Holographic approach to QCD and neutron stars

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Holography and dense matter workshop

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Outline

- Motivation
- Features from holographic approach
- Results for transport
- Summing up

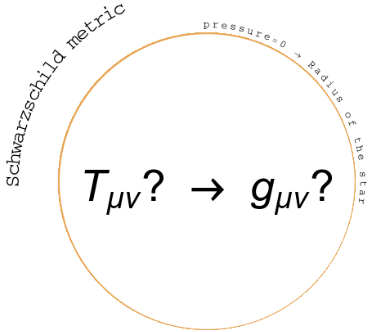
Motivation: understand nature at the fundamental level

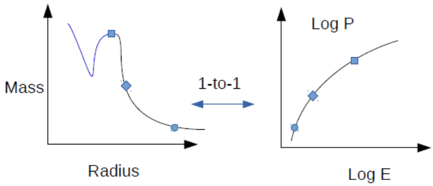
- Matter at extremes is interesting
  - quark-gluon plasma
  - neutron stars
- Low-energy physical QCD is complicated
  - perturbation theory has limited applicability
  - lattice approach is either too expensive or not trustworthy
  - all-encompassing effective models do not exist
- Alternative approach 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

Holography stems from string theory

- Theoretical green house, where new ideas grow to be transplanted elsewhere

Solve QCD using a neutron star?





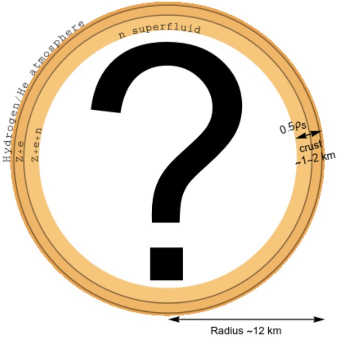
- Isotropy and perfect fluid model

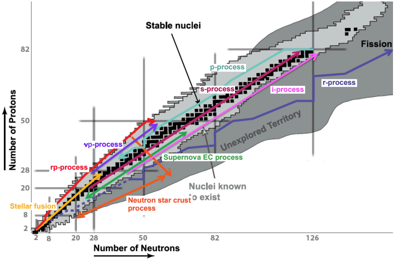
$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = 8\pi G_N T_{\mu\nu}(\epsilon, P(\epsilon)) \quad , \quad \nabla_\mu T^{\mu}{}_{\nu} = 0$$

$$T_{\mu\nu} = u_\mu u_\nu (\epsilon + P(\epsilon)) + g_{\mu\nu} P(\epsilon) + (\text{~~interesting~~})$$

later

Solve QCD using a neutron star?





- Laboratory experiments challenging, especially at high density
- Recent and future progress (LHC, RHIC, FAIR, NICA, . . .)
- Incoming experimental data from neutron star measurements! (LIGO/Virgo/Kagra, NICER, . . .)

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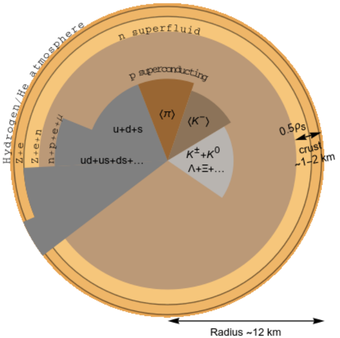

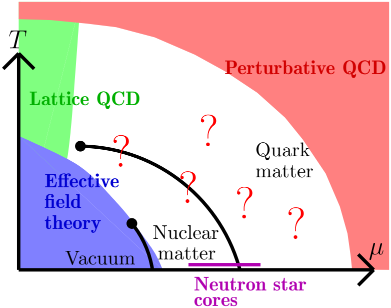

Theoretical results for the phase diagram

- 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

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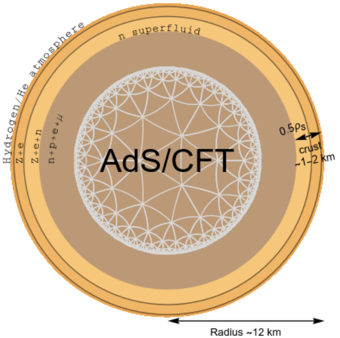

