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

Paul Chesler

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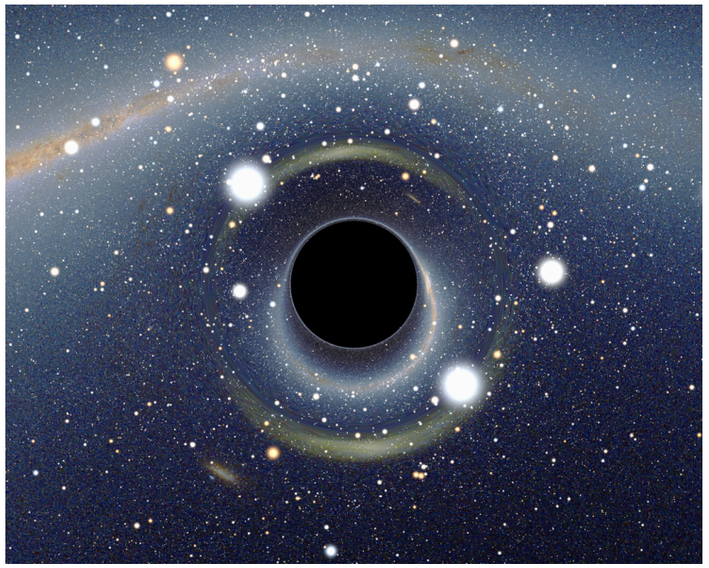
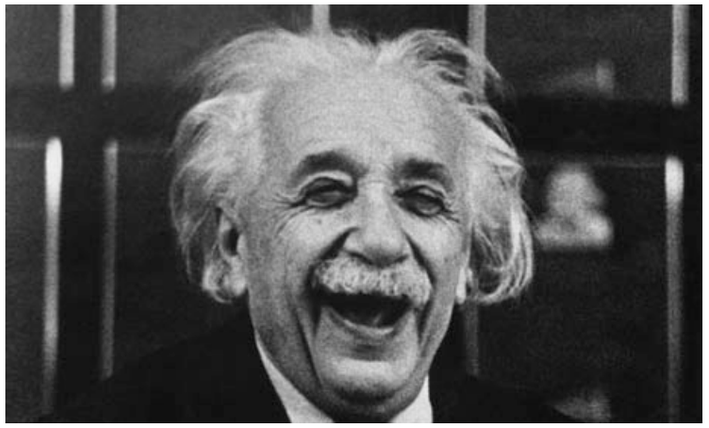
Black holes & fluid mechanics

Black holes

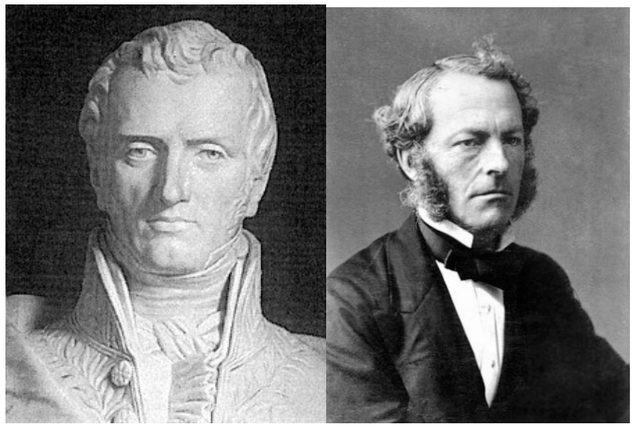


Fluids

Dynamics governed by gravity



Dynamics governed by hydrodynamics



Black holes & fluid mechanics

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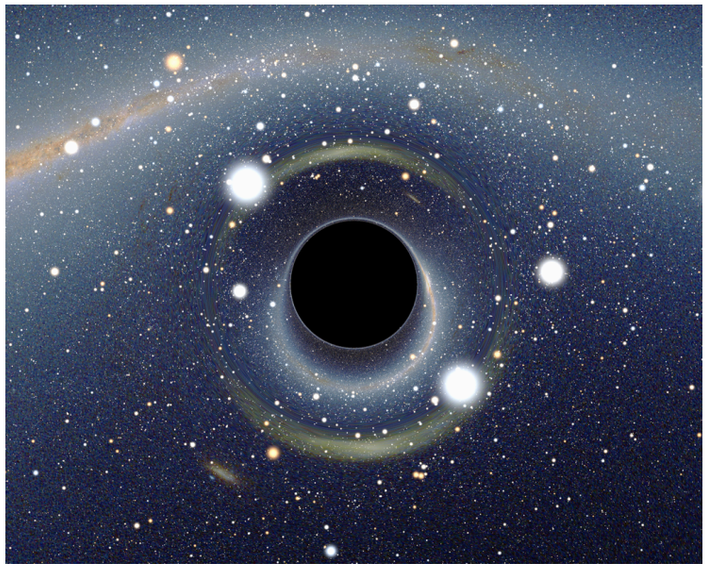
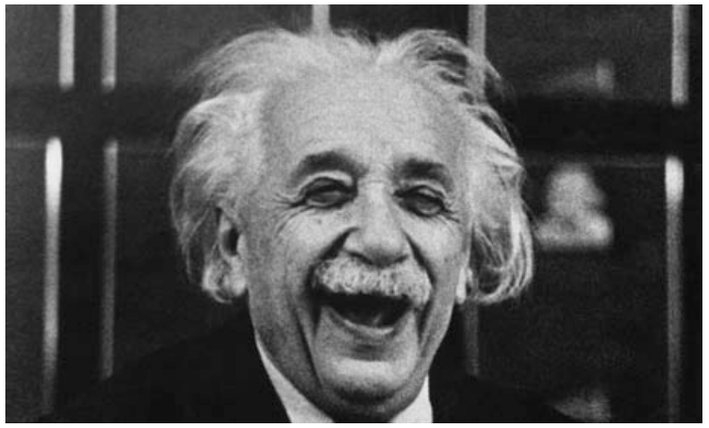


$\Leftrightarrow$

Fluids

Dynamics governed by gravity



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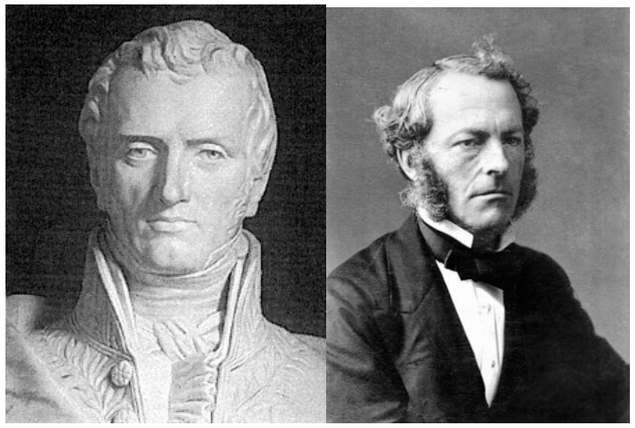
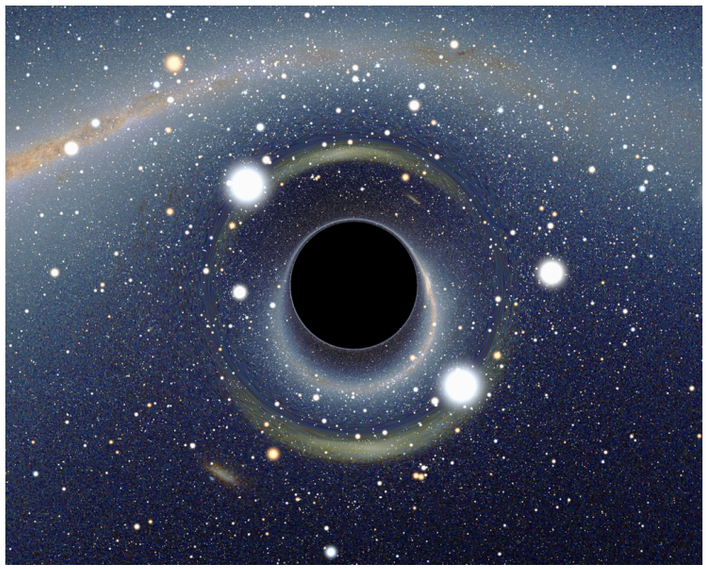


Black holes & fluid mechanics

Black holes | **Fluids**



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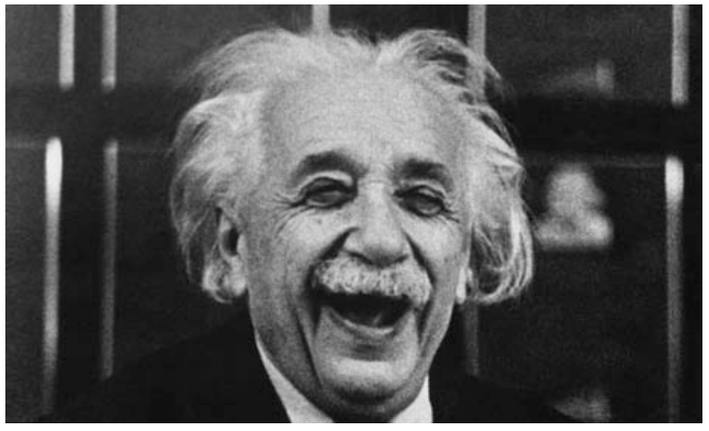
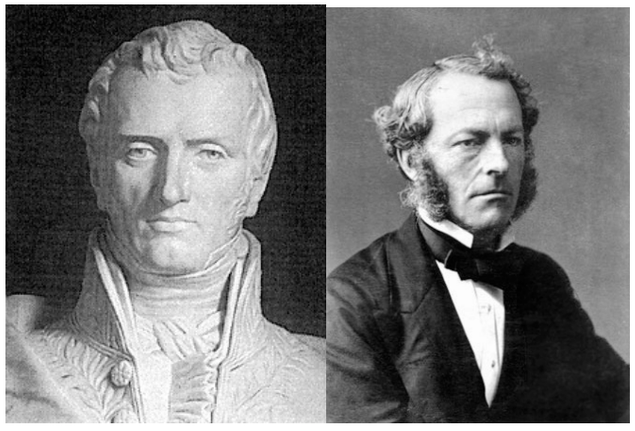
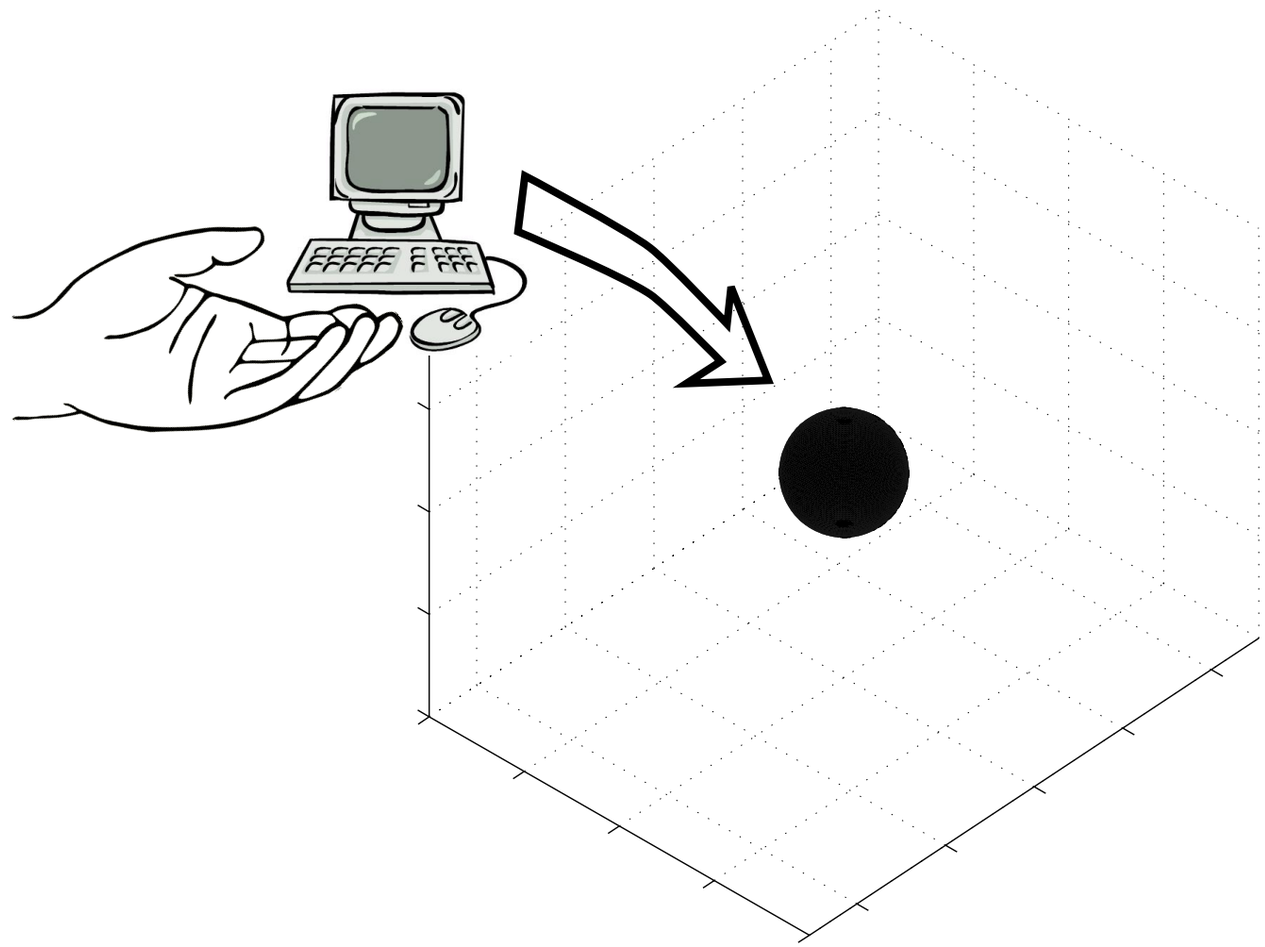
Dynamics governed by gravity | **Dynamics governed by hydrodynamics**

