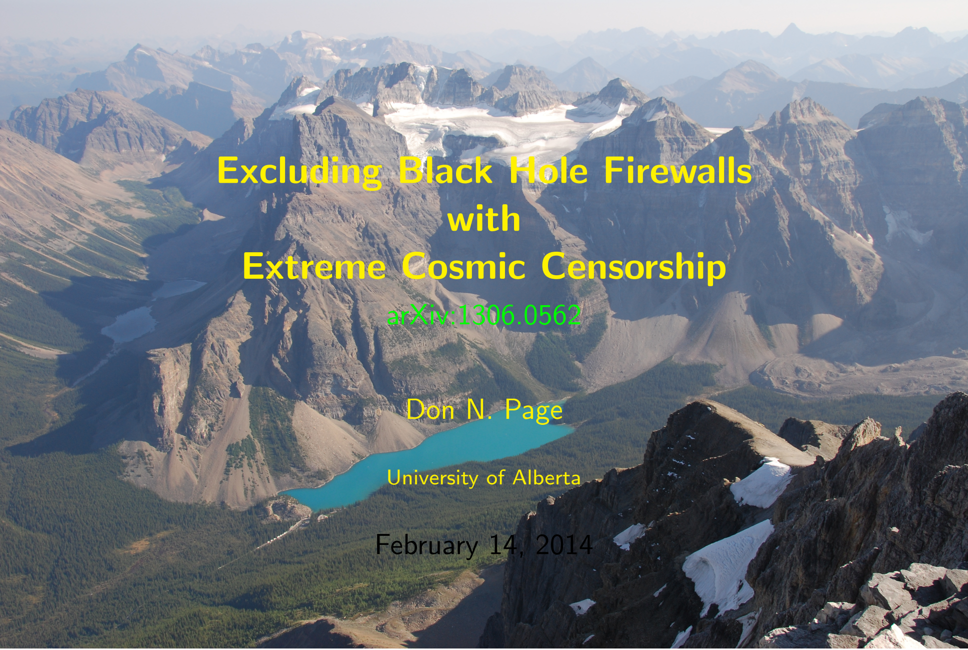

Excluding Black Hole Firewalls with Extreme Cosmic Censorship

arXiv:1306.0562

Don N. Page

University of Alberta

February 14, 2014

Introduction

A goal of theoretical cosmology is to find a quantum state of the universe that explains our observations.

A goal of black hole physics is to find a quantum description of the evolution of black holes.

In both cases it may be useful to find a restriction that eliminates unphysical states.

Extreme Cosmic Censorship (ECC):

The universe is entirely nonsingular (except for singularities inside black or white holes which do not persist).

Quantum Models of the Universe

A. Vilenkin, “Creation of Universes from Nothing,” Phys. Lett. B **117**, 25 (1982) (tunneling wave function)

J. B. Hartle and S. W. Hawking, “Wave Function of the Universe,” Phys. Rev. D **28**, 2960 (1983) (no-boundary wave function).

A. D. Linde, “Quantum Creation of the Inflationary Universe,” Lett. Nuovo Cim. **39**, 401 (1984) (Linde’s wave function)

D. N. Page, “Symmetric-Bounce Quantum State of the Universe,” JCAP **0909**, 026 (2009) (symmetric-bounce wave function)

Infinite or Finite Numbers of Quantum States?

An ultimate goal would be to find the actual quantum state of the universe.

An intermediate goal might be to find a restriction to a finite number of states.

String theory is supposed to give an infinite number of states.

It has been argued that $\Lambda > 0$ allows only a finite number of states, such as $\exp(A/4)$ where $A = 12\pi/\Lambda$ is the area of the cosmological event horizon of pure de Sitter spacetime.

However, $\Lambda > 0$ by itself does not seem to be sufficient.

Extreme Cosmic Censorship

I do not have the final answer as to what the quantum state of the universe is, but I suggest that a reasonable state might obey

Extreme Cosmic Censorship (ECC):

The universe is entirely nonsingular (except for singularities inside black or white holes which do not persist in the future or past).

Although I came to this idea independently, it is a strong extension to the future as well as to the past of Anthony Aguirre's proposal in "Eternal Inflation, Past and Future," arXiv:0712.0571:

Consistent Cosmic Censorship (CCC):

Without exception, no physical observer can physically observe a past singularity.

Details of Extreme Cosmic Censorship

I want to exclude big-bang and big-crunch singularities but not those arising from gravitational collapse inside black or white holes.

If one has a spacelike curve running through a hole but joining two timelike curves that stay outside, by distorting the spacelike curve one can bring it outside the hole and then move it and its endpoints arbitrarily far backward or forward in time, before the formation or after the evaporation of the hole.

