# Predictions for dense matter and neutron stars from the gauge/gravity duality

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POSTECH
POHANG UNIVERSITY OF SCIENCE AND TECHNOLOGY

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# Outline

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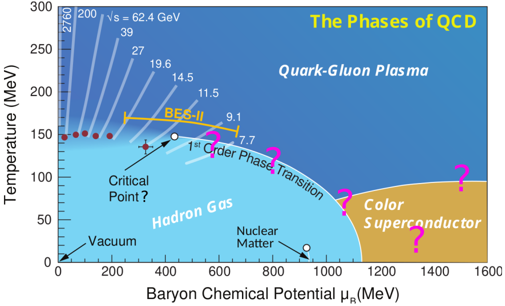
# QCD phase diagram and the critical point

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

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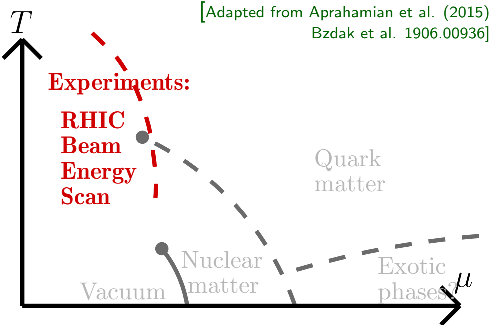

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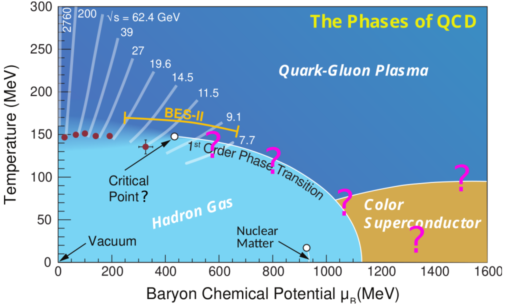


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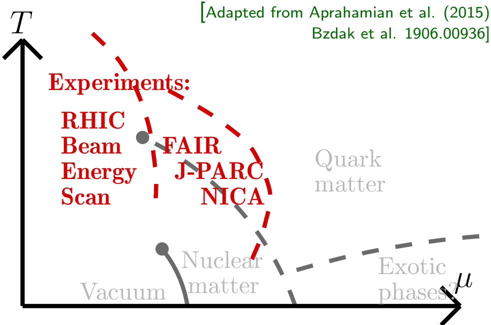

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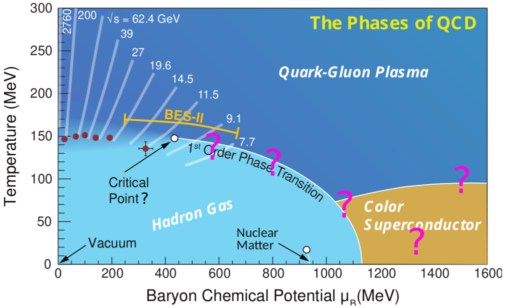
Neutron star observations give complementary information at high density

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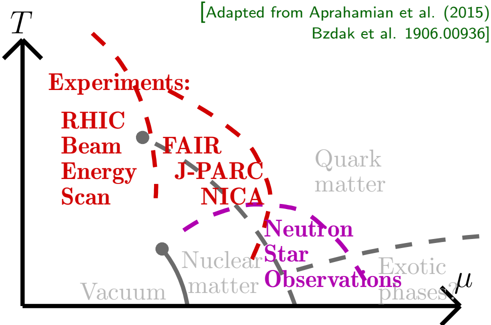

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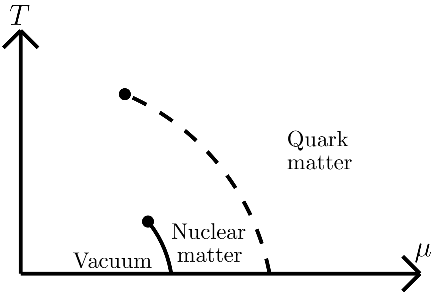

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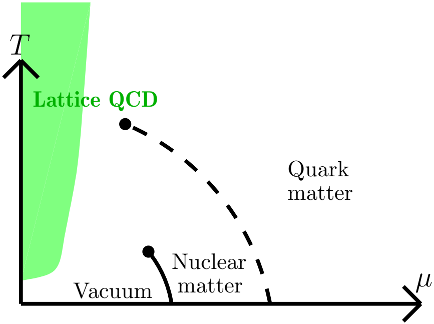

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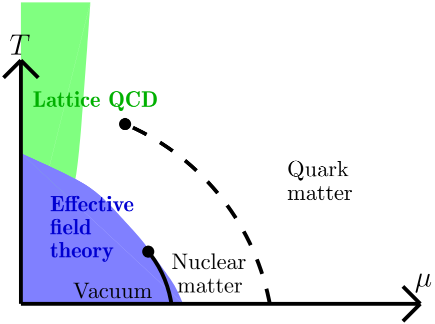

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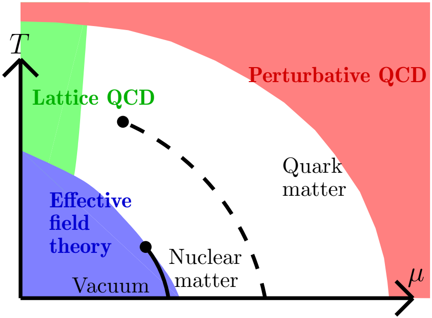

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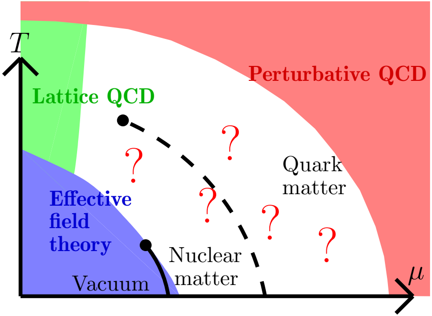

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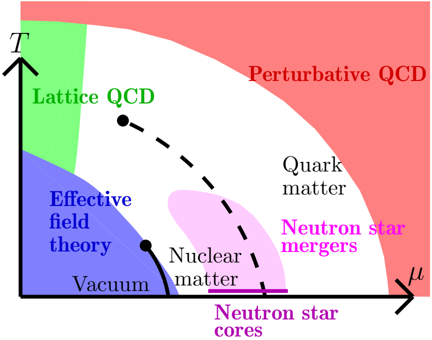


- This region is highly relevant for neutron star physics!
- Improving theoretical predictions important!
- Strongly coupled physics – use the gauge/gravity duality?

