Holographic dense QCD in the Veneziano limit

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POSTECH
POHANG UNIVERSITY OF SCIENCE AND TECHNOLOGY

XVth Quark Confinement and the Hadron Spectrum
UiS – Stavanger – 5 August 2022

NRF
National Research Foundation of Korea

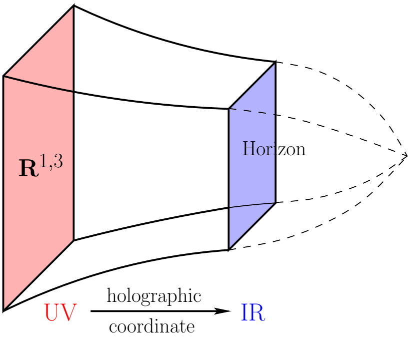
Outline

1. Introduction to V-QCD
2. Applications and extensions
   - Homogeneous nuclear matter
   - Cold neutron stars and observational constraints
   - Transport in quark matter
   - Holographic baryons
   - Model at finite temperature and density + neutron star mergers [Christian Ecker's talk on Monday]

1. Introduction

Gauge/gravity duality for QCD

- Motivated by the original AdS/CFT correspondence for $\mathcal{N} = 4$ SYM: strongly coupled field theory $\leftrightarrow$ classical gravity in higher dimensions
- Instead of conformality, confinement: non-AdS/non-CFT duality
- Field theory lives on the boundary of the 5D geometry



- Operators $O_i(x^\mu) \leftrightarrow$ classical bulk fields $\phi_i(x^\mu, r)$

$$Z_{\mathrm{grav}}(\phi_i|_{\mathrm{bdry}} = J_i(x^\mu)) = \int \mathcal{D}\, e^{iS_{QCD} + i\int d^4x J^i(x^\mu) O_i(x^\mu)}$$

  - E.g. $\bar{\psi}^j \psi^i \leftrightarrow \phi^{ij}$ $\quad T_{\mu\nu} \leftrightarrow g_{\mu\nu}$ $\quad J_\mu \leftrightarrow A_\mu$
- Thermodynamics of QCD $\leftrightarrow$ thermodynamics of a planar bulk black hole

Gauge/gravity duality for QCD: approaches

Top-down: models directly based on string theory

- Concrete, fixed string models in 10/11 d with brane configurations
- Control on what dual field theory is (it's not QCD though)
- E.g., $D3$-$D7$ models and Witten-Sakai-Sugimoto model: $D4$-$D8$-$\overline{D8}$

[Talk by Nicolas Kovensky]

Bottom-up: models constructed "by hand"

- Follow generic ideas of holography, inspiration from top-down
- Introduce fields for most important operators
- Lots of freedom $\rightarrow$ effective 5d description, no link to specific dual theory, comparison with QCD data essential
- Either a fixed geometry (AdS) or dynamical gravity
- Examples: hard/soft wall models

[Talk by Lorenzo Bartolini]

This talk: a rich bottom-up model; lots of input from string theory

- Goal: all-purpose model which mimics QCD closely

Holographic V-QCD

A holographic model for QCD

- Bottom-up, but trying to follow principles from string theory closely [MJ, Kiritsis 1112.1261; Review MJ 2110.08281]

The model is obtained through a fusion of two building blocks:

1. IHQCD: model for glue inspired by string theory [Gürsoy, Kiritsis, Nitti; Gubser, Nellore]
2. Adding flavor and chiral symmetry breaking via a D-brane setup [Klebanov,Maldacena; Bigazzi,Casero,Cotrone,Iatrakis,Kiritsis,Paredes]

Two bulk scalars: $\lambda \leftrightarrow \mathrm{Tr} F^2$, $\tau \leftrightarrow \bar{q}q$

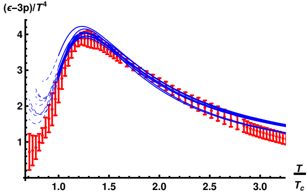
$$\mathcal{S}_{\mathrm{V-QCD}} = N_c^2 M^3 \int d^5x \sqrt{g}\left[R - \frac{4}{3}\frac{(\partial\lambda)^2}{\lambda^2} + V_g(\lambda)\right]$$
$$-N_f N_c M^3 \int d^5x\, V_{f0}(\lambda) e^{-\tau^2} \sqrt{-\det(g_{ab} + \kappa(\lambda)\partial_a\tau\partial_b\tau + w(\lambda)F_{ab})}$$

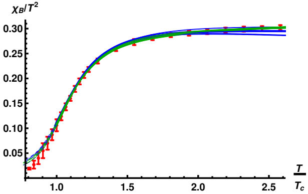
Effective model, many potentials V_g, V_{f0}, w, κ – essential to fix them by fitting QCD data $\rightarrow$ predictions for other observables

Comparison to data

Constraining the model:

