The Information Paradox

Quantum Mechanics and Black Holes

FokionFest
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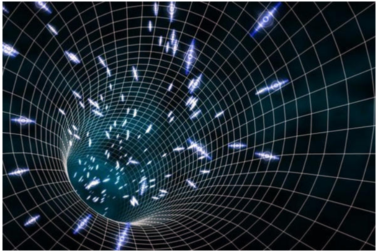
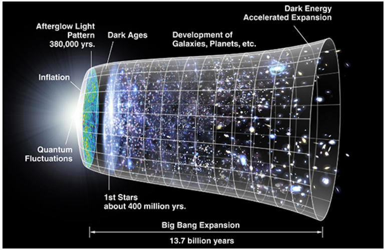
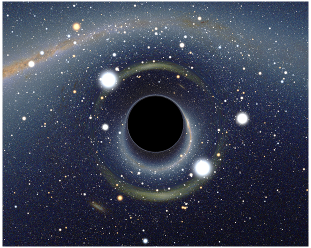
CERN

Space-Time and Quantum Gravity







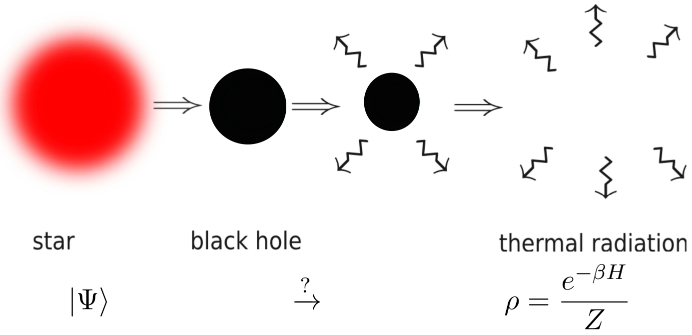
Space-time at short scales/scattering at $E \gtrsim 10^{19}$ GeV

Cosmology (Big Bang, Dark Matter/Energy)

Black holes (Entropy, Singularity, Black Hole Information Paradox)

The information paradox

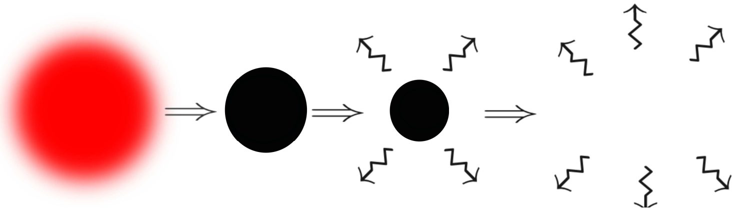
Hawking found that black holes emit thermal body radiation at temperature $T = \frac{1}{8\pi GM}$



Inconsistent with **unitary** evolution in quantum mechanics

$$|\Psi(t)\rangle = e^{-iHt}|\Psi(0)\rangle$$

Unitarity from small corrections



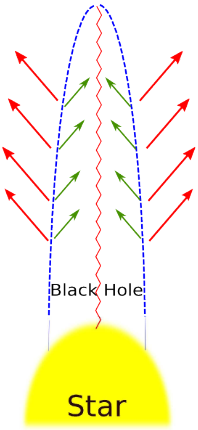
Hqwking's computation is **semiclassical**, there are quantum corrections

$$\rho = \rho_{\text{thermal}} + e^{-S}\rho_{\text{cor}}$$

Exponentially small correlations between the outgoing Hawking particles contain the information.

To preserve unitarity the Hawking particles must be **entangled** to each other.