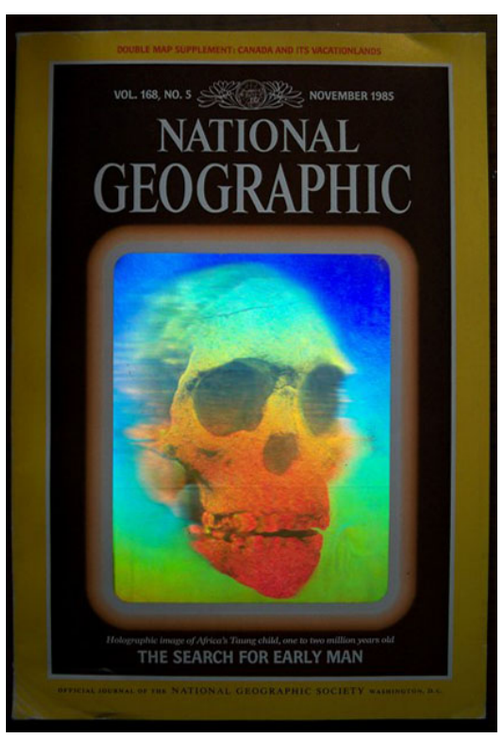




Connection comes from string theory and holographic principle.

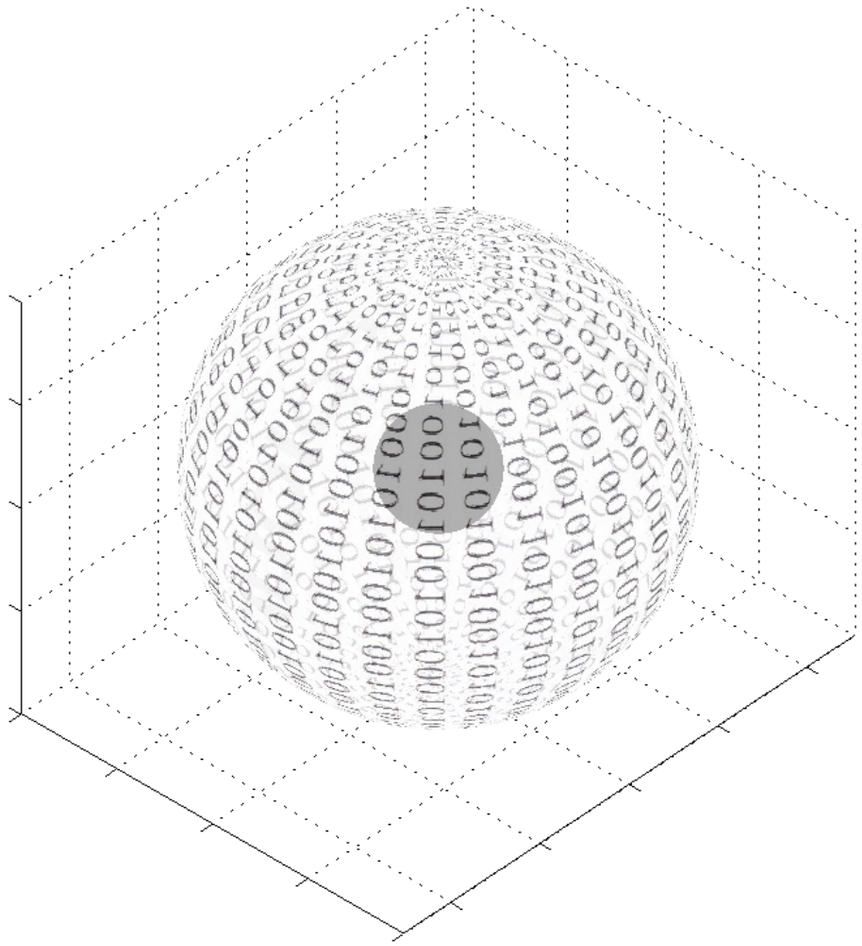
Holographic principle





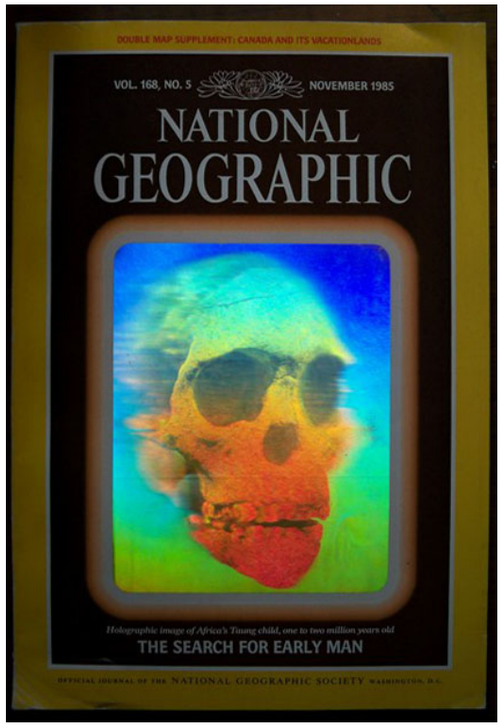
Hologram:
2D image containing 3D information

Holographic principle



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:

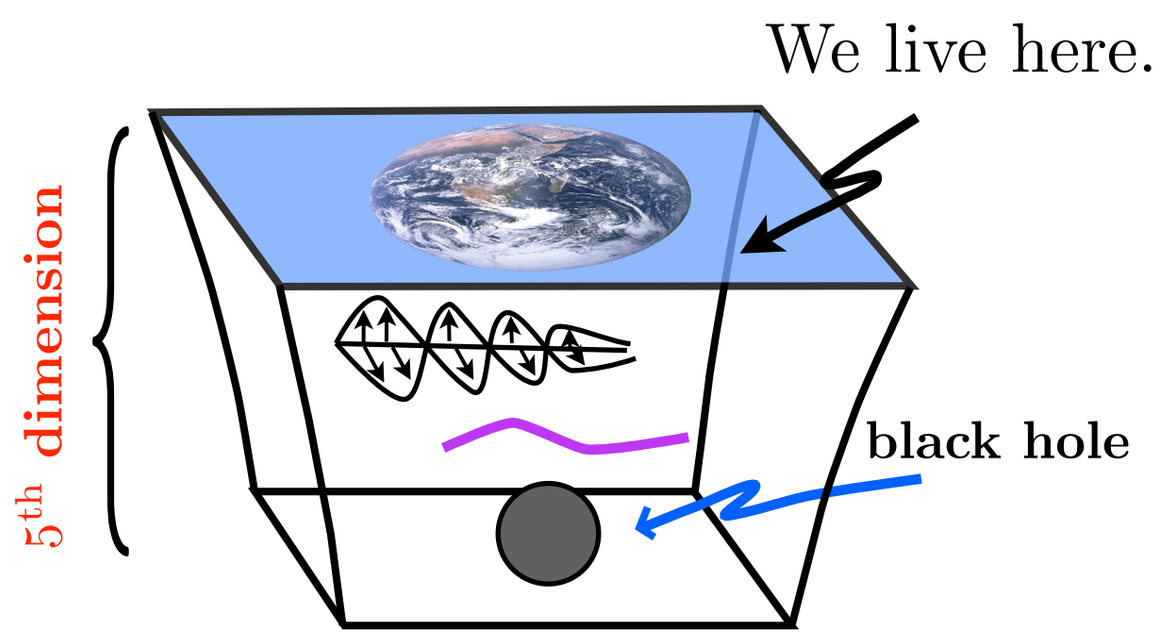
String theory in a 5D "box"

= 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



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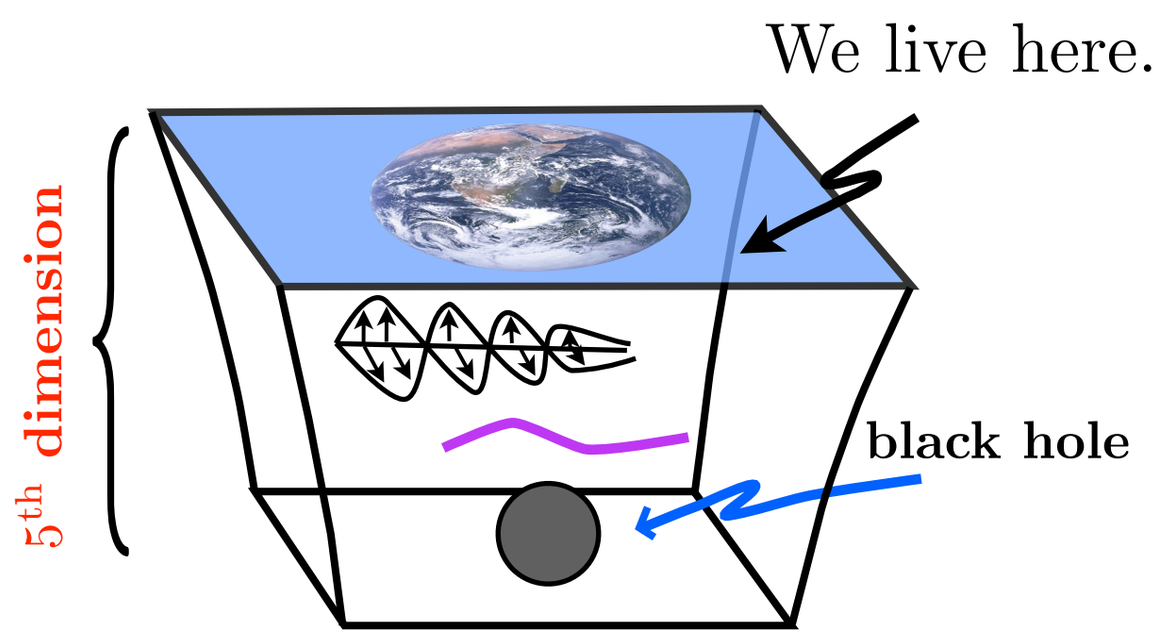
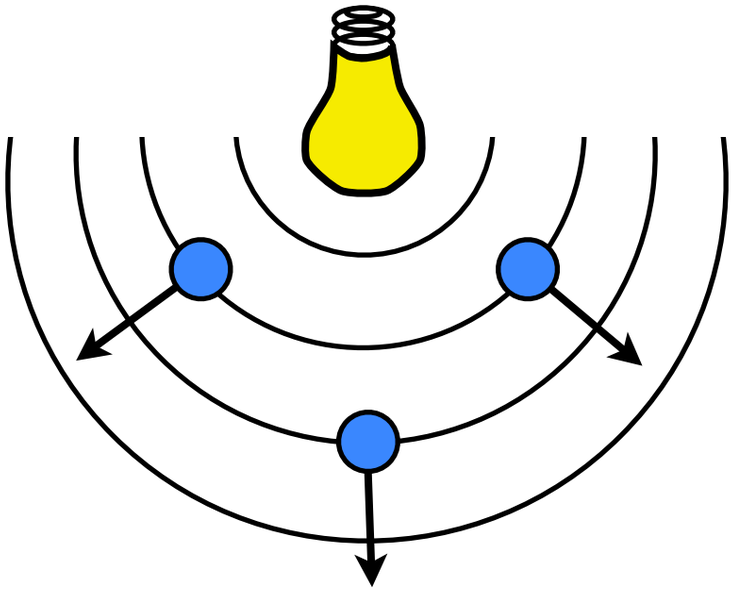
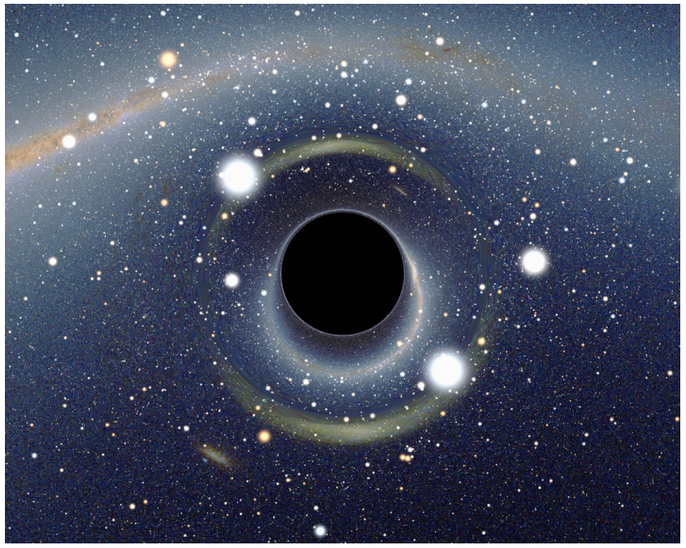


The utility of holography

- Offers new perspective.



