Title: Introduction to Quantum Gravity

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Abstract:

INTRODUCTION TO QUANTUM GRAVITY

Daniele Oriti

Perimeter Institute for Theoretical Physics, Canada

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Microsoft Windows xp Professional

PLAN AND AIM OF THE TALK

- Plan
  - Quantum Gravity: what is the problem, why we care and why is difficult
  - possible strategies/points of view and some current approaches (briefly)
  - one example: group field theories and spin foam models
  - back to physics? from Planck to here....
- Aim
  - general overview and motivation
  - some basic concepts
  - context for technical talks
  - cautionary remarks: no technical details, no real review of past or recent results, no history of subject .... and no strings

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WHAT WE KNOW ABOUT GRAVITY

- gravitational physics well described by GR[1]
  - well-tested in solar system and several astrophysical systems (e.g. pulsars)
  - well-tested on earth (Newtonian approx.) down to $10^{-4}cm$
  - "implicitly well-tested" at nuclear and sub-nuclear scales (down to quark scale $10^{-18}cm$)
  - "implicitly tested" at cosmological scales, as background field for quantum matter fields
  - basis of our description of astrophysics and cosmology
- basic lesson from GR
  - Gravitational field is spacetime geometry $g_{\mu\nu}(x) \rightarrow$ spacetime itself is physical system, interacting locally with other fields $G_{\mu\nu}(g(x)) \propto T_{\mu\nu}(x)$
  - there is no background stage over which things happen, if not as approximation (background independence)
  - deeper understanding of gravity is deeper understanding of spacetime structure and dynamics

[1] Rychkov '08, Lammerzahl '06

What we don't know about gravity

- breakdown of GR for strong gravitational fields/large energy densities → spacetime singularities → quantum effects expected to be important
  - main examples: inside black holes, cosmological singularity (big bang)
- interaction with quantum matter (and gauge) fields: no complete description if gravity not quantized → either gravity treated as background field or quantum properties of matter neglected
  - signs of this incompleteness: a) black hole entropy and radiation suggest microscopic (quantum) structure of spacetime; b) early universe and origin of inflation (what is the inflaton? trans-planckian modes?)
- large scales puzzles: "dark matter" and "dark energy" → either 95% of the content of the universe is unknown/not understood or we do not understand correctly the dynamics of spacetime on very large (galactic and cosmological) scales
  - in the second case, we need better theory of spacetime to explain modifications of GR necessary to account for observations - quantum origin of large scale modifications (e.g. cosmological constant)?
- not least: conceptual/philosophical schizophrenia due to the very different foundations of General Relativity and Quantum Mechanics

GOAL

A new quantum theory of spacetime microscopic structure and dynamics, reproducing known GR description of gravity as a continuum geometry and matter at appropriate scale, and its corrections/modifications, if needed

- how to get there? many possible approaches
  - quantization of (modified/extended) GR
    - Loop QG, (continuum) spin foam models
  - quantization of some discrete geometric theory, sort of “reduced to essential”version of GR
    - Regge calculus, (causal) dynamical triangulations, causal sets, (discrete) Spin Foam models
  - definition of quantum dynamical model of pre-geometric and pre-spacetime d.o.f. from which a notion of spacetime and geometry emerges only in some limit
    - Quantum Graphity, Matrix Models, analog gravity models
  - different approaches/perspectives not mutually exclusive or necessarily incompatible

WHY IS IT DIFFICULT?

- no background spacetime: a) even if one retains geometry/spacetime as fundamental → quantum superposition of geometries/spacetime; b) if they are not, fundamental theory must be formulated in absence of them
  - no background spacetime → no locality, no causality, no symmetries,....(no spacetime dimensionality?).....
  - what is quantum mechanics (or QFT) in absence of spacetime?
- just quantize GR! → GR is highly complicated (diffeomorphism invariance, non-linearity, ...) - LQG only partially successful approach
- diffeo invariance (background independence): what is a QG observable (no dependence on spacetime point - no QFT n-point functions)?
- dynamical quantum geometry.....dynamical quantum topology? superposition of spacetime topologies?
- emergence of (continuum) spacetime
  - what from? what are the "atoms of space"?
  - what type of spacetime? what sort of geometry? signature? dimension?
- experiments and phenomenology? QG effects too much suppressed? recent progress (e.g. tests of fundamental symmetries).....more later....

