Black Holes as Quantum Bound States

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Contents

Classical Black Holes

General Relativity:

$$S = M_p^2 \int d^4x \sqrt{-g}(R + g^{\mu\nu} T_{\mu\nu}) \tag{1}$$

- Schwarzschild Black holes: Spherically symmetric solutions with source radius $R = r_g = 2G_N M$
- event horizon: "nothing can escape from a black hole"
- in general: Black Holes characterized by mass M, charge Q, angular momentum L

Semiclassical Black Holes

Basic Idea: Quantize matter field in classical background

- Consequence: Hawking radiation
  $T \sim 1/r_g$, $\Gamma \sim 1/r_g$
- Remark:
  Quantum Corrections believed to be exponentially suppressed
- Mysteries:
  - negative heat capacity
  - no hair theorems
  - information paradox

No resolution within semiclassical approach

Graviton Bound States

- interpret GR as EFT of graviton on flat spacetime
- Black holes: Bound states of N soft gravitons ($\lambda \sim r_g$)[1]
  (analogy: Hadrons in QCD)

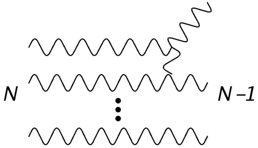
$$M = \sqrt{N} M_p, \;\; r_g = \sqrt{N} L_p, \;\; \alpha = 1/N \tag{2}$$

- e.g. for solar mass black hole: $N \sim 10^{71}$
- coupling weak, but large collective effect $\alpha N = 1$
  (compare to baryons in large N QCD)

[1] Dvali, Gomez; 1112.3359 [hep-th]

Implications

- known results recovered as $N \to \infty$
  e.g. Hawking radiation:



$$\Gamma \sim 1/r_g + \mathcal{O}(1/N) \tag{3}$$

- **new $1/N$ corrections large enough to resolve all the black hole mysteries!**
- Question: Quantitative theoretical framework?

QCD Analogy

Use methods inspired from QCD to describe black hole bound states[2]

- confining potential at low energies → large collective effects
- hadrons → large N graviton bound states
- condensates of quarks and gluons → condensates of gravitons and curvature invariants
- hadronic currents, e.g. $\mathscr{J}(x) \sim \bar{q}q(x)$ → black hole currents $\mathscr{J}(x) \sim h^N(x)$

[2] Hofmann, Rug; 1403.3224 [hep-th]

Explicit Construction

Model black hole state $\mathscr{B}$ by auxiliary current $\mathscr{J}(x)$:
$\langle\mathscr{B}|\mathscr{J}(x)|\Omega\rangle \neq 0$

- $\mathscr{J}(x)|\Omega\rangle$: same quantum numbers as $|\mathscr{B}\rangle \Rightarrow \mathscr{J}(x) = h^N(x)$ (take scalar fields for simplicity)
- consistency with isometries: $\mathscr{J}(x) = \mathscr{J}(r)$
  Ward: implement symmetries at the end of computations
- $$|\mathscr{B}\rangle = \Gamma_B^{-1}\int \frac{\mathrm{d}^4 p}{(2\pi)^4} B(p) \int \mathrm{d}^4 x e^{ipx} \mathscr{J}(x)|\Omega\rangle \qquad (4)$$
- Remark:
  Generalization to other spacetimes (including perturbations) and topological defects possible!

Observables at Parton Level

- Light-cone constituent distribution:

$$\mathscr{D}(r) = \int \mathrm{d}^3 k\, \mathrm{e}^{-\mathrm{i} k \cdot r} \langle \mathscr{B} | n(\mathbf{k}) | \mathscr{B} \rangle \tag{5}$$

- Energy density:

$$\mathscr{E} = \langle \mathscr{B} | T_{\mu\nu}(x) | \mathscr{B} \rangle \tag{6}$$

- Evaluation using (4) in $N, M \to \infty$, N/M fixed limit leads to

$$M_{\mathscr{B}}^2 = \frac{\langle \Phi^{2(N-1)} \rangle}{\langle \Phi^{2(N-2)} \rangle} N^2 \tag{7}$$

Remarks

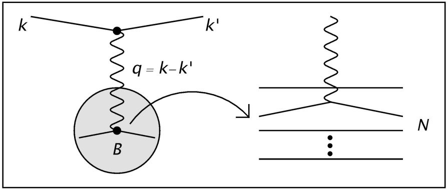
- scaling: $M \sim N$ expected at parton level (compare to large N baryons in $1/N$ expansions)
- finite $N \Rightarrow 1/N$ corrections
- higher-order corrections can be implemented in a gauge-invariant way via Wilson lines:

$$\mathscr{P} \exp\left(-\oint \mathrm{d}z^{\lambda} \Gamma^{\mu}_{\mu\lambda}(z)\right) \tag{8}$$

- $x^{\mu} x^{\nu} \Gamma^{\lambda}_{\mu\nu}$ gauge: all condensates automatically gauge-invariant (analogue: External field methods and Fock-Schwinger gauge in QCD sum rule calculations)

Scattering

- $\langle \mathscr{B}'\Phi'|\mathscr{B}\Phi\rangle$ in tree approximation[3]



- $r_g^{-2} \ll q^2 \ll M_p^2$: EFT description valid, but resolution of bound state possible
- ACD and OPE lead to

$$k'^0 \frac{\mathrm{d}\sigma}{\mathrm{d}^3 k'} \sim \mathscr{D}(r) \tag{9}$$

[3] Gruending, Mueller, Hofmann, Rug; 1407.1051 [hep-th]

Summary and Outlook

Summary:

- treat black holes as large N bound state of gravitons
- employ QCD inspired methods
- $1/N$ corrections as solution to black hole mysteries
- scaling $M \sim N$, embedding of observables in scattering experiments

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Outlook:

- large N baryons
- black hole formation
- application to different spacetimes

Thank You for Your Attention