Lessons from holography: probing universality

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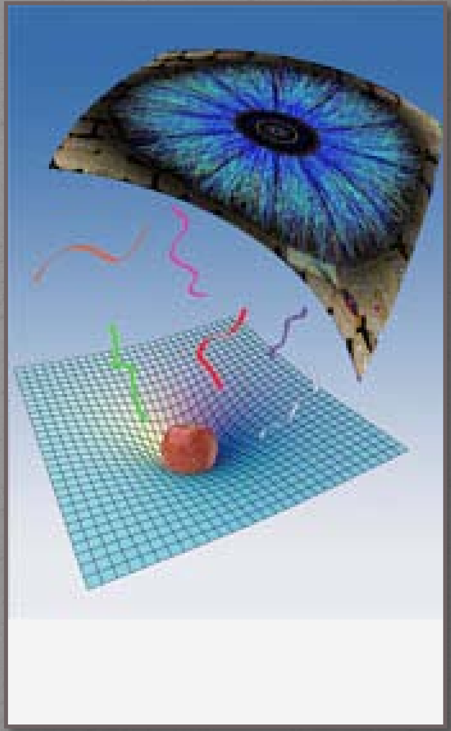
Insight into strong coupling

Many faces of holography:

- Top-down studies (string/M-theory based) focused on **probing features of quantum gravity**
- Bottom-up approaches
  → **'pheno' applications** to QCD-like
  and condensed matter systems



valuable tool for probing
thermal and hydrodynamic properties
of strongly coupled field theories

few theoretical tools available

Microscopic description of such systems is challenging

- often we want their macroscopic behavior, at large distances and long time scales

system typically exhibits universal features

(independent of details of underlying micro description)

Given ‘exotic’ nature of AdS/CFT constructions, crucial to find universal properties:

- gain intuition about real systems in same universality class
- input into realistic simulations

Focus on a particular universal quantity, η/s

Relativistic Hydrodynamics:

$$T^{\mu\nu} = (\epsilon + P)u^\mu u^\nu + P g^{\mu\nu} - \sigma^{\mu\nu}$$

$$\sigma_{ij} = \eta \left(\partial_i u_j + \partial_j u_i - \frac{2}{3}\delta_{ij}\partial_k u^k \right) + \zeta \delta_{ij}\partial_k u^k$$

$$G^R_{xy,xy}(\omega, \mathbf{0}) = \int dt\, d\mathbf{x}\, e^{i\omega t}\theta(t)\langle [T_{xy}(t,\mathbf{x}),\, T_{xy}(0,\mathbf{0})]\rangle = -i\eta\omega + O(\omega^2)$$

$$\eta = -\lim_{\omega\to 0}\frac{1}{\omega}\,\mathrm{Im}\, G^R_{xy,xy}(\omega, \mathbf{0})$$

effective description **of dynamics of system at large wavelengths and long time scales**

Many lessons and still some challenges…

Why interest in η/s ?

Lessons we learned from:

- String theory/sugra constraints
- Consistency of the theory as a relativistic QFT
- 'toy models' not realized in string theory

Interesting behavior in systems with very different physics in IR vs UV → open issues

Work with:
- J.Liu, K. Hanaki, P. Szepietowski (Michigan)
- A. Buchel (PI)

  - arXiv:0812.3572, 0903.3244, 0910.5159
  - arXiv:1007.2963
  - arXiv:1109.xxxx
  - → arXiv:1108.0677 (Review)

Why interest in η/s ?

I) universality of η/s

- For $\mathcal{N}=4$ SU(N) SYM plasma [PSS hep-th/0104066] (planar limit, infinite 't Hooft coupling)

$$\boxed{\frac{\eta}{s} = \frac{1}{4\pi}}$$

UNIVERSAL

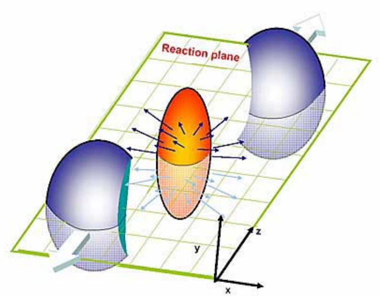
$\lambda,\, N \to \infty$

- universal in all gauge theories with <u>Einstein gravity duals</u> [Buchel, Liu th/0311175] regardless of
  - matter content
  - amount of SUSY
  - conformality
  - with or without chemical potential

