Heavy Quarks in Strongly Coupled Plasmas at Finite Chemical Potential via Holography

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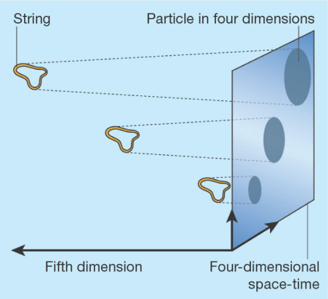
Outline

Holographic Principle

- Holographic principle: ['t Hooft, Susskind]
  QFT in D dimensions $\longleftrightarrow$ Quantum gravity in $D+1$ dimensions



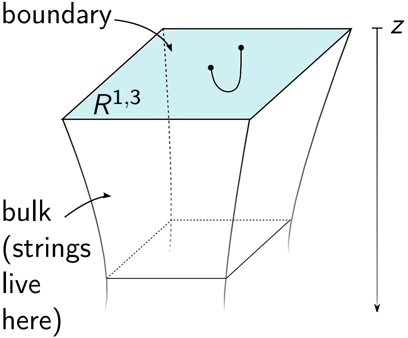
Maldacena, 2003

- Concrete realization: [Maldacena, Gubser, Klebanov, Polyakov, Witten, 1997/98]
  $\mathcal{N}=4$ super Yang-Mills $\longleftrightarrow$ Type IIB String Theory on AdS_5

AdS/CFT Correspondence

- **AdS_5**: 5-dim. spacetime, negative curvature

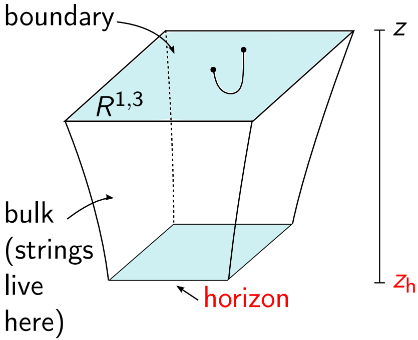
$$ds^2 = \frac{R^2}{z^2}\left(-dt^2 + d\vec{x}^2 + dz^2\right)$$



AdS/CFT Correspondence

- **AdS₅**: 5-dim. spacetime, negative curvature with black hole

$$ds^2 = \frac{R^2}{z^2}\left(-h(z)dt^2 + d\vec{x}^2 + \frac{1}{h(z)}dz^2\right)$$



- Temperature:
  $T > 0 \longleftrightarrow$ Black hole
  $T \sim z_h^{-1}$

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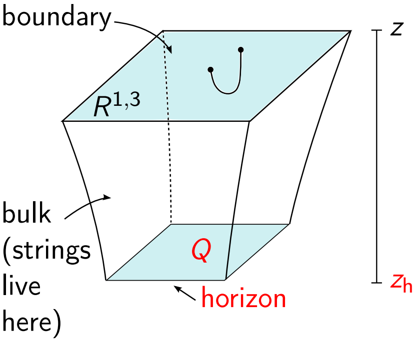

- Temperature:
  $T > 0 \longleftrightarrow$ Black hole
  $T \sim z_h^{-1}$
- Chemical potential:
  $\mu > 0 \longleftrightarrow$ Charged BH
  $\mu \sim Q$

AdS/CFT Correspondence—And Beyond

- **AdS$_5$**: 5-dim. spacetime, negative curvature with black hole

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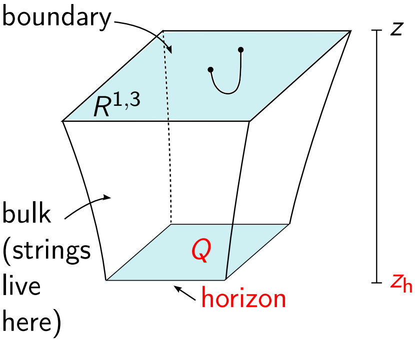


- Temperature:
  $T > 0 \longleftrightarrow$ Black hole
  $T \sim z_h^{-1}$
- Chemical potential:
  $\mu > 0 \longleftrightarrow$ Charged BH
  $\mu \sim Q$
- don't want $\mathcal{N} = 4$ SYM
  $\Longrightarrow$ Deform AdS_5

