Unexpected connections: hot quark matter, black holes and string theory

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Black holes & fluid mechanics

Black holes

Fluids

Dynamics governed by gravity
Dynamics governed by hydrodynamics
Black holes & fluid mechanics

Black holes

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Dynamics governed by gravity  Dynamics governed by hydrodynamics
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Dynamics governed by gravity

Dynamics governed by hydrodynamics

Connection comes from string theory and holographic principle.
Holographic principle

Hologram:
2D image containing 3D information
Holographic principle:
Information thrown in BH encoded in surface enclosing BH.

(t’ Hooft, Suskind: 93, 94)

Hologram:
2D image containing 3D information
A (or perhaps the) concrete example of the holographic principle

The Maldacena conjecture:
String theory in a 5D “box”
   = quantum theory on “surface” of box.
(Maldacena: 97), (many, many others)

Dictionary:

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The utility of holography

- Offers new perspective.

- Difficult quantum physics = easy-ish stringy physics.
  - String theory can be approximated with classical gravity!

Same physics that governs astrophysics & cosmology encodes physics of quantum theories!!!
Qualitative similarities between black holes and liquids (I)

**Fluid mechanics:** Mechanics governing transport of conserved quantities over long distances.

- **Universal**
  - Same physical principles for smoke, magma, milk & coffee, and QGP.

- **Thermodynamic:** Fluids have a temperature & entropy.

- **Dissipative**
  - Longest lifetime excitations = longest wavelength.
Qualitative similarities between black holes and liquids (II)

Classical black holes:

- **Universal dynamics:**
  - Gravitational dynamics only depend on conserved properties of matter that created black hole.

- **Dissipative:**
  - Absorb radiation, long wavelength absorbed slowest.

- **Thermodynamic:** Black holes have a temperature & entropy.
Qualitative similarities between black holes and liquids (III)

Late times: spreading out of conserved quantities falling into event horizon.
Qualitative similarities between black holes and liquids (III)

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Holographic charge density = flux of electric field through surface.
Qualitative similarities between black holes and liquids (III)

Late times: spreading out of conserved quantities falling into event horizon.

Holographic charge density = flux of electric field through surface.
Two very difficult problems in quantum theory

Heavy ion collisions

$\text{time} \quad \longleftrightarrow \quad t_{\text{liquid}} \sim 1 \text{ fm/c} \quad \longleftrightarrow \quad \text{liquid}$

Experimental observations:

1. Rapid “hydrodynamization.”

2. QGP has extremely small viscosity.
**Just how fast and how small?**

**Hydrodynamization time:**

![Earth and Moon](image)

$4 \times 10^5$ km

Light travel time $\sim 1.3$ s.

**Viscosity:**

![Viscosity graph](image)

A proton

$10^{-15}$ m

Light travel time $\sim t_{\text{hydro}}$.

quark-gluon plasma
Just how fast and how small?

Hydrodynamization time:

Light travel time $\sim 1.3$ s.

Understanding rapid hydrodynamization & small viscosity from first principles calculations in quantum theory has proven extremely challenging!
A gravitational toy model of heavy ion collisions

All physics — from far-from-equilibrium dynamics to hydrodynamics — encoded in classical 5D gravitational physics.
Hydrodynamization results illustrated

(Chesler & Yaffe, 11)

Energy density

Pressures $\mu z = 0$

Hydrodynamic prediction
Hydrodynamization results illustrated

(Chesler & Yaffe, 11)

Hydrodynamic prediction

For RHIC energies,

\[ \mu \sim 2.3 \text{ GeV} \]

and \( t_{\text{hydro}} \sim 0.35 \text{ fm/c} \).
Lower bound on $t_{\text{hydro}}$:

- $t_{\text{hydro}} \gtrsim \text{“size of box”} \sim \frac{1}{T_{\text{QGP}}}$
Lower bound on $t_{\text{hydro}}$ from uncertainty principle:

Qualitative argument:

- $t_{\text{hydro}} \bar{\epsilon}_{\text{quark, gluons}} \gtrsim 1$
- $\bar{\epsilon}_{\text{quark, gluons}} \sim T_{\text{QGP}}$
- $\Rightarrow t_{\text{hydro}} \gtrsim \frac{1}{T_{\text{QGP}}}$
Viscosity of QGP from holography

\[ \text{viscosity} \propto \text{long wavelength absorption rate} \]

Famous result from holography:

\[ \text{viscosity} = \frac{1}{4\pi} \times \text{entropy density} \]

(Kovtun, Policastro, Son, Starinets, 01, 05)
Viscosity of QGP from holography

\[ \mu z = 0 \]

\[ 0 \leq P \leq 0.75 \]

\[ -2 \leq \mu t \leq 6 \]

\[ 0 \leq \mu z \leq 3 \]

Famous result from holography:

\[ \text{viscosity} = \frac{1}{4\pi} \times \text{entropy density} \]

(Kovtun, Policastro, Son, Starinets, 01, 05)

A few times smaller than experimental observations!
Concluding remarks

- **Remarkable** connection between black holes, string theory and quark-gluon plasma.
- **Difficult** quantum physics is accessible via classical gravity.
- String theory is **useful**!
Conclusions
Equilibration of sound waves

How does the system approach equilibrium?

