Title: Non-conformal Gauge Theory Plasma in String Theory

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Abstract:

Non-conformal gauge theory plasma from gauge/string correspondence

Alex Buchel

(University of Western Ontario & Perimeter Institute)

Based on: hep-th/0311175,0405200,0406264,0408098,0506002,0507026,0507275,0509083 0510041,0605076, 0605178, 0608002, 0610145

Collaborators: J.Liu, A.Starinets, O.Aharony, A.Yarom, P.Benincasa, R.Naryshkin

Original work: **D.Son**, **A.Starinets**, · · ·

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ZoneAlarm Security Alert

REPEAT PROGRAM

Adobe Reader 7.0 is trying to access the Internet.

Identification: Not available in ZoneAlarm
Application: AcroRd32.exe
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Motivation:

Find a useful (experimentally testable) application of gauge theory/ string theory correspondence

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

- $g_{YM}^2 N \ll 1$ (weak effective coupling) $\Longrightarrow$ perturbative gauge theory description
- $g_{YM}^2 N \gg 1$ (strong effective coupling) $\Longrightarrow$ IIB string theory on $AdS_5 \times S^5$

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Gauge theory/string theory (Maldacena correspondence)

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Gauge theory/string theory (Maldacena correspondence)

- Effective description of a dynamics of a thermal system on length and time scales much longer than any relevant microscopic scale is provided by hydrodynamics
- microscopic system can be strongly coupled; in this case its hydrodynamic description (if valid) is characterized by a few "phenomenological parameters"

In this talk we discuss hydrodynamic properties of strongly coupled hot gauge theory plasma

$\Updownarrow$ gauge/string correspondence

hydrodynamics of metric fluctuations in IIB SUGRA black hole background

- The latter map would allow to compute "phenomenological parameters" of the hydrodynamics from first principles

Outline of the talk:

- Consistencies of hydrodynamic description (gauge theory perspective)
- Consistencies of hydrodynamic description (SUGRA perspective)
- Applications **A**

- renormalization of cascading gauge theories
- dynamical vs. thermodynamic instabilities of the horizon geometries
- beyond SUGRA: α' corrections in $\mathcal{F}_5$ backgrounds of string theory

As with any duality information flows in both directions:

A: gauge theory $\Longrightarrow$ string theory

B: string theory $\Longrightarrow$ gauge theory

- **A** What hydrodynamics can teach us about string theory?
- **B** What are the lessons for the transport properties of hot gauge theory plasma from string theory?

$$A \Longrightarrow B$$

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- Applications **B**

- small shear viscosity of $\mathcal{N} = 4$ plasma and why this could by of relevance to RHIC physics
- bulk viscosity of "realistic plasma"
- Jet quenching in strongly coupled plasma
- Universality of shear viscosity with chemical potential

- Conclusions, future directions, open problems

Hydrodynamics (gauge theory perspective)

