Quantum Black Holes: An LQG Perspective

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Will summarize what I think is a general consensus in LQG that has emerged from work of many, many researchers. My remarks are taken largely from the review arXiv:2001.08833

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Preamble

Two main ingredients underlying a broad consensus within LQG:

i) Singularity resolution: In the resulting, larger space-time, the quantum state can evolve through the Planck regime all the way to $\mathcal{I}^+$. However, within LQG the details of how to describe Planck scale physics in the BH context are still work in progress (Gambini, Olmedo, Pullin; Bianchi, Christodoulou, D'Ambrosio, Haggard, Rovelli; AA, Olmedo, Ori, Singh; Bodendorfer, Mele, Münch; Perez; Wilson-Ewing; $\cdots$)

ii) Relevant notion of Horizon: No event horizons. What forms and evaporates are dynamical horizons which are time-like during evaporation. A lot of confusion can arise because of the explicit or implicit assumption that there is an absolute event horizon.

As a result, black hole evaporation can be unitary without having to invoke "quantum xexox machines, fast scramblers, firewalls" etc, or worry about "quantum monogamy".

As in Ahmed's talk, I will not discuss the full quantum regime. But already there is an apparent tension in the semi-classical regime and I will summarize the LQG viewpoint on this tension. So: Plan of the talk:

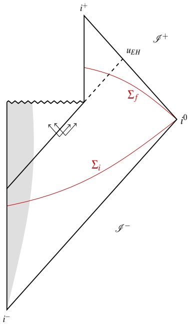
1. LQG Viewpoint 2. Semi-classical Regime

Recall: Hawking's Argument

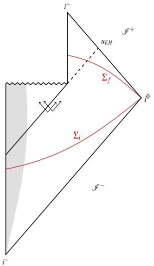
- External field approximation: Hawking Effect In quantum field theory on a black hole background space-time. Approximations: (i) Space-time treated classically: represents a star collapsing to form a black hole. (ii) Test quantum fields; ignore back reaction of the quantum field on the geometry; (iii) Matter field which collapses is classical, distinct from the test quantum field considered. Then: If the incoming state on $\mathcal{I}^-$ is the vacuum, the outgoing state at $\mathcal{I}^+$ is a mixed state which, at late times, is thermal.

- Inclusion of back reaction: Addressing (ii)

No detailed calculation in 4-d even today. General expectation based on physically motivated heuristics led Hawking to propose the space-time diagram shown on the right. Black hole loses mass and therefore the horizon shrinks to zero. Because the future boundary of space-time again includes a singularity, again information is lost. State at $\mathcal{I}^-$ determines the state at $\mathcal{I}^+$ but not vice versa. (Hawking changed is mind a few years ago, but) surprisingly the original diagram still heavily used in many arguments: It is assumed that correlations must be restored before the last ray $u = u_{EH}$.



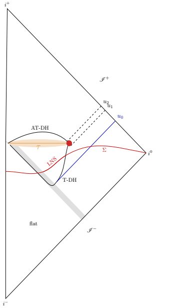
Singularity Resolution



Suppose the singularity is resolved in a quantum gravity theory, as in many current proposals including Hawking's Take 2, (Hawking, Pope, Strominger). In Loop Quantum Gravity this expectation is met in a variety of cosmological models and various directions that are being pursued for the Schwarzschild black hole lead to singularity resolution.

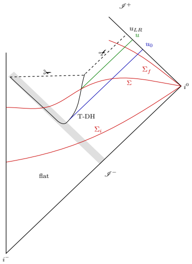
Let us consider a closed system in which we only have a scalar field collapse (rather than an 'external' star). What forms classically and evaporates quantum mechanically is a Dynamical Horizon (DH): World tube of marginally trapped 2-spheres that is space-like and growing during collapse and time-like and shrinking during evaporation. DH is not a 1-way membrane like an EH. The state on any Cauchy surface Σ is pure: outgoing modes outside the DH are correlated with their ingoing partners and the infalling quantum state.

Expectation: A neighborhood of what was a singularity classically will be replaced by a genuinely quantum region. Correlations between modes that escaped to $\mathcal{I}^+$ early on, and those that were trapped 'inside the DH' in the semi-classical regime could be restored at $\mathcal{I}^+$, because the 'trapped modes' could pass through the quantum region and reach $\mathcal{I}^+$ (AA & Bojowald). They don't have to be restored before "the last ray" $u = u_1$.



