep-th].

[43] Szabocls Borsanyi, Zoltan Fodor, Christian Hoelbling, Sandor D. Katz, Stefan Krieg, Kalman K. Szabo, Full result for the QCD equation of state with 2+1 flavors, Phys. Lett. B 730 (2014) 99–104, arXiv:1309.5258 [hep-lat].

[44] A. Bazavov, P. Petreczky, J.H. Weber, Equation of state in 2+1 flavor QCD at high temperatures, Phys. Rev. D 97 (2018) 014510, arXiv:1710.05024 [hep-lat].

[45] Steven S. Gubser, Abhinav Nellore, Silviu S. Pufu, Fabio D. Rocha, Thermodynamics and bulk viscosity of approximate black hole duals to finite temperature quantum chromodynamics, Phys. Rev. Lett. 101 (2008) 131601, arXiv:0804.1950 [hep-th].

[46] Aleksey Cherman, Thomas D. Cohen, Abhinav Nellore, A bound on the speed of sound from holography, Phys. Rev. D 80 (2009) 066003, arXiv:0905.0903 [hep-th].

[47] Stefano I. Finazzo, Romulo Rougemont, Hugo Marrochio, Jorge Noronha, Hydrodynamic transport coefficients for the non-conformal quark-gluon plasma from holography, J. High Energy Phys. 02 (2015) 051, arXiv:1412.2968 [hep-ph].

[48] Joaquin Grefa, Jorge Noronha, Jacquelyn Noronha-Hostler, Israel Portillo, Claudia Ratti, Romulo Rougemont, Hot and dense quark-gluon plasma thermodynamics from holographic black holes, Phys. Rev. D 104 (2021) 034002, arXiv:2102.12042 [nucl-th].

[49] James B. Hartle, Bounds on the mass and moment of inertia of non-rotating neutron stars, Phys. Rep. 46 (1978) 201–247.

[50] Ya.B. Zel'dovich, The equation of state at ultrahigh densities and its relativistic limitations, Zh. Eksp. Teor. Fiz. 41 (1961) 1609–1615.

[51] Sidney A. Bludman, M.A. Ruderman, Possibility of the speed of sound exceeding the speed of light in ultradense matter, Phys. Rev. 170 (1968) 1176–1184.

[52] Y.B. Zel'dovich, I.D. Novikov, Stars and Relativity, Dover Books on Physics (Dover Publications, 2014.

[53] Stefano Carignano, Luca Lepori, Andrea Mammarella, Massimo Mannarelli, Giulia Pagliaroli, Scrutinizing the pion condensed phase, Eur. Phys. J. A 53 (2017) 35, arXiv:1610.06097 [hep-ph].

