Holography probing neutron star interior

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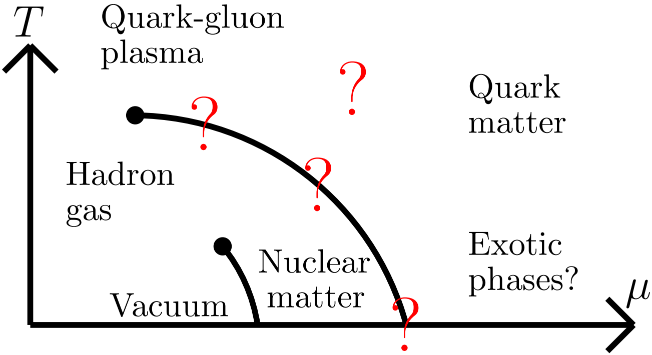
The QCD phase diagram

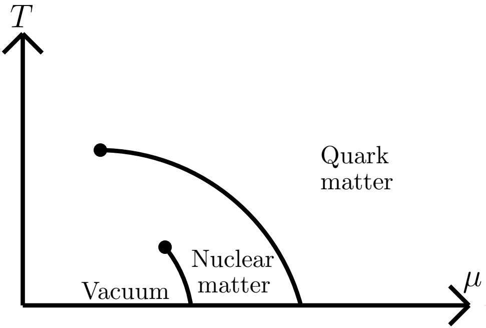
- Nuclear matter: dense liquid of protons and neutrons – density $\gtrsim$ density of atomic nuclei
- Quark matter: densely packed phase of free quarks and gluons



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, . . .

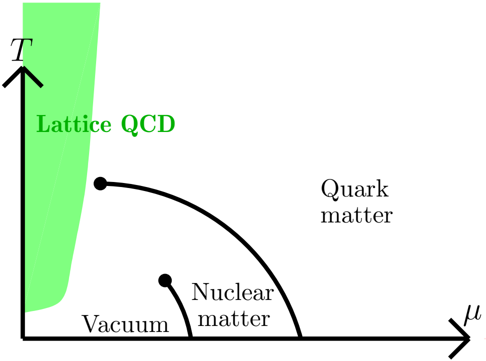
Theoretical results for the phase diagram



[Image: M. Järvinen]

Theoretical results for the phase diagram

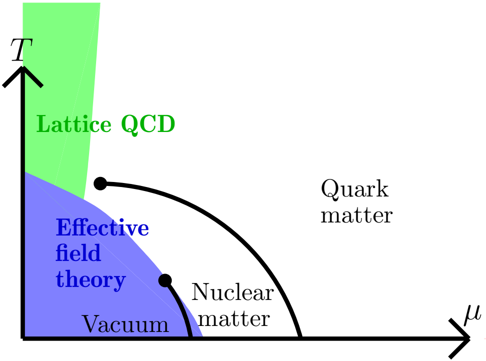
- Lattice data only available at zero/small chemical potentials



[Image: M. Järvinen]

Theoretical results for the phase diagram

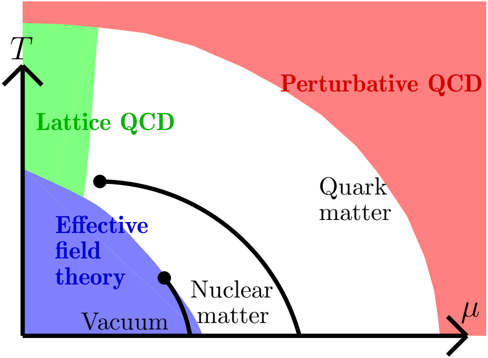
- Lattice data only available at zero/small chemical potentials
- Effective field theory works at small densities



[Image: M. Järvinen]

