1997–1998 ACADEMIC TRAINING PROGRAMME

LECTURE SERIES

SPEAKER : L. SUSSKIND / Stanford University, USA
TITLE : The Physics of Black Holes
TIME : 15 & 16 December from 10.30 to 12.00hrs
PLACE : Auditorium

ABSTRACT

I will describe the profound revolution in our understanding of black holes and their relation to Quantum Mechanics that has occurred over the last few years as a result of a deeper understanding of string theory.
SLAC $10^2$ GeV

$M_{\text{Planck}} = 10^9$ GeV
\[ R \sim G E_{\text{cm}} \]

**BLACK HOLE**
Total cross section: \(\sim \frac{E_{\text{c.m.}}^2}{M_p^4}\)

Particle multiplicity: \(\sim \frac{E_{\text{c.m.}}^2}{M_p^2}\)

Secondary particle energy: \(\sim \frac{M_p^2}{E_{\text{c.m.}}}\)

Asymptotic inclusive spectrum

\[C_X P - \left\{ \frac{P E_{\text{c.m.}}}{M_p^2} \right\}\]
The Black Hole Horizon

\[ R_s = 2MG \]

\[ \frac{1}{2} m v^2 = \frac{G M m}{R} \]
FORMATION OF A BLACK HOLE

\[ \text{Area Theorem} \]
\[ \frac{dA}{dt} > 0 \]

BLACK HOLES CAN NOT SPLIT

\[ M \rightarrow \frac{M}{2} + \frac{M}{2} \]

\[ \text{Area} \rightarrow 2 \times \frac{\text{Area}}{4} = \frac{\text{Area}}{2} \]

BHs are eternal
A particle physicist's "confusion"

Form a black hole out on neutral matter.

How can a neutral object be stable against decay?

It is only forbidden to decay by classical equations of motion.

Fission via tunneling?
Bekenstein and Hawking

$S$ decreases !!!

Unless

The black hole has entropy

$S \sim \text{Area}$ ?

Bekenstein

$S \sim \frac{\text{Area}}{4G \frac{\hbar}{c}}$

$= \frac{4M^2 G \pi}{\hbar}$
**Thermodynamics:** \( dE = TdS \)

\[
T = \frac{dM}{dS} = \frac{\hbar}{8 \pi MG}
\]

- **Black Hole**
- **Black Body**

\[
L \approx \text{Area} \ T^4 \sim \frac{\hbar}{(MG)^2}
\]

\[
L \times \text{Time} = M
\]

\[
\text{Time} \approx \frac{M^3 G^2}{\hbar}
\]
BLACK HOLE COMPLEMENTARITY

1) To an external observer the horizon of a black hole is equipped with Planckian degrees of freedom which absorb, thermalize, and ultimately reemit all information.

2) An observer in free fall detects nothing out of the ordinary at the horizon. However, any attempt to communicate this fact is frustrated by the extreme "red shift."

No contradiction! 😊
The Mystery of Entropy

\[ S = \log N \]

What are the microstates which are counted by \( S_{\text{BH}} \)?

Is the Black Hole really bald?

Is the usual gravitational field some sort of "coarse graining"?

Are there microscopic degrees of freedom that "cover" the horizon, one per Planck area?

Why doesn't someone falling into the Black Hole "feel" them?
The Spectrum

Black Holes
The Holographic Principle

\[ S > \frac{A}{4G} \]
\[ M < M_{\text{Max}} \]

Now drop in enough matter to make a black hole of area \( A \) and \( S = \frac{A}{4G} \).

The law violated:

\[ S_{\text{max}} = \frac{A}{4G} \]

Number of quantum states \( \leq \exp \frac{A}{4G} \).
Maximum Entropy?

Number of states = $2^n = 2^{\sqrt{10}}$

$S_{\text{max}} = \log N = \sqrt{10}$

Holographic Principle

The degrees of freedom of a region of space reside on the surface with no more than one per Planck area.

$P = N e$

$r = N^{1/2} l_p$
Black Holes Are Thermal

\[ S = \frac{A}{4GM^2} \]

\[ T = \frac{k}{8\pi MG} \]

\[ \omega \sim \frac{k}{MG} \]

Hawking Particle

Unruh

\[ T = M_p \]

Black Hole Complementarity
String Theory

\[ M = \text{LENGTH} \cdot T \]

Point Particle

String Loop of size \( L_s \approx 10^{-32} \text{ cm} \)

Feynman Diagram

Excited Strings!

8 \( M \approx 10^{-6} \text{ gr} \)
EFFECTS OF INTERACTION

GRAVITY

\[ G_N = g^2 \ell_s^2 \]

As \( g \) is increased, a highly excited string will evolve into a black hole.

string \[\rightarrow\] black hole
WHAT HAPPENS TO A BLACK HOLE AS $\phi$ DECREASES

\[ R_s = \ell_s \]

\[ 2MG = 2M \phi^2 \ell_s^2 = \ell_s \]

\[ \phi \sim \frac{1}{H \ell_s} \]
Strings Have Entropy

\[ \text{Mass} = \frac{\text{Length}}{\ell_s^2} \]

Number of states

\[ = 4^{\frac{L}{\ell_s}} \]

\[ S \approx \frac{L}{\ell_s} \]

or

\[ S = \text{Mass} \cdot \ell_s \]
Could Black Holes and Strings Be the Same Thing?

\[ S_{\text{string}} = M S \]

\[ S_{\text{BH}} = M^2 l_p^2 \]

\[ S_{\text{ST}} \rightarrow S_{\text{BH}} \]
HAWKING RADIATION
EXTREMAL BLACK HOLES

CHARGED

$M \text{ decreases until}$

$$G \frac{M^2}{R^2} = \frac{Q^2 e^2}{R^2} \text{ or } GM^2 = Q^2 e^2$$

Now we have an extremal B.H.

ELECTRICAL FORCES BALANCE GRAVITATIONAL

$$S \approx Q^2$$
EXTREMEAL BLACK HOLES

M

\[ g \]
COMPACTIFICATION OF SPACE
(KALUZA KLEIN)

10 DIMENSIONS
$X^1, \ldots, X^9$ → 4 DIMENSIONS
$X^1, X^2, X^3, \Theta^4, \ldots, \Theta^5$

MOMENTUM IN $\Theta$ DIRECTION = CHARGE
D-BRANES

D2-brane

D1-brane

D0-brane

WRAPPING CHARGE + KK CHARGE

W

KK

W + KK
D-BRANE
\[ S = 2\pi \sqrt{NQ_4 Q_5} \]

GRAVITY
\[ S = \frac{A}{4G} \]

Einstein's equations
\[ A = 8\pi G \sqrt{NQ_4 Q_5} \]

HAWKING RADIATION
BLACK HOLE COMPLEMENTARITY?

\[ X(\sigma) = \sum a(m) e^{i\sigma} \frac{e^{i\sigma}}{\sqrt{m}} + c.c. \]

ZERO POINT OSCILLATIONS

\[ \langle X^2 \rangle = \sum m_{\text{max}} \frac{1}{m} \sim \log m_{\text{max}} \]

\[ m_{\text{max}} \sim \exp \left( \frac{4t}{MG} \right) \]