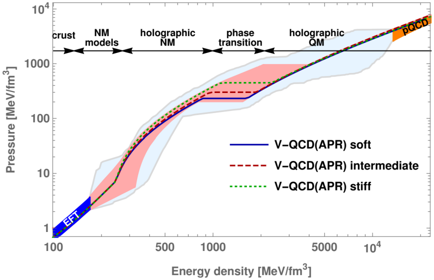

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- Approach from strong coupling: AdS/CFT

[reviews: Järvinen 2110.08281, Hoyos–NJ–Vuorinen 2112.08422]

Generic holographic approach: fitting strategies

Basic idea: extrapolate lattice data to higher density using holography

Two main strategies:

Strategy I: Include confined phase, with $S_{\text{on-shell}} = \mathcal{O}(N_c^0)$, and the transition to a deconfined phase, with $S_{\text{on-shell}} = \mathcal{O}(N_c^2)$

- Used in Improved Holographic QCD and V-QCD models [Gürsoy–Kiritsis 0707.1324; Gürsoy–Kiritsis–Nitti 0707.1349; Järvinen–Kiritsis 1112.1261]
- Fit lattice data above $T = T_c$ [Gürsoy–Kiritsis–Mazzanti–Nitti 0903.2859; NJ–Järvinen–Remes 1809.07770]
- Faithful to the behavior in the limit of large N_c

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Strategy II: Only deconfined black holes: no phase transition at low density

- Fit lattice data at all temperatures [Gubser–Nellore–Pufu–Rocha 0804.1950; Gubser–Nellore 0804.0434; DeWolfe–Gubser–Rosen 1012.1864; . . . ; NJ–Järvinen–Piispa 2405.02394]
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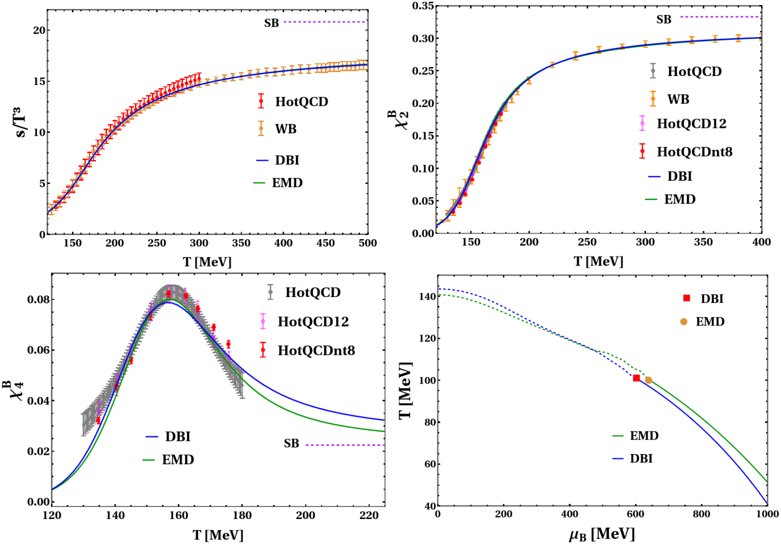
(Strategy 0: D3-D7 QFT soluble using string/gravity.)

Strategies 0&I have been extended in NS context.

Fitting example: Strategy II

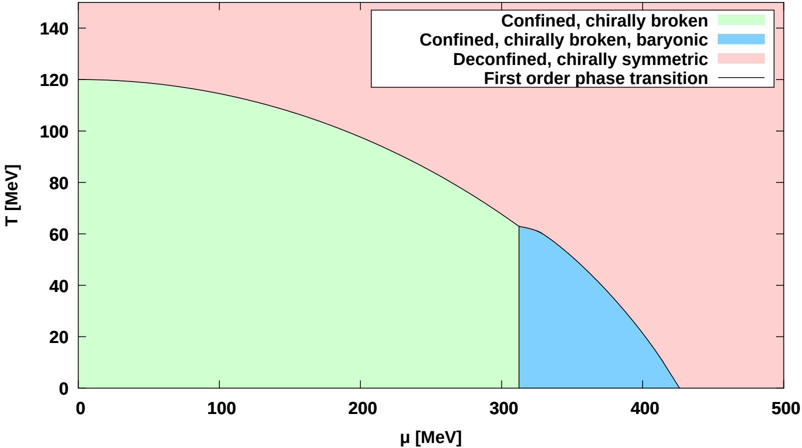
- No phase transition, predict a critical point at nonzero μ



