Abstract: What is the ultimate fate of black holes? Since the discovery of Hawking evaporation process, the issue has been much discussed. Loop quantum gravity suggests that black hole could ultimately turn into white holes. In this talk, we investigate several possible mixed scenario where black holes first evaporate to a Planckian size before tunnelling to white holes. We build various spacetime models, taking Hawking backreaction into account, and we discuss some aspects of the expected phenomenology. Finally, we will draw the path for a full LQG amplitude computation that could lead to observational predictions.
Evaporating Black-to-White Hole

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soon in Class. Quantum Grav.
White hole

White holes are anti-trapped regions!

[Novikov '65]
[Ne’eman '65]
White hole

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[Novikov '65]
[Ne’eman '65]
White hole

White holes are anti-trapped regions!

[Novikov ‘65]
[Ne’eman ‘65]
White hole

White holes are anti-trapped regions!

White holes are attractive!

[Novikov '65]
[Ne'eman '65]

[Barcelo, '16]
[Szekeres '73]
Black-to-White hole scenario

Motivations:
- effective Lagrangian of the gravitational field at the one-loop level

[Frolov, Vilkovinski '79]
Black-to-White hole scenario

Also dubbed Fireworks, Planck stars...

[Haggard, Rovelli '14]
[Rovelli, Vidotto '14]
Black-to-White hole scenario

Also dubbed Fireworks, Planck stars...

A playground to apply full covariant loop quantum gravity.

Compute the lifetime of black holes!

Guess: \( \tau \sim m^2 \ll \tau_H \sim m^3 \)

Computation: \( \tau \sim me^{\alpha m^2} \)

[Christodoulou, D’Ambrosio ‘18]

Probability of transition: \( p \sim e^{-m^2} \)

[Bianchi et al. ‘18]
Hawking evaporation
Hawking evaporation

\[ \langle T_{uu} \rangle = \frac{h}{24\pi} \left[ -\frac{m}{r^3} - \frac{3m^2}{2r^4} + \frac{m}{r(u,v_0)^3} - \frac{3m^2}{2r(u,v_0)^4} \right] \]

\[ \langle T_{vv} \rangle = \frac{h}{24\pi} \left[ -\frac{m}{r^3} - \frac{3m^2}{2r^4} \right] \]

\[ \langle T_{uv} \rangle = -\frac{h}{24\pi} \left( 1 - \frac{2m}{r} \right) \frac{m}{r^3}. \]

[Davies, Filling, Unruh '76]
Hawking evaporation

\[ \langle T_{uu} \rangle = \frac{\hbar}{24\pi} \left[ -\frac{m}{r^3} + \frac{3m^2}{2r^4} + \frac{m}{r(u, v_0)^3} - \frac{3m^2}{2r(u, v_0)^4} \right] \]

\[ \langle T_{vv} \rangle = \frac{\hbar}{24\pi} \left[ -\frac{m}{r^3} + \frac{3m^2}{2r^4} \right] \]

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[Davies, Fulling, Unruh '76]

\[ \langle T_{\mu\nu} \rangle = \langle B|T_{\mu\nu}|B \rangle + \langle \text{in}|: T_{\mu\nu} :|\text{in} \rangle \]

Vacuum polarisation  Hawking quanta
Hawking evaporation

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Vacuum polarisation  Hawking quanta

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Hiscock model for black hole evaporation

Semi-classical Einstein equations:

\[ G_{\mu\nu}(g_{\mu\nu}) = \langle \psi | \hat{T}_{\mu\nu}(g_{\mu\nu}) | \psi \rangle \]

[Møller '62]

[Hiscock '81]
Hiscock model for black hole evaporation

Semi-classical Einstein equations:

\[ G_{\mu\nu}(g_{\mu\nu}) = \langle \psi | \hat{T}_{\mu\nu}(g_{\mu\nu}) | \psi \rangle \]

["Møller '62"]

\[ ds^2 = - \left( 1 - \frac{2\mu(u,v)}{r} \right) du dv + r^2 d\Omega^2 \]

["Hiscock '81"]
Model for black-to-white hole evaporation (I)

1. Mathematically well-defined Penrose diagram

Gluing conditions along boundaries.

\[
\begin{align*}
(I) & \quad ds^2 = -dudv + r^2d\Omega^2 \\
& \quad r = \frac{1}{2}(v - u) \\
(II) & \quad ds^2 = -\left(1 - \frac{2m}{r}\right)dudv + r^2d\Omega^2 \\
& \quad r = 2m \left(1 + W\left(e^{\frac{\sqrt{u^2 - 4m^2}}{4m}} - 1\right)\right) \\
(III) & \quad ds^2 = -\left(1 - \frac{2N(v)}{r}\right)dv^2 + 2dvdr + r^2d\Omega^2 \\
(IV) & \quad ds^2 = -\left(1 - \frac{2M(u)}{r}\right)du^2 - 2dudr + r^2d\Omega^2 \\
(V) & \quad ds^2 = -\left(1 - \frac{2m_1}{r}\right)dudv + r^2d\Omega^2 \\
& \quad r = 2m_1 \left(1 + W\left(e^{-\frac{\sqrt{u^2 - 4m_1^2}}{4m_1}} - 1\right)\right) \\
(VI_a) & \quad ds^2 = \left(1 - \frac{2m_1}{r}\right)dudv + r^2d\Omega^2 \\
& \quad r = 2m_1 \left(1 + W\left(-e^{-\frac{\sqrt{u^2 - 4m_1^2}}{4m_1}} - 1\right)\right) \\
(VI_b) & \quad ds^2 = -\left(1 - \frac{2N(v)}{r}\right)dv^2 + 2dvdr + r^2d\Omega \\
(VII) & \quad ds^2 = -\left(1 - \frac{2m_1}{r}\right)dudv + r^2d\Omega^2 \\
(VIII) & \quad ds^2 = -\left(1 - \frac{2\rho(u,v)}{r}\right)du^2 - 2dudr + r^2d\Omega \\
(IX) & \quad ds^2 = -dudv + r^2d\Omega^2 \\
& \quad r = \frac{1}{2}(v - u)
\end{align*}
\]
Model for black-to-white hole evaporation (I)