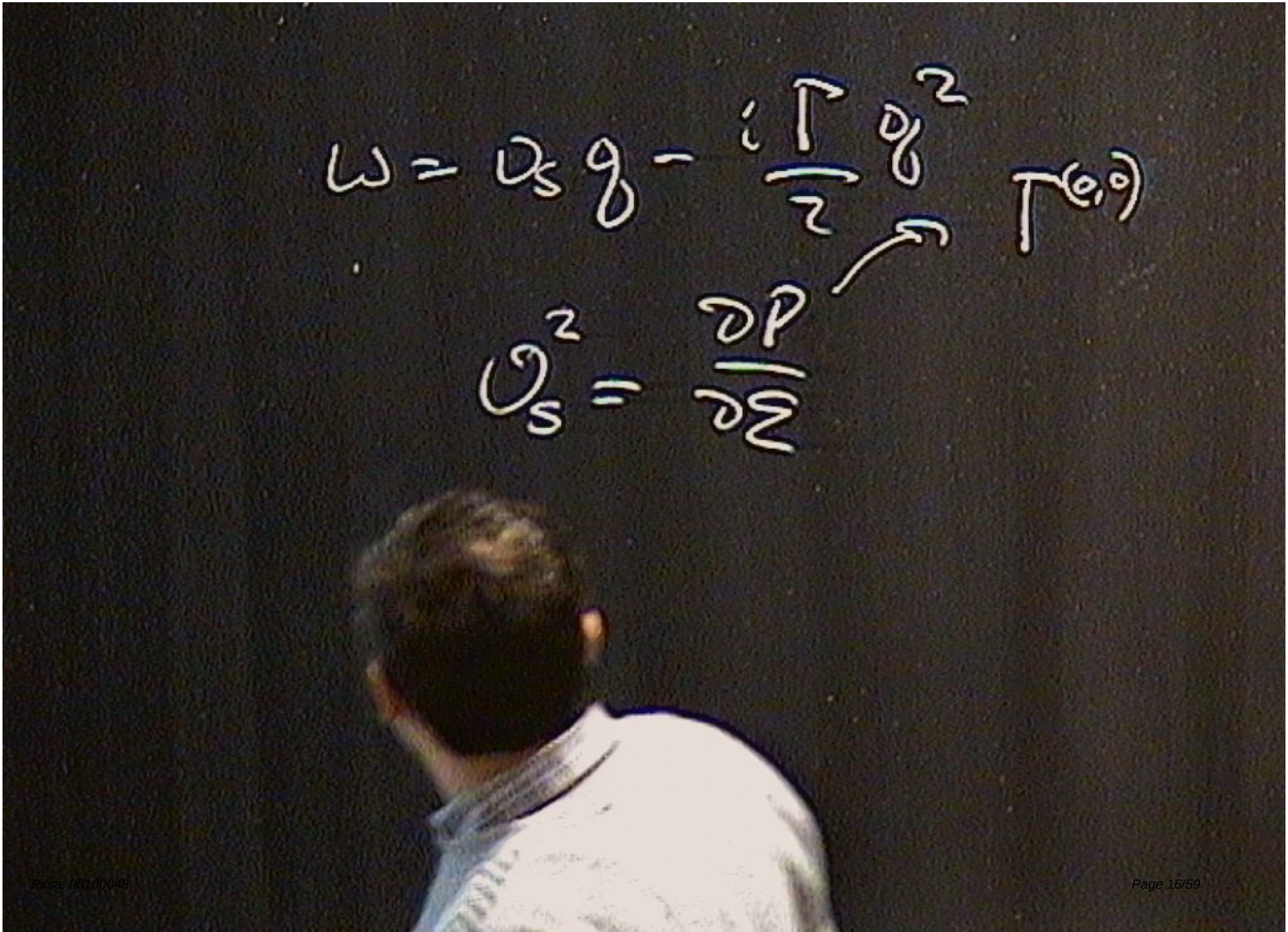
hydro mode	**computation**	**produces**
shear **(sh.1)**	$< T_{xy,xy} >_{R,A}$ +Kubo formula	η
shear **(sh.2)**	$< T_{xz,xz} >_R$ +pole	$D = \frac{\eta}{Ts}$
sound **(sw.1)**	$< T_{00} >, < T_{ii} >$	v_s
sound **(sw.2)**	$< T_{00,00} >_R$ +pole	v_s, Γ

- **(sh.1)** and **(sh.2)** produces η — must be consistent
- **(sw.1)** and **(sw.2)** produces v_s — must be consistent, also $\Gamma = \frac{4}{3}\frac{\eta}{Ts}\left[1 + \frac{3\xi}{4\eta}\right]$ is sensitive to D, η

$$\omega = c_s q - i \frac{\Gamma}{2} q^2$$

$$\omega = v_s q - i \frac{\Gamma}{2} q^2$$

$$v_s^2 = \frac{\partial P}{\partial \varepsilon}$$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$\Gamma(\omega, q)$
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$$v_s^2 = \frac{\partial P}{\partial \varepsilon} \longrightarrow T^{(0,0)}$$

