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Loop quantum gravity: overview and recent developments

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Plan of the talk

- What is the problem with quantum gravity?
- Loop quantum gravity
- Applications: cosmology
- Applications: black holes
- Summary

Why quantum gravity?

Our current understanding of nature is that there are four fundamental interactions in nature: strong, weak, electromagnetic and gravitational.

Processes involving strong, weak and electromagnetic interactions require the use of quantum mechanics for their description.

Do we need a quantum description for gravity?

Not for practical reasons. Gravity is a weak, macroscopic force.

Yes for conceptual reasons: one cannot couple classical and quantum mechanical theories consistently. (S. Carlip Class.Quant.Grav.25:154010,2008)

Need to quantize for conceptual reasons. No experiments to explain.
This should be a theorist's field day!

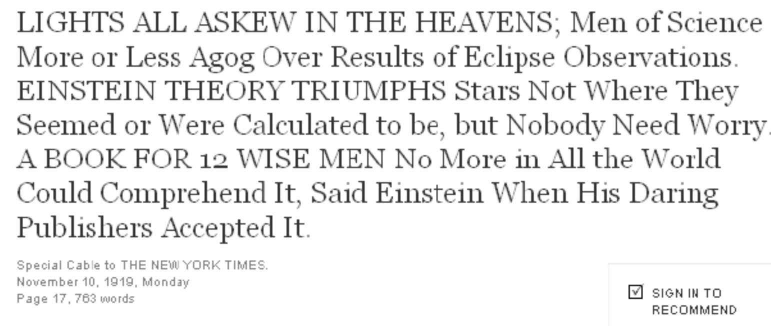
It is not.

Our modern understanding of gravity is that it is described by Einstein's general theory of relativity. In such a theory gravity is accounted for by a deformation of space-time. Quantizing gravity therefore implies quantizing the geometry of space time. This is unlike anything attempted before.

A bit of history:

1916 General relativity formulated as a classical theory, some initial consequences worked out. Gravitational waves. Gravitons!

1919 Eclipse observations by Eddington validate the theory and launch Einstein to fame.



LIGHTS ALL ASKEW IN THE HEAVENS; Men of Science More or Less Agog Over Results of Eclipse Observations. EINSTEIN THEORY TRIUMPHS Stars Not Where They Seemed or Were Calculated to be, but Nobody Need Worry. A BOOK FOR 12 WISE MEN No More in All the World Could Comprehend It, Said Einstein When His Daring Publishers Accepted It.

Special Cable to THE NEW YORK TIMES.
November 10, 1919, Monday
Page 17, 763 words

SIGN IN TO RECOMMEND

1927 Oskar Klein discusses briefly quantum implications in space-time (Z. Phys 46, 188 (1927))

1930 Born, Jordan, Dirac, quantize EM field.

1930 Leon Rosenfeld publishes the first technical papers on quantum gravity (Ann Physik 5, 113 (1930), Z. Phys 65, 589 (1930))

1934 Matvei Bronstein realizes some of the difficulties unique to quantizing gravity Writes first Ph.D. thesis on the subject (Z. Phys. Sowiet. 9, 140 (1936))

1950's Dirac and Bergmann finalize the Hamiltonian formulation of general relativity.

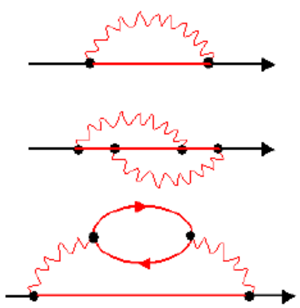
1960's Feynman, DeWitt and others realize that usual perturbative quantization techniques do not work in general relativity.

What goes wrong?

The usual technique to treat quantum (field) theories is the use of perturbations. One starts with the theory eliminating the interactions, which is easy (free theory) and then treats the interactions as small perturbations.

In principle this looks like it would work. The only physical constants involved in the formulation of gravity are G, c, and in quantization we add $\hbar$. They can be combined to give a unit of energy $(\hbar c^5)^{1/2}/G \sim 10^{19}$ GeV. So clearly for ordinary energies a perturbative approximation should be really good.

One expands $\exp(iH_{int})$ in powers of the coupling constant, leading to the Feynman diagrams.



These types of calculations lead to infinities, that can be dealt with with a process called renormalization.

However, in the case of gravity the procedure fails.

The theory is what is known as nonrenormalizable.

It is clear that these types of arguments, although they represent a significant practical obstruction, are not definitive:

-It could be that the series can be resummed and divergences absorbed in a few parameters.

-It could be that expanding around a different background changes things. (e.g. gravity in 2+1 dimensions).