# Gauge/gravity duality for QCD

- Motivated by the original AdS/CFT correspondence for $\mathcal{N} = 4$ Super Yang-Mills
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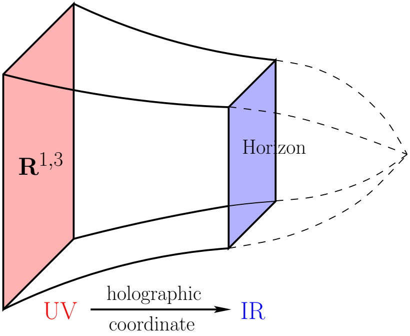

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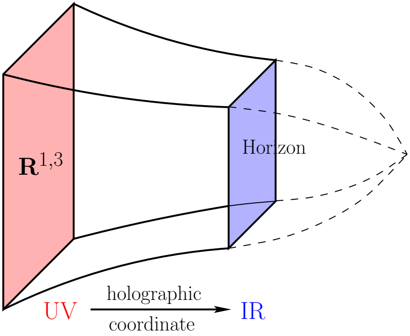


- Operators $O_i(x^\mu) \leftrightarrow$ classical bulk fields $\phi_i(x^\mu, r)$

$$Z_{\text{grav}}(\phi_i|_{\text{bdry}} = J_i(x^\mu)) = \int \mathcal{D}\, e^{iS_{QCD} + i\int d^4x J^i(x^\mu) O_i(x^\mu)}$$

- Thermodynamics of QCD $\leftrightarrow$ thermodynamics of a planar bulk black hole

# 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:

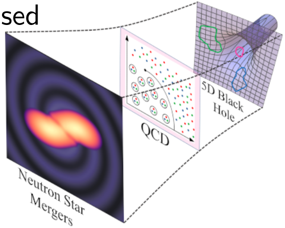
- Strongly coupled physics: holography may work better than many other approaches
- Different phases (quark, nuclear, color superconducting, quarkyonic . . . ) in the same footing or even in a single model
  - Typically not achieved in the literature
  - Gives rise to predictions for phase transitions
- 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
  - I will show examples later in this talk

# Outline

# The approach

Goal: construct 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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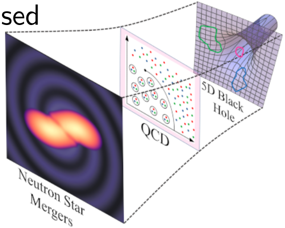


I choose a specific holographic model (V-QCD)

- Many other approaches available, I will cover only this one
- Some parts could also be covered using simpler models (e.g. quark matter using Einstein-Maxwell-dilaton)

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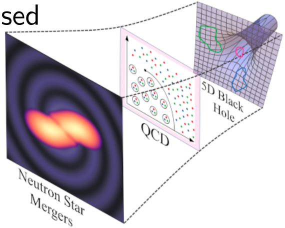


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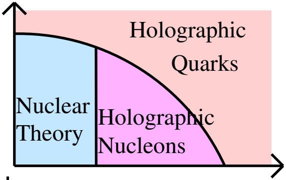
Main ingredients are

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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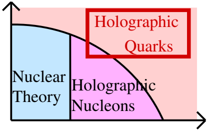
# Model for quark matter

V-QCD: a holographic bottom-up model for QCD with backreacted quarks

- Combines model for glue (IHQCD) with flavor (brane action) [Gürsoy, Kiritsis, Nitti] [Bigazzi,Casero,Cotrone,Kiritsis,Paredes] [MJ, Kiritsis 1112.1261]



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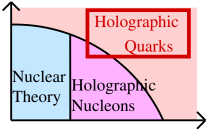


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- Quark matter chirally symmetric ⇒

$$\mathcal{S}_{\mathrm{V-QCD}} = N_c^2 M^3 \int d^5x \sqrt{g} \left[ R - \frac{4}{3} \frac{(\partial\lambda)^2}{\lambda^2} + V_g(\lambda) \right] - N_f N_c M^3 \int d^5x \; V_{f0}(\lambda) \sqrt{-\det(g_{ab} + w(\lambda) F_{ab})}$$

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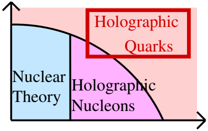


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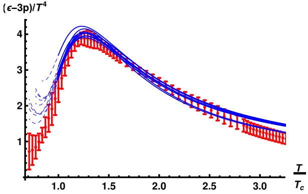
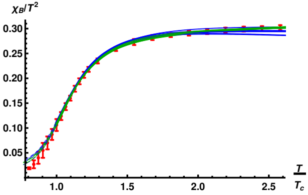
Effective model: choose potentials by comparing to QCD at $\mu \approx 0$



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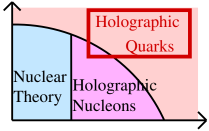


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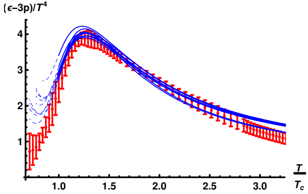
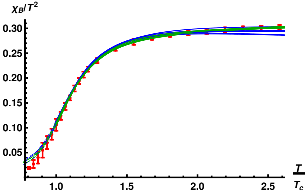
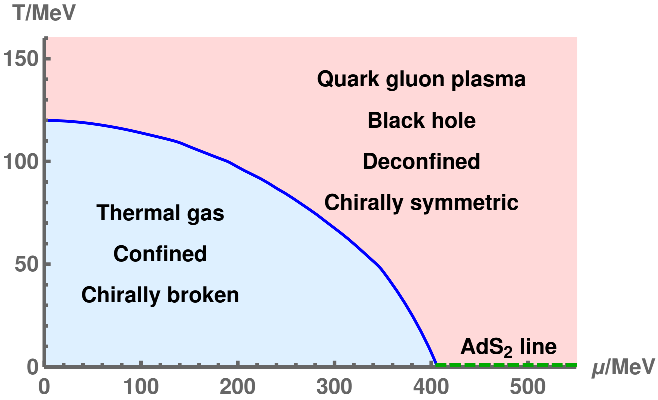



Equation of state obtained numerically from black hole thermodynamics of charged black holes

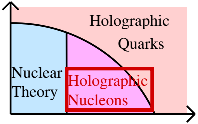
# Phase diagram with quark matter




- With quark matter only, expected phase diagram
- Cold QM EOS and location of the $T = 0$ phase transition agree with constraints

# Model for nuclear matter

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




- Already constructing an isolated instanton solution is nontrivial
- Such instantons have been studied in many models, including V-QCD
  [MJ, Kiritsis, Nitti, Préau 2209.05868; 2212.06747]
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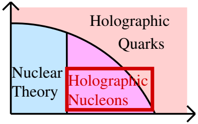


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- Dense nuclear matter requires studying many-instanton solutions ... extremely challenging!
- Our approach: V-QCD with two flavors and a homogeneous gauge field, mimicking dense solitons: $A^i = h(r)\sigma^i$

[Rozali, Shieh, Van Raamsdonk, Wu 0708.1322]

[Ishii, MJ, Nijs, 1903.06169]

# 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]

$$S_{\mathrm{DBI}} = -\frac{1}{2} M^3 N_c \, \mathbb{T}r \int d^5x \, V_{f0}(\lambda) e^{-\tau^2} \left( \sqrt{-\det \mathrm{A}^{(L)}} + \sqrt{-\det \mathrm{A}^{(R)}} \right)$$

$$\mathrm{A}^{(L/R)}_{MN} = g_{MN} + \delta^r_M \delta^r_N \kappa(\lambda) \tau'(r)^2 + \delta^{rt}_{MN} w(\lambda) \Phi'(r) + w(\lambda) F^{(L/R)}_{MN}$$

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]

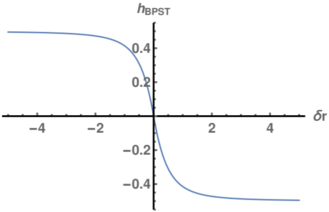
$$A^i_L = -A^i_R = h(r) \sigma^i$$

[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 $h(r)$:

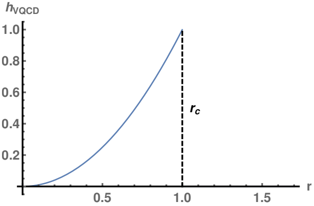
$$N_b \propto \int dr \frac{d}{dr}\left[\mathrm{CS} - \mathrm{term}\right] = 0$$




How can this issue be avoided?

