**AFRL-AFOSR-JP-TR-2023**

# Through a ring of fire: Information Preservation across Horizons

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**01/27/2023**
**Final Technical Report**

Air Force Research Laboratory
Air Force Office of Scientific Research
Asian Office of Aerospace Research and Development
Unit 45002, APO AP 96338-5002

# REPORT DOCUMENTATION PAGE

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| | | | |
|---|---|---|---|
| **1. REPORT DATE**<br>20230127 | **2. REPORT TYPE**<br>Final | **3. DATES COVERED**<br>**START DATE**<br>20190821 | **END DATE**<br>20220620 |

**4. TITLE AND SUBTITLE**
Through a ring of fire: Information Preservation across Horizons

| | | |
|---|---|---|
| **5a. CONTRACT NUMBER** | **5b. GRANT NUMBER**<br>FA2386-19-1-4077 | **5c. PROGRAM ELEMENT NUMBER**<br>61102F |
| **5d. PROJECT NUMBER** | **5e. TASK NUMBER** | **5f. WORK UNIT NUMBER** |

**6. AUTHOR(S)**
Robert Mann

| | |
|---|---|
| **7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)**<br>UNIVERSITY OF WATERLOO<br>200 UNIVERSITY AVE W<br>WATERLOO, ON N2L 3G1<br>CAN | **8. PERFORMING ORGANIZATION REPORT NUMBER** |

| | | |
|---|---|---|
| **9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)**<br>AOARD<br>UNIT 45002<br>APO AP 96338-5002 | **10. SPONSOR/MONITOR'S ACRONYM(S)**<br>AFRL/AFOSR IOA | **11. SPONSOR/MONITOR'S REPORT NUMBER(S)**<br>AFRL-AFOSR-JP-TR-2023-0056 |

**12. DISTRIBUTION/AVAILABILITY STATEMENT**
A Distribution Unlimited: PB Public Release

**13. SUPPLEMENTARY NOTES**

**14. ABSTRACT**

The goal of this proposal was to investigate the relationship between quantum information and the structure of spacetime. Information is always encoded by preparing a physical system in a given state, and it is processed by changing its state upon interaction with other systems. The simplest idealization of this is a 2-level system (a simple atom known as an Unruh DeWitt detector; henceforth called a qubit for simplicity) that has a ground and excited state – it is the basic component of information storage in a quantum computer, and can be regarded as an idealized detector. The qubit is sensitive to the presence of quantum fields analogous to the way an atom is sensitive to the presence of photons (light). Under the right circumstances, 2 qubits interacting with the field can become entangled with each other. Entanglement is a particular kind of extra correlation present only in quantum physics and known to exponentially increase processing power. In recent years it has become clear that spacetime itself has the capacity to both entangle non-interacting qubits and to destroy the information that they carry. The extraction (or swapping) of quantum entanglement from the spacetime vacuum itself into a pair of qubits is called entanglement harvesting.

**15. SUBJECT TERMS**

| | | | | |
|---|---|---|---|---|
| **16. SECURITY CLASSIFICATION OF:** | | | **17. LIMITATION OF ABSTRACT**<br>SAR | **18. NUMBER OF PAGES**<br>12 |
| **a. REPORT**<br>U | **b. ABSTRACT**<br>U | **c. THIS PAGE**<br>U | | |

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| **19a. NAME OF RESPONSIBLE PERSON**<br>MICHAEL RICHARDS | **19b. PHONE NUMBER** *(Include area code)*<br>3152277000 |

Final Report for AOARD Grant FA2386-19-1-4077

# Through a ring of fire: Information Preservation across Horizons

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DUNS number:
EIN number:

Project Grant Period: Aug 20 2019 – Aug 30 2022
Reporting Period End date: December 14 2022
Report Term Frequency: Annual

