### RHIC physics and String Theory: The Fundamental Story



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# Plan

i) Motivation. ii) Phase transitions. iii) Viscosity. iv) Photon production. v) Finite density. vi) Future prospects.

# i) Motivation.

# The QCD challenge

• QCD remains a challenge after 34 years!



# The QCD challenge

- QCD remains a challenge after 34 years!
- A string reformulation might help.
- Lots of gauge/gravity examples.
- Unfortunately, QCD dual is not accessible via supergravity.

# Therefore:

• Certain quantitative observables (eg. T=0 spectrum) will require going beyond supergravity.

- However, certain predictions may be universal enough to apply in certain regimes.
- Good example:  $\eta/s = 1/4\pi$  Gubser, Klebanov & Peet '96

Policastro, Son & Starinets '01

Same for all non-Abelian plasmas with gravity dual!

• How about QCD just above deconfinement?



#### Results from RHIC indicate  $\eta/s$  -  $1/4\pi$ .



*Animation by Jeffery Mitchell (Brookhaven National Laboratory). Simulation by the UrQMD Collaboration*

# Observations:

• Did not know  $\eta/s$  was going to be universal!

Kovtun, Son & Starinets '03

TD7

 $\frac{1}{2}$ 

<sup>µ</sup><sup>ν</sup> <sup>∼</sup> <sup>δ</sup><sup>2</sup>SD7

**MAR** 

 $\frac{1}{2}$ 

BH

 $\bullet$ 

• Based on universal property: First order phase of the phase of  $\frac{1}{3}$  deconfined

Gravity dual of a deconfined plasma contains a black hole

# Observations:

• Combine with another one:

N<sub>f</sub> <<N<sub>c</sub> quark flavours correspond

Karch & Katz '02

For concreteness will concentrate on D7 probes in D3 background.  $\Gamma$ <sub>c</sub>  $\alpha$ .



This operator is not gauge-invariant in the five-dimensional gauge theory, since the

left- and right-handed quarks live at different values of <sup>x</sup>4. If it is to be understood as



#### ii) Fundamental phase transitions.

D.M., Myers & Thomson '06

Previous related work:

Babington, Erdmenger, Guralnik & Kirsch '03 Kruczenski, D.M., Myers & Winters '03 Kirsch '04



#### iii) Viscosity of fundamental matter.

D.M., Myers & Thomson '06

# Universal viscosity bound  $\overline{c}$ <sup>1</sup> $\overline{c}$ versal viscosity bound an operator in the effective four-dimensional theory, then what is the gauge-invariant is the gauge-invariant is omiver sai and in the effective found-dimensional theory, the effective found-invariant is the gauge-invariant intervalse in the gauge-invariant intervalse in the gauge-invariant intervalse in the gauge-invariant intervalse in the ga  $\blacksquare$

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left- and right-handed quarks live at different values of x<sup>4</sup>. If it is to be understood as

· Conjectured universal bound for relativistic plasmas: An additional minor point is that, with the definition of χ<sup>g</sup> just above eq. (1.1), five-dimensional operator it descends from? An additional minor point is that, with the definition of χ<sup>g</sup> just above eq. (1.1),  $T_{\text{e}}$  operator is not gauged-independent in the formulativistic plasmacy left- and right-handed quarks live at different values of x4. If it is to be understood as a set of x4. If it is to be understood as a set of x4. If it is to be understood as a set of x4. If it is to be understood as a set

$$
\frac{\eta}{s} \geq \frac{1}{4\pi}
$$
 Kovtun, Son & Starinets 'o<sub>3</sub>

left- and right-handed quarks live at different values of at different values of x4. If it is to be understood

This is a beautiful paper that I very much enjoyed reading. I will be happy to be happy to be happy to be happy

recommend its publication provided the authors can clarify the precise meaning of

Kovtun, Son & Starinets '03

• Saturated at  $N_c \to \infty$ ,  $\lambda \to \infty$  by all holographic theories with adjoint matter.  $\bullet$  Seturated at  $N \rightarrow \infty$ , i.e., hy all holographic theories five-dimensional operator it descends from? and additional minor point is that, with adjoint matter.

