Applying gauge/gravity duality to neutron stars

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POSTECH

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HoloTube

4th of May 2021

[arXiv:1809.07770 with N. Jokela, J. Remes;
arXiv:1903.06169 with T. Ishii, G. Nijs;
arXiv:1908.03213 with C. Ecker, G. Nijs, W. van der Schee;
arXiv:2005.14205 with C. Hoyos, N. Jokela, J. Subils, J. Tarrio, A. Vuorinen;
arXiv:2006.01141 with N. Jokela, G. Nijs, J. Remes;
arXiv:2009.10731 with T. Demircik, C. Ecker]

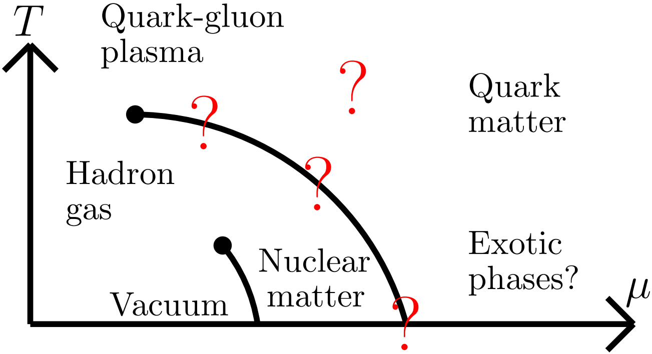
Outline

1. Introduction, motivation and overview
2. Dense holographic quark matter
3. Dense holographic nuclear matter and hybrid equations of state
4. Applications to neutron stars
    - Properties of isolated (static and spinning) neutron stars
    - Holographic neutron star mergers

1. Introduction

The QCD phase diagram

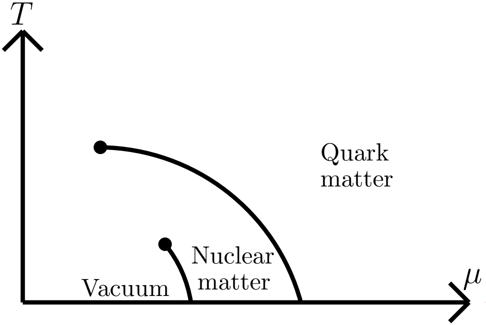
- Nuclear matter: dense liquid of protons and neutrons – density $\gtrsim$ density of atomic nuclei
- Quark matter: densely packed phase of free quarks and gluons



Laboratory experiments challenging ($T_{QCD} \sim 10^{12}$ K), in particular at high density – lots of effort

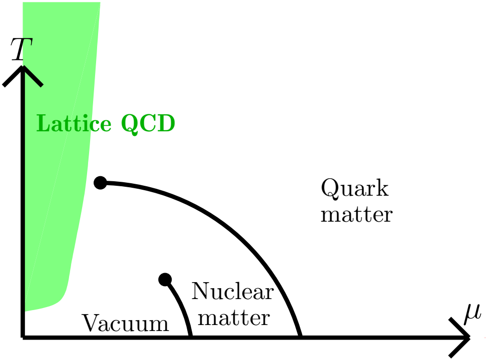
- Recent and future progress: LHC, RHIC, FAIR, NICA, ...

Theoretical results for the phase diagram



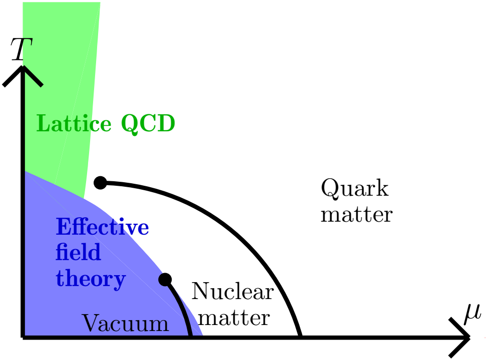
Theoretical results for the phase diagram

- Lattice data only available at zero/small chemical potentials



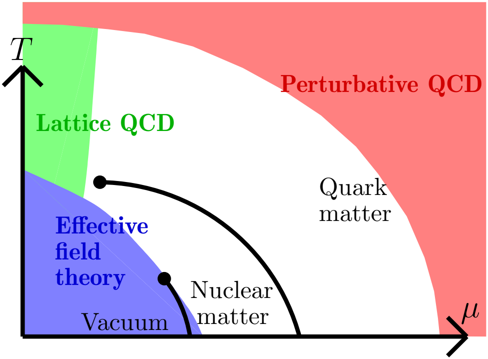
Theoretical results for the phase diagram

- Lattice data only available at zero/small chemical potentials
- Effective field theory works at small densities



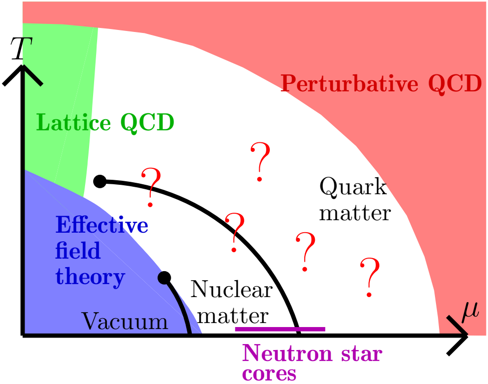
Theoretical results for the phase diagram

- Lattice data only available at zero/small chemical potentials
- Effective field theory works at small densities
- Perturbative QCD: only at high densities and temperatures



Theoretical results for the phase diagram

- Lattice data only available at zero/small chemical potentials
- Effective field theory works at small densities
- Perturbative QCD: only at high densities and temperatures
- Open questions at intermediate densities – relevant for neutron stars

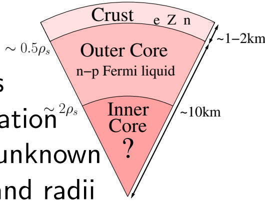


1. Improving theoretical predictions important!
2. Incoming experimental data from neutron star measurements!

Neutron stars

Neutron stars: extremely dense cold QCD matter

- Tolman-Oppenheimer-Volkoff (TOV) equations map equation of state (EoS) to mass-radius relation
- Uncertainty in EoS $\Rightarrow$ inner core composition unknown
- EoS can be constrained by measuring masses and radii



