Quantum Gravity Inside and Outside Black Holes

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International Loop Quantum Gravity Seminar

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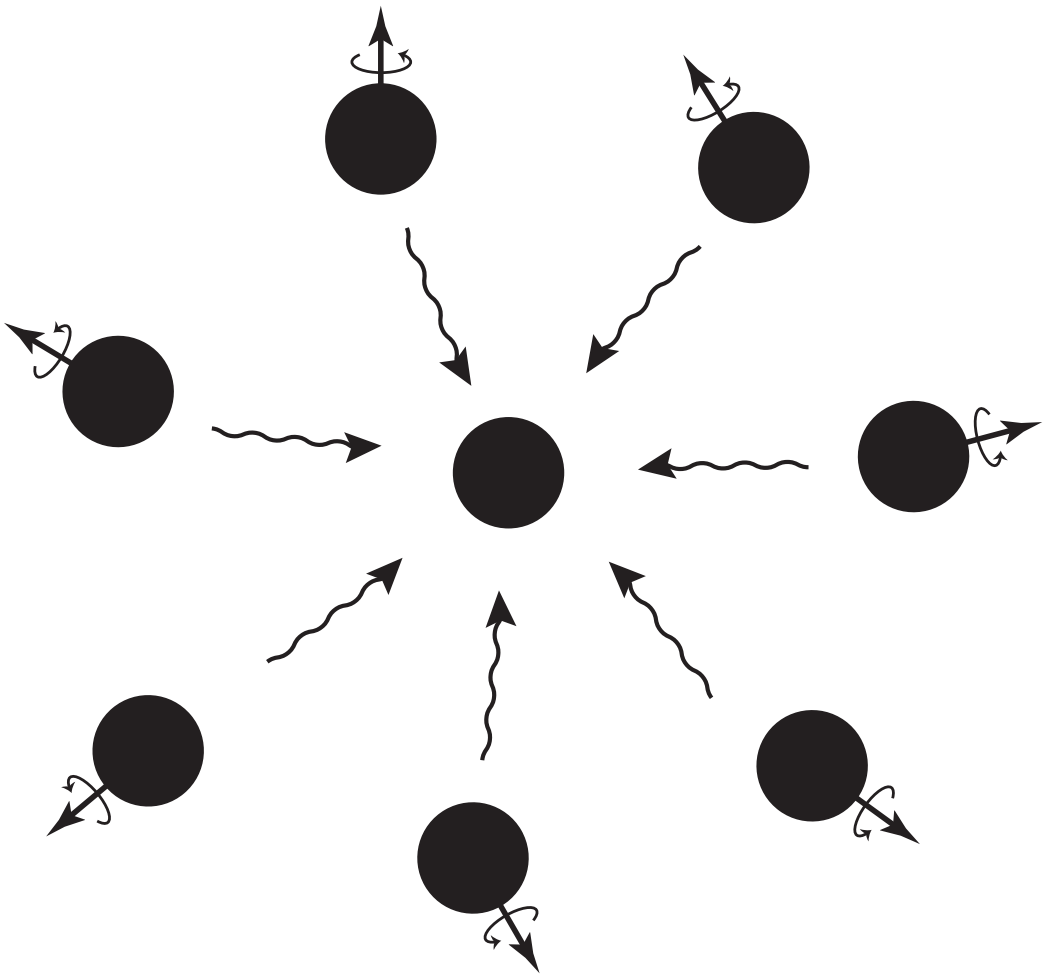
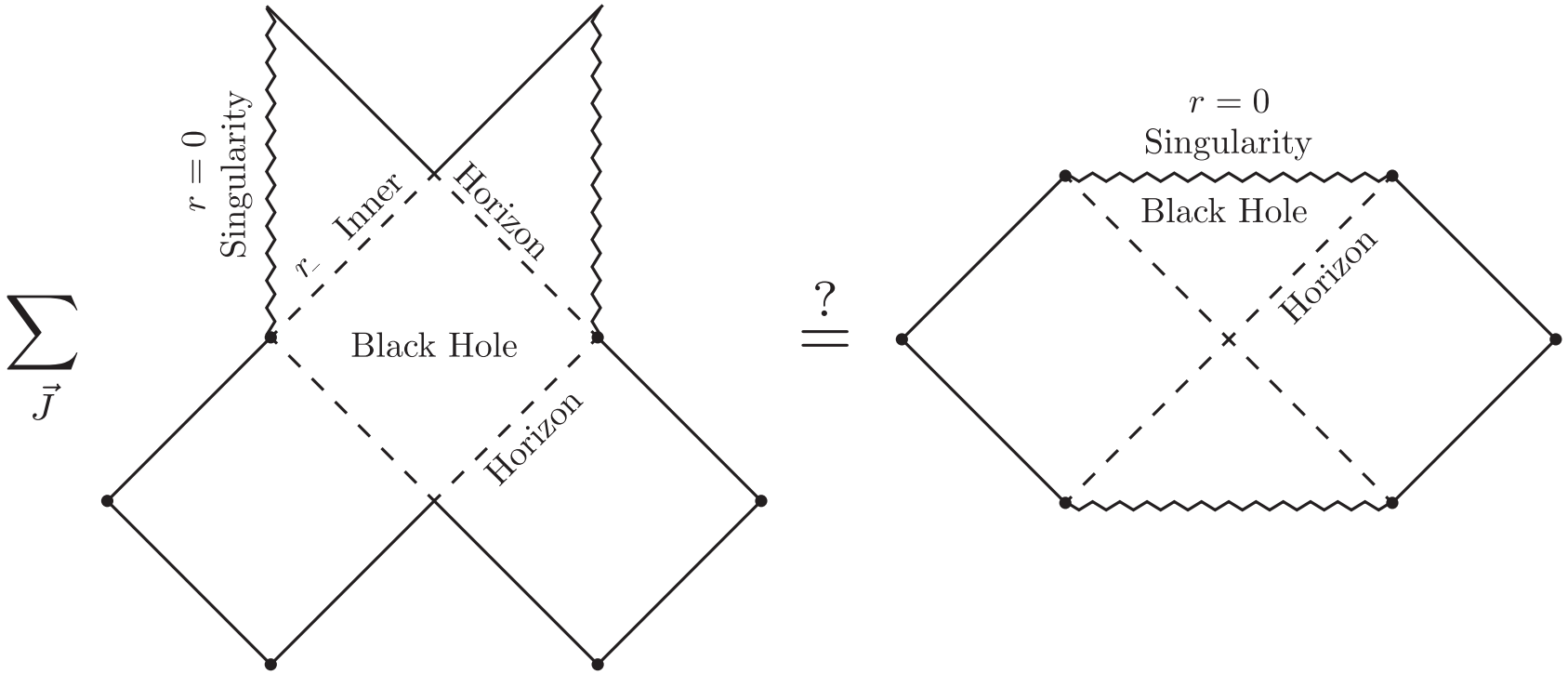
If spacetime is quantum then it fluctuates, and a Schwarzschild black hole is an ensemble average over rotating black holes



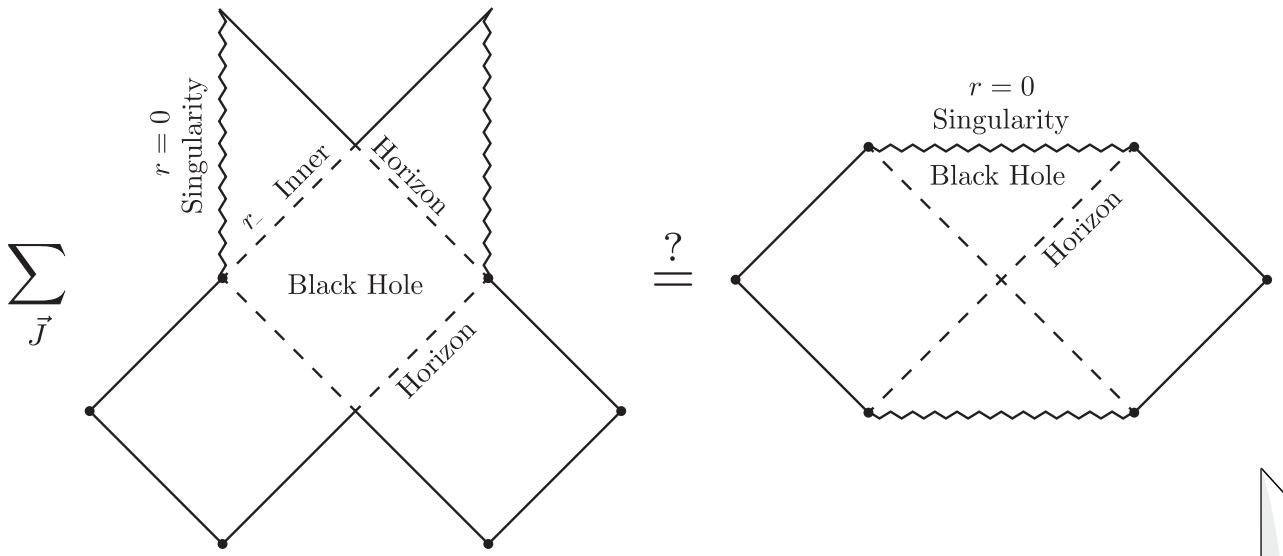
But, then a puzzle arises...

