Black Holes as Quantum Bound States

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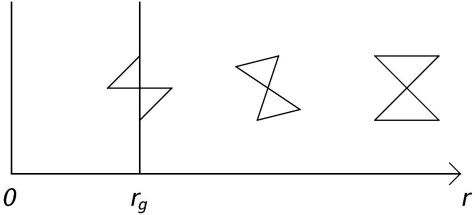
Contents

Classical Black Holes

General Relativity:

$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = 8\pi G_N T_{\mu\nu} \tag{1}$$

- Schwarzschild black holes: spherically symmetric solutions with source radius $R = r_g = 2G_N M$
- event horizon: "nothing can escape from a black hole"



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

$\boxed{\text{No resolution within semiclassical approach}}$

Graviton Bound States (Dvali, Gomez; 1112.3359)

- interpret GR as EFT of graviton on flat spacetime, $g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}$
- Black holes: Bound states of N soft gravitons ($\lambda \sim r_g$) (analogy: Hadrons in Quantum Chromodynamics (QCD))

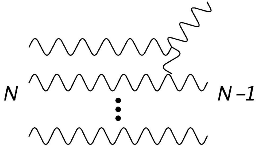
Scaling Relations

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

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

Implications

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



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

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

Basic Idea (Hofmann, Rug; 1403.3224)

- construct observables connected to black hole state $|\mathscr{B}\rangle$
- represent $|\mathscr{B}\rangle$ in terms of graviton fields

$$\langle\mathscr{B}|J(x)|\Omega\rangle \neq 0, \quad J(x) = \Phi^N(x) \tag{4}$$

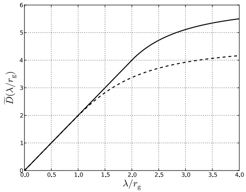
- construct observables $\langle\mathscr{B}|\mathscr{O}|\mathscr{B}\rangle$
- use Wick's theorem to evaluate these observables

Remark: Non-perturbative effects due to non-vanishing normal-ordered products of fields $\Rightarrow$ condensates

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:

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

Remarks

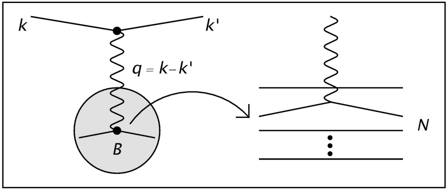
- evaluation using in $N, M \to \infty$, N/M fixed limit leads to

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

- scaling: $M \sim N$ expected at parton level
- finite $N \Rightarrow 1/N$ corrections
- observables dominated by non-perturbative condensates
- higher-order corrections can be accounted for perturbatively
- construction possible for arbitrary spacetimes

Scattering (Gruending, Mueller, Hofmann, Rug; 1407.1051)

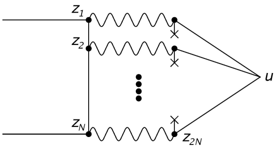
- $\langle \mathscr{B}'\Phi' | \mathscr{B}\Phi \rangle$ in tree approximation



- $r_g^{-2} \ll q^2 \ll M_p^2$: EFT description valid, but resolution of bound state possible
- $$k'^0 \frac{\mathrm{d}\sigma}{\mathrm{d}^3 k'} \sim \mathscr{D}(r) \qquad (8)$$

Black Hole Formation (Gruending, Mueller, Hofmann, Rug; to appear)

Transplanckian scattering ($E = \sqrt{s}$) with impact parameter smaller than corresponding Schwarzschild radius
$\Rightarrow$ Possibility of black hole formation



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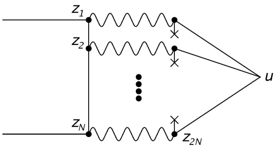

Amplitude: $\langle \mathscr{B} | a^\dagger(k_1) a^\dagger(k_2) \rangle \sim f(N) e^{-N}$
Factorization of perturbative and non-perturbative contributions!

Summary

Summary:

- treat black holes as large N bound state of gravitons
- $1/N$ corrections as solution to black hole mysteries
- employ QCD inspired methods
- scaling $M \sim N$, embedding of observables in scattering experiments
- black hole production: $\mathscr{A} \sim e^{-N}$
- construction applicable to generic spacetimes

Outlook

Outlook:

- computation of $1/N$ corrections
- RG evolution
- black hole merger
- de Sitter spacetime and inflation
- AdS/CFT correspondence

Thank You for Your Attention