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$\nearrow \ \Gamma$

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$$\langle T_{\mu\nu} \rangle$$

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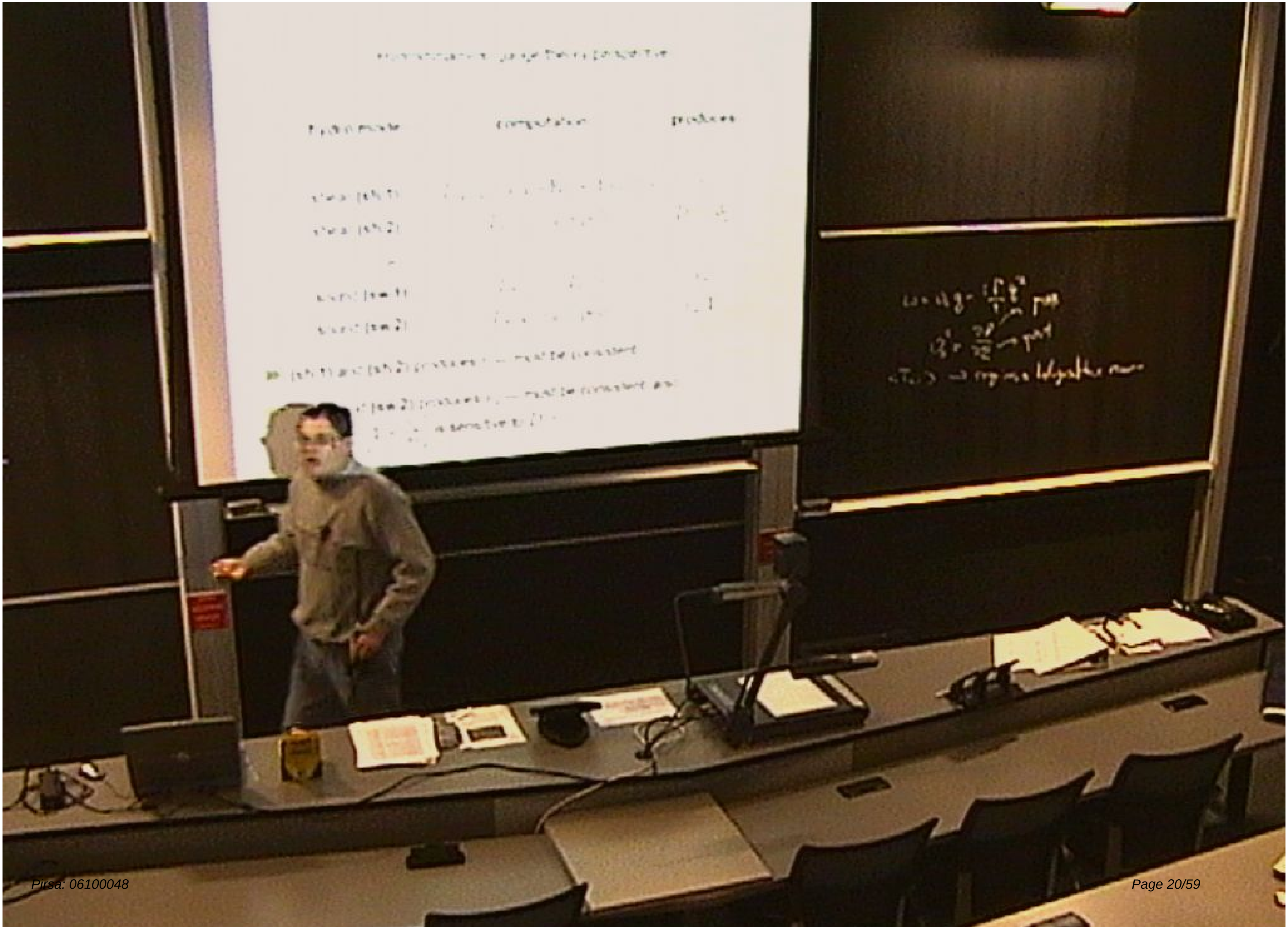

