Title: Researcher Presentation: Pavel Kovtun

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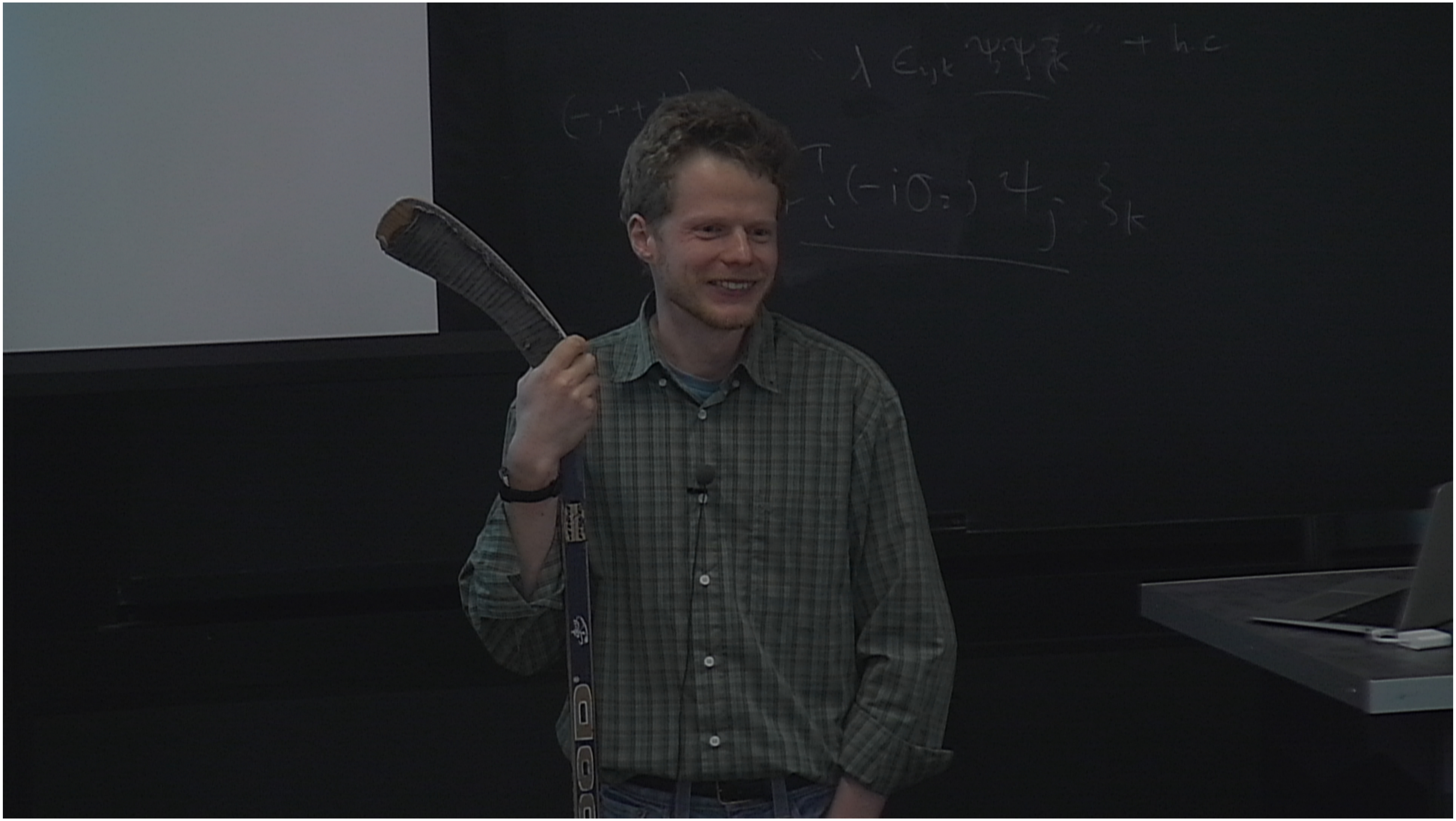
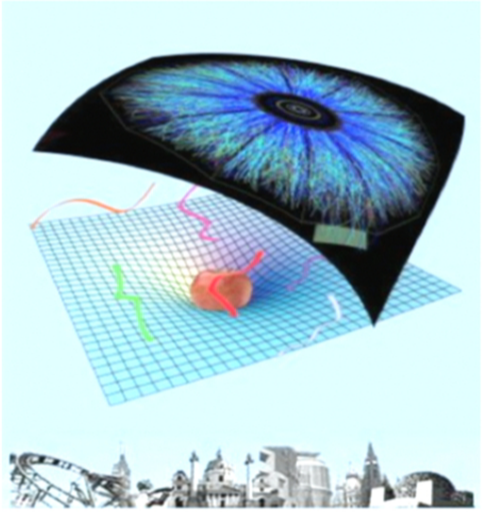
URL: http://pirsa.org/11120044

Abstract:

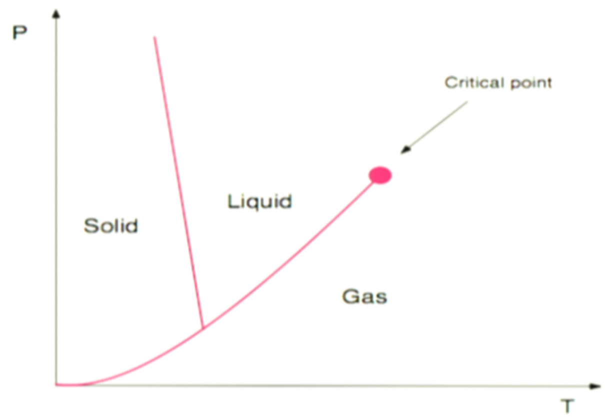


Basic idea

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,
  $T_c = 374°C$, $P_c = 220 P_{\rm atm}$
  $T_3 = 0.01°C$, $P_3 = 0.006 P_{\rm atm}$
- No sharp distinction liquid vs gas

Expect similar equations to describe the flow of liquids and gases

Simple ideal fluids

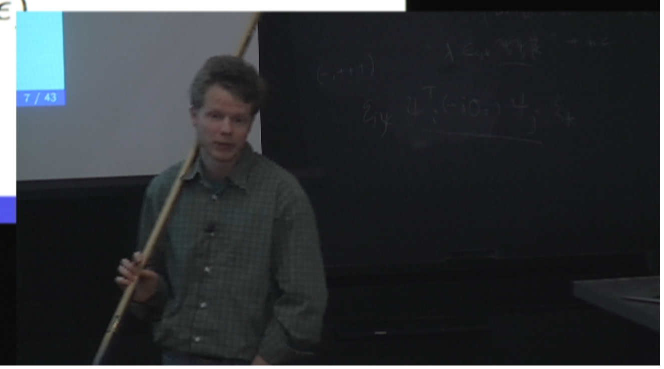
Conservation laws for the fluid (Euler equations)

$$\text{mass}: \quad \partial_t \rho + \partial_i(\rho v_i) = 0\,,$$

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

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

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)

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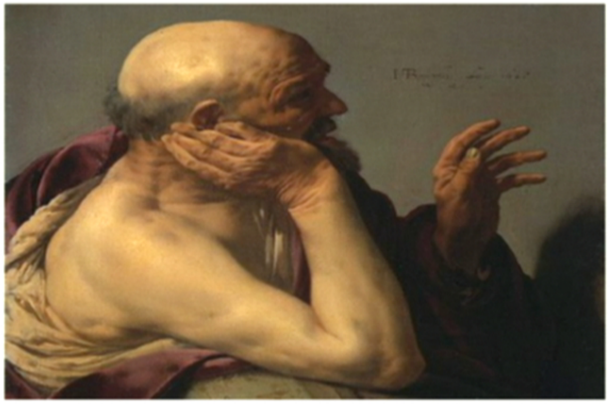
$$\sigma_{ij} = \eta(\partial_i v_j + \partial_j v_i - \frac{2}{3}\delta_{ij}\partial_k v_k) + \zeta \delta_{ij}\partial_k v_k$$

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

η, ζ, κ are responsible for the dissipation

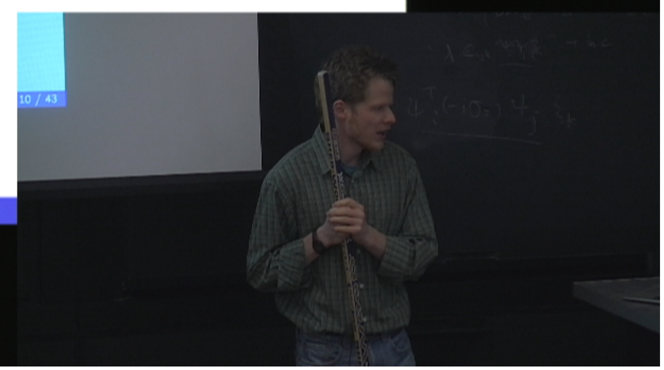
Hydrodynamic equations describe quite a lot



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

The pitch drop experiment (U of Queensland)

- Pitch does not look like it's a liquid

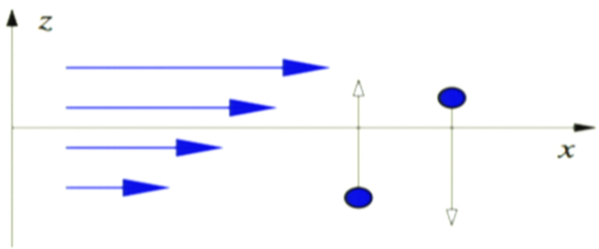


The pitch drop experiment (U of Queensland)

- 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

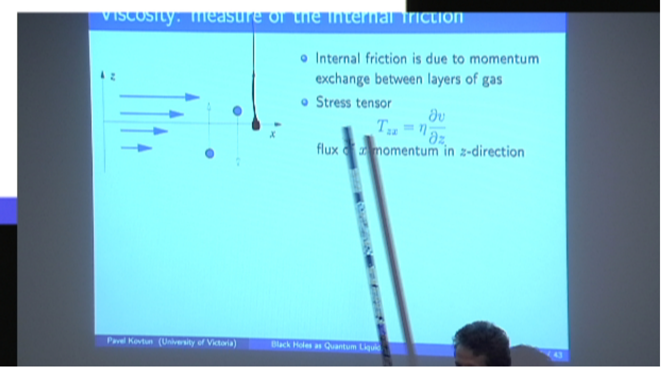
Viscosity: measure of the internal friction



- 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



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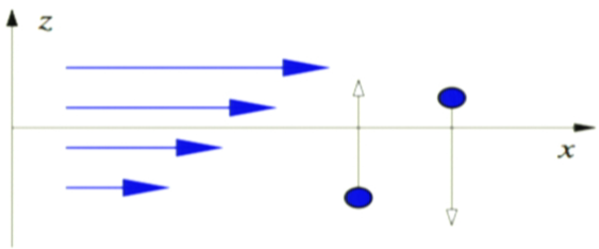

