Bottom up versus top down thermalization

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D. Steineder, SS, A. Vuorinen, arXiv:1209.0291 (accepted in PRL)
OUTLINE

INTRODUCTION

HOLOGRAPHIC THERMALIZATION

RESULTS

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Motivation

**quark gluon plasma**
- produced in heavy ion collisions at RHIC and LHC
- behaves as a strongly coupled liquid
- hydrodynamic simulations work surprisingly well
- apparent puzzle: fast thermalization: $\tau < 1\, fm/c$

**goal**
- gain insight into thermalization process
- which modes thermalize first?
- production rates of weakly interacting particles

**strategy**
- use photons/dileptons as probes of the QGP
THERMALIZATION SCENERIOS

bottom up scenario

- at weak coupling
- scattering processes:
  - in the early stages many soft gluons are emitted which then thermalize the system (Baier et al)
  - driven by instabilities
    - instabilities isotropize the momentum distribution more rapidly than scattering processes (Kurkela, Moore)

top down scenario

- at strong coupling
- UV modes thermalize first
- In AdS calculations at infinite coupling, follows naturally from causality
Photon emission in heavy ion collisions

- direct photons from initial hard scattering and thermalizing plasma
- additional (uninteresting) emissions from charged hadron decays
- virtual photons → Dilepton pairs
Probing the Plasma

Probing the plasma

- once produced photons and dileptons stream through the plasma almost unaltered
- provide observational window in thermalization process of the plasma

Quantity of Interest

- number of photons emitted with given momentum
- differential production rate per unit volume

\[
\frac{d\Gamma^\gamma}{dk_0} = \frac{\alpha_{\text{EM}}}{\pi} k_0 n_B(k^0) \chi^\mu = \frac{-2\alpha_{\text{EM}}}{\pi} k_0 n_B(k^0) \text{Im}(\Pi^\text{ret})^\mu_\mu(k_0)
\]

Problem

- very hard to study out of equilibrium in strongly coupled regime
Our approach

use SYM theory where strongly coupled regime is accessible

gauge gravity duality

- strongly coupled large $N_c$, $\mathcal{N} = 4$ SYM at finite $T$ ⇔ classical gravity in $AdS_5$ black hole background
- temperature of the black hole can be identified with field theory temperature

similarities to QCD at finite $T$

- deconfinement
- Debye screening
- SUSY and conformal symmetry broken
- finite spatial screening length

advantage: can calculate observables at weak and strong coupling
Photon emission in equilibrium SYM plasma

Caron-Huot et al. (2006) & Hassanain et al. (2011):

- Effect of increasing coupling in perturbative result: Slope at $k = 0$ decreases, hydro peak broadens and moves right
- Effect of decreasing coupling from $\lambda = \infty$: Peak sharpens and moves left
Out of equilibrium

- equilibrium picture in SYM fairly complete
- how does photon/dilepton emission rate get modified out of thermal equilibrium?
- can one access thermalization at finite coupling?
AdS/CFT duality: Thermalizing system

- Simplest way to take system out of equilibrium: Begin with a thin massive shell at $r = r_s > r_h$ and let it collapse towards $r_s = r_h$ (Danielsson, Keski-Vakkuri, Kruczenski (1999))

\[
\begin{array}{|c|c|c|c|}
\hline
\text{center} & \text{horizon} & \text{shell} & \text{boundary} \\
\hline
r = 0 & r = r_h & r = r_s & r = \infty \\
\hline
\end{array}
\]

- 2-point functions ‘see’ the location of the shell through modified boundary conditions ⇒ Out-of-equilibrium effects

- **quasistatic approximation**: static shell; $\omega \gg 1/\tau_s$; energy scale of interest $\gg$ characteristic time scale of shells motion
**Photon and dilepton spectral density**

![Graphs showing photon and dilepton spectral densities.]

- Left: photon spectral density $\chi_\gamma(\omega = k = 2\pi T\hat{\omega}, r_s/r_h)$ for $r_s/r_h = 1.001, 1.01, 1.1$.
- Right: dilepton spectral density for $q = 0, 1, 2$.

- Out of equilibrium effect: oscillations around thermal value
- As the shell approaches the horizon, equilibrium is reached.

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**Bottom up versus top down thermalization**
Thermalization at infinite coupling: photons

- Relative deviation from thermal equilibrium

\[ R(\hat{\omega}) = \frac{\chi(\hat{\omega}) - \chi_{th}(\hat{\omega})}{\chi_{th}(\hat{\omega})} \]

Relative deviation \( R_\gamma \) for \( r_s/r_h = 1.01, 1.1 \) and \( \lambda = \infty \).

- Top down thermalization: highly energetic modes are closer to their equilibrium value

\[ \chi(\hat{\omega}) \approx \hat{\omega}^2 \left( 1 + \frac{f_1(\omega_s)}{\hat{\omega}} \right) \]
THERMALIZATION DEPENDING ON THE VIRTUALITY

virtuality
\[ v = \frac{\hat{\omega}^2 - \hat{q}^2}{\hat{\omega}^2} \]

parametrize
\[ q = c \hat{\omega} \]

Relative deviation \( R_\gamma \) for \( r_s/r_h = 1.1 \) and \( c = 1, 0.7, 0. \)

thermalization depends on the virtuality
photons are last to thermalize
same conclusion was reached in other models of holographic thermalization
Arnold et al., Chesler and Teaney

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**Photon production rate**

left: Photon production rate for $r_s/r_h = 1.001, 1.01, 1.1$. right: Photon production rate in equilibrium for $\lambda = \infty, 75, 50$.

- enhancement of production rate
- hydro peak broadens and moves right
- Can one combine the two calculations to study thermalization at finite coupling?
Photon emission spectrum with $\gamma$ corrections

Photon emission rate for $r_s/r_h = 1.01$ and $\lambda = \infty, 150, 75, 50$.

- behavior very similar to thermal limit.
THERMALIZATION AT FINITE COUPLING

- relative deviation from thermal equilibrium

Relative deviation $R_\gamma$ for $r_s/r_h = 1.01$ and $\lambda = \infty, 500, 300, \ldots$.

- behavior of relative deviation changes at large frequencies
Thermalization at finite coupling

- relative deviation from thermal equilibrium

Relative deviation $R_\gamma$ for $r_s/r_h = 1.01$ and $\lambda = 150, 100, 75$.

$$\chi(\hat{\omega}) \approx \hat{\omega}^{2/3} \left( 1 + \frac{f_1(u_s)}{\hat{\omega}} + \frac{f_2(u_s)\hat{\omega}}{\lambda^{3/2}} \right)$$

- might indicate a change of the thermalization pattern from top-down towards bottom up.
Conclusions

thermalization at infinite coupling

- enhancement of production rate
- observe top down thermalization

thermalization at finite coupling

- thermalization scenario depends on the coupling
- bottom up thermalization also possible at strong coupling?

future directions

- go beyond the quasistatic approximation
- look at plasma constituents itself (components of the stress energy tensor)