Theoretical results for the phase diagram

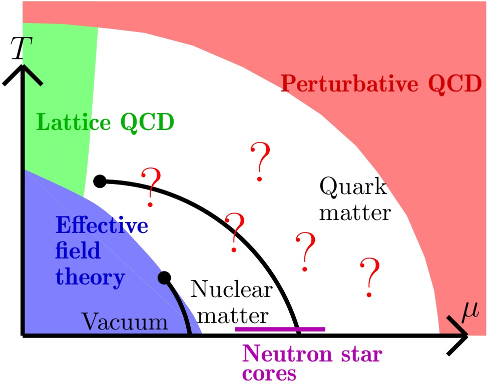
- Lattice data only available at zero/small chemical potentials
- Effective field theory works at small densities
- Perturbative QCD: only at high densities and temperatures



[Image: M. Järvinen]

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

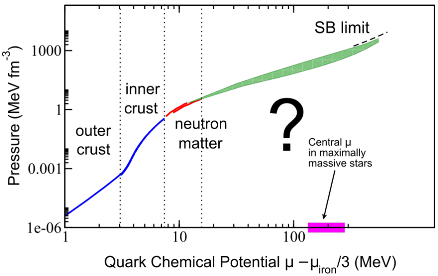


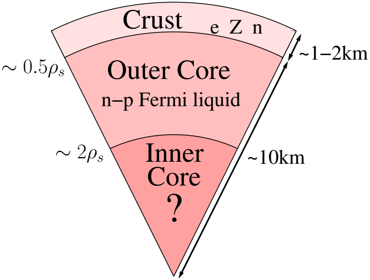
[Image: M. Järvinen]

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

Traditionally two choices

- Pheno models
- Controlled interpolation between low and high energy





[Left image: Kurkela-Fraga-SchaffnerBielich-Vuorinen 1402.6618]

No man's land

- Theoretical uncertainties welcome alternative approaches

Insights from string theory

- Theoretical greenhouse where new ideas grow to be transplanted elsewhere

AdS/CFT or holographic duality

Best known example

- Super-Yang-Mills is secrectly a theory of closed strings
- Low energy effective theory (strong coupling of SYM) is dual to a supersymmetric classical gravity theory in ten dimensions

Duality

- Two theories containing very different dofs and interactions (w/ and w/o gravity) turn out to be the same
- Mapped to each other by a very complicated coordinate trafo
- Action related to expansion about a point

Example of a duality via bosonization

$$\int d^2x \bar{\psi}(i\partial\!\!\!/ - m_F)\psi - \frac{g}{2}(\bar{\psi}\gamma^\mu\psi)^2 = \int d^2x (\partial\phi)^2 + \frac{m}{\beta^2}(\cos\beta\phi - 1)$$

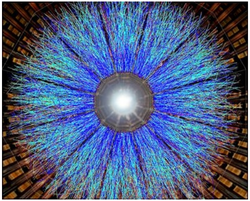
if $\frac{\beta}{4\pi^2} = \frac{1}{1+g\pi}$ (S-duality) + details w/ renormalization

[S. Coleman '75]

Practical application: AdS/QCD

Quark-gluon plasma

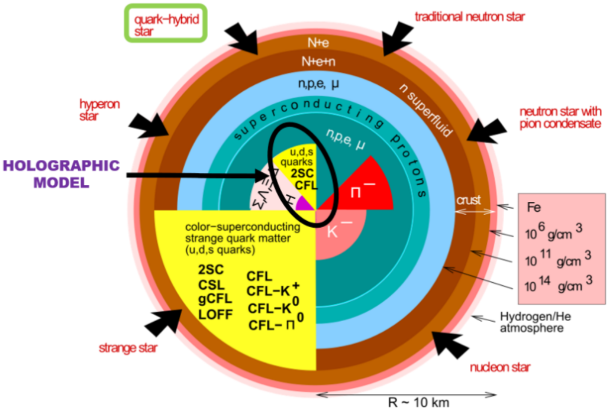
- Surprising results from RHIC: QGP behaves more like an opaque strongly coupled fluid instead of hot gas
- The fluid has extremely low viscosity, hydro good approx
- Strongly coupled $\mathcal{N} = 4$ SYM is not QCD but has similar universal features at RHIC regime
- Calculations in strongly coupled SYM are hard, but very easy in SUGRA
- SUGRA gives surprisingly good effective description for various aspects of heavy ion collisions!



