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# A "novel" (?) approach to diffusing the black hole information loss issue: A detailed example.

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

“ 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 " *Gen. Rel. & Gravitation* **47** , 120 (2015); arXiv:1406.4898 [gr-qc]

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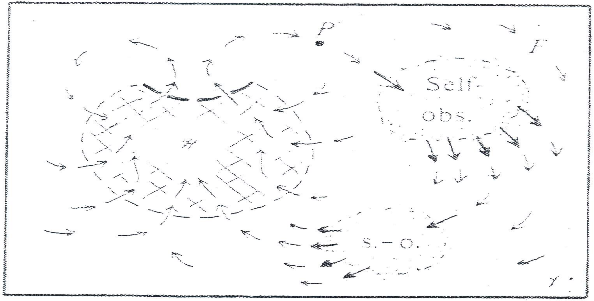
We are strongly influenced by R. Penrose's ideas suggesting that *in putting together QM and GR, we might have to modify both, and not just adapt the latter to the formalism of the former.* ( Not an exact quote).
In particular he long ago argued that, "dynamical reduction" might be required for self consistency in a theory involving Black Holes:



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

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

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

( $\hat{\mathcal{T}}$ 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:

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

Unified $U$ and $R$ processes For non-relativistic QM : $\hat{A}$ is taken as a $\hat{\vec{X}}$ (smeared) . Here $\lambda$ must be small (no conflict with tests of QM) and big enough (rapid localization of “macroscopic objects"). GRW suggested : $\lambda \sim 10^{-16} sec^{-1}$ (Exp. bounds suggest $\lambda^{(i)} = \lambda(m^{(i)}/m_N)^2$).

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

Dynamical reduction theories use the notion of “ time" ( the collapse takes place in time).
QG has a problem with time. Its resolution must involve passing to a sort of semiclassical regime. Our analysis assumes we can rely on a semi-classical framework.

Even if at the deepest levels gravitation must be quantum mechanical in nature, at the meso/macro scales, it corresponds to an emergent phenomena ( hydro-dynamical analogy).
Traces of the QG regime survive in the form of an effective dynamical state reduction for matter fields.

Assume that if $R << 1/l^2_{Planck}$ the description of gravitation in terms of classical geometric notions would be justified, matter fields might still require a quantum treatment.

How to accommodate dynamical collapse within semi-classical treatment of gravitation? ( Page and Geilker ). Following the hydro-dynamical analogy we view E.E. as not always holding exactly just as Navier-Stokes equations would break down when describing a wave that breaks in the ocean.

A) Introduce Semi classical Self- consistent Configurations (SSC) : The set $\{g_{ab}(x), \hat{\varphi}(x), \hat{\pi}(x), \mathcal{H}, |\xi\rangle \mathrm{in} \mathcal{H}\}$ represents a SSC if and only if $\hat{\varphi}(x)$, $\hat{\pi}(x)$ and $\mathcal{H}$ correspond to a quantum field theory constructed over a space-time with metric $g_{ab}(x)$. and the state $|\xi\rangle$ in $\mathcal{H}$ is such that

$$G_{ab}[g(x)] = 8\pi G \langle\xi|\hat{T}_{ab}[g(x), \hat{\varphi}(x)]|\xi\rangle. \qquad (3)$$

B) An individual collapse would correspond to the gluing of two SSC's. Close connection with W. Israel's matching recipe.

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

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

Mixed states occur when we consider either:

a) “proper" An ensemble of (identical) systems each in a –possibly different– 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.

A “proper " (quantum) thermal state, (in statistical mechanics) represents an ensemble, with weights characterized by temperature, and chemical potentials, etc .
An " improper" thermal state is a mixed state of type b) where the weights are thermal.
In this approach, resolving the BH information paradox, requires explaining how a pure state becomes a proper thermal state: the inside region will simply disappear!

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.

