Dynamical Reduction in General Relativistic Contexts.

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PLAN OF THIS TALK:

1) Some general observations about the Quantum Measurement Problem in Gravitational Contexts .

2) Exploring the Gravity/ Quantum Interface.

3) The inflationary account for the emergence of the seeds of cosmic structure and the CMB

4) The Black Hole Information Puzzle.

5) Other promising aspects.

Ontological Aspects: Usually classical space-time taken as given: I.e. the question is posed in terms of "what according to the theory is it that exists in space-time regions"?.

Flashes : $\rightarrow$ distinguished space-time events .

Mass density: $\rightarrow$ amount of matter per unit volume (in some space-time region).

Treating everything, including space-time, quantum mechanically would require other type of fundamental ontology.

However, as of today, we do not have a fully viable and workable theory of QG.

We do not even know what it would mean for the world to be in a superposition of various (relatively well defined) space-times.

The search for a fundamental ontology might, at this point, be premature.

Content ourselves with some provisional & effective ontology.

In this semiclassical context however : Identify "what exists" with "what gravitates". It must have a T_{ab}.

Detailed postures generate their own problems:

1) In dBB type theories (of say a single particle) , does the pilot wave gravitate? or is it the particle's position? (is the T_{ab} of a dBB particle conserved ?)

2) Flashes (can we associate them with a conserved T_{ab} ?)

3) What is the space-time geometry of a bifurcating world ? Can Einstein's equations hold ?

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.) and attempt to connect to regimes of interest of the "world out there" : Cosmology, Black Holes, etc.

The top - bottom approach, push 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.

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) involving an experiment that claims to show 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).

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 !).

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

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:

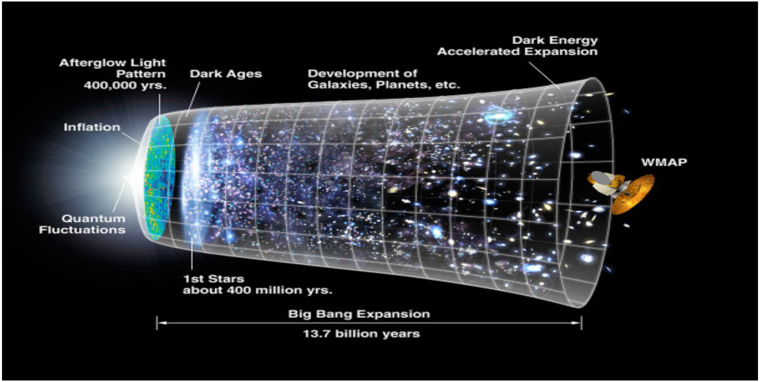
I) The Problem of Time. In Can Q.G. leads to timeless theory.

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

These show the extra difficulties of looking for a fundamental ontology at this point.

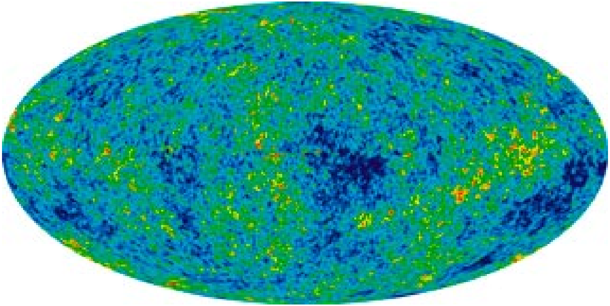
Solutions to I) use a dynamical variable as a physical clock and consider relative probabilities (and wave functions). Following that line might lead to approx. Schrödinger eq. with corrections that violate unitarity (see Gambini-Pullin ! ?) .
Regarding II) there are many suggestions indicating space-time might be an emergent phenomena... T. Jacobson, R. Sorkin, N. Seiberg and many others.... It is not clear that, as such, g_{ab} should be " quantized ".
Talk about space-time concepts implies a classical description. Some traces of QG regime might remain relevant, and "look like collapses"?

COSMIC INFLATION : Contemporary cosmology includes inflation as one of its most attractive components.



