Lessons from Holography:
the Shear Viscosity Bound and UV/IR Decopling

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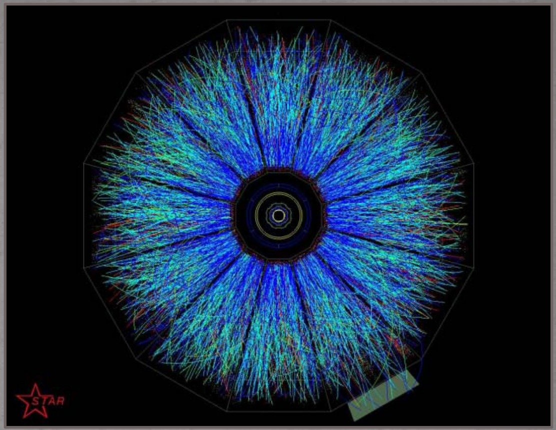
Talk based on:

- arXiv:0812.3572
- arXiv:0903.3244
- arXiv:0910.5159
- arXiv:1007.2963
- arXiv:1106.xxxx

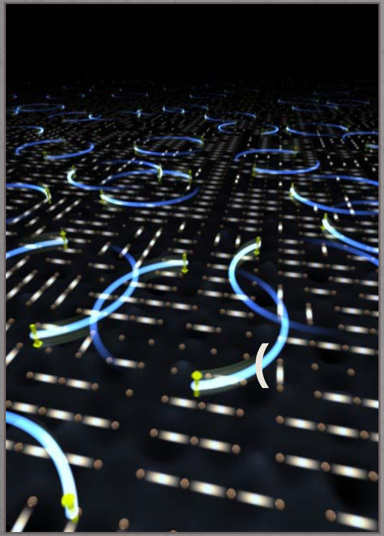
In collaboration with:

A. Buchel (Perimeter Institute)
J. Liu, K. Hanaki, P. Szepietowski (Michigan)

The behavior of many important physical phenomena is governed by the physics of interacting many-body systems, whose dynamics involves a very large number of constituents

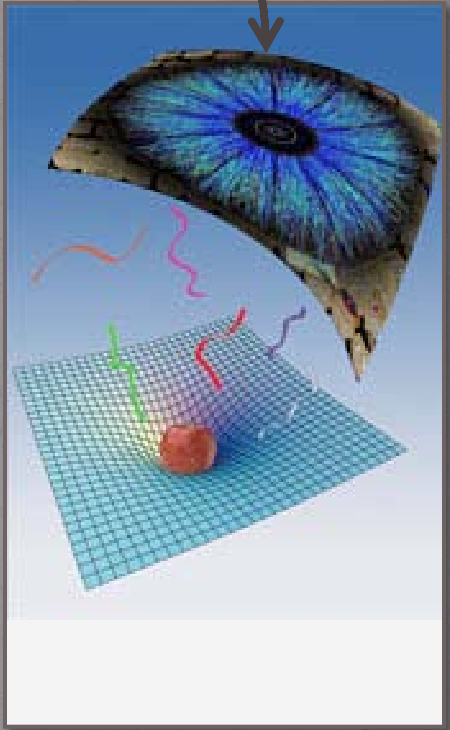


Typically, one is interested in the **macroscopic** behavior (at large distances and long time scales)



In this regime, a system generically exhibits features which are **universal** (independent of the fine details of the underlying microscopic description)

Holographic methods emerging from AdS/CFT have been applied to a variety of strongly coupled gauge theories



valuable tool for probing
thermal and hydrodynamical properties
of field theories at strong coupling

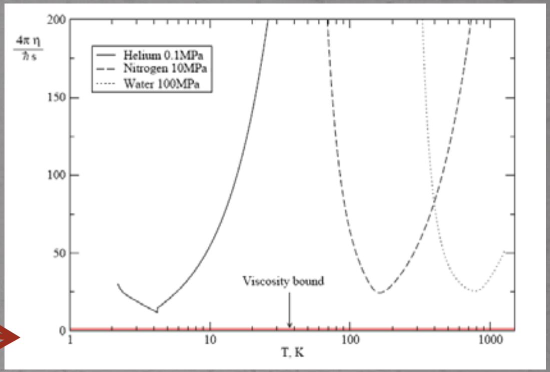
few theoretical tools available
for real-time processes