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

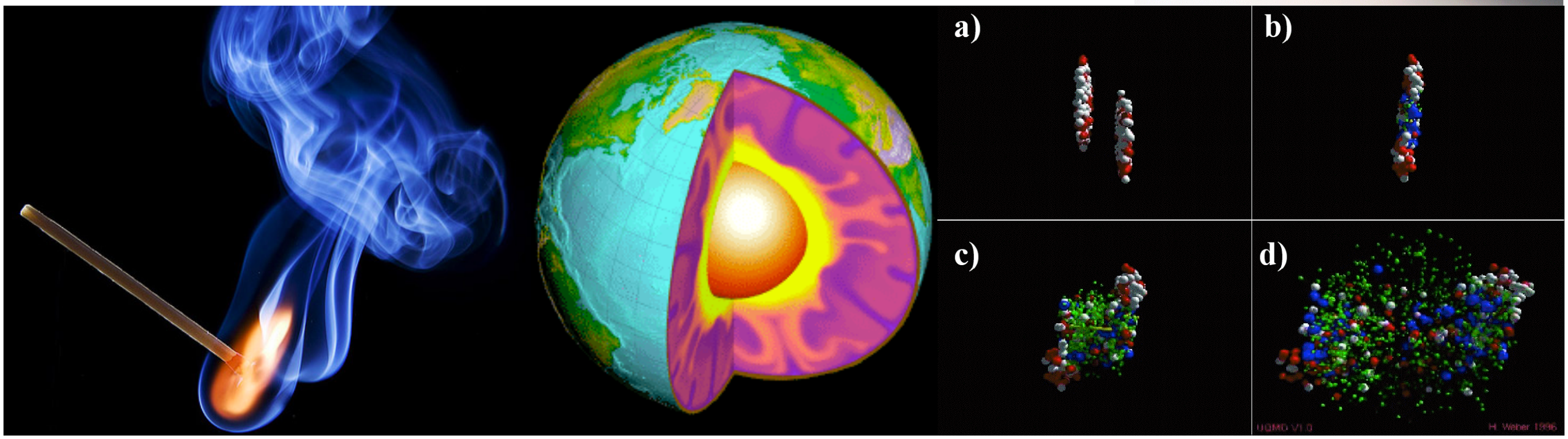


Same physics that governs astrophysics & cosmology encodes physics of quantum theories!!!

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)

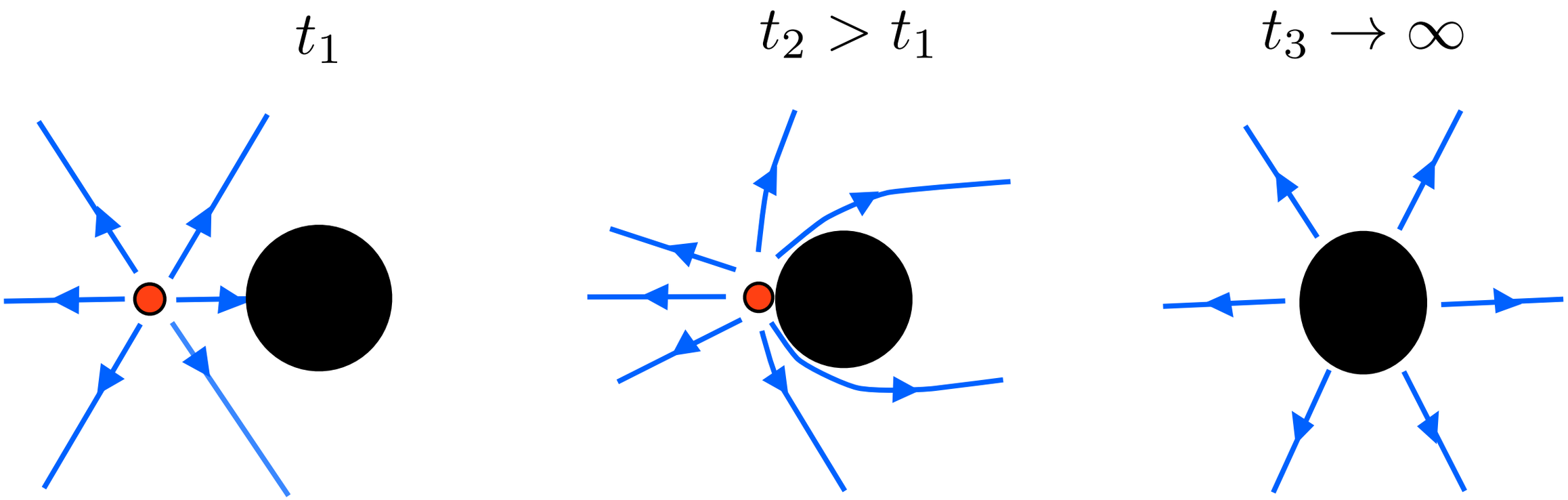
Classical black holes:

- **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.



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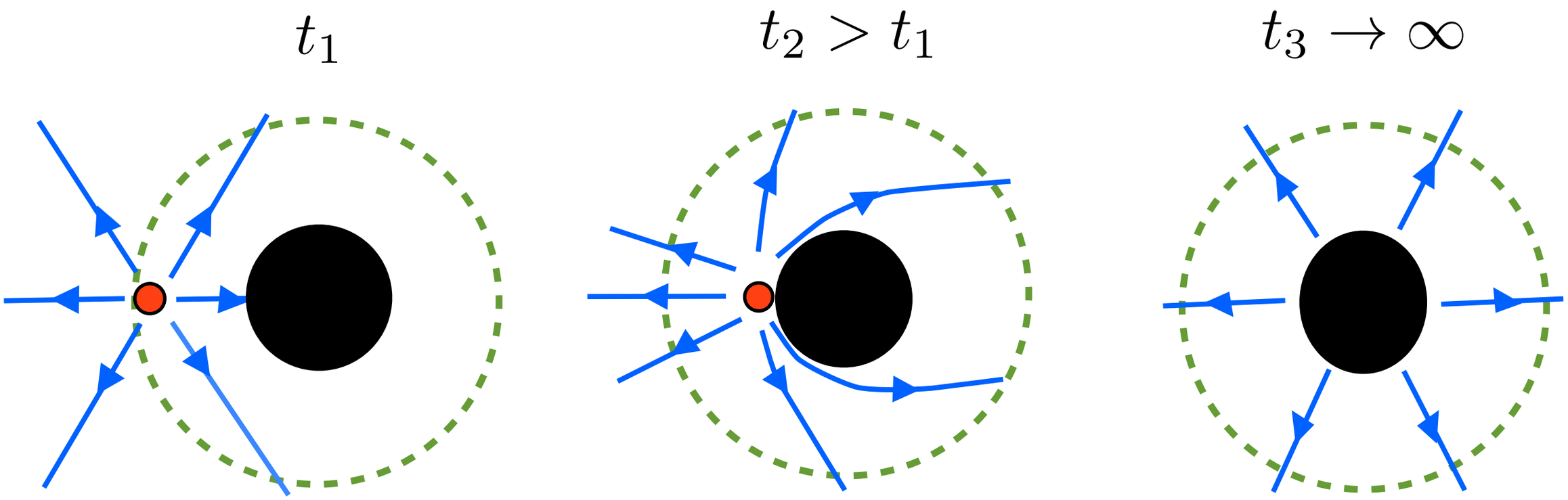

Holographic charge density = flux of electric field through surface.

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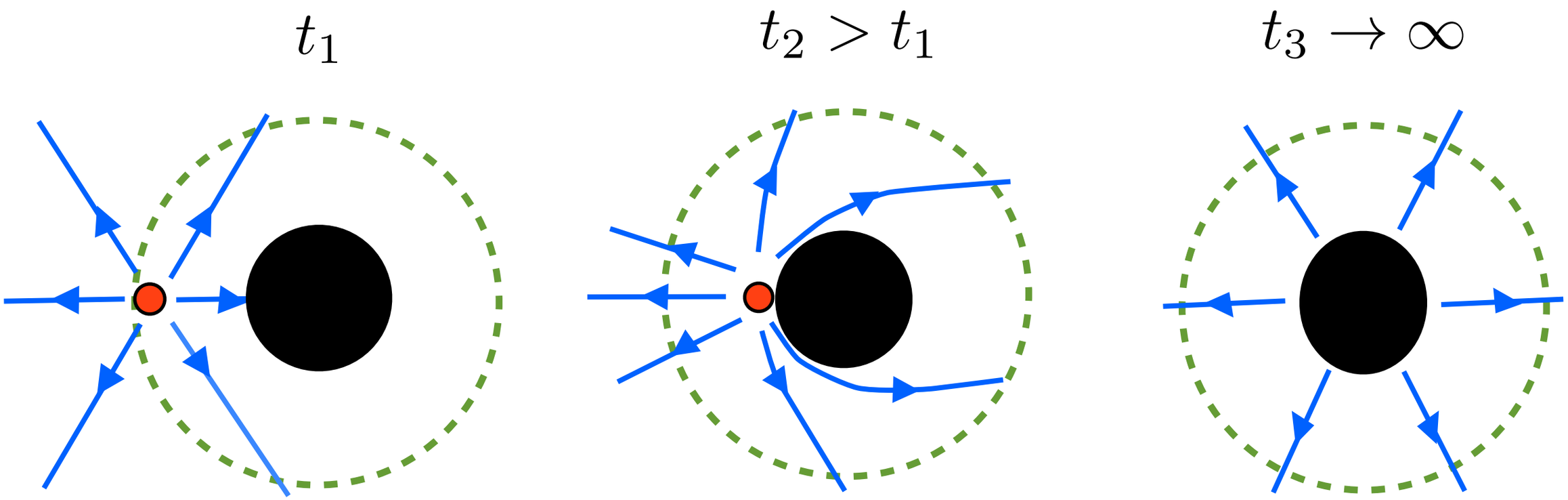

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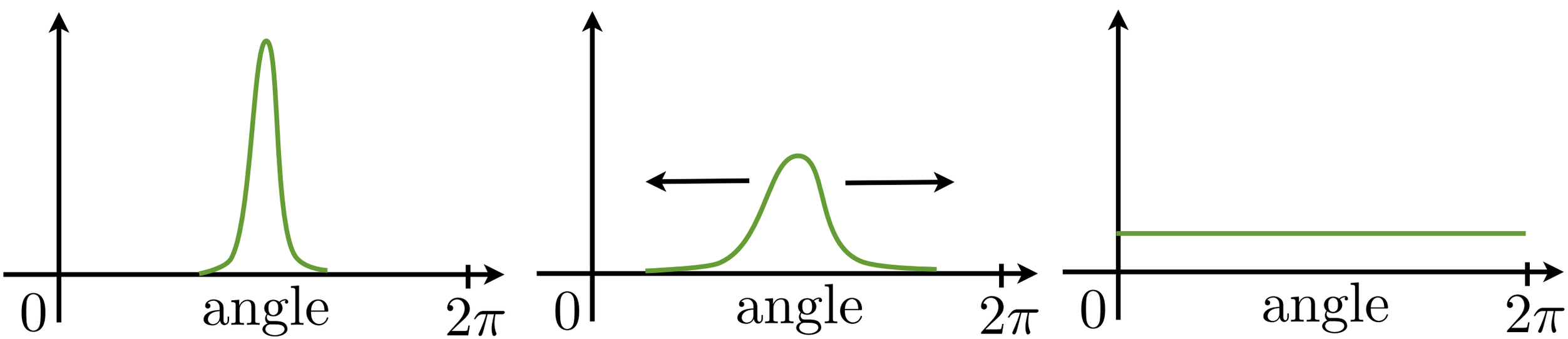
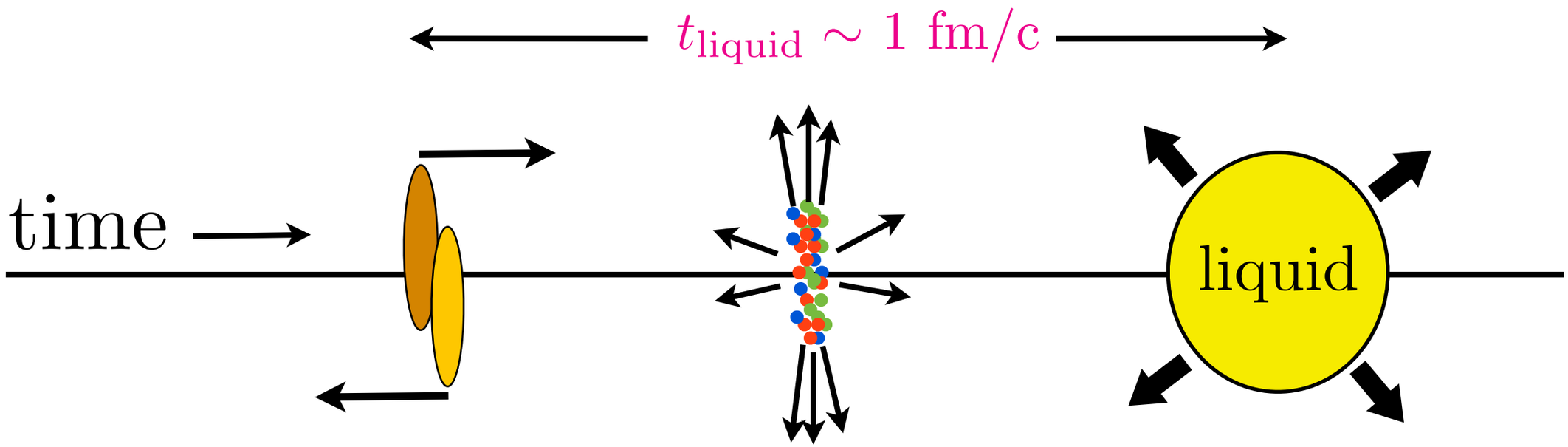


Two very difficult problems in quantum theory

Heavy ion collisions



Experimental observations:

1. Rapid "hydrodynamization."

2. QGP has extremely small viscosity.

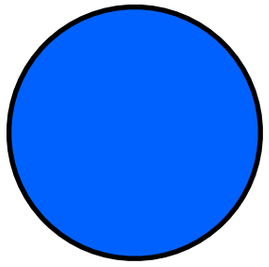
Just how fast and how small?

