CERN Colloquium, 28/04/11

THE COMMON ORIGIN OF GRAVITY
DARK ENERGY AND MATTER

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Matter and Forces

- **Quarks**
- **Leptons**

**Forces**

- **Electro Magnetic**
- **Weak**
- **Strong**

**Gravity**
Current Paradigm

FUNDAMENTAL FORCES: carried by elementary particles
We may need to reconsider our current paradigms

theory & observation
96% of the Energy in our Universe is not understood!
String Theory

FUNDAMENTAL FORCES: carried by vibrating strings
D-branes
EMERGENCE

We use concepts and observe phenomena at a macroscopic scale, which are derived from a microscopic scale where they have no a priori meaning.
Open/closed string
or
gauge theory/gravity duality
Black Holes

\[ R = \frac{2GM}{c^2} \]
Black Holes
Consider a particle gradually lowered into a black hole. Classically, the energy associated with the particle gets redshifted, and vanishes when the particle is at the horizon.
Now take a gas of particles lowered in to a black hole. What happens to the entropy?

Bekenstein Hawking
Black Hole Entropy

\[ S_{BH} = k_B \frac{Ac^3}{4G\hbar} \]
Hawking Temperature

\[ T = \frac{1}{2\pi} \frac{\hbar g}{k_B c} \]

\[ g = \frac{GM}{R^2} \]
Unruh Temperature

\[ T = \frac{\hbar a}{2\pi k_B c} \]
in accelerated frame
Holographic principle

The information associated with a certain part of space may be (heuristically) represented as bits on the surface surrounding it.
ADS/CFT CORRESPONDENCE

EQUIVALENCE BETWEEN FIELD THEORY ON THE “BOUNDARY” AND GRAVITY IN THE “BULK”

ONE SPACE DIMENSION EMERGES CORRESPONDING TO THE “SCALE” OF THE BOUNDARY THEORY. RADIAL EVOLUTION IS LIKE RENORMALIZATION GROUP FLOW.
Bulk description
Particle gets lowered in to black hole

Boundary description:
Delocalized state gets thermalized by heat bath

Hot CFT
Thermal Heat Bath
An entropic force is a macroscopic force whose properties are determined not by the character of an underlying microscopic force, but by the whole system's statistical tendency to increase its entropy.
Warmtebad

Polymeer
$F \Delta x = T \Delta S$

Polymer

Entropic Force
Gravity as an Emergent Force

- At a fundamental scale our notions of space and time and matter cease to exist: they are derived concepts.

- In describing Nature in terms of space-time and matter, we ignore many degrees of freedom.

- Gravity arises because the amount of phase space (information) available for these degrees of freedom is influenced by the location of matter in space and time.
A HEURISTIC ARGUMENT
A HEURISTIC ARGUMENT
A heuristic argument

\[
\Delta x = \frac{\hbar}{mc}
\]
A HEURISTIC ARGUMENT

\[ \Delta x = \frac{\hbar}{mc} \]

\[ \Delta S = 2\pi k_B \]
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A HEURISTIC ARGUMENT

\[ F \Delta x = T \Delta S \]

\[ k_B T = \frac{\hbar a}{2 \pi c} \]

\[ \Delta S = 2\pi k_B \frac{m c}{\hbar} \Delta x \]
A heuristic argument

\[ F \Delta x = T \Delta S \]

\[ k_B T = \frac{\hbar \alpha}{2\pi c} \]

\[ F = ma \]

\[ \Delta S = 2\pi k_B \frac{mc}{\hbar} \Delta x \]
A HEURISTIC ARGUMENT
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\[ \# \text{ bits} = \frac{4\pi R^2}{\ell^2} \]
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\[ \text{# bits} = \frac{4 \pi R^2}{\ell^2} \]

\[ \ell^2 = \frac{G \hbar}{c^3} \]

\[ \frac{1}{2} k_B T = E / \text{# bits} \]
A HEURISTIC ARGUMENT

# bits = \( 4\pi R^2 \)

\[ \ell^2 = \frac{G\hbar}{c^3} \]

\[ \frac{1}{2} k_B T = E / \# \text{bits} \]

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A HEURISTIC ARGUMENT

\[ F \Delta x = T \Delta S \]

\[ \Delta S = 2\pi k_B \frac{mc}{\hbar} \Delta x \]

\[ F = \frac{GMm}{R^2} \]

\[ \frac{1}{2} k_B T = E / \# \text{bits} \]

\[ \ell^2 = \frac{G\hbar}{c^3} \]

\[ \# \text{bits} = \frac{4\pi R^2}{\ell^2} \]

\[ E = Mc^2 \]
This is heuristic, so far...

