Towards an improved holographic equation of state for hot and dense QCD

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Outline

1. Holographic equation of state in V-QCD: starting point
2. Quark flavors and masses
   [MJ, Mitra 2507.08087]
3. Modeling color superconductivity
   [Cruz Rojas, Demircik, Ecker, MJ 2505.06338]
4. Isospin asymmetric nuclear matter
   [Bartolini, Gudnason, MJ 2504.01758]
5. Conclusion

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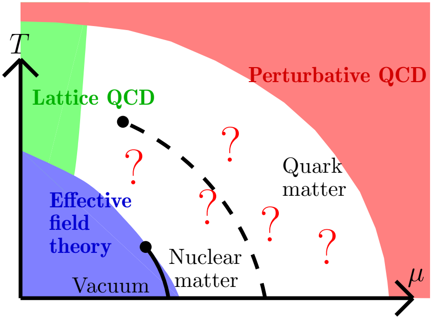
QCD phase diagram: theory status

- Lattice data only available at zero/small chemical potentials
- Effective field theory works at small densities
- Perturbative QCD: only at high densities and temperatures
- At intermediate densities no first-principles methods available – lots of open questions



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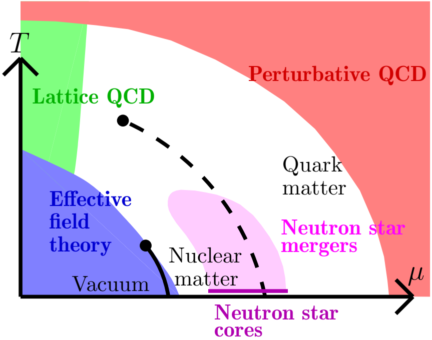

- This region is highly relevant for neutron star physics!
- Improving theoretical predictions important!
- Strongly coupled physics – use the gauge/gravity duality?

Why use holography for dense matter?

Already various models available in the literature – perhaps the gauge/gravity duality is just another uncontrolled approximation?

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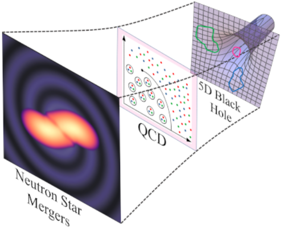
There is however strong motivation for this approach:

- Strongly coupled physics: holography may work better than many other approaches
- Different phases (quark, nuclear, color superconducting, quarkyonic . . .) in the same footing or even in a single model
  - Typically not achieved in the literature
  - Gives rise to predictions for phase transitions
- As it turns out, predictions do make sense!
  - Highly nontrivial – as the precise holographic dual for QCD is not known, these model cannot be derived
  - In particular, many details work out of the box at finite density

The starting point: our earlier EOS

A state-of-the-art EOS, to be used

1. to describe (isolated) neutron stars
2. in simulations of neutron star mergers
3. in simulations of core collapse supernovae
4. when analyzing heavy-ion collisions (?)



[Based on Demircik, Ecker, MJ 2112.12157 (PRX) + earlier work]

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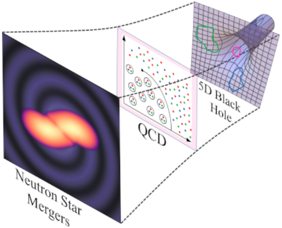

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- Some parts could also be covered using simpler models (e.g. quark matter using Einstein-Maxwell-dilaton)

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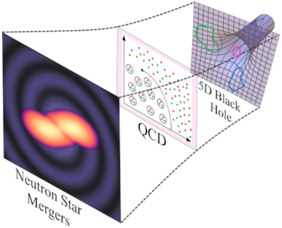

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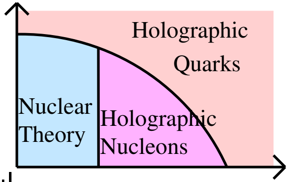
Main ingredients are

1. Holographic model for quark matter
2. (Slightly adjusted) holographic model for nuclear matter
3. Nuclear theory model for hadronic phase – at low density holography not very useful



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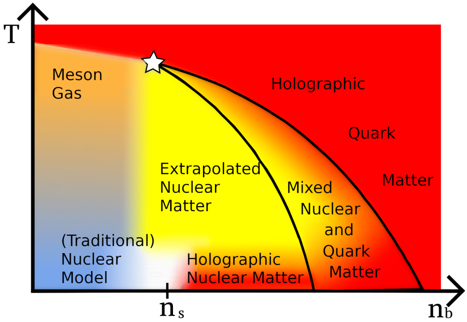
Combining the building blocks: the hybrid model



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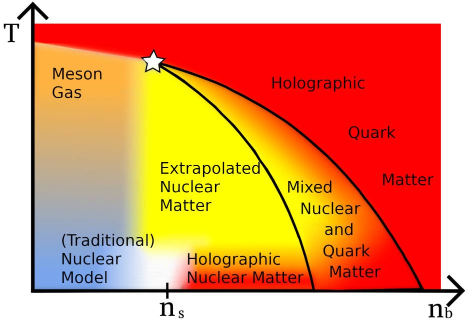

Covers regions relevant for neutron stars and heavy-ion collisions!

