Loop Quantum Gravity: Future Directions

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Quantum Gravity

The goal of quantum gravity is to understand:

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

I will focus on cosmological and black hole space-times.

In studying these space-times, there are typically three main goals:

- Make contact with observations,
- Address shortcomings of (semi-)classical theory,
- Partial guidance for theory development.

Current Status

Recent and ongoing work in loop quantum gravity on these topics has been fruitful:

- Cosmology:
  - Loop quantum cosmology: background + perturbations,
  - Singularity resolution, bounce,
  - Contact with cosmic microwave background,
  - Relation between LQC and full loop quantum gravity,
- Black Holes:
  - Black hole entropy,
  - Singularity resolution,

and more.

Exciting progress! But many important open problems remain.

Future Directions: Cosmology (in progress)

Goal: extract cosmology (background + perturbations) from LQG.

- Promising work from the various perspectives of canonical LQG, spin foams, group field theory.
- Does the flatness (non-)problem suggest that cosmological boundary states should have many nodes?
- Challenges: graph-changing, connectivity, (non-)flatness, . . .

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GFT suggests a hydrodynamical approximation: large-scale geometric observables can be extracted from microstates.

- At what scale is the hydrodynamical approximation valid?
  $\rightarrow$ Emergence of continuum geometry.
- Is there an ultraviolet cutoff for cosmological perturbations?
  $\rightarrow$ Trans-Planckian Problem.

These questions can be asked more generally.

Future Directions: Trans-Planckian Problem

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

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

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Do trans-Planckian modes exist?

- If yes, how are their dynamics modified by quantum gravity?
  $\rightarrow$ Is there no ultraviolet cutoff?
- If no, how are new modes created in an expanding universe?
  $\rightarrow$ What about unitarity? An effective description seems to require an 'evolving Hilbert space'.

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- Early stages: singularity avoidance during collapse,
- Late stages: Hawking evaporation, information loss problem.

Goal: evolution of a quantum black hole, at all time scales.

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Some key points:

- General agreement: singularity resolution by bounce.
- Ambiguities: use input from full theory? (Electric shift. . .)
- Include matter, local degrees of freedom.
- Information loss problem—can information be recovered?
  Expectation: unitarity evolution, but this is vague.
  Can we be more precise? (Asymptotic symmetries. . .)

Ultimately: rotating black holes.

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Thank you for your attention!