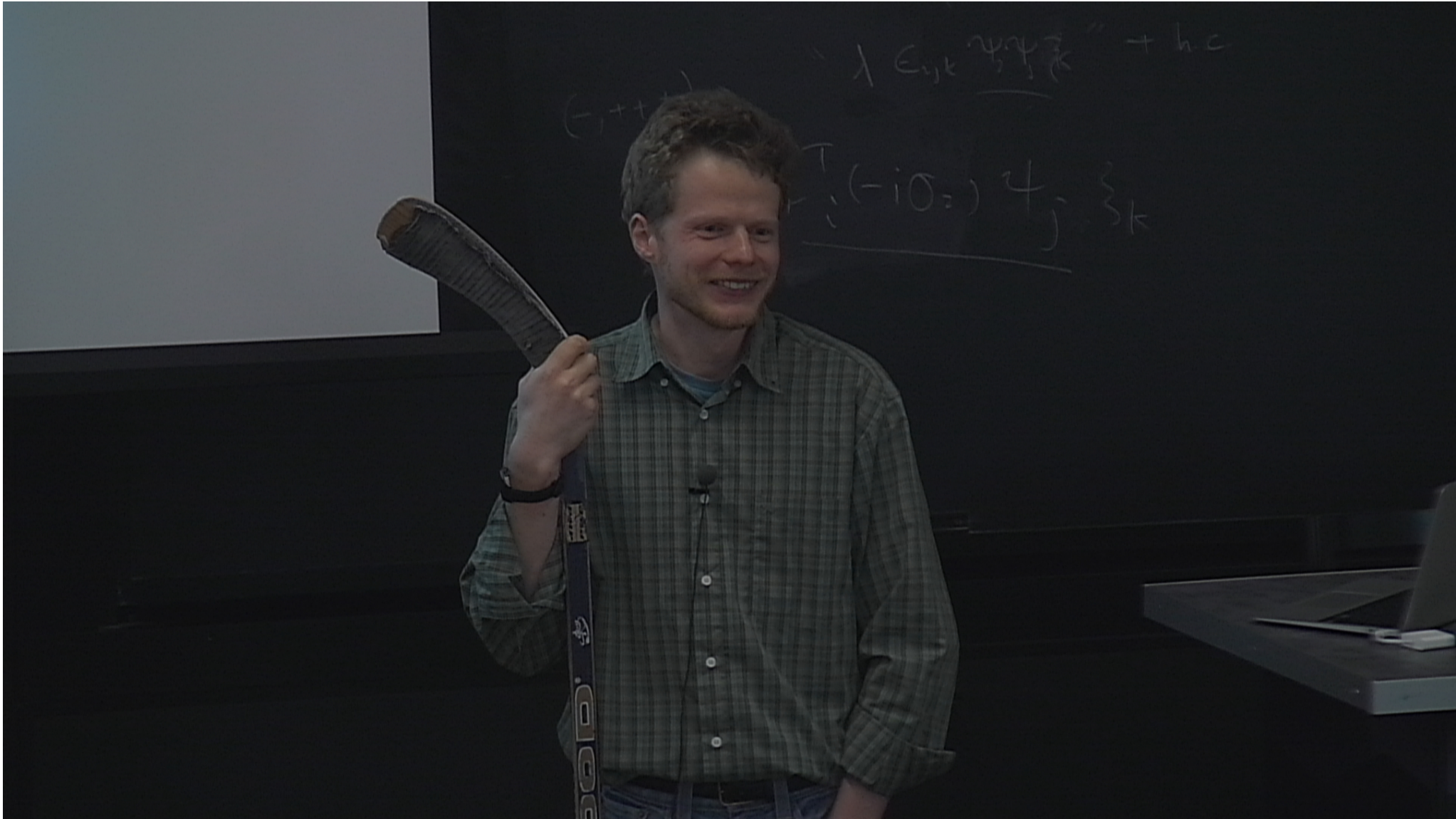


Title: Researcher Presentation: Pavel Kovtun

Date: Dec 02, 2011 03:30 PM

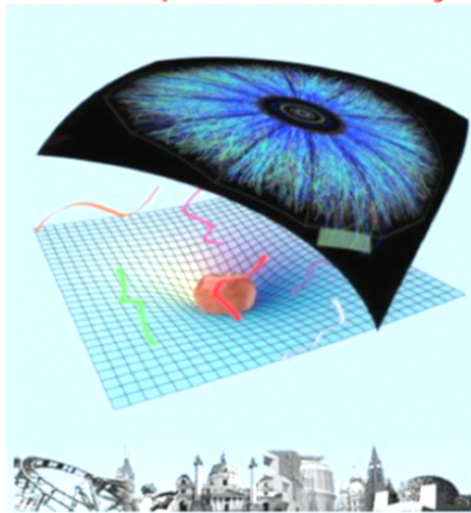
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Abstract:

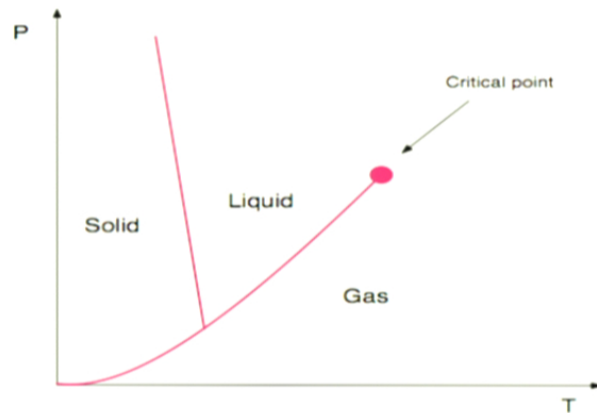


Basic idea

As you know, gravity describes how space is curved by matter.
But gravity is more than merely a dynamics of spacetime.
It secretly describes quantum many-body systems.



A typical phase diagram



- Gas at high T , solid at low T
- A critical point in between
- E.g., for water,
 $T_c = 374^\circ\text{C}$, $P_c = 220P_{\text{atm}}$
 $T_3 = 0.01^\circ\text{C}$, $P_3 = 0.006P_{\text{atm}}$
- No sharp distinction liquid vs gas

Expect similar equations to describe the flow of liquids and gases

Simple ideal fluids

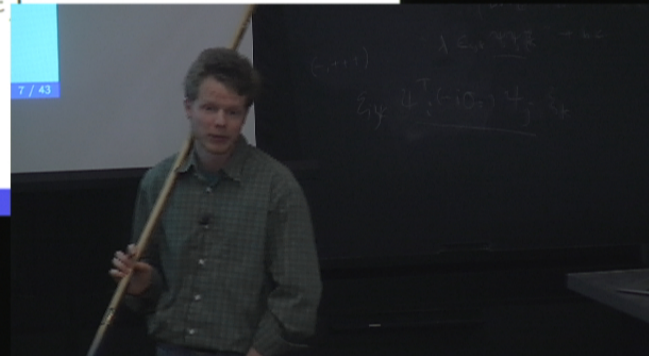
Conservation laws for the fluid (Euler equations)

mass : $\partial_t \rho + \partial_i (\rho v_i) = 0,$

momentum : $\partial_t (\rho v_i) + \partial_j \Pi_{ij} = 0, \quad \Pi_{ij} = P \delta_{ij} + \rho v_i v_j,$

energy : $\partial_t \left(\epsilon + \frac{\rho \mathbf{v}^2}{2} \right) + \partial_i \left((w + \frac{\rho \mathbf{v}^2}{2}) v_i \right) = 0.$

Here $w \equiv \epsilon + P$, and EoS for example is $P = P(\rho, \epsilon)$



Simple viscous fluids

Conservation laws for the fluid (Navier-Stokes equations)

mass : $\partial_t \rho + \partial_i (\rho v_i) = 0,$

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energy : $\partial_t \left(\epsilon + \frac{\rho \mathbf{v}^2}{2} \right) + \partial_i \left((w + \frac{\rho \mathbf{v}^2}{2}) v_i - \sigma_{ij} v_j - \kappa \partial_i T \right) = 0.$

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$$\sigma_{ij} = \eta (\partial_i v_j + \partial_j v_i - \frac{2}{3} \delta_{ij} \partial_k v_k) + \zeta \delta_{ij} \partial_k v_k$$

η = shear viscosity, ζ = bulk viscosity, κ = thermal conductivity

η, ζ, κ are responsible for the dissipation

Hydrodynamic equations describe quite a lot



Heraclitus (535 – 475 BC) : *Everything flows...*

The pitch drop experiment (U of Queensland)



- Pitch does not look like it's a liquid



The pitch drop experiment (U of Queensland)

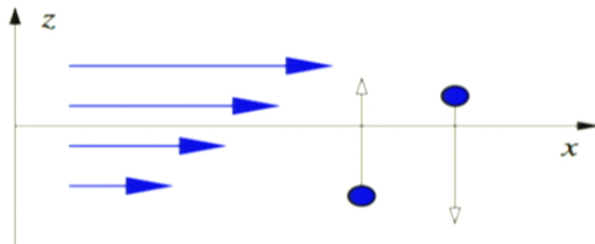


- Pitch does not look like it's a liquid
- But in fact it is.



