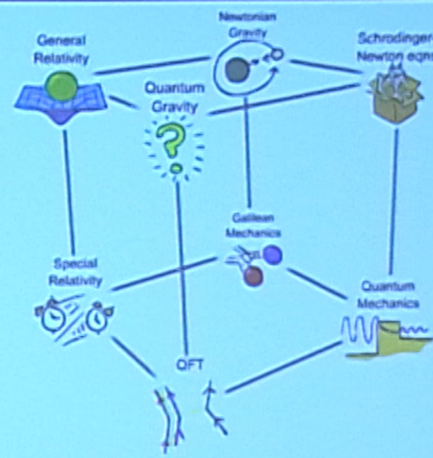
Title: PSI 2018/2019 - Explorations in Quantum Gravity - Lecture 1

Speakers: Bianca Dittrich

Collection: PSI 2018/2019 - Explorations in Quantum Gravity (Dupuis)

Date: March 04, 2019 - 10:15 AM

URL: http://pirsa.org/19030068



- What is Quantum Gravity?
- Why Quantum Gravity?

After all, atoms do fall, so the relationship between gravity and quantum is not a problem for nature,
Three roads to Quantum Gravity, Lee Smolin (2001)

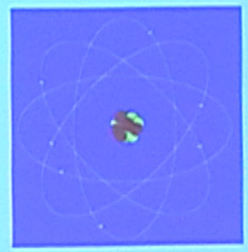
But no calls from experimentally accessible situations....

$$\frac{F_{\text{grav}}}{F_{\text{elect}}}(\text{proton - electron}) \sim 10^{-40}$$

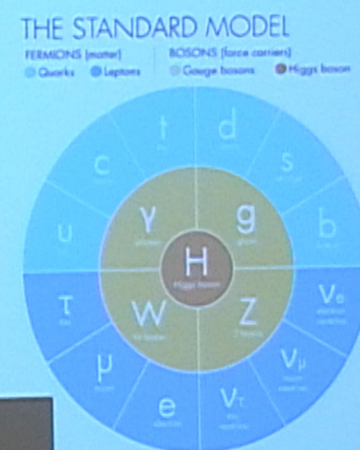
- Loop Quantum Gravity

What we know about the elementary physical world.

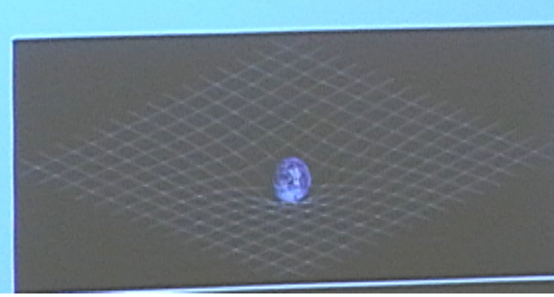
- Quantum Mechanics



- The SU(3)xSU(2)xU(1) Standard Model of particle physics



- General Relativity

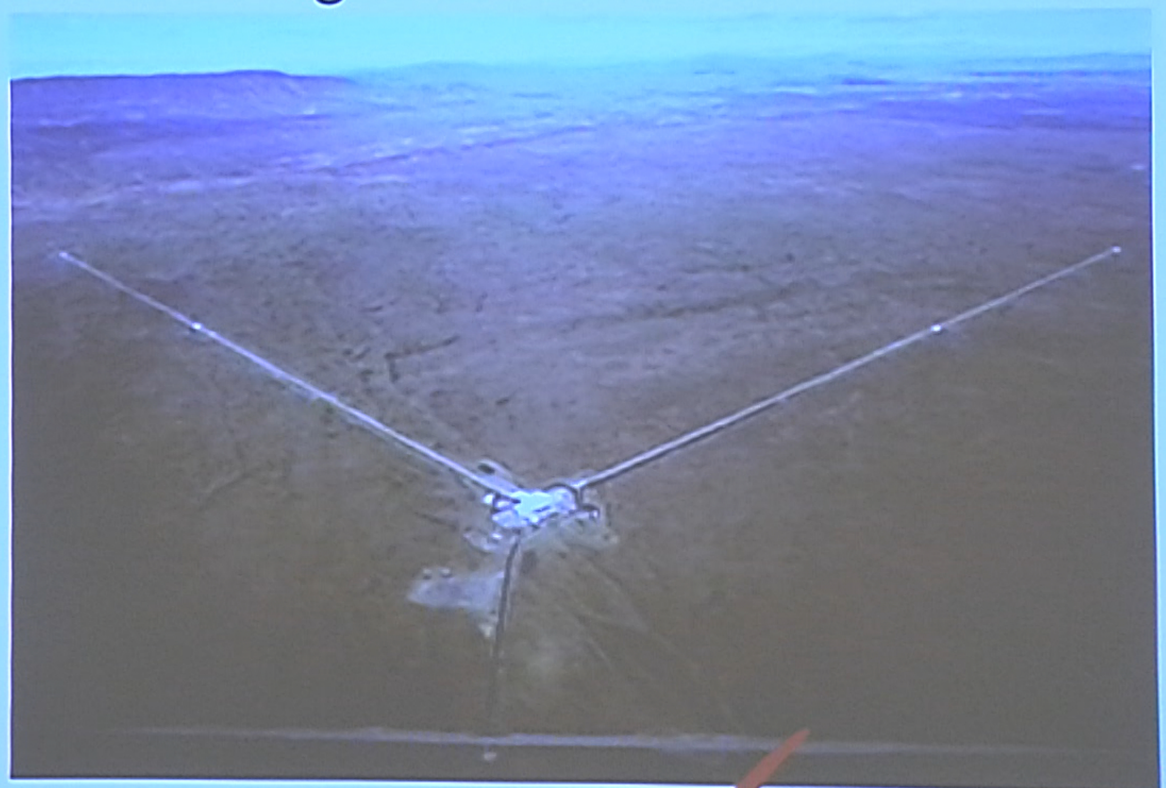


July 4th, 2012

Announcement of the observation of the Higgs boson as predicted by the Standard Model!

Standard Model

February 11th, 2016
Announcement of the detection of gravitational waves

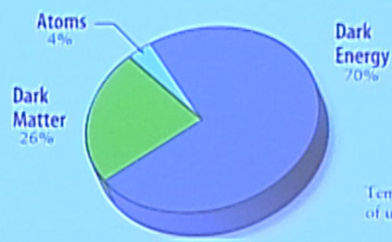


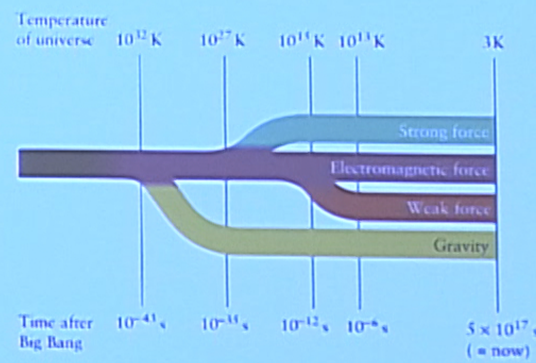
General Relativity ✓

But not the final story about the elementary world...

Among the open problems...

