Title: Spacetime Atoms and the Unity of Physics

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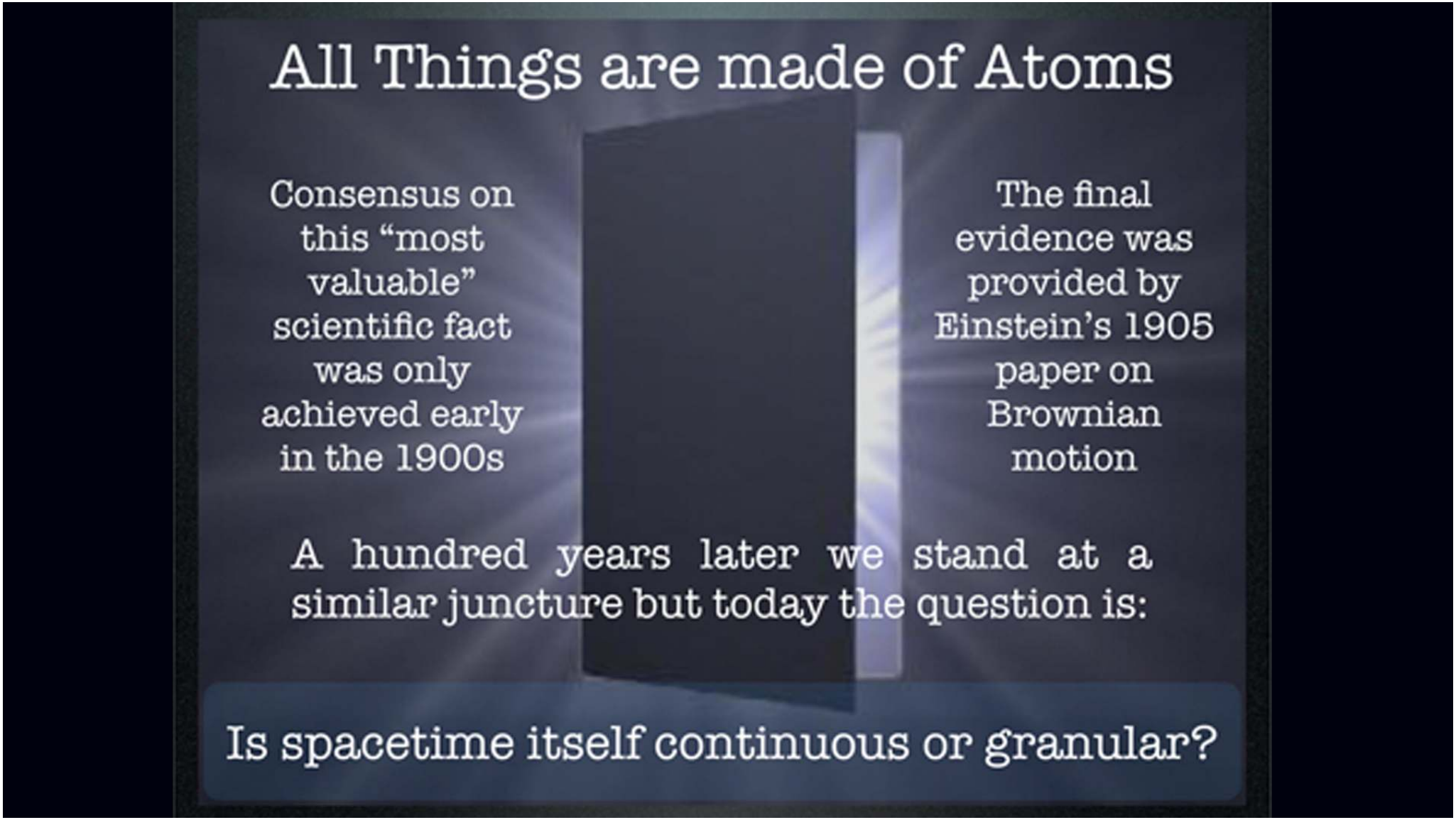
Abstract: Black holes are hot! This discovery made by Stephen Hawking ties together gravity, spacetime, quantum matter, and thermal systems into the beautiful and exciting science of "Black Hole Thermodynamics". Its beauty lies in the powerful way it speaks of the unity of physics. The excitement arises because it tells us that there is something lacking in our understanding of spacetime and, at the same time, gives us a major clue as to what the missing ingredient should be. Theoretical physicists at Perimeter Institute and elsewhere are pioneering a proposal, known as Causal Set Theory, for the structure held by these most fundamental atoms of spacetime. In this talk, Professor Dowker describes black hole thermodynamics and argue that it is telling us that spacetime itself is granular or "atomic" at very tiny scales.

