Title: New "Best Hope" for Quantum Gravity?

Date: Feb 09, 2011 02:00 PM

URL: http://pirsa.org/11020085

Abstract: How many interacting quantum (field) theories of four-dimensional geometry are there which have General Relativity as their classical limit? Some of us still harbour hopes that a quantum theory of gravity is "reasonably unique", i.e. characterized by a finite number of free parameters. One framework in which such universality may manifest itself is that of "Quantum Gravity from Causal Dynamical Triangulations (CDT)". I will summarize the rationale behind this nonperturbative formulation and CDT's main achievements in trying to explain the micro- and macro-structure of spacetime from first principles. This includes the remarkable property of "dynamical reduction" of the spacetime dimension from four to two at the Planck scale.

New "Best Hope" for Quantum Gravity?

Perimeter Institute,
9 Feb 2011

Renate Loll, Institute for Theoretical Physics
Utrecht University

New "Best Hope" for Quantum Gravity?

Perimeter Institute,
9 Feb 2011

Renate Loll, Institute for Theoretical Physics
Utrecht University

New "Best Hope" for Quantum Gravity?

Perimeter Institute,
9 Feb 2011

Renate Loll, Institute for Theoretical Physics
Utrecht University

Does Quantum Gravity really exist?

- there is no direct evidence, and little "phenomenology"
- gravity is very weak; perhaps it need not be quantized? (would still need to show consistency)

On the other hand,

- gravity is universal (and so is quantum theory, apparently)
- there exist situations where gravity is strong and short distances are involved (big bang, black hole singularities)

Perhaps the question is ill posed? Which degrees of freedom "take over" at the Planck scale (pre-geometry, spacetime foam, causal sets, ...)?

Let us agree to call this "quantum gravity" too, and let us assume that something like quantum gravity indeed exists, "grandly unified" or otherwise.

Spacetime Foam?

Does Quantum Gravity really exist?

- there is no direct evidence, and little "phenomenology"
- gravity is very weak; perhaps it need not be quantized? (would still need to show consistency)

On the other hand,

- gravity is universal (and so is quantum theory, apparently)
- there exist situations where gravity is strong and short distances are involved (big bang, black hole singularities)

Perhaps the question is ill posed? Which degrees of freedom "take over" at the Planck scale (pre-geometry, spacetime foam, causal sets, ...)?

Let us agree to call this "quantum gravity" too, and let us assume that something like quantum gravity indeed exists, "grandly unified" or otherwise.

Spacetime Foam?

Does Quantum Gravity really exist?

- there is no direct evidence, and little "phenomenology"
- gravity is very weak; perhaps it need not be quantized? (would still need to show consistency)

On the other hand,

- gravity is universal (and so is quantum theory, apparently)
- there exist situations where gravity is strong and short distances are involved (big bang, black hole singularities)

Perhaps the question is ill posed? Which degrees of freedom "take over" at the Planck scale (pre-geometry, spacetime foam, causal sets, ...)?

Let us agree to call this "quantum gravity" too, and let us assume that something like quantum gravity indeed exists, "grandly unified" or otherwise.

Spacetime Foam?

How many theories of Quantum Gravity✪ are there?

✪ Interacting Q(F)T of geometry, reproducing classical, four-dimensional General

How many theories of Quantum Gravity✪ are there?

The evidence so far: 0 (zero!).

Let us call n the number of free parameters of the putative QG theory, and m the number of independent observations available to fix the values of these free parameters. We distinguish two cases:

(i) n is a small finite number and $n \lesssim m$ (special case $n = 0$)

(ii) $n \gg m$ (special cases $n = 10^{500}$, $n = \infty$)

Our *best hope* for quantum gravity is clearly case (i). In the old days, string theory was thought to realize (i), but no more. Our *new best hope* is that no 'fancy' ingredients at all may be needed to construct a nonperturbative theory of quantum gravity - no strings, no branes, no loops, no supersymmetry.

→ corroborating evidence will be given in the remainder of this talk

✪ interacting Q(F)T of geometry, reproducing classical, four-dimensional General

How many theories of Quantum Gravity✪ are there?

The evidence so far: 0 (zero!).