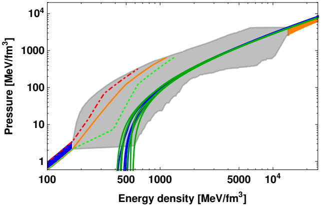
- Many parameters already fixed by requiring qualitative agreement with QCD
- Stiff fit to lattice data near $\mu = 0$ (still lots of parameters, but results insensitive to them)
[Gürsoy, Kiritsis, Mazzanti, Nitti 0903.2859;
MJ, Jokela, Remes, 1809.07770]
- Good description of lattice data – nontrivial result!
[Lattice data: Borsanyi et al. 1112.4416, 1309.5258]





Extrapolated V-QCD cold quark matter result compares nicely with known constraints:

[MJ, Jokela, Remes, 1809.07770]



2. Applications and extensions

Recent work on applications of V-QCD

1. Phase diagram at finite μ and B
   [Gürsoy, MJ, Nijs 1707.00872]
2. Interplay of B and anisotropy
   [Gürsoy, MJ, Nijs, Pedraza 1811.11724; 2011.09474]
3. Regge physics with flavor
   [Amorim, Costa, MJ 2102.11296]
4. Homogeneous nuclear matter
   [Ishii, MJ, Nijs 1903.06169]
5. Cold matter EoS and constraints from neutron star observations
   [Jokela, MJ, Nijs, Remes 2006.01141;Jokela, MJ, Remes 2111.12101]
6. Rotating (cold) neutron stars
   [Demircik, Ecker, MJ 2009.10731]
7. Transport in quark matter
   [Hoyos, Jokela, MJ, Subils, Tarrio, Vuorinen 2005.14205; 2109.12122]
8. Baryons as soliton/instanton solutions
   [MJ, Kiritsis, Nitti, Préau to appear]
9. Equation of state at finite T and μ
   [Demircik, Ecker, MJ 2112.12157]
10. (Holographic) neutron star mergers
    [Ecker, MJ, Nijs, van der Schee 1908.03213]
    [Tootle, Ecker, Topolski, Demircik, MJ, Rezzolla 2205.05691]

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Homogeneous holographic nuclear matter

Each baryon maps to a solitonic "instanton" configuration of gauge fields in the bulk

[Witten; Gross, Ooguri; ...]

- Such instantons have been studied in many models, including V-QCD (see below)
- However, dense nuclear matter requires studying many-instanton solutions
- Extremely challenging!
- Set $N_f = 2$ and try first a simple approximation scheme (homogeneous), reasonable at high densities?

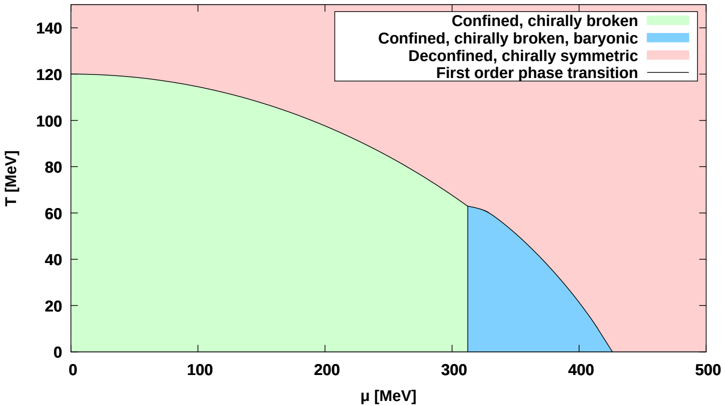
[Rozali, Shieh, Van Raamsdonk, Wu 0708.1322]

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

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

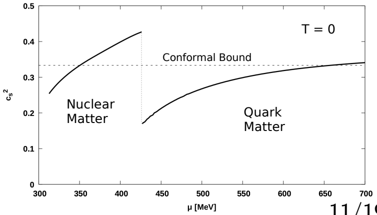
[See also talks by Kovensky and Bartolini]

Phase diagram at zero quark mass



Stiff EoS (high c_s^2) in the nuclear matter phase $\Rightarrow$ helps to pass the bounds from neutron star observations!

[Ishii, MJ, Nijs, 1903.06169]

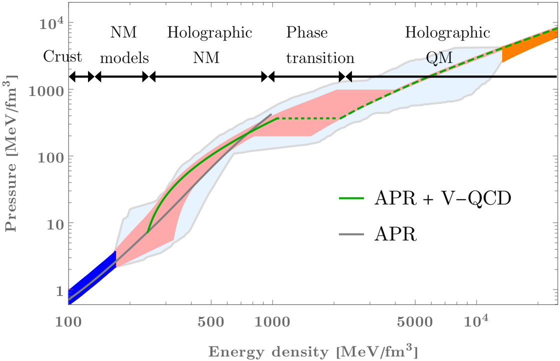


Hybrid Equations of State

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)
- Variations in model parameters give rise to the band
- Same (holographic) model for nuclear and quark matter phases!