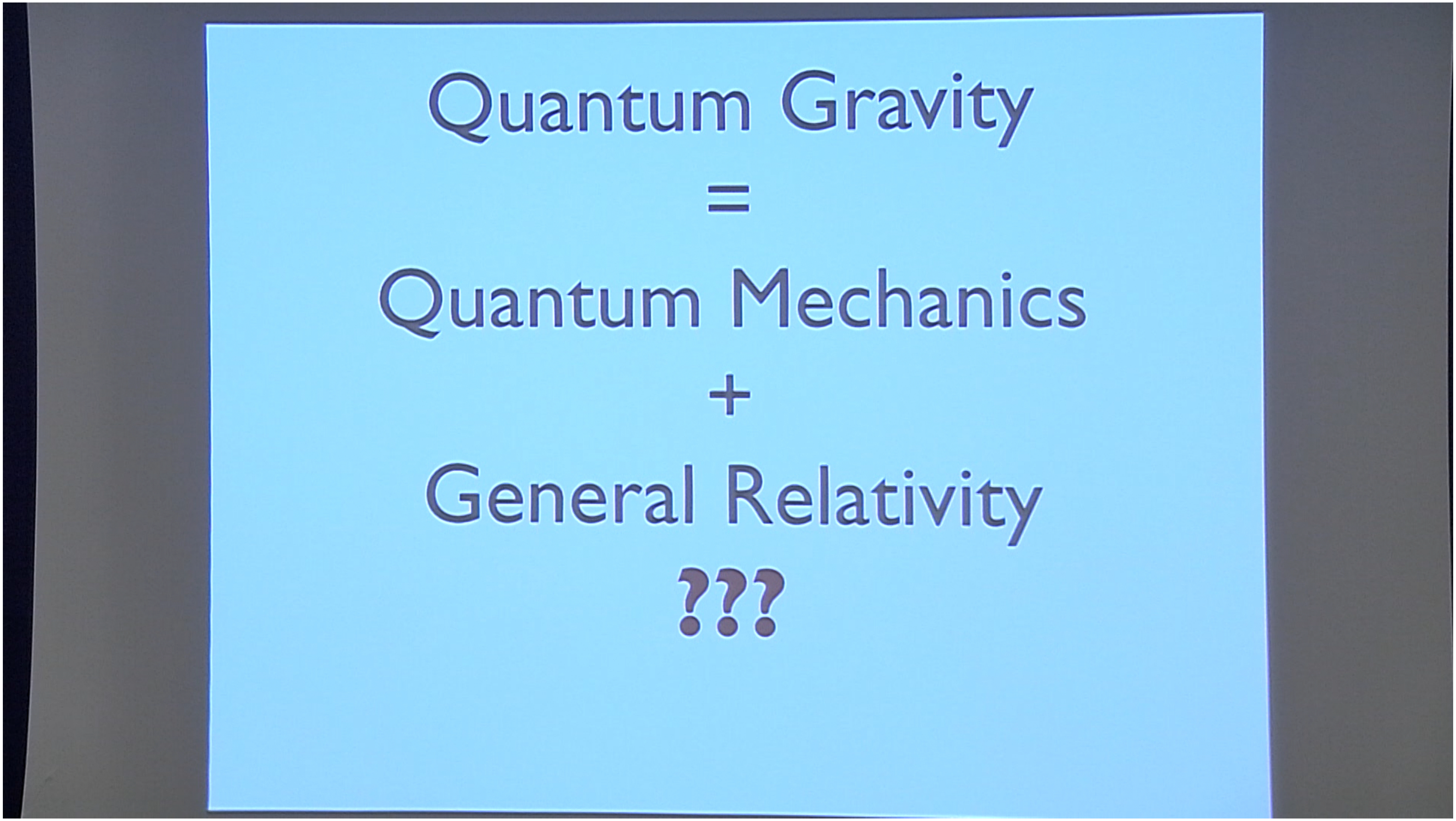
- Dark Matter

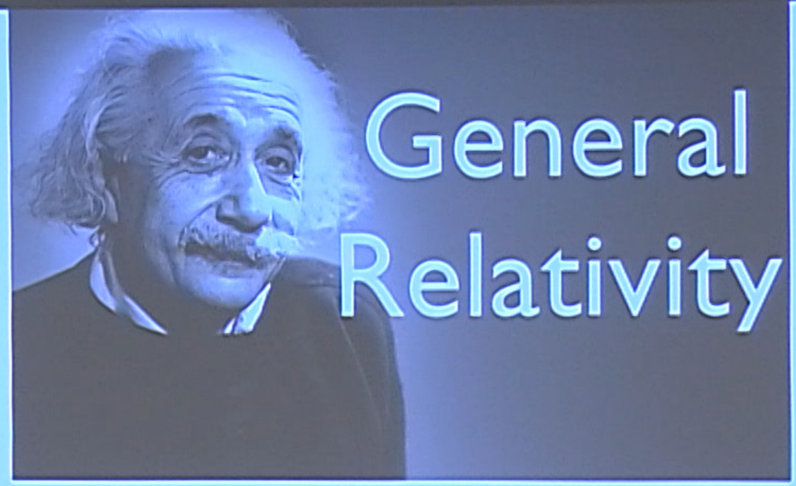




- Unification

- **Quantum Gravity**


Quantum Gravity
=
Quantum Mechanics
+
General Relativity
???

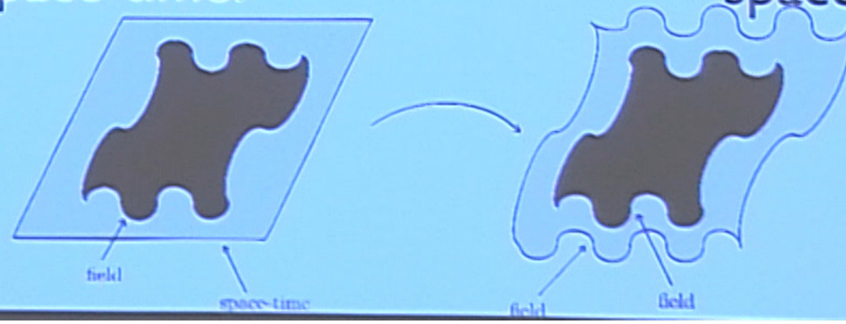


<u>General Relativity:</u> a theory of the gravitational field

$$S = \frac{1}{16\pi G}\int \sqrt{g}R$$

<u>Pre-GR:</u> Fields, particles ON space-time.

<u>GR</u>: gravitational field = space-time



Quantum mechanics

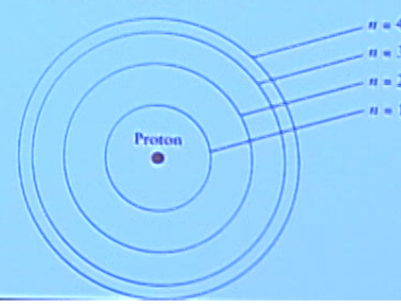
Classical

$$F = \frac{q_1 q_2}{R^2}$$

Hydrogen
atom

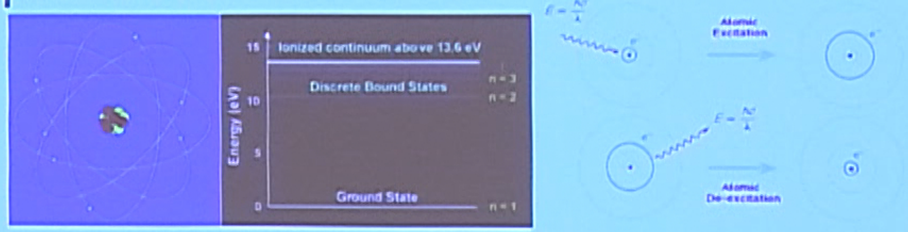
→

Quantum



General Relativity and Quantum Mechanics?

- <u>Quantum Mechanics</u>: any dynamical quantity = quantized.



World formed by discrete quanta jumping over a flat space-time governed by global symmetries (Poincaré).

- <u>General Relativity</u>: space-time is curved; everything is smooth and determinist.

➡ QM and GR = 2 different worlds!

Planck scale?

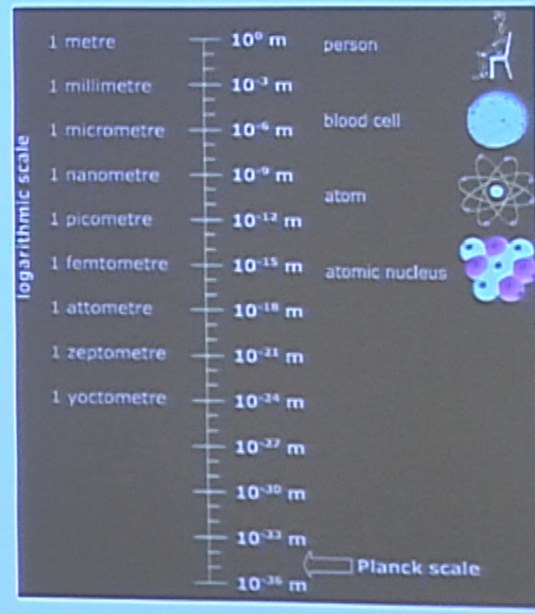
$$L_{\text{Planck}} = \sqrt{\frac{\hbar G}{c^3}} = 1.6 \times 10^{-35} m$$

- In QM, Compton wave length,

$$\lambda_{\text{min}} \sim \frac{\hbar}{mc}$$

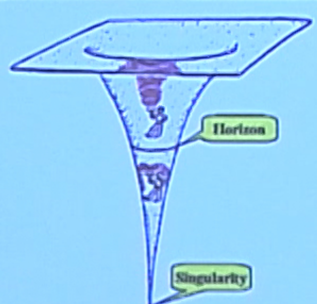
- In GR, Schwarschild radius,

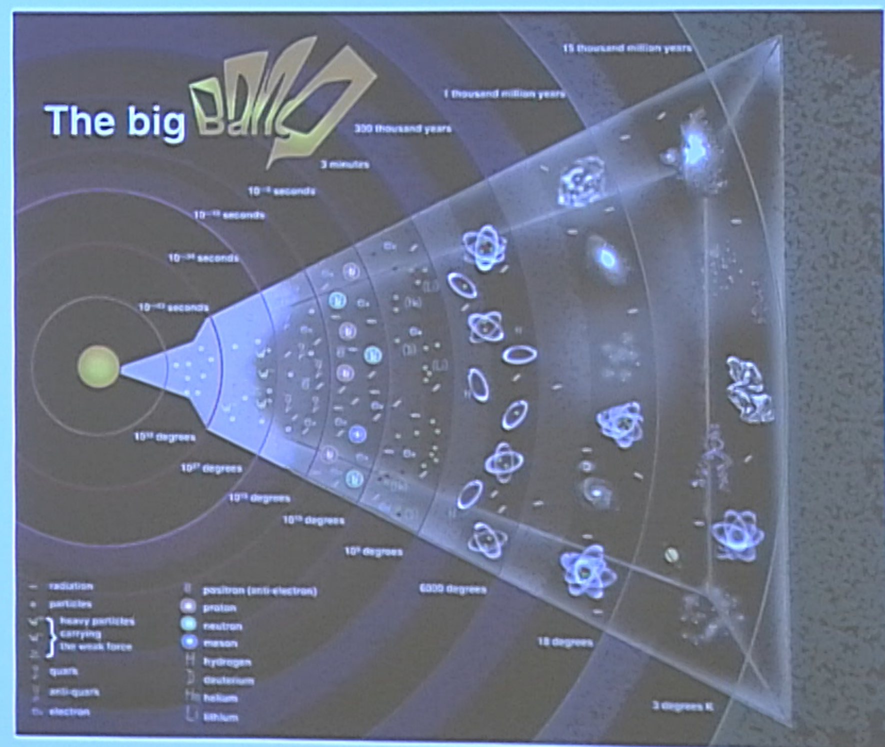
$$R \sim \frac{mG}{c^2}$$



$$L_{\text{min}} \equiv \lambda_{\text{min}} = R \qquad \Rightarrow \qquad L_{\text{min}} = L_{\text{Planck}}$$

Something very dense and very small?

