BLACK HOLE SINGULARITY RESOLUTION:

LESSONS FROM LQC

Alejandro Corichi

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WHAT CAN QUANTUM GRAVITY TELL US ABOUT BLACK HOLE SINGULARITIES?

- **Is there singularity resolution?**
- **How generic is that result?**
- **Is there a "classical spacetime" beyond the singularity?**
- **What is the causal structure of the resulting spacetime?**
- **Implications for the information loss issue?**

PLAN OF THIS TALK

- **Answer the simpler question:**
- **What can we learn from minusuperspace models?**
- **More concretely:**
- **What does loop quantum cosmology tell us?**

Work of many people, including Ashtekar, Bojowald, Bohmer, Campiglia, Cartin, AC, Chiou, Gambini, Khanna, Modesto, Pullin, Singh and Vandersloot.

1. SOME HISTORY

- **00' LQC is born (Bojowald)**
- **04' Modesto and Ashtekar & Bojowald quantize Schwarzschild interior.**
- **06' APS "improved quantization" for k=0 FLRW introduced.**
- **06' Vandersloot et al introduce 'improved' quantization**
- **04'-05' Some attempts at numerics (Khanna at al).**
- **15' new quantization based on original "μ_o" ideas (AC, Singh)**
- **15' Singh et al explore more generic Kantowski-Sachs**

Minisuperspace Approach

Idea: Consider the interior of Schwarzschild:

$$\mathrm{d}s^2 = -(2M/t - 1)^{-1}\mathrm{d}t^2 + (2M/t - 1)\mathrm{d}r^2 + r^2\mathrm{d}\Omega^2 \tag{1}$$

It is a homogeneous spacetime with homogeneous slices Σ of the form $\Sigma = S^2 \times \mathbb{R}$. Can we apply LQC techniques to solve the singularity? Yes/maybe

Ashtekar and Bojowald applied same techniques as in the "μ_o" quantization. Idea is to regularize curvature by a holonomy over a fixed, Planck scale plaquette.

Same problems as in LQC: 'physics' depends on a fiducial quantity L_0 that is arbitrary and unphysical.

Vandersloot et al defined a $\bar{\mu}$ version, correcting so that area of plaquette is "physical".

But still there are some problems, important problems: An artificial bounce at low curvature. The improved quantization is taylored to 'act' when extrinsic curvature blows-up. This happens near the horizon, where curvature may be as small as you want.

We do *not* recover Einstein's equations in the regime where we should.

There is a consistent quantization a la Ashtekar-Bojowald AC, Singh, (arXiv:1506.08015). **There is no dependence on fiducial quantities.**

The effective equations approach Einstein's equations near the horizon, as one expects.

One finds that the singularity is resolved, so the universe bounces into a new expanding region.

In the asymptotic future one again recovers the classical equations, so the system is in a Schwarzschild interior solution again. That region can be interpreted as the "near-horizon" interior region of a white hole.

Unexpected feature:

In the new quantization the 'white hole' has a mass:

$$M_{\mathbf{wh}} \approx M_{\mathbf{BH}}^3 \,.$$

What is the meaning of such relation? (IDK)

But a very asymmetric bounce scenario, unlike FLRW models. Need to update intuition.

The problem is that one is only looking at the interior of the black hole region, and one can not match with the exterior, within the LQC formalism (See Campiglia, Gambini and Pullin)

It is not clear what global non-singular spacetime picture will arise.

Good news is that one can hope that in the interior of "black holes", there will be no singularity.

But, if there is no singularity, is there a black hole?

Ashtekar-Bojowald "paradigm"

If there is no singularity but a "quantum region" the spacetime Penrose diagram could look like global Minkoswki, with a quantum region inside a trapped region. So, there *is* a trapped region and a horizon that looks from nearby like a black hole horizon, but with no black hole and no event horizon. Only one asymptotic region.

Strictly speaking, quantum gravity would make black holes disappear!

Paradigm supported by the 1+1 CGHS model (Ashtekar-Taveras-Varadarajan) via series of numerical studies (Pretorius). Partial solution for the 'Information loss problem': Even when there is no black hole, there is Hawking radiation emanating near the dynamical horizon. Information is eventually recovered.

What does LQC tell us?

We are neglecting any interaction with matter, i.e., Hawking radiation, shrinking horizon, etc. The model tells us that in the asymptotic past there is black hole type horizon and in the asymptotic future a WH type horizon.
Since both regions satisfy Einsteins equations, an extension of the spacetime outside the horizon necessarily means that one has *two* exterior Schwarzschild spacetimes, one of mass M_{bh} to the past and one of mass M_{wh} to the future.

There are *two* asymptotic regions connected by a quantum throat.

Is there problem with energy conservation? NO

Does this support AB paradigm? N/A

Same with "Planck Stars"!

SUMMARY

- **Black holes interior as a homogeneous cosmology.**
- **Can use some LQC techniques, but no "improved" quantization.**
- **Singularity is resolved**
- **quantum region yields new baby universe with a different BH mass.**
- **Not a useful model to support AB paradigm nor Planck stars.**

- **A lot of work needed**