Possible Astrophysical Observables of Quantum Gravity Effects near Black Holes

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Recent implications of results from quantum information theory applied to black holes has led to the confusing conclusions that requires either abandoning the equivalence principle (e.g. the firewall picture), or the no-hair theorem (e.g. the fuzzball picture), or even more impalatable options.

The recent discovery of a pulsar orbiting a black hole opens up new possibilities for tests of theories of gravity. We examine possible observational effects of semiclassical quantum gravity in the vicinity of black holes, as probed by pulsars and event horizon telescope imaging of flares. Pulsar radiation is observable at wavelengths only two orders of magnitude shorter than the Hawking radiation, so precision interferometry of lensed pulsar images may shed light on the quantum gravitational processes and interaction of Hawking radiation with the spacetime near the black hole. This paper discusses the impact on the pulsar radiation interference pattern, which is observable through the modulation index in the foreseeable future, and discusses a possible classical limit of BHC.

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Introduction – The recent discovery of PSR J1745-2900 [1-3] orbiting the galactic center black hole opens up new possibilities for precision tests of gravity. It allows us to investigate possible outcomes as its orbit is mapped, and possible quantum deviations from standard Einstein gravity.

It has proven challenging to find experimental consequences of quantum gravitational effects. At the same time, precision experimental probes of classical general relativity have a dearth of alternate theories to compare with.

In this letter, we explore possible semi-classical consequences of pulsar-black hole binaries and flares in the galactic center black hole accretion flow. This is meant to stimulate concrete discussions of quantum mechanics applied to gravitational systems in scenarios that may be testable in the foreseeable future.

Motivation – The quantum mechanical nature of black holes has provided a fruitful testbed for thought experiments and discussions. Hawking’s calculation led to the possibility of black hole radiation and evaporation. The radiation appears thermal, and appears not to depend on the interior of the black hole, or its formation history. This leads to the well known information loss problem [4].

Historically the resolution of the problem included violation of unitarity (i.e. causality), or the possibility of remnants. String theory is a constructive example which is unitary and contains the same black hole entropy and evaporation, and no remnants. In this context, the resolution of the paradox has to lie in the purity of Hawking radiation vs the breakdown of the equivalence principle near the horizon. As discussed in [5] (hereafter AMPS), a modification of Hawking radiation purity requires macroscopic changes in space-time of order unity outside the Scharzschild radius (see also [6] for a complementary view). Different groups arrive at opposite aesthetic conclusions from this line of reasoning: the firewall [5] picture maintains radiation purity, and instead sacrifices the equivalence principle for infalling observers, who burn up at the horizon, thus preventing them from measuring violations of quantum mechanics. The fuzzball picture explores the opposite path [7]: the Hawking photons are emitted by a substantially non-Scharzschild geometry, but classical observers see a general relativistic spacetime including the equivalence principle on both sides of the horizon. This latter framework is consistent with principle of Black Hole Complementarity [8] (BHC, see also the Fuzzball interpretation of BHC [7]), that the classical and quantum pictures depend on the nature of the measurement. Specifically, low energy probes, such as Hawking radiation or grazing pulsar radiation, would be subject to the quantum nature, while high energy probes, including protons, stars, and other likely matter see a classical space-time. In this Letter we follow this scenario to explore possible consequences for quantum measurement using pulsar radiation, which provide realistic probes of BHC, using wavelengths comparable in energy to the Hawking radiation. This opens up the possibility of testing physics using real experiments instead of aesthetic considerations.

Pulsars are highly compact, very bright light sources and exquisite clocks, enabling precision measurements of space-time. A pulsar orbiting a black hole provides a scenario which accentuates potential experimental outcomes. Very recently, the first candidate has been discovered [1-3], likely orbiting the galactic center black hole. While the orbital parameters are not known to the author, there is a possibility that its orbit in projection passes close behind the black hole, such that a gravitational lensed image becomes visible. Depending on orbital parameters, such a conjunction could take decades to occur during which time more pulsar-black hole binaries may be discovered. In addition to the galactic centre supermassive black-hole pulsar binary, ten double neu-
tron star systems are known, and discovery of a pulsarstellar mass black hole binary appears likely \[9\]. For purposes of this discussion, slow and fast pulsars are both suitable, with slow pulsars dominating the predicted populations. This is one of the goals of the planned Square Kilometer Array\[22\].

**Strong Gravitational Lensing** – We consider the dynamics of a pulsar orbiting a black hole. As a pulsar passes behind a black hole, multiple images of the pulsar appear. In the weak field limit, one sees two images. This phenomenon is called “strong lensing”. In the strong field regime, an infinite number of exponentially fainter images appear \[10, 11\]. In this section, we will confine our discussion to the two images under “weak field” strong gravitational lensing.