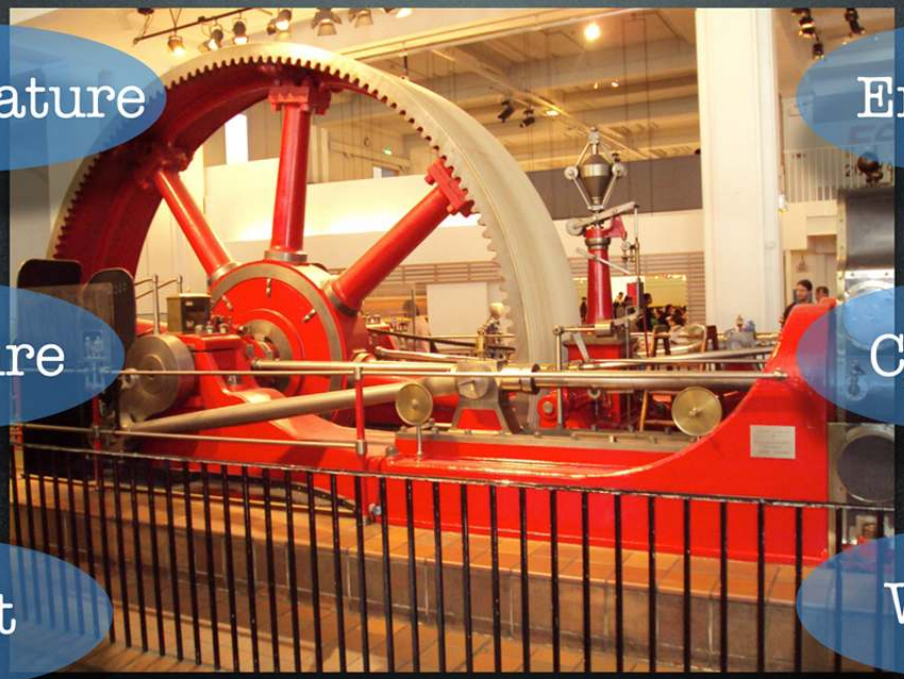
Spacetime Atoms and the Unity of Physics

Fay Dowker
Imperial College London
& Perimeter Institute

Waterloo ON, Canada, November 2nd 2011


All Things are made of Atoms
Consensus on this "most valuable" scientific fact was only achieved early in the 1900s
The final evidence was provided by Einstein's 1905 paper on Brownian motion
A hundred years later we stand at a similar juncture but today the question is:
Is spacetime itself continuous or granular?