In this program, important to find universal features
→ gain intuition about **real systems that are in same universality class**

Plan

Focus on a “universal” quantity that has played key role in studies of the QCD quark gluon plasma:

shear viscosity/entropy ratio η/s



Conjectured to be bounded from below:

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

QGP value measured at RHIC close to that predicted by gauge/gravity duality

Outline:

- A bit of background on η/s :
  the QGP plasma and why so much attention from AdS/CFT

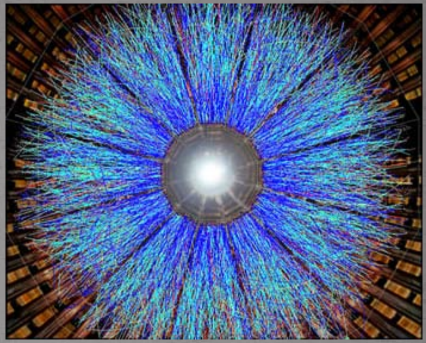
- What AdS/CFT has taught us about η/s
  → focus on **higher derivative corrections**

- It's now well understood that the **bound is violated**
  - features in string theory-based models and
    models with decoupling of UV from IR physics

Part I

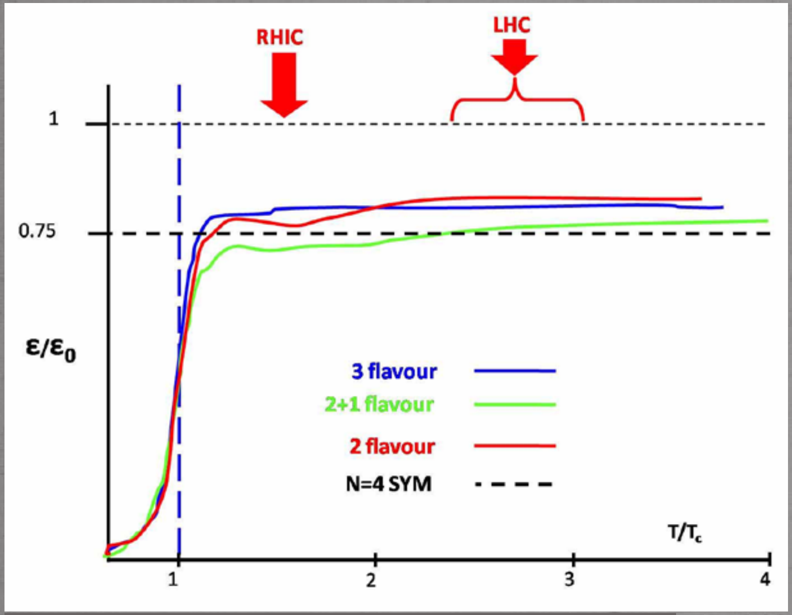
The quark gluon plasma: the perfect fluid

Insight into the quark gluon plasma



RHIC → Au+Au, 200 GeV per nucleon (LHC ~ 2.7 TeV)
→ probe QGP behavior (transport properties)

Can we use CFTs to study properties of QCD?



Karsch, hep-lat/0106019

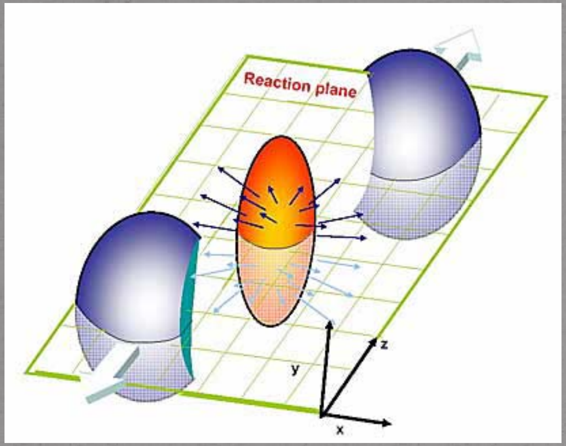
$\mathcal{N} = 4$ SYM at finite T is not QCD but:

- Some features *qualitatively* similar to QCD (for $T \sim T_c$ - $3T_c$)
  - **strongly coupled**
  - **nearly conformal** (small bulk viscosity away from T_c)
- Some properties may be ***universal***

generic relations might provide INPUT into realistic simulations of sQGP

Elliptic Flow at RHIC

Off-central heavy-ion collisions at RHIC:



Anisotropic Flow
(large pressure gradient
in horizontal direction)
Large "Elliptic Flow"

Well described by hydrodynamical calculations with
very small shear viscosity/entropy density ratio -- "perfect fluid"

RHIC data favors $4\pi\eta/s < 2.5$ (e.g. Song et al. 1011.2783)

Nearly Ideal, Strongly Coupled QGP

<u>Weak coupling</u> calculations in thermal gauge theories:

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

QGP with $\frac{\eta}{s} \ll 1$ **→ <u>strong coupling</u> regime**

$$\frac{\eta}{s} \sim p\, l_{mfp}$$

Strongly coupled system → natural setting for AdS/CFT applications

Shear Viscosity from AdS/CFT

Relativistic Hydrodynamics:

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

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

- η can be extracted from certain correlators of the boundary $T_{\mu\nu}$ **(Kubo's formula)**

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

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

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

Part II

The Viscosity Bound

Universality of η/s

For $\mathcal{N}$=4 SU(N) SYM plasma:

planar limit, infinite 't Hooft coupling

[Policastro,Son,Starinets hep-th/0104066]

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

UNIVERSAL

$\lambda,\ N \to \infty$

Result is universal in all gauge theories whose gravity duals are dictated by Einstein gravity

[Buchel & Liu th/0311175]

- **regardless of matter content, amount of SUSY, conformality**

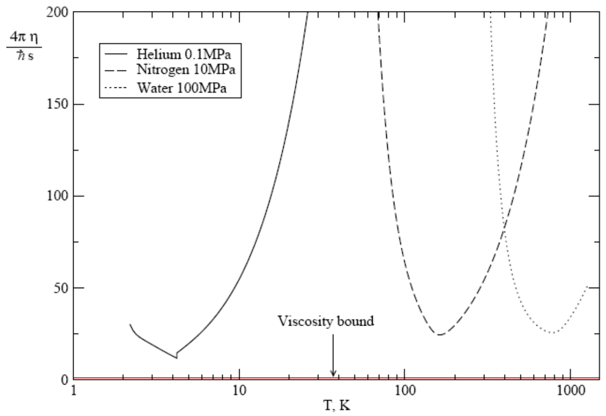
Shear Viscosity Bound

Conjectured lower bound for finite T QFTs → $\boxed{\frac{\eta}{s} \geq \frac{1}{4\pi}}$

[Kovtun,Son,Starinets th-0309213]

Fundamental in nature?

- **Lower than any observed fluid**



- **RHIC value at most a few times**

$$\frac{\eta}{s} = \frac{1}{4\pi} \sim .08$$

- **Simple dilute gas estimate seemed to suggest QM bound:**

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

Ratio $\frac{\eta}{s} = \frac{1}{4\pi}$ **is universal in Einstein GR:**

$$\mathcal{L} = R - \frac{1}{2n!} F_n^2 + \ldots$$

How does it change with higher derivative corrections?

$$\mathcal{L} = R - \frac{1}{2n!} F_n^2 + \ldots + \alpha' R^2 + \alpha'^2 R^3 + \alpha'^3 R^4 + \ldots$$

CFT side:

finite λ, N **corrections**

Testing The Bound

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

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

- Possible bound violations ? YES

  Gauss-Bonnet gravity [Brigante et al, arXiv:0712.0805]

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

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

come back to this later

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 sitting inside 8 D7's coincident on O7 plane)

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

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

small violation for $c_3 > 0$

Couplings → determined by (fundamental) matter content of the theory

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]

Our interest in this story…

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

- **Role of chemical potential (R-charge) on the bound?**
  - at two-derivative level, it has no effect (universality)
  - with higher derivatives, is bound restored with sufficiently large chemical potential?