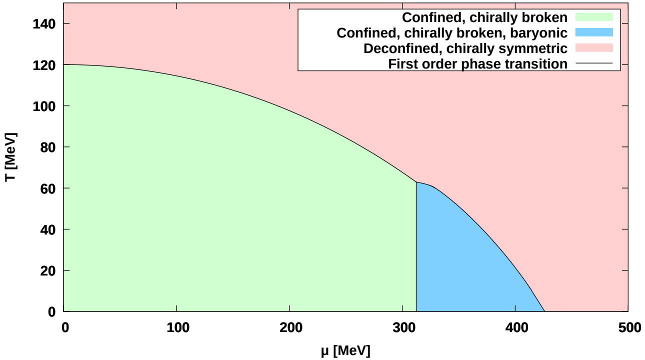
- Smearing the BPST soliton in singular Landau gauge:

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




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

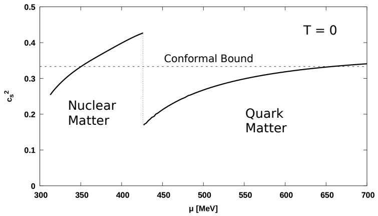
# Phase diagram after including nuclear matter




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:

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- This is likely to be a good first approximation, but not enough for a state-of-the-art model

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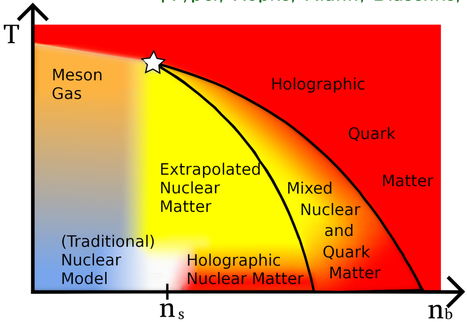
Our solution: we extrapolate the holographic nuclear matter EOS to nonzero $T$ by a using a van der Waals approach

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

[Demircik, Ecker, MJ 2112.12157]

# Combining the building blocks: the hybrid model

- For low density nuclear matter, Hempel-Schaffner-Bielich DD2
  [Hempel, Schaffner-Bielich 0911.4073]
  [Typel, Ropke, Klahn, Blaschke, Wolter 0908.2344]



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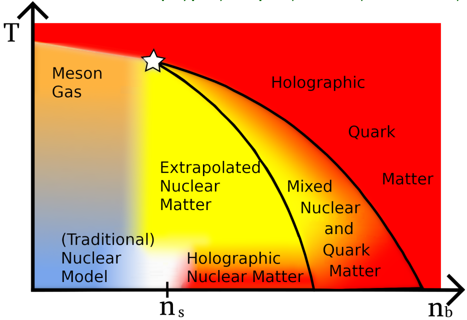


Covers regions relevant for neutron stars and heavy-ion collisions!

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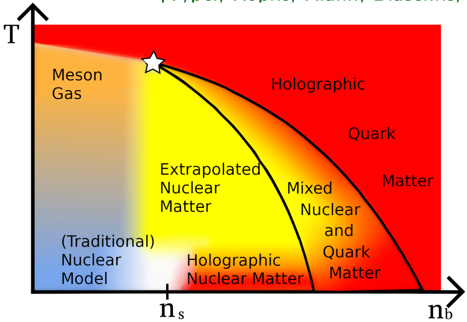


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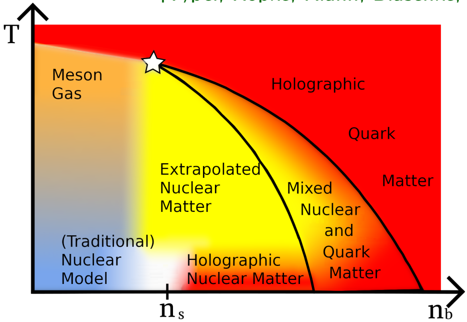
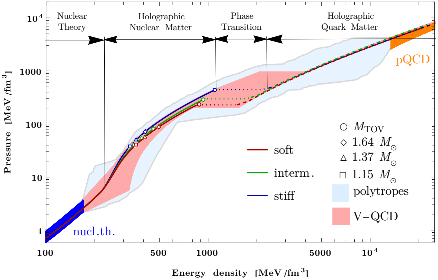



Covers regions relevant for neutron stars and heavy-ion collisions!

- One of the most ambitious attempts to describe the QCD EOS to date, in any approach
- Consistent with theoretical and observational constraints
- Pick 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]

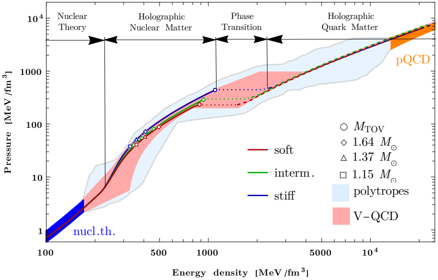
# Cold EoS and known constraints

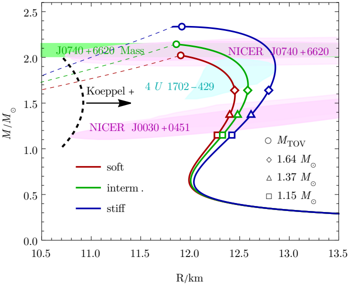
- Three choices of EoSs: soft, intermediate, and stiff $\leftrightarrow$ the degrees of freedom of V-QCD left free by fit to lattice data
- Compared to bands of all feasible cold matter EoS: Without and with holography



# Cold EoS and known constraints

- Three choices of EoSs: soft, intermediate, and stiff ↔ 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




- 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]

# Advantages of the model

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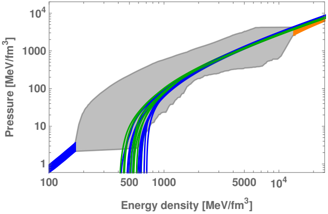

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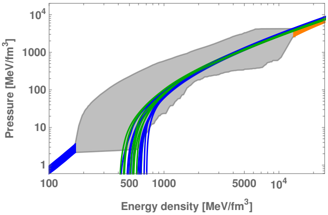


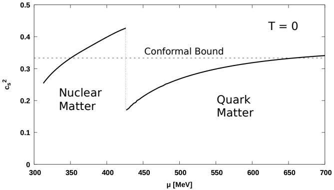

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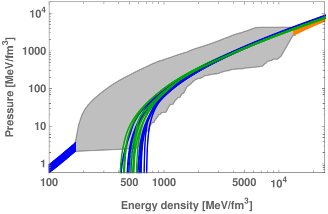
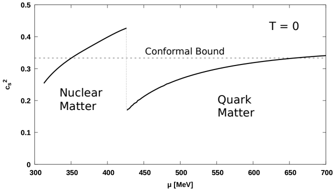
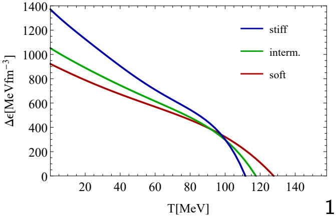
   - Predictions for the phase transition



