Numerical Relativity in AdS, Holography and Thermalization

Christian Ecker

Institute for Theoretical Physics
Vienna University of Technology
Wiedner Hauptstrasse 8-10/136 1040 Vienna, (Austria)

christian.ecker@tuwien.ac.at

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Introduction

- **Motivation**
  - Quark-gluon plasma (QGP) produced at RHIC and LHC behaves like a strongly coupled liquid.
  - Thermalization happens on a small time scale ($\leq 1\text{fm}/c \approx 100\text{ns}$).
  - **Question**: What are the mechanisms responsible for the fast thermalization?

- **Complications**
  - Due to strong coupling perturbative QCD is not applicable.
  - Time dependent processes are problematic for lattice QCD.

- **AdS/CFT approach**
  - Employ AdS/CFT to study dynamics of $\mathcal{N} = 4$ SYM theory.
  - Dynamics of 4-dim. QFT is mapped to class. gravity on 5-dim. AdS.
  - QFT observables we use to study thermalization are the energy momentum tensor, two-point functions and entanglement entropy.
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Anti-de Sitter spacetime and the AdS/CFT correspondence

- Anti-de Sitter spacetime
  - Solution of vacuum Einstein equations with negative $\Lambda$.
  - Boundary at $r = \infty$. 

Asymptotic anti-de Sitter spacetimes
- "look" near $r = \infty$ like AdS.
- e.g.: AdS-black hole
  - BH-temperature $T_H \propto$ horizon radius $r_H$.

Black Hole ($r_H \propto T_H$)

Gravity Theory

Gauge Theory

AdS/CFT correspondence
- Classical gravity on AdS$_5$ ↔ strongly-coupled N=4 SYM on $\partial$AdS$_5$
  - At finite temperature:
    - AdS$_5$-BH ↔ strongly-coupled N=4 SYM at $T = T_H$.

Black hole formation in AdS ↔ thermalization in gauge theory.
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Thermalization of $\mathcal{N} = 4$ SYM Plasma

Energy momentum tensor (EMT) of the anisotropic SYM-plasma:

$$T_{\mu\nu} \propto \text{diag}[\epsilon, P_{\parallel}(t), P_{\perp}(t), P_{\perp}(t)]$$

}\[O(2)\]

AdS/CFT relates $T_{\mu\nu}$ to the metric of an anisotropic AdS-BH.

Line element in Eddington-Finkelstein coordinates:

$$ds^2 = 2drdt - A(r, t)dt^2 + \sum(r, t)^2(e^{-2B(r, t)}dx^2_\parallel + e^{B(r, t)}d\vec{x}^2_\perp)$$

Chesler-Yaffe method

In characteristic formulation (null-slicing) the Einstein eq. decouple to a nested system of linear ODEs.

Use spectral method to solve BVP on each null-slice.

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Numerical Solution: Anisotropy Function $B(u,t)$

\[
\begin{align*}
\dot{H} &= \pi T \\
\dot{\Sigma} |_{r_A} &= 0 \\
\frac{dr_G}{dt} &= \frac{1}{2} A(r, t)
\end{align*}
\]
EMT of the anisotropic $\mathcal{N} = 4$ SYM plasma

$T_E = 1/\pi$
$\varepsilon = 3/4$

$|\Delta P(t)/P_E| < 0.1$
$\forall t > t_{iso} \approx 2.04$

$t = 0.279$
Two-Point Functions and Entanglement Entropy

Various non-local observables in the boundary theory have holographic prescriptions in terms of extremal surfaces:

- Two-point functions: \( G(R, t) \propto e^{-mL(R, t)} \)
- Entanglement entropy: \( S_\Sigma = \frac{A_\Sigma(t)}{4G_N} \)

![Diagram of AdS space and holographic prescription](image)
Spacelike geodesics anchored to the boundary of the anisotropic $AdS_5$ geometry

Geodesic equation as two-point boundary value problem (2PBVP):

\[ \ddot{X}^\mu(\tau) + \Gamma^\mu_{\alpha\beta} \dot{X}^\alpha(\tau) \dot{X}^\beta(\tau) = 0, \quad \text{BCs} : X^\mu(\pm 1) = \begin{pmatrix} V(\pm 1) \\ Z(\pm 1) \\ X(\pm 1) \end{pmatrix} = \begin{pmatrix} t_0 \\ 0 \\ \pm L/2 \end{pmatrix} \]
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- Within AdS/CFT various non-local observables can be computed from geodesics and extremal surfaces.
- In time dependent backgrounds there is information from behind the black hole horizon encoded in the two point functions.

Outlook

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