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$\langle T_{\mu\nu} \rangle \Rightarrow$ requires a holographic renorm

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Hydrodynamics of supergravity fluctuations

$\underline{T = 0}$

gauge theory		string theory
$SU(N)$ SYM	$\Longleftrightarrow$	N-units of 5-form flux
g^2_{YM}	$\Longleftrightarrow$	g_s

- we study the theory in the 't Hooft (planar limit), $N \to \infty$, $g^2_{YM} \to 0$ with $N g^2_{YM}$ kept fixed
- SUGRA is valid $N g_s \to \infty$

$\frac{1}{N}$-corrections	$\Longleftrightarrow$	g_s-corrections
$\frac{1}{N g^2_{YM}}$-corrections	$\Longleftrightarrow$	α'-corrections

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$$\frac{1}{N}\text{-corrections} \Longleftrightarrow g_s\text{-corrections}$$
$$\frac{1}{N g^2_{YM}}\text{-corrections} \Longleftrightarrow \alpha'\text{-corrections}$$

$\underline{T \neq 0}$

gauge theory at temperature T $\Longleftrightarrow$ black brane in $AdS_5 \times S^5$ at Hawking temperature $T_H = T$

- Both finite and $T = 0$ gauge/gravity correspondence can be extended to non-conformal gauge theories (by turning on fluxes) and to quiver gauge theories (by starting with branes on conical singularities)

We would end up computing correlation functions of gauge theory operators on SUGRA side

- We will be interested in correlation functions of the stress-energy tensor $T_{\mu\nu} \Rightarrow$ so the relevant SUGRA mode is the 5D metric fluctuations $\delta g_{\mu\nu}$

➤ Complication: in cases with reduced SUSY and broken conformal invariance $\delta g_{\mu\nu}$ fluctuations mix with "matter" fluctuations

➤ one has to worry about the issue of gauge (reparametrization) invariance —not all fluctuations are physical

- Suppose that Z represents gauge invariant fluctuation —analog of Bardeen potentials in cosmology —for a retarded correlation function

➤ Z is an incoming wave at the horizon

➤ near the boundary

$$Z = \mathcal{A}\, r^{-\Delta_-}\,(1+\cdots) \quad + \quad \mathcal{B}\, r^{-\Delta_+}\,(1+\cdots)$$

$$\Uparrow \qquad\qquad \Uparrow$$

non-normalizable mode   normalizable mode

It is straightforward to evaluate using the general prescription above [P.Kovtun,A.Starinets, hep-th/0506184+other people]

$$< \mathcal{O}\mathcal{O} >_R \quad \sim \quad \frac{\mathcal{B}}{\mathcal{A}} + \text{contact terms}$$

so to extract the poles of a 2-point correlation function one has to find the spectrum of black brane quasinormal frequencies

Definition: Z is a quasinormal mode if it is:

(i) an incoming wave at the horizon;

(ii) satisfy a Dirichlet condition at the boundary

Some important points:

- the poles of the retarded correlation functions can be extracted without renormalizing the theory: boundary counterterms (on top of the standard Gibbons-Hawking counterterm) can modify only contact terms of correlators (which are renormalization prescription dependent anyway)

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- Recall that for the sound wave mode v_s can be computed from

(sw.1) $v_s^2 = \frac{\partial P}{\partial \epsilon}$ [1-point $< T_{\mu\nu} >$] $\Longleftarrow$ needs renormalization

(sw.2) From the sound pole of $< T_{00} T_{00} >$ $\Longrightarrow$ using quasinormal mode approach <u>without</u> holographic renormalization

Consistency of **(sw.1)** and **(sw.2)** provides a highly nontrivial check on holographic renormalization of the theory