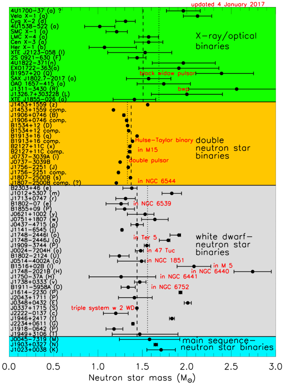
Mass measurements: dozens of results using various methods

- Highest masses from Shapiro delay measurement of NS – white dwarf binaries J0348+0432 and J0740+6620:

  $M_{\max} \gtrsim 2M_\odot$ [Antoniadis et al arXiv:1304.6875 Cromartie et al arXiv:1904.06759]

Radius measurements: more challenging, high uncertainties

- Cooling after X-ray bursts $\Rightarrow$ radii around 10-15 km

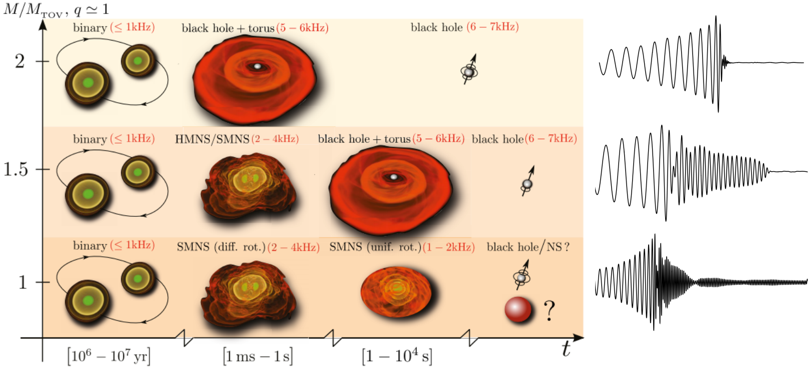


[Lattimer]

More and better results expected in near future! E.g. NICER

Neutron star mergers

- Significant sources of gravitational radiation
- Microscopic properties of dense matter encoded in GW and EM signal
- Likely the origin of short gamma-ray-bursts and heaviest elements

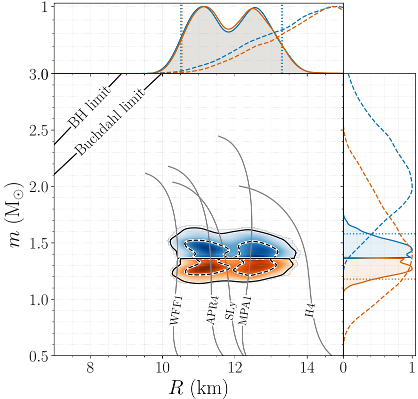


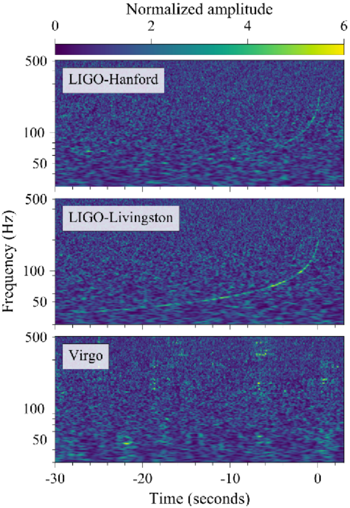
[picture: Baiotti, Rezzola arXiv:1607.03540]

One good event (GW170817) and a few other candidates already observed! [LIGO/Virgo, arXiv:1710.05832]

LIGO/Virgo constraints from GW170817

- The tidal deformability Λ measures how strongly neutron stars deform in gravitational field
- Inspiral phase GW signal gives an upper bound $\Lambda \lesssim 580$
- Implies a rough upper bound for neutron star radius: $R \lesssim 13.5$ km

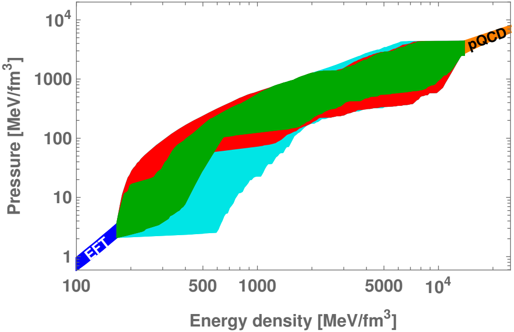




Constraints on equation of state (EoS)

State of the art for QCD EoS at $T = 0$: interpolations between nuclear EoS and pQCD, constrained by

1. Mass bound $M_{\max} > 2M_{\odot}$ (excludes cyan area)
2. LIGO constraint from GW170817: (excludes red area)



[Adapted from Annala, Gorda, Kurkela, Vuorinen arXiv:1711.02644]

Source of uncertainties: physics at strong coupling $\Rightarrow$
Can holographic methods be used to reduce uncertainties further?

2. Dense holographic quark matter

Recent progress on dense holographic QCD

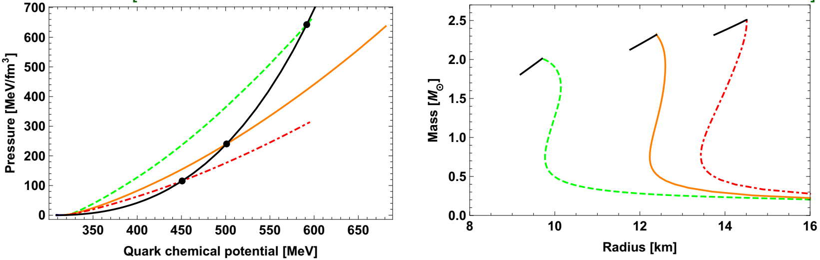
For quark matter, use D3-D7 top down model: $\epsilon = 3p + \frac{\sqrt{3}m^2}{2\pi}\sqrt{p}$

[Karch, O'Bannon, arXiv:0709.0570]

