Applications of Holography to Strongly Coupled Systems

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Review talk: Parts of it based on works with:
U. Gursoy(Utrecht Univ.), J. Pedraza(Univ. of Amsterdam);
D-S Lee, C-P Yeh (NDHU), ...
and works in progress.

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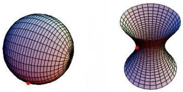
Outline

Briefly on AdS/CFT

- Gauge/Gravity duality: A way to map and answer quantum questions to gravity geometric questions!
- The initial AdS/CFT correspondence($\sim$ 20 years ago): $\mathcal{N} = 4$ sYM with gauge group $SU(N)$ on flat space $\Leftrightarrow$ $AdS_5 \times S^5$, is the harmonic oscillator of the gauge/gravity dualities.
- Reminder $AdS \times S^5$:

$$ds^2 = \frac{R^2}{u^2}\left(-dt^2 + d\vec{x}^2 + du^2\right) + R^2 d\Omega_5^2$$



- It is a Strong/Weak duality

$$R^4 = l_s^4 N g_{YM}^2 = \lambda l_s^4 \ , \qquad l_P^2 = \frac{\pi}{2^{1/4}} g_{YM} l_s^2 = \frac{\pi}{2^{1/4}\sqrt{N}} R$$

Small Curvature: $R \gg l_p$, means no quantum corrections $\equiv N \gg 1$.
No string corrections: $R \gg l_s$, no string corrections $\equiv \lambda \gg 1$.

On AdS/CFT

Planar (=Large N), strongly coupled (large λ) field theory, is described as a classical gravity(small curvature).

The initial correspondence is simple:

QFT	**The gravity dual theory**
Conformal,	$SO(2,4)$ isometry (conformal group)
Maximally Supersymmetric,	internal space: S^5
$SU(4)$-R symmetry group,	$SO(6)$ symmetry
No Temperature,	No black hole.

More complicated=realistic gauge/gravity dualities exist: This is the subject of this talk!

A demonstration for the Static potential:

Example: The Wilson loop, is a physical gauge invariant object and can measure the interaction potential between the external quarks and acts as an order of confinement.
The Wilson loop operator is

$$W(\mathcal{C}) = TrPe^{i\oint_{\mathcal{C}} A_\mu dx^\mu} \ , \qquad \lim_{T\to\infty} \langle W \rangle \sim e^{-T\ E(L)} \ .$$

where $\mathcal{C}$ close curve. If

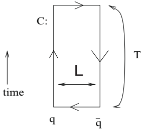
$$E(L) = \sigma\ L\ , \qquad \text{Confining Theory, Area Law}\ .$$

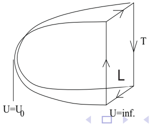
In the gravity dual theory *(Maldacena; Rey, Yee 1998)*

$$\langle W \rangle = Z_{string}(\partial\Sigma = \mathcal{C}) = e^{-S(\mathcal{C})} \qquad N \gg 1\ .$$

$S(\mathcal{C})$: on-shell extremal Nambu-Goto action for string world-sheet.

$$\langle W[C] \rangle = e^{-S_{string[\mathcal{C}]}}$$

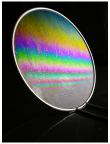




The Static potential in $\mathcal{N} = 4$ sYM:

- We parametrize the surface $(x_1 = \sigma,\ t = \tau)$ and in the interior of the space by $u(\sigma)$.

$$ds^2 = \frac{R^2}{u^2}\left(-dt^2 + d\vec{x}^2 + du^2\right) + R^2 d\Omega_5^2$$



- To minimize its area we solve the Euler-Lagrange differential equation coming from the Nambu-Goto action.

$$S_{NG} \sim \frac{1}{u^2}\sqrt{(1 + u'^2)}, \qquad \frac{u^4}{\sqrt{u'^4 + u^4}} = constant$$

- The $\mathcal{N} = 4$ sYM is not a confining theory, the static potential is

$$S_{NG} \sim V_{Q\bar{Q}} \propto \frac{1}{L}$$

Directions of Developments

- Since the discovery of the initial correspondence, there is an extensive research aiming to construct more realistic gauge/gravity dualities.