Let us call n the number of free parameters of the putative QG theory, and m the number of independent observations available to fix the values of these free parameters. We distinguish two cases:

(i) n is a small finite number and $n \lesssim m$ (special case $n = 0$)

(ii) $n \gg m$ (special cases $n = 10^{500}$, $n = \infty$)

Our *best hope* for quantum gravity is clearly case (i). In the old days, string theory was thought to realize (i), but no more. Our *new best hope* is that no 'fancy' ingredients at all may be needed to construct a nonperturbative theory of quantum gravity - no strings, no branes, no loops, no supersymmetry.

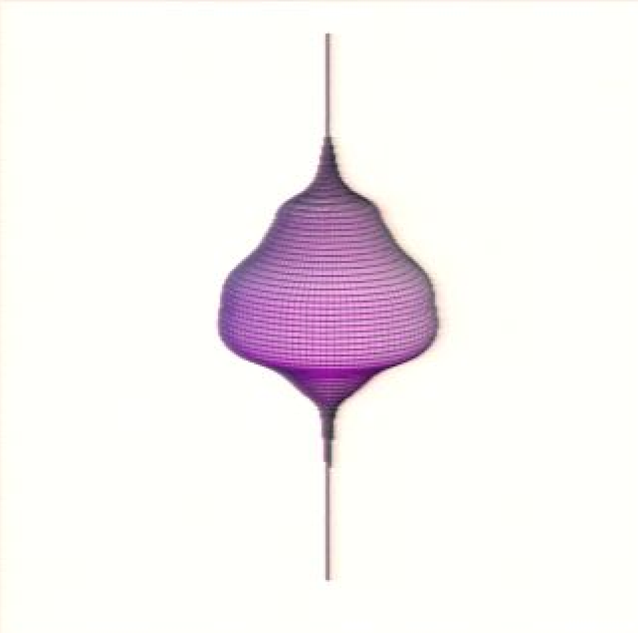
→ corroborating evidence will be given in the remainder of this talk

✪ interacting Q(F)T of geometry, reproducing classical, four-dimensional General

Quantum Gravity from Causal Dynamical Triangulation (QG from CDT)*

CDT is a no-frills nonperturbative implementation of the gravitational path integral, much in the spirit of lattice quantum field theory, but based on *dynamical* lattices, reflecting the dynamical nature of spacetime geometry.

The key result that has put QG from CDT on the map as a serious contender for a quantum theory of gravity is the fact that it can generate dynamically a sensible semiclassical background geometry from pure quantum excitations, in an a priori background-independent formulation. This has so far not been achieved in any other approach to quantum gravity.



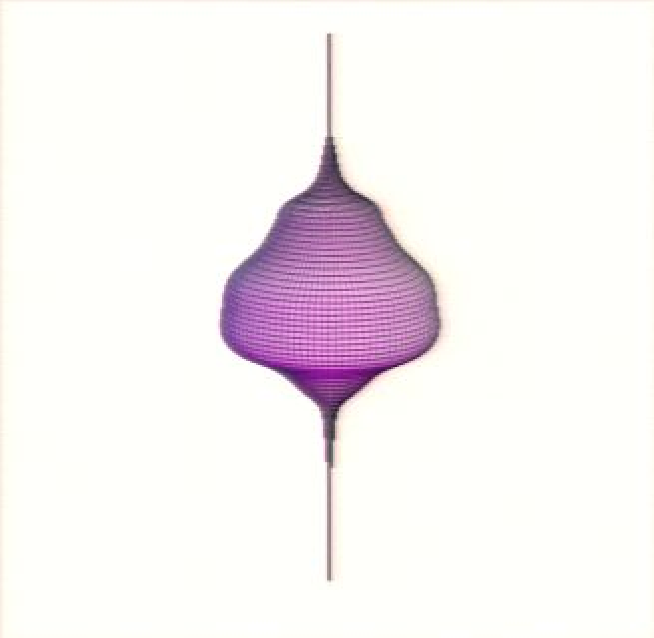
(PRL 93 (2004) 131301, PRD 72 (2005) 064014, PLB 607 (2005) 205)

*my talk is based on joint work with J. Ambjørn, A. Görlich, S. Jordan,

Quantum Gravity from Causal Dynamical Triangulation (QG from CDT)*

CDT is a no-frills nonperturbative implementation of the gravitational path integral, much in the spirit of lattice quantum field theory, but based on *dynamical* lattices, reflecting the dynamical nature of spacetime geometry.