- $\mathcal{N} = 4$ SYM + $N_f = 3$ probe hypermultiplets in the fundamental representation

For nuclear matter use with stiff, intermediate, and soft "extrapolations" of EFT results

[K. Hebeler, J. M. Lattimer, C. J. Pethick, A. Schwenk arXiv:1303.4662]



- Strong first order nuclear to quark matter transitions
- Neutron stars with "holographic" quark matter core (black curves) are unstable

[Hoyos, Rodriguez, Jokela, Vuorinen arXiv:1603.02943]

Varying the quark mass m one can get quark stars and hybrid stars
[Annala, Ecker, Hoyos, Jokela, Rodriguez-Fernandez, Vuorinen arXiv:1711.06244]

- Sizeable deviations from universal I-Love-Q relations
[Yagi, Yunes, arXiv:1303.1528]

Including running of the quark mass + color superconductivity
[Bitaghsir Fadafan, Cruz Rojas, Evans, arXiv:1911.12705; 2009.14079]

- Possibility of an intermediate χSB deconfined phase
- Stiffer holographic equations of state (high speed of sound)
- Quark matter cores

Also studying Witten-Sakai-Sugimoto model suggests a weaker transition/crossover possible
[Bitaghsir Fadafan, Kazemian, Schmitt, arXiv:1811.08698]

Using Einstein-Maxwell-dilaton for quark matter
[Mamani, Flores, Zanchin, arXiv:2006.09401]

(Largish) quark stars also studied in Witten-Sakai-Sugimoto and in D4-D6 models [Burikham, Hirunsirisawat, Pinkanjanarod, arXiv:1003.5470
Kim, Shin, Lee, Wan, arXiv:1404.3474]

This talk: towards more realistic model of quark matter?

Holographic V-QCD

A holographic bottom-up model for QCD in the Veneziano limit (large N_f, N_c with $x = N_f/N_c$ fixed): V-QCD

- Bottom-up, but trying to follow principles from string theory as closely as possible
- Many parameters: effective description of QCD
- Comparison with QCD data essential
- Works surprisingly well! (I will show examples)

The model is obtained through a fusion of two building blocks:
[MJ, Kiritsis arXiv:1112.1261]

1. IHQCD: model for glue inspired by string theory (dilaton gravity)
   [Gürsoy, Kiritsis, Nitti; Gubser, Nellore]
2. Adding flavor and chiral symmetry breaking via tachyon brane actions
   [Klebanov,Maldacena; Bigazzi,Casero,Cotrone,Iatrakis,Kiritsis,Paredes]

Full backreaction between the two sectors in the Veneziano limit!

V-QCD at finite T and μ (without nucleons)

Two bulk scalars: $\lambda \leftrightarrow \mathrm{Tr} F^2$ ($\lambda \approx g^2 N_c$ near boundary), $\tau \leftrightarrow \bar{q}q$

$$\mathcal{S}_{\mathrm{V-QCD}} = N_c^2 M^3 \int d^5x \sqrt{g} \left[R - \frac{4}{3} \frac{(\partial\lambda)^2}{\lambda^2} + V_g(\lambda) \right]$$
$$- N_f N_c M^3 \int d^5x \; V_{f0}(\lambda) e^{-\tau^2}$$
$$\times \sqrt{-\det(g_{ab} + \kappa(\lambda)\partial_a\tau\partial_b\tau + w(\lambda)F_{ab})}$$

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

[Alho, Kajantie, Kiritsis, MJ, Tuominen arXiv:1210.4516;
Alho, Kajantie, Kiritsis, MJ, Rosen, Tuominen arXiv:1312.5199]

Effective model: choose potentials by comparing to QCD data

- Many potentials V_g, V_{f0}, w, κ – however need to be "simple" functions – still lot of predictivity!
- Constrained asymptotically by properties of QCD
- Remaining degrees of freedom fitted to lattice data

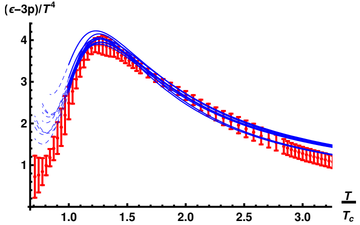
Constraining the model at $\mu \approx 0$

Stiff fit to lattice data near $\mu = 0$ (many parameters, but results insensitive to them) [Gürsoy, Kiritsis, Mazzanti, Nitti arXiv:0903.2859; MJ, Jokela, Remes, arXiv:1809.07770]

- Many parameters already fixed by requiring qualitative agreement with QCD
- Good description of lattice data – nontrivial result!

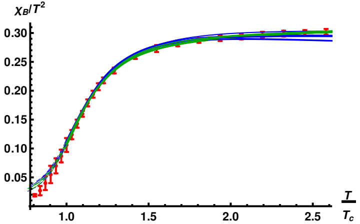
Interaction measure, 2+1 flavors

Lattice data: Borsanyi et al. arXiv:1309.5258



Baryon number susceptibility

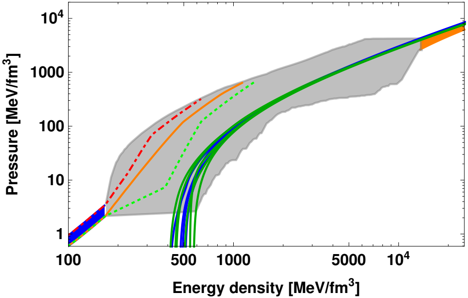
Lattice data: Borsanyi et al. arXiv:1112.4416



Extrapolated EoSs of cold QCD

The V-QCD quark matter result compares nicely to
[MJ, Jokela, Remes, arXiv:1809.07770]

- Interpolated EoSs (gray band)
- Stiff, intermediate, and soft nuclear EoSs [Hebeler, Lattimer, Pethick, Schwenk arXiv:1303.4662]



Approach similar in spirit to studies of the QCD critical point
[DeWolfe,Gubser,Rosen 1012.1864; Knaute,Yaresko,Kämpfer 1702.06731; Critelli, Noronha, Noronha-Hostler, Portillo, Ratti, Rougemont, arXiv:1706.00455]