- for the shear mode certain correlation functions do not have a pole (because they do not couple to energy or momentum fluctuations) $\Leftrightarrow$ corresponding (=transverse) metric fluctuations $\delta g_{\mu\nu}$ **<u>do not</u>** couple to SUGRA matter and their dynamics is that of the minimally coupled scalar in black brane geometry

(sh.1) $\eta = \lim_{\omega \to 0} \frac{1}{2\omega i} \Big[G^A(\omega, 0) - G^R(\omega, 0) \Big]$

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(sw.2) $\omega = v_s q - \frac{i}{2} \frac{4}{3} \frac{\eta}{Ts} \left[1 + \frac{3\zeta}{4\eta} q^2 \right]$

Suppose we study conformal theory ($\mathcal{N} = 4$)

Conformal invariance of $\mathcal{N} = 4$ is not broken by finite 't Hooft coupling

$\Rightarrow v_s = \frac{1}{\sqrt{3}}, \xi = 0$ even including α' corrections

but dispersion relation **(sw.2)**

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- Check on holographic renormalization of cascading gauge theories

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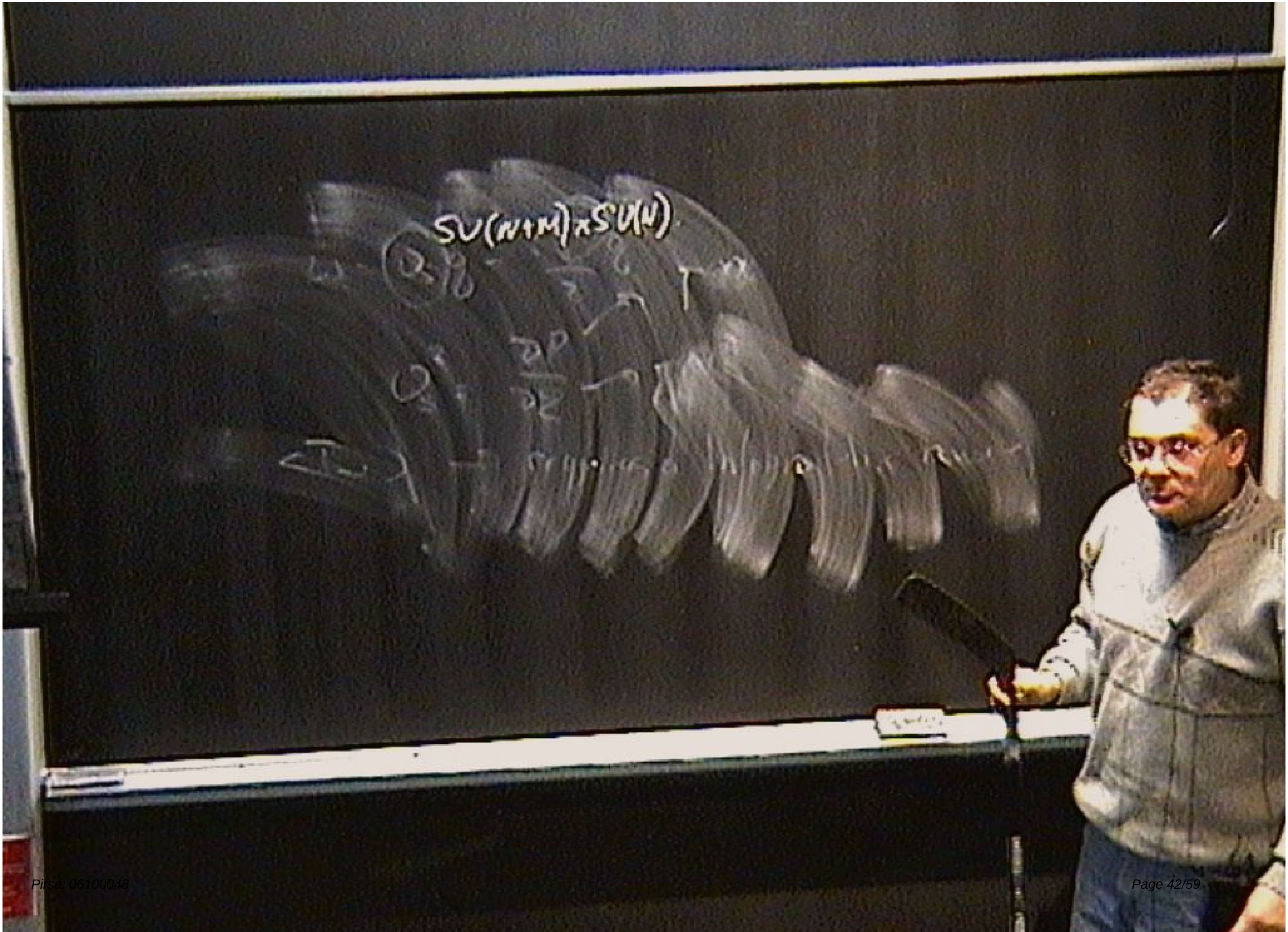
SU(N+M)xSU(N)

