Suppression of baryon diffusion in a baryon rich strongly coupled QGP

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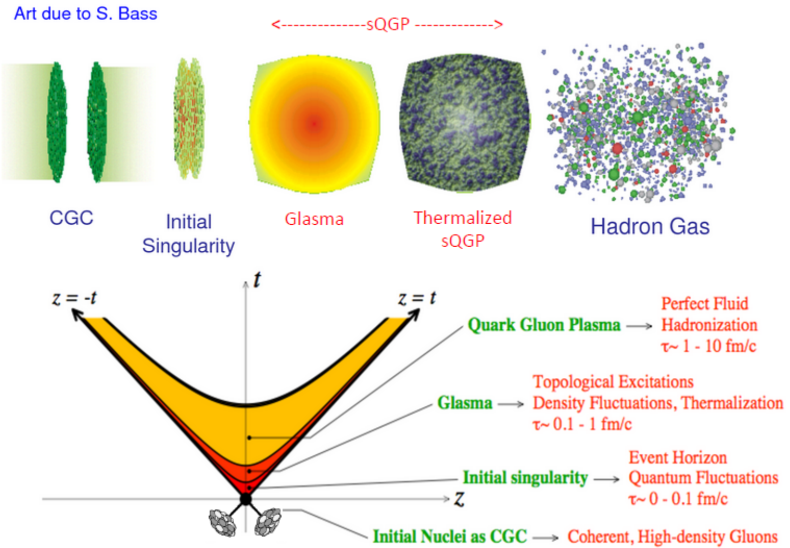
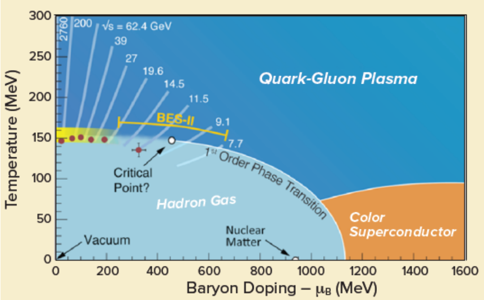
1 - Introduction and motivation

Stages of relativistic heavy ion collisions



QCD PHASE DIAGRAM IN THE (T, μ_B) PLANE

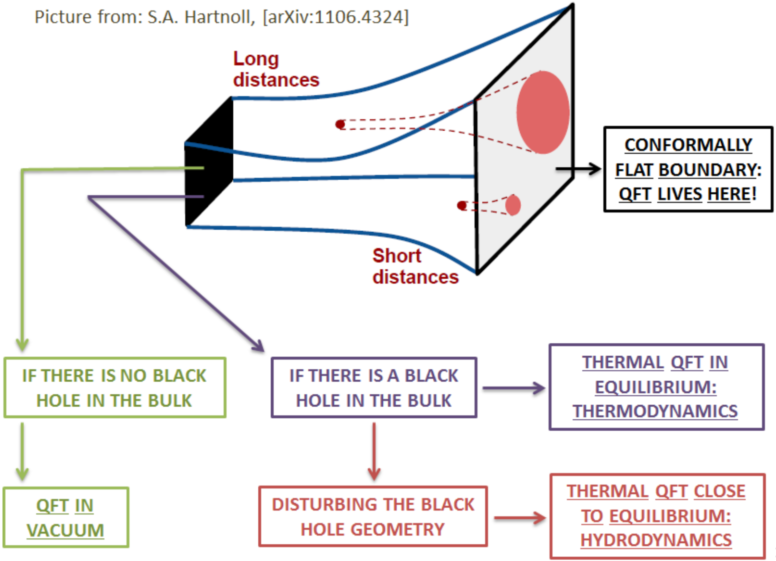


Hard tasks for lattice QCD:
i) Nonzero baryon chemical potential
ii) Real time observables

Resort to models: NJL, EMD holography, etc...

Holographic Gauge/Gravity duality

Picture from: S.A. Hartnoll, [arXiv:1106.4324]



Can holography be used to extract realistic insights for the sQGP?!