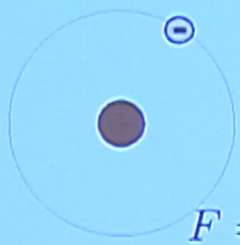




Quantization?

Quantization?

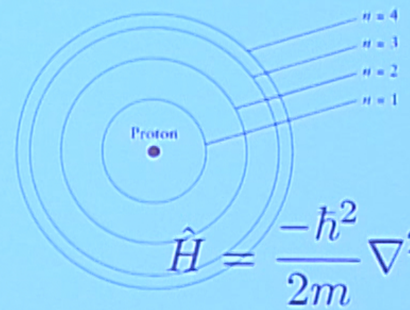
Classical



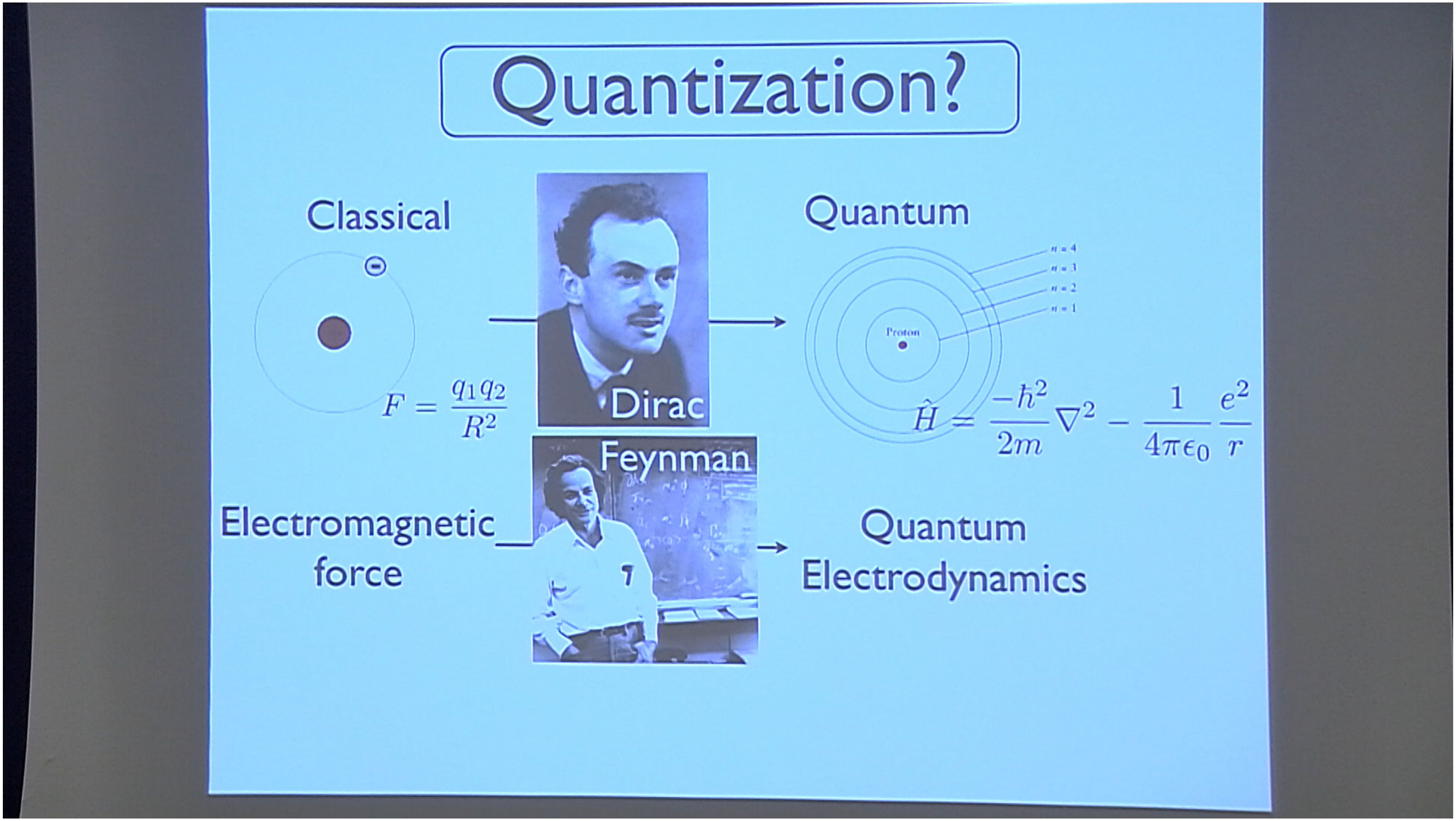
$$F = \frac{q_1 q_2}{R^2}$$

Hydrogen atom →

Quantum



$$\hat{H} = \frac{-\hbar^2}{2m}\nabla^2 - \frac{1}{4\pi\epsilon_0}\frac{e^2}{r}$$


Quantization?
Classical
$F = \frac{q_1 q_2}{R^2}$
Dirac
Quantum
Proton
$n = 4$
$n = 3$
$n = 2$
$n = 1$
$\hat{H} = \frac{-\hbar^2}{2m}\nabla^2 - \frac{1}{4\pi\epsilon_0}\frac{e^2}{r}$
Feynman
Electromagnetic force
Quantum Electrodynamics

Quantum Gravity

- Perturbative approach... $g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}$ with $|h_{\mu\nu}| \ll 1$

Volume 160B, number 1,2,3 PHYSICS LETTERS 3 October 1985

QUANTUM GRAVITY AT TWO LOOPS

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and

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Received 29 April 1985

We show that the S matrix of pure Einstein gravity diverges at the two loop order in four dimensions.

It doesn't work!

Quantum Gravity

- Perturbative approach... $g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}$ with $|h_{\mu\nu}| \ll 1$

... String theory...

- Go back to Dirac's approach (canonical quantization)...

→ Loop Quantum Gravity

GR (background independence; $g_{\mu\nu}$ = gravitational field) +
QM (uncertainty principle)
= Theory of Quantum Geometry?

Loop Quantum Gravity

- Einstein-Hilbert formulation (1915)

$$S = \frac{1}{16\pi G}\int d^4x\sqrt{g}R$$

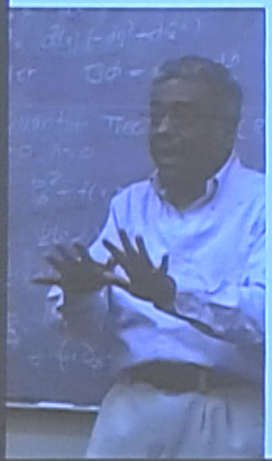
Loop Quantum Gravity

- Einstein-Hilbert formulation (1915)

$$S = \frac{1}{16\pi G}\int d^4x\sqrt{g}R$$

- Ashtekar formulation (1986)

$$S = \frac{1}{8\pi G\gamma}\int d^4x\left(\tilde{E}^a_i\dot{A}^i_a + \underset{\sim}{N}\epsilon_{ijk}\tilde{E}^a_i\tilde{E}^b_jF^k_{ab} + \lambda^i(D_a\tilde{E}^a)^i\right)$$



with γ the Barbero-Immirzi parameter.

$$\{A^i_a(x), \tilde{E}^b_j(y)\} = 8\pi G\gamma\delta^a_b\delta^i_j\delta^3(x-y)$$

VOLUME 57, NUMBER 18 PHYSICAL REVIEW LETTERS 3 NOVEMBER 1986

New Variables for Classical and Quantum Gravity

Abhay Ashtekar

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(Received 18 December 1985; revised manuscript received 29 August 1986)

A Hamiltonian formulation of general relativity based on certain spinorial variables is introduced. These variables simplify the constraints of general relativity considerably and enable one to imbed the constraint surface in the phase space of Einstein's theory into that of Yang-Mills theory. The imbedding suggests new ways of attacking a number of problems in both classical and quantum gravity. Some illustrative applications are discussed.

Loop Quantum Gravity

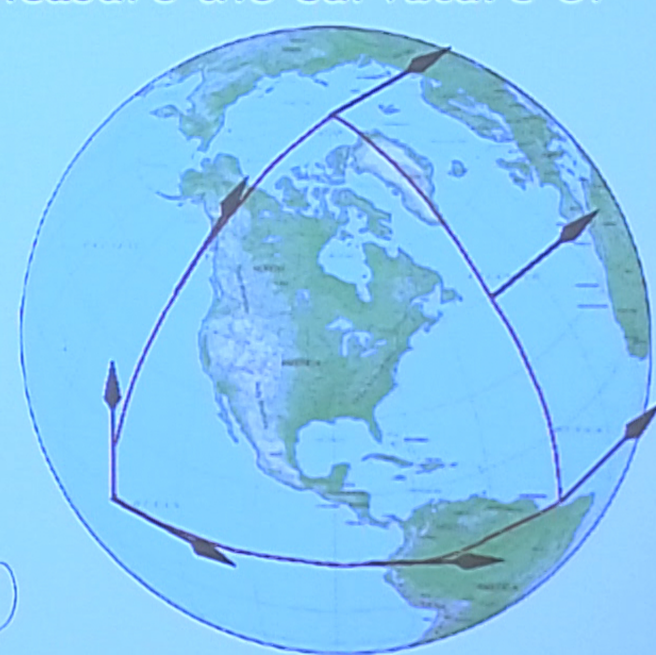
- First step: Ashtekar variables.

