NICER view on holographic QCD

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Holotube seminar

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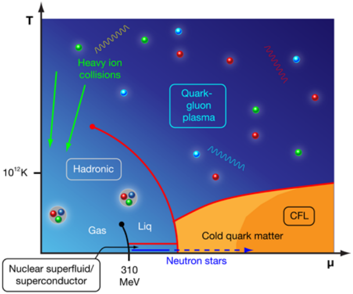
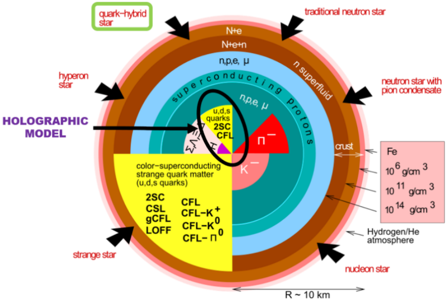
Decomposing the title of the talk

"NICER view on holographic QCD"





2019: $\sim 1.4 M_\odot$ J0030+0451 & 2021: $\gtrsim 2 M_\odot$ J0740+6620

Reviews on the topic

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]

Matti Järvinen[b,1,2]

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[2]Department of Physics, Pohang University of Science and Technology, Pohang 37673, Republic of Korea

[Järvinen 2110.08281]

Choosing your holographic model

Incomplete list of holographic works in this area:

- "Top-down" (correct calculation, wrong theory)
  - Compact stars in AdS_5 [de Boer-Papadodimas-Verlinde 0907.2695]
  - 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]
  - Add quenched flavors to $\mathcal{N} = 4 \to$ D3-D7 models [1603.02943,1711.06244,2005.14205] [BitaghsirFadafan-CruzRojas-Evans 1911.12705]
  - 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 [this talk]

Outline

1. Equilibrium
2. Applications to compact/neutron stars
3. Out-of-equilibrium
4. Outlook

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!

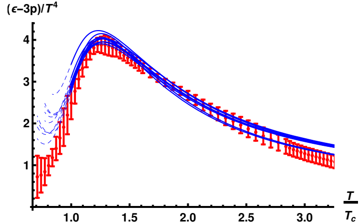
Constraining the model at $\mu \approx 0$

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

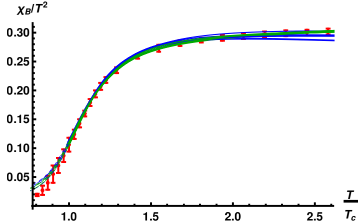
Interaction measure, 2+1 flavors

Lattice data: Borsanyi et al. arXiv:1309.5258



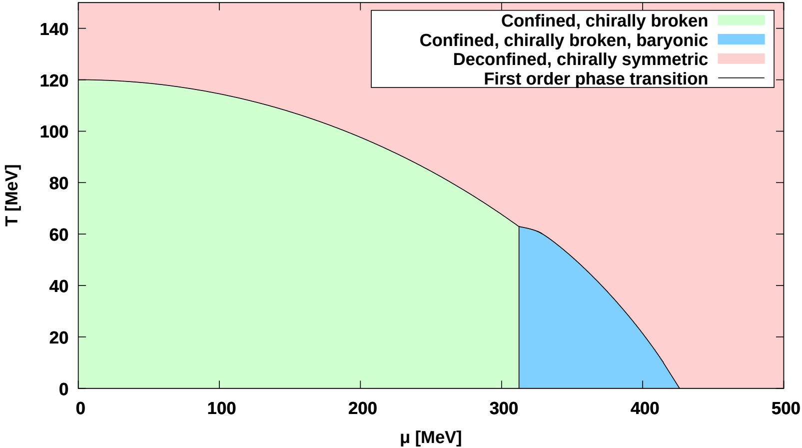
Baryon number susceptibility

Lattice data: Borsanyi et al. arXiv:1112.4416



Phase diagram at zero quark mass

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

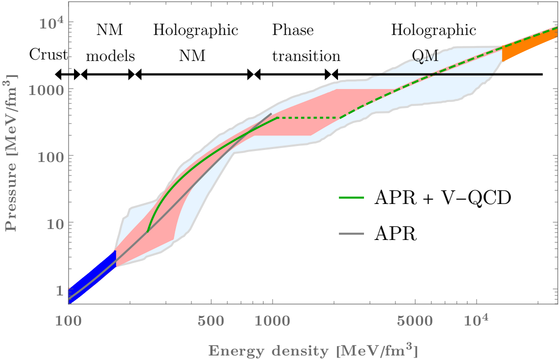


[Ishii-Järvinen-Nijs 1903.06169]