[Image: Brookhaven National Laboratory]

Practical application: AdS/QCD

- Can holography be useful in studying quark/nuclear matter relevant for neutron stars?



Choosing your holographic model

Incomplete list of holographic works in this area:

- "Top-down" (correct calculation, wrong theory)
  - Add quenched flavors to $\mathcal{N} = 4 \rightarrow$ D3-D7 models [1603.02943...many]
    [BitaghsirFadafan-CruzRojas-Evans ...1911.12705]
  - Quark stars in Sakai-Sugimoto and D4-D6 [Burikham-Hirunsirisawat-Pinkanjanarod 1003.5470]
    [Kim-Lee-Shin-Wan 1108.6139,1404.3474]
    [Ghoroku-Kubo-Tachibana-Toyoda 1311.1598]
  - Sakai-Sugimoto with baryons [Hirayama-Lin-Luo-Zhang 1902.08477]
    [Kovensky-Poole-Schmitt ...2111.03374]
- Bottom-up (less correct calculation, less wrong theory)
  - Einstein-Maxwell-scalar [Mamani-Flores-Zanchin 2006.09401]
  - (Double) Hard wall [Bartolini-Gudnason-Leutgeb-Rebhan 2202.12845]
  - V-QCD with baryons [exemplify in this talk]

Outline

1. Equilibrium
2. Applications to neutron stars
3. Out-of-equilibrium
4. Summary and outlook

1. Equilibrium

Holographic V-QCD

Recall real world QCD:

- $N_c = 3$ and $N_f = \cancel{6} \to 3$

which is too hard to solve, hence approximate with

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

[Järvinen-Kiritsis 1112.1261]

[. . . many extensions. . .]

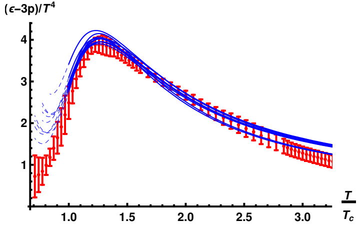
- Bottom-up, try follow string theory as closely as possible
- Many parameters: effective description of QCD
- Comparison with QCD data essential
- Works surprisingly well!

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

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

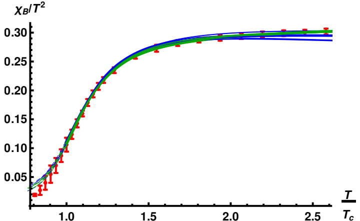
Interaction measure, 2+1 flavors

Lattice data: Borsanyi et al. arXiv:1309.5258



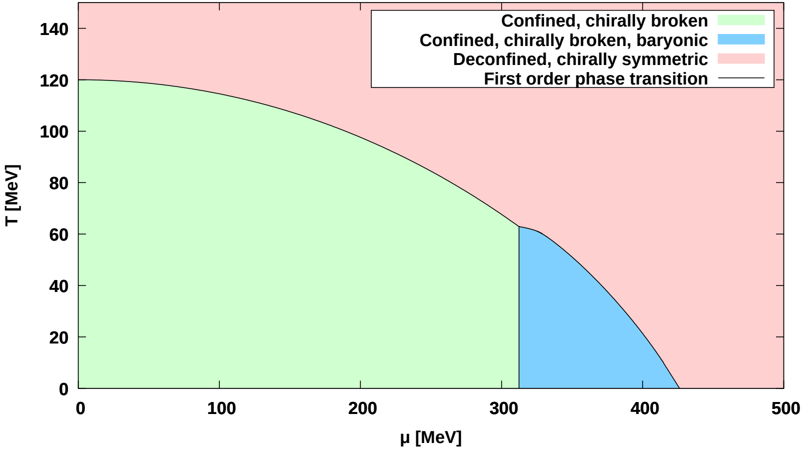
Baryon number susceptibility

Lattice data: Borsanyi et al. arXiv:1112.4416



Phase diagram at zero quark mass

- Extrapolate to finite μ
- Intermediate-μ, low-T instanton solution appears: baryons

