Black Holes: Information Loss but No Paradox?

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Contents

1. Meaning of conservation of information
2. Black hole information paradox: general overview
3. Major historical twists in BHIP
4. Our approach using foundation of quantum theory
5. Summary, Future Plan etc.

- Information conservation (in Minkowski spacetime) due to standard quantum evolution:

$$\psi(t) = U(t)\psi \tag{1}$$

such that $U^\dagger U = I$.

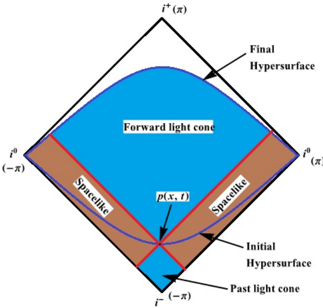


Figure: Penrose (conformal) diagram of Minkowski spacetime

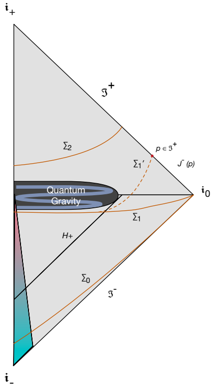
Black holes with classical fields

- Black holes are the final stage of massive collapsing bodies or stars. There is a region bounded by event horizon from where nothing, not even light can escape.
- Any object that enters inside the event horizon is causally disconnected with outside observer. However, note that this is not “information paradox”. *This loss of information refers only to outside observers. When one takes into account also the interior of the horizon one can use the data inside and outside the horizon to reconstruct the initial state of the space-time and matter.*

Black holes with quantum fields

- Quantum treatment of fields in a black hole background changes the picture dramatically. Black hole emits *Hawking radiation* and looses its energy.
- With respect to a distant observer, mass of the black hole becomes zero in finite time. If one keep aside dramatic possibilities (like Planck size remnant etc) the final spacetime becomes Minkowskian and entire mass of the black hole is converted into radiation.
- *How does this alter the information problem?*

- Black hole spacetime: No one has been able to connect the states (initial and final) *unitarily*!



It has been a long, confusing and unsolved problem!

- 1976: Hawking's proposal that information is lost in black holes.
- 1993: Susskind saying no loss of information due to Black Hole Complementarity.
- 2003: Maldacena speculating information recovery via AdS/CFT.
- 2005: Hawking (changing side), no loss of information.
- 2012: Almheiri, Marolf, Polchinski and Sully (AMPS) arguing it is impossible to get information back by respecting GR equivalence principle at EH.
- 2014: Hawking saying, no event horizon, information is lost due to our inability to restore it!
- etc. etc.

A successful resolution may well open a "Door to a new physics"!

- *What should be a reasonable solution of the paradox where information is lost?*
- From our point of view a correct resolution of information paradox where information is lost would require to explain how a pure state becomes thermal state corresponding a “proper mixture” rather than an “improper mixture”.
- Note that a proper mixture represents an actual ensemble of systems, and an improper mixture represents a partial description, as provided by the reduced density matrix, of a subsystem which is part of a larger system which is, as a whole, is in a pure state.

- The root of the paradox lies at the foundation of quantum theory.
- We shall explicitly show that a *stochastically modified* version of the quantum theory, given by the theory of “Continuous Spontaneous Localization” (hereafter CSL), along with a new hypothesis, provides an interesting path to resolve the problem.

- Macro-objectification Problem: Linear property of Schrodinger equation implies macroscopic superpositions which are never observed.
- Measurement Problem: Continuous and deterministic process of unitary evolution of a quantum system is replaced by a discontinuous and stochastic process of state reduction by a vague notion of “measurement’.
- Preferential Basis Problem: While comparing quantum mechanics with experiment there is a preferential basis usually chosen by an observer. Without observer there is no reality in QM.

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Non-Relativistic Collapse Models
Pearle, PRD 1976;
Ghirardi-Rimmini-Weber PRD 1986;
Ghirardi-Pearle-Rimmini PRD 1990

Relativistic versions
Bedingham, Found. Phys. 2011:
Pearle 2015...