II) elliptic flow measurements at RHIC

- **RHIC DATA → very small η/s for QGP**

  comparable to 1/4π



well described by hydrodynamics with a very small
shear viscosity/entropy density ratio -- "perfect fluid"

DATA FAVORS $4\pi\,\eta/s \leq 2.5$ **(e.g. Song et al. 1101.2783)**

- **Contrast to <u>weak coupling</u> calculations in thermal gauge theories:**

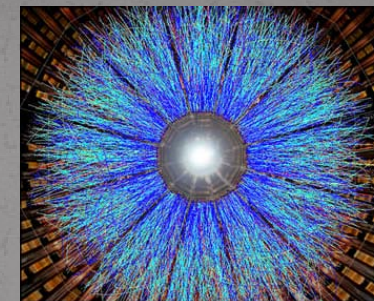
$$\frac{\eta}{s} \sim \frac{1}{\lambda^4 \log 1/\lambda^2} \gg 1$$

Order of magnitude agreement with data

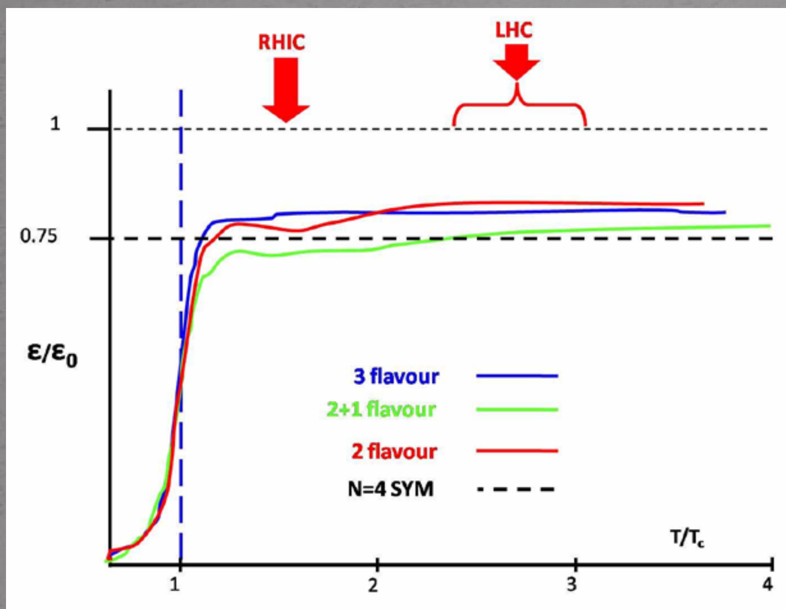
⬇

large effort to use ads/cft to
probe transport properties of sQGP

Can we use CFTs to probe QCD?



N = 4 SYM at finite T somewhat 'exotic'
but some features qualitatively similar:



Karsch, hep-lat/0106019

RHIC ~ 200 GeV
LHC ~ 2.7 TeV

For T ~ T_c - $3T_c$

- Both strongly coupled
- QGP is nearly conformal

(small bulk viscosity away from T_c)

Some properties may be universal

<u>generic</u> relations provide INPUT
into realistic simulations of sQGP

Shear Viscosity Bound

- $\frac{\eta}{s} = \frac{1}{4\pi}$ agrees well with <u>naïve dilute gas approximation</u> suggesting QM bound:

$$\frac{\eta}{s} \sim p\, l_{mfp} \quad \Rightarrow \quad \frac{\eta}{s} \gtrsim \mathcal{O}(\hbar)$$

$$\Downarrow$$

Conjecture that any fluid in nature would obey a bound:

[Kovtun,Son,Starinets th-0309213]

$$\boxed{\frac{\eta}{s} \geq \frac{1}{4\pi}}$$

FUNDAMENTAL IN NATURE?

Natural Next Step: Role of Higher Derivatives?

Motivations?