Is the average of timelike singularities really spacelike?

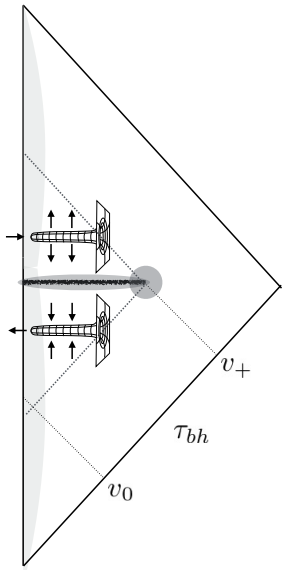


Outline

I. Is the average of timelike singularities really spacelike?



II. The White Hole Remnant Scenario



III. Quantum Gravity Inside and Out

The Kerr metric

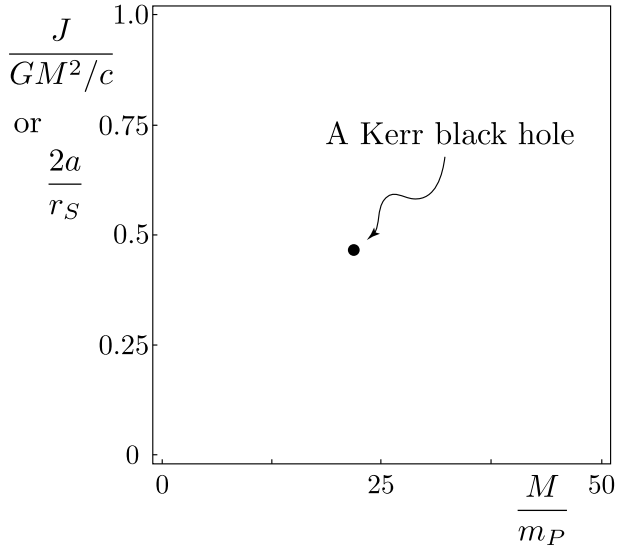
$$ds^2_{\text{Kerr}} = -\frac{\rho^2\Delta}{\Sigma}c^2dt^2 + \frac{\Sigma}{\rho^2}\sin^2\theta(d\phi - \omega dt)^2 + \frac{\rho^2}{\Delta}dr^2 + \rho^2 d\theta^2,$$

is intricate:

$$\rho^2 \equiv r^2 + a^2\cos^2\theta, \;\; \Delta \equiv r^2 - r_S r + a^2, \;\; \& \;\; \Sigma \equiv \frac{\rho^4\Delta - a^2 r_S^2 r^2 \mathrm{s}^2\theta}{(\rho^2 - r_S r)}.$$

Horizons at $\Delta = 0$, i.e. $r_\pm \equiv \frac{r_S}{2}\left[1 \pm \sqrt{1 - (2a/r_S)^2}\right]$.

But, the parameter space is just the mass M and angular mom. J or, equivalently, two length scales: the Schw. radius $r_S = 2GM/c^2$ and the Kerr parameter $a = J/Mc$.

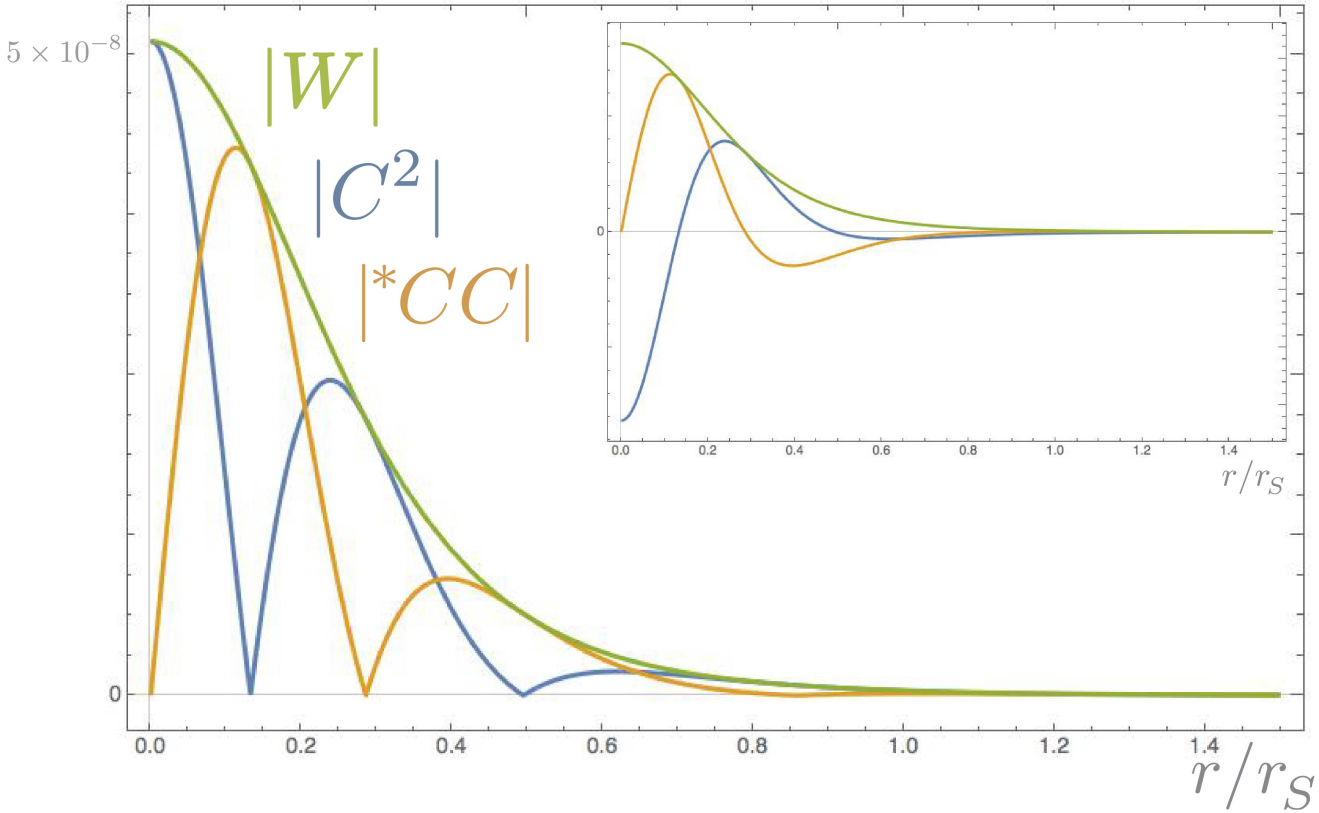


To assess the role of quantum gravity, consider curvature invariants

$$\text{vacuum soln: } W \equiv (C_{\mu\nu\rho\sigma} + i\ {}^*C_{\mu\nu\rho\sigma})C^{\mu\nu\rho\sigma}$$

with ${}^*C_{\mu\nu\rho\sigma} \equiv \frac{1}{2}\epsilon^{\alpha\beta}_{\rho\sigma}C_{\mu\nu\alpha\beta}$. Each term oscillates, but