Holographic curves do not intersect nuclear models on (ϵ, p) plane

$\Rightarrow$ Strongly first order transitions

- Similar to the simplest D3-D7 model but in some contrast with Witten-Sakai-Sugimoto model where the transition appears smoother

Transport of cool quark matter

Beyond the EoS: transport properties

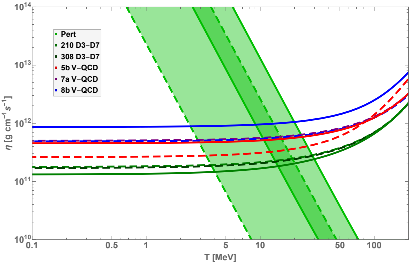
- (Bulk) viscosity relevant for neutron star merger dynamics?
- Viscosities $\leftrightarrow$ instabilities (r-modes) in spinning NSs
- Conductivities relevant for NS cooling and equilibration after NS merger
  [Review: Schmitt, Shternin, arXiv:1711.06520]

However transport is challenging to analyze...

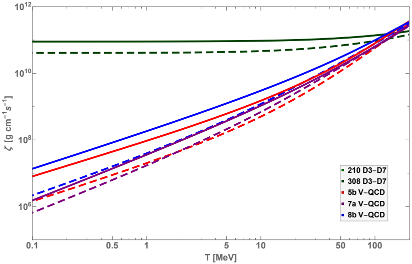
- While the EoS of dense and cold QCD matter has large uncertainties, even less is known about transport
- Only available first-principles result for quark matter: leading order pQCD analysis in the unpaired phase
  [Heiselberg, Pethick, PRD 48(1993)2916]
- We carry out the strong coupling analysis in both D3-D7 and V-QCD models
  [Hoyos, Jokela, MJ, Subils, Tarrio, Vuorinen, arXiv:2005.14205]

Transport of cool quark matter

log η vs. log T



log ζ vs. log T



- Predictions for viscosities for unpaired quark matter (dashed $\mu = 450$ MeV, solid $\mu = 600$ MeV)
- Large deviation from perturbative results
- Notice that our (small) results assume “idealized” case: only QCD contributions, no weak interactions or electrons

3. Holographic nuclear matter and hybrid EoSs

Nuclear matter in holographic models

Each baryon maps to a solitonic "instanton" configuration of gauge fields in the bulk [Witten; Gross, Ooguri; ...]

- Studied a lot in Witten-Sakai-Sugimoto model
  [Sakai, Sugimoto; Kim, Sin, Zahed; Hong, Rho, Yee, Yi; Hata, Sakai, Sugimoto, Yamato; Hashimoto, Sakai, Sugimoto;...]
  - Rough model for physics of QCD at finite density
    [Bergman, Lifschytz, Lippert; Rozali, Shieh, Van Raamsdonk,Wu; Kim, Sin, Zahed; Preis, Schmitt;...]
  - Baryonic phase has soliton crystals with nontrivial transitions
    [Kaplunovsky, Melnikov, Sonnenschein; ...]
    [MJ, Kaplunovsky, Sonnenschein]
  - Quarkyonic phase possible
    [de Boer, Chowdhury, Heller,Jankowski; Kovensky, Schmitt]
- Solution constructed in "hard-wall" models
  [Pomarol, Wulzer]
  - And will also be constructed in V-QCD
    [MJ, Kiritsis, Nitti, Préau, in progress...]

Simple approach: homogeneous bulk field

Extending the instanton approach reliably to neutron star core densities is hard

- At low densities, one can work with instantons + two-body interactions
- At higher densities, many body interactions important, instantons overlap
- Phase is crystal instead of fluid at large N_c
- $\Rightarrow$ Set $N_f = 2$ and try first a simple approximation scheme (homogeneous), perhaps more reasonable at high densities?

[Rozali, Shieh, Van Raamsdonk, Wu arXiv:0708.1322]

$$A^i = h(r)\sigma^i$$

[Li,Schmitt,Wang arXiv:1505.04886; Elliot-Ripley,Sutcliffe,Zamaklar arXiv:1607.04832]

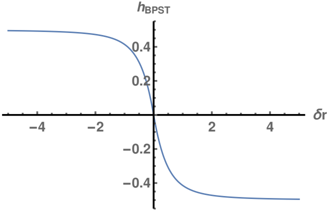
Our approach: add homogeneous nuclear matter in a rich bottom-up model (V-QCD) $\Rightarrow$ realistic results?

[Ishii, MJ, Nijs, arXiv:1903.06169]

Discontinuity and smeared instantons

With the homogeneous Ansatz $A_i^a(r) = h(r)\delta_i^a$ baryon number vanishes for any smooth $h(r)$:

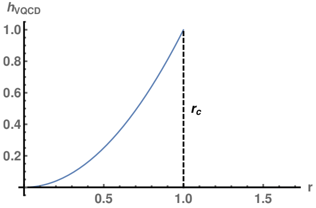
$$N_b \propto \int dr \frac{d}{dr}\,[\mathrm{CS-term}] = 0$$



How can this issue be avoided?

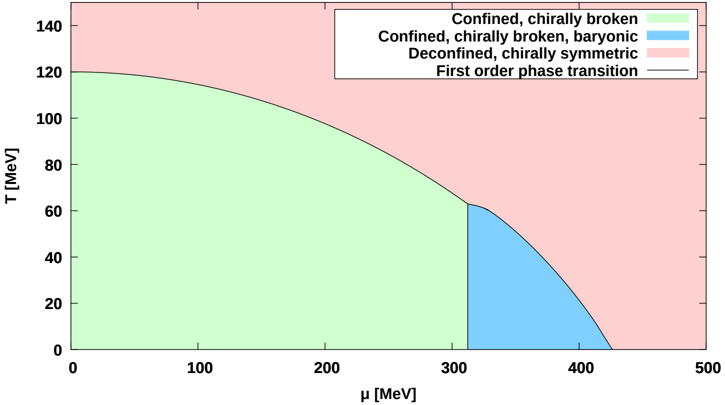
- Smearing the BPST soliton in singular Landau gauge:

$$\langle A_i^a \rangle \sim \int \frac{d^3x \;\; \eta_{i4}^a \; \delta r}{(\delta r^2 + x^2 + \rho^2)(\delta r^2 + x^2)}$$
$$\sim -\frac{\delta_i^a \; \delta r}{\sqrt{\delta r^2 + \rho^2} + |\delta r|}$$



- This suggests a solution: introduce a discontinuity in $h(r)$ at $r = r_c$
- The discontinuity sources nonzero baryon charge!