- Experiment set up in 1927
- 8 drops fell so far (last one in 11/2000)
- Ig Nobel prize in Physics (2005)
- No-one has ever seen the drop fall
- Viscosity is $10^{11} \times$ viscosity of water

Viscosity: measure of the internal friction

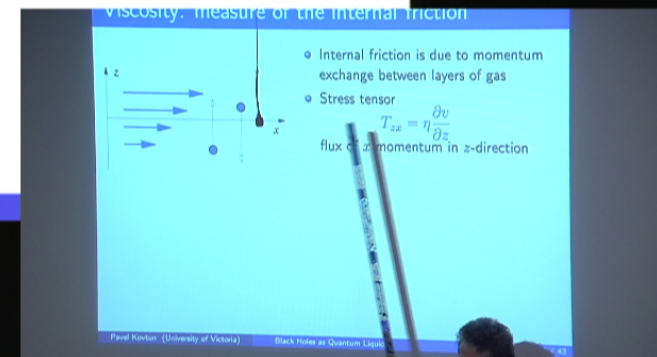


- Internal friction is due to momentum exchange between layers of gas

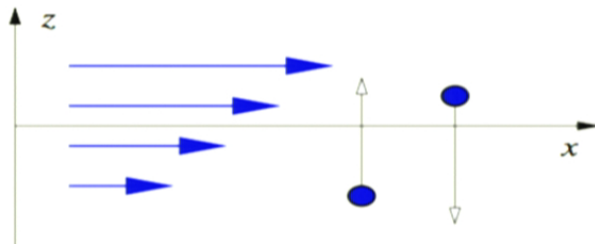
- Stress tensor

$$T_{zx} = \eta \frac{\partial v}{\partial z}$$

flux of x -momentum in z -direction



Viscosity: measure of the internal friction



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Particle number per unit surface per unit time: (nv_{th})

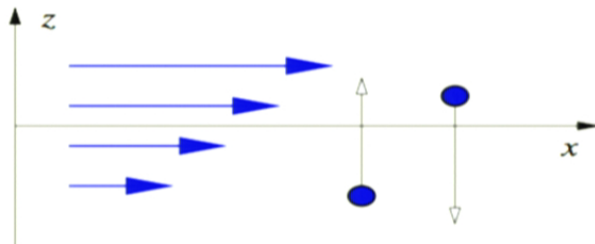
Momentum per unit surface per unit time: $(nv_{\text{th}})(mv)$

Flux up: $nv_{\text{th}}m(v_0 - l_{\text{mfp}}\frac{\partial v}{\partial z})$, flux down: $nv_{\text{th}}m(v_0 + l_{\text{mfp}}\frac{\partial v}{\partial z})$,

$T_{zx} = \text{flux}_{\text{up}} - \text{flux}_{\text{down}}$

$$\therefore \eta \sim nv_{\text{th}}ml_{\text{mfp}} \sim \frac{mv_{\text{th}}}{\sigma} \sim \frac{(mT)^{1/2}}{\sigma}$$

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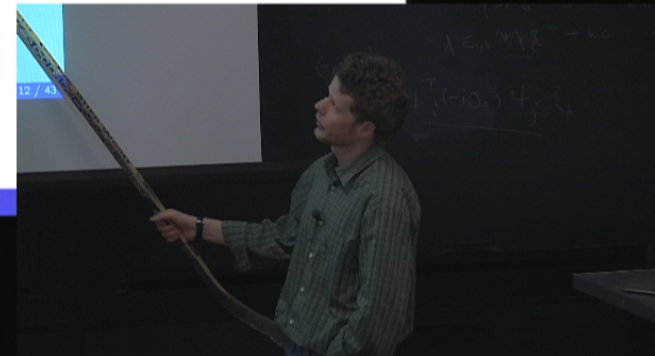
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This was derived by Maxwell in 1860

Viscosity: measure of the internal friction (2)

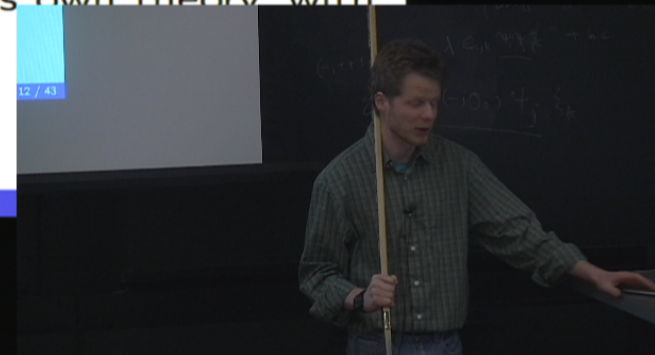
- Viscosity of a gas depends on temperature, but not on density
- Maxwell himself was puzzled:

Such a consequence of the mathematical theory is very startling and the only experiment I have met with on the subject does not seem to confirm it.



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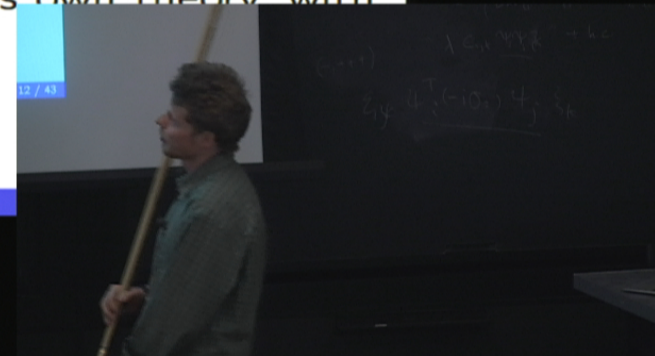
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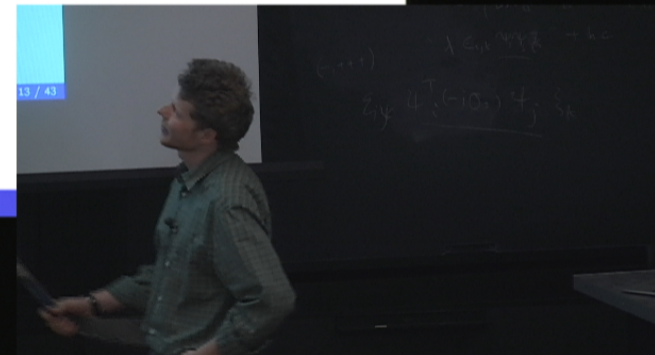
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Ideal gas vs ideal fluid

Common definitions:

- Ideal gas is a gas with no interactions between the particles
- Ideal fluid is a fluid with no viscosity



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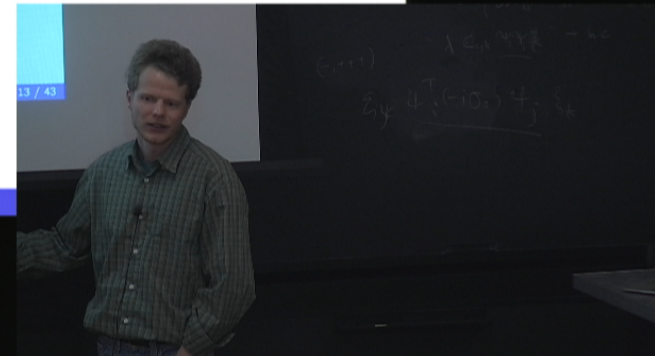
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Remember,

$$\eta \sim \frac{(mT)^{1/2}}{\sigma}$$

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- Near-ideal gas has huge viscosity ($\sigma \rightarrow 0$)



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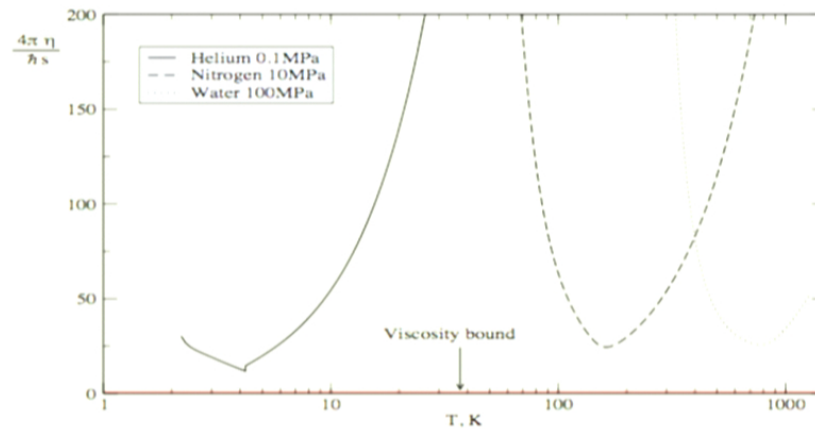
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Ideal gas behaves as a very non-ideal fluid!