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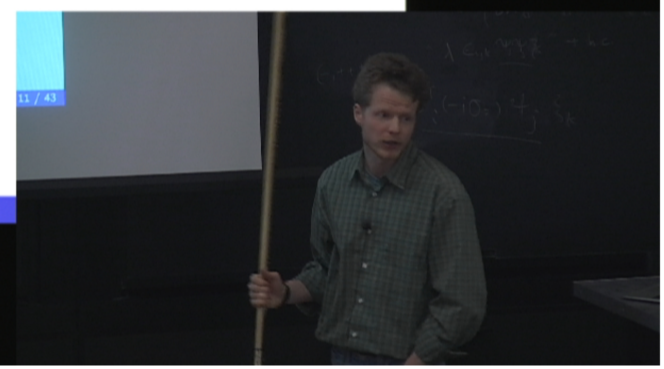
Particle number per unit surface per unit time: $(n v_{\rm th})$
Momentum per unit surface per unit time: $(n v_{\rm th})(m v)$
Flux up: $n v_{\rm th} m (v_0 - l_{\rm mfp} \frac{\partial v}{\partial z})$, flux down: $n v_{\rm th} m (v_0 + l_{\rm mfp} \frac{\partial v}{\partial z})$,
$T_{zx} = \text{flux}_{\rm up} - \text{flux}_{\rm down}$



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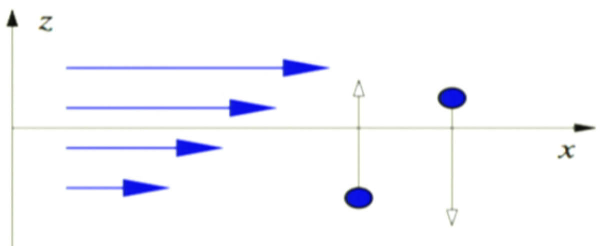

- Internal friction is due to momentum exchange between layers of gas
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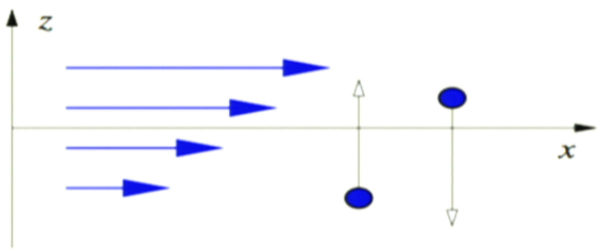
$$T_{zx} = \eta \frac{\partial v}{\partial z}$$
flux of x-momentum in z-direction

Particle number per unit surface per unit time: $(nv_{\rm th})$
Momentum per unit surface per unit time: $(nv_{\rm th})(mv)$
Flux up: $nv_{\rm th}m(v_0 - l_{\rm mfp}\frac{\partial v}{\partial z})$, flux down: $nv_{\rm th}m(v_0 + l_{\rm mfp}\frac{\partial v}{\partial z})$,
$T_{zx} =$ flux$_{\rm up}$ - flux$_{\rm down}$

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

Viscosity: measure of the internal friction



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$$\therefore \ \eta \sim n v_{\rm th} m l_{\rm mfp} \sim \frac{m v_{\rm th}}{\sigma} \sim \frac{(mT)^{1/2}}{\sigma}$$

This was derived by Maxwell is 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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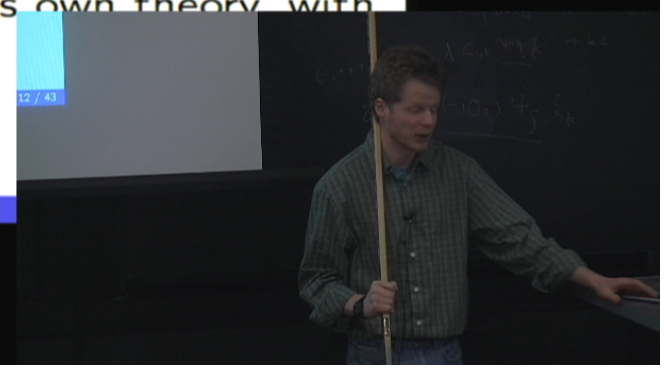

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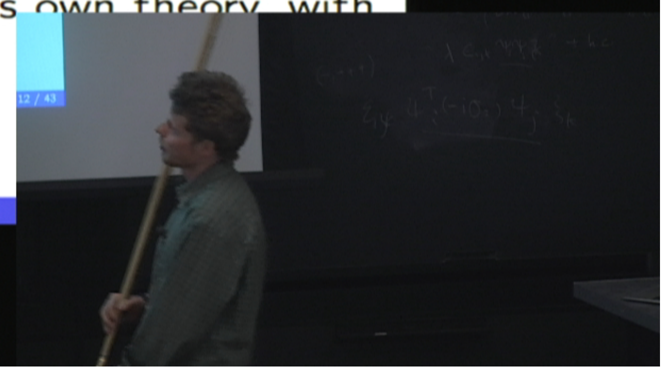

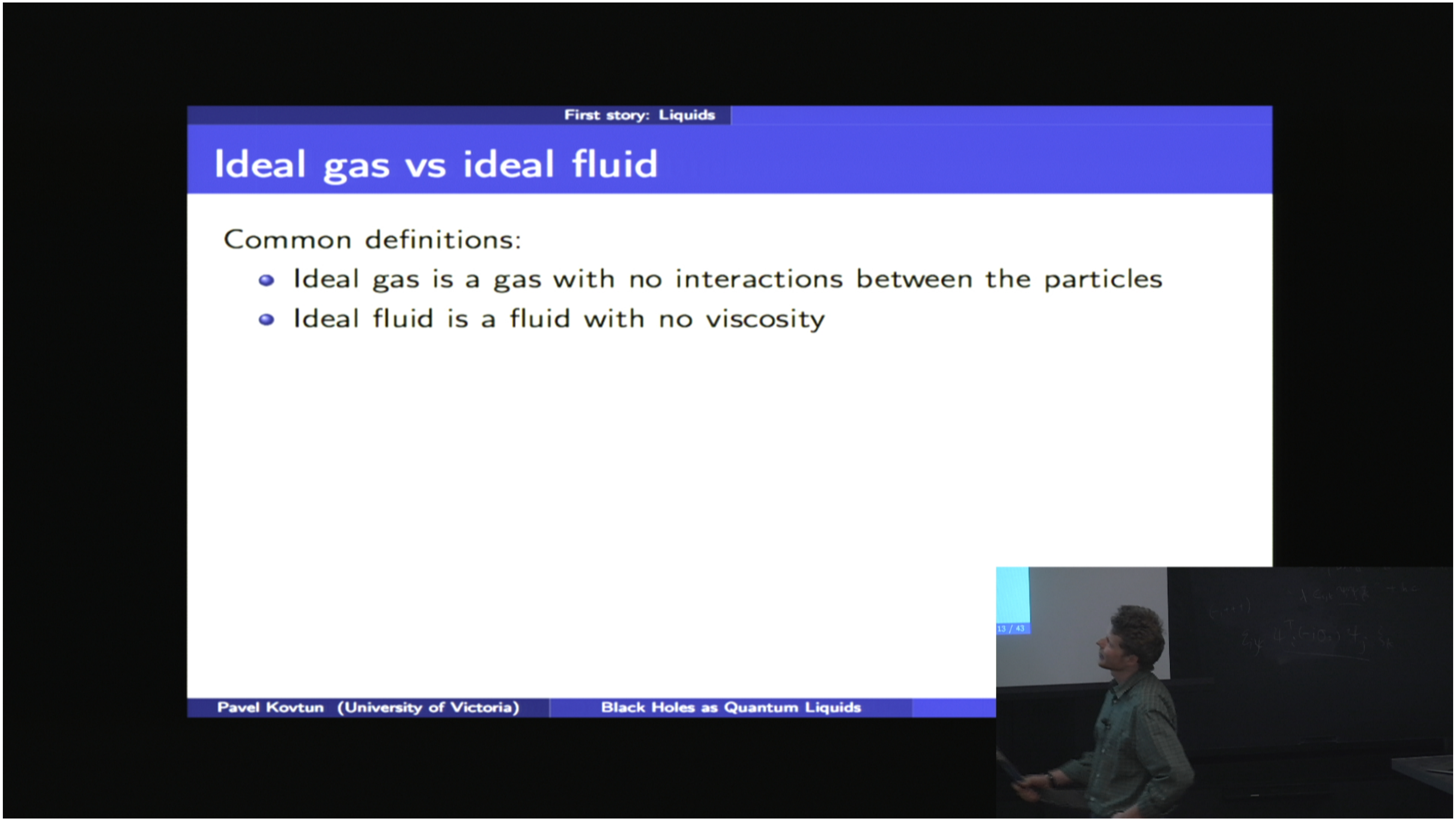
First story: Liquids
Ideal gas vs ideal fluid
Common definitions:
Ideal gas is a gas with no interactions between the particles
Ideal fluid is a fluid with no viscosity
Pavel Kovtun (University of Victoria)
Black Holes as Quantum Liquids

Ideal gas vs ideal fluid

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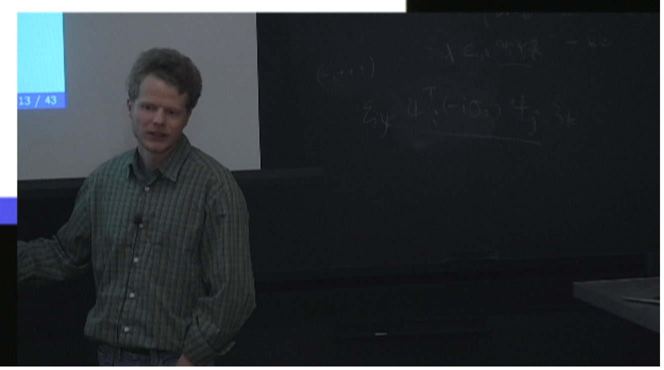
Remember,

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

- Ideal gas has infinite viscosity ($\sigma = 0$)
- Near-ideal gas has huge viscosity ($\sigma \to 0$)



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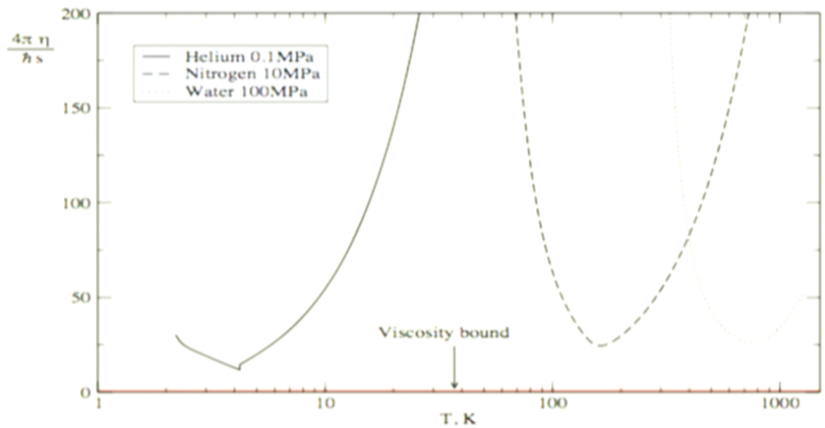
Ideal gas behaves as a very non-ideal fluid!