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

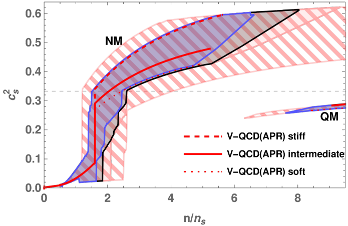
- Match nuclear models (low densities) with V-QCD (high densities)
- Variations in model parameters give rise to the band
- Same (holographic) model for nuclear and quark matter phases

Without and with holography

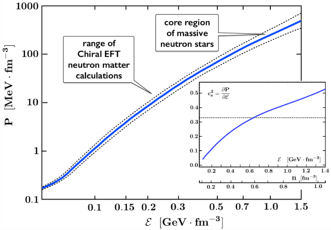


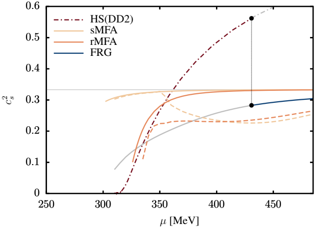
[Ecker-Järvinen-Nijs-van der Schee 1908.03213]
[NJ-Järvinen-Nijs-Remes 2006.01141]

Speed of sound (squared) as a function of density



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

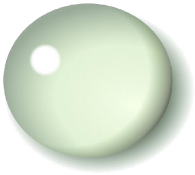




[Drews-Weise 1610.07568; Friman-Weise 1908.09722]
[Otto-Oertel-Schaefer 1910.11929]

2. Applications to neutron stars

Building a star from e.g. holography



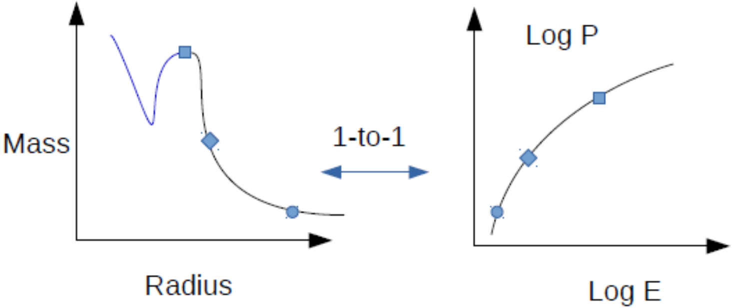
"Droplet" of self-gravitating perfect fluid

$$T^{\mu}_{\nu} = \begin{pmatrix} \varepsilon & \\ & p\,\delta^i_j \end{pmatrix} \qquad ds^2 = -e^{\nu}dt^2 + e^{\lambda}dr^2 + r^2 d\Omega_2$$

$$\lambda = -\log\left(1 - \frac{2M}{r}\right)$$

Tolman-Oppenheimer-Volkoff (TOV) equations

$$M' = 4\pi r^2 \varepsilon \qquad \nu' = -\frac{2}{\varepsilon + p}p' \qquad p' = -\frac{e^{\lambda}}{r^2}(\varepsilon + p)(M + 4\pi r^3 p)$$



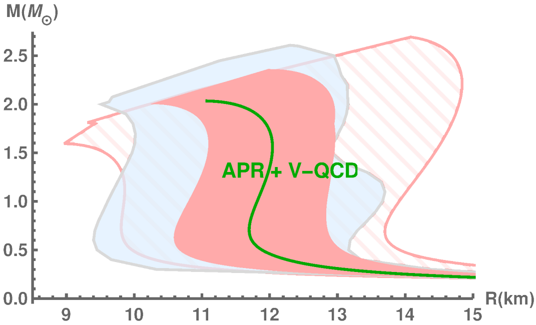
- "Catch": need to maintain charge neutrality and β-equilibrium