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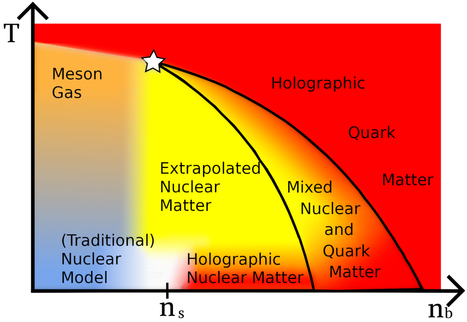

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- One of the most ambitious attempts to describe the QCD EOS to date
- Consistent with theoretical and observational constraints

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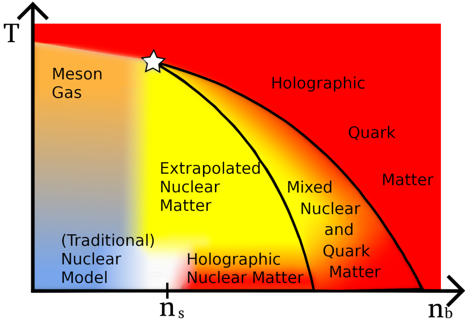

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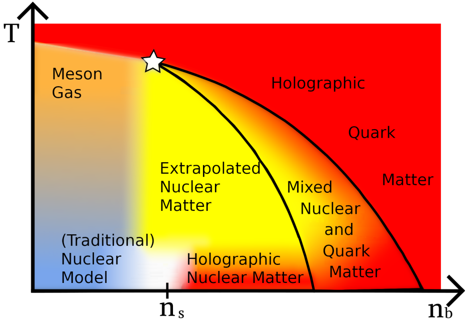

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- Three variants (soft, intermediate, stiff) — different fits of the holographic model to lattice data — published in the CompOSE database of EOSs [http://compose.obspm.fr]
- Probabilistic approach using these EOSs: see Christian's talk

Shortcomings of the current EOSs

However our model has some obvious shortcomings:

I. Deviation from β-equilibrated or isospin symmetric matter not implemented through holography
   - Neutron star merger EOSs depend on temperature T, baryon number density n_b, and charge fraction Y_q
   - Y_q dependence not coming from holography so far in any phase

II. No dependence on quark masses
   - So far matching $N_f = 2 + 1$ data with a massless model

III. No model for "exotic" color superconducting or color-flavor locked phases

IV. Holographic nuclear matter model overly simple (homogeneous field instead of instantons)

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This talk: developments towards fixing these problems

1. Quark flavor dependence in V-QCD (issues I and II)
2. Simple model for color superconductor (issue III)
3. Simple model for isospin asymmetric nuclear matter (issue I)

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V-QCD model

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

- Bottom-up, but trying to follow principles from string theory as closely as possible
- Many parameters: effective description of QCD
- Comparison with QCD data essential

The model is obtained through a fusion of two building blocks:
[MJ, Kiritsis arXiv:1112.1261]

1. IHQCD: model for glue inspired by string theory (dilaton gravity)
[Gürsoy, Kiritsis, Nitti; Gubser, Nellore]
2. Adding flavor and chiral symmetry breaking via tachyon brane actions
[Bigazzi,Casero,Cotrone,Iatrakis,Kiritsis,Paredes]

Full backreaction between the two sectors in the Veneziano limit!

Quark flavors in V-QCD

- Goal: construct a model for $N_f = 2 + 1$
- The tachyonic brane action readily implements N_f flavors and full chiral symmetry
- Optimally, one would just take the "old" model and turn on quark masses or chemical potentials for each flavor
- We actually tried this in order to analyze the bulk viscosity [Cruz Rojas, Gorda, Hoyos, Jokela, MJ, Kurkela, Paatelainen, Säppi, Vuorinen 2402.00621 (PRL)]
- However, the details of the flavor dependence turn out to be in conflict with lattice data $\Rightarrow$ model needs adjusting [MJ, Mitra 2507.08087]

Quark flavors in V-QCD

Dictionary (with $i, j = 1, \dots N_f$; only vectorial gauge fields)

- Dilaton $\lambda \leftrightarrow \mathrm{tr}\, G^2$
- Tachyon $T_{ij} \leftrightarrow \bar{q}_i q_j$
- Gauge fields $A_{ij}^{\mu} \leftrightarrow \bar{q}_i \gamma^{\mu} q_j$

- source = 't Hooft coupling
- sources = quark masses
- sources = chemical potentials

$$\mathcal{S}_{\mathrm{V-QCD}} = S_{\mathrm{IHQCD}} + S_{\mathrm{DBI}}$$

$$= N_c^2 M^3 \int d^5x \sqrt{-g} \left[R - \frac{4}{3} \frac{(\partial\lambda)^2}{\lambda^2} + V_g(\lambda) \right]$$

$$-N_c M^3 \int d^5x \, \mathrm{Tr} \Big[V_f(\lambda, T) \sqrt{-\det(g_{ab} + \kappa(\lambda) \partial_a T \partial_b T^\dagger + w(\lambda, T) F_{ab})} \Big]$$

