Title: A novel approach to diffusing the black hole information paradox

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Abstract: <p>We will briefly review the issue of "information loss" during the Hawking evaporation of a black hole, and argue that the quantum dynamical reduction theories, which have been developed to address the measurement problem in quantum mechanics, possess the elements to diffuse the ``paradoxâ€• at the qualitative and at the quantitative level, leading to what seems to be an overall coherent picture. </p>

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The information loss during black hole evaporation: A novel approach to diffusing the ”paradox”

Daniel Sudarsky, ICN-UNAM.
Collaboration with: E. Okon, S. Modak, L. Ortíz, & I. Pena

“Benefits of Objective Collapse Models for Cosmology and Quantum Gravity” *Found. of Phys.* **44**, 114 (2014);
“The Black Hole Information Paradox and the Collapse of the Wave Function” *Found. of Phys.* **45**, 461 (2015).
“ Non-Paradoxical Loss of Information in Black Hole Evaporation in Collapse Theories” *Phys. Rev. D* **91**, 124009 (2015);
“Black Holes: Information Loss But No Paradox ” arXiv:1406.4898 [gr-qc]

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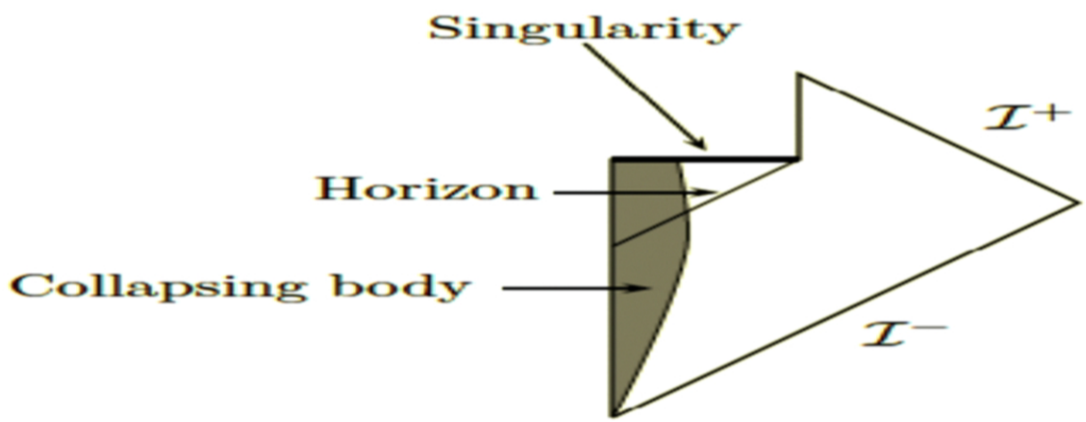

Let us, for simplicity, assume the collapsing mater is in a pure state. Is there an loss of information issue ?

People's postures depend on what they assume about the singularity, and even on their ideas regarding what physical theories should be about.

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The information loss paradox

The real problem emerges if QG resolves the singularity, otherwise a possible way out is to consider the singularity (or, more precisely, a region arbitrarily close to it) as the boundary of space-time. Then, the issue could be addressed by saying that information “ends up” at, or, if one wants to use a more pictorial language, “escapes through” the singularity.

This is not satisfactory for workers on QG. as they believe that QG will resolve the singularity (say, as proposed Ashtekar and Bojowald in CQG 22, 3349 (2005).).

They see the inclusion of an extra boundary, not just as uncalled for, but as removing from consideration the regime for which TQG are devised!.

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On the other hand QG is expected to lead to strong deviations from GR only “close” to the singularity.

The only trace of quantum gravity that one usually think might outlast the evaporation process is something like a stable Planck mass remnant.

Its information content would be bounded by the number of its internal DoF, which is not expected to be large, given the small size and small energy of the remnant. So it is not believed to play an important role regarding the amount of ultimately retrievable information originally in the objects that formed of the BH.

We will not contemplate this option any further.

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The puzzle: if QG removes the singularity, and the need to incorporate an extra boundary, then the quantum state, at late times, should be unitarily related to the quantum state at early times.

The PROBLEM is that reconciling this with the picture that we saw emerges from consideration based on general relativity and quantum field theory, in regimes that the two theories ought to be valid, has proven to be extremely difficult.