Its biggest success: the account for emergence of the seeds of cosmic structure and a correct estimate of the corresponding spectrum.

The Observations



This map on the sky is expanded as

$$\frac{\Delta T(\theta, \varphi)}{\bar{T}} = \sum_{lm} \alpha_{lm} Y_{lm}(\theta, \varphi) \tag{1}$$

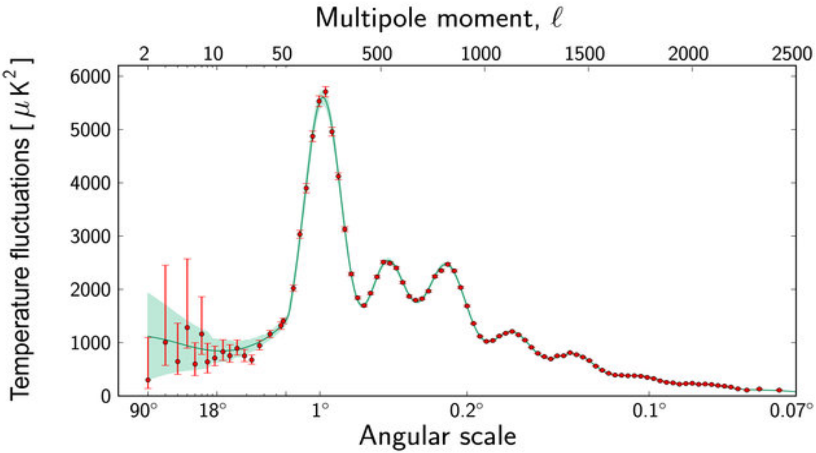
The coefficients α_{lm} extracted and combined into the orientation averaged

$$C_l = \frac{1}{2l+1} \sum_{m} |\alpha_{lm}|^2 \tag{2}$$

The theoretical analysis leads to a remarkable agreement with observations:

Oscillations related to late time plasma physics and ignored hereon.

(Image: ESA/ Planck Collaboration)



The staring point of the analysis is a RW space-time background

$$dS^2 = a(\eta)^2\{-d\eta^2 + d\vec{x}^2\}$$

inflating under the influence of an inflaton background field $\phi = \phi_0(\eta)$ (taken as $\langle\hat{\phi}_0(\eta)\rangle$ in a sharply peaked state for the zero mode). The scale factor then behaves approximately as $a(\eta) = \frac{-1}{\eta H_I}$.

On top of this, one considers quantum fluctuations: $\delta\phi, \delta\psi, ..., \delta h_{ij}$ assumed to be characterized by the " vacuum state" (essentially the BD vacuum) $|0\rangle$.

The argument is that inflation dilutes all preexisting features and drives all space dependent fields towards their vacuum states.

NOTE on QFT : A quantum field $\phi(x)$ can be regarded as a infinite collection of harmonic oscillators , one for each Fourier Mode $\vec{k}$ of the field ($e^{i\vec{k}\vec{x}}$).

The vacuum state $|0\rangle$ is by definition the one satisfying $\hat{a}_{\vec{k}}|0\rangle = 0$ for all $\vec{k}$.

NOTE on QFT of the INFLATON : the zero mode of the field is assumed to be in highly excited (and sharply peaked) state, while the space dependent modes are in the vacuum state.

However even in the vacuum state the field variables have fluctuations (i.e. uncertainties !). From these, it is argued, the primordial inhomogeneities and anisotropies emerge.

These represent the primordial inhomogeneities which evolved into all the structure in our Universe: galaxies, stars planets, etc... THE THEORY FITS VERY WELL ALSO WITH THE

OBSERVATIONS OF LARGE SCALE STRUCTURE .

According to this picture: The Universe was H&I, (both in the part that could be described at the “classical level", and the quantum level) as a result inflation.

[A displacement of the state by $\vec{D}$ is $e^{i\hat{\vec{P}}.\vec{D}}|0\rangle = |0\rangle$ so it is completely homogeneous.]