Trace over flavor indices

Plug in diagonal Ansatz in flavors $T_{ij} = \tau_i(r)\delta_{ij}$, $A_{ij} = A^{(i)}(r)\delta_{ij}$:

$$S_{\mathrm{DBI}} \propto \sum_{i=1}^{N_f} \int d^5x \, V_f(\lambda, \tau_i) \sqrt{-\det\left(g_{ab} + \kappa(\lambda)\delta_a^r \delta_b^r (\tau_i')^2 + w(\lambda, \tau_i) F_{ab}^{(i)}\right)}$$

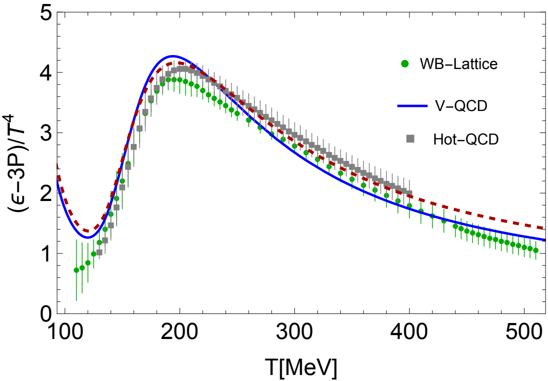
- Take $N_f = 2 + 1$; two massless and one massive quark
- Functions V_g, V_f, κ and w determined by comparing to QCD

Adjusting the potentials

Asymptotics unchanged wrt. the unflavored case

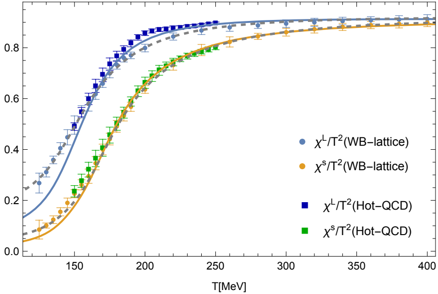
- Require confinement, discrete spectrum, linear meson trajectories ...
- Working potentials turn out to have power law asymptotics
- E.g. $V_g \sim \lambda^{4/3}$, $w \sim \lambda^{-4/3}$

Rest fitted to lattice data sequentially, e.g. V_f to EOS at $\mu = 0$



Fitting the susceptibilities

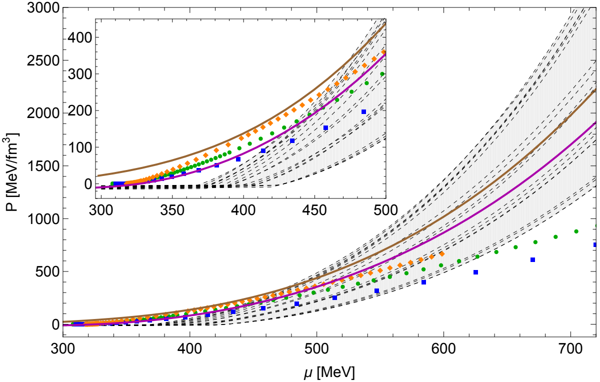
Fitting susceptibilities $\chi_{ij} = \frac{\partial^2 p}{\partial\mu_i \partial\mu_j}$ more tricky — constrains gauge field coupling function $w(\lambda, \tau_i)$



[WB 1112.4416]
[hotQCD 1203.0784]

- Lattice results for light/strange quarks significantly different
- Strange quark mass sources tachyons — tachyon dependence of potentials modifies χ's
- Tachyon dependence in $V_f(\lambda, \tau_i)$ way too weak to reproduce the effect $\Rightarrow$ strong tachyon dependence in $w(\lambda, \tau_i)$ required
- N.B. We fit only diagonal χ_{ij} and NOT χ_B: nondiagonal components vanish in our model

Implications for neutron star EOS



Comparison of

1. Our models (solid curves)
2. Nuclear theory models (colored dots)
3. Old unflavored V-QCD EOSs

[Jokela, MJ, Remes 1809.07770]

- New EOSs match more smoothly with nuclear theory than old
- May lead to stable quark cores inside neutron stars!

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Paired phases in QCD

Model computations, and analysis at large μ, indicate that at low T deconfined quarks become paired

- Color–flavor locking (CFL)
  - Known to be present at asymptotically high μ
  - $SU(3)_c \times SU(3)_L \times SU(3)_R \times U(1)_B \to SU(3)_{c+L+R}$
- Two-flavor color superconductivity (2SC)

Symmetry breaking patterns involve the gauge group — tricky in holography, where observables are gauge singlets . . .

Despite this, many studies already exist (see also talk by Edwan Préau) . . . we did the first attempt in V-QCD

Simple model for paired phases in V-QCD

We model the quark condensate through an additional charged scalar field ψ

$$S_\psi = -M^3 N_c N_f \int d^5x \, \sqrt{-\det g} \, Z(\lambda) \left[|D_M\psi|^2 + M(\lambda)^2 \, |\psi|^2 \right]$$

$$D_M\psi = \partial_M\psi - i\hat{A}_M\psi \ , \qquad \hat{A}_M = Tr[A_M]/N_f$$

- Trivial (massless) flavors so far
- Unit charge: allows generalization to a matrix field
- Allow for dilaton dependent potential functions Z, M
- Here restrict to probe field ψ: no backreaction to metric
- Similar to "holographic superconductor"