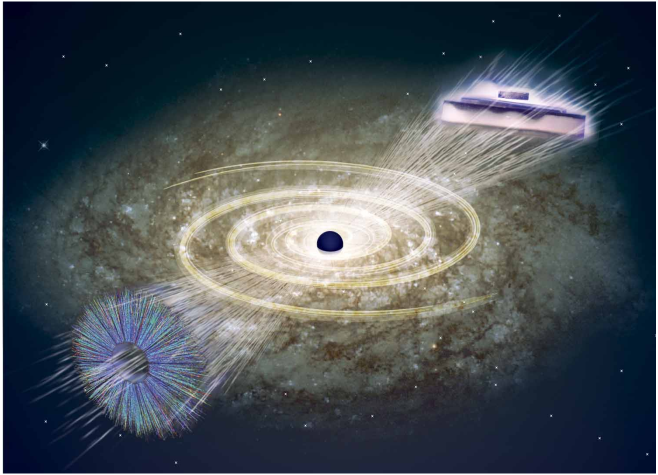
Weak/Strong Duality

- String theory on $AdS_5 \times S^5$: Tough!
- **But:** The AdS/CFT duality is weak $\longleftrightarrow$ strong

't Hooft coupling $\lambda \to \infty$	$\longleftrightarrow$	Strings are pointlike
Number of colors $N_c \to \infty$	$\longleftrightarrow$	Strings behave classically

In limit of many colors & strong coupling:
Strongly coupled QFT $\longleftrightarrow$ Classical (super-)gravity

Many Different Applications

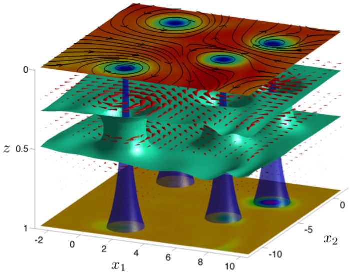


Zaanen, 2007

AdS/Condensed Matter

- Holographic superconductors *e. g.* [Hartnoll, Herzog, Horowitz; Gubser; . . .]
- Holographic non-Fermi liquids *e. g.* [Liu, McGreevy, Vegh; . . .]
- Holographic superfluid turbulence

Holographic methods can help develop (new) intuition about (old) problems.



Adams, Chesler, Liu, 2012

AdS/Condensed Matter

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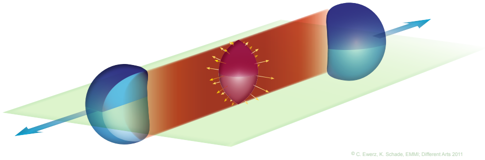
Holographic methods can help develop (new) intuition about (old) problems.

The video that was shown in the talk can be found here.
Click this link.

Adams, Chesler, Liu, 2012

Heavy Ion Collisions: Quark-Gluon Plasma



Ewerz, Schade, Different Arts, 2011

- Thermodynamics: energy density ϵ, pressure p, trace anomaly $\epsilon - 3p$, *etc.*
- Transport coefficients: Shear viscosity, bulk viscosity, *etc.*
  - Famous conjecture:

$$\eta/s \geq \frac{1}{4\pi}$$ for all physical substances [Kovtun, Son, Starinets, 2005]

- Parton energy loss, jet quenching
- $Q\bar{Q}$ potential, color screening

Apply AdS/CFT to QCD?

- *In vacuo*, $\mathcal{N} = 4$ SYM very different from QCD:
    - Maximally supersymmetric
    - Conformal, constant coupling
    - No confinement, no chiral symmetry breaking
    - $N_c \to \infty$ for the duality
- But, at finite temperature T, differences are smaller:
    - Above $2T_c$, QCD almost conformal
    - No confinement in QCD above T_c
    - Finite T breaks supersymmetry in $\mathcal{N} = 4$ SYM
    - Also, we can go away from $\mathcal{N} = 4$ SYM

We work on the *gravity side* (5D) of the duality and *deform* the AdS space, thereby deforming the dual field theory.

Our Rationale

- One way: Try to mimic QCD.
  Difficult, as one does not exactly know what one is doing on the field theory side.
- Other way: Try to find *universal features* of strongly coupled systems.