Thermodynamics: the science of heat



Temperature

Energy

Pressure

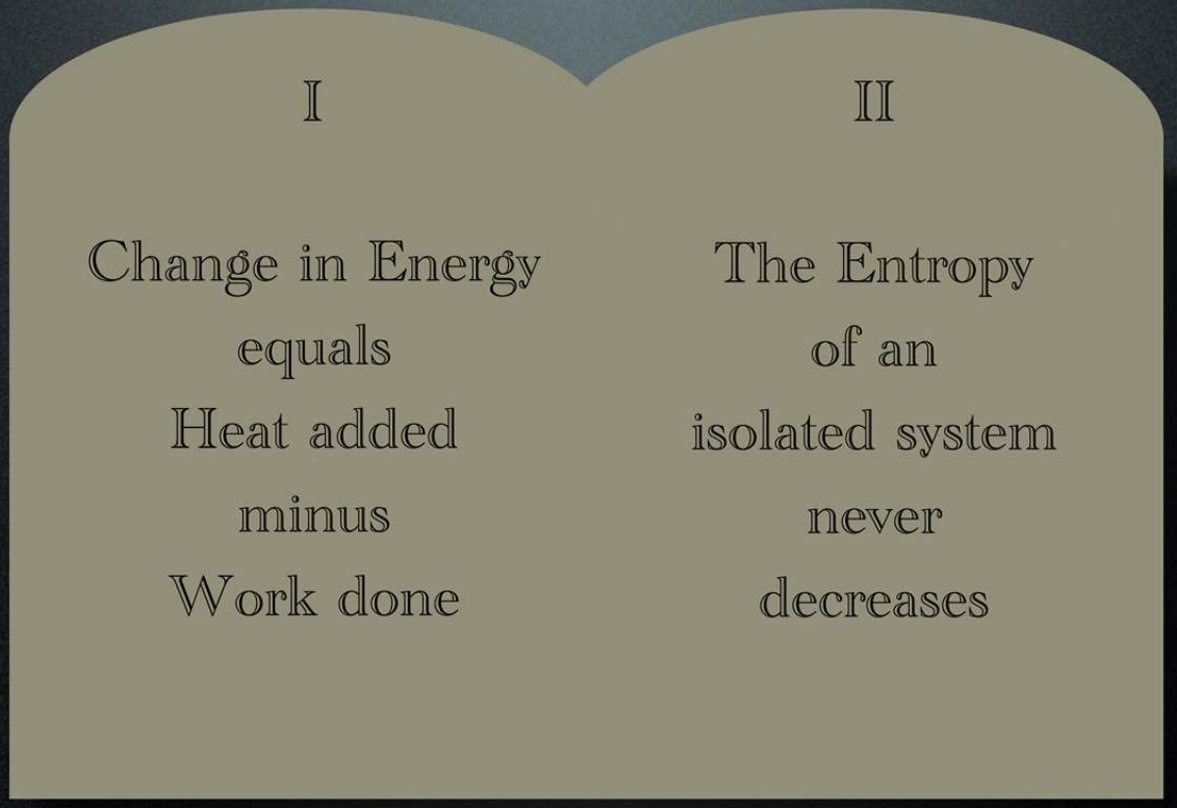
Cycles

Heat

Work

Corliss mill engine (1903) Science Museum London

The Laws of Thermodynamics



What is heat?

What is heat?

Heat is energy of disordered motion of atoms and molecules

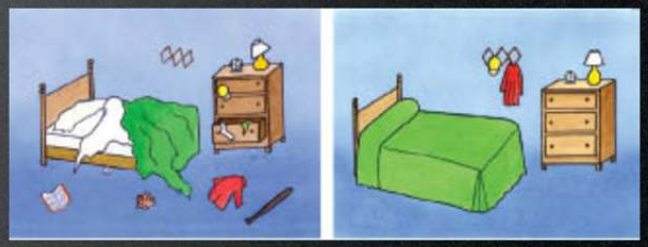
This **unifies** the First Law with the law that mechanical energy cannot be created or destroyed.

What is entropy?

Entropy is a measure of how many ways the atoms can be configured so that you can't tell the difference macroscopically Boltzmann

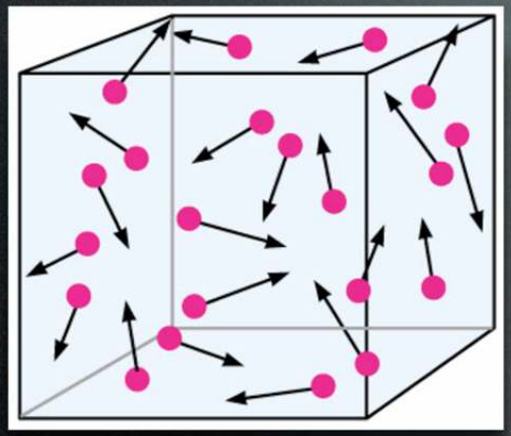
This makes the Second Law comprehensible