[54] Simon Hands, Seyong Kim, Jon-Ivar Skullerud, Deconfinement in dense 2-color QCD, Eur. Phys. J. C 48 (2006) 193, arXiv:hep-lat/0604004.
[55] Carlos Hoyos, Niko Jokela, David Rodríguez Fernández, Aleksi Vuorinen, Breaking the sound barrier in AdS/CFT, Phys. Rev. D 94 (2016) 106008, arXiv:1609.03480 [hep-th].
[56] Christian Ecker, Carlos Hoyos, Niko Jokela, David Rodríguez Fernández, Aleksi Vuorinen, Stiff phases in strongly coupled gauge theories with holographic duals, J. High Energy Phys. 11 (2017) 031, arXiv:1707.00521 [hep-th].
[57] Andres Anabalon, Tomas Andrade, Dumitru Astefanesei, Robert Mann, Universal formula for the holographic speed of sound, Phys. Lett. B 781 (2018) 547–552, arXiv:1702.00017 [hep-th].
[58] Paul M. Chesler, Niko Jokela, Abraham Loeb, Aleksi Vuorinen, Finite-temperature equations of state for neutron star mergers, Phys. Rev. D 100 (2019) 066027, arXiv:1906.08440 [astro-ph.HE].
[59] Takaaki Ishii, Matti Järvinen, Govert Nijs, Cool baryon and quark matter in holographic QCD, J. High Energy Phys. 07 (2019) 003, arXiv:1903.06169 [hep-ph].
[60] Tyler Gorda, Paul Romatschke, Equation of state in two-, three-, and four-color QCD at nonzero temperature and density, Phys. Rev. D 92 (2015) 014019, arXiv:1412.6712 [hep-ph].
[61] Yuki Fujimoto, Kenji Fukushima, Equation of state of cold and dense QCD matter in resummed perturbation theory, Phys. Rev. D 105 (2022) 014025, arXiv:2011.10891 [hep-ph].
[62] Larry McLerran, Sanjay Reddy, Quarkyonic matter and neutron stars, Phys. Rev. Lett. 122 (2019) 122701, arXiv:1811.12503 [nucl-th].
[63] Kie Sang Jeong, Larry McLerran, Srimoyee Sen, Dynamically generated momentum space shell structure of quarkyonic matter via an excluded volume model, Phys. Rev. C 101 (2020) 035201, arXiv:1908.04799 [nucl-th].
[64] Tianqi Zhao, James M. Lattimer, Quarkyonic matter equation of state in beta-equilibrium, Phys. Rev. D 102 (2020) 023021, arXiv:2004.08293 [astro-ph.HE].
[65] J. Margueron, H. Hansen, P. Proust, G. Chanfray, Quarkyonic stars with isospin-flavor asymmetry, Phys. Rev. C 104 (2021) 055803, arXiv:2103.10209 [nucl-th].
[66] Dyana C. Duarte, Saul Hernandez-Ortiz, Kie Sang Jeong, Larry D. McLerran, Quarkyonic effective field theory, quark-nucleon duality, and ghosts, Phys. Rev. D 104 (2021) L091901, arXiv:2103.05679 [nucl-th].
[67] D.B. Blaschke, D. Gomez Dumm, A.G. Grunfeld, T. Klahn, N.N. Scoccola, Hybrid stars within a covariant, nonlocal chiral quark model, Phys. Rev. C 75 (2007) 065804, arXiv:nucl-th/0703088.
[68] Toru Kojo, Philip D. Powell, Yifan Song, Gordon Baym, Phenomenological QCD equation of state for massive neutron stars, Phys. Rev. D 91 (2015) 045003, arXiv:1412.1108 [hep-ph].
[69] M. Leonhardt, M. Pospiech, B. Schallmo, J. Braun, C. Drischler, K. Hebeler, A. Schwenk, Symmetric nuclear matter from the strong interaction, Phys. Rev. Lett. 125 (2020) 142502, arXiv:1907.05814 [nucl-th].
[70] Gordon Baym, Shun Furusawa, Tetsuo Hatsuda, Toru Kojo, Hajime Togashi, New neutron star equation of state with quark-hadron crossover, Astrophys. J. 885 (2019) 42, arXiv:1903.08963 [astro-ph.HE].
[71] Zacharias Roupas, Grigoris Panotopoulos, Ilídio Lopes, QCD color superconductivity in compact stars: color-flavor locked quark star candidate for the gravitational-wave signal GW190814, Phys. Rev. D 103 (2021) 083015, arXiv:2010.11020 [astro-ph.HE].
[72] German Malfatti, Milva G. Orsaria, Ignacio F. Ranea-Sandoval, Gustavo A. Contrera, Fridolin Weber, Delta baryons and diquark formation in the cores of neutron stars, Phys. Rev. D 102 (2020) 063008, arXiv:2008.06459 [astro-ph.HE].
