Black hole information loss and the measurement problem in quantum theory

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Workshop : " **Do Black Holes Exist?: The Physics and Philosophy of Black Holes** ".
Pyzikzentrum Bad Honnef, Germany

May 1, 2017

Talk based on:

1)“The Black Hole Information Paradox and the Collapse of the Wave Function" *Foundations of Physics* **45**, Issue 4, 461-470 (2015).

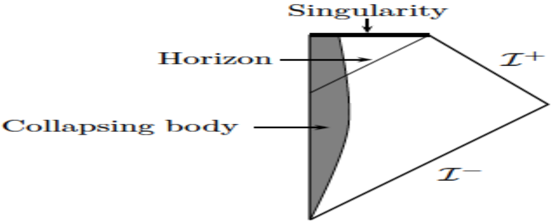
2) “ Non-Paradoxical Loss of Information in of Black hole evaporation in Collapse theories"*Physics Review D* **91**, 12, 124009 (2015).

3) “ Loss of Information in Black hole evaporation with no paradox" *General Relativity and Gravitation* **47** , 120 (2015).

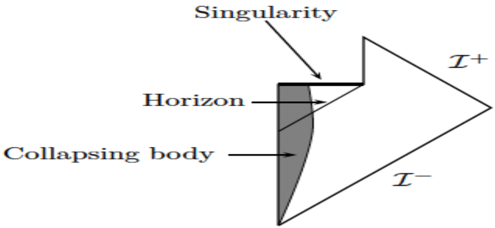
4) “Relativistic collapse dynamics and black hole information loss" *Physics Review D*, **94** no.4, 045009 (2016).

5) “Black Holes, Information Loss and the Measurement Problem" *Foundations of Physics* **47**, 120 (2017).

The BH Information Issue. The end point of evolution of sufficiently massive bodies is thought to be a stationary BH.



Such BH are completely described in terms of just 3 parameters: M, Q & J.
All other information regarding the initial state is gone ?
No, it is just hidden behind the Horizon (and the radiation escaped during its formation).
If the BH was eternal there would be no issue.



However S. Hawking: QFT effects cause BH to radiate. It should loose mass and, unless something strange happens (like a remnant), the process continues until the BH eventually disappears .

QT requires a unitary relation between the final state and the initial one. Very difficult to achieve in this case.

Is there a Black Hole Information Paradox? Only under several assumptions:

A) Hawking radiation, leads to a decrease of the BH mass, and it thus evaporates completely or leaves a small remnant (of bounded mass M_{Planck}or so) . (issue of “Back Reaction")

B) In the latter case the number of internal states of the remnant is bounded by its mass, so it can’t possibly encode all the information that characterized an arbitrarily massive initial state.

C) Information is not transferred to “ baby universes".

D) Quantum gravity effects cure the singularities and remove the need to consider internal boundaries in the space-time.

E) Information is not encoded in arbitrarily low energy modes that go through the quantum gravity region (i.e. ex- singularity).

F) The outgoing radiation does not encode the initial information (Fire-Walls etc).

G) Quantum mechanical evolution is always unitary.

We focus on the latter, in part because of difficulties with others, but mainly because that statement on its own (independently of BH considerations) is not without problems. We are thus lead to considerations often regarded as “ just for philosophers".

Order ideas using the following result Tim Maudlin (*Topoi* 14 1995).

The following 3 premises can not be held simultaneously in a self consistent manner.

i) The characterization of a system by its wave function is complete. Its negation leads, for instance, to hidden variable theories.

ii) The evolution of the wave function is always according to Schrödinger's equation. Its negation leads, for instance, to spontaneous collapse theories.

iii) The results of experiments lead to definite results. Its negation leads, for instance, to Many World/ Minds Interpretations, Consistent histories approach, etc.