- **Role of SUSY/stringy constraints?**
  - we were interested in consistent string theory reductions, and therefore corrections constrained by supersymmetry

Corrections to η/s at finite chemical potential

[arXiv:0903.3244, SC,K.Hanaki,J.Liu,P.Szepietowski]

The setup: D=5 $\mathcal{N}=2$ gauged SUGRA (electrically charged black holes)

To leading order:

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

$$ds^2 = H^{-2}f\,dt^2 - H\left(f^{-1}dr^2 + r^2 d\Omega_{3,k}^2\right) \qquad H(r) = 1 + \frac{Q}{r^2},$$

$$A = \sqrt{\frac{3(kQ+\mu)}{Q}}\left(1 - \frac{1}{H}\right)dt, \qquad f(r) = k - \frac{\mu}{r^2} + g^2 r^2 H^3$$

$$\Omega = E - TS - Q\Phi$$

- In this theory higher derivative corrections start at R^2 (sensitive to amount of SUSY)
- They include the **mixed gauge-gravitational CS term:**

$$\mathbf{A} \wedge \mathbf{Tr}(\mathbf{R} \wedge \mathbf{R})$$

SUSY R^2 terms in 5D

- Recall that we are interested in R^2 terms constrained by SUSY

- Instead of brute-force compactification (on Sasaki-Einstein), make use of SUSY [Hanaki,Ohashi,Tachikawa, th/0611329]

SUSY completion of mixed CS term

$$\mathbf{A} \wedge \mathbf{Tr}(\mathbf{R} \wedge \mathbf{R})$$

coupled to arbitrary # of vector multiplets

- Off-shell formulation of *N*=2, D=5 gauged SUGRA (superconformal formalism). End Result

off shell action, lots of auxiliary fields,
supersymmetric curvature-squared term in 5D

On-shell Lagrangian (minimal SUGRA)

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

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

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

controls strength of higher derivative terms

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

- Hologra

Interpretation on dual gauge theory side?

- R-current anomaly

The Link to the Central Charges

For us: 4D CFT with N=1 SUSY

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

$$\langle T^\mu_\mu \rangle = \frac{c}{16\pi^2} C - \frac{a}{16\pi^2} E$$

Prescription for extracting trace anomaly for higher derivative GR:

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

$$\Updownarrow$$

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

$$\Rightarrow \quad c_2 = \frac{24}{g^2} \frac{c - a}{a}$$

sensitive to higher derivative corrections

Finite N effect

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

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

- R^2 Correction will correspond to a 1/N correction

- Contrast to IIB on AdS_5 x S^5

Note: these are not 1-loop corrections in the bulk

(open string effects instead)

Thermodynamics and Hydrodynamics of R-charged black-holes

Putting all ingredients together…

electrically charged black holes

$$s = \frac{2a(1+Q)^{3/2}}{\pi L^6}\left(1 + \frac{c-a}{a}\frac{3Q^2-14Q-21}{8(Q-2)}\right)$$

$$\eta \sim \frac{(1+Q)^{3/2}}{16\pi}\left[1 - \frac{c-a}{a}\frac{5Q^2+6Q+5}{8(Q-2)}\right]$$

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

Suprisingly simple dependence on R-charge: some form of universality?

Bound Violation

[See also Myers et al, 0903.2834]

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

- Bound violated for c-a > 0
- R-charge makes violation worse
- Correction is 1/N effect
- Only terms with explicit Riemann tensor matter:

$$\mathcal{L} = -R - \frac{1}{4}F^2 + \ldots + \frac{c_2}{g^2}\left[\alpha_1 R^2_{\mu\nu\rho\sigma} + \alpha_2 R_{\mu\nu\rho\sigma}F^{\mu\nu}F^{\rho\sigma} \right.$$
$$\left. + \alpha_3 \nabla^\mu F^{\nu\rho}\nabla_\mu F_{\nu\rho} + \alpha_4 \nabla^\mu F^{\nu\rho}\nabla_\nu F_{\rho\mu} + \cdots \right]$$

reminiscent of Wald's entropy formula

Part III

Microcausality violation and the link to η/s

In holographic models realized in string theory, the violation of the bound is necessarily <u>perturbative</u>, and therefore always small (curvature corrections must be small)

Although the original KSS bound was clearly violated, the question of whether a bound on eta/s existed was still open.