  Gauge/Gravity Dualities with: Less/No Supersymmetry; Broken conformal symmetry, confinement; fundamental matter(quenched or unquenched fermions); etc.

✓ We study Anisotropic theories in Gauge/Gravity correspondence.

Why? Attempts for Realization in Nature

The existence of strongly coupled anisotropic systems.

- The expansion of the plasma along the longitudinal beam axis at the earliest times after the collision results to momentum anisotropic plasmas.
- Strong Magnetic Fields in strongly coupled theories.
- New interesting phenomena in presence on such fiels, i.e. inverse magnetic catalysis.

  eg: (Bali, Bruckmann, Endrodi, Fodor, Katz, Krieg et al. 2011)
- Anisotropic low dimensional materials in condensed matter.

Why? More:

- Weakly coupled vs strongly coupled anisotropic theories.

  (Dumitru, Strickland, Romatschke, Baier,... 2008,...)

- Consistent top-down models. Properties of the supergravity solutions, that are dual to the anisotropic theories.
- Black hole solutions that are AdS in UV **flowing** to Lifhitz-like in IR :

  ⋆ Why there is a fixed scaling parameter z for such solutions?

  (Azeyanagi, Li, Takayanagi, 2009)

  ⋆ Other systems that have fixed scaling IR solution (e.g. in Heavy quark density). Why?

  (Kumar 2012; Faedo, Kundu, Mateos, Tarrio 2014)

  ⋆ New flows to Hyperscaling violation IR backgrounds?

Reminding Slide:

- The anisotropic hyperscaling violation metric

$$ds^2 = u^{-\frac{2\theta}{d}}\left(-u^{2z}\left(dt^2 + dy_i^2\right) + u^2 dx_i^2 + \frac{du^2}{u^2}\right) .$$

which exhibits a critical exponent z and a hyperscaling violation exponent θ.

- The metric is not scale invariant

$$t \to \lambda^z t, \qquad y \to \lambda^z y, \qquad x \to \lambda x, \qquad u \to \frac{u}{\lambda} , \qquad ds \to \lambda^{\frac{\theta}{d}} ds .$$

Why? Even More:

- Ⓢtriking Features! Several Universality Relations predicted for the isotropic theories are violated!

  ⋆ Shear viscosity over entropy density ratio takes parametrically low values $\frac{\eta}{s} < \frac{1}{4\pi}$!

  (Rebhan, Steineder 2011; Jain, Samanta, Trivedy 2015; D.G., Gursoy, Pedraza, 2017;...)

  ⋆ Langevin coefficients inequality for heavy quark motion in the anisotropic plasma gets inverted $\kappa_L > < \kappa_T$.

  (Gursoy, Kiritsis, Mazzanti, Nitti 2010; D.G, Soltanpanahi, 2013a, 2013b)

  ⋆ ...

  ⋆ Implications to QGP hydrodynamic simulations.

Brownian Motion in Strongly Coupled Theories?

- A Heavy Quark in a thermal environment (Quark Gluon Plasma): $M \gg T, \;\; p^2 \sim MT \gg T^2, \;\; v^2 \sim \frac{T}{M} \ll 1.$
- Typical Momentum transfer is of order $Q^2 \sim T^2$ for hard collisions.
- Good approximation to model the interaction of the heavy quark with the medium as uncorrelated kicks.
- The momentum evolves according to the macroscopic Langevin equations

$$\dot{p}_i(t) = -\eta_D p_i(t) + \xi_i(t) \; ,$$

where p is the momentum of the particle, η_D is the friction coefficient or the momentum drag coefficient and ξ is the random force:

$$\langle \xi(t) \rangle = 0 \; , \qquad \langle \xi(t) \xi(t') \rangle = \kappa \delta(t - t') \; ,$$

where κ is the mean squared momentum per unit of time.

