Locating the QCD critical point using neutron-star observations

Niko Jokela

UNIVERSITY OF HELSINKI
HELSINKI INSTITUTE OF PHYSICS

Holographic applications:
from Quantum Realms to the Big Bang
University of Chinese Academy of Sciences, Yanqi Lake campus
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Collaborators

- Work based on past and ongoing collaborations with:

Eemeli Annala, Fëanor Ares, Paul Chesler, Jesus Cruz Rojas, Tuna Demircik, Christian Ecker, Tyler Gorda, Oscar Henriksson, Mark Hindmarsh, Carlos Hoyos, Matti Järvinen, Aleksi Kurkela, Avi Loeb, Govert Nijs, Andrea Olzi, Risto Paatelainen, Jere Remes, Aleksi Piispa, Javier G. Subils, Saga Säppi, David Rodriguez Fernandez, Javier Tarrio, Aleksi Vuorinen

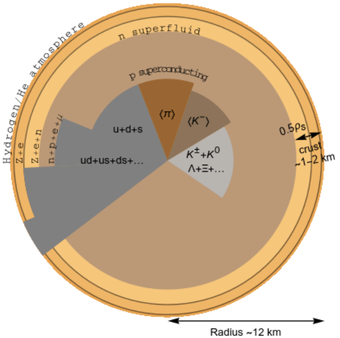
Outline

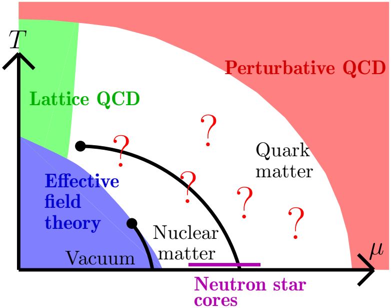
- Motivation
- Features from holographic approach $\leftrightarrow$ lattice QCD
- Confront astrophysics
- Phase diagram of QCD
- Summary / outlook

Motivation: understand nature at the fundamental level

- Matter at extremes is interesting
  - quark-gluon plasma
  - neutron stars
- Low-energy physical QCD is complicated
  - perturbation theory has limited applicability
  - lattice approach is either too expensive or not trustworthy
  - all-encompassing effective models do not (did not used to) $\exists$
- Alternative approach is to use holography
  - Nomenclature: AdS/CFT, string or gauge/gravity duality, top-down, bottom-up
  - get somewhat close but not QCD (eg. $N_c = \infty \approx 3$)
  - can give an all-encompassing effective model, but uncontrolled approximation
  - gain insights

Solve QCD using a neutron star?

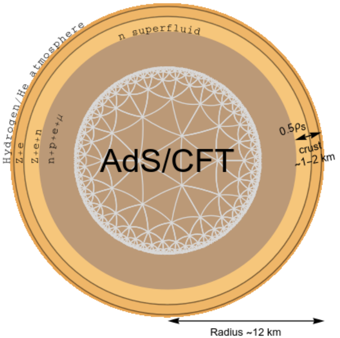


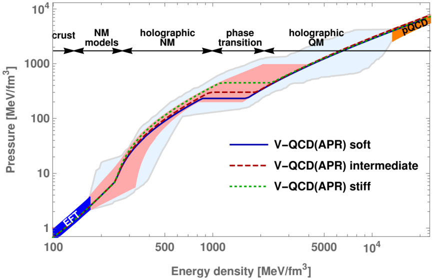


Theoretical results for the phase diagram

- 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

Solve QCD using a neutron star?





Theoretical results for the phase diagram

- Lattice data only available at zero/small chemical potentials
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- Approach from strong coupling: AdS/CFT

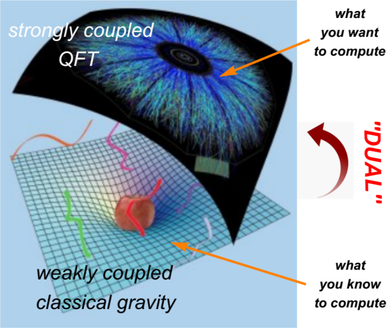
[reviews: Järvinen 2110.08281, Hoyos–NJ–Vuorinen 2112.08422]
[talks by: Lorenzo Bartolini & Kilar Zhang]

