Multipartite Superposition of Spacetime from an Operational Perspective

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THEORY CANADA 17, 2025, REGINA

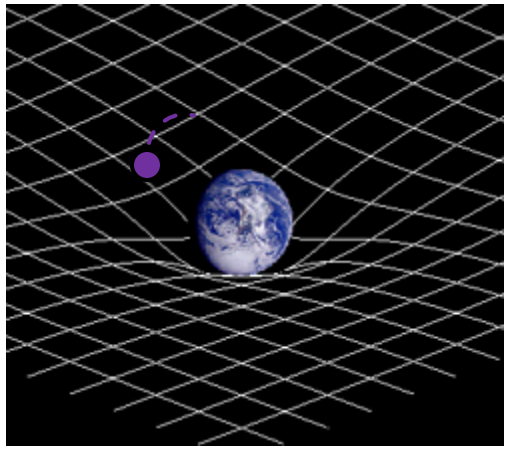
EVERETT A. PATTERSON

UNIVERSITY OF WATERLOO | FACULTY OF SCIENCE

MOTIVATION: QUANTUM GRAVITY (QG)

GRAVITY: CLASSICAL OR QUANTUM?

Classical (GR)

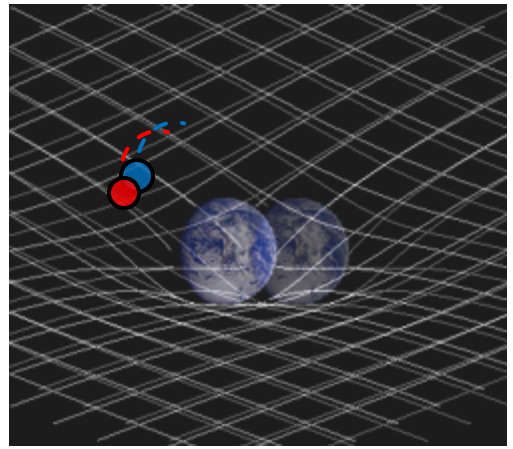


Classical spacetime

Classical matter

→ ? →

Quantum Gravity (QG)



Quantum spacetime

Quantum matter

QUANTUM GRAVITY – HOW TO GET THERE?

Two Directions

Top-Down Approaches:

1. Posit new fundamental concept (strings, loops)
2. Try to recover existing theories in appropriate limits (GR, QM)
3. Offer insights into new (testable) physics

Bottom-up Approaches:

1. Start from existing theories (GR, QM)
2. Modify current assumptions / combine between theories
3. Offers results in approximate regimes to new physics

→ We will take this approach, using the framework of Relativistic Quantum Info. (RQI)

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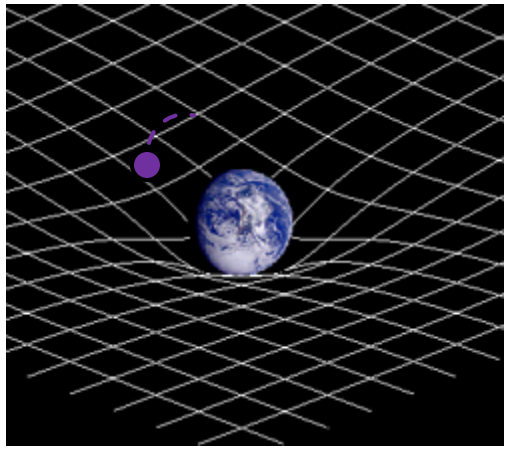

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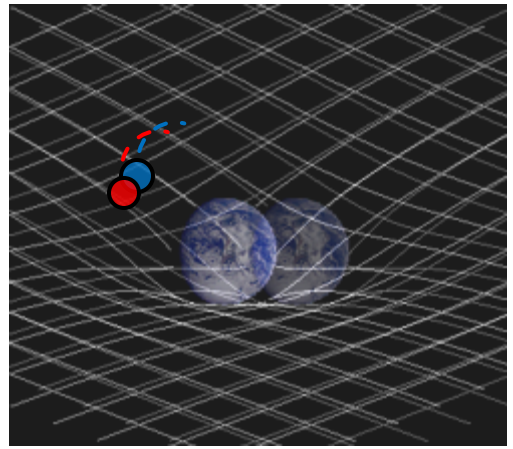

