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

Paul Chesler
Black holes & fluid mechanics

Black holes

Dynamics governed by gravity

Fluids

Dynamics governed by hydrodynamics
Black holes & fluid mechanics

**Black holes**

Dynamics governed by gravity

**Fluids**

Dynamics governed by hydrodynamics

Sunday, August 12, 12
Black holes & fluid mechanics

Black holes

Fluids

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:**

| 5D object       | 4D holographic image       |
|-----------------|--------------------------|
| strings         | quarks & gluons          |
| EM fields       | electric currents        |
| black holes     | liquids                  |

We live here.

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A (or perhaps *the*) concrete example of the holographic principle

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   = quantum theory on “surface” of box.
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Dictionary:

| 5D object    | 4D holographic image           |
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| strings      | quarks & gluons                |
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We live here.

{black hole
\text{5th dimension}}

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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)

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

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

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

Experimental observations:

1. Rapid “hydrodynamization.”

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

Hydrodynamization time:

\[4 \times 10^5 \text{ km}\]

Light travel time \(\sim 1.3\) s.

Viscosity:

\[
\begin{align*}
\text{Helium } 0.1\text{MPa} & : \text{Helium } 0.1\text{MPa} \\
\text{Nitrogen } 10\text{MPa} & : \text{Nitrogen } 10\text{MPa} \\
\text{Water } 100\text{MPa} & : \text{Water } 100\text{MPa}
\end{align*}
\]

A proton

\[10^{-15} \text{ m}\]

Light travel time \(\sim t_{\text{hydro}}\).

Quark-gluon plasma

\[
\begin{align*}
\text{viscosity} & \sim 100 \\
T (\text{K}) & \sim 1000
\end{align*}
\]

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References

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[2] J.D. Bekenstein, "Black holes and entropy," Phys. Rev. D 7, 2333 (1973).

[3] G.T. Horowitz and A. Strominger, "Black strings and p-branes," Nucl. Phys. B 360, 197 (1991).

[4] L.D. Landau and E.M. Lifshitz, Fluid Mechanics (Pergamon Press, New York, 1987).

[5] G. 't Hooft, "Dimensional reduction in quantum gravity," gr-qc/9310026.
Hydrodynamization time:

Just how fast and how small?

A remarkable result from RHIC

• Dynamics of QGP well modeled by near-ideal hydrodynamics.
  - Hydrodynamics applies 1 fm/c after collision [Heinz: nucl-th/0407067]

• Most perfect fluid discovered
  - $s \ll \text{mean free time between collisions}$
  - $s \ll \text{strongly coupled QGP}$

$\approx 10^{-4}$

$\approx 10^{-15}$ m

Light travel time $\sim 1.3$ s.

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

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

Hydrodynamic prediction
Hydrodynamization results illustrated
(Chesler & Yaffe, 11)

Hydrodynamic prediction

For RHIC energies,
\( \mu \sim 2.3 \text{ GeV} \)
and \( t_{\text{hydro}} \sim 0.35 \text{ fm}/c. \)
Gravitational origin of $t_{\text{hydro}}$

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

\[ \mu z = 0 \]

\[ \begin{array}{c}
\text{mirror} \\
\text{absorber}
\end{array} \]

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

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

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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 microscopically.

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

- At large distances surviving sound wavelength.

Gravitational description

- Shooting quark through QGP ⇔ throwing string into black hole.
- String emits full spectrum of radiation.
- Short wavelength absorption: infall horizon radius.
- Long wavelength absorption: absorb $\propto \lambda^2$.
- Gravitational disturbance becomes longer wavelength.

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

“Holographic image”

energy density

String ⇔ Black hole
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
  - \( \text{surviving sound wavelength} \Rightarrow \text{gravitational disturbance becomes longer wavelength} \)

Gravitational description

- Shooting quark through QGP
  - \( \Rightarrow \text{throwing string into black hole} \)
- String emits full spectrum of radiation
  - Short wavelength absorption: \( \text{infall} \Rightarrow \text{horizon radius} \)
  - Long wavelength absorption: \( \text{absorb} \Rightarrow \text{zwavelength)} \)

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

"Holographic image"
Equilibration of sound waves

Non conserved quantities: relax \(ightarrow\) microscopic.

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

At large distances surviving sound wavelength \(\uparrow\rightarrow\).

Gravitational description

- Shooting quark through QGP \(\Rightarrow\) throwing string into black hole.
- String emits full spectrum of radiation.
  - Short wavelength absorption: infall \(\rightarrow\) horizon radius.
  - Long wavelength absorption: absorb \(\rightarrow\) scale\(^2\).

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.
FIG. 3: Left—Position space plot of $|x|\Delta S(x)/T^3\sqrt{\lambda}$ for $v = 1/4$. Right—Position space plot of $|x|\Delta S(x)/T^3\sqrt{\lambda}$ 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 $|x| > 1/\pi T$.

FIG. 4: Left—Plot of $|x|\Delta S(x)/T^3\sqrt{\lambda}$ for $v = 3/4$. Right—Plot of $|x|\Delta S(x)/T^3\sqrt{\lambda}$ 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 $\theta_M = 50$ 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 $|x| E(x)/T^3 p$ for $v = 1/4$. Right—Position space plot of $|x| S(x)/T^3 p$ 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 $|x| > 1/(\pi T)$.

FIG. 4: Left—Plot of $|x| E(x)/T^3 p$ for $v = 3/4$. Right—Plot of $|x| S(x)/T^3 p$ 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 $\theta \approx 50^\circ$ 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.