QUANTIZE GR: LOOP QG AND SPIN FOAM MODELS[3]

- 1st order gravity, basic variables: Lorentz connection → holonomies (group elements) , triad (Lie algebra element) (Ashtekar, '87)
- canonical quantization: define kinematical states and define and impose quantum constraints - Gauss (done), spatial diffeomorphism (done), Hamiltonian (in progress, but difficult)
- states of gravitational field given by spin networks (graphs labelled by group representations) (Rovelli, Smolin '95) → geometry encoded in combinatorics and algebra
- *unique* (LOST theorem) kinematical vacuum = no geometry; excitations of geometry along edges ("chunks of area") and vertices ("chunks of volume") - discrete spectra for geometric operators (area, volume, length,...)
- interesting physical results at kinematical level: black hole entropy calculation[2] (see Borja's talk), ...

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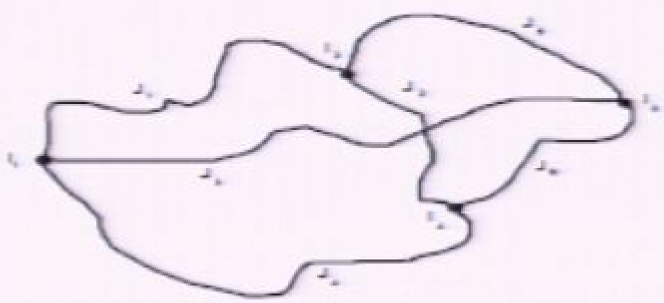
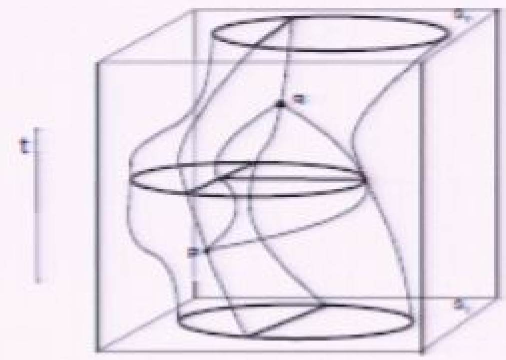
[2] Ashtekar, Krasnov, Rovelli, Lewandowski, Barbero, Borja, Diaz-Polo, Agullo,...

[3] Ashtekar, Lewandowski, Thiemann, Rovelli, Smolin, Dittrich, Reisenberger, Baez, Barrett, Crane, Freidel, Krasnov, Perez, Livine, Speziale, Oriti, ...

Loop Quantum Gravity and Spin Foam models

- alternative route to quantum dynamics: covariant sum over histories
- fundamental histories are given by spin foams (2-complexes labelled by group representations) (Resisenberger, Rovelli, Baez, Barrett, Crane,...), with boundary data encoded in spin networks





- dynamics defined by choice of quantum amplitudes for spin foams with:

$$Z = \sum_{\sigma|\Psi,\Psi'} w(\sigma) \sum_{\{J\}} \prod_f A_f(J_f) \prod_e A_e(J_{f|e}) \prod_v A_v(J_{f|v})$$

- several models; recently, new spin foam models by Engle,Pereira, Rovelli, Livine, and Freidel, Krasnov (see Engle's and Pereira's talks)

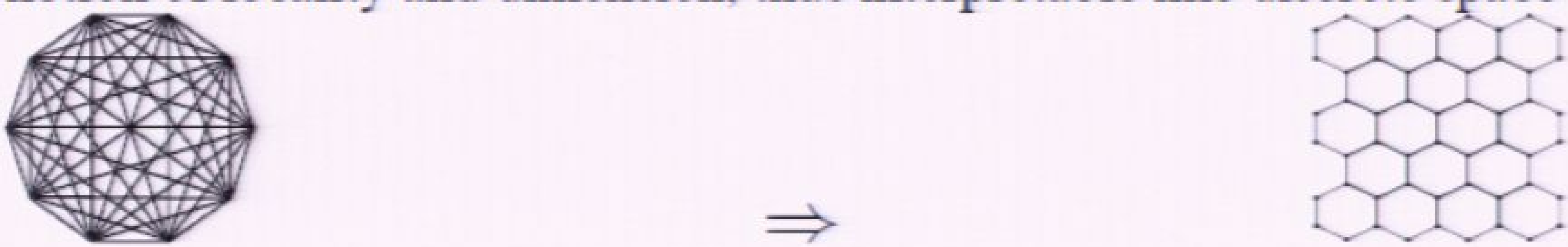
QUANTIZE DISCRETE GEOMETRY: DYNAMICAL TRIANGULATIONS[4]