Without and with holography

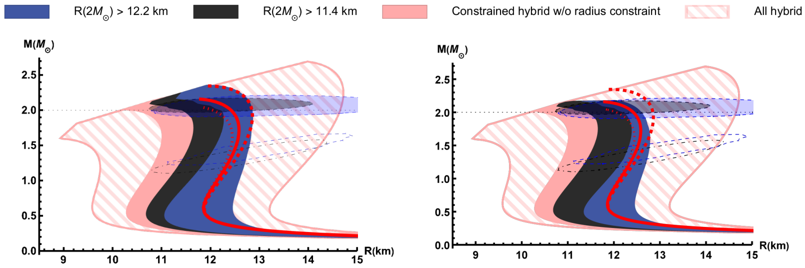


[Polytropes: Annala, Gorda, Kurkela, Vuorinen 1711.02644]
[Jokela, MJ, Nijs, Remes 2006:01141]

Comparison to neutron star observations

Plug the equations of state into TOV equations
$\Rightarrow M(R)$ curves for neutron stars

- Pink region: GW170817 measurement and $M_{\rm TOV} > 2.0 M_\odot$
- Black and blue regions: additional constraints from Neutron Star Interior Composition Explorer (NICER) data [Miller et al. 2105.06979; Riley et al. 2105.06980]



[Jokela, MJ, Remes, 2111.12101]

- Right: additional constraint from GW170817: $M_{\rm TOV} < 2.19 M_\odot$ [Margalit, Metzger 1710.05938; Annala et al. 2105.05132]

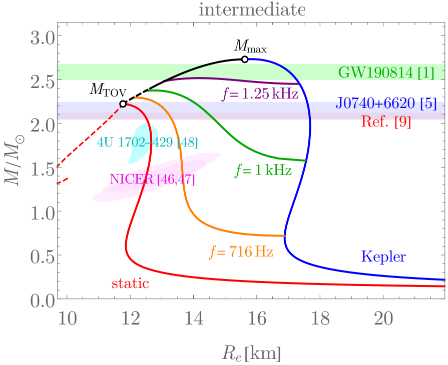
Rapidly spinning holographic neutron stars

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

[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, 2009.10731]

Transport of cool quark matter

Beyond the EoS: transport properties

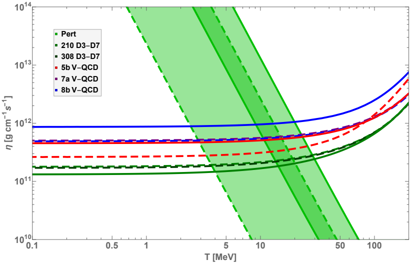
- (Bulk) viscosity relevant for neutron star merger dynamics?
- Viscosities $\leftrightarrow$ instabilities (r-modes) in spinning NSs
- Conductivities relevant for NS cooling and equilibration after NS merger
  [Review: Schmitt, Shternin, 1711.06520]

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 2005.14205; 2109.12122]

Transport of cool quark matter

log η vs. log T



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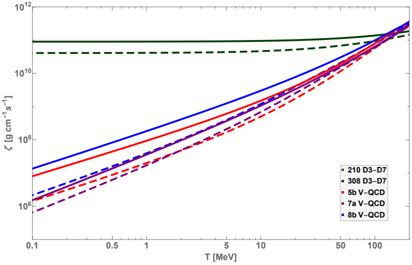


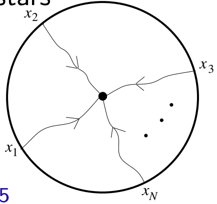
- Predictions for viscosities for unpaired quark matter (dashed $\mu = 450$ MeV, solid $\mu = 600$ MeV)
- Large deviation from perturbative results
- Notice that our (small) results assume "idealized" case: only QCD contributions, no weak interactions or electrons

[Improvement on this in progress]

The holographic baryon

Holographic description of the baryon may be useful

- To understand the properties and structure of baryons
- To model dense nuclear matter and neutron stars



Recall the standard AdS/CFT duality:
$\mathcal{N} = 4$ SYM is dual to IIB sugra on $\mathrm{AdS}_5 \times \mathrm{S}^5$

- Baryons are objects where N_c fundamental strings ($\leftrightarrow$ quarks) can end
- Obtained by wrapping a D5 brane over the S^5

[Witten hep-th/9805112]

- For AdS_5, boils down to solitons of 5D gauge fields in the bulk

$$\mathcal{L}_{\mathrm{B}} \sim -\kappa \int d^5x \, \mathrm{Tr} F_{\mu\nu}^2$$

- Similar to the BPST instanton in 4D Yang-Mills
- "Upgrade" of the Skyrmion picture
- Studied a lot in Witten-Sakai-Sugimoto and hard-wall models

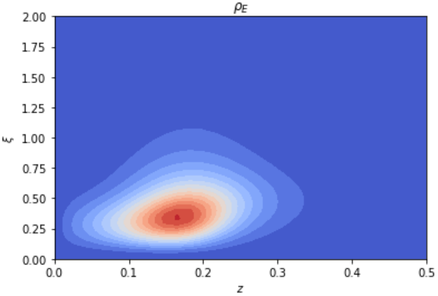
Solitons in V-QCD

Towards a realistic holographic description of baryons

- Use V-QCD: a model with gluons and (dynamical) quarks
- Solve numerically
  1. The fully backreacted background – quark and gluon sectors simultaneously
  2. The soliton in the probe limit
- Highly technical and challenging problem!