- Holography is a *framework* encompassing many physically different Gauge/Gravity models;
- **Any isotropic and translationally invariant Gauge/Gravity model with at most two derivatives for the metric field gives $\eta/s = 1/4\pi$;**
- Therefore, we need to investigate more observables to check whether there are holographic models really akin to the real-world sQGP;
- The most popular holographic approach to obtain "insights" for thermal QCD employs the $\mathcal{N} = 4$ SYM plasma as a proxy for the sQGP: **is this a realistic approach?!**

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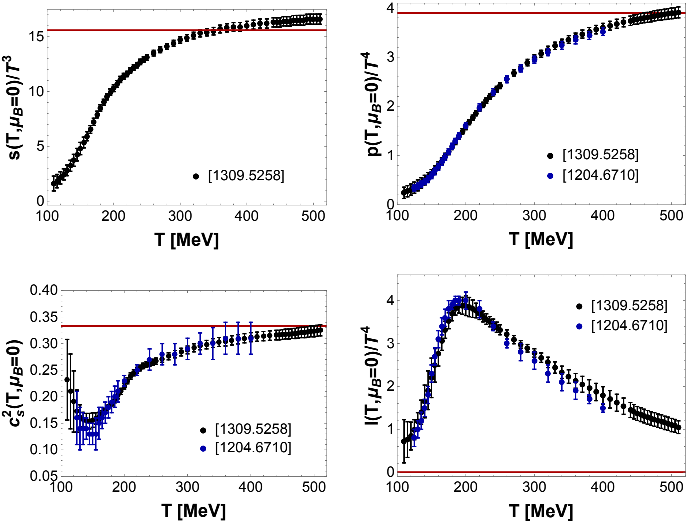
LQCD and $\mathcal{N} = 4$ SYM EoS' (lesson: do not use SYM as a proxy for sQGP!)



2 - Einstein-Maxwell-Dilaton (EMD) holography at finite baryon chemical potential

Bottom-up holographic EMD action

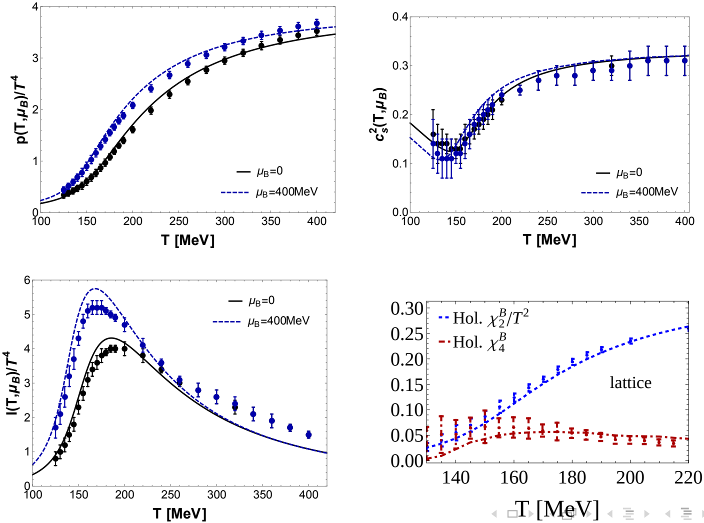
$$S = \frac{1}{16\pi G_5} \int_{\mathcal{M}_5} d^5x \sqrt{-g} \left[R - \frac{1}{2}(\partial_\mu \phi)^2 - V(\phi) - \frac{f(\phi)}{4} F_{\mu\nu}^2 \right] + S_{\mathrm{GHY}} + S_{\mathrm{CT}}. \quad (1)$$

We dynamically fix the free parameters of the EMD model using LQCD thermodynamical inputs at $\mu_B = 0$:

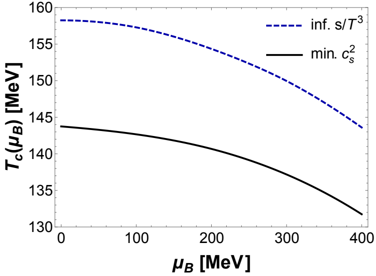
i) G_5 and $V(\phi)$ fixed by the LQCD EoS with $(2+1)$-flavors and physical quark masses;

ii) $f(\phi)$ fixed by the LQCD χ_2^B with $(2+1)$-flavors and physical quark masses.