Loop Quantum Gravity

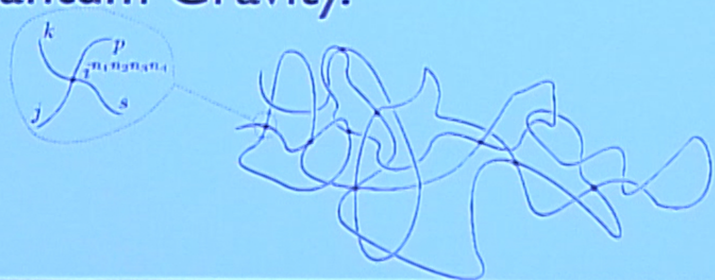
- First step: Ashtekar variables.
- Second step: the loops... to measure the curvature of space-time.

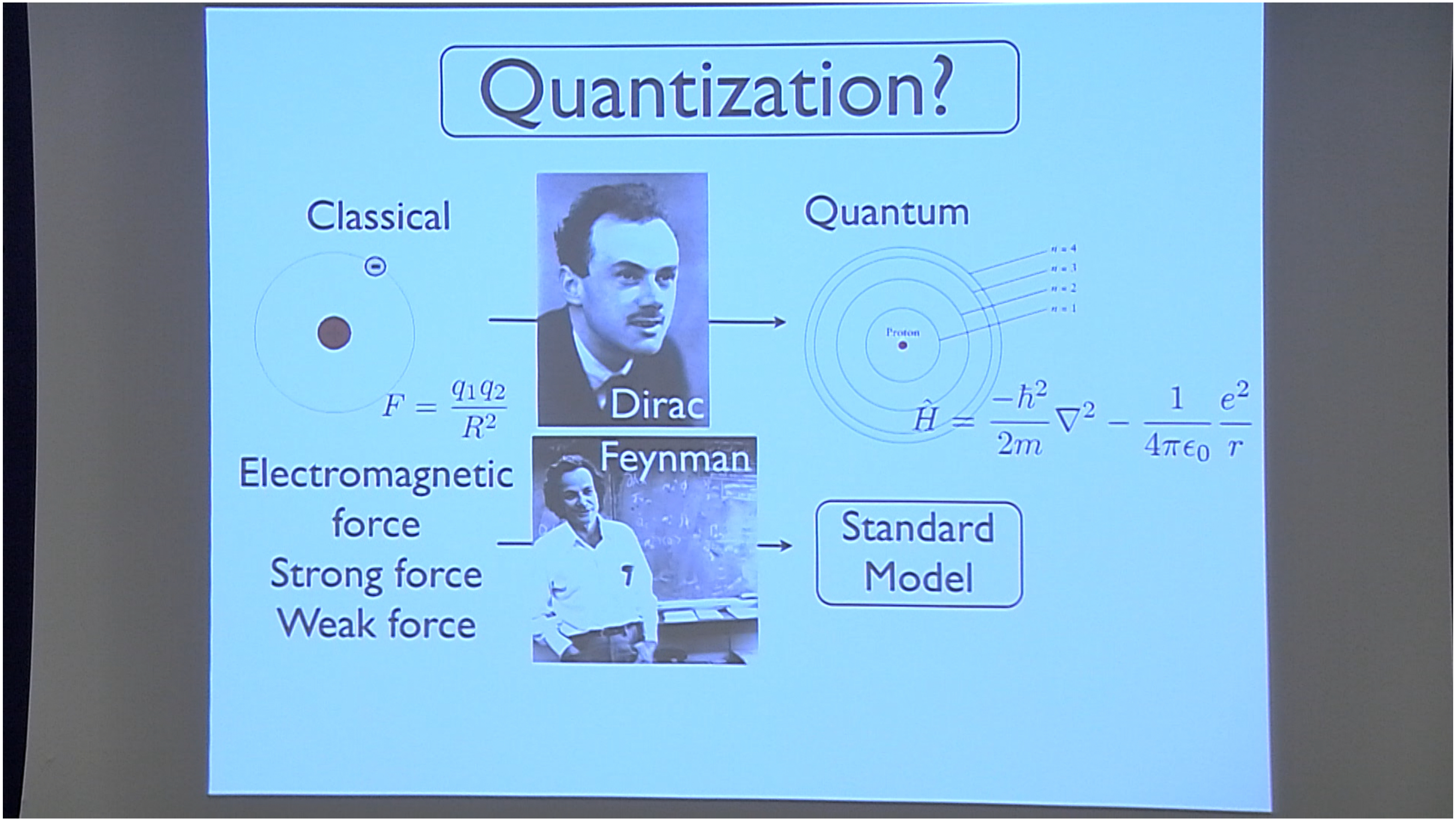
Loop Quantum Gravity

- First step: Ashtekar variables.
- Second step: the loops... to measure the curvature of space-time.
- Spin networks:



basis of the kinematical Hilbert space of Loop Quantum Gravity.




Quantization?
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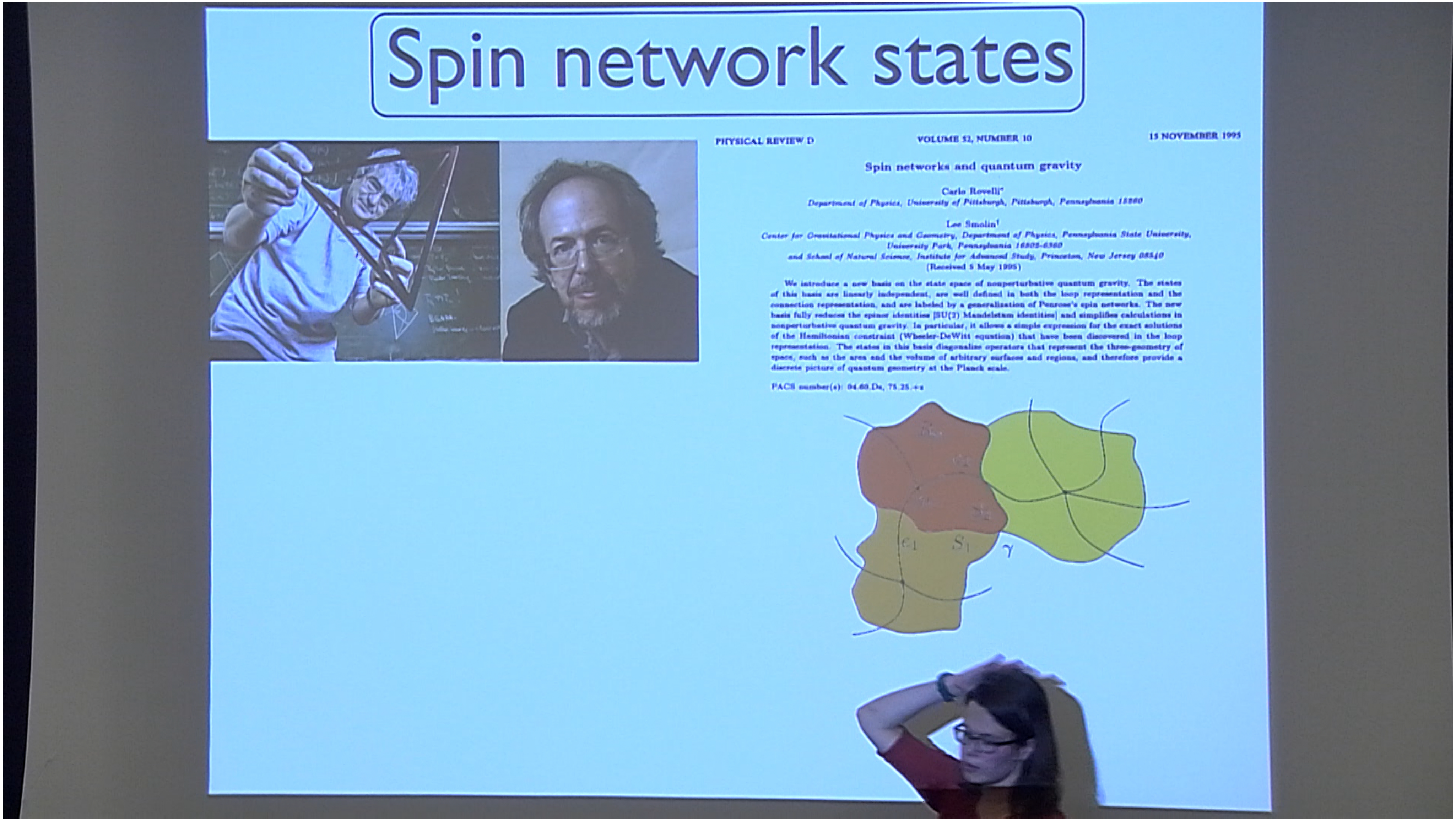
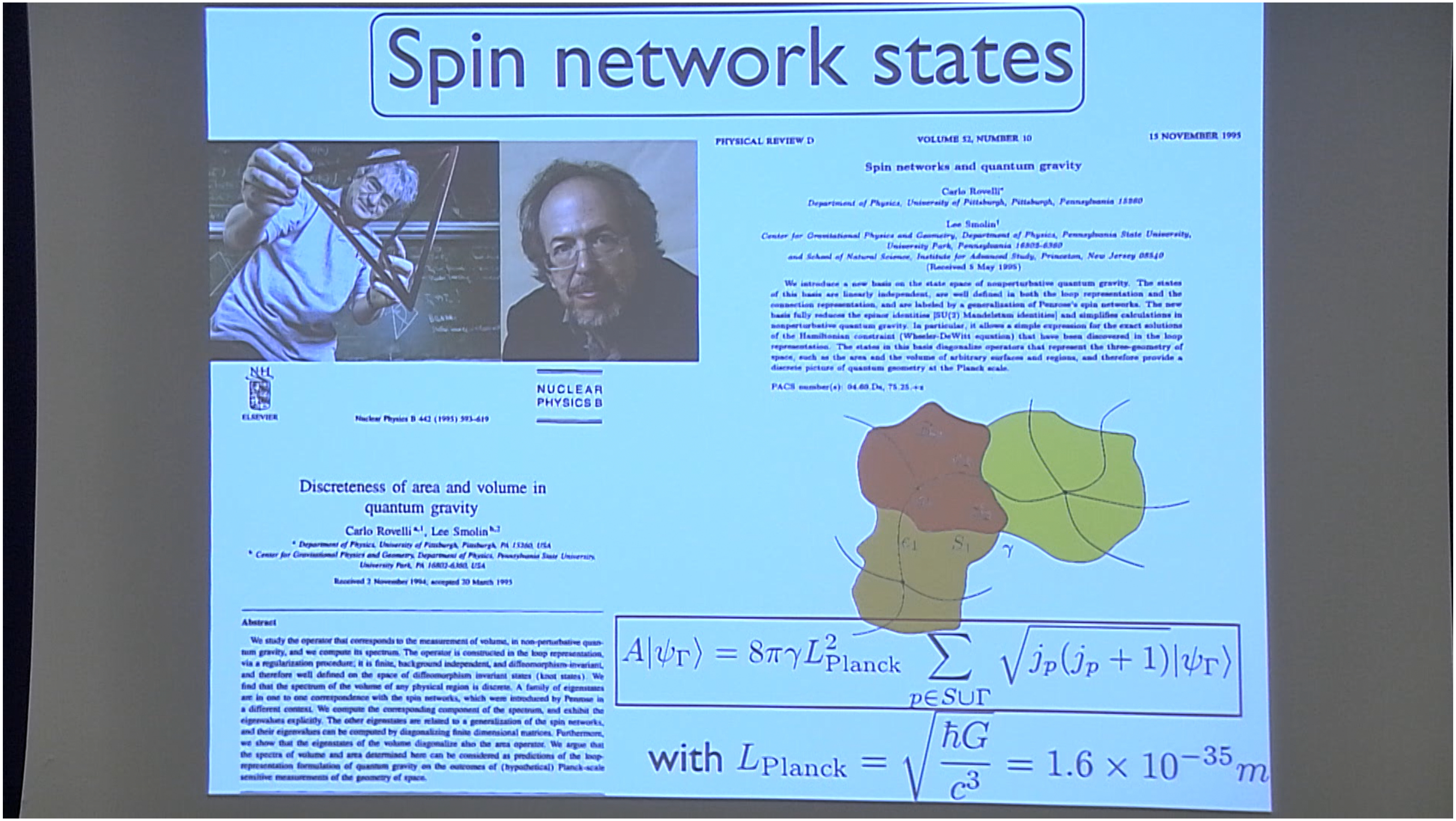
Feynman
Electromagnetic force
Strong force
Weak force
Standard Model