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Close agreement with functional renormalization group (FRG)

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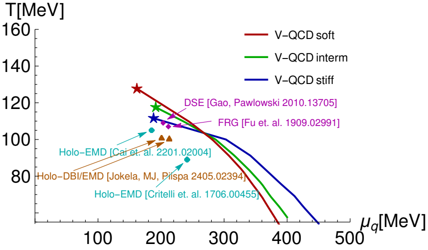


- Critical point

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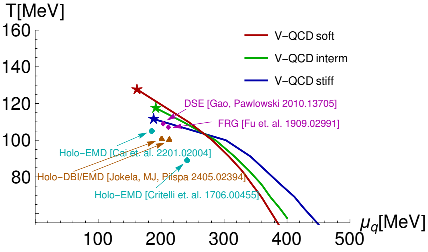


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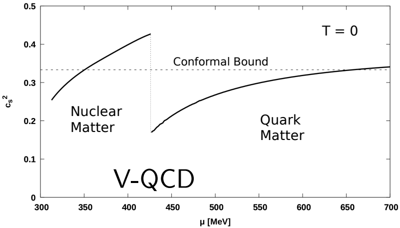
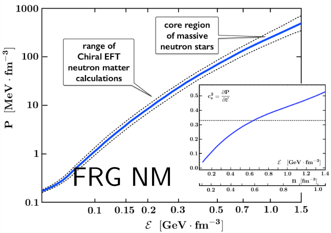
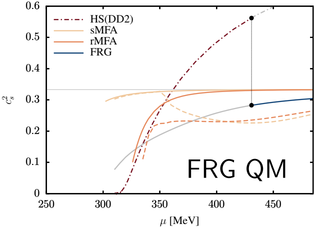



- Speed of sound at $T = 0$




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

# Outline

# Neutron star mergers

- Significant sources of gravitational radiation
- Microscopic properties of dense matter encoded in the gravitational waves and the electromagnetic signal

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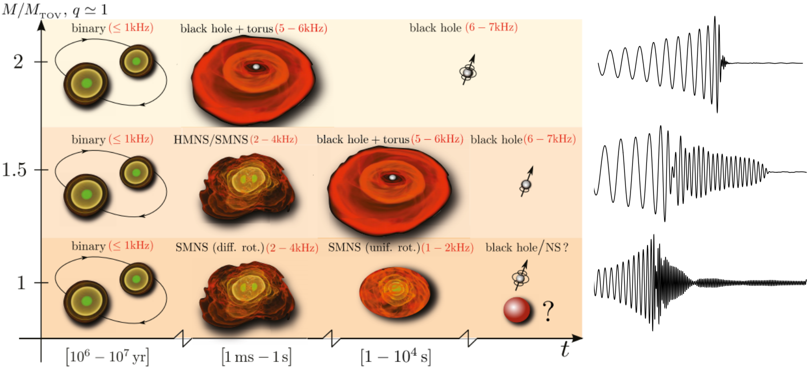


[picture: Baiotti, Rezzola 1607.03540]

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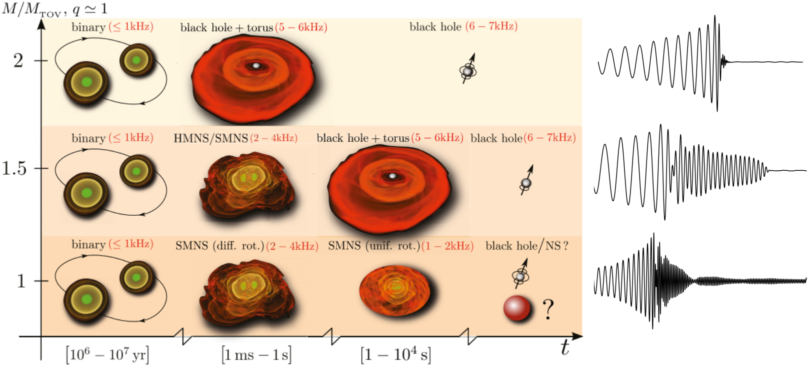

[picture: Baiotti, Rezzola 1607.03540]

One good event (GW170817) and a few other events already observed! [LIGO/Virgo, 1710.05832]

# Simulating neutron star mergers

Have to solve the 3+1D General Relativistic hydrodynamics equations:

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

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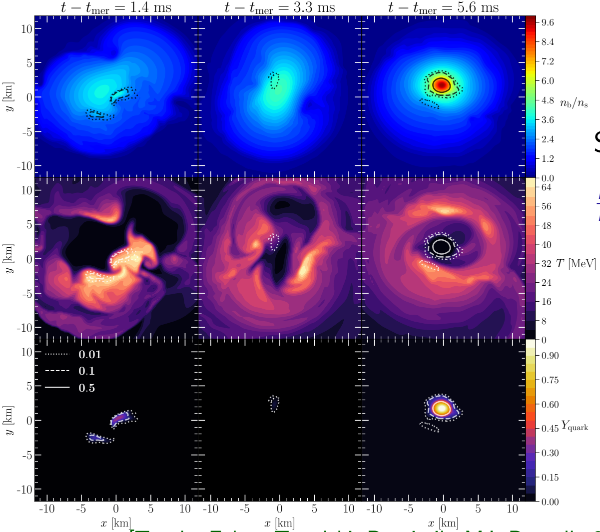
# Hot, warm and cold quarks

After-merger quark matter production (GW170817 parameters):

Hot quarks    Warm quarks    Cold quarks




Soft EOS

$\frac{M_1}{M_2} = 0.7$

[Tootle, Ecker, Topolski, Demircik, MJ, Rezzolla 2205.05691]

# Threshold mass of prompt black hole formation

Analysis of mergers at high mass where the system collapses to a black hole

- Idea: use curvature invariants for precise classification of "prompt" collapse

[CE, Topolski, Järvinen, Stehr 2402.11013]

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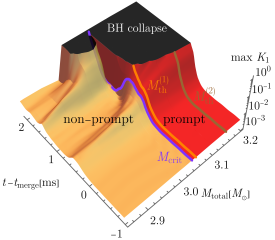


Motivated by simulations, in particular dependence of $K_1$ on $t$ and $M_{\text{total}}$, we define

1. The critical mass

$$M_{\text{crit}} = \min(M) : \frac{dt_{\text{crit}}}{dM_{\text{total}}} < 0 \quad \forall\ M_{\text{total}} > M\,,$$

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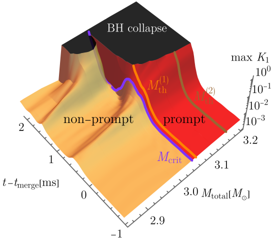


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where $t_{crit}$ is the time of formation of an apparent horizon