However, if one has a perturbed Nariai metric that evolves to multiple asymptotically de Sitter regions, a spacelike curve joining one to another cannot be pushed arbitrarily far backward without running into a big bang, or arbitrarily forward without running into a big crunch, separating the different asymptotic de Sitter regions.

Thus I am proposing to exclude singularities that a sequence of spacelike curves cannot go around.

Refinement of Extreme Cosmic Censorship for Excluding Firewalls

Actually, for the later use I want to make of Extreme Cosmic Censorship to exclude firewalls, I want to exclude not only big bang and big crunch singularities that a sequence of spacelike curves cannot bo around, but also all all naked or almost naked singularities that effectively have a dimensionality greater than zero, singularities that in some sense are larger than the point singularities (or Planck-size regions of Planckian curvature) at the final point of evaporation of a black hole.

Thus I would also want to exclude timelike one-dimensional singularities such as $r = 0$ for negative-mass Schwarzschild, and nearly-null singularities of positive dimensionality just inside black holes that are the putative firewalls.

The most elegant formulation of Extreme Cosmic Censorship remains to be developed.

What is the Quantum Version of Extreme Cosmic Censorship?

For classical models of the universe, it is fairly easy to say which ones obey Extreme Cosmic Censorship and which ones do not.

For a quantum universe, one might be able exclude quantum states that have any nonzero amplitudes for an initial big bang. However, then it seems difficult also to exclude quantum states that also have any nonzero amplitudes for a final big crunch. The uncertainty principle may forbid excluding all amplitudes for singularities both at the beginning and at the end of the evolution of the universe.

However, if the quantum state is restricted to have time-symmetric 'initial' conditions at a time-symmetric bounce and can also be chosen to avoid amplitudes for a big crunch in the future, then by the time symmetry it would also avoid amplitudes for a big bang in the past.

Extreme Cosmic Censorship and Black Hole Firewalls

Although I have proposed Extreme Cosmic Censorship mainly for cosmology, it seems to apply to the firewall problem for black holes.

A. Almheiri, D. Marolf, J. Polchinski and J. Sully, "Black Holes: Complementarity or Firewalls?," JHEP **1302**, 062 (2013) (AMPS) give a provocative argument that suggests that an "infalling observer burns up at the horizon" of a sufficiently old black hole, so that the horizon becomes what they called a "firewall."

Unitary evolution suggests that at late times the Hawking radiation is maximally entangled with the remaining black hole and neighborhood (including the modes just outside the horizon).
This further suggests that what is just outside cannot be significantly entangled with what is just inside.
But without this latter entanglement, an observer falling into the black hole should be burned up by high-energy radiation.

Excluding Firewalls with Extreme Cosmic Censorship

Allowing quantum states without the entanglement across a black hole horizon is allowing states that are singular just inside the black hole or would rapidly become singular when evolved back in time.

Such quantum states would be excluded by Extreme Cosmic Censorship, unless possibly they are consistent with white hole states that seem to violate the thermodynamic arrow of time.

Without such an exclusion, the number of quantum states for a black hole could be unbounded, greatly exceeding the Bekenstein-Hawking $\exp(A/4)$.

I suggest that it is impossible to form firewall states from nonsingular initial conditions (or from sending in regular data from a boundary of AdS in AdS/CFT).

When firewall states are excluded, the early Hawking radiation can be maximally entangled with the physically allowed black hole states without violating quantum monogamy.

Maximal Entanglement without Maximal Entanglement

A black hole and its nearby environment of mass M has area $A \sim M^2$ and may be considered to have volume $V \sim M^3$. If each Planck volume were like a qubit, then the black hole and the nearby environment out to $r \sim 3M$ would have $\sim \exp(M^3)$ states.

However, almost all of these states would lead to singularities violating Extreme Cosmic Censorship. To avoid such singularities near the horizon, there must be nearly maximal entanglement between these qubits outside and inside the horizon.

Nevertheless, there can be $\sim \exp(M^2)$ physically allowed states of the black hole and nearby environment that can in principle be maximally entangled with the distant early radiation from the black hole if it is sufficiently old (e.g., much older than I am).

Maximal entanglement of $\sim \exp(M^2)$ physically allowed independent states with early radiation does not violate quantum monogamy when the $\sim \exp(M^3)$ not-physically-independent states have nearly maximal entanglement amongst themselves.

Does Extreme Cosmic Censorship Allow Nearly Singular Firewalls?

It has been objected that even if Extreme Cosmic Censorship forbids singular firewalls, it would allow high-energy nonsingular ones that would destroy an infalling observer.

However, if the anomalous energy density just inside the horizon were even of the order of M^{-2}, which is of the order of the Weyl curvature, it would blueshift back to the Planck density in a time of the order of the scrambling time $\sim M \ln M$.

Therefore, it seems that if a black hole is nonsingular at any time, after a time of the order of the scrambling time, any anomalous energy density would redshift away to become negligible in comparison with the Weyl curvature, and then the black hole would look as traditionally expected in the semiclassical picture of a nearly vacuum black hole slowly decaying by Hawking radiation.

When Is Nonlocality Important?

The solution to the firewall problem probably also involves nonlocality, the fact that one does not have localized operators that commute in quantum gravity. For example, generically changing the quantum state in the bulk changes the mass and angular momentum recorded in the gravitational field at infinity.

Y. Kiem, H. L. Verlinde, and E. P. Verlinde, "Black-Hole Horizons and Complementarity," Phys. Rev. **D52**, 7053-7065 (1995):

"**Space-time complementarity (kinematical)**.

Different microscopic observables that are spacelike separated on a Cauchy surface Σ, but have support on matter field configurations that, when propagated back in time, have collided with macroscopically large center of mass energies, are not simultaneously contained as commuting operators in the physical Hilbert space. Instead such operators are complementary."

Possible Criterion for When Nonlocality Is Important

Double Stress-Tensor Criterion:

Relevant operators at two events X and Y do not commute if there is no third event Z in the spacetime connected by causal geodesics to both X and Y such that when the stress-energy tensor at X is parallel propagated along the XZ geodesic to give $T_{\mu\nu}(X,Z)$ at Z and the the stress-energy tensor at Y is parallel propagated along the YZ geodesic to give $T^{\mu\nu}(Y,Z)$ at Z, the trace of the contraction, $T_{\mu\nu}(X,Z)T^{\mu\nu}(Y,Z)$, is less than one in Planck units.

Applying the Double Stress-Tensor Criterion

Consider a $k = 0$ FLRW universe with points X and Y at the present time t_0 and present Hubble constant H_0.

In many cases the minimum for $T_{\mu\nu}(X,Z)T^{\mu\nu}(Y,Z)$ is for point Z at $a/a_0 = 1/(1+z)$ from which null geodesics sent in opposite directions reach X and Y. Then the gamma-factor between the comoving frames parallel-transported back from X and Y to Z is

$\gamma = \frac{1}{2}[(1+z)^2 + (1+z)^{-2}]$.

$$T_{\mu\nu}(X,Z)T^{\mu\nu}(Y,Z) = (\rho+P)^2\gamma^2 - 2P(\rho-P) \approx \left[\tfrac{3}{16\pi}H_0^2(1+z)^2\right]^2.$$

If our past has inflation with inflationary Hubble expansion rate H, this reaches unity when X and Y are separated by a distance

$$D \approx \frac{8}{H_0 H}\sqrt{\frac{\pi}{3\Omega_m}} \sim \frac{15 t_0}{H},$$

which is a few times the present horizon scale multiplied by the ratio of the inflationary horizon scale to the Planck scale.

Boost Measure Weighting

Choose a fiducial point X in the spacetime, and count only observations at points Y such that there exists a point Z in the spacetime causally related to both X and Y and for which $T_{\mu\nu}(X, Z)T^{\mu\nu}(Y, Z) < 1$.

This **Boost Measure** is somewhat similar to the causal patch measure, but it is not quite so restrictive.

In typical nonvacuum cosmologies with comoving matter, this boost measure criterion will keep the spatial region of the observations finite, though it will not restrict the temporal separation along the matter worldlines.

One would still need something, such as Agnesi weighting, to regulate the time, or else assume that any vacuum in the landscape will decay faster than the formation of Boltzmann brains, as is typically done in certain other measures such as the causal patch measure.

Summary

Extreme Cosmic Censorship (ECC) *(The universe is entirely nonsingular, except for transient black or white holes)* may be useful for restricting quantum states in cosmology and in black holes and in solving the firewall problem.

The **Double Stress-Tensor Criterion** *(Operators at X and Y may not commute unless there is a causally related Z such that $T_{\mu\nu}(X,Z)T^{\mu\nu}(Y,Z) < 1$)* may be useful for suggesting when nonlocality is important in quantum gravity.

The related **Boost Measure** *(Only include observations at points Y such that there exists a point Z causally related to both Y and a fiducial point X for which $T_{\mu\nu}(X,Z)T^{\mu\nu}(Y,Z) < 1$)* might be useful as another alternative for the measure problem of cosmology.

There are certainly many deep open problems in black holes and cosmology,