Spin network states
PHYSICAL REVIEW D
VOLUME 52, NUMBER 10
15 NOVEMBER 1995
Spin networks and quantum gravity
Carlo Rovelli*
Department of Physics, University of Pittsburgh, Pittsburgh, Pennsylvania 15260
Lee Smolin†
Center for Gravitational Physics and Geometry, Department of Physics, Pennsylvania State University, University Park, Pennsylvania 16802-6360
and School of Natural Science, Institute for Advanced Study, Princeton, New Jersey 08540
(Received 5 May 1995)
We introduce a new basis on the state space of nonperturbative quantum gravity. The states of this basis are linearly independent, are well defined in both the loop representation and the connection representation, and are labeled by a generalization of Penrose's spin networks. The new basis fully reduces the spinor identities [SU(2) Mandelstam identities] and simplifies calculations in nonperturbative quantum gravity. In particular, it allows a simple expression for the exact solutions of the Hamiltonian constraint (Wheeler-DeWitt equation) that have been discovered in the loop representation. The states in this basis diagonalize operators that represent the three-geometry of space, such as the area and the volume of arbitrary surfaces and regions, and therefore provide a discrete picture of quantum geometry at the Planck scale.
PACS number(s): 04.60.Ds, 75.25.+z
e_1
S_1
γ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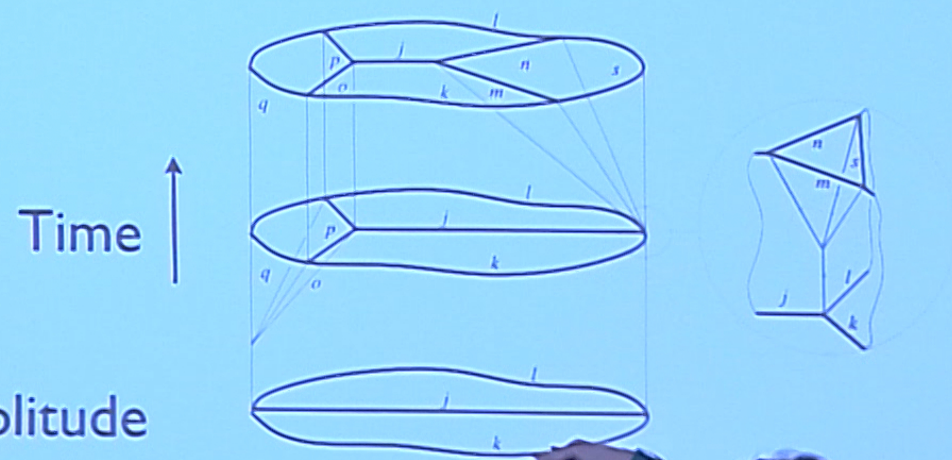
NUCLEAR PHYSICS B
ELSEVIER
Nuclear Physics B 442 (1995) 593–619
Discreteness of area and volume in quantum gravity
Carlo Rovelli, Lee Smolin
Department of Physics, University of Pittsburgh, Pittsburgh, PA 15260, USA
Center for Gravitational Physics and Geometry, Department of Physics, Pennsylvania State University, University Park, PA 16802-6360, USA
Received 2 November 1994; accepted 20 March 1995
Abstract
We study the operator that corresponds to the measurement of volume, in non-perturbative quantum gravity, and we compute its spectrum. The operator is constructed in the loop representation, via a regularization procedure; it is finite, background independent, and diffeomorphism-invariant, and therefore well defined on the space of diffeomorphism invariant states (knot states). We find that the spectrum of the volume of any physical region is discrete. A family of eigenstates are in one to one correspondence with the spin networks, which were introduced by Penrose in a different context. We compute the corresponding component of the spectrum, and exhibit the eigenvalues explicitly. The other eigenstates are related to a generalization of the spin networks, and their eigenvalues can be computed by diagonalizing finite dimensional matrices. Furthermore, we show that the eigenstates of the volume diagonalize also the area operator. We argue that the spectra of volume and area determined here can be considered as predictions of the loop-representation formulation of quantum gravity on the outcomes of (hypothetical) Planck-scale sensitive measurements of the geometry of space.
e_1
S_1
γ
$A|\psi_\Gamma\rangle = 8\pi\gamma L^2_{\rm Planck} \sum_{p\in S\cup\Gamma} \sqrt{j_p(j_p+1)}\,|\psi_\Gamma\rangle$
with $L_{\rm Planck} = \sqrt{\frac{\hbar G}{c^3}} = 1.6\times 10^{-35} m$

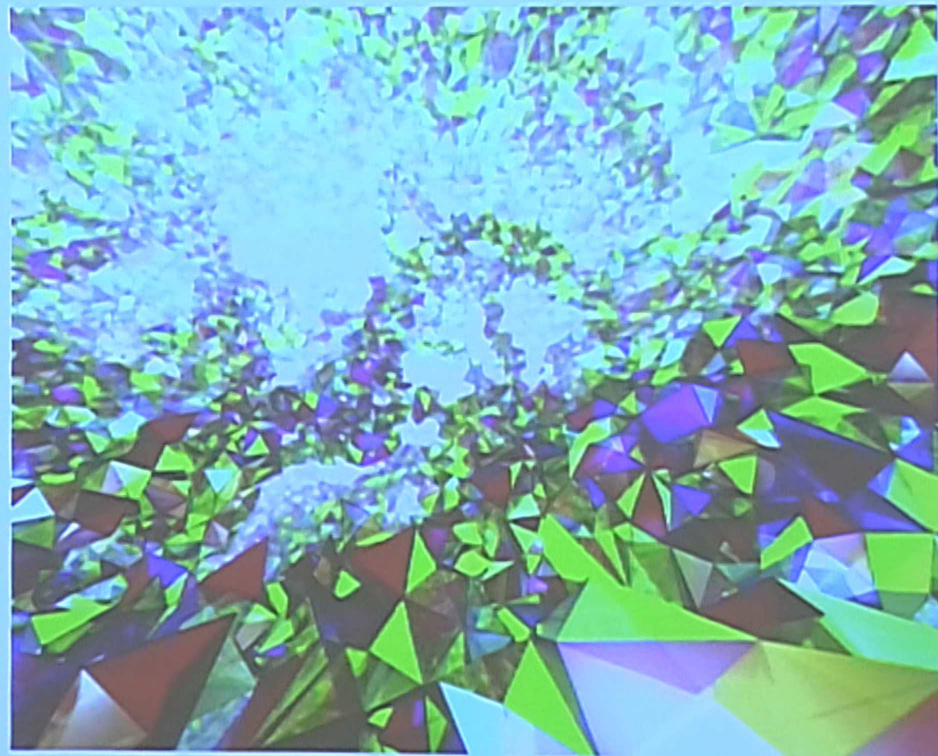
And the dynamics?