-It could be that the theory is essentially non-perturbative. There are some examples of such theories (Neveu-Schwarz model).

Ordinary lattices do not help either for reasons we will discuss.

Some people believe that the failure of the perturbative treatment is an ominous sign for the theory. They cite a well known example: Fermi's four vertex theory of weak interactions. Such theory has similar pathologies. But it turns out it is not a fundamental theory, but an effective theory that approximates the true fundamental theory: electroweak theory. Could something similar be happening in gravity?

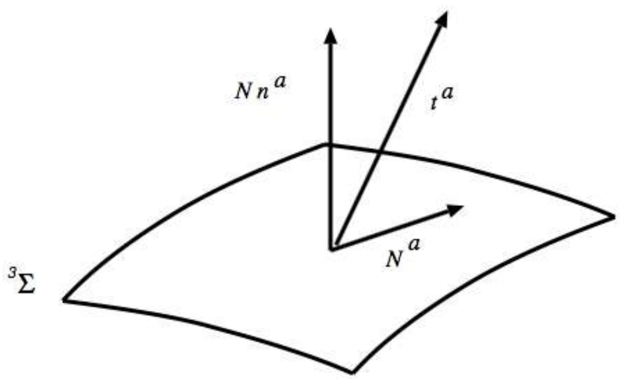
Those who take this point of view believe Einstein's theory is only an effective theory valid at low energies and a more fundamental theory is needed to explain things. A leading exponent of this point of view is string theory. In addition to explaining quantum gravity it attempts to explain all other interactions as well.

The point of view we will take today is that we do not have definitive proof that Einstein's theory cannot be quantized by itself and that perhaps techniques different than the perturbative treatment should be analyzed.

The approach we will describe is **loop quantum gravity.**

Loop quantum gravity: beginnings

-In 1986 Ashtekar shows that one can write canonical gravity with variables similar to those in Yang-Mills theory.



$$x, q : \quad {}^3g_{ab} \longrightarrow \tilde{E}^a_i$$

$$\dot{x}, p : \quad {}^3K_{ab} \longrightarrow A^i_a$$

-General relativity looks like an SU(2) Yang-Mills theory with extra constraints.

-Opened hopes that techniques used to quantize YM could be applied to gravity.

-Initial hopes too optimistic, however, some techniques prove useful: loops.

Loop variables: an analogy in Maxwell theory:

$$\oint_{\partial\Sigma} \vec{A} \bullet d\vec{l} = \int_{\Sigma} \vec{B} \bullet d\vec{s}$$

If one gives the value of the circulation of A for all curves, it is tantamount to giving B.

One would be giving you information about a field by giving you a **function of a loop.**

Similar results hold for non-Abelian connections (vector potentials) like those in Yang-Mills theory or gravity. The path dependent quantity is the trace of the **holonomy**.

Giles theorem: if one knows all holonomies of a connection, one can reconstruct all gauge invariant information in it.

The loop representation:

Using the previous ideas, one can introduce a quantum representation for gravity where wavefunctions are functions of loops living in space.
This representation was first introduced by Gambini and Trias for Yang-Mills theory in the early 1980's. When Ashtekar introduced a new set of variables for gravity that made the theory look more like a Yang-Mills theory (described gravity in terms of an SU(2) vector potential) in 1986 the same type of representation was introduced for gravity by Rovelli and Smolin in 1988.

An important point is that in the gravitational case, the theory is invariant under coordinate transformations. This can be cast in an "active" way by keeping the coordinates fixed and "moving around" other things. So in particular, the states should be functions of loops that are invariant under diffeomorphisms.

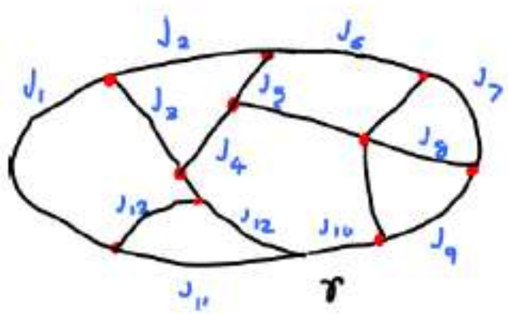
This severely limits the type of states and Hilbert space one can use. They become essentially unique (LOST-F theorem, Lewandowski, Okolow, Sahlmann, Thiemann, Fleischack)

Inner product due to Lewandowski and Ashtekar.