It is bit of a “swindle” but it catches the essence.

It should be seen as a metaphor. But of what?

• Why does it work?
• What is the meaning of the temperature?
• What is the nature of this information?
• Why is it stored on screens? Can this be derived?
• Why is gravity attractive?
• What about the other forces?
• Are there observable consequences?
Holographic screens at equipotential (= equal redshift) surfaces
The phase space can be described by counting the ways in which the energy can be distributed over the cells on the boundary.
Adiabatic principle:

When a fast dynamical system is driven by a slow system the fast reacts back on the slow and creates a reaction force.

When the time scales are widely separated the force is determined by the principle that the phase space volume is preserved.

In quantum mechanics this is a consequence of the Born-Oppenheimer approximation.
The system stays in an energy eigenstate of the fast variables (adiabatic theorem).
Adiabatic Reaction Force

Assuming eigenvalues don’t cross, the force follows from an adiabatic argument

\[ \Omega(E, x) = \int d^N p \, d^N q \left| H(p, q, x) \leq E \right. \]

\[ S(E, x) = k_B \log \Omega(E, x) = \text{const} \]

\[ F = -\frac{\partial E}{\partial x} = T \frac{\partial S}{\partial x} \]

\[ \frac{1}{k_B T} = \frac{S}{E} \]
Degenerate Fermions

GRAVITATIONAL COLLAPSE:

What happens to the phase space occupied by the fermions?
What about the fermi statistics?
Statistics operation: discrete

\[ |\Psi\rangle_{\text{particle 1}} \iff |\Psi\rangle_{\text{particle 2}} \]
Statistics operation: why not continuous?

\[ |\Psi\rangle_{\text{particle 1}} \rightarrow \alpha |\Psi\rangle_{\text{particle 1}} + \beta |\Psi\rangle_{\text{particle 2}} \]
Positions get ambiguous

\[ \langle \Psi_1 | \hat{x} | \Psi_2 \rangle \square 0 \]

\[ x_{ij} = \langle \Psi_i | \hat{x} | \Psi_j \rangle \]

Coordinates turn into matrices
At horizons space and time disappear.

At horizons the separation of time scales between the eigenvalues and the "off diagonal modes" breaks down and the coordinates become non commuting matrices.
GRAVITATIONAL COLLAPSE:

What happens to the phase space occupied by the fermions?

Answer: It goes into the off diagonal phase. Not of gravity!

After collapse one can no longer integrate out the off diagonal modes!!

Eigenvalues and off diagonal modes equilibrate and together form “black hole stuff”.

$X =$
**Thought experiment**

\[ X = \begin{array}{cccc} x_1 & \cdots & x_{1N} & z_1 \\ \vdots & \ddots & \vdots & \vdots \\ x_{N1} & \cdots & x_{NN} & z_N \\ \end{array} \]

\[ F = T \frac{\sqrt{S}}{\sqrt{x}} \]

**Entropic force**
Why do we need to reconsider the origin of gravity and change our current paradigms?

96% of our Universe is not understood!

Our current paradigms ignore a lot of information (phase space).

What went wrong?
Cosmological Horizon

\[ kT = \frac{\hbar H_0}{2\pi} \]

De Sitter Space

\[ H_0^2 = c^2 \Lambda \]
These ideas can be applied to our universe

\[ kT = \frac{\hbar H_0}{2\pi} \]

\[ S = \frac{c^2 H_0 V}{4G\hbar} \]
Dark energy and matter are made of the same stuff.
At horizons space and time disappear.
Dark Energy and Dark Matter

- 73% Dark Energy
- 23% Dark Matter
- 3.6% Intergalactic Gas
- 0.4% Stars, etc.

13.6% 34.1% 34.1% 13.6%
Clusters

Galaxies
Flattening of rotation curves
Flattening of rotation curves

\[ V^4 = GM_B a_0 \]

\[ a_0 = 1.24 \pm 0.14 \times 10^{-10} \text{ m/s}^2 \]