Black Holes viewed as Bose-Einstein Condensates of Gravitons

Peter Labus
Advisor: Prof. Gia Dvali

LMU Munich

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Introduction

- Usual treatment of gravitational systems:
  Description by background geometry which is produced by the gravitating system (Black Holes, universes).
- Semi-classical approximation:
  Take small fluctuations about background, but leave the background itself an intrinsically classical entity.
- BUT: $\hbar \neq 0$
- Quantum nature of the background cannot be resolved in this picture.

Introduction

- Instead:
  Classical geometry $\equiv$ effective description of the quantum state with large graviton occupation number N
- If such a state is a ground state:
  Gravitational field is effectively a Bose-Einstein condensate (BEC) of gravitons
- A Black Hole can be viewed as a self-sustained BEC

Introduction

Special properties of Black Holes:

- self-sustained
- maximal packed, i.e. one cannot increase N without increasing the size L of the BEC
  Maximal Packing corresponds to the critical point of a quantum phase transition.
- N is the sole characteristic of the Black Hole:
  - occupation number: N
  - wave-length: $\lambda = \sqrt{N} L_p$
  - coupling: $\alpha = 1/N$
  - mass: $M = \sqrt{N}/L_p$
- condensate is leaky $\longleftrightarrow$ (self-similar) quantum depletion

Introduction

$\Rightarrow$ Emergence of thermality

- Hawking radiation with thermal spectrum up to $1/N$ corrections and effective temperature $T_H = \frac{\hbar}{\sqrt{N}L_p}$
- Negative heat capacity is a simple result of decreasing N

Black Holes as Bose-Einstein Condensates

Strength of graviton-graviton interaction is measured by the "coupling constant":

$$\alpha \equiv \frac{L_p^2}{\lambda^2}, \tag{1}$$

where λ is the typical wave-length of the gravitons.
One may think of it as the relativistic version of the Newtonian attraction and define:

$$V(r)_{Newton} = -\hbar \frac{\alpha}{r}. \tag{2}$$

Black Holes as Bose-Einstein Condensates

Now, localize as many soft gravitons as possible within space region L, i.e. form a BEC of gravitons with characteristic wave-length $\lambda = L$.
To get a self-sustained condensate we need to equate (individual) kinetic energy and (collective) binding energy:

$$E_{tot} = E_{kin} + N_c\, V(L)_{Newton} = \frac{\hbar}{\lambda} - N_c\, \alpha\, \frac{\hbar}{L} = 0. \tag{3}$$

This gives the critical occupation number and the size of the Black Hole:

$$N = 1/\alpha \;\Rightarrow\; L = \sqrt{N}\, L_p. \tag{4}$$

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The condensate undergoes a quantum depletion which diminishes N. Due to interaction the gravitons can be excited above the ground state energy, leave the condensate and join the continuum.This process is dominated by $2 \rightarrow 2$ scattering. The depletion rate can be estimated as follows

$$\Gamma_{leakage} = \frac{1}{N^2} N^2 \frac{\hbar}{\sqrt{N}\, L_p} + L_p^{-1}\, \mathcal{O}\left(N^{-3/2}\right). \qquad (5)$$

This rate sets a typical time-scale $\Delta t = \hbar\, \Gamma^{-1}$ from which we can deduce the leakage law

$$\dot{N} = -\frac{1}{\sqrt{N}\, L_p} + L_p^{-1}\, \mathcal{O}\left(N^{-3/2}\right). \qquad (6)$$

Black Holes as Bose-Einstein Condensates

The leakage law reproduces Hawking radiation precisely in the semi-classical limit

$$N \to \infty, \; L_p \to 0, \; \sqrt{N}\, L_p = \text{finite}, \; \hbar = \text{finite}\,, \tag{7}$$

in which the condensate has infinitely many infinitely soft non-interacting gravitons.
This unphysical treatment might be the origin of the semi-classical Black Hole mysteries.
In this limit we recover Stefan-Boltzmann law for Black Holes

$$\dot{M} = -\frac{\hbar}{L^2} = -\frac{T^2}{\hbar}\,, \tag{8}$$

where $M = N/\lambda$ and $T_H = \hbar/L$ are the Black Hole mass and Hawking temperature respectively.

Outlook

- More general Black Holes and higher dimensions
- Microscopic description and connection to ordinary BECs (like cold atoms)
- Generalizations to AdS/dS?
  - Implications for cosmology
  - AdS/CFT?
- Connection to Classicalization

References

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Many thanks for your attention!