  For example:

  - KSS bound on η/s
  - Screening distance conjecture and proof by Ewerz, Schade

Simple Models at Finite Temperature and Chemical Potential

- **Conformal:** AdS-Reissner–Nordström $\longleftrightarrow$ $\mathcal{N} = 4$ SYM

$$\mathrm{d}s^2 = \frac{R^2}{z^2}\left(-h(z)\mathrm{d}t^2 + \mathrm{d}\vec{x}^2 + \frac{1}{h(z)}\mathrm{d}z^2\right)$$

$$h(z) = 1 - \left(1 + \frac{\mu^2 z_\mathrm{h}^2}{3}\right)\frac{z^4}{z_\mathrm{h}^4} + \frac{\mu^2 z_\mathrm{h}^2}{3}\frac{z^6}{z_\mathrm{h}^6}$$

- **Non-conformal:** CGN model metric [Colangelo, Giannuzzi, Nicotri]

$$\mathrm{d}s^2 = \mathrm{e}^{c^2 z^2}\frac{R^2}{z^2}\left(-h(z)\mathrm{d}t^2 + \mathrm{d}\vec{x}^2 + \frac{1}{h(z)}\mathrm{d}z^2\right)$$

  - *Ad hoc* deformation à la 'soft wall' due to scale c
  - Has its shortcomings at low μ and/or T

More Sophisticated Model

- **Non-conformal:** 1-parameter model
  - Action [DeWolfe, Gubser, Rosen]

$$S = \frac{1}{2\kappa^2} \int \mathrm{d}^5 x \sqrt{-G} \left(\mathcal{R} - \frac{1}{2} \partial_\mu \phi \partial^\mu \phi - V(\phi) - \frac{f(\phi)}{4} F_{\mu\nu} F^{\mu\nu} \right)$$

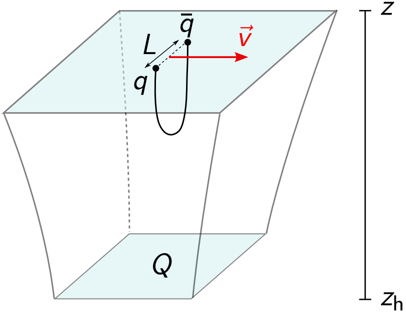
  - *Solve* with ansatz

$$\mathrm{d}s^2 = \mathrm{e}^{2A(z)} \left(-h(z)\mathrm{d}t^2 + \mathrm{d}\vec{x}^2 \right) + \frac{\mathrm{e}^{2B(z)}}{h(z)} \mathrm{d}z^2$$

$$A(z) = \log\left(\frac{R}{z}\right) \quad \text{and} \quad \phi(z) = \sqrt{\frac{3}{2}} \kappa z^2$$

  - Solves 5d gravity action: Consistent deformation due to scale κ
  - Evades problems of CGN model at low μ/T

Screening Distance



- Consider *heavy, moving* $Q\bar{Q}$ pair
- $Q\bar{Q}$ pair $\longleftrightarrow$ endpoints of string

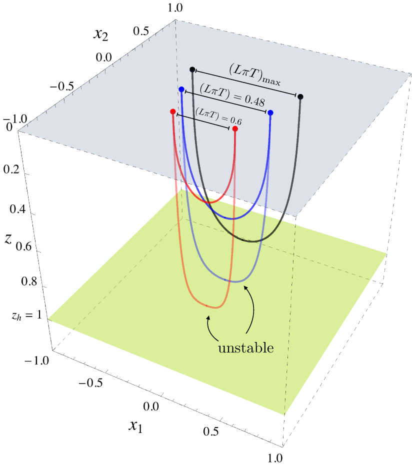
$\Rightarrow$ Nambu–Goto action

$$S_{\mathrm{NG}} = \int \mathrm{d}^2\sigma \sqrt{-\det g_{ab}}$$

$\Rightarrow$ string EOM from classical condition

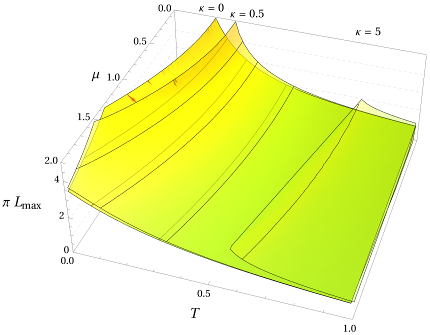
$$0 \stackrel{!}{=} \delta S_{\mathrm{NG}}$$