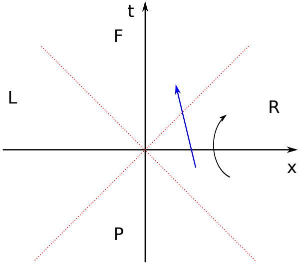
Entanglement near the horizon

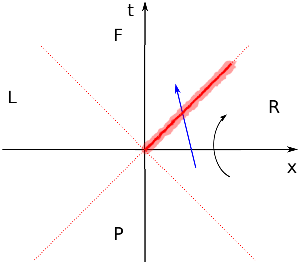


Hawking particles are produced in **entangled pairs**

This entanglement is **necessary** for the smoothness of spacetime near the horizon

Example: flat space, Unruh effect

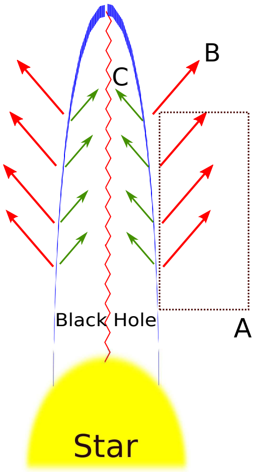




$$|0\rangle_M = \sum_{n=0}^{\infty} e^{-\pi\omega n} |n\rangle_L \otimes |n\rangle_R \qquad |\Psi\rangle = |0\rangle_L \otimes |0\rangle_R \to \langle T_{\mu\nu}\rangle \neq 0$$

The firewall paradox

[Mathur],[Almheiri, Marolf, Polchinski, Sully]

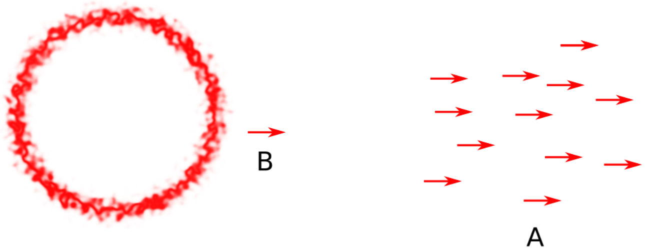


For information to escape black hole: B must be entangled with A.

For horizon to be smooth: B must be entangled with C.

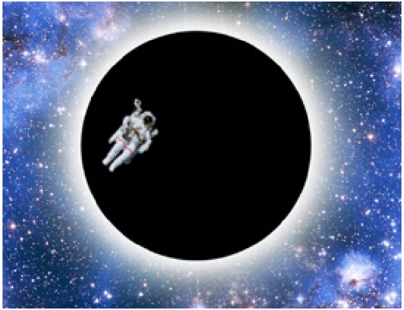
This violates the **monogamy of entanglement** for the particle B.

Is the horizon smooth?



Breaking the B-C entanglement near the horizon creates a huge energy density creating a "**firewall**" on the horizon, which would burn up an infalling observer.

General Relativity vs Quantum Mechanics



The firewall would be able to solve the information paradox, however it leads to massive violations of general relativity.

The curvature of spacetime near the black hole horizon is

$$R_{ijkl}R^{ijkl} \sim \frac{1}{(GM)^4}$$

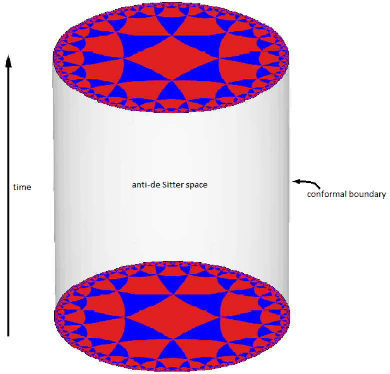
For a large black hole this curvature is very low and we expect standard general relativity to hold.

Unitarity vs Equivalence Principle?