FIGURES HUILT AND ARRIVE.  $\frac{1}{s}$  and  $\frac{1}{4\pi}$  Roma **• Results from RHIC are close:**  $\frac{1}{2} \sim \frac{1}{4}$  Shuryak '03<br>Romatschke & Romatschke '07

s

• Results from RHIC are close: 
$$
\frac{\eta}{s} \sim \frac{1}{4\pi} \max_{\text{Homatschke }\&\text{ Romatschke 'o7}}^{\text{Teaney 'o3}} \left\{\frac{\text{Shuryak 'o3}}{\text{Heinz 'o7}}\right\}
$$

Romatschke & Romatschke '07<br>Heinz '07 Teaney '03 Shuryak '03 Heinz '07

"Chiral

graphic Dual of Large-N QCD" (1994) , J. High Energy Phys. 05 (2004) 041.  $\sum_{i=1}^{\infty} \sum_{i=1}^{\infty} \frac{1}{i}$  $N$  correction • What about when quarks are included? Tdec = 175 MeV (3) MeV<br>Tdec = 175 MeV (3) MeV  $\text{QCD}$  and leading  $N_\text{f}/N_\text{c}$  correction.

<sup>∼</sup> <sup>λ</sup>N<sup>f</sup>

MT357AS



#### iv) Holographic photon production.

D.M., Patiño-Jaidar (to appear)

# Why photons?

• QGP is optically thin <sup>→</sup> Photons carry valuable information.



#### • Holographic results for massless matter:

Caron-Huot, Kovtun, Moore, Starinets & Yaffe '06 Parnachev & Sahakian '06

The distribution of the extremated to be added to the electromagneer in the electromagneer of the state o  $\begin{array}{c} \text{or in the electromagnetic couplings} \\\\2\end{array}$ nB(k0) ! To leading order in the electromagnetic coupling cons  $n-1$  $\sum$ magnetic coupling constant: · To leading order in the electromagnetic coupling constant:  $\overline{\phantom{a}}$ c coupling constant:

**de** 

d<br>d−1200 d−1200

at leading order in the electromagnetic coupling constant e, is then given by [22]

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<sup>ν</sup> (0)]\$ (2.6)

<sup>µ</sup> (x), J EM

 $\frac{1}{2}$  (2.6)

eko 1 (2.7)

 $(x,y)$ 

**de** 

µ

GRI

 $\frac{1}{2}$ 

 $\frac{1}{2}$ 

 $\mathcal{X}^{\text{R}}$ 

 $\frac{1}{2}$ 

legs) is given in fig. 2. Finally,

$$
\frac{d\Gamma}{d^d\mathbf{k}} = \frac{e^2}{(2\pi)^d 2|\mathbf{k}|} \frac{1}{e^{k^0/T} - 1} \eta^{\mu\nu} \chi_{\mu\nu}(k)
$$

, k), with known  $\lambda$ , with known number  $\lambda$  $k = (k^0, \mathbf{k})$ , with  $k^0 = |\mathbf{k}|$ , is the photon null momentum  $\mathbf{m}$  (k) (2.5)  $dt_{\rm th}$   $\mu^0 = |{\bf k}|$  is the photon pull momentum.  $t_{\rm tot} \approx -\mathbf{K}$ , is the photon fight inometrically

 $\alpha_{\rm P}$  (*k*)  $\alpha$  images **μν (2.5)** (2.5) (2.5) (2.5) (2.5) (2.5) (2.5) (2.5) (2.5) (2.5) (2.5) (2.5) (2.5) (2.5) (2.5) (2.5) (2.5) (2.5)  $\chi_{\mu\nu}(k) = -2 \operatorname{Im} G_{\mu\nu}^{\rm R}(k)$  is the spectral density  ${\rm ty}$  $\lim_{\mu\nu}$   $\int_{\mu}$  is the spectral density

$$
G_{\mu\nu}^{\rm R}(k) = -i\int d^{d+1}x \, e^{-ik\cdot x}\, \Theta(x^0)\langle [J_{\mu}^{\rm EM}(x),J_{\nu}^{\rm EM}(0)]\rangle
$$

 $\mathcal{H}^{\mathcal{U}}$ 

n<br>B(ko) = 100 minut



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nB(ko) = 100 km<br>B(k0) = 100 km<br>B(k0) = 100 km