Hydrodynamization time:

$\longleftarrow 4 \times 10^5$ km $\longrightarrow$

Light travel time ~ 1.3 s.

A proton

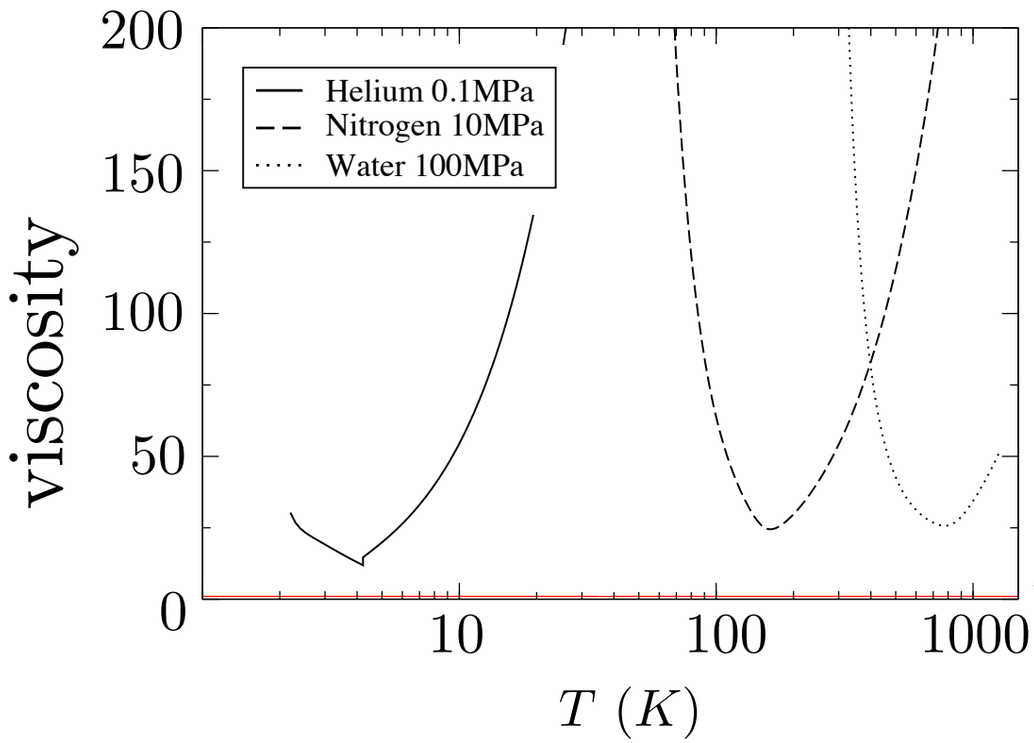


$\longleftrightarrow$

10^{-15} m

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

Viscosity:



quark-gluon plasma

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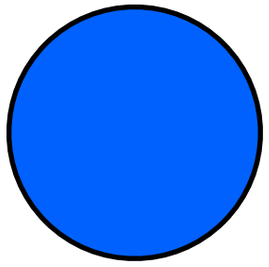
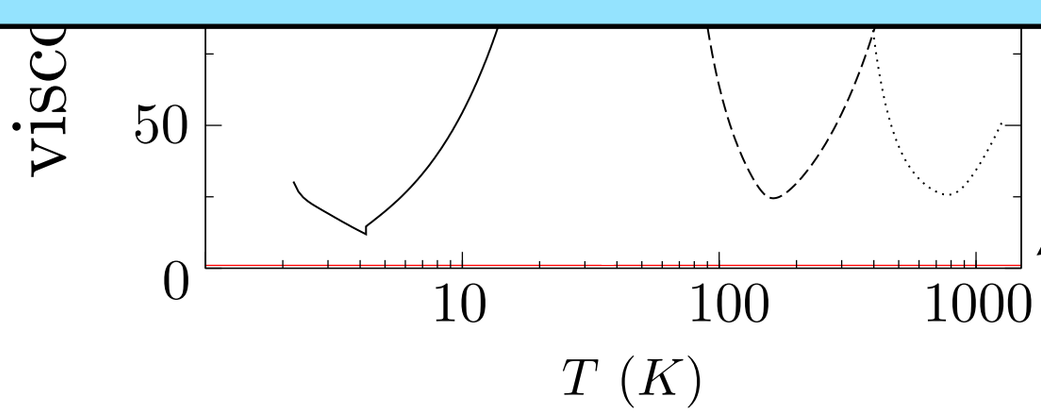


$\longleftrightarrow$

10^{-15} m

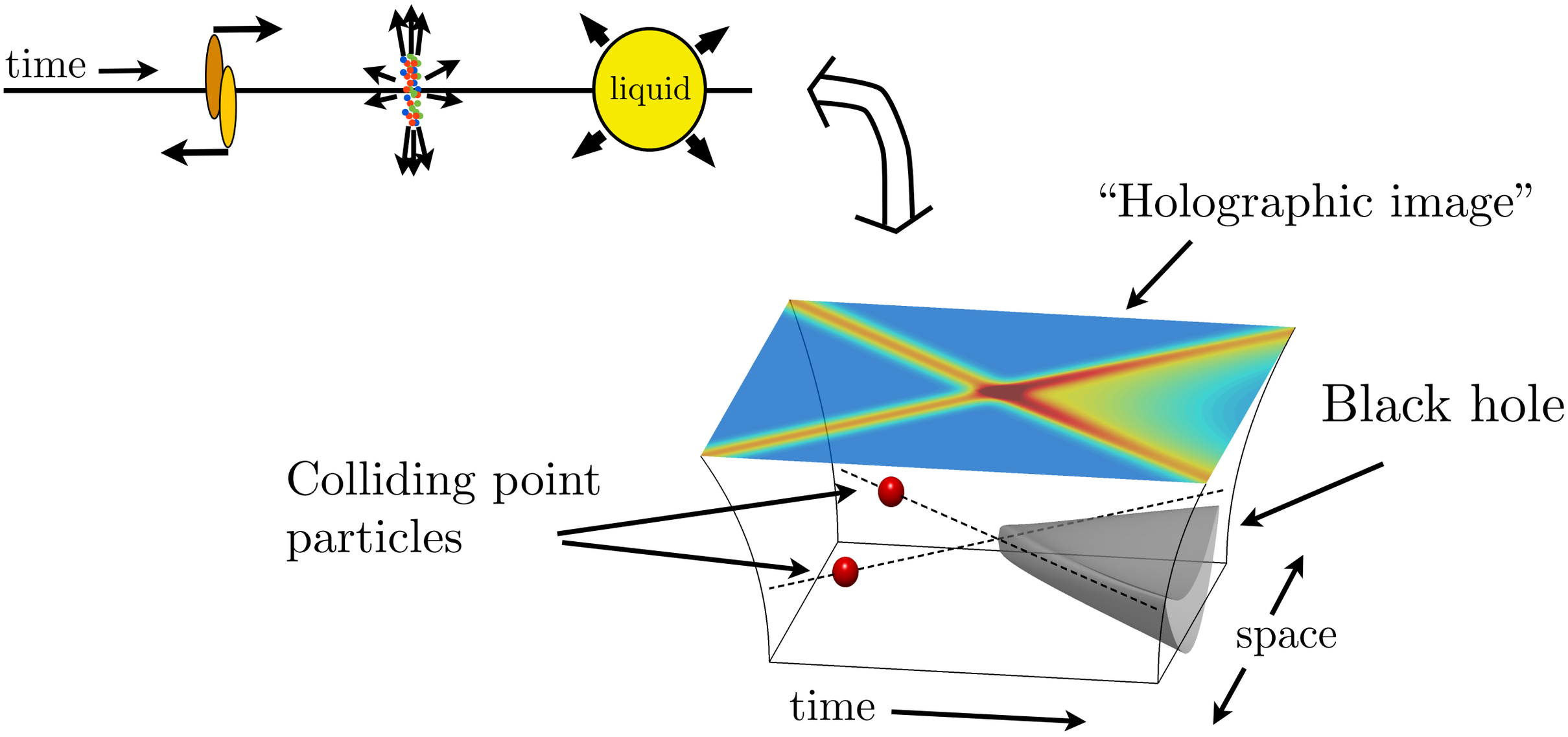
Light travel time $\sim t_{\rm hydro}$.

Understanding rapid hydrodynamization & small viscosity from first principles calculations in quantum theory has proven extremely challenging!



quark-gluon plasma

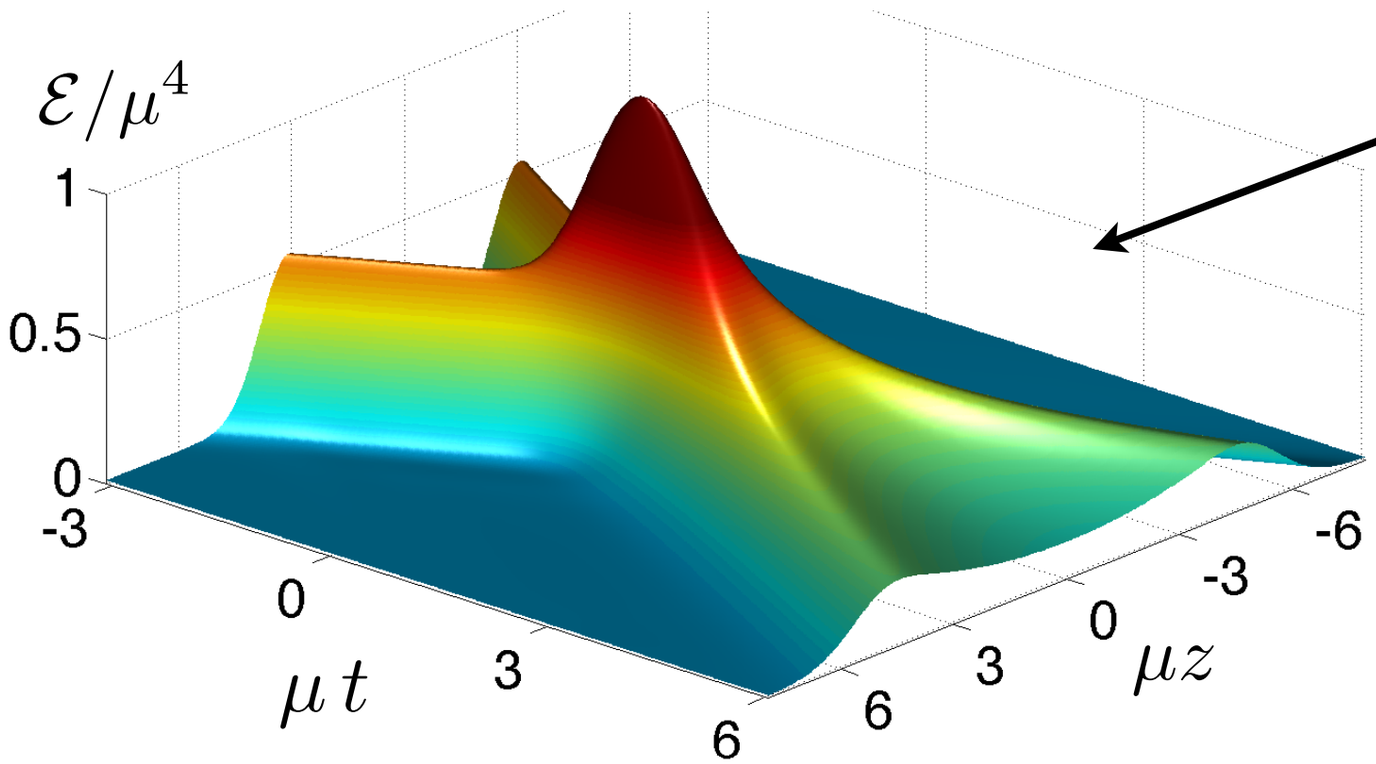
A gravitational toy model of heavy ion collisions