The key result that has put QG from CDT on the map as a serious contender for a quantum theory of gravity is the fact that it can generate dynamically a sensible semiclassical background geometry from pure quantum excitations, in an a priori background-independent formulation. This has so far not been achieved in any other approach to quantum gravity.

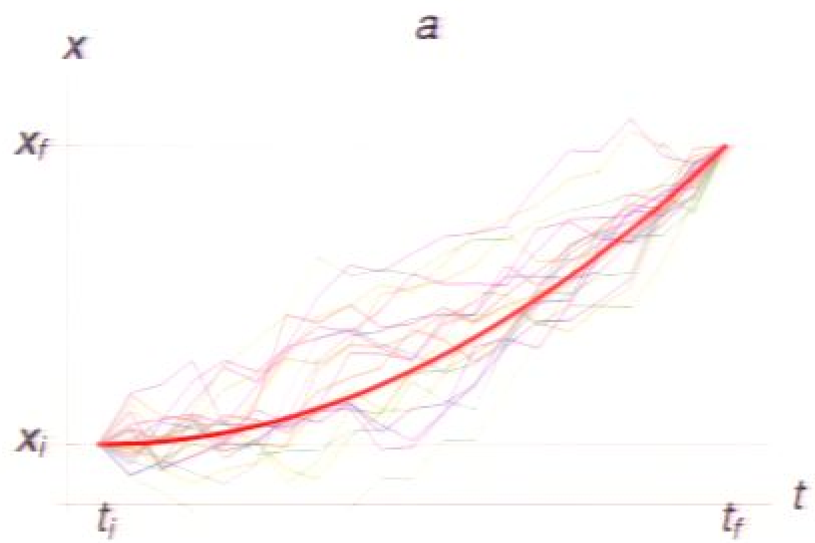


(PRL 93 (2004) 131301, PRD 72 (2005) 064014, PLB 607 (2005) 205)

* my talk is based on joint work with J. Ambjørn, A. Görlich, S. Jordan,

Basic tool: the good old path integral

Textbook example: the nonrelativistic particle (h.o.) in one dimension



$$x(t) = \langle x(t) \rangle + y(t)$$
$$\langle |y| \rangle \propto \sqrt{\hbar / m\omega}$$

In QG we want $\langle x(t) \rangle$

$$\langle |y| \rangle \propto \sqrt{\hbar G}$$

Quantum superposition principle: the transition amplitude from $x_i(t_i)$ to $x_f(t_f)$ is given as a weighted sum over amplitudes exp $iS[x(t)]$ of all possible trajectories, where $S[x(t)]$ is the classical action of the path.

(here, time is discretized in steps of length *a*, and the trajectories are piecewise linear)

The same superposition principle, applied to gravity

"Sum over histories"

a.k.a. gravitational path integral

$$Z(G_N, \Lambda) = \int \mathcal{D}g \; e^{i S^{E\text{-}H}_{G_N,\Lambda}[g]}$$

cosmol. const.

Newton const.

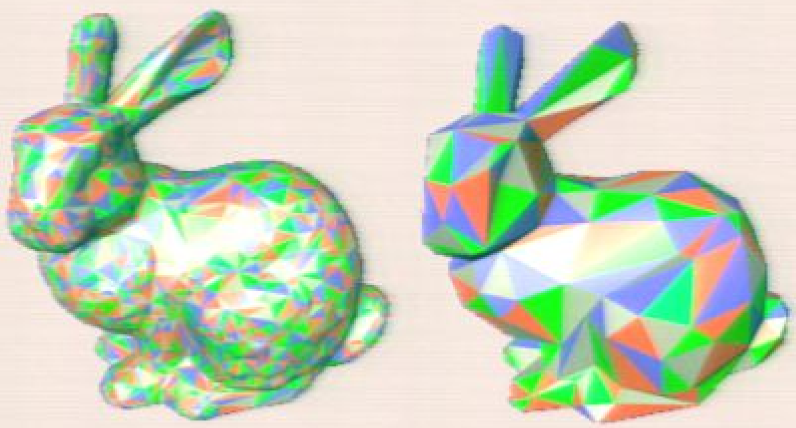
spacetime geom.s $g \in \mathcal{G}$

Each "path" is now a four-dimensional, curved spacetime geometry g which can be thought of as a three-dimensional, spatial geometry developing in time. The weight associated with each g is given by the corresponding Einstein-Hilbert action $S^{EH}[g]$,

$$S^{\mathrm{EH}} = \frac{1}{G_{\mathrm{N}}} \int d^4x \sqrt{-\det g}\,(R[g, \partial g, \partial^2 g] - 2\Lambda)$$