For instance in proposals based on LQG there is an issue regarding signature change or fluctuations around 0 in the metric conformal factor... perhaps there is a way out...(?) , other proposals like “ black hole complementarity” led to ”Firewals ”, etc.

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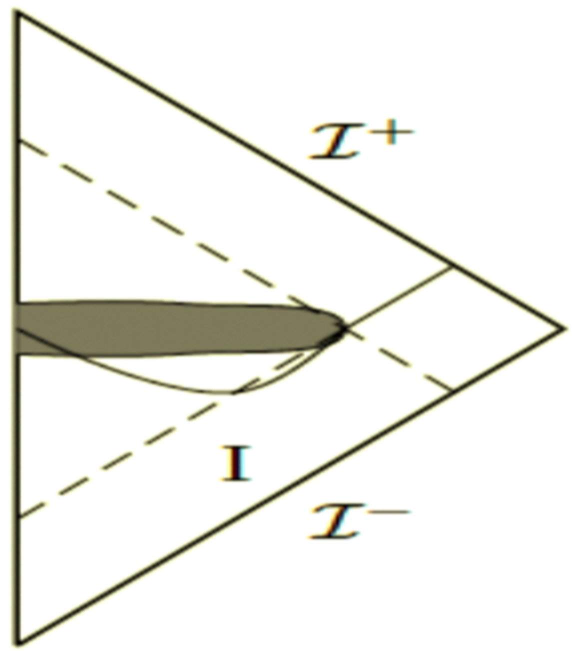

What about the loss of information issue now?

A part of the difficulty is tied to the fact that, associated with the region after the singularity there must be very little energy but a lot of *information*.

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Our approach : Contemplate addressing the issue based on modified versions of quantum theory.

Q.M. , THE MEASUREMENT PROBLEM & Q.G.

i) Normally, the evolution law $i\frac{d|\xi\rangle}{dt} = \hat{H}|\xi\rangle$. which is unitary and deterministic.

ii) Upon a measurement of the observable $\hat{O}$ the system passes to a state $|o_n\rangle$ (corresponding to the eigenvalue o_n) : $|\xi\rangle \to |o_n\rangle$ Such evolution is stochastic (probability $P(o_n) = |\langle\xi|o_n\rangle|^2$).

What is a measurement ? When, according to the theory, should the evolution be i) (U Process) and when ii) (R Process)?

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Instead of a long discussion let us illustrate the situation with a few quotes:

"Either the wave function as given by Schrödinger equation is not everything, or it is not right" Bell, J. S. , in " Are there quantum jumps?", in Speakable and unspeakable in quantum mechanics. Cambridge: Cambridge University Press, 201?212 (1987)

"I think our best hope is to find some successor theory, to which quantum mechanics as we now know it is only a good approximation." S. Weinberg , in reply to an interview by J. Horgan about a "Final Theory of Everything", March 1, 2015.

R. Penrose *joining QM and GR, we might have to modify both* (not a quote). Also that, "dynamical reduction" might be required for self consistency in a theory involving Black Holes in thermodynamic (statistical) equilibrium with other systems.

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Dynamical Collapse Theories : P. Pearle, Ghirardi -Rimini -Weber (GRW), L. Diosi, R. Penrose & recently S. Weinberg. (Rel Versions by Bedingham , Tumulka, Pearle)

Example, CSL: i) A modified Schrödinger equation, whose solution is:

$$|\psi, t\rangle_w = \hat{T} e^{-\int_0^t dt' \left[i\hat{H} + \frac{1}{4\lambda}[w(t') - 2\lambda\hat{A}]^2\right]} |\psi, 0\rangle. \qquad (1)$$

($\hat{T}$ is the time-ordering operator). $w(t)$ is a random classical function of time, of white noise type, whose probability is given by the second equation, ii) the Probability Rule:

$$PDw(t) \equiv {}_w\langle\psi, t|\psi, t\rangle_w \prod_{t_i=0}^{t} \frac{dw(t_i)}{\sqrt{2\pi\lambda/dt}}. \qquad (2)$$

The processes U and R (corresponding to the observable $\hat{A}$) are unified. For non-relativistic QM the proposal assumes : $\hat{A} = \hat{\vec{X}}$. Here λ must be small enough not to conflict with tests of QM in the domain of subatomic physics, and big enough to result in rapid localization of “macroscopic objects”. GRW suggested : $\lambda \sim 10^{-16} sec^{-1}$

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We need to adapt the approach to situations involving both Quantum Fields and Gravitation.

