Title: Reality Check for Quantum Gravity

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Abstract:

Reality Check for Quantum Gravity

Quantum Gravity Afternoon
Perimeter Institute,
22 May 2014

Renate Loll, IMAPP - Institute for Mathematics, Astrophysics and Particle Physics, Radboud University Nijmegen

Thursday, May 22, 14

Reality, *what reality*?

- re-examine our aims, the problems we encounter, and the tools needed to overcome them
- a plea for using numerical tools to explore the nonperturbative regime of quantum gravity and provide "reality checks"
- some lessons from Causal Dynamical Triangulations (CDT)

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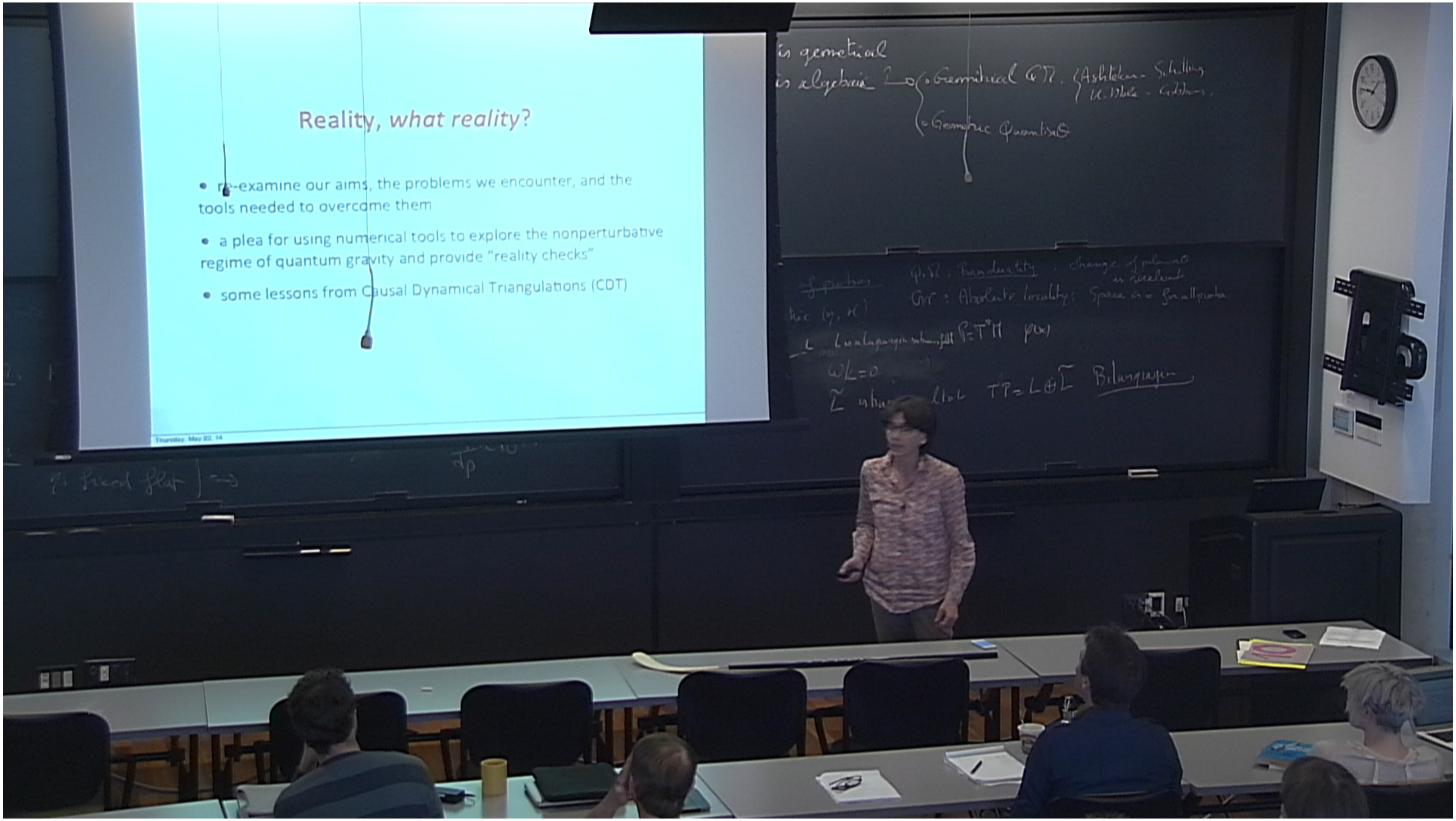
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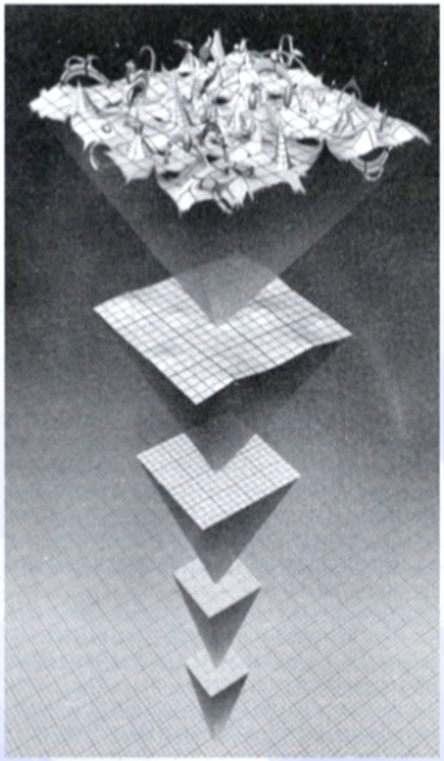
Fundamental issues in quantum gravity