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

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

- **Consistency of the GB plasma as a relativistic QFT** ensures small violation of the bound
- GB example suggests **link between violation of viscosity bound and violation of microcausality/positivity of energy**

Such a link cannot 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

- <u>shear viscosity</u>: coupling of effective hydro description at low momentum and frequency

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

- <u>microcausality</u>: d … UV

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

UV microcausality

IR viscosity

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

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)

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

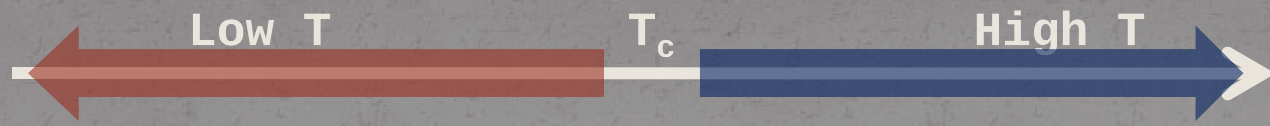
$$\mathcal{L}_{scalar} = -\frac{1}{2}\left[(\partial_\mu\phi)^2 + 4\phi^2 A_\mu A^\mu\right] + \frac{12}{L^2} + \frac{3}{2L^2}\phi^2$$

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

dual operator develops a VEV below T_c

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

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



$T < T_c$

- **broken symmetry phase**
- **Gauss-Bonnet higher-derivative corrections**

$$\lambda_{GB} \neq 0$$

- **Black hole develops scalar hair**

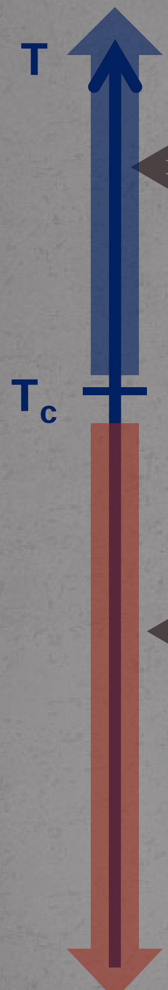
$T > T_c$

- **unbroken phase**
- **no higher derivatives (Einstein GR with U(1) gauge field)**

$$\lambda_{GB} = 0$$

- **electrically charged AdS black hole**

The shear viscosity bound [arXiv:1007.2963]

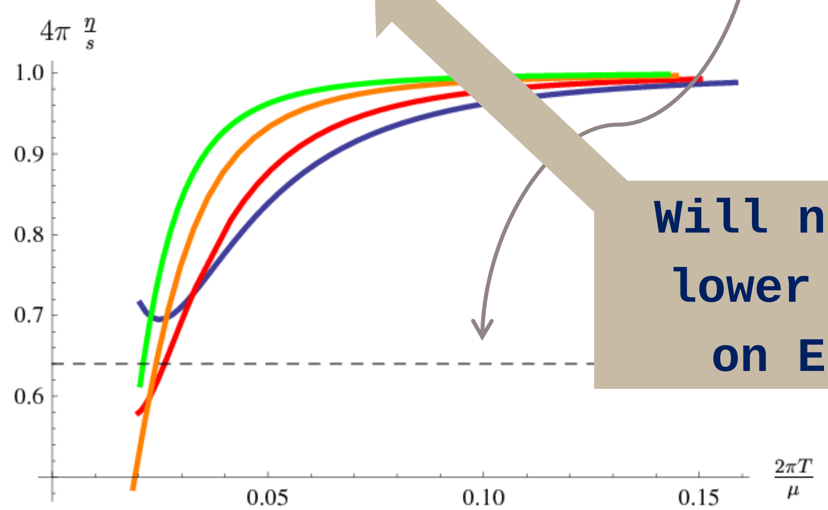


$$\boxed{\frac{\eta}{s} = \frac{1}{4\pi}}$$

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> (scalar channel)



Will not set lower bound on Eta/s

“UV/IR Decoupling”