Generic holographic approach to match QCD: fields

In order to describe QCD holographically, lay out dictionary for the most important (relevant and marginal) operators

[see lectures by: Matti Järvinen]

- $T_{\mu\nu}$, dual to the metric $g_{\mu\nu}$
- Gluon operator $G^2_{\mu\nu}$, dual to a scalar (the dilaton) ϕ
- Flavor currents $\bar{\psi}_i \gamma_\mu (1 \pm \gamma_5) \psi_j$, dual to gauge fields $(A_\mu^{L/R})_{ij}$ (with $i, j = 1 \ldots N_f$) – global $\mathrm{U}(N_f)_L \times \mathrm{U}(N_f)_R$ of QCD promoted to gauge symmetry
- Flavor bilinears $\bar{\psi}_i \psi_j$ dual to a complex scalar T_{ij}



- What are our options for the choice of dual gravity action?

We write down expected (two-derivative) terms

$$S = S_{\rm gr} + S_{\rm matter} + S_{\rm CS}$$

where $S_{\rm CS}$ is mostly fixed by anomalies, and

$$S_{\rm gr} = M_{\rm p}^3 N_c^2 \int \mathrm{d}^5 x \sqrt{-\det g}\left[R - \frac{4}{3}(\partial\phi)^2 + V_{\rm g}(\phi)\right]$$

Choice of $S_{\rm matter}$ less obvious. Options: $S_{\rm matter} = S_{\rm DBI}$ or $S_{\rm matter} = S_{\rm YM}$, with

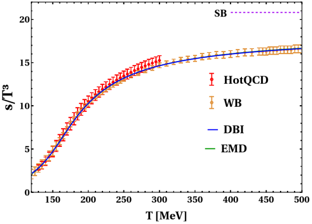
1. $S_{\rm DBI} = M_{\rm p}^3 N_c \int V_{\rm f}(\phi)\,\mathrm{Tr}\left[\sqrt{-\det\left[g_{\mu\nu} + w(\phi)(F_L)_{\mu\nu}\right]} + (L \leftrightarrow R)\right]$
2. $S_{\rm YM} = M_{\rm p}^3 N_c \int Z(\phi)\,\mathrm{Tr}\left[F_L^2 + F_R^2\right]$

- Background gauge fields sourced by $\mu_B \Rightarrow$ at small density, $F_{L/R}$ small
  $\Rightarrow$ DBI and YM reduce to the same choice
- Potentials (V_g, V_f, w or V_g, Z) to be fixed by QCD data

Fitting the potentials to data

Potentials determined by comparison to lattice data

- Data for Yang-Mills (V_g)
- Data for full QCD (other potentials): equation of state, $\chi_2^B = \frac{d^2p}{d\mu_B^2}\Big|_{\mu_B=0}$ . .

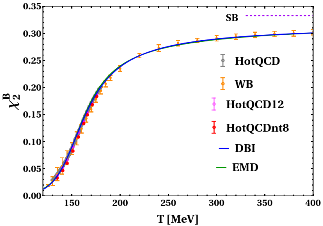


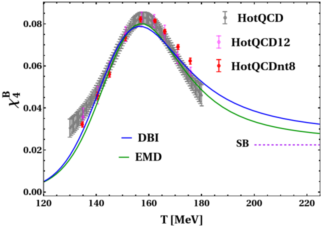
[Gubser–Nellore 0804.0434 . . .]

In case of DBI action, two approaches

1. W/o confinement, direct fit to data
2. W/ confinement & phase transition (V-QCD)

[Järvinen–Kiritsis 1112.1261 . . .]