## Accomplishments

### Major Goals and Objectives

The goal of this proposal was to investigate the relationship between quantum information and the structure of spacetime. Information is always encoded by preparing a physical system in a given state, and it is processed by changing its state upon interaction with other systems. The simplest idealization of this is a 2-level system (a simple atom known as an Unruh DeWitt detector; henceforth called a qubit for simplicity) that has a ground and excited state – it is the basic component of information storage in a quantum computer, and can be regarded as an idealized detector. The qubit is sensitive to the presence of quantum fields analogous to the way an atom is sensitive to the presence of photons (light). Under the right circumstances, 2 qubits interacting with the field can become entangled with each other. Entanglement is a particular kind of extra correlation present only in quantum physics and known to exponentially increase processing power. In recent years it has become clear that spacetime itself has the capacity to both entangle non-interacting qubits and to destroy the information that they carry. The extraction (or swapping) of quantum entanglement from the spacetime vacuum itself into a pair of qubits is called *entanglement harvesting*.

Horizons -- boundaries of inaccessible regions of spacetime (such as the edge of a black hole) – tend to thermalize qubits, eroding (or even destroying) the information they contain. The goal of this project was to investigate what happens to quantum entanglement of qubits in the presence of horizons.

The specific objectives of the project were to answer the following questions.

1. How does a single qubit respond as it crosses the horizon of a black hole?
2. What happens to the extra correlation in entanglement of a pair of qubits in the presence of an horizon?
3. Does entanglement survive passage of one (or both) qubits across an horizon?
4. How do other causal spacetime structures affect qubit entanglement?
5. Can qubits be used as probes of expected features in quantum gravity?
6. What happens to the enhanced processing power of entangled qubits in such spacetime settings? In particular, can this be understood via some kind of laboratory simulation?

The goal was to advance our understanding of quantum information in both foundational and practical terms. Concerning the former, by shedding light on what actually happens to quantum entanglement between two qubits (and by implication, any two objects) when they become causally separated, we will learn new things about the basic entangling properties of quantum fields in spacetime and about how black holes actually evaporate. On the pragmatic side, the new methods developed will be applicable to a broad range of problems of benefit to both the experimental and theoretical relativistic quantum information communities. This is expected to translate in ways of testing (or simulating) the extraction of spacetime entanglement into qubits.

## What Was accomplished

**Context:** My research group has pioneered methods for computing both qubit response and qubit entanglement in the presence of horizons. During the course of the AOARD grant we have extended these methods in three ways: (i) superpositions of different causal structures (as anticipated from quantum gravity) (ii) superpositions of different spacetimes (likewise anticipated from quantum gravity), and (iii) qubits falling through horizons. To address the specific objectives of the project we have taken two approaches.

One is to work with simplified spacetimes in less than 3 dimensions, where the mathematics is much more tractable analytically but the qualitative features of actual horizons are still present.

Calculations that are not in idealized lower-dimensional spacetimes generally involve computationally intensive mode sums. Our other approach is to deal with these necessary mode sums over fields in a new way: rather than sum over all modes at each point in space, we instead calculate the response of a qubit to each mode individually, at each point in time. The total response is then obtained simply by summing over all such responses.

I now outline the specific accomplishments of this project.

1. How does a single qubit respond as it crosses the horizon of a black hole?

We computed for the first time the response of a qubit as it falls across the horizon of a real-world Schwarzschild black hole. To carry out this project required mode summation using the second method above. Within the context of semiclassical theory (treating gravity as classical but all other matter as quantum-mechanical), the expectation was that the response of the qubit would smoothly increase as it fell toward the black hole and through its horizon, in accord with the equivalence principle.

What we found was not quite the expected result. The response of the qubit did indeed smoothly increase, but just after it crossed the horizon the response "spiked" by about a percent. Put another way, the transition probability attained a small local extremum near the horizon-crossing, after which it increased as it approached the singularity at the centre of the black hole.

We checked that this "little bit of excitement" was not a numerical artifact. It has no counterpart for the analogous detector infall in (1+1) dimensions. We rather found that the extremum came from the superposition of contributions from low and high angular momentum modes of the quantum field. A deeper physical explanation of this spike remains an intriguing topic for further study. For example, is a similar feature present in all spacetime dimensions higher than two, and for quantum fields of any spin?

Answering this question was the major objective of the AOARD grant, and I am pleased to say we accomplished it. We published these results in the New Journal of Physics in 2022 [1].