Typical



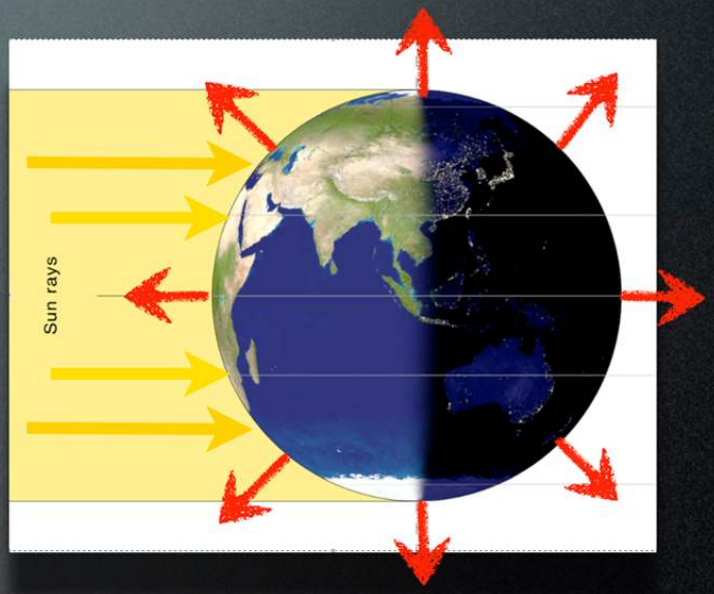
Not possible without a lot of shouting

A Box of Gas



has entropy proportional to the Number of particles

Life on Earth



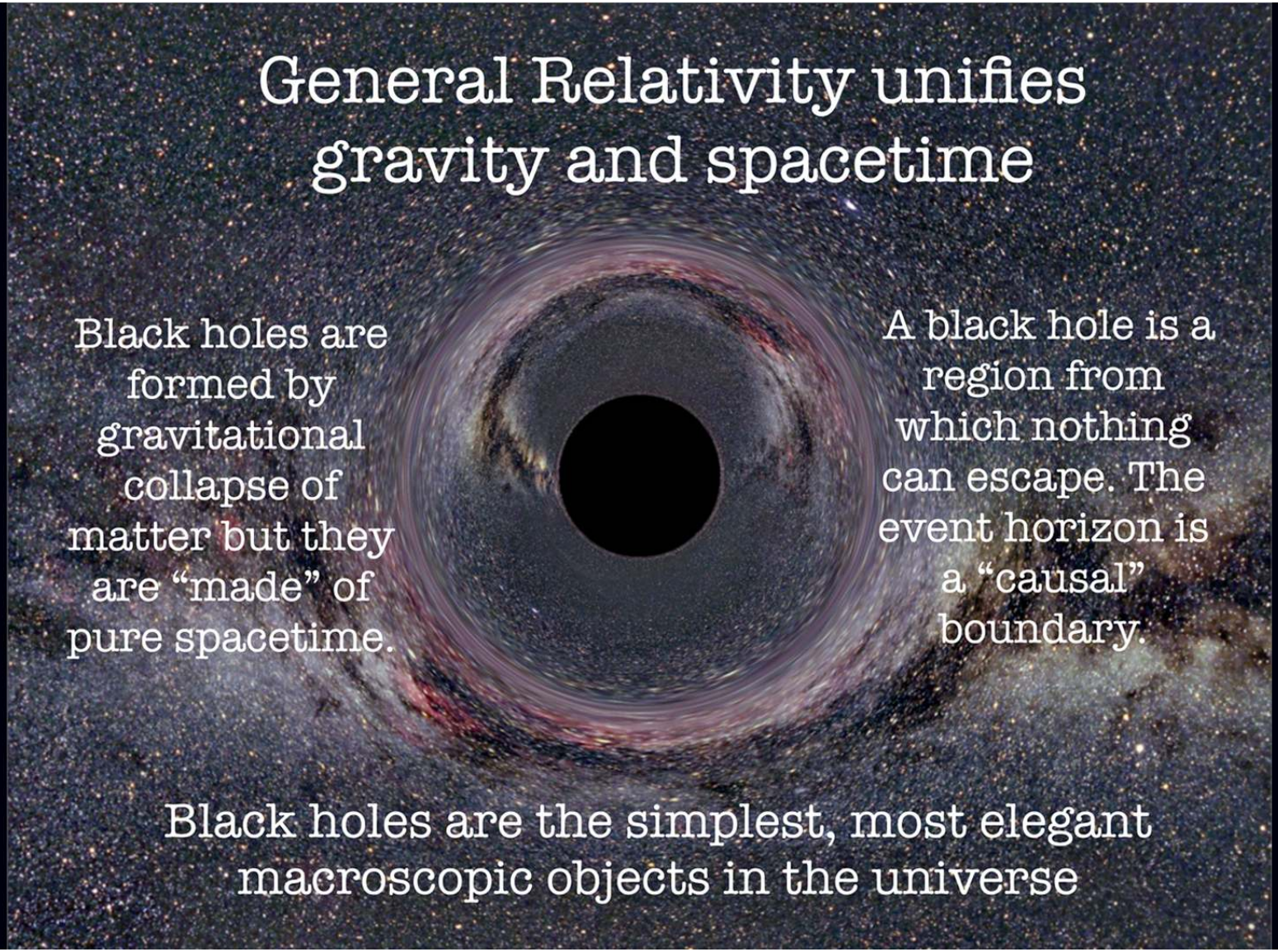
is possible because of the throughput of solar energy so total entropy increases