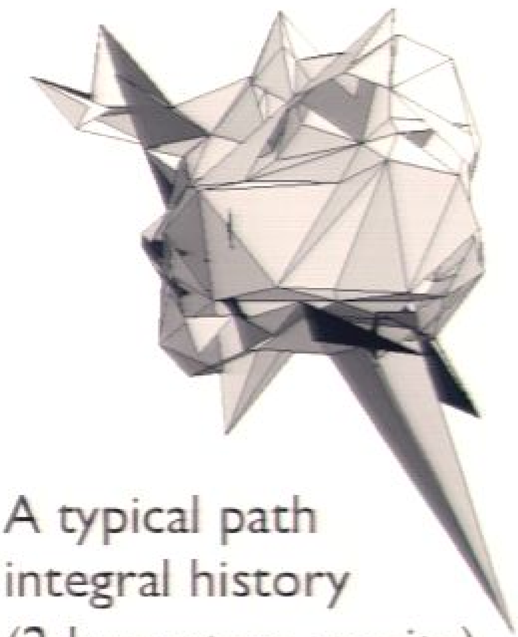
How can we make $Z(G_N,\Lambda)$ into a meaningful, well-defined quantity?

Regularizing gravity by "dynamical triangulations"



approximating *classical* curved surfaces through triangulation

<u>triangulation = regularization</u>



A typical path integral history (2d quantum gravity)

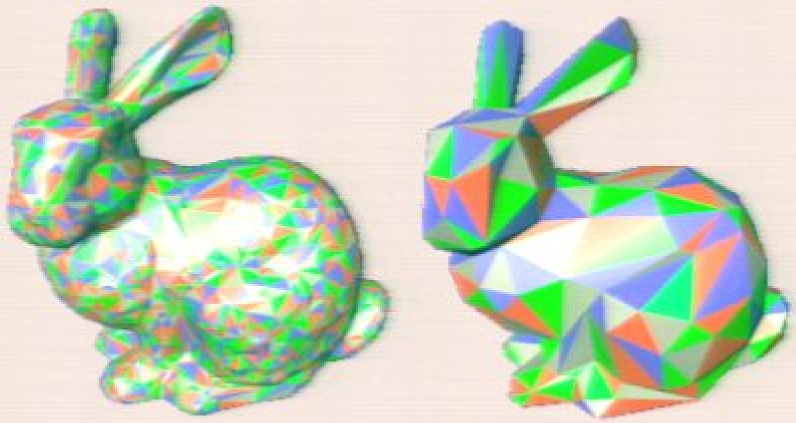
N.B.: no coordinates!

(Regge's 1961 idea of "GR without coordinates")

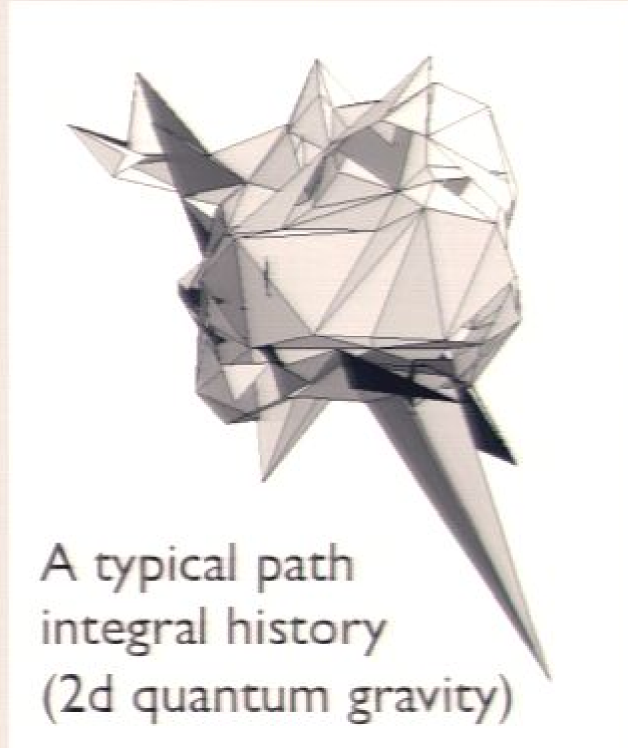
Quantum Theory: approximating the space of all curved geometries by a space of triangulations one needs to integrate over this space(*)!