- triangulate given continuum manifold → discrete spacetime obtained by gluing D-simplices
- geometry is about distances → fundamental variables: edge lengths
- discretize GR action → S_{Regge} = Regge action for simplicial gravity
- edge lengths = a; geometry encoded in combinatorics
- theory given by: $Z(\Lambda, a, G) = \sum_T \frac{1}{sym(T)} e^{i S_{Regge}(T,a,G,\Lambda)}$, T = triangulations (fixed topology)
- aim: continuum limit (with correct dimensionality) as $a \to 0$ and T is refined (G,Λ get renormalised)
- in Lorentzian setting, for trivial topology and some additional (causal) restrictions, there are indications of good continuum limit

[4] Ambjorn, Loll, Jurkiewicz, Benedetti, ...

EMERGENT GRAVITY: QUANTUM GRAPHITY[5]

- a model of emergent locality (therefore, emergent space)
- take complete graph of N vertices and $\frac{N(N-1)}{2}$ edges, with edges labelled by parameters $j = 0, 1$ and $m = -j, 0, +j$, with $j = 0$ interpreted as absence of corresponding edge
- assignment of labels to complete graph identifies subgraph
- define dynamics by means of total graph Hamiltonian H_G, and treat as statistical mechanics system at temperature (time) T
- analyze dynamics leading to "local"graph, i.e. regular lattices with notion of locality and dimension, thus interpretable like discrete space



- study possibility of emergence of gravitational and matter fields as collective excitations of fundamental d.o.f. (j, m) - similar to condensed matter models (Wen, Levin, Gu,...)

[5] Markopoulou, Konopka, Smolin, Severini,....

EMERGENT GRAVITY: CONDENSED MATTER ANALOG MODELS[7]

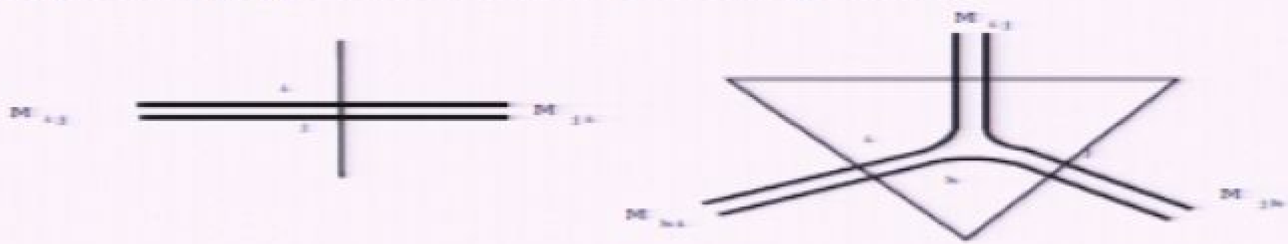
- suggestions from condensed matter perspective[6]:
  - spacetime as a condensate/liquid phase of fundamental discrete constituents
  - continuum is hydrodynamic approximation
  - General Relativity is effective description of collective variables
- quasi-particles (excitation over fluid) see effective spacetime and geometry
- hydrodynamics can approximate gravitational dynamics for effective metric
- examples: Bose-Einstein condensates, superfluid fermionic Helium ^3He at $T \rightarrow 0$, even generic fluids:
- see Sindoni's talk

[6] Jacobson, Hu, Volovik, Laughlin

[7] Unruh, Volovik, Visser, Liberati, Weinfurtner, Girelli, Sindoni, ...