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

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

$\phi$ is the dilaton field, $\Lambda^2$ a cosmological constant, and $f$ is a scalar field (matter) .
In the conformal gauge, using null coordinates:

$$ds^2 = -e^{2\rho} dx^+ dx^- \tag{5}$$

The field $f$ decouples and the general solution (KG Eq.) is

$$f(x^+, x^-) = f_+(x^+) + f_-(x^-). \tag{6}$$

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

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

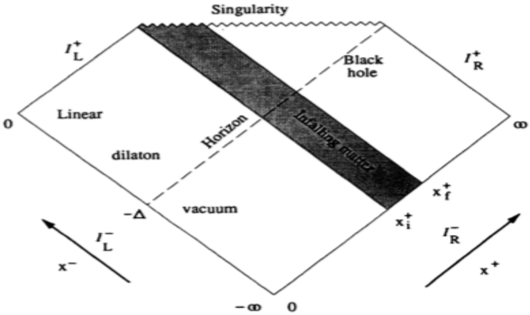
Before the pulse, the solution corresponds to the linear dilaton vacuum solution and after $x_0^+$ it turns into a black hole solution.

The Ricci scalar in the BH region

$$R = \frac{4M\Lambda}{M/\Lambda - \Lambda^2 x^+(x^- + \Delta)}. \tag{7}$$

where $\Delta = M/\Lambda^3 x_0^+$.

The singularity corresponds to $R = \infty$ and the event horizon is located at $x^- = -\Delta$.


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

Besides these global coordinates, useful coordinates in various regions.

In the dilation vacuum region:

$$ds^2 = -dy^+ dy^- \tag{8}$$

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

$$ds^2 = \frac{(-dt^2 + dr^2)}{1 + (M/\Lambda)e^{-2r\Lambda}} \tag{9}$$

Another set of Schwarzschild like coordinates to cover the inside horizon region

## Field quantization:

QFT constructions for $f$: uses the $I_L^-$ and $I_R^-$ as the *in* region, and the black hole (exterior and interior) region as the *out* region.

In the *in* region the field operator can be expanded as

$$\hat{f}(x) = \sum_{\omega} (\hat{a}_\omega^R u_\omega^R + \hat{a}_\omega^{R\dagger} u_\omega^{R*} + \hat{a}_\omega^L u_\omega^L + \hat{a}_\omega^{L\dagger} u_\omega^{L*}). \qquad (10)$$

The mode- functions are positive energy ones $\omega > 0$ for the region . $R$ and $L$ mean right and left moving modes. Then $(|0_{in}\rangle_R \otimes |0_{in}\rangle_L)$ is the *" in "* vacuum.

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

Expand the field in the *out* region in terms of the complete set of modes both outside (exterior) and inside (interior) the event horizon. The field operator has the form:

$$\hat{f}(x) = \sum_{\sigma}(\hat{b}^R_\sigma v^R_\sigma + \hat{b}^{R\dagger}_\sigma v^{R*}_\sigma + \hat{b}^L_\sigma v^L_\sigma + \hat{b}^{L\dagger}_\sigma v^{L*}_\sigma) + \quad (11)$$

$$\sum_{\tilde{\sigma}}(\hat{\tilde{b}}^R_{\tilde{\sigma}} \tilde{v}^R_{\tilde{\sigma}} + \hat{\tilde{b}}^{R\dagger}_{\tilde{\sigma}} \tilde{v}^{R*}_{\tilde{\sigma}} + \hat{\tilde{b}}^L_{\tilde{\sigma}} \tilde{v}^L_{\tilde{\sigma}} + \hat{\tilde{b}}^{L\dagger}_{\tilde{\sigma}} \tilde{v}^{L*}_{\tilde{\sigma}}) \quad (12)$$

Tildes refer to the inside the horizon. ($\sigma$ stands for $(n, j)$ ).

The relevant Bogolubov transformations are those in the right moving sector.

The transformation from *in* to *exterior* modes, which accounts for the Hawking flux.