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

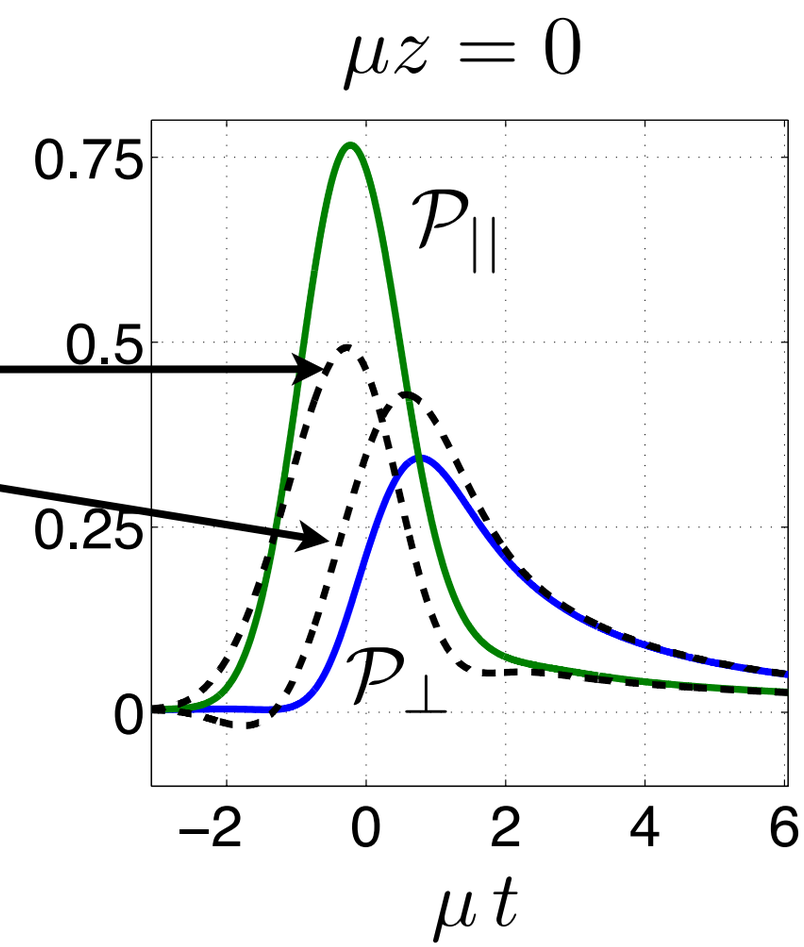
Hydrodynamization results illustrated

(Chesler & Yaffe, 11)



Energy density

Pressures



Hydrodynamic prediction

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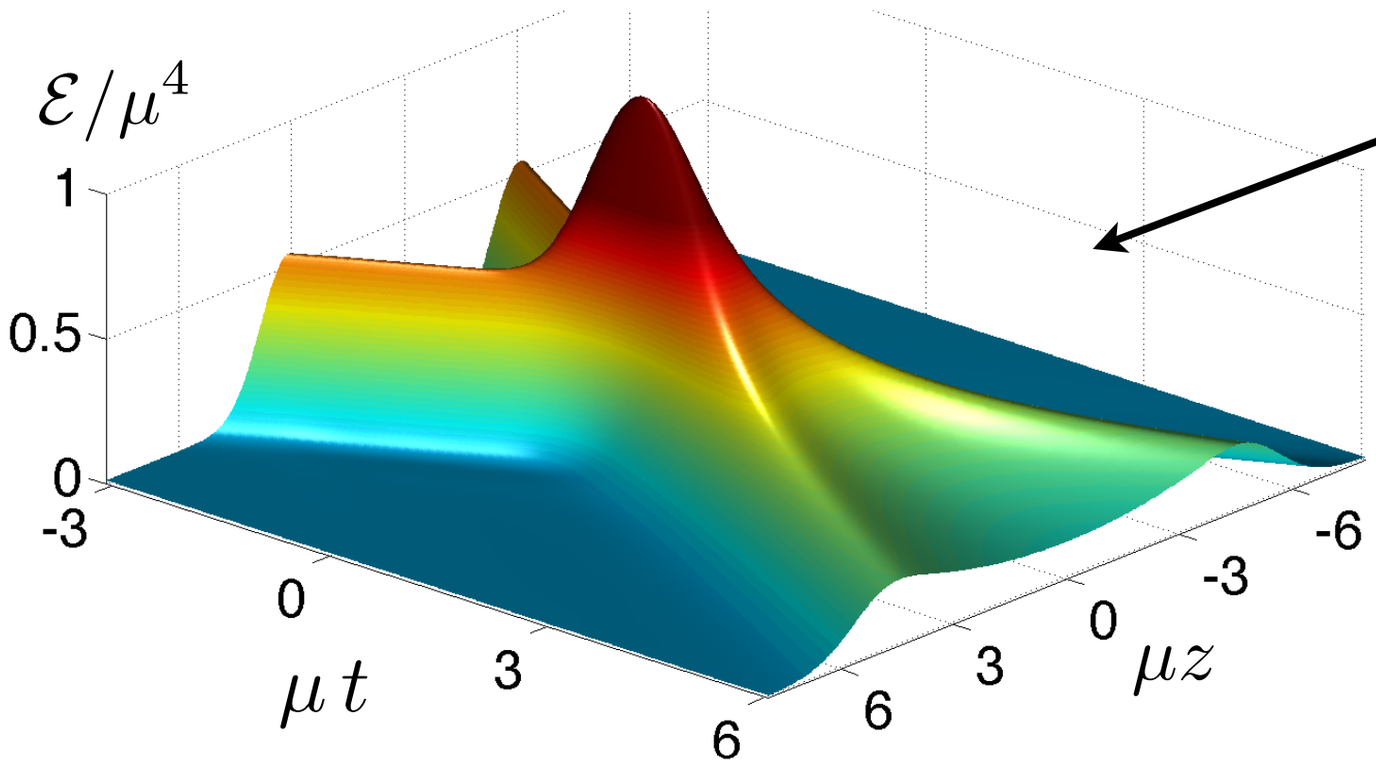
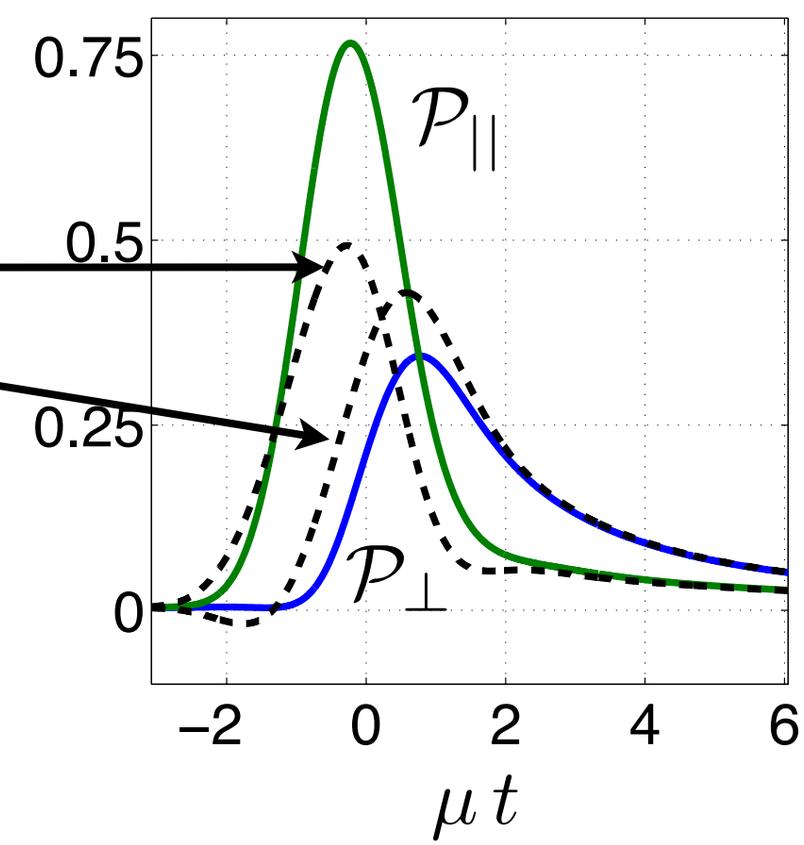


Energy density

Pressures

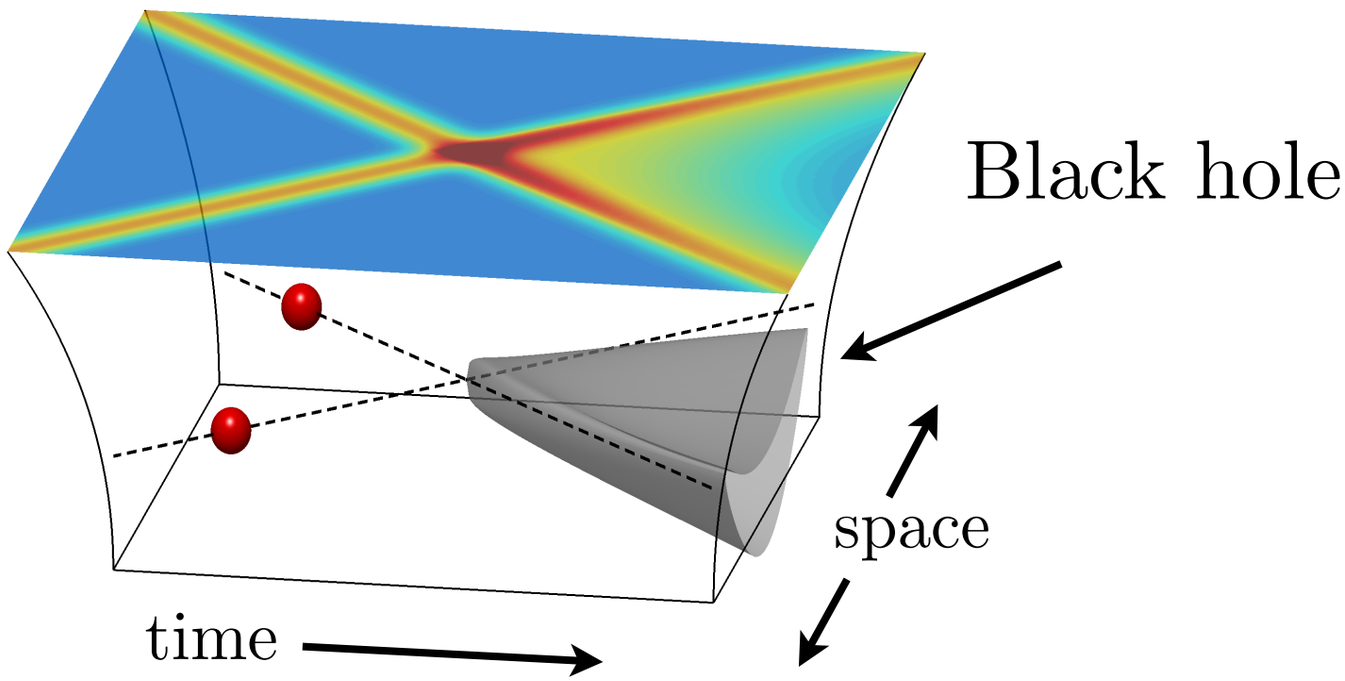
$\mu z = 0$



Hydrodynamic prediction

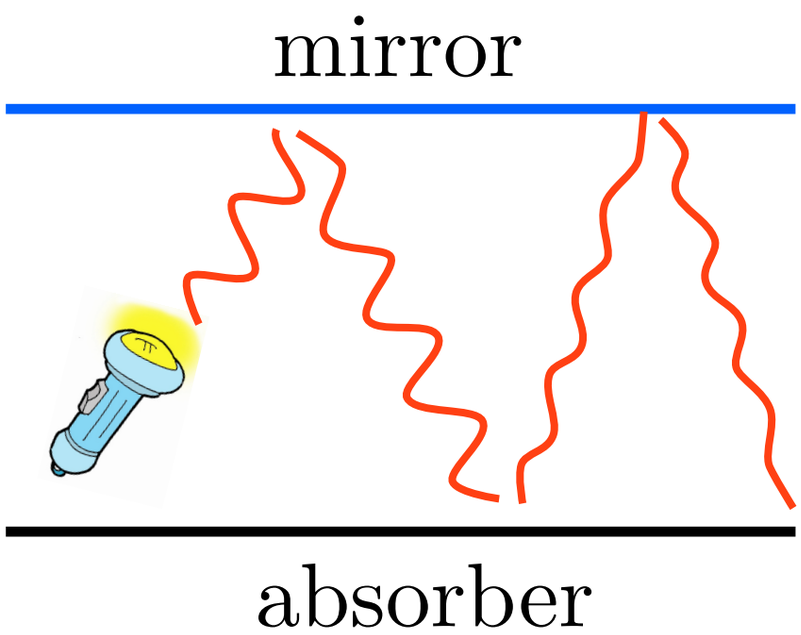
For RHIC energies,
$\mu \sim 2.3$ GeV
and $t_{\rm hydro} \sim 0.35$ fm/c.

