Out of equilibrium dynamics: how to deal with it

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- pertubative QFT
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- classical aspects
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  - How its dynamics differ from (adiabatic) hydrodynamic approximation?
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  - How its dynamics differ from (adiabatic) hydrodynamic approximation?
  - How (how fast) does the system relax?
  - Evolution of gauge invariant observables
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- **Gauge/string correspondence**: the gauge theories *practically* accessible within the holographic framework are not QCD:
  
  - the gauge group
    
    $$SU(3) \longrightarrow SU(N), \quad N \rightarrow \infty$$
  
  - matter representation: 3 families of quarks in the fundamental representation $\longrightarrow$ (typically) matter in adjoint/bifundamental representation, with additional scalar fields (in the same representation and masses as quarks), more massless scalars and fermions in the adjoint representation. (All this is the consequence of the fact that the gauge theories models are supersymmetric, or their close cousins)
  
  - no asymptotic freedom (must always be at strong coupling over the full energy range)
Not to despair!

- Often, strongly coupled conformal dynamics is a useful approximation

\[ \frac{1}{3} \approx \frac{1}{N}, \quad N \gg 1 \]

- some aspects of the gauge theory dynamics are universal

- sometimes, there is no other choice but to use holography
Caveats:

- Top down/bottom up approaches:
  - It is easy to generate (simple) phenomenological models of holographic, and use the holographic dictionary to compute stuff — the price is that we don’t know what are we doing, and more importantly we don’t know if ’singularities’ that arise are physical or shortcomings of the phenomenology
  - Real string theory examples of holography are far and between — know exactly what theory we are talking about, sometimes can do precision tests of holography, real physics, but obviously more restrictive (more difficult to ’engineer’ phenomena/features of interest)
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    - top-down models with confinement/chiral symmetry breaking exist (quiver gauge theories)
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⇒ Often, not much difference between ’real’ and ’phenomenological’ holography (gravitational universality)
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⇒ It is possible to 'prepare' the non-equilibrium state by changing in a time-dependent fashion QFT parameters (masses, background metric, external magnetic field, etc.) from equilibrium state — the philosophy behind holographic quantum quenches
Outline of the talk:

• Holographic thermal equilibrium
  ■ conformal gauge theory plasma at strong coupling
  ■ non-conformal gauge theory plasma at strong coupling

• Holographic hydrodynamics
  ■ shear viscosity
  ■ bulk viscosity

• Physics far from equilibrium
  ■ quantum quenches
  ■ role of nonhydrodynamic modes

• Equilibration in (non-)CFT gauge theory plasmas

• Conclusions and future directions
Consider $\mathcal{N} = 4$ supersymmetric $SU(N)$ Yang-Mills theory.

- The field content of $\mathcal{N} = 4$ SYM theory includes (all in the adjoint representation):
  - the gauge field $A_\mu$
  - 4 Majorana fermions $\psi_a$
  - 3 complex scalars $\phi_i$
  - the gauge coupling $g_{YM}$ is exactly marginal
  - $\mathcal{L}$ is Lagrangian density of the theory, completely constraint by maximal $\mathcal{N} = 4$ supersymmetry
There is a useful holographic dual of this theory when

- \( N \to \infty \) and \( g_{YM}^2 \to 0 \) with 't Hooft coupling \( \lambda \equiv g_{YM}^2 N \) kept constant
- \( \lambda \gg 1 \)

The holographic dual is 5d Einstein gravity with the negative cosmological constant

\[
S_5 = \frac{1}{16\pi G_5} \int d^5x \sqrt{-g} (R + 12), \quad G_5 = \frac{\pi}{2N^2}
\]

SYM thermal states \( \iff \) black holes of \( S_5 \)
Thermal properties of BH are interpreted as thermal properties of strongly coupled $\mathcal{N} = 4$ SYM plasma:

- the energy density
  \[ \epsilon = \frac{3}{8} \pi^2 N^2 T^4 \]

- the pressure
  \[ p = \frac{1}{8} \pi^2 N^2 T^4 \]

- the entropy density
  \[ s = \frac{1}{2} \pi^2 N^2 T^3 \]

Note the $\frac{3}{4}$ factor between the weak and strong coupling

\[ \epsilon = \frac{3}{4} \epsilon_{SB} \]
• QCD thermodynamics from lattice; (Karsch, Laermann, hep-lat/0305025). The plateau is $\sim 80\%$ of the SB result — close to $3/4$ in SYM thermodynamics.
From A. Bazarov et al. (HotQCD Collaboration), arXiv:1407.6387:

The violation of the conformality,

\[ \frac{\epsilon - 3p}{\epsilon} \sim 50\% \]

at the maximum
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⇒ how to go beyond CFT in top-down:
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⇒ how to go beyond CFT in top-down:
- on a gauge theory side ($\mathcal{N} = 2^*$ model)

$$
\delta \mathcal{L} = -2 \int d^4x \left[ m^2 \mathcal{O}_b + m \mathcal{O}_f \right]
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where

$$\mathcal{O}_b = \frac{1}{3} \text{Tr} \left( |\phi_1|^2 + |\phi_2|^2 - 2 |\phi_3|^2 \right)$$

$$\mathcal{O}_f = -\text{Tr} \left( i \psi_1 \psi_2 - \sqrt{2} g_{YM} \phi_3 [\phi_1, \phi_1^\dagger] + \sqrt{2} g_{YM} \phi_3 [\phi_2, \phi_2] + \text{h.c.} \right) + \frac{2}{3} m \text{Tr} \left( |\phi_1|^2 + |\phi_2|^2 + |\phi_3|^2 \right)$$
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\[ \Rightarrow \text{how to go beyond CFT in top-down:} \]

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\[
+ \frac{2}{3} m \text{Tr} \left( |\phi_1|^2 + |\phi_2|^2 + |\phi_3|^2 \right)
\]

\[ \Rightarrow \]

\[
\langle T^\mu_\mu \rangle = -\epsilon + 3p = -2m \langle \mathcal{O}_f \rangle - m^2 \langle \mathcal{O}_b \rangle
\]
on the gravity side:

\[ S = \frac{1}{16\pi G_5} \int d^5 x \sqrt{-g} (R + 12) \]

\[ \Uparrow \]

\[ S = \frac{1}{16\pi G_5} \int d^5 x \sqrt{-g} (R - 12(\partial\alpha)^2 - 4(\partial\chi)^2 - V(\alpha, \chi)) \]
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- gravitational scalar \( \alpha \leftrightarrow \mathcal{O}_b \) (dimension \( \Delta = 2 \), bosonic mass term)
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• gravitational scalar \( \chi \leftrightarrow O_b \) (dimension \( \Delta = 3 \), fermionic mass term)
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- gravitational scalar \( \alpha \leftrightarrow \mathcal{O}_b \) (dimension \( \Delta = 2 \), bosonic mass term)
- gravitational scalar \( \chi \leftrightarrow \mathcal{O}_b \) (dimension \( \Delta = 3 \), fermionic mass term)
- 
  \[ V(\alpha, \chi) = -12 + \mathcal{O}(\alpha^2, \chi^2) \]
From $\mathcal{N} = 2^*$ BH thermodynamics:

- (L) Trace of the energy-momentum tensor normalized to the energy density of $\mathcal{N} = 4$ SYM ($\epsilon_0 = \frac{3}{8} \pi^2 N_c^2 T^4$ with $N_c$ denoting the number of colors) as a function of $m/T$. The results indicate that, thermodynamically, the effects of the conformal symmetry breaking are the strongest at $m/T \approx 4.8$.

- (R) Trace anomaly in deep IR — approach to a $CFT_5$
Alternative top-down model for breaking scale invariance is Klebanov-Strassler (KS) gauge theory plasma

Some notable differences between $\mathcal{N} = 2^*$ and KS models:

- in $\mathcal{N} = 2^*$ the scale invariance is broken explicitly (mass terms); in the scale invariance is broken by quantum effects (nonzero $\beta$-function)
- unlike $\mathcal{N} = 2^*$, KS gauge theory confines in the IR with the spontaneous chiral symmetry breaking

How do we like compare different non-conformal models with QCD?
(Proposed) general framework for comparing the thermodynamics of the models is the $\Theta$ vs. $\delta$ plane, where

$$\Theta \equiv \frac{\epsilon - 3P}{\epsilon}, \quad \delta \equiv \frac{1}{3} - c_s^2$$

with $c_s$ being the speed of sound waves in plasma,

$$c_s^2 = \frac{\partial P}{\partial \epsilon}$$

The advantage of this framework is that

- is not sensitive as to how exactly is the scale invariance broken
- no need to relate $N$ and $T$
- we can compare with lattice QCD
\[ \Theta = \frac{\epsilon - 3p}{\epsilon} \]

- lattice QCD (the red dots)
- \( \mathcal{N} = 2^* \) (the solid green line)
- KS gauge theory (the solid blue line)
- vertical lines: \( T = 0.3\text{GeV} \) (red), phase transitions in KS (blue)
Over the years, the holographic dictionary has been developed to extract $\langle T_{\mu\nu} \rangle$ of the gauge theory plasma as the series of the local-velocity gradients.