However the end situation is not.

How does this happen if the dynamics of the closed system does not break those symmetries.?

OUR APPROACH:

Needed: a physical process occurring in time, explaining the emergence of the seeds of structure. Emergence means : Something that was not there at a time, is there at a latter time. We need to explain the breakdown of the symmetry of the initial state: Collapse can do this.

Collapse Theories: Large amount of previous work: GRW, Pearle, Diosi, Penrose, Bassi (recent advances to make it compatible with relativity Tumulka, Bedningham, Pearle).

So we Add to the standard inflationary paradigm, a quantum collapse of the wave function as a self induced processes.

Adapt to the GR context through the SSC formalism.

PRACTICAL TREATMENT:

Checked : this is equivalent at the lowest order in perturbation theory with the one based on SSC.

Again split the treatment into that of a classical homogeneous ('background') part and a potentially in-homogeneous part ('fluctuation'), i.e.

$$g = g_0 + \delta g, \qquad \phi = \phi_0 + \delta\phi.$$

Background : Friedmann-Robertson universe, and the homogeneous scalar field $\phi_0(\eta)$. (in the SSC treatment this corresponds to the zero mode of the quantum field).

Our approach calls for quantizing the the scalar field but not the metric perturbation.

Space-time is treated classically (using a specific gauge):

$$ds^2 = a^2(\eta)\{-(1+2\Psi)d\eta^2 + [(1-2\Psi)\delta_{ij} + h_{ij}]dx^i dx^j\}$$

We will set $a = 1$ at the "present cosmological time", assume that inflationary regime ends at a value of $\eta = \eta_0$.

$$a(\eta) = \frac{-1}{\eta H_I} \text{ with } \eta \text{ in } (-\mathcal{T}, \eta_0), \eta_0 < 0.$$

The scalar field must be treated using QFT in curved space-time. The quantum state of the scalar field and the space-time metric satisfy Einstein's semi-classical eq.

$$G_{\mu\nu} = 8\pi G \langle \xi | \hat{T}_{\mu\nu} | \xi \rangle.$$

Delicate issue of the self-consistency (We have shown how to deal with it in a single discrete collapse using SSC: *JCAP*. **045**, 1207, (2012); 1108.4928 [gr-qc]) .

Concentrate on the $\vec{k} \neq 0$ modes .

Early stages of inflation $\eta = -\mathcal{T}$, the state of the $\hat{\delta}\phi$ is the Bunch-Davies vacuum, and the space-time is 100 % homogeneous and isotropic.

In the vacuum state , the operators $\hat{\delta}\phi_k$ $\hat{\pi}_k$ are characterized by gaussian wave functions centered on 0 with uncertainties $\Delta\delta\phi_k$ and $\Delta\pi_k$.

The collapse modifies the quantum state, and the expectation values of $\widehat{\delta\phi_k}(\eta)$ and $\hat{\pi}_k(\eta)$.

Assume the collapse occurs mode by mode and described by an adapted version of collapse theories.

Our universe would correspond to one specific realization of the stochastic functions (one for each $\vec{k}$).

The semi classical Einstein Equation gives:

$$-k^2\Psi(\eta,\vec{k}) = \frac{4\pi G\phi_0'(\eta)}{a}\langle\hat{\pi}(\vec{k},\eta)\rangle \tag{3}$$

At ($\eta = -\mathcal{T}$) state is the vacuum, so $\langle\hat{\pi}(\vec{k},\eta)\rangle = 0$, and THUS the space-time is 100% homogeneous and isotropic. A quantity of observational interest is:

$$\frac{\Delta T(\theta,\varphi)}{\bar{T}} = \Psi(\eta_D, R_D, \theta, \varphi) = c\int d^3k e^{i\vec{k}\cdot\vec{x}}\frac{1}{k^2}\langle\hat{\pi}(\vec{k},\eta_D)\rangle, \tag{4}$$

corresponding to the point on the intersection of our past light cone with the last scattering surface ($\eta = \eta_D$) in the direction specified by θ, φ.Thus:

$$\alpha_{lm} = c\int d^2\Omega Y_{lm}^*(\theta,\varphi)\int d^3k e^{i\vec{k}\cdot\vec{x}}\frac{1}{k^2}\langle\hat{\pi}(\vec{k},\eta)\rangle. \tag{5}$$

No analogous to this expression in the standard approaches!