Gravitational origin of $t_{\rm hydro}$



Lower bound on $t_{\rm hydro}$:

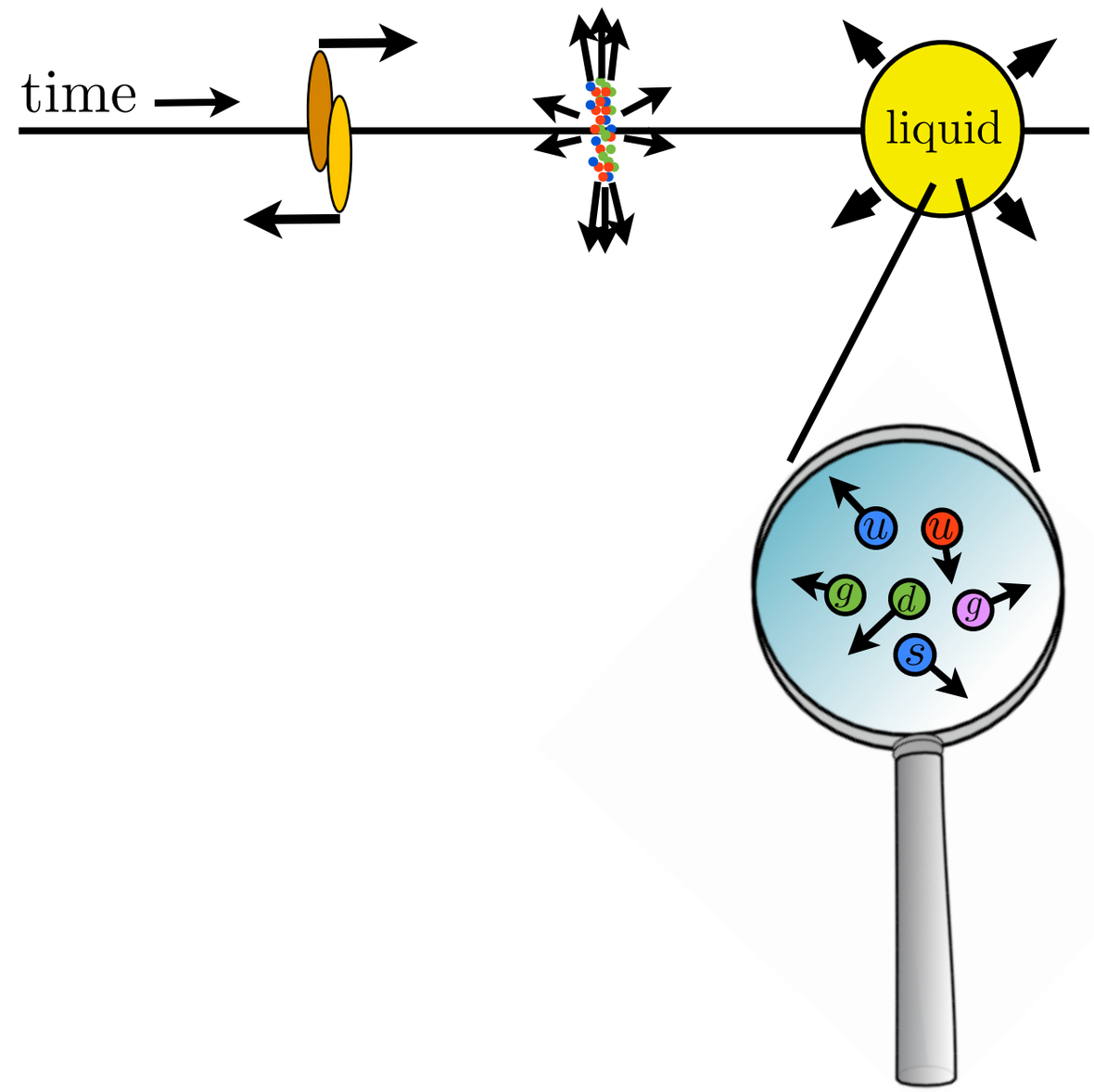
- $t_{\rm hydro} \gtrsim$ "size of box" $\sim \frac{1}{T_{\rm QGP}}$



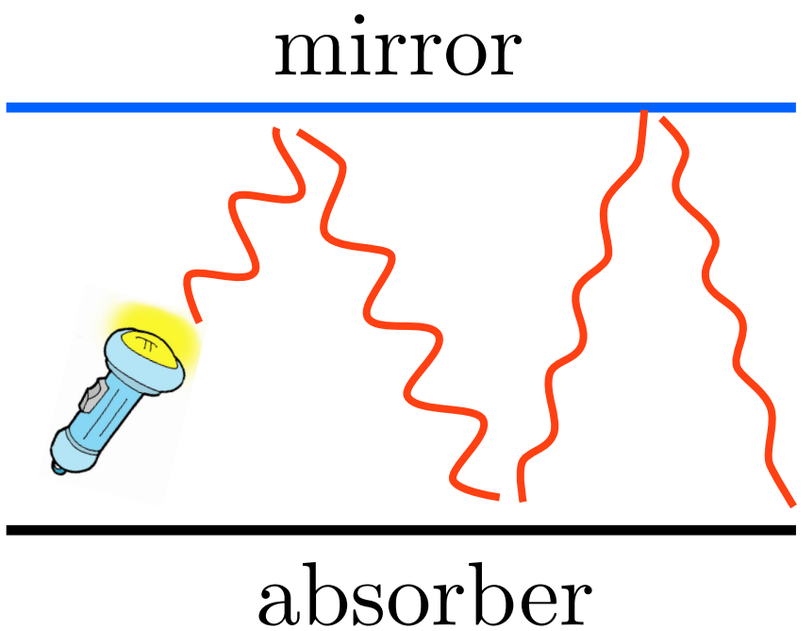
Lower bound on $t_{\rm hydro}$ from uncertainty principle:

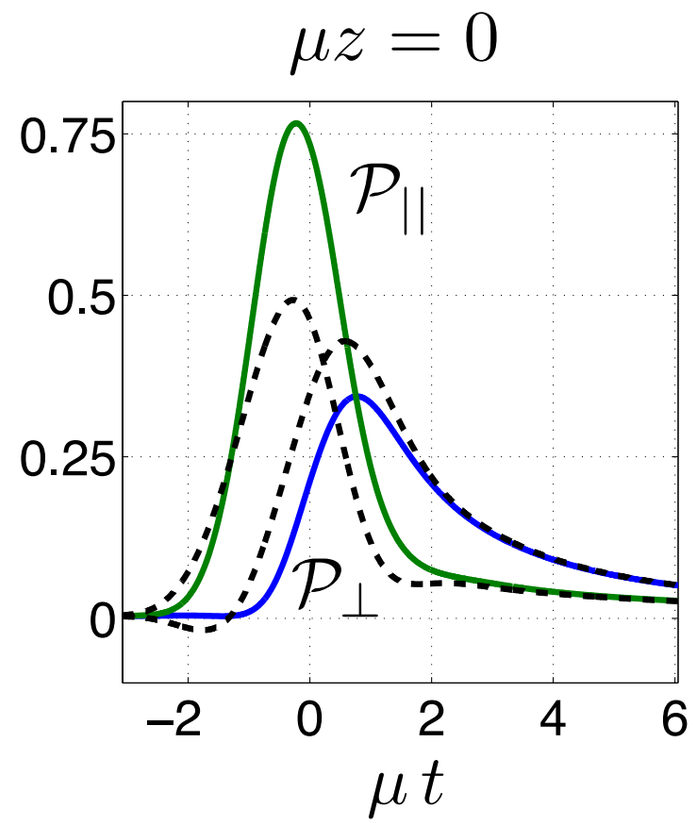
Qualitative argument:

- $t_{\rm hydro}\,\bar{\epsilon}_{\rm quark,\ gluons} \gtrsim 1$
- $\bar{\epsilon}_{\rm quark,\ gluons} \sim T_{\rm QGP}$
- $\Rightarrow t_{\rm hydro} \gtrsim \frac{1}{T_{\rm QGP}}$



Viscosity of QGP from holography





viscosity $\propto$ long wavelength absorption rate

Famous result from holography:

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

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

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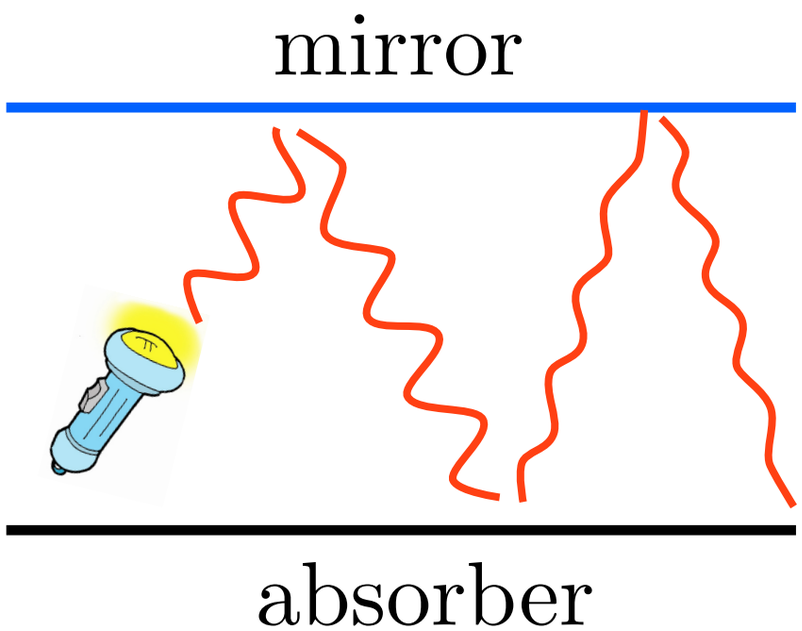

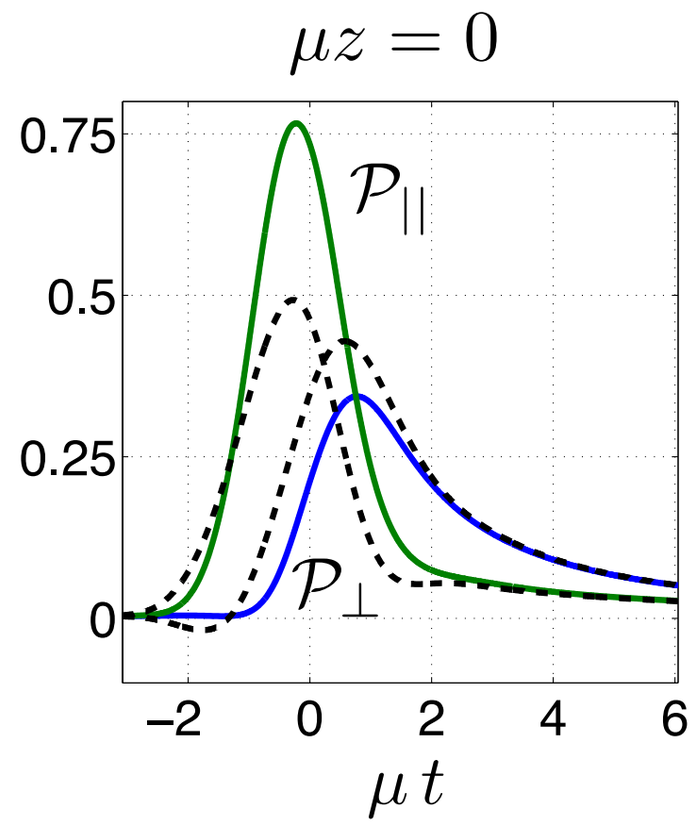

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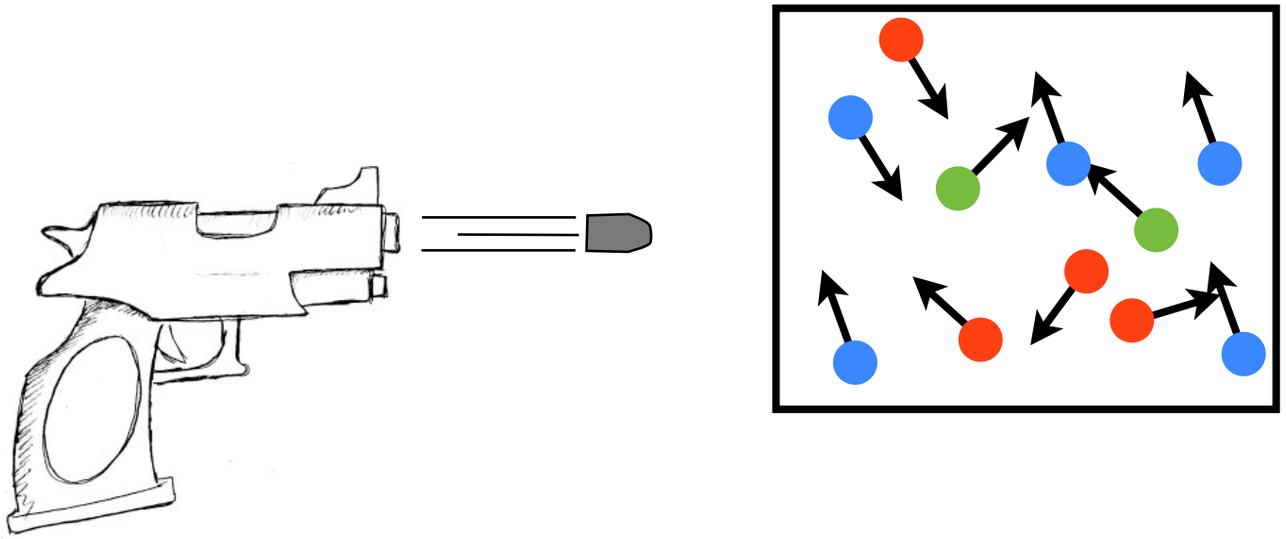
A few times smaller than experimental observations!