2. What happens to the extra correlation in entanglement of a pair of qubits in the presence of an horizon?

We addressed this question in (1+1) dimensions (1 spatial dimension plus time) due to the computational complexity of the problem. In two separate papers we studied how qubits harvest correlations in settings where (i) a shell of matter collapses to a black hole [2] and (ii) where one or both qubits fall across the horizon of a black hole [3].

In the first case we found that the black hole horizon inhibited the extraction of any correlations, not just entanglement, consistent with earlier studies for a static black hole. We also found that the efficiency of the entanglement harvesting protocol depended strongly on the signalling ability of the detectors, which is highly non-trivial in presence of curvature.

In the second case we found that the amount of correlations extracted by the qubits from the black hole vacuum, at least nearby but outside the horizon, was mostly due to their relative velocities (the nearer qubit moves faster). More surprisingly we found that the qubits could harvest correlations from the black hole vacuum even when they on opposite sides of the event horizon (and so are causally disconnected).

These results were respectively published in the Journal of High Energy Physics [2] and Physical Review D [3].

3. Does entanglement survive passage of one (or both) qubits across an horizon?

This question was addressed above. Entanglement does indeed survive the passage of qubits across the horizon (as expected from the equivalence principle) and can even be harvested by qubits on opposite sides of the black hole horizon. The studies were carried out in (1+1) dimensions, but we expect they will generalize to the real world of (3+1) dimensions.

4. How do other causal spacetime structures affect qubit entanglement?

An expected feature of quantum gravity is that cause-and-effect are no longer sharply defined concepts, and that the actual time-order of events is indefinite. We carried out the first investigation of entanglement extraction from spacetimes with such Indefinite Causal Order. We found that the qubits can extract information about field correlations that is otherwise provably inaccessible. This has relevant consequences for information theoretic quantities, such as the entanglement and mutual information that can harvested from the field. This work was published in Physical Review Letters [4].

5. Can qubits be used as probes of expected features in quantum gravity?

We addressed this question in a novel way by constructing a situation in which a single qubit was in a spacetime consisting of a superposition of two black holes. This work was the culmination of a series of papers [5,6,7] in which we considered how a single qubit would respond if the qubit were placed in superposition, analogous to the way a single photon passing through a beamsplitter is placed in superposition. We found, for example, that while a qubit in uniform acceleration responds as though it were in a thermal bath (a well-known prediction called the Unruh effect), a qubit in a superpostion of accelerations does not have a thermal response.

Making use of these methods we found that there was a mathematical mapping that took a superposed qubit in a single spacetime to a single qubit in a superposed spacetime. Once we understood this mapping, we found that it was possible to construct spacetime superpositions that cannot be mapped back to superpositions of a qubit – in other words, to construct genuine spacetime superpositions.

Our methods require a high degree of symmetry to be computationally tractable. Fortunately there is a simple black hole spacetime in (2+1) dimensions that has the necessary degree of symmetry. We were able to construct a superpostion of a black hole with two different masses and then compute the response of a qubit in this superposed spacetime.

A single qubit outside of the horizon responds as though it is in a thermal bath whose temperature is the Hawking temperature of the black hole. We found that in a superposed spacetime the qubit exhibited signatures of quantum gravitational effects that corroborated (and extended) a conjecture of Bekenstein's, namely that mass spectrum of a black hole in quantum gravity is quantized. So the answer to the above question is a clear "yes".

Our work opens up a new approach to quantum gravity. Spacetime superposition is generically expected in any quantum theory of gravity, and our approach provides a path for computing how physical object (such as a qubit) will behave in such situations. Our work was published in Physical Review Letters [8].

6. What happens to the enhanced processing power of entangled qubits in such spacetime settings? In particular, can this be understood via some kind of laboratory simulation?

This question – that of simulating detector responses and entanglement extraction – is still under investigation. I made a visit to Silke Weinfurtner's group at the University of Nottingham, where they are in the process of constructing the idealized qubit used in many studies (including the ones here) into an actual experimental probe using lasers. Working with Prof. Weinfurtner and her postdoctoral fellow, Dr. C. Gooding, we have a draft of a paper (based on the doctoral work of A. Sachs) that shows how two such "real world qubits" could extract entanglement from the surface fluctuations of a Bose-Einstein condensate.