Range of viscosities

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



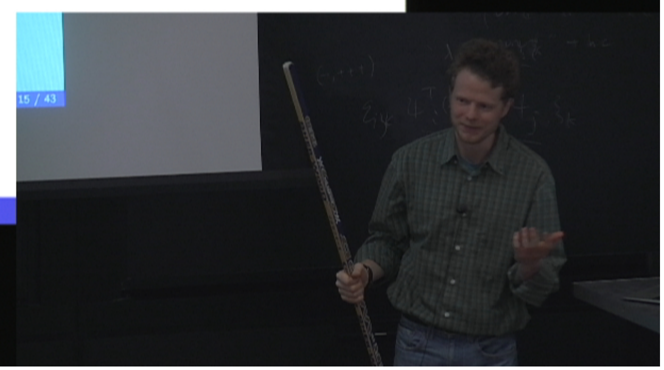
Glycerine at $P = P_{\rm atm}$:
$\eta(T{=}0°C) = 12070$ mPa s
$\eta(T{=}100°C) = 14.8$ mPa s

Water at $P = P_{\rm atm}$:
$\eta(T{=}0°C) = 1.8$ mPa s
$\eta(T{=}100°C) = 0.28$ mPa s

Purcell's question to Weisskopf

Life at low Reynolds number

E. M. Purcell



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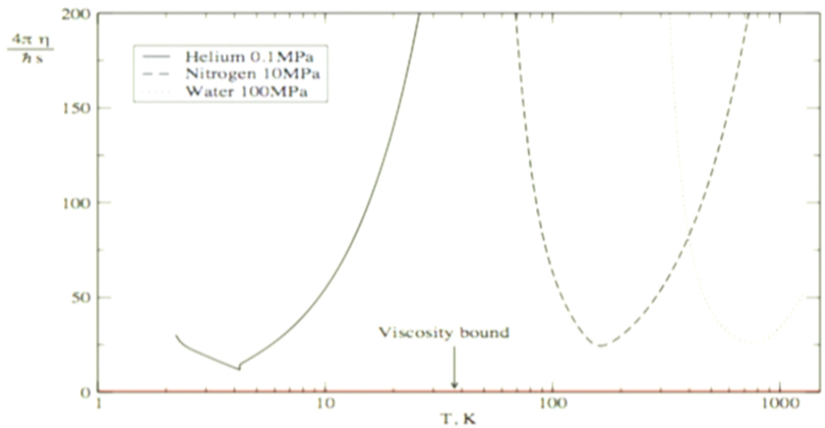

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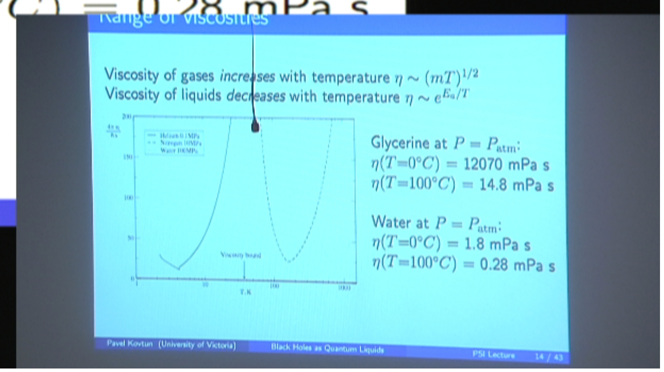

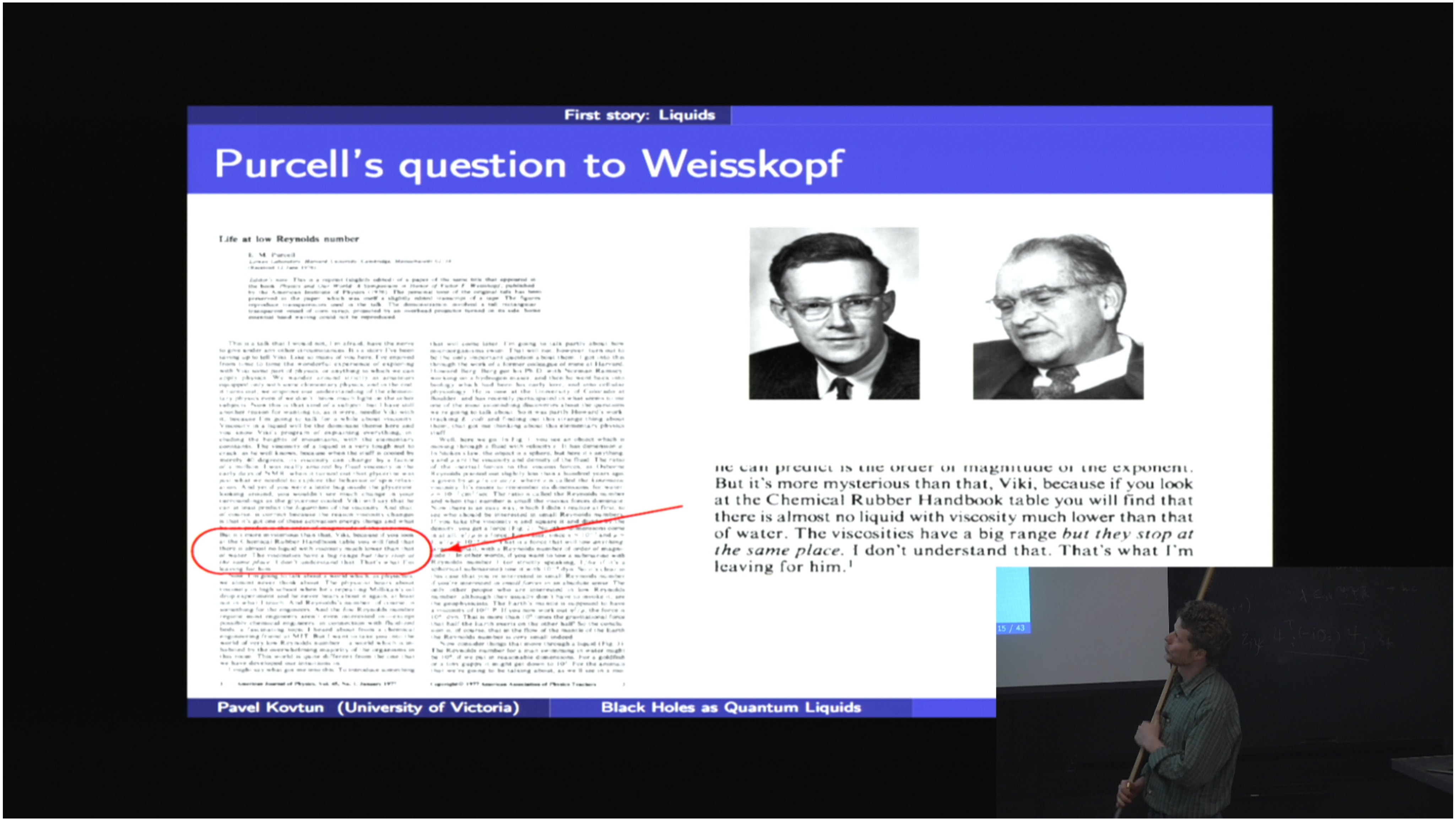

First story: Liquids
Purcell's question to Weisskopf
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E. M. Purcell
he can predict is the order of magnitude of the exponent. But it's more mysterious than that, Viki, because if you look at the Chemical Rubber Handbook table you will find that there 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]
Pavel Kovtun (University of Victoria)
Black Holes as Quantum Liquids

How small can viscosity be?

"Viscosity per particle" η/n, where $n =$ number density

On the gas side:

$$\frac{\eta}{n} \sim \frac{m n v_{\rm th} l_{\rm mfp}}{n} = l_{\rm mfp}\, m v_{\rm th} \gtrsim \hbar$$

otherwise point particle not well defined

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Two lessons:

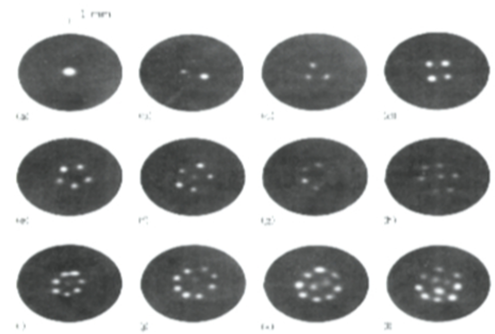
- This suggests that the Heisenberg uncertainty relation prevents the existence of ideal fluids in nature
- Strongly interacting quantum liquids are likely to be the most ideal liquids in nature

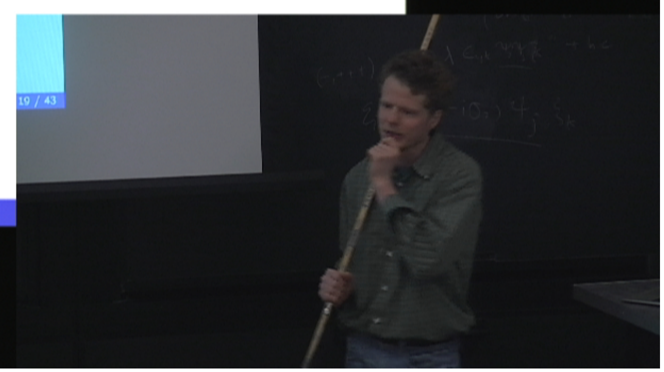
PK+Son+Starinets, 2004

Different types of quantum liquids

Different types of quantum liquids

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





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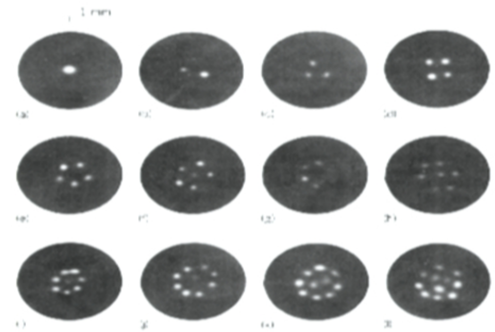
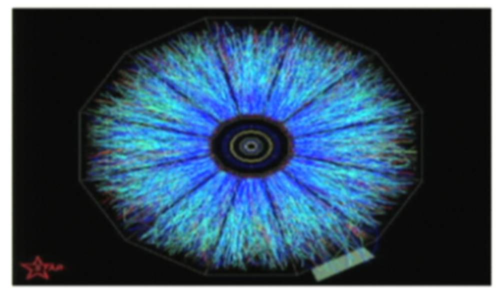


Quantum effects produce extremely low viscosity in normal fluids. These were discovered recently when studying very hot ($T \gtrsim 10^{12}K$) gases of subnuclear particles.

