Loop Quantum Gravity

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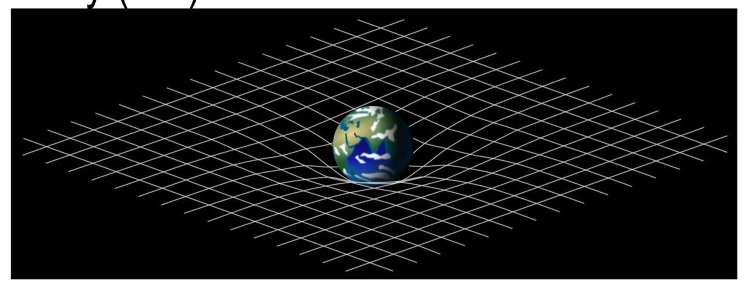
Introduction

The Problem:

Two major new theories in the 20th century:

1. Albert Einstein, Theory of General Relativity (GR)

- Explains the effects of gravity
- Predicts the bending of space and time
- Well tested, many true predictions like the precession of Mercury's orbit, time dilation relevant for the GPS, gravitational lensing and gravitational waves



2. Quantum Mechanics/Quantum Field Theory

- Explains behaviour of the world on extremely small scales (the size of atoms)
- Particles behave like waves and waves behave like particles
- Creation and annihilation of particles, also out of pure vacuum
- World is probabilistic

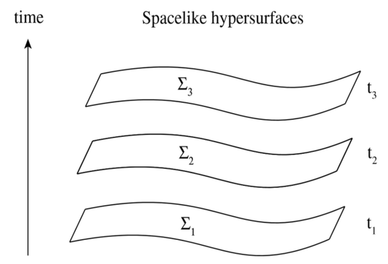
But: These theories don't fit together. Both explain their own domain (gravity/large scales or small scales) very well on their own

Physicists try to bring both theories together with different approaches to quantum gravity, e.g. **Loop Quantum Gravity**

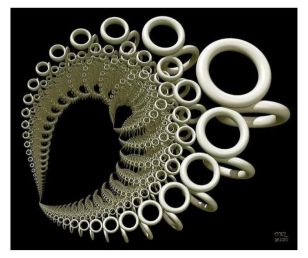
Methods

Loop Quantum Gravity (LQG) tries to fit General Relativity in the framework of Quantum Mechanics, i.e.:

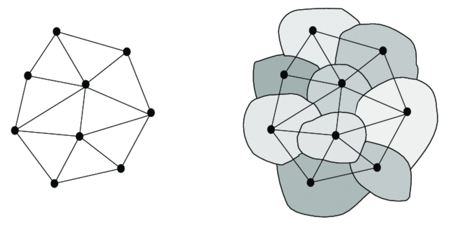
- "Break the symmetry and relativity of space and time to compute quantum mechanical time evolution like usually
- Extract metric just for space
- Use space-like weaves that can be curved like we see in GR
- From the quantum mechanical formalism we receive constraints that determine the shape of space over time



- New variables (triads) help us to bring our equations in a form we can work with more easily: $\delta_{ij} = q_{ab} e_i^c e_j^b$
- Quantize by holonomies of loops (closed paths): $h_\ell(A) = \mathcal{P} \int_\ell A_a^i \tau^i d\ell^a$

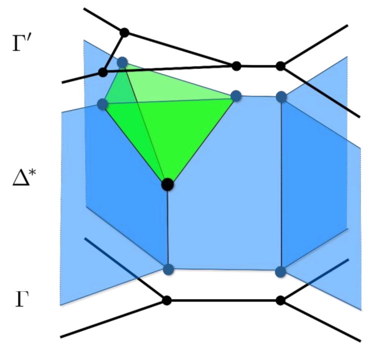


- Mathematical description of space by so called spin-networks with edges and vertices, where states can be excited from vacuum similar to the quantum mechanical harmonic oscillator