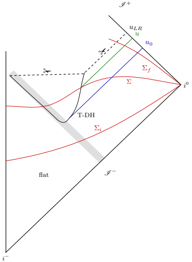
Semi-classical Regime

Consider the phase in which a $M_\odot$ initial black hole shrinks to Lunar mass $\sim 10^{-7}\, M_\odot$ (time u in the figure.). The process should be well-described by semi-classical gravity. Process takes some 10^{64} years and so a large number $\mathcal{N} \sim 10^{75}$ modes escape to infinity. The total quantum state on Σ is pure because the outgoing modes are correlated the ingoing partners and the infalling quantum state.



Apparent 'information' Paradox: But the lunar mass BH has radius of ~ 0.1mm! How can such a small ball hold so many modes? Heuristically, "even if they all have the maximum wavelength of ~ 0.1 mm, $\mathcal{N}$ modes would have a mass $\sim 10^{22}$ times the lunar mass!" Put differently, the "horizon area should account for the total entropy of everything contained inside the horizon, and this is way too small compared to the entropy associated with radiation at $\mathcal{I}^+$ emitted until this time". This suggests to many that "significant purification must have occurred at $\mathcal{I}^+$ restoring correlations, well before we reach lunar mass". A general belief enshrined in the Page curve: restoration should begin at Page time when $M_\odot$ shrinks to $\frac{1}{2} M_\odot$. This implies that something must go wrong with the usual space-time, semi-classical picture even while the BH has a macroscopic mass.

Semi-classical Regime:contd.



Resolution: When one solves the semi-classical equations with physically motivated approximations in the region enclosed by the Dynamical Horizon, one finds that the space-like surfaces Σ develop astronomically long necks over the 10^{64} years needed for the DH to shrink from ~ 3 kms to ~ 0.1 mm, stretching $\sim\ 10^{62}\ -\ 10^{64}$ lyrs! (for Σ given by $r = \mathrm{const}$ or Kretch$=$ const. respectively). Their 'mouth' at the horizon is a sphere only of 0.1mm radius!

So, in the slow dynamical evolution in the semi-classical phase, the infalling modes get stretched (as during inflation, which however, is extremely quick; here the stretching is much tamer by comparison!) and become infrared. One can easily accommodate $\mathcal{N}$ of them inside the Dynamical Horizon! Once we replace EH with DH, and study the back reaction on space-time geometry inside the DH the tension with information loss in the semi-classical regime simply disappears. There is no reason for semi-classical arguments not to be valid for lunar-mass objects!

But then don't we have 'long lived remnants' with lot of internal states? Yes, but they are astronomically long objects, not 'balls of ~ 0.1 mm radius'–let alone balls of elementary particle size. They need 10^{64} years to grow; they cannot be instantaneously created in particle accelerators or car collisions (see, e.g., Ori (arXiv:1208.6480)) .

Summary

- To many of us in LQG, it seems that several standard difficulties disappear if one recognizes that:

1. As in classical GR, while event horizons (EHs) are very useful idealized notions, they are not very useful in the analysis of actual physical processes. (For example, they can form and grow in flat regions of space-time!) Use of them as absolute boundaries for the entire evaporation process causes unnecessary confusion. What forms in a collapse and evaporates due to quantum processes are dynamical horizons (AA, Krishnan).

2. There is no reason to abandon semi-classical gravity well away from the Planck regime. One has to carefully study the geometry inside the DH (Christodoulou, De Lorenzo, Rovelli; AA & Ori, $\cdots$). A very interesting avenue is to understand the relation between this semi-classical description and the recent path-integral analyses.

- In all LQG investigations (Gambini, Olmedo, Pullin; Bianchi, Christodoulou, D'Ambrosio, Haggard, Rovelli; AA, Olmedo, Ori, Singh; Bodendorfer, Mele, Münch; Perez; $\cdots$) the singularity is resolved and replaced by a transition surface that separates a trapped region from an anti-trapped region. However none of these investigations is complete & there is no unanimity on how exactly correlations will be restored. (One recent rigorous result may help: Surprisingly, one can consistently evolve test quantum fields even across singularities, and $\langle \hat{T}_{ab} \rangle$ continues to be a well-defined distribution. Provides useful technical tools to unravel the nature of the quantum space-time satisfying quantum Einstein's equations across what was a singularity classically.)