[Cruz Rojas, Demircik, Ecker, MJ 2505.06338]

The holographic mechanism

Mechanism leading to instabilities at low T

- Deconfined quark matter phase $\leftrightarrow$ black hole geometry
- As $T \to 0$, black hole (nearly) extremal: IR geometry $\sim \mathrm{AdS}_2 \times \mathbb{R}^3$
- This geometry easily leads to instabilities due to its low Breitenlohner-Freedman (BF) bound for fluctuations
  - Violation at zero momentum: instability towards a homogeneous condensate
  - Violation at nonzero momentum: instability towards an inhomogeneous condensate
- Both kind of instabilities possible in V-QCD
  - The charge scalar ψ may condense homogeneously (focus in this talk)
  - Gauge fields may condense inhomogeneously: Nakamura–Ooguri–Park instability driven by the Chern–Simons term

[Cruz Rojas, Demircik, MJ 2405.02399; Demircik, Jokela, MJ, Piispa 2405.02392]

- $\mathrm{AdS}_2 \times \mathbb{R}^3$ geometry implies nonzero entropy at zero T
  - Condensing charged ψ expected to absorp the charge supporting the AdS_2, leading to zero entropy at zero T

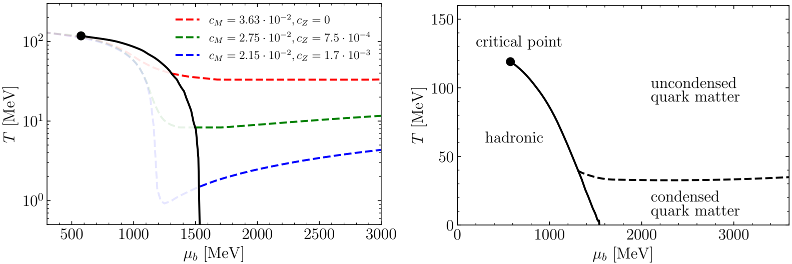
Choice of potentials and extent of instability

$$\mathcal{L}_\psi \propto Z(\lambda)\left[\left|D_M\psi\right|^2 + M(\lambda)^2\left|\psi\right|^2\right]$$

How to choose the potentials M and Z in the Lagrangian?

- Earlier observation: working potentials obey asymptotics such that they become flat in the string frame, $g_s = \lambda^{4/3} g$
- Require the same as $\lambda \to \infty$:

$$Z(\lambda) = 1 + c_Z\lambda^2\,, \qquad M(\lambda) = -3(1 + c_M\lambda^{4/3})$$

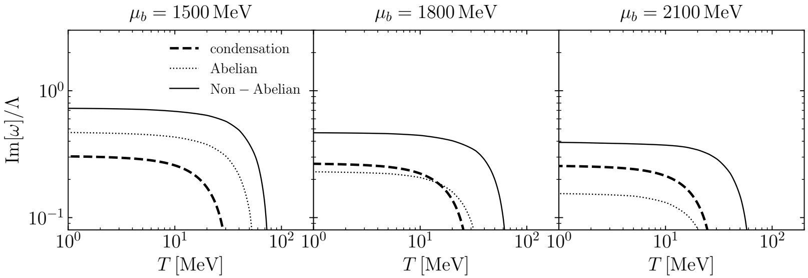


- Vary other parameters such that no instability in deconfined region at $\mu = 0 \Rightarrow$ maximal phenomenologically viable effect
- N.B. constant M does not "work": essentially no instability

Competition with modulated instability

Compare the (maximal) frequency of the unstable mode to the frequency of the modulated Nakamura–Ooguri–Park instability

- Both singlet (Abelian) and non-singlet (non-Abelian) gauge fields unstable



The color superconducting instability (thick dashed)

- appears only at lower temperature
- is “weaker” than the modulated instability

But the final ground state could include both effects . . . merits further study

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Model for nuclear matter

Standard method for baryons in holographic models: Each baryon maps to a solitonic 5D "instanton" of gauge fields

- Such instantons have been studied in many models, including V-QCD
[MJ, Kiritsis, Nitti, Préau 2209.05868; 2212.06747]
- Already constructing an isolated instanton solution is nontrivial
- Dense nuclear matter requires studying many-instanton solutions ... extremely challenging!

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- Already constructing an isolated instanton solution is nontrivial
- Dense nuclear matter requires studying many-instanton solutions . . . extremely challenging!
- Simple approach: V-QCD with two flavors and a homogeneous gauge field, mimicking dense solitons: $A^i = h(r)\sigma^i$
  [Rozali, Shieh, Van Raamsdonk, Wu 0708.1322; Li, Schmitt, Wang 1505.04886]
  [Ishii, MJ, Nijs, 1903.06169]
  - Note: spatial and flavor indices linked
- This is what we used so far . . . however by construction isospin symmetric: no distinction between protons and neutrons

Going away from symmetric case

Introduce asymmetric gauge field and isospin chemical potential

$$A_t(r) = \widehat{a}_0(r)\mathbb{1} + a_0(r)\sigma^3 \ , \qquad a_0(0) = \mu_I$$

