# Holographic QCD in the NICER era

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A Virtual Tribute to Quark Confinement
and the Hadron Spectrum 2021

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# Outline

1. Equilibrium
   - equation of state of dense nuclear and quark matter
2. Applications to neutron stars
3. Out-of-equilibrium
   - transport properties of cool quark matter

# 1. Equilibrium

# Holographic V-QCD

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!

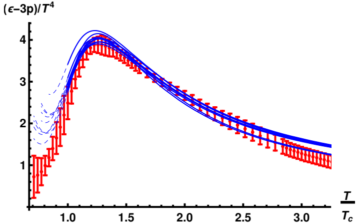
# Constraining the model at $\mu \approx 0$

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

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

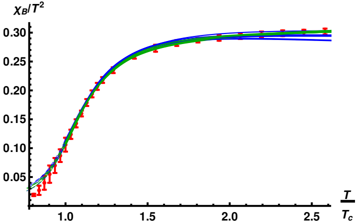
Interaction measure, 2+1 flavors

Lattice data: Borsanyi et al. arXiv:1309.5258



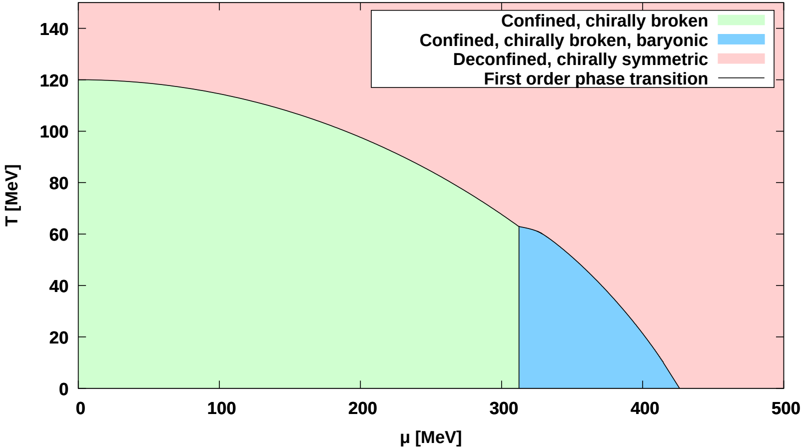

Baryon number susceptibility

Lattice data: Borsanyi et al. arXiv:1112.4416



# Phase diagram at zero quark mass

- Extrapolate to finite $\mu$
- Intermediate-$\mu$, low-$T$ instanton solution appears: baryons



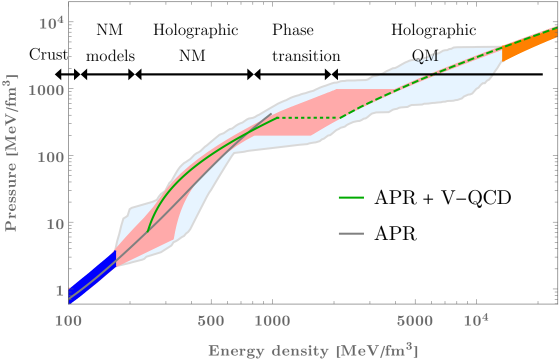

[Ishii-Järvinen-Nijs 1903.06169]

# 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!

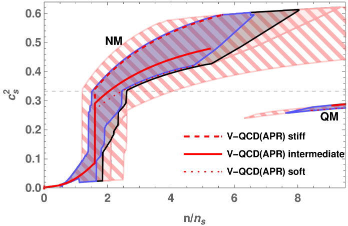
Without and with holography



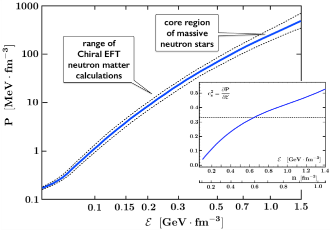

[Ecker-Järvinen-Nijs-van der Schee 1908.03213]
[NJ-Järvinen-Nijs-Remes 2006:01141]

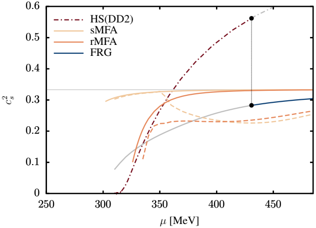
# Speed of sound and comparison to FRG

Speed of sound (squared) as a function of density




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



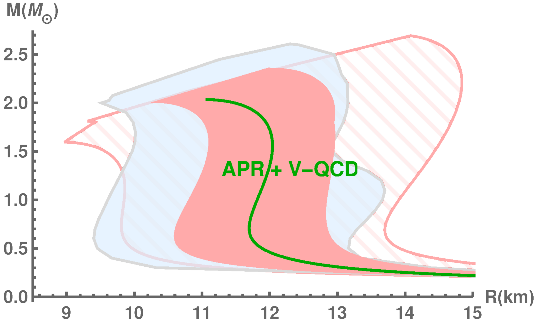

[Drews-Weise 1610.07568; Friman-Weise 1908.09722]
[Otto-Oertel-Schaefer 1910.11929]