The AdS/CFT correspondence

[Maldacena '97]

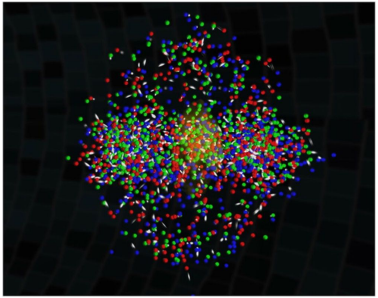
A $d+1$-dimensional theory of gravity with negative cosmological constant, is equivalent to a d-dimensional large N $SU(N)$ gauge theory (CFT) without gravity



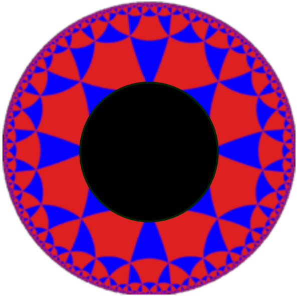
Questions about quantum gravity can be translated in the QFT

Black Holes in AdS/CFT

Quark gluon plasma



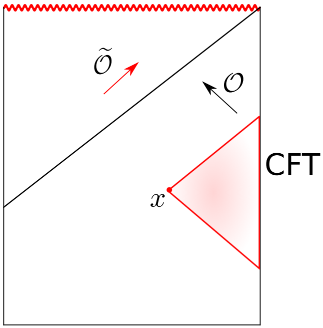
Black Hole in AdS



Understanding of black hole entropy = entropy of QGP

AdS/CFT settles that information is not lost

Spacetime behind the horizon



$$\mathcal{O} = \mathrm{Tr}[F_{\mu\nu}F^{\mu\nu}]$$

$$\phi(x) = \int dy K(y;x)\mathcal{O}(y)$$

What are the operators $\widetilde{\mathcal{O}}$?

Spacetime behind the horizon

- Until recently, understanding of black hole interior in AdS/CFT was limited
- In the last few years we developed a proposal for the holographic description of the BH interior [K.P. and S. Raju]

  based on JHEP 1310 (2013) 212, PRL 112 (2014) 5, Phys.Rev. D89 (2014), PRL 115 (2015), JHEP 1605 (2016)
- Concretely: we identified CFT operators $\widetilde{\mathcal{O}}$ relevant for describing the black hole interior
- This has provided some new insights for the modern version of the information paradox

Tomita-Takesaki modular theory

Define antilinear map

$$SA|\Psi\rangle = A^\dagger|\Psi\rangle$$

$$\widetilde{\mathcal{O}}_\omega|\Psi\rangle = e^{-\frac{\beta\omega}{2}}\mathcal{O}^\dagger_\omega|\Psi\rangle$$

and

$$\widetilde{\mathcal{O}}_\omega\mathcal{O}....\mathcal{O}|\Psi\rangle = \mathcal{O}...\mathcal{O}\widetilde{\mathcal{O}}_\omega|\Psi\rangle$$

$$\Delta = S^\dagger S \qquad J = S\Delta^{-1/2}$$

$$[H,\widetilde{\mathcal{O}}_\omega]\mathcal{O}....\mathcal{O}|\Psi\rangle = \omega\widetilde{\mathcal{O}}_\omega\mathcal{O}....\mathcal{O}|\Psi\rangle$$

Then the operators

$$\boxed{\widetilde{O} = JOJ}$$

i) commute with $\mathcal{O}$

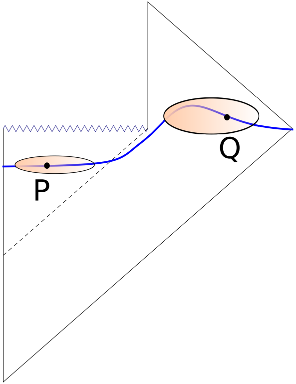
ii) are correctly entangled with $\mathcal{O}$

These are the operators that we need to describe the Black Hole interior.

$$\phi(t,r,\Omega) = \int_0^\infty d\omega\Big[\mathcal{O}_\omega\, f_\omega(t,\Omega,r) + \widetilde{\mathcal{O}}_\omega g_\omega(t,\Omega,r) + \mathrm{h.c.}\Big]$$

This shows that it is possible to reconcile unitarity with the equivalence principle and the smoothness of the horizon, thus resolving the firewall paradox.