EMERGENT GRAVITY: MATRIX MODELS[8]

- define for an $N \times N$ hermitian matrix M_{ij} the action $S(M) = \frac{1}{2} tr(M^2) - \frac{\lambda}{3!\sqrt{N}} tr(M^3)$
- and the partition function $Z = \int dM \, e^{-S(M)} = \sum_T \frac{1}{sym(T)} \lambda^{n_2(T)} N^{\chi(T)}$
- Feynman graphs are dual to 2d triangulations



- 2d QG as a sum over 2d triangulations of all topologies
- in suitable (double scaling) limit, equivalent to path integral of 2d gravity on sum over 2d surfaces

[8] David, Ginsparg, Di Francesco, Kazakov, Migdal, ...

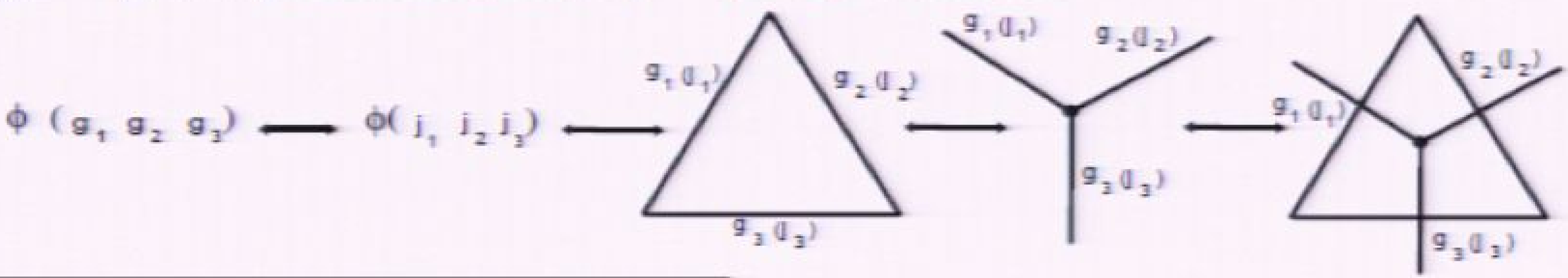
One more example:

Group Field Theory

GFT FORMALISM[9]: KINEMATICS

GFTs are a QFT description for microscopic "space quanta", that can be depicted as simplices or graphs labeled by "pre-geometric" data

- consider a complex field ϕ over D copies of a group manifold G (e.g. Lorentz group, for QG): $\phi(g_1, ..., g_D) : \underbrace{G \times ... \times G}_{D} \rightarrow \mathbb{C}$
- field can be expanded in modes: $\phi(g_1, ..., g_D) = \sum_{J_1,...,J_D} \phi^{J_1...J_D}_{k_1 l_1,...,k_D l_D} D^{J_1}_{k_1 l_1}(g_1)...D^{J_D}_{k_D l_D}(g_D)$
- $\phi \simeq$ fundamental building block of quantum geometry - "2nd quantized (D-1)-simplex" (or spin net vertex)
- arguments of field have interpretation of geometric data $g_i \simeq$ gravity holonomies; $J_i \simeq$ (D-2)-volumes



[9] Boulatov, Ooguri, De Pietri, Freidel, Krasnov, Rovelli, Oriti, Perez, Livine, Ryan,