$$|W| = \frac{12r_S^2}{(r^2 + a^2\cos^2\theta)^3}$$

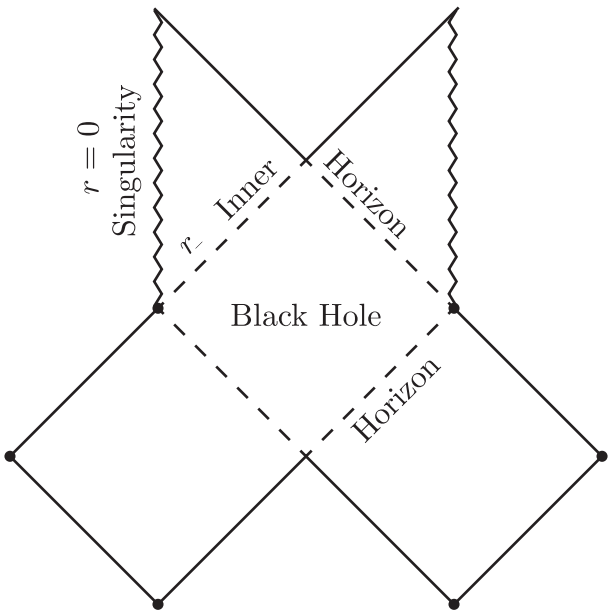


No matter the theory, the common expectation is that quantum gravitational phenomena are significant at Planckian curvatures.

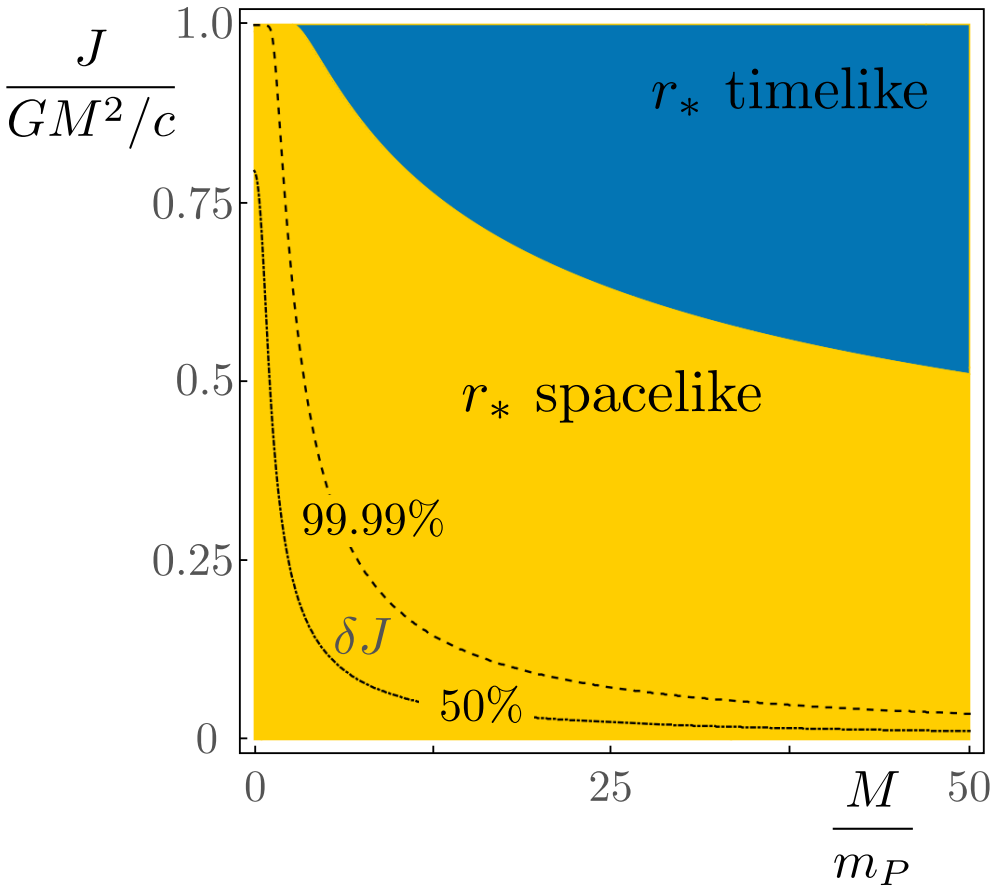
So we define the *onset of quantum gravity* as the surface on which the curvature first becomes Planckian, or, the

Planckian curvature radius r_* by $|W(r_*, \pi/2)| = 1/\ell_P^4$.

A mechanism: the inner horizon



Our result: *the onset of quantum gravity is always spacelike.*



E. Bianchi & HMH arXiv:1803.10858

The J resulting from quantum fluctuations (black contours) are hidden in the quantum fog of high curvatures; resolves our puzzle.

How did we do this calculation? It is based on two assumptions:

(i) that quantum black holes fluctuate according to a probability distribution determined by the Bekenstein-Hawking entropy, &

(ii) that Planckian values for any curvature invariant lead to quantum gravity.

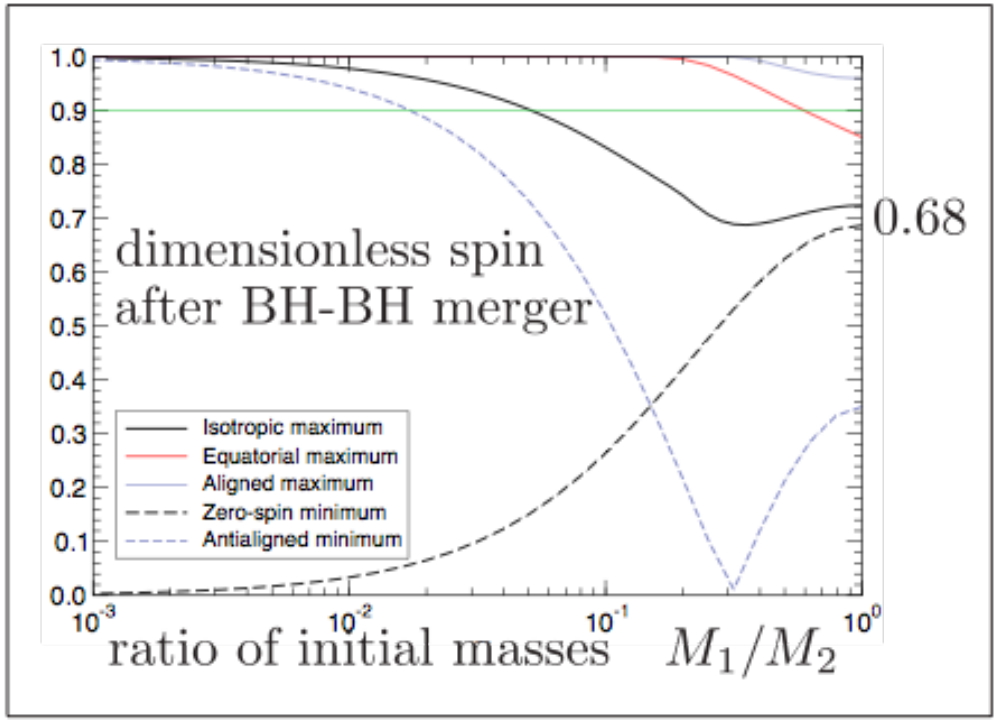
The first leads to

$$P_M(\vec{J}) = e^{\frac{A(M,J)}{4\ell_P^2}} \Big/ \int e^{\frac{A(M,J)}{4\ell_P^2}} d\vec{J},$$

which should be read as a the conditional probability of $\vec{J}$ given a black hole of mass M in the microcanonical ensemble.

Contours above were constructed by scanning through M and identifying the value of J for which the indicated fraction of the distribution is achieved.