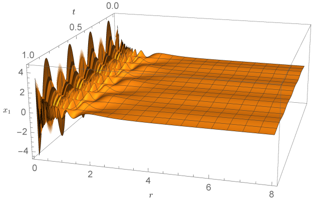
Brownian Motion in Gauge/Gravity duality

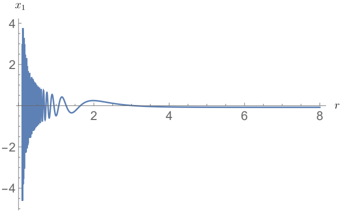
- Let us consider a class of theories as

$$ds^2 = -u^{a_0} f(u) dx_0^2 + \frac{1}{u^{a_u} f(r)} dr^2 + \sum_{i=1}^{d} u^{a_i} dx_i^2 \ ,$$

where f is the blackening factor ($= 1$ for theories at zero temperature, $= (u - u_h)(...)$ for finite temperature theories).

- Special Case: $a_0 = a_i = a_u = 2$ is the AdS_5 metric.
- The straight string from the UV boundary, to the IR represents a heavy quark $(t = \tau, u = \sigma, x_1 = 0)$.
- Fluctuation on the straight string $(t = \tau, u = \sigma, x_1 = 0 + \delta x_1(\sigma, \tau))$ in the holographic space look like this





The Analysis for zero point energy

Expanding as

$$\delta x_1(t,u) = \int_0^\infty d\omega h_\omega(u)\Big(\alpha(\omega)e^{-i\omega\tau} + \alpha(\omega)^\dagger e^{i\omega\tau}\Big) \ ,$$

the fluctuation equation are

$$\frac{\partial}{\partial u}\Big(u^{a_1+\frac{a_0+a_u}{2}} h_\omega(u)'\Big) + \omega^2 u^{a_1-\frac{a_0+a_u}{2}} h_\omega(u) = 0 \ ,$$

and has solutions of Bessel type, which after some manipulation can be written as

$$h_\omega(u) = u^{-\nu\kappa} A_\omega [J_\nu(\omega\tilde{u}) + B_\omega Y_\nu(\omega\tilde{u})] \ ,$$

where

$$\nu := \frac{a_0 + 2a_1 + a_u - 2}{2(a_0 + a_u - 2)} \ , \qquad \tilde{u} := \frac{2r^{\frac{1}{2}(2-\alpha_0-\alpha_u)}}{a_0 + a_u - 2} = \frac{u^{-\kappa}}{\kappa} \ , \qquad \kappa := \frac{a_0 + a_u}{2} - 1$$

and $J_\nu(\tilde{u})$, $Y_\nu(\tilde{u})$ are the Bessel functions of first and second kind.

Notice that a whole class of theories: Relativistic and Non-Relativistic can be treated under a unified study scheme! Powerful Method!

(D.G., Lee, Yeh 2018; D.G. 2018)

- The two-point function at the low frequency limit

$$\langle X_1(t)X_1(0)\rangle \sim \begin{cases} E^{\frac{4\kappa(1-\nu)}{(a_0-\kappa)}}\ |t|^{3-2\nu}\ , & \text{when} \quad \nu \geq 1\ , \\ E^0\ |t|^{2\nu-1}\ , & \text{when} \quad \nu \leq 1\ , \end{cases}$$

  where E is the energy of the string.

- Fluctuation-Dissipation theorem holds from holography for the whole class of theories!
- The inertial mass and the self energy of the particle can be read from the response function ($\delta x \sim \chi F$)

$$\chi(\omega) = \frac{2\pi\alpha'}{\omega} u_b^{-a_1} \frac{H_\nu(\omega\tilde{u}_b)}{H_{\nu-1}(\omega\tilde{u}_b)}\ , \quad m = \frac{u_b^{2\kappa(\nu-1)}}{2\kappa(\nu-1)}\ , \quad \gamma = \frac{1 - i\tan\left[\left(\nu-\frac{1}{2}\right)\pi\right]}{\left((2i\kappa)^{2\nu-1}\Gamma(\nu)^2\right)}\pi\ .$$

Brownian Motion in the Quark-Gluon Plasma

- Black hole background ($u_h \sim T$). There is no analytic solution for the fluctuation of the strings. It can be found with the monodromy patching method

$$\delta x_{1\omega}(u) = c_1 \left(1 + i\omega c_0 u_h^{a_1} + \frac{i\omega u_h^{a_1}}{2\kappa\nu} u^{-2\kappa\nu} \right) ,$$

- The diffusion coefficient

$$D = T \lim_{\omega \to 0} \left(-i\, \omega \chi(\omega) \right) \sim T^{2(1-\nu)} .$$

- Fluctuation-Dissipation theorem holds along each direction;The noise is white; Self energy and thermal mass of the particle can be found...