*Other Accomplishments*

Several other projects were completed during the period of this grant that are related to the questions above. These were

1) Moving mirrors (which impose moving reflecting boundary conditions) were employed as a theoretical tool to study the entanglement harvested between two qubits with and without strict horizons. The entanglement extracted was not sensitive to the emitted radiation flux of the mirrors, but was sensitive to the global dynamics of the mirror trajectories. This disclosed aspects of the effects that global information loss of the type horizons induce has on local qubits. The results were published in the Journal of High Energy Physics [9].

2) We discovered a new phenomenon, in which a qubit outside a black hole responds less often as the temperature of the black hole increases. We refer to this as "anti-Hawking phenomena", and demonstrated it explicitly for a black hole in 3 spacetime dimensions. The implications of this work is that a qubit is not necessarily a reliable thermometer in taking the temperature of the vacuum outside of a black hole. These results were published in Physics Letters B [10].

3) We showed that a single qubit can observe gravitomagnetism (or frame-dragging) in situations where this phenomenon cannot be detected by classical means. By placing a qubit inside a slowly rotating shell (where spacetime is flat everywhere inside), we found that it could distinguish whether or not the shell was rotating, even within times shorter than that required for a light signal to travel to the shell and back, which could classically convey the presence of rotation. This work

was published in Physical Review D [11,12].

4) We found that rotating black holes can amplify entanglement. By considering a rotating black hole in 3 spacetime dimensions, we found that the entanglement two co-rotating qubits outside the black hole can be amplified by as much as an order of magnitude at intermediate distances from the black hole relative to that at large distances. The effect is most pronounced for near-extremal small mass black holes, and allows for harvesting at large spacelike qubit separations. These results were published as a letter in Classical and Quantum Gravity [13].

5) A similar situation was subsequently found to hold for the anti-Hawking effect: rotation can significantly amplify the strength of the weak anti-Hawking effect, whereas it can either amplify or reduce the strength of the strong anti-Hawking effect depending on boundary conditions. These results were published in Physical Review D [14].

## Training and Professional Development

During the period of this AOARD grant, 8 doctoral students, 1 Masters student, and 2 postdoctoral fellows were supported, and participated in the work described above. All were co-authors on at least one paper that resulted due to the work carried out in this project (see publication list below).

## List of Publications and Significant Collaborations

During the period of this AOARD grant, there have been 15 papers written connected with the project , 14 of which have been published and one of which is near completion. Underlined names are graduate students in my group; underlined with italics are postdoctoral fellows in my group.

*Papers Published in peer-reviewed journals*

1. K.K. Ng, *C. Zhang*, J. Louko and R.B. Mann, "A little excitement across the horizon," New J. Phys. 24 (2022) 103018
2. E. Tjoa and **R.B. Mann**, ``Harvesting correlations in Schwarzschild and collapsing shell spacetimes," JHEP **2020** (2020) 155
3. K. Gallock-Yoshimura, E. Tjoa and R.B. Mann, "Harvesting entanglement with detectors freely falling into a black hole," Phys. Rev. **D104** (2021) 025001
4. L. J. Henderson, A. Belenchia, E. Castro-Ruiz, C. Budroni, M. Zych, C. Brukner and **R.B. Mann**, "Quantum Temporal Superposition: the case of QFT," Phys. Rev. Lett. **125** (2020) 131602
5. J. Foo, S. Onoe, R. B. Mann and M. Zych, "Thermality, causality and the quantum-controlled Unruh-deWitt detector", Phys. Rev. Res. **3** (2021) 043056
6. J. Foo, R. B. Mann and M. Zych, "Schrodinger's cat for de Sitter spacetime", Class. Quant. Grav. **38** (2021) 115010