Polymer geometry:

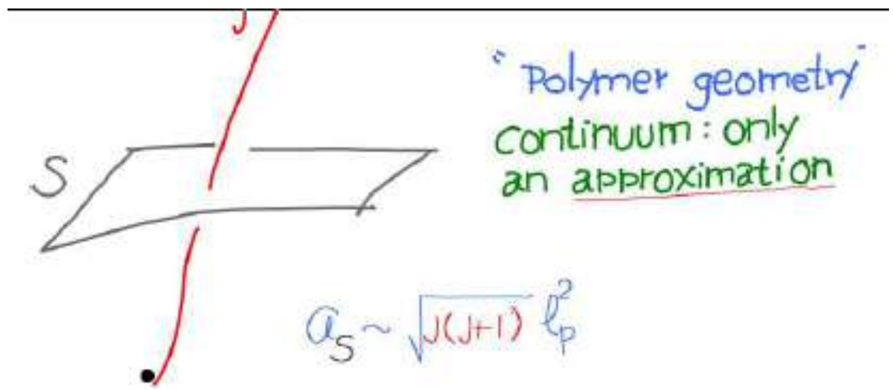
This unique kinematics was first constructed explicitly in the early nineties. High mathematical precision. Provides a Quantum Geometry.
Replaces the Riemannian geometry used in classical gravity theories.
(many authors contributed: Ashtekar, Baez, Corichi, Lewandowski, Marolf, Mourão, Rovelli, Smolin, Thiemann)

The quantum states are “spin networks” (multivalent colored graphs). The “color” comes from the SU(2) nature of the Ashtekar variables (one can use holonomies in different representations of SU(2) labeled by the “color”).



Fundamental excitations of geometry 1-dimensional. Polymer geometry at the Planck scale. Continuum arises only in the coarse grained approximation.

Each colored line can be thought of as carrying a "quantum of area". If one chooses a surface its area will depend on how many lines thread it and their color.



Novel features:

Eigenvalues of geometric operators (areas, volumes) discrete. Eigenvalues not equally spaced but crowd in a rather sophisticated way. Geometry is quantized in a specific way.

Using these structures, Thomas Thiemann was able in 1996 to write the first non-trivial, mathematically well defined, finite, anomaly free theory of quantum gravity (including coupling to matter).

$$\widehat{\text{Einstein Equations}}_{\mu\nu} = 8\pi G \hat{T}_{\mu\nu}$$

Are we therefore done? Not quite….

It turns out it is very difficult to get physics out of this theory (think of QCD without asymptotic freedom nor lattices). So, we do not know if this is the correct theory of quantum gravity.

There have been some results for black hole entropy, but they do not probe the entire theory.

So, people are attempting to probe physics in situations simplified by assuming symmetries: cosmologies and spherical symmetry.

T. Thiemann, "Modern canonical general relativity", Cambridge Univ. Press (2008)

Controversies:

Loop quantum gravity has been criticized in various fora. Perhaps most remarkable are the papers by Nicolai, Peeters and Zamarklar, and shorter but more up to date, Nicolai and Peeters. These papers are carefully written and the criticisms well explained. Thiemann has responded in detail in a paper to the first article.
Class.Quant.Grav.22:R193,2005. Lect.Notes Phys.721:151-184,2007.
Lect.Notes Phys.721:185-263,2007

The use of these types of spaces, although mathematically precise, has created some unease from the physical point of view.

Their properties appear rather counterintuitive. On the other hand, one expects that counterintuitive elements may have to be introduced to overcome the issues facing conventional quantum gravity.

In simple examples, like the harmonic oscillator, it has been shown that these types of quantizations admit states (complicated superpositions) that approximate the usual Fock space coherent states that lead to the correct semi-classical behavior. Examples, however, can never convince critics.

Does the Thiemann Hamiltonian contain the correct physics?

Applications: Cosmology

In general relativity fairly general theorems due to Hawking and Penrose indicate that all space-times become singular at some point.

In cosmological settings one usually assumes that the metric is very simple, being homogeneous and isotropic. There is only one non-trivial components, the "scale factor" a(t). The volume goes as |a(t)|^3 and the curvature as its inverse.

At the Big Bang the volume goes to zero and the curvature diverges. Classically physics stops!!

The general expectation is that we have pushed the classical theory beyond the realm of applicability and quantum effects may change things (example: Bohr atom, classically the energy is unbounded below, quantum mechanically there is a ground energy $E_0=-me^4/2h^2$).

Does loop quantum gravity predict something similar? YES!

The usual story:

Since one is only studying the homogeneous degree of freedom a(t) one is dealing with a mechanical system (finite number of degrees of freedom). One can readily proceed to quantize. Quantum states $\hat{a}\Psi(a) = a\Psi(a)$ etc.