[73] A. Ayriyan, D. Blaschke, A.G. Grunfeld, D. Alvarez-Castillo, H. Grigorian, V. Abgaryan, Bayesian analysis of multimessenger M-R data with interpolated hybrid EoS, Eur. Phys. J. A 57 (2021) 318, arXiv:2102.13485 [astro-ph.HE].
[74] Kazem Bitaghsir Fadafan, Jesús Cruz Rojas, Nick Evans, Deconfined, massive quark phase at high density and compact stars: a holographic study, Phys. Rev. D 101 (2020) 126005, arXiv:1911.12705 [hep-ph].
[75] Chengjun Xia, Zhenyu Zhu, Xia Zhou, Ang Li, Sound velocity in dense stellar matter with strangeness and compact stars, Chin. Phys. C 45 (2021) 055104, arXiv:1906.00826 [nucl-th].
[76] J.R. Stone, V. Dexheimer, P.A.M. Guichon, A.W. Thomas, S. Typel, Equation of state of hot dense hyperonic matter in the quark–meson-coupling (QMC-A) model, Mon. Not. R. Astron. Soc. 502 (2021) 3476–3490, arXiv:1906.11100 [nucl-th].
[77] A. Li, Z.Y. Zhu, E.P. Zhou, J.M. Dong, J.N. Hu, C.J. Xia, Neutron star equation of state: quark mean-field (QMF) modeling and applications, J. High Energy Astrophys. 28 (2020) 19–46, arXiv:2007.05116 [nucl-th].
[78] Robert D. Pisarski, Remarks on nuclear matter: how an ω_0 condensate can spike the speed of sound, and a model of $Z(3)$ baryons, Phys. Rev. D 103 (2021) L071504, arXiv:2101.05813 [nucl-th].
[79] Somenath Pal, Guruprasad Kadam, Abhijit Bhattacharyya, Hadron resonance gas model with repulsive mean-field interactions: specific heat, isothermal compressibility and speed of sound, Nucl. Phys. A 1023 (2022) 122464, arXiv:2104.08531 [hep-ph].
[80] T.F. Motta, P.A.M. Guichon, A.W. Thomas, On the sound speed in hyperonic stars, Nucl. Phys. A 1009 (2021) 122157, arXiv:2009.10908 [nucl-th].
[81] Yong-Liang Ma, Mannque Rho, The sound speed and core of massive compact stars: a manifestation of hadron-quark duality, arXiv:2104.13822 [nucl-th], 2021.
[82] Maurício Hippert, Eduardo S. Fraga, Jorge Noronha, Insights on the peak in the speed of sound of ultradense matter, Phys. Rev. D 104 (2021) 034011, arXiv:2105.04535 [nucl-th].
[83] Carlos Hoyos, Niko Jokela, Matti Jarvinen, Javier G. Subils, Javier Tarrio, Aleksi Vuorinen, Transport in strongly coupled quark matter, Phys. Rev. Lett. 125 (2020) 241601, arXiv:2005.14205 [hep-th].
[84] Carlos Hoyos, Niko Jokela, Matti Järvinen, Javier G. Subils, Javier Tarrio, Aleksi Vuorinen, Holographic approach to transport in dense QCD matter, Phys. Rev. D 105 (2022) 066014, arXiv:2109.12122 [hep-th].
[85] W. Israel, J.M. Stewart, Transient relativistic thermodynamics and kinetic theory, Ann. Phys. 118 (1979) 341–372.
[86] Pavel Kovtun, Guy D. Moore, Paul Romatschke, The stickiness of sound: an absolute lower limit on viscosity and the breakdown of second order relativistic hydrodynamics, Phys. Rev. D 84 (2011) 025006, arXiv:1104.1586 [hep-ph].
[87] Andreas Schmitt, Introduction to superfluidity: field-theoretical approach and applications, vol. 888, arXiv:1404.1284 [hep-ph], 2015.
[88] Lorenzo Gavassino, Stability and causality of Carter's multifluid theory, Class. Quantum Gravity 39 (2022) 185008, arXiv:2202.06760 [gr-qc].
[89] D.T. Son, Misha A. Stephanov, QCD at finite isospin density, Phys. Rev. Lett. 86 (2001) 592–595, arXiv:hep-ph/0005225.
[90] J.B. Kogut, D.K. Sinclair, Lattice QCD at finite isospin density at zero and finite temperature, Phys. Rev. D 66 (2002) 034505, arXiv:hep-lat/0202028.
[91] L.D. Landau, E.M. Lifshitz, Fluid Mechanics - Volume 6 (Corse of Theoretical Physics), 2nd ed., Butterworth-Heinemann, 1987, p. 552.
[92] Fábio S. Bemfica, Marcelo M. Disconzi, Jorge Noronha, Causality and existence of solutions of relativistic viscous fluid dynamics with gravity, Phys. Rev. D 98 (2018) 104064, arXiv:1708.06255 [gr-qc].