- What are the quantum laws underlying General Relativity, and how are we likely to find them?
- Are space, time, causality, ..., fundamental or merely emergent on macroscopic scales?
- Can we explain gravitational attraction and the observed large-scale structure of our universe from first principles?
- What is the quantum microstructure of spacetime, and what are its phenomenological implications?



(zooming in on the Planck scale)

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Quantum gravity: where do we stand?

- perturbative quantum gravity does not work ("non-renormalizable")
- we have several nonperturbative candidate theories, working from different premises
- they are too incomplete and/or have too many free parameters to make any solid predictions; comparing them is also difficult
- there is hardly any quantum gravity phenomenology to speak of
- in the absence of experimental verification, and with $l_{Pl} = l_{LHC} \times 10^{-16}$, it is even difficult to nail down what constitutes true "progress"

Still, some lessons have been learned (or so we hope!), both general and more specific.

A small personal subselection

• low-dimensional toy models of quantum gravity can play a role in providing "proofs of principle", but this is in many respects limited, and can be misleading (and one usually ends up spending far too much time on them ...)

• by contrast, gravity in 4D has local excitations, and its quantum theory will need to be regularized/renormalized; it cannot be reduced to quantum mechanics, and qualitatively different tools are needed

• be wary of assertions that these issues are not there because "gravity is different" (e.g. background-independent), and that exotic and radically new ingredients are needed in its quantization

• human (and even theoretical physicists') imagination and intuition for "what happens at the Planck scale" is *very* limited; set up a theory that uses as little guess work as possible and make it robust; this will also reduce non-uniqueness; in addition, use numerical reality checks!

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Less may be more

Formulations with "exotic" ingredients lead to an *embarassment of riches* (many free parameters, no predictive power), and a backlash seems to be under way, e.g. asymptotic safety, Horava-Lifshitz gravity

Also in nonperturbative quantum gravity, we can adopt a 'radically conservative' approach in terms of input and method by

(i) being minimalist in terms of ingredients and prior assumptions, with little background structure,

(ii) using standard quantum field-theoretic methods and

(iii) using nonperturbative(*) computational tools for quantitative evaluation.

CDT quantum gravity embodies this. Despite its conceptual simplicity, it leads to nontrivial (and unexpected) results.