Ghirardi-Rimini-Weber, Pearle, Diosi, Penrose and recently Weinberg

CSL main two equations

- A (stochastically) modified Schrodinger equation
  (i) $|\psi, t\rangle = \mathcal{T} e^{-\int_0^t dt' \left[i\hat{H} + \frac{1}{4\lambda}[w(t') - 2\lambda\hat{A}]^2 \right]} |\psi, 0\rangle$. (where $\mathcal{T}$ 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: $PDw(t) \equiv {}_w\langle\psi, t|\psi, t\rangle_w \prod_{t_i=0}^{t} \frac{dw(t_i)}{\sqrt{2\pi\lambda/dt}}$;
  $[\int PDw(t) = \langle\psi, 0|\psi, 0\rangle = 1]$
- In the NR limit the theory assumes $\hat{A} = \hat{X}_\delta$ (the smeared position operator X with width δ). Also it introduces a new fundamental constant of Nature, "the collapse parameter" (λ), which is small enough not violate subatomic predictions of standard QM, however, big enough to provide rapid localization of "macro objects". Experimentally suggested value $\lambda \sim 10^{-16} sec^{-1}$.

CSL evolution of the density matrix:

- It follows from a Lindblad type equation:
  $\frac{d}{dt}\rho(t) = -i[\hat{H}, \rho(t)] - \frac{\lambda}{2}[\hat{A}, [\hat{A}, \rho(t)]]$
- With solution: $\rho(t) = \mathcal{T} e^{-\int_0^t dt' \left[i(\underset{\rightarrow}{\hat{H}} - \underset{\leftarrow}{\hat{H}}) + \frac{\lambda}{2}[\underset{\rightarrow}{\hat{A}} - \underset{\leftarrow}{\hat{A}}]^2 \right]} \rho(0)$

We shall need these later on!

Our Point of View

- We consider that even if at the deepest level, gravitation must be quantum mechanical in nature, at a lower (much lower than Planck scale) energy scale it corresponds to an emergent phenomena, with traces of the QG regime surviving in the form of an effective dynamical state reduction for matter fields.
- Recently this point of view was supported in the article "Information loss, made worse by quantum gravity?" by M. Bojowald [arXiv: 1409.1357]. He mentions "The signature-change models analyzed here may also arise as effective versions of wave-function collapse models proposed in [37, 38]. Free boundary data around the high-curvature core would then correspond to the undetermined wave function obtained by quantum collapse."

Outline of the calculation

Ingredients:

1. The Calan-Giddings-Harvey-Strominger (CGHS) black hole model,
2. A toy version of CSL adapted to a field theory on a curved space-time,
3. An assumption that the CSL collapse parameter is not fixed but depends (increases) with the local curvature, and
4. Some simplifying, but rather natural, assumptions about what happens when QG “cures” a singularity.

This 2D model has been used as a toy model for many applications.

- This model corresponds to the action

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

  where ϕ is the dilaton field, Λ is a constant, and f is a scalar field.

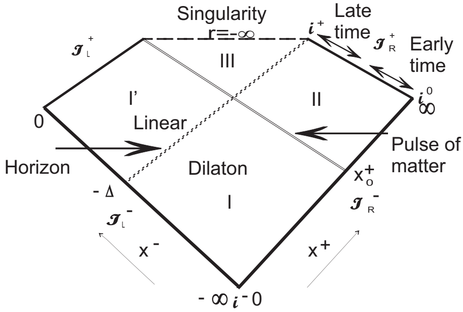
- Conformal gauge: $ds^2 = -e^{2\rho}dx^+dx^-$.
- Left and right moving modes are independent:

$$f(x^+, x^-) = f_+(x^+) + f_-(x^-)$$

.

The model is composed of two main regions glued together:

- Linear dilaton vacuum (I and I') :
  $ds^2 = -\frac{dx^+dx^-}{-\Lambda^2 x^+ x^-}$
  In this region the metric can be written as $ds^2 = -dy^+dy^-$ for coordinates
  $y^+ = \frac{1}{\Lambda}\ln(\Lambda x^+), y^- = \frac{1}{\Lambda}\ln(-\frac{x^-}{\Delta})$
- BH metric (II and III):
  $ds^2 = -\frac{dx^+dx^-}{\frac{M}{\Lambda} - \Lambda^2 x^+(x^- + \Delta)}$
  Asymptotic form in Reg. II,
  $ds^2 = -d\sigma^+ d\sigma^-, \sigma^\pm = \sigma^\pm(x^\pm)$