Fitting the potentials to data (eg. Strategy I)

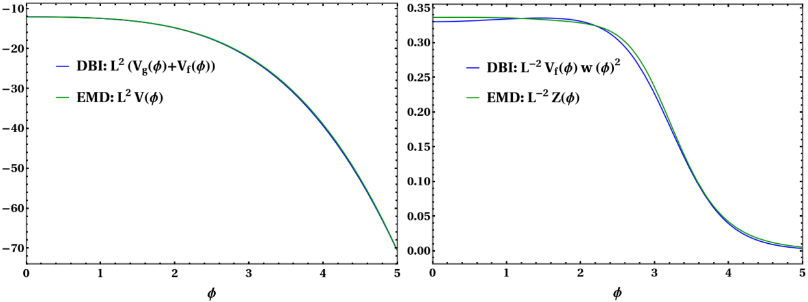
- Parameterize your ignorance, e.g. for the $Z(\phi)F^2$ term: [NJ–Järvinen–Piispa 2405.02394]

$$Z(\phi)^{-1} = z_0 \cosh(\tilde{\gamma}_2\phi) + z_2\phi^2 + z_4\phi^4 + z_6\phi^6 \dots$$

- Optimize the number of paras
- Lattice-χ_n^B data "too good" so better use weighted least-squares

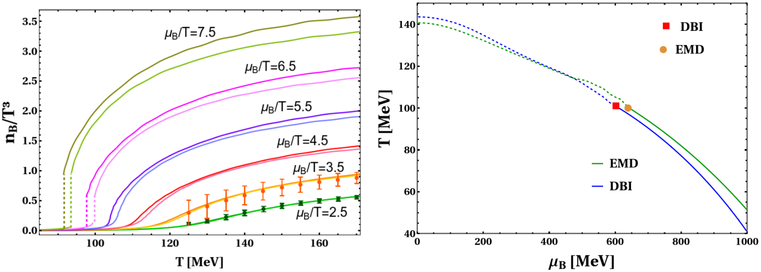
$$\mathrm{chi}^2_{\mathrm{susc}} = \frac{1}{n}\sum_{i=1}^{n} W(\text{data set})\frac{(X - X_i^{\mathrm{fit}})^2}{\Delta X_i^2}$$

- Find smooth potentials

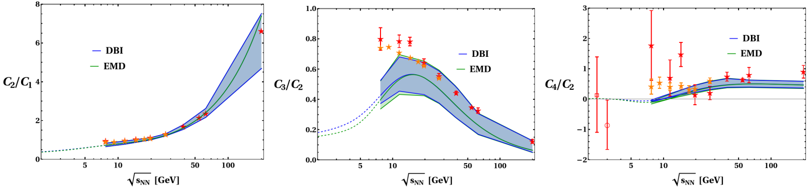


- No phase transition, predict a critical point at nonzero μ

[NJ–Järvinen–Piispa 2405.02394]
[See also talk by Liqiang Zhu]

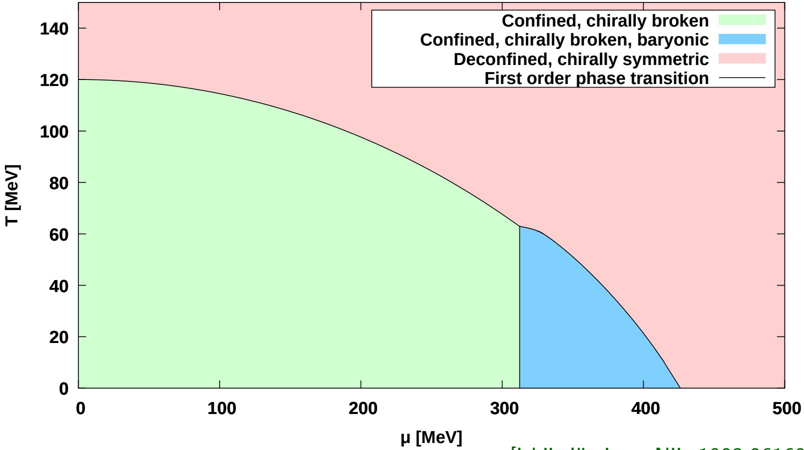


- Predictions consistent with heavy-ion collision data at RHIC



Follow Strategy II (w/ confinement)

- Phase transition at zero μ, extrapolate to NS matter regime
- Intermediate-μ: low-T instanton solution appears: baryons



