Journey to the Center of a Black Hole Using Quantum Computing

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August 11, 2021

Introduction

de Sitter Universe

- ➔ Positively curved spacetime
- ➔ Positive cosmological constant, Λ
- ➔ Empty of matter

Our Universe

- ➔ In D = 3 + 1 dimensions, it's positively curved
- ➔ Observed positive Λ (dark energy)
- ➔ Has matter but exponentially expanding

$\therefore$ Asymptotically de Sitter

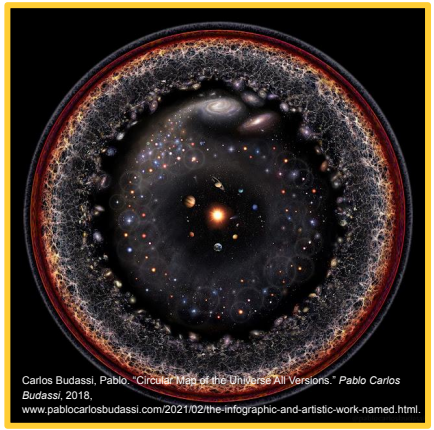
Motivation

$$G_{\mu\nu} + g_{\mu\nu}\,\Lambda = 8\,\pi G T_{\mu\nu}$$

- ➔ Existence of dark energy driving the observed exponential expansion of the Universe
  - ◆ Solution to Einstein's equation = de Sitter space
- ➔ New info about properties of black holes
  - ◆ Solution to Einstein's equation = Schwarzschild solution
- ➔ Cosmological horizon is similar to the event horizon of a black hole
  - ◆ Temperature and entropy

If the Universe is truly de Sitter, one can apply the quantum properties of black holes to our Universe.

The Universes of Max Tegmark, space.mit.edu/home/tegmark/wmap.html.



Carlos Budassi, Pablo. "Circular Map of the Universe All Versions." *Pablo Carlos Budassi*, 2018, www.pablocarlosbudassi.com/2021/02/the-infographic-and-artistic-work-named.html.

Study the abilities of quantum computing!

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Method

- ➔ Goal: Explore the features of SdS black holes!
- ➔ Start with classical computations using Mathematica
- ➔ Use quantum computing (QISkit) to study VQE and EOH
  - ◆ Main function was the Variational Quantum Eigensolver

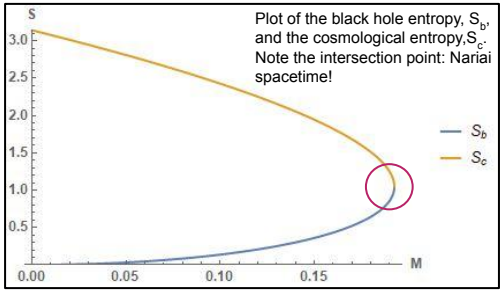
Variational Quantum Eigensolver

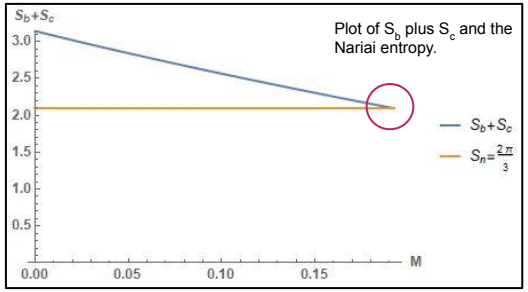
- ➔ Variational Quantum Eigensolver (VQE)
  - ◆ Repeatedly modifies an ansatz for a wavefunction in an effort to get as accurate of a result as possible.
  - ◆ Just like the variational method in quantum mechanics!
- ➔ Use 4 different optimizers and compare the accuracy.
  - ◆ SLSQP, COBYLA, L-BFGS-B, NELDER-MEAD

Thermodynamics

Simplified entropy equation

$$S = \frac{1}{4}A \rightarrow S_b = \pi r_b^{\,2} \text{ and } S_c = \pi r_c^{\,2}$$



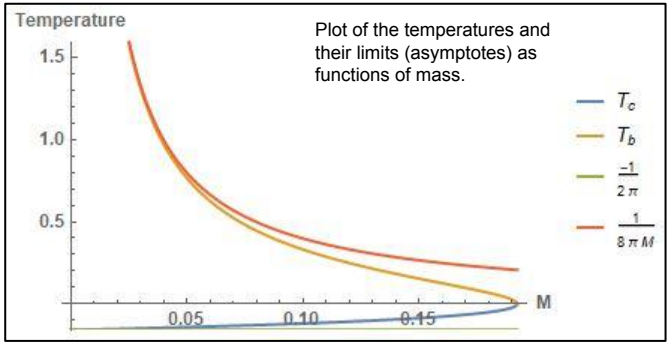


An important solution to note is the **Nariai black hole**. This is the largest possible black hole in de Sitter space. Its event horizon radius approaches that of the cosmological horizon, $r_b \rightarrow r_c$, so that the two radii coincide.

No spacial singularity! It appears to be a singularity in time.