- Testing validity of bound

fixes signs of higher derivatives

More than that:

- role of string constraints on hydrodynamics (if any)

- Dependence of eta/s on physical parameters of the theory (various charges, chemical potential…) → valuable for pheno applications

Important point: leading sugra approximation hides any interesting sub-structure (eta/s is universal)

String Construction Satisfying Bound

- **Leading α′ correction** on $AdS_5 \times S^5$ (*N* = 4 SYM) increased the ratio [Buchel,Liu,Starinets th/0406264]

$$\frac{\eta}{s} = \frac{1}{4\pi}\left[1 + 15\zeta(3)\lambda^{-3/2} + \ldots\right]$$

$\alpha'^3 R^4$

in Type IIB

finite λ correction

to *N* = 4 SYM

String Construction Violating Bound

Kats & Petrov (arXiv:0712.0743)

- **Type IIB on** $\mathrm{AdS}_5 \times \mathrm{S}^5/\mathbb{Z}_2$
  (decoupling limit of N D3's with collection of D7's and 07)

$$S = \int d^D x \sqrt{-g} \left(\frac{R}{2\kappa} - \Lambda + c_1 R^2 + c_2 R_{\mu\nu} R^{\mu\nu} + c_3 R_{\mu\nu\rho\sigma} R^{\mu\nu\rho\sigma} \right)$$

$$\frac{\eta}{s} = \frac{1}{4\pi} \left[1 - 4(D-4)(D-1) \frac{c_3}{L^2/\kappa} \right]$$

<u>small</u> violation for $c_3 > 0$

c_3 from effective action on world-volume of D7/07 system
(determined by fundamental matter content of theory)

By now many examples of corrections violating the bound

what have we learned?

Questions you can ask:

- What parametrizes bound violation on gauge theory side?
- Role of SUSY/stringy constraints?
- Any remnant of universality with higher derivatives?
- Dependence on various physical parameters?

will answer some of these questions by looking at a specific example (string theory construction)

Corrections to η/s at finite chemical potential

[SC,K.Hanaki,J.Liu,P.Szepietowski,0812.3572, 0903.3244, 0910.5159]

Here we are interested in:

- Electrically charged black holes (chemical potential)

$$\boxed{\mathcal{L}_0 = -R - \frac{1}{4}F_{\mu\nu}^2 + \frac{1}{12\sqrt{3}}\epsilon^{\mu\nu\rho\lambda\sigma}F_{\mu\nu}F_{\rho\lambda}A_\sigma + 12g^2}$$

R-charge Q

- Curvature terms constrained by supersymmetry

higher derivative corrections start at R^2

→ their SUSY completion is known

[off-shell, Hanaki,Ohashi,Tachikawa, th/0611329]

With curvature corrections…

[arXiv:0812.3572, SC,K.Hanaki,J.Liu,P.Szepietowski]

$$\mathcal{L} = -R - \frac{1}{4}F^2 + \frac{1}{12\sqrt{3}}\left(1 - \frac{1}{6}c_2 g^2\right)\epsilon^{\mu\nu\rho\lambda\sigma}A_\mu F_{\nu\rho}F_{\lambda\sigma} + 12g^2 + \frac{c_2}{24}\left[\frac{1}{48}RF^2 + \frac{1}{576}(F^2)^2\right] + \mathcal{L}_1^{\text{ungauged}},$$

$$\begin{aligned}\mathcal{L}_1^{\text{ungauged}} = \frac{c_2}{24}\Big[&\frac{1}{16\sqrt{3}}\epsilon_{\mu\nu\rho\lambda\sigma}A^\mu R^{\nu\rho\delta\gamma}R^{\lambda\sigma}{}_{\delta\gamma} + \frac{1}{8}C^2_{\mu\nu\rho\sigma} + \frac{1}{16}C_{\mu\nu\rho\lambda}F^{\mu\nu}F^{\rho\lambda} - \frac{1}{3}F^{\mu\rho}F_{\rho\nu}R^\nu_\mu \\ &- \frac{1}{24}RF^2 + \frac{1}{2}F_{\mu\nu}\nabla^\nu\nabla_\rho F^{\mu\rho} + \frac{1}{4}\nabla^\mu F^{\nu\rho}\nabla_\mu F_{\nu\rho} + \frac{1}{4}\nabla^\mu F^{\nu\rho}\nabla_\nu F_{\rho\mu} \\ &+ \frac{1}{32\sqrt{3}}\epsilon_{\mu\nu\rho\lambda\sigma}F^{\mu\nu}(3F^{\rho\lambda}\nabla_\delta F^{\sigma\delta} + 4F^{\rho\delta}\nabla_\delta F^{\lambda\sigma} + 6F^\rho{}_\delta\nabla^\lambda F^{\sigma\delta}) \\ &+ \frac{5}{64}F_{\mu\nu}F^{\nu\rho}F_{\rho\lambda}F^{\lambda\mu} - \frac{5}{256}(F^2)^2\Big].\end{aligned}$$