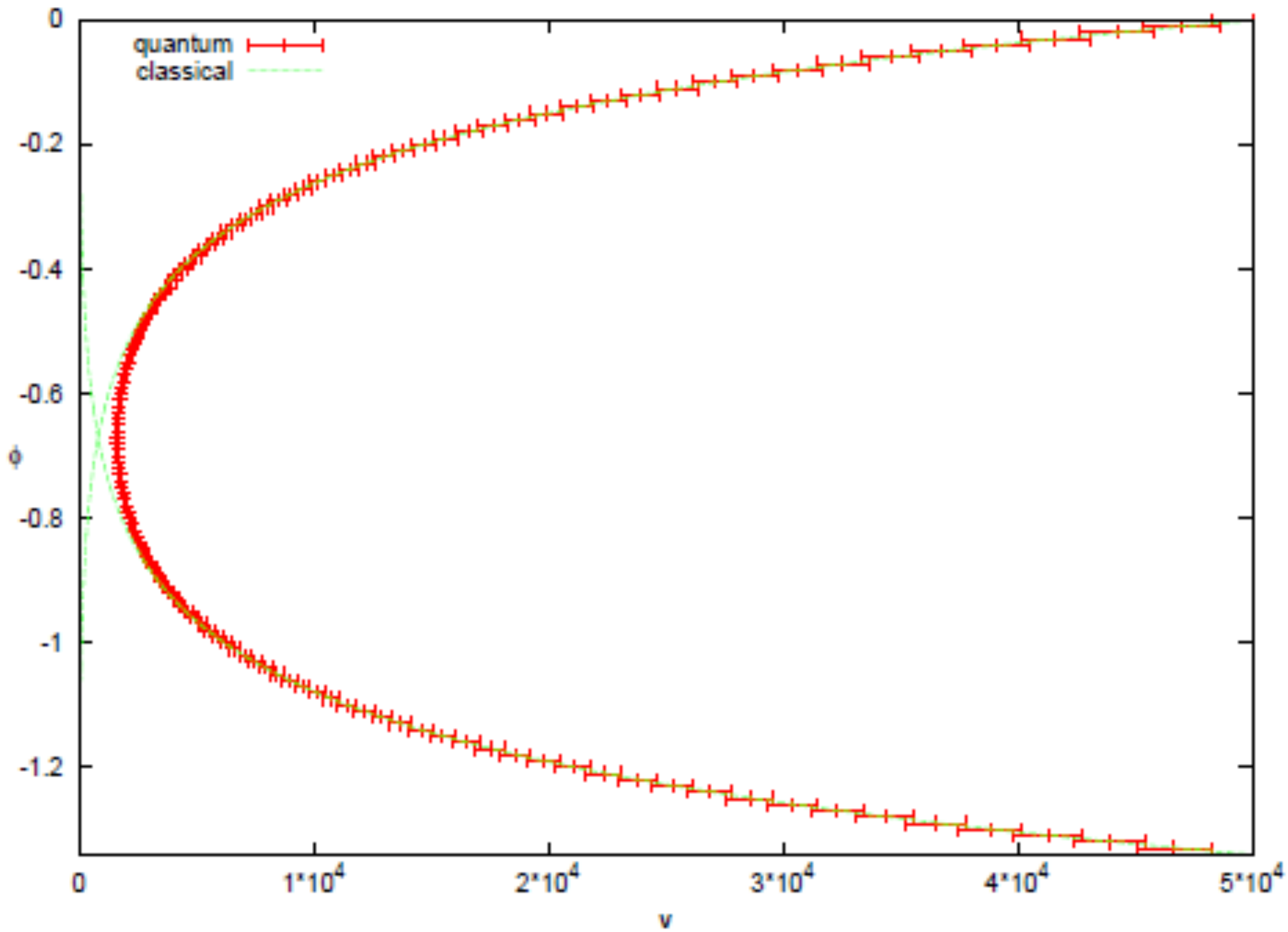
The Einstein equations become a simple ordinary differential equation known as the Wheeler-DeWitt equation. This was study extensively and the conclusion is that the singularity is not resolved.

Since the 1970's this created an impasse. Because one is dealing with quantum mechanics rather than field theory, the Stone-VonNeumann theorem implies there is no place to escape.

Loop quantum gravity is a game-changer. It violates one of the assumptions of the Stone-VonNeumann theorem that therefore does not apply.