Temperature equation

$$\beta = T^{-1} = \frac{\partial S}{\partial M}$$



Notice the convergence point of the two temperatures at the Nariai point,

$$M = \frac{1}{\sqrt{27}}$$

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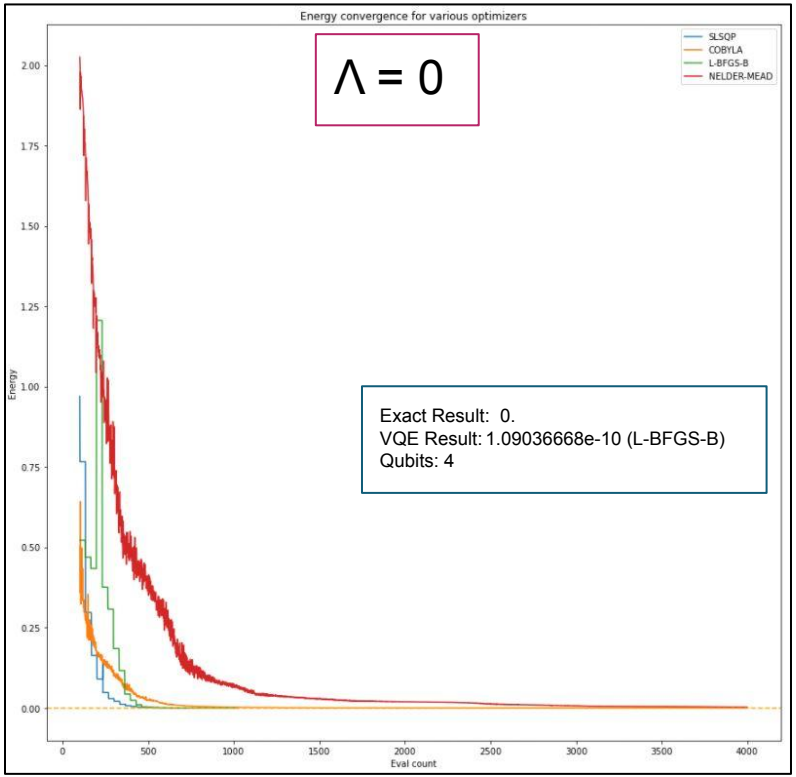
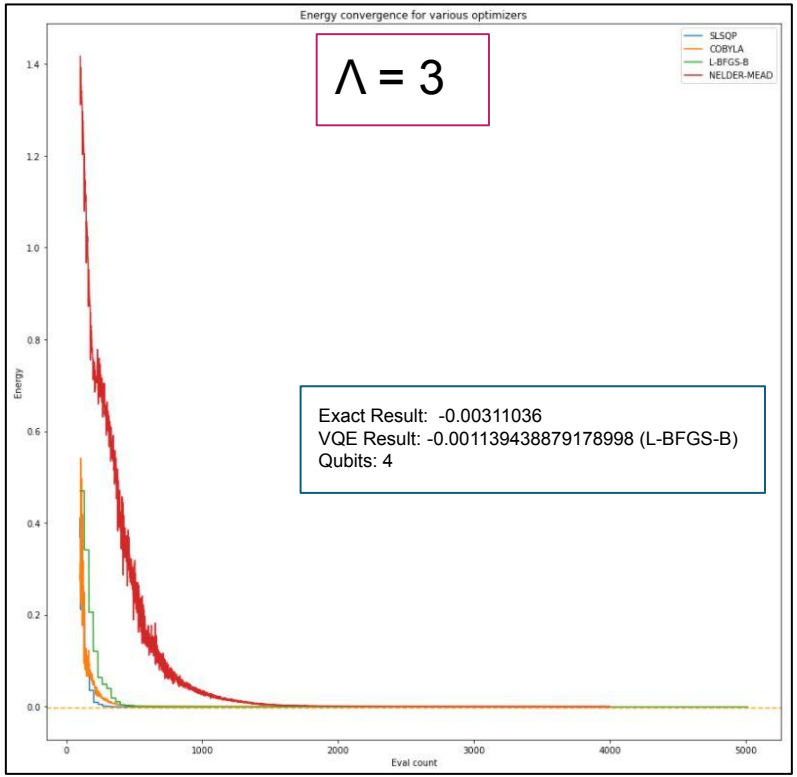
Hamiltonian VQE