Predictions for neutron stars

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

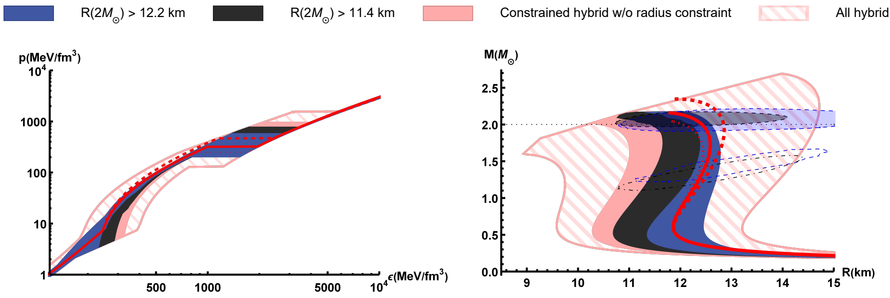
1. without holography
2. with holography (hybrid EoSs)

[NJ-Järvinen-Nijs-Remes 2006.01141]



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

NICER predictions for neutron stars

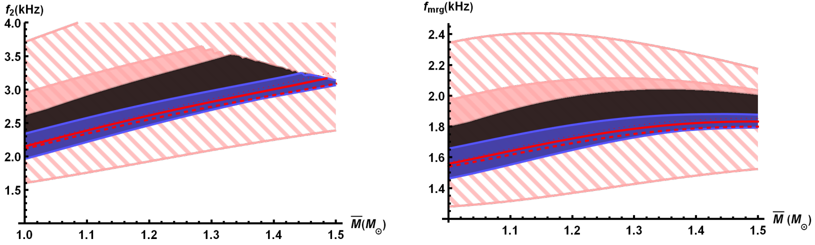


[NJ-Järvinen-Remes 2111.12101]

- Red curves V-QCD(APR); submitted in CompOSE
- 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-Nijs-Remes 2006.01141]

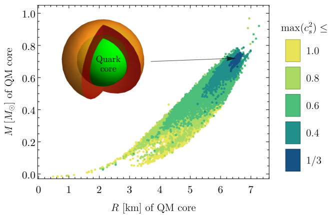
[NJ-Järvinen-Remes 2111.12101]

- 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 ∃ but are expensive [Ecker-Järvinen-Nijs-van der Schee 1908.03213] [Bartolini-Gudnason-Leutgeb-Rebhan 2202.12845]
- Red curves V-QCD(APR)

No quark matter cores?!

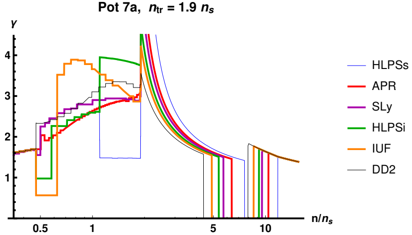
A recent model independent study claims that most massive neutron stars have quark matter cores

[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



Vindication for holography

Good signal for (of?) holography:

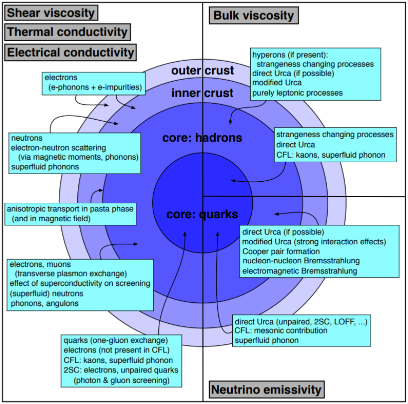
- V-QCD predics low γ
- Sakai-Sugimoto model also yields small γ [Kovensky-Poole-Schmitt 2111.03374]
- (insert your holographic NM model here)