Holographic EoS compared to lattice data from [1204.6710] and [1507.04627]



Curvature of the crossover band [1507.06556]



Expansion for the crossover temperature:

$$\frac{T_c(\mu_B)}{T_c(0)} = 1 - \kappa \left(\frac{\mu_B}{T_c(0)}\right)^2 + \lambda \left(\frac{\mu_B}{T_c(0)}\right)^2 + \mathcal{O}\left(\frac{\mu_B}{T_c(0)}\right)^6. \quad (2)$$

$\kappa_{\mathrm{EMD}} \approx 0.013$ [1507.06556], $\kappa_{\mathrm{latt.I}} = 0.0135(20)$ [1507.03571], $\kappa_{\mathrm{latt.II}} = 0.0149(21)$ [1507.07510].

Baryon transport (see Kapusta and Young [1404.4894])

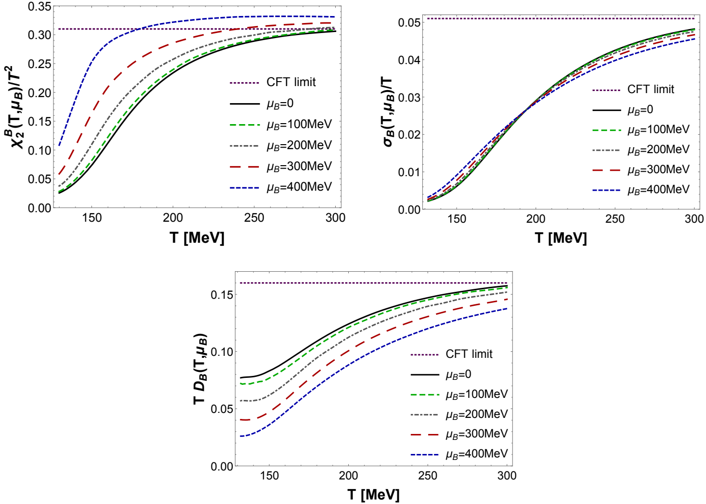
In the Maxwell-Cattaneo formulation of 2nd order viscous hydrodynamics, ρ_B evolves in spacetime according to:

$$\left(\partial_t - D_B \nabla^2 + \tau_B \partial_t^2\right) \rho_B = 0, \tag{3}$$

where D_B **controls the fluid response to inhomogeneities in ρ_B** and is given by:

$$D_B = \frac{\sigma_B}{\chi_2^B}, \quad \sigma_B = -\lim_{\omega\to 0} \frac{\mathrm{Im}\left[G^{(R)}_{J_B^x J_B^x}(\omega, \vec{k} = \vec{0})\right]}{\omega}, \quad \chi_2^B = \frac{\partial \rho_B}{\partial \mu_B}. \tag{4}$$

Suppression of baryon diffusion in the hot and dense sQGP



3 - Conclusions and perspectives

Conclusions and perspectives

- We made predictions for transport coefficients of the sQGP at finite μ_B currently out of the reach of LQCD;
- Realistic holographic constructions may be engineered using a dilaton field in the gravity action to break conformal invariance in the infrared;
- The thermodynamics of the EMD model is in good agreement with LQCD results at finite μ_B, and nearly perfect fluidity is naturally enclosed, making our EMD predictions for the baryon transport coefficients good candidates to be used as inputs in hydro simulations of the hot and dense sQGP;
- Ongoing calculations include a complete determination of the phase diagram of the model: CEP, 1st order and freeze-out lines.