[93] Pavel Kovtun, First-order relativistic hydrodynamics is stable, J. High Energy Phys. 10 (2019) 034, arXiv:1907.08191 [hep-th].
[94] Fábio S. Bemfica, Fábio S. Bemfica, Marcelo M. Disconzi, Marcelo M. Disconzi, Jorge Noronha, Jorge Noronha, Nonlinear causality of general first-order relativistic viscous hydrodynamics, Phys. Rev. D 100 (2019) 104020, arXiv:1907.12695 [gr-qc], Erratum: Phys. Rev. D 105 (2022) 069902.
[95] Raphael E. Hoult, Pavel Kovtun, Stable and causal relativistic Navier-Stokes equations, J. High Energy Phys. 06 (2020) 067, arXiv:2004.04102 [hep-th].
[96] Fabio S. Bemfica, Marcelo M. Disconzi, Jorge Noronha, First-order general-relativistic viscous fluid dynamics, Phys. Rev. X 12 (2022) 021044, arXiv:2009.11388 [gr-qc].
[97] Michal P. Heller, Alexandre Serantes, Michał Spaliński, Benjamin Withers, Rigorous bounds on transport from causality, Phys. Rev. Lett. 130 (2023) 261601, arXiv:2212.07434 [hep-th].
[98] Michal P. Heller, Alexandre Serantes, Michał Spaliński, Benjamin Withers, The hydrohedron: bootstrapping relativistic hydrodynamics, arXiv:2305.07703 [hep-th], 2023.
[99] Paul Romatschke, Ulrike Romatschke, Relativistic Fluid Dynamics in and Out of Equilibrium, Cambridge Monographs on Mathematical Physics, Cambridge University Press, 2019, arXiv:1712.05815 [nucl-th].
[100] Jacopo Ghiglieri, Guy D. Moore, Derek Teaney, Second-order hydrodynamics in next-to-leading-order QCD, Phys. Rev. Lett. 121 (2018) 052302, arXiv:1805.02663 [hep-ph].
[101] Mark Abraao York, Guy D. Moore, Second order hydrodynamic coefficients from kinetic theory, Phys. Rev. D 79 (2009) 054011, arXiv:0811.0729 [hep-ph].
[102] Amaresh Jaiswal, Radoslaw Ryblewski, Michael Strickland, Transport coefficients for bulk viscous evolution in the relaxation time approximation, Phys. Rev. C 90 (2014) 044908, arXiv:1407.7231 [hep-ph].
[103] Lorenzo Gavassino, Applying the Gibbs stability criterion to relativistic hydrodynamics, Class. Quantum Gravity 38 (2021) 21LT02, arXiv:2104.09142 [gr-qc].
[104] Lorenzo Gavassino, Marco Antonelli, Brynmor Haskell, Thermodynamic stability implies causality, Phys. Rev. Lett. 128 (2022) 010606, arXiv:2105.14621 [gr-qc].
[105] W.A. Hiscock, L. Lindblom, Stability and causality in dissipative relativistic fluids, Ann. Phys. 151 (1983) 466–496.
[106] Timothy S. Olson, Stability and causality in the Israel-Stewart energy frame theory, Ann. Phys. 199 (1990) 18.
[107] Casey Cartwright, Matthias Kaminski, Marco Knipfer, Hydrodynamic attractors for the speed of sound in holographic Bjorken flow, Phys. Rev. D 107 (2023) 106016, arXiv:2207.02875 [hep-th].
[108] Paul Romatschke, New developments in relativistic viscous hydrodynamics, Int. J. Mod. Phys. E 19 (2010) 1–53, arXiv:0902.3663 [hep-ph].
[109] L.D. Landau, E.M. Lifshitz, Statistical Physics, vol. 5, Elsevier Science, 2013.
[110] Yakovich Ilich Frenkel, Kinetic Theory of Liquids, Dover, New York, NY, 1955.
[111] K. Trachenko, V.V. Brazhkin, Collective modes and thermodynamics of the liquid state, Rep. Prog. Phys. 79 (2015) 016502.
[112] Matteo Baggioli, Mikhail Vasin, Vadim V. Brazhkin, Kostya Trachenko, Gapped momentum states, Phys. Rep. 865 (2020) 1–44, arXiv:1904.01419 [cond-mat.stat-mech].
[113] Gabriel S. Rocha, David Wagner, Gabriel S. Denicol, Jorge Noronha, Dirk H. Rischke, Theories of relativistic dissipative fluid dynamics, Entropy 26 (2024) 189, arXiv:2311.15063 [nucl-th].
[114] William Detmold, Kostas Orginos, Zhifeng Shi, Lattice QCD at non-zero isospin chemical potential, Phys. Rev. D 86 (2012) 054507, arXiv:1205.4224 [hep-lat].