- Relativistic hydrodynamics (without conserved charges/anomalies):

$$T_{\mu\nu} = \epsilon u^\mu u^\nu + p \Delta^{\mu\nu} + T_{\text{hydro}}^{\mu\nu}$$

where

$$u^\mu u_\mu = -1, \quad \Delta^{\mu\nu} = g^{\mu\nu} + u^\mu u^\nu, \quad u_\mu \Delta^{\mu\nu} = 0$$

$$T_{\text{hydro}}^{\mu\nu} = -\eta \left[ \Delta^{\mu\lambda} \left( \nabla_\lambda u^\nu + \nabla^\nu u_\lambda - \frac{2}{3} \delta^\nu_\lambda \nabla_\alpha u^\alpha \right) \right] - \zeta \left[ \Delta^{\mu\nu} \nabla_\alpha u^\alpha \right]$$

- $\eta$ — shear viscosity
- $\zeta$ — bulk viscosity
⇒ from holographic computations:

- shear viscosity (Kovtun-Son-Starinets, ...)

\[ \frac{\eta}{s} = \frac{\hbar}{4\pi k_B} \]
\[ \eta_s = \frac{1}{4\pi} \left( \frac{\hbar}{k_B} \right) \]

- universal for all gauge theories with a holographic dual, provides the equilibrium state is isotropic and homogeneous.
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- the viscosity bound

\[
\frac{\eta}{s} \geq \frac{1}{4\pi}
\]

can be violated

- arbitrarily close to zero in holographic phenomenological models
- to leading order in \( O \left( \frac{1}{N} \right) \) in top-down holographic examples
- violated in anisotropic plasma (top-down/bottom-up models) at \( O(1) \)
bulk viscosity in holography is model dependent; for large class (but not all) models

$$\frac{\zeta}{\eta} \geq 2 \left( \frac{1}{3} - c_s^2 \right)$$
- bulk viscosity in holography is model dependent; for large class (but not all) models

\[
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- the bound is saturated if one reduces a conformal hydrodynamics in \( D > 3 \) (spatial) to \( d = 3 \) dimensional hydrodynamics:

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\frac{\zeta}{\eta} = 2 \left( \frac{1}{3} - c_s^2 \right) = 2 \left( \frac{1}{3} - \frac{1}{D} \right)
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• in $\mathcal{N} = 2^*$ plasma

![Graph showing the bound for bulk viscosity](image)
• in KS plasma: $\frac{\zeta}{\eta} = 4\pi \frac{\zeta}{s}$,

- dashed blue: the bulk viscosity bound
- dashed vertical: $T_c$ for the deconfinement transition in KS
Physics far from equilibrium

- Recall, we deformed $\mathcal{N} = 4$ CFT with

$$\delta \mathcal{L} = -2 \int d^4 x \left[ m^2 \mathcal{O}_b + m \mathcal{O}_f \right]$$
Physics far from equilibrium

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- Now,

$$m \rightarrow m(t) \quad \text{with} \quad \lim_{t \rightarrow \pm \infty} m(t) = \text{const}$$

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  \[ \delta \mathcal{L} = -2 \int d^4 x \left[ m^2 \mathcal{O}_b + m \mathcal{O}_f \right] \]

- Now,
  
  \[ m \to m(t) \quad \text{with} \quad \lim_{t \to \pm \infty} m(t) = \text{const} \]

then:

- we start with the equilibrium state in the infinite past
- can use a profile $m(t)$ to bring the system out of equilibrium in a controlled fashion
- expect to reach the equilibrium state in the infinite future
• This can be implemented in holography in precise manner: specifically, we choose

\[ m = \left( \frac{1}{2} + \frac{1}{2} \tanh \frac{t}{\mathcal{T}} \right) \times m_0, \quad \mathcal{T} = \frac{\alpha}{T_{\text{initial}}}, \quad m_0 = \text{const} \]

• Note:

\[ \alpha \ll 1 \quad \Rightarrow \quad \text{fast quenches} \]
\[ \alpha \gg 1 \quad \Rightarrow \quad \text{slow (adiabatic) quenches} \]

• Once mass becomes time-dependent,

\[ \mathcal{O}_b(t), \quad \mathcal{O}_f(t) \]

as well as \( \epsilon(t) \) and \( p(t) \)
Introducing $\tau \equiv \frac{t}{T}$:

- Evolution of the normalizable component $O_f(\tau)$ (left panel) and $O_b(\tau)$ (right panel) during the quenches with $\alpha = 1$. The dashed red lines represent the adiabatic response.