  (D.G., Lee, Yeh 2018)

- Quarks moving with a large velocity v? Langevin coefficients for generic theories can be obtained! Are related to the observed energy loss of quarks in QGP.

  (D.G, Soltanpanahi, 2013a, 2013b; Gursoy, Kiritsis, Mazzanti, Nitti 2010)

Phase transitions in Holography and Inverse Magnetic Catalysis

We introduce the Theory in One Page:

- Strongly coupled anisotropic theory.
- How the theory looks like and how to obtain it?
  - ✓ 4d $SU(N)$ gauge theory in the large N_c-limit.
  - ✓ Its dynamics are affected by a scalar operator $\mathcal{O} \sim TrF^2$.
  - ✓ Anisotropy is introduced by another operator $\tilde{\mathcal{O}} \sim \theta(x_3) TrF \wedge F$ with a space dependent coupling.
  - ✓ On the gravity dual side we have a "backreacting" scalar field depending on spatial directions, the axion; and a non-trivial dilaton.
- Eventually the gravity dual theory is an Einstein-Axion-Dilaton theory in 5 dimensions with a non-trivial potential.
  - ✓ Solutions are RG flows:
    AdS in UV $\Rightarrow$ Anisotropic (Hyperscaling Lifshitz-like) in IR.
- Formally interesting theories. And a solid ground to study strongly coupled phenomena in presence of anisotropy.

Parts of the Theory Timeline-Related bibliography:

Non-Confining Anisotropic Theories:

(Azeyanagi, Li, Takayanagi, 2009; Mateos, Trancanelli, 2011; Jain, Kundu, Sen, Sinha, Trivedi, 2015;...)

Confining Anisotropic Theories:

(D.G., Gursoy, Pedraza, 2017)

Similar ideas in different context. For example:

(Gaiotto, Witten 2008; Chu, Ho, 2006; Choi, Fernadez, Sugimoto 2017;...)

How is Anisotropy introduced? A Pictorial Representation:

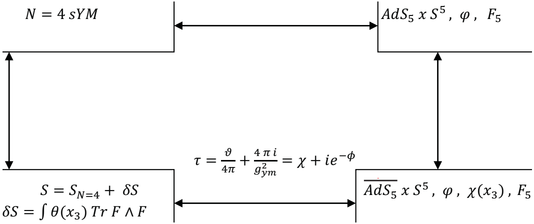
- For the Lifshitz-like IIB Supergravity solutions

$$ds^2 = u^{2z}(dx_0^2 + dx_i^2) + u^2 dx_3^2 + \frac{du^2}{u^2} + ds^2_{S^5}.$$

Introduction of additional branes: *(Azeyanagi, Li, Takayanagi, 2009)*

	x_0	x_1	x_2	x_3	u	S^5
D3	x	x	x	x		
D7	x	x	x			x

- Which equivalently leads to the following AdS/CFT deformation.



- $dC_8 \sim \star d\chi$ with the non-zero component $C_{x_0 x_1 x_2 S^5}$.
- Possible to compactify x_3 to get dual to the pure Chern-Simons gauge theory.

The Anisotropic Theory

The generalized Einstein-Axion-Dilaton action with a potential for the dilaton and an arbitrary coupling between the axion and the dilaton:

$$S=\frac{1}{2\kappa^2}\int d^5x\sqrt{-g}\left[R-\frac{1}{2}(\partial\phi)^2+V(\phi)-\frac{1}{2}Z(\phi)(\partial\chi)^2\right].$$