(*) *by Monte Carlo simulations* (for CDT models in d=2, 3 have also exact stat. mech. solutions methods, see e.g. D. Benedetti, F. Zamponi, R.L., PRD 76 (2007) 104022; in

Regularizing gravity by "dynamical triangulations"



approximating *classical* curved surfaces through triangulation



triangulation = regularization

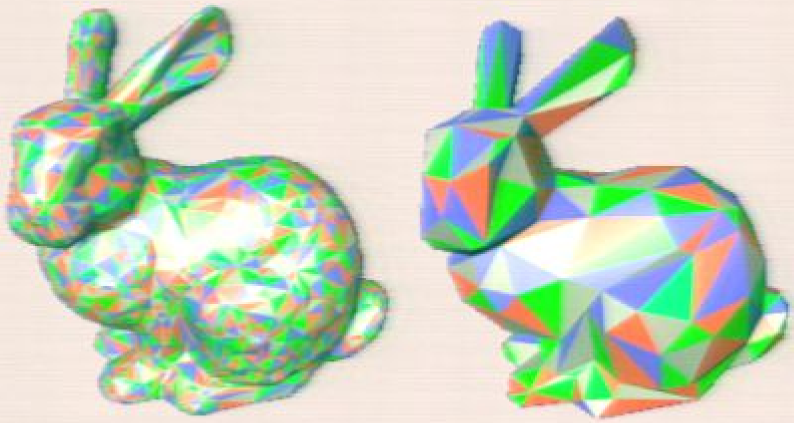
N.B.: no coordinates!

(Regge's 1961 idea of "GR without coordinates")

Quantum Theory: approximating the space of all curved geometries by a space of triangulations one needs to integrate over this space(*)!

(*) *by Monte Carlo simulations* (for CDT models in d=2, 3 have also exact stat. mech. solutions methods, see e.g. D. Benedetti, F. Zamponi, R.L., PRD 76 (2007) 104022; in d=2, the problem becomes purely combinatorial)

Regularizing gravity by "dynamical triangulations"



approximating *classical* curved surfaces through triangulation

<u>triangulation = regularization</u>

A typical path integral history (2d quantum gravity)

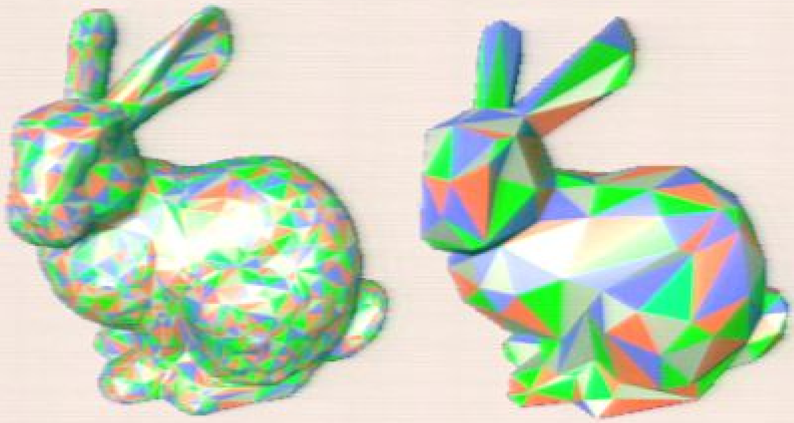
N.B.: no coordinates!

(Regge's 1961 idea of "GR without coordinates")

Quantum Theory: approximating the space of all curved geometries by a space of triangulations one needs to integrate over this space$^{(*)}$!

$^{(*)}$ *by Monte Carlo simulations* (for CDT models in d=2, 3 have also exact stat. mech. solutions methods, see e.g. D. Benedetti, F. Zamponi, R.L., PRD 76 (2007) 104022; in d=2, the problem becomes purely combinatorial)

Regularizing gravity by "dynamical triangulations"



approximating *classical* curved surfaces through triangulation

A typical path integral history (2d quantum gravity)

triangulation = regularization

