Fluid viscosity: from Maxwell to string theory

Dam T. Son (INT, University of Washington)
Aspen, Feb 2011

Water and honey

Water and honey flow with different rates: different viscosity

Viscosity

Viscosity can be quantified:

water: 1 centipoise (cp)
air: 0.02 cp
honey: 2000-10000 cp

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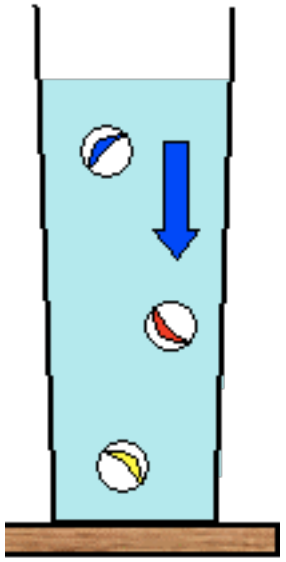
Stokes' law: how fast a small ball falls in a fluid



slower in a more viscous fluid

James Clerk Maxwell

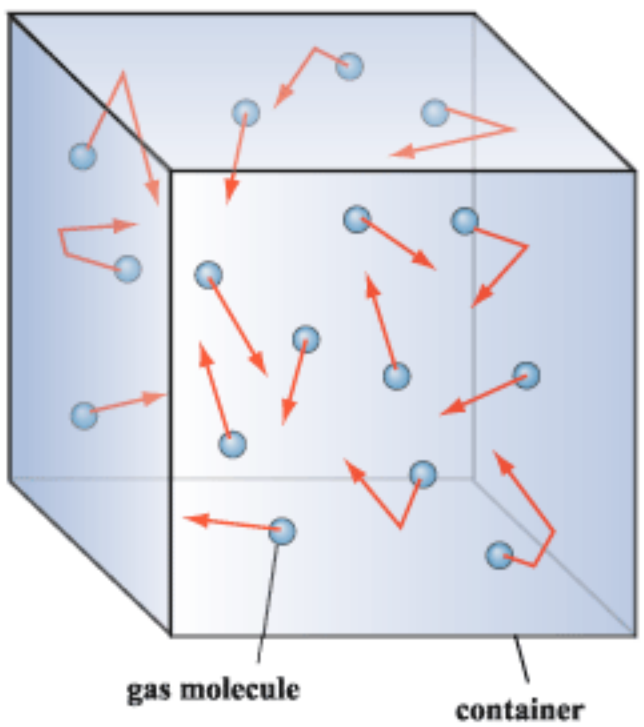
J.C.Maxwell thought about the origin of viscosity

Maxwell (1831-1879) was one of the most famous scientists of all times

- Unification of electricity and magnetism
  - predicted the existence of electromagnetic waves, which enable radio communication
  - laid the foundation for Einstein's work on relativity
- Kinetic theory of gases

Kinetic theory of gases

At Maxwell's time, people was speculating about molecules



And they speculated that in air the molecules would move mostly in straight lines.

Occasionally they bump onto each other

But no one had seen a molecule
No one was sure that molecules exist

Maxwell's formula

1860: James Clerk Maxwell showed that, if a gas is actually made of molecules

then its viscosity can be computed by multiplying 3 things

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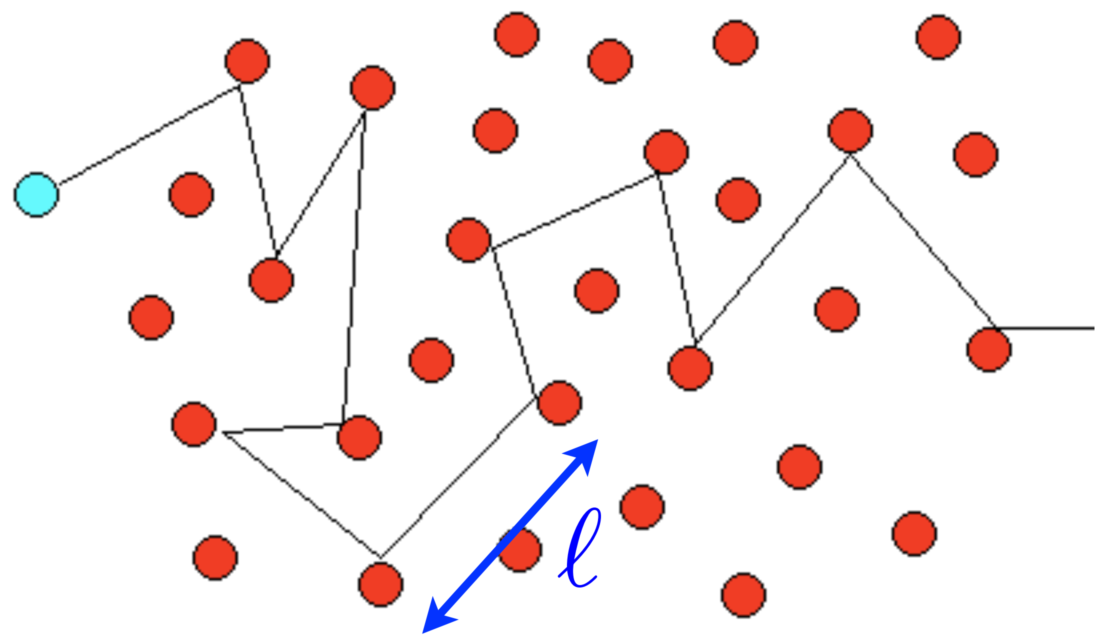
the *mean free path*

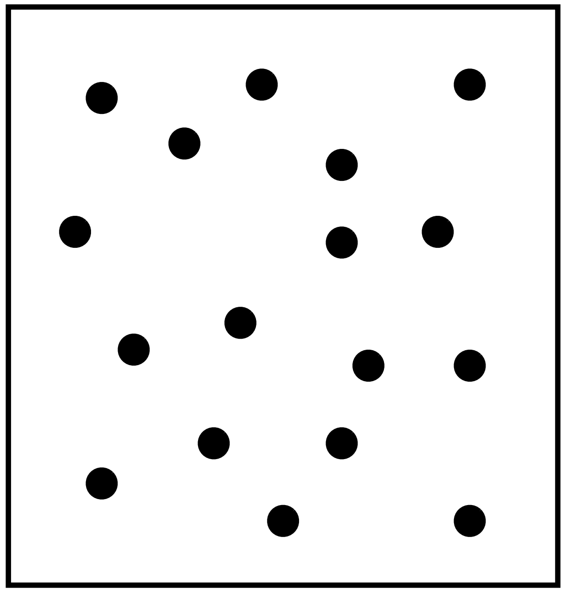
Mean free path



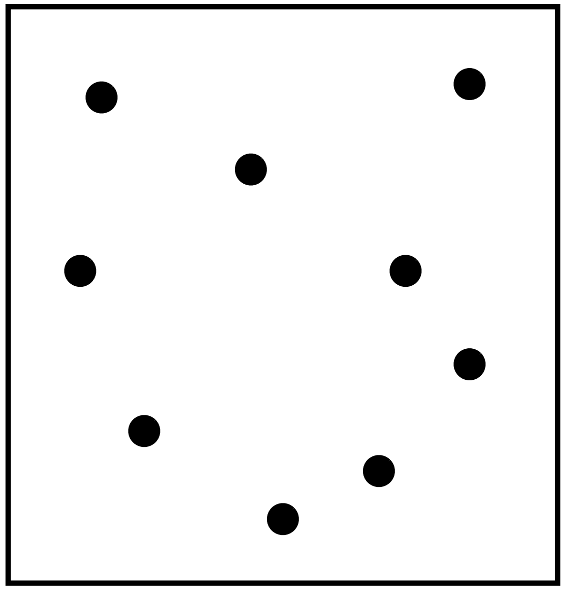
is the mean distance between molecule travels between collisions