The Laws Again

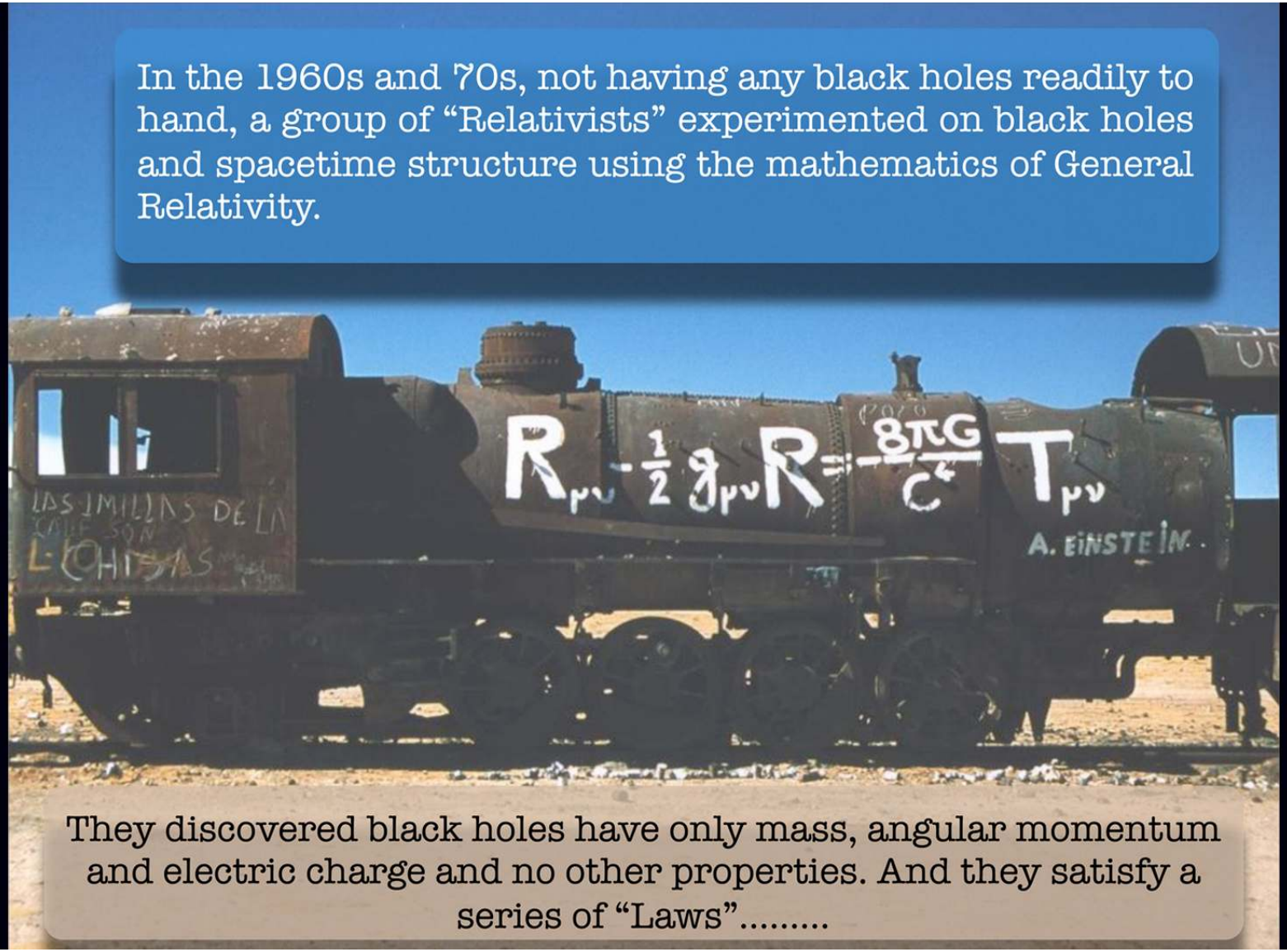
I $\Delta E = T\,\Delta S - W$

II S never decreases

General Relativity unifies gravity and spacetime



In the 1960s and 70s, not having any black holes readily to hand, a group of "Relativists" experimented on black holes and spacetime structure using the mathematics of General Relativity.



They discovered black holes have only mass, angular momentum and electric charge and no other properties. And they satisfy a series of "Laws".....

The Laws of Black Hole Mechanics

Bardeen, Carter & Hawking

I $$\Delta M = \frac{1}{8\pi}\,\kappa\,\Delta A - W$$

II A never decreases

The Laws of Black Hole Mechanics

Bardeen, Carter & Hawking

$\mathbb{I}$ $\quad \Delta M = \frac{1}{8\pi}\,\kappa\,\Delta A - W$

$\quad \Delta E = T\Delta S - W$

$\mathbb{II}$ $\quad A$ never decreases

$\quad S$ never decreases

Entropy/Horizon area: More than an analogy?

Bekenstein said yes, horizon area is physical entropy. Otherwise the Second Law can be violated. Which would be bad:

> "If your theory is found to be against the second law of thermodynamics I can give you no hope; there is nothing for it but to collapse in deepest humiliation."
> A. Eddington, The Nature of the Physical World, Gifford Lectures 1926-27