[115] Ryan Abbott, William Detmold, Fernando Romero-López, Zohreh Davoudi, Marc Illa, Assumpta Parreño, Robert J. Perry, Phiala E. Shanahan, Michael L. Wagman, NPLQCD, Lattice quantum chromodynamics at large isospin density, Phys. Rev. D 108 (2023) 114506, arXiv:2307.15014 [hep-lat].
[116] Bastian B. Brandt, Gergely Endrodi, Eduardo S. Fraga, Mauricio Hippert, Jurgen Schaffner-Bielich, Sebastian Schmalzbauer, New class of compact stars: pion stars, Phys. Rev. D 98 (2018) 094510, arXiv:1802.06685 [hep-ph].
[117] Bastian B. Brandt, Francesca Cuteri, Gergely Endrodi, Equation of state and speed of sound of isospin-asymmetric QCD on the lattice, J. High Energy Phys. 07 (2023) 055, arXiv:2212.14016 [hep-lat].
[118] Jens O. Andersen, Qing Yu, Hua Zhou, Pion condensation in QCD at finite isospin density, the dilute Bose gas, and speedy Goldstone bosons, Phys. Rev. D 109 (2024) 034022, arXiv:2306.14472 [hep-ph].
[119] Jangho Kim, Pratitee Pattanaik, Wolfgang Unger, Nuclear liquid-gas transition in the strong coupling regime of lattice QCD, Phys. Rev. D 107 (2023) 094514, arXiv:2303.01467 [hep-lat].
[120] Ryuji Chiba, Toru Kojo, Sound velocity peak and conformality in isospin QCD, Phys. Rev. D 109 (2024) 076006, arXiv:2304.13920 [hep-ph].
[121] Alejandro Ayala, Bruno S. Lopes, Ricardo L.S. Farias, Luis C. Parra, Describing the speed of sound peak of isospin-asymmetric cold strongly interacting matter using effective models, arXiv:2310.13130 [hep-ph], 2023.
[122] Scott Lawrence, Paul Romatschke, Gravitational-wave-to-matter coupling of superfluid Fermi gases near unitarity, Phys. Rev. A 107 (2023) 033327, arXiv:2206.04765 [cond-mat.str-el].
[123] Tyler Gorda, Aleksi Kurkela, Risto Paatelainen, Saga Säppi, Aleksi Vuorinen, Cold quark matter at N3LO: soft contributions, Phys. Rev. D 104 (2021) 074015, arXiv:2103.07427 [hep-ph].
[124] Tyler Gorda, Aleksi Kurkela, Risto Paatelainen, Saga Säppi, Aleksi Vuorinen, Soft interactions in cold quark matter, Phys. Rev. Lett. 127 (2021) 162003, arXiv:2103.05658 [hep-ph].
[125] Tyler Gorda, Oleg Komoltsev, Aleksi Kurkela, Aleksas Mazeliauskas, Bayesian uncertainty quantification of perturbative QCD input to the neutron-star equation of state, J. High Energy Phys. 06 (2023) 002, arXiv:2303.02175 [hep-ph].
[126] Seamus Cotter, Pietro Giudice, Simon Hands, Jon-Ivar Skullerud, Towards the phase diagram of dense two-color matter, Phys. Rev. D 87 (2013) 034507, arXiv:1210.4496 [hep-lat].
[127] M.C. Miller, et al., PSR J0030+0451 mass and radius from $NICER$ data and implications for the properties of neutron star matter, Astrophys. J. Lett. 887 (2019) L24, arXiv:1912.05705 [astro-ph.HE].
[128] Thomas E. Riley, et al., A $NICER$ view of PSR J0030+0451: millisecond pulsar parameter estimation, Astrophys. J. Lett. 887 (2019) L21, arXiv:1912.05702 [astro-ph.HE].
[129] M.C. Miller, et al., The radius of PSR J0740+6620 from NICER and XMM-Newton data, Astrophys. J. Lett. 918 (2021) L28, arXiv:2105.06979 [astro-ph.HE].
[130] Thomas E. Riley, et al., A NICER view of the massive pulsar PSR J0740+6620 informed by radio timing and XMM-Newton spectroscopy, Astrophys. J. Lett. 918 (2021) L27, arXiv:2105.06980 [astro-ph.HE].
[131] Justin Alsing, Hector O. Silva, Emanuele Berti, Evidence for a maximum mass cut-off in the neutron star mass distribution and constraints on the equation of state, Mon. Not. R. Astron. Soc. 478 (2018) 1377–1391, arXiv:1709.07889 [astro-ph.HE].