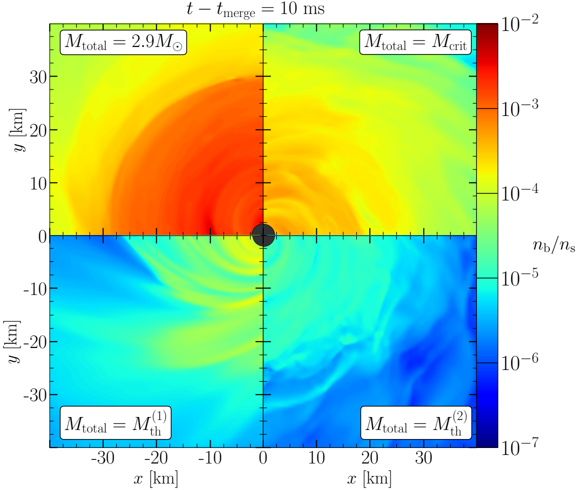
2. Threshold masses of promptness $p$

$$\left\{ M_{th}^{(p)} = \min(M_{total}) : \frac{d^p}{dt^p} \max(K_1) \geq 0\ \forall\ t > t_{merge} \right\}$$

[CE, Topolski, Järvinen, Stehr 2402.11013]

# Residual matter

- Significant drop in residual matter outside horizon at $M_{\text{crit}}$



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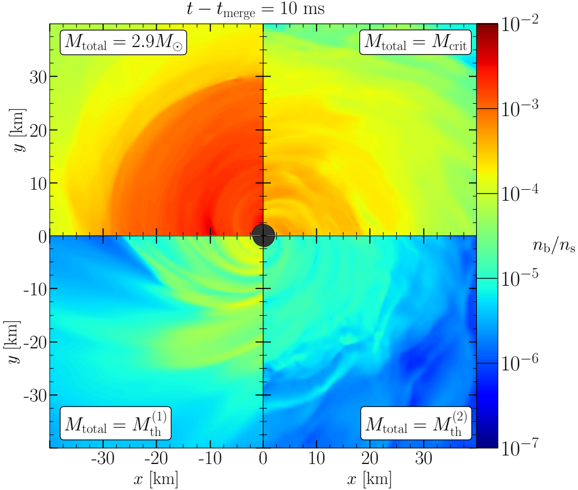


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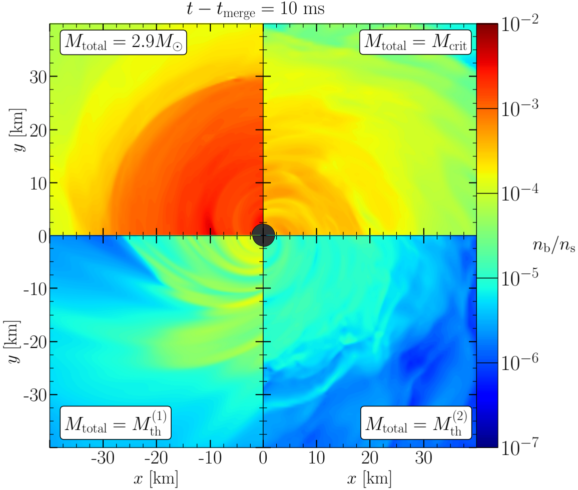



- Enhanced by the transition to quark matter
- So $M_{\mathrm{crit}}$ can potentially be measured precisely by observing the EM counterpart

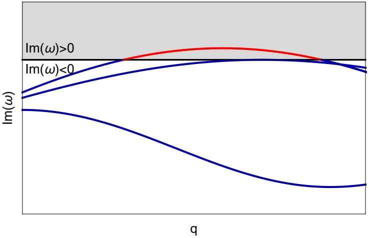
# Outline

# Inhomogeneity in holographic plasma?

Spatially modulated phases

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

- Exponentially growing perturbation at $q \neq 0$: a quasi-normal mode with $\mathrm{Im}\,\omega > 0$



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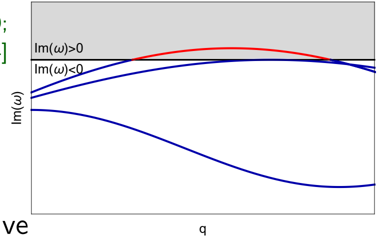
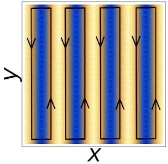



- Exponentially growing perturbation at $q \neq 0$: a quasi-normal mode with $\mathrm{Im}\,\omega > 0$
- The Chern-Simons term can drive a modulated instability at finite density
- Modulated 5D gauge fields dual to modulated persistent chiral currents in field theory
- Somewhat different from "chiral density wave" no chiral condensate involved



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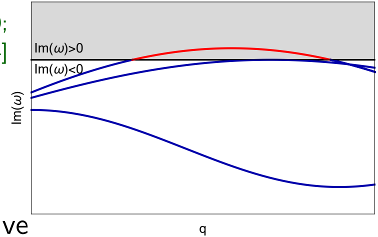


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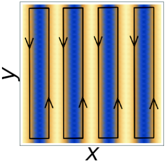


Schematic fluctuation equation

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

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

# Instability in our setup

We checked the extent of the instability in V-QCD and Einstein-Maxwell-dilaton models

- Note that CS terms required by the anomalies in QCD

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

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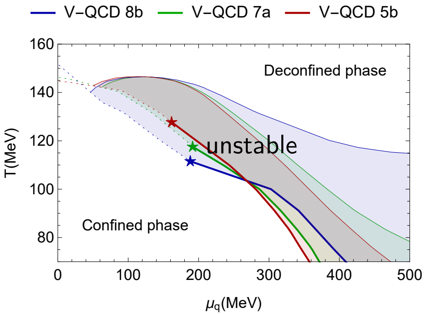


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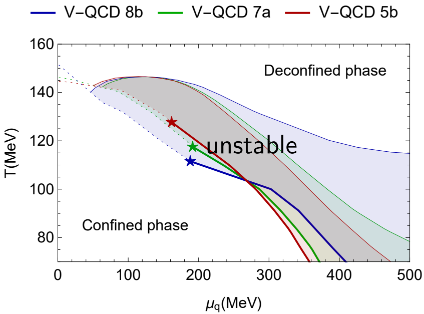


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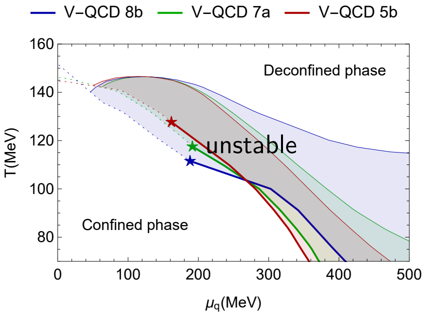
- However, might be sensitive to strange quark mass – requires further study

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# Outline

1. Introduction and motivation
2. Holographic equation of state
   - Holographic quark matter
   - Holographic nuclear matter
   - Hybrid model
3. Holographic neutron star mergers
   - Production of quark matter
   - Prompt collapse to a black hole
4. Modulated instabilities
5. Bulk viscosity
6. Conclusion

# Bulk viscosity in dense QCD matter

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- Twenty orders of magnitude larger than the pure QCD viscosity for neutron star frequencies and temperatures (kHz/MeV range)
- Potentially affects significantly the aftermerger phase of neutron star merger

[Alford, Bovard, Hanauske, Rezzolla, Schwenzer 1707.09475]