Phase diagram at zero quark mass



- Nuclear matter appears at medium μ in the confined phase

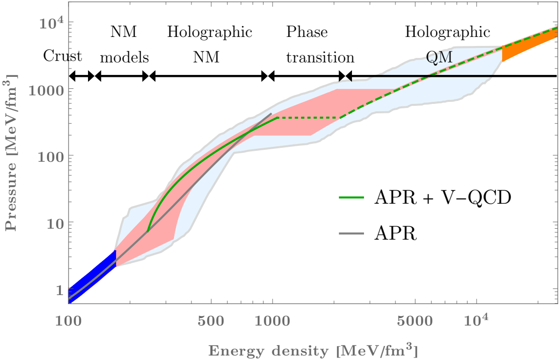
[Ishii, MJ, Nijs, arXiv:1903.06169]

Hybrid Equations of State

V-QCD nuclear matter description not reliable at low densities
⇒ use traditional models (effective field theory) instead

- Match nuclear models (low densities) with V-QCD (high densities)
- Variations in model parameters give rise to the band
- Same (holographic) model for nuclear and quark matter phases!

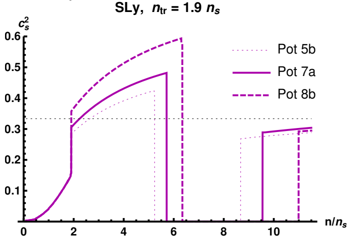
Without and with holography



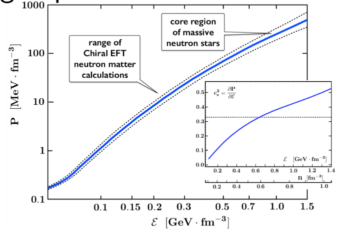
[Ecker, MJ, Nijs, van der Schee arXiv:1908.03213]
[Jokela, MJ, Nijs, Remes arXiv:2006:01141]

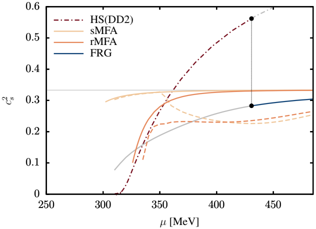
Speed of sound and comparison to FRG

Speed of sound (squared) as a function of density



- Relatively mild dependence on model parameters
- Similar predictions as with the functional renormalization group method!





[Drews, Weise arXiv:1610.07568; Otto, Oertel, Schaefer arXiv:1910.11929]

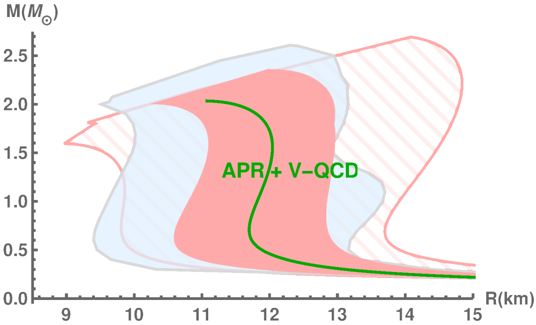
4. Applications to neutron stars

Predictions for (non-rotating) neutron stars

Plug EoSs in the TOV equations $\Rightarrow$ Mass-Radius relations

1. without holography
2. with holography (hybrid EoSs)

[Jokela, MJ, Nijs, Remes arXiv:2006:01141]



- Strong first order nuclear to quark matter phase transitions: quark cores unstable
- Large radii of neutron stars preferred

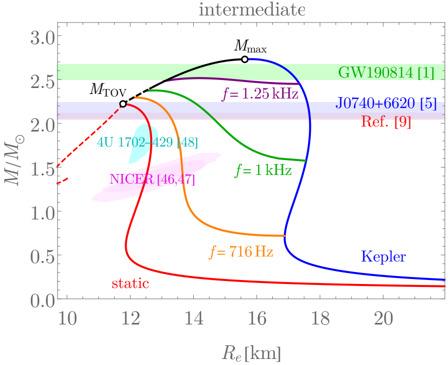
Rapidly spinning holographic neutron stars

GW190814: LIGO/Virgo observed a merger of a $23M_\odot$ black hole with a $2.6M_\odot$ compact object

[arXiv:2006.12611]

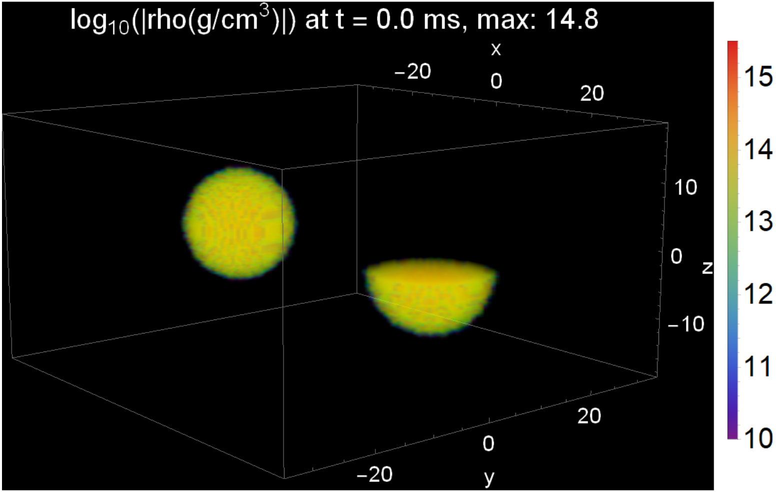
- $2.6M_\odot$ falls in the "gap": a black hole or a neutron star?