The eoms read

$$R_{\mu\nu}-\frac{1}{2}Rg_{\mu\nu}=\frac{1}{2}\partial_\mu\phi\partial_\nu\phi+\frac{1}{2}Z(\phi)\partial_\mu\chi\partial_\nu\chi-\frac{1}{4}g_{\mu\nu}(\partial\phi)^2-\frac{1}{4}g_{\mu\nu}Z(\partial\chi)^2+\frac{1}{2}g_{\mu\nu}V(\phi)\ ,$$

$$\frac{1}{\sqrt{-g}}\partial_\mu\left(\sqrt{-g}g^{\mu\nu}\partial_\nu\phi\right)=\frac{1}{2}\partial_\phi Z(\phi)(\partial\chi)^2-V'(\phi)\ ,$$

$$\frac{1}{\sqrt{-g}}\partial_\mu\left(\sqrt{-g}g^{\mu\nu}\partial_\nu\chi\right)=0\ .$$

Where

$$V(\phi)=12\cosh(\sigma\phi)+\left(\frac{m(\Delta)^2}{2}-6\sigma^2\right)\phi^2,\qquad Z(\phi)=e^{2\gamma\phi},$$

(Gursoy, Kiritsis, Nitti, 2007; (Gubser, Nellore), Pufu, Rocha 2008a,b)

Remark: For $\sigma=0,\gamma=1,m(\Delta)=0$ the action and the solution of eoms, are reduced of IIB supergravity.

Special case: IIB Supergravity

Remark:
The ten dimensional action gives our generalized model, when the internal space is an S^5 supported by fluxes and $\sigma = 0, \gamma = 1, \Delta = 4$:

$$S = \frac{1}{2\kappa_{10^2}} \int d^{10}x \sqrt{-g} \left[R + 4\partial_M \phi \partial^M \phi - e^{2\phi} \left(\frac{1}{2} F_1^2 + \frac{1}{4 \cdot 5!} F_5^2 \right) \right], \; F_1 := d\chi \,.$$

where $M = 0, \ldots, 9$ and F_1 is the axion field-strength. The equations of motion for the background are:

$$R + 4g^{MN} \left(\nabla_M \nabla_N \phi - \partial_M \phi \partial_N \phi \right) = 0 \,,$$

$$R_{MN} + 2\nabla_M \nabla_N \phi + \frac{1}{4} g_{MN} e^{2\phi} \partial_P \chi \partial^P \chi - \frac{1}{2} e^{2\phi} \left(F_M F_N + \frac{1}{48} F_{MABCD} F_N{}^{ABCD} \right) = 0 \,.$$

plus the Bianchi identities and self duality constraints. The axion field equation is satisfied trivially for linear axion.

Solutions of the Generalized Einstein-Axion-Dilaton Action

- The background solution

$$ds^2 = \frac{1}{u^2}\left(-\mathcal{F}(u)\mathcal{B}(u)\,dt^2 + dx_1^2 + dx_2^2 + \mathcal{H}(u)dx_3^2 + \frac{du^2}{\mathcal{F}(u)}\right),$$
$$\chi = \alpha x_3\,, \qquad \phi = \phi(u)\,,$$

- Solutions: e.g. For $\Delta = 4$: (D.G., Gursoy, Pedraza, 2017)
  AdS in UV flowing to Hyperscaling Lifshitz-like violation geometries in IR :

$$ds^2 = u^{-\frac{2\theta}{3}}\left(-u^{2z}\left(f(u)dt^2 + dx_{1,2}^2\right) + \tilde{\alpha}u^2 dx_3^2 + \frac{du^2}{f(u)u^2}\right)\,,$$

Axion-Dilaton Coupling and Potential, rule the Scaling Coefficients

- The values of (θ, z) dependence on (γ, σ)

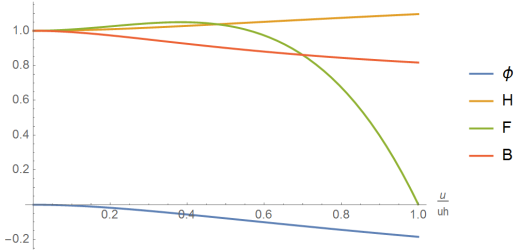
$$z = \frac{4\gamma^2 - 3\sigma^2 + 2}{2\gamma(2\gamma - 3\sigma)} , \qquad \theta = \frac{3\sigma}{2\gamma} .$$

- Special case: $(\sigma = 0, \ \gamma = 1)$ supergravity truncated action with a single solution $(\theta = 0, \ z = 3/2)$. *(Mateos, Trancanelli, 2011)*
- The scaling factors z and θ are determined by the constants in the Axion-Dilaton Coupling and the Potential. This is the reason that in the particular setup the supergravity solutions have them fixed.

