Beyond Schwarzschild: quantum implications for black holes

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Karl Schwarzschild Meeting 2015
FIAS
Black holes are the most profoundly mysterious objects in nature.

While the BH concept first originated w/ Michell (1783) and Laplace (1796), Schwarzschild first placed them in our current understanding of gravity:

1916: Schwarzschild solution

\[ ds^2 = (1 - \frac{\alpha}{R}) dt^2 - \frac{dR^2}{1 - \frac{\alpha}{R}} + R^2 (d\theta^2 + \sin^2 \theta d\phi^2) \]

\[ R = (r^2 + \alpha^2)^{1/2} \]
Interestingly, their existence, and the need to explain their evolution, calls for a major revision of current laws of nature.

This conclusion arises from increasingly strong arguments for a significant modification of Schwarzschild’s original picture ...
A first crucial update: Hawking 1974

Include quantum effects;

Black holes evaporate

$$\omega \sim \frac{1}{R}$$

$$\frac{dM}{dt} \sim -\frac{1}{R^2}$$

Black holes evaporate
This is based on physics we know and love ... 

Semiclassical spacetime + local QFT

... but yields a fundamental conflict

- Entanglement between BH and environment grows: monotonic
- If BH disappears, unitarity violated

Failure of quantum mechanics

Conflict among basic principles:

Principles of relativity
Principles of quantum mechanics
Principles of locality
Apparently one or more of these principles must be modified.

A goal:

Find more basic physics that:

- Matches LQFT in "ordinary circumstances"
  E.g. doesn’t violate locality, etc.

- Saves quantum mechanics

- Minimally disrupts semiclassical picture

The need to unitarize BH evolution is a crucial constraint
What is required?

In order to

1) approximately maintain spacetime,
2) save unitarity/QM:

Need to transfer q. information (entanglement) from BH to environment.

LQFT doesn’t do this (*locality*)

How is SCST + LQFT modified?
A first proposal for nonlocal transfer: hep-th/9203059

Massive Remnant

Nonlocal information transfer

Subsequent incarnations:
- Fuzzballs
- Firewalls (if $R_{rem} = R$)
- Planck stars
The problems with such massive remnant alternatives:

- They represent a violent breakdown of semiclassical spacetime (not minimal disruption)

- They “artificially” introduce new short-scale (“hard”) physics to resolve a long-distance problem

Is there a less violent alternative?
Proposal: Nonviolent nonlocality -- basic picture

Characteristics:

1) Information transfer from “internal” DOF to BH exterior. Locality w.r.t. SC geom forbids: “nonlocal”

2) Relevant scales

\[ L \gg l_{Pl} \quad \text{e.g.} \quad L \sim R^p, \quad p > 0 \]

(characterizes horizon separation, wavelengths)

“Soft,” or nonviolent

(see e.g. arXiv:0911.3395, 1108.2015, 1201.1037, 1211.7070; Dodelson/Silverstein?)
Another way to state:

**Complementarity/AMPS postulates**

I) Unitary QM / S-matrix

II) Semiclassical field eqns outside stretched horizon

III) BH is Q. system with # states given by $S_{BH}$

IV) Free-faller sees nothing unusual crossing horizon

**Violate postulate II**

specifically: info transfer allowed, over characteristic scale L
How does this arise from a fundamental theory?

Don’t yet have complete picture.

Dovetails w/understanding: *locality not sharp in QG*

(See, e.g., hep-th/010323, hep-th/0604072, 1503.08207)

Maybe comes out of AdS/CFT, somehow.

(If/when we understand what AdS/CFT tells us.)

Or: BH as key *guide* to principles?  (cf: atom/QM)
A possible approach:

If “small” corrections near BH: can model as *modification to LQFT*?

Can begin to test:

What sharp constraints?
(firewall, or more radical, necessary?)

What do we have to give up?
(we know something!)

Are there observational consequences?

[arXiv:1211.7070, 1302.2613, 1310.5700]
Let’s avoid double standards:

Objection: no fundamental theory, or complete model

E.g. “I can find problem X in your model. Therefore, there must be a firewall.”

Well, one doesn’t have a fundamental theory or complete model of firewalls either, and if people started to write them down I expect there would be various serious objections.

So: can we infer reasonable physical behavior by making more detailed models,

Or is there a sharp argument against such models on reliable physical grounds?