(*)nonperturbative = allowing for large quantum fluctuations, not just linear perturbations around a fixed, classical background metric

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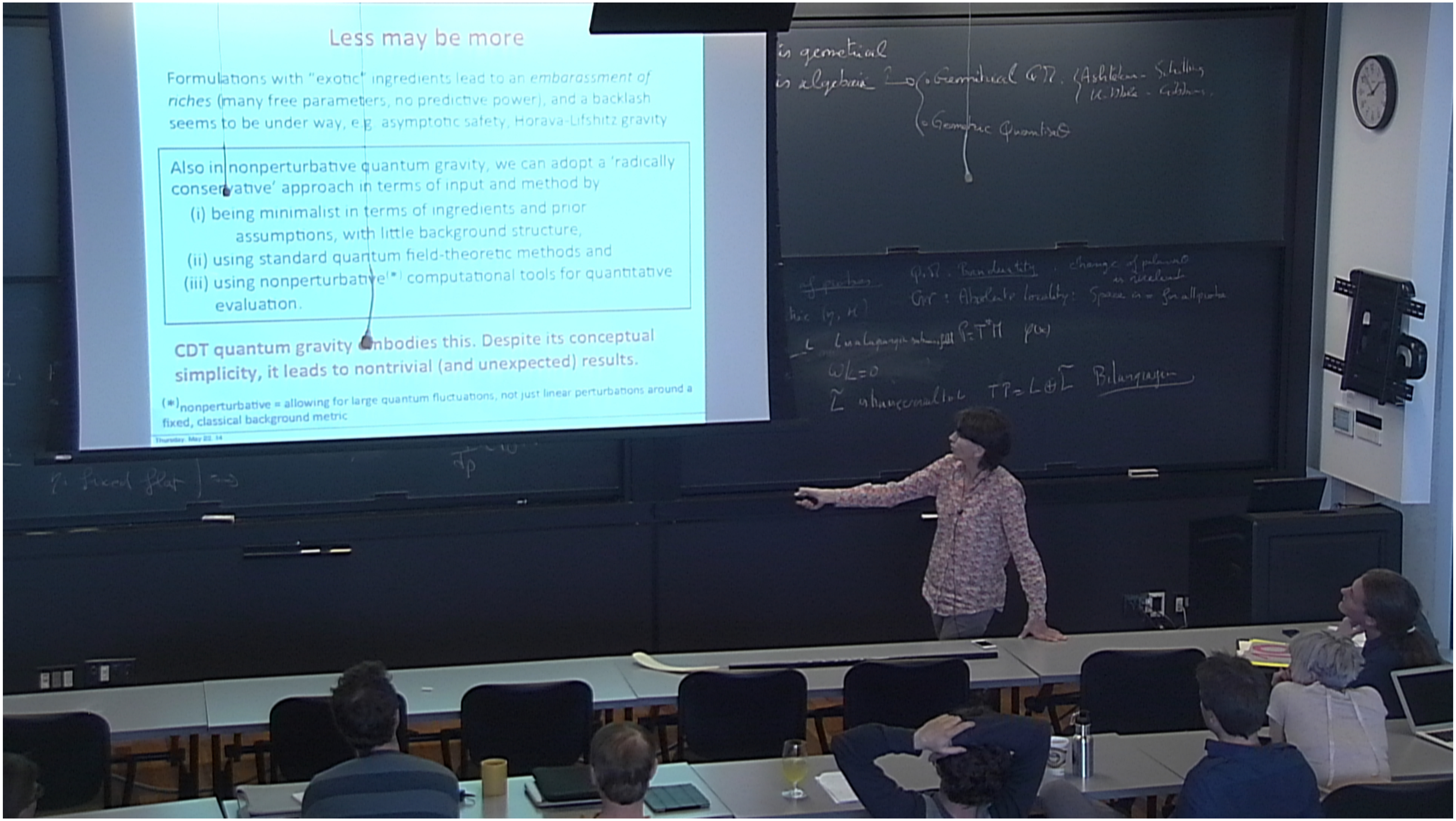
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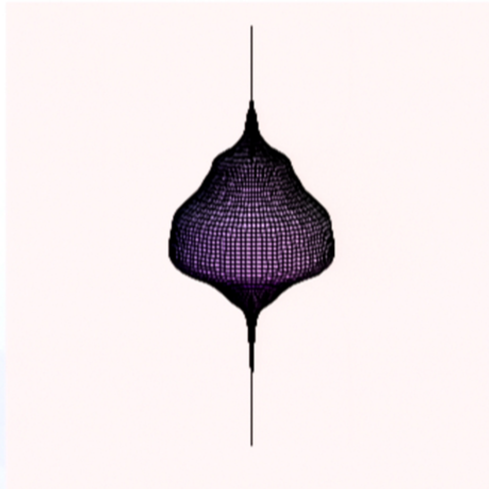
The Story of (Causal) Dynamical Triangulations