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Backup slides

Brief remarks on the AdS/CFT correspondence

- In its original form, the Gauge/String duality relates superconformal gauge theories defined at the conformally flat boundary of an AdS bulk with type-II B superstrings in $\text{AdS}_5(L) \times S^5(L)$, and also M-branes in $\text{AdS}_4(L/2) \times S^7(L)$ and $\text{AdS}_7(2L) \times S^4(L)$;
- This correspondence is mainly manageable in its classical SUGRA limit, known as the Gauge/Gravity duality, where the dual QFT has a large number of colors, $N_c \to \infty$, and is strongly coupled, $\lambda_t = g_s N_c = (L/\ell_s)^4 \gg 1$ (with $g_s \to 0$);
  - Bulk $(\ell_s/L)^2$ (high curvature) corrections $\Rightarrow 1/\sqrt{\lambda_t}$ corrections at the QFT;
  - Bulk $g_s(\ell_s/L)^4$ (string loop) corrections $\Rightarrow 1/N_c$ corrections at the QFT;
- Nonconformal and non-SUSY dual QFT's may be obtained by deforming the bulk geometry, usually by considering the backreaction of KK modes of SUGRA fields on the bulk metric.

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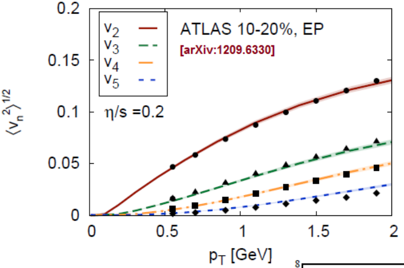
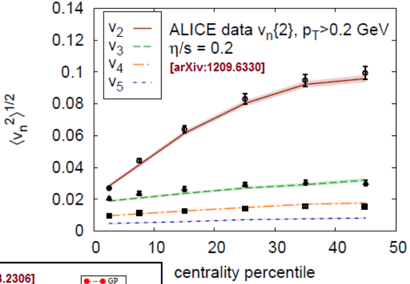
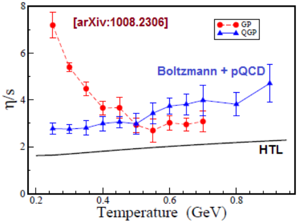
HOLOGRAPHIC DICTIONARY [1205.5180]

Boundary QFT				Bulk Gravity
Operator	$\mathcal{O}(x)$	$\longleftrightarrow$	$\Phi(x,r)$	Field
Spin	$s_{\mathcal{O}}$	$\longleftrightarrow$	s_Φ	Spin
Global Charge	$q_{\mathcal{O}}$	$\longleftrightarrow$	q_Φ	Gauge Charge
Scaling dimension	$\Delta_{\mathcal{O}}$	$\longleftrightarrow$	m_Φ	Mass
Source	$J(x)$	$\longleftrightarrow$	$\Phi(x,r)\vert_\partial$	Boundary Value (B.V.)
Expectation Value	$\langle\mathcal{O}(x)\rangle$	$\longleftrightarrow$	$\Pi_\Phi(x,r)\vert_\partial$	B.V. of Radial Momentum
Global Symmetry Group	G	$\longleftrightarrow$	G	Gauge Symmetry Group
Source for Global Current	$A_\mu(x)$	$\longleftrightarrow$	$A_\mu(x,r)\vert_\partial$	B.V. of Gauge Field
Expectation of Current	$\langle\mathcal{J}^\mu(x)\rangle$	$\longleftrightarrow$	$\Pi^\mu_A(x,r)\vert_\partial$	B.V. of Momentum
Stress Tensor	$T^{\mu\nu}(x)$	$\longleftrightarrow$	$g_{\mu\nu}(x,r)$	Spacetime Metric
Source for Stress-Energy	$h_{\mu\nu}(x)$	$\longleftrightarrow$	$g_{\mu\nu}(x,r)\vert_\partial$	B.V. of Metric
Expected Stress-Energy	$\langle T^{\mu\nu}(x)\rangle$	$\longleftrightarrow$	$\Pi^{\mu\nu}_g(x,r)\vert_\partial$	B.V. of Momentum
# of Degrees of Freedom Per Spacetime Point	N^2	$\longleftrightarrow$	$\left(\frac{L}{\ell_P}\right)^{d-1}$	Radius of Curvature In Planck Units
Characteristic Strength of Interactions	λ	$\longleftrightarrow$	$\left(\frac{L}{\ell_s}\right)^{d}$	Radius of Curvature In String Units
QFT Partition Function with Sources $J_i(x)$	$Z_{\mathrm{QFT}_d}[J_i]$	$\longleftrightarrow$	$Z_{\mathrm{QG}_{d+1}}[\Phi_i[J_i]]$	QG Partition Function in AdS w/ $\Phi_i\vert_\partial = J_i$
QFT Partition Function at Strong Coupling	$Z^{\lambda,N\gg1}_{\mathrm{QFT}_d}[J_i]$	$\longleftrightarrow$	$e^{-I_{\mathrm{GR}_{d+1}}[\Phi[J_i]]}$	Classical GR Action in AdS w/ $\Phi_i\vert_\partial = J_i$
QFT n-Point Functions at Strong Coupling	$\langle\mathcal{O}_1(x_1)\ldots\mathcal{O}_n(x_n)\rangle$	$\longleftrightarrow$	$\left.\frac{\delta^n I_{\mathrm{GR}_{d+1}}[\Phi[J_i]]}{\delta J_1(x_1)\ldots\delta J_n(x_n)}\right\vert_{J_i=0}$	Classical Derivatives of the On-Shell Classical Gravitational Action
Thermodynamic State		$\longleftrightarrow$		Black Hole
Temperature	T	$\longleftrightarrow$	T_H	Hawking Temperature $\sim$ Mass
Chemical Potential	μ	$\longleftrightarrow$	Q	Charge of Black Hole
Free Energy	F	$\longleftrightarrow$	$I_{\mathrm{GR}}\vert_{(\mathrm{on-shell})}$	On-Shell Bulk Action
Entropy	S	$\longleftrightarrow$	A_H	Area of Horizon