Dynamical reduction in the quantum state requires the notion of " time" (the collapse takes place in time), as QG has a problem with time, and its resolution generically involves passing to a sort of semiclassical regime. We make our analysis assuming we can rely on a semiclassical framework.

We consider that even if at the deepest levels gravitation must be quantum mechanical in nature at the meso/macro scales, it corresponds to an emergent phenomena, with traces of the quantum regime surviving in the form of an effective dynamical state reduction for matter fields.

Assume that in the regime one already has a good description of gravitation in terms of classical geometric notions, however , matter fields must still be considered using quantum theory . This seems reasonable if we consider scales where $R << 1/l^2_{Planck}$.

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A word about pure, mixed, proper and improper states.

Take the view that individual isolated systems that are not entangled with others systems are represented by pure states.

Mixed states occur when we consider either:

a) “proper” An ensemble of (identical) systems each in a $\neq$ pure state. (terminology borrowed from B. d’Espagnat)

b) “improper” The state of a subsystem of a larger system (which is in a pure state), after we ” trace over” the rest of the system.

An ordinary (quantum) thermal state, (in statistical mechanics) represents an ensemble, where the weights are simple functions, characterized by temperature, and chemical potentials, etc . An ” improper” thermal state is a mixed state of type b) where the weights happen to be thermal.
Resolving the BH information paradox requires explaining how a pure state becomes an ordinary (quantum) thermal state (rather than an ”improper” one) : the inside region will simply disappear!

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To deal with all these issues, we make our analysis using a toy model based on :

i) The CGHS black hole,

ii) A toy version of CSL adapted to QFT on CS,

iii) Some simple, and simplifying, assumptions about what happens when QG cures a singularity, and

iv) An assumption that the CSL collapse parameter is not fixed but depends (increases) with the local curvature.

NOTES:

1) Some seeds of the basic idea were contemplated by R. Penrose, (in *Quantum Gravity II*, C. J. Isham, R. Penrose D. W. Sciama eds. Clarendon Press, Oxford,1981).

2) The scheme can be related to something contemplated in W. G. Unruh and R. M. Wald, Phys. Rev. D 52, 2176 (1995).

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Review of The Callan-Giddings-Harvey-Strominger (CGHS) model. The action is given by:

$$S = \frac{1}{2\pi}\int d^2x\sqrt{-g}\left[e^{-2\phi}\left[R + 4(\nabla\phi)^2 + 4\Lambda^2\right] - \frac{1}{2}(\nabla f)^2\right], \tag{3}$$

where ϕ is the dilaton field, Λ^2 is a cosmological constant, and f is a scalar field, representing matter .

We write the metric in the *"conformal gauge"* using null coordinates:

$$ds^2 = -e^{2\rho}dx^+dx^- \tag{4}$$

Then the field f decouples and the general solution of the corresponding KG equation is

$$f(x^+, x^-) = f_+(x^+) + f_-(x^-). \tag{5}$$

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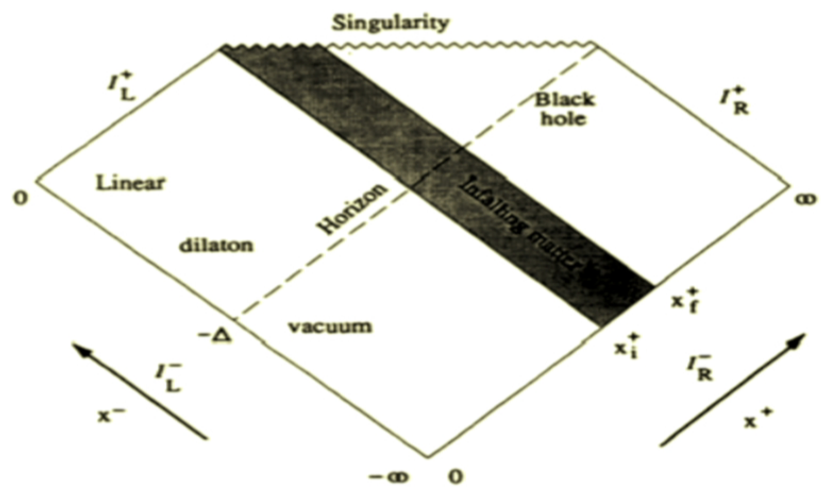
The solution corresponding to a left moving pulse of the field f is