- Holographic EoSs easily compatible with the neutron star interpretation
- However requires fast rotation, $f \gtrsim 1$ kHz



[Demircik, Ecker, MJ, arXiv:2009.10731]

Neutron star mergers with holographic EoS



Simulations: LORENE+EinsteinToolkit+WhiskyTHC on Cartesius

[Ecker, MJ, Nijs, van der Schee arXiv:1908.03213]

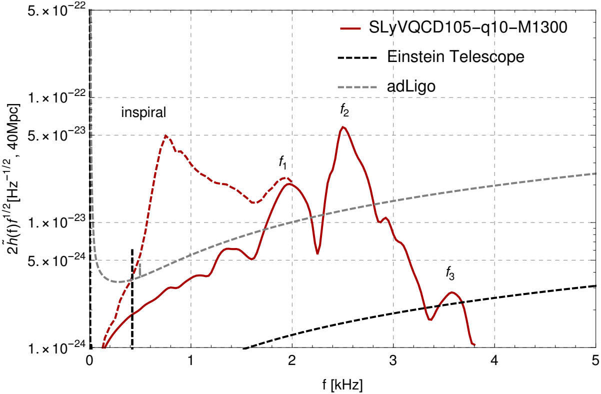
[We are grateful for support by Helvi Witek and Elias Most!]

Power Spectral Density

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

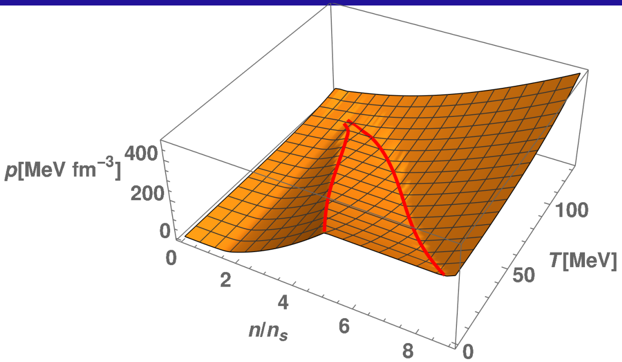
$$\tilde{h}(f) \equiv \sqrt{\frac{|\tilde{h}_+(f)|^2+|\tilde{h}_\times(f)|^2}{2}}\,, \quad \tilde{h}_{+,\times}(f) \equiv \int h_{+,\times}(t)e^{-i2\pi ft}dt\,.$$

Characteristic frequencies f_1, f_2, f_3 encode information about EoS



- Holographic EoSs predict low frequencies f_2 of the strongest peak
- Signal will be visible at advanced LIGO for nearby mergers

Ongoing work: temperature dependence



- Add realistic temperature dependence for nuclear matter [See also: Chesler, Jokela, Loeb, Vuorinen, arXiv:1906.08440]
- Required for state-of-the-art merger simulations
- Temperature dependence for nuclear matter is tricky using holography
- $\Rightarrow$ Use simple van der Waals/mean field model adjusted to match with holography [Demircik, Ecker, MJ, in progress]
- Nuclear to quark matter transition ends at a critical point!

Conclusions

- Gauge/gravity duality (combined with other approaches) is useful to study dense QCD
- Using V-QCD with simple approximations, many details work really well:
  - ✓ Precise fit of lattice thermodynamics at $\mu \approx 0$
  - ✓ Extrapolated EoS for cold quark matter reasonable
  - ✓ Simultaneous model for nuclear and quark matter
  - ✓ Stiff EoS for nuclear matter
- Predictions for
  - equation of state of cold matter
  - transport in quark matter phase
  - properties of static and spinning neutron stars
  - gravitational wave spectrum in neutron star mergers
  - ...

Backup slides

Ansatz for potentials, $(x = 1)$

$$V_g(\lambda) = 12\left[1 + V_1\lambda + \frac{V_2\lambda^2}{1+\lambda/\lambda_0} + V_{\rm IR}\, e^{-\lambda_0/\lambda}(\lambda/\lambda_0)^{4/3}\sqrt{\log(1+\lambda/\lambda_0)}\right]$$

$$V_{f0}(\lambda) = W_0 + W_1\lambda + \frac{W_2\lambda^2}{1+\lambda/\lambda_0} + W_{\rm IR}\, e^{-\lambda_0/\lambda}(\lambda/\lambda_0)^2$$

$$\frac{1}{w(\lambda)} = w_0\left[1 + \frac{w_1\lambda/\lambda_0}{1+\lambda/\lambda_0} + \bar{w}_0\, e^{-\lambda_0/\lambda w_s}\frac{(w_s\lambda/\lambda_0)^{4/3}}{\log(1+w_s\lambda/\lambda_0)}\right]$$

$$V_1 = \frac{11}{27\pi^2}\ , \quad V_2 = \frac{4619}{46656\pi^4}$$

$$W_1 = \frac{8 + 3\,W_0}{9\pi^2}\ ; \quad W_2 = \frac{6488 + 999\,W_0}{15552\pi^4}$$

Fixed UV/IR asymptotics $\Rightarrow$ fit parameters only affect details in the middle

Constraining the potentials

In the UV ($\lambda \to 0$):

- UV expansions of potentials matched with perturbative QCD beta functions $\Rightarrow$ asymptotic freedom and logarithmic flow of the coupling and quark mass, as in QCD

[Gürsoy, Kiritsis arXiv:0707.1324; MJ, Kiritsis arXiv:1112.1261]

In the IR ($\lambda \to \infty$): various qualitative constraints

- Linear confinement, discrete glueball & meson spectrum, linear radial trajectories
- Existence of a "good" IR singularity
- Correct behavior at large quark masses
- Working potentials often string-inspired power-laws, multiplied by logarithmic corrections (i.e, first guesses usually work!)