Range of viscosities

Viscosity of gases *increases* with temperature $\eta \sim (mT)^{1/2}$

Viscosity of liquids *decreases* with temperature $\eta \sim e^{E_a/T}$



Glycerine at $P = P_{\text{atm}}$:

$$\eta(T=0^\circ\text{C}) = 12070 \text{ mPa s}$$

$$\eta(T=100^\circ\text{C}) = 14.8 \text{ mPa s}$$

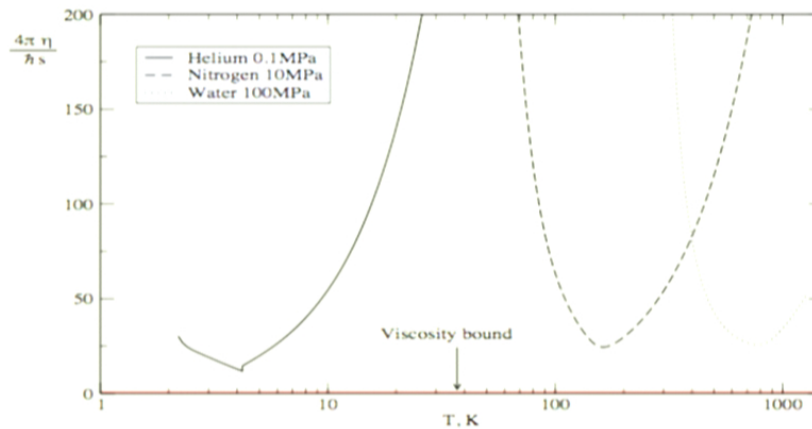
Water at $P = P_{\text{atm}}$:

$$\eta(T=0^\circ\text{C}) = 1.8 \text{ mPa s}$$

$$\eta(T=100^\circ\text{C}) = 0.28 \text{ mPa s}$$

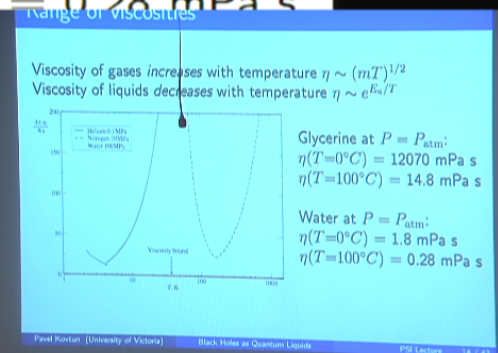
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Purcell's question to Weisskopf

Life at low Reynolds number

E. M. Purcell
Lecturer, Laboratory of Chemical Physics, Harvard University, Cambridge, Massachusetts 02138
(Received 12 June 1977)

Editor's note: This is a reprint (slightly edited) of a paper of the same title that appeared in the book *Physics and the World: A Symposium in Honor of Victor F. Weisskopf*, published by the American Institute of Physics (1978). The original text of the original title has been preserved in the paper, which was itself a slightly edited transcript of a tape. The figures reproduced here are from the book. The diagrams in numbers 1 and 2 are reproduced in the original form of the text, printed by an overhead projector turned on its side. Some essential hand-drawn details not reproduced.

This is a talk that I would not, I'm afraid, have the nerve to give under any other circumstances. It's short. I've been talking up to half a year. Like so many of you here, I've enjoyed with you some sort of glimpse of something to which we can apply physics. We wonder around strictly as amateurs equipped only with some elementary physics and in the end, at various points, we are not understanding of the elementary physics even if we don't know much more at the other end of the spectrum. Now this is that kind of a subject. So I have still another reason for wanting to, as it were, needle Viki with it. Because I'm going to talk for a while about viscosity. Viscosity in a liquid will be the dominant theme here and you know Viki's progress in expounding everything, including the heights of mountains, with the elementary constants. The viscosity of a liquid is a very tough nut to crack, as he well knows. Because when the stuff is moved by merely 40 degrees, its viscosity can change by a factor of a million. I was really amazed by fluid viscosity in the early days of NMR, when it occurred that this property was just what we needed to explore the behavior of spin relaxation. And one of you here is still big inside the physics looking around, you wouldn't see much of the spin relaxation as the gyromagnetic ratio. Viki will say that he can at least predict the logarithm of the viscosity. And then of course is correct because the reason viscosity changes is that it's got one of those activation energy things and what

he is more mysterious than that. Viki, because 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 viscosity has a big range that they call it the same place. I don't understand that. That's what I'm leaving for him.

Now I'm going to talk about a world where the physics is almost never think about. The physics is never about viscosity in high school where for a typical Millikan cell drop experiment and he goes back about 1910, as far as we know is what I know. And Reynolds number of course is something for the engineers. And the low Reynolds number regime most engineers know is even increased in viscosity because of chemical energy, in connection with fluid and both a fascinating topic. I heard about from a chemical engineering friend at MIT. But I want to take you into the world of very low Reynolds number, a world which is inhabited by the overwhelming majority of the organisms in this world. This world is quite different from the one that we have developed our intuitions in.

I might say what you see this. To introduce something

that will come later. I'm going to talk partly about how the organisms work. The way the organisms work is to be the only important question about them. I got into this through the work of a former colleague of mine at Harvard, Howard Berg. Berg got his Ph.D. with Norman Ramsey working on a hydrogen maser, and then he went back into biology with his husband. He's very keen, and some of the physics. He is now at the University of Colorado at Boulder, and has recently participated in what seems to me one of the more successful discussions about the organisms we're going to talk about. So it was partly Howard's work tracking it, and finding out this strange thing about them, that got me thinking about the elementary physics stuff.

Well, here we go. In Fig. 1 you see an object which is moving through a fluid with velocity v . It has diameter a . It's like a low speed in a sphere, but here it's anything, a rod or a disk or the viscosity and density of the fluid. The ratio of the inertial forces to the viscous forces, as Osborne Reynolds pointed out slightly less than a hundred years ago is given by $\rho v a^2 / \eta$, where ρ is called the kinematic viscosity. It's easier to remember in dimensions for water $\rho = 10^{-3}$ g/cm³. The ratio is called the Reynolds number and when this number is small the viscous forces dominate. Now there is an easy way, which I didn't realize at first, to see who should be interested in small Reynolds number. If you take the viscosity η and square it and divide by the density, you get a value (η^2 / ρ) . Now the Reynolds number is $\rho v a^2 / \eta$ or $v a^2 / (\eta^2 / \rho)$. So if you have a number that will give anything, a number that will give a Reynolds number of order of magnitude 1, or other words, if you want to use a number with Reynolds number 1 for strictly speaking, if the η^2 / ρ is a numerical value of order 1 with $(10^{-3})^2$ dyn/cm² is a factor in the case that you're interested in small Reynolds number. If you're interested in small forces on an absolute sense. The other people who are interested in low Reynolds number, although they usually don't have to make it, are the geophysicists. The Earth's viscosity is supposed to have a viscosity of 10^{21} P. If you now work out η^2 / ρ , the force is 10^{21} dyn. That is more than 10^{21} times the gravitational force that the Earth exerts on the other half of the globe. Now is, of course, that the flow of the mantle of the Earth, the Reynolds number is very small indeed.