Screening Distance



- For $L < L_{\max}$, two solutions, lower one unstable
- $L_{\max}$ is the *screening distance*
- No $Q\bar{Q}$ bound state for larger distance

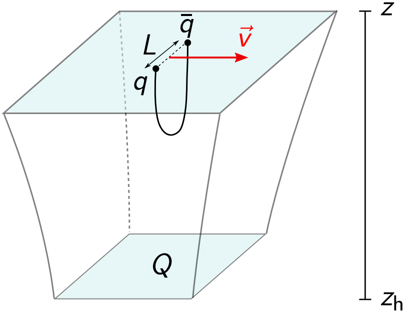
Screening Distance in (μ, T) Plane



(1-parameter model string frame, $v = 0$)

- At finite μ and velocity: Screening distance in conformal theory *no longer* lower bound
- But: Deviations small $\Longrightarrow$ Screening distance is *robust* observable

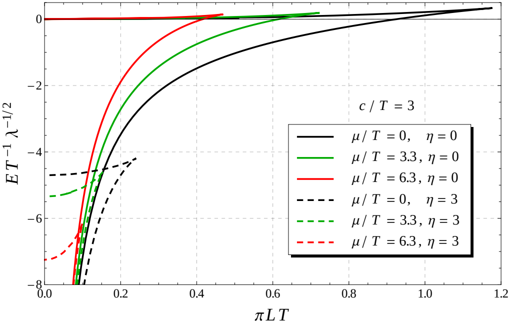
Free Energy of Heavy Quark-Antiquark



- Need on-shell Nambu–Goto action, *i. e.* extremal string action

$$E(L) \sim S_{NG}$$

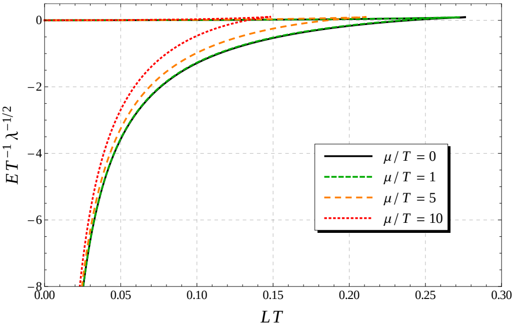
$Q\bar{Q}$ Free Energy at Finite Chemical Potential



(CGN model)

- Lower branch is stable string configuration
- Increasing μ lowers binding energy
- Faster velocity decreases screening distance $\propto 1/\sqrt{\gamma} \propto (\text{boosted energy dens.})^{-1/4}$ *cf.* [Caceres, Natsuume, Okamura]

Running Coupling $\alpha_{Q\bar{Q}}$



(AdS-Reissner–Nordström, $v = 0$)

- Restrict $Q\bar{Q}$ free energy to stable configurations

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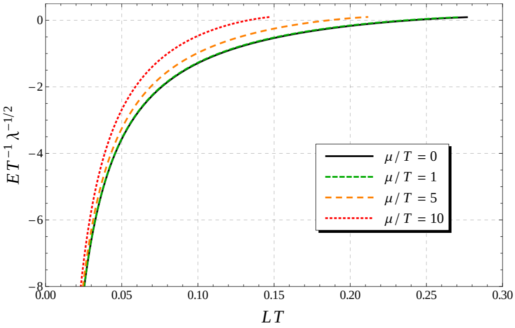

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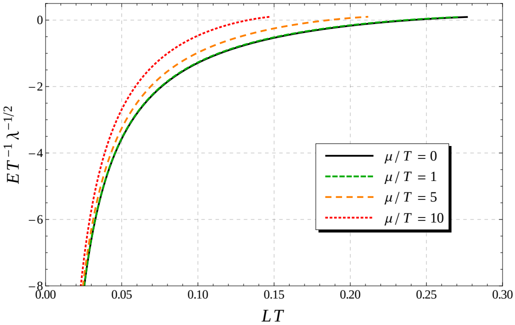

(AdS-Reissner–Nordström, $v = 0$)