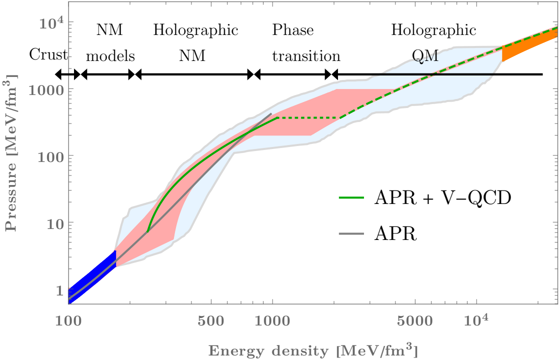


[Ishii-Järvinen-Nijs 1903.06169]

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

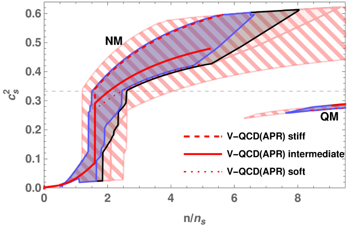
Without and with holography



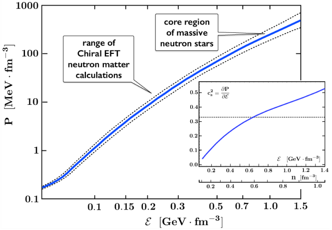
[Ecker-Järvinen-Nijs-van der Schee 1908.03213]
[NJ-Järvinen-Nijs-Remes 2006.01141]

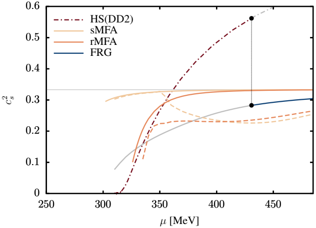
Speed of sound and comparison to FRG

Speed of sound (squared) as a function of density



- Relatively mild dependence on model parameters
- Similar predictions as with FRG method





[Drews-Weise 1610.07568; Friman-Weise 1908.09722]
[Otto-Oertel-Schaefer 1910.11929]

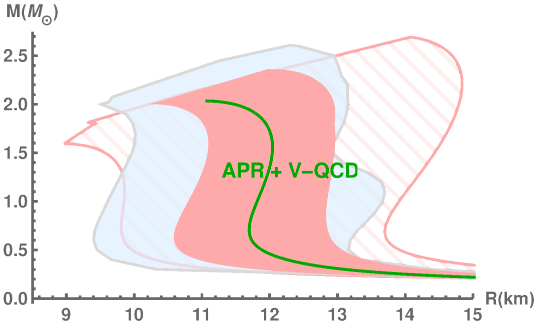
2. Applications to neutron stars

Predictions for neutron stars

Plug V-QCD EoSs in the TOV equations ⇒ Mass-Radius relations

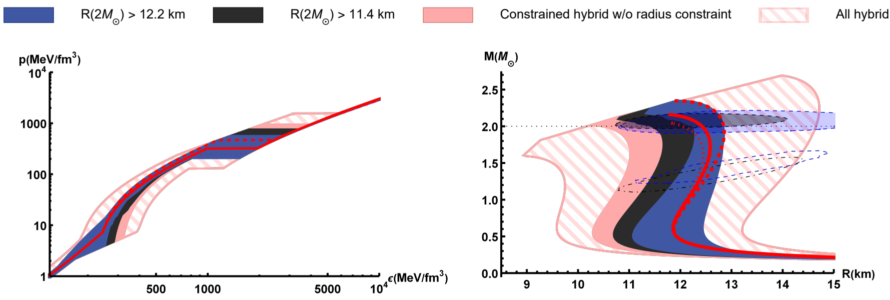
1. without holography
2. with holography

[NJ-Järvinen-Nijs-Remes 2006.01141]



- Strong 1st order nuclear to quark matter phase transitions: quark cores unstable; universal?
  [RodriguezFernandez-Hoyos-NJ-Vuorinen 1603.02943]
- Large radii of neutron stars preferred