- Consider $\mathcal{N}=1$ SUSY quiver gauge theory $SU(N)\times SU(N+M)$ with two bifundamentals and two anti-bifundamentals + certain quartic superpotential —this theory is known as KS cascading gauge theory

$$N = N(E) \sim 2M^2 \ln \frac{E}{\Lambda}, \qquad E \gg \Lambda$$

where Λ is the strong coupling scale of the theory

- If we define cascading theory at some scale μ with $g_{YM}^2 N(\mu) \ll 1$, in the UV we always encounter $g_{YM}^2 N \gg 1 \qquad \Rightarrow \qquad$ it is not possible to renormalize the theory conventionally and one unavoidably has to use holographic renormalization

- Holographic renormalization of this theory was done in hep-th/0506002, O.Aharony,A.Yarom,AB. Specifically, we computed $< T_{\mu\nu} >$ at finite temperature and extracted

$$v_s^2 = \frac{1}{3} - \frac{2}{9\ln\frac{T}{\Lambda}}, \qquad T \gg \Lambda$$

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- Gubser-Mitra conjecture

Gravitational backgrounds with translationary invariant horizon develop an instability precisely when the specific heat of a black brane geometry is negative

$\Updownarrow$ translate to gauge theory via Maldacena correspondence

Finite temperature gauge theories with a negative specific heat must have a dynamical instability

$\Uparrow$

trivial to identify such an instability:

- Consider a sound wave mode in such gauge theory plasma

$$\omega(q) = v_s q + \mathcal{O}\left(\frac{q^2}{T}\right), \qquad v_s^2 = \frac{\partial P}{\partial \epsilon}$$

now, at zero chemical potential, $f = -P$

$$-\left(\frac{\partial P}{\partial T}\right)_V = \left(\frac{\partial f}{\partial T}\right)_V = -s, \qquad \text{also} \qquad c_v = \left(\frac{\partial \epsilon}{\partial T}\right)_V$$

so

$$v_s^2 = \frac{\partial P}{\partial \epsilon} = \frac{\left(\frac{\partial P}{\partial T}\right)_V}{\left(\frac{\partial \epsilon}{\partial T}\right)_V} = \frac{s}{c_v}$$

$\Rightarrow \qquad c_v < 0 \Longleftrightarrow v_s \qquad$ is imaginary

- sound wave amplitude grows (dynamical instability)

$\Updownarrow$ translate back to gravity

- sound wave quasinormal mode is unstable

Example:

Consider $\mathcal{N}=1$ SYM from NS5 branes wrapping S^2 of the resolved conifold — Maldacena-Nunez model