- Predictions consistent with heavy-ion collision data at RHIC

Follow Strategy I

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



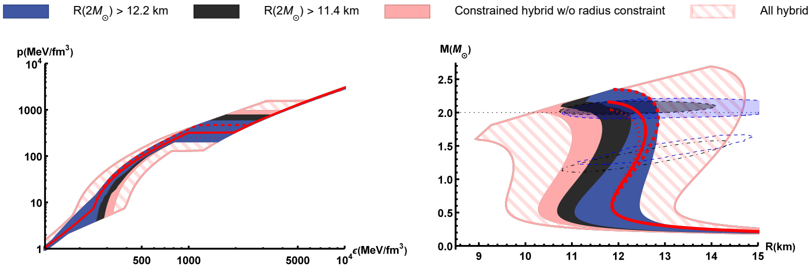
[Ishii–Järvinen–Nijs 1903.06169]

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]

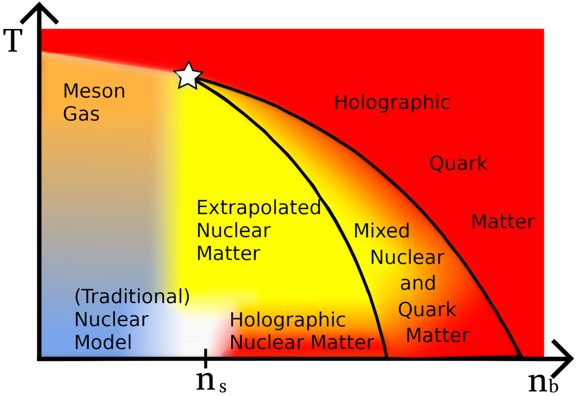


[NJ–Järvinen–Remes 2111.12101]

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

Holographically aided QCD phase diagram

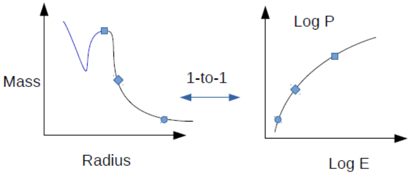
- Given EoS can be extended to finite-T
- Refined phase diagram, CompOSE: $3\times$ 3d DEJ(DD2-VQCD)
  [Demircik–Ecker–Järvinen 2112.12157]



- EoS has been used in NS merger simulations
  [see Christian Ecker's talk]
- Systematic extension to finite-T: posterior distributions
  [work in progress w/ Ecker&Järvinen]

Does deconfined QM exist in nature?

- Equation of state determines most important properties of stars,



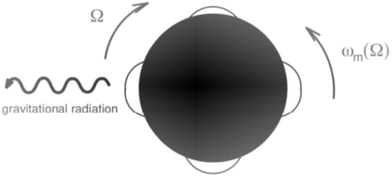
  but is insufficient (masquerading) to address if $\exists$ quark matter.
- No symmetry arguments: quark-hadron continuity
- Sharp deconfinement (Occam's razor) phase transition <u>may</u> lead to distinct signals
- Caveats: surface tension$\neq 0, \infty$ really, inhomogeneity, anisotropy
- Need to go beyond EoS: root for transport
  - quarks are relativistic unlike hadrons

r-mode instability window

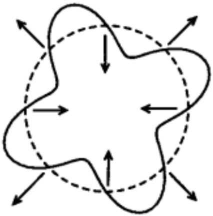
- Non-radial modes are driven unstable if the star rotates fast enough.
- These modes are strongly sheared and damped.
- ∄full GR study, estimate: [Andersson–Kokkotas gr-qc/0010102]

$$\frac{dE}{dt} = -2\frac{E}{\tau}$$

$$\propto \exp\left(i\omega_m(\Omega)t + im\phi - t/\tau_m(\Omega)\right)$$



[Figure:Bratton et al.'22]



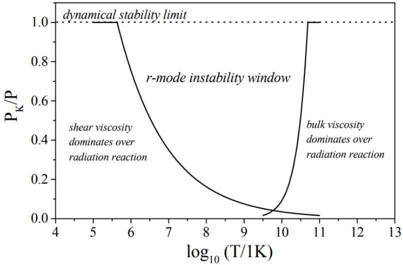
[Figure: Lindblom'98]