Universal nearly perfect fluidity from holography and the sQGP





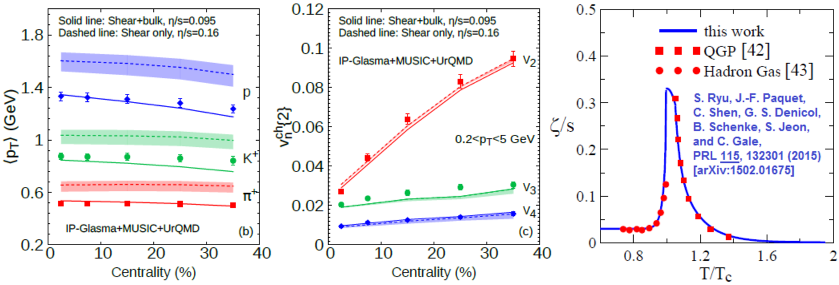


Any isotropic holographic model with at most 2 derivatives in the gravity action gives:

$\eta/s = 1/4\pi$

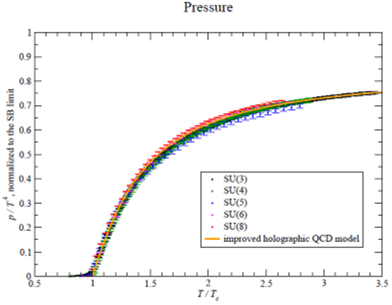
pQCD cannot describe the sQGP formed in current relativistic heavy ion collisions!

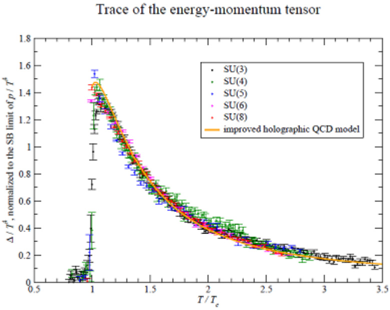
Nonzero bulk viscosity of the sQGP



Dilaton bottom-up holography

Pure glue YM plasma EoS from the lattice [arXiv:0907.3719] for large values of N_c ("$N_c = 3$ is not that far from $N_c \to \infty$"):





Above there is a 1st order phase transition; next, we are going to use an adequate dilaton potential to mimic the $(2+1)$-flavor QCD EoS and the associated *crossover* transition!