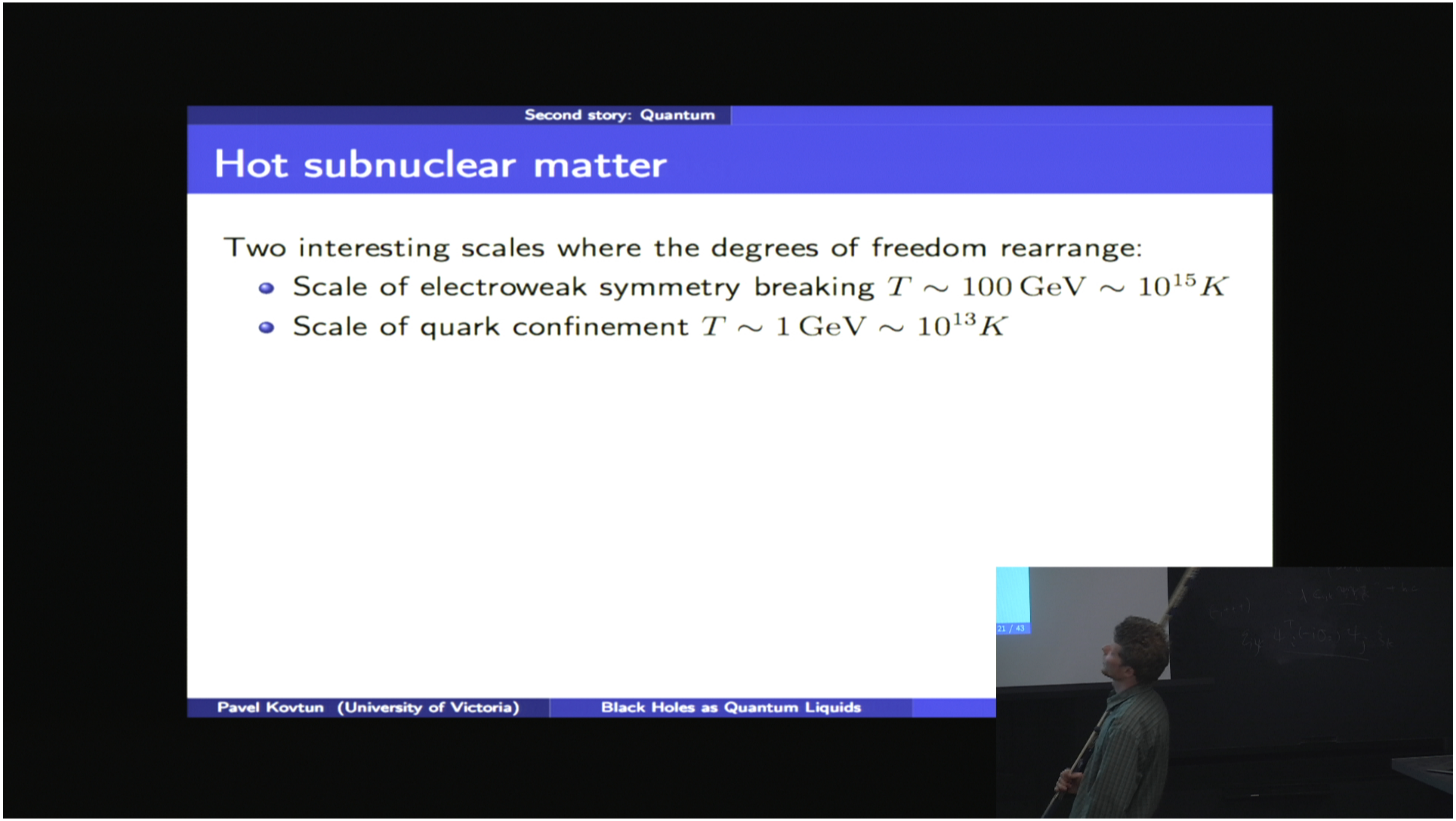


Superfluids

- Spontaneous breaking of particle number symmetry $\Psi \to \Psi\, e^{i\alpha}$
- 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


Second story: Quantum
Hot subnuclear matter
Two interesting scales where the degrees of freedom rearrange:
Scale of electroweak symmetry breaking $T \sim 100\,\mathrm{GeV} \sim 10^{15} K$
Scale of quark confinement $T \sim 1\,\mathrm{GeV} \sim 10^{13} K$
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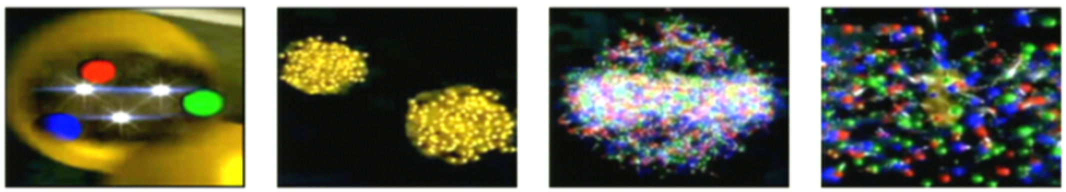
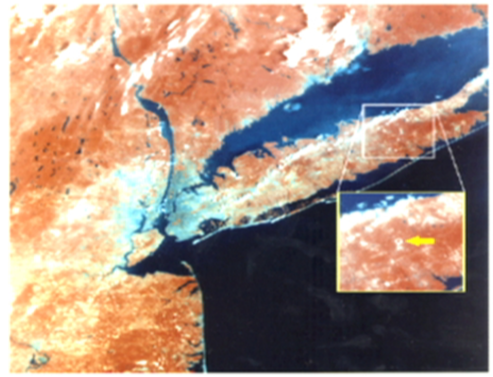
Protons, neutrons $\Rightarrow$ Quarks $+$ Gluons

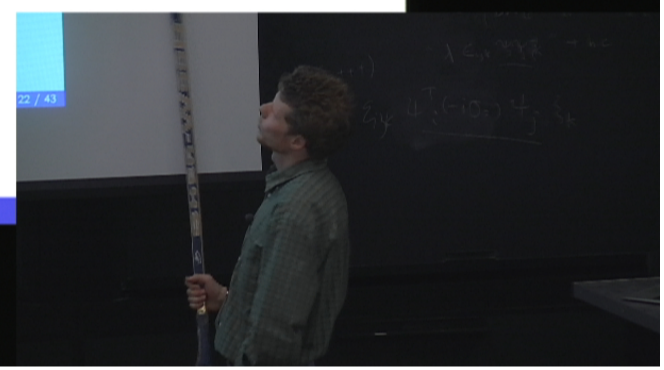


Collide two heavy nuclei $\Rightarrow$ Quark-Gluon liquid

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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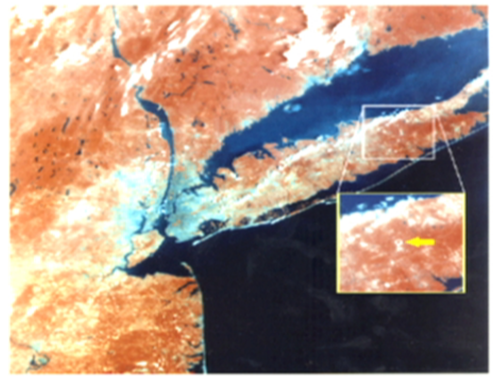

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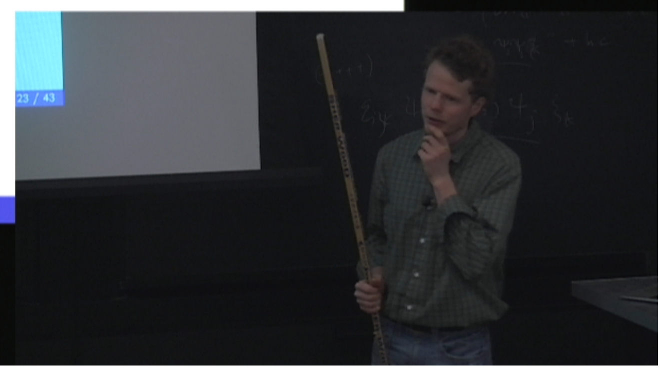
BNL Press Release 2005:

> *...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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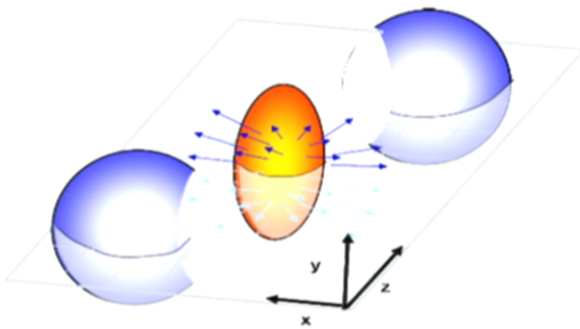
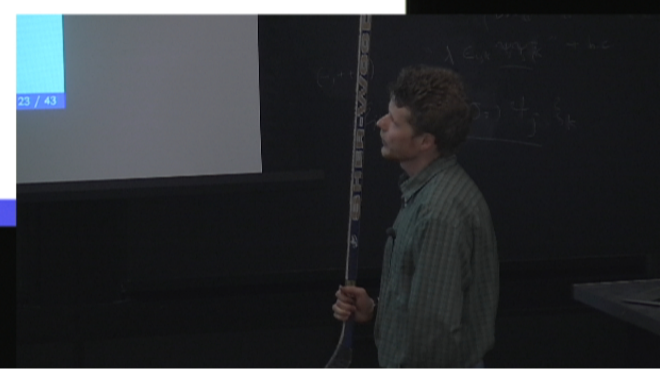


Hydro simulations:

Luzum+Romatschke, arXiv:0804.4015

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



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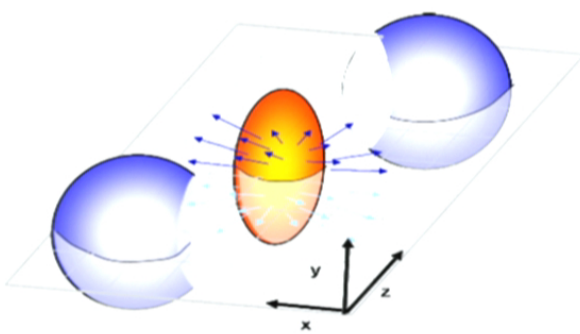

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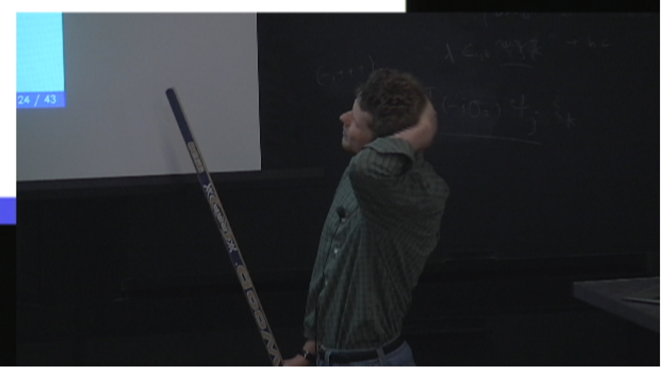
Perturbative QCD: $\frac{\eta}{s} \gtrsim 1.6$

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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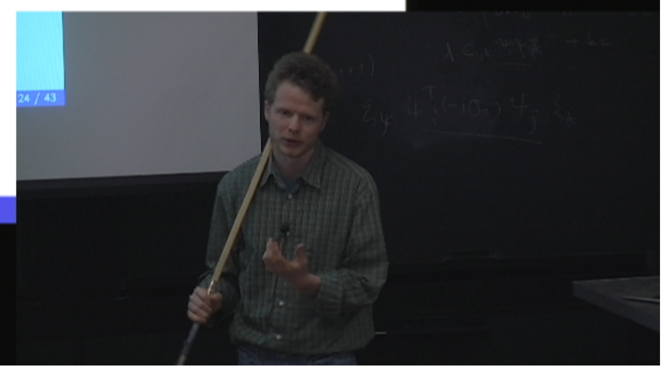
Wait... isn't string theory only supposed to be relevant at very-very high energies $E_{\text{Planck}} \sim 10^{19}\text{GeV}$?