- Here r is the holographic coordinate, bdry at $r = 0$

Then consistency requires a more general Ansatz

$$A_i = H(r)\sigma^i, \qquad (i = 1, 2)$$
$$A_3 = H_3(r)\sigma^3 + L_3(r)\mathbb{1}$$

[Kovensky, Schmitt 2105.03218; Bartolini, Gudnason 2209.14309; Kovensky, Poole, Schmitt 2302.10675]

- A discontinuity at some $r = r_c$ required for nonzero n_b
- Beyond the discontinuity, $r > r_c$, gauge fields vanish
- Solution found by minimizing the action, both wrt functions and r_c

See also talk by Andreas Schmitt

Model parameters and the Chern–Simons term

We follow the approach from isospin symmetric construction

[Ishii, MJ, Nijs, 1903.06169; Demircik, Ecker, MJ 2112.12157]

- Match with a nuclear theory model at $\sim 1.5 n_s \Rightarrow$ determine remaining model parameters
- These include the parameters from the Chern–Simons action, in our case (including L/R components) [MJ, Kiritsis, Nitti, Préau]

$$S_{\rm TCS} \sim i N_c \int F_1(\tau)\,\mathrm{tr}\left[A \wedge A \wedge A \wedge \left(F^{(L)} + F^{(R)}\right)\right] - i F_3(\tau)\,\mathrm{tr}\left[A \wedge \left(F^{(L)} - F^{(R)}\right) \wedge \left(F^{(L)} - F^{(R)}\right)\right]$$

with $A = A^{(L)} - A^{(R)}$ and taking

$$F_1(\tau) = e^{-b_1 \tau^2}\ , \qquad F_3(\tau) = e^{-b_3 \tau^2}$$

- b_3 does not appear in iso-symmetric setup, we set it to $b_3 = 1$
- b_1 and normalization of the action c_f determined by matching with nuclear models

Symmetry energy

A key characteristic of EOS away from isospin symmetry: symmetry energy S_N

$$\frac{\mathcal{E}}{n_b} = \frac{\mathcal{E}}{n_b}\bigg|_{\delta=0} + S_N(n_b)\delta^2 + \cdots \qquad \delta = \frac{n_p - n_n}{n_p + n_n} = \frac{2n_I}{n_b}$$

Two ways to compute in holography:

- "Directly" by turning on small μ_I and analyzing the energy
- Computing the isospin density by quantizing the iso–rotation of the homogeneous nuclear matter in analogy to what one does with instanton solutions

Both give the same answer

[Bartolini, Gudnason 2209.14309]

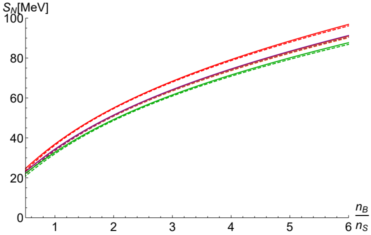
Computation done in the literature for WSS and hard-wall models, giving too large $S_N(n_b = n_s)$ as compared to experiments

Symmetry energy: results

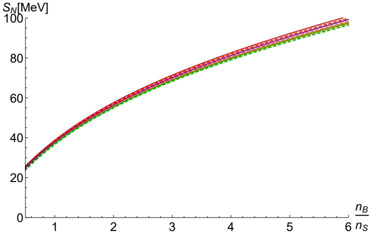
Our results for various nuclear models and matching points

- Value $\sim 30\,\text{MeV}$ at saturation, agreement with experiment!
- Comes at the expense of playing with parameters (we set $b_3 = 1$ and matched b_1)

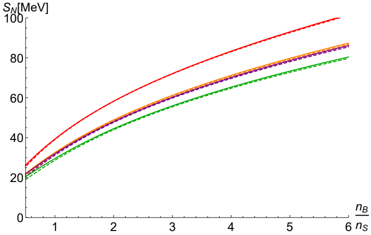
Matching at $1.5 n_s$



Matching at $1.2 n_s$



Matching at $1.8 n_s$



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Summary

1. We analyzed V-QCD with flavors, and strange quark mass
   - Obtained good agreement with lattice data, including different quark susceptibilities
   - Weaker phase transition in the neutron star regime than earlier, leading to stable quark cores?
2. Considered a simple model for color superconducting phase
   - Indentified the maximal extent of the phase
   - Compared to the inhomogeneous (Nakamura–Ooguri–Park) instability
3. Studied isospin asymmetric nuclear matter
   - Symmetry energy in agreement with experimental results

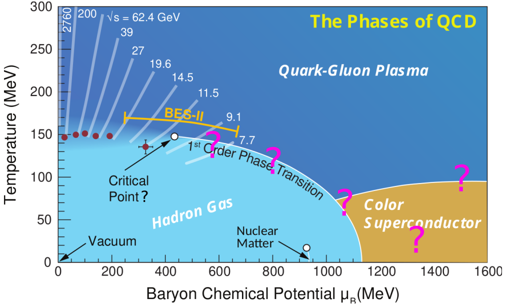
(Some) future directions

- Further analysis of the effect of strange quark mass
  - Map the EOS and the phases at all T and μ
  - What happens to the critical point??
  - Range of the modulated instability
  - Transport ... in particular bulk viscosity
- Backreacted color superconductivity, maybe with improved flavor structure
- Putting all improvements together to construct a new hybrid EOS
  - Use in merger simulations, e.g., effect of quark cores?