Again, we will focus on ii): GRW/ CSL. Specifically on CSL

Continuous Spontaneous Localization. The theory (for a single particle in NR QM) is defined by two equations:
i) A modified Schrödinger equation, whose solution is:

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

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

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

The processes U and R (corresponding to the observable $\hat{A}$) are unified. For non-relativistc 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 range: $\lambda \sim 10^{-16} sec^{-1}$. (Likely depends on particle mass).

We need to adapt this to the contexts involving field theory and gravitation.

NOTE: The exploration of the GR/ QT regime is done here in a top - bottom approach.

Usual bottom -up approach: (String Theory , LQG, Causal sets, dynamical triangulations, etc.) assumes one has THE theory of QG at hand, and then attempts to connect to regimes of interest of the "world out there" : Cosmology, Black Holes, etc.

The top - bottom approach, pushes existing, well tested and developed theories, to address open issues that seem to lie beyond their domain. Possible modifications can serve as clues about the nature of the more fundamental theory .

The idea is to push GR together with QFT (i.e. semi-classical gravity) into realms/questions usually not explored.

Let me first emphasize that: The interface between QT and Gravitation need not involve the Planck regime: (space-time associated with a macroscopic body in quantum superposition of being in two location).

Page and Gleiker (PRL 1981) considered an experiment which they claim shows semi-classical GR is not viable.

They argue that:

1) If there are no Quantum Collapses, then semi-classical GR conflicts with their experiment.

2) If there are Quantum Collapses, then semi-classical GR equations are inconsistent.

We will regard semi-classical GR as an approximated description with limited domain of applicability and to push that domain beyond what is usual : incorporate quantum collapses. It is clear that during the collapse the equations can not be valid. The proposal is to adopt an hydro-dynamical analogy:

Navier- Stokes equations for a fluid can not hold in some situations but they can be taken to hold before and after . Take Semi-classical GR equations to hold before and after a collapse but not during the collapse.

The approach will require providing a recipe to join the descriptions just before and just after the collapse.

Incorporate collapse to GR. At the formal level we rely on the notion of *Semi-classical Self-consistent Configuration* (SSC). *JCAP*. **045**, 1207, (2012); arXiv:1108.4928 [gr-qc]

DEFINITION: The set $g_{\mu\nu}(x), \hat{\varphi}(x), \hat{\pi}(x), \mathcal{H}, |\xi\rangle \mathrm{in} \mathcal{H}$ represents a SSC iff $\hat{\varphi}(x)$, $\hat{\pi}(x)$ y $\mathcal{H}$ corresponds to QFT in CS over the space-time with metric $g_{\mu\nu}(x)$, and MOREOVER the state $|\xi\rangle$ in $\mathcal{H}$ is such that:

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

Note that this is a kind of GR version of the Schödinger -Newton system (and, as non-linear, beyond GR !).

Collapse: a transition for one complete SSC to another one. That is, in general we **do not have simple jumps in states withing a single Hilbert space** but jumps of the form $....SSC1.... \to ....SSC2....$

Matching conditions: for space-time and states in the Hilbert space. Involves delicate issues. Will become highly nontrivial when using a theory like CSL.

Could this fit with our current views regarding quantum gravity? Outstanding issues and conceptual difficulties:

I) The Problem of Time. In Can Q.G. leads to timeless theory.

II) More generally how do we recover space-time from canonical approaches to QG ? (i.e. Wheler-deWitt, LQG).

Solutions to I) use a dynamical variable as a physical clock and consider relative probabilities (and wave functions). Following that line might lead to approx. Schrödinger eq. with corrections that violate unitarity (see Gambini-Pullin ! ?) .

Regarding II) there are many suggestions indicating space-time might be an emergent phenomena... T. Jacobson, R. Sorkin, N. Seiberg and many others.... It is not clear that, g_{ab}, as such, should be " quantized ".
Talk about space-time concepts implies a classical description. Some traces of QG regime might remain relevant, and "look like collapses"?

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 of the BH will simply disappear!

Quantum Fields In a BH space-time.