NICER predictions for neutron stars

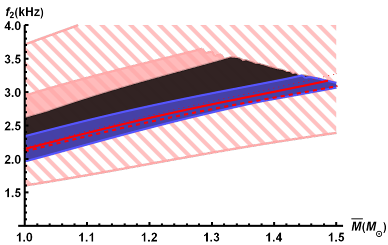


[NJ-Järvinen-Remes 2111.12101]

- Red curves V-QCD(APR); submitted in CompOSE
- Even stringest NICER results compatible with no quark matter cores
- $R(2M_\odot) > 12.2$km results in very constrained bands

  $\Rightarrow$ predictions for QCD at strong coupling

NICER predictions for neutron stars



[NJ-Järvinen-Nijs-Remes 2006.01141]

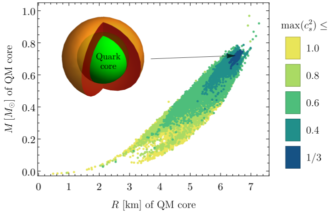
[NJ-Järvinen-Remes 2111.12101]

- Predictions for GW peak etc. frequencies
- Generated using "universal" relations
  [Takami-Rezzolla-Baiotti 1403.5672,1412.3240; Breschi et al. 1908.11418]
- Some numerical simulations $\exists$ but are expensive
  [Ecker-Järvinen-Nijs-van der Schee 1908.03213]
  [Bartolini-Gudnason-Leutgeb-Rebhan 2202.12845]

No quark matter cores?!

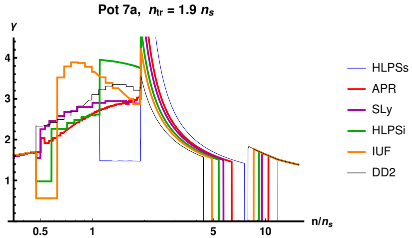
A recent model independent study claims that most massive neutron stars have quark matter cores

[Annala-Gorda-Kurkela-Nättilä-Vuorinen 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?

Our model predicts lower adiabatic index $\gamma = d\log p/d\log\epsilon$ for nuclear matter than what they expect



Vindication for holography

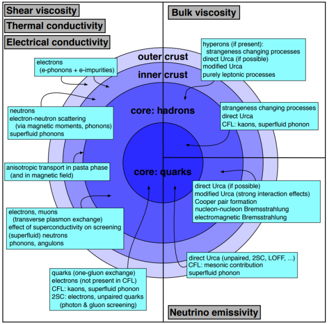
Good signal for (of?) holography:

- V-QCD predics low γ
- Sakai-Sugimoto model also yields small γ
  [Kovensky-Poole-Schmitt 2111.03374]
- (insert your holographic NM model here)

3. Out-of-equilibrium

Transport of cool quark matter

Beyond the EoS: transport properties



- (Bulk) viscosity relevant for neutron star merger dynamics?
- Viscosities ↔ instabilities (r-modes) in spinning NSs

  [N. Andersson '98]
- Conductivities relevant for NS cooling and equilibration after NS merger

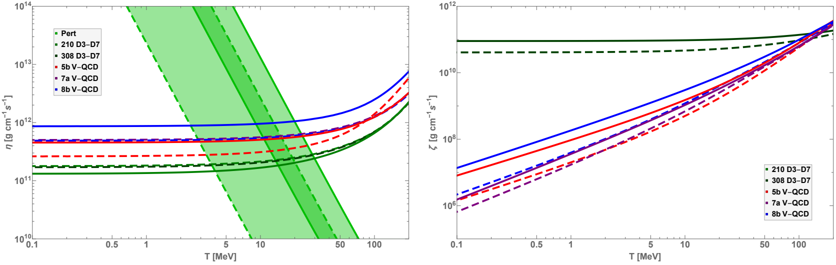
  [Review: Schmitt-Shternin 1711.06520]

