Strong Cosmic Censorship Conjecture: Recent Developments

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Outline

1. Strong cosmic censorship conjecture: Basics.
2. Relation with black hole quasi-normal modes.
3. Generalization to various scenarios.
4. Possible resolution with quantum fields.

Main References

1. Cardoso et. al., Phys. Rev. Lett. 120, 031103 (2018).
2. Dias et. al., Phys. Rev. D 97, 104060 (2018).
3. Rahman, **SC**, Sen and SenGupta [arXiv:1811.08538].
4. Mishra and **SC** [arXiv:1911.09855].
5. Rahman, Mitra and **SC** [arXiv:2001.00599].

To Begin With

- There are two versions of cosmic censorship conjecture — (a) weak and (b) strong.
- In the "weak" version, the conjecture asserts that there will be no naked singularity.

[Penrose, GRG 34, 1141 (2002)]

[Sorce and Wald, PRD 96, 104014 (2017)]

[Eperon, Ganchev and Santos, arXiv: 1906.11257]

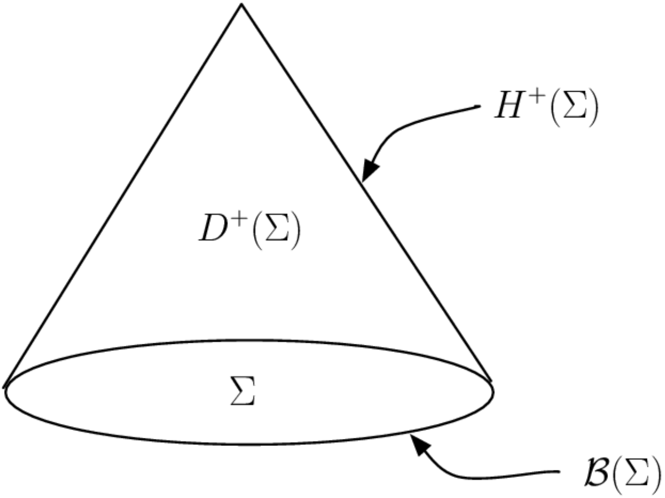
- The "strong" version asserts that evolution of an initial data cannot be extended outside the domain of dependence.

[Wald, General Relativity, Chicago University Press (1984)]

[Hawking and Ellis, The Large Scale Structure of Spacetime, Cambridge University Press (2011)]

Domain of Dependence

Figure Courtsey: Google

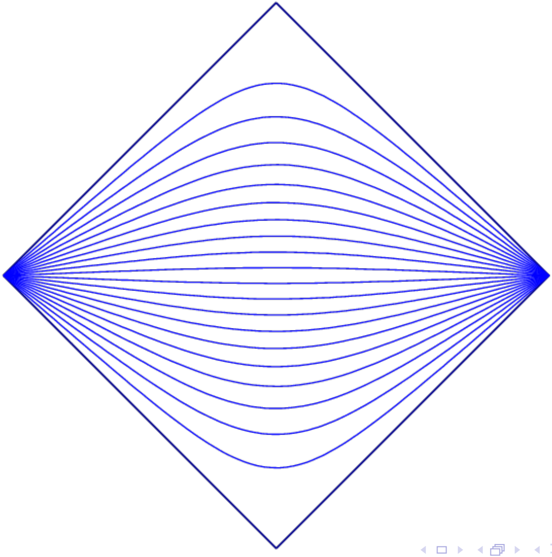


Why we need the Strong censorship?

- The strong censorship ensures that general relativity is deterministic in nature.
- Given an initial data on a Cauchy slice, the entire future of the spacetime geometry can be determined.
- Evolution in general relativity, generically leads to globally hyperbolic spacetime.

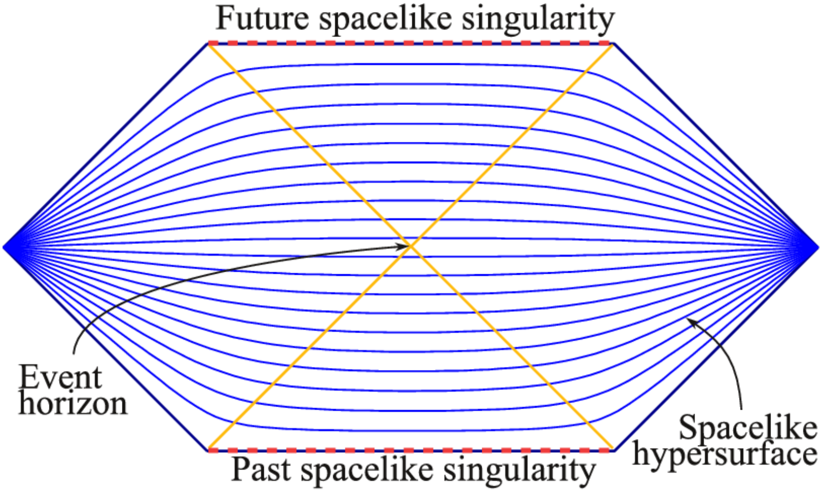
Strong Censorship: Minkowski Spacetime

Figure Courtsey: Google



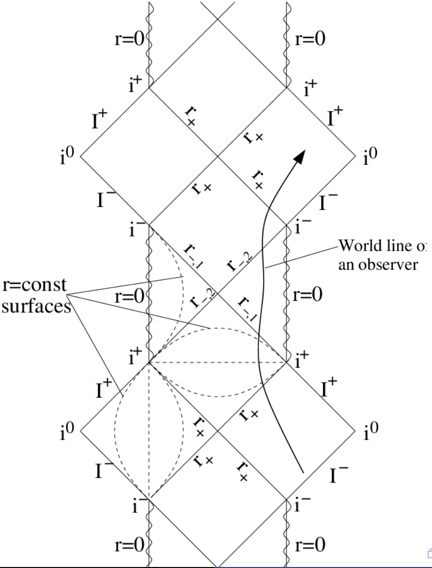
Strong Censorship: Schwarzschild Spacetime

Figure Courtsey: Google



Strong Censorship: Charged Black Hole

Figure Courtsey: Google

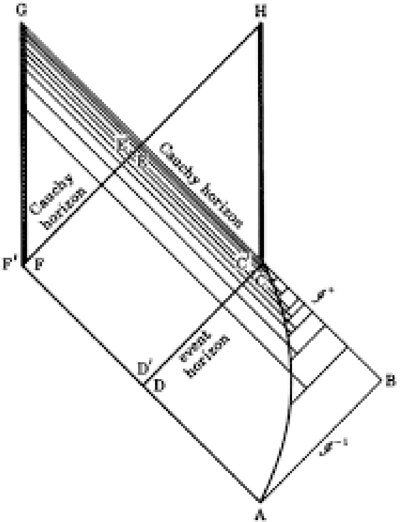


Charge Black Holes: Violation of Strong Censorship?

- Given initial data on a Cauchy slice, the evolution beyond the Cauchy horizon cannot be predicted.
- Identical conclusion holds for rotating black holes as well.
- Breakdown of predictability of General relativity in all astrophysical scenarios.
- Because spacetime is regular at the Cauchy horizon.

Accumulating energy at the Cauchy horizon

Figure Courtsey: Google



What about perturbations?

- The problem of predicting evolution beyond the Cauchy horizon is due to the regular nature of the Cauchy horizon.
- Thus the question arises, is the Cauchy horizon stable under perturbations, in particular, due to the infinite blueshift at the Cauchy horizon.
- Thus instability of the Cauchy horizon may lead to evolution beyond Cauchy horizon impossible, restoring determinism.

[Simpson and Penrose, IJTP 7, 183 (1973)]

Cauchy horizons are Unstable!

- Consider a scalar field living in a spacetime, which inherits a Cauchy horizon.
- The perturbation will satisfy a Schrödinger-like equation.
- The flux observed by an observer crossing the Cauchy horizon due to these perturbations $\sim \exp(\kappa_- - \kappa_+)v$ and diverges as $v \to \infty$.

[Chandrasekhar and Hartle, Proc. R. Soc. Lond. A 384, 301 (1982)]

- An identical phenomenon, known as mass inflation also shows that some of the curvature invariants diverge at the Cauchy horizon.

[Poisson and Israel, PRL 63, 1663 (1989)]

[Ori, PRL 67, 789 (1991)]

But ...

- The singularity at Cauchy horizon is rather "weak". As the tidal forces remain finite even at the Cauchy Horizon.
- Thus possibility of classical extension cannot be ruled out.
- This is because, even if the mass diverges, the integral of the mass over the full affine distance remains finite.
- A more stronger version is necessary.

Christodoulou's Version of Strong Censorship

- To prevent extension of the spacetime beyond the Cauchy horizon, the following version was put forward: *It is impossible to extend the spacetime across the Cauchy horizon with square integrable Christoffel symbols with matter fields belonging to Sobolev space.*
- For all asymptotically flat solutions, including charged and rotating black holes in general relativity the above version of strong censorship is respected.
- This is because, for asymptotically flat spacetimes, the perturbations decay as power law, while the Cauchy horizon amplified the radiation exponentially, leading to Christodulou's version being respected.

[Dafermos et. al. 1402.7034]

[Dafermos et. al. Commun. Math. Phys. 332, 729 (2014)]

[Luke and Oh, 1712.05716]

Cosmological constant did not come for rescue

- For asymptotically de Sitter spacetime, the story becomes different, as the perturbations also decay exponentially, $\sim \exp(-\alpha t)$, where $\alpha = \mathrm{Inf}_{\ell n}(-\mathrm{Im}\ \omega_{\ell n})$.

[Hintz and Vasy, J. Math. Phys. 1512.08004]

- Thus it will compete with the blueshift amplification, governed by κ_-.
- The regularity of a scalar field in the Reissner-Nordström-de Sitter spacetime, violating Christodoulou's version, demands

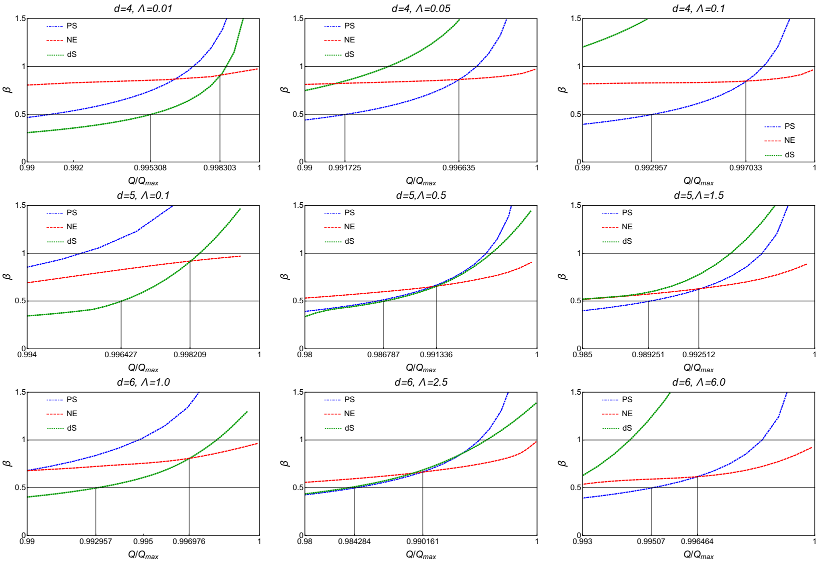
[Cardoso et. al. Phys. Rev. Lett. 120, 031103 (2018)]

violation of strong cosmic censorship conjecture

$$\beta \equiv \frac{\alpha}{\kappa_-} > \frac{1}{2}$$

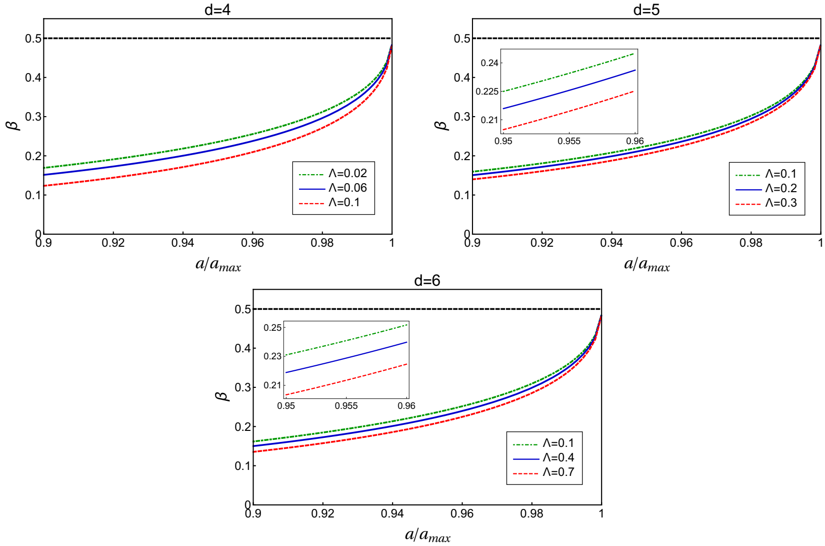
Violation!

[Rahman, SC, Sen and SenGupta, arXiv:1811.08538]

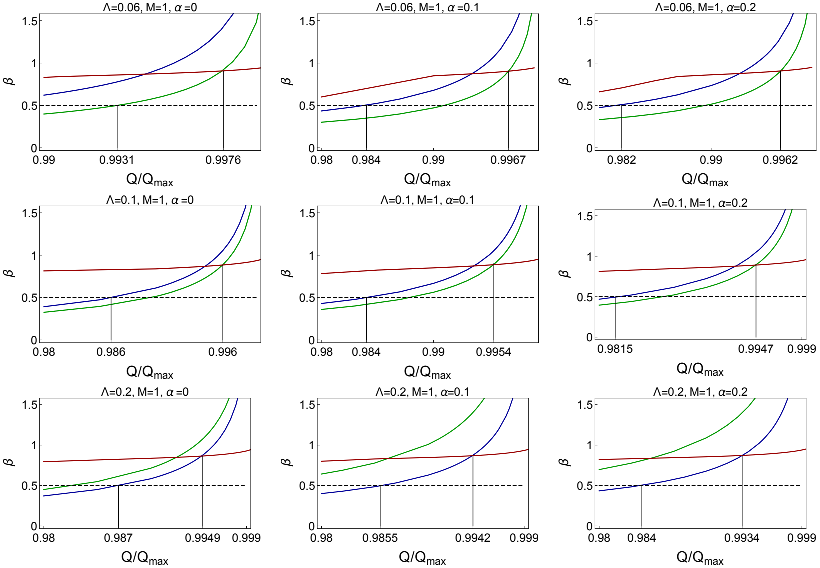


For Rotating Black Holes

[Rahman, SC, Sen and SenGupta, arXiv:1811.08538]

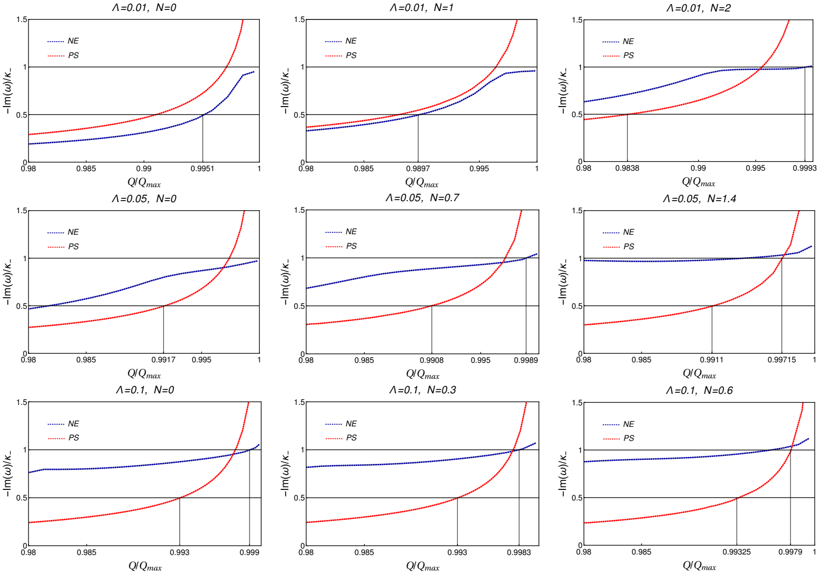


In presence of higher curvature terms [Mishra and SC, arXiv:1911.09855]



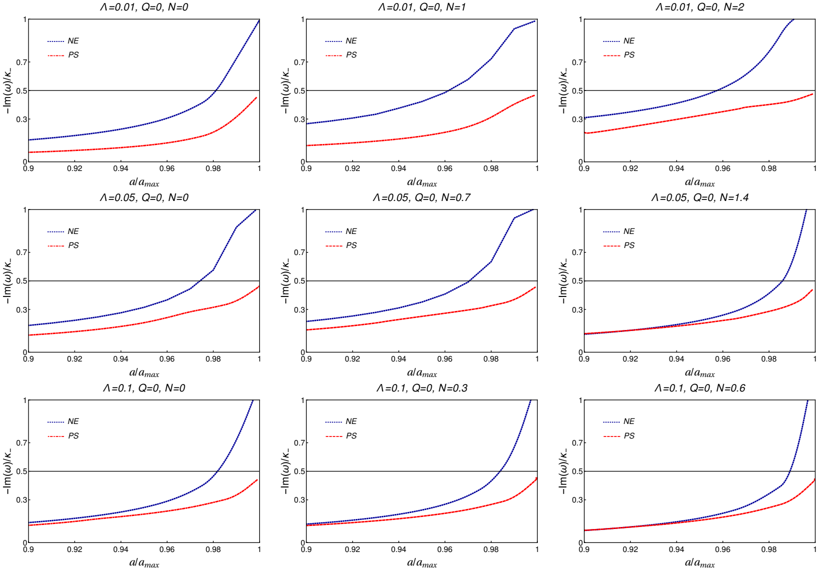
With conformal coupling

[Rahman, Mitra and SC, arXiv:2001.00599]



Conformal coupling and rotation

[Rahman, Mitra and SC, arXiv:2001.00599]



Welcoming quantum effects

- This brings back to the question, what happens when semi-classical Einstein's equations are considered?

[Dias, Reall and Santos, arXiv:1906.08265]

- For massless and conformally coupled scalar field in Reissner-Nordström-de Sitter spacetime, for Hadamard states, one obtains:

[Hollands, Wald and Zahn, arXiv:1912.06047]

Vacuum Expectation Value

$$\langle T_{VV} \rangle = C\hbar |V|^{-2} + t_{VV}$$

- t_{VV} can be regular and for $\beta > (1/2)$ can be extended beyond the Cauchy horizon.

Implications

- The problem with Christodoulou's version of strong cosmic censorship conjecture in the presence of cosmological constant is demonstrated.
- Generic nature of the problem for charged black holes and influence on rotating black hole has been discussed.
- The violation possibly holds in higher curvature theories as well.
- Back-reaction due to the quantum effects may lead to the desired singular behaviour at the Cauchy horizon.

Thank You