Quantum Filed theory treatment for the matter fields ϕ. First in the *in* region, before the black hole forms.

Usually the treatment is done using the Heisenberg picture: The state remains fixed, but the field operators depend on time (and space) $\hat{\phi}(x)$.

The initial state can be written schematically as

$$|\Psi_{in}\rangle = |0_{in}\rangle \otimes |Matter\rangle \tag{3}$$

The matter undergoes gravitational collapse and the space-time develops a Black Hole region.

Describing the state of a quantum field at late times is best done in terms of DOF inside and outside the Black Hole.

When the vacuum state is described in this form:

$$|0_{in}\rangle = \sum_{F_\alpha} C_{F_\alpha} \, |F_\alpha\rangle^{ext} \otimes |F_\alpha\rangle^{int} \qquad (4)$$

where a particle state F_α consists of arbitrary but *finite* number of particles (or individual mode excitations).

Tracing over the interior DOF, would lead to a thermal state of type b) (i.e. an improper one) corresponding to the Hawking flux.

The complete initial state can thus be written schematically as

$$|\Psi_{in}\rangle = \sum_{F_\alpha} C_{F_\alpha} \, |F_\alpha\rangle^{ext} \otimes |F_\alpha\rangle^{int} \otimes |Matter\rangle \qquad (5)$$

Consider the evolution of the initial state using a modified theory involving spontaneous collapse. For instance a CSL type theory.

Look at the detailed picture that emerges if we assert that all information lost in BH evaporation is the result of such modified dynamics.

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

$$i\delta\,|\Psi(\Sigma)\rangle = \mathcal{H}_I(x)\delta^4 x\,|\Psi(\Sigma)\rangle \tag{6}$$

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

To use CSL we need a foliation: Use one that has $W^2 = \text{const.}$ in the inside, and extend arbitrarily outside.

Introduce the foliation's time parameter τ.

We have done this explicitly only in a 2-D Model (CGHS).

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 $\hat{A}^I$, $[\hat{A}^I, \hat{A}^J] = 0$. For each $\hat{A}^I$ there will be one $w^I(t)$. In this case,we have

$$|\psi, t\rangle_w = \hat{\mathcal{T}} e^{-\int_0^t dt' \left[i\hat{H} + \frac{1}{4\lambda} \sum_I [w^I(t') - 2\lambda \hat{A}^I]^2 \right]} |\psi, 0\rangle. \qquad (7)$$

We call $\hat{A}^I$ the *set of collapse operators*. Here we make simplifying choices:

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

ii) Work in the interaction picture, so $\hat{H} \to 0$ in the above equation.

The curvature dependent coupling λ in modified CSL

Assume that the CSL collapse mechanism is amplified by the curvature of space-time: i .e. that the rate of collapse λ, will depend,on the Weyl tensor scalar:

$$\lambda = \lambda_0 \left[1 + \left(\frac{W^2}{\mu} \right)^{\gamma} \right] \quad (8)$$

where $W^2 = W_{abcd} W^{abcd}$ space-time and $\gamma > 1/2$ is a constant, μ 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:

$$|\Psi_{in}\rangle = |0_{in}\rangle \otimes |MPulse\rangle = N \sum_{F_\alpha} C_{F_\alpha} |F_\alpha\rangle^{ext} \otimes |F_\alpha\rangle^{int} \otimes |MPulse\rangle \tag{9}$$

It drives 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

$$\left|\Psi_{in,\tau}\right\rangle = NC_{F_\alpha} |F_\alpha\rangle^{ext} \otimes |F_\alpha\rangle^{int} \otimes |MPulse\rangle \tag{10}$$

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:

$$\left|\Psi_{in,\tau}\right\rangle = NC_{F_\alpha} \left|F_\alpha\right\rangle^{ext} \otimes \left|F_\alpha\right\rangle^{int} \otimes \left|MPulse\right\rangle$$

$$\to NC_{F_\alpha} \left|F_\alpha\right\rangle^{ext} \otimes \left|0^{post-singularity}\right\rangle \qquad (11)$$

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 up with a pure quantum state, but we do not know which one. That depends on the particular realization of the functions w^α.