Soliton mass ~ 1050 MeV
Work in progress:
stay tuned for
further results. . .

[MJ, Kiritsis, Nitti, Préau to appear]

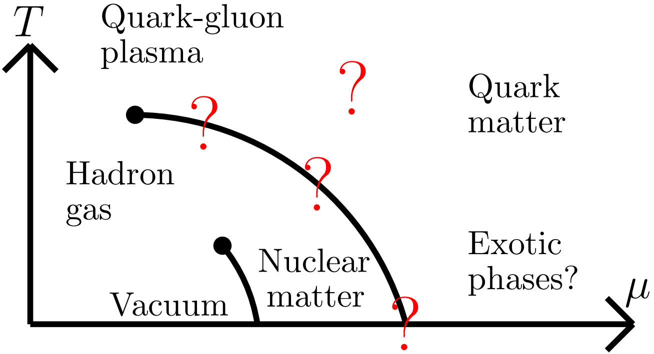


Conclusion

- (Effective) holography, combined with other approaches, is useful to study dense QCD
- Using V-QCD with simple approximations, we obtained predictions for
  - Cold equation of state
  - Neutron star $M(R)$ curves
  - Transport of quark matter
  - Static properties of baryons
  - And also finite T model and neutron star mergers [C. Ecker's talk]
- Lots of work in progress...
  - Proper implementation of different quark flavors
  - Coupling to weak currents
  - Striped instabilities and color superconductivity
  - ...

Thank you!

The QCD phase diagram



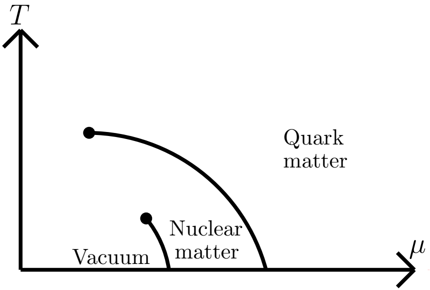
Focus in this talk: phases at high density

- Nuclear matter: dense liquid of protons and neutrons – density $\gtrsim$ density of large 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

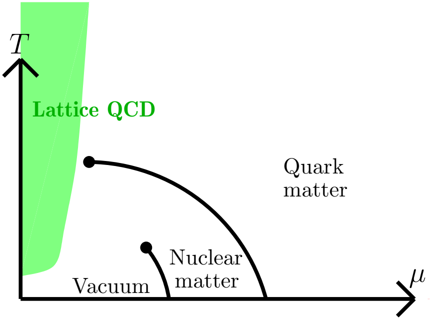
- Recent and future progress: LHC, RHIC, FAIR, NICA, ...

QCD phase diagram: theoretical results



QCD phase diagram: theoretical results

- Lattice data only available at zero/small chemical potentials



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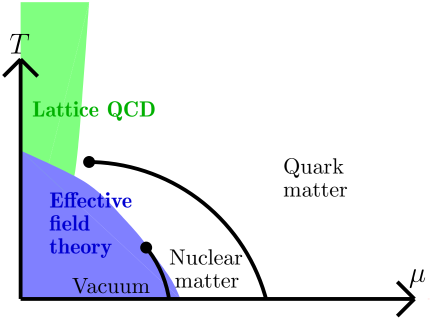

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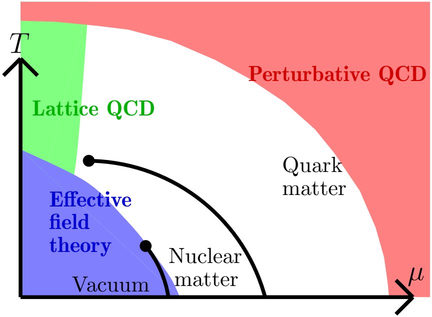
- Perturbative QCD: only at high densities and temperatures



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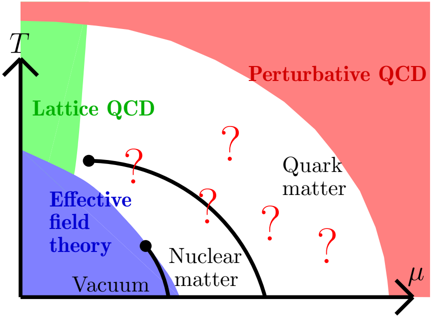

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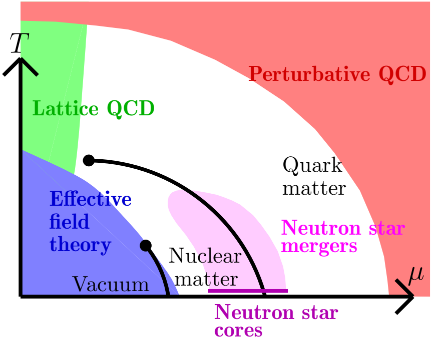