$$ds^2 = -\frac{dx^+ dx^-}{-\Lambda^2 x^+ x^- - (M/\Lambda x_0^+)(x^+ - x_0^+)\Theta(x^+ - x_0^+)},$$

$$(0 \leq x^+ \leq \infty, -\infty \leq x^- \leq 0). \qquad (6)$$

Before the pulse, the solution corresponds to the, so called, linear dilaton vacuum solution and after x_0^+ it turns into a black hole solution.


Singularity
Black
hole
Linear
dilaton
vacuum
Horizon
Infalling matter
0
∞
−Δ
−∞
0

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For later purposes it is useful to write the metric for the black hole region as

$$ds^2 = -\frac{dx^+ dx^-}{\frac{M}{\Lambda} - \Lambda^2 x^+ (x^- + \Delta)}, (x_0^+ \leq x^+ \leq \infty, -\infty \leq x^- \leq 0) \tag{7}$$

where $\Delta = M/\Lambda^3 x_0^+$. The position of the horizon is given by $x^- = -\Delta = -M/\Lambda^3 x_0^+$. The Ricci curvature scalar has the form

$$R = \frac{4M\Lambda}{M/\Lambda - \Lambda^2 x^+ (x^- + \Delta)}. \tag{8}$$

The position of classical singularity (where R blows up) is given by the zero of the above denominator.
Besides these global coordinates, there are other useful coordinates in various regions.

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In the dilation vacuum region:

$$ds^2 = -dy^+ dy^-; \ -\infty < y^- < \infty; \ -\infty < y^+ < 0 \qquad (9)$$

while in the BH exterior region one can use Schwarzschild like coordinates (t, r) so that,

$$ds^2 = \frac{(-dt^2 + dr^2)}{1 + (M/\Lambda)e^{-2r\Lambda}} \qquad (10)$$

One can define another set of Schwarzschild-like coordinates to cover the inside horizon region

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Field quantization Quantum Field Theory (QFT) constructions for the field f one uses the I_L^- and I_R^- as our asymptotic past *in* region, and the black hole (exterior and interior) region as our asymptotic *out* region.
In the *in* region the field operator can be expanded as

$$\hat{f}(x) = \sum_\omega (\hat{a}_\omega^R u_\omega^R + \hat{a}_\omega^{R\dagger} u_\omega^{R*} + \hat{a}_\omega^L u_\omega^L + \hat{a}_\omega^{L\dagger} u_\omega^{L*}). \qquad (11)$$

where, the basis of functions (modes) are the natural positive energy ones $\omega > 0$ for the region and where R and L mean right and left moving modes. These modes will define an "in vacuum" right ($|0_{in}\rangle_R$) and "in-vacuum" left ($|0_{in}\rangle_L$) whose tensor product ($|0_{in}\rangle_R \otimes |0_{in}\rangle_L$) will define our *in* vacuum.

Instead of the usual plane wave modes we will use a complete orthonormal set of localized wave packets modes $u_{jn}^{L/R}$ labeled by the integers $j \geq 0$, n.

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One can also expand the field in the *out* region in terms of the complete set of modes that have support both outside (exterior) and inside (interior) the event horizon. The field operator has the form:

$$\hat{f}(x) = \sum_{\omega}(\hat{b}^R_\omega v^R_\omega + \hat{b}^{R\dagger}_\omega v^{R*}_\omega + \hat{b}^L_\omega v^L_\omega + \hat{b}^{L\dagger}_\omega v^{L*}_\omega) + \tag{12}$$

$$\sum_{\tilde{\omega}}(\hat{\tilde{b}}^R_{\tilde{\omega}} \tilde{v}^R_{\tilde{\omega}} + \hat{\tilde{b}}^{R\dagger}_{\tilde{\omega}} \tilde{v}^{R*}_{\tilde{\omega}} + \hat{\tilde{b}}^L_{\omega} \tilde{v}^L_{\tilde{\omega}} + \hat{\tilde{b}}^{L\dagger}_{\tilde{\omega}} \tilde{v}^{L*}_{\tilde{\omega}}) \tag{13}$$

The convention: modes and operators with and without tildes are defined inside and outside the horizon, respectively.