Now consider things that move through a liquid (Fig. 2). The Reynolds number for a small swimming in water might be 10^4 if we put it in a small stream. For a goldfish in a very deep pool it might get down to 10^2 . For the animals that we're going to be talking about, as we'll see in a mo-



he can predict the order of magnitude of the exponent. But it's more mysterious than that, Viki, because 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. That's what I'm leaving for him.¹

15 / 43

How small can viscosity be?

“Viscosity per particle” η/n , where n = number density

On the gas side:

$$\frac{\eta}{n} \sim \frac{mnv_{\text{th}}l_{\text{mfp}}}{n} = l_{\text{mfp}} mv_{\text{th}} \gtrsim \hbar$$

otherwise point particle not well defined



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Two lessons:

- This suggests that **the Heisenberg uncertainty relation prevents the existence of ideal fluids** in nature
- Strongly interacting **quantum liquids** are likely to be the most ideal liquids in nature

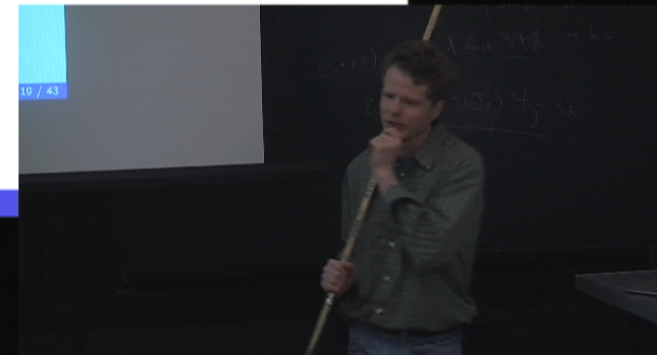
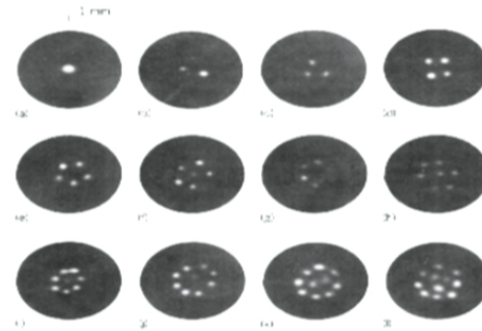
PK+Son+Starinets, 2004

Different types of quantum liquids



Different types of quantum liquids

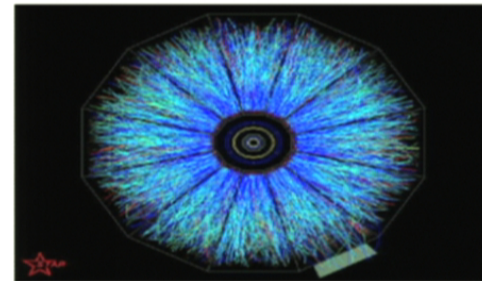
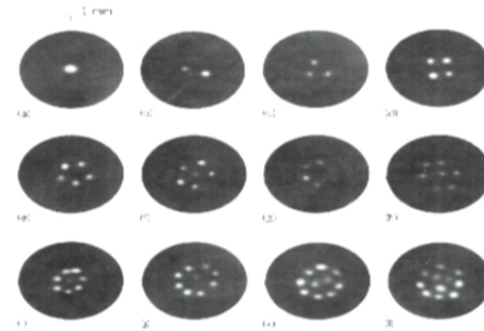
Quantum effects produce macroscopic long-range correlations between particles. These are superfluids, e.g. ^4He below 2.17K .



Different types of quantum liquids

Quantum effects produce macroscopic long-range correlations between particles. These are superfluids, e.g. ^4He below 2.17K .

Quantum effects produce extremely low viscosity in normal fluids. These were discovered recently when studying very hot ($T \gtrsim 10^{12}\text{K}$) gases of subnuclear particles.

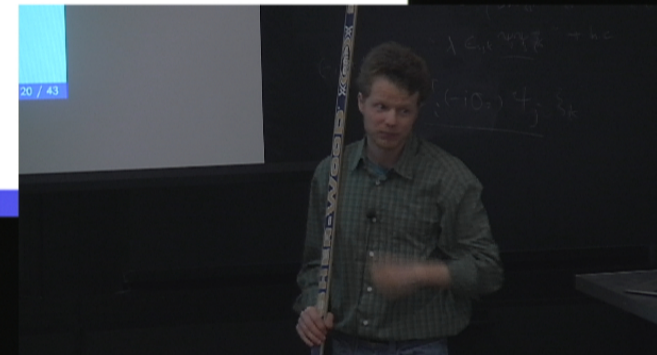


Superfluids

- Spontaneous breaking of particle number symmetry $\Psi \rightarrow \Psi e^{i\alpha}$
- Variation of the phase (Goldstone boson) makes its way into the Navier-Stokes equations,

$$\mathbf{v}_s = \frac{\hbar}{m} \nabla \alpha$$

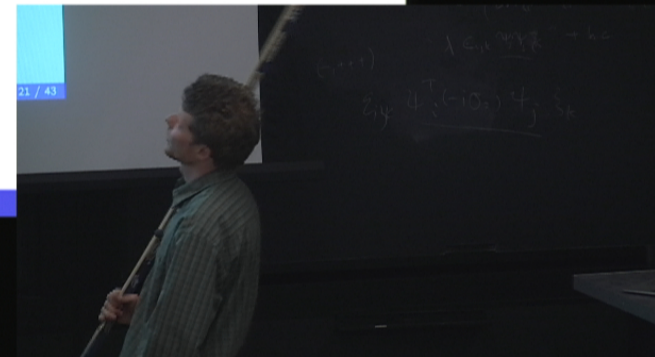
- Superfluids have *non-zero* viscosity which can be measured using a torsional pendulum



Hot subnuclear matter

Two interesting scales where the degrees of freedom rearrange:

- Scale of electroweak symmetry breaking $T \sim 100 \text{ GeV} \sim 10^{15} K$
- Scale of quark confinement $T \sim 1 \text{ GeV} \sim 10^{13} K$

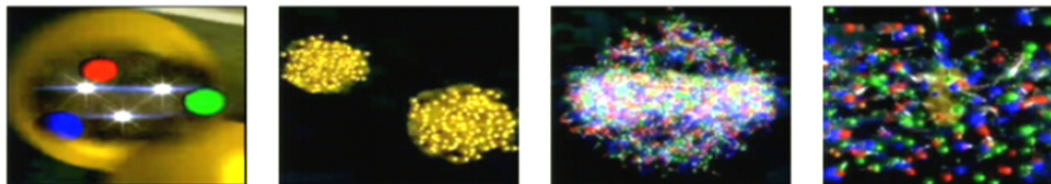


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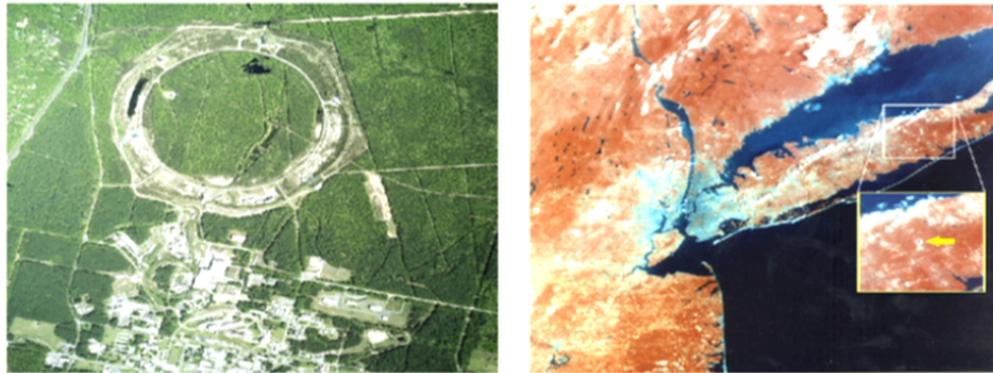
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Protons, neutrons \Rightarrow Quarks + Gluons