[von Neumann's uniqueness theorem: There is a unique IRR of the Weyl operators $\hat{U}(\lambda), \hat{V}(\mu)$ by 1-parameter unitary groups on a Hilbert space satisfying:
i) $\hat{U}(\lambda)\hat{V}(\mu) = e^{i\lambda\mu}\,\hat{V}(\mu)\hat{U}(\lambda)$; and ii) Weak continuity in λ, μ. This is the standard Schrödinger representation. $(U(\lambda) = e^{i\lambda x}$ and $V(\mu) = e^{i\mu p})$]

Loop quantum cosmology:

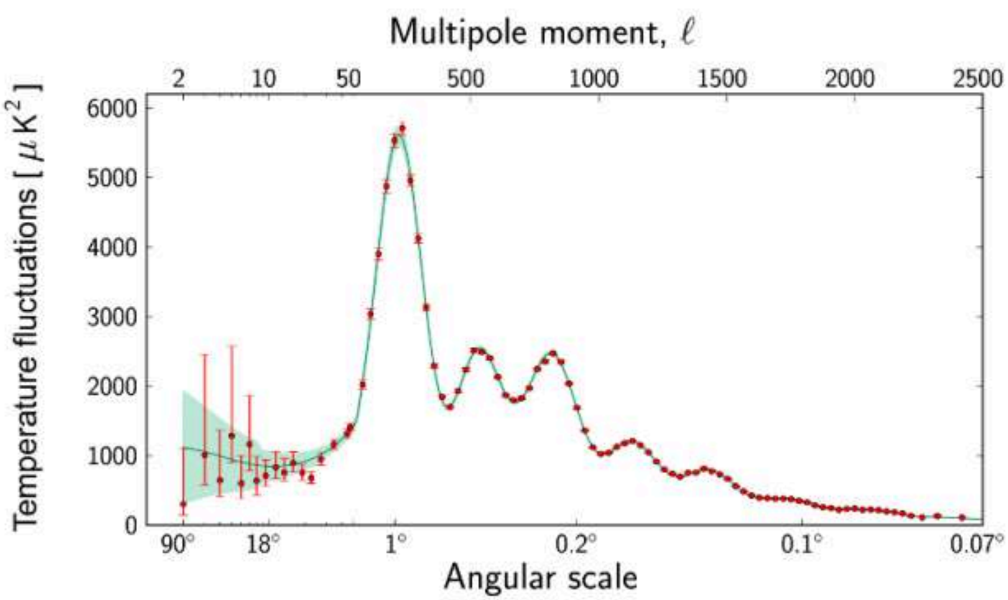


Martin Bojowald; Abhay Ashtekar, Tomasz Pawlowski, Parampreet Singh

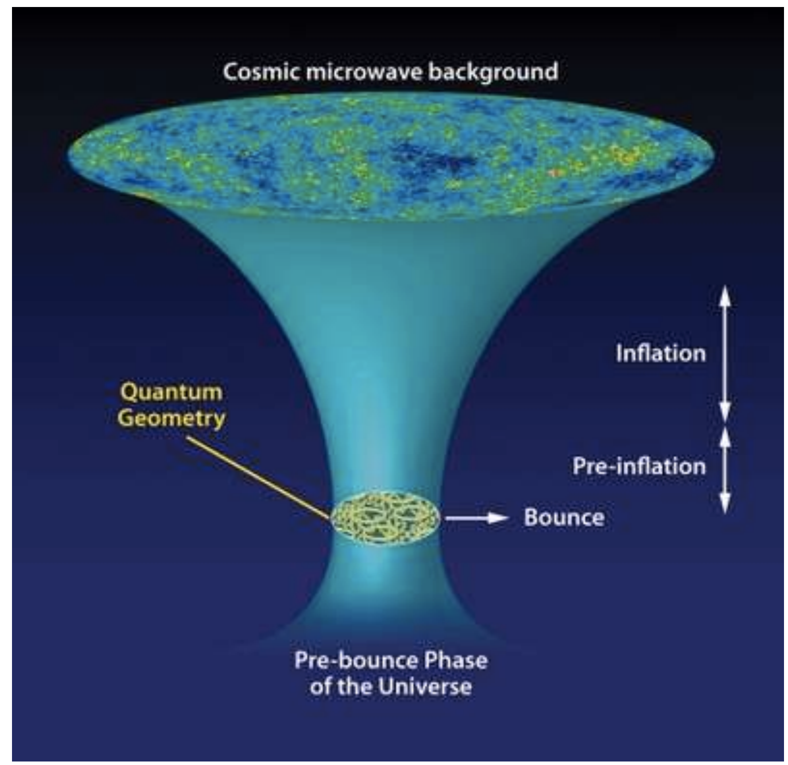
Is that is? No. Beyond homogeneity: perturbations

-Study fields living on the previously discussed cosmology. See if one can get the CMB spectrum and compare to experiments.