- However, $\exists$ one non-holographic NM model. . . [Paeng et al. 1704.02775, Ma-Rho 2006.14173]
- $\leftrightarrow$ $\exists\infty$-ly many due masquerading [Alford-Braby-Paris-Reddy nucl-th/0411016]

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
- 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

- Strong coupling analysis for actions: [Hoyos-NJ-Järvinen-Subils-Tarrio-Vuorinen 2005.14205,2109.12122]

$$
\begin{aligned}
S &= N_c^2 M_{\rm Pl}^3 \int d^5x\sqrt{-g}\left(R - \frac{1}{2}(\partial\phi)^2 - V(\phi)\right) \\
&- N_f N_c M_{\rm Pl}^3 \int d^5x\, \mathcal{Z}(\phi,\chi)\sqrt{-\det\left(g_{\mu\nu} + \kappa(\phi,\chi)\partial_\mu\chi\partial_\nu\chi + \mathcal{W}(\phi,\chi)F_{\mu\nu}\right)}
\end{aligned}
$$

- ∃ "attractor" formulas too
- V-QCD results to-be-submitted in CompOSE : https://compose.obspm.fr/
- N.B. VQCD(APR) EoS curves in above slides are already there

CompOSE CompStar Online Supernovæ Equations of State compstar

EoS

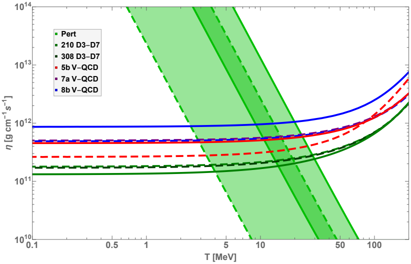
Family : **Cold Neutron Star EoS**
Particles : **hybrid (quark-hadron) model**
C.M. Homogeneous Matter : **Holographic models**
C.M. Inhomogeneous Matter : **Non unified models (crust model matched)**

Show 10 entries Search:

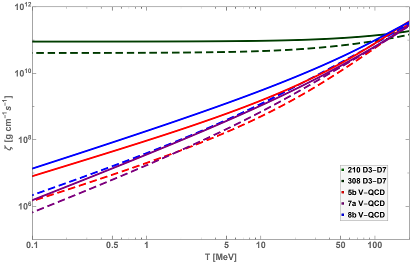
Nparam	Name	Family	Particles Content	C.M. Homogeneous	C.M. Inomogeneous	Particles	T min MeV	T max MeV	T pts	nb min fm^{-3}	nb max fm^{-3}	nb pts	Y min	Y max	Y pts	
1	JJ(VQCD(APR)), stiff	Cold Neutron Star EoS	hybrid (quark-hadron) model	Holographic models	Non unified models (crust model matched)	npNq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

Transport of cool quark matter

$\log \eta$ 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
- Our (small) results assume "idealized" case: only QCD contributions, no weak interactions or electrons
- Also computed electrical σ and heat κ conductivities

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

Outlook

Where/why/how can holography be useful in compact object context?

[Hoyos-NJ-Vuorinen 2112.2.08422]

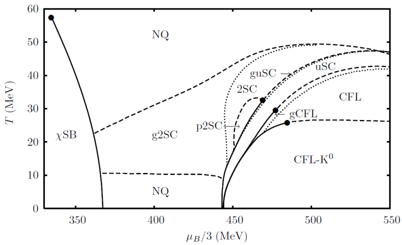
1. differing quark masses
2. finite-T
3. finite-B
4. inhomogeneous and mixed phases
5. anisotropy

Advances in any of these topics is important.

1. Differing quark masses

All holographic models assume that quark flavors share the mass.