The non-trivial Bogolubov transformations are only relevant in the right moving sector.

The transformation from *in* to *exterior* modes, which accounts for the Hawking flux, and we will focus just on these.

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The point is that the initial state can be written ' ' at late times" as

$$|\Psi_{in}\rangle = |0_{in}\rangle_R \otimes |Pulse\rangle_L = N \sum_{F_{nj}} C_{F_{nj}} \left|F_{nj}\right\rangle^{ext} \otimes \left|F_{nj}\right\rangle^{int} \otimes |Pulse\rangle_L \tag{14}$$

where a particle state F_{nj} consists of arbitrary but *finite* number of particles, N is a normalization constant, and the coefficients $C_{F_{nj}}$'s are determined using the Bogolubov transformations. For CGHS model, all the coefficients can be determined explicitly.

If we traced over the interior DOF, we would end up with a thermal state of type b) (i.e. an improper one).

With that, we are in a position to proceed to show how a true thermal state is obtained using CSL, and some reasonable assumptions about QG.

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In order to apply the CSL theory, which involves a modification of the time evolution of the quantum states, we need to select a foliation of our space-time associated with a "global time parameter".

Next we consider the modified evolution of the states of our quantum field f.

We will be using an interaction-type picture: the free part of the evolution is encoded in the field operators, and the interaction, which in our case is just the new CSL part, drives the evolution of the states.

In a relativistic context, based in a truly covariant version of CSL, one would be using a Tomonaga-Schwinger type interaction picture evolution:

$$i\delta\,|\Psi(\Sigma)\rangle = \mathcal{H}_I(x)\delta^4 x\,|\Psi(\Sigma)\rangle \tag{15}$$

giving the change in the state associated with the hypersurface obtained by an infinitesimal deformation with four volume $\delta^4 x$ around the point x in Σ.

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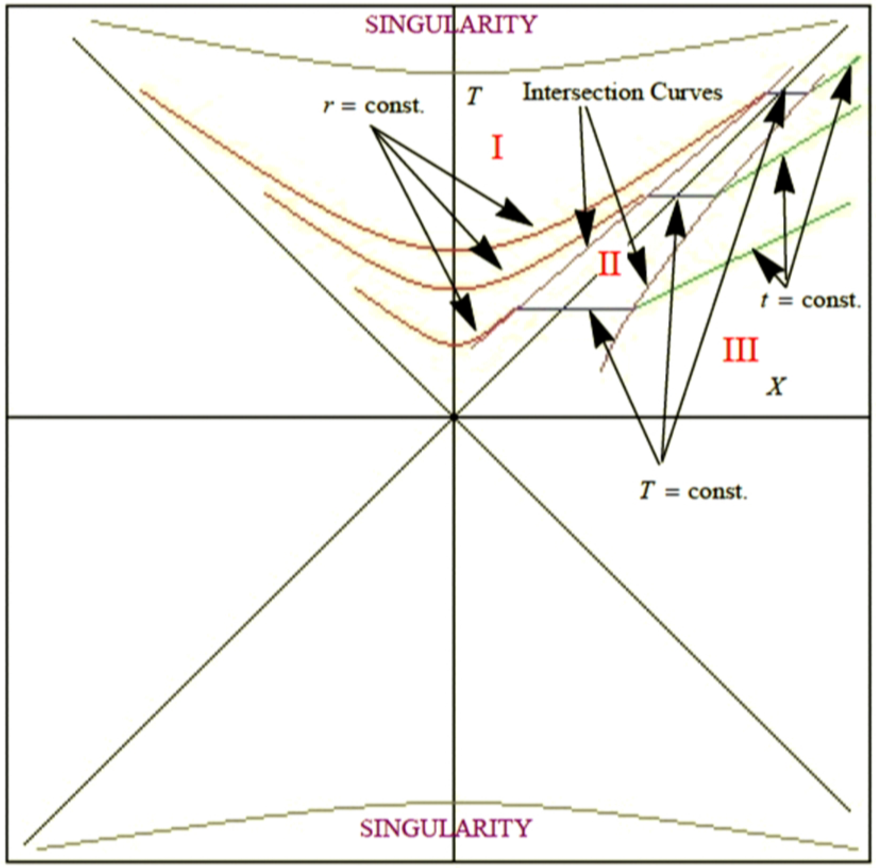
The foliation we use (has $R =$ const. in the inside) and takes the following form :