In air, mean free path = 65 nanometers
short, but much bigger than the molecules themselves

Maxwell’s law

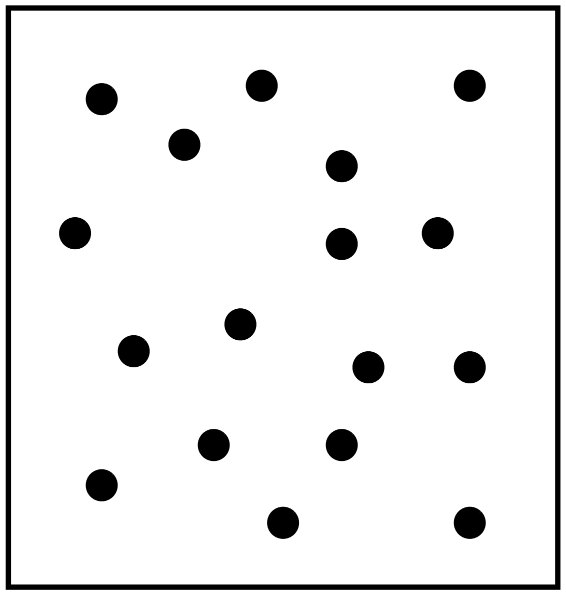


1 atmosphere



0.5 atmospheres

Maxwell’s law



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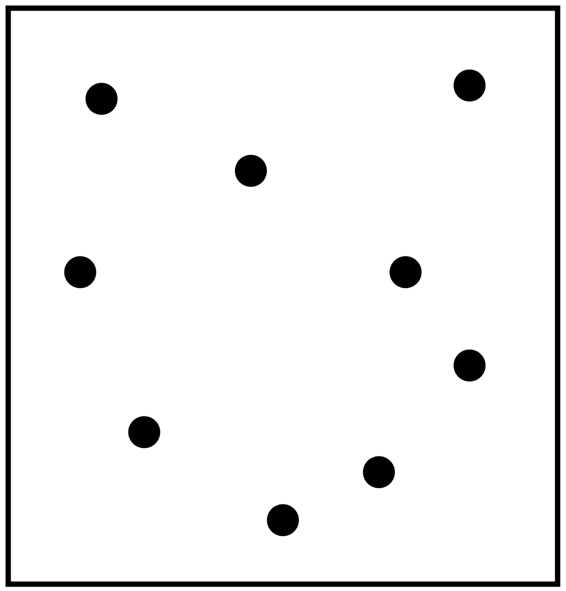
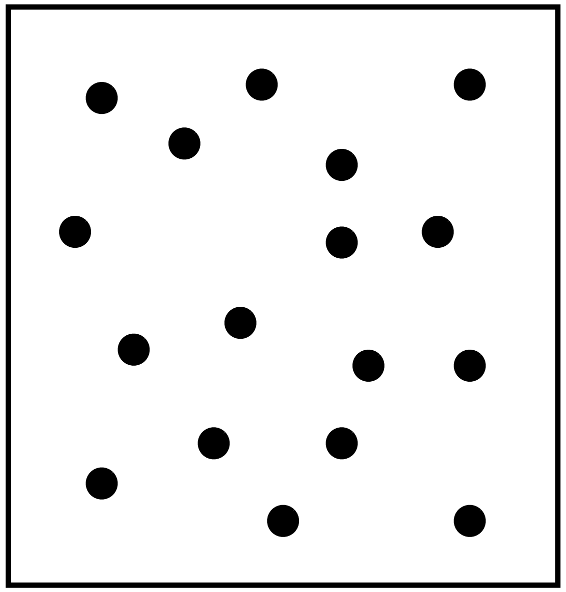


0.5 atmospheres
density twice smaller

Maxwell's law



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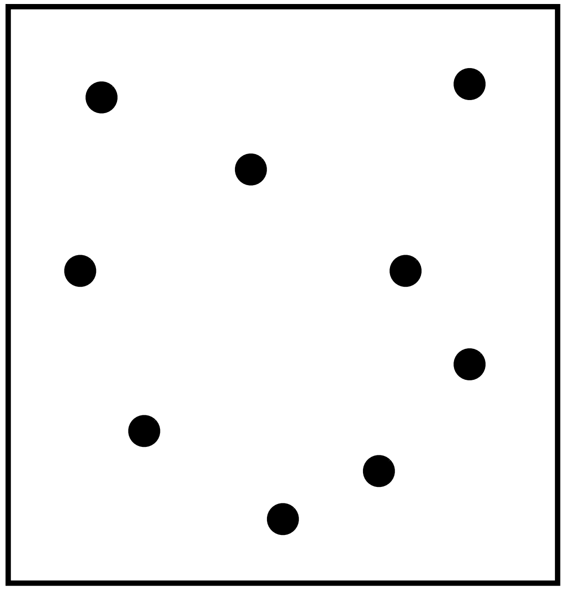

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density twice smaller

mean free path: twice bigger

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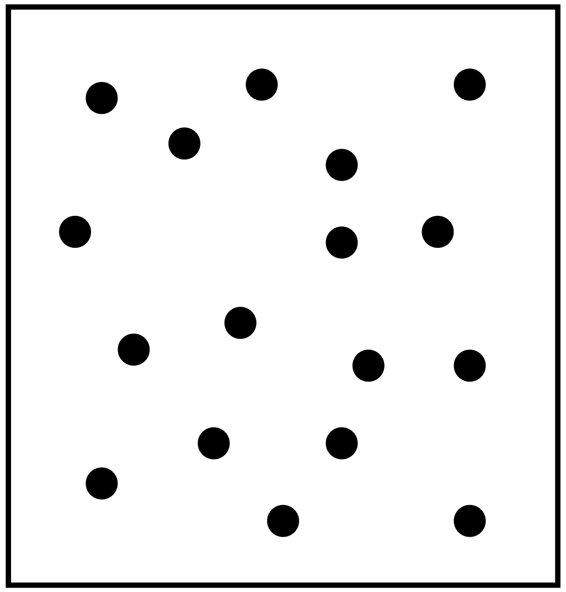

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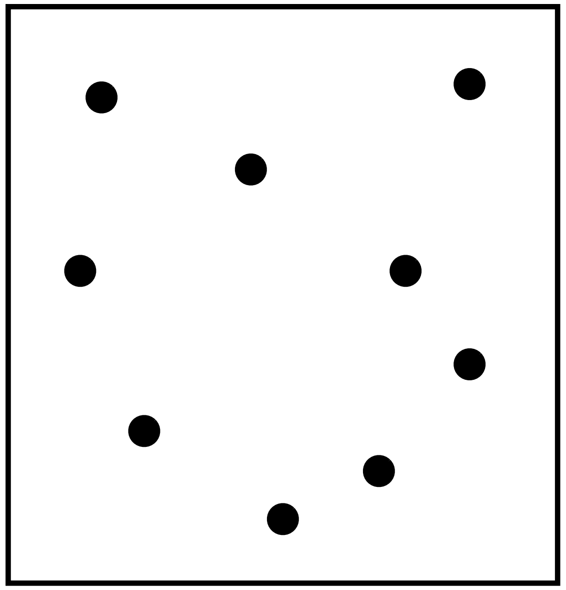

