Constructing and Investigating Modified Black Hole Models With Quantum Corrections

Källan Berglund (she/her), Physics PhD Candidate
Penn State Institute for Gravitation and the Cosmos

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With the Indigenous Peoples Student Association and the Indigenous Faculty and Staff Alliance:

The PSU campuses are on the original homelands of the Erie, Haudenosaunee (Seneca, Cayuga, Onondaga, Oneida, Mohawk, and Tuscarora), Lenape (Delaware Nation, Delaware Tribe, Stockbridge-Munsee), Monongahela, Shawnee (Absentee, Eastern, and Oklahoma), Susquehannock, and Wahzhazhe (Osage) Nations. As a land grant institution, we acknowledge and honor the traditional caretakers of these lands and strive to understand and model their responsible stewardship. We also acknowledge the longer history of these lands and our place in that history.

Personal acknowledgement of Labor (PSU does not have an official statement on this yet):

The USA's knowledge, culture, wealth, and growth was enabled by the work of enslaved Africans and their descendents who experience(d) trafficking, slavery, Jim Crow, and other ongoing forms of bias and violence. We are indebted to them, and must recognize the generational trauma and systems of oppression present to this day.

Invitation to move/stim

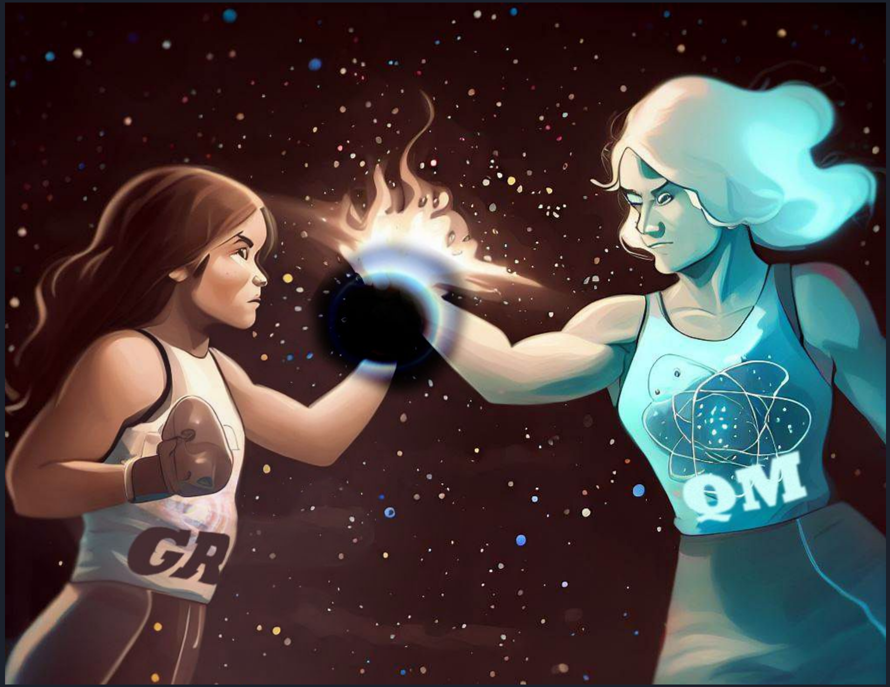
We have been conditioned for years to sit still and quiet in classroom environments. I invite you to take steps to make yourself comfortable and facilitate your own focus and learning in this space. If you need to get up and walk around, draw, or otherwise stim, please feel free to do so.

Motivation

QM and GR are essential to modern life, from nuclear power and quantum computing, to GPS and space exploration, but they are in conflict.

We need a theory of Quantum Gravity, and black holes are a useful testing ground.

I research Modified Gravity, specifically quantum-corrected black holes.



Overview

1. Recent paper:
    a. establishing non-local effects from quantum-corrected black hole
2. Current paper:
    a. relate to a quantum superposition of classical black hole spacetimes
    b. found modification of Newtonian potential
    c. want to connect to quantum switch experimental predictions
3. Next project:
    a. potential gravitational wave predictions, with quasinormal mode calculations

Quasiclassical solutions for static quantum black holes

Coauthors: Gianni Sims, Manuel Díaz, and Martin Bojowald

https://journals.aps.org/prd/abstract/10.1103/PhysRevD.109.024006

Goal: calculate quasiclassical space-time dynamics with non-local quantum corrections, using canonical methods of non-adiabatic quantum dynamics, and ultimately extend this to an effective quantum field theory

