Applications of Holography in Hot Strongly Coupled Plasmas

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- Physics Days 2011
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GSI, November 07, 2011
...many realisations, but one concept.
Holographic Principle

The physics in a \((d+1)\)-dimensional volume can be described by a theory living on the \(d\)-dimensional boundary.

- e.g.: duality between gauge theories in \(d\)-dimension and gravity theories (string theories) in higher dimensions.
Practical Realisation of Holography

- AdS/CFT
- AdS/QCD
- Fluid/Gravity Correspondence
- Gauge/Gravity Dualities
- Non-Relativistic AdS/CFT
- Non-Fermi liquids using gauge/gravity duality
- Holographic Superconductors
- Holographic Neutron Stars
- Condensed Matter Physics

- High Energy Physics

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- O'Hara et al., 2002
- ALICE, 2010
Gauge/Gravity Duality

SU\((N_c)\ N = 4\) SYM

\(d\)-dim. **gauge theory**
(without gravity)

\[
\text{entropy of gauge theory} \propto \text{volume}
\]

\[\AdS_5 \times S^5\]

\(d+1\)-dim. **gravitational theory**

\[
\text{entropy of gravitational theory} \propto \text{area}
\]

Why is that duality useful?

\[
g_{YM}^2 = 2\pi g_s, \quad R^4 = 4\pi g_s N_c l_s^4, \quad \lambda = g_{YM}^2 N_c
\]

\[
\lambda \ \text{fixed}, \quad N_c \rightarrow \infty : \quad g_s \sim \lambda/N_c
\]

\[
\lambda \rightarrow \infty : \quad R^4 \sim \lambda l_s^4
\]

strongly coupled QFT \(\leftrightarrow\) weakly coupled gravity
QCD $\leftrightarrow N = 4$ super Yang-Mills

- $N = 4$ SYM very different from QCD
  - Maximally supersymmetric
  - Conformal theory, coupling is constant
  - No confinement, no chiral symmetry breaking
  - $N_c \rightarrow \infty$ for duality

- At finite $T$, differences are smaller:
  - Above $2T_c$ QCD almost conformal
  - No confinement in QCD above $T_c$
  - Finite $T$ breaks supersymmetry
Basic Properties of AdS

- AdS$_5$ metric:

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

with $R$ being the AdS curvature

- Solution to 5D Einstein-Hilbert action:

\[ S = \frac{1}{16\pi G} \int d^5x \sqrt{-g}(\mathcal{R} - 2\Lambda) \]
Basic Properties of AdS

- $AdS_5$ black hole metric:

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

with

\[ h = 1 - \frac{z^4}{z_h^4} \]

and

\[ T = \frac{1}{\pi z_h} \]

- Solves the same e. o. m.:
Metric models at finite temperature

- AdS$_5$ BH metric at finite temperature:
  \[ ds^2 = \frac{R^2}{z^2} \left( -h \, dt^2 + d\vec{x}^2 + \frac{dz^2}{h} \right) \text{ with } h = 1 - \frac{z^4}{z_h^4} \text{ and } T = \frac{1}{\pi z_h} \]

- SW$_T$ model:

Kajantie, Tahkokallio, Yee

\[ ds^2 = \frac{R^2}{z^2} e^{cz^2} \left( -h dt^2 - d\vec{x}^2 - \frac{dz^2}{h} \right) \]

- 2-parameter model:

DeWolfe, Rosen; Gubser

\[ ds^2 = e^{2A(\Phi)} \left( -h(\Phi) dt^2 + d\vec{x}^2 \right) + \frac{e^{2B(\Phi)}}{h(\Phi)} d\Phi^2 \]

is a solution to equations of motion.
Screening distance in hot moving plasmas
Screening distance in hot moving plasmas

Nambu-Goto action:

\[ S = \frac{1}{2\pi \alpha'} \int d\sigma d\tau \sqrt{-\det g_{\alpha\beta}} \]

with \( g_{\alpha\beta} = \mathcal{G}_{\mu\nu} \partial_\alpha x^\mu \partial_\beta x^\nu \)
Screening distance in hot moving plasmas