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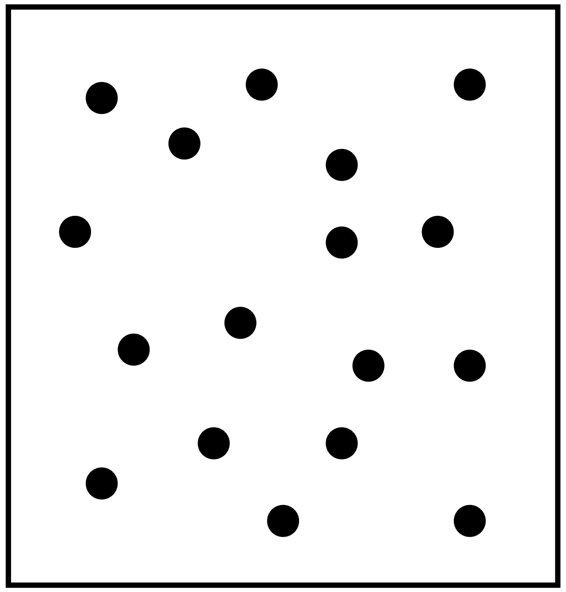
mean free path: twice bigger

same velocity

Maxwell's law



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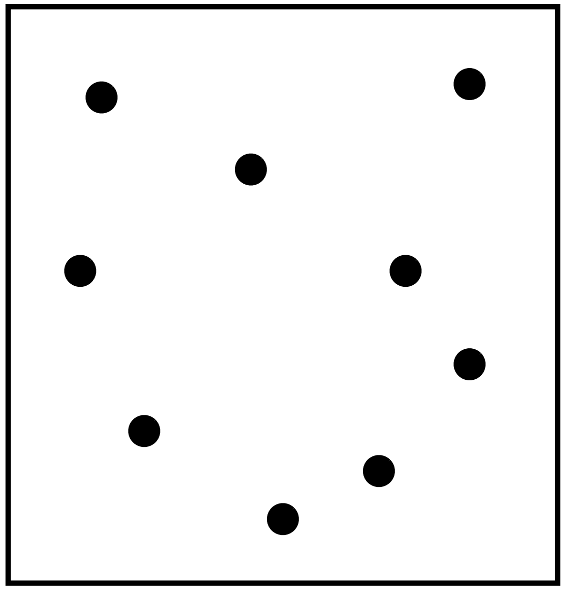

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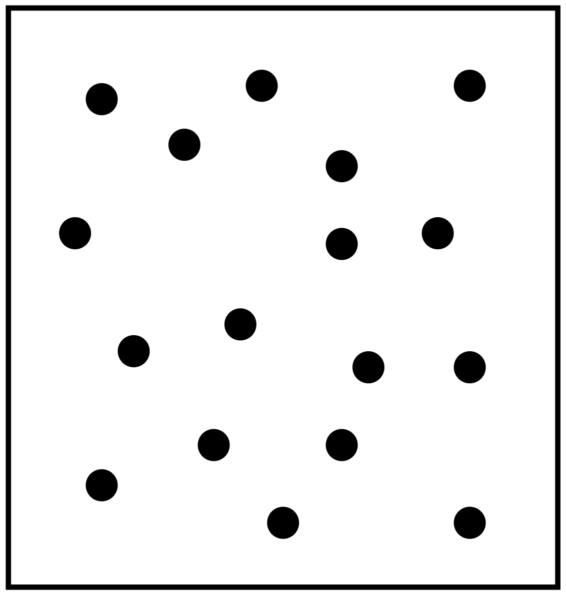
Viscosity = density x velocity x mean free path

Maxwell’s law



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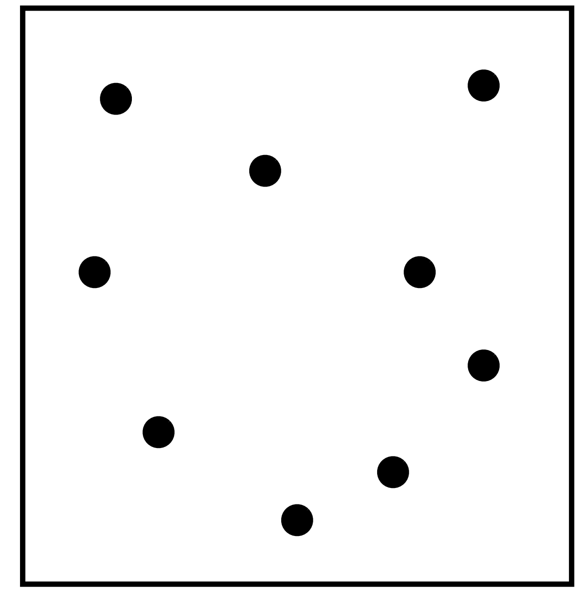

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density twice smaller

mean free path: twice bigger

same velocity

Viscosity = density x velocity x mean free path

viscosity does not vary with pressure!

Stokes lead Maxwell astray

Maxwell: My theory predicts that viscosity of air does not change with pressure!

Stokes: No way! Someone did the measurement and surely viscosity changed!

Maxwell losing faith in the existence of molecules

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...but then he had a second thought...

Maxwell got his wife's help

James Clerk and Katherine Maxwell

Maxwell the experimentalist

During the next few years, Maxwell (with the help of his wife), designed and carried out his own experiment

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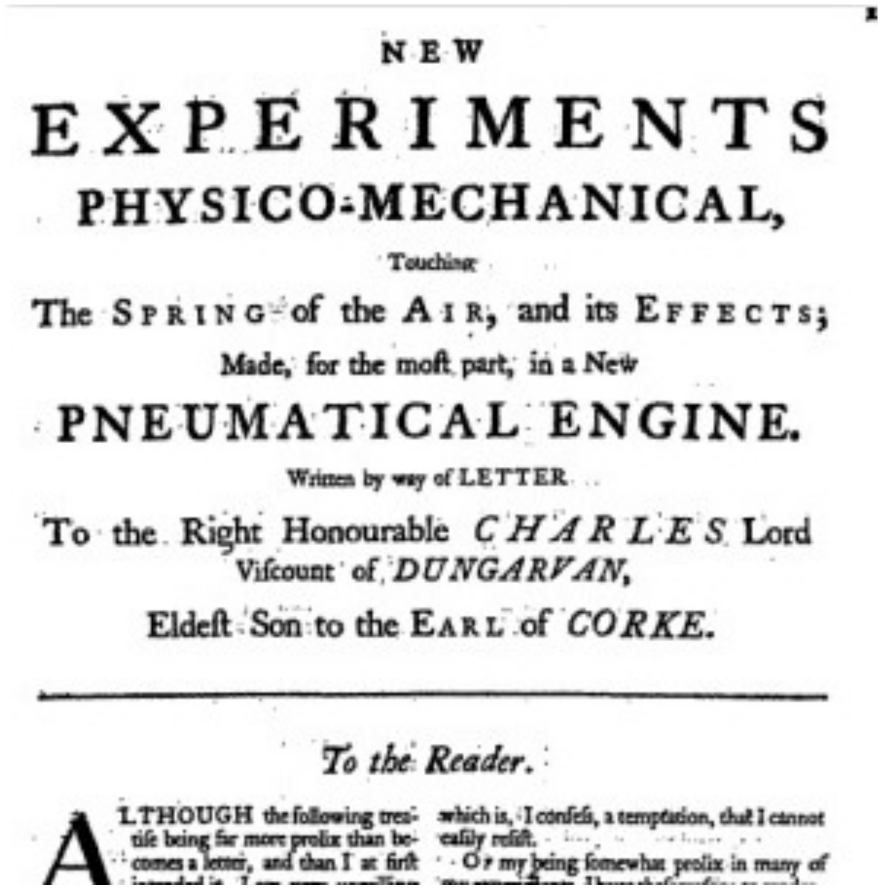
Perhaps this fact has been stumbled upon long before Maxwell?

Robert Boyle's experiment



NEW

EXPERIMENTS

PHYSICO-MECHANICAL,

Touching

The SPRING of the AIR, and its EFFECTS;

Made, for the most part, in a New

PNEUMATICAL ENGINE.