UV microcausality

IR viscosity

We have decoupled the UV physics from that of the IR

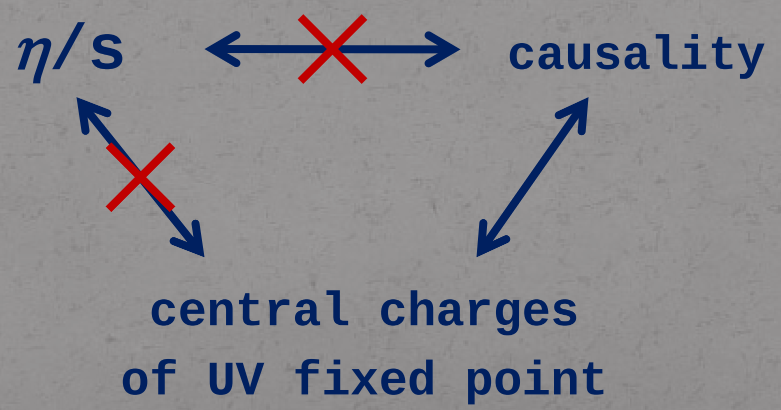
The link between eta/s and causality violation is <u>not fundamental</u>

hydrodynamics is described by IR theory -- in general this is not connected in a trivial way to the UV CFT

Link to the Central Charges?

Even perturbatively, here there is <u>no link between eta/s and the UV central charges</u> of the dual theory:

$$\cancel{\eta/s = \frac{1}{4\pi}\left(1 - \sharp\,\frac{c-a}{a}\right)}$$



Holographic Wilsonian RG Flow

Over the past year, several attempts at refining and developing the **Wilsonian approach** to gauge/gravity duality

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

Eta/s doesn’t run in any Wilsonian sense:

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

but still has non-trivial behavior as a function of temperature

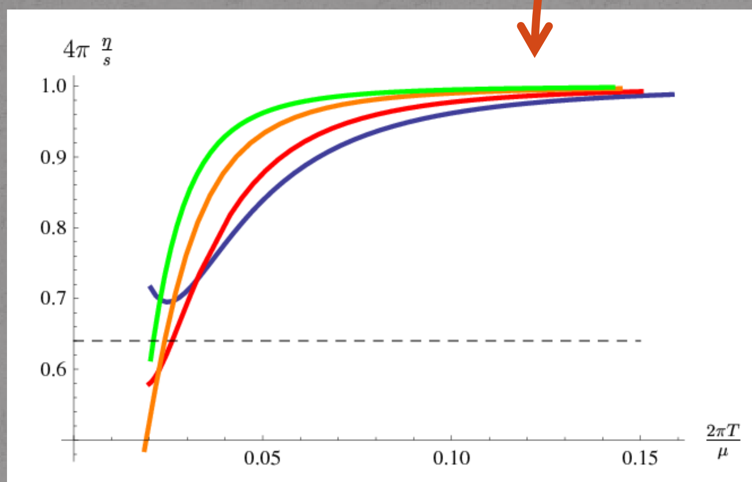
Non-trivial Eta/s "flow"

T

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

jump in Eta/s and temperature flow (first known example)

T_c



temperature dependence may be relevant for QGP

- Can we understand **jump in eta/s**, in Wilsonian approach? (relevant double trace deformations of CFT, triggering RG-flow)

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

Non-Trivial Scalar Profile?

Charged dilatonic branes with Lifshitz solutions:

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

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

Geometries exhibiting Lifshitz scaling

$$t \to \lambda^z t, \quad x_i \to \lambda x_i$$

have played a key role in probing quantum critical systems (dilatonic b.h. → zero entropy at zero temperature)

From Lifshitz to AdS [SC and P. Szepietowski]

T

AdS brane

Finite T solutions constructed (1101.1980)
→ smooth interpolation between the two
(no phase transition)

Lifshitz brane
(dynam exp z)

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…

- Original KSS bound is violated, and with higher derivatives **universality of eta/s is seemingly lost**

- Idea behind GB superfluid is generic:

  transport coefficients are IR features of the theory, while causality/central charges are a property of the UV.

- **Microscopic constraints** - while important for the general consistency of the plasma as a relativistic field theory - **are NOT responsible for setting the lower bound on η/s**

The question of a bound on η/s – whether it exists and what is the physics that determines it – remains open.

- 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 better understand non-trivial eta/s (hydro more generally) within new Wilsonian approach?
Relevant deformations, etc?

- How much more mileage can we can get from gravity setups to model interesting field theory systems (and any constraints arising from consistency of the theory)?

- Development of **universal relations** particularly important (they provide useful inputs into realistic simulations of strongly coupled systems)

The End