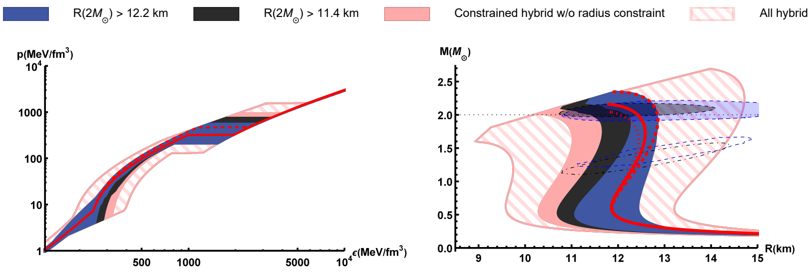
[Ishii–Järvinen–Nijs 1903.06169]

[NJ–Järvinen–Nijs–Remes 2006.01141]

Hybrid equations of state

Holo-NM description not reliable at low densities:

- Match nuclear models (low densities) with holography (high densities)
- Variations in model parameters give rise to the band
- Same (holographic) model for NM and QM phases
  [Ecker–Järvinen–Nijs–van der Schee 1908.03213; NJ–Järvinen–Nijs–Remes 2006.01141]

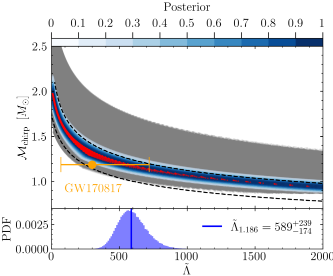


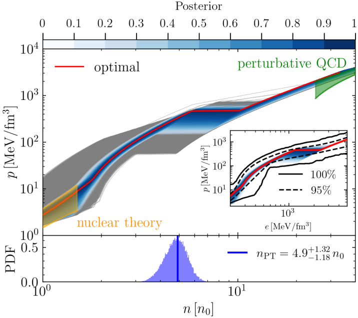
[NJ–Järvinen–Remes 2111.12101]

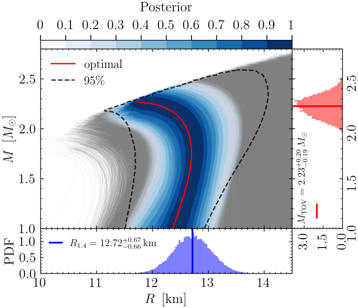
- CompOSE: 3× 1d JJ(VQCD) follows APR up to $1.6n_s$

Bayesian analysis

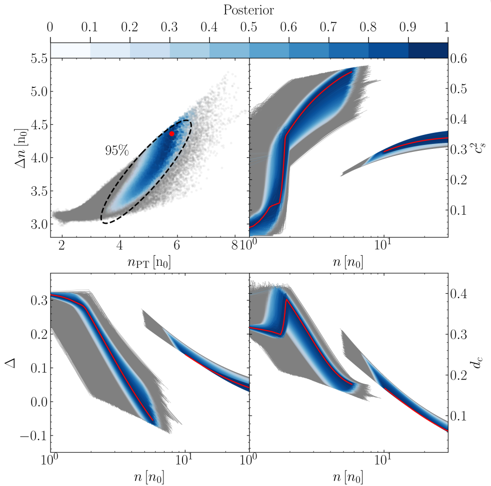
- SFHo $n < 0.4n_0$, N-segm. linear-c_s^2($\mu < \mu_B^{\rm match} \sim$ 1GeV)
- V-QCD: 3 params
- implement constraints
  - CET [Drischler et al. 2009.06441]
  - mass measurement PSR J1614-2230
  - PSR J0740+6620 by NICER
  - Ligo/VIRGO for $\tilde{\Lambda}$







Bayesian analysis



- Trace anomaly Δ, conformal distance d_c, speed of sound...

$$\Delta = \frac{1}{3} - \frac{p}{e} \ , \quad d_c = \sqrt{\Delta^2 + \Delta'^2} \ , \ \Delta' = \frac{\mathrm{d}\Delta}{\mathrm{d}\log \mathrm{e}}$$

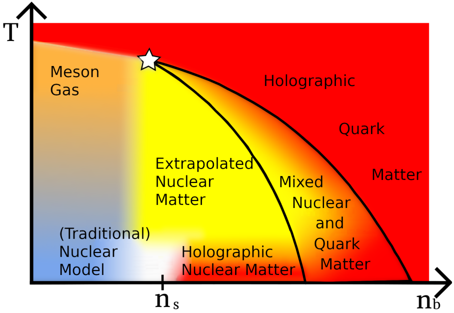
- Criterion for existence of QM not met

[Annala–Gorda–Hirvonen–Komoltsev–Kurkela–Nättilä–Vuorinen 2303.11356]

$d_c < 0.2$!?!