# Bulk viscosity for periodic compression

Straightforward analysis for periodic compression using weak reaction rate to leading order in $G_F$ and $\alpha_s$

$$\zeta = \frac{\lambda_1 A_1^2}{\omega^2 + (\lambda_1 C_1)^2}$$

with strong contributions given as

$$A_1, C_1 = F(\{n_i\}, \{\chi_{ij}\}) \qquad \chi_{ij} = \frac{\partial n_i}{\partial \mu_j} = \frac{\partial^2 p}{\partial \mu_i \partial \mu_j} \qquad i, j = u, d, s$$

and weak contributions given through the rate

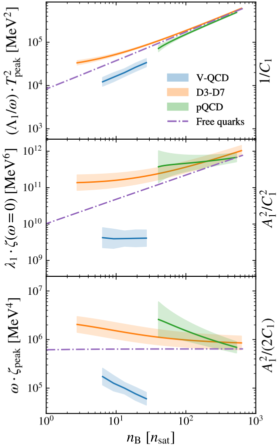
$$\lambda_1 = \frac{64}{5\pi^3} G_F^2 \sin^2\theta_c \cos^2\theta_c \mu_d^5 T^2$$

- Sensitive to strange quark mass: $\zeta \sim m_s^4$

# Estimating the susceptibilities

We computed the susceptibilities (that is, the coefficients $A_1$ and $C_1$) using [Cruz Rojas, Gorda, Hoyos, Jokela, MJ, Kurkela Paatelainen, Säppi, Vuorinen 2402.00621 (PRL)]

1. Perturbative QCD
   - Using a scheme where $m_s$ is a perturbation [Gorda, Säppi 2112.11472]
2. Probe D3-D7 setup with quark masses matched with perturbation theory
   - Simple analytic expressions
3. V-QCD – turning on the strange quark mass without refitting the model
   - Numerical result, taking the derivatives of number densities



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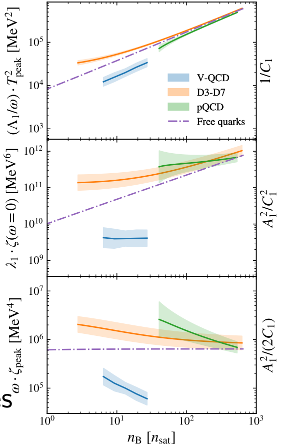
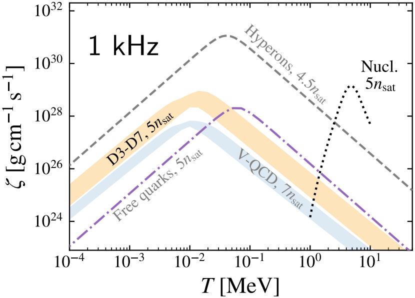



- D3-D7 gives a reasonable extrapolation of the perturbative results to low densities
- V-QCD underestimates $A_1$?
- Not surprising – our simplistic approach for the strange quark mass also leads to tension with lattice data at small density

# Result for the bulk viscosity

Final results for the bulk viscosity at $n \sim 5n_{\rm sat}$

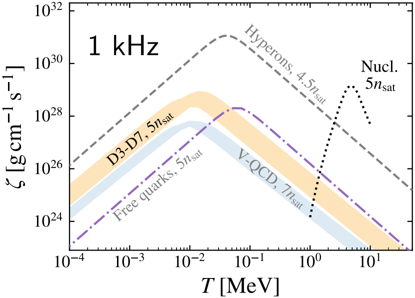
- The D3-D7 result expected to be the best estimate
- V-QCD qualitatively similar, but too low by a constant factor
- Free quarks also give a reasonable estimate
- Results for nuclear and hyperonic matter shown for comparison



# Result for the bulk viscosity

Final results for the bulk viscosity at $n \sim 5 n_{\mathrm{sat}}$

- The D3-D7 result expected to be the best estimate
- V-QCD qualitatively similar, but too low by a constant factor
- Free quarks also give a reasonable estimate
- Results for nuclear and hyperonic matter shown for comparison




The best estimate (D3-D7) takes a simple form

$$\zeta = \frac{4\lambda_1 \mu_d^6 (M_s^2 - M_d^2)^2}{K_d^2 K_s^2 \omega^2 + \pi^4 \lambda_1^2 (K_d + K_s)^2}, \qquad K_i \equiv 3\mu_d^2 - M_i^2$$

# Outline

# Conclusion

- Holographic description of dense QCD works 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

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- Computed predictions for the bulk viscosity both using perturbation theory and holography
- Ongoing/future improvements: careful analysis of strange quark mass, more transport (e.g. neutrino transport), isospin asymmetry, color superconducting phases, improving predictions for spatial modulation ...

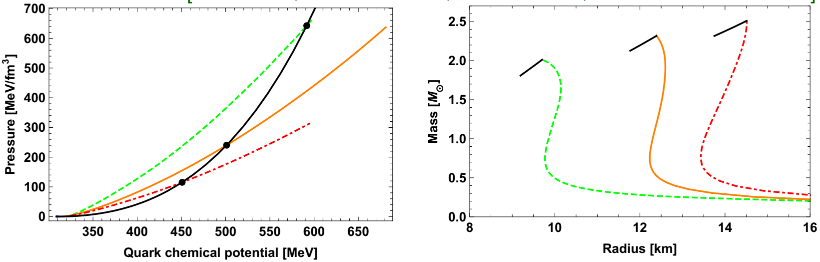
Thank you!

# Recent progress on dense holographic QCD

For quark matter, use D3-D7 top down model: $\epsilon = 3p + \frac{\sqrt{3}m^2}{2\pi}\sqrt{p}$
[Karch, O'Bannon, 0709.0570]

- $\mathcal{N} = 4$ SYM + $N_f = 3$ probe hypermultiplets in the fundamental representation

For nuclear matter use with stiff, intermediate, and soft "extrapolations" of EFT results
[K. Hebeler, J. M. Lattimer, C. J. Pethick, A. Schwenk 1303.4662]




- Strong first order nuclear to quark matter transitions
- Neutron stars with "holographic" quark matter core (black curves) are unstable

[Hoyos, Rodriguez, Jokela, Vuorinen 1603.02943]

Varying the quark mass $m$ one can get quark stars and hybrid stars

[Annala, Ecker, Hoyos, Jokela, Rodriguez-Fernandez, Vuorinen 1711.06244]

- Sizeable deviations from universal I-Love-Q relations

[Yagi, Yunes, 1303.1528]

Including running of the quark mass + color superconductivity

[Bitaghsir Fadafan, Cruz Rojas, Evans, 1911.12705; 2009.14079]

- Possibility of an intermediate $\chi$SB deconfined phase
- Stiffer holographic equations of state (high speed of sound)
- Quark matter cores

Using Einstein-Maxwell-dilaton for quark matter

[Mamani, Flores, Zanchin, 2006.09401]

(Largish) quark stars also studied in Witten-Sakai-Sugimoto and in D4-D6 models

[Burikham, Hirunsirisawat, Pinkanjanarod, 1003.5470
Kim, Shin, Lee, Wan, 1108.6139, 1404.3474]

This talk: towards more realistic model of quark matter?