- Field can be decomposed in two spacetime regions. In asymptotic past (before the formation of black hole) and asymptotic future (late time evaporation of black hole).
- One can define vacuum states in corresponding regions. The initial vacuum state can be expressed in terms of particle states defined in the Fock space of asymptotic future.
- Note that the initial state is vacuum for “right movers” and a “pulse” peaked at a classical value for left movers: $|\Psi_{in}\rangle = |0_{in}\rangle_R \otimes |Pulse\rangle_L$. Now our task is to evolve this initial quantum state using a CSL evolution.

CSL evolution of quantum state

Recall the CSL evolution of state vector:

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

Note:

- We shall be working in a interaction picture with the CSL process an interaction term, so that the state will evolve under this "interaction hamiltonian". This is equivalent to $\hat{H} \to 0$ in above eqn.

New Hypothesis: We make a new hypothesis that in presence of gravity the rate of collapse λ will be dependent on the Ricci scalar (for 2D):

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

where μ is an appropriate scale and $\gamma \geq 1$. (Will be more clearer later on!)

Specifying collapse operators

- CSL equations can be generalized to drive collapse into a state of a joint basis of a set of operators A^α which commute, $[A^\alpha, A^\beta] = 0$. This requires a white noise function w^α for each A^α.
- We propose

$$A_\alpha \to \tilde{N}_{nj} \equiv (N_R^{int})_{nj} \otimes \mathbb{I}_L^{int} \otimes \mathbb{I}_R^{ext} \otimes \mathbb{I}_L^{ext}$$

where $(N_R^{int})_{nj}$ is the number operator inside the horizon.

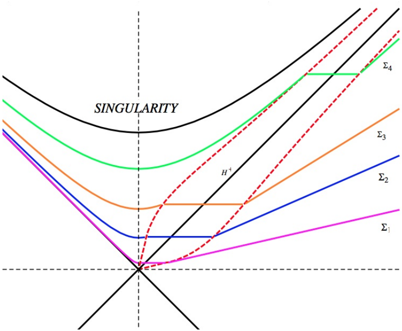
The initial state of the quantum field, defined in $\mathscr{I}^-$, can be expressed in the out basis (again we are restricting to the right moving sector)

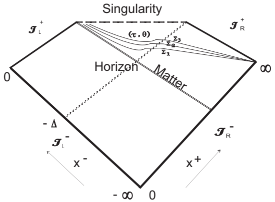
$$|\Psi_i\rangle = |0\rangle_R^{in} \otimes |Pulse\rangle_L = N \sum_F e^{-\frac{\pi}{\Lambda} E_F} |F\rangle_R^{int} \otimes |F\rangle_R^{ext} \otimes |Pulse\rangle_L \qquad (2)$$

where $E_F = \sum_{nj} \omega_{nj} F_{nj}$ and Λ is a parameter (constant) of CGHS model. We have already specified set of collapse operators as well as the “curvature dependent” collapse rate. The other requirement to facilitate the CSL evolution is a well defined Cauchy slicing of the spacetime.

Spacetime Foliation

Cauchy slices (Σ_τ) are defined by following manner– in the interior of the horizon a curve with $r = const.$ and in the region II a $t = const.$ line connecting them via a line $T = const.$ The prescription is defined once we provide the joining conditions (points were the matching takes place). These are given by the curves $T_{1,2}(X)$ with $T_1(X) = \left(X^2 + \frac{M}{\Lambda^3} e^{-2\Lambda/\sqrt{X}}\right)^{1/2}$ and $T_2(X)$ is found by reflection of $T_1(X)$.