# 2. Applications to neutron stars

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

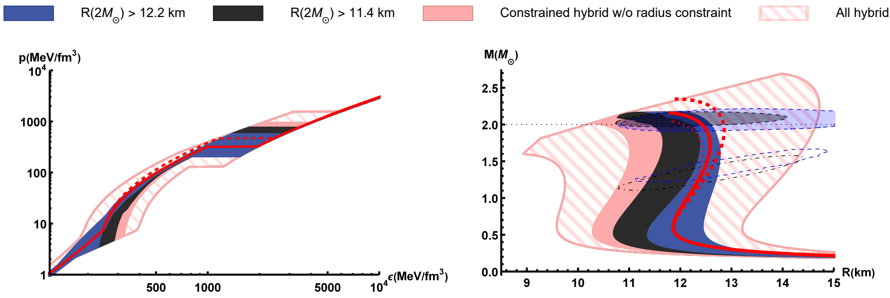
1. without holography
2. with holography (hybrid EoSs)

[NJ-Järvinen-Nijs-Remes 2006.01141]




- Strong 1st order nuclear to quark matter phase transitions: quark cores unstable
- Large radii of neutron stars preferred

# NICER predictions for neutron stars

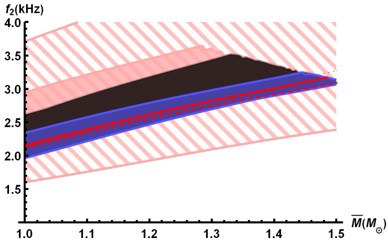


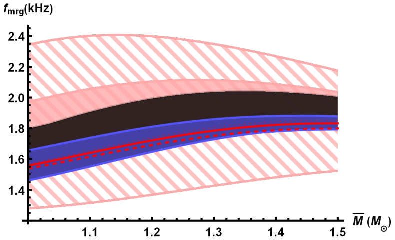

[NJ-Järvinen-Remes to appear]

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

$\Rightarrow$ predictions for QCD

# NICER predictions for neutron stars




[NJ-Järvinen-Remes to appear]

- Predictions for GW peak etc. frequencies
- Generated using "universal" relations
  [Takami-Rezzolla-Baiotti 1403.5672,1412.3240; Breschi et al. 1908.11418]
- Red curves V-QCD(APR)

# 3. Out-of-equilibrium

# 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

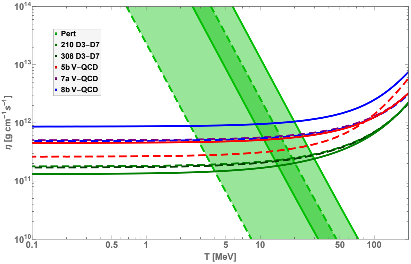
[Review: Schmitt-Shternin 1711.06520]

However transport is challenging to analyze...

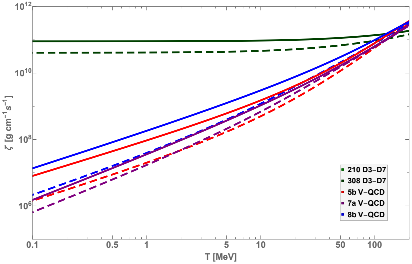
- While the EoS of dense and cold QCD matter has large uncertainties, even less is known about transport
- Only available first-principles result for quark matter: leading order pQCD analysis in the unpaired phase

  [Heiselberg-Pethick PRD 48(1993)2916]
- We carried out the strong coupling analysis (also at $\omega \neq 0$)
  - to-be-submitted in CompOSE

[Hoyos-NJ-Järvinen-Subils-Tarrio-Vuorinen 2005.14205 + to appear] log $\eta$ vs. log $T$




log $\zeta$ 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
- Also computed electrical $\sigma$ and heat $\kappa$ conductivities

# Conclusions and outlook

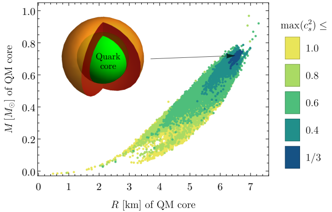
- Gauge/gravity duality (combined with other approaches) is useful to study dense QCD
- Using V-QCD with simple approximations, many details work really well:
  - ✓ Precise fit of lattice thermodynamics at $\mu \approx 0$
  - ✓ Extrapolated EoS for cold quark matter reasonable
  - ✓ Simultaneous model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

# Backup slides

# No quark matter cores?!

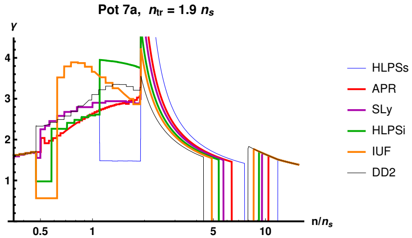
A recent model independent study claims that most massive neutron stars have quark matter cores

[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?

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



# 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 $\eta$ – "standard" viscosity
- Bulk viscosity $\zeta$ – viscosity in compression/expansion
- Electric conductivity $\sigma$ – defined by $\vec{J} = \sigma \vec{E}$
- Thermal conductivity $\kappa$ – 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)