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

$$|\Psi_{in}\rangle = |0_{in}\rangle_R \otimes |Pulse\rangle_L = N \sum_{F_{nj}} C_{F_{nj}} \left|F_{nj}\right\rangle^{ext} \otimes \left|F_{nj}\right\rangle^{int} \otimes |Pulse\rangle_L \tag{13}$$

where a particle state $F_{nj}$ consists of arbitrary but *finite* number of particles.

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

$$\lim_{\tau \to \tau_s} \rho(\tau) = N^2 \sum_F e^{-\frac{2\pi}{\Lambda} E_F} |F\rangle^{\text{out}} \otimes \langle F|^{\text{out}} \tag{14}$$

To apply the CSL theory, we need a foliation of our space-time ( a “global time parameter")

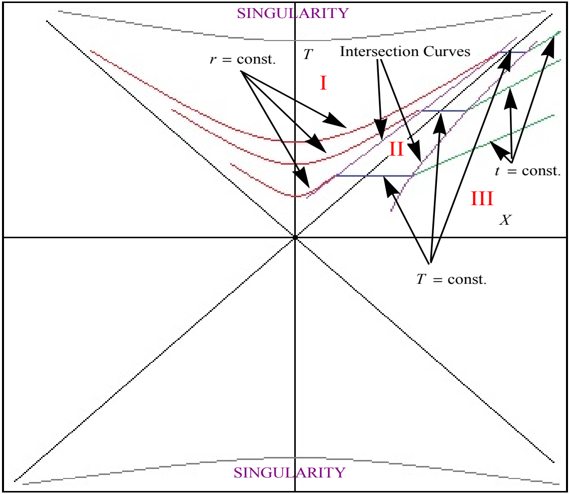
Use interaction-type picture: the free part of the evolution encoded in the field operators, the interaction, ( the new CSL part), in the evolution of the states.

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

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

change in the state tied to an infinitesimal deformation of the hypersurface with four volume $\delta^4 x$ around $x$ in $\Sigma$.

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




Introduce the foliation's time the parameter $\tau$

## The CSL collapse operator

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

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

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, so $\hat{H} \to 0$ in the above equation.

## The curvature dependent coupling $\lambda$ in modified CSL

Assume that the CSL collapse mechanism is amplified by the curvature of space-time: i .e. that the rate of collapse $\lambda$, will depend, in this case, of the Ricci scalar:

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

where $R$ is the Ricci scalar of the CGHS space-time and $\alpha > 1$ is a constant, $\mu$ provides an appropriate scale.
In the region of interest we will have $\lambda = \lambda(\tau)$.

This evolution achieves, in the finite time to the singularity, what ordinary CSL achieves in infinite time, i.e. drives the state to one of the eigenstates of the collapse operators.

Thus, the effect of CSL on the initial state:

$$|\Psi_{in}\rangle = |0_{in}\rangle_R \otimes |Pulse\rangle_L = N \sum_{F_{nj}} C_{F_{nj}} \left|F_{nj}\right\rangle^{ext} \otimes \left|F_{nj}\right\rangle^{int} \otimes |Pulse\rangle_L \tag{18}$$

is to drive it to one of the eigenstates of the joint number operators. Thus at the hypersurfaces $\tau = Constant$ very close to the singularity the state will be

$$\left|\Psi_{in,\tau}\right\rangle = NC_{F_{nj}} \left|F_{nj}\right\rangle^{ext} \otimes \left|F_{nj}\right\rangle^{int} \otimes |Pulse\rangle_L \tag{19}$$

There is no summation. It is a pure state. We do not know which one!

Next ingredient: The role of quantum gravity: Assume that QG :
a) : resolves the singularity and leads, on the other side, to a reasonable space-time.
b) : does not lead to large violations of the basic space-time conservation laws.

Thus, the effects of QG can be represented by the curing of the singularity and the transformation of the state:

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

$$\to NC_{F_{nj}} \left|F_{nj}\right\rangle^{ext} \otimes \left|0^{post-singularity}\right\rangle \tag{20}$$

Where $\left|0^{post-singularity}\right\rangle$ represents a zero energy momentum state corresponding to a trivial region of space-time. ( We ignored possible small remnants).