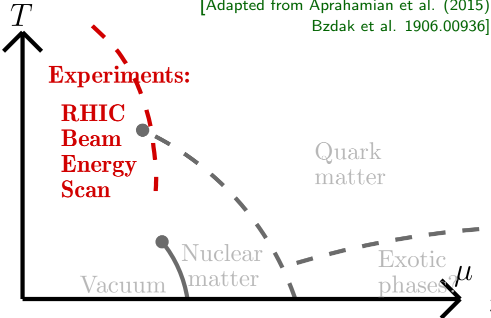
Thank you!

QCD phase diagram and the critical point

Search for the critical point: ongoing effort at RHIC (Beam Energy Scan)



[Adapted from Aprahamian et al. (2015) Bzdak et al. 1906.00936]



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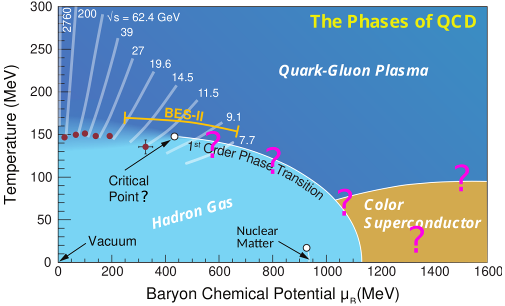
Search for the critical point: ongoing effort at RHIC (Beam Energy Scan)

Will be extended by future experiments at FAIR, J-PARC, NICA



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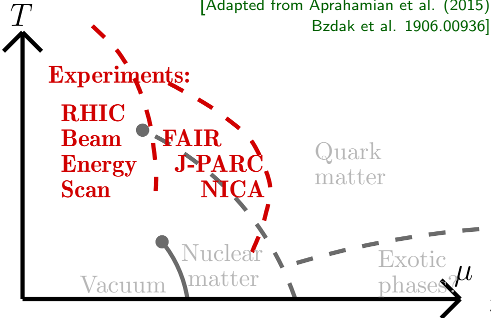
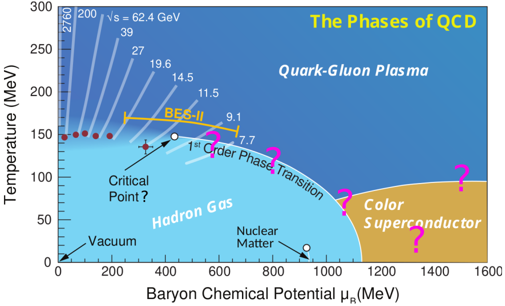


QCD phase diagram and the critical point

Search for the critical point: ongoing effort at RHIC (Beam Energy Scan)

Will be extended by future experiments at FAIR, J-PARC, NICA

Neutron star observations give complementary information at high density



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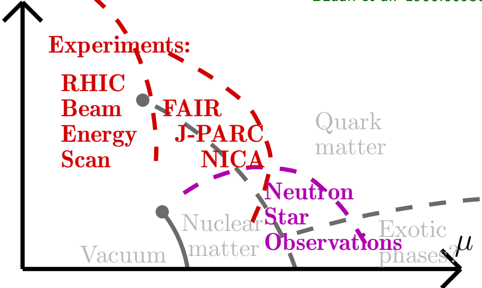


Homogeneous nuclear matter in V-QCD

Nuclear matter in the probe limit: consider full brane action $S = S_{\mathrm{DBI}} + S_{\mathrm{CS}}$ where

[Bigazzi, Casero, Cotrone, Kiritsis, Paredes; Casero, Kiritsis, Paredes]

$$S_{\mathrm{DBI}} = -\frac{1}{2}M^3 N_c \,\mathbb{T}r \int d^5x\, V_{f0}(\lambda) e^{-\tau^2} \left(\sqrt{-\det \mathbf{A}^{(L)}} + \sqrt{-\det \mathbf{A}^{(R)}}\right)$$
$$\mathbf{A}^{(L/R)}_{MN} = g_{MN} + \delta^r_M \delta^r_N \kappa(\lambda)\tau'(r)^2 + \delta^{rt}_{MN} w(\lambda)\Phi'(r) + w(\lambda) F^{(L/R)}_{MN}$$

gives the dynamics of the solitons (will be expanded in $F^{(L/R)}$) and

$$S_{\mathrm{CS}} = \frac{N_c}{8\pi^2}\int \Phi(r) e^{-b\tau^2} dt \wedge \left(F^{(L)} \wedge F^{(L)} - F^{(R)} \wedge F^{(R)} + \cdots\right)$$

sources the baryon number for the solitons

- Extra parameter, $b > 1$, to ensure regularity of solutions

Set $N_f = 2$ and consider the homogeneous SU(2) Ansatz

[Rozali, Shieh, Van Raamsdonk, Wu 0708.1322]

$$A^i_L = -A^i_R = h(r)\sigma^i$$

[Ishii, MJ, Nijs, 1903.06169]

Discontinuity and smeared instantons

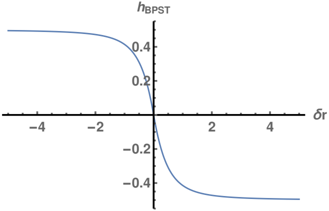
With the homogeneous Ansatz $A_i^a(r) = h(r)\delta_i^a$ baryon number vanishes for any smooth $h(r)$:

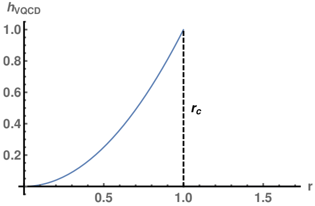
$$N_b \propto \int dr \frac{d}{dr}\left[\mathrm{CS}-\mathrm{term}\right] = 0$$

How can this issue be avoided?

