Panel Discussion: Future Directions in LQG

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Ultimate Goal

The ultimate goal of any physical theory is to **describe nature**, or at least some aspect of nature.

For quantum gravity, this means understanding:

- the role of quantum mechanics in space-time physics,
- the microscopic structure of space-time,
- physics of the early universe,
- physics of black holes,
- ...

There are many important open problems, I will focus on those concerning applications to cosmology and black holes.

General Comments

Studying cosmology and black holes for:

- Contact with observations,
- Partial guidance for theory development.

Recent and ongoing work has been fruitful:

- Cosmology:
  - Loop quantum cosmology: background + perturbations,
  - Singularity resolution, bounce,
  - Contact with cosmic microwave background,
- Black Holes:
  - Black hole entropy,
  - Singularity resolution,

and more.

Here I will point out some directions for future research that I think are especially important and promising.

Next Steps: Relation between LQC and LQG

Loop quantum cosmology has been very successful. Its construction is motivated by loop quantum gravity, but it is not derived from LQG.

- How can we extract the cosmological sector of LQG? Does this give LQC (at least approximately)?
- Is it easier to construct cosmological states in a particular framework (canonical LQG, spin foams, group field theory)?
- In terms of spin-networks, do cosmological states in LQG correspond to graphs with many small-volume nodes with dynamical N, or a few large-volume nodes with dynamical V, or something in between? Is a different representation better?

Next Steps: Trans-Planckian Problem in Cosmology

In an expanding universe, the physical wavelength of Fourier modes of cosmological perturbations are red-shifted.

So long-wavelength modes today, satisfying $\lambda(t_{\mathrm{today}}) \gg \ell_{\mathrm{Pl}}$, had a shorter wavelength in the early universe.

Some would have initially been trans-Planckian: $\lambda(t_i) < \ell_{\mathrm{Pl}}$.

Do trans-Planckian modes exist?

- If yes, how are their dynamics modified by quantum gravity?
  - Is there no Planck-scale cutoff?
- If no, how are new modes created in an expanding universe?
  - What about unitarity?

Next Steps: Black Hole Collapse

The lifetime of a black hole is complex and not fully understood:

- Late stages: Hawking evaporation, information loss problem,
- Early stages: singularity formation/avoidance.

Can we track the evolution of a quantum black hole, from its formation to its eventual disappearance?

Key points:

- Include matter. (Is classical GR misleading for QG?)
- How is the singularity avoided? Is the space-time extended?
- Are young and old black holes different?
- Track information: where does it go, how is it transferred between geometry and matter at different times, is it lost?

Next Steps: Rotating Black Hole

The black holes that we have observed and know of in our universe are rotating (although not extremal).

To make contact with observations, it will be necessary to go beyond spherically symmetric black holes.

Wishlist:

- Quantum description of rotating black holes,
- Follow their dynamics through their entire lifetime,
- Address the information loss problem in detail,
- Effect of accretion,
- Quantum corrections to quasi-normal modes,
- Inspiral, merger, and ringdown of binary quantum black holes.

Thank you for your attention!