controls strength of higher derivative terms

c_2 can be related to the **central charges** of dual UV CFT via:

- Holograp
- R-current anomaly

Interpretation on dual gauge theory side?

The Link to the Central Charges

Dual theory: 4D CFT with N=1 SUSY

- **4D CFT central charges** ***a,c*** **defined in terms of trace anomaly: (CFT coupled to external metric)**

$$\langle T^\mu{}_\mu \rangle_{CFT} = \frac{c}{16\pi^2}(\mathrm{Weyl})^2 - \frac{a}{16\pi^2}(\mathrm{Euler})$$

Prescription for extracting trace anomaly for higher derivative GR:

$$\langle T^\mu_\mu \rangle = \frac{1}{16\pi^2}\left[\left(\frac{c}{3} - a\right)R^2 + (4a - 2c)R^2_{\mu\nu} + (c - a)R^2_{\mu\nu\rho\sigma}\right]$$

$$\Updownarrow$$

sensitive to higher derivatives

$$\mathcal{L} = R + \alpha_1 R^2 + \alpha_2 R^2_{\mu\nu} + \alpha_3 R^2_{\mu\nu\rho\sigma} + \ldots$$

For us: $c_2 = \dfrac{24}{g^2}\dfrac{c-a}{a}$

Finite N effect

To recap: $\mathcal{L} = R + \alpha_3 R^2_{\mu\nu\rho\sigma} + \dots$ → $\alpha_3 \sim \dfrac{c-a}{a}$

For $\mathcal{N} = 4$ SYM $\quad a = c \quad$ (no R^2 corrections)

In general $\quad a = c = \mathcal{O}(N^2)$ only, and $\quad \dfrac{c-a}{a} \sim \dfrac{1}{N}$

- R^2 terms will correspond to a **1/N correction**
  → non-trivial physics parametrized by (c-a)

- Contrast to $\alpha'^3 R^4$ → finite λ (IIB on $AdS_5 \times S^5$)

Features

$$\frac{\eta}{s} = \frac{1}{4\pi}\left[1 - \frac{c-a}{a}(1+Q)\right]$$

- Bound violated for c-a > 0 (finite N effect)

- R-charge (chemical potential) makes violation worse (surprisingly simple dependence on Q: universality?)

- Eta/s affected only by terms with explicit Riemann tensor:

$$R^2_{\mu\nu\rho\sigma}, \;\; R_{\mu\nu\rho\sigma}F^{\mu\nu}F^{\rho\sigma}$$

reminiscent of Wald's entropy formula

→ SUSY completion did not play any role (except for a,c)

Partially justifies looking at `effective models' and scanning through CFTs

Features…

- Correlation between sign of higher derivative terms required by weak gravity conjecture and bound violation? [see arXiv:0910.5159]

- What happens to universality (appeal behind eta/s)? Seemingly lost with higher derivatives…

$$\frac{\eta}{s} = \frac{1}{4\pi}\left[1 + \frac{(\ldots)}{\lambda^{3/2}} + \frac{(\ldots)}{N} + \ldots\right]$$

But we see `sub-structure' which was masked by universality → useful for pheno applications

Violation of the bound can be traced to inequality of central charges of dual CFT:

$$c - a > 0$$

generic in superconformal gauge theories with unequal central charges

[Buchel et al. 0812.2521]

In holographic models realized in string theory,
violation of the KSS bound is
necessarily perturbative → **always small**
(curvature corrections small)

Original KSS bound is clearly violated.
Is there a bound at all?
How low can eta/s get?