This approach to quantum gravity grew out of a confluence of ideas:



- the primacy of pure geometry in the sense of Einstein's rods and clocks (measuring distances, not metrics),
- using powerful numerical methods to describe such geometry far away from a flat-space, perturbative regime,
- subsequently, the realization that the imposition of a local causal structure on path integral histories appears to be necessary to obtain a good classical limit in 4D (DT → CDT)

(PRL 93 (2004) 131301, PRD 72 (2005) 064014, PLB 607 (2005) 205)

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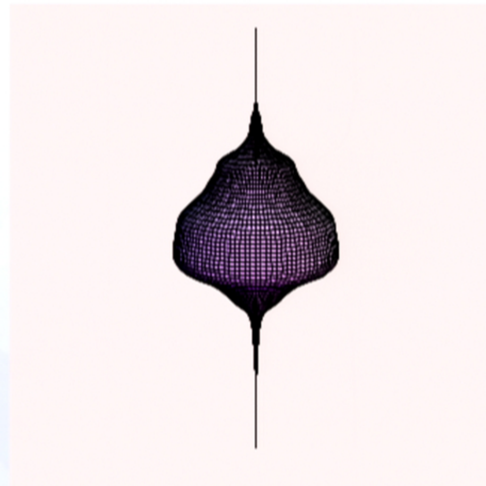

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Quantum Gravity from CDT*

is a *nonperturbative* implementation of the gravitational path integral,

$$Z(G_N, \Lambda) = \int_{\substack{\text{spacetimes} \\ g \in \mathcal{G}}} \mathcal{D}g \; e^{iS^{\mathrm{EH}}_{\mathrm{G_N},\Lambda}[g]}$$

(Newton's constant: G_N; cosmological constant: Λ)

much in the spirit of lattice quantum field theory, but based on *dynamical* triangular lattices, reflecting the dynamical nature of spacetime geometry:

$$Z(G_N, \Lambda) := \lim_{\substack{a \to 0 \\ N \to \infty}} \sum_{\substack{\text{inequiv.} \\ \text{triangul.s} \\ T \in \mathcal{G}_{a,N}}} \frac{1}{C(T)} \; e^{iS^{\mathrm{Regge}}_{\mathrm{G_N},\Lambda}[T]}$$

(UV cutoff: a; # building blocks: N; $C(T)$: |Aut(T)|)

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UV cutoff

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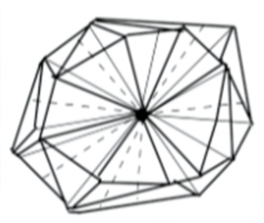
Nonperturbative 'geometry' behaves strangely

Isn't it obvious that by gluing together four-dimensional building blocks, one obtains a (quantum) spacetime of dimension 4?

No. Generically it does not happen when quantum fluctuations are large.

This feature was only gradually understood, with the help of computer "experiments". In DT quantum gravity models prior to CDT, one of two things happened to "quantum geometry" away from the cut-off scale:

it polymerized (small G_N^{bare}), $d_{eff} = 2$



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<u>The raison d'être of *Causal* Dynamical Triangulations is to fix this problem:</u>

elementary building blocks are given a Lorentzian (=light cone) structure, and gluing rules ensure a *well-behaved causal structure* overall.

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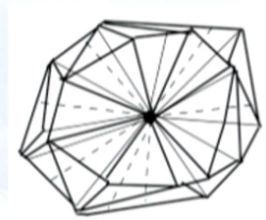

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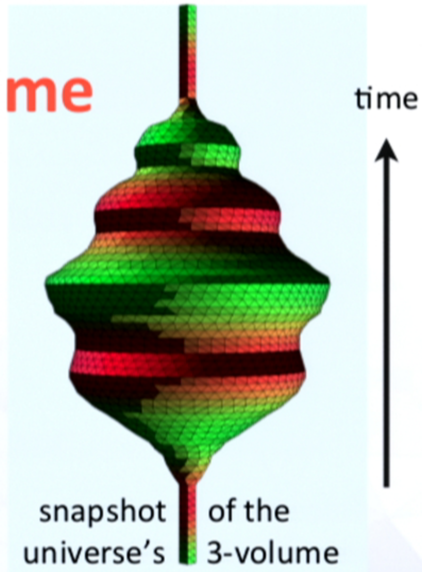
Dynamical emergence of spacetime

For suitable bare coupling constants, CDT quantum gravity dynamically produces a "quantum spacetime", that is, a ground state ("vacuum"), whose macroscopic scaling properties are ***four-dimensional*** and whose macroscopic shape is that of a well known cosmology, ***de Sitter space***.