Holographic EMD model parameters

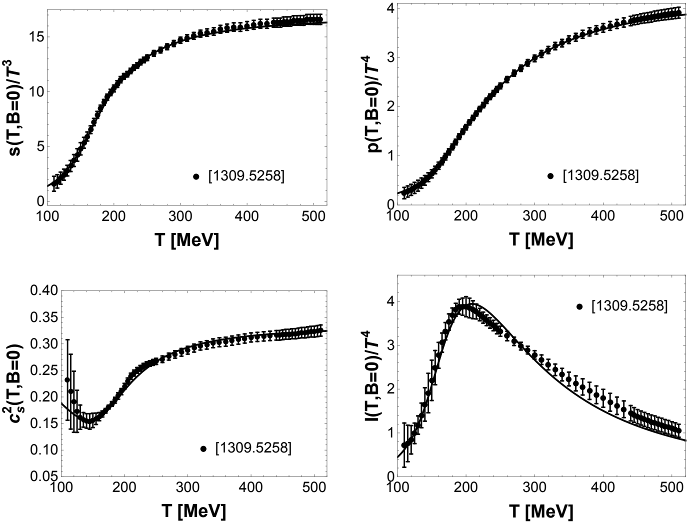
- **EMD-μ_B (with old potential, G_5, and Λ):**

$$V(\phi) = -12\cosh(0.606\phi) + 0.703\phi^2 - 0.1\phi^4 + 0.0034\phi^6,$$
$$G_5 = 0.497, \quad \Lambda = 831\,\mathrm{MeV},$$
$$f_B(\phi) = \frac{\mathrm{sech}(1.2\phi - 0.69)}{3\,\mathrm{sech}(0.69)} + \frac{2e^{-100\phi}}{3}. \quad (5)$$

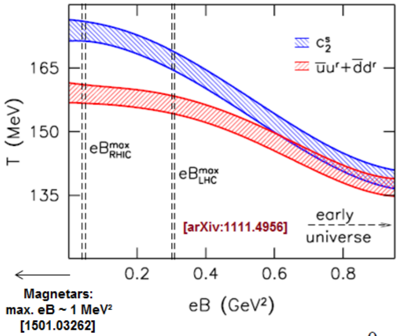
- **EMD-B (with improved potential, G_5, and Λ):**

$$V(\phi) = -12\cosh(0.63\phi) + 0.65\phi^2 - 0.05\phi^4 + 0.003\phi^6,$$
$$G_5 = 0.46, \quad \Lambda = 1058.83\,\mathrm{MeV},$$
$$f_Q(\phi) = 0.95\,\mathrm{sech}(0.22\phi^2 - 0.15\phi - 0.32). \quad (6)$$

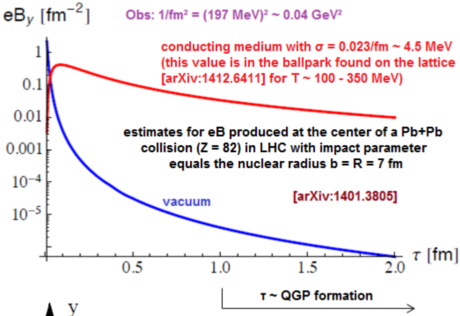
(Improved) Holographic EoS at $\mu_B = \mu_S = \mu_Q = B = 0$



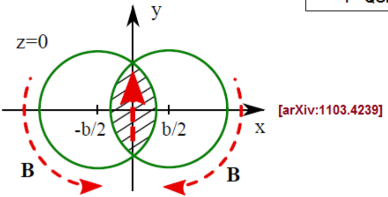
Magnetic fields in non-central collisions