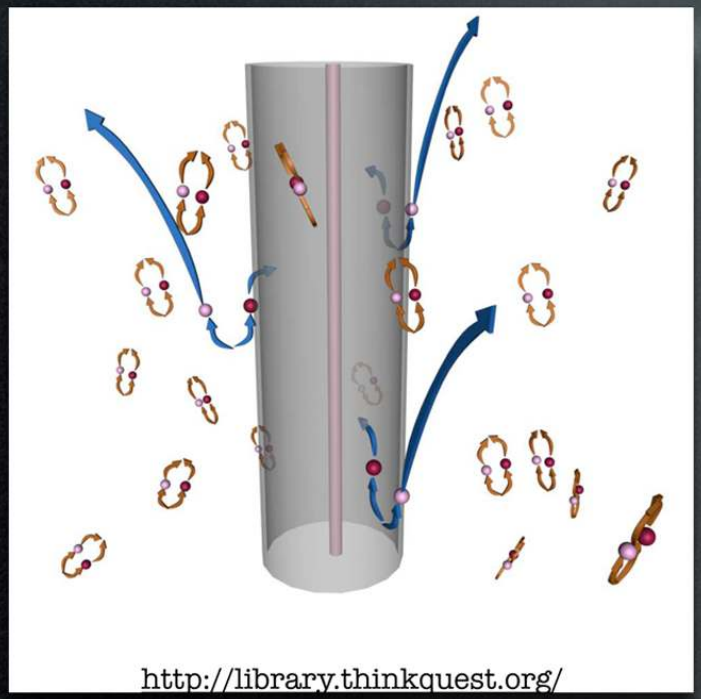
Bekenstein proposed the Generalised Second Law:

Entropy outside the Black Hole plus the Entropy of the Black Hole never decreases

Drama and Irony

Hawking thought Bekenstein was wrong but then made the discovery that ties it all together:

BLACK HOLES ARE HOT!



http://library.thinkquest.org/

The temperature of a black hole is its surface gravity

$$T = \frac{\kappa}{2\pi}$$

The entropy of a black hole is the area of its horizon

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

$$\Delta M = \frac{1}{8\pi}\,\kappa\,\Delta A - W$$

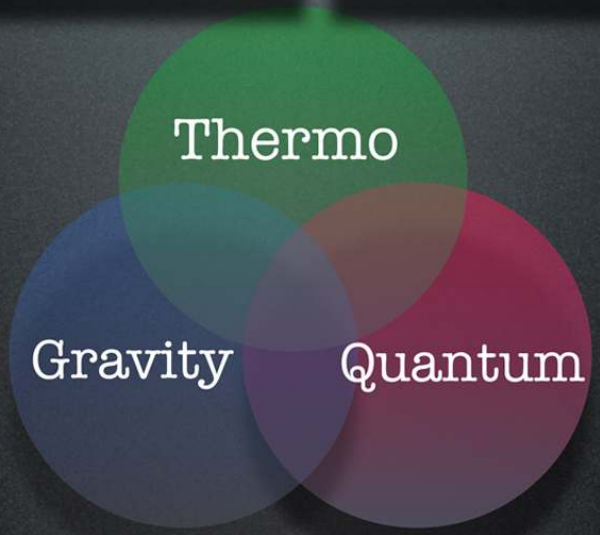
is

$$\Delta E = T\Delta S - W$$

A never decreases

is

S never decreases



On the threshold of unity...

What is the microscopic physics that explains black hole thermodynamics?

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

in "Planck" units

Entropy is roughly number of "Planck" sized pixels on the horizon

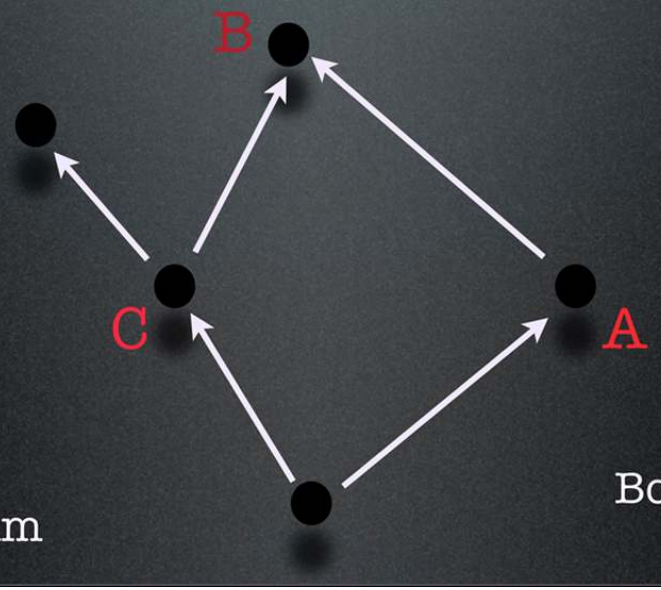
The horizon is just a surface in empty spacetime. This suggests that spacetime itself is granular or "atomic" at Planckian scales

Spacetime itself is granular, made of "atoms"

marries

"Causality" is spacetime's most basic structure

Their union is a hypothesis about the microstructure of spacetime: Causal Set Theory