Transport from gauge/gravity duality

- 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]
- Transport: deviation from equil. $\leftrightarrow$ metric fluctuations
- Leading order deviation characterized by 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 $\vec{Q} = -\kappa \nabla T$
- 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 of cool quark matter

log η vs. log T log ζ vs. log T



[Hoyos-NJ-Järvinen-Subils-Tarrio-Vuorinen 2005.14205,2109.12122]

- Predictions for viscosities for unpaired quark matter (dashed $\mu = 450$ MeV, solid $\mu = 600$ MeV)
- Large deviation from perturbative results
- Our (small) results assume "idealized" case: only QCD contributions, no weak interactions or electrons
- Also computed electrical σ and heat κ conductivities

Utility of the results

- Holographists:
  - Transport coeffs provided for a class of holographic models
- General relativists:
  - VQCD(APR) EoS curves already in CompOSE : https://compose.obspm.fr/
  - V-QCD transport results to-be-submitted

CompOSE

CompStar Online Supernovæ Equations of State

EoS

Family : **Cold Neutron Star EoS**
Particles : **hybrid (quark-hadron) model**
C.M. Homogeneous Matter : **Holographic models**
C.M. Inhomogeneous Matter : **Non unified models (crust model matched)**

Show 10 entries

Search:

Nparam	Name	Family	Particles Content	C.M. Homogeneous	C.M. Inomogeneous	Particles	T min MeV	T max MeV	T pts	nb min fm^{-3}	nb max fm^{-3}	nb pts	Y min	Y max	Y pts	
1	JJ(VQCD(APR)), stiff	Cold Neutron Star EoS	hybrid (quark-hadron) model	Holographic models	Non unified models (crust model matched)	npNq	0	0	1	1e-12	10	651	0	0	1	details
1	JJ(VQCD(APR)), intermediate	Cold Neutron Star EoS	hybrid (quark-hadron) model	Holographic models	Non unified models (crust model matched)	npeNq	0	0	1	1e-12	10	651	0	0	1	details
1	JJ(VQCD(APR)), soft	Cold Neutron Star EoS	hybrid (quark-hadron) model	Holographic models	Non unified models (crust model matched)	npeNq	0	0	1	1e-12	10	651	0	0	1	details

4. Summary and outlook

Holographic approach to compact stars and their binary mergers

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Abstract

In this review article, we describe the role of holography in deciphering the physics of dense QCD matter, relevant for the description of compact stars and their binary mergers. We review the strengths and limitations of the holographic duality in describing strongly interacting matter at large baryon density, walk the reader through the most important results derived using the holographic approach so far, and highlight a number of outstanding open problems in the field. Finally, we discuss how we foresee holography contributing to compact-star physics in the coming years.

Keywords: Quantum Chromodynamics, AdS/CFT duality, Quark matter, Nuclear matter, Neutron stars
Preprint numbers: HIP-2021-49/TH

[Hoyos-NJ-Vuorinen 2112.2.08422]

Holographic modeling of nuclear matter and neutron stars[a]

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[Järvinen 2110.08281]

Selected lessons from holography

- "Universal" I-Love-Q relations can be violated by a lot
- Conformal speed limit is fake news
- Strongly coupled
  - framework simultaneously for nuclear and quark matter
  - Nuclear matter is very stiff, distinct from "standard" EFT ones
  - (Unpaired) quark matter is generically soft[1]
- Implications for astrophysics
  - Realistic quiescent neutron stars
  - Transport phenomena for simulators
  - Massive quiescent neutron stars are void of deconfined matter

[1] Unless . . .

[BitaghsirFadafan-Rojas-Evans 2009.14079]

Summary

- 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 and matter
  - transport in quark matter phase
  - properties of neutron stars
  - gravitational wave spectrum in neutron star mergers
  - $\cdots$

Outlook

Where to expect results from holography next?

1. differing quark masses
   - quark pairing
   - leading contribution to bulk viscosity
2. finite temperature nuclear matter ($T > 0$ quark matter ✓)
3. magnetic field
4. inhomogeneous and mixed phases
5. anisotropy

Advances in any of these topics is foreseen in near future.
What is in your wishlist?

Thank you!