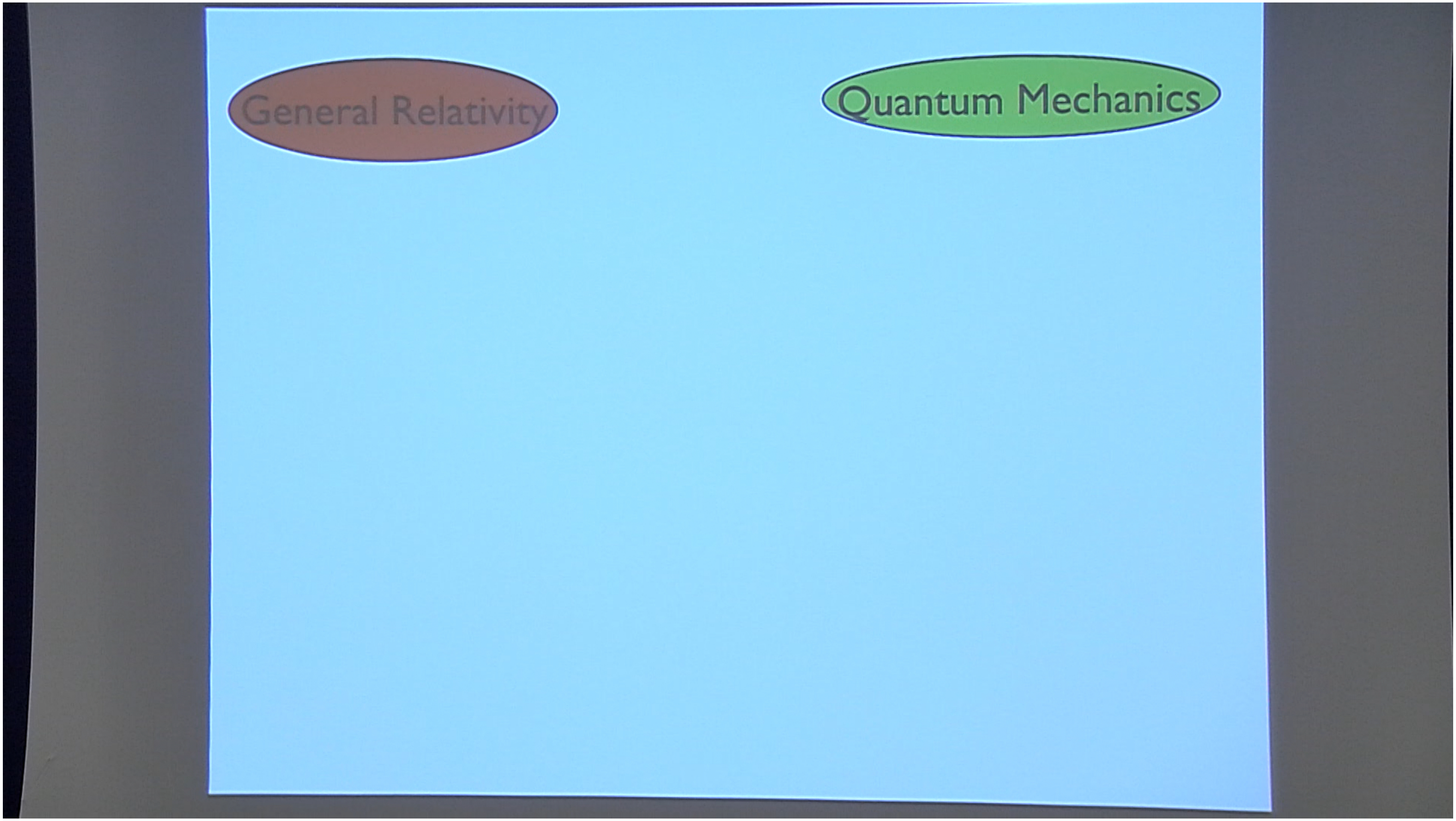
- Canonical approach: solve the Hamiltonian constraint...
- Spin Foam framework: the path integral à la Feynman...

