Theoretical Physics Foundations
Black Holes Session

Part I: generalities, insights from string theory (Jan de Boer, Amsterdam)

Part II: (loop) quantum gravity perspective and scenario's (Francesca Vidotto, Bilbao)

Part III: discussion of scenario's and GW tests (Steve Giddings, Santa Barbara/CERN)

Theoretical Physics Foundations
Black Holes
Part 1

Jan de Boer, Amsterdam

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Disclaimer: impossible to properly cover the subject or to give proper credit

General Relativity is a (great) classical theory but such incomplete. The world is quantum!

Could try to consider field equations of the type

$$R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} = 8\pi G \langle T_{\mu\nu} \rangle$$

which can be a good approximation if fluctuations in the energy-momentum tensor are small. But this cannot be a complete description.

General relativity is usually interpreted in terms of *low-energy effective field theory* (EFT).

What do we know?

- There should be additional fields (standard model, dark matter(?), …) in the theory.
- From an effective field theory point of view one expects that generic higher-order corrections will be present.

$$S = \frac{1}{16\pi G}\int d^4x\sqrt{-g}\,\Big(R + \ldots + c\ell_P^{2k-2}R^k + \ldots$$
$$\ldots + \frac{1}{g_{YM}^2}F_{\mu\nu}F^{\mu\nu} + \ldots + a_{k,l}\ell_P^{2k+2l-2}F^{2k}R^l + \ldots\Big)$$

Issues: difficult to model inspiral/merger/ringdown, initial value problem, instabilities, how to distinguish?

There is also the exciting possibility that the EFT framework itself breaks down near black holes due to quantum gravitational effects. Observing this would be spectacular!

Why do we believe this is in some sense inevitable? Recall:

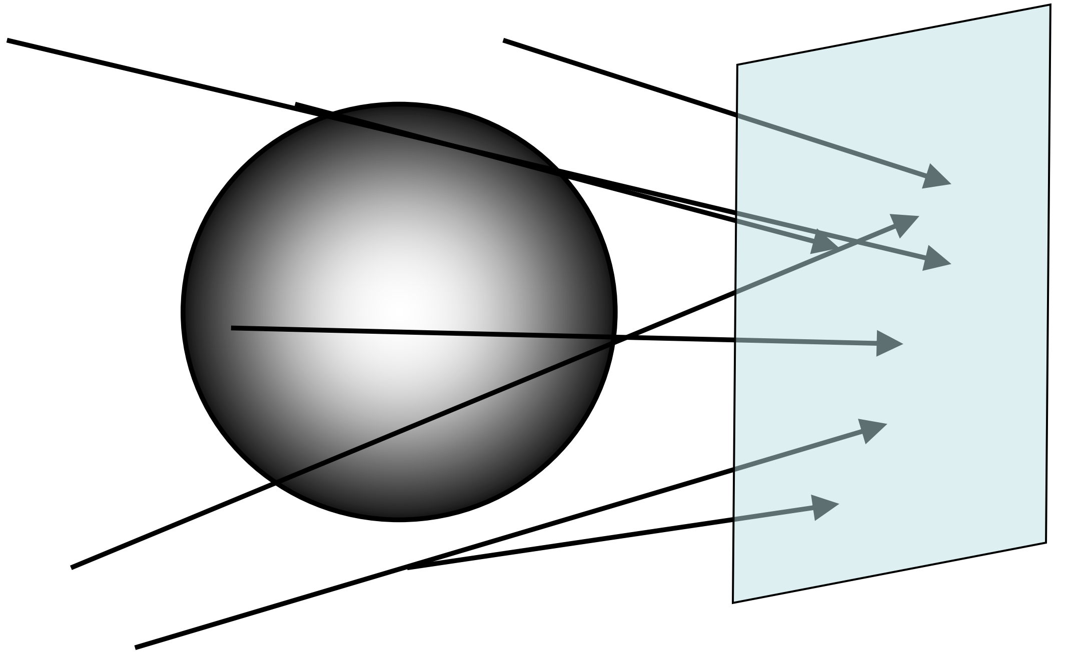
Equilibrium Thermodynamics	Black Hole Mechanics Carter,Bardeen,Hawking
0th law $T=\text{const.}$	0th law $\kappa=\text{const.}$
1st law $dE = T\, dS$	1st law $dM = \kappa/(8\pi G)\, dA$
2nd law $dS \geq 0$	2nd law $dA \geq 0$

This plus the famous computation of Hawking led to the Bekenstein-Hawking formula for the entropy of a black hole:

$$S = \frac{Ac^3}{4G\hbar}$$

'‘t Hooft, Susskind

and also to the “holographic principle” which states that quantum gravitational degrees of freedom behave like ordinary degrees of freedom in one dimension less.



Holographic screen

The Bekenstein-Hawking entropy formula has been verified in many examples in string theory, and the holographic principle has been made precise in the AdS/CFT correspondence.

Conclusion: quantum gravity is fundamentally *not* a local quantum field theory and there is no a priori reason to expect all physics to be captured by a local effective field theory.

When does this become relevant? For black holes!

Why? Because EFT leads to the information loss paradox which in turn leads to an apparent loss of unitarity.

→ EFT must break down for evaporating black holes made from low entropy initial configurations. But where? How? And when? Can we observe this?

Problem becomes most apparent around “Page time”, which is of order M^3 where a black hole has shrunk to half its original size. There are then no longer enough degrees of freedom left in the black hole to make the full state (black hole plus radiation) pure.

But timescales could be as short as the scrambling time which is of order M log M.

A few possibilities from the literature:

- Firewalls (Almheiri, Marold, Polchinski, Sully) Not entirely clear where firewall should be located, precise model of firewall is lacking.
- Fuzzballs (Mathur) Not clear what the generic prediction is.
- ➢ Both have “structure at or near horizon” but is it hot/absorbing/reflecting?
- ER=EPR (Maldacena Susskind) – mini wormholes create non-locality but no obvious signature
- Nothing (Papadodimas Raju) – EFT only breaks down for very complicated observables – no signature
- AdS/CFT supports validity of EFT for low-energy observers.
- ➢ Both have some issues with quantum mechanics
- See also Part II and Part III

My 10 cents

- Include generic higher order terms in effective field theories – don’t focus too much on fine-tuned models with artificial properties
- Discard EFT’s that violate causality.
- Be suspicious of EFT’s with instabilities due to higher order corrections
- Be aware of ongoing theoretical work to discard classes of EFT’s (e.g. “swampland” discussion)
- It seems hard to systematically study the breakdown of EFT; can perhaps test generic statements like the Bekenstein-Hawking entropy formula and the second law.
- Conservative scenario: we may not see a breakdown of EFT.
- Ringdown may be the most promising place to look (cf Cardoso, Franzin, Pani)