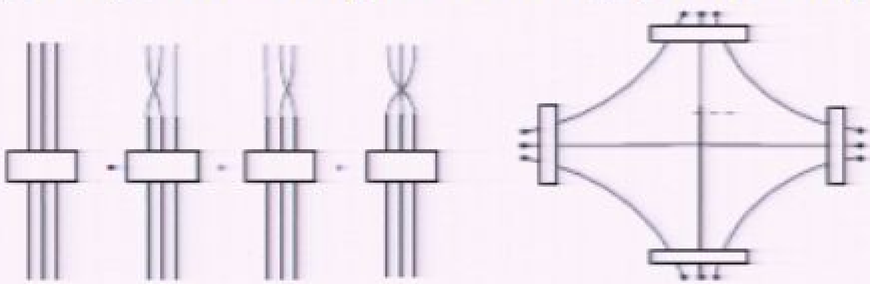
GFT FORMALISM: CLASSICAL DYNAMICS

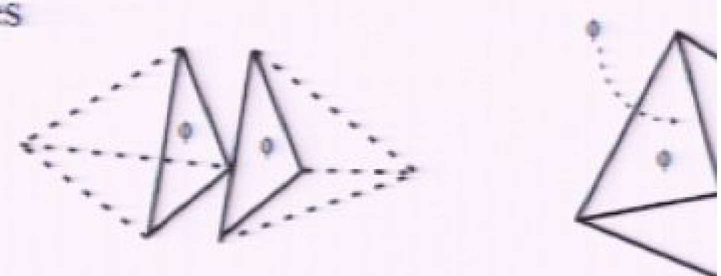
- GFT action $S(\phi)$ characterized by non-local pairing of field variables

$$S_D(\phi,\lambda) = \frac{1}{2}\prod_{i=1,..,D}\int dg_i d\tilde{g}_i \phi(g_i)\mathcal{K}(g_i\tilde{g}_i^{-1})\phi(\tilde{g}_i) +$$
$$+ \frac{\lambda}{(D+1)!}\prod_{i\neq j=1}^{D+1}\int dg_{ij}\phi(g_{1j})...\phi(g_{D+1j})\,\mathcal{V}(g_{ij}g_{ji}^{-1})$$

  exact choice of the $\mathcal{K}$ and $\mathcal{V}$ defines the model

- combinatorics of arguments in $\mathcal{V}$ reflects gluing of (D-2)-faces in a D-simplex, basic interaction of (D-1)-simplices to form D-simplices
  $\mathcal{K} \rightarrow$ gluing of D-simplices along (D-1)-simplices



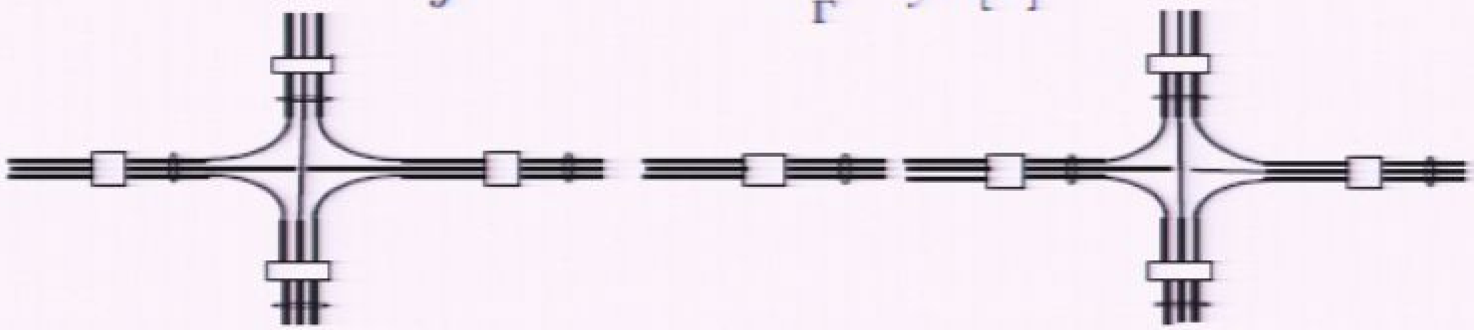


- generalization of matrix models for 2d QG:
  more complicated combinatorics + group-theoretic data

GFT FORMALISM: QUANTUM DYNAMICS

- the quantum theory is defined by the Feynman expansion:

$$Z = \int \mathcal{D}\phi \, e^{iS[\phi]} = \sum_{\Gamma} \frac{\lambda^{N_\Gamma}}{sym[\Gamma]} Z(\Gamma)$$



- Feynman diagrams Γ are fat graphs/cellular complexes topologically dual to D-dimensional triangulated (pseudo-)manifolds of arbitrary topology
- Feynman amplitudes are written in configuration (g_i) or momentum (J_i) space

$$Z(\Gamma) = \prod \int dg_i \, A_\Gamma(g_i) = \prod \sum_{J_i} A_\Gamma(J_i)$$