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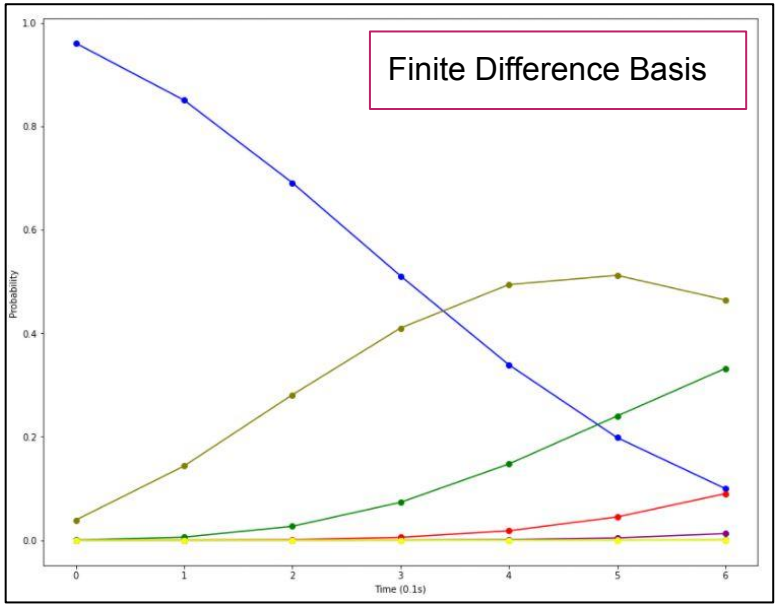
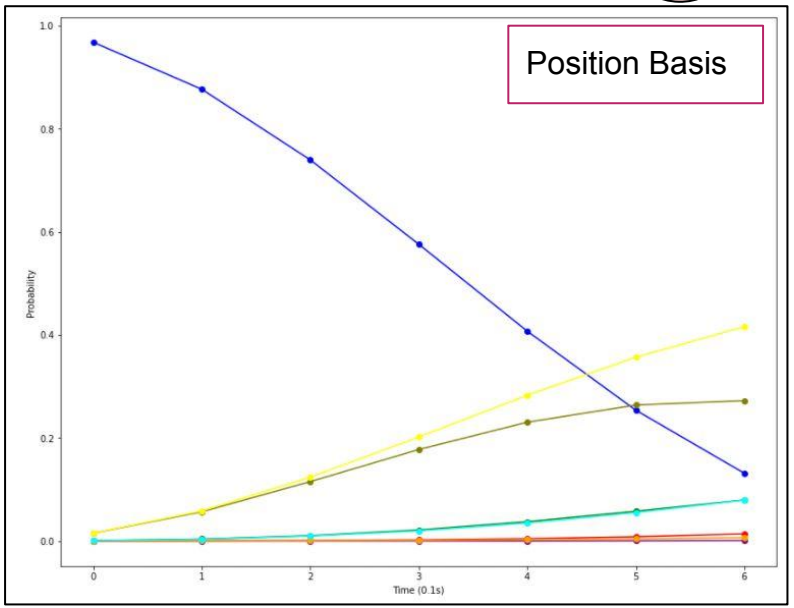
Evolution of the Hamiltonian

The Hamiltonian represents the quantum version of the Friedmann equation which describes the evolution of the Universe.





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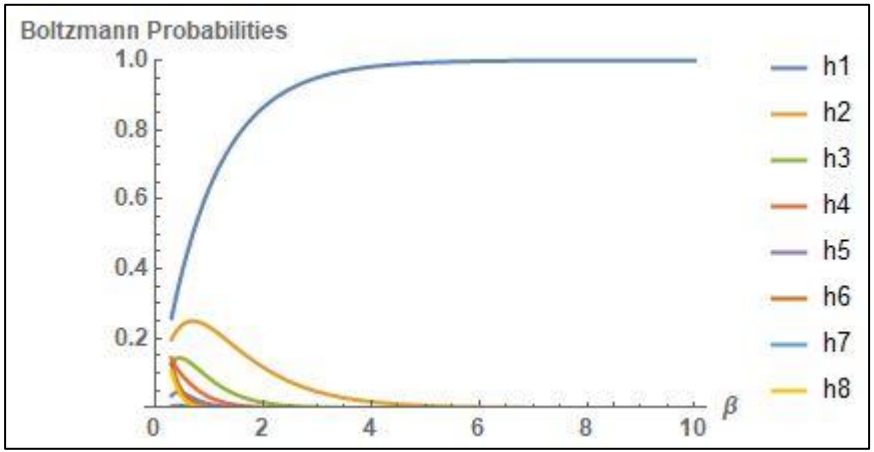
Thermofield Double

- Essentially, the TFD is a special entangled state that cannot be denoted as a mixture of states.
- Similar to the EOH, except we evolve in temperature rather than time.
- Way to study a thermal system by introducing a “double” particle (in our case, boson) into the TFD state.

$$G = -i\theta[\beta]\left(a_{Bd}\, a_B - a_B{}^{+}\, a_{Bd}{}^{+}\right)$$

$e^{-i\theta G}$ Evolve in temperature



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Conclusion

- ➔ The Nariai black hole is the largest possible bh.
- ➔ Useful connections can be drawn between a dS black hole and the Universe.
- ➔ The TFD state is useful in the study of black holes since it involves a special entangled state which can be applied to two sides of the black hole.

Acknowledgements

Thank you to Dr. McGuigan for allowing me to work with him again during this summer and continue our research progress. I appreciate all of the support, guidance, and knowledge shared. This project was supported in part by the U.S. Department of Energy, Office of Science, Office of Workforce Development for Teachers and Scientists (WDTS) under the Science Undergraduate Laboratory Internships Program (SULI).

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