Any finite (large) violation of the bound will entail working in a **model** of gauge/gravity duality (not a ST realization)

Gauss-Bonnet as a toy model [Brigante et al, 0712.0805, 0802.3318]

Black brane solutions known for finite GB coupling

$$I = \frac{1}{16\pi G_N}\int d^5x\,\sqrt{-g}\left[R - 2\Lambda + \frac{\lambda_{GB}}{2}L^2(R^2 - 4R_{\mu\nu}R^{\mu\nu} + R_{\mu\nu\rho\sigma}R^{\mu\nu\rho\sigma})\right]$$

Finite λ_{GB} leads to natural question: arbitrary violation of the bound?

$$\frac{\eta}{s} = \frac{1}{4\pi}[1 - 4\lambda_{GB}].$$

No! Must look at the consistency of the dual QFT:

- **once the coupling becomes too large, one finds modes that propagate faster than light**

microcausality violation $\lambda_{GB} > \frac{9}{100}$ $\Rightarrow$ $\frac{\eta}{s} > \frac{1}{4\pi}\frac{16}{25}$

same bound by requiring positivity of energy measured by a detector in the plasma (Hofman 0907.1625)

Causality Violation and the Link to η/s

- In this model (and many generalizations), **consistency of the GB plasma as a relativistic QFT** ensures small violation of the bound (and gives new lower bound)

causality violation ⟷ **bound violation**

this link may not be of fundamental nature
[S.C.,A.Buchel arXiv:1007.2963]

We considered a slight modification of the GB model, realized in a theory with a superfluid **phase transition**

Idea is generic:

While transport properties are determined by the IR features of the theory, causality is determined by the propagation of UV modes (whose dynamics is not that of hydro)

IR vs. UV Physics

- shear viscosity: coupling of effective hydro description at low momentum and frequency

$$\omega \ll \min(T, \mu, \cdots)\,, \qquad |\vec{k}| \ll \min(T, \mu, \cdots)$$

- microcausality: d … UV

$$\omega \gg \max(T, \mu, \cdots)\,, \qquad |\vec{k}| \gg \max(T, \mu, \cdots)$$

UV microcausality

Link only if same phase of the theory extends over all energy scales (e.g. no phase transitions decoupling UV from IR)

IR viscosity

Features of our Toy Model [S.C.,A.Buchel arXiv:1007.2963]

Based on: holographic model of superfluidity proposed by GHPT 0907.3510 (consistent truncation of Type IIB)

$$\mathcal{L} = R - \frac{L^2}{3} F_{\mu\nu} F^{\mu\nu} + \left(\frac{2L}{3}\right)^3 \frac{1}{4} \epsilon^{\lambda\mu\nu\sigma\rho} F_{\lambda\mu} F_{\nu\sigma} A_\rho + \mathcal{L}_{scalar}$$

$$\mathcal{L}_{scalar} = -\frac{1}{2}\left[(\partial_\mu \phi)^2 + 4\phi^2 A_\mu A^\mu\right] + \frac{12}{L^2} + \frac{3}{2L^2}\phi^2$$

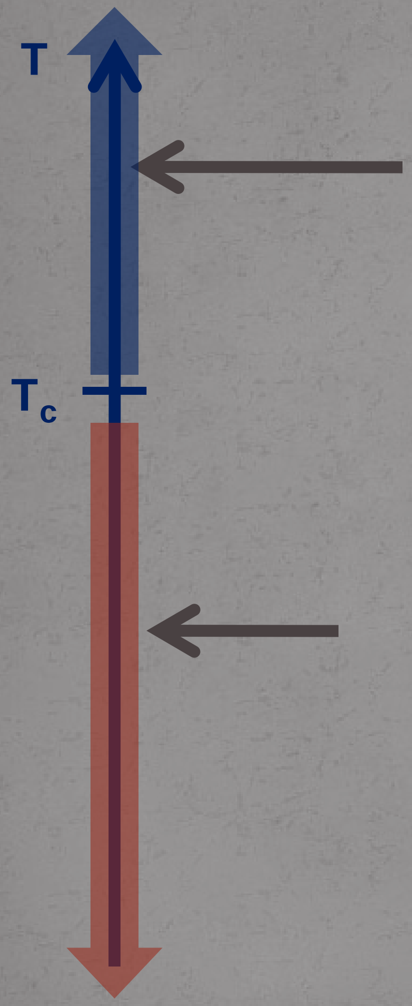
$$\mathcal{L}_{GB} = \beta \phi^4 L^2 \left(R^2 - 4R_{\mu\nu}R^{\mu\nu} + R_{\mu\nu\rho\lambda}R^{\mu\nu\rho\lambda}\right)$$