1. Improving theoretical predictions important!
2. Incoming experimental data from neutron star measurements!

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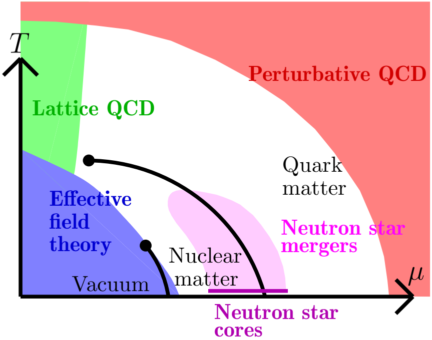

1. Improving theoretical predictions important!
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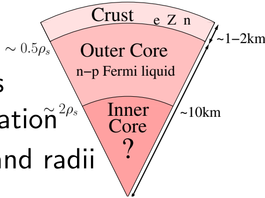
White region strongly coupled $\Rightarrow$ use holography?
Interpolate between known results using holography?

Neutron stars

Neutron stars: extremely dense cold QCD matter

- Tolman-Oppenheimer-Volkoff (TOV) equations map equation of state (EoS) to mass-radius relation
- EoS can be constrained by measuring masses and radii

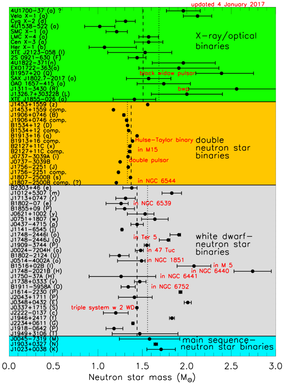


Mass measurements: dozens of results using various methods

- Highest masses from Shapiro delay measurement of NS – white dwarf binaries J0348+0432 and J0740+6620:
  $M_{\mathrm{max}} \gtrsim 2M_\odot$ [Antoniadis et al 1304.6875 Cromartie et al 1904.06759]

Radius measurements: more challenging, high uncertainties

- Cooling after X-ray bursts ⇒ radii around 10-15 km

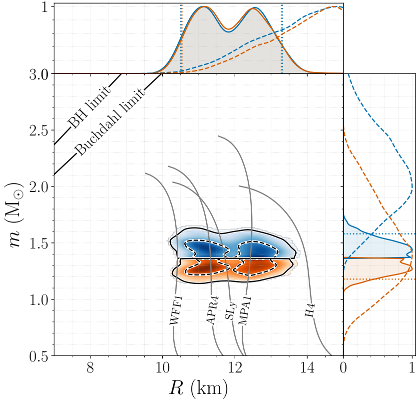


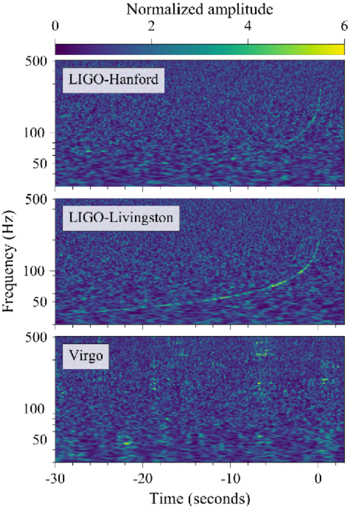
[Lattimer]

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

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

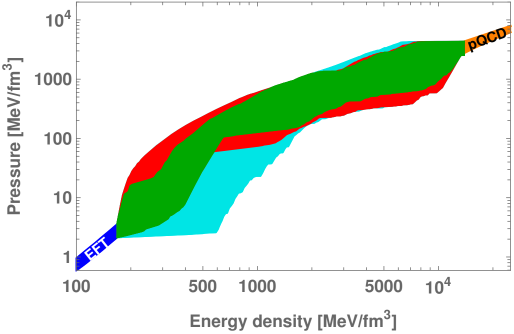




Constraints on equation of state (EoS)

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

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



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

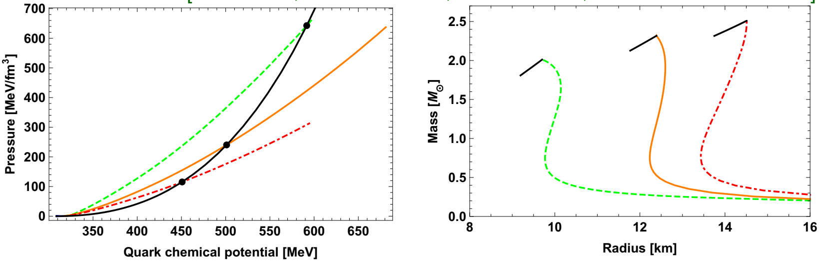
Source of uncertainties: physics at strong coupling $\Rightarrow$
Can holographic methods be used to reduce uncertainties further?