[132] Yong-Liang Ma, Mannque Rho, Sound velocity and tidal deformability in compact stars, Phys. Rev. D 100 (2019) 114003, arXiv:1811.07071 [nucl-th].
[133] Na Zhang, Dehua Wen, Houyuan Chen, Imprint of the speed of sound in nuclear matter on global properties of neutron stars, Phys. Rev. C 99 (2019) 035803.
[134] Mark G. Alford, G.F. Burgio, Sophia Han, Gabriele Taranto, Dario Zappalà, Constraining and applying a generic high-density equation of state, Phys. Rev. D 92 (2015) 083002, arXiv:1501.07902 [nucl-th].
[135] Fabrizio Grill, Helena Pais, Constança Providência, Isaac Vidaña, Sidney S. Avancini, Equation of state and thickness of the inner crust of neutron stars, Phys. Rev. C 90 (2014) 045803, arXiv:1404.2753 [nucl-th].
[136] Hong Shen, Fan Ji, Jinniu Hu, Kohsuke Sumiyoshi, Effects of symmetry energy on equation of state for simulations of core-collapse supernovae and neutron-star mergers, Astrophys. J. 891 (2020) 148, arXiv:2001.10143 [nucl-th].
[137] Olfa Boukari, Helena Pais, Sofija Antić, Constança Providência, Critical properties of calibrated relativistic mean-field models for the transition to warm, nonhomogeneous nuclear and stellar matter, Phys. Rev. C 103 (2021) 055804, arXiv:2007.08852 [nucl-th].
[138] J.M. Pearson, N. Chamel, A.Y. Potekhin, A.F. Fantina, C. Ducoin, A.K. Dutta, S. Goriely, Unified equations of state for cold non-accreting neutron stars with Brussels–Montreal functionals – I. Role of symmetry energy, Mon. Not. R. Astron. Soc. 481 (2018) 2994–3026, arXiv:1903.04981 [astro-ph.HE], Erratum: Mon. Not. R. Astron. Soc. 486 (2019) 768.
[139] M. Oertel, M. Hempel, T. Klähn, S. Typel, Equations of state for supernovae and compact stars, Rev. Mod. Phys. 89 (2017) 015007, arXiv:1610.03361 [astro-ph.HE].
[140] Chun Yuen Tsang, ManYee Betty Tsang, William G. Lynch, Rohit Kumar, Charles J. Horowitz, Determination of the equation of state from nuclear experiments and neutron star observations, Nat. Astron. 8 (2024) 328–336, arXiv:2310.11588 [nucl-th].
[141] Ch.C. Moustakidis, T. Gaitanos, Ch. Margaritis, G.A. Lalazissis, Bounds on the speed of sound in dense matter, and neutron star structure, Phys. Rev. C 95 (2017) 045801, arXiv:1608.00344 [nucl-th], Erratum: Phys. Rev. C 95 (2017) 059904.
[142] Pavel Kovtun, Ashish Shukla, Kubo formulas for thermodynamic transport coefficients, J. High Energy Phys. 10 (2018) 007, arXiv:1806.05774 [hep-th].
[143] Sebastian Grieninger, Ashish Shukla, Second order equilibrium transport in strongly coupled $\mathcal{N} = 4$ supersymmetric SU(N_c) Yang-Mills plasma via holography, J. High Energy Phys. 08 (2021) 108, arXiv:2105.08673 [hep-th].
[144] Max Weiner, Thermodynamic susceptibilities for a unitary Fermi gas, arXiv:2311.10906 [nucl-th], 2023.
[145] Claudia Ratti, Wolfram Weise, Thermodynamics of two-colour QCD and the Nambu Jona-Lasinio model, Phys. Rev. D 70 (2004) 054013, arXiv:hep-ph/0406159.
[146] Sinan Altiparmak, Christian Ecker, Luciano Rezzolla, On the sound speed in neutron stars, Astrophys. J. Lett. 939 (2022) L34, arXiv:2203.14974 [astro-ph.HE].
[147] Christian Ecker, Luciano Rezzolla, A General, scale-independent description of the sound speed in neutron stars, Astrophys. J. Lett. 939 (2022) L35, arXiv:2207.04417 [gr-qc].
[148] Jin-Liang Jiang, Christian Ecker, Luciano Rezzolla, Bayesian analysis of neutron-star properties with parameterized equations of state: the role of the likelihood functions, Astrophys. J. 949 (2023) 11, arXiv:2211.00018 [gr-qc].