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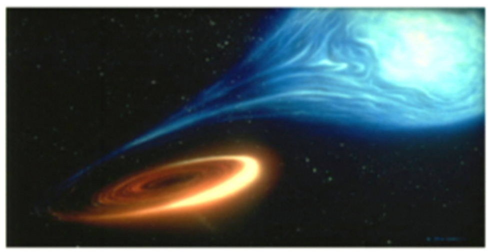
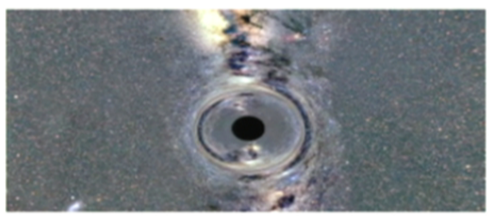
Artists impressions

Modernist



Realist



Physicist

Black hole flight simulator by A.Hamilton

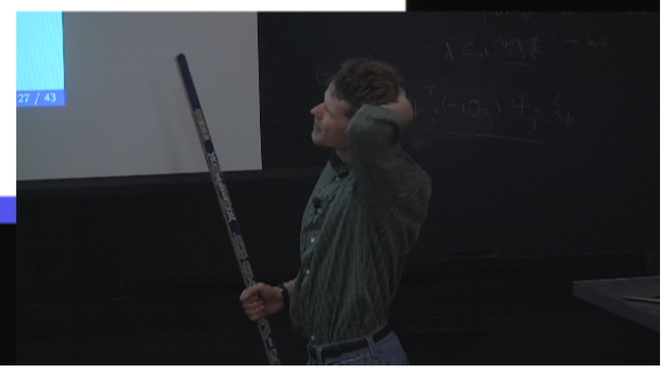
Black holes

- 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



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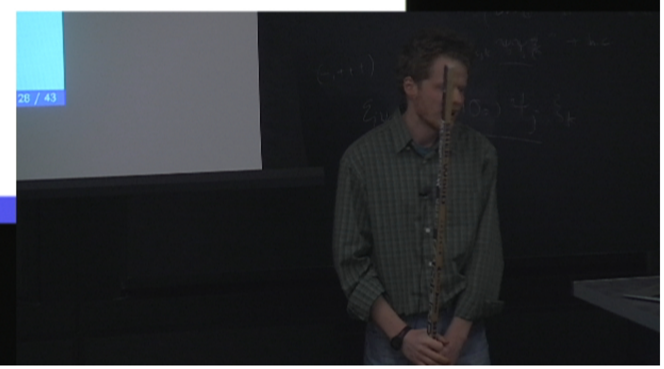

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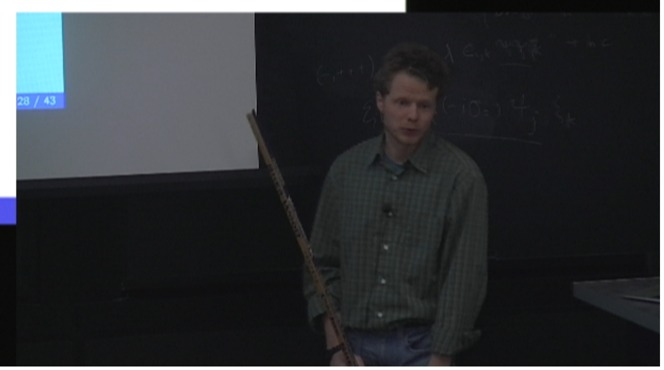

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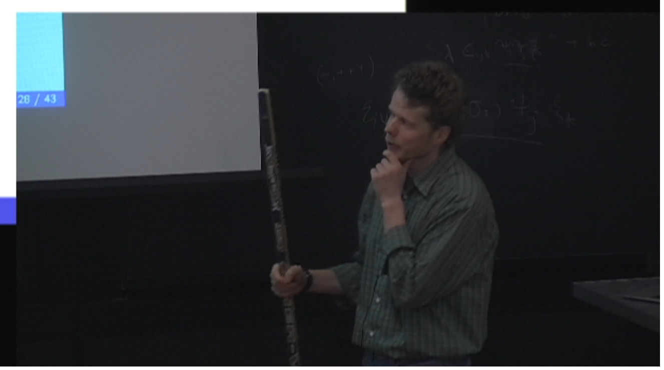
- This was only found in 1970's, many years after the original Schwarzschild solution

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:

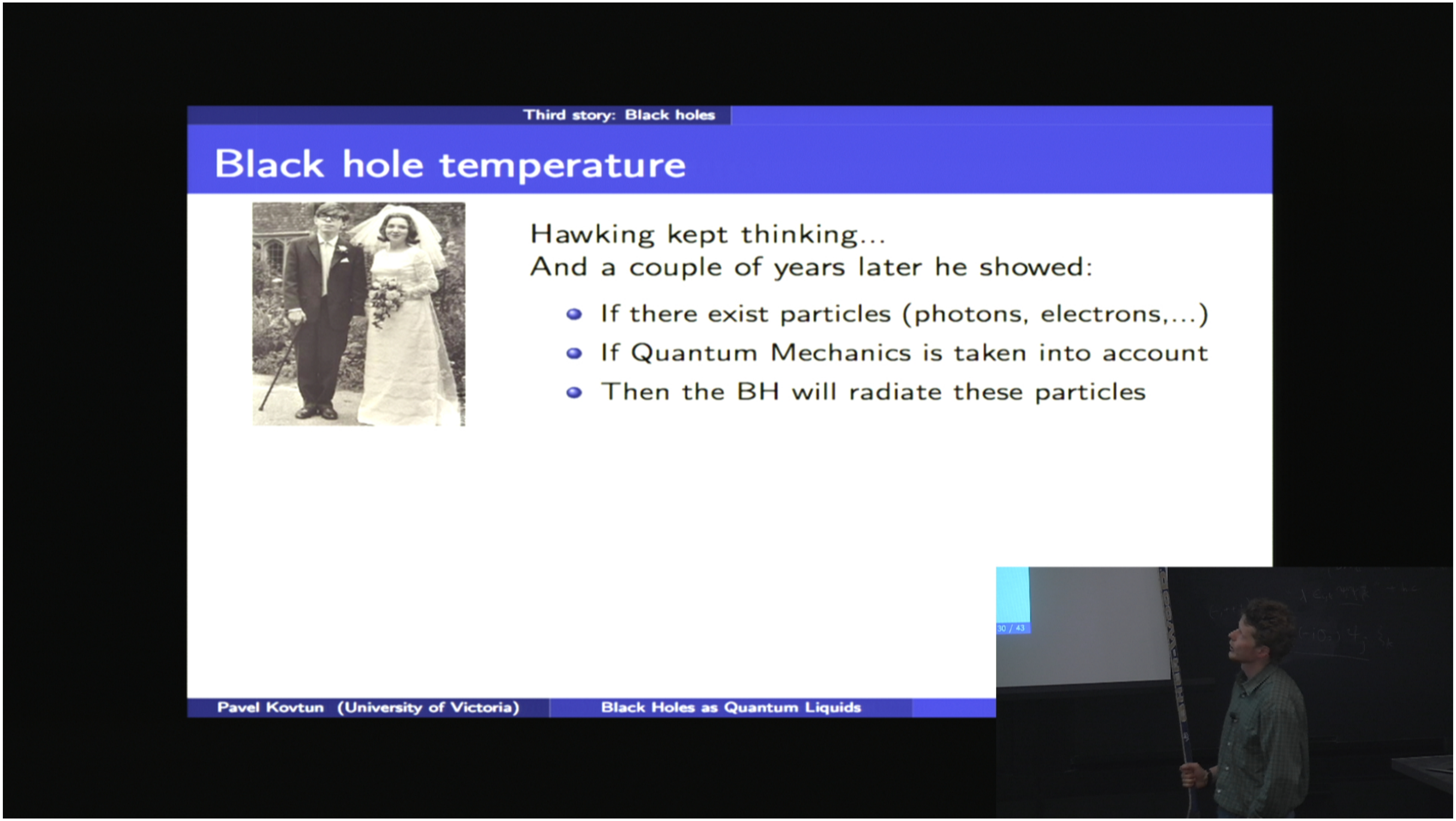
- BH stationary state is determined by M, Q, and J ("no hair" theorem)
- Entropy is proportional to the *area*, not to the volume,

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

- Temperature is inversely proportional to the mass,

$$T = \frac{1}{8\pi G M}$$

- Hence the heat capacity is negative


Third story: Black holes
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
Pavel Kovtun (University of Victoria)
Black Holes as Quantum Liquids

Black hole temperature

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And a couple of years later he showed:

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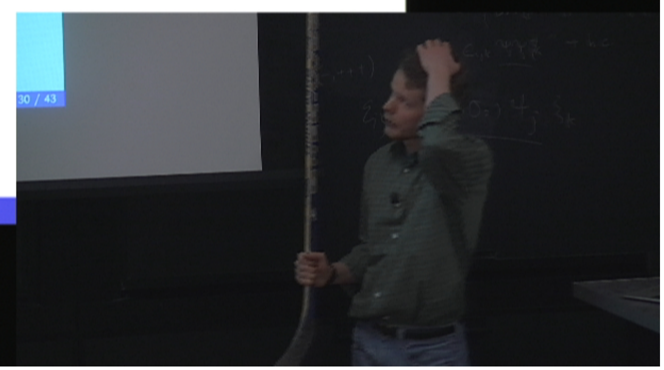
- Then the BH will radiate these particles