Written by way of LETTER

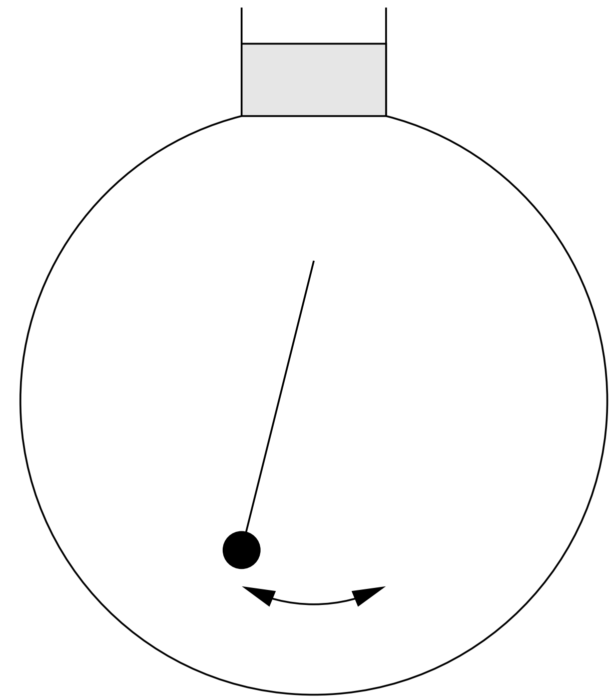
To the Right Honourable *CHARLES* Lord Viscount of *DUNGARVAN*,

Eldest Son to the EARL of *CORKE*.

To the Reader.

ALTHOUGH the following treatise being far more prolix than becomes a letter, and than I at first ... which is, I confess, a temptation, that I cannot easily resist.

Of my being somewhat prolix in many of ...



Experiment #26: pendulum in a glass container

pump out air: Boyle hoped to see the pendulum to go on for a longer time

actual result: no appreciable change at all

Viscosity of liquids

- Viscosity of liquids is much less understood
  - cannot be connected to the mean free path: molecules interact too strongly
- Cover a huge range, from water to pitch (tar)

Pitch drop experiment

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8 drops fell so far

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  - but no one has ever witnessed a drop fall

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2005 Ig Nobel Prize in Physics

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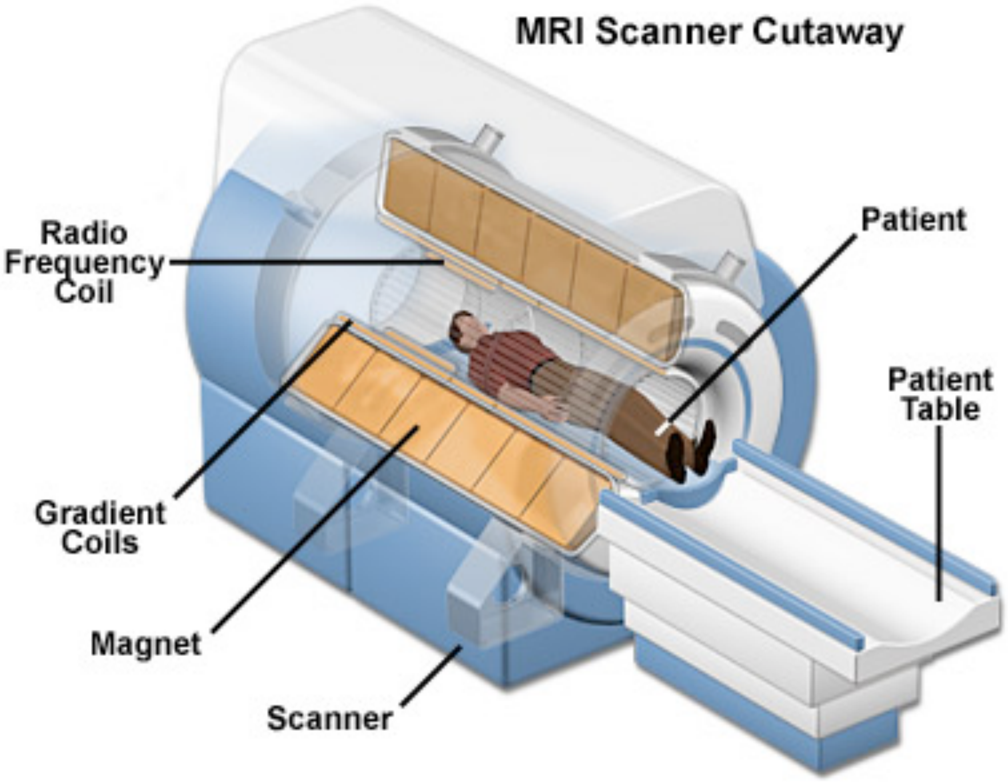
2005 Ig Nobel Prize in Physics

Viscosity of pitch: 230 billions times that of water

Purcell



Edward Mills Purcell (1912-1997)

Shared 1952 Nobel Prize in Physics for the discovery of nuclear magnetic resonance

used for MRI

Purcell’s observation

“if you look at the Chemical Rubber Handbook table you will find that there is almost no liquid with viscosity much lower than that of water. The viscosities have a big range *but they stop at the same place*. I don't understand that.”

Purcell, “Life at low Reynolds number” 1976

Viscosity of liquids can be very large (pitch) but for some reason cannot be too small!

2000

- When I started thinking about viscosity, I (and perhaps most people in my field) was not aware of the history related to viscosity
- Instead, our thinking was mostly driven by experiments with the the most extreme states of matter