- Restrict $Q\bar{Q}$ free energy to stable configurations
- Define coupling $\alpha_{Q\bar{Q}}(L) \equiv \frac{3}{4} L^2 \frac{\mathrm{d}E(L)}{\mathrm{d}L}$ as in QCD

Running Coupling $\alpha_{Q\bar{Q}}$

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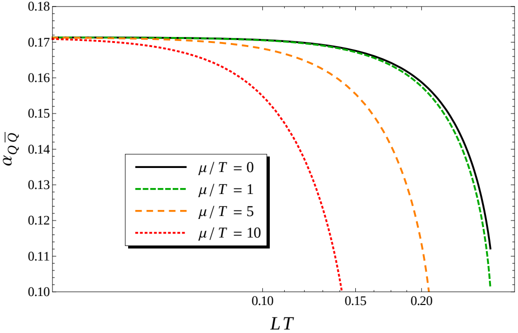

(AdS-Reissner–Nordström)

- Thermal scale $L_{\mathrm{th}} \sim 1/T$ sets fall-off scale
- Analysis of $\alpha_{Q\bar{Q}}$ in non-conformal models at finite μ underway
- Comparison with lattice results

Summary

- Using gauge/gravity duality one can tackle strongly coupled problems in QFTs.
- We apply it to hot plasmas at finite chemical potential, and for moving probes.
- Find that screening distance and free energy are *robust* observables. Running coupling $\alpha_{Q\bar{Q}}(L)$ is work in progress.
- Many other more sophisticated models available which naturally reproduce many QCD features.

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Thank you!

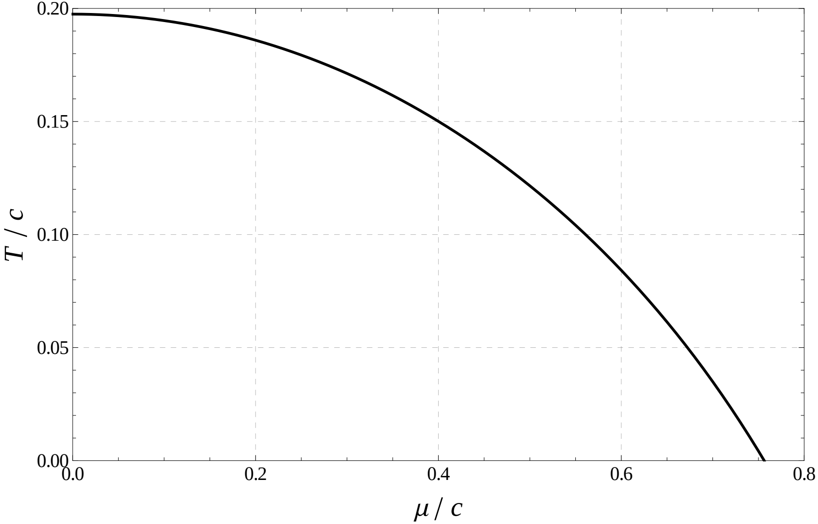

Figure: Phase diagram of the CGN model.

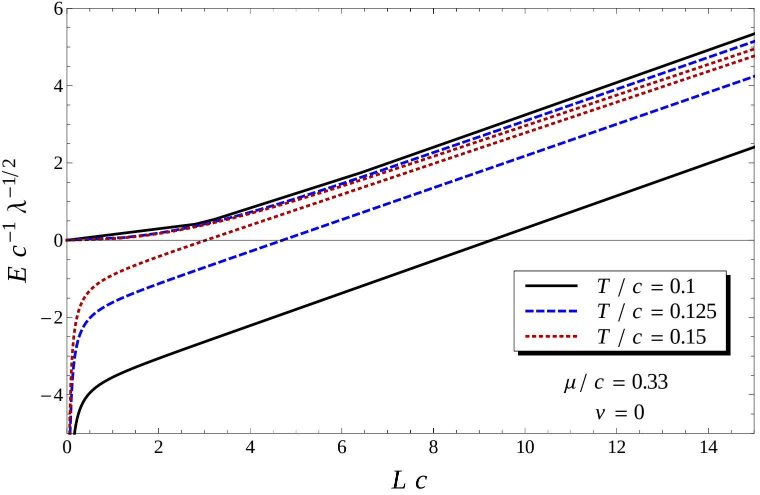

Figure: Free energy in 'confining' phase of CGN model.