• Non conserved quantities: relax ⇨ microscopic.

• Conserved quantities cannot locally disappear. Ex: energy transported via sound waves.

At large distances surviving sound wavelength ⇨ horizon.

• Gravitational description
  • Shooting quark through liquid ⇐ throwing string into black hole.

“Holographic image”

energy density

String ⇐ Black hole

Shooting quark through liquid ⇐ throwing string into black hole.
Equilibration of sound waves

How does the system approach equilibrium?

- Non conserved quantities:
  - Relaxation at microscopic scales.

- Conserved quantities cannot locally disappear:
  - Example: energy transported via sound waves.

- At large distances, surviving sound wavelength:
  - Surviving sound wavelength.

Gravitational description:

- Shooting quark through QGP (Quark Gluon Plasma) is equivalent to throwing string into black hole.
- String emits full spectrum of radiation.
  - Short wavelength absorption:
    - Infall horizon radius.
  - Long wavelength absorption:
    - Absorbed wavelength $\lambda \propto \frac{1}{M}$, where $M$ is the black hole mass.

All dynamics – from far from equilibrium quantum dynamics to hydrodynamics – is encoded in the classical gravitational problem.

"Holographic image" energy density

Shooting quark through liquid $\Leftrightarrow$ throwing string into black hole.
Equilibration of sound waves

• Non conserved quantities:

  - Relaxation of microscopic quantities.

• Conserved quantities cannot locally disappear:
  - Ex: energy transported via sound waves.

• At large distances surviving sound wavelength:

  - Gravitational description:
    - Shooting quark through liquid $\rightleftharpoons$ throwing string into black hole.
    - String emits full spectrum of radiation.
    - Short wavelength absorption: infall $\rightarrow$ horizon radius.
    - Long wavelength absorption: absorb $\rightarrow$ $\frac{1}{2}$ wavelength $^2$.
    - Gravitational disturbance becomes longer wavelength.

All dynamics — from far from equilibrium quantum dynamics to hydrodynamics is encoded in the classical gravitational problem.

“Holographic image”

Black hole

String

Energy density
FIG. 3: Left—Position space plot of $|x| E(x) / T^3 p$ for $v = \frac{1}{4}$. Right—Position space plot of $|x| S(x) / T^3 p$ for $v = \frac{1}{4}$. The flow lines on the surface are the flow lines of the energy flux $S(x)$. There is a surplus of energy in front of the quark and a deficit behind it. Correspondingly, trailing the quark there is a stream of energy flux which moves in the same direction as the quark. Note the absence of structure in $E(x)$ for distances $|x| > 1 / (\frac{\pi}{T^3 p})$.

FIG. 4: Left—Plot of $|x| E(x) / T^3 p$ for $v = \frac{3}{4}$. Right—Plot of $|x| S(x) / T^3 p$ for $v = \frac{3}{4}$. The flow lines on the surface are the flow lines of $S(x)$. There is a surplus of energy in front of the quark and a deficit behind it. Correspondingly, trailing the quark there is a narrow stream of energy flux which moves in the same direction as the quark. A Mach cone, with opening half angle $\theta_M ~ 50^\circ$ is clearly visible in both the energy density and the energy flux. Near the Mach cone, the bulk of the energy flux flow is orthogonal to the wavefront.
FIG. 3: Left—Position space plot of $|x| E(x) / (T^3 \rho)$ for $v = 1/4$. Right—Position space plot of $|x| S(x) / (T^3 \rho)$ for $v = 1/4$. The flow lines on the surface are the flow lines of the energy flux $S(x)$. There is a surplus of energy in front of the quark and a deficit behind it. Correspondingly, trailing the quark there is a stream of energy flux which moves in the same direction as the quark. Note the absence of structure in $E(x)$ for distances $|x| \geq 1/(\pi T)$.

FIG. 4: Left—Plot of $|x| E(x) / (T^3 \rho)$ for $v = 3/4$. Right—Plot of $|x| S(x) / (T^3 \rho)$ for $v = 3/4$. The flow lines on the surface are the flow lines of $S(x)$. There is a surplus of energy in front of the quark and a deficit behind it. Correspondingly, trailing the quark there is a narrow stream of energy flux which moves in the same direction as the quark. A Mach cone, with opening half angle $\theta_M \approx 50^\circ$ is clearly visible in both the energy density and the energy flux. Near the Mach cone, the bulk of the energy flux flow is orthogonal to the wavefront.