The Issue of information loss: Current status

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Goal: to provide a global view of the current status from an LQG perspective.
Discussions with Bianchi, Campiglia, Laddha and Ori
played a major role in the recent developments.

ILQG seminar of February 23rd, 2015

Organization

Two main parts:

1) Broad-brush summary of the main points in the long (and sometimes confusing) history of the subject:

- Hawking effect;
- Inclusion of back reaction;
- Issue of 'purification' and Page time;
- AdS/CFT and unitarity;
- Consequences of standard assumptions including firewalls;

2) Present an update on the LQG viewpoint

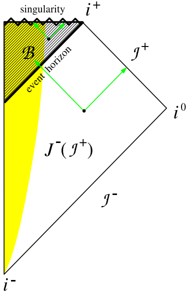
- Implications of singularity resolution;
- Formation and evaporation of dynamical horizons;
- Space-time geometry 'inside the DH' in the dynamical semi-classical theory;
- Non-trivial vacua at $\mathcal{I}^+$ and 'soft hair' of Hawking, Perry, Strominger
- Purification versus unitarity.

Because of the time constraint, will not be able to cover complementary ideas of Barrau, Haggrd, Rovelli, Vidotto, ... But they were discussed earlier in ILQG.

1. Information Loss: Main Ideas

- Information loss in the classical gravitational collapse:

While $\mathcal{I}^-$ is a good 'initial data surface', $\mathcal{I}^+$ is not. Part of any incoming field from $\mathcal{I}^-$ falls across the horizon into the singularity and is thus lost for observers in the asymptotic region.
Second, independent point: BH uniqueness theorems.



- Quantum theory: The Hawking Effect

Analysis used 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. Thus, information is lost in also in quantum theory in this approximation.

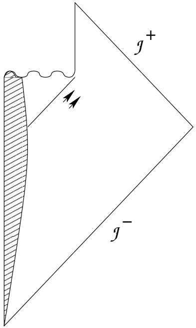
- Again, not surprising because singularity in the future serves as a sink of information.

Inclusion of back reaction

- No detailed calculation in 4-d even today because:

(i) Even in the spherically symmetric case, is difficult to compute $\langle \hat{T}_{ab} \rangle$ on a time-varying geometry; and
(ii) even more difficult to solve the semi-classical Einstein equations.

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 and the black hole disappears.



- However, the future boundary of space-time again includes a singularity,. Therefore, information is lost also in this approximation. State at $\mathcal{I}^-$ determines the state at $\mathcal{I}^+$ but not vice versa. This led Hawking to advocate a generalization of quantum mechanics in which dynamics is not unitary and pure states can evolve to mixed states. S-matrix replaced by a \$-matrix.

- Scenario preferred by some relativists. Ex: Penrose uses this information loss idea in the entropy considerations of his cyclic conformal cosmology.

Possibility of Purification

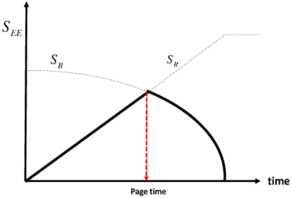
- However, some relativists did pursue the idea that the state on $\mathcal{I}^+$ only appears to be thermal for a long time but is in fact pure state: expectation values of all obsevables with support on an 'intermediate' region of $\mathcal{I}^+$ in this pure state are well approximated by the expectations in a thermal state.

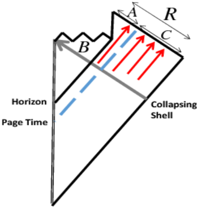
- Analogy with lighting a piece of coal and letting it burn out completely. At the instant we light the charcoal, there is no radiation and the coal is in a highly excited state. Then for a long time the quantum state of the coal is correlated with that of outgoing radiation. At the end, the ashes cool down to their ground state. Since this state is unique, and since the evolution is unitary, the quantum electromagnetic field is also in a pure state. For photons, the correlations that seemed to be lost early-on are restored at late times by long wave length modes.