We will consider the regime where the pulsar is many Schwarzschild radii behind the black hole, and the weak field limit applies, with only small perturbations. The pulsar radiation is lensed by the black hole’s gravitational field, which is well described by geometric optics. We first review the geometric optics, and then estimate the interference pattern of this double-slit experiment.

Generally, the brighter image is further away from the black hole, and less affected by post Einsteinian effects. This two image scenario is much like a quantum double slit experiment. The wavelength of the photons is not drastically different from that of the thermally emitted slit experiment. The wavelength of the photons is not sensitive to the stochastic quantum fluctuations in time delay (7), which induce phase differences of order unity for a 1 GHz bandwidth, due to the self-interference pattern by the geometric delay, one expects time delays of order unity, and by isotropy the delay becomes

$$\varphi(\theta, \phi) = \theta_E^2 \ln(\theta/\theta_E) + \theta_E^2 \sum m a_m \theta_E^m \cos[m(\phi - \phi_m)].$$

with the apparent Schwarzschild radius \(\theta_s=r_s/D_d\). We define the ratio \(b=\theta_E/\theta_s\), which is the impact parameter of the lensed image in units of Schwarzschild radii. The generic orbit has \(b \gg 1\), and our data probes \(\theta \sim \theta_E\). At these large radii, the low \(m\) harmonics dominate. Since the deviations to the space-time are of order unity near the horizon, one expects \(a_m\) to be order unity, and by isotropy the \(\phi_m\) are uniformly distributed. In a firewall picture, all coefficients \(a_m = 0\).

The lowest order perturbation is a dipole, \(m=1\). This is analogous to a displacement of the black hole position by a Schwarzschild radius. This results in a variation of time delay

$$\delta \Delta t = \alpha \frac{r_s}{b}$$

for an order unity proportionality constant \(\alpha\).

In a fuzzball scenario, the delayed pulse will appear broadened: its pulse profile will appear wider, convolved by the distribution of delays from the different multipole perturbations. While the actual separation of images may be challenging to resolve in angle, the delays are readily observable. As in interstellar plasma lensing, the multiple images interfere constructively and destructively when observed in a single dish telescope\[14\]. For time estimates, we will scale to a solar mass black hole. When applied to the galactic center supermassive black hole, we will explicitly state that. Typical pulsars have the most sensitive detections at \(\sim\) GHz. In a classical black hole, this results in a very precise measurement of delay and dopplershift: with a 1 GHz bandwidth, delays are measurable to a nanosecond. The characteristic delay \(\Delta t\) for a solar mass black hole is several microseconds, and expected fuzzball fluctuations smaller by \(b\). For a given set of orbital parameters, the fringe pattern is fully determined, and can be tracked. After shifting the self-interference pattern by the geometric delay, one is sensitive to the stochastic quantum fluctuations in time delay \(\delta \Delta t\), which induce phase differences of order unity for \(b \lesssim 1000\).

To estimate the observational signature, we consider a pulsar orbiting a 10 M\(_{\odot}\) BH, at \(4 \times 10^4 r_S\). The orbital
The ALMA[24] telescope might detect negligible. It is not known how bright the pulsar is at  THz frequencies. The modulation index is reduced due to exterior quantum effects.

The Event Horizon Telescope (EHT)[25] could image radiation emitted by the plasma near the horizon of the galactic center black hole. This flow is known to be unsteady, with flares and other phenomena, that are strongly lensed[20]. As for the pulsar case, the accretion flow and flare are classical objects, and expected to follow the classical dynamics. The low energy photons emitted from the flare are low energy probes, and subject to interaction in BHC. Here, the effects would be large. In a fuzzball picture, the interior lensed image would appear extended, i.e. fuzzy. Normally, this fainter image, the one closer to the black hole, is smaller due to conservation of surface brightness. The opposite could happen in a fuzzball picture: any lensed image would be observable. The low energy photons emitted from the flare are low energy probes, and subject to interaction in BHC. Here, the effects would be large. In a fuzzball picture, the interior lensed image would appear extended, i.e. fuzzy. Normally, this fainter image, the one closer to the black hole, is smaller due to conservation of surface brightness. The opposite could happen in a fuzzball picture: any lensed image would be observable. The low energy photons emitted from the flare are low energy probes, and subject to interaction in BHC. Here, the effects would be large. In a fuzzball picture, the interior lensed image would appear extended, i.e. fuzzy. Normally, this fainter image, the one closer to the black hole, is smaller due to conservation of surface brightness. The opposite could happen in a fuzzball picture: any lensed image would be observable. The low energy photons emitted from the flare are low energy probes, and subject to interaction in BHC. Here, the effects would be large. In a fuzzball picture, the interior lensed image would appear extended, i.e. fuzzy. Normally, this fainter image, the one closer to the black hole, is smaller due to conservation of surface brightness. The opposite could happen in a fuzzball picture: any lensed image would be observable. The low energy photons emitted from the flare are low energy probes, and subject to interaction in BHC. Here, the effects would be large. In a fuzzball picture, the interior lensed image would appear extended, i.e. fuzzy. Normally, this fainter image, the one closer to the black hole, is smaller due to conservation of surface brightness. The opposite could happen in a fuzzball picture: any lensed image would be observable. The low energy photons emitted from the flare are low energy probes, and subject to interaction in BHC. Here, the effects would be large. In a fuzzball picture, the interior lensed image would appear extended, i.e. fuzzy. Normally, this fainter image, the one closer to the black hole, is smaller due to conservation of surface brightness. The opposite could happen in a fuzzball picture: any lensed image would be observable. The low energy photons emitted from the flare are low energy probes, and subject to interaction in BHC. Here, the effects would be large. In a fuzzball picture, the interior lensed image would appear extended, i.e. fuzzy. Normally, this fainter image, the one closer to the black hole, is smaller due to conservation of surface brightness. The opposite could happen in a fuzzball picture: any lensed image would be observable. The low energy photons emitted from the flare are low energy probes, and subject to interaction in BHC. Here, the effects would be large. In a fuzzball picture, the interior lensed image would appear extended, i.e. fuzzy. Normally, this fainter image, the one closer to the black hole, is smaller due to conservation of surface brightness. The opposite could happen in a fuzzball picture: any lensed image would be observable.
erally extended. Here, the test would rely on localized flares, where multiple strongly lensed images would be visible, and time profiles are observables.