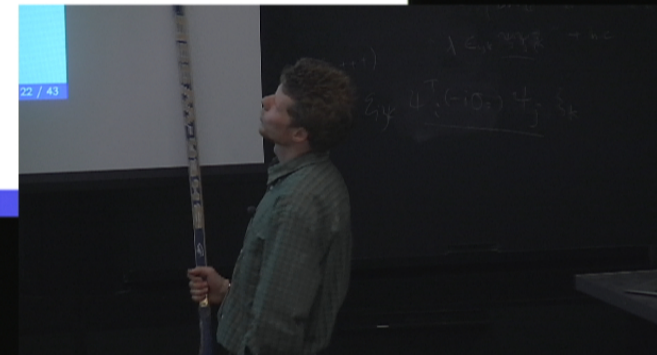


Collide two heavy nuclei \Rightarrow Quark-Gluon liquid

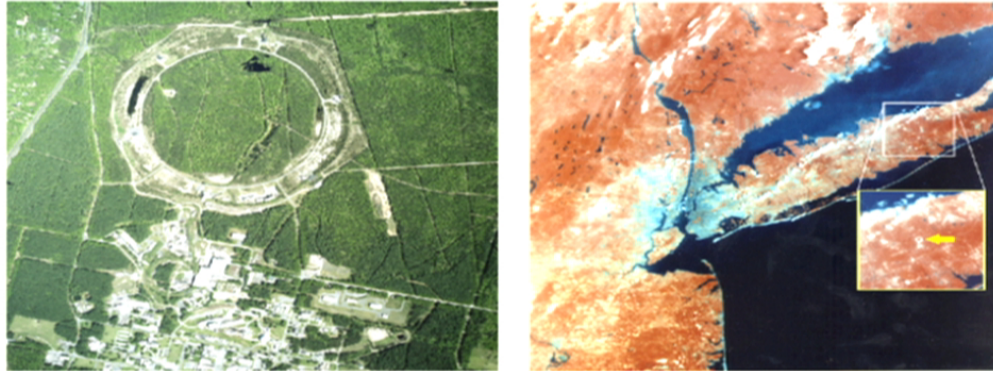
How to make hot subnuclear matter: RHIC



Started in year 2000; collides Au nuclei at $\sqrt{s} = 200\text{GeV}$ per nucleon



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BNL Press Release 2005:

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

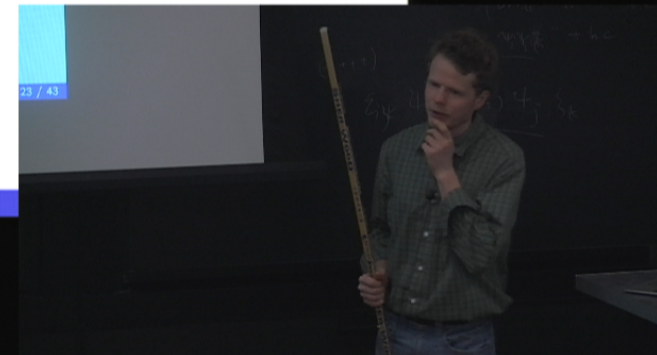
Viscosity of the quark-gluon liquid

Would be nice to use a torsional pendulum...

But unfortunately the temperature $T \gtrsim 10^{12} K$ is too high.

Instead use the relativistic hydro evolution of the initial state

Large uncertainties due to the initial conditions



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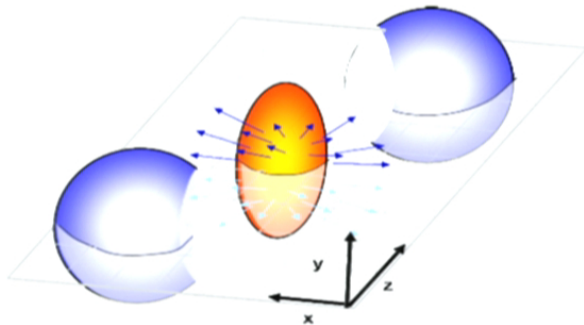
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Luzum+Romatschke, arXiv:0804.4015

$$\frac{\eta}{s} = 0.1 \pm 0.1 (\text{theory}) \pm 0.08 (\text{experiment})$$



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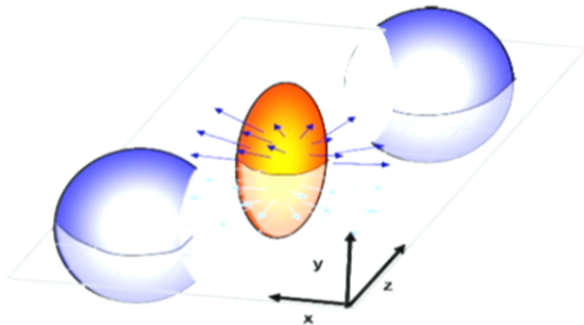
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Perturbative QCD: $\frac{\eta}{s} \gtrsim 1.6$

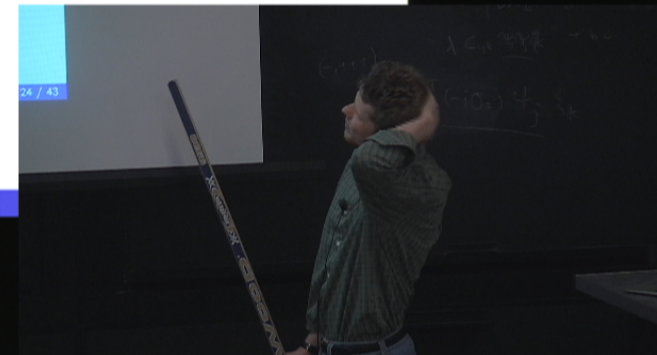
Non-perturbative QCD: **very hard**



Puzzle

- Static thermodynamic properties of the quark-gluon liquid are very close to the ideal gas
- Dynamic flow properties of the quark-gluon liquid are very different from the ideal gas

Need a better theoretical handle for the quark-gluon liquid

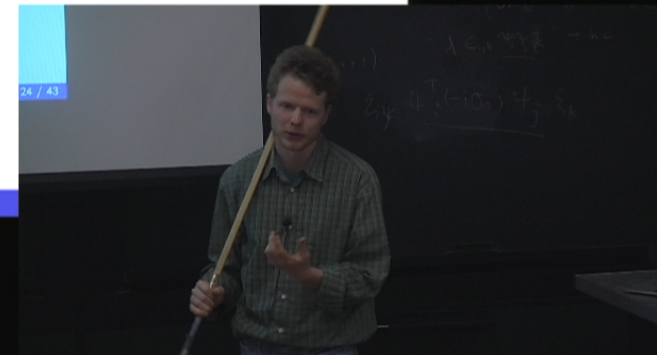


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String theory is big. Really big. You just won't believe how vastly, hugely, mindbogglingly big it is. I mean, you may think it's a long way down the road to the chemist's, but that's just peanuts to string theory. We only need some of the mathematical structures emerging from string theory, not its putative connection to the high-energy physics.

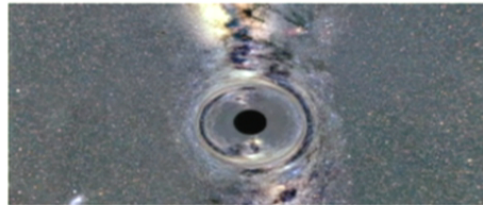
Artists impressions



Modernist



Realist



Physicist

Black hole flight simulator by A. Hamilton

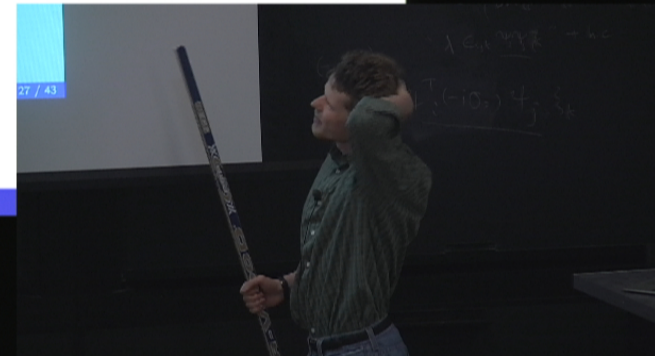
Black holes

- Strongly self-gravitating lumps of spacetime
- Solutions to the Einstein equations of General Relativity
- If stick BH in flat space, measure distance by

$$ds^2 = -f(r)dt^2 + \frac{dr^2}{f(r)} + r^2 d\Omega^2,$$

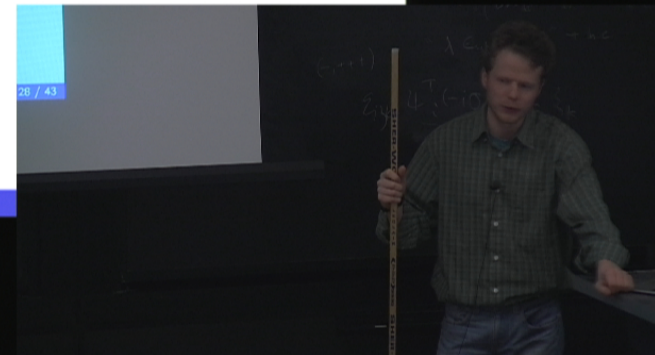
where $f(r) = 1 - 2GM/r$.