- Don Page pursued this analogy to develop a scenario for how purity can be restored in the black hole evaporation process. Again, at the end of evaporation we have Minkowski space-time 'so the quantum state of geometry is unique' whence the radiation at $\mathcal{I}^+$ should be in a pure state if the process is unitary. How is purity achieved at $\mathcal{I}^+$? Proposed plots are on the next slide.

Page curve and Page time

- Left figure. Dashed lines: evolution of the BH entropy and entropy in thermal radiation. Solid line: The Page curve depicting how entanglement entropy must behave if the final state at $\mathcal{I}^+$ is pure. Page-time: when the solid curve turns around.





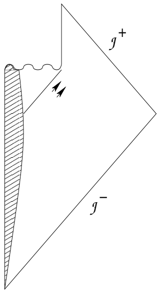
- Ideas made precise through the notion of entanglement entropy (Bianchi, de Lorenzo, Smerlak, ...) Careful and detailed considerations show that if the Page curve turns over when the BH still has macroscopic (say 50% of the original) mass, *'purification'* takes time of the order M_o^3 (the same as the Hawking evaporation time). Seems to be generally preferred because if it turns over when the BH is microscopic, purification requires time of the order M_o^4 –much longer!

- Counter-intuitive consequences of Page Purification: (i) An 'old' black hole of $1\,M_\odot$ behaves very differently from a 'young' BH of $1\,M_\odot$! (ii) $\Delta(S_{\mathcal{I}^+} + S_{BH}) < 0$ between any times beyond the page time even though the BH is large!

AdS/CFT and Firewalls

- In all these considerations, it is explicitly or implicitly assumed that:

1. The space-time diagram is the one given by Hawking, with a future singularity;
2. The space-time has an event horizon, which serves as an absolute 1-way membrane.



- On the other hand, in the string theory community, there is also a strong belief in the AdS/CFT conjecture. So far, attempts to decode what happens in the black hole region 'inside' the event horizon from the CFT side have not succeeded. Still, because the conjecture has had so many successes in other areas, they invoke the unitarity of the boundary CFT to conclude that the S-matrix of the BH space-time must also be unitary. This implies that the outgoing state is pure.

- By and large, in the GR community, unitarity in this space-time seems absurd. And indeed the string theory community finds a contradiction if they try to enforce it: The 'quantum monogamy'. So, they conclude that one of the assumptions is incorrect and favor the possibility that semi-classical physics will fail to hold at the horizon already when the BH is macroscopic; there must be a firewall.

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2. Singularity Resolution

- Let us summarize the main points so far:

(i) If $\mathcal{I}^+$ is not the entire future boundary of space-time after the back reaction is taken into account, we are led to Hawking's \$-matrix scenario in which pure states can evolve to mixed states.

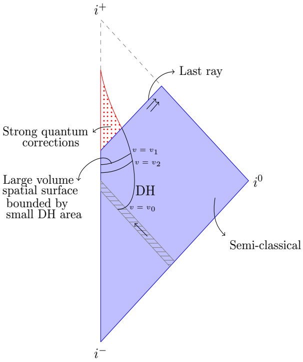
(ii) Even if $\mathcal{I}^+$ is the entire future boundary, we encounter puzzling features in the semi-classical regime if the Page curve turns over when the BH is macroscopic.

- LQG Viewpoint: It is natural to expect that in a viable quantum gravity theory, singularities of classical general relativity will be resolved. In Loop Quantum Gravity (LQG), this expectation is met in a variety of cosmological models (Bojowald, AA, Pawlowski, Singh, Wilson-Ewing,....), and also for the Schwarzschild black hole (Gambini, Olmedo, Pullin,..). Although gravitational collapse is yet to be treated in detail in LQG, accumulated results strongly suggest that the singularity will be resolved.

