WHY BLACK HOLES PHYSICS?

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General motivations I

Find a microscopic description of gravity, compatibile with the Standard Model (SM) and whose low-energy limit is described by General Relativity (GR).

- Physical scale for quantum gravity:

$$l_P \sim 1.6 \times 10^{-35}\,\mathrm{m} \qquad m_P \sim 1.2 \times 10^{19}\,\mathrm{GeV}/c^2$$

- Superstring theories are the best candidates as quantum theories of gravity because they admit GR as low energy limit and contain the SM. But **supersymmetry (SUSY) must hold**!

General motivations II

Black holes and their thermodynamics: Study macroscopic configurations of (super)gravity in order to get new insights on the correspondent microstates.

Black holes and supergravity

A black hole is a classical solution of the equations of motion for a field theory containing gravity. The gravitational field describes the metric of spacetime and, for black holes, it has a singular point and an event horizon.

- **General Relativity**: The simplest theory of gravity without SUSY.
- **Supergravities**: SUSY generalizations of GR.
  - Many fields are present ($s = 2$, $s = 3/2$, $s = 1$, $s = 1/2$, $s = 0$).
  - Many supergravities for different dimensions, D, and for different numbers of supersymmetries, $\mathcal{N}$.

Black holes and thermodynamics I

In the early seventies an analogy between the laws of black hole dynamics and the laws of thermodynamics was discovered:

Laws of thermodynamics

0) T constant at the thermal equilibrium, 2) $\delta S \geq 0$ for every system,

1) $\mathrm{d}E = T\mathrm{d}S + \delta W\,,$ 3) $T = 0$ is a lower limit.

Laws of dynamics of a black hole

0) κ constant on the event horizon of a stationary black hole,

1) $\mathrm{d}M = \frac{1}{8\pi}\,\kappa\,\mathrm{d}A + \Omega_H \mathrm{d}J\,,$ 2) $\delta A \geq 0$ for every process,

3) $\kappa = 0$ is a lower limit.

Black holes and thermodynamics II

This is something more than a simple analogy:

- $E \longleftrightarrow M$. They are the same physical quantity: The total energy of the system.
- $T \longleftrightarrow \kappa$. Hawking radiation and quantum effects: Black holes have the physical temperature $T_H = \frac{h}{4\pi^2}\,\kappa$.
- $S \longleftrightarrow A$. Bekenstein-Hawking (BH) entropy, $S_{BH} = \frac{A}{4}$.

The missing link is the physical interpretation of S_{BH}, this means knowing and counting the microstates of black holes, i.e.

$$S = k_B \log N \qquad\qquad N = \; ?$$

Microscopic interpretation and superstring theory

Black holes belonging to SUSY-invariant theories represent the low energy limit of configurations of superstrings and branes:

- solutions on a spacetime background with cosmological constant,
- solutions of supergravity models.

Entropy calculations starting from some superstring configurations $\Longrightarrow$ the results match exactly with the S_{BH} of black hole solutions of supergravity!!!

Microstates of black holes describe configurations of quantum theories strongly coupled to gravity.

The research of new solutions in supergravity I

The aim of our research is finding new black hole solutions in the matter-coupled $\mathcal{N} = 2$, $D = 4$ gauged supergravity

- Multiplets of fields:
  - **supergravity multiplet**, $(e^a_\mu, \psi^i_\mu, A^0_\mu)$,
  - **vector multiplets**, $(A^\alpha_\mu, z^\alpha, \chi^{i\alpha})$ with $\alpha = 1, \cdots, n_V$,
  - **hypermultiplets**, (q^u, ζ^A) with $u = 1, \cdots, 4n_H$ and $A = 1, \cdots, 2n_H$.
- "Gauged" because vector fields are the gauge fields respect to various local symmetries.
- The action is determined by the **scalar geometry**: The scalars are the coordinates of particular target manifolds → sigma-models.

The research of new solutions in supergravity II

- Discard fermionic fields in order to get classical solutions.
- Equations of motion $\rightarrow$ strongly non-linear second-order system of PDEs.
- System of first-order PDEs belonging to SUSY called BPS equations.
- Prescriptions on the black hole solution: $SO(3)$ symmetry, staticity, etc...
- Physical properties of the solutions: near horizon limit and asymptotic limit, etc...
- Calculate the Bekenstein-Hawking entropy S_{BH}.

Example of solution: hypermultiplets

$$ds^2 = \frac{16\, r^2}{g^2 k_1 c}\left[\left(1+\frac{k_0}{c}\frac{1}{r^2}\right)^2 r^2 dt^2 - \left(1+\frac{k_0}{c}\frac{1}{r^2}\right)^{-2}\frac{dr^2}{r^2} - \frac{1}{2}d\Omega^2_{H^2}\right]\,,$$

$$A^0 = -\frac{\cosh\vartheta}{gc}d\varphi\,, \qquad A^1 = \frac{k_0}{k_1}\frac{\cosh\vartheta}{gc}d\varphi\,,$$

$$\phi = -\log r\,, \qquad Z = \frac{c}{k_1}\,r^2\,.$$

- Model with one vector multiplet and one hypermultiplet.
- First black hole solution in presence of hypermultiplets $\rightarrow\ \phi$.
- Magnetically charged $\rightarrow p^0, p^1$.
- Hyperbolic horizon and $S_{BH} = 32\,\pi^2\,p^0 p^1$.

[Chimento, Klemm, Petri, 15]

Example of solution: quantum corrections I

- Model belonging to the first-order corrections of type IIA superstring.
- Three vector multiplets, No hypermultiplets.
- Dyonic black hole: Both electric and magnetic charges.
- The solution can have an horizon with spherical, hyperbolic or flat symmetry, i.e.

$$ds^2 = e^{2U}\,dt^2 - e^{-2U}\,dr^2 - e^{2\psi-2U} d\Omega^2_{\Sigma^2} \qquad \text{with} \qquad \psi = ar^2 + c$$

- BH entropy depending only on charges.

Example of solution: quantum corrections II

$$e^{2U} = \frac{2g_0 g^3 (ar^2 + c)^2}{\lambda^3_\infty \left(ar - g_0\beta^0 - \frac{g_0}{(\lambda^3_\infty)^2}\beta_3\right)\sqrt{(ar + 2g_0\beta^0)\left(ar + \frac{2g_0}{(\lambda^3_\infty)^2}\beta_3\right)}} \,.$$

$$\lambda^1 = \frac{a\,\frac{g^1}{g^3}\left(\lambda^3_\infty\right)^2 r - g_0\,\beta_3\left(\frac{g^1}{g^3} - A\,\frac{g^3}{g^2}\right) - \beta^0\,\frac{g_0^2}{g^2}}{\sqrt{(2g_0\,\beta^0 + a\,r)\left(2g_0\,\beta_3 + a\,r\,(\lambda^3_\infty)^2\right)}}\,,$$

$$\lambda^2 = \frac{g^2}{g^3}\lambda^3\,, \qquad \lambda^3 = \lambda^3_\infty\sqrt{\frac{ar + \frac{2\,g_0}{(\lambda^3_\infty)^2}\,\beta_3}{ar + 2g_0\beta^0}}\,,$$

[Klemm, Marrani, Petri, Santoli, 15]

Conclusions

- We introduced the general motivations supporting the research of new black hole solutions.
- We explained the central role of the BH entropy of black holes in relation to the microscopic configurations belonging to the superstring theory.
- We presented the field content of $\mathcal{N} = 2$, $D = 4$ gauged supergravity and sketched how to find new black hole solutions.
- We presented two concrete examples of black hole solutions obtained in this theory.

Thanks for your attention!