-Why is quantum gravity relevant? Isn't CMB formed after inflation when QG is irrelevant? Indeed QG irrelevant during and after inflation, but it influences initial states for the quantum fields, that inflation turns into the spectrum of the CMB.



Source: ESA/Planck.



Credit: P. Singh

-Predictions of LQG: Departures at large scales. Dependent on the value of the inflaton at the bounce, therefore not a concrete prediction.

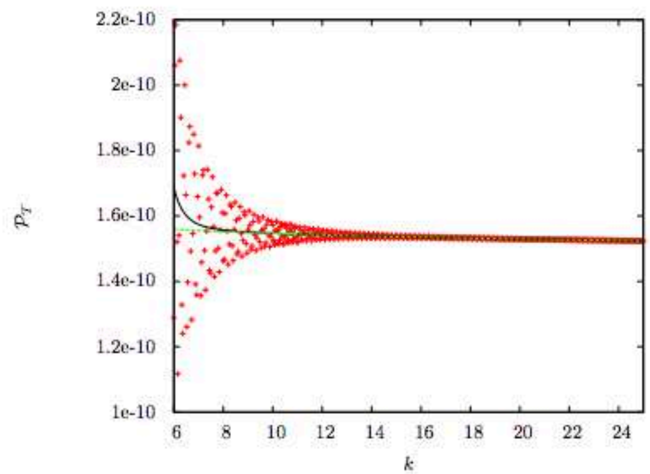


FIG. 7: The LQC power spectrum for tensor modes. As for scalar modes, we have set $\phi_B = 1.15$

-Difference in consistency relations. Depending on the value of r, predictions could be experimentally tested relatively soon.
(Agullo, Ashtekar, Nelson 2012 PRL 109, 251301; 2013 CQG 30, 085014).

$$r_{\rm LQC} \approx -8\left(n_t - \frac{d\ln(1+2|\beta_k^{(\mathcal{T})}|^2)}{d\ln k}\right)$$

Applications: black holes

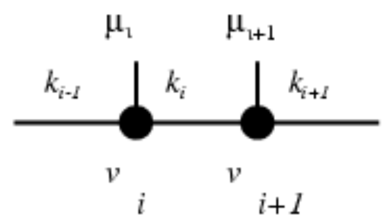
Spherically symmetric LQG Kastrup, Thiemann, mid 90's.

We use the variables adapted to spherical symmetry developed by Bojowald and Swiderski (CQG23, 2129 (2006)). One ends up with two canonical pairs, E^x, E^φ, K_x, K_φ.

$$g_{xx} = \frac{(E^\varphi)^2}{|E^x|}, \qquad g_{\theta\theta} = |E^x|,$$

$$K_{xx} = -\text{sign}(E^x)\frac{(E^\varphi)^2}{\sqrt{|E^x|}} K_x \qquad K_{\theta\theta} = -\sqrt{|E^x|}\frac{A_\varphi}{2\gamma},$$

Kinematical states are given by one dimensional spin networks,

$$T_{g,\vec{k},\vec{\mu}}(K_x, K_\varphi) = \langle K_x, K_\varphi \Big|$$  $$\Big\rangle$$

$$= \prod_{e_j \in g} \exp\left(\frac{i}{2} k_j \int_{e_j} K_x(x)dx\right) \prod_{v_j \in g} \exp\left(\frac{i}{2}\mu_j \gamma K_\varphi(v_j)\right)$$

We were able to solve in closed form for the space of physical states of spherically symmetric vacuum LQG (RG, JP PRL 110, 211301)The singularity is eliminated! One can go through it to a new region of space-time in the future.

So essentially we were in 2013 at a quantum level where Schwarzschild was in 1916[*]. We have the exact solution of the quantum Einstein equations in spherical symmetry.

A journalist in New Scientist misunderstood the last statement…

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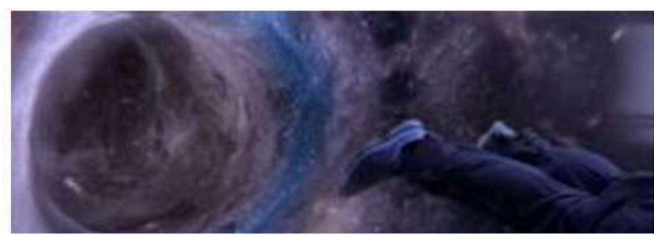
Quantum gravity takes singularity out of black holes

› 12:17 29 May 2013 by **Katia Moskvitch**
› For similar stories, visit the **Cosmology** Topic Guide

In its place is something that looks a lot like an entry point to another universe. Most immediately, that could help resolve the nagging information loss paradox that dogs black holes.



This broke the internet...