- Consequence: Situation changes vis a vis (i) and (ii) above. Quantum space-time –and its $\mathcal{I}^+$– is quite a bit larger than the classical space-times of GR. So there is 'new room' for restoration of correlations that seemed to be lost. This opens the possibility that the Page curve turns over when the black hole is microscopic, avoiding major surprises in the semi-classical regime.

Evaporation process in the enlarged, 'quantum' space-time

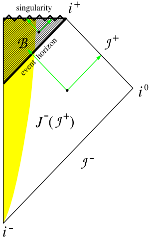
- General Expectation: (AA & Bojowald) A neighborhood of the singularity will be replaced by a quantum region (shown in red) in which quantum corrections would be large, as in LQC. But the region would be localized since LQG effects die rapidly once the curvature falls below $\sim 10^{-6}\ell_{\rm Pl}^{-2}$. Also, as in LQC, there may be a quantum corrected, dressed, effective metric in this region that adequately describe the propagation of quantum radiation in this region. Then quantum space-time would again be asymptotically flat. $\mathcal{I}^+$ will be the complete future boundary. The 'raison d'être' for information loss is removed.



- There is no event horizon for the dressed effective metric. What forms and evaporates is a dynamical horizon DH. The space-time region shown in blue is well-described by semi-classical gravity. Purification occurs on $\mathcal{I}^+$ beyond this region to the future of the last ray. Thus, the implicit assumption in the firewall scenario is violated.

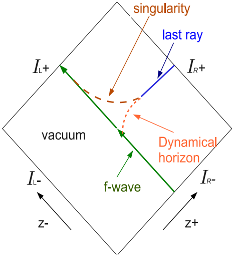
- I will now describe important features of this space-time.

Why event horizons are irrelevant



- Recall basic definitions from classical GR:

(M, g_{ab}) asymptotically flat space-time with complete $\mathcal{I}^+$.
Black Hole region: $\mathcal{B} := M \quad J^-(\mathcal{I}^+)$
Event Horizon $E :=$ Future boundary of $J^-(\mathcal{I}^+)$.



Limitations of BH Event Horizons

- Teleology! An event horizon may be forming in this room in anticipation of a gravitational collapse in the center of our galaxy in a billion years from now!

- Sketch: 2-d CGHS black hole. Detailed calculation: In semi-classical space-time the singularity persists but is softened (metric C^0). We have the last ray. This is not an event horizon because $\mathcal{I}^+$ to its past is not complete.

- Dynamical horizons DH are defined (quasi-)locally. No teleology. Change of area directly related to energy flux across DH. Studied in detail in CGHS.

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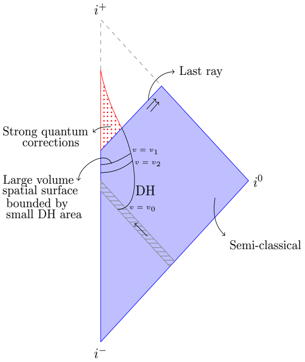

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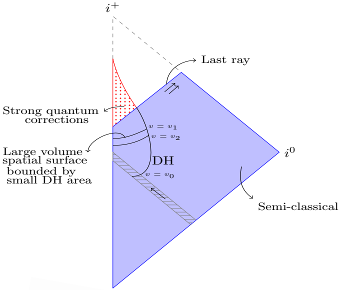
Quandary: So little energy but need so many states!

• First reaction: Since DH is time-like, 'information' can come out of it and purity could be largely restored already in the semi-classical region. No so because there is very little time between the end of the collapse and start of the quantum region along the vertical line, and hence on $\mathcal{I}^+$.



• So purification has to happen after the DH has shrunk to a microscopic radius of, say, $10^3 \ell_{\rm Pl}$. So the mass 'inside' the dynamical horizon is only $m_{\rm DH} \lesssim 10^3 m_{\rm Pl}$. But since the Hawking radiation has been thermal for a long time ($t_{\rm Haw} \sim M^3 \sim 10^{55}$ Gy for a solar mass BH!), purification at $\mathcal{I}^+$ requires a HUGE number of states 'inside' the DH when its area has shrunk to $10^3 \ell_{\rm Pl}$. How is this possible?