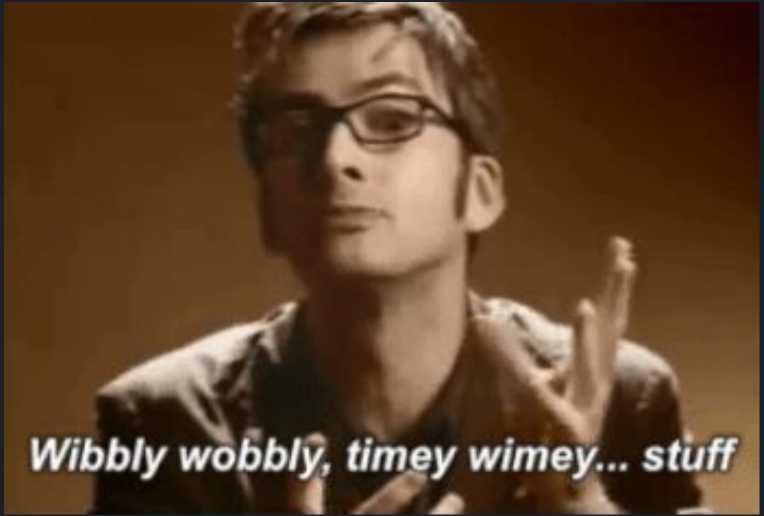
Calculation Outline

Goal: model coordinate-independent BH quantum corrections

1) Quantum Correction: scalar field modification in H

2) Preserve Covariance: brackets closed

3) Static Simplification: solve EOM's for the allowed structure of the quantum correction



Results and Analysis

Analyzing the asymptotic behavior around the event horizon and at infinity, we see that the quantum corrections have a ripple effect that extends beyond their local area. We succeeded in constructing explicit non-local quantum corrections! These corrections may be crucial for understanding the behavior around the event horizon of quantum black holes, and our methods are promising for future work.

Spacetime Superpositions as Fluctuating Geometries

Coauthors: Martin Bojowald, Aurora Colter, and Manuel Díaz

Goal: Interpret this quantum-corrected spacetime as providing covariant formulations of the gravitational force implied by a distribution of black holes in superposition, or by a superposition of quantum matter constituents in superposition around a single black hole.

Calculation Outline

Set the modified Hamiltonian constraint to zero.

Recalculate the equation of motion for using only the first order correction to the Hamiltonian.

Solve constraint and equation of motion in the weak field limit for power series solutions for the scalar fields and lapse function.

Use these solutions to construct the quantum-corrected Newton potential and bounds on constants.

Results and Analysis

Is there an action principle or some other fundamental description that has superpositions of gravitational fields among its solutions?

Detailed analysis in the weak-field limit reveals quantum corrections to Newton's potential and potentially paves the way for a broader range of predictions to be compared with observations.

$$V(x) = \frac{c^2}{2}(N(x)^2 - 1) \approx -\frac{GM}{x} + \frac{G^2M^2}{x^2c^2} + \frac{d_2}{2x^2} + O(x^{-3})$$

Defining coefficients

$$\phi_2 = \phi_2^{(0)} + c_1 + \frac{c_2}{x} + \cdots \quad , \quad N = N^{(0)} + \frac{d_1}{x} + \frac{d_2}{x^2} + \cdots$$

$$\phi_3(x) = C\left(1 + \frac{3b}{x} + \frac{3b^2}{x^2} + \cdots\right)$$

$$\begin{aligned}
c_1 &= \epsilon C\sqrt{64bU_0/C^4 - 1} \\
c_2 &= \epsilon\frac{27}{8}bC\frac{560bU_0/(9C^4) - 1}{\sqrt{64bU_0/C^4 - 1}} \\
d_2 &= \epsilon\frac{47}{96}bC\frac{3152bU_0/(47C^4) - 1}{\sqrt{64bU_0/C^4 - 1}} \\
c_3 &= \epsilon\frac{b^2\left(625920b^2U_0^2 - 20224bC^4U_0 + 163C^8\right)}{40C\left(64bU_0 - C^4\right)^{3/2}} \\
d_3 &= -\epsilon\frac{b^2\left(2492160b^2U_0^2 - 75392bC^4U_0 + 569C^8\right)}{320C\left(64bU_0 - C^4\right)^{3/2}}
\end{aligned}$$

Connecting to quantum switch experiments

Time & space metric components affected differently by quantum corrections. Our results imply a more precise geometry combining interrelated gravitational and quantum effects.