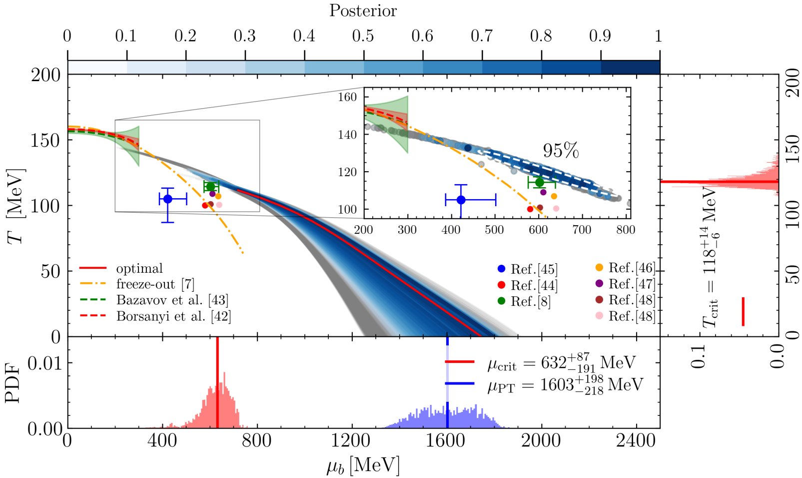
Holographically aided QCD phase diagram

- Given EoS can be extended to finite-T (and relax Y_q) [Chesler–NJ–Loeb–Vuorinen 1906.08440]
- QM+$e, \bar{e}, \gamma$: CompOSE: 3× 3d HJJSTV(VQCD) $\ni \sigma, \kappa, \eta, \zeta$
- NM: borrow T from vdW (v_0) and Y_q dependence from NM of your choice and add meson gas
- Refined phase diagram, CompOSE: 3× 3d DEJ(DD2-VQCD) [Demircik–Ecker–Järvinen 2112.12157]



- "One" EoS has been used in NS merger simulations
- Systematic extension to finite-T: posterior distributions [Ecker–NJ–Järvinen 2506.10065]

Locating the QCD critical point



- CEP for locally charge neutral, β-equilibrated QCD matter is inferred at the position compatible with low-μ estimates

[Ecker–NJ–Järvinen 2506.10065]

Summary

- Gauge/gravity duality (combined with other approaches) is useful to study dense QCD
- 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 finite-T matter
    - CEP for β-equilibrated QCD matter
  - (transport in unpaired quark matter phase)
    - shear η, bulk ζ viscosity, electrical α, thermal κ conductivity [Hoyos–NJ–Järvinen–Subils–Tarrio–Vuorinen 2005.14205,2109.12122]
    - QCD contribution to (dominant!) electroweak ζ w/ $m_s \neq m_d$ [CruzRojas–Gorda–Hoyos–NJ–Järvinen–Kurkela–Paatelainen–Säppi–Vuorinen 2402.00621]
  - (properties of neutron stars)
  - (gravitational wave spectrum in neutron star mergers)

Outlook

- Observable effects in neutron star physics?
- Plausible extensions:
  - flavor dependent masses [2402.00621]
  - isospin/other chemical potentials → heavy-ion collisions (CEP) [. . . Bartolini–Gudnason–Järvinen 2504.01758]
  - neutrino emissivity in NS regime [build on Järvinen–Kiritsis–Nitti–Préau 2306.00192]
  - magnetic field, anisotropic equation of state
  - quark pairing (color “superconductivity”) [Hashimoto&al,NJ&al. . . CruzRojas–Ecker–Demircik–Järvinen 2505.06338]
- Caveats:
  - Maxwell construction: calculate interface tension! [Ares–Henriksson–Hindmarsh–Hoyos–NJ 2109.13784,2110.14442] [cf. lattice results: Rindlisbacher–Rummukainen–Salami 2506.15509]
  - homogeneity seems lost: all holographic models are unstable [Demircik–NJ–Järvinen–Piispa 2405.02392,CruzRojas–Demircik–Järvinen 2405.02399]