Quantum spacetime

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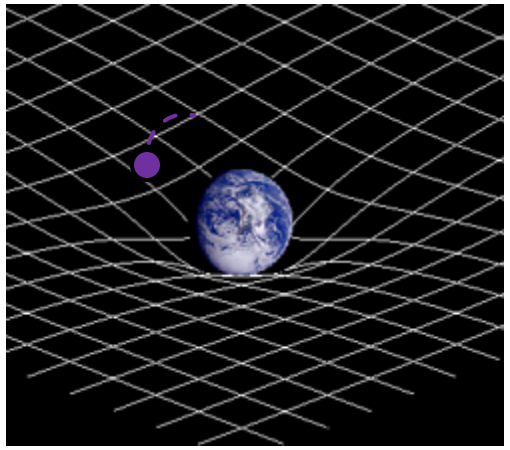
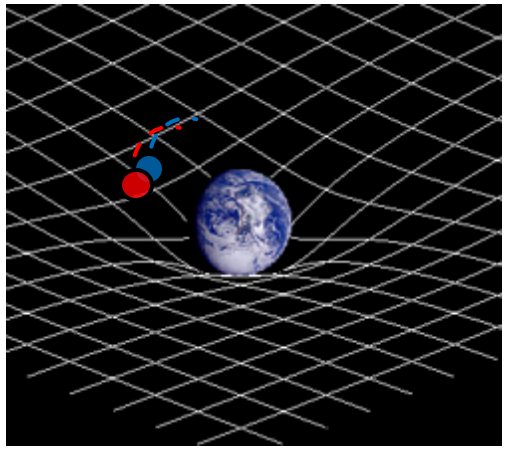


Classical spacetime

Classical matter

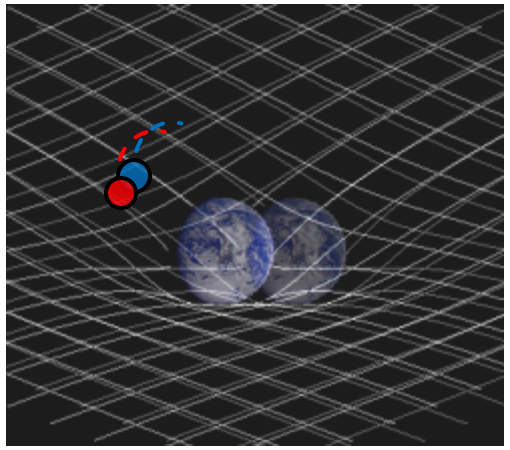
Semiclassical QG



Classical spacetime

Quantum matter

Quantum Gravity (QG)



Quantum spacetime

Quantum matter

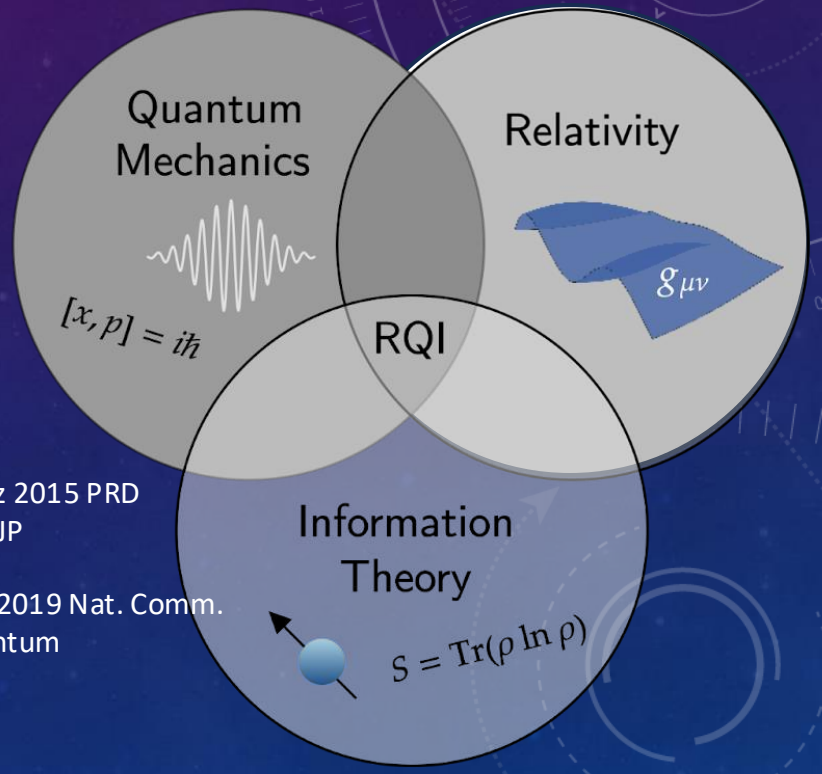
RELATIVISTIC QUANTUM INFORMATION (RQI)