- Time evolution of the structure of space (the spin network) via spin foams
- Use a Feynman path integral modified for the LQG formalism with $S[e,\omega] = \frac{1}{16\,\pi G} \int_M \left(0.5\, \epsilon_{IJKL} e^K \wedge e^L - \frac{1}{\gamma} e_i \wedge e_j\right) \wedge \mathcal{F}^{IJ}(\omega)$ to get transition amplitudes

Visualization of a spin foam with vertical axis as time

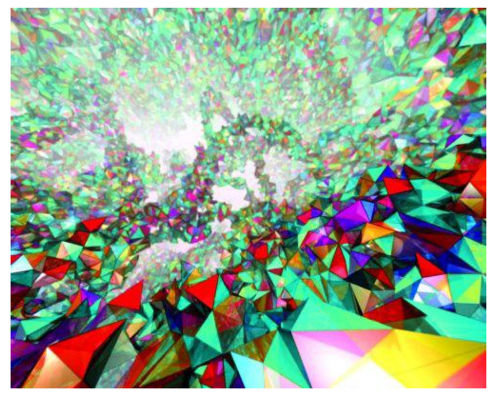


1: "Semi-classical quantisation of space-times with apparent horizons" (2006), A. Dasgupta, e-Print: gr-qc/0505017 [gr-qc], DOI: 10.1088/0264-9381/23/3/007

Results

LQG yields several different results about the physical world:

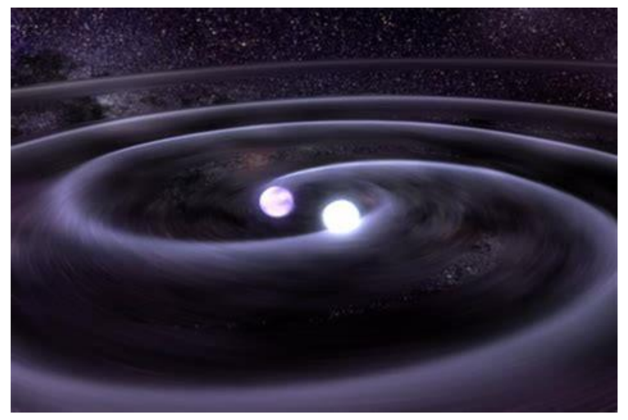
- Predicts "quanta" of space-time as quanta of geometric area
  - Area and volume operators with discrete eigenvalues
  - Smallest possible unit of area order $10^{-70} m^2$
  - Smallest possible volume order $10^{-99} cm^2$
  - Space itself discretized in cells/ "space atoms"



Visualization of a spin network state:
Space itself exists only in coloured cells, "outside of them" is nothing, not even vacuum
Spin's face label (area) is visualized by the colour of the cell.
Over time, the area (colour) changes, cells disappear and new cells form.

Thanks to the Albert-Einstein-Institute for the image

- Depicts semiclassical gravitational waves and effects of quantum gravity from coherent states (similar to light from coherent states of photons)

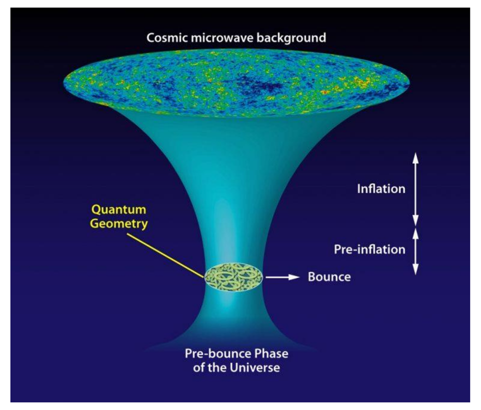


- Finds the origin of Black Hole Thermodynamics, entropy and Hawking Radiation Predicts existence of a "Planck star" inside of every black hole, would be able to solve the Black Hole Information Paradox

Loop Quantum cosmology:

- Finds quantum behaviour of cosmology at the birth of the universe and theorizes that there was no big bang but a minimum of extension after a period of contraction (big crunch)

Visualization of the big bounce, horizontal axis describes the extension of space, vertical axis is time.