Schwarzschild, 1915



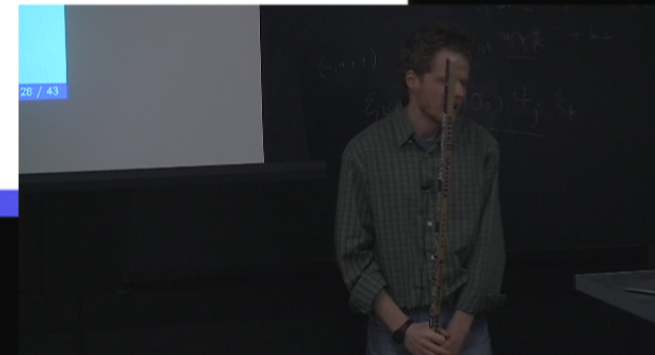
In which sense are BH thermal systems?

- First, “Black hole thermodynamics” does *not* refer to the thermodynamics of hot gas around astrophysical black holes.



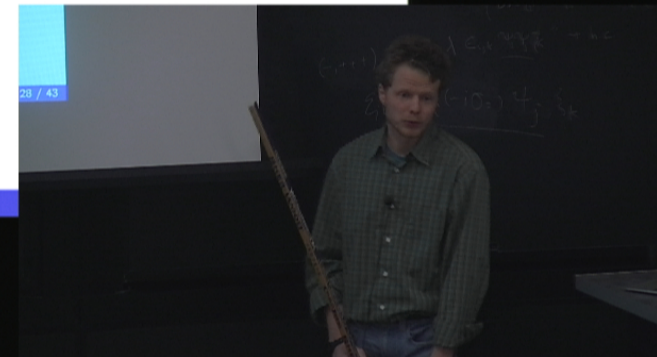
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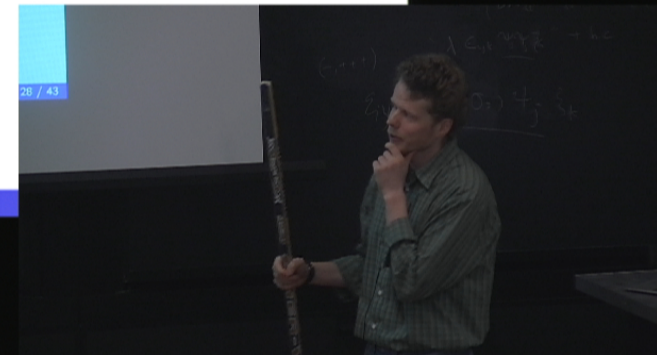
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Bardeen+Carter+Hawking, Bekenstein, 1973



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- For BCH, the black hole thermodynamics was a pure mathematical analogy, but Bekenstein thought there may be something deeper in it...

Funny thermodynamics

The mathematical analogy gives:

- BH stationary state is determined by M , Q , and J (“no hair” theorem)
- Entropy is proportional to the *area*, not to the volume,

$$S = \frac{A}{4G}$$

- Temperature is inversely proportional to the mass,

$$T = \frac{1}{8\pi GM}$$

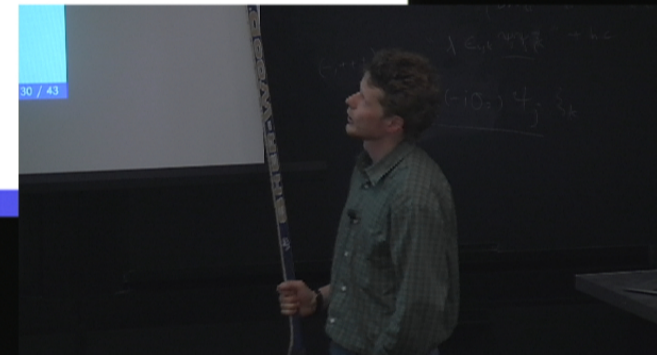
- Hence the heat capacity is negative

Black hole temperature



Hawking kept thinking...
And a couple of years later he showed:

- If there exist particles (photons, electrons,...)
- If Quantum Mechanics is taken into account
- Then the BH will radiate these particles



Black hole temperature



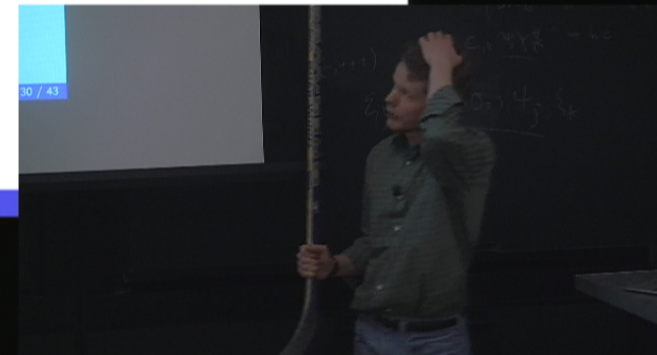
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An observer far away from the black hole will see a gas of particles with

$$T = \frac{\hbar}{8\pi GM}$$

Hawking, 1975



Black hole temperature (2)

So this gives a physical interpretation to the BH temperature...

Note however that thermodynamics of the Hawking radiation is not the same as the black hole thermodynamics

In particular:

- Hawking radiation is a regular black-body radiation
- Its entropy is proportional to the volume, not the area
- It has positive specific heat

The Hawking radiation does not explain the black hole entropy, which is a much harder problem

The BH entropy was more difficult to interpret...

and in fact the complete solution is still not known.

But a partial solution is known



Bekenstein proposed that the BH entropy is to be taken seriously (the generalized second law of thermodynamics)

Bekenstein, 1973



't Hooft proposed that there must be degrees of freedom that live on the surface, accounting for entropy \sim area

't Hooft, 1993

The effort of many people in string theory in the 1990's produced working realizations with strings, branes, and supersymmetry (Polchinski, Strominger, Vafa, Witten, Susskind, Klebanov, Polyakov,...)

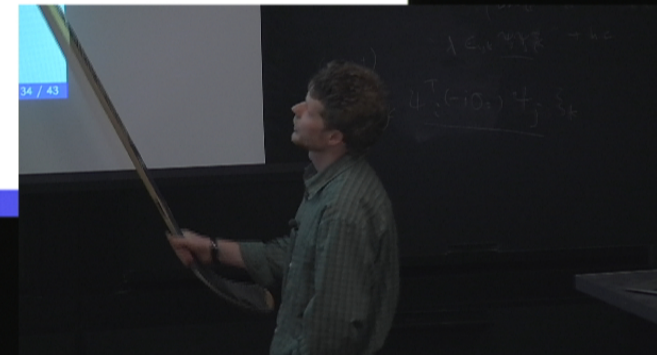
Gauge-gravity duality



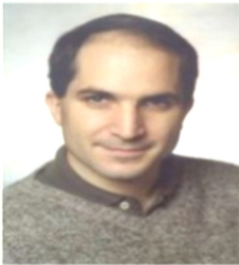
Maldacena proposed that gravity in $4+1$ dim is equivalent to a quantum system in $3+1$ dim, and how you can do it in string theory

Maldacena, 1997

As of 2010, this is 2nd most cited paper of all time in the high-energy physics (1st one is the electroweak unification)



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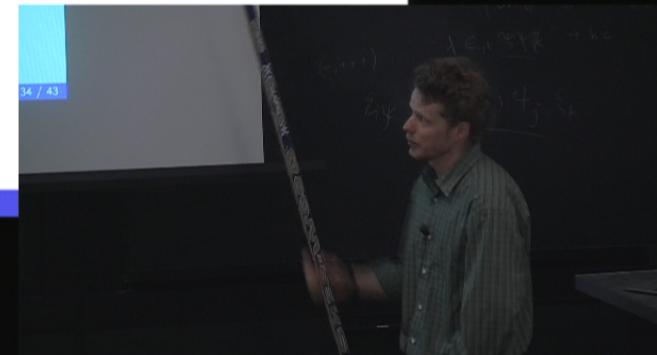
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$$\psi(x) \Leftrightarrow \psi(p)$$