- Smearing the BPST soliton in singular Landau gauge:

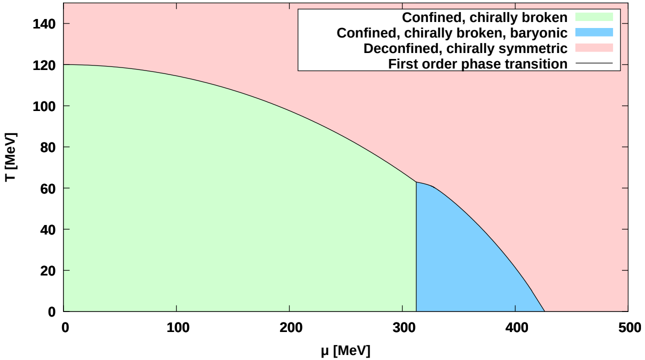
$$\langle A_i^a \rangle \sim \int \frac{d^3\mathbf{x}\ \ \eta^a_{i4}\ \delta r}{(\delta r^2 + \mathbf{x}^2 + \rho^2)(\delta r^2 + \mathbf{x}^2)} \sim -\frac{\delta_i^a\ \delta r}{\sqrt{\delta r^2 + \rho^2} + |\delta r|}$$





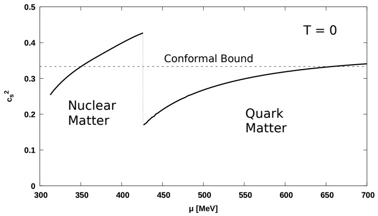
- This suggests a solution: introduce a discontinuity in $h(r)$ at $r = r_c$
- The discontinuity sources nonzero baryon charge!

Phase diagram after including nuclear matter



Stiff EOS (high c_s^2) in the nuclear matter phase ⇒ helps to pass the bounds from neutron star observations!

Such a stiff EOS also found in WSS and hard wall models
[Kovensky, Poole, Schmitt 2111.03374; Bartolini, Gudnason, Leutgeb, Rebhan 2202.12845]



Adjusting the nuclear matter model

The V-QCD nuclear matter EOS as such is however not fully satisfactory:

- Temperature dependence is absent in the confined phases, and therefore also for holographic nuclear matter
- This is likely to be a good first approximation, but not enough for a state-of-the-art model

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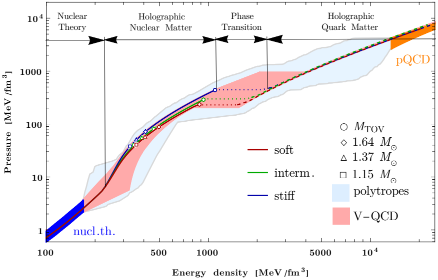
Our solution: we extrapolate the holographic nuclear matter EOS to nonzero T by a using a van der Waals approach

- Gas of protons, neutrons and electrons with an excluded volume correction and a potential term

[Demircik, Ecker, MJ 2112.12157]

Cold EoS and known constraints

- Three choices of EoSs: soft, intermediate, and stiff $\leftrightarrow$ the degrees of freedom of V-QCD left free by fit to lattice data
- Compared to bands of all feasible cold matter EoS: Without and with holography



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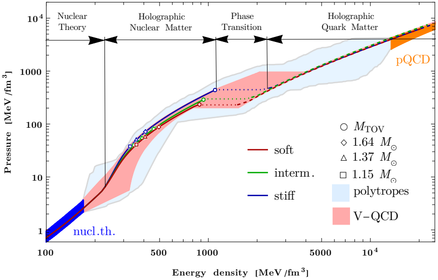

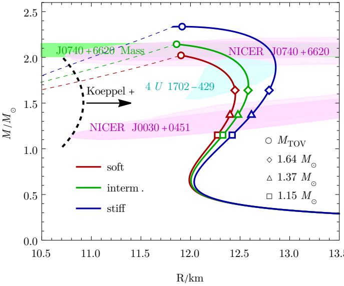

- Plug EoSs in TOV: neutron star $M(R)$ curves (left plot)
- Compares well with mass/radius observations
- No stable quark cores inside neutron stars

[Ecker, MJ, Nijs, van der Schee 1908.03213]
[Jokela, MJ, Nijs, Remes 2006:01141]
[Demircik, Ecker, MJ 2112.12157]

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The model has various nice features:

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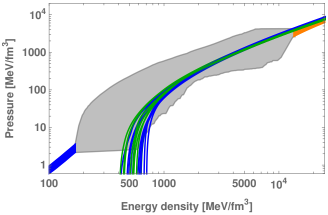