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

$$|\Psi_{in}\rangle = |0_{in}\rangle_R \otimes |Pulse\rangle_L \tag{12}$$

We describe this ensemble, by the pure density matrix:

$$\rho(\tau_0) = |\Psi_{in}\rangle \langle\Psi_{in}| \tag{13}$$

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

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

$$\rho^{Final} = N^2 \sum_F C_F^2 \, |F\rangle^{\rm out} \otimes \left|0^{post-sing}\right\rangle \langle F|^{\rm out} \otimes \left\langle 0^{post-sing}\right|$$

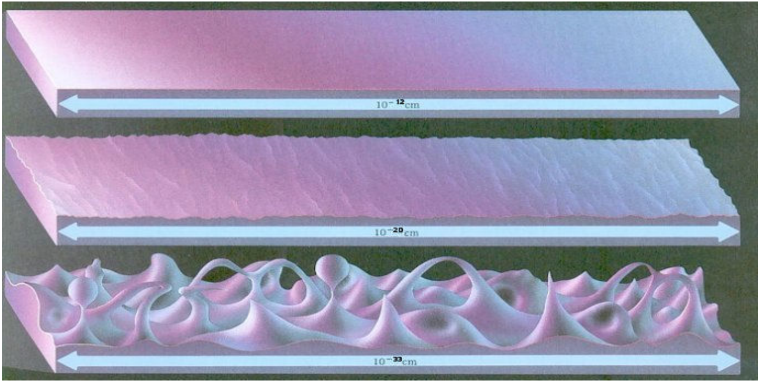
$$= \left|0^{post-sing}\right\rangle \left\langle 0^{post-sing}\right| \otimes \rho^{out}_{Thermal} \tag{14}$$

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!

Information was lost as a result of general quantum evolution (in a slightly modified theory). !!

And there is nothing paradoxical.

Now, let us say one takes the view that information (and unitary evolution) is lost in association with BH evaporation. . It seems natural to think that at a more fundamental level space-time looks like:



BH and related fundamental excitations might appear in virtual processes. As in any situation involving quantum fields.

Violations of unitarity associated with excitation of QG degrees of freedom (which we might want to describe as "virtual black holes") would generate modification of the Schrödinger evolution equation in essentially all situations. Could this be the source of the collapse events in collapse theories?

CONCERNS:

Energy violation: Early concerns by Banks-Susskind-Peskin. Further analysis by Unruh and Wald showed 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 relativistic versions of collapse dynamics.

Relativistic Covariance: In the paper : PRD, 94, 045009 (2016) we carried out a detailed analysis as using a relativistic version of Dynamical collapse theory of D. Bedingham.
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.

SOME 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) Specific relativistic version.
B) The generic choice of the collapse driving operators.
C) The exact form of the curvature dependence in the collapse coupling.

OTHER APPLICATIONS Some are even more speculative.

1) Emergence of primordial Inhomogeneities and Anisotropies from the fluctuations of the inflaton's vacuum. The anomalous low power in CMB spectrum at large angles.

2) Dark Energy as cumulative effect of non-conservation of $\langle \hat{T}_{ab} \rangle$ in "unimodular gravity". *P.R.L.* **118**, 021102 (2017).

3) Problem of Time in Quantum Gravity.

4) Possible explanation for Penrose's Weyl Curvature hypothesis, for the initial state of the Universe.

This whole approach could, in the future, be shown to be non-viable. However as noted by Sir Francis Bacon when considering the scientific enterprise in general: "Truth emerges more readily from error than from confusion".

We believe that ignoring " the measurement problem" in application of QT to macro problems can be a serious source of confusion, particularly when referring to situations beyond the Lab, as those considered here.

THANKS