Put differently: since the unitarity crisis tells us we have to give up something, assess: what could it plausibly be?
Phenomenological *models* (not yet theories)

Assume SCST, LQFT, +corrections, for \( r > R/2 \)

\[
\int \! dt \Delta H \sim - \Delta S \sim \sum_{AB} \int_{r > R/2} dV_4 \; O_A \; G_{Ab}(x) \; O_b(x)
\]

acts on “\( \mathcal{H}_{r < R/2} \)”

acts on “\( \mathcal{H}_{r > R/2} \)”

coupling functions

Simple examples:

\[
\int dV_4 J(x) \Phi(x)
\]

J’s: quantum sources;

\[
\int dV_4 J^{\mu\nu}(x) T_{\mu\nu}(x)
\]

\~ classical

[arXiv:1302.2613, 1310.5700, 1401.5804]
These interactions transfer information (entanglement) from BH to its atmosphere; it then escapes.

A challenge:

Generically, unless disrupt Hawking process, these yield

$$\frac{dE}{dt} > \frac{dE}{dt} \bigg|_{\text{Hawk}}$$

So \( S_{bh} < S_{BH} \) by detailed balance

So, we face a choice:

1) Make peace w/ \( S_{bh} < S_{BH} \)?

2) Find special evolution w/ Hawking flux (or, no go)

3) Firewall, or more radical ...
Do we know BH density of states $\sim e^{S_{BH}}$?

Alternative: $S_{BH}$ characterizes semiclassical near-horizon geometry (which we know doesn’t give exact physics - extreme case FW)

Any incontrovertible evidence for $S_{BH}$?

1) BTZ/Cardy formula 2+1 special; assumes AdS=CFT
2) Strominger/Vafa weak coupling; $\sim$BPS
3) Hanada et al
These are strongly suggestive.

Are they incontrovertible?

If $S_{bh} = S_{BH}$ did imply firewalls, would we believe it?

$.\cdot$ perhaps $S_{bh} < S_{BH}$ consistent.

But this is a little inelegant; people are uncomfortable giving up such a simple story.
An apparent alternative, with intriguing features:

\[ G^{\mu\nu}(x) \]
\[ \int dV_4 T^{\mu\nu}(x) T_{\mu\nu}(x) \]

I.e. effective description: BH state-dependent metric fluctuations
(think of as \( \sim \) inaccuracy of classical geometry)

universality \( \sim \) gravity

These can “modulate” Hawking radiation; possibility of small (vanishing?) increase of energy flux.

\[ \delta P_-(x^-) = \int dx^- \langle \delta T_{--} \rangle_G = 0 \]

2d model: to linear order in \( G \)

[arXiv:1401.5804]

(helps address mining)
How large are these effective fluctuations?

Constraint: \( \frac{dS_{vN}}{dt} \sim - \frac{1}{R} \)

Suppose (e.g.) \( L \sim 1/\omega \sim R \)

\[ \Rightarrow \quad \text{e.g.} \quad \langle I | G^{\mu \nu}(x) | J \rangle \sim e^{-i\omega v + ikr} f_L(r) \]

\[ \mathcal{O}(1) \quad \text{restricts to} \quad r \lesssim R + L \]

\[ \therefore \quad \text{Strong, soft effective metric fluctuations} \]

A new firewall alternative (significant mods. to HR...)

(Some superficial similarity to Dvali/Gomez; though strong interacting, closer to Schwarzschild; not just weak graviton “gas”)

[arXiv:1401.5804]
An opportunity:

**BH**

Event horizon telescope:

BH shadow, photon ring

(see talk by S. Britzen)

Thursday, July 23, 15
An opportunity: Event horizon telescope:

BH

arXiv:1406.7001

"Shimmering" BHs: distort

r=3R/2
(Schwarzschild)

Sgr A*

SBG/Psaltis, WIP

"Shimmering" BHs: distort

Theoretical uncertainty:

\[ t_{qn} \sim t_{Fast\,Sc} \sim R \log R \sim 8 \text{ hr} \]
\[ t_{1/2} \sim R^3 \sim 10^{74} t_{\text{Universe}} \]

\} \text{ bounds}

If due to inaccuracy of geometrical description, R lnR reasonable
Summary:

BHs have led us to a “Unitarity crisis;” represents a conflict among fundamental principles ... something has to give

“NVNL” proposes “soft” information transfer to the “atmosphere” of a BH; violates macro. SC locality

Typical models give $S_{bh} < S_{BH}$; $S_{bh} = S_{BH}$ requires significant modifications of Hawking radiation

Effective metric fluctuations: a natural, universal alternative

Necessary info transfer: strong, soft fluctuations; big departure from Schwarzschild’s solution!

These present observational opportunity as we image BHs (EHT, etc.)