- $Z(\Gamma)$ are, in momentum space, Spin Foam models (labelled 2-complexes), histories of spin networks, and, in most models, directly related to/derived from discretization of continuum gravity action $\Rightarrow Z(\Gamma) \simeq$ discrete QG path integral
- merging of structures and insights from different approaches (LQG, QRC, DT)

EXAMPLE: 3D RIEMANNIAN QUANTUM GRAVITY

$G = SU(2)$. Real field: $\phi(g_1, g_2, g_3) = \phi(g_1 g, g_2 g, g_3 g) : SU(2)^{\times 3} \to \mathbb{R}$

$$S[\phi] = \frac{1}{2}\int dg_i\, \phi(g_1, g_2, g_3)^2 + \frac{\lambda}{4!}\int dg_j\, \phi(g_1, g_2, g_3)\phi(g_3, g_5, g_4)\phi(g_4, g_2, g_6)\phi(g_6, g_5,$$

The Feynman amplitude for this model is:

$$Z(\Gamma) = \prod_{e*\in\Gamma}\int dg_{e*} \prod_{f*} \delta(\prod_{e*\in\partial f*} g_{e*})$$

same result from path integral quantization of 3d Riemannian gravity on triangulation Δ dual to Γ

$$S_{\mathcal{M}}(e,\omega) = \int_{\mathcal{M}} tr(e \wedge F(\omega)) \to S_{\Delta}(X_e, g_{e*}) = \sum_e tr\left(X_e G_e(g_{e*})\right)$$

$$Z(\Gamma) = \prod_e \int_{su(2)} dX_e \prod_{e*} \int_{SU(2)} dg_{e*}\; e^{i\sum_e tr(X_e G_e(g_{e*}))}$$

in representation space, $Z(\Gamma)$ gives Ponzano-Regge spin foam model

BACK TO GEOMETRY AND SPACETIME

- Big open issue: recover description of gravity in terms of continuum spacetime and geometry
- Several limits/approximations intertwined (but conceptually distinct):
  - semi-classical
  - continuum
  - large scale
- exact nature and manifestation of the problem depend on details of QG framework chosen
- the problem is:
  - conceptual - from no spacetime to geometry: which d.o.f.? which organization principle? which observables?
  - huge gap in scales (quark/Planck $\simeq$ human/quark !!!)
  - of course, technical/mathematical difficulties....
- nevertheless, several ideas, avenues and many results leading close to testable physics $\rightarrow$

BACK TO PHYSICS!

- Loop Quantum Cosmology[10]
  - use symmetry reduction to drastically simplify theory
  - very intriguing results (singularity avoidance, semiclassical limit, effective classical dynamics,...)
- LQG and SF coherent states and n-point functions[11]
  - background independent formalism for n-point functions, based on coherent states of quantum geometry
  - computation of gravity correlations at simplicial level (lowest order)
- statistical GFT and GFT hydrodynamics (a proposal - Oriti '07)

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[10] Bojowald, Ashtekar, Singh, Corichi, ...

[11] Thiemann, Bahr, Rovelli, Modesto, Speziale, Bianchi, Alesci, ...

BACK TO PHYSICS!

- condensed matter analog gravity models
  - concrete models of emergence of geometry and effective spacetimes
  - examples of possible phenomenological consequences of emergence
- non-commutative models of QG[12]
  - non-commutative geometry as general framework for effective QG kinematics (weak gravity but quantum effects still relevant)
  - effective NC QFT for matter fields (e.g. from SF and GFT[13])

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- Quantum Gravity Phenomenology (deformation/breaking of fundamental symmetries, minimal length scenarios, ...)[14] $\rightarrow$ experiments may be already waiting for us!

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[12] Majid, Kowalski-Glikman, Arzano,...

[13] Freidel, Livine, Noui, Girelli, Oriti,...

[14] Amelino-Camelia, Smolin, Hossenfelder, ...

CONCLUSIONS AND OUTLOOK

- Quantum Gravity still an open problem
- truly fundamental, and therefore challenging, physics
- big questions and important physical consequences
- ....not yet there....but we are progressing fast and learning a lot, in many different directions....