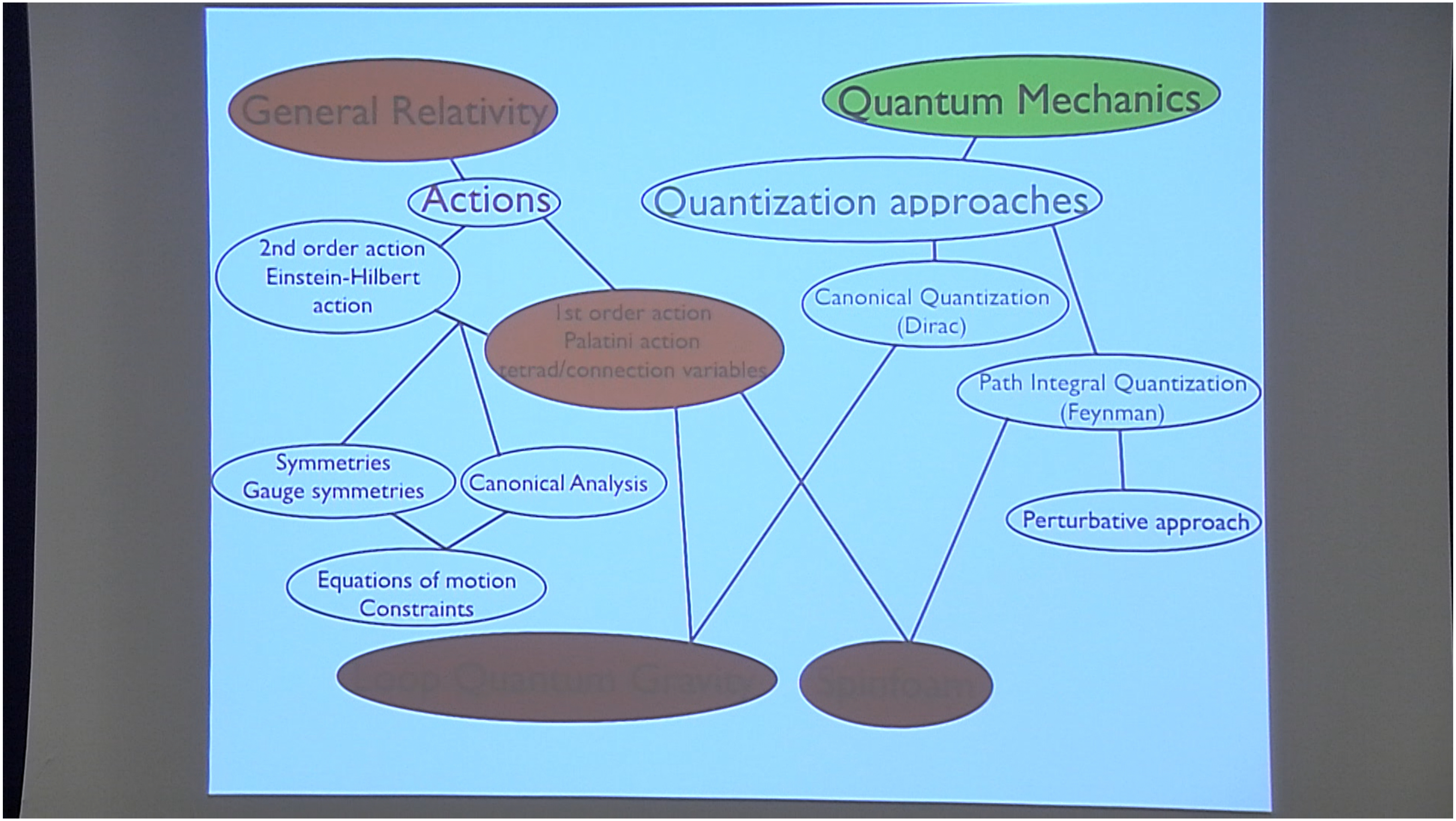


Transition amplitude between spin network states of Loop Quantum Gravity

Loop Quantum Gravity/ Spinfoam

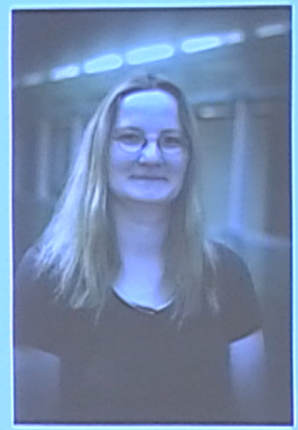



General Relativity
Quantum Mechanics

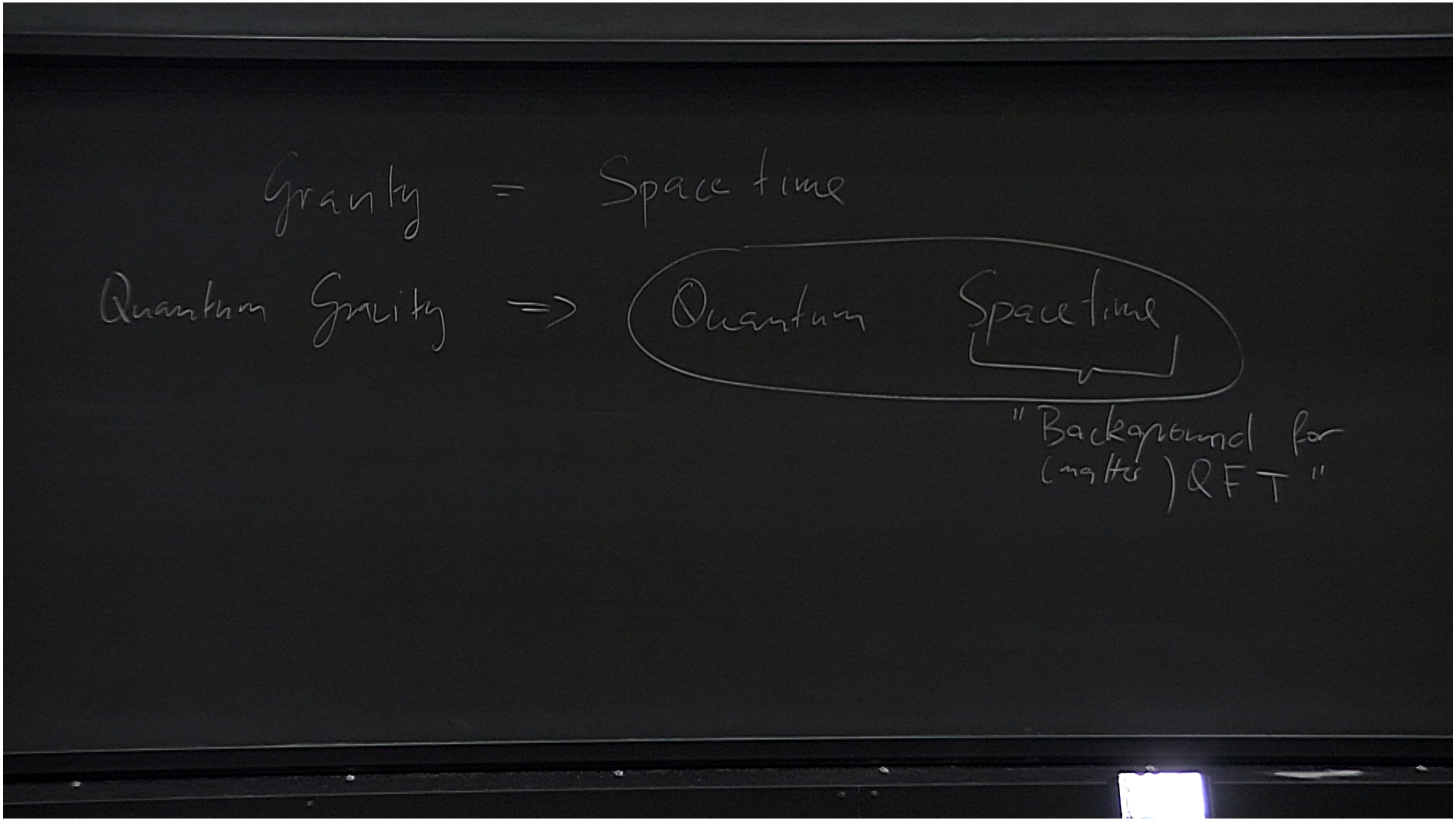


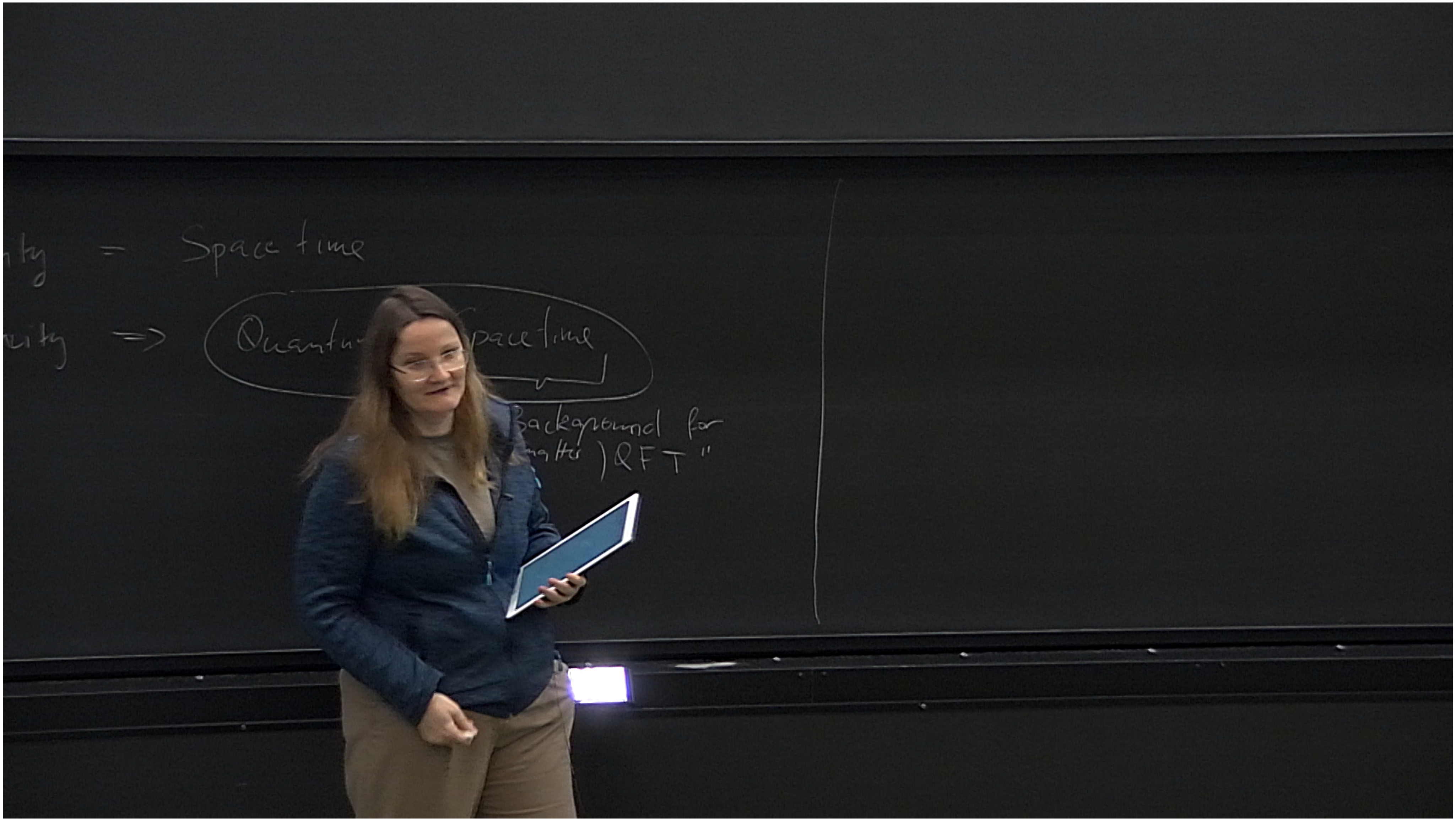
General Relativity
Quantum Mechanics
Actions
Quantization approaches
2nd order action
Einstein-Hilbert
action
1st order action
Palatini action
tetrad/connection variables
Canonical Quantization
(Dirac)
Path Integral Quantization
(Feynman)
Symmetries
Gauge symmetries
Canonical Analysis
Perturbative approach
Equations of motion
Constraints

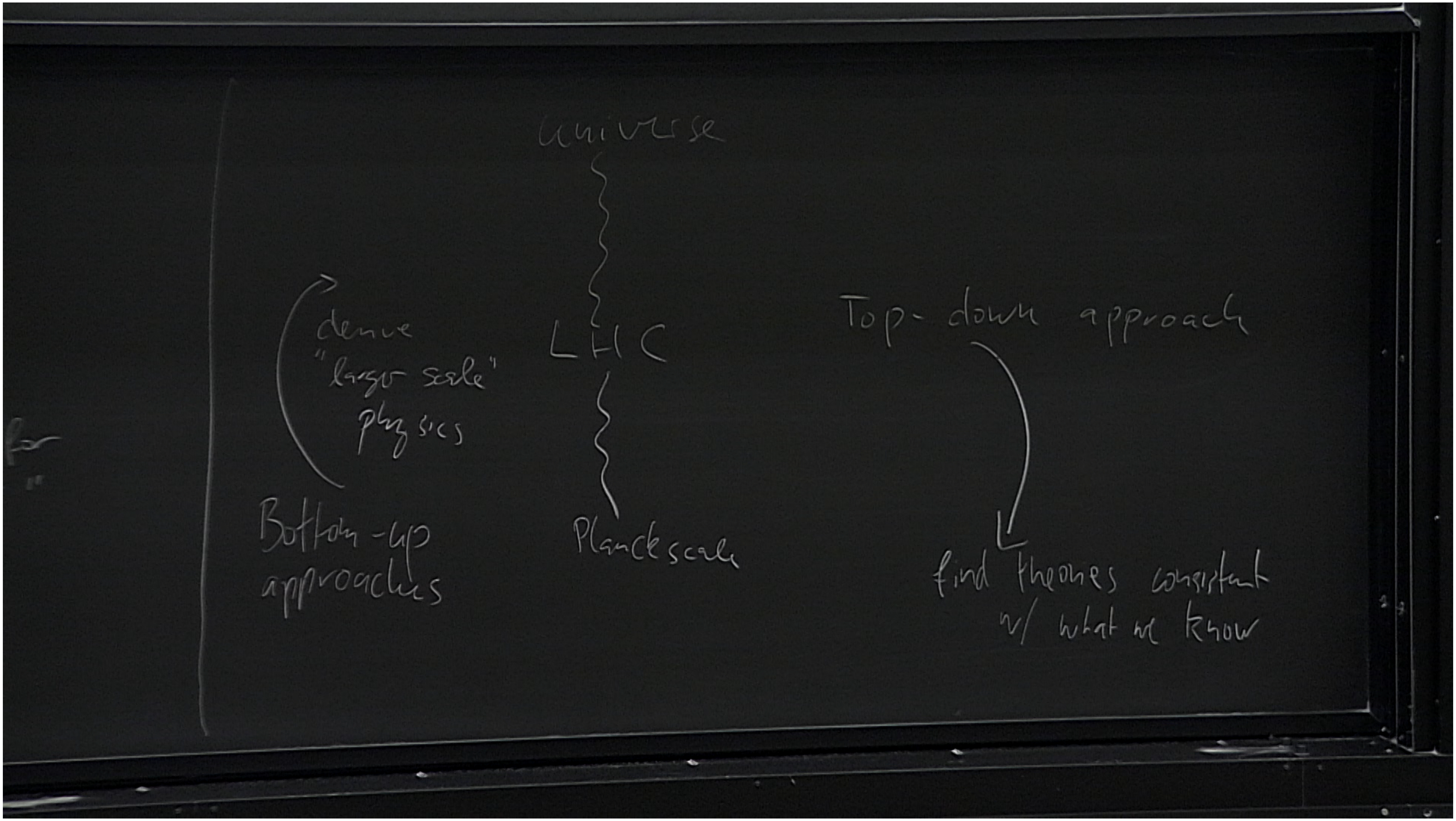
Now, ...