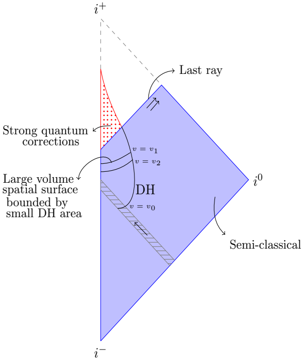
• Obvious possibility: Wheeler's bags of gold! Space-like 3-surfaces 'inside the DH' with large volume and tiny 'throats'. But is this realized in the semi-classical space-time on surfaces such as $v = v_1$ and $v = v_2$ with small throats?

Semi-classical analysis

• We will consider a BH formed by a Gravitational collapse with $M_o = 1$ solar mass and focus on the semi-classical space-time to the future of the collapse. We make two very plausible assumptions:
(1)the metric has the Vaidya form:

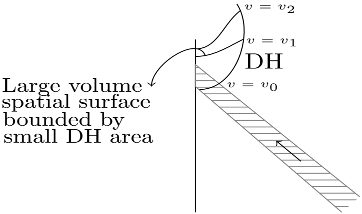
$$dS^2 = \frac{2Gm(v)}{r}dv^2 + 2dvdr + r^2 d\omega^2 \text{ where,}$$

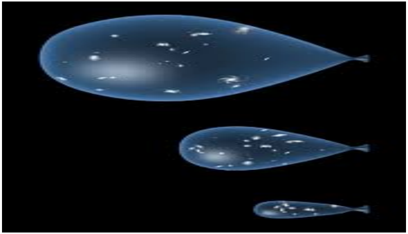
(2) $m(v)$ satisfies the standard Hawking equation $\frac{dm(v)}{dv} = \frac{\hbar}{m^2 G^2}$, (which leads to the life time $\sim M_o^3$). (2-d versions of) both assumptions are satisfied in the CGHS semi-classical solution.



• Consider space-like 3-surfaces Σ inside the 'DH' defined geometrically by $r =$ const. Let us focus on 3 of these surfaces: (Because it is busy, the figure shows only 2.)
(i) Black hole has shrunk to 1/10th of its original size. So, at the DH boundary of Σ_1 the mass is 1/10th the solar mass, 2×10^{31}gm; so $r_{\rm DH} = 300$m
(ii) At the DH boundary of Σ_2 the mass is that of that of the moon 7×10^{25}gm, so $r_{\rm DH} = 1$mm
(iii) At the DH boundary of Σ_3 the mass is $5 \times 10^4 m_{\rm Pl}$, so $r_{\rm DH} = 10^{-3}\ell_{\rm Pl}$

'Bags of gold' do exist





Large volume 3-Surfaces 'inside' the DH

- For these three times in the semi-classical evaporation phase, we have:
(i) 1/10th solar mass: $r = 300$m; proper length of the cylinder $\ell = 10^{50}$ ly!
(ii) Lunar Mass: $r = 1$mm; $\ell = 10^{55}$ ly!
(iii) Mass $= 2 \times 10^3 m_{\rm Pl}$ $\ell = 10^{79}$ ly!!

Ori and I also considered another family of 3-surfaces on which Kretchmann scalar const. (In the Kruskal space-time this is the same family as $r =$ const but not in the dynamical semi-classical space-time.) Now r changes along the 3-surface Σ: $r_{\rm max}/r_{\rm min} = 4.7$ for case (i); $= 250$ for case (ii) and $= 2 \times 10^{10}$ for case (iii). For this family of surfaces Σ, the 'length of the cylinders' is again astronomically large by the time one arrives at (iii). But because MATHEMATICA refused to perform the required integral, we have only crude estimates.