Discussion—The lensing framework gives a simplified picture to discuss Hawking radiation entanglement. Instead of the typical $\exp(10^{380})$ microstates, we can focus on the low order multipoles, reducing the variables to $a_1, \theta_1$. To clarify the situation further, we consider a further restricted subspace: $\phi_1 = 0$, with the axis chosen such that the classical interior lensed image is at $\phi = 0$. We will further restrict $a_1 \in \{-1, 1\}$, i.e. a 2-state system $|+\rangle, |−\rangle$, and consider a pure state black hole. Any incoming photon state becomes entangled with the perturbed lensing eigenstates: $|i\rangle = \alpha |+, \uparrow\rangle + \beta |−, \downarrow\rangle$, where $|\alpha|^2 + |\beta|^2 = 1$. It may be perturbed outward ($\uparrow$) or inward ($\downarrow$), resulting in a different phase delay as discussed above. An ensemble of photons, as expected from pulsars or flares, is projected one photon at a time. This has some analogies to Stern-Gerlach space quantization, with the distinction that here the deflection field is quantum mechanical, perhaps like SQUID quantum superposition experiments[21]. The photon becomes effectively entangled with the fuzzball. For a static fuzzball, whose eigenstates are not spherically symmetric, the interference pattern is affected. When we then add the degrees of freedom that the perturbations not discrete, we see the persistence of quantum perturbations due to non-commutation of propagation operators and fuzzball eigenstates.

In any matter flow, for example an orbiting neutron star or accretion flow, one needs to compare the rate at which particles exchange energy with each other, compared to the differential energy shift from the fuzzball entanglement. For a star the outcome is clear: its large orbital radius, requires its self-interaction to be larger than the differential tidal effect, and the flare is also treated classically. This interpretation differs slightly from the commonly stated BHC picture about energy: a high energy photon may still be seeing a quantum space time, while an infalling observer with sufficient complexity to be considered classical, will see the classical space-time. An interesting intermediate question would be the trajectory of a complex composite particle, such as a proton. Its constituent strongly interacting gluons and quarks might each probe a different space-time, and the full proton would see an averaged effect, closer to classical.

This analysis combines uncertain speculation from opposite opinion camps on the nature of black hole evaporation, namely the firewall group and the fuzzball group. We caution that the scenario is by no means inevitable, even in a fuzzball picture it is not clear that the $O(1)$ variation of the space-time coefficients This was argued by AMPS as a weakness of the fuzzball picture.

Summary.—We have explored semiclassical quantum effects of black holes. A pulsar black hole binary provides a concrete setup where such effects might become observable. This proposed experiment distinguishes between classical measurements, such as a star orbiting a black hole, and quantum measurements, such as the interference of two light paths bent by the gravitational field of the black hole. The interference pattern could be confused by the quantum nature of the black hole if the resolution of the Hawking paradox lies in the non-purity of Hawking radiation. The outcome is speculative in nature, and is hoped to stimulate further investigation of non-Einsteinian outcomes of strong lensing experiments. We have argued that the recent pulsar-black hole system, and likely more future discoveries, allow us to probe new aspects of quantum gravity. At least, until the ideal pulsar-black hole system is discovered it provides a new sandbox to test ideas, to answer questions about complementarity and the interaction of Hawking radiation with space-time.

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