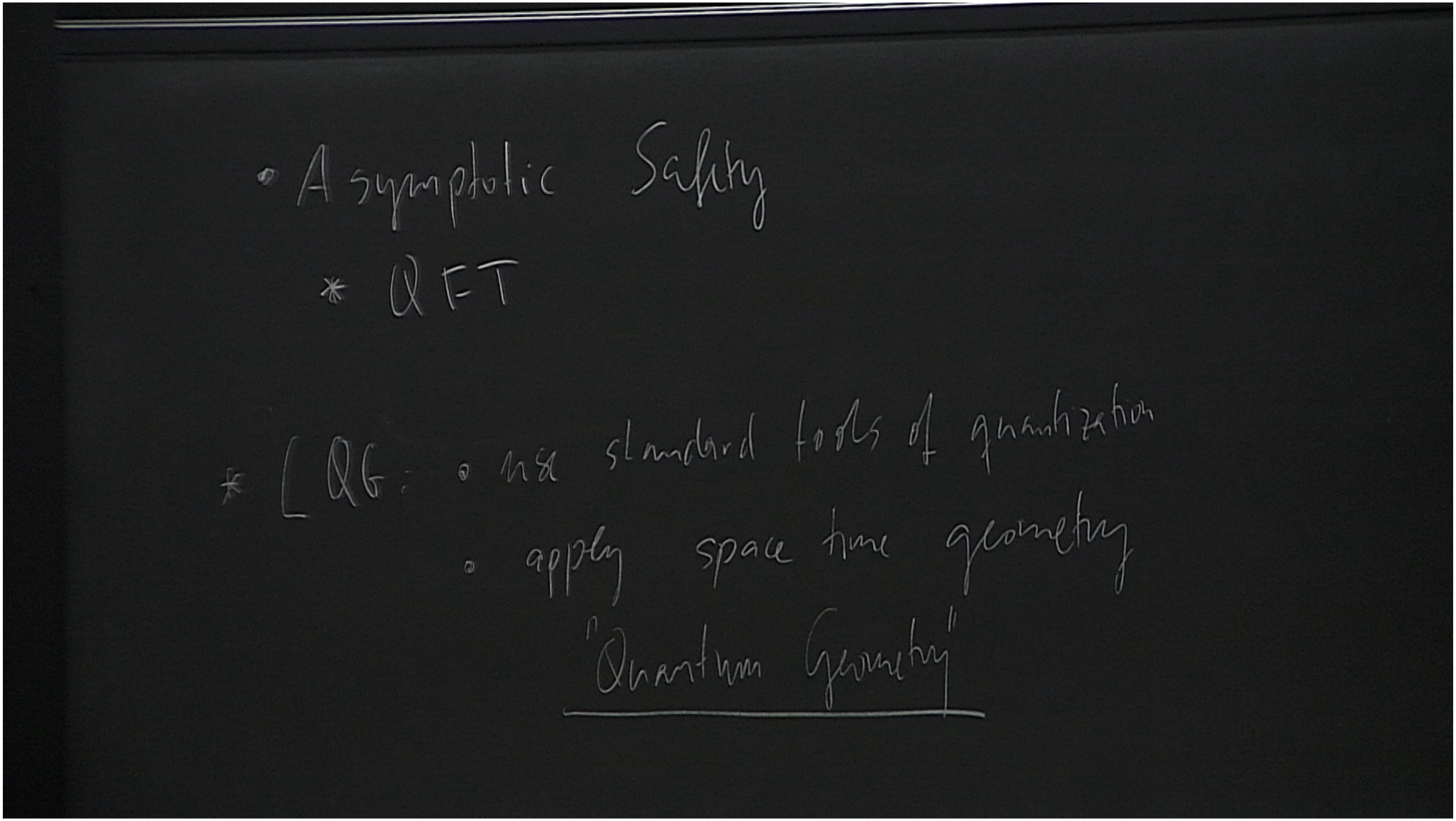


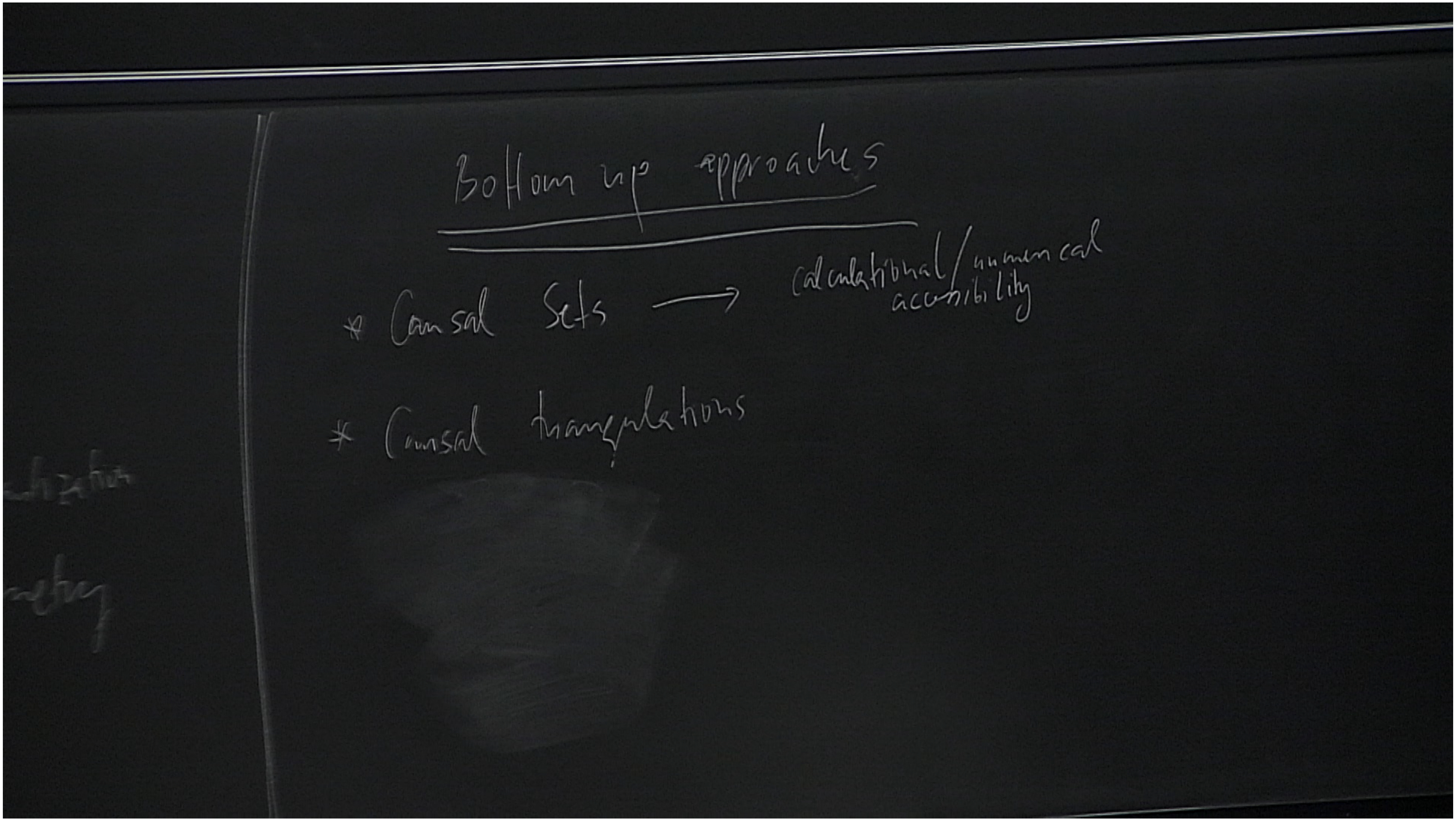
- Bianca Dittrich, on the different approaches to Quantum Gravity


Gravity = Spacetime
Quantum Gravity => Quantum Spacetime
"Background for (matter) QFT"


ity = Space time
uity => Quantum Spacetime
Background for
matter) QFT"


universe
LHC
Planck scale
dense
"large scale"
physics
Bottom-up
approaches
Top-down approach
find theories consistent
w/ what we know


• Asymptotic Safety
* QFT
* LQG: • use standard tools of quantization
• apply space time geometry
"Quantum Geometry"


Bottom up approaches
* Causal Sets ⟶ calculational/numerical accessibility
* Causal triangulations