Article

Searching for Quantum Black Hole Structure with the Event Horizon Telescope

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Abstract: The impressive images from the Event Horizon Telescope (EHT) sharpen the conflict between our observations of gravitational phenomena and the principles of quantum mechanics. Two related scenarios for reconciling quantum mechanics with the existence of black hole-like objects, with "minimal" departure from general relativity and local quantum field theory, have been explored; one of these could produce signatures visible to EHT observations. A specific target is temporal variability of images, with a characteristic time scale determined by the classical black hole radius. The absence of evidence for such variability in the initial observational span of seven days is not expected to strongly constrain such variability. Theoretical and observational next steps towards investigating such scenarios are outlined.

The impressive success [1] of the Event Horizon Telescope (EHT) in imaging of the apparent black hole in M87 has opened a second observational window to the regime of strong gravity, following the detection of gravitational waves from black hole mergers [2]. It has been widely believed that, due to the smallness of the curvature near the horizon of a large black hole (BH), this is a regime governed by classical general relativity (GR). However, it has been increasingly appreciated that the inconsistency of BH evolution with the principles of quantum mechanics, given the Hawking effect [3], strongly motivates the need to modify the classical description of a BH at horizon scales [4–10]. This suggests searching for signatures of such modification in EHT or gravitational wave observations [11–13]. As this note will elaborate on, a particularly interesting target is temporal variability of EHT images [14].

Without such modification of BH behavior on horizon scales, BH evolution appears to contradict quantum mechanics. Suppose we think of a BH as a subsystem of a larger quantum system including its environment. Either through interaction with surrounding matter and radiation, or just through the Hawking process itself, the BH subsystem will absorb information from its environment.[1] However, the Hawking process also indicates that BHs ultimately evaporate away. Locality of the geometric description of a BH states that a BH cannot release information while evaporating. Moreover, if an information-containing subsystem ceases to exist without releasing its information, that violates the basic quantum-mechanical principle of unitary evolution.

To preserve unitarity, BHs must release their information; simple arguments [15,16] indicate that this should begin midway through a BH's decay, while the BH is comparable to its original size. Such information release requires some modification to the description of a BH that is based local

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1   More precisely, it develops entanglement with its environment.

quantum field theory (LQFT) evolution on a classical BH geometry; this modification needs to occur on scales comparable to the size of the event horizon, for an arbitrarily large black hole.

In searching for the physics that makes BHs consistent with quantum mechanics, a reasonable approach is to seek a minimal departure from the conventional GR/LQFT description of BHs, possibly corrected for small backreaction effects. In fact, such a "correspondence principle" is a third postulate for BH evolution, beyond the postulates of consistency with quantum mechanics and of approximate validity of a subsystem description [17].

While there are various other conjectured scenarios for how BH evolution can be consistent with quantum mechanics [7,9,18], the correspondence postulate strongly suggests an effective parameterization of BH evolution in terms of interactions between the BH quantum state, and the quantum degrees of freedom of the BH atmosphere. Such an effective description has been developed in [8,17,19–21].

Beyond the three preceding postulates, a fourth [17] is that such interactions between a black hole and its environment couple universally to all degrees of freedom. This is plausible for an effect that is intrinsically gravitational, and is also strongly motivated both by Gedanken experiments involving black hole mining [22–25] and by the desire to maintain as many features as possible of the beautiful story of BH thermodynamics.

The interactions are most easily described in a hamiltonian approach, where they provide modifications of the usual hamiltonian evolution of LQFT, on a chosen set of time slices.[2] Combining the four postulates then strongly motivates interactions described by an effective Hamiltonian

$$H_I = \int \sqrt{-g_{tt}}\, dV\, H^{\mu\nu}(x) T_{\mu\nu}(x) \,. \tag{1}$$

Here dV is the volume element on the time slices and g_{tt} is the metric component in slice-time t, $T_{\mu\nu}(x)$ is the stress tensor for field excitations,[3] and $H^{\mu\nu}(x)$ parameterize the interactions with the BH.[4] Specifically, the $H^{\mu\nu}$ are operators that act on the BH quantum state, and these have spatial dependence that localizes them near the BH. The simplest way to satisfy the correspondence principle is if these are localized within a distance of $\mathcal{O}(R)$ from the event horizon of the classical geometry, of radius R, although more complicated scalings are possible [12]. One immediately sees that the interactions Equation (1) behave like BH state dependent metric perturbations. This raises the prospect of observational signatures in EHT images, due to the effect of such interactions on light propagation near the horizon.