Solution : The Full Flow

- Fixing (γ, σ) and α and u_h we get the metric flow from boundary to horizon:

$$ds^2 = \frac{e^{-\frac{1}{2}\phi(u)}}{u^2}\left(-\mathcal{F}\mathcal{B}\,dt^2 + dx_1^2 + dx_2^2 + \mathcal{H}dx_3^2 + \frac{du^2}{\mathcal{F}}\right),$$



UV Boundary IR Horizon

An exact solution

The potential and the axion-dilaton coupling

$$V(\phi) = 6e^{\sigma\phi}, \qquad Z(\phi) = e^{2\gamma\phi}.$$

A Lifshitz-like anisotropic hyperscaling violation background which may accommodate a black hole

$$ds_s^2 = \alpha^2 C_R e^{\frac{\phi(u)}{2}} u^{-\frac{2\theta}{3z}} \left(-u^2 \left(f(u)dt^2 + dx_i^2 \right) + C_Z u^{\frac{2}{z}} dx_3^2 + \frac{du^2}{f(u)\alpha^2 u^2} \right) ,$$

where

$$f(u) = 1 - \left(\frac{u_h}{u} \right)^{3+(1-\theta)/z} , \qquad e^{\frac{\phi(u)}{2}} = u^{\frac{\sqrt{\theta^2+3z(1-\theta)-3}}{\sqrt{6}z}} ,$$

$$C_R = \frac{(3z-\theta)(1+3z-\theta)}{6z^2} , \quad C_Z = \frac{z^2}{2(z-1)1+3z-\theta} ,$$

$$z = \frac{4\gamma^2 - 3\sigma^2 + 2}{2\gamma(2\gamma - 3\sigma)} , \qquad \theta = \frac{3\sigma}{2\gamma} .$$

We have obtained the theories, are they physical and stable?

$\Downarrow$
$\Downarrow$

✓ Energy Conditions Analysis

AND

✓ Local Thermodynamical Stability Analysis

$\Downarrow$
$\Downarrow$

YES!

Null Energy Condition

- The averaged radial acceleration between two null geodesics is

$$A_r = -4\pi T_{\mu\nu} N^\mu N^\nu \ ,$$

if it is negative the null geodesics observe a non-repulsive gravity on nearby particles along them.

- This imposes the Null Energy Condition

$$T_{\mu\nu} N^\mu N^\nu \geq 0 \ , \quad N^\mu N_\mu = 0 \ ,$$

leading to the following constrains:

- For the Lifshitz-like space $z \geq 1$.
- For the Hyperscaling violation anisotropic metric in 3+1-dim spacetime and anisotropic in 1-dim reads

$$(z-1)(1-\theta+3z) \geq 0 \ ,$$
$$\theta^2 - 3 + 3z(1-\theta) \geq 0 \ .$$

Additional conditions from thermodynamics?

Local Thermodynamic Stability

- The necessary and sufficient conditions for local thermodynamical stability in the canonical ensemble are

$$c_\alpha = T\left(\frac{\partial S}{\partial T}\right)_\alpha \geq 0\ , \qquad \Phi' = \left(\frac{\partial \Phi}{\partial \alpha}\right)_T \geq 0$$

  c_α is the specific heat: increase of the temperature leads to increase of the entropy.
  Φ' is derivative of the potential: the system is stable under infinitesimal charge fluctuations.

