The Secret Quantum Life of Black Holes

Gia Dvali

LMU-MPI & NYU
Collaborators:

Cesar Gomez
Daniel Flasig
Alex Pritzel
Nico Wintergerst
Andre Franca
Mischa Panchenko
Dieter Lüst
Alex Gussmann
Artem Averin
Sebastian Zell
Units: $C = 1$

Planck length:

$$L_P = \hbar G_N$$

Planck mass:

$$M_P = \frac{\hbar}{L_P}$$
What is black hole? 
(classical portrait)

Every object, of mass $M$, 
has an associated radius

$$R_g \equiv 2 \, G_N \, M$$

called gravitational 
or Schwarzschild radius.
An object contracted beyond $R_g$ becomes a black hole.

Escape velocity = speed of light
Classically black holes are featureless.

\[ M, J, Q \]

**mam**

angular momentum

electric charge
This means I cannot send you a message encoded in black hole features!
From here one would naively conclude that black holes carry very little information.

\[ \text{Info} = 0 \]

But, quantum theory tells us a very different story!
Some remarks about quantum theory:

Planck constant
\[ \hbar \sim 10^{-34} \text{ J} \cdot \text{s} \]

Quantum of action. For macroscopic objects
\[ S \gg \hbar \]
Heisenberg’s uncertainty principle

\[ \Delta x \Delta p \geq \hbar \]

\[ \Delta t \Delta E \geq \hbar \]

no free lunch!
It follows from Heisenberg that information costs energy:

<table>
<thead>
<tr>
<th>photon is a box</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E \geq \frac{\hbar}{\lambda}$</td>
</tr>
</tbody>
</table>

But, energy gravitates. So information gravitates!
Box with information

gravitational force
Consequences:

1. The shortest length of nature!

Planck length

\[ L_p = \sqrt{\frac{\hbar}{G_N}} \sim 10^{-33} \text{ cm} \]
photon of $\lambda \ll L_p$

$E_{\text{photon}} \sim \frac{h}{\lambda}$

But, such a photon is a black hole? $R_g \gg L_p$
Bound on Information (Bekenstein)

\[ N_{\text{max}} = \left( \frac{R}{L_p} \right)^2 \]

Saturation by black hole!
So black hole carries a maximal amount of information that one can fit within the radius $R_g$.

$$N = \left( \frac{R_g}{L_P} \right)^2$$
Black hole carries a maximal information (per size) given by Bekenstein entropy 

\[ N = \left( \frac{R_g}{L_p} \right)^2 \]
But then, there is a puzzle. $L_p$ is quantum:

In classical limit ($\hbar \to 0$)

$L_p \to 0$.

So information carried by a classical black hole is:

$$N = \left( \frac{R_g}{\hbar} \right)^2 = \infty$$
But, I told you minute ago that classical black hole is featureless!

\[ \text{info} = 0 \]

\[ 0 = \infty \]

? 😞
Bekenstein entropy of a black hole

$$N = \left( \frac{R_g}{L_p} \right)^2$$

Understanding this from quantum information point of view: Black hole is a menage

\[ (0,1,0, \ldots, 1,1, \ldots) \]
$N$ qubits: $|0\rangle$ or $|1\rangle$

$2^N$ possibilities = $2^N$ quantum micro-states

$(0, 1, 1, \ldots 0, 1, 1, \ldots,)$
What are these qubits?

Qubit: A two-state system $|0\rangle$ or $|1\rangle$

Energy gap

$\Delta E = E_1 - E_0$
For a normal system, e.g. particle in a box

\[ \Delta E \sim \frac{\hbar}{R} \]

But, for a black hole

\[ \Delta E \sim \frac{\hbar}{R} \frac{1}{N} \]
Example

\[ \Delta E \sim 10^{-4} \text{ eV} \]

\[ \Delta E \sim 10^{-70} \text{ eV}! \]

\[ \text{Black hole} \]
Black hole has the cheapest qufits!

Understanding black holes in terms of universal phenomenon of quantum criticality of attractive cold bosons (gravitons)
Gravitons are quanta of gravitational field. They attract each other with the strength

\[ \alpha = \left( \frac{L_p}{\alpha} \right)^2 \]
$N$ bosons (gravitons) in a box

Wave function $\alpha N < 1$

$\alpha N > 1$

Collapse
\( \alpha N = 1 \leftarrow \text{Critical point of quantum phase transition} \)

\[ \begin{array}{c}
1 \\
E
\end{array} \]

Many cheap (gapless) qubits!
Energy Levels
One particle Entanglement Entropy

\[ S_{\text{ent}} = \ln \left( 1 + \frac{1}{N} \right) \]

- \( N=10 \)
- \( N=2000 \)
- \( \ln(3) \)
Black hole = Many gravitons at quantum critical point!

Self-sustained quantum criticality.
There is no paradox.\n$\theta \to 0$ black hole indeed carries $\infty$ information.\n
\[=\]

However it takes $t = \infty$ to read it!
At the critical point, quantum effects are very important:

particle depletion (Hawking radiation)

\[ N \uparrow \rightarrow N - 1 \uparrow + \text{graviton} \]
Experimental prospects:

- Simulating black holes;
- Black hole based quantum computing in labs!
It is commonly accepted that black holes should be produced in trans-Planckian scattering.

e.g.

\[ e^+ + e^- \rightarrow BH \]

(’t Hooft; Amati, Giafalconi, Venezio; Gross, Mende, ........)

Was even predicted at LHC (Antoniadis, Arkani-Hamed, Dimopoulos, GD)
We have such a microscopic theory which predicts that the relevant process is

\[ 2 \rightarrow N \text{ gravitons} \]

\[ N = \frac{S}{M_{Pl}^2} \gg 1 \]
2 → N graviton scattering

G.D. Gomez, Isermann, Lüst, Stieberger, hep-th/1409.7405

\[ \int \cdots \]

In our kinematic regime loops are suppressed by \( \sim \frac{1}{N} \).
for 2→N amplitude we get

\[ \sigma_{2→N} = \frac{S}{M_p^4} \left( \frac{1}{N} \right)^N N! = \frac{S}{M_p^4} \tilde{c}^N \]

This exactly matches the black hole entropy factor!
Our result are UV-insensitive; we get the same result in field theory and string theory.