The eq. above shows that the quantity of interest can be thought of as a result of a “random walk" on the complex plane.

One can’t predict the end point of such “walk", but can focus on the magnitude of the total displacement and estimate its ML value by an ensemble average. Compute the ensemble average at “late times"

$$\overline{(\langle\hat{\pi}(\mathbf{k},\eta)\rangle\langle\hat{\pi}(\mathbf{k}',\eta)\rangle^*)} = f(k)\delta(\mathbf{k}-\mathbf{k}').$$

Then,

$$\overline{|\alpha_{lm}|^2} = (4\pi c)^2 \int_0^\infty dk j_l(kR_D)^2 \frac{1}{k^2} f(k). \tag{6}$$

Agreement with observations require $f(k) \sim k$. The oscillations are generated by plasma physics on top of the primordial flat spectrum.

Making reasonable choices in the details of the collapse theory one can achieve this behavior :

In CSL version: Collapse in the field operator or the momentum conjugate operators with $\lambda = \tilde{\lambda} k^{\pm 1}$ fixed by dimensional considerations (or collapse in the operators $(-\nabla^2)^{-1/4}\hat{\pi}(\vec{x})$ or $(-\nabla^2)^{1/4}\hat{\phi}(\vec{x})$) . Why is this the right thing?

Finally, comparisons with observations, using GUT scale inflation potential value, and standard values for the slow-roll parameter (order a few percent), leads to the estimate:

$$\tilde{\lambda} \sim 10^{-5} MpC^{-1} \approx 10^{-19} sec^{-1}.$$

Not very different from GRW suggestion !.

TENSOR MODES

Similarly, the equation of motion for the tensor perturbations is

$$(\partial_0^2 - \nabla^2)h_{ij} + 2(\dot{a}/a)\dot{h}_{ij} = 16\pi G \langle(\partial_i\delta\phi)(\partial_j\delta\phi)\rangle_{Ren}^{tr-tr} \qquad (7)$$

$tr - tr$ stands for the transverse trace-less part of the expression. Note that it is quadratic in the collapsing quantities Thus the prediction for the power spectrum of tensor perturbations is:

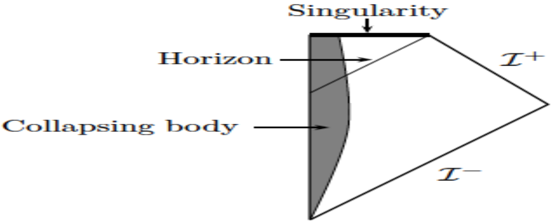
$$P_h^2(k) \sim (1/k^3)(V/M_{Pl}^4)^2(P_{UV}/k) \qquad (8)$$

substantially smaller than the standard prediction, and that for the scalar ones:

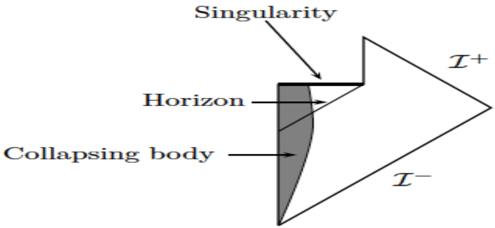
$$P_S^2(k) \sim (1/k^3)(1/\epsilon)(V/M_{Pl}^4) \qquad (9)$$

Thus, expected not to see tensor modes as the level they are being looked for!! The problem of the un-observed B-modes.

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.
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 disappear .

QT requires a unitary relation between the final state and the initial one. This seems almost impossible in this case.

Beware: The BH information paradox only arises when we assume that QG cures the singularity, (and the need for an additional boundary to space-time). One then faces that lack of unitarity indicated by the Hawking evaporation of the BH (assume no remnants), and the conflict with QM.