Non-locality in Quantum Gravity



Locality in Quantum Gravity is approximate

$$[\phi(P), \phi(Q)] = O(e^{-S})$$

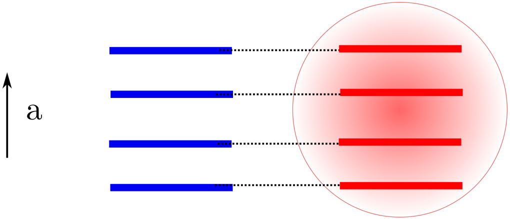
Hilbert space of Quantum Gravity does not factorize as

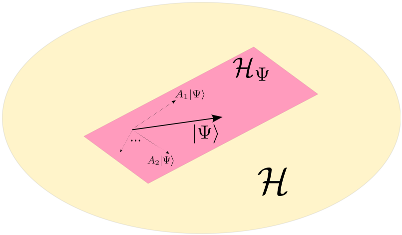
$$\mathcal{H} \neq \mathcal{H}_{\text{inside}} \otimes \mathcal{H}_{\text{outside}}$$

Solves problem of Monogamy of Entanglement

Concrete realization of “Black Hole Complementarity”. We showed it is consistent with approximate locality in effective field theory

State-dependence of observables





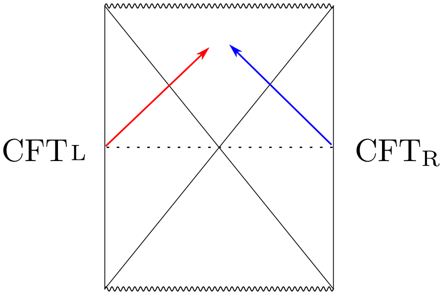
- Interior operators defined by

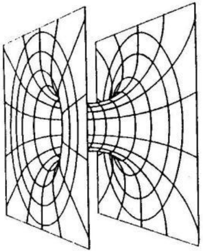
$$\widetilde{\mathcal{O}}|\Psi\rangle = e^{-\frac{\beta H}{2}}\mathcal{O}e^{\frac{\beta H}{2}}|\Psi\rangle \qquad \widetilde{\mathcal{O}}\mathcal{O}...\mathcal{O}|\Psi\rangle = \mathcal{O}...\mathcal{O}\widetilde{\mathcal{O}}|\Psi\rangle$$

- We notice the specific black hole microstate $|\Psi\rangle$ entering the equation
- Operators depend on the state, they are defined in "patches" on the Hilbert space
- Novel feature

Connection to ER = EPR

Entanglement & Wormholes



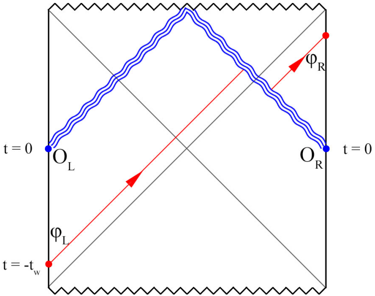


$$H = H_L + H_R$$

$$|\mathrm{TFD}\rangle = \sum_E \frac{e^{-\beta E/2}}{\sqrt{Z}} |E\rangle_L \otimes |E\rangle_R$$

Traversable wormholes

[Gao, Jafferis, Wall] [van Breukelen, KP] [van Breukelen, de Boer, Lokhande, KP, Verlinde]



Possibility to probe black hole interior via simple CFT correlators

Equivalent to **quantum teleportation** between two CFTs

New evidence for smoothness of horizon and for state-dependent proposal

Summary

1. The information paradox, and its recent reformulation as the firewall paradox is a fundamental conflict between general relativity and quantum mechanics.

2. Understanding how to resolve it may lead us towards the fundamental principles of quantum gravity.

3. I presented a proposal for its resolution, which relies on the idea that locality in quantum gravity is emergent and not exact, as well as the state-dependence of certain observables.

4. More generally entanglement and quantum information seem to be increasingly important for understanding the quantum nature of spacetime.

Thank you!