#### Universality and Scaling in AdS/CFT with Flavour with Flavour with Flavour with Flavour with Flavour with Flavo  $U(N_f) \simeq SU(N_f) \times U(1)_{\rm B}$  /gauge  $\Rightarrow$ Conserved  $J^{\text{\tiny B}}_{\mu}=J^{\text{\tiny EM}}_{\mu}$  $\mu$ The Company of η r 1 pres<br>°°  $\dot{\mathbf{r}}$  $\overline{a}$  $G_{\mu\nu} \sim$  $\frac{\partial^2 D_{\rm D7}}{\partial A_\mu \delta A_\nu}$ g2 Gauge theory String theory  $\mathbf y$ String theory in Additional Company of the Additional Company of the Additional Company of the Additional Company of the Addi<br>The Additional Company of the Additional Company of the Additional Company of the Additional Company of the Ad  $A_\mu$  /  $\overline{\phantom{a}}$  $r^2 + r^2$ U(Nf) 30 U(1)B (3) η ! (2 − 4) × 1 1 Nf !! YMNcT<sup>3</sup> (5) gauge five-dimensional operator it descends from? A ADIO graphic calculation which is the usual one, I believe the usual factor in the numerical factor in the numerical factor in the numerator of  $\frac{S(\text{tring theory})}{S(\text{tring theory})}$ be a 4, not a 2. Similarly, the a 2. Similarly, there is a factor of 1/2 missing on the right-most term of eq.  $U(N_f) \cong SU(N_f) \times U(1)_B$  (gauge  $\sim$  MeV)  $\mu$  (1) and Nf/N<sup>c</sup> (2) AdS/CFT prescription:  $\frac{\partial^2 \mathcal{L}}{\partial x^2}$ ption:<br>7  $A$  and the ditional minor point is that, with the definition of  $\mathcal{A}$ which is the usual orientation  $\mathcal{L}^{\mathcal{L}}_{\mathcal{L}}$  and d  $\mathcal{L}^{\mathcal{L}}_{\mathcal{L}}$  and c  $\mathcal{L}^{\mathcal{L}}_{\mathcal{L}}$  and  $\mathcal{L}^{\mathcal{L}}_{\mathcal{L}}$  and  $\mathcal{L}^{\mathcal{L}}_{\mathcal{L}}$  and  $\mathcal{L}^{\mathcal{L}}_{\mathcal{L}}$  and  $\mathcal{L}^{\mathcal{L}}_{\mathcal{L}}$  and  $\mathcal{L}^{\mathcal{L}}_{\mathcal{L}}$  and  $\$  $\sim$ ∼  $N<sub>s</sub>$ )  $A_{\mu}$  $\overline{\mathcal{L}}$ "  $\sqrt{2}$ gij (3) de la provincia de la resc (4)  $G_{\mu\nu}^{\scriptscriptstyle{\mathrm{R}}} \sim$  $\delta^2 S_{\text{\tiny D7}}$  $\delta A_\mu \delta A_\nu$ η 1 Holographic calculation

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(6)

#### **Comments:** Universality and Scaling in AdS/CFT with Flavour and Scaling in AdS/CFT with Flavour and Scaling in AdS/CFT with F

eq. (2.6).

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eq. (2.6).

#### • Concentrate on BH embeddings:

e2

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recommend its publication provided the authors can clarify the authors can clarify the precise means of the pre



 $F_{\text{r}}$  the viewpoint of  $\mathbf{M}_{\text{r}}$  dependence to back  $\Omega$ • No obvious comparison of  $\rm M_q$ -dependence to pQCD: proportional to the quark mass, whereas the size of the black hole horizon is proportional  $M_{\rm thermal} \sim \sqrt{\lambda} T \gg M_q$  Arnold, Moore  $\propto$  rane of be a 4, not a 2. Similarly, there is a factor of 1/2 minutes of 1/2 minutes on the right-most term of 1/2 mi Arnold, Moore & Yaffe '01 omparis m  $\mathbb{R}$  . The set of  $\mathbb{R}$  is the set of  $\mathbb{R}$  , we have the set of  $\mathbb{R}$  ,  $\mathbb{R}$  ,

> But this assumes existence of quasi-particles! gravitational force overcomes the tension of the branes and these are pulled into the horzion. λ (1961) (1961) (1961) (1962) (1961) (1961) (1961) (1961) (1961) (1961) (1961) (1961) (1961) (1961) (1961) (19

In the dual field theory, this phase transition is exemplified by discontinuities in physical

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# To compare with experiment

• Calculate photon production rate:





### To compare with experiment

• Plug into hydrodynamic simulation of spacetime evolution of the plasma.

• Experimentally distinguish different sources: QGP photons, prompt photons, decay photons, etc.

#### v) Finite baryon density.

Kobayashi, D.M., Matsuura, Myers & Thomson '06







# vi) Future prospects.

## Towards far from equilibrium

BH

Horizons encode properties of QGPs:

- Static  $\rightarrow$  Thermodynamics: S=A/4G.
- Small perturbations  $\rightarrow$  Near equilibrium, eg. transport coefficients.
- Large perturbations  $\rightarrow$  Far from equilibrium, eg. collective instabilities.

# Lots to do at finite density



#### Caveats: Scalar fields (but not always) and large N<sub>c</sub>.

Sakai & Sugimoto

# Towards holographic condensed matter



Herzog, Kovtun, Sachdev & Son '07 Hartnoll & Kovtun '07 Hartnoll, Kovtun, Mueller & Sachdev '07

# Heavy ion collisions at LHC TRHIC ~2Tdec , TLHC ~4Tdec