- Static $q\bar{q}$- pair in a hot moving plasma “wind” blowing in $x_2$-direction

- velocity $\nu = \tanh \eta$

- orientation angle $\theta$

Nambu-Goto action:

$$S = \frac{1}{2\pi \alpha'} \int d\sigma d\tau \sqrt{-\det g_{\alpha\beta}}$$

with $g_{\alpha\beta} = G_{\mu\nu} \partial_{\alpha} x^\mu \partial_{\beta} x^\nu$
Configuration of the strings

The string configuration coming closer to the horizon is unstable.
The string configuration coming closer to the horizon is unstable.
$L_{\text{max}}$ is minimal for $\mathcal{N} = 4$. 

\[
\frac{\pi T \sqrt{\cosh(\eta)}}{L_{\text{max}}} = 0.84, 0.86, 0.88, 0.90, 0.92, 0.94
\]
$ar{Q}Q$ -free energy: results

- Free energy of $q\bar{q}$-pair at finite rapidity $\eta = 1$.
- Unstable configurations are weaker bounded.
Coupling $\alpha_{qq}$ is defined as $\alpha_{qq} = \frac{3r^2}{4} \frac{dF(r, T)}{dr}$ in QCD.

Many possibilities by rescaling the parameters.
Running Coupling from Free Energy

Kaczmarek, Karsch, Petreczky and Zantow, 2006

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Is energy loss due to synchrotron radiation or due to drag dominant?

What happens in deformed models?

- dE/dt is very robust.
Rotating Quark in Deformed Metric Models

- Is $\omega \ll \pi T$, $R_0 \ll 1/\omega$
  
  \[\frac{dE}{dt}\bigg|_{\text{RotQ}} \approx \frac{dE}{dt}\bigg|_{\text{Drag}}\]

- Is $\omega \gg \pi T$, $R_0 \omega = v \approx 1$
  
  \[\frac{dE}{dt}\bigg|_{\text{RotQ}} \approx \frac{dE}{dt}\bigg|_{\text{VacRad}}\]

  Vacuum radiation of conformal $N = 4$

- Vacuum radiation is independent of the deformation $\phi$.

- Universal scaling in the crossover regime.

$T = 0.01$, $\omega = 0.7$, $R_0 = 1$, $\phi = \phi_{\text{max}}$
Conclusions

- Although being a conjecture the AdS/CFT correspondence as a realisation of the *Holographic principle* is a very powerful tool for qualitative and quantitative analysis, e.g.:

  - *Robustness* and *Universality* of the screening distance.
  - Running coupling of $q\bar{q}$ - pairs resembles Lattice QCD data.
  - *Robustness* of the energy loss of rotating quarks in deformed models.

- Many other more sophisticated models (e.g. including D3/D7 branes) available that nicely reproduce many QCD features.
Thank you for your attention!
Rotating Quark in Deformed Metric Models

Vacuum radiation is independent of the deformation. Universal scaling in the crossover regime.

\[ \frac{dE}{dt} \left\rvert_{\text{VacRad}} \right. \approx \frac{dE}{dt} \left\rvert_{\text{Drag}} \]

\[ \frac{\Pi \omega z_s^2}{v^2} \]

\[ \gamma^4 \omega^2 z_s^2 \]

\[ \omega \approx 0.7, R_0 = 1, \phi = \phi_{\text{max}} \]

Is then

\[ \omega \ll \pi T, R_0 \ll 1/\omega \]

\[ \omega \gg \pi T, R_0 \]

Vacuum radiation of conformal

\[ N = 4 \]

\[ \Gamma \ll \Omega \ll 0.2 \]

\[ \Omega_0^2 \ll 0.02 \]

\[ \Omega \ll 0.2 \]

Universal scaling in the crossover regime.