## ENSEMBLES

We ended with a pure quantum state, but do not know which one. That depends on the particular realization of the functions $w^{\alpha}$.

Consider now an ensemble of systems prepared in the same initial state:

$$|\Psi_{in}\rangle = |0_{in}\rangle_R \otimes |Pulse\rangle_L \tag{21}$$

We describe this ensemble, by the pure density matrix:

$$\rho(\tau_0) = |\Psi_{in}\rangle \langle \Psi_{in}| \tag{22}$$

Consider the CSL evolution of this density matrix up to the hypersurface just before the singularity.

We start at the initial hypersurface $\Sigma_{\tau_0}$, and evolve it to the final hypersurface $\Sigma_\tau$ which yields

$$\rho(\tau) = \mathcal{T} e^{-\int_{\tau_0}^{\tau} d\tau' \frac{\lambda(\tau')}{2} \sum_{nj} [\tilde{N}^L_{nj} - \tilde{N}^R_{nj}]^2} \rho(\tau_0) \qquad (23)$$

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

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

Then, as $\tau \to \tau_s$ the non diagonal elements of $\rho(\tau)$ cancel out (don‘t confuse with decoherence *), and we have:

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

* Here the unraveling deals with individual realizations!!

Finally add the left moving pulse and use what was assumed about QG. The density matrix characterizing the ensemble after the would-be-singularity, is then :

$$\rho^{Final} = N^2 \sum_F e^{-\frac{2\pi}{\Lambda} E_F} |F\rangle^{\rm out} \otimes \left|0^{post-sing}\right\rangle \langle F|^{\rm out} \otimes \left\langle 0^{post-sing}\right| = \left|0^{post-sing}\right\rangle \left\langle 0^{post-sing}\right| \otimes \rho^{out}_{Thermal} \tag{25}$$

Start: a pure state of $\hat{f}$, and space-time initial data on past null infinity. End: a “proper " thermal state on future null infinity followed by an empty region!

We assumed that a QG theory resolves the singularity and, it leads to no GROSS violations of conservation laws.

CONCERNS:

Energy violation: Early concerns by Banks Susskind and Peskin , but further analysis by Unruh and Wald indicated these were exaggerated. Dynamical collapse theories have been constructed to ensure compatibility with experimental bounds.

Foliation dependence: When using the non-relativistic CSL version this is an issue. Eliminated by passing to the relativistic versions of collapse dynamics.

Relativistic Covariance: In the paper : Relativistic collapse dynamics and black hole information loss D. J. Bedingham , S. K. Modak , & D. Sudarsky . arXiv:1604.06537 [gr-qc] we carried out a similar analysis as the one performed here using a relativistic version of Dynamical collapse theory recently developed " Relativistic state reduction dynamics " D. J. Bedingham. Found.Phys. 41 (2011) 686-704.

Dependence on Collapse Operators: Just as in EPR-B situation the no signaling theorems (respected by GRW or CSL proposals) ensure that the density matrix characterizing the situation outside is insensitive to the choice of collapse operators relevant for the inside dynamics.

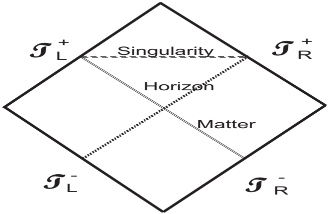
OPEN ISSUES:

i) Back reaction:

This work is being carried out at the moment and we expect to put a paper out soon. Use of SSC and gluing.

ii) Universal form of the Dynamical collapse theory: A) The generic choice of the collapse driving operators. B) The exact form of the curvature dependence in the collapse coupling .

At this point, what we have are toy models, 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 “ Black Hole Information Loss Paradox".




Finally .. thinking of QG and virtual BH’s we obtain an attractive "boot-strap" picture...

In retrospect this is reviving S. Hawking’s old posture... ?

And perhaps, this is just the thing to do, given that in 2007 S. Hawking conceded to D. Page *"in light of the weakness of the US $"* , whereas :



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