- Richer phase diagram due complicated pairing pattern [cf. NJL model by Warringa hep-ph/0606063]



- Only very limited studies of pairing phases in holography
- Same quark masses misses the leading contribution to bulk viscosity (weak processes $u + d \longleftrightarrow u + s$) [Madsen'93,Schmitt-Shternin 1711.06520]

$$\zeta \approx \frac{\Gamma_1 B^2}{\Gamma_1 C^2 + \omega^2} ,$$

Γ_1 production rate of d ($\mu_d - \mu_s \neq 0$), $B = n_d\chi_d - n_s\chi_s$, $C = \chi_d + \chi_s$, (inverse) susceptibilities $\chi_{d,s} = (\partial\mu_{d,s}/\partial n_{d,s})$

2. Finite temperature

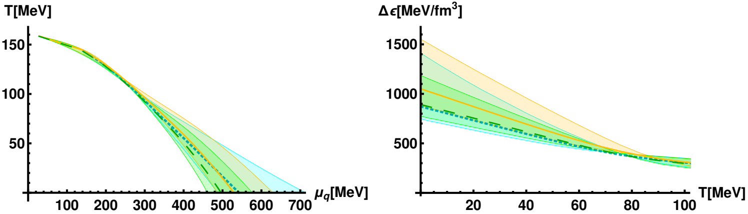
For quiescent NS $T = 0$ suffices. In dynamical processes such as supernovae and mergers, T can reach tens of MeVs.

- Most simulations use unrealistic constant-in-density thermal index to mimic finite-T:

$$\Gamma_{\rm th}(T, \cancel{n_B}) = 1 + \frac{p(T, n_B) - p(0, n_B)}{\epsilon(T, n_B) - \epsilon(0, n_B)}$$

- In quark matter phase, deconfining, just include black hole in the dual description

[Chesler-NJ-Loeb-Vuorinen 1906.08440]

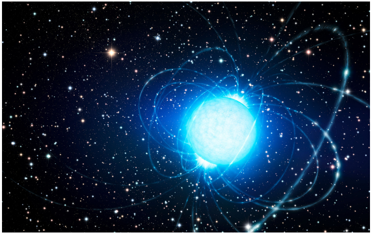


- in confining case, no T-effects for NM, need to incorporate $1/N_c$ corrections or inherit from nuclear physics models

[Demircik-Ecker-Järvinen 2112.12157]

3. Finite magnetic fields

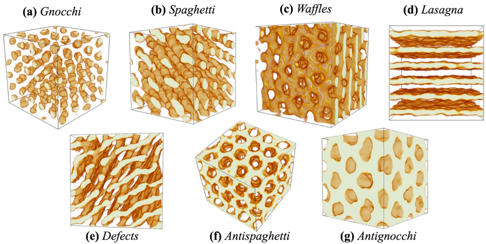
Magnetars can have HUGE magnetic fields $\sim 10^{10} - 10^{12}$T



- Expect however miniscule effect on EoS, but
  - Leads to an explosion of new transport coefficients
  - Integral part of understanding glitches
- In holography external magnetic fields are easy to incorporate
  - No studies in neutron star context thus far

4. Inhomogeneous and mixed phases

- At $T \sim 0$, finite-density systems develop ordered phases
- Ground state of QCD is inhomogeneous? (nuclear pasta, instanton crystal, LOFF. . .)



[MC simulations of nucleons: Caplan-Horowitz 1606.03646]

- Ground states for QM using flavor D-branes are striped [Bergman-NJ-Lifschytz-Lippert 1106.3883]
- For spatially separated homogeneous mixed phases one needs surface tension, known only at $\mu = 0$ via holography [Ares-Henriksson-Hindmarsh-Hoyos-NJ 2109.13784]

5. Anisotropic phases

- Most studies of neutron stars assume isotropy. But, matter in cores could be anisotropic: radial pressure $\neq$ angular pressure.
- Can lead to continuous deformation of a neutron star to a black hole, evading Buchdahl's bound
  - Neutron stars are quasi-universal (I-Love-Q relations) [Yagi-Yunes 1608.02582]
  - Black holes are super-universal, related? [Alexander-Yagi-Yunes 1810.01313]
- Einstein equations singular unless $p_{radial} = p_{angular}$ at the center
  - $\rightarrow$ spontaneous anisotropy in holography [Hoyos-NJ-Penin-Ramallo 2001.08218]