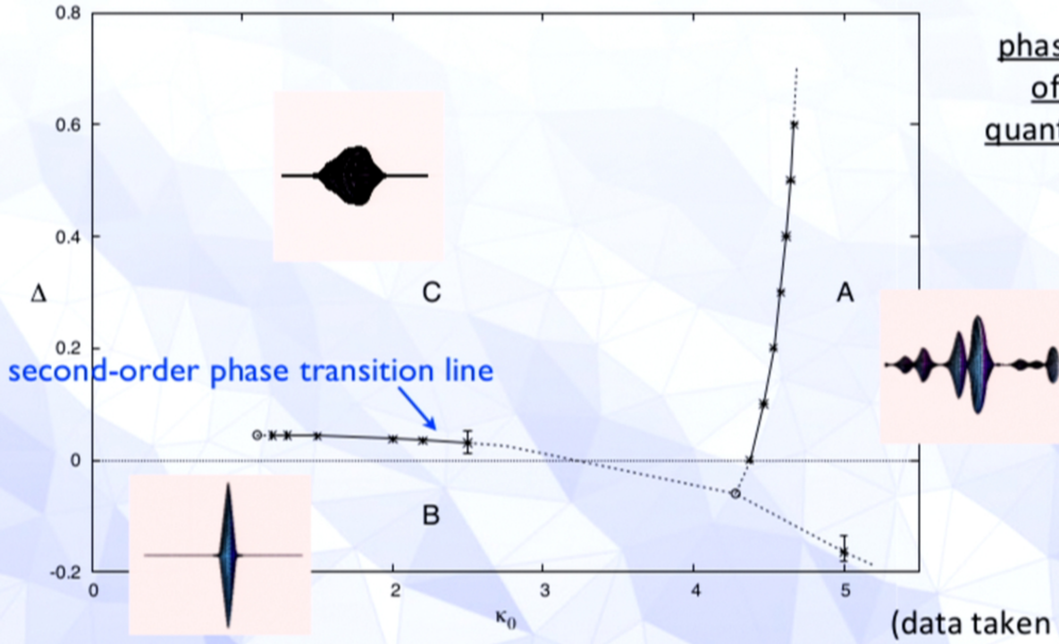


This is brought about by a ***nonperturbative*** mechanism, with "energy" (the bare action) and "entropy" (the measure, i.e. number of microscopic spacetime configurations) contributing in equal measure.

The region in coupling constant space where we see interesting physics is far away from the perturbative regime; quantum fluctuations are large and entropy matters; impossible to see e.g. in quantum cosmology.

They simply reach where other methods don't

None of the nonperturbative results and insights in 4D would have been possible without using Monte Carlo simulations: matching of volume profiles, determining Hausdorff and spectral dimensions (and uncovering the degeneracies of Euclidean ensembles), understanding the phase structure and the importance of being causal.