Infrared issues: Soft radiation at $\mathcal{I}^+$

- Summary of part II so far: Because of the singularity resolution, there is no event horizon. Purification can start in ernest only to the future of the semi-classical space-time. This is plausible because the geometry in the semi-classical region is such that it easily accommodates extremely long wave modes. The number of these modes (or, 'information content') can be very large even though the DH mass is tiny. Thus, the horizon mass or size is not a measure of the number of states 'inside' the DH for an evaporating BH!

- These modes leak out of the boundary of the quantum region but move towards $\mathcal{I}^+$ very slowly. Considerations at $\mathcal{I}^+$ (e.g. of Bianchi, de Lorenzo and Smerlak) show that 'purification time scale' at $\mathcal{I}^+$ is likely to be extremely large $\sim M_o^4$. Recall the analogy with the burning of a lump of coal.

- We do not have a remnant in the standard particle physics effective field theory sense because, although it lives very long, it is spread over astronomical length scales. When it leaks out, the wave length is further red shifted and becomes hugely larger. We do not see how the arguments of 'copious production of elementary particle type remnants in car accidents' can apply to these soft/infrared configurations.

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Infrared sectors and Purity at $\mathcal{I}^+$

• Late time infrared sectors also feature in the recent proposal by Hawking, Perry and Strominger (HPS). Will make a small detour to explain my understanding of this point. Seems to be similar to the LQG viewpoint I have explained so far.

• Main point: at late times we have no radiation at $\mathcal{I}^+$. State normally assumed to be the Fock vacuum (i.e., if we evaluate it on late time observables, answer is the same as that in the Fock vacuum). But because of infrared problems, the quantum vacuum is in fact degenerate, $|Q(\theta,\phi)\rangle$, labelled by a complex functions on a S^2. (Explained on the next slide.)

• External field approximation: incoming state $|0_{\rm in}\rangle$ on $\mathcal{I}^-$. Outgoing state $|\Psi_{\rm out}\rangle = \sum_{i,j} A_{ij} |i\rangle_H \otimes |j\rangle_{\mathcal{I}^+}$. Density matrix $\rho|_{\mathcal{I}^+}$ arises on tracing over $|i\rangle_H$.

HPS Proposal for restoration of purity (in semi-classical gravity (?)/QG (??)): Incoming state $|\Psi_{\rm in}\rangle$; Outgoing state $|\Psi_{\rm out}\rangle = \sum_{i,j} B_{ij}\, |Q_i(\theta,\phi)\rangle_{\mathcal{I}^+} \otimes |j\rangle_{\mathcal{I}^+}$ on $\mathcal{I}^+$ is entangled. Density matrix $\rho|_{\mathcal{I}^+}$ arises on tracing over the 'vacuum modes'.

Had there been no vacuum degeneracy, purity of $|\Psi_{\rm out}\rangle$ would not be possible if the modes $|j\rangle_{\mathcal{I}^+}$ are due to Hawking radiation.

Origin of the inequivalent soft vacua

- HPS have based their analysis on the interplay between geometry of $\mathcal{I}^+$ and Ward identities (Weinberg's soft photon/graviton theorems) recently discovered by Strominger et al. (See also papers by Campiglia and Laddha.) But these sectors were derived in the GR literature in the 1980s using the algebraic QFT framework. I will now explain those results. (Details can be found in references given on the next slide.)

- Consider Maxwell fields F_{ab} in Minkowski space-time. Consider the shift automorphism Λ on the algebra of field operators: $\Lambda(\hat{F}_{ab}) = \hat{F}_{ab} + \mathring{F}_{ab}\hat{1}$ (where $\mathring{F}_{ab}$ is a classical solution). Λ is unitarily implemented on the Fock rep if $\mathring{F}_{ab}$ has finite 1-particle norm and then $U_\Lambda|0\rangle = |C_{\mathring{F}}\rangle$, the coherent state peaked at $\mathring{F}_{ab}$.

- But because of infrared issues, there are perfectly decent classical solutions $\mathring{F}_{ab}$ that naturally arise in the classical theory that do not have a finite Fock norm. Then we obtain a rep of the CCR which is unitarily inequivalent to the Fock representation.