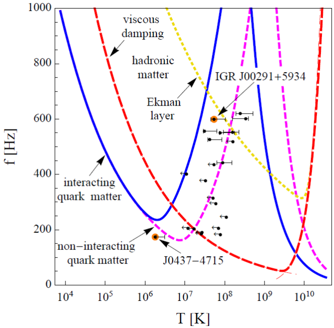
- Maximum stable frequency for the star:

$$0 = 1/\tau_m(\Omega) = -1/\tau_{\mathrm{GW}} + 1/\tau_\eta + 1/\tau_\zeta$$

r-mode instability window

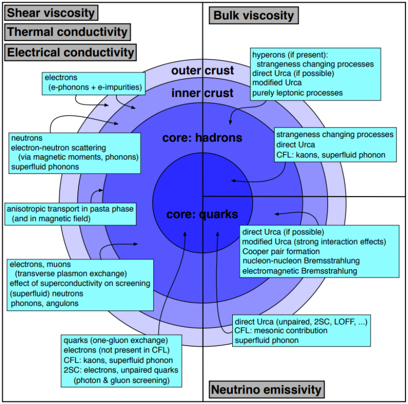
- Indirect evidence for quark matter?
  [Figures: Andersson–Kokkotas gr-qc/0010102,Alford–Schwenzer 1310.3524]





- Bulk viscocity ζ seems interesting

Relevance of transport in stars



[Schmitt–Shternin 1711.06520]

- Damping of oscillations: shear η and bulk ζ viscosities
- Cooling: thermal conductivity κ, neutrino emissivities
- Magnetic fields: electric σ and thermal conductivities
- Mergers: viscosities, conductivities, evolution far from equilibrium

Caution. . .

- Computing conductivities need care since spatial homogeneity
  - Lorentz invariance: only one hydro transport coeff σ
  - No force condition:

[Davison–Goutéraux 1505.05092; Davison–Goutéraux–Hartnoll 1507.07137]

$$E_i = \underbrace{\frac{s}{\rho}}_{Seebeck\ \ coeff} \nabla_i T$$

  - Conductivities

$$J^i = \sigma^{ij} E_j \quad , \quad \sigma^{ij} = \sigma \frac{\epsilon + p}{Ts} \delta^{ij}$$

$$Q^i = -\kappa^{ij} \nabla_j T \quad , \quad \kappa^{ij} = \frac{\mu}{T} \sigma \frac{\epsilon + p}{\rho} \delta^{ij}$$

- Quiescent stars
  - Local charge neutrality: $\frac{2}{3} n_u - \frac{1}{3} n_d - \frac{1}{3} n_s - n_e = 0$
  - Beta equilibrium: $\mu_s = \mu_d$, $\mu_u = \mu_d - \mu_e$

Holographic models encompassed

Action $S = S_{\text{glue}} + S_{\text{flavor}}$ w/ $\kappa_5^2 \sim 1/N_c^2, \mathcal{T}_b \sim N_f/N_c$:

$$S_{\text{glue}} = \frac{1}{2\kappa_5^2} \int d^5x \sqrt{-g} \left(R - \frac{1}{2}\partial_\mu \phi \partial^\mu \phi - V(\phi, \chi) \right)$$

$$S_{\text{flavor}} = -\frac{\mathcal{T}_b}{2\kappa_5^2} \int d^5x Z(\phi, \chi) \sqrt{-\det(g_{\mu\nu} + \kappa(\phi, \chi)\partial_\mu \chi \partial_\nu \chi + w(\phi, \chi) F_{\mu\nu})}$$

- metric $g_{\mu\nu}$ $\leftrightarrow$ energy-momentum tensor
- flavor gauge field A_μ $\leftrightarrow$ baryon charge
- "dilaton" ϕ $\leftrightarrow$ gauge coupling
- "tachyon" χ $\leftrightarrow$ quark masses

Our examples include:

- bottom-up V-QCD model (Strategy I)
- top-down D3-D7 model in the quenched approximation (Strategy 0)
- can be applied to Strategy II: predictions in Beam Energy Scan regime @RHIC

[see eg. Grefa et al. 2312.11449]