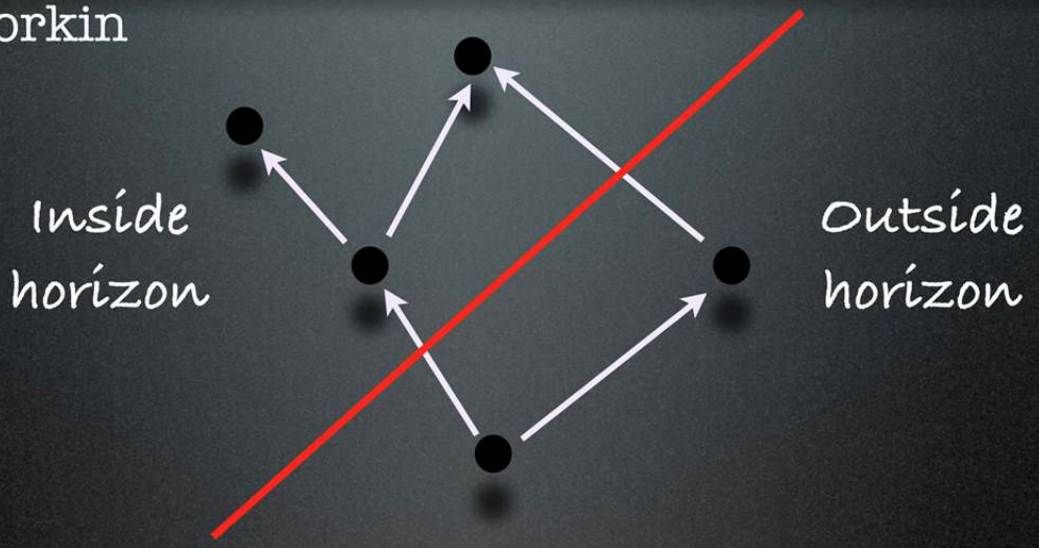


't Hooft, Myrheim

Bombelli, Lee, Meyer & Sorkin

Proposal: entropy counts the number of simplest causal relations that straddle the horizon.

Dou & Sorkin



Has potential to explain entropy of ALL causal horizons (not just black holes). Watch this space!

Causal sets were used to predict a Nobel Prizewinning observation

Perlmutter, Riess and Schmidt won this year's Physics prize for measuring the acceleration of the universe's expansion (1998)

Oh, this is a terrible mistake

It doesn't make any sense... it'll go away

But that mistake never went away.

Most theorists were shocked

...but not those of us working on causal sets

The big puzzle about the smallest number: The Cosmological "Constant", Λ

Supernovae $\Lambda \approx 10^{-120}$

Calculation $\Lambda \approx 1$

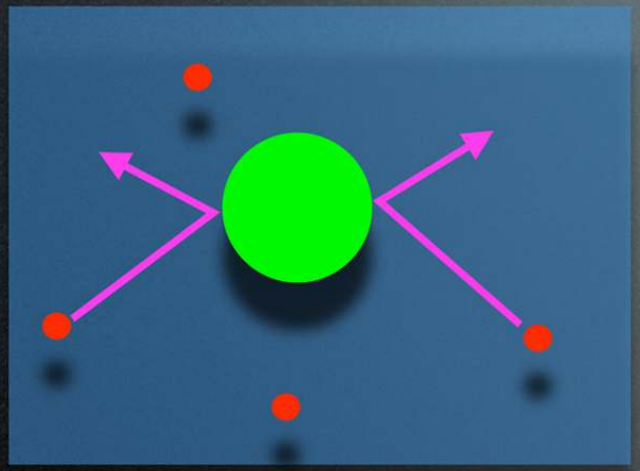
So most theorists had thought $\Lambda = 0$

In 1990 Sorkin predicted that Λ should be nonzero and of roughly the measured value

Λ wants to be zero but has quantum fluctuations. There's a Heisenberg uncertainly relation between Λ and spacetime volume.

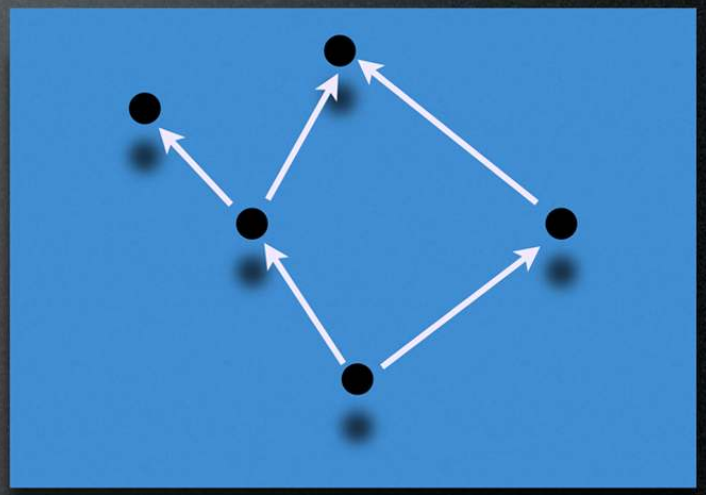
$$\Lambda \approx \pm \frac{1}{\sqrt{Volume}} \approx \pm 10^{-120}$$