2000: RHIC experiment started

Relativistic Heavy Ion Collider, Long Island, NY

Collision

Gold nucleus

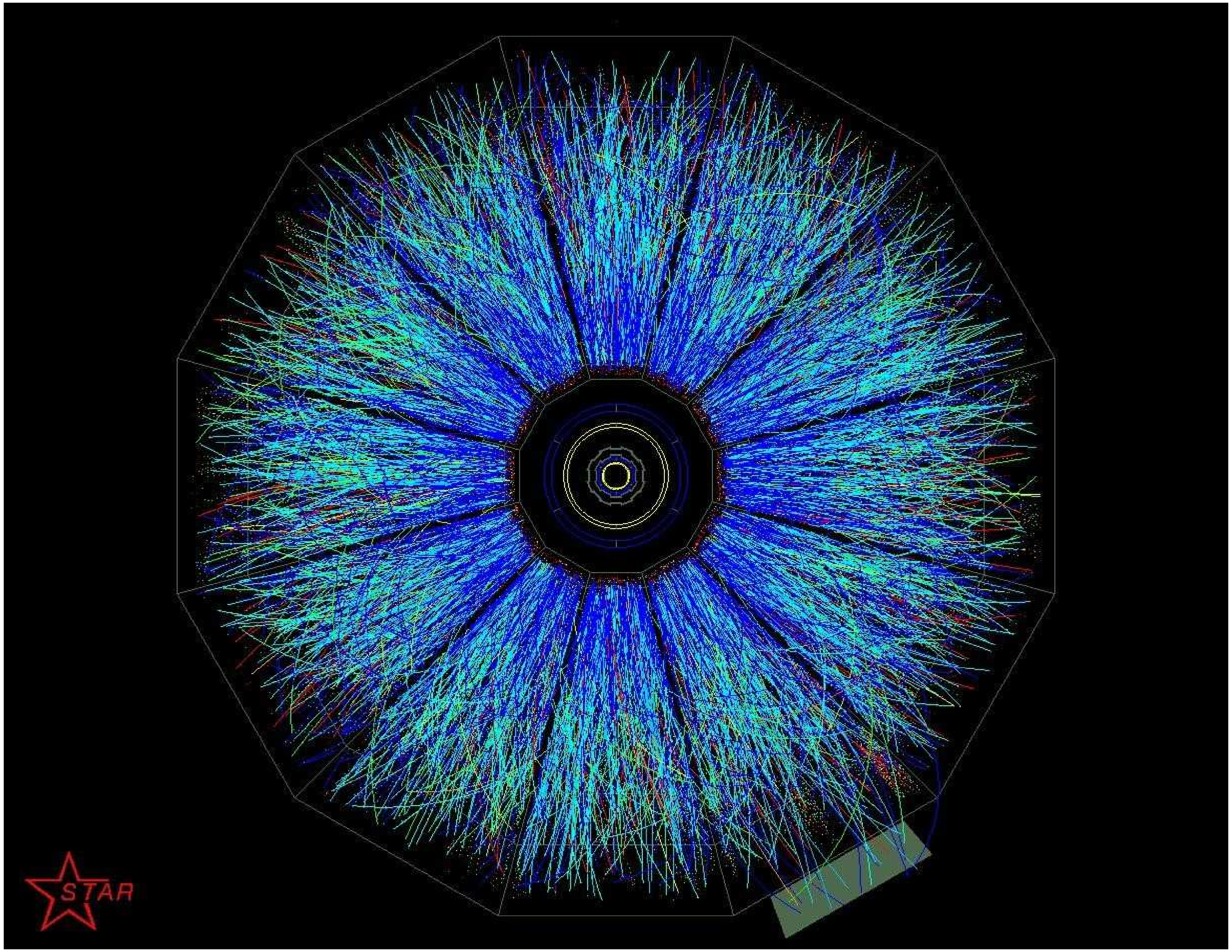
v=0.99995 c

Gold nucleus

v=0.99995 c

Such collisions produce thousands of particles

production of particles



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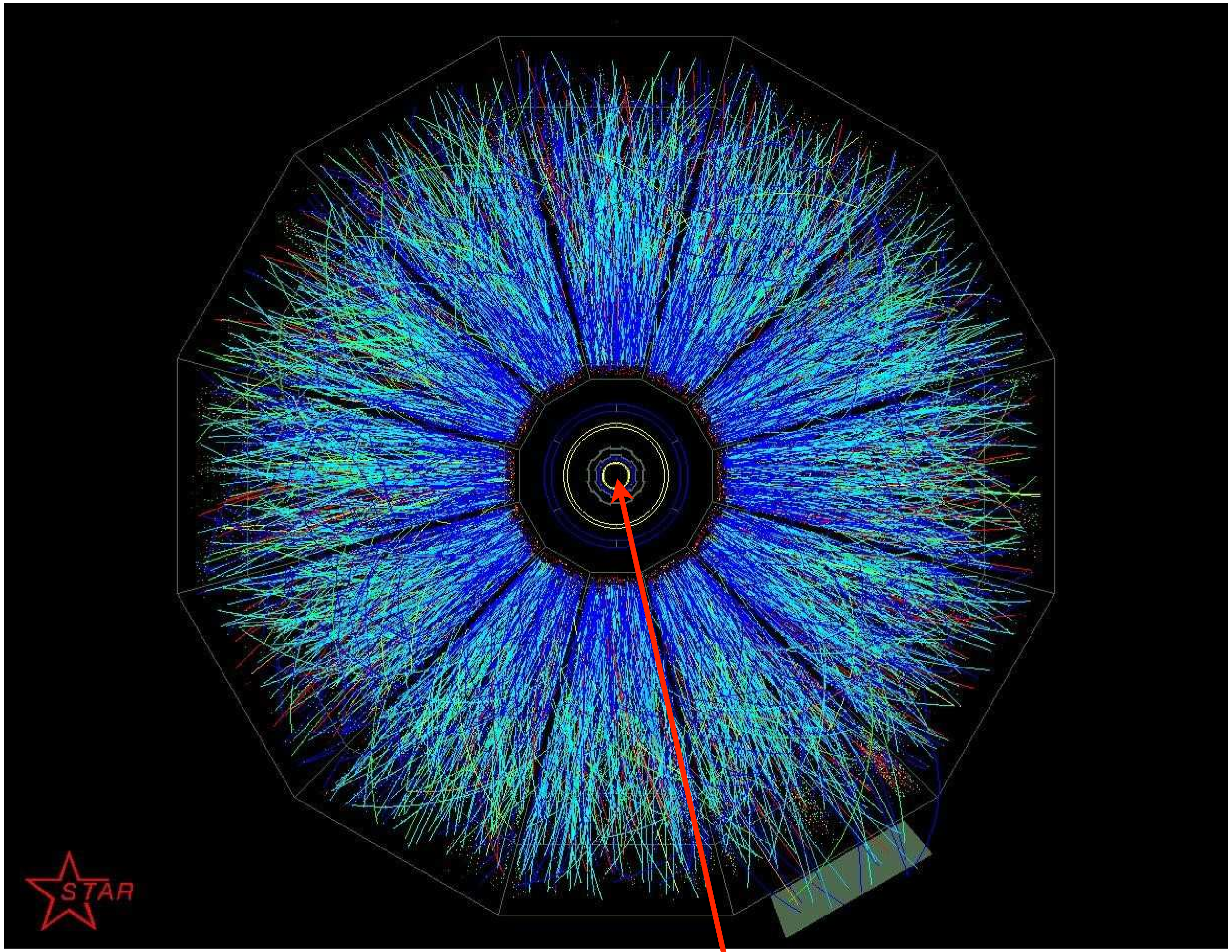


a very dense droplet of matter
in the beginning

Extreme matter at RHIC

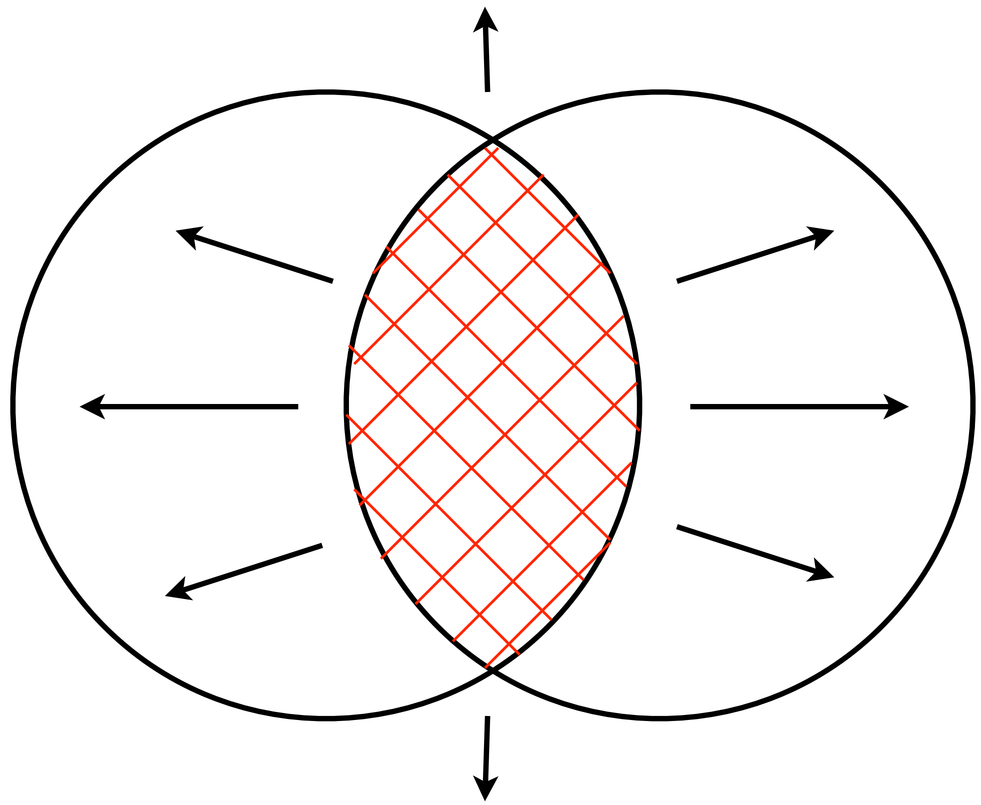
- Extremely hot: thousands billion degrees
- As hot as the Universe during the first millionths of a second
- But we get only a fleeting glimpse: the whole thing decays very quickly

Findings of RHIC
a two-sentence summary

RHIC has created a medium which behaves like a fluid with little viscosity

Viscosity is so small that Maxwell’s theory has to be stretched to the limit

How do we know it is a fluid?