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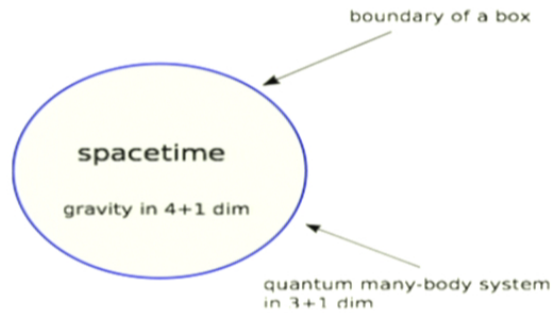
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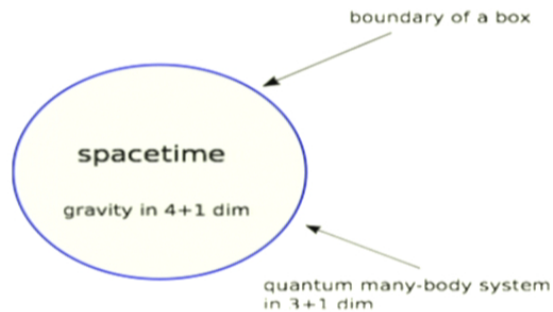
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Classical gravity \Leftrightarrow Quantum Field theory

Basic idea: put gravity in a box



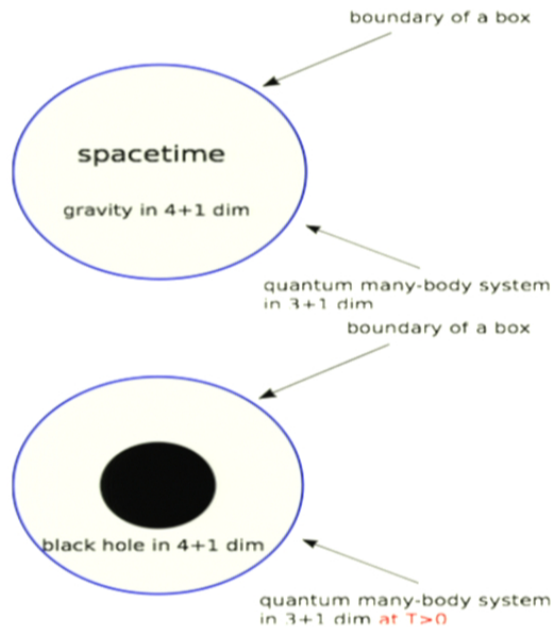
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The box is not made by some kind of matter around the space, but is automatically provided by a special type of dark energy

The curvature of spacetime near the boundary encodes information about the quantum system at the boundary

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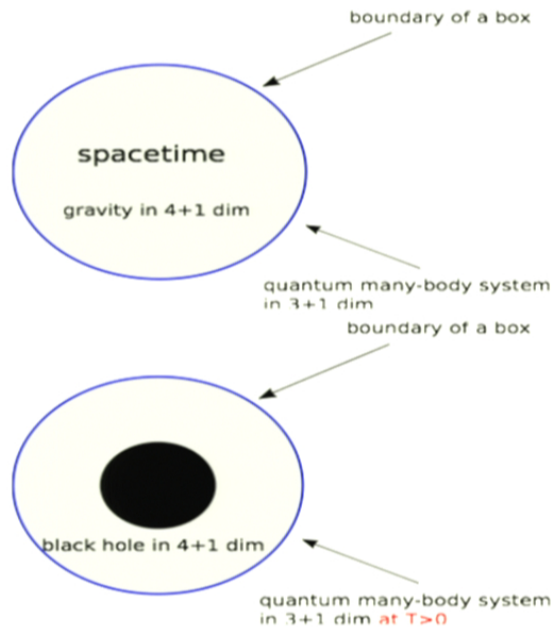


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Placing a BH in the box corresponds to **heating up** the quantum system at the boundary

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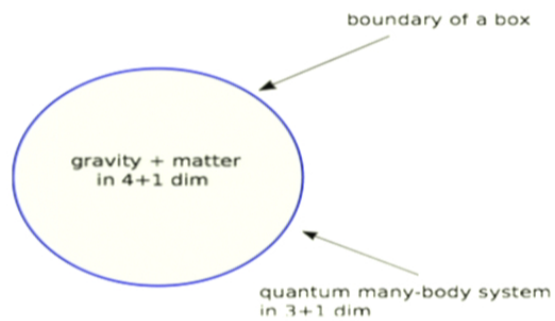
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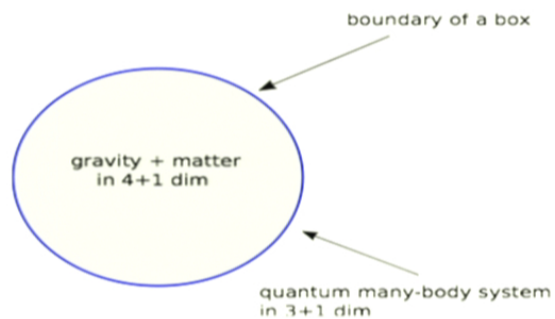
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Entropy of BH in d dim = Entropy of the quantum system in $d-1$ dim

Who lives on the boundary?

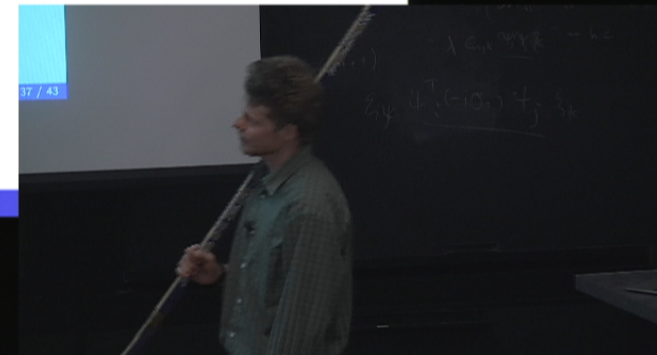


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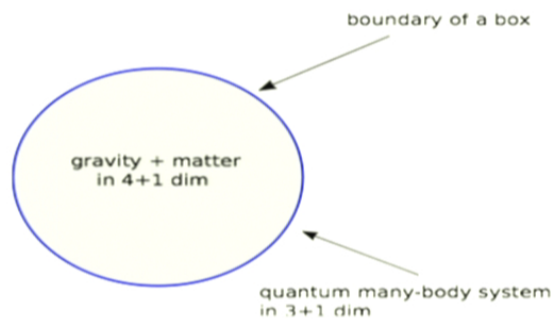


Different types of matter give rise to different Hamiltonians at the boundary

Typically: gluons + quarks + other stuff



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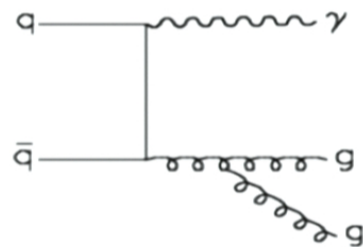


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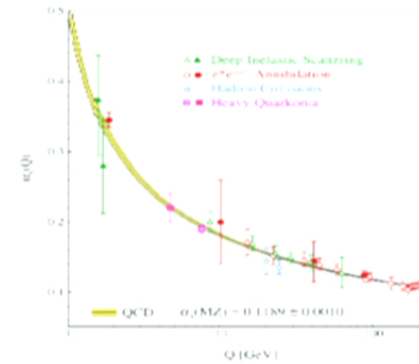
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Prototypical example: $SU(N_c)$ supersymmetric Yang-Mills theory
Many features are similar to Quantum Chromodynamics

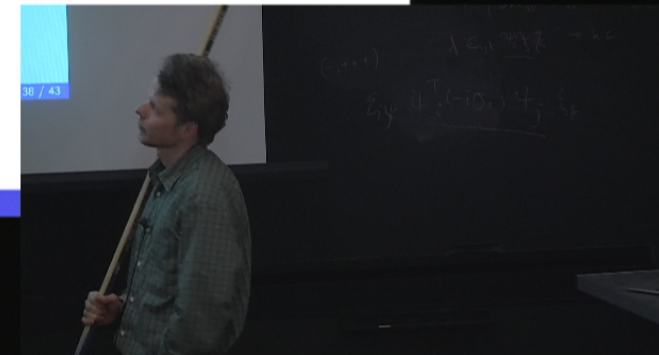
Why is the gauge-gravity duality useful?