# Constraining the potentials

In the UV ( $\lambda \to 0$):

- UV expansions of potentials matched with perturbative QCD beta functions $\Rightarrow$ asymptotic freedom and logarithmic flow of the coupling and quark mass, as in QCD

[Gürsoy, Kiritsis 0707.1324; MJ, Kiritsis 1112.1261]

In the IR ($\lambda \to \infty$): various qualitative constraints

- Linear confinement, discrete glueball & meson spectrum, linear radial trajectories
- Existence of a "good" IR singularity
- Correct behavior at large quark masses
- Working potentials often string-inspired power-laws, multiplied by logarithmic corrections (i.e, first guesses usually work!)

[Gürsoy, Kiritsis, Nitti 0707.1349; MJ, Kiritsis 1112.1261; Arean, Iatrakis, MJ, Kiritsis 1309.2286, 1609.08922; MJ 1501.07272]

Final task: determine the potentials in the middle, $\lambda = \mathcal{O}(1)$

- Qualitative comparison to lattice/experimental data

# Ansatz for potentials, $(x = 1)$

$$V_g(\lambda) = 12\left[1+V_1\lambda+\frac{V_2\lambda^2}{1+\lambda/\lambda_0}+V_{\rm IR}e^{-\lambda_0/\lambda}(\lambda/\lambda_0)^{4/3}\sqrt{\log(1+\lambda/\lambda_0)}\right]$$

$$V_{f0}(\lambda) = W_0 + W_1\lambda + \frac{W_2\lambda^2}{1+\lambda/\lambda_0} + W_{\rm IR}e^{-\lambda_0/\lambda}(\lambda/\lambda_0)^2$$

$$\frac{1}{w(\lambda)} = w_0\left[1+\frac{w_1\lambda/\lambda_0}{1+\lambda/\lambda_0}+\bar{w}_0 e^{-\lambda_0/\lambda w_s}\frac{(w_s\lambda/\lambda_0)^{4/3}}{\log(1+w_s\lambda/\lambda_0)}\right]$$

$$V_1 = \frac{11}{27\pi^2}\ , \quad V_2 = \frac{4619}{46656\pi^4}$$

$$W_1 = \frac{8+3\,W_0}{9\pi^2}\ ; \quad W_2 = \frac{6488+999\,W_0}{15552\pi^4}$$

Fixed UV/IR asymptotics $\Rightarrow$ fit parameters only affect details in the middle

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

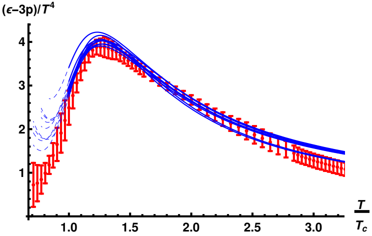
Standard recipe (charged black holes) $\Rightarrow$ lots of numerical work
$\Rightarrow$ description of hot and dense quark matter

Fit to lattice data near $\mu = 0$ [MJ, Jokela, Remes, 1809.07770]

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

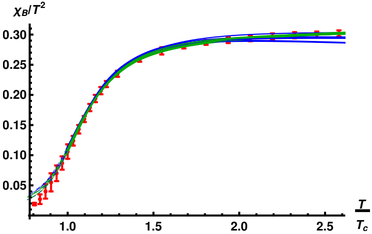
Interaction measure $\frac{\epsilon - 3p}{T^4}$, 2+1 flavors

[Data: Borsanyi et al. 1309.5258]




Baryon number susceptibility $\chi_B = \left.\frac{d^2p}{d\mu^2}\right|_{\mu=0}$

[Data: Borsanyi et al. 1112.4416]

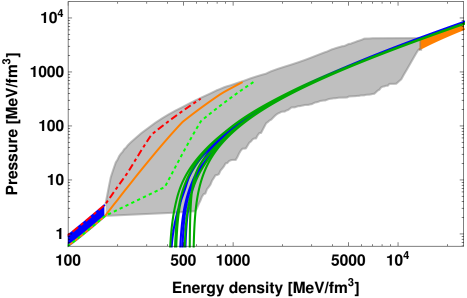


# Extrapolated EOSs of cold quark matter

The V-QCD cold quark matter result compares nicely to known constraints:

[MJ, Jokela, Remes, 1809.07770]

- Band of allowed equations of state (EOSs) (gray, polytropic interpolations)
- Stiff, intermediate, and soft nuclear EOSs [Hebeler, Lattimer, Pethick, Schwenk 1303.4662]




Approach similar in spirit to studies of the QCD critical point

[DeWolfe,Gubser,Rosen 1012.1864; Knaute,Yaresko,Kämpfer 1702.06731; Critelli, Noronha, Noronha-Hostler, Portillo, Ratti, Rougemont, 1706.00455; Cai, He, Li, Wang 2201.02004]

# Van der Waals model

Ideal gas of protons, neutrons and electrons with

- Excluded volume correction for nucleons

$$\begin{aligned} p_{\rm ex}(T, \{\mu_i\}) &= p_{\rm id}(T, \{\tilde{\mu}_i\}) \\ \tilde{\mu}_i &= \mu_i - v_0 p_{\rm ex}(T, \{\mu_i\}) \qquad (i = p,\ n) \end{aligned}$$

  $v_0 \sim$ volume of one nucleon

- (Mostly) attractive potential term to match with (APR and) V-QCD at $T = 0$

$$p_{\rm vdW}(T, \{\mu_i\}) = p_{\rm ex}(T, \{\mu_i\}) + \Delta p(\{\mu_i\})$$

  schematically:

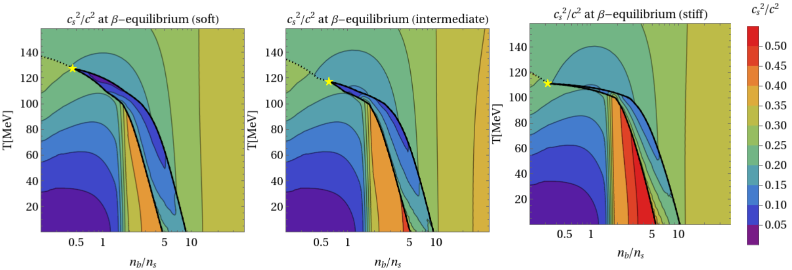
$$\Delta p(\{\mu_i\}) = p_{\rm V-QCD}(T = 0, \{\mu_i\}) - p_{\rm ex}(T = 0, \{\mu_i\})$$

[Rischke, Gorenstein, Stoecker, Greiner, Z Phys. C 51, 485 (1991)]

[Vovchenko, Gorenstein, Stoecker, 1609.03975]

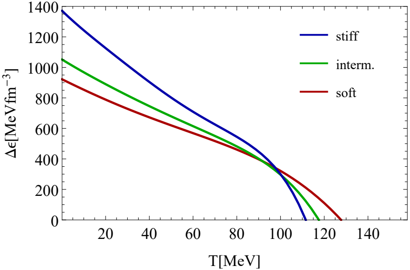
[Vovchenko, Motornenko, Alba, Gorenstein, Satarov, Stoecker, 1707.09215]