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, 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 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 1603.02943]

Varying the quark mass m one can get quark stars and hybrid stars

[Annala, Ecker, Hoyos, Jokela, Rodriguez-Fernandez, Vuorinen 1711.06244]

- Sizeable deviations from universal I-Love-Q relations

[Yagi, Yunes, 1303.1528]

Including running of the quark mass + color superconductivity

[Bitaghsir Fadafan, Cruz Rojas, Evans, 1911.12705; 2009.14079]

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

Using Einstein-Maxwell-dilaton for quark matter

[Mamani, Flores, Zanchin, 2006.09401]

(Largish) quark stars also studied in Witten-Sakai-Sugimoto and in D4-D6 models

[Burikham, Hirunsirisawat, Pinkanjanarod, 1003.5470
Kim, Shin, Lee, Wan, 1108.6139, 1404.3474]

This talk: towards more realistic model of quark matter?

Ansatz for potentials, $(x = 1)$

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

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

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

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

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

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 0707.1324; MJ, Kiritsis 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 0707.1349; MJ, Kiritsis 1112.1261; Arean, Iatrakis, MJ, Kiritsis 1309.2286, 1609.08922; MJ 1501.07272]

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

- Qualitative comparison to lattice/experimental data

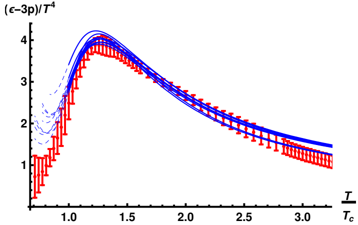
Constraining the model at $\mu \approx 0$

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

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

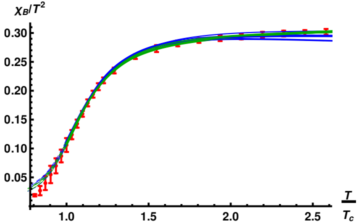
Interaction measure, 2+1 flavors

Lattice data: Borsanyi et al. 1309.5258



Baryon number susceptibility

Lattice data: Borsanyi et al. 1112.4416

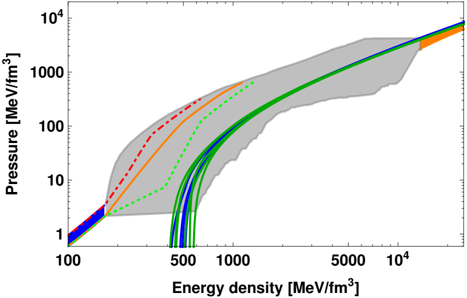


Extrapolated EoSs of cold quark matter

The V-QCD cold quark matter result compares nicely to known constraints:

[MJ, Jokela, Remes, 1809.07770]

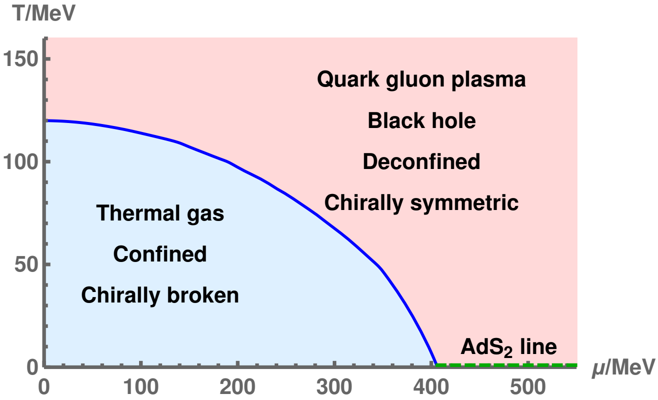
- Band of allowed equations of state (EoSs) (gray, polytropic interpolations)
- Stiff, intermediate, and soft nuclear EoSs
  [Hebeler, Lattimer, Pethick, Schwenk 1303.4662]



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, 1706.00455]

Phase diagram with quark matter



- With quark matter only, expected phase diagram
- Cold QM equation of state (EoS) and location of the $T = 0$ phase transition agree with contraints

Homogeneous nuclear matter in V-QCD

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

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

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

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

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

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

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 0708.1322]

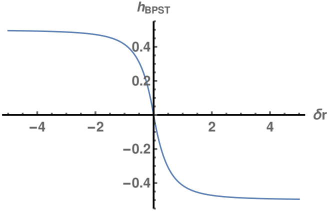
$$A^i_L = -A^i_R = h(r) \sigma^i$$

[Ishii, MJ, Nijs, 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 $h(r)$:

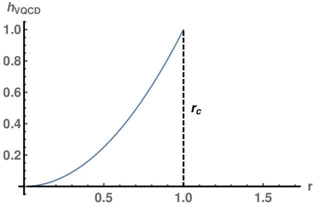
$$N_b \propto \int dr \frac{d}{dr}\,[\mathrm{CS-term}] = 0$$



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!