Bottom-up framework for exploring QG

Examples of RQI ideas:

- Gravity induced entanglement (GIE) Bose et al. 2017 PRL, Marletto, Vedral 2017 PRL
- Quantum Entanglement Harvesting Pozas-Kerstjens, Martin-Martinez 2015 PRD, Salton, Mann, Menicucci 2015 NJP
- Quantum Reference Frames (QRFs) Giacomini, Castro-Ruiz, Brukner 2019 Nat. Comm., de la Hamette, Galley 2020 Quantum

RQI is inherently operational



ENTANGLEMENT HARVESTING PROTOCOL

- Exploits the entanglement of the quantum vacuum in QFT
- Locally couple two quantum particle detectors to the vacuum
- Can entangle even spacelike two detectors
- Entanglement is a function of the non-local Wightman function

$$P_A \sim \langle 0|\phi(x_A)\phi(x'_A)|0\rangle = W(x_A, x'_A)$$
$$L_{AB} \sim \langle 0|\phi(x_A)\phi(x'_B)|0\rangle = W(x_A, x'_B)$$

QUANTUM-CONTROLLED SPACETIME SUPERPOSITION

Foo, Mann, Zych 2021 CQG
Foo et al. 2022 PRL

Assume:

- Hilbert space associated to quantum spacetime states, spanned by orthonormal basis

$$\mathcal{H}_S \sim \{|l\_D\rangle\}$$

- Control degree of freedom, entangled with spacetime states

$$|\uparrow\rangle \sim |l_A\rangle$$

$$|\downarrow\rangle \sim l_B\rangle$$

- Prepare the control qubit in superposition → Superposition of semiclassical spacetimes

$$|\uparrow\rangle + |\downarrow\rangle \sim |l_A\rangle + |l_B\rangle$$

QUANTUM-CONTROLLED SPACETIME SUPERPOSITION (QDSS)

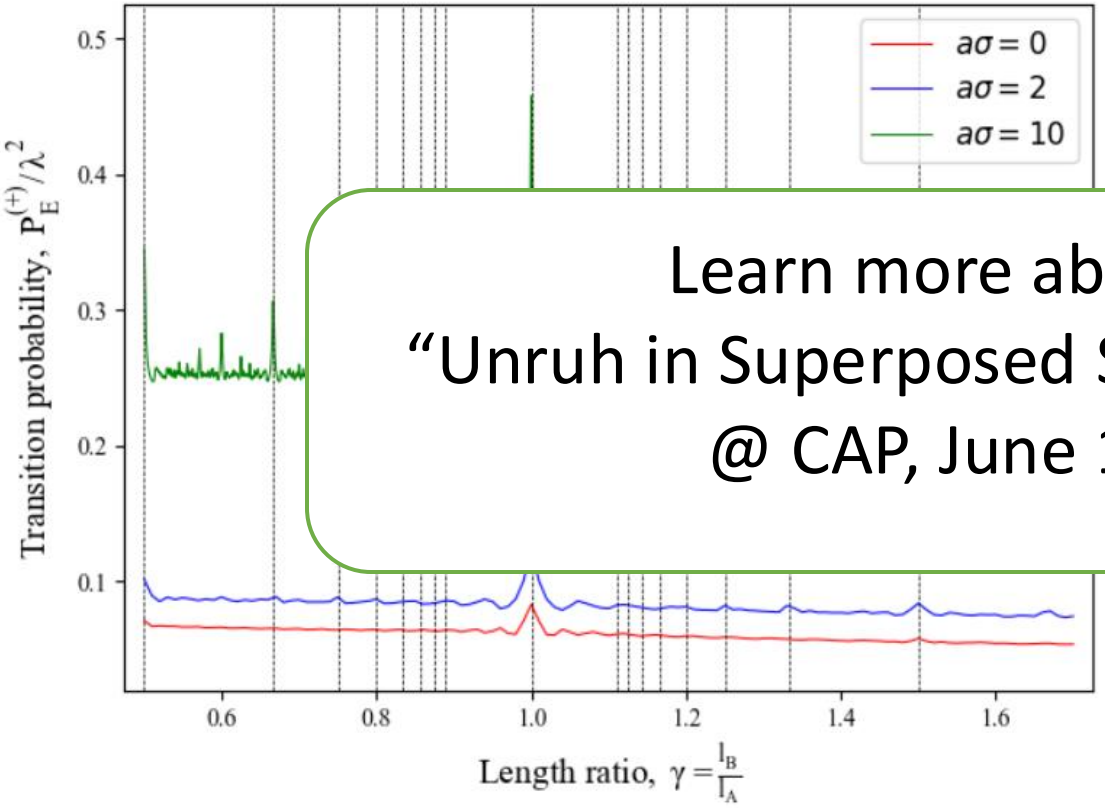
Procedure

- Couple a particle detector to the quantum fields in each spacetime
- Compute the time-evolution
- Measure the control qubit in the superposed basis, trace over the field
- Obtain “quantum spacetime” dynamics, encoded in detector’s response