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The adaptation of CSL to this situation

The CSL equations can be generalized to drive collapse into a state of a joint eigen-basis of a set of commuting operators A^α , $[A^\alpha, A^\beta] = 0$. For each A^α there will be one $w^\alpha(t)$. In this case,we have

$$|\psi, t\rangle_w = \hat{\mathcal{T}} e^{-\int_0^t dt' \left[i\hat{H} + \frac{1}{4\lambda} \sum_\alpha [w^\alpha(t') - 2\lambda \hat{A}^\alpha]^2 \right]} |\psi, 0\rangle. \quad (16)$$

We call $\{A^\alpha\}$ the *set of collapse operators*. In this work we make simplifying choices

i) States will collapse to a state of definite number of particles in the inside region.

ii) We are working in the interaction picture which requires the replacement $\hat{H} \rightarrow 0$ in the above equation.

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The curvature dependent coupling λ in modified CSL

We assume that the rate of collapse λ, depends on the Ricci scalar:

$$\lambda(R) = \lambda_0 \left[1 + \left(\frac{R}{\mu}\right)^{\alpha}\right] \qquad (17)$$

where R is the Ricci scalar of the CGHS space-time and $\alpha > 1$ is a constant, μ provides an appropriate scale.

In $4 - D$ we would expect something like $\lambda = \lambda(W^2)$.

The hypersurfaces given by the foliation have constant R inside the black hole (in almost all the part of Σ_τ that lies inside). Then, for the region of interest we have $\lambda = \lambda(\tau)$.

The resulting evolution will achieve, in the finite time to the singularity, what ordinary CSL achieves in infinite time. That is, to drive the state to one of the eigenstates of the collapse operators.

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A role for quantum gravity:

We assume that a theory of QG will resolve the singularity and lead, on the other side, to a reasonable space-time.
We assume that such a theory will not lead to large violations of the basic space-time conservation laws.
Looking at the “energetics” in the region just before the singularity:

i) The Incoming positive energy flux corresponding to the left moving pulse that formed the BH.

ii) The incoming flux of the left moving vacuum state for the rest of the modes which is known to be negative and essentially equal to the total Hawking Radiation flux.

iii) The flux associated with the right moving modes that crossed the collapsing matter but fell directly into the singularity.

Only missing in this *energetic budget* is the Hawking radiation flux.

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If energy is to be essentially conserved by QG, the state in the post singularity region must be one with a very small value of the energy. It might be associated with some remnant radiation or perhaps a Plank mass remnant.

Those possibilities would represent some information surviving the whole process. We will ignore that, and replace it by the simplest thing: A " zero energy momentum" state corresponding to a region of space-time that would be trivial. We denote it by $\left|0^{post-singularity}\right\rangle$.
Thus, we completed our characterization of the evolution by assuming that the effects of QG can be represented by the curing of the singularity and the transformation:

$$\left|\Psi_{in,\tau}\right\rangle = NC_{F_{nj}}\left|F_{nj}\right\rangle^{ext} \otimes \left|F_{nj}\right\rangle^{int} \otimes \left|Pulse\right\rangle_L$$

$$\to NC_{F_{nj}}\left|F_{nj}\right\rangle^{ext} \otimes \left|0^{post-singularity}\right\rangle \tag{18}$$

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So far we have end up with a pure quantum state, but we do not know which one. That depends on the particular realization of the w^α that appear in the CSL evolution.

So let us consider now an ensemble of systems identically prepared in the same initial state:

$$|\Psi_{in}\rangle = |0_{in}\rangle_R \otimes |Pulse\rangle_L \tag{19}$$

We describe this ensemble, by the pure density matrix:

$$\rho(\tau_0) = |\Psi_{in}\rangle \langle\Psi_{in}| \tag{20}$$

Consider the evolution of this density matrix up to the hypersurface just before the singularity. This can be explicitly done using CSL.