phase diagram of 4D CDT quantum gravity

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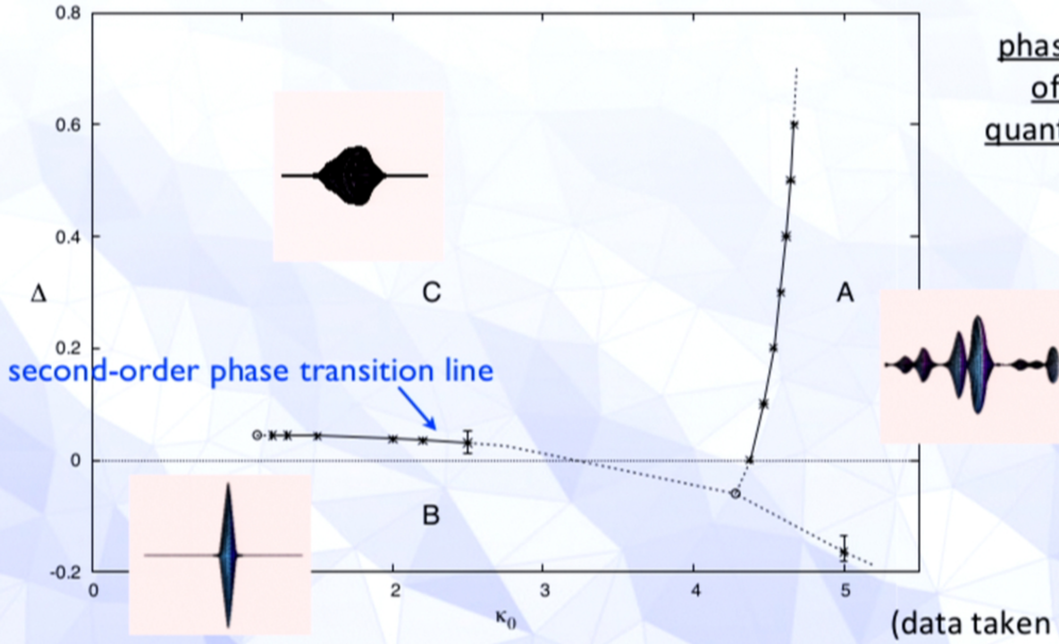

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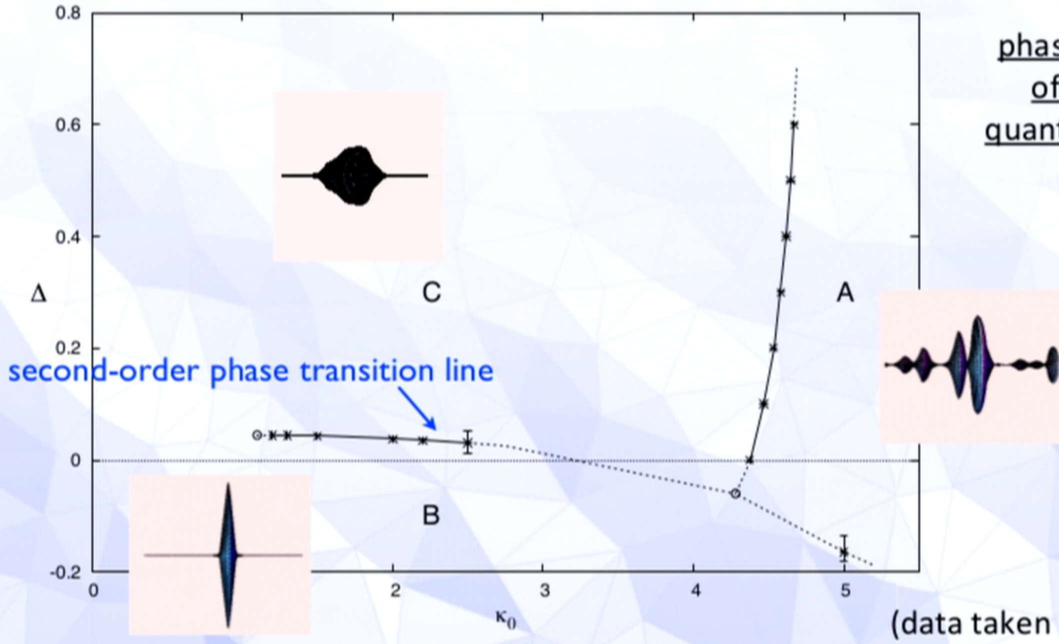

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In addition, the CDT toolbox provides a powerful "numerical lab" to perform reality checks on continuum approaches of quantum gravity, e.g. those using functional renormalization group techniques, and there is fruitful interaction; most recent example is the computation of RG flows in CDT (arXiv: 1405.4585).

Still, many in the (nonperturbative) QG community appear reluctant to accept numerical investigation as a valid tool.

Possible explanations:

- insufficient knowledge of Monte Carlo techniques, QFT&stat mech tools
- too much exposure to soluble toy models?
- strong influence from the classical GR community: proving theorems in mathematical physics?
- wrong expectations/hopes of what an interacting quantum theory of four-dimensional geometry will look like?

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