- from thermodynamics of MN black branes

$$v_s^2 = -2\left(\frac{T}{T_H}-1\right)^2, \qquad \text{as} \qquad \left(\frac{T}{T_H}-1\right) \ll 1$$

where the regime $\left(\frac{T}{T_H}-1\right) \ll 1$ corresponds to the size of the resolved conifold $S^2 \to \infty$ (NS5 branes are almost flat); T_H is a Hagedorn temperature of flat NS5 branes

$$T_H \propto \frac{1}{\sqrt{\#\text{of branes}}}$$

Identical v_s^2 can be extracted from the pole of the appropriate correlation functions of the stress energy tensor, or equivalently the dispersion relation of the sound quasinormal mode

- α' corrections in IIB SUGRA

- In hep-th/9808126 GKT constructed α' corrected nonextremal 3-brane geometry based on the following type IIB corrected SUGRA action:

now, at zero chemical potential, $f = -P$

$$-\left(\frac{\partial P}{\partial T}\right)_V = \left(\frac{\partial f}{\partial T}\right)_V = -s, \qquad \text{also} \qquad c_v = \left(\frac{\partial \epsilon}{\partial T}\right)_V$$

so

$$v_s^2 = \frac{\partial P}{\partial \epsilon} = \frac{\left(\frac{\partial P}{\partial T}\right)_V}{\left(\frac{\partial \epsilon}{\partial T}\right)_V} = \frac{s}{c_v}$$

$\Rightarrow \qquad c_v < 0 \Longleftrightarrow v_s \qquad$ is imaginary

- sound wave amplitude grows (dynamical instability)

$\Updownarrow$ translate back to gravity

- sound wave quasinormal mode is unstable

Example:

Consider $\mathcal{N}=1$ SYM from NS5 branes wrapping S^2 of the resolved conifold — Maldacena-Nunez model

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$$S_{IIB} = \frac{1}{16\pi G_{10}} \int d^{10}x\sqrt{-g}\left[R - \frac{1}{2}(\partial\phi)^2 - \frac{1}{4\cdot 5!}(F_5)^2 + \cdots + \gamma e^{-\frac{3}{2}\phi} W + \cdots\right]$$

where ϕ is a dilaton, $\gamma = \frac{1}{8}\xi(3)(\alpha')^3$, and W is constructed from the Weyl tensor C_{mnpq}

$$W \equiv C^{hmnk} C_{pmnq} C_h{}^{rsp} C^q{}_{rsk} + \frac{1}{2} C^{hkmn} C_{rqmn} C_h{}^{rsp} C^q{}_{rsk}$$

and $\cdots$ denote other SUGRA modes and higher order α' corrections

Some features of the α' corrected geometry at $T \neq 0$

$\alpha' = 0$	$\alpha' \neq 0$
$\phi = 0$	$\phi \neq 0$, depends on r
size of S^5 is constant	size of S^5 depends on r
$S = \frac{A_{horizon}}{4G_{10}}$	$S \neq \frac{A_{horizon}}{4G_{10}}$ use Wald formula
$T_H \equiv T_0$	$T_H \equiv T_0(1 + 15\gamma)$

Notice crucial assumption: **only** metric receives α' corrections; 5-form does not

Claim: consistency of hydrodynamics provides a highly nontrivial check on all these features & above assumption

- Using Kubo formula (correlation functions without a pole) one finds, hep-th/0406264 J.Liu,A.Starinets,AB:

$$\frac{\eta}{s} = \frac{1}{4\pi}\Big(1 + 135\gamma\Big) + \mathcal{O}(\gamma^2)$$

- Alternatively, one can study dispersion relation for the shear quasinormal mode, hep-th/0510041 P.Benincasa,AB:

$$\omega = -iDq^2 = -i\,\Gamma_\eta\,\frac{q^2}{2\pi T_0}, \qquad \text{where} \qquad \Gamma_\eta = \frac{1}{2}\Big(1 + 120\gamma\Big)$$

According to hydro consistency relation $\frac{\Gamma_\eta}{2\pi T_0} = D$ (the shear diffusion constant)

$$\frac{\eta}{s} = DT = \frac{\Gamma_\eta}{2\pi}\,\frac{T}{T_0} = \frac{1}{4\pi}\Big(1 + 120\gamma\Big)\Big(1 + 15\gamma\Big) = \frac{1}{4\pi}\Big(1 + 135\gamma\Big) + \mathcal{O}(\gamma^2)$$