- As $\tau \to +\infty$ the expectation values approach their equilibrium values in a damped-oscillatory manner (More on this later).
How do we characterize equilibration time?

- Introduce

\[ \delta_{neq}(\tau) \equiv \left| \frac{\mathcal{O}_\Delta(\tau) - [\mathcal{O}_\Delta(\tau)]_{adiabatic}}{[\mathcal{O}_\Delta(\tau)]_{adiabatic}} \right|, \]

where \([\mathcal{O}_\Delta(\tau)]_{adiabatic}\) is the adiabatic response that can be computed analytically.

- Note,

\[ \lim_{\tau \to \pm \infty} \delta_{neq}(\tau) \to 0 \]

as at early/late times the system is in equilibrium.
In practice,

Extraction of the excitation/equilibration rates for $\alpha = 1$ quench. The horizontal green line is the threshold for excitation/equilibration which we define to be 5% away from local equilibrium as determined by $\delta_{neq}$. The dashed red lines indicate the earliest and latest times of crossing this threshold, which we denote as $\tau_{ex}$ (for excitation time) and $\tau_{relax}$ (for equilibration time), respectively.
Going to small $\alpha$ ($\ln \alpha \to -\infty$) corresponds to preparing the state with an abrupt quench of a dim-$\Delta$ operator. The dashed scaling line translates into a universal relaxation time:

$$t_{relax} \sim \frac{1}{T}$$

independent of $\alpha$!
We can do more:

Behavior of the response coefficients versus time for representative fast quenches. As is evident in the picture, the same quasinormal mode governs the dynamics very quickly after the quench:

\[
\Delta = 3 : \quad \left. \frac{\omega}{2\pi T} \right|_{fit} \simeq (1.095 - i 0.87) , \quad \left. \frac{\omega}{2\pi T} \right|_{BH} \simeq (1.099 - i 0.879) \\
\Delta = 2 : \quad \left. \frac{\omega}{2\pi T} \right|_{fit} \simeq (0.64 - i 0.4) , \quad \left. \frac{\omega}{2\pi T} \right|_{BH} \simeq (0.644 - i 0.411)
\]
Moral of the story:

*Lowest quasinormal modes of the black hole in the gravitational dual control the relaxation in strongly coupled gauge theory plasma*

- Such feature was also observed in various other holographic examples
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To which extent the lowest quasinormal mode is universal? (universality in relaxation)?
\[
(T \tau_{relax})^{-1} \sim -\text{Im} \frac{\omega}{2\pi T}
\]

\[
\delta = \frac{1}{3} - c_s^2
\]

- $\mathcal{N} = 2^*$ plasma — the solid green line
- KS plasma — the solid blue line
- red line represents $\delta$ in QCD at $T = 0.3\text{GeV}$
- vertical blue lines represent the phase transitions in KS plasma
Conclusions and future directions:

- I argued that *holographic correspondence* is a useful tool in understanding non-equilibrium properties of strong coupled gauge theory plasma:
  - it is possible to formulated correspondence in precise manner for (limited class) of non-conformal gauge theories
  - $\eta_s$ is small, and universal
  - $\zeta_s \lessapprox 0.1$
    - it is challenging to obtain large bulk viscosity in holography
  - one can use holography to reliably prepare non-equilibrium states via quantum quenches from equilibrium states and study
    - relaxation of local ($O_\Delta$, $T_{\mu\nu}$) and nonlocal (2-point correlation functions, entanglement entropy) operators
    - higher-order hydrodynamic transport coefficients
    - validity of adiabatic/hydrodynamic approximation
    - role (and universal character) of non-hydrodynamic modes
In the future:

- (short term) understanding collective phenomena in small systems
- (long term) building up holographic dictionary and learning how to better model initial states (the process) of a collision

Thank you!
⇒ Extra slides
The response of $\mathcal{O}_\Delta$ depends on $\Delta$:
- for fast quenches, $\alpha$ is small,
Momentum dependence of the lowest quasinormal mode of the transverse traceless fluctuations of the stress-energy tensor in KS gauge theory plasma at the ultraviolet fixed point (solid lines), the deconfinement phase transition (dashed lines), and the chiral symmetry breaking phase transition (dotted lines). The green/red lines represent the real/minus imaginary parts of the frequencies. The data is normalized to zero momentum values of the frequencies.