Can be used for consistent descriptions of quantum superpositions, defined by suitable values of the moments or parameters C and U0. Spherical symmetry implies a superposition state can only be formulated for masses at the same position, defining the center of symmetry. Quantum fluctuations given indirectly by mass fluctuations, rather than position fluctuations.

The final line element can be analyzed by computing geodesics and proper-time intervals.

$$\begin{aligned} \mathrm{d}s^2 &= -\left(N^{(0)} + \frac{d_1}{x} + \frac{d_2}{x^2} + O(x^{-3})\right)^2 c^2 \mathrm{d}t^2 \\ &\quad + \left(\frac{\phi_2^{(0)}}{2x} + \frac{c_1}{2x} + \frac{c_2}{2x^2} + O(x^{-3})\right)\left(\mathrm{d}x^2 + x^2(\mathrm{d}\vartheta^2 + \sin^2\vartheta \mathrm{d}\varphi^2)\right) \end{aligned}$$

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Spacetime Superpositions as Fluctuating Geometries by Källan Berglund, Martin Bojowald, Aurora Colter, and Manuel Díaz

Funding

Penn State University Physics Department

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PA NASA Space Grant

Women+ International in Theoretical Physics

WIThPhys: an international, online community for networking and mutual support

Who should join? Women and nonbinary theoretical physicists!

Who should share? Everyone!

https://sites.google.com/view/withphys/home

Follow-up

Källan Berglund
kmb670@psu.edu

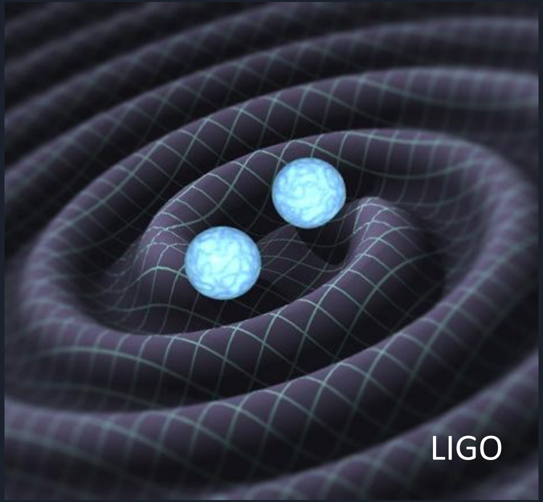
On the job market for 2025!

Quasinormal Mode Collaboration

Collaborating with Karim Noui at Université Paris-Saclay

Method: Applying novel derivation method for quasinormal mode equations (Hugo Roussille's Thesis) to these modified black hole models. In the process, generalizing this method to apply to other modified spacetimes.

Goal:Calculate gravitational wave quasinormal mode signals detectable by next generation detectors, like LISA. These measurements could either rule out or support certain modifications, limiting possible theories of quantum gravity.



Volumes of Quantum Corrected Black Holes

Coauthors: Martin Bojowald and Allison Taylor Colarelli

Goal: Using established definitions for the volume inside the event horizon as maximal spatial hypersurfaces (*Maximally Slicing a Black Hole*, Estabrook and Wahlquist), we calculate this for a spacetime model with a similar modification (*An effective model for the quantum Schwarzschild black hole*, Alonso-Bardaji, Brizuela, and Vera).

Expectations: This modification should shift the radius at which these spatial leaves converge (3M/2), which could offer insights into both the information paradox and the late-stages of black hole evaporation.

Bonus equations

$$\phi_2 = \phi_2^{(0)} + \delta\phi_2 = 2x\left(1 + \frac{b}{x}\right)^4 + \delta\phi_2$$
$$N = N^{(0)} + \delta N = \frac{x - b}{x + b} + \delta N$$

$$\phi_3 \sim C \leq 2\sqrt{2}(bU_0)^{1/4}$$

$$\Delta\phi_2 \leq 2\sqrt{2}u^{1/4}\ell_{\mathrm{P}}$$

$$\Delta p_2 \geq \frac{u^{1/4}\ell_{\mathrm{P}}}{2\sqrt{2}b}$$

$$C^4 = \frac{3152bU_0}{47} \approx 67.1bU_0$$