7. J. Foo, R. B. Mann and M. Zych, “Entanglement amplification between superposed detectors in flat and curved spacetimes” Phys. Rev. **D103** (2021) 065013
8. J. Foo, C.S. Arabaci, R. B. Mann and M. Zych, “Quantum signatures of black hole mass superpositions” Phys. Rev. Lett. **129** (2022) 181301
9. W. Cong, C. Qian, M.R.R. Good and **R.B. Mann**, ``Effects of Horizons on Entanglement Harvesting," JHEP **2020** (2020) 067
10. *L. J. Henderson*, R. A. Hennigar, **R. B. Mann**, A. R. H. Smith and J. Zhang, “Anti-Hawking Phenomena” Phys. Lett. **B809** (2020) 135732
11. W. Cong, J. Bicak, D. Kubiznak, and **R.B. Mann**, “Quantum Detection of Inertial Frame Dragging”, Phys. Rev. **D103** (2021) 024027
12. W. Cong, J. Bicak, D. Kubiznak and **R.B. Mann**, “Quantum distinction of inertial frames: Local versus global,” Phys. Rev. **D101** (2020) 104060
13. M. P. G. Robbins, L.J. Henderson, and **R.B. Mann**, “Entanglement Amplification from Rotating Black Hole”, Class. Quant. Grav. 39 (2022) 02LT01
14. M. P. G. Robbins and R.B. Mann, “Entanglement Amplification from Rotating Black Hole”, Phys. Rev. **D106** (2022) 045018.

*Conference Presentations without papers*

1. `Signatures of Quantum Superpositions of Black Holes’, IBS-PNU Joint Workshop on Particle Physics and Cosmology, Busan, Korea (December 2022)
2. `Signatures of Quantum Superpositions of Black Holes’, 31st Japan meeting on General Relativity and Gravitation, Tokyo, Japan (October 2022) (online)
3. `Vacuum Entanglement from Cold Atoms’, QSimFP workshop, London, U.K. (September 2022)
4. `Mining the Quantum Vacuum’, Baylor-Casper-Princeton-TAMU Summer School on Quantum Physics, Caspar, Wyoming, USA (July 2022) (online)
5. `Analogue Entanglement Harvesting’, online workshop on Analog Experiments in Quantum Gravity, Nottingham, U.K. (July 2022)
6. ‘The anti-Hawking Effect’, Relativistic Quantum Information South (2020), Brisbane Australia (Feb 2020) (invited speaker).
7. ‘Causal Cheats in Black Hole Physics’, workshop on Indefinite Causal Order, Perimeter Institute (December 2019).

## Plans for next reporting period

Nothing to Report

## Participants & Other Collaborating Organizations

### What individuals have worked on this project?

1) Name: Cemile Arabaci
Total Number of Months: 12
Project Role: Graduate Student
Contribution to Project: Ms. Arabaci carried out analytic and numeric calculations in quantum signature of black hole superpositions
Country of Residence: Canada
Collaborated with Individual in a foreign country: Yes

Countries of foreign collaborators: Australia

2) Name: Wan Cong
Total Number of Months: 24
Project Role: Graduate Student
Contribution to Project: Ms. Cong carried out analytic and numeric calculations in quantum detection of inertial frame dragging
Country of Residence: Canada
Collaborated with Individual in a foreign country: Yes
Countries of foreign collaborators: China, Czech republic, Uzbekistan

3) Name: Ken Gallock-Yoshimura
Total Number of Months: 12
Project Role: Graduate Student
Contribution to Project: Mr. Gallock-Yoshimura carried out analytic and numeric calculations of entanglement harvesting for detectors freely falling into a black hole
Country of Residence: Canada
Collaborated with Individual in a foreign country: No

4) Name: Laura Henderson
Total Number of Months: 24
Project Role: Graduate Student (12 months); Postdoctoral Fellow (12 months)
Contribution to Project: Dr. Henderson carried out analytic and numeric calculations of entanglement harvesting in spacetimes with indefinite causal order and for rotating black holes
Country of Residence: Canada
Collaborated with Individual in a foreign country: Yes
Countries of foreign collaborators: Austria, Australia

5) Name: Matthew Robbins
Total Number of Months: 24
Project Role: Graduate Student
Contribution to Project: Mr. Robbins carried out analytic and numeric calculations of entanglement harvesting and the anti-Hawking effect for rotating black holes
Country of Residence: Canada
Collaborated with Individual in a foreign country: No