- Consider a sound wave mode , hep-th/0510041 P.Benincasa,AB:

$$\omega = v_s q - i\,\Gamma_{sound}\,\frac{q^2}{2\pi T_0}, \qquad \text{where} \qquad \Gamma_{sound} = \frac{1}{3}\Big(1+120\gamma\Big)+\cdots$$

$$v_s = \frac{1}{\sqrt{3}}\Big(1+0\cdot\gamma+\cdots\Big) \Leftarrow \text{does not receive } \alpha' \text{ corrections}$$

Consistency of hydro

$$\frac{\Gamma_{sound}}{2\pi T_0} = \frac{2}{3T}\frac{\eta}{s}\left(1+\frac{3\xi}{4\eta}\right) = \frac{2}{3T}\frac{1}{4\pi}\Big(1+135\gamma\Big)\left(1+\frac{3\xi}{4\eta}\right)$$

or

$$3\,\Gamma_{sound}\,\frac{T}{T_0} = \Big(1+135\gamma\Big)\left(1+\frac{3\xi}{4\eta}\right)$$

$$\Updownarrow$$

$$3\,\frac{1}{3}\Big(1+120\gamma\Big)\Big(1+15\gamma\Big) = \Big(1+135\gamma\Big)\left(1+\frac{3\xi}{4\eta}\right) \Rightarrow \xi = 0\cdot\gamma$$

Again, η computation is not sensitive to α' corrections in matter sector (in this case 5-form flux) of IIB SUGRA, while sound dispersion relation (which depends on η) **is** sensitive

Applications B

- shear viscosity at RHIC

- Experimental data at RHIC suggest very fast thermalization of the quark-gluon plasma produced in heavy ion collisions

- (for review: hep-ph/0510232, Kovchegov) the thermalization time τ_T

$$\tau_T \propto \left(\frac{\eta}{T^3}\right)^{4/3}$$

$$\Updownarrow$$

small thermalization times $\Longleftrightarrow$ small $\frac{\eta}{s}$

Drag force vs. jet quenching parameter

- For a massive quark $m \gg \sqrt{\lambda}T$

$$\frac{dp}{dt} = -\frac{\pi\sqrt{\lambda}T^2}{2}\frac{v}{\sqrt{1-v^2}}$$

Problem: in SUGRA approximation $\lambda = \infty$

- Consider a light-like Wilson loop C with large extension L^- in x^- direction and small extension L in transverse direction. Introduce a 'jet quenching parameter' $\hat{q}$

$$< W^A(C) >= \exp\left(-\frac{1}{4}\hat{q}L^-L^2 + \mathcal{O}(L^4)\right)$$

Problem: in SUGRA approximation $\lambda = \infty$

$$relation\,?$$

Shear viscosity in the presence of chemical potential

- Recently (A.Starinets, D.Son, $\cdots$) it was shown that introducing R-charge chemical potential for $N = 4$ SYM leads to

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

$$\Downarrow$$

Can it be generalized?

$$\Downarrow$$

- (with J.Liu) We constructed new gauged supergravities by gauging $U(1)$ isometry of $Y^{p,q}$ manifolds

- Leads to **new** examples of SUGRA dual to CFT plasmas with a chemical potential
- Dual (rotating/charged) black hole solution is found analytically
- $$\frac{\eta}{s} = \frac{1}{4\pi}\,\frac{\hbar}{k_B}$$
- **Claim:** Above result implies universality for shear viscosity even with a chemical potential
- **Proof:** (with P.Benincasa and R.Naryshkin) hep-th/0610145

Conclusions

- fun to study non-equilibrium AdS/CFT correspondence

➤ In the future:

- relation between different approaches to jet quenching in plasma
- photon and dilepton production in non-conformal QGP