Brownian motion

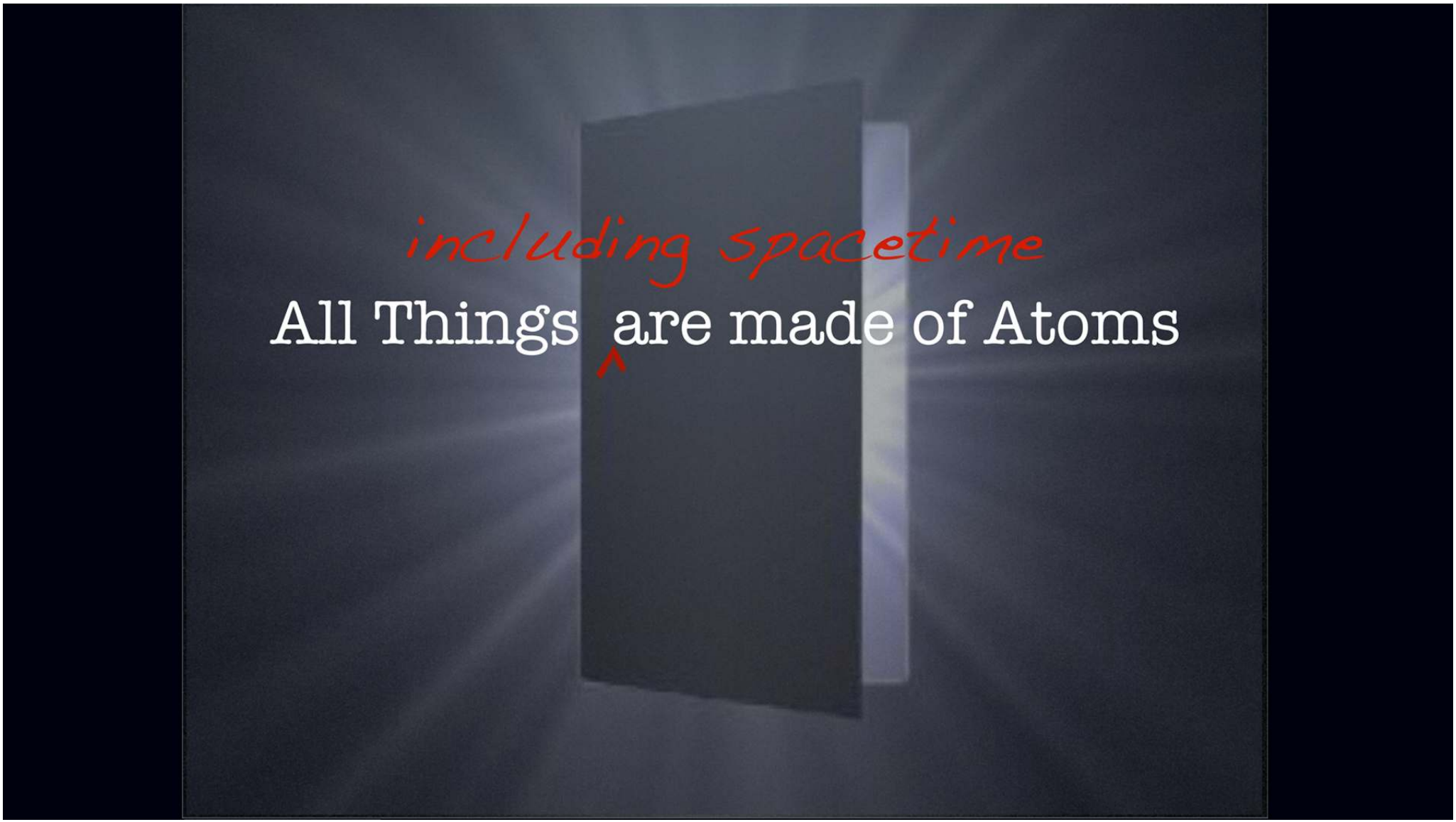


The molecules reveal themselves by their effect on much larger things

Look for effects that the atomicity of spacetime has on matter moving through it over long distances




All Things are made of Atoms


including spacetime
All Things are made of Atoms