INTERNATIONAL BUSINESS TIMES

"I Buchi Neri sono portali verso altri universi", suggerisce uno studio

THE FREE PRESS JOURNAL

HOME / WEB SPECIAL / BLACK HOLES ARE PORTALS TO OTHER UNIVERSES?

Black holes are portals to other universes?

hype science

Buracos negros podem ser portais para outros universos

REAL CLEAR SCIENCE

June 5, 2013

Black Holes May Not Be Infinitely Dense

TOPNEWS

Loop Quantum Gravity Simplifies Black Hole Mystery

Black Hole Cores May Not Be Infinitely Dense

Artist's concept of a supermassive black hole

Image credit: NASA/JPL-Caltech

They may also serve as bridges to the future.

Z NEWS

News » Sci-Tech » Space

`Black holes are portals to other universes`

NBC NEWS

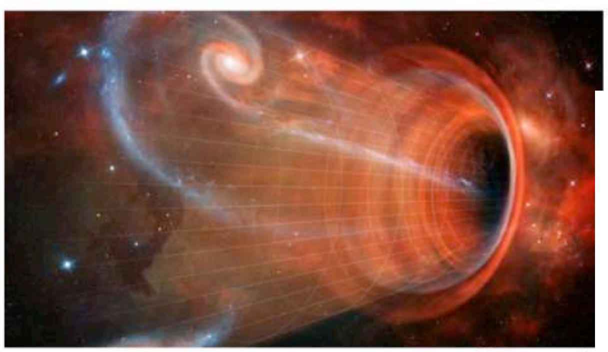
SCIENCE / SCIENCE NEWS

Space-time loops may help explain black holes

明日科學

如果人掉進黑洞下場會如何？

黃威翔 02/11/2019 明日科學



圖：Space magazin

你即將要掉入一個黑洞。儘管困難重重，若是你存活了下來，在你面前等待的會是什麼？你最後會出現在哪裡，若是你設法回來，你又會經歷怎樣的故事呢？

那麼，黑洞會放射出保存的訊息，並透過白洞將其丟出嗎？或許如此。在 2013 發表的一篇研究中，路易斯安那州立大學（Louisiana State University）的霍爾赫·普林教授（Jorge Pullin）及烏拉圭蒙得維的亞共和國大學（University of the Republic in Montevideo, Uruguay）的羅多佛·甘比尼教授（Rodolfo Gambini）將迴圈量子重力論（loop quantum gravity）應用於黑洞，並發現重力往核心增加，但會減少並掉下任何進入宇宙另一區域的東西。這個結果給予黑洞作為入口想法的額外支持。在這個研究中，奇異點不存在，所以不會形成堅不可摧的障礙而壓毀任何遇到的事物。這也代表訊息不會消失。

Applications: Black holes

Hawking radiation on the quantum space-time has been studied.
(R. Gambini, JP CQG 31 (2014) 115003)

The Casimir effect has been studied on the quantum space-time. One obtains the correct result without regularization nor renormalization. The discreteness of the quantum geometry makes everything finite.
(R. Gambini, J. Olmedo, JP CQG. 32 (2015) no.11, 115002)

The collapse of null shells has been formulated. Here one cannot solve for the dynamics in closed form.
(M. Campiglia, R. Gambini, J. Olmedo, JP CQG 33 (2016) no.18, 18LT01)

Investigations of the interior of black holes at York U

Deformed algebra and the effective dynamics of the interior of black holes

Pasquale Bosso (Lethbridge U.), Octavio Obregón (Guanajuato U.), Saeed Rastgoo (York U., Canada), Wilfredo Yupanqui (Guanajuato U.) (Dec 8, 2020)

e-Print: 2012.04795 [gr-qc]

pdf cite

Black hole singularity resolution via the modified Raychaudhuri equation in Loop Quantum Gravity

Keagan Blanchette (York U., Canada), Saurya Das (Lethbridge U.), Samantha Hergott (York U., Canada), Saeed Rastgoo (York U., Canada) (Nov 23, 2020)