- The issue has a transparent description at $\mathcal{I}^+$. F_{ab} is completely determined by its data at $\mathcal{I}^+$: $\mathcal{E}_a = F_{\underleftarrow{ab}}n^b$. One finds:

$$\|F\|^2 < \infty \quad \text{iff} \quad q_a(\theta,\phi) = \int_{-\infty}^{\infty} du\, \mathcal{E}_a(u,\theta,\phi) = 0.$$

Or, in the Newman-Penrose (NP) language, $Q(\theta,\phi) = \int_{-\infty}^{\infty} du\; \Phi_2^0(u,\theta,\phi) = 0.$

Therefore, the infrared non-Fock sectors are labelled by $Q(\theta,\phi)$. Physically, this is essentially the difference between electric and magnetic 'charge aspects' at i^+ and i^-.

Soft vacua for the non-linear gravitational field

- The asymptotic quantization framework of the 1980s provides the Hilbert spaces of in and out states at $\mathcal{I}^{\pm}$. As in the Maxwell theory we have non-Fock representations labelled by the charge: $Q(\theta, \phi) = \int_{-\infty}^{\infty} N(u, \theta, \phi)\, du$ or, in the NP notation, $Q(\theta, \phi) = \int_{-\infty}^{\infty} \dot{\sigma}(u, \theta, \phi)\, du = [\sigma]_{u=-\infty}^{u=\infty} (\theta, \phi)$. Now the vacuum degeneracy is intertwined with the enlargement of the Poincaré group to the BMS group.

- These ideas were spelled out in the 1980s:

Radiative modes and Classical Vacua:

A. Ashtekar, Radiative degrees of freedom of the gravitational field in exact general relativity, J. Math. Phys. 22, 2885-2895 (1981).
A. Ashtekar and M. Streubel, Symplectic geometry of radiative modes and conserved quantities at null infinity, Proc. R. Soc. (London) A376, 585-607 (1981).
A. Ashtekar and A. Magnon, On the symplectic structure of general relativity, Comm.Math. Phys. 86, 55-68 (1982).

Quantization:

A. Ashtekar, Asymptotic quantization of the gravitational field, Phys. Rev. Lett. 46, 573-577 (1981);
A. Ashtekar, Quantization of radiative modes of the gravitational field, In: Quantum Gravity 2; Edited by C. J. Isham, R. Penrose, and D. W. Sciama (Oxford University Press, Oxford, 1981).

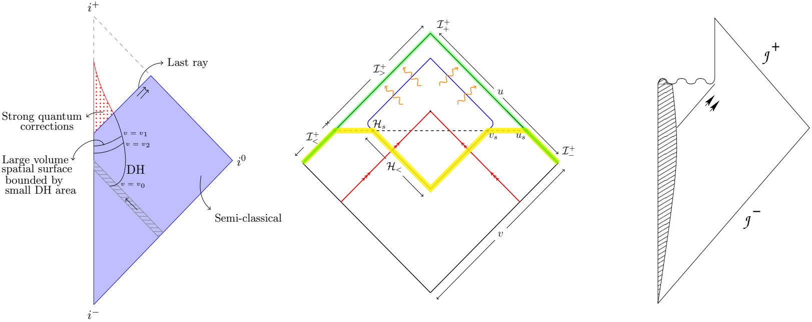
Summaries:

Detailed summary: A. Ashtekar, Asymptotic Quantization (Bibliopolis, Naples (1987));

Main ideas: A. Ashtekar: Geometry and Physics of Null infinity, in the Bieri-Yau volume celebrating the GR Jubilee, arXiv: arXiv:1409.3816

Comparing LQG scenario with the HPS proposal

Figs: 1. LQG paradigm; 2. HPS, and 3. The original Hawking Proposal



• Similarities: Note that the middle (HPS) Penrose diagram is similar to the first on the left (LQG) (and very different from the one on the right (earlier Hawking's proposal)). No singularity. No firewall. Seemingly thermal modes that reach $\mathcal{I}^+$ at 'intermediate times' are correlated with the late time infrared/soft state.