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

$$T = \frac{\hbar}{8\pi G M}$$

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

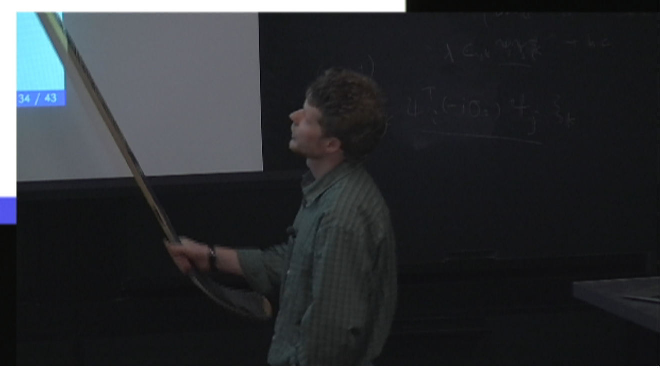
't Hooft proposed that there must be degrees of freedom that live on the surface, accounting for entropy $\sim$ area 't Hooft, 1993

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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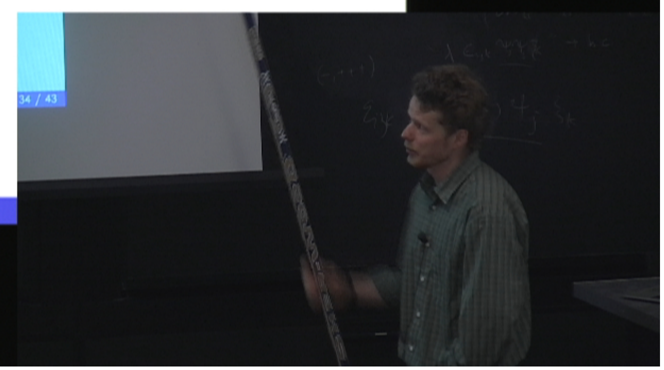
This relation is a *duality*, analogous to position-space wf vs momentum-space wf in Quantum Mechanics

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



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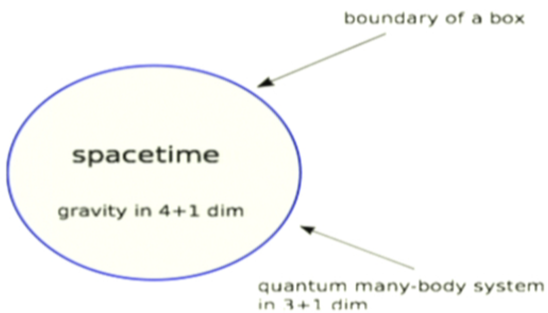
Classical gravity $\Leftrightarrow$ Quantum Field theory

Basic idea: put gravity in a box



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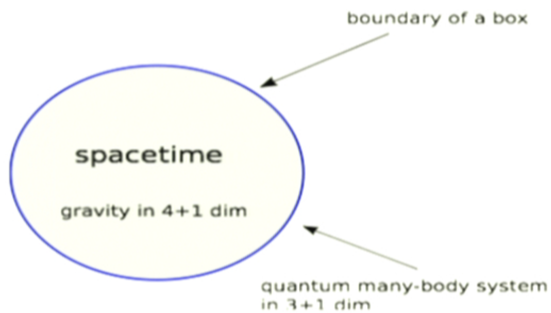

The box is not made by some kind of matter around the space, but is automatically provided by a special type of dark energy

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

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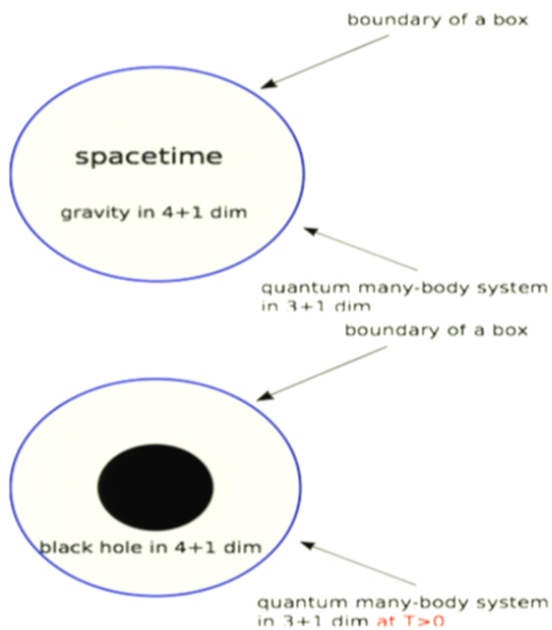

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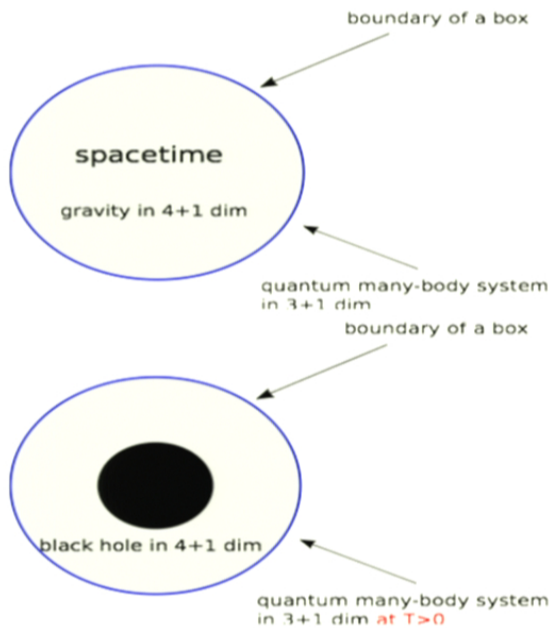

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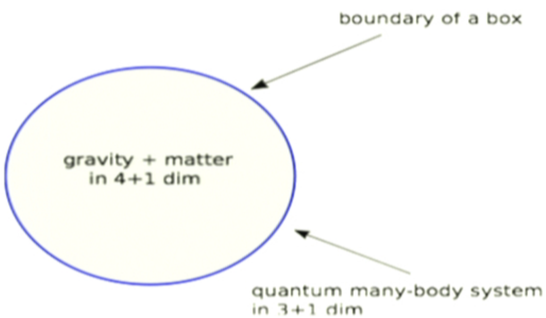
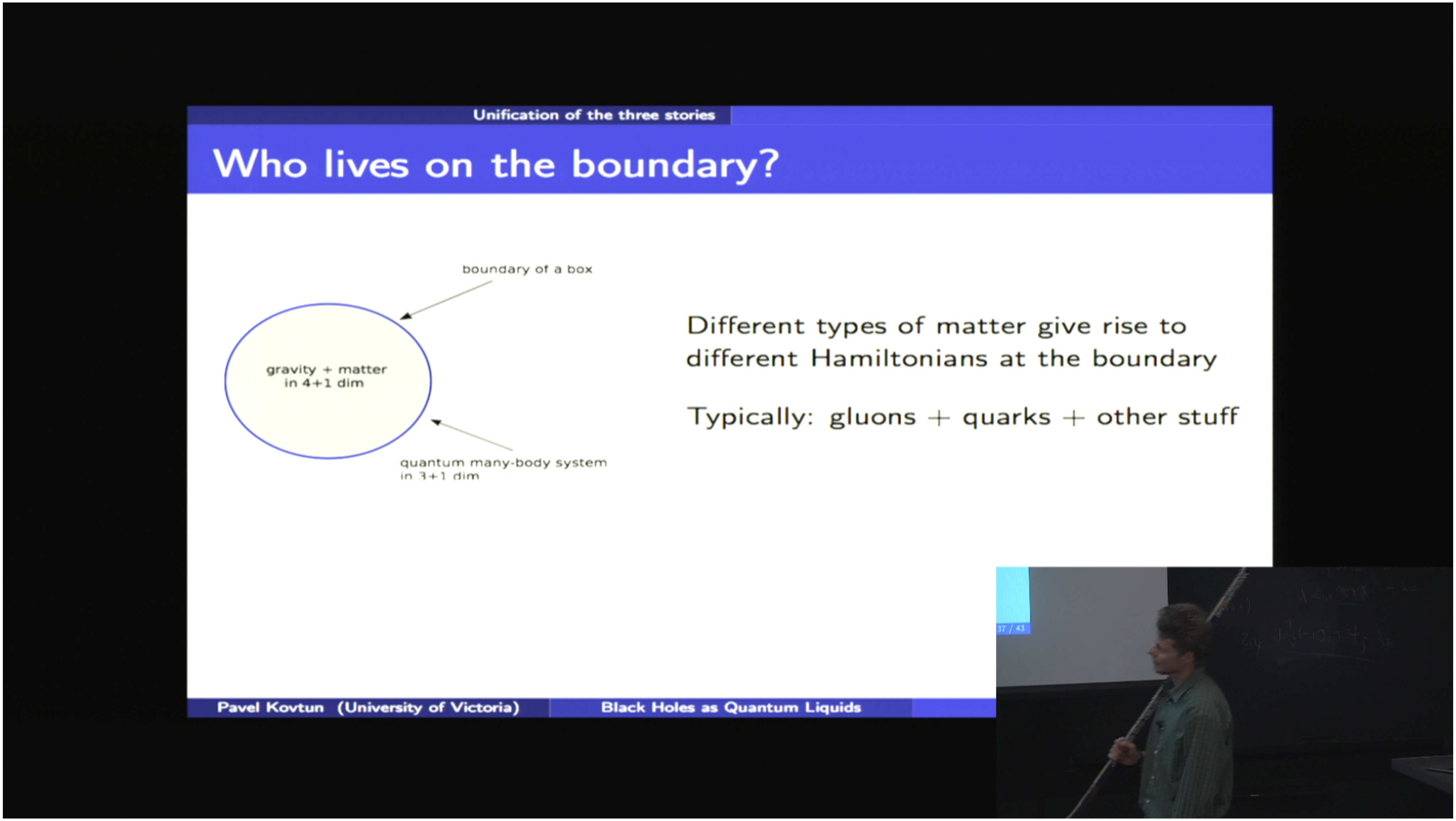
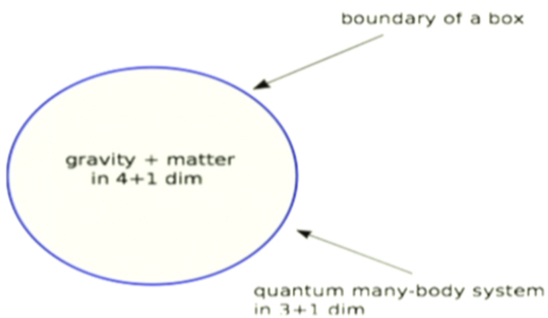
Entropy of BH in d dim = Entropy of the quantum system in $d-1$ dim

Who lives on the boundary?




Unification of the three stories
Who lives on the boundary?
boundary of a box
gravity + matter
in 4+1 dim
quantum many-body system
in 3+1 dim
Different types of matter give rise to
different Hamiltonians at the boundary
Typically: gluons + quarks + other stuff
Pavel Kovtun (University of Victoria)
Black Holes as Quantum Liquids

Who lives on the boundary?