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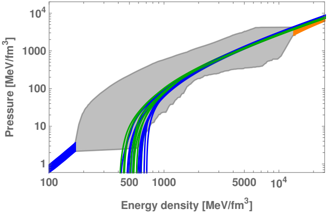

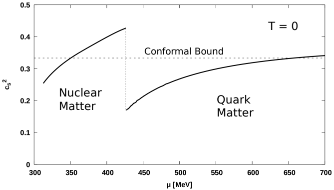

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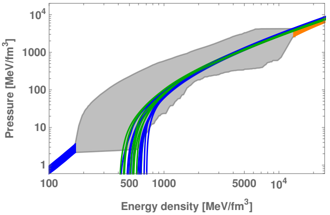
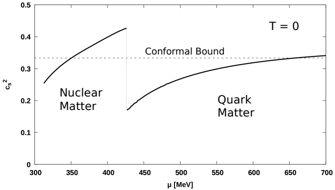
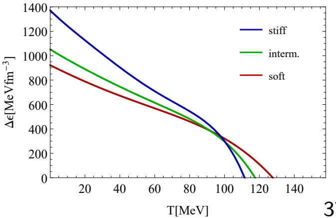
4. Simultaneous modeling of nuclear and quark matter phases
   - Predictions for the phase transition







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Close agreement with functional renormalization group (FRG)

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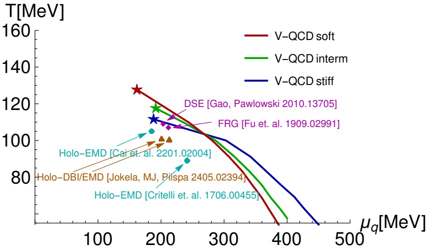

- Critical point

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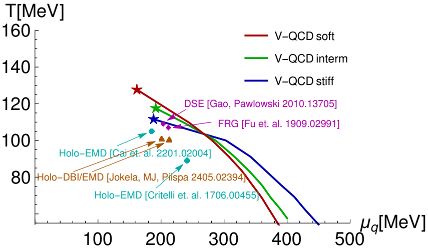

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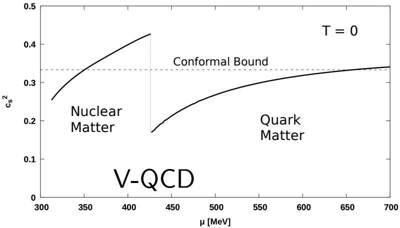
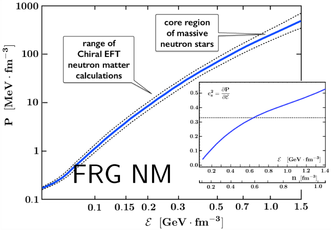
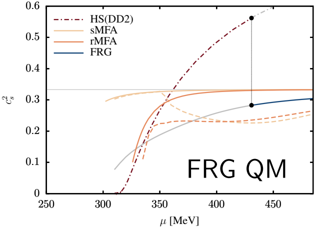


- Speed of sound at $T = 0$





[Drews, Weise 1610.07568; Otto, Oertel, Schaefer 1910.11929]

Ansatz for potentials

$$V_{\mathrm{g}}(\lambda) = 12\left[1 + V_{g,1}\lambda + \frac{V_{g,2}\lambda^2}{1+c_\lambda\lambda/\lambda_0} + V_{\mathrm{IR}}\, e^{-\lambda_0/(c_\lambda\lambda)}\left(\frac{c_\lambda\lambda}{\lambda_0}\right)^{4/3}\sqrt{\log(1+c_\lambda\lambda/\lambda_0)}\right]$$

$$V_{\mathrm{f}}(\lambda,\tau_i) = V_{\mathrm{f}\lambda}(\lambda)\left(1+\tau_i^4\right)^{\tau_p}\exp\left(-\tau_i^2\right)$$

$$V_{\mathrm{f}\lambda}(\lambda) = W_0 + W_1\lambda + \frac{W_2\lambda^2}{1+c_\lambda\lambda/\lambda_0} + W_{\mathrm{IR}}\, e^{-\lambda_0/(c_\lambda\lambda)}(c_\lambda\lambda/\lambda_0)^2$$

$$\kappa(\lambda) = \kappa_0\left[1 + \bar{\kappa}_0\left(1+\frac{\bar{\kappa}_1\lambda_0}{c_\lambda\lambda}\right)e^{-\lambda_0/(c_\lambda\lambda)}\frac{(c_\lambda\lambda/\lambda_0)^{4/3}}{\sqrt{\log(1+c_\lambda\lambda/\lambda_0)}}\right]^{-1}$$

$$w(\lambda,\tau) = \frac{w_0}{1+\beta_s\tanh(\gamma_s^2\tau_i^2)}\left[1 + \frac{w_1 c_\lambda\lambda/\lambda_0}{1+c_\lambda\lambda/\lambda_0} + \bar{w}_0 e^{-\lambda_0/(c_w\lambda)}\frac{(c_w\lambda/\lambda_0)^{4/3}}{\log(1+c_w\lambda/\lambda_0)}\right]^{-1}.$$