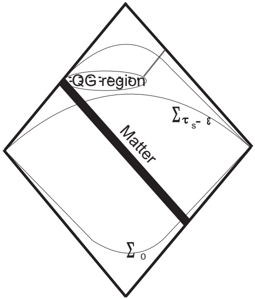


Final state after CSL evolution

- CSL evolves the state towards an eigenstate of the collapse operators. Note that $R(\tau) = \frac{4M\Lambda}{M/\Lambda - \Lambda^2\tau^2}$ diverges in finite "time" (τ) as $\tau \to \tau_s$ making $\lambda(R)$ diverging. The final state at a hypersurface $\Sigma_{\tau_s-\epsilon}$ is

$$\left|\Psi_{in,\tau_{s-\epsilon}}\right\rangle = Ne^{-\frac{\pi E_F}{\Lambda}} \left|F\right\rangle^{ext} \otimes \left|F\right\rangle^{int} \otimes \left|Pulse\right\rangle_L$$

- Here is no summation: the state is pure but *undetermined* (we don't know the actual realization of the stochastic function w).



Evolution of an ensemble

- Let us consider an *ensemble of systems* identically prepared in the same initial state $|\Psi_i\rangle$ The (initial) density matrix corresponds to a pure state $\rho(\tau_0) = |\Psi_i\rangle \langle\Psi_i|$

Final density matrix

- CSL evolution gives: $\rho(\tau) = \mathcal{T} e^{-\int_{\tau_0}^{\tau} d\tau' \frac{\lambda(\tau')}{2} \sum_{nj} [\underrightarrow{\tilde{N}}_{nj} - \underleftarrow{\tilde{N}}_{nj}]^2} \rho(\tau_0)$
- Final density matrix:

$$\rho_R(\tau) = N^2 \sum_{F,G} e^{-\frac{\pi}{\Lambda}(E_F+E_G)} e^{-\sum_{nj}(F_{nj}-G_{nj})^2 \int_{\tau_0}^{\tau} d\tau' \frac{\lambda(\tau')}{2}} |F\rangle_R^{int} \otimes |F\rangle_R^{ext} \langle G|_R^{int} \otimes \langle G|_R^{ext}$$

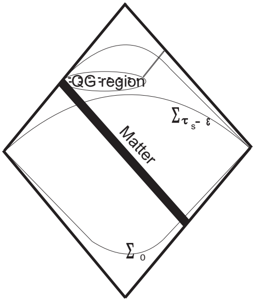
As $\tau \to \tau_s$ the non diagonal elements of $\rho(\tau)$ cancel out and we have in this limit:

$$\lim_{\tau \to \tau_s} \rho(\tau) = N^2 \sum_{F} e^{-\frac{2\pi}{\Lambda} E_F} |F\rangle_R^{int} \otimes |F\rangle_R^{ext} \langle F|_R^{int} \otimes \langle F|_R^{ext} \otimes |Pulse\rangle_L \langle Pulse|_L$$

- We will assume that a reasonable theory of QG will resolve the singularity and lead, on the other side, to a reasonable space-time. Moreover it will not violate the basic spacetime conservation laws.

We complete the quantum evolution of the state by assuming that QG cures the singularity and makes the following transformation

$$\begin{aligned} |\Psi_{\tau\to\tau_s}\rangle &= |F\rangle_R^{ext} \otimes |F\rangle_R^{int} \otimes |Pulse\rangle_L \\ &\longmapsto |F\rangle_R^{ext} \otimes \left|0^{post-singularity}\right\rangle \end{aligned}$$



The final density matrix:

$$\begin{aligned} \rho_{final} &= N^2 \sum_F e^{-\frac{2\pi}{\Lambda}E_F} |F\rangle_R^{ext} \otimes \left|0^{post-sing}\right\rangle \langle F|_R^{ext} \otimes \left\langle 0^{post-sing}\right| \\ &= \left|0^{post-sing}\right\rangle \left\langle 0^{post-sing}\right| \otimes \rho_{thermal}^{ext}. \end{aligned}$$

- The loss of information in black hole evaporation is non-paradoxical under the hypothesis that strong gravitational field collapses the state of the quantum field in a stochastic manner.
- Due to this stochastic nature, given an initial state the final state becomes unpredictable and if one wants to time reverse the process it is impossible to reconstruct the initial state and hence information is lost.
- This is the new physics we are highlighting. Whether or not this happens in nature needs to be checked.

- Proof of foliation independence: a relativistic version [already done PRD 2016].
- Back-reaction of the emitted field into account [ongoing project].
- Influence of gravity in quantum dynamics! Particularly, evidence regarding the curvature induced collapse of wave-function. Are neutron stars good candidates?
- Anything relevant you may suggest!