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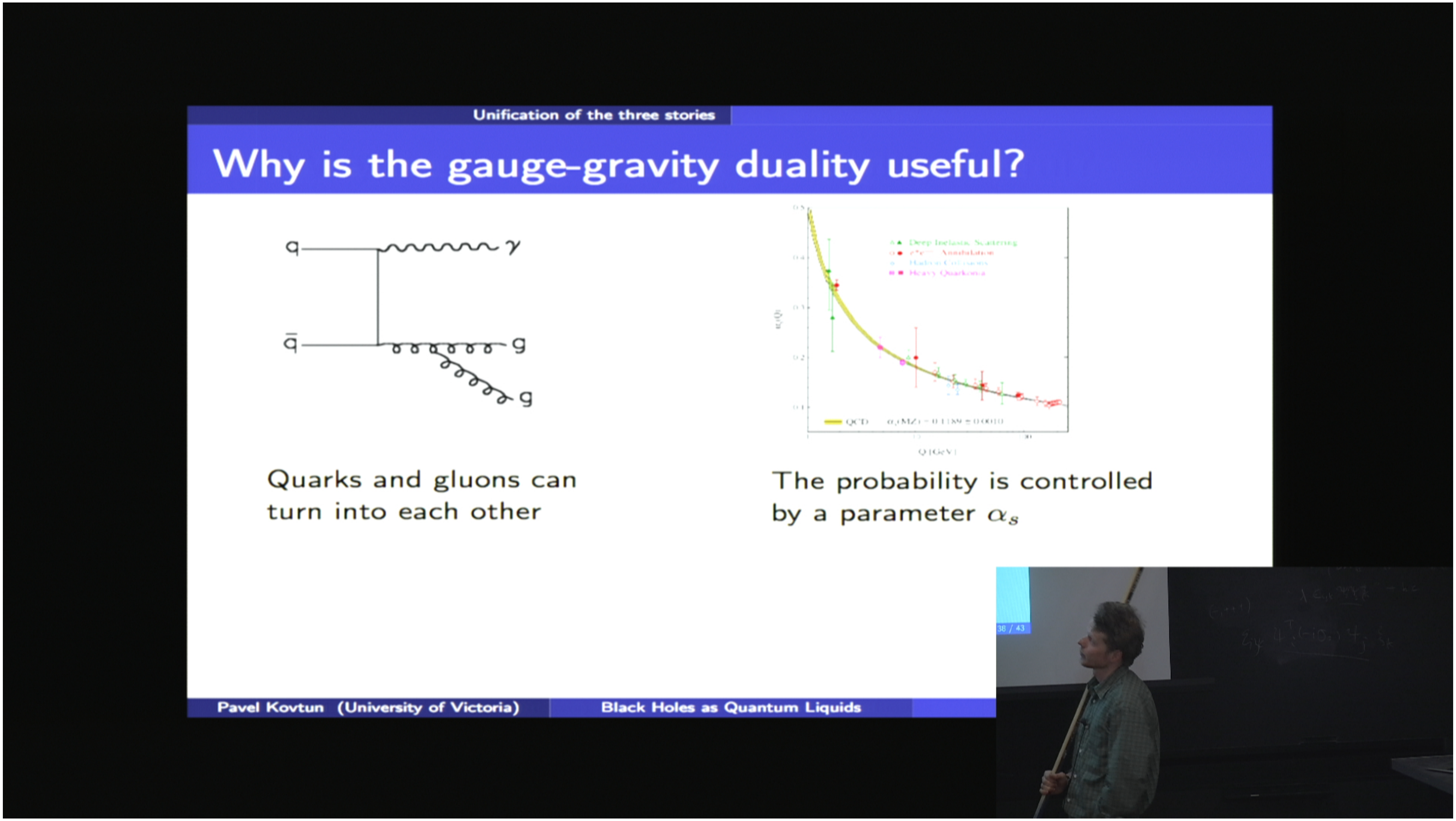
Prototypical example: $SU(N_c)$ supersymmetric Yang-Mills theory
Many features are similar to Quantum Chromodynamics


Unification of the three stories
Why is the gauge-gravity duality useful?
q
γ
$\bar{q}$
g
g
Quarks and gluons can turn into each other
The probability is controlled by a parameter α_s
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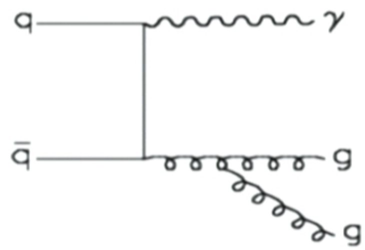
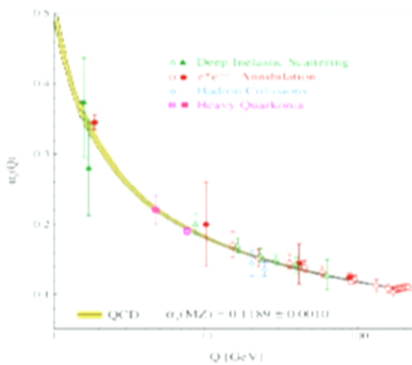
Why is the gauge-gravity duality useful?

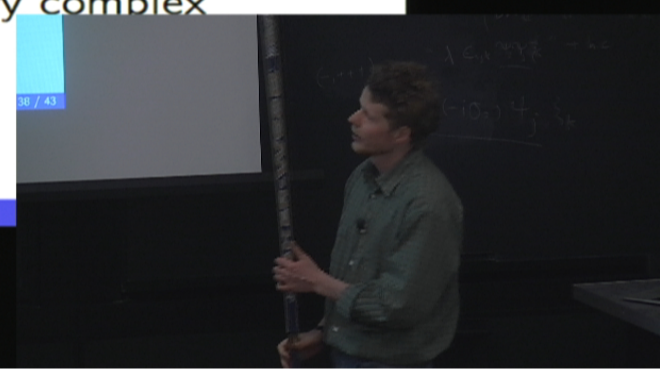




Quarks and gluons can turn into each other

The probability is controlled by a parameter α_s

When α_s is large, the quantum system is very complex



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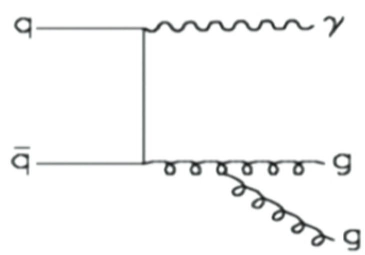

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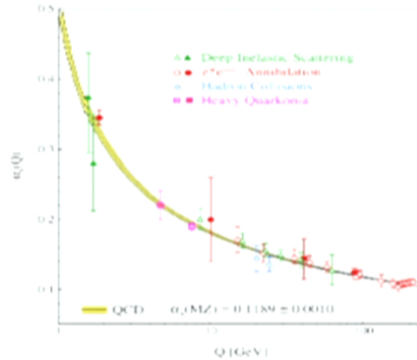

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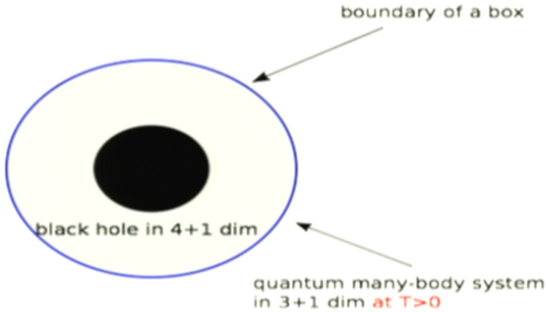
The duality reduces the problem to classical gravity
Dealing with classical gravity is not easy
But it's peanuts compared to Quantum Chromodynamics

Viscosity of the boundary liquid



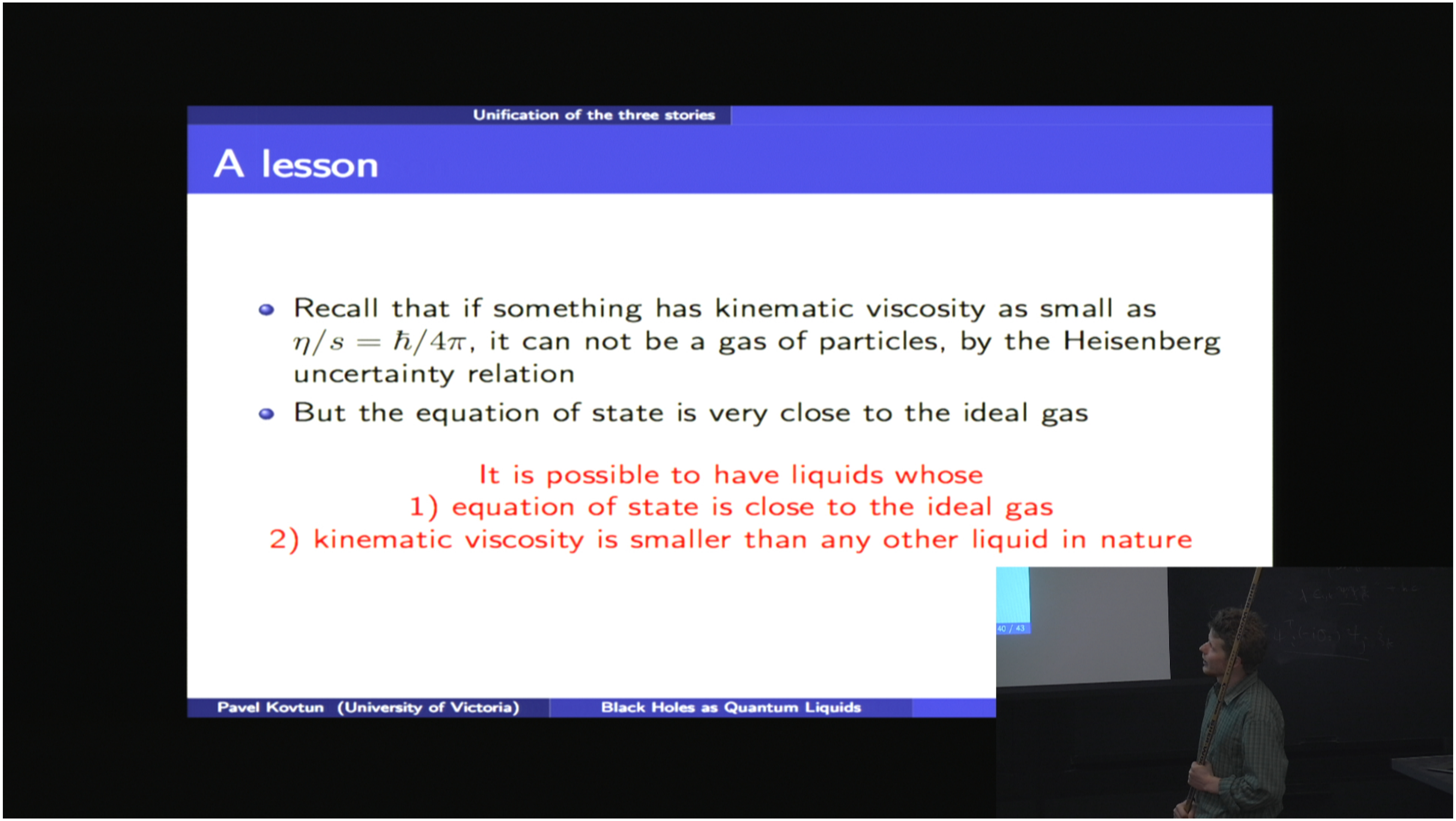
- Nudge the black hole a bit
- It will start oscillating
- The disturbance of spacetime propagates to the boundary
- The fluctuations of BH are described by the Navier-Stokes equations