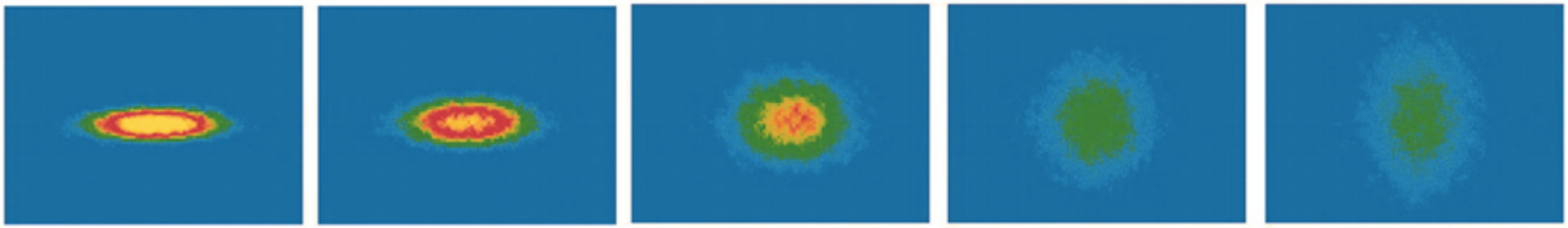
get the nuclei to glance through each other

almond-shape droplet

wait for it to expand

Surprisingly, the result is exactly like what condensed matter physicists saw in a completely different system

Expansion of a atomic gas cloud



(Cao et al, Science 2010)

Extremely low temperatures: 1 billionth of a degree

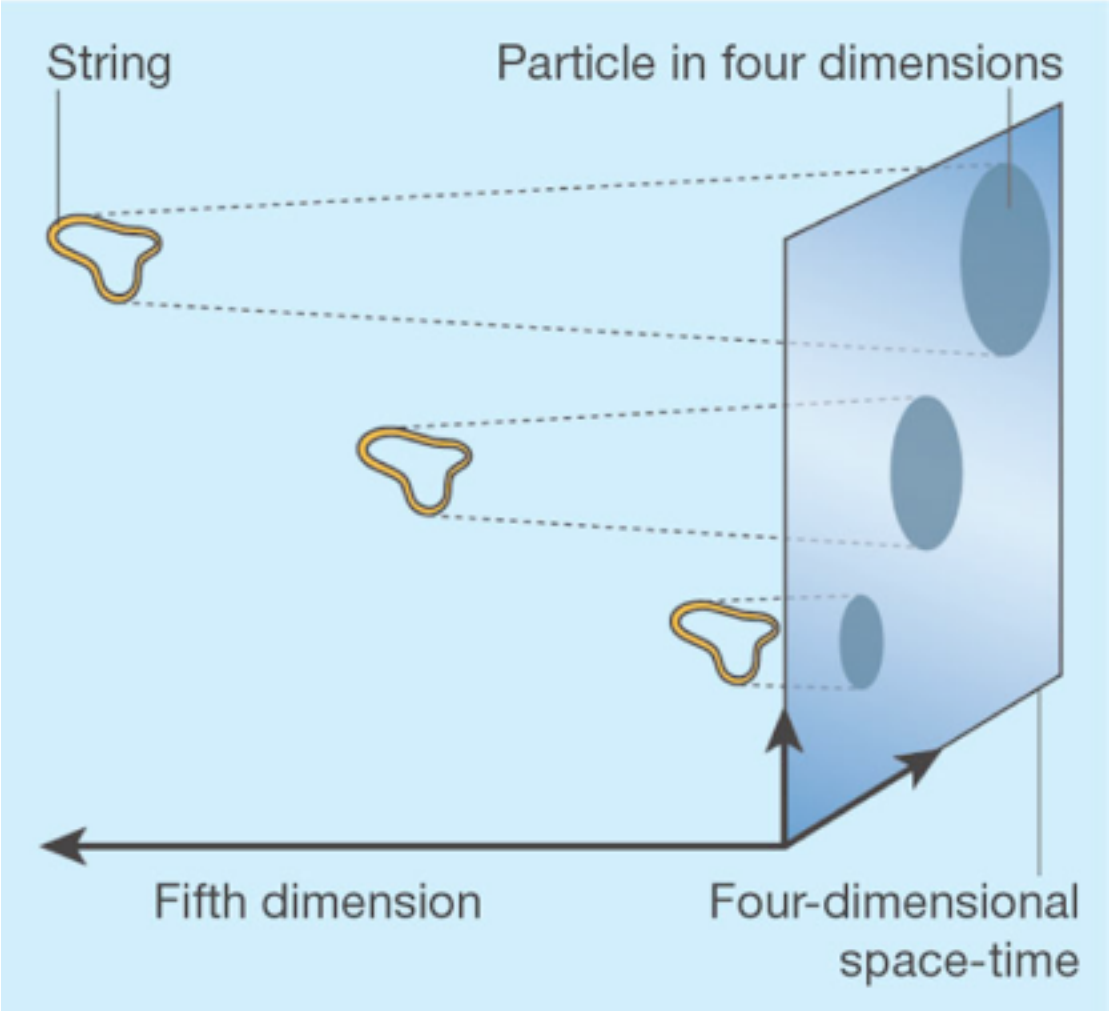
In both cases, the shorter axis becomes the longer one, and vice versa

Can only be explained if the droplet is a fluid, not a collection of independent particles

Strong interactions

- In the matter created by RHIC, particles collide too frequently to be considered as a good gas
  - a dense gas, bordering on a liquid state
- None of the methods of theoretical physics work in this regime
- Enter string theory

Maldacena's crucial breakthrough



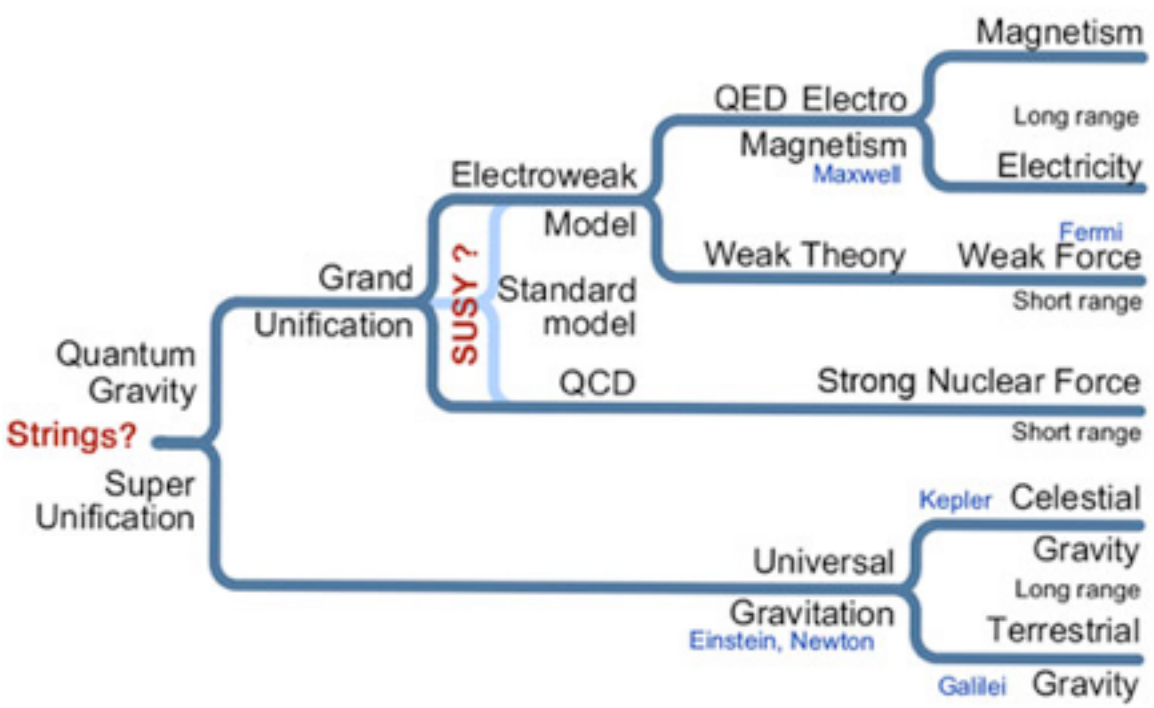
(from Nature)