Transport for flavor independent masses

- DC transport determined at the black hole horizon
[Hoyos–NJ–Järvinen–Subils–Tarrio–Vuorinen 2005.14205,2109.12122]

$$T(\text{surface gravity}) \ , \ \ s(\text{area}) \ , \ \ \rho(\text{electric flux})$$
$$\phi_H = \phi(r_H) \ , \ \ \chi_H = \chi(r_H)$$

- Boundary values determine thermo: ϵ, p, μ
- Thermal and electric conductivities

$$\sigma = \frac{w_H}{2\kappa_5^2 g_{xx}^H}\sqrt{(2\kappa_5^2\rho)^2 + (g_{xx}^H)^3 \mathcal{T}_b^2 w_H^2 Z_H^2}$$

- Shear viscosity

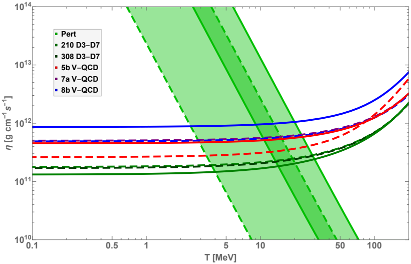
$$\eta = \frac{s}{4\pi} = \frac{(g_{xx}^H)^{3/2}}{2\kappa_5^2} + \frac{s_{\text{flavor}}}{4\pi}$$

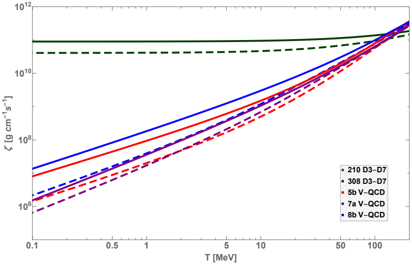
- Bulk viscosity (QCD part)

$$\frac{\zeta}{\eta} = (s\partial_s\phi_H + \rho\partial_\rho\phi_H)^2 + \frac{2\kappa_5^2}{(g_{xx}^H)^{1/2}}\frac{\kappa_H}{w_H^2}(s\partial_s\chi_H + \rho\partial_\rho\chi_H)^2$$

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 pQCD LO results

[Heiselberg–Pethick 1993]

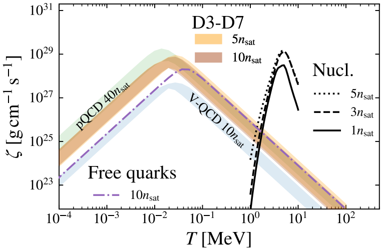
- Tiny results due "idealized" case. Flavor-independent masses so get only QCD contributions, no weak interactions or electrons
- CompOSE: $3\times$ 3d HJJSTV(VQCD) includes transport for QM

Flavor dependence

- Bulk viscosity can be enhanced by resonant EW processes
  [Alford–Mahmoodifar–Schwenzer '12]

$$u + d \leftrightarrow u + s \quad , \quad \frac{dn_d}{dt} = -\frac{dn_s}{dt} \approx \lambda_1(\mu_s - \mu_d)$$

- Relevant for flavor-dependent quark masses
  [CruzRojas–Gorda–Hoyos–NJ–Järvinen–Kurkela–Paatelainen–Säppi–Vuorinen 2402.00621]



$$\zeta = \frac{\lambda_1 A_1(\chi_{ij})^2}{\omega^2 + (\lambda_1 C_1(\chi_{ij}))^2}\Bigg|^{\text{D3-D7}}_{T=0} = \frac{4\lambda_1\mu_d^6\left(M_s^2 - M_d^2\right)^2}{\omega^2\left(M_d^2 - 3\mu_d^2\right)^2\left(M_s^2 - 3\mu_d^2\right)^2 + \pi^4\lambda_1^2\left(-6\mu_d^2 + M_d^2 + M_s^2\right)^2}$$

$$\lambda_1 = \frac{64\,G_F^2\sin^2\theta_c\cos^2\theta_c}{5\pi^3}\mu_d^5 T^2 + \dots \quad , \quad \forall\ A_1(T) \approx A_1\ ,\ C_1(T) \approx C_1$$