- In the GCE these conditions should be equivalent of having no positive eigenvalues of the Hessian matrix of the entropy with respect to the thermodynamic variables. *(Gubser, Mitra 2001)*

- In the IR the positivity of the specific heat imposes

$$c_\alpha = 1 - \theta + 2z \geq 0$$

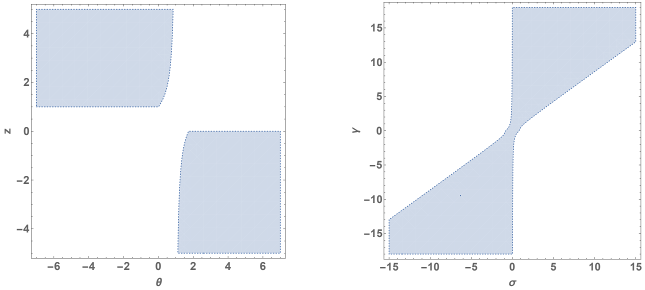
Three conditions that constrain (z, θ) and as a result (γ, σ).

$$(z-1)(1-\theta+3z) \geq 0 \ , \qquad z = \frac{2+4\gamma^2-3\sigma^2}{2\gamma(2\gamma-3\sigma)} \ ,$$

$$\theta^2 - 3 + 3z(1-\theta) \geq 0 \ , \qquad \theta = \frac{3\sigma}{2\gamma} \ ,$$

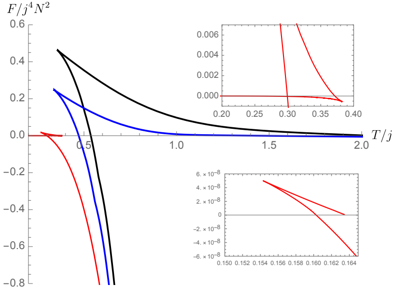
$$1 - \theta + 2z \geq 0 \ .$$

The blue region is the acceptable for the theory parameters.



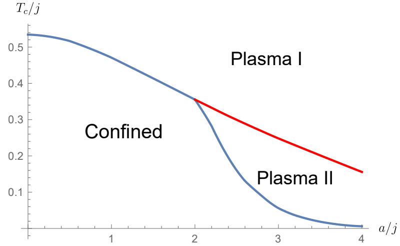
Confinement/Deconfinement Phase transitions

- Competition for dominance between different gravitational backgrounds.
- At least three different solutions compete. The one that wins have the lowest energy!
- The free energy of the theories vs the temperature T for different anisotropy (α/j=0,1,3):



- Horizontal Axis: Confining Phase.
- Upper Branch: Black hole A:Deconfining Plasma Phase.
- Lower Branch: Black hole B:Deconfining Plasma Phase.

- The Critical Temperature of the theories vs the anisotropy gives:



- The T_c is reduced in presence of anisotropies of the theory.

The Proposal

- The $Tc(\alpha)$ decrease with α, resembling the phenomenon of inverse magnetic catalysis where the confinement-deconfinement temperature decreases with the magnetic field B (where an anisotropy is introduced as in our plasma).
- No charged fermionic degrees of freedom in our case; our plasma is neutral.
- Our findings suggest that the anisotropy by itself could instead be the cause of lower T_c in presence of anisotropies.

η/s for our theories

- Shear Viscosity over Entropy Density

$$\eta_{ij,kl} = -\lim_{\omega\to 0} \frac{1}{\omega} \mathrm{Im} \int dtdx e^{i\omega t} \langle T_{ij}(t,x),\, T_{kl}(0,0) \rangle$$

$$s = \frac{2\pi}{\kappa^2} A \ .$$

The two-point function is obtained by calculating the response to turning on suitable metric perturbations in the bulk.

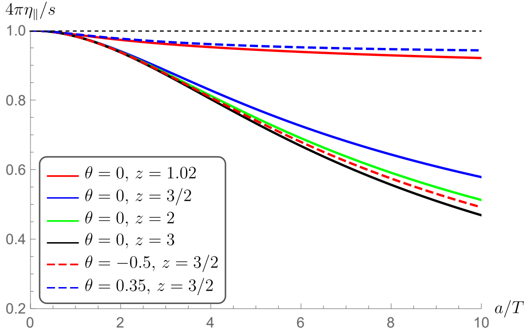
- The relevant part of the perturbed action is mapped to a Maxwell system with a mass term.

$$S = \frac{1}{2\kappa^2} \int d^4x \sqrt{-g} \left(-\frac{1}{4g_{eff}^2} F^2 - \frac{1}{4} m^2(u) A^2 \right) ,$$

where

$$m^2(u) = Z(\phi + \frac{1}{4} \log g_{33}) \alpha^2 \ , \qquad \frac{1}{g_{eff}^2} = g_{33}^{3/2}(u) \ , \qquad A_\mu = \frac{\delta g_{\mu 3}}{g_{33}}$$

- The shear viscosity over entropy ratio for arbitrary (z, θ).