Obs: (pion mass)² ~ 0.02 GeV² ~ 3 x 10^14 T

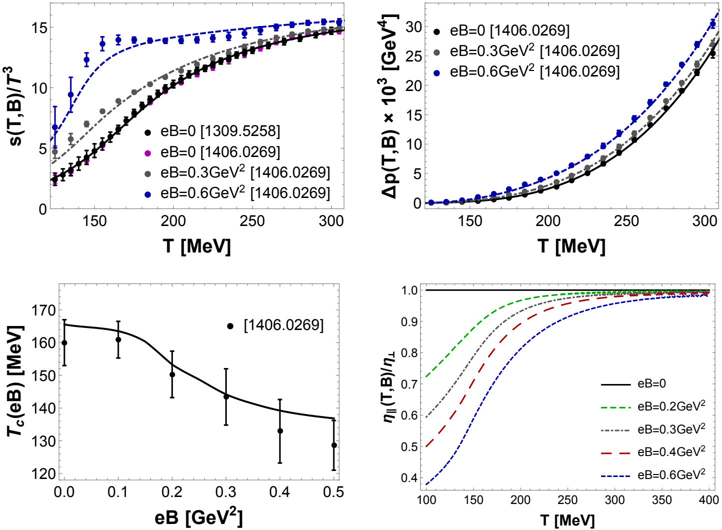


NON-CENTRAL HEAVY ION COLLISON:

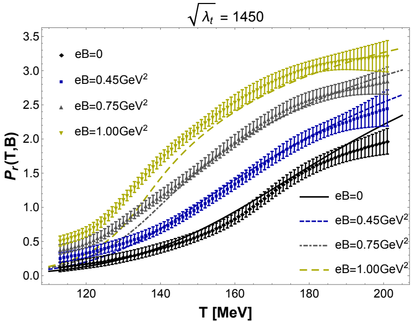


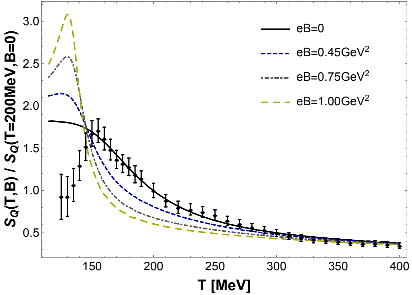
Some results for the anisotropic EMD model at $B \neq 0$, with $\mu_B = \mu_S = \mu_Q = 0$

Magnetic EoS, crossover temperature and anisotropic shear viscosities at $B \neq 0$



Polyakov loop and heavy quark entropy (data: [1303.3972,1504.08280,1603.06637])





Some limitations of the holographic EMD setup

- 1. It does not describe hadron thermodynamics setting in at low T (in the confined phase the pressure goes like[1] $\sim N_c^0$, probably requiring string loop corrections in the bulk);
- 2. At sufficiently high T, any holographic dual in the classical SUGRA limit goes to a strongly coupled UV fixed point, missing asymptotic freedom present in QCD;
- 3. It does not describe the chiral condensate.
- 4. No "rigorous" theoretical justification yet (e.g., embedding into string theory).

[1] See Chapter 4 of the book *From Gravity to Thermal Gauge Theories: The AdS/CFT Correspondence*, Editor: E. Papantonopoulos, Lecture Notes in Physics (Book 828), (Springer, 2011).

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Some alternative, non-stringy routes to holography?!

- **Worldline holography:** D. Dietrich, PRD **89**, 086005 (2014) [1312.5718]; PRD **89**, 106009 (2014) [1404.0011]; PRD **90**, 045024 (2014) [1405.0487]; [1507.04350]; [1509.04294].

- **Higher dimensional geometries from QFT's via gradient (Wilson) flow:** S. Aoki, K. Kikuchi, T. Onogi, PTEP (2015) **101B01** [1505.00131]; [1606.07617]; S. Aoki, J. Balog, T. Onogi, P. Weisz, [1605.02413].

- **Some hard theoretical questions:** Which are the essential ingredients needed to derive the holographic dictionary(ies)?! Is such kind of dictionary unique?! Why some bottom-up constructions work so well in addressing real-world phenomenology?!