• Differences: But the 'horizons' in HPS seem rather mysterious since they are neither event horizons nor dynamical. Apparent differences in the notion of 'horizon hair'. They call the diagram 'semi-classical space-time' but because there is no singularity, perhaps they mean what we call 'effective, dressed' space-time.

Purification versus Unitarity

- Purification refers to rendering the final state on $\mathcal{I}^+$ pure. Unitarity is stronger. It implies that the map from the asymptotic Hilbert space at $\mathcal{I}^-$ to $\mathcal{I}^+$ is 1-1 and onto.

- suppose I make a BH by throwing in TV sets and you make it by throwing in books so that the classical BH has mass M and spin zero. The Hawking radiation will look the same at $\mathcal{I}^+$ because it is determined by M. Therefore, naively, the purified states at $\mathcal{I}^+$ should also look the same. But then dynamics would not be unitary!

- From our dynamical perspective, while in the classical theory the two BHs are spherical and have the same mass, the two DHs are quite different at first: their invariantly defined multipoles (AA, Campiglia, Shah) have distinct evolution in the dynamical phase. In the classical theory, these differences are registered at $\mathcal{I}^+$ because there is a tight correlation between what happens to the DH geometry and radiation at $\mathcal{I}^+$ (Jaramillo, Rezzolla et al). This information on $\mathcal{I}^+$ is crucial for unitarity.

- This point is often overlooked because one ignores classical dynamics prior to the thermal Hawking radiation. But the quantum state at $\mathcal{I}^+$ will have this information from the earlier epoch, helping us to distinguish between the two ways the BH was formed, thereby playing a key role in ensuring unitarity.

3. Summary

• Thanks to advances over the past two years (Bianchi, de Lorenzo, Smerlak; Gambini, Olmedo, Pullin; Ori, ...) we have significantly refined our understanding of the salient features of the quantum dynamics of BH evaporation compared to the 2004 paradigm (AA, Bojowald) and the detailed work on CGHS BHs in 2008-10 (AA, Pretorius, Ramazanoglu, Taveras, Varadarajan).

• The general scenario is that purification occurs after the semi-classical epoch. This violates a key (but often implicit) assumption in the firewall scenario. We have no solid reason to cast doubt on physics of semi-classical gravity during the phase when the BH is macroscopic.

• The information recovery requires very soft (i.e., infrared) modes but the semi-classical geometry 'behind the DH' has astronomically long necks to accommodate them. The importance of these soft modes opens a door for exchanging LQG and HPS type ideas, although so far the detailed relation is far from being clear.

Open Issues

Many important issues remain: Just a few examples.

$\star$ Need a much better control on the semi-classical calculations beyond 2-d models. Systematic 4-d calculation of $\langle \hat{T}_{ab} \rangle$ has begun. Will need strong collaboration with numerical relativists for solving the semi-classical equations.

$\star$ How exactly do the soft modes lead to a restoration of correlations, i.e., purification? We can write down pure states at $\mathcal{I}^+$ that look approximately thermal at the 'intermediate' times. But don't have any real control or systematic understanding of the bulk geometry they come from!

$\star$ How would purification work in the 'Fireworks' type of scenario? For a solar mass BH, $M_o^2 = 1.3 \times 10^{17}$ Gy. So issue of purification still non-trivial!

$\star$ Quantum dynamics! Will have to better understand the quantum region. Is there a useful dressed effective metric there? If not, does the small throat persist or does it pinch-off (as in water drops). The pinching-off would yield a baby universe! Then, although there could still be 'global' unitarity, it would be lost from 'our' universe. But perhaps charge, energy-momentum and angular momentum wold still be conserved in our universe since the baby universe would be closed. Only full quantum gravity will settle issues like this.