# Results: critical point



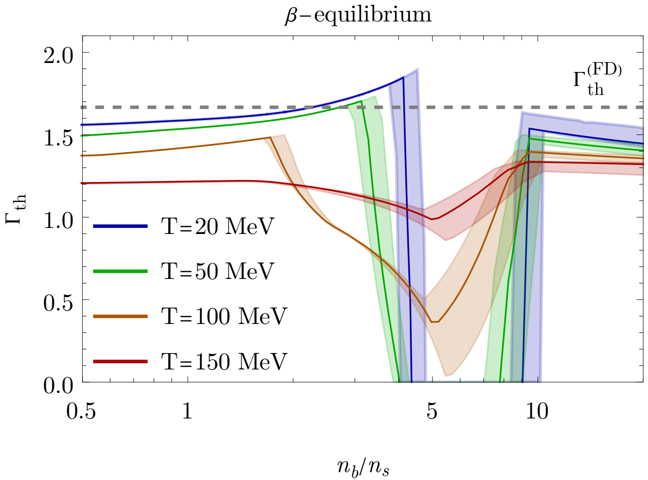

110 MeV $\lesssim T_c \lesssim$ 130 MeV

$0.3n_s \lesssim n_c \lesssim 0.6n_s$




Critical point is determined by fitting the latent heat in the region of strong phase transition and extrapolating

# Results: thermal index



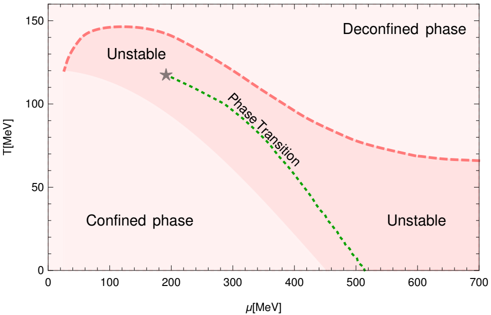

$$\Gamma_{\text{th}}(n_b, T) = 1 + \frac{p(n_b,T) - p(n_b,0)}{e(n_b,T) - e(n_b,0)}$$

- Values in expected range
- Low values in the mixed phase

# Modulated instability in V-QCD

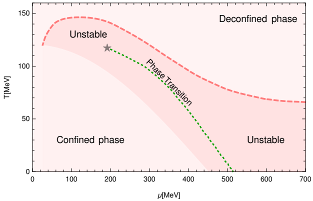
The region where instability exists [Cruz Rojas, Demircik, MJ 2405.02399]

- Estimate for transition and critical point from earlier work [Demircik, Ecker, MJ 2112.12157]




- The Chern-Simons term is strong enough to create an instability of the charged black hole in V-QCD (unsurprising)
- 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)

# How does the instability arise?




Looks quite different from Nakamura-Ooguri-Park, where the onset was at fixed $\mu/T$... what is going on?

- Also differs from result in Witten-Sakai-Sugimoto [Ooguri, Park 1011.4144]
- Look at the fluctuation equation

$$\psi'' + \left(A' + \frac{f'}{f}\right)\psi' + \frac{qn}{M_p^3 f e^{2A} Z(\phi)^2}\psi + \left(\frac{\omega^2}{f^2} - \frac{q^2}{f}\right)\psi = 0$$

- Values of $\phi$ largest near horizon, and grow for smaller black holes
- Smallest black holes found near the deconfinement transition [Alho, MJ, Kajantie, Kiritsis, Rosen, Tuominen 1312.5199]
- $Z(\phi)$ determined by fit to $\chi_2$: fast increase of $\chi_2$ with $T$ $\Rightarrow$ fast decrease of $Z$ with $\phi$
- Enhances instability strongly for small black holes

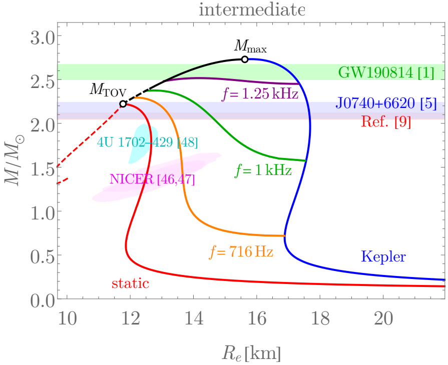
# Rapidly spinning holographic neutron stars

GW190814: LIGO/Virgo observed a merger of a $23M_\odot$ black hole with a $2.6M_\odot$ compact object

[2006.12611]

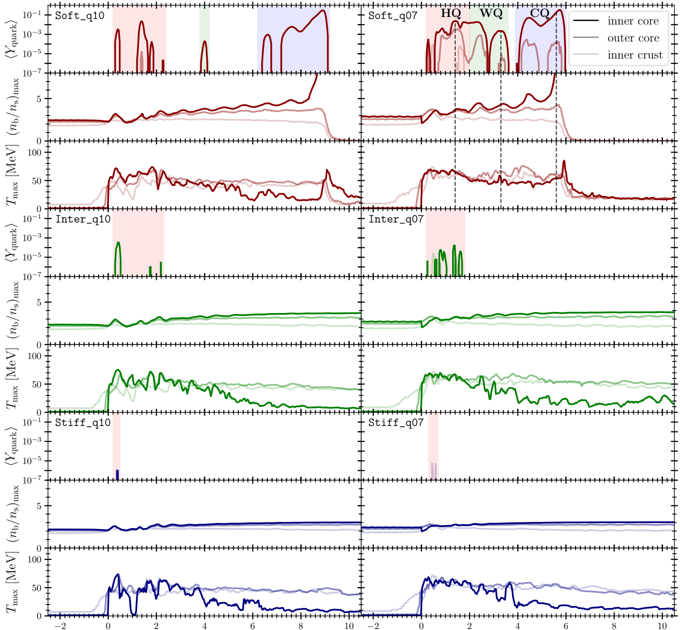
- $2.6M_\odot$ falls in the "gap": a black hole or a neutron star?

- Holographic EOSs easily compatible with the neutron star interpretation
- However requires fast rotation, $f \gtrsim 1$ kHz




[Demircik, Ecker, MJ, 2009.10731]

# Details on quark formation

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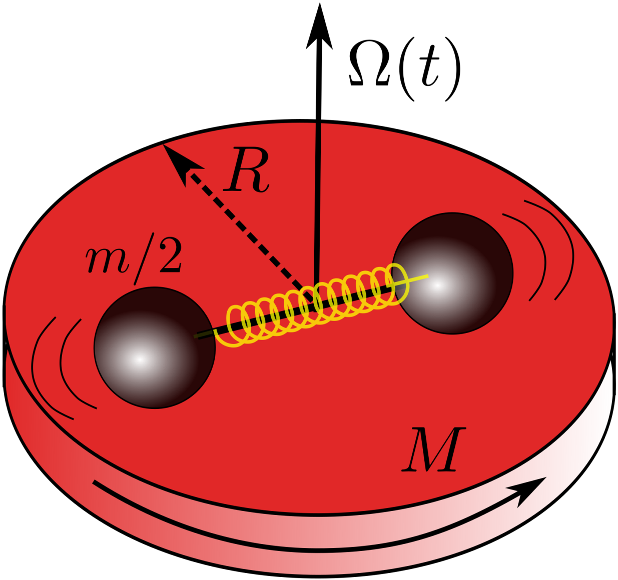
# Mechanical Toy Model




[Takami, Rezzolla, Baiotti 1412.3240]