1997: gauge/gravity duality

particles in 4 dimensions = strings in 5 dimensions

Sometimes, the string picture is clearer than the particle picture!

String theory's dual role

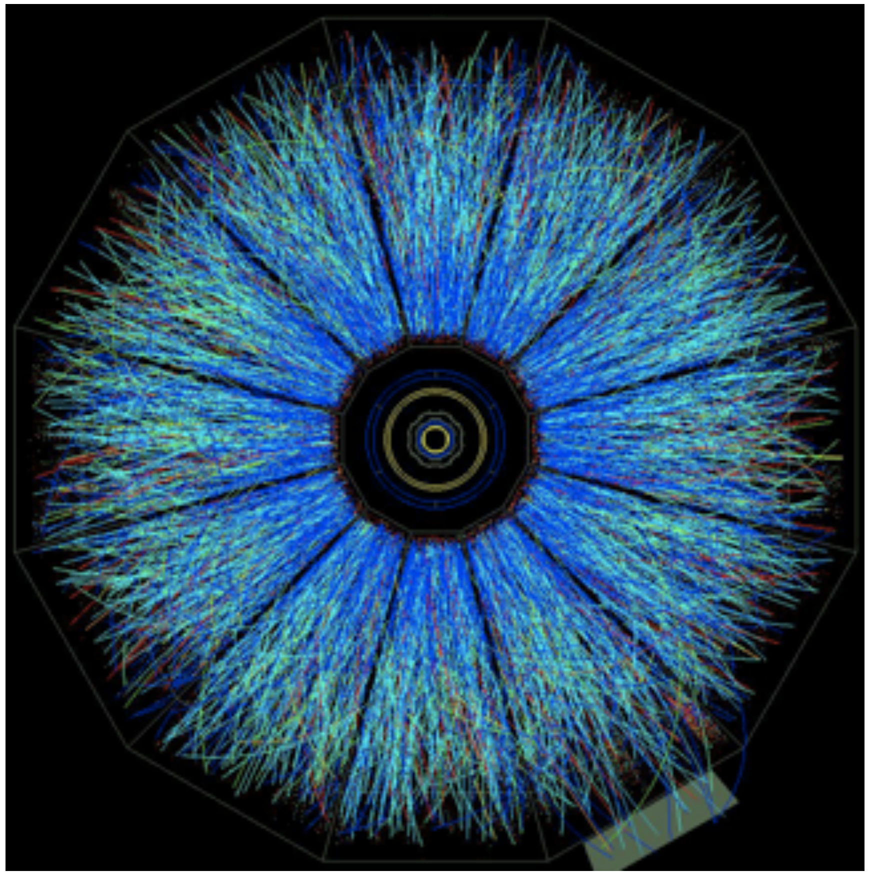


A candidate for theory unifying all interactions

A set of mathematical tools

Richness of string theory means that we now can explore many more different possibilities than before.

Gauge gravity duality makes things simpler



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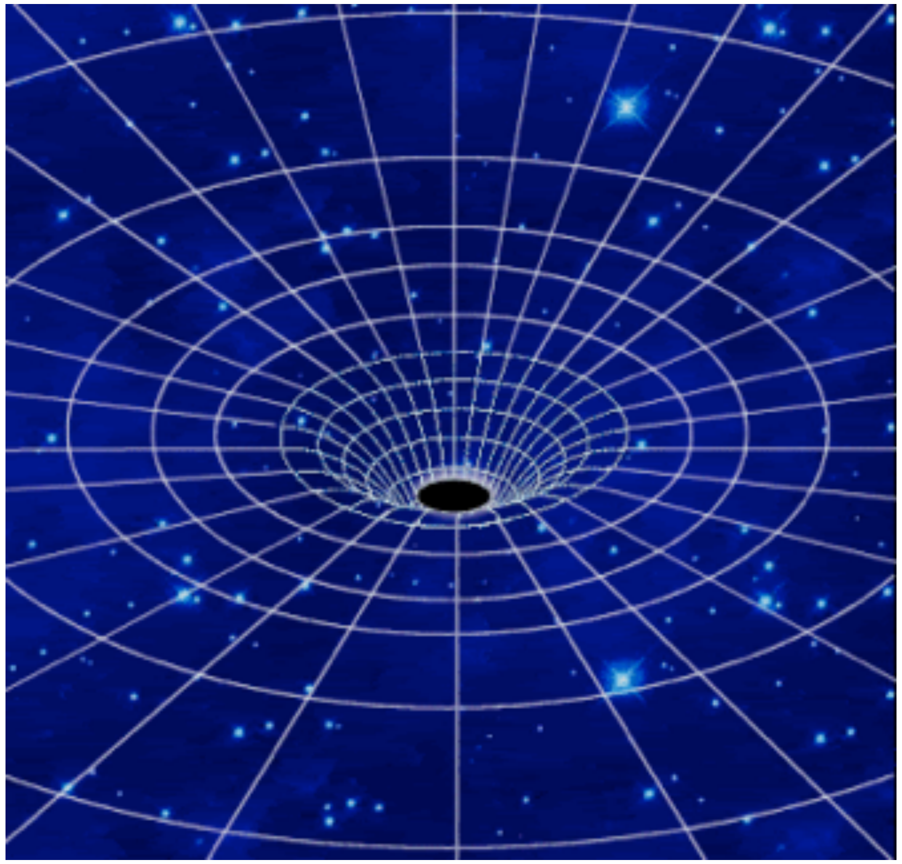

Hot matter

Black hole
(not in real life, but only
as a mathematical description)

Viscosity entropy ratio

2003: Kovtun, Starinets and myself, using gauge/gravity duality, found that

viscosity by itself is not that interesting

but

$$\frac{\text{viscosity}}{\text{entropy density}}$$

could be much more interesting!

Entropy density

Entropy is the measure of our ignorance of the state of a body:

How many bits of information needed to know all information about a given cubic centimeter of water?

$$\underbrace{001001110\ldots00101}_{S}$$

$S=4 \times 10^{23}$ bits/cm^3

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in an average

Consequence of Maldacena's theory

In a large class of systems:

$$\frac{\eta}{s} = \frac{\hbar}{4\pi}$$

Consequence of Maldacena's theory

In a large class of systems:

viscosity
fluid dynamics

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Consequence of Maldacena's theory

In a large class of systems:

viscosity
fluid dynamics

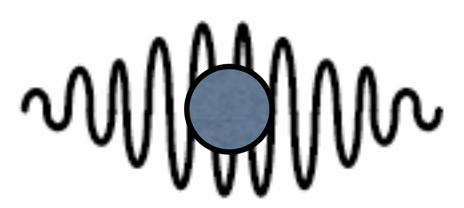
Planck's constant
quantum mechanics

$$\frac{\eta}{s} = \frac{\hbar}{4\pi}$$

entropy
thermodynamics

Why quantum mechanics?

