Quantum signatures of black hole mass superpositions–Phys. Rev. Lett. 129 (2022)

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Joshua Foo[†], Cemile Senem Arabaci[‡], Magdalena Zych[§] & Robert B. Mann[‡*]

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[†] Centre for Quantum Computation and Communication Technology
University of Queensland, Australia
[‡] Department of Physics and Astronomy
University of Waterloo, Canada
[§] Centre for Engineered Quantum Systems
University of Queensland, Australia
[*] Perimeter Institute, Waterloo, Canada

Collaborators

The University of Queensland
Australia

University of Waterloo

Spacetime superpositions

- Quantum gravity: superpositions of spacetime geometry
- Spatial superpositions of the metric:

$$
\begin{aligned}
|\psi\rangle &= (|g_A\rangle + |g_B\rangle)|\phi\rangle, \\
\hat{U}|\psi\rangle &= (\hat{U}_A|g_A\rangle + \hat{U}_B|g_B\rangle)|\phi\rangle, \\
\langle\Omega|\hat{U}|\psi\rangle &= \langle\Omega|\hat{U}_A|g_A\rangle|\phi\rangle + \langle\Omega|\hat{U}_B|g_B\rangle|\phi\rangle, \\
&= \langle\Omega|\hat{U}_A|g_A\rangle|\phi\rangle + \langle\Gamma^{-1}\Omega|\hat{U}_A|g_A\rangle|\Gamma^{-1}\phi\rangle,
\end{aligned}
$$

since $|g_B\rangle = \hat{\Gamma}|g_A\rangle$ (diffeomorphic). Not unambiguously QG! (see J. Foo, R.B. Mann, M. Zych arXiv:23... soon)

Superpositions of non-diffeomorphic metrics

- Superpositions of a black hole mass:

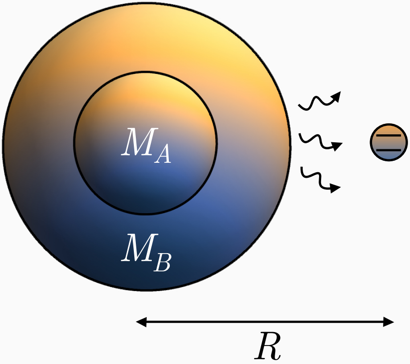
$$|M\rangle \xrightarrow{\text{superpose}} \frac{1}{\sqrt{2}}(|M_A\rangle + |M_B\rangle)|\phi\rangle|g\rangle$$

Different solutions to Einstein field equations. Physically distinguishable spacetimes.

What are the operational signatures of a mass-superposed black hole?

Time is what clocks measure, temperature is what a thermometer records, etc.

Physical setup



Assumptions

- QFT in CS–each amplitude has independent field quantisation
- Qubit at fixed R couples to superposed field

(2+1)-DIMENSIONAL BTZ BLACK HOLE

Banados-Teitelboim-Zanelli black hole

- Line element:

$$\mathrm{d}s^2 = -\left(\frac{r^2}{l^2} - M\right)\mathrm{d}t^2 + \left(\frac{r^2}{l^2} - M\right)^{-1}\mathrm{d}r^2 + r^2\mathrm{d}\phi^2$$

  Obtained through periodic identification $\phi \to \phi + 2\pi n\sqrt{M}$ of AdS_3 in Rindler-type coordinates
- Asymptotically AdS_3 (l is the AdS length scale)
- Analytically tractable QFT calcalations (two-point correlators)

Unruh-deWitt model

$$|\psi_i\rangle = \frac{1}{\sqrt{2}}(|M_A\rangle + |M_B\rangle) \otimes |0\rangle \otimes |g\rangle$$

$$\hat{H}_{\text{int.}}(\tau) \propto (|e\rangle\langle g| e^{i\Omega\tau} + \text{h.c}) \sum_{D=A,B} \hat{\phi}(\mathsf{x}_D) \otimes |M_D\rangle\langle M_D|$$

1. Time-evolve initial state

$$|\psi_f\rangle = e^{-i\hat{H}_{0,S}t_f}\hat{U}_{\text{int.}}(t_i, t_f)e^{i\hat{H}_{0,S}t_i}|\psi_i\rangle$$

2. Condition BH in superposition basis, e.g. $\langle\pm|\psi_f\rangle\langle\psi_f|\pm\rangle$
3. Trace out field $\Rightarrow$ detector transition probability

Factorizable clock state

- $r \gg r_{H_{A,B}}$ proper time difference of “clocks” in spacetimes M_A, M_B is negligible. t_i, t_f defined with respect to faraway observers