A key question for prospects of observing such a "quantum halo" is the size of the $H^{\mu\nu}$. In units, $\hbar = c = 1$, $H^{\mu\nu}$ is dimensionless, as is appropriate for a metric perturbation. Since $H^{\mu\nu}$ is an operator on BH states, one characteristic of its size is its expectation value $\langle H^{\mu\nu}\rangle$ in a typical BH state. Another key question is the time dependence of $H^{\mu\nu}$. In a Schrödinger picture description, $H^{\mu\nu}$ can be time independent, but from the viewpoint of the BH exterior it gains time dependence because it mediates transitions between BH quantum states. Again, by correspondence, the simplest possibility is if $H^{\mu\nu}$ dominantly connects states with energy separations $\Delta E \sim 1/R$, and thus $H^{\mu\nu}$ produces exterior excitations with energies comparable to that of Hawking quanta.

The size of $H^{\mu\nu}$ is constrained by the requirement of unitary evolution. Arguments related to those of [15,16] indicate that the interaction Equation (1) needs to transfer information from the BH at a rate

$$\frac{dI}{dt} \sim \frac{1}{R}\,, \tag{2}$$

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[2]　For further details, see [17].
[3]　This is also expected to contain perturbative gravitons.
[4]　In Equation (1), H_I is given in Schrödinger picture.

i.e., at roughly one qubit per light crossing time. A bilinear hamiltonian of the form Equation (1) will generically transfer information, but one needs to determine the rate at what it does so.

The simplest way to achieve the required rate Equation (2) follows purely from dimensional analysis. All important dimensional quantities have scale governed by R, and so this rate arises from

$$\langle H^{\mu\nu}(x)\rangle \sim 1 \,, \tag{3}$$

for x an $\mathcal{O}(R)$ distance from the horizon. Such an $\mathcal{O}(1)$ metric perturbation raises the prospect of important observational consequences.

One can inquire whether Equation (3) is the minimum possible size. This leads to general question in information theory [17,26]: Given two subsystems coupled by a Hamiltonian with a bilinear interaction like Equation (1), how fast does information transfer? In the BH context, reference [17] argued that the operators $H^{\mu\nu}$ could have a much smaller typical size than Equation (3) and still achieve the rate Equation (2), due to a quantum enhancement in the rate if there is a large number of final possible states. BHs are expected to have an enormous number of possible internal states,

$$N \sim e^{S_{bh}} \,, \tag{4}$$

where, for example S_{bh} might be given by the Bekenstein–Hawking entropy, Area/$4G$. A simple argument for the rate estimate follows from Fermi's golden rule, and yields the result that

$$\langle H^{\mu\nu}\rangle \sim 1/\sqrt{N} \tag{5}$$

can achieve the rate Equation (2).

Thus, there are two distinct possible scenarios, the strong/coherent scenario of Equation (3), and the weak/incoherent scenario of Equation (5).

Clearly for an astronomical-sized black hole, Equation (5) leads to tiny metric perturbations, which might be naïvely expected to have small effects. However, consider scattering from a BH, mediated by the interaction Equation (1). Fermi's golden rule can be again used to estimate the transition probability, which takes the form

$$P \sim |\langle\alpha|H_I|\beta\rangle|^2 \rho(E) \,, \tag{6}$$

where the states α, β include the initial and final states of the scattered particle, and ρ is the density of final states. By the same logic as above, this can be $\mathcal{O}(1)$, given a typical size as in Equation (5). However, while the transition probability can be $\mathcal{O}(1)$, this occurs for transitions with momentum transfer $\sim 1/R$. For a mm wavelength photon scattering off Sgr A*, the fractional momentum transfer is $\mathcal{O}(10^{-13})$, which is negligible. However, for gravitational waves, which in binary mergers commonly have wavelength $\sim R$, this is potentially a relevant effect. Since the present discussion is of EHT observations, without prejudicing which answer nature prefers we will focus attention on the strong/coherent scenario for the remainder of this note.

To reiterate the relevant parameters for the simplest version of a strong/coherent scenario, Equation (3), it specifies that there are $\mathcal{O}(1)$ perturbations in the effective metric, spatially varying over a scale $\sim R$ outside what would be the horizon, and time-varying on scales $\sim R$. This suggests more detailed examination of observational prospects.

A preliminary investigation of possible impact of such perturbations on BH images was conducted in [14], based on ray tracing in the presence of simple examples for such perturbations. These simple examples demonstrated significant distortion of the simulated images, compared to those from an

unperturbed black hole. This work thus serves as an important check that sensitivity to time-varying perturbations of size given by Equation (3) is clearly possible.