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We start at the initial hypersurface Σ_{τ_0}, and evolve it to the final hypersurface Σ_τ which yields

$$\rho(\tau) = \mathcal{T} e^{-\int_{\tau_0}^{\tau} d\tau' \frac{\lambda(\tau')}{2} \sum_{nj} [\tilde{N}_{nj}^L - \tilde{N}_{nj}^R]^2} \rho(\tau_0) \qquad (21)$$

We express $\rho(\tau_0) = |0\rangle^{\rm in} \langle 0|^{\rm in}$ in terms of the *out* quantization (ignoring left moving modes):

$$\rho(\tau_0) = |0\rangle^{in} \langle 0|^{in} = N^2 \sum_{F,G} e^{-\frac{\pi}{\Lambda}(E_F + E_G)} |F\rangle^{bh} \otimes |F\rangle^{out} \langle G|^{bh} \otimes \langle G|^{out}, \qquad (22)$$

where Λ is the parameter of the CGHS model and $E_F \equiv \sum_{nj} \omega_{nj} F_{nj}$ is the energy of either state $|F\rangle^{bh}$ or $|F\rangle^{out}$ with respect to late-time observers near I^+.

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The operators $\tilde{N}_{nj}$ and their eigenvalues are independent of τ. Thus,

$$\rho(\tau) = N^2 \sum_{F,G} e^{-\frac{\pi}{\mu}(E_F+E_G)} e^{-\sum_{nj}(F_{nj}-G_{nj})^2 \int_{\tau_0}^{\tau} d\tau' \frac{\lambda(\tau')}{2}}$$

$$|F\rangle^{\mathrm{bh}} \otimes |F\rangle^{\mathrm{out}} \langle G|^{\mathrm{bh}} \otimes \langle G|^{\mathrm{out}} \qquad (23)$$

In general, this is not a thermal state. Nevertheless, as τ approaches the singularity, say at $\tau = \tau_s$, the integral $\int_{\tau_0}^{\tau} d\tau' \lambda(\tau')/2$ diverges since $\lambda(\tau)$ is evaluated at hypersurfaces of high curvature.

Then, as $\tau \to \tau_s$ the non diagonal elements of $\rho(\tau)$ cancel out (don't confuse with decoherence), and we have:

$$\lim_{\tau \to \tau_s} \rho(\tau) = N^2 \sum_F e^{-\frac{2\pi}{\Lambda} E_F} |F\rangle^{\mathrm{bh}} \otimes |F\rangle^{\mathrm{out}} \langle F|^{\mathrm{bh}} \otimes \langle F|^{\mathrm{out}} \qquad (24)$$

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Now we add the left moving pulse and use what we assumed about QG, the density matrix characterizing the ensemble after the the would be singularity, is:

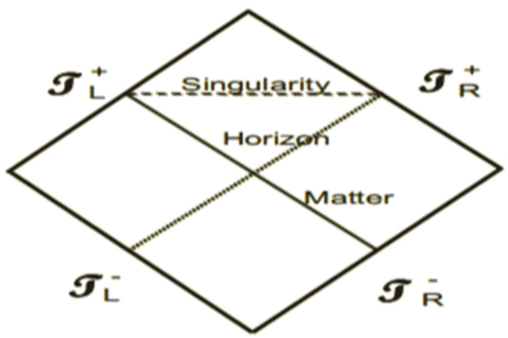
$$\rho^{Final} = N^2 \sum_F e^{-\frac{2\pi}{\Lambda}E_F} |F\rangle^{\text{out}} \otimes \left|0^{post-sing}\right\rangle \langle F|^{\text{out}} \otimes \left\langle 0^{post-sing}\right|$$

$$= \left|0^{post-sing}\right\rangle \left\langle 0^{post-sing}\right| \otimes \rho^{out}_{Thermal} \qquad (25)$$

We started with an initial pure state of the quantum field, and the corresponding space-time initial data on past null infinity, and ended up, with a “proper ” thermal state on future null infinity followed by an empty region.

We assumed that a QG theory would resolve the singularity and that it leads to no gross violations of conservation laws, with potentially observable implications in the regions where something close to a classical space-time description is expected.

A this point, this is only a toy model, but we believe that reasonable models with the same basic features would give essentially the same picture, and thus represent an interesting path to resolving the long standing conundrum known as the " Black Hole Information Loss Paradox".



An even more speculative idea.... THANK YOU