Combining with other approaches

The V-QCD EoS as such is however not fully satisfactory:

1. Our (homogeneous) approach for nuclear matter only works at high densities
2. Temperature dependence is trivial in the confined phases, and therefore also for holographic nuclear matter
   - This is a large N_c issue, T dependence would arise from loops

Solutions:

1. At low densities for nuclear matter, use "traditional" nuclear theory results

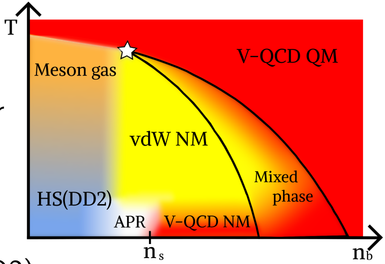
   ⇒ choose the Hempel-Schaffner-Bielich model with DD2 interactions (HS(DD2))

   [Typel et al. 0908.2344; Hempel, Schaffner-Bielich 0911.4073]
2. Since no reliable results available, borrow T dependence from basically the simplest reasonable model

   ⇒ use van der Waals (vdW) gas (protons, neutrons, electrons)

   [Ecker, MJ, Nijs, van der Schee 1908.03213]
   [Jokela, MJ, Nijs, Remes 2006:01141]
   [Demircik, Ecker, MJ 2112.12157]

Overview of the hybrid model

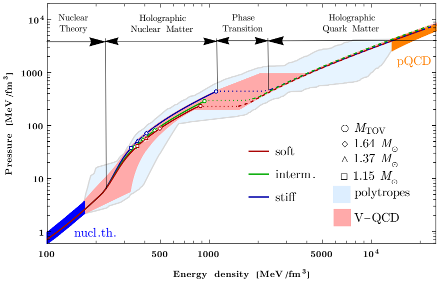


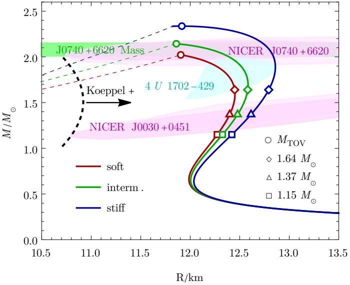
- V-QCD for quark matter and cold dense nuclear matter
- Van der Waals model extrapolates dense V-QCD nuclear matter to finite T
- At low density, choose HS(DD2)
- At medium density, use APR cold EoS (using only HS(DD2) would lead to tension with neutron star observations)
- Add QCD mesons to HS(DD2), important to describe the critical point

[Demircik, Ecker, MJ 2112.12157]

Cold EoS and known constraints

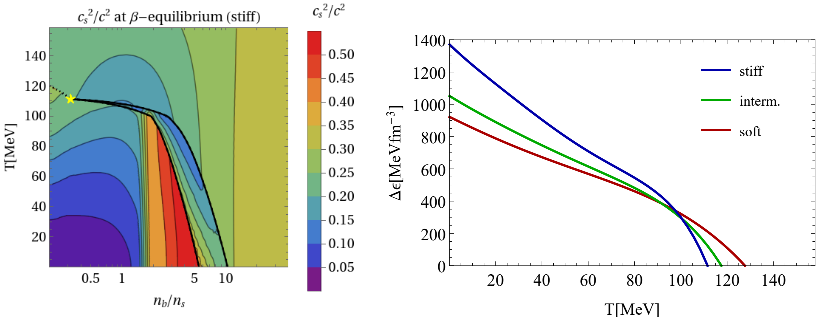
- Three choices of EoSs: soft, intermediate, and stiff $\leftrightarrow$ the degrees of freedom of V-QCD left free by fit to lattice data
- Compared to bands of all feasible cold matter EoS: Without and with holography





- Plug EoSs in TOV: neutron star $M(R)$ curves (left plot)
- Compares well with mass/radius observations

Results: phase transition and critical point



- Low T: strong 1st order nuclear to quark matter transition and mixed phase
- High T: weak first order transition $\approx$ crossover
- Critical point with
  $110\text{ MeV} \lesssim T_c \lesssim 130\text{ MeV}$
  $480\text{ MeV} \lesssim \mu_{bc} \lesssim 580\text{ MeV}$
- Close to results in other (simpler) holographic models
  [DeWolfe et al. 1012.1864; Knaute et al. 1702.06731; Critelli et al. 1706.00455]

Simulating Binary Neutron Star Mergers

Have to solve the 3+1D General Relativistic hydrodynamics equations:

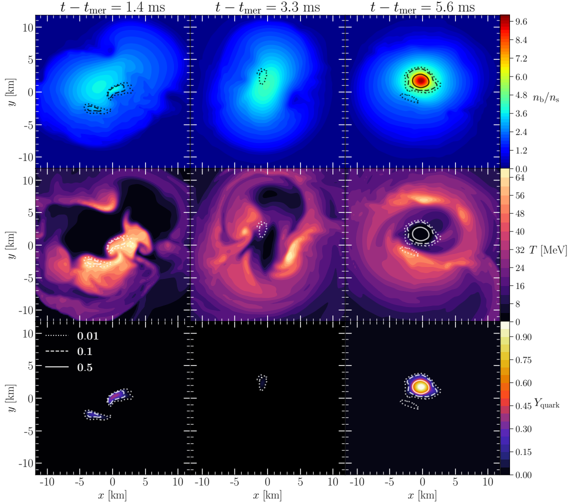
$$R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} = 8\pi G_N T_{\mu\nu}\,, \quad \nabla_\mu T^{\mu\nu} = 0\,, \quad \nabla_\mu J^\mu = 0$$

with initial spacetime and fluid distribution modelling a NS binary system

- Equation of State $p = p(n_b, T, Y_e)$ as input – use V-QCD hybrid EoS
- Spectral code Frankfurt University/Kadath (FUKA) for initial data
  [Papenfort, Tootle, Grandclement, Most, Rezzolla 2103.09911]
- Frankfurt/Illinois (FIL) code for binary evolution with tabulated EoS
  [Most, Papenfort, Rezzolla 1907.10328]
- Implemented in the Einstein Toolkit
  [http://einsteintoolkit.org]
- Need supercomputing: Project BNSMIC with 100 million core-hours on HAWK at the High-Performance Computing Center Stuttgart

Hot, Warm and Cold Quarks

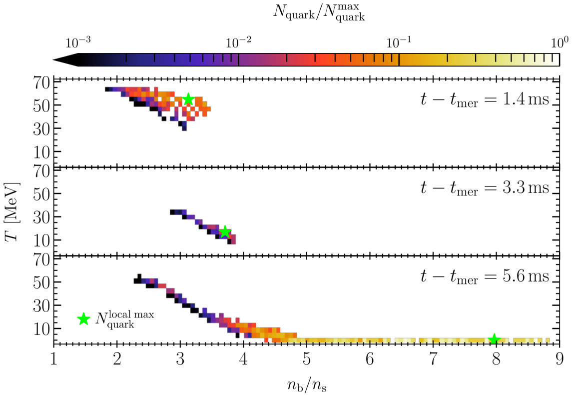
Simulations with parameters chosen to match with GW170817



Hypermassive neutron star after merger (soft EoS, $M_1/M_2 = 0.7$)

[Tootle, Ecker, Topolski, Demircik, MJ, Rezzolla 2205.05691]

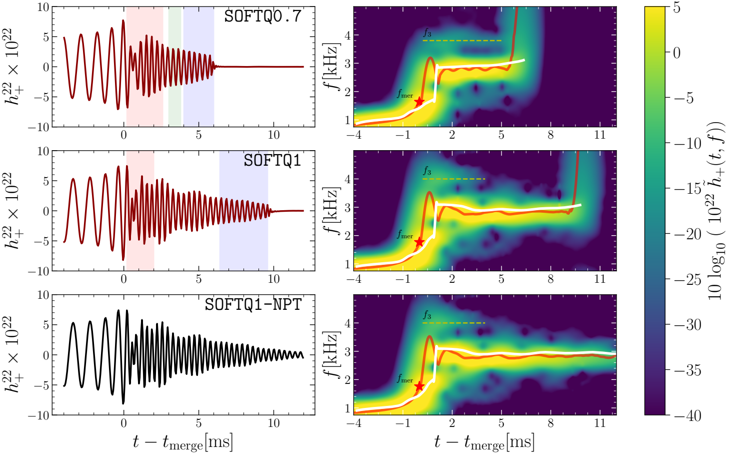
- Hot quarks: in the hottest region at early times
- Warm quarks: at intermediate times due to complicated post-merger dynamics
- Cold quarks: in the densest core at late times



[Tootle, Ecker, Topolski, Demircik, MJ, Rezzolla 2205.05691]

details

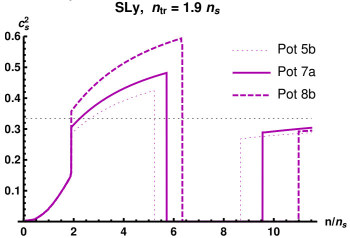
Imprint on Gravitational Waves



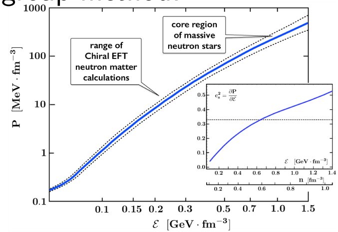
- Most significant signature of the phase transition: short lifetime of remnant
- Early collapse in tension with electromagnetic signal from GW170817 $\Rightarrow$ constrains the EoS – soft model disfavored

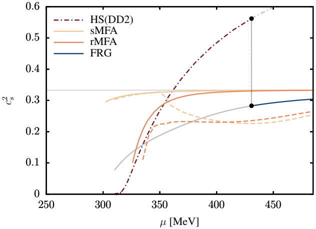
Speed of sound and comparison to FRG

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 1610.07568; Otto, Oertel, Schaefer 1910.11929]