Acknowledgements and References

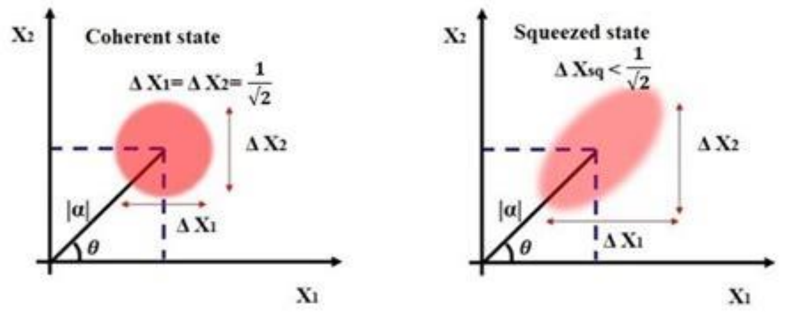
This work would not have been possible with the numerous discussions with my supervisor, Prof. Arundhati Dasgupta, who was always open for my questions and ideas.

Much of my input about the topic, especially considering the basics, is based on two of the leaders of LQG, Abhay Ashtekar and Thomas Thiemann and particularly their works "A short review of loop quantum gravity" and "Introduction to Modern Canonical Quantum General Relativity"

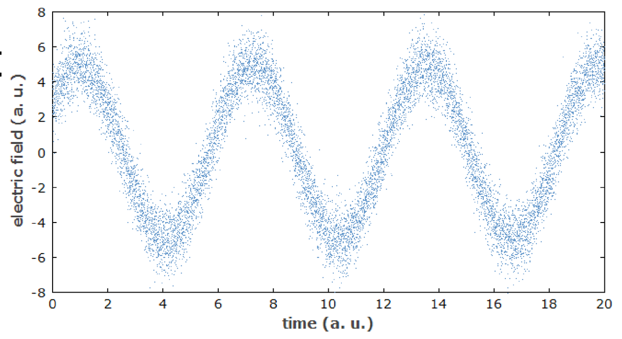
Research Aim

Every scientific theory is judged for the validity of its predictions and explanations. A promising way for LQG is a potential measurement of the graviton:

- Must emerge out of small perturbations of the Minkowski metric: $g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}$
- Gravitational waves already observed, Graviton is one quanta of them like the photon is for electromagnetic waves
- Coherent state[1] is a superposition of excitation states of the field which has the form $|\alpha\rangle = \sum_{n=0}^{\infty} C_n |n\rangle$ which satisfies:
  - Eigenstate of the annihilation operator $\hat{a}$: $\hat{a}|\alpha\rangle = \alpha|\alpha\rangle$
  - Minimizes Heisenberg's uncertainty principle $\sigma_x \sigma_p \geq \frac{\hbar}{2}$



- Gravitational waves are the coherent state of the gravitons:



- As in gravity objects of the same charge attract each other, the graviton transforms as a spin-2-spinor
- Gauge particle of the Lorentz group, the Gauge group of gravity
- Believed to be massless as they have a very long range but if one could measure that they travel slower than the speed of light, they would have mass
- Ultimately, my research aims to calculate properties of the Graviton that could help to verify it experimentally

Conclusions & Future Directions

Interesting results like the quantization of area and volume or the complicated explanation of space as a „spin foam". We also receive some new explanations about cosmological processes and objects like black holes.

A major issue of every highly theoretical theory remains unsolved:
LQG can't be tested until the present day. The goal is to make unique predictions, e.g. about the nature of the graviton, the proposed interaction particle of gravitation, that can be measured and tested. So far the theory is interesting and somewhat promising but will need to be verified or falsified to determine whether it actually tells us more about the world we are living in.
Other open questions concern mostly mathematical problems within the theory and the uncertainty about the behaviour of certain physical systems where a solutions remains to be found, e.g. the coupling to the standard model for particles.