Particle-wave duality: particle is wave



mean free path cannot be shorter than wavelength

otherwise a particle does not have time to “live” as a particle

What does it mean to have

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

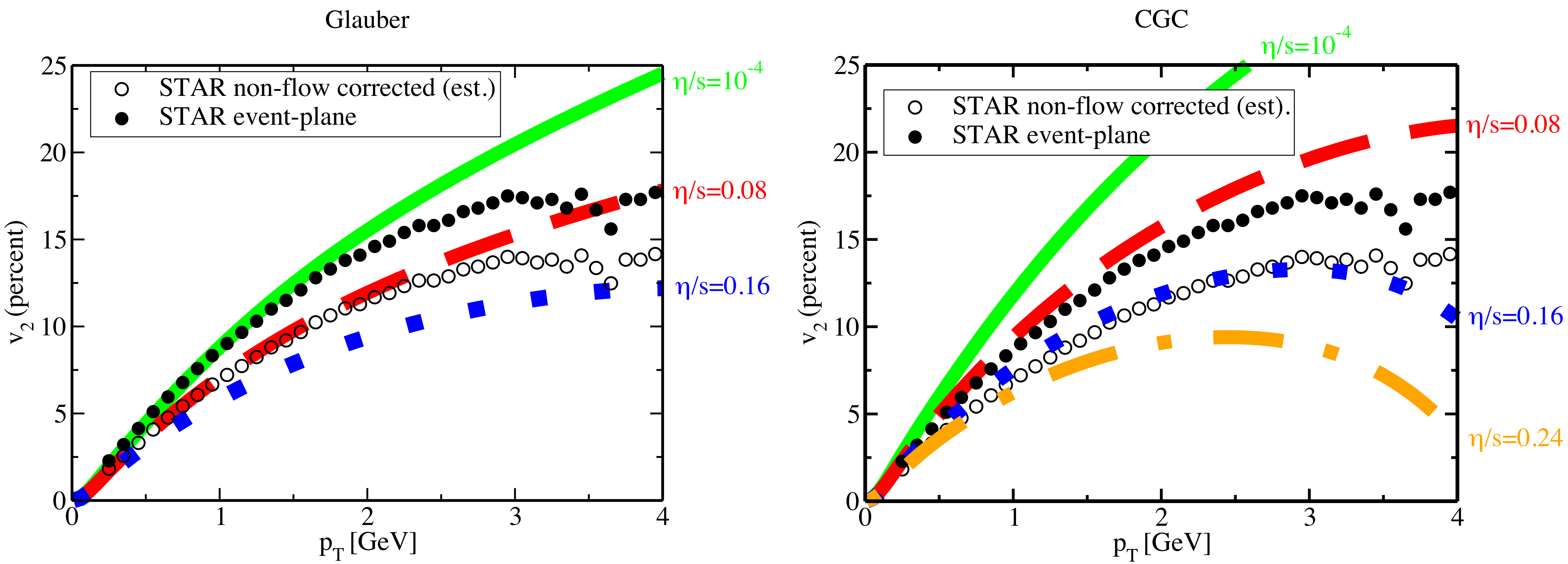
Particles barely have enough time to make one beat before bumping to another

Probably the shortest mean free path allowed

Viscosity cannot be much smaller than that: Purcell

All laboratory liquids have viscosity/entropy density at least 8 times larger than the value above

Matter created at RHIC



Romatschke and Luzum

$$\frac{\eta}{s} = 0.1 \pm 0.1(\mathrm{th}) \pm 0.08(\mathrm{exp})$$

Not too far away from 1/4π=0.08, in any case much smaller than any known liquid

High or low viscosity?

BNL press release 2005:

"The degree of collective interaction, rapid thermalization, and extremely low viscosity of the matter being form at RHIC makes this the most nearly perfect liquid ever observed."

Estimating the viscosity of the RHIC matter:

$$\eta \sim \frac{\hbar}{4\pi} s \sim \frac{10^{-27}\text{erg} \cdot \text{s}}{(10^{-13}\text{cm})^3} \sim 10^{14}\text{cp}$$

In absolute term, almost as viscous as a glass!

Low viscosity: in the sense of small η/s, suggested by gauge/gravity duality.

Aspen winter workshop

- Is string theory useful for physics of new materials?
- Can string theory be used as a tool to explain high-temperature superconductivity?

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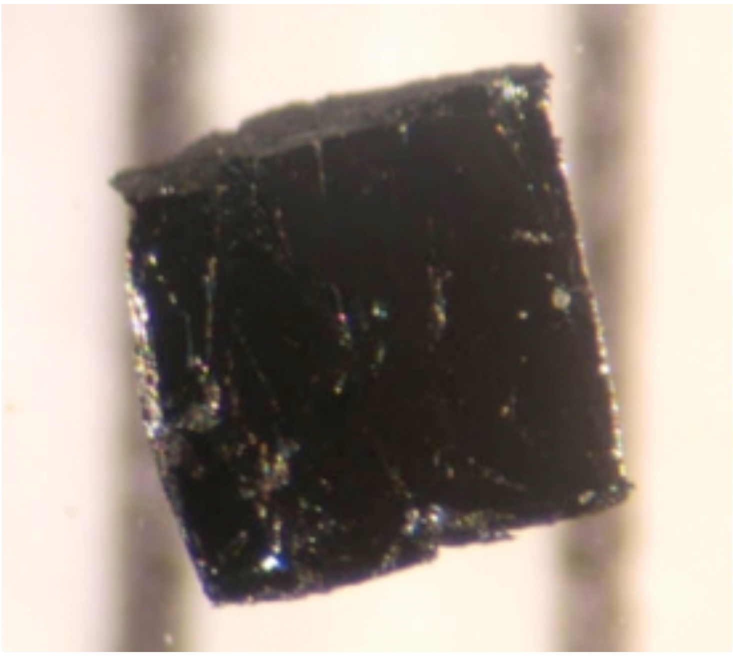

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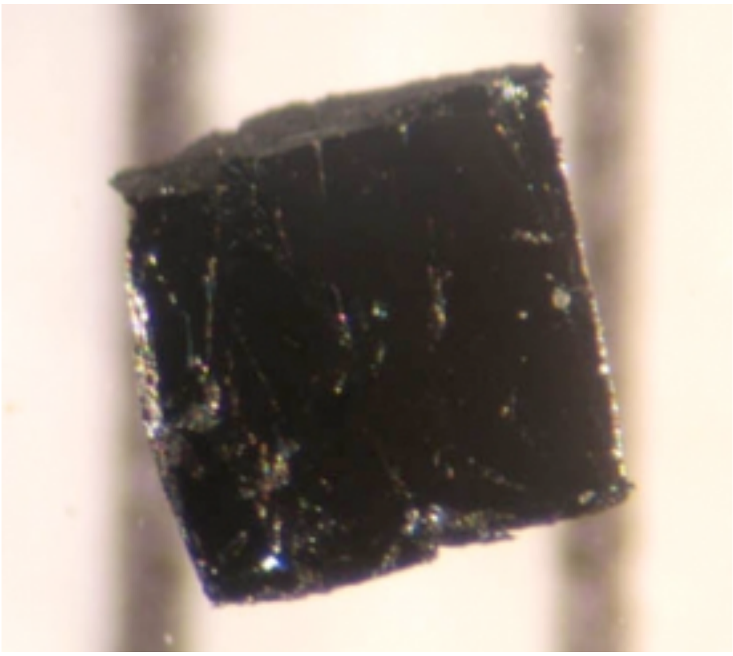

We have reasons to be cautiously optimistic

The End