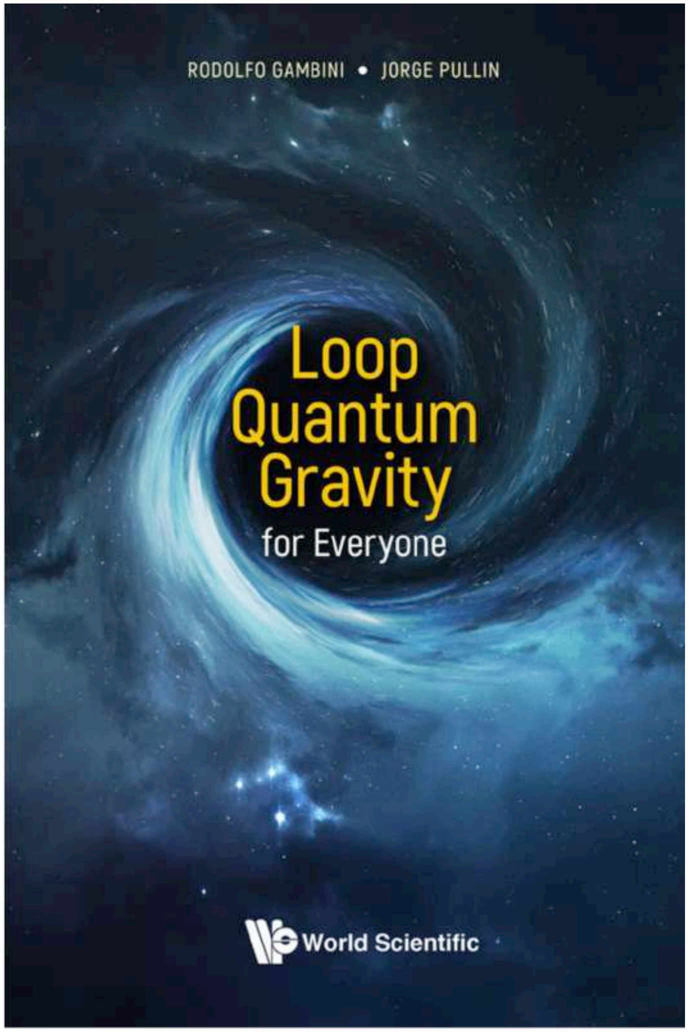
e-Print: 2011.11815 [gr-qc]

Summary

- Loop quantum gravity is an approach to quantizing the geometry of space-time.
- It is based on novel mathematics that may break long confronted logjams of the field.
- There are skeptics about the approach.
- Some physical results are starting to emerge in situation of physical interest.
- Research in the field is progressing apace.

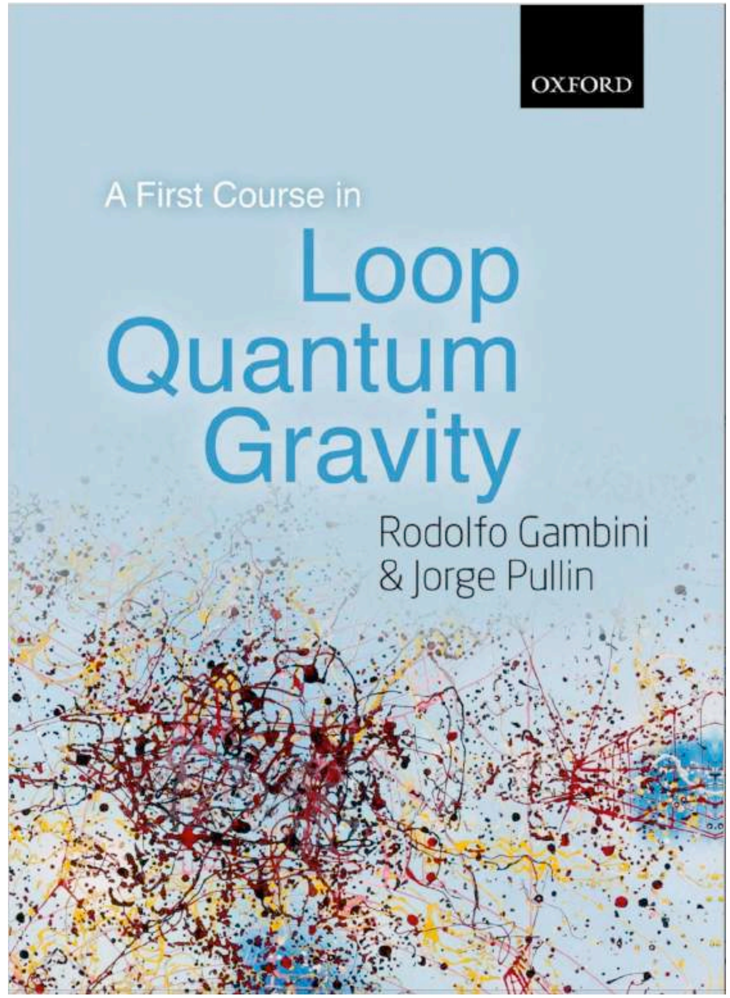
If you want to know more...

With no formulas!



http://lqg4everyone.com

With formulas!



http://afirstcourseinloopquantumgravity.com