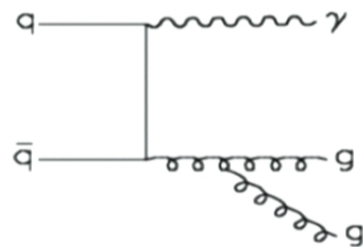
Quarks and gluons can turn into each other



The probability is controlled by a parameter α_s

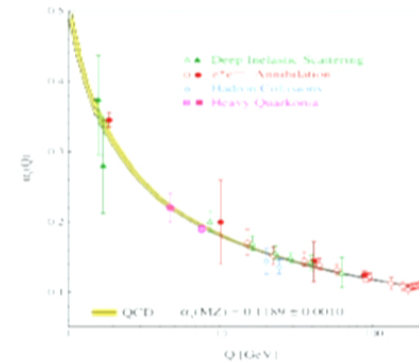


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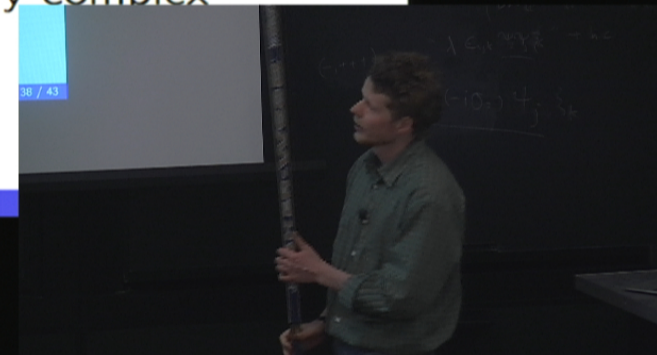


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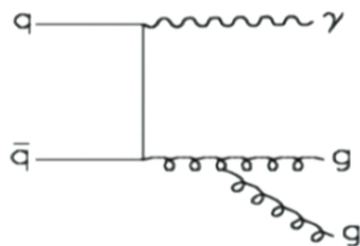
When α_s is large, the quantum system is very complex



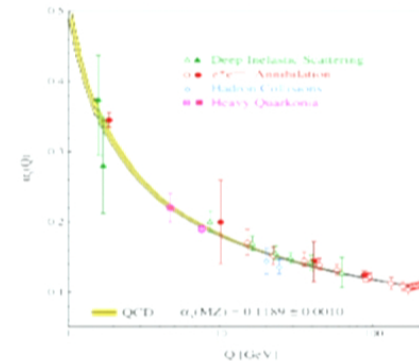
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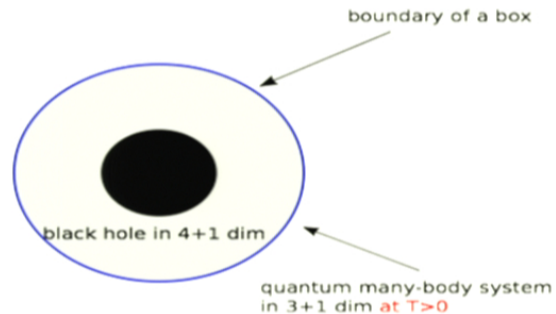
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The duality reduces the problem to classical gravity

Dealing with classical gravity is not easy
But it's peanuts compared to Quantum Chromodynamics

Viscosity of the boundary liquid



- Nudge the black hole a bit
- It will start oscillating
- The disturbance of spacetime propagates to the boundary
- The fluctuations of BH are described by the Navier-Stokes equations

Find: *all* BH described by Einstein gravity give

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

PK+Son+Starinets, 2004

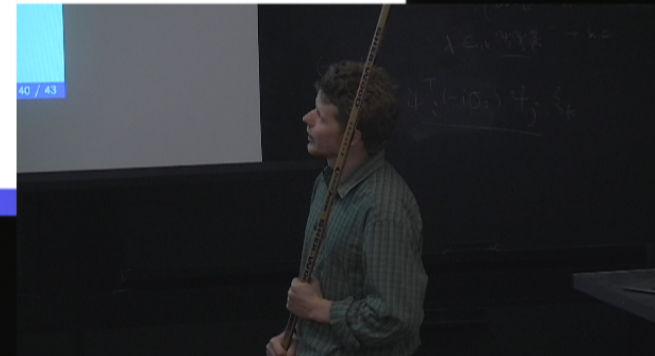
Holography produces a huge variety of strongly interacting quantum liquids, all with $\frac{\eta}{s} = \frac{\hbar}{4\pi} \approx 0.08\hbar$

A lesson

- Recall that if something has kinematic viscosity as small as $\eta/s = \hbar/4\pi$, it can not be a gas of particles, by the Heisenberg uncertainty relation
- But the equation of state is very close to the ideal gas

It is possible to have liquids whose

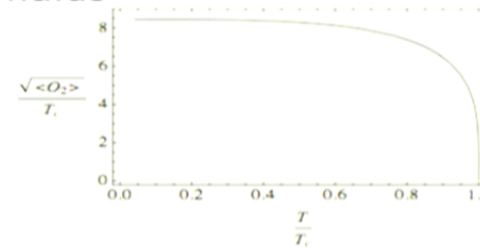
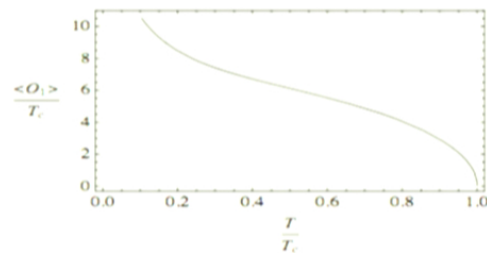
- 1) equation of state is close to the ideal gas
- 2) kinematic viscosity is smaller than any other liquid in nature



These were BH similar to the quark-gluon liquid

Now, are there black holes which behave similar to superfluids, like liquid ^4He below 2.2K?

Yes! These BH (and the dual quantum systems) are called “holographic superconductors” or “holographic superfluids”

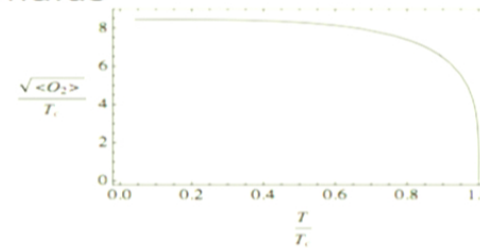
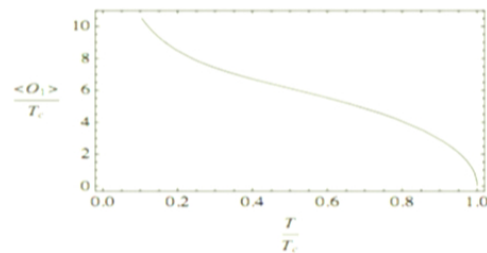


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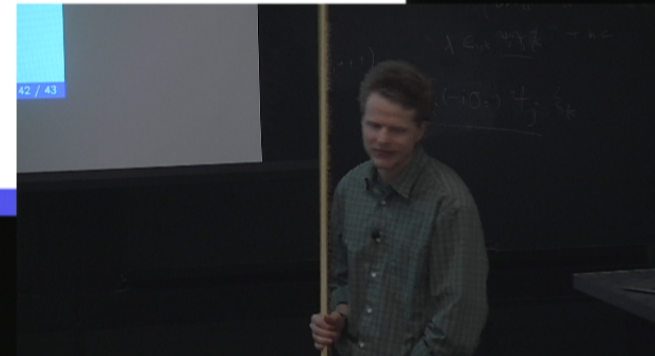


Hartnoll+Herzog+Horowitz, 2008

At $T < T_c$, the black hole in a box develops hair
This appearance of hair corresponds to the superfluid phase transition

Lessons to remember from this talk

- Black hole physics has been useful to learn lessons about strongly interacting quantum liquids
- The connection between black holes and quantum liquids comes from string theory
- The universal relation $\frac{\eta}{s} = \frac{\hbar}{4\pi}$ makes you think seriously that nature dislikes perfect fluidity
- The most perfect fluid found to date is about a billion times hotter than the Sun





HAPPY PLAYING WITH VISCOSITY!