dual operator develops a VEV below T_c

$$\langle \mathcal{O}_c \rangle \begin{cases} = 0\,, & T > T_c \\ \neq 0\,, & T < T_c \end{cases}$$

$$\lambda_{GB}\Big|^{effective} \begin{cases} = 0\,, & \text{UV} \\ \neq 0\,, & \text{IR}\,. \end{cases}$$

In pictures…



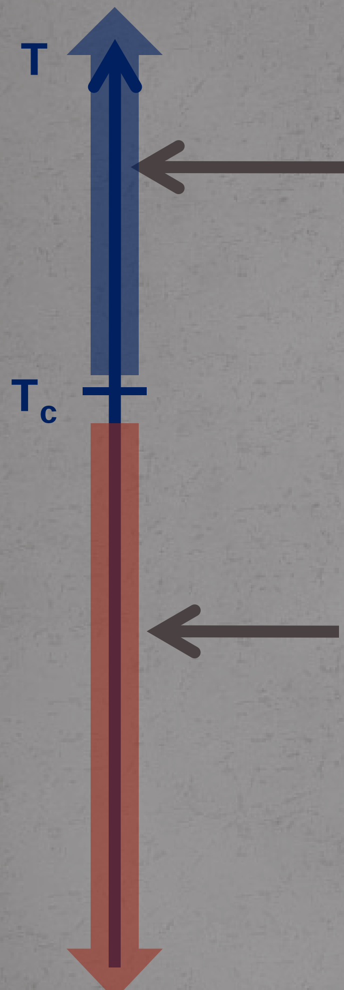
unbroken phase

- electrically charged bh
- Einstein GR

broken symmetry phase

- bh develops scalar hair
- GB higher derivative corrections

The shear viscosity bound [arXiv:1007.2963]

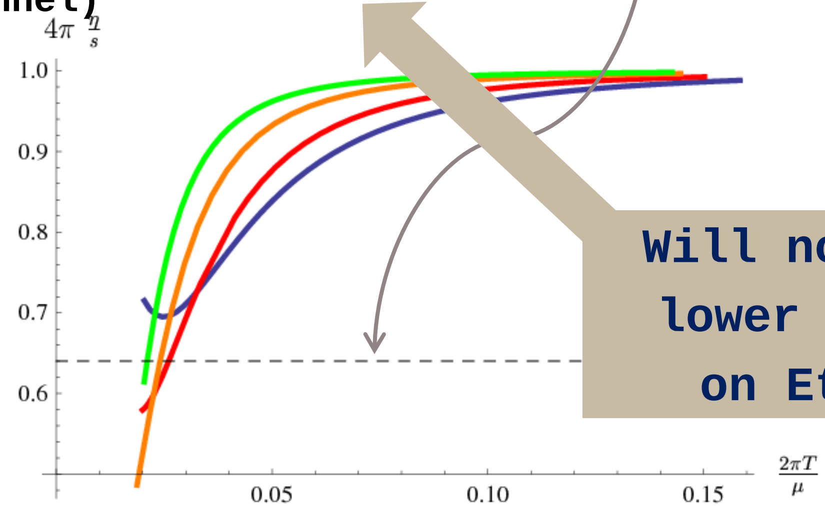


$$\frac{\eta}{s} = \frac{1}{4\pi}$$

expected from universality

when λ_{GB} is non-zero eta/s gets corrected:

- eta/s goes well below pure GB bound (finite λ_{GB})
- <u>no causality violation</u> (down to low T, scalar channel)



Will not set lower bound on Eta/s

"UV/IR Decoupling"

Phase transition has decoupled UV from IR physics

→ example suggests that link between a lower bound on eta/s and causality violation is not fundamental

UV microcausality

IR viscosity

η/s ⟷ causality

central charges of UV fixed point

Radial vs. Temperature Flow

Well known that eta/s doesn't run in any Wilsonian sense (membrane paragigm):

$$\partial_r \Pi = 0 + \mathcal{O}(\omega^2)$$

trivial radial flow between horizon and boundary <u>even with higher derivatives</u>

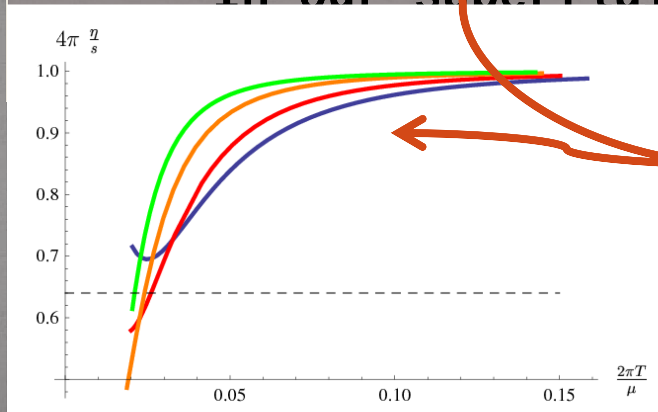
T

$$\frac{\eta}{s} = \frac{1}{4\pi}$$

T_c

In our superfluid GB model, eta/s has

s a function of temperature



jump in Eta/s and temperature flow

Temperature dependence relevant for QGP

Any other ways to get interesting behavior/flow (or “UV/IR decoupling”) for η/s ?

Non-Trivial Scalar Profile?

Charged dilatonic branes with Lifshitz solutions:

$$S = \frac{1}{16\pi G_{d+2}} \int d^{d+2}x \sqrt{-g} \left(R - 2\Lambda - 2(\nabla\phi)^2 - e^{2\alpha\phi}\mathcal{G}^2\right)$$

$$ds^2 = L^2 \left(r^{2z} dt^2 + r^2 dx^i dx^j \delta_{ij} + \frac{dr^2}{r^2} \right)$$

T

AdS brane

Finite T solutions interpolate smoothly between the two (no phase transition)

Lifshitz brane

(dynam exp z)

Probing Lifshitz hydro with higher derivatives

[SC and P. Szepietowski]

T >> μ — AdS brane

No z-dependence (z=1)

Temperature flow

T << μ — Lifshitz brane (dynam exp z)

$$\frac{\eta}{s} = \frac{1}{4\pi}\left(1 + f\left(z, \frac{\mu}{T}\right)\right)$$

IR behavior (Lifshitz) is different enough from UV behavior (AdS) that we expect interesting eta/s behavior <u>without need for phase transition</u>

In Conclusion…

- We are learning to **use gravity to model interesting field theory systems** – how much more mileage can we get?
- Important to identify **universal relations** – but also understand more systematically how they are modified
- Role of string constraints on hydrodynamics, if any?
- KSS bound is violated. But is there **a new lower bound** on eta/s? What is the physics underlying it?

Transport properties: IR feature of theory
→ micro constraints (although important for consistency of theory) should not set lower bound on eta/s

- Although eta/s does not flow in any Wilsonian sense, it still has a **different behavior in the UV than in the IR**

can we understand non-trivial temperature flow
of eta/s in a more systematic way?
(valuable for QGP applications)

More broadly, **generate interesting IR physics by adding relevant deformations** to CFT

Recent attempts to refine the **Wilsonian approach** to gauge gravity duality + apply to fully fledged viscous hydro

1006.1902 (Bredberg,Keeler,Lysov,Strominger)
1009.3094 (Nickel and Son)
1010.1264 (Heemskerk and Polchinski)
1010.4036 (Faulkner, Liu, Rangamani)
…

Thank you