Signatures of Bekenstein's conjecture

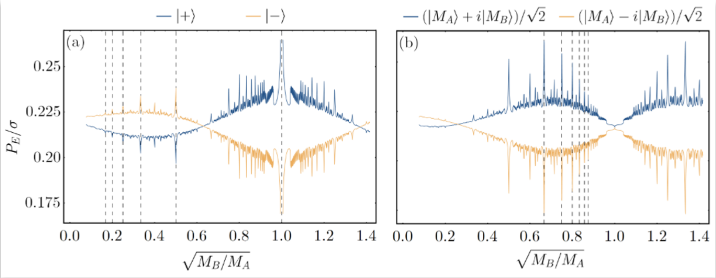


Figure 1: Conditioning BH onto (left) $|\pm\rangle$ (right) $|i\pm\rangle$

Detector resonances $\Longleftrightarrow$ Bekenstein's conjecture

$$r_H = \sqrt{Ml} = n\hbar \xrightarrow{\text{superpose}} r_{H_B}/r_{H_A} = \sqrt{M_B/M_A} = n/m \in \mathbb{Q}$$

Metric for spacetime superpositions

Two-point correlation functions

- Through interaction with the field, detector accesses two-point correlation functions $W(x_i, x_j)$, $i, j = A, B$

Superposed metric

Kempf:[1] $\sigma(\mathrm{x}, \mathrm{x}') \Leftrightarrow W(\mathrm{x}, \mathrm{x}')$ at the level of the metric:

$$g_{\mu\nu} = -\lim_{x \to x'} \frac{\partial}{\partial x^\mu} \frac{\partial}{\partial x'^\nu} \sigma(x, x') \propto \lim_{x \to x'} \frac{\partial}{\partial x^\nu} \frac{\partial}{\partial x'^\mu} W(x_i, x_i')^{\frac{2}{d-2}}$$

For a spacetime superposition, $\hat{\phi}(x) \to \hat{\phi}(\mathbf{x}) = \sum_i f_i \hat{\phi}(x_i)$

$$g_{\mu\nu} \propto \lim_{x \to x'} \frac{\partial}{\partial x^\nu} \frac{\partial}{\partial x'^\mu} \sum_{i,j} f_i f_j^\star W(x_i, x_j')^{\frac{2}{d-2}}$$

[1] Kempf, Front. Phys. 9, (2021)

Cavity QFT

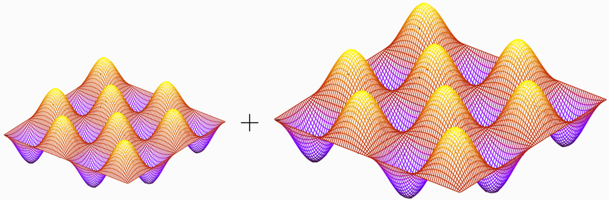


Figure 2: See also arXiv:2208.12083

$$\hat{\phi}_{\text{small}}(x,t) = \sum_{n=1}^{\infty} \frac{1}{\sqrt{\pi n}} \left(\sin(k_n x) e^{-ik_n t} \hat{a}_{k_n} + \text{h.c} \right)$$

$$\hat{\phi}_{\text{big}}(x,t) = \sum_{n=1}^{\infty} \frac{1}{\sqrt{\pi n}} \left(\sin(\bar{k}_n x) e^{-i\bar{k}_n t} \hat{a}_{\bar{k}_n} + \text{h.c} \right)$$

CONCLUSIONS

Results[2]

- In quantum gravity, spacetime should be quantum
- Calculated the operational effect of a mass-superposed black hole
- Showed that a quantum detector is sensitive to Bekenstein's conjecture
- Quantum metric constructed from two-point functions of the field
- Full paper: Phys. Rev. Lett. **129** 181301 (2022)

[2] Email jfoobles@gmail.com for ideas, discussion, collaboration!

Thank You!

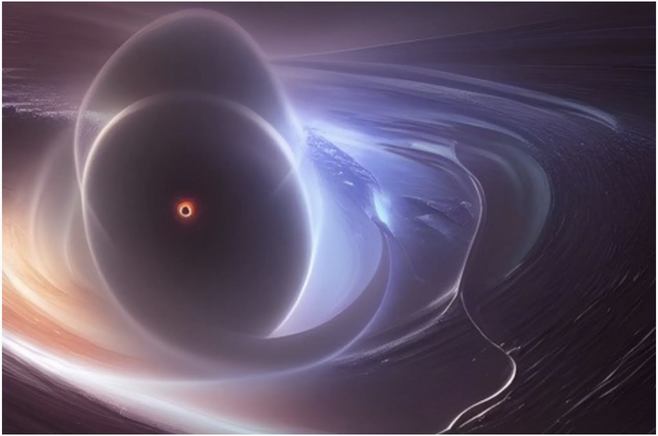


Figure 3: AI impression of a mass-quantised black hole