$$P_A \sim \langle 0|\phi(x_A)\phi(x'_A)|0\rangle = W(x_A, x'_A)$$
$$L_{AB} \sim \langle 0|\phi(x_A)\phi(x'_B)|0\rangle = W(x_A, x'_B)$$

$$P_E^{(\pm)} = \frac{\lambda^2}{4}(P_A + P_B \pm 2L_{AB})$$

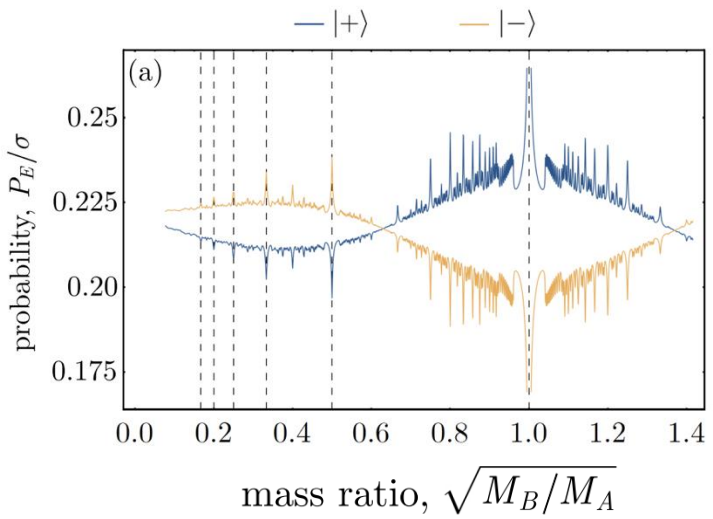
RESULTS – RESONANCE PEAKS



Accelerated detector, identified Minkowski

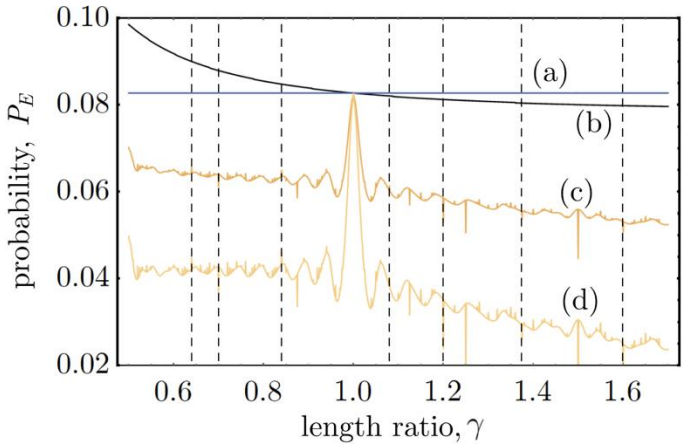
Goel et al., 2025, PRD 111 (incl. E.A.P)

Learn more about
"Unruh in Superposed Spacetimes"
@ CAP, June 10



Static detector, BTZ black hole

Foo et al., 2022, PRL 129



Static detector, identified Minkowski

Foo et al., 2023, PRD 107

RESULTS – QUDITS IN RQI

Multipartite Quantum-Controlled Superposition of Spacetimes

- Use a control qudit instead of qubit

$$P_E^{(++)} = \frac{\lambda^2}{9}[P_A + P_B + P_C + 2(L_{AB} + L_{AC} + L_{BC})]$$

Reminiscent of correlations from tripartite entanglement harvesting

- Though entanglement measures are tricky for $d \geq 3$ systems
- Entanglement is in general non-linear in the non-local correlation terms

Can this relationship be examined more closely?

THANKS FOR YOUR ATTENTION!

Summary

1. Quantum-Controlled Spacetime Superpositions (QCSS) can offer insights into QG,
2. Correlation from QCSS resemble those from Entanglement Harvesting,
3. How robust is this connection for multipartite systems?

Learn more: June 10, @ CAP

Everett A. Patterson
PhD Candidate
University of Waterloo
Funded by NSERC CGS-D

Email: ea2patterson@uwaterloo.ca