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



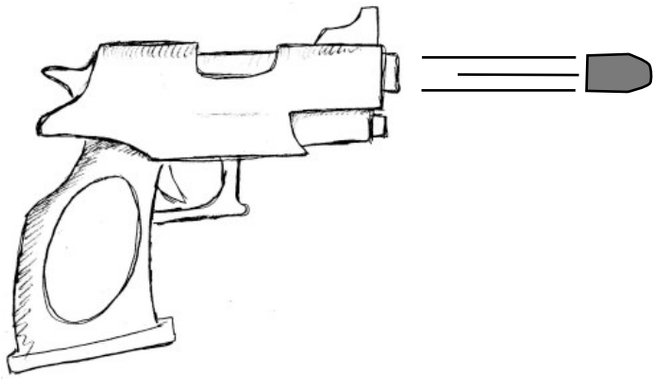
Shooting quark through liquid ⇔ throwing string into black hole.

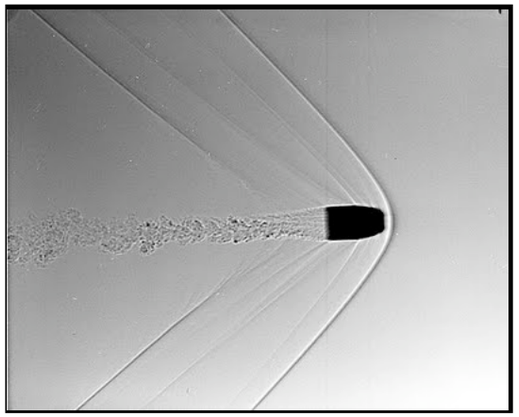
"Holographic image"
energy density

Black hole

String

Equilibration of sound waves





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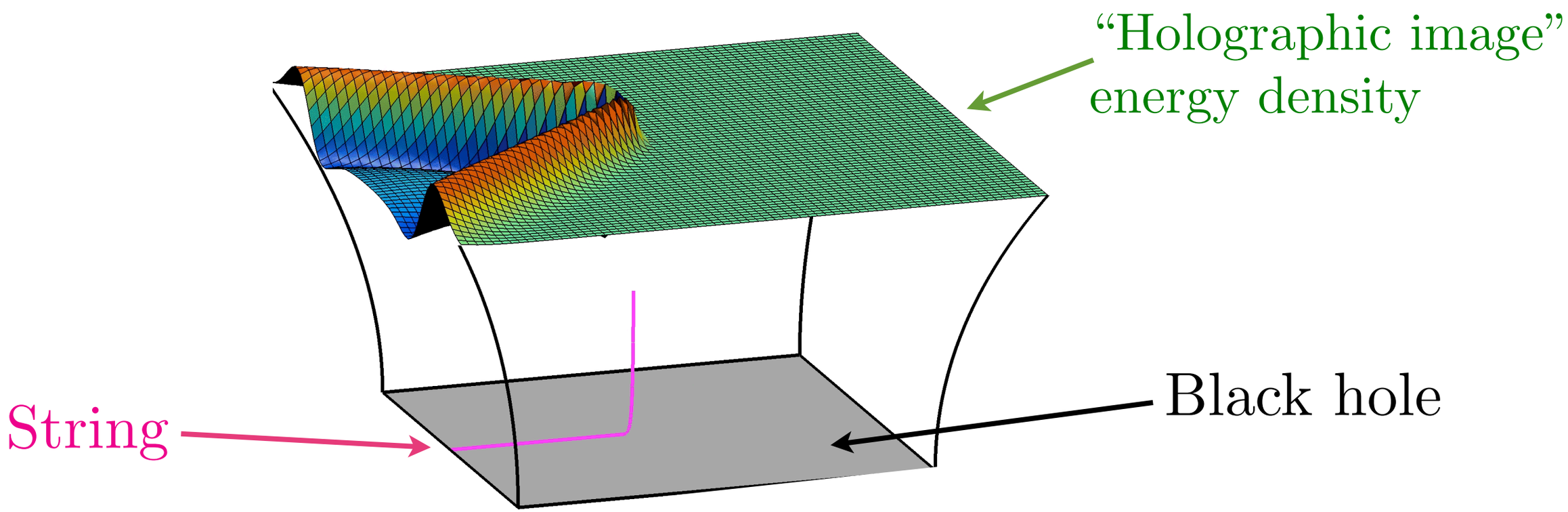

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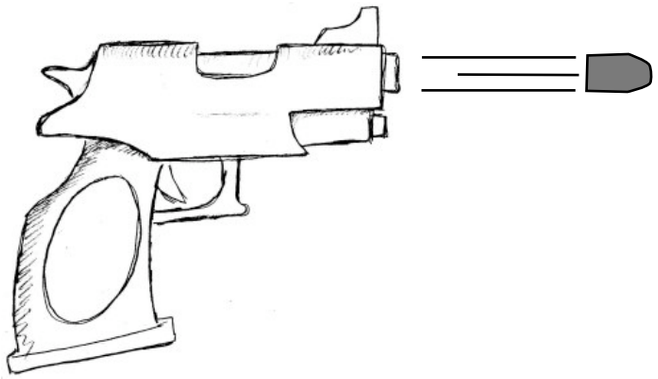