6) Name: Allison Sachs
Total Number of Months: 12
Project Role: Graduate Student
Contribution to Project: Ms. Sachs carried out analytic and numeric calculations in analog entanglement harvesting
Country of Residence: Canada
Collaborated with Individual in a foreign country: Yes
Countries of foreign collaborators: United Kingdom

7) Name: Erickson Tjoa
Total Number of Months: 24
Project Role: Graduate Student
Contribution to Project: Mr. Tjoa carried out analytic and numeric calculations of entanglement harvesting for detectors freely falling into a black hole and for detectors outside of a shell collapsing into a black hole.
Country of Residence: Canada
Collaborated with Individual in a foreign country: No

8) Name: Chen Zhang
Total Number of Months: 12
Project Role: Postdoctoral Fellow
Contribution to Project: Dr. Zhang carried out analytic and numeric calculations of the response of a qubit freely falling into a Schwarzschild black hole
Country of Residence: Canada
Collaborated with Individual in a foreign country: Yes
Countries of foreign collaborators: Singapore, United Kingdom

## What other organizations have been involved as partners?

Nothing to report; none of my collaborators made any financial contribution to the AOARD grant apart from their own self-support

## Has there been a change in the active other support of the PD/PI(s) or senior/key personnel since the last reporting period?

Nothing to report

## Have other collaborators or contacts been involved?

1) Name: Jiri Bicak
Country: Czech Republic
2) Name: Alessio Belenchia
Country: Austria
3) Name: Caslav Brukner
Country: Austria
4) Name: Michael Good
Country: Uzbekistan
5) Name: Cisco Gooding
Country: United Kingdom
6) Name: Robie Hennigar
Country: Canada
7) Name: Jorma Louko
Country: United Kingdom
8) Name: Keith Ng
Country: Singapore
9) Name: Alexander Smith
Country: United States
10) Name: Silke Weinfurtner
Country: United Kingdom
11) Name: Jialin Zhang
Country: China
12) Name: Magdalena Zych
Country: Australia

## Impact

### What was the impact on the development of the principal discipline(s) of the project?

The project advanced our understanding of the relationship between quantum physics and gravity, particularly in terms of our model quantum objects (qubits) respond to and become entangled in the quantum vacuum as modified by gravity (for example black holes and collapsing objects). The most significant impacts were

A) Development formalism to compute entanglement in situations where causal structure is indefinite

B) Developing a formalism to describe how physical objects (represented by qubits) respond in spacetimes in quantum superposition

C) Performing the first calculation of the response of a qubit as it falls across the horizon of a real-world black hole

These results are already influencing how we think about the effects of quantum gravity, and of how we compute related quantities.

There was also significant advancement in the development of numerical methods for computing qubit response and entanglement in curved spacetime. This was particularly significant for item (C) above (ref [1]) where new methods had to be developed to compute the response of a detector.

### What was the impact on other disciplines?

Nothing to Report

### What was the impact on the development of human resources?

8 doctoral students, 1 MSc student, and 2 postdoctoral fellows got training in advanced analytic and numerical methods. Most of these students obtained scholarship support from the Canadian government for part of the duration of the grant (the AOARD grant supported them otherwise). All of these students had opportunities to present their work at national and international meetings. 4 of the 8 personnel listed above are female.

**What was the impact on teaching and educational experiences?**

I delivered 7 international seminars on the work in this project (see above), and my students also delivered seminars on their work at various national and international meetings.

**What was the impact on physical, institutional, and information resources that form infrastructure?**

Nothing to Report

**What was the impact on technology transfer?**

Nothing to Report

**What was the impact on society beyond science and technology?**

The work on black hole superposition [8] was highlighted in an article in Physics World: https://physicsworld.com/a/black-holes-could-reveal-their-quantum-superposition-states-new-calculations-reveal/

**What percentage of the award's budget was spent in foreign country(ies)?**

100% of the money was spent in Canada supporting graduate students and postdoctoral fellows, with a small amount used to buy computer equipment.

## Changes/Problems

Nothing to Report