Find: *all* BH described by Einstein gravity give

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

PK+Son+Starinets, 2004

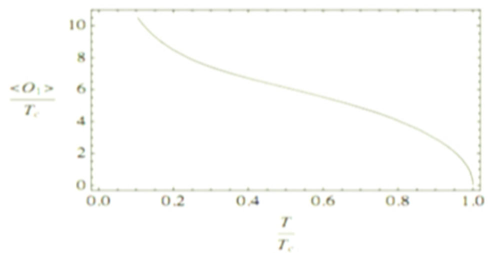
Holography produces a huge variety of strongly interacting quantum liquids, all with $\frac{\eta}{s} = \frac{\hbar}{4\pi} \approx 0.08\hbar$

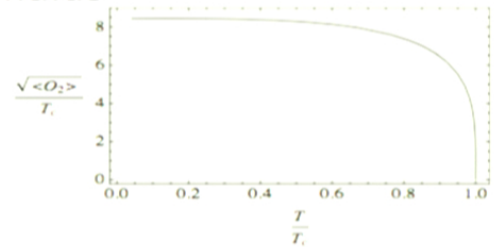

Unification of the three stories
A lesson
Recall that if something has kinematic viscosity as small as $\eta/s = \hbar/4\pi$, it can not be a gas of particles, by the Heisenberg uncertainty relation
But the equation of state is very close to the ideal gas
It is possible to have liquids whose
1) equation of state is close to the ideal gas
2) kinematic viscosity is smaller than any other liquid in nature
Pavel Kovtun (University of Victoria)
Black Holes as Quantum Liquids

These were BH similar to the quark-gluon liquid

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

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





Hartnoll+Herzog+Horowitz, 2008

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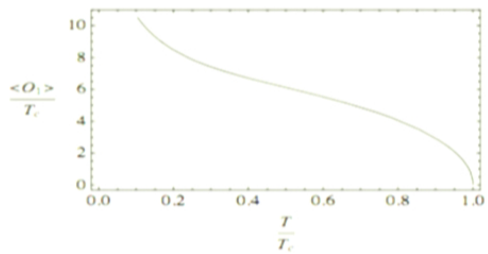

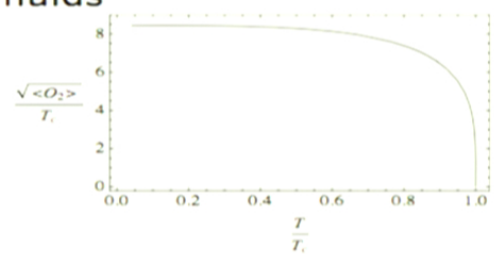

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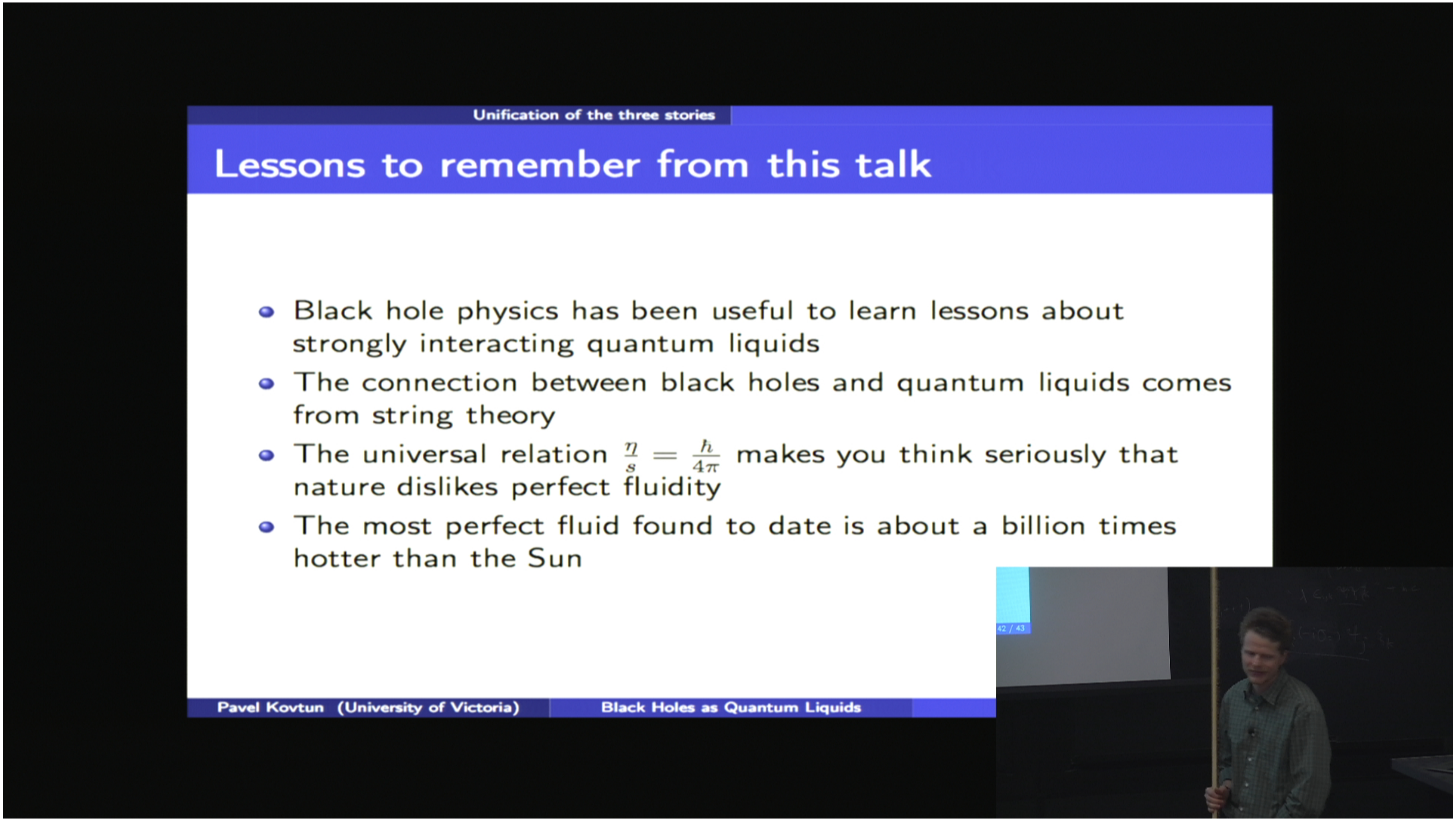
At $T < T_c$, the black hole in a box develops hair
This appearance of hair corresponds to the superfluid phase transition


Unification of the three stories
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
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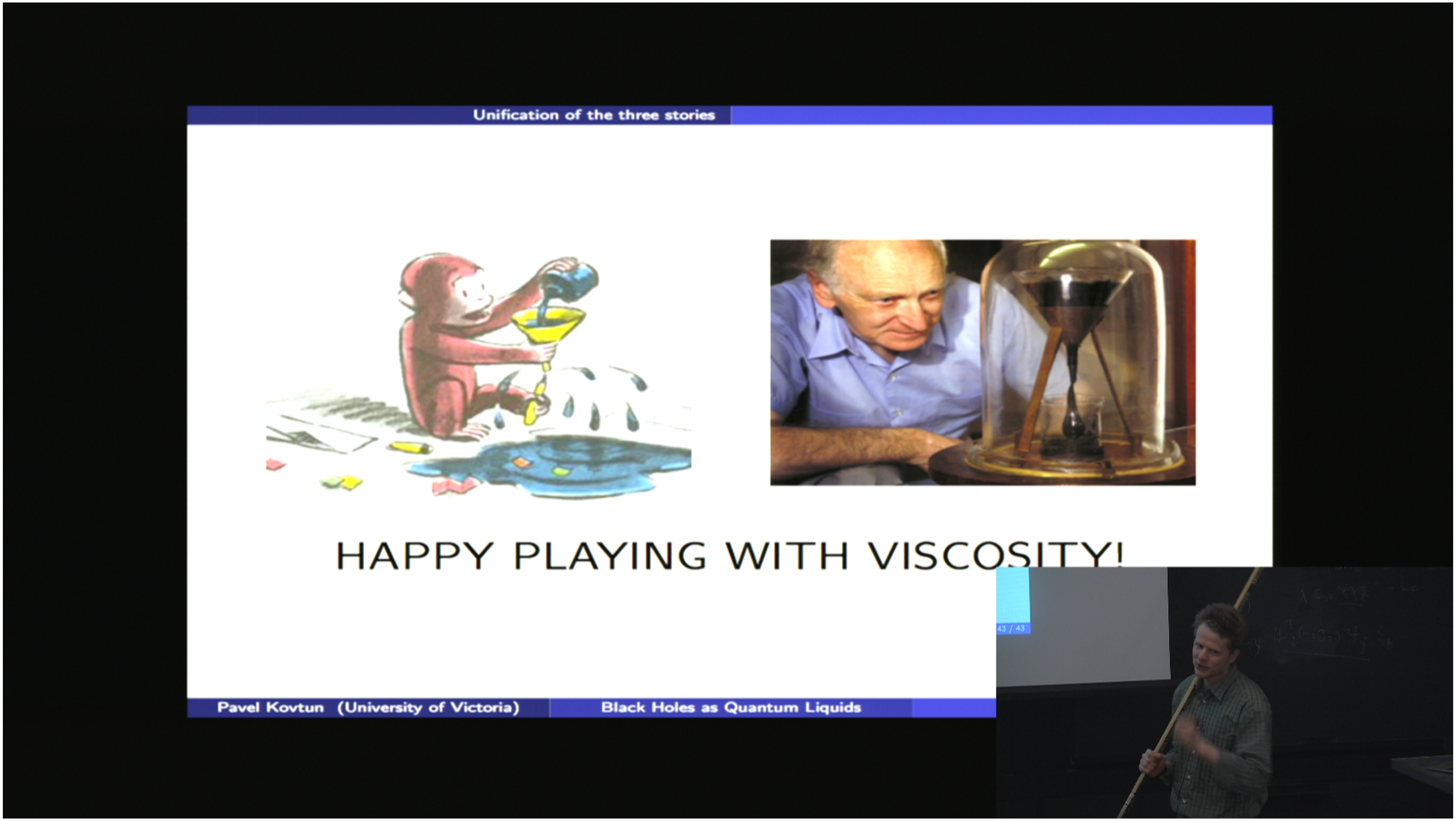
Unification of the three stories
HAPPY PLAYING WITH VISCOSITY!
Pavel Kovtun (University of Victoria)
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