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

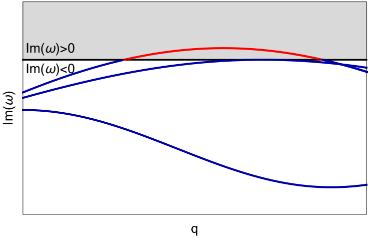
Outlook

- Observable effects in neutron star physics?
- Possible extensions:
    - flavor dependent masses
    - isospin/other chemical potentials
    - neutrino emissivity in NS regime [build on Järvinen–Kiritsis–Nitti–Préau 2306.00192]
    - magnetic field
    - anisotropic equation of state
    - quark pairing (color "superconductivity")
    - inhomogeneous phases
- Recall caveats:
    - homogeneity seems lost [CruzRojas–Demircik–Järvinen 2405.02399; Demircik–NJ–Järvinen–Piispa 2405.02392]
    - surface tension between deconfined and confined phases: accurate lattice results coming up

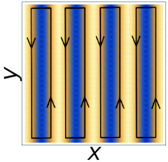
Thank you!

Spatially modulated phases

[Nakamura, Ooguri, Park 0911.0679; Ooguri, Park 1011.4144]



- Exponentially growing perturbation at $q \neq 0$: a quasi-normal mode with $\mathrm{Im}\,\omega > 0$
- Chern-Simons term can drive a modulated instability at finite density
- Such CS terms automatically included in the holographic model $\leftrightarrow$ QCD chiral anomaly
- Modulated 5D gauge fields dual to modulated persistent chiral currents in field theory

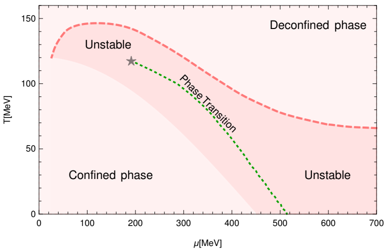


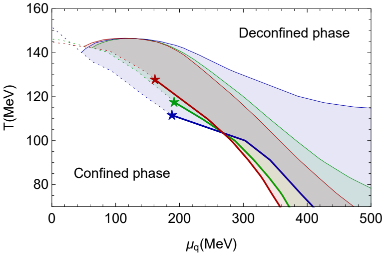
Schematic fluctuation equation

$$\psi''(r) + \left(A' + \frac{f'}{f}\right)\psi'(r) + \underbrace{\frac{qn}{M_p^3 f e^{2A} w(\phi)^2}\psi(r)}_{\text{From CS term}} + \left(\frac{\omega^2}{f^2} - \frac{q^2}{f}\right)\psi(r) = 0$$

$\psi = \delta A^x_{L/R} \pm i\delta A^y_{L/R}$ $\qquad r =$ holographic coord.

The region where instability exists
[CruzRojas–Demircik–Järvinen 2405.02399; Demircik–NJ–Järvinen–Piispa 2405.02392]

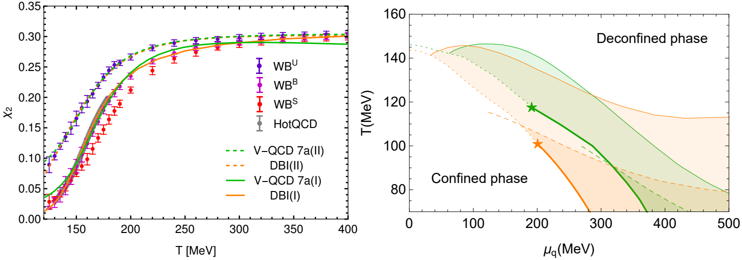




- Instability is found at low T and large density – region relevant for neutron stars (expected)
- Instability is also found at higher T, near the regime with critical point?! (a big surprise)

Model dependence: strange quark mass

- Model dependence is really mild: [Demircik–NJ–Järvinen–Piispa 2405.02392]
  - varied model parameters ↔ freedom in fitting to lattice data
  - varied fitting using Strategy I ↔ Strategy II
  - varied the flavor action DBI ↔ Yang–Mills truncation
- All holographic massless QM models fitted to lattice data has instability at high-T
- Flavor dependence in susceptibilities, visible in lattice data? [Borsanyi et al. 1112.4416]
- Naive test: fit instead of the full χ_2 the light quark χ_2 (dashed curves) of the $N_f = 2 + 1$ lattice result



- Strong suppression of the instability!