The initially reported EHT observations [1] spanned a seven day period; within instrumental resolution, there was no clear indication for temporal variability.[5] In order to test the strong/coherent scenario, it is obviously important to go beyond these initial impressive results, with both further theoretical and observational work.

On the theoretical side, one problem is to more completely explore the parameter space of possible perturbations, and the dependence of observable signatures on these parameters. Reference [14] considered a simple parameterization of such coherent perturbations, in terms of their radial wavenumber k, their radial extension R_G above the horizon, their angular profile determined by spherical harmonics with angular momenta l, m, their amplitude, and their frequency ω. The example spectrum of perturbations assumed in [14] produced a rather dramatic time dependence of images. These include changes in the shape and size of the shadow and surrounding ring. However, variation of these parameters can of course yield much less dramatic effects. It is also important to extend the models of [14] to the case of a black hole with angular momentum.

In particular, the fact that the initial EHT images produced a clearly identifiable shadow should place an important bound on this parameter space, which could be inferred with further work to study dependence of the simulated images on the parameters.

A particularly promising signature is the temporal variability, which has prospects to be a key test for the effects described here. A first question is the relevant time scale, particularly given the initially limited observation window. The characteristic time scale that was used in the simulations of [14] is determined by the constraint that the perturbations do minimal damage to the thermodynamic description of BHs. Specifically, if there are interactions of the form in Equation (1), where $H^{\mu\nu}$ effectively varies with frequency ω, that will create radiation from the BH with frequency $\sim \omega$. So, the minimal departure from the thermal Hawking spectrum arises if $\omega \approx \omega_T$, given by the Hawking temperature, where for a BH with mass M and angular momentum $L = aGM^2$:

$$\omega_T = \frac{1}{4\pi GM} \frac{\sqrt{1-a^2}}{1+\sqrt{1-a^2}} \, . \tag{7}$$

The corresponding periods are:

$$P = \frac{2\pi}{\omega_T} \quad \begin{aligned} &\simeq 0.93 \left(\frac{M}{4.3 \times 10^6 M_\odot} \right) \left(\frac{1}{2} + \frac{1}{2\sqrt{1-a^2}} \right) \text{ hr} \\ &\simeq 59 \left(\frac{M}{6.5 \times 10^9 M_\odot} \right) \left(\frac{1}{2} + \frac{1}{2\sqrt{1-a^2}} \right) \text{ d} \, , \end{aligned} \tag{8}$$

for Sgr A* and M87, with respective masses $M \simeq 4.3 \times 10^6 M_\odot$ and $6.5 \times 10^9 M_\odot$.

For Sgr A*, such a period is short as compared to the multi-hour imaging scan time used by EHT, except in case of high spin,[6] and so EHT images will average over fluctuations on these time scales. The EHT images are not produced from a simple average, but rather based on a more complex algorithm involving the magnitudes of Fourier components and closure phases of baseline triangles. This presents a problem requiring more analysis, to determine the impact of the perturbations on these averaged images, once they are obtained, and their distinguishability from other sources of variability, such as turbulence in the accretion.

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[5] Apparent variations in reconstructed images can so far be attributed to observational/instrumental systematic effects [27].
[6] Note that a spin parameter $a = 0.98$ multiplies the period by 3.0.

For M87, it appears easier to see such a time dependence directly [14]. However, the currently reported observations span a time of seven days. While relaxing the demand for agreement with BH thermodynamics could yield shorter time scale variations, investigating the scale of Equation (8) requires longer span observations. If the spin is high, this period may be significantly extended. Thus, on the observational end, longer span observations will be useful in searching for strong/coherent fluctuations.

It is also important to disentangle any observed variability from other possible origins; in addition to turbulence in the accretion flow, there can be scattering from the interstellar medium. This is another place where combined theoretical and observational efforts may be needed, both in order to better model such time-dependence, particularly from a conventional accretion origin, and to investigate ways to better distinguish these possible origins observationally. One important aspect of this [14] is the achromaticity of effective metric perturbations; they affect light of all frequencies uniformly, so that their effects should be observed at different EHT operating wavelengths.

Further such theoretical and observational investigations are important for determining EHT sensitivity to the strong/coherent scenario. Ultimately such efforts could reveal the existence of strong/coherent perturbations, or rule them out over a large range of parameter space. The latter would point towards the weak/incoherent scenario, or to an even more exotic reconciliation of the existence of black hole-like objects with quantum mechanics.

Conflicts of Interest: The authors declare no conflict of interest.

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