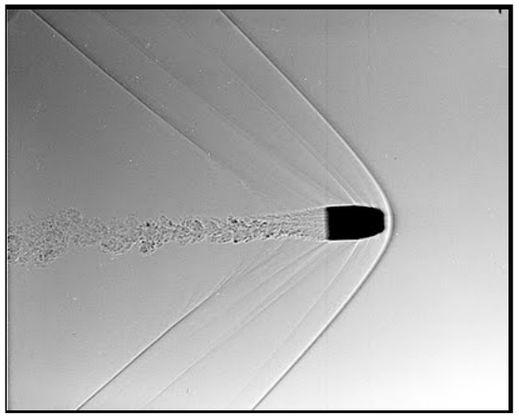

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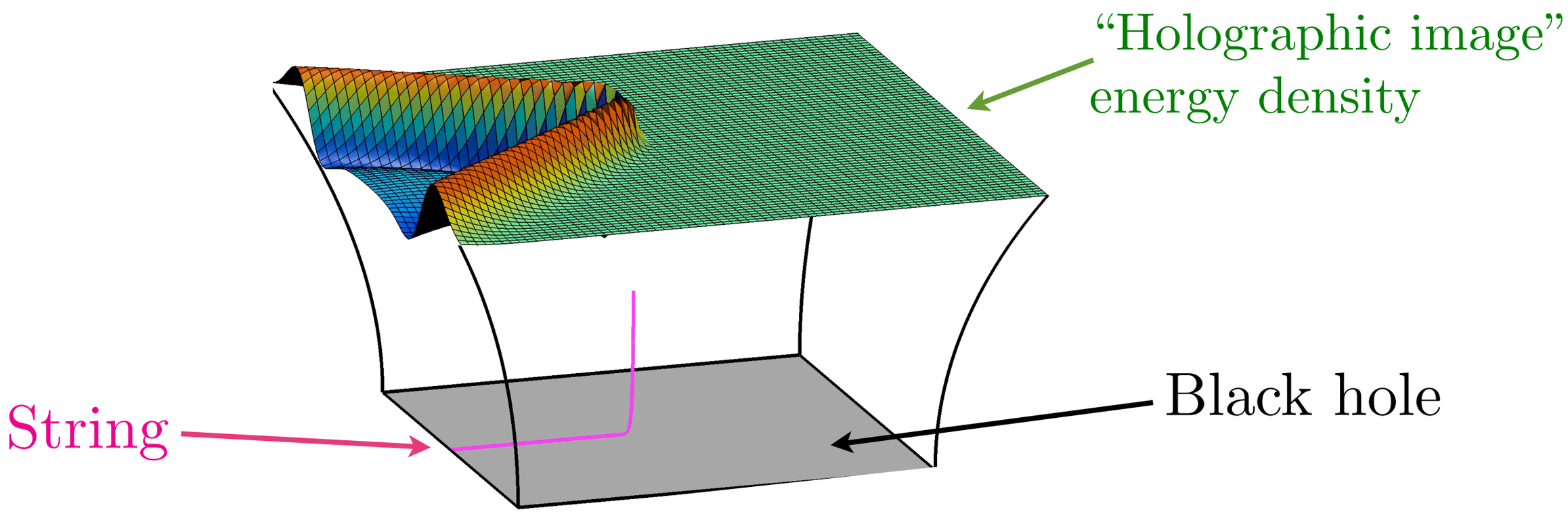
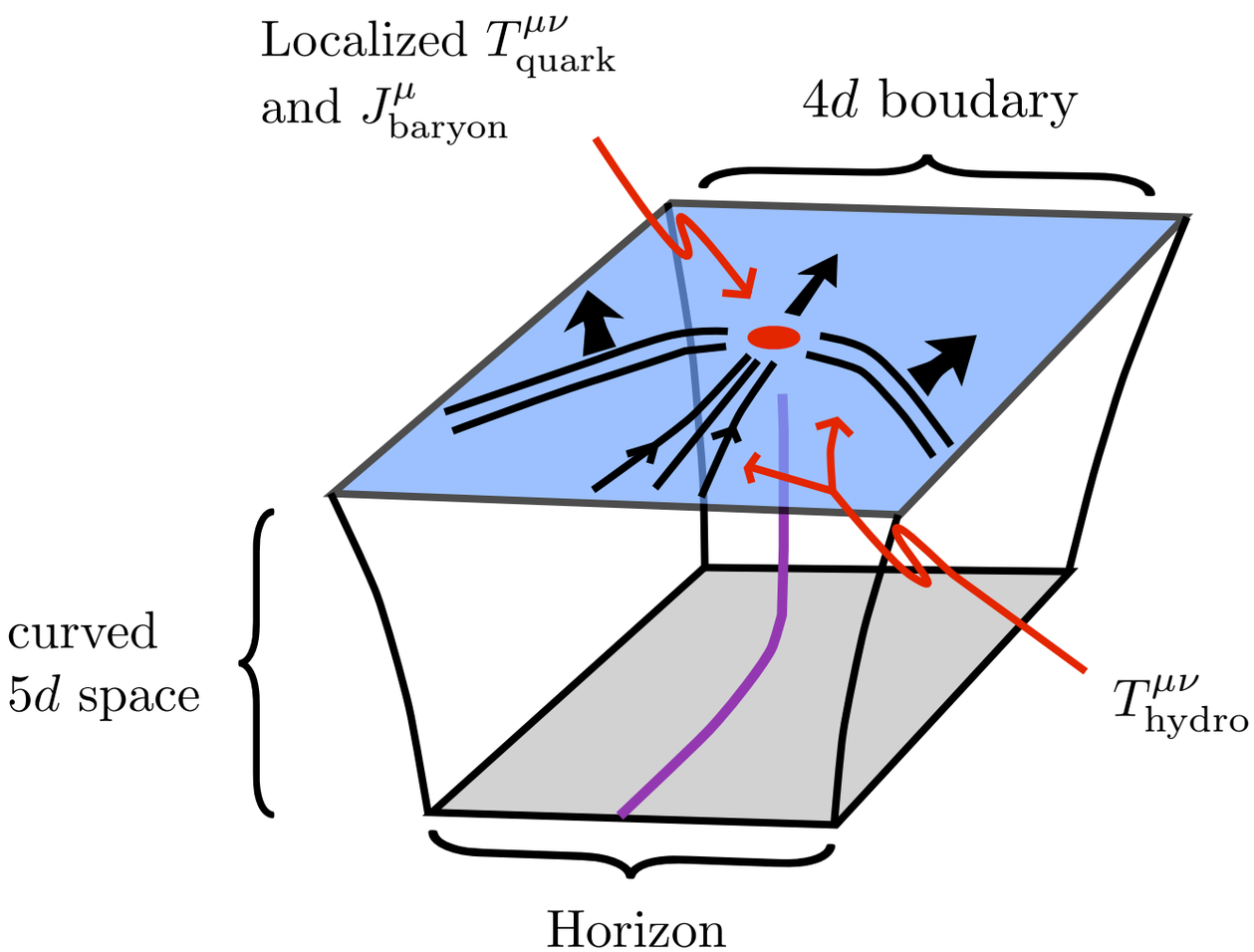
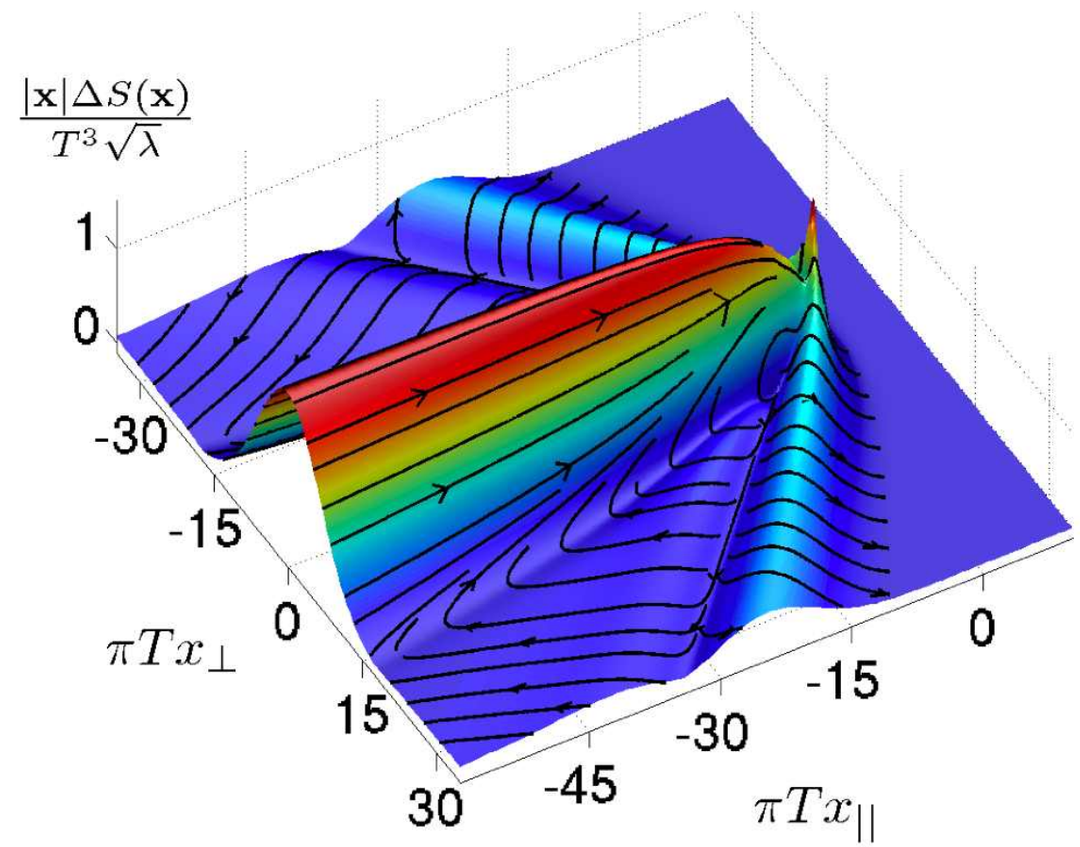
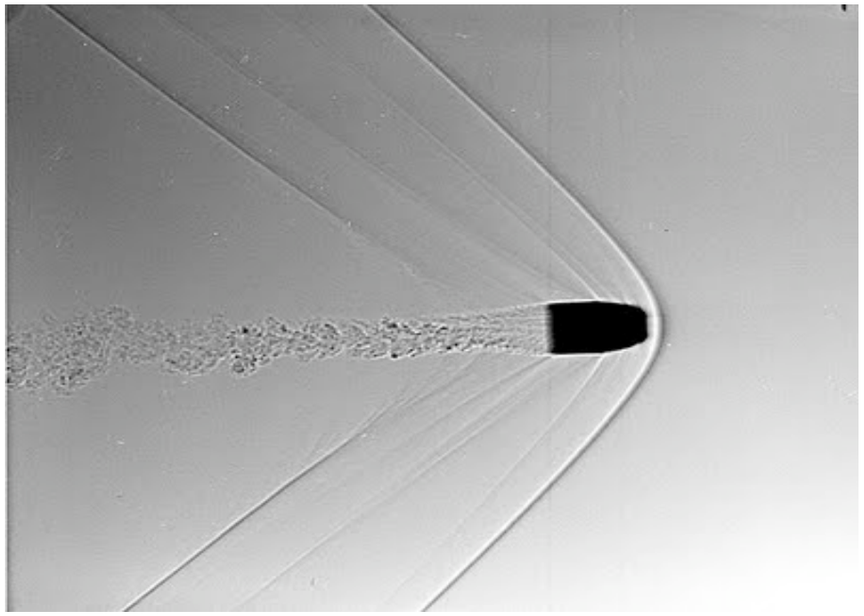
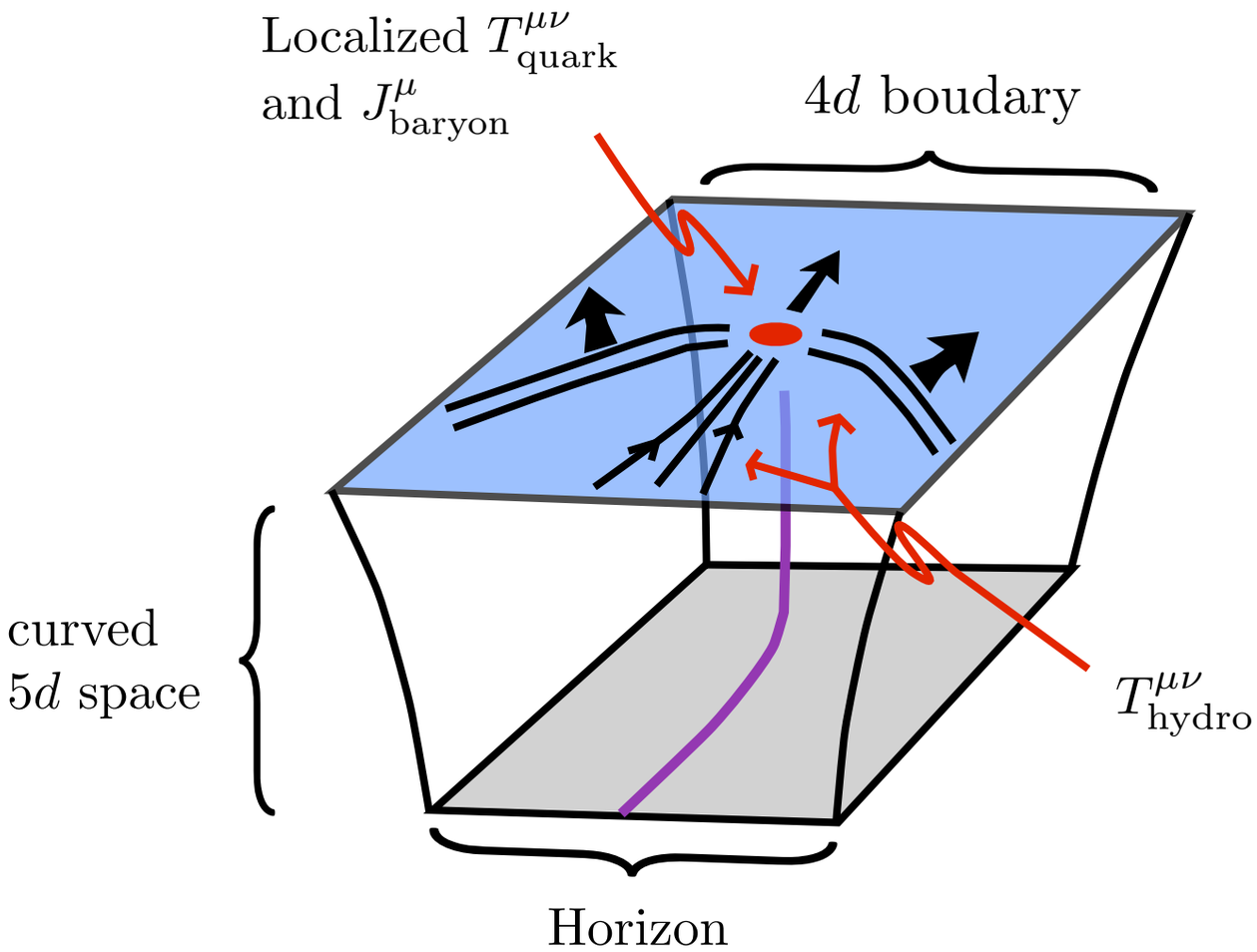



Localized $T^{\mu\nu}_{\text{quark}}$
and J^{μ}_{baryon}
$4d$ boudary
curved
$5d$ space
$T^{\mu\nu}_{\text{hydro}}$
Horizon


$\frac{|\mathbf{x}|\Delta S(\mathbf{x})}{T^3\sqrt{\lambda}}$
1
0
-30
-15
0
15
30
$\pi T x_{\perp}$
0
-15
-30
-45
$\pi T x_{||}$

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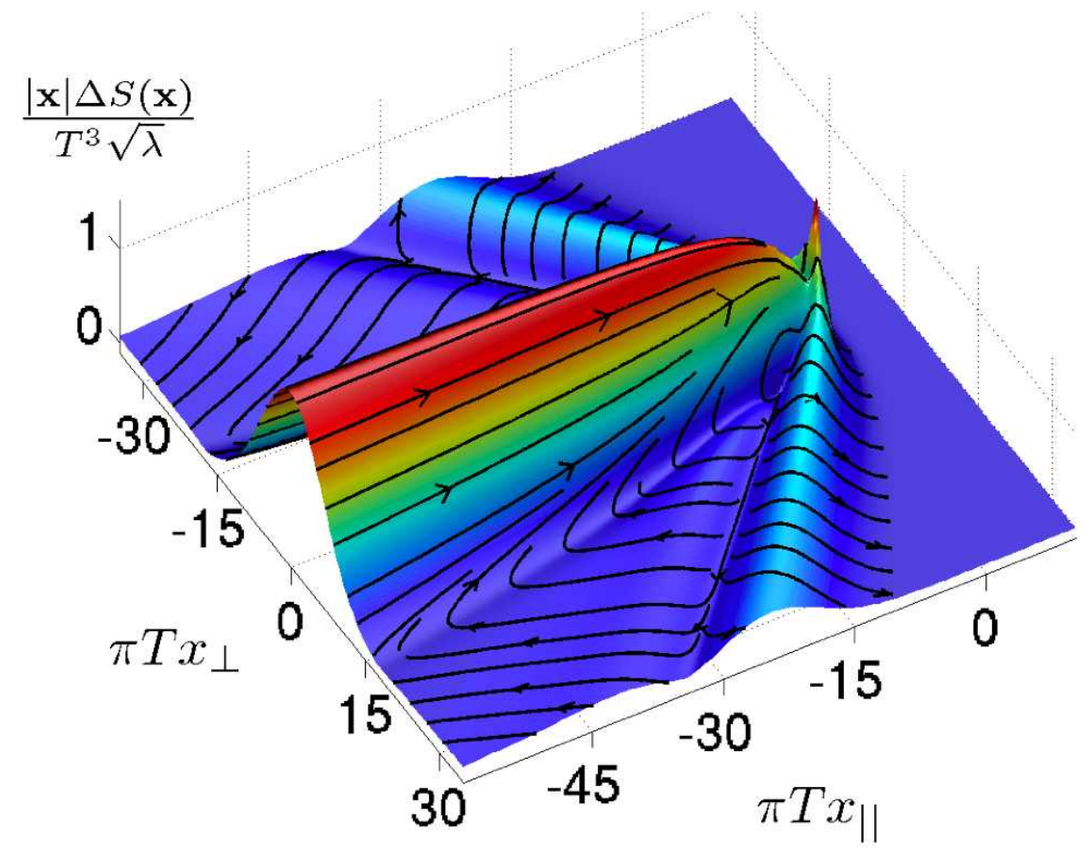
$4d$ boudary
curved
$5d$ space
$T^{\mu\nu}_{\text{hydro}}$
Horizon


$\frac{|\mathbf{x}|\Delta S(\mathbf{x})}{T^3\sqrt{\lambda}}$
1
0
-30
-15
0
15
30
$\pi T x_{\perp}$
0
-15
-30
-45
$\pi T x_{||}$