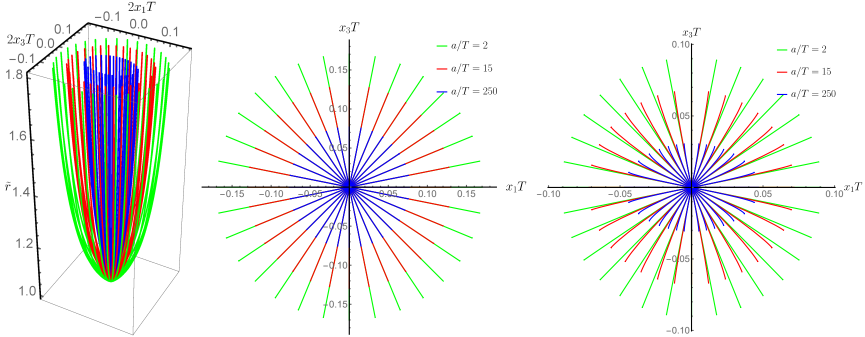
- The ratio depends on the temperature at $\alpha/T \gg 1$ as

$$4\pi\frac{\eta_{\parallel}}{s} = \frac{g_{11}}{g_{33}} \sim \left(\frac{T}{\tilde{\alpha}|1+3z-\theta|}\right)^{2-\frac{2}{z}} .$$

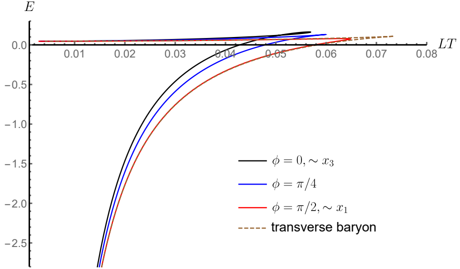
- The range of the temperature power is $[0, \infty)$.

Baryons in Theories with External Fields

- The quark distributions for baryons in theories with magnetic fields:
- Three plots:
  - The baryon in the holographic space, where the strings start from the boundary, go to the deep IR where they meet with a heavy Dp-brane!
  - Projection of the strings on the (x_1, x_3) plane. The endpoints are where the quarks are. Baryon on the transverse plane to the field and Baryon on the plane that the field lies.



- The baryon dissociates at stages, and pair of quarks leaving the state depending on the proximity angle to the anisotropic direction.
- The Energy versus the radius of the baryon along each direction. Pairs abandon the state for $E = 0$.



(D.G. 2018)

Observation

- ✓ In strongly coupled theories most of the observables are sensitive to the presence of the anisotropy and not the source that triggers it.
- ✓ Examples for heavy quarks are: Langevin coefficients, Static potential, Jet quenching.
- ✓ Other examples: Viscosity coefficients, Inverse magnetic Catalysis.

Conclusions

- ✓ We have obtained and studied a)Confining Anisotropic theories. b) Hyperscaling Lifshitz-like Anisotropic black holes with arbitrary scalings. (1st construction in the literature)
- ✓ The theories are physical and stable for a wide range of parameters of the theory.
- ✓ The Confinement/Deconfinement phase transitions occur at lower critical Temperature as the anisotropy is increased!
- ✓ The anisotropy by itself could instead be the cause of the inverse magnetic catalysis.
- The shear viscosity over entropy density ratio, takes values parametrically lower than $1/4\pi$, and depends on the Temperature as $(T/\alpha)^{2-2/z}$.
- The diffusion (butterfly velocity) of chaos occurs faster than isotropic systems.
- Baryons dissociate at stages in theories with strong fields. (D.G. 2018)
- Fluctuation and dissipation of heavy quarks belongs to a unified study scheme.

Thank you!