[Gürsoy, Kiritsis, Nitti arXiv:0707.1349; MJ, Kiritsis arXiv:1112.1261; Arean, Iatrakis, MJ, Kiritsis arXiv:1309.2286, arXiv:1609.08922; MJ arXiv:1501.07272]

Final task: determine the potentials in the middle, $\lambda = \mathcal{O}(1)$

- Qualitative comparison to lattice/experimental data

Transport from gauge/gravity duality

Transport: deviation from equilibrium $\leftrightarrow$ fluctuations of the 5D metric

Leading order deviation characterized in terms of transport coefficients:

- Shear viscosity η – "standard" viscosity
- Bulk viscosity ζ – viscosity in compression/expansion
- Electric conductivity σ – defined by $\vec{J} = \sigma\vec{E}$
- Thermal conductivity κ – defined by $\vec{Q} = -\kappa\nabla T$

Coefficients can be computed from correlators via using Kubo formulae + standard dictionary

- E.g.
$$\eta = -\frac{1}{\omega}\mathrm{Im}\left\langle T_{xy}(\omega,\vec{k}_1)T_{xy}(\omega,\vec{k}_2)\right\rangle\Big|_{\omega\to 0,k_i\to 0}$$
- Famous result: $\eta = \frac{s}{4\pi}$ ("universal", holds also in our models)

Transport from gauge/gravity duality

The result for the bulk viscosity boils down to the Eling-Oz formula: [Eling, Oz arXiv:1103.1657]

$$\frac{\zeta}{\eta} = \left(s \frac{\partial \phi_H}{\partial s} + \rho \frac{\partial \phi_H}{\partial \rho} \right)^2$$

Expressed in terms of horizon data with $\lambda = e^{\phi}$, $\rho =$ charge density

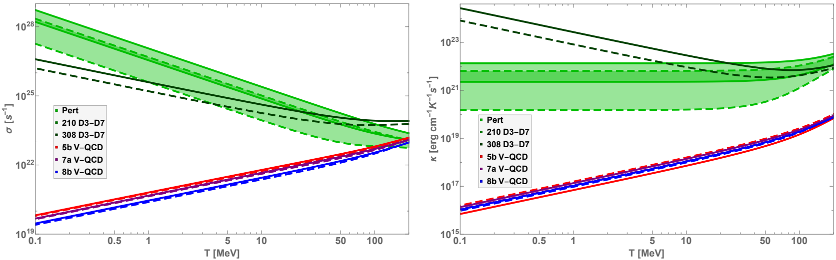
For relativistic fluid at rest (no convection), charge and thermal conductivities are related:

$$\kappa = \frac{\mu s}{\rho} \sigma$$

$\Rightarrow$ both can be expressed in terms of horizon data

Transport of cool quark matter

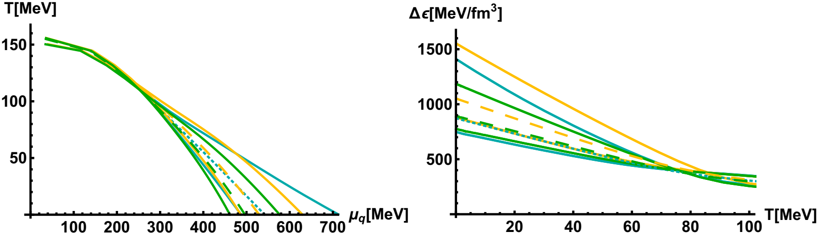
$\log\sigma$ vs. $\log T$ $\qquad$ $\log\kappa$ vs. $\log T$



- Predictions for electric and thermal conductivities (dashed $\mu = 450$ MeV, solid $\mu = 600$ MeV)
- V-QCD deviates from D3-D7 and perturbative results due to the backreaction of quarks to the gluon background

EoS of V-QCD quark matter (with various potential choices) combined with DD2, SFHx, and IUF nuclear matter EoSs

[Chesler, Jokela, Loeb, Vuorinen, arXiv:1906.08440]



- Reasonable EoS at all μ and T
- Sizable latent heat, decreases with T

Homogeneous nuclear matter in V-QCD

Nuclear matter in the probe limit: consider full brane action $S = S_{\mathrm{DBI}} + S_{\mathrm{CS}}$ where

[Bigazzi, Casero, Cotrone, Kiritsis, Paredes; Casero, Kiritsis, Paredes]

$$S_{\mathrm{DBI}} = -\frac{1}{2} M^3 N_c \, \mathbb{T}r \int d^5x \, V_{f0}(\lambda) e^{-\tau^2} \left(\sqrt{-\det \mathrm{A}^{(L)}} + \sqrt{-\det \mathrm{A}^{(R)}} \right)$$

$$\mathrm{A}^{(L/R)}_{MN} = g_{MN} + \delta^r_M \delta^r_N \kappa(\lambda) \tau'(r)^2 + \delta^{rt}_{MN} w(\lambda) \Phi'(r) + w(\lambda) F^{(L/R)}_{MN}$$

gives the dynamics of the solitons (will be expanded in $F^{(L/R)}$) and

$$S_{\mathrm{CS}} = \frac{N_c}{8\pi^2} \int \Phi(r) e^{-b\tau^2} dt \wedge \left(F^{(L)} \wedge F^{(L)} - F^{(R)} \wedge F^{(R)} + \cdots \right)$$

sources the baryon number for the solitons

- Extra parameter, $b > 1$, to ensure regularity of solutions

Set $N_f = 2$ and consider the homogeneous SU(2) Ansatz

[Rozali, Shieh, Van Raamsdonk, Wu arXiv:0708.1322]

$$A^i_L = -A^i_R = h(r)\sigma^i$$

[Ishii, MJ, Nijs, arXiv:1903.06169]

Hybrid Equations of State ($T = 0$)

V-QCD nuclear matter description not reliable at low densities
$\Rightarrow$ use traditional models (effective field theory) instead

- Match nuclear models (low densities) with V-QCD (high densities)
- Easy to pass astrophysical constraints thanks to stiffness of V-QCD EoS
- Same (holographic) model for nuclear and quark matter phases!

[Ecker,MJ,Nijs,van der Schee arXiv:1908.03213;
Jokela, MJ, Nijs, Remes arXiv:2006.01141]

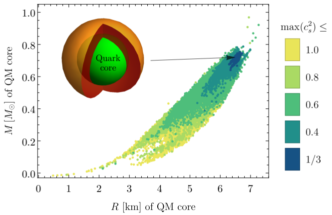
Construct "all possible" hybrid EoSs, depending on

1. The nuclear model EoS: different models with varying stiffness
2. Parameters of the holographic model still free after lattice fit
3. The matching density between nuclear matter/holography

No quark matter cores?!