2. Crossing the singularity

[Synge '50]
Model for black-to-white hole evaporation (I)

3. What is happening when a Hawking quantum crosses the bouncing shell?

[Dray, t'Hooft '85]

\[(r_0 - 2m_1)(r_0 - 2m_2) = (r_0 - 2m_3)(r_0 - 2m_4)\]
Model for black-to-white hole evaporation (I)

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Model for black-to-white hole evaporation (I)

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**Theorem 1.** Under the above assumptions, \(\mu_{ij}\) is a decreasing function of \(i\) and an increasing function of \(j\). This implies notably that for all \(i, j\)

\[0 < \mu_{ij} < m_1.\]
Model for black-to-white hole evaporation (I)

4. Only positive energy is observed!
Model for black-to-white hole evaporation (I)

5. Violation of Einstein equations in a region of Planckian size.
Model for black-to-white hole evaporation (I)

6. Stable white hole
Model for black-to-white hole evaporation (I)

7. Long-lived remnant

[ Bianchi et al. '18]

Black hole lifetime: $m^3$

White hole lifetime: $m^4$
Model for black-to-white hole evaporation (I)

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[Bianchi et al. ‘18]

Black hole lifetime: \( m^3 \)

White hole lifetime: \( m^4 \)

Information loss paradox ‘90s:

1. Information is lost
2. Long-lived remnants

[Aharonov, Casher, Nussinov ‘87]

[Banks et al. ‘92]
Model for black-to-white hole evaporation (I)

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[Banks et al. ‘92]

Too small to encode BH entropy? Remnants have a huge volume!

$S_{BH} = \frac{A}{4l_P^2}$

Infinite production rate of Planck mass particles?
Model for black-to-white hole evaporation (I)

1. Well-defined Penrose diagram
2. Crossing over the singularity
3. Crossing over the bouncing shell
4. Positive energy at null infinity
5. Quantum region of planckian size
6. Stable white hole
7. Long-lived remnant
Model for black-to-white hole evaporation (II)

\[ \langle T_{uu} \rangle \sim -\frac{\hbar}{24\pi} \frac{m}{r^3} \]
\[ \langle T_{uv} \rangle \sim -\frac{\hbar^2}{24\pi} \frac{m}{r^3} \]
\[ \langle T_{uv} \rangle \sim -\frac{\hbar}{24\pi} \frac{m}{r^3} \]

[Bardeen '18]
Transition amplitude
Covariant Loop Quantum Gravity
in the General Boundary Formalism [Oeckl '08]
(in progress)
Transition amplitude

Covariant Loop Quantum Gravity

in the General Boundary Formalism [Oeckl '08]

(in progress)

\[ ds_1^2 = \beta(2 - \beta(1 - 2m/r))dr^2 + r^2d\Omega^2 \]
\[ ds^2 = dr^2 + r^2d\Omega^2 \]
\[ k_{ab} = \frac{m}{2r^3}dr^2 - \sqrt{2mr}d\Omega^2 \]
\[ k_{ab} = \frac{m^{3/2}(r(3 - \beta) + 2m\beta)}{\sqrt{r^2(r(2 - \beta) + 2m\beta)}}dr^2 - \frac{r(1 - \beta) + 2m\beta}{\sqrt{\beta(2 - (1 - 2m/r)\beta)}}d\Omega^2 \]

1. Describe the geometry of a boundary surface
2. Triangulate
3. Build the dual spin-network
4. Find a suitable spin-foam
5. Compute its amplitude
6. Deduce the transition rate
7. Compare to experiment
Transition amplitude

Covariant Loop Quantum Gravity

in the General Boundary Formalism [Oeckl ‘08]

(in progress)

\[ ds_4^2 = \beta(2 - \beta(1 - 2m/r))dr^2 + r^2 d\Omega^2 \]
\[ ds^2 = dr^2 + r^2 d\Omega^2 \]
\[ k_{ab} = \frac{m}{2\gamma^3}dr^2 - \sqrt{2mr}d\Omega^2 \]
\[ k_{ab} = \frac{m^3/2(r(3 - \beta) + 2m\beta)}{\sqrt{r^3(r(2 - \beta) + 2m\beta)}}dr^2 - \frac{r(1 - \beta) + 2m\beta}{\beta(2 - (1 - 2m/r)\beta)}d\Omega^2 \]

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\[ \mathcal{A}(\kappa, j, t) = \left( \prod_{j \in \mathcal{E}} (2j_f + 1) \right) \left( \prod_{c \in \mathcal{V}} (2c_i + 1) \right) \left( \prod_{v \in \mathcal{V}} A_v(j, t) \right) \]

\[ A_v(j, t) = \left( P_{SL_2(C)} Y_{\gamma} \Psi(\Gamma, j, t) \right) (1) \]
Conclusion

We get a consistent and mathematically well-defined semi-classical model of an evaporating black-to-white hole.

We are on our way to compute the transition rate from planckian black-to-white hole.
Thank you

"Evaporating Black-to-White Hole"
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