Bridging Quantum Gravity and Quantum Information

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panel discussion with

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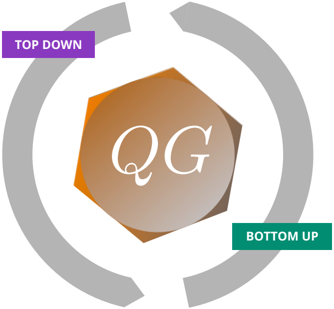
The chair’s three questions



- Top-down: What can quantum information do for quantum gravity?
- Bottom-up: How does QG alter the way we think about quantum information?
- What’s next?

Confluence of ideas and results here at FAU^2 on QG/QI [Chen, Kabel, Brukner, Kirklin, Bianchi, Rejzner, Ferrero, ...].

Quantum information for quantum gravity

Lesson from Eugenio Bianchi's talk

Quantum theory can give us shortcuts to classical physics.

Examples:

- $\mathrm{Tr}(U^\dagger \rho U) = \mathrm{Tr}(\rho U U^\dagger) = \mathrm{Tr}(\rho) = 1 \rightsquigarrow$ Liouville theorem.
- $\Delta P\, \Delta Q \geq \frac{1}{2}\langle [P, Q] \rangle \rightsquigarrow$ Gromov's non-squeezing theorem.
- $\hbar \neq 0 \rightsquigarrow$ justification for $S = k_{\mathrm{B}} \ln \Omega < \infty$,

  Gibb's factor.

  ...
- GR positive mass theorem $\rightsquigarrow$ ADM energy is square of auxiliary supergravity charges [Witten].

  Van Raamsdonk and collaborators strongly argued in the past along these lines as well to derive new such inequalities for classical GR from quantum information theory (mostly in the context of AdS/CFT).
- $S_{\mathrm{BH}} \sim A_{\mathrm{Kerr}} \rightsquigarrow$ population of BH parameters [Bianchi *et al.*].

Non-perturbative LQG/CFT-type quantisation of null congruences leads to an inequality for geometric data

$$\vartheta^2_{(\ell)} - 4(1+\gamma^2)\sigma_{(\ell)}\bar{\sigma}_{(\ell)} \geq 0.$$

Bondi mass loss formula connects it to gravitational wave luminosity

$$\boxed{\mathscr{L}_{\mathrm{B}}(u,\zeta,\bar{\zeta}) = \frac{4c^5}{G}\lim_{r\to\infty}\frac{\bar{\sigma}_{(\ell)}(u,r,\zeta,\bar{\zeta})\sigma_{(\ell)}(u,r,\zeta,\bar{\zeta})}{(\vartheta_{(\ell)}(u,r,\zeta,\bar{\zeta}))^2} \leq \frac{c^5}{G}\frac{1}{1+\gamma^2}.}$$

In the S-matrix approach, the $\mathcal{O}(r^{-1})$ term in $\vartheta_{(\ell)}$ is a commuting c-number. In the quasi-local quantisation of gravity, it becomes a q-number akin to LQG area operator.

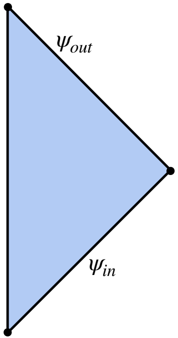
Argument relies on transition between positive to negative central charge in the boundary CFT/exclusion of negative norm states [ww (2025)].

How does QG alter the way we think about quantum information?

Local S-Matrix theory: Concepts and Foundations

Contrast LQG with standard perturbative approach,
$\hat{g}_{ab} = \eta_{ab}\mathbb{1}_{\mathscr{H}} + \sqrt{32\pi\hbar G/c^3}\,\hat{f}_{ab}$.

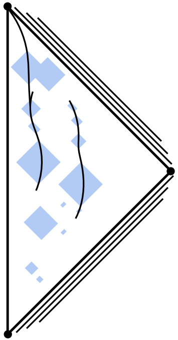
S-matrix approach problematic for conceptual and technical reasons.



- UV divergencies.
- IR divergencies.
- Effects of LQG area quantisation washed away: zeroth order is a commuting c-number, always continuous area spectrum in perturbative gravity. LQG makes here a very strong case for non-pertubative quantisation.

Contrast LQG with standard perturbative approach,
$\hat{g}_{ab} = \eta_{ab}\mathbb{1}_{\mathscr{H}} + \sqrt{32\pi\hbar G/c^3}\,\hat{f}_{ab}$.

S-matrix approach problematic for conceptual and technical reasons.

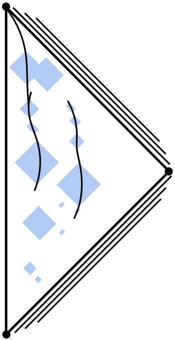


- Tension with Heisenberg relations. Infinitely many measurements with infinite precision required to know global asymptotic structure.
- Tension with observations. We live in a cosmological spacetime.
- S-matrix scattering represent transitions between different universes, no local observers have access to such ensembles.

  Less problematic in ordinary QFT: S-matrix appropriate at sufficiently large distance L from the interaction region. In gravity, $r \equiv L[g_{ab}, \phi]$.

Contrast LQG with standard perturbative approach,
$\hat{g}_{ab} = \eta_{ab}\mathbb{1}_{\mathscr{H}} + \sqrt{32\pi\hbar G/c^3}\,\hat{f}_{ab}$.

How a theory of quantum gravity can function:



Humean Mosaic [David Lewis].

- Local observers collect data inside the same universe.
- Born rule predicts best possible fit to observed correlations measured in ensembles of equally prepared experiments on the observer's worldline.
- Dynamics from local amplitudes (process matrices) for quantum transitions/processes in finite regions.

What is next?

Making sense of local amplitudes

$$
\begin{tikzcd}[column sep=huge, row sep=huge]
\textit{local amplitudes} \arrow[r, "\hbar \to 0"] \arrow[d, dashed, "r \to \infty"'] & \begin{array}{c}\textit{subregion}\\ \textit{phase space}\end{array} \arrow[d, "r \to \infty"] \\
\begin{array}{c}\textit{graviton}\\ \textit{S-matrix}\end{array} & \begin{array}{c}\mathscr{I}_{\pm}\textit{radiative}\\ \textit{phase space}\end{array} \arrow[l, "\begin{array}{c}\textit{asymptotic}\\ \textit{quantisation}\end{array}"']
\end{tikzcd}
$$