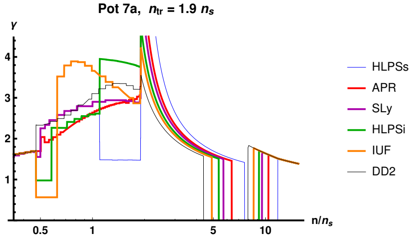
A recent model independent study claims that most massive neutron stars have quark matter cores

[Annala, Gorda, Kurkela, Nättilä, Vuorinen arXiv:1903.09121, Nature Phys.]

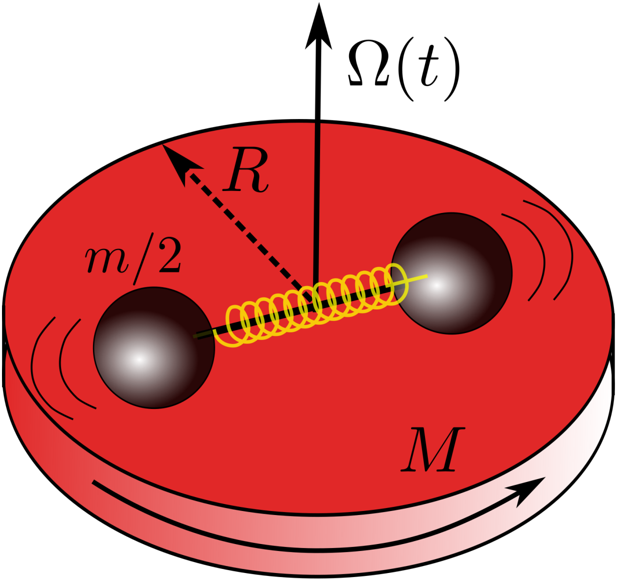


- They find that purely hadronic stars require very high speeds of sound in nuclear matter, $c_s^2 \gtrsim 0.7$
- Seems to contradict our results, what's going on?

(Simplified) answer: our model predicts lower adiabatic index $\gamma = d \log p / d \log \epsilon$ for nuclear matter than what they expect

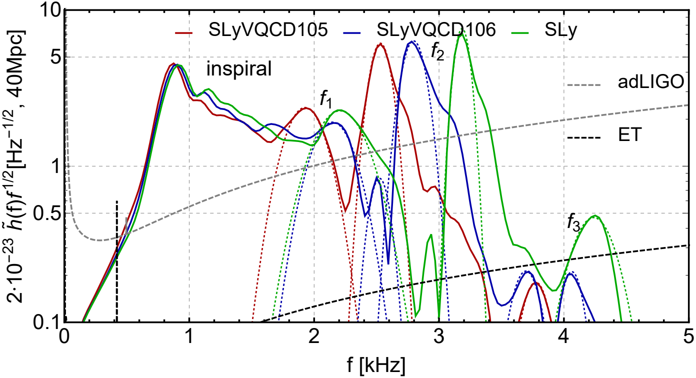


Mechanical Toy Model



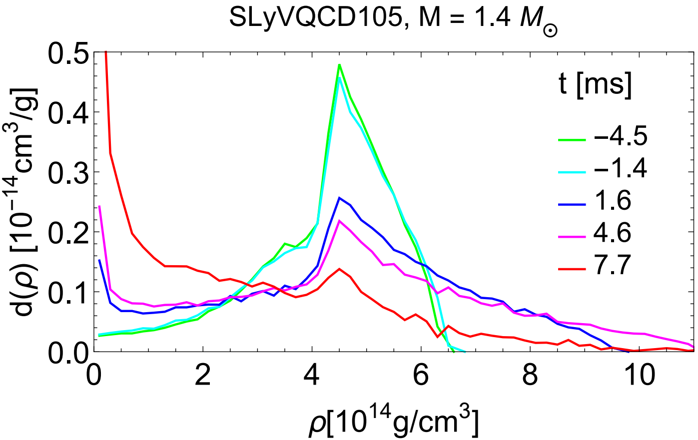
[Takami, Rezzolla, Baiotti arXiv:1412.3240]

EoS dependence of the Power Spectral Density



$M[M_\odot]$	EoS	b	f_1[kHz]	f_2[kHz]	f_3[kHz]
1.30	SLyVQCD105	10.5	1.93	2.53	3.77
1.30	SLyVQCD106	10.6	2.15	2.80	3.70 (4.06)
1.30	SLy	-	2.21	3.19	4.24

Density distributions

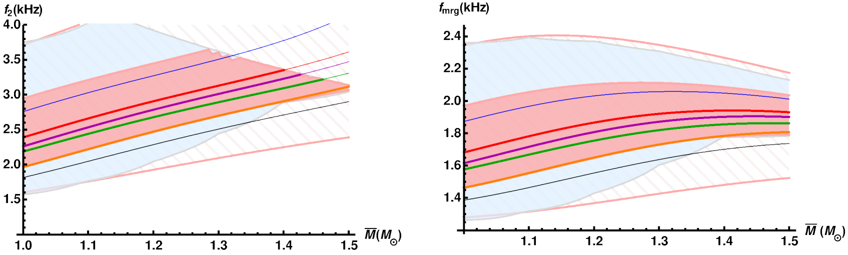


Evolution of density in the merger: no quark matter produced (outside possible horizon): transition at $\sim 17 \times 10^{14} g/cm^3$

Frequencies and universal relations

Estimated characteristic frequencies of the gravitational wave signal may also be estimated by using (quasi) universal relations [Takami, Rezzolla, Baiotti arXiv:1412.3240; Tsang, Dietrich, Van Den Broeck arXiv:1907.02424; Breschi et al. arXiv:1908.11418]

- Functions of neutron star masses and tidal deformabilities fitted to simulation data



- Again, holographic hybrid EoSs favor low frequencies
- Our simulation results fall within the band, and compare rather well with the predictions from the relations