But wait!!... What exactly is the conflict with QM ?. After all textbook QM involves departures of unitarity in connection to measurements.
This bring us to the measurement problem.

In the BH situation we do not consider any kind of measuring device or observer as being the cause of the departure from unitary evolution. However in theories of spontaneous collapse that feature is present in general (that is how they solve the measurement problem).

We want to present a picture where the two kinds of departures from unitarity are unified.

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

$$|\Psi_{in}\rangle = |0_{in}\rangle \otimes |Matter\rangle \tag{10}$$

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 FOF inside and outside the Black Hole.

When the vacuum state is described in this form:

$$|0_{in}\rangle = \sum_{F_\alpha} C_{F_\alpha} \, |F_\alpha\rangle^{ext} \otimes |F_\alpha\rangle^{int} \tag{11}$$

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

$$|\Psi_{in}\rangle = \sum_{F_\alpha} C_{F_\alpha} \, |F_\alpha\rangle^{ext} \otimes |F_\alpha\rangle^{int} \otimes |Matter\rangle \tag{12}$$

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.

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

Introduce the foliation's time the 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

$$|\psi, t\rangle_w = \hat{\mathcal{T}} e^{-\int_0^t dt' \left[i\hat{H} + \frac{1}{4\lambda}\sum_I [w^I(t') - 2\lambda \hat{A}^I]^2\right]} |\psi, 0\rangle. \qquad (13)$$

We call $\hat{A}^I$ 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) 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:

$$\lambda = \lambda_0 \left[1 + \left(\frac{W^2}{\mu} \right)^{\gamma} \right] \tag{14}$$

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:

$$|\Psi_{in}\rangle = |0_{in}\rangle \otimes |MPulse\rangle = N \sum_{F_\alpha} C_{F_\alpha} |F_\alpha\rangle^{ext} \otimes |F_\alpha\rangle^{int} \otimes |MPulse\rangle \tag{15}$$

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

$$\left|\Psi_{in,\tau}\right\rangle = NC_{F_\alpha} |F_\alpha\rangle^{ext} \otimes |F_\alpha\rangle^{int} \otimes |MPulse\rangle \tag{16}$$

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:

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

$$\to NC_{F_\alpha}\left|F_\alpha\right\rangle^{ext} \otimes \left|0^{post-singularity}\right\rangle \tag{17}$$

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:

$$|\Psi_{in}\rangle = |0_{in}\rangle_R \otimes |Pulse\rangle_L \tag{18}$$

We describe this ensemble, by the pure density matrix:

$$\rho(\tau_0) = |\Psi_{in}\rangle \langle\Psi_{in}| \tag{19}$$

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 :

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

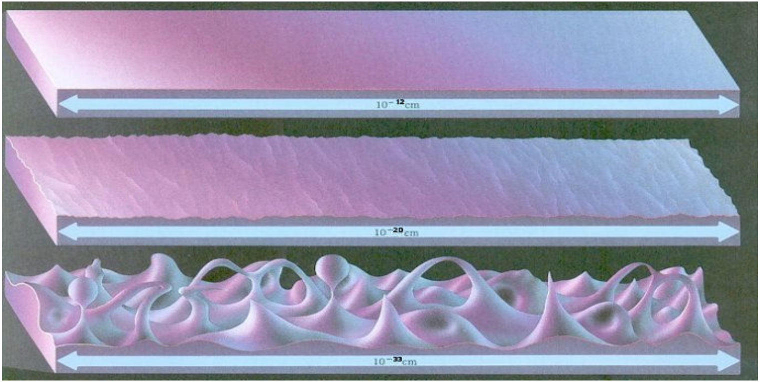
$$= \left|0^{post-sing}\right\rangle \left\langle 0^{post-sing}\right| \otimes \rho^{out}_{Thermal} \tag{20}$$

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 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 relativistic versions of collapse dynamics.

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

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) Accounting for 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".

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 the ones considered here.

THANKS