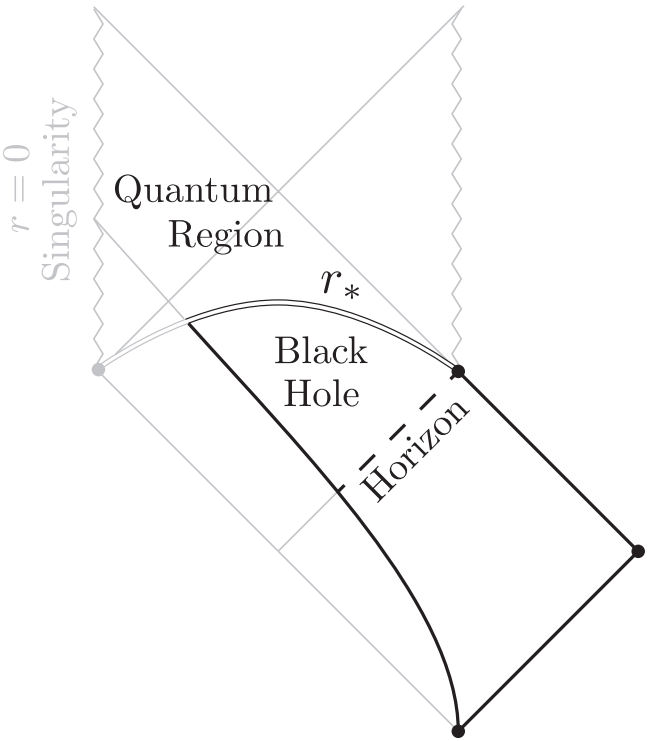
The microcanon ensemble $P_M(\vec{J})$ applies to primordial black holes. Gravitatnl waves may allow us to probe $P_M(\vec{J})$ and through it (i).

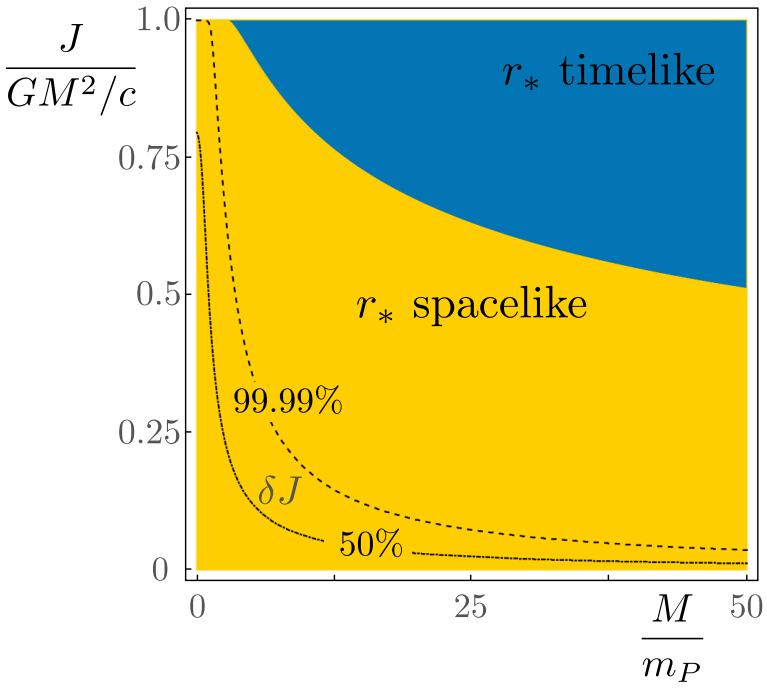


E. Berti & M. Volonteri arXiv:0802.0025

The prior on the spins of such a population would be different from the usual uniform prior. This would be an exciting opportunity to get an experimental glimpse of the Bekenstein-Hawking result.

The onset of quantum gravity should always be spacelike...





...but, astrophys'l BHs reside outside the domain of our argument. Penrose, Poisson & Israel, Flanagan, Marolf & Ori all suggest that non-perturbative effects leave the conclusion intact.

What happens after the onset of quantum gravity?

Outline

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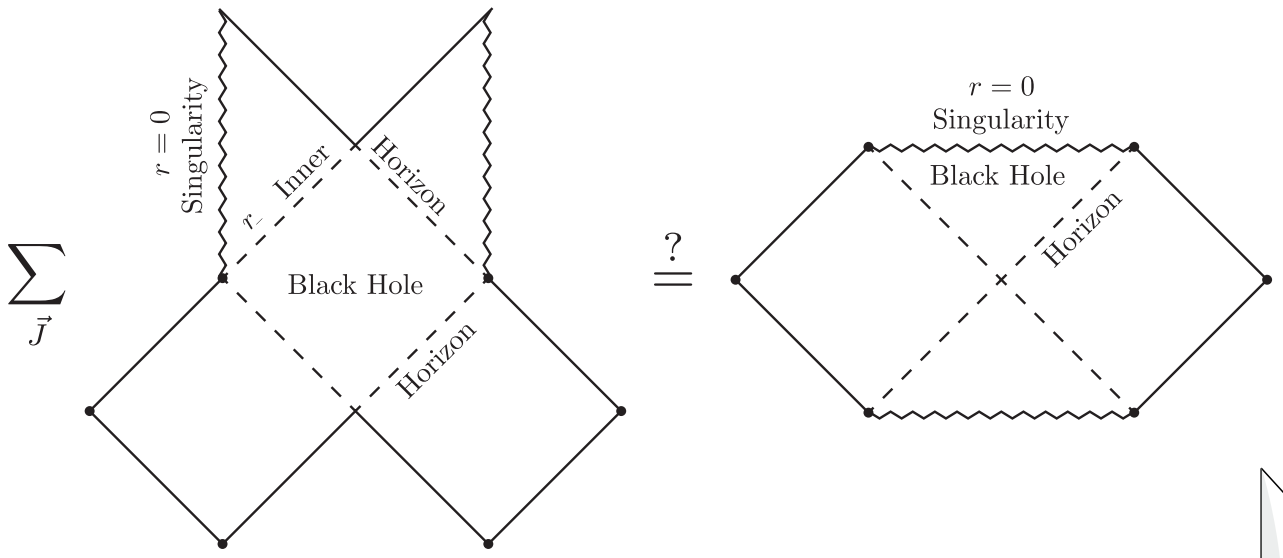

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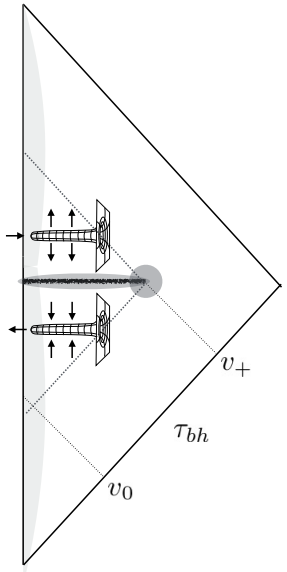
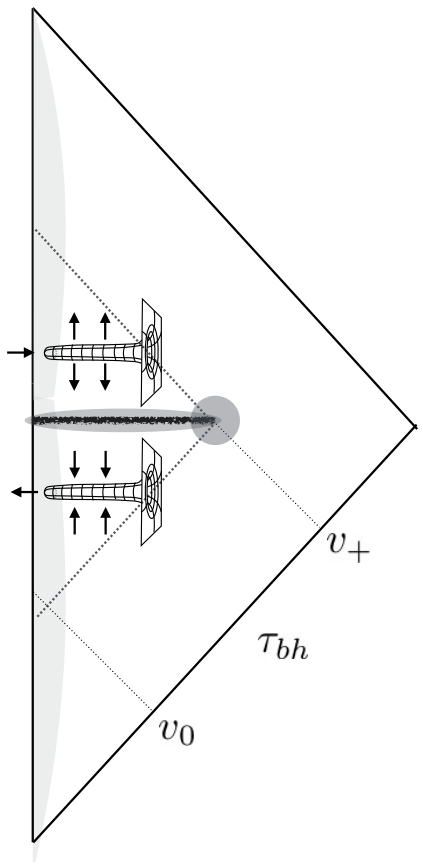


III. Quantum Gravity Inside and Out

Tunneling of geometry allows a black to white hole transition.
Evolution of the interior provides long final white hole lifetime.



White holes realize the long-lived remnant scenario and provide a resolution to the black hole information paradox. arXiv:1802.04264

Three desiderata we require of a remnant resolution of the info prb

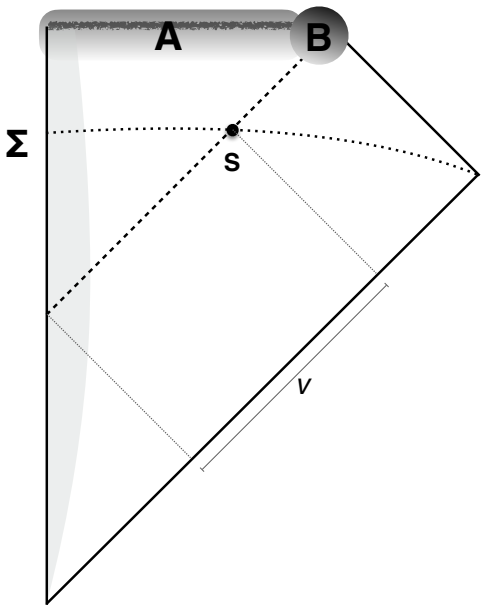
Let S be the (renormalized) entanglement entropy of a quantum field evolving on a black hole background. Then:

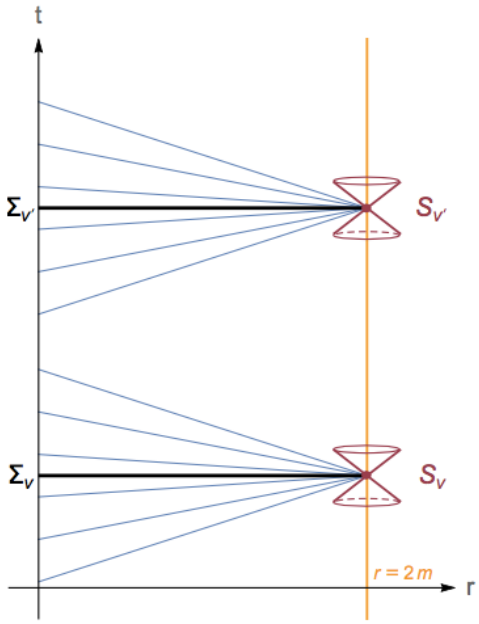
(a) The remnant has to store info with entropy $S \sim M_0^2/\hbar$, where M_0 is the initial mass of the black hole before evaporation. This is needed to purify Hawking radiation.

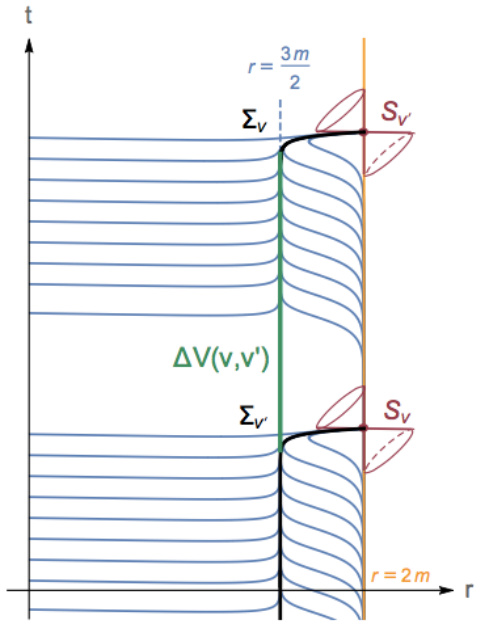
(b) Because of its small mass, the remnant can release the inside information only slowly—hence it must be long-lived. Unitarity and energy considerations impose that its lifetime be equal to or larger than $\tau_R \sim M_0^4/\hbar^{3/2}$.

(c) The remnant metric has to be stable under perturbations, so as to guarantee that information can be released.

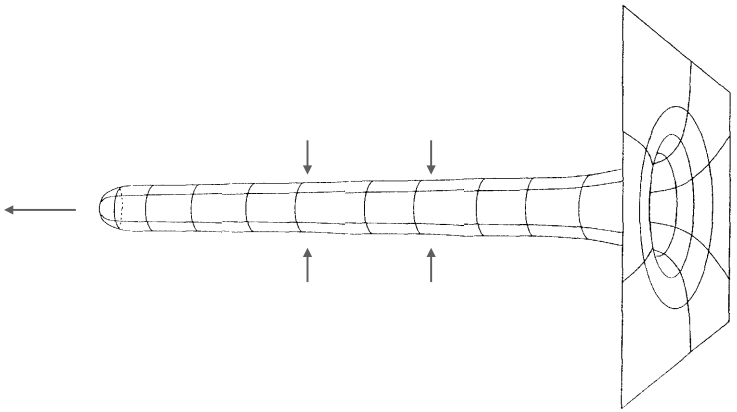
There are two distinct regions where we expect GR to break down: (A) at high curvatures and (B) after sufficiently long times







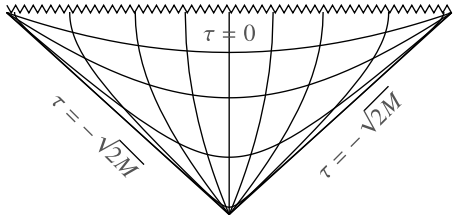
Distinguishing old from young black holes is a large interior vol V



$$V \sim 3\sqrt{3}M^2 v$$

First region A: There is support for good evolution through the singularity from a number of directions.

$$ds^2 = -g_{\tau\tau}(\tau)d\tau^2 + g_{xx}(\tau)dx^2 + g_{\Omega\Omega}(\tau)d\Omega^2$$



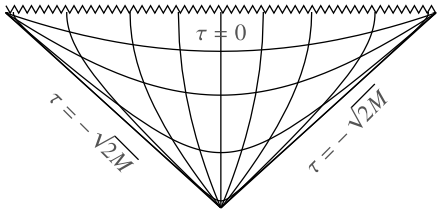
This is a Kontowski-Sachs geometry and a bounce is plausible. In fact, change vars to $g_{\tau\tau} = N^2 a/b$, $g_{xx} = b/a$ and $g_{\theta\theta} = a^2$ sol is

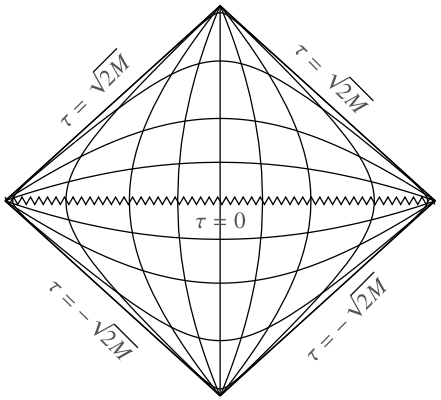
$$ds^2 = -\frac{4\tau^4}{2M - \tau^2}d\tau^2 + \frac{2M - \tau^2}{\tau^2}dx^2 + \tau^4 d\Omega^2,$$

and Synge ['56] noticed no trouble with evolution through the singularity: $\partial_\tau(\dot{a}/N) = \partial_\tau(\dot{b}/N) = 0$, and $\dot{a}\dot{b} + N^2 = 0$, give

$$a(\tau) = \tau^2, \qquad b(\tau) = 2M - \tau^2, \qquad \& \qquad N^2 = 4a(\tau).$$

This is Schw. interior with $t = x$, $r = \tau^2$ and for $-\sqrt{2M} < \tau < 0$,





but can be continued ($\tau < \sqrt{2M}$) into the interior of a white hole.

Large curvatures near $\tau = 0$ will modify evolution, e.g.,

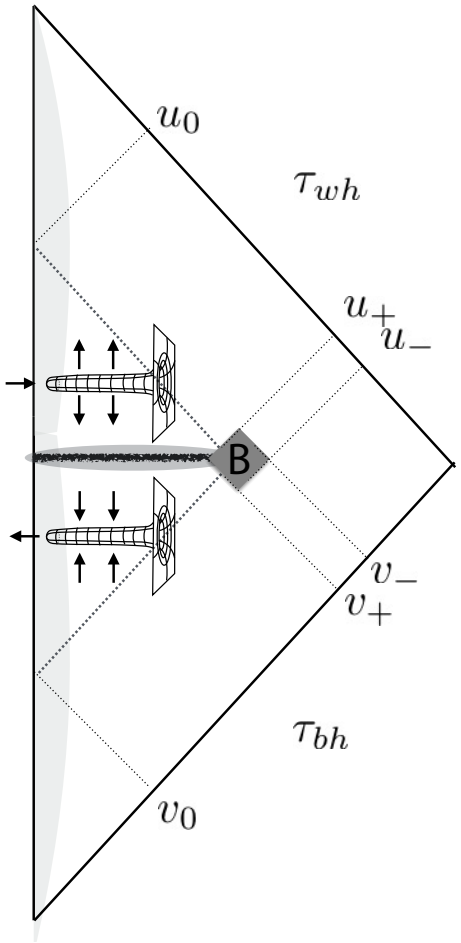
$$ds^2 = -\frac{4(\tau^2+\ell)^2}{2M-\tau^2}d\tau^2 + \frac{2M-\tau^2}{\tau^2+\ell}dx^2 + (\tau^2+\ell)^2 d\Omega^2, \qquad (1)$$

where ℓ is an effective parameter that bounds the curvature. For large masses

$$K(\tau) \equiv R_{\mu\nu\rho\sigma}R^{\mu\nu\rho\sigma} \approx \frac{9\ell^2 - 24\ell\tau^2 + 48\tau^4}{(\ell+\tau^2)^8}M^2$$

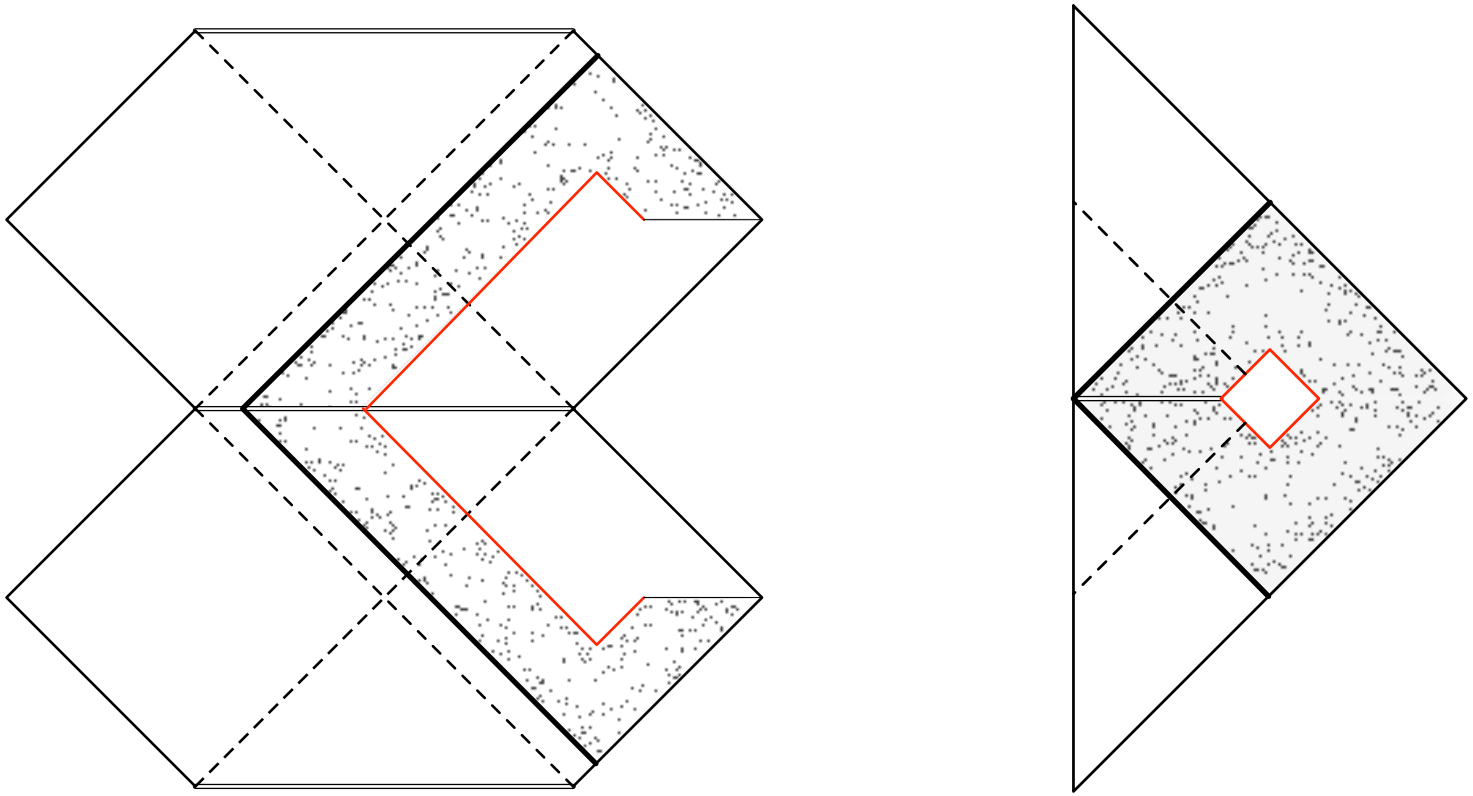
and has a finite max $K(0) = 9M^2/\ell^6$.

A large black hole region goes over into a large white hole region. Evolution of latter tube provides long final white hole lifetime.



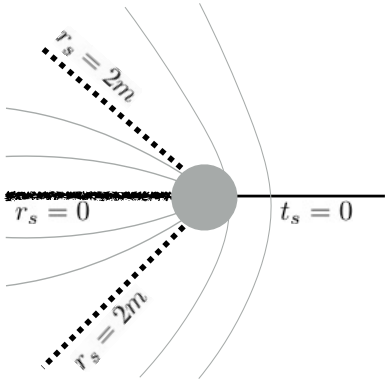
Using amp $\sim e^{-M^2/m_P^2}$ and imposing volume of the tubes equal across the transition we will estimate the time scales.

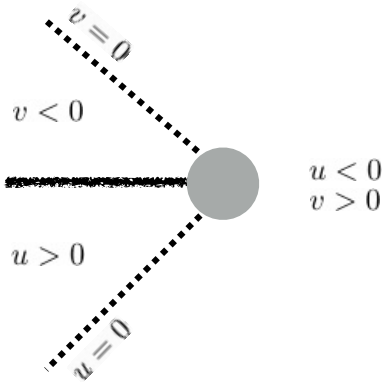
The metric around the B region is constructed out of two copies of Kruskal:



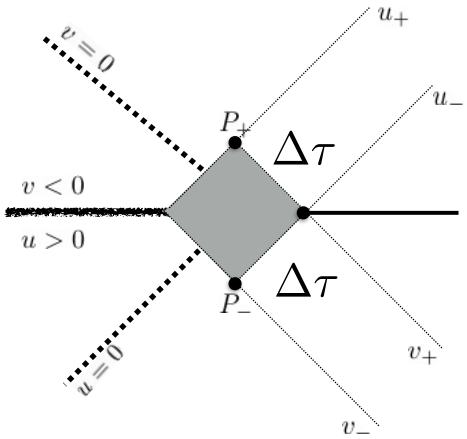
A concrete proposal for the B region metric has not been made yet.

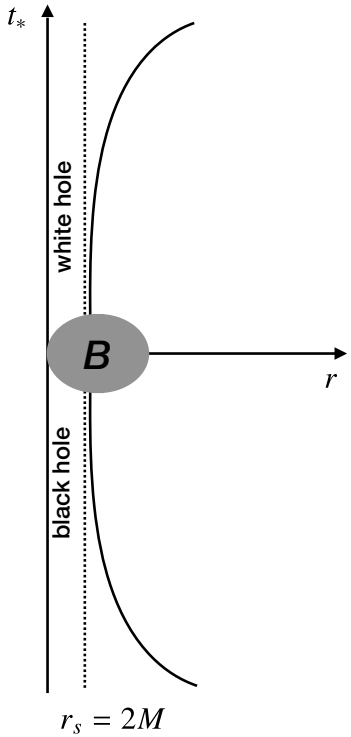
Surroundings of the B region in more detail:





Duration: $\boxed{\Delta\tau = v_+ - v_- = u_+ - u_- \overset{\text{take}}{\sim} \sqrt{\hbar}}$





$$u_+ v_+ = u_- v_- \equiv \left(1 - \frac{r_P}{2M}\right) e^{\frac{r_P}{2M}}$$

$$u_- = -v_+$$

$$u_- v_+ \equiv \left(1 - \frac{r_m}{2M}\right) e^{\frac{r_m}{2M}}$$

Using the effective metric of Eq. (1), $ds_3^2 = \frac{2M}{\ell} dx^2 + \ell^2 d\Omega^2$ at $\tau = 0$ transition, and

$$V = 4\pi\ell^2 \sqrt{\frac{2M}{\ell}} (x_{max} - x_{min}).$$

The 'duration' is given by $x = t$, with the latter the Schw. time.

Take Planckian curvature $K \sim 1/\hbar^2$ to determine $\ell \sim (M_0\hbar)^{1/3}$, $x = t$ of order evaporation time to get $\Delta x \sim M_0^3/\hbar$, and find

$$V_{bh}(\text{final}) \sim M_0^4/\sqrt{\hbar}.$$

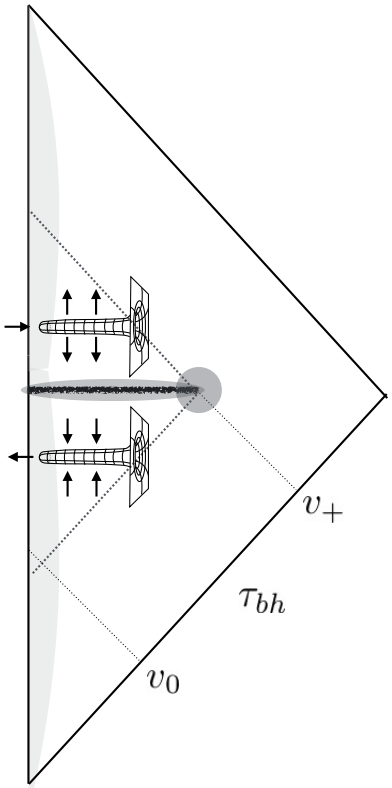
The white hole begins life Planckian, $\ell \sim m_P = \sqrt{\hbar}$, and so

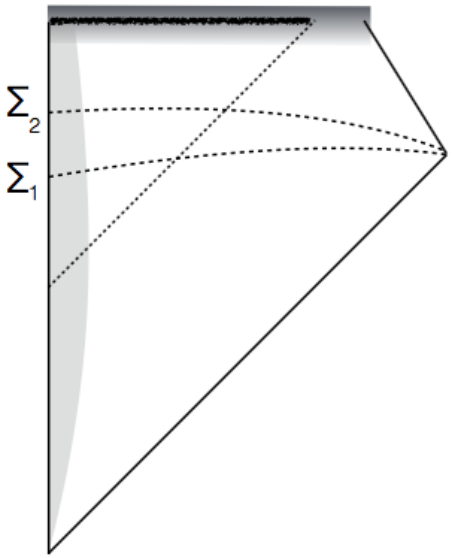
$$V_{wh}(\text{initial}) \sim \hbar\tau_{wh}.$$

Setting $V_{bh} = V_{wh}$ gives $\tau_{wh} \sim M_0^4/\hbar^{3/2}$, a long-lived remnant.

We have shown that this model satisfies the desideratum (b), what about (a) and (c)?

(a) Plenty of room to store information. No event horizons, only apparent horizons—entropy is not just the horizon states.





(c) Planck-sized white hole. No tranplanckian perturbations means no white hole instability.

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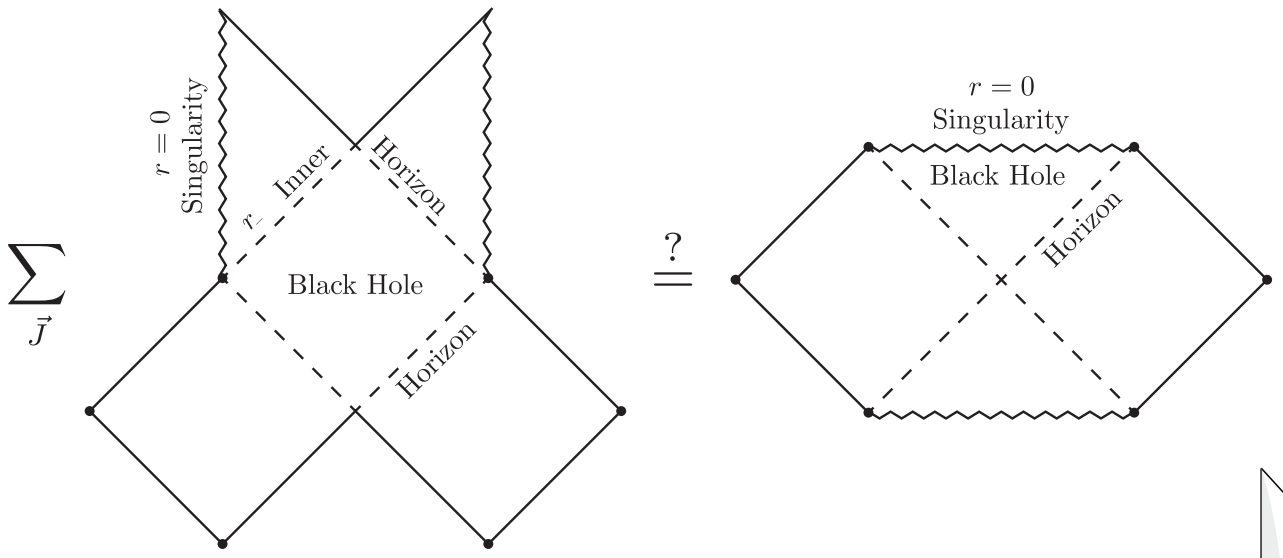

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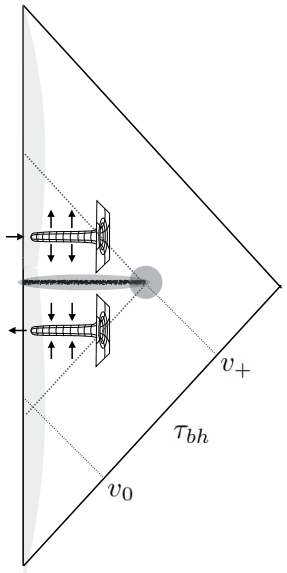
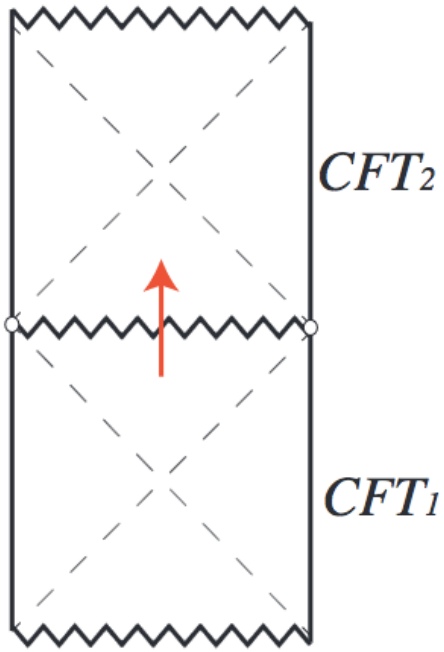
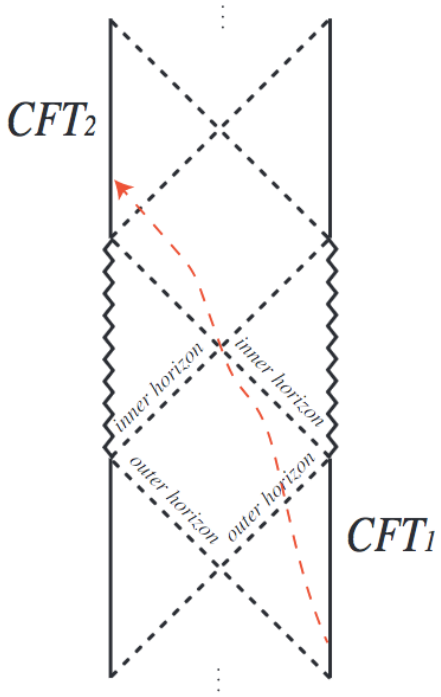


III. Quantum Gravity Inside and Out

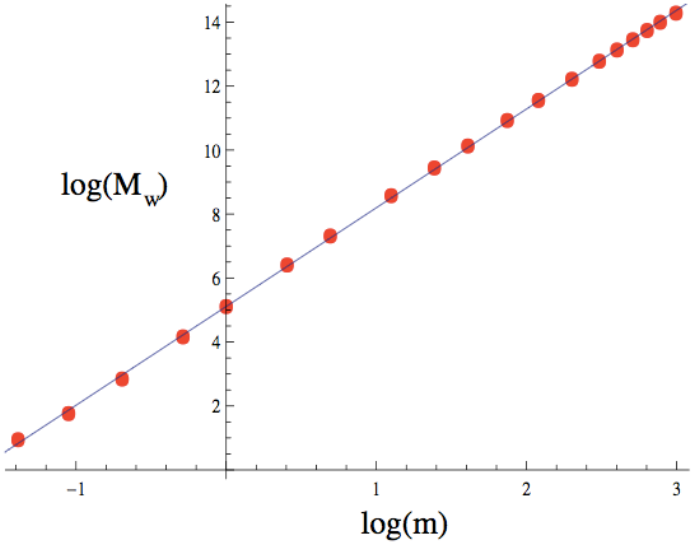
Naive causal isolation might lead one to neglect the inner lives of black holes, but this would be a mistake. There's much to be done.

Interesting connections to the recent 'No Transmission Principle' in gauge/gravity due to Engelhardt & Horowitz arXiv:1509.07509





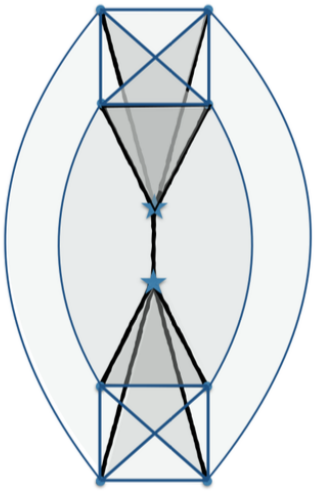
A year ago, P. Singh reported on canonical BH to WH bounces. With A. Corichi they had found "The final white hole mass is approximately a quartic power of the initial black hole mass."

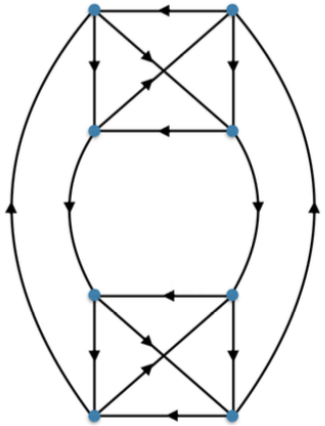


arXiv:1707.07333

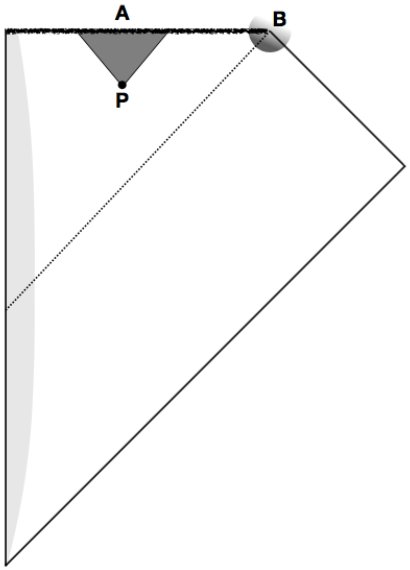
He also discussed work with J.Olmedo and S. Saini which led to symmetric mass bounce. Recently, with A. Ashtekar they have found a consistent quantization prescription of BH to WH bounces which leads to a symmetric bounce and resolves previous problems.

Christodoulou, D'Ambrosio, Rovelli, Speziale, Vilensky '16-'18

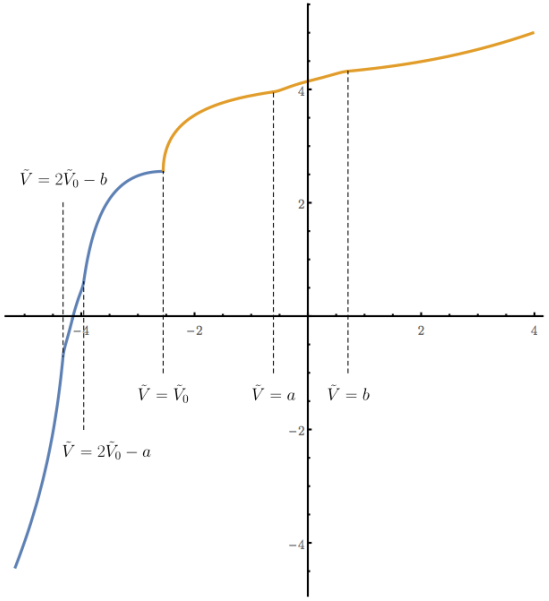




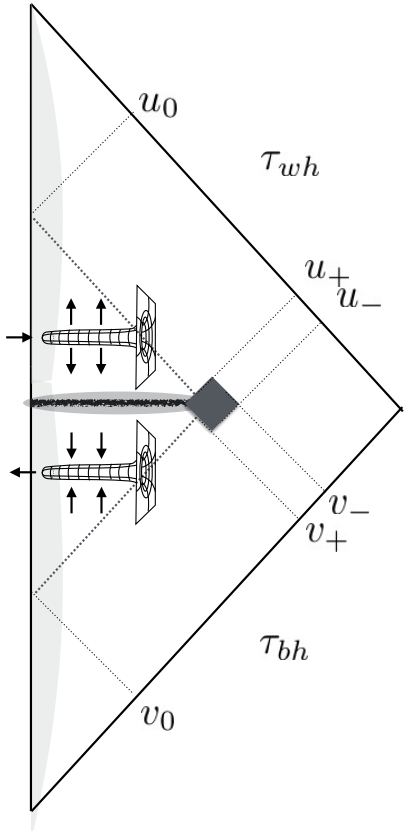
D'Ambrosio & Rovelli '18

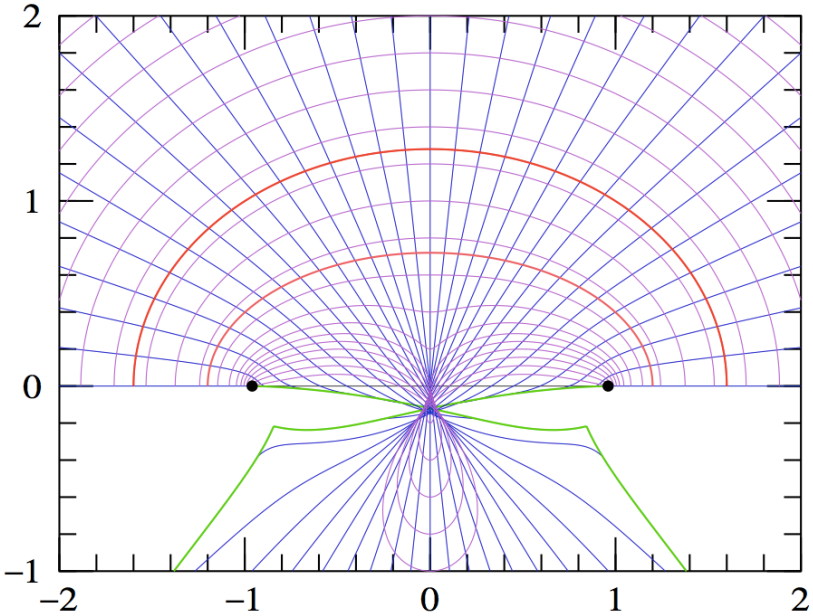


Rovelli & Martin-Dussaud '18



Our metric sets up the classical b.c.s needed to do a complex spacetime tunneling calculation for a black to white hole transition.





see HMH PI QG Seminar

I am involved in using a midisuperspace approach á la Kuchař...
...I expect $\sim e^{-\eta A/m_{\rm Pl}^2} \sim e^{-M^2/m_{\rm Pl}^2}$.
Tackling BTZ w K. Clements, M. Dupuis, F. Girelli, & A. Osumanu

Life would be so much more dull without wonderful collaborators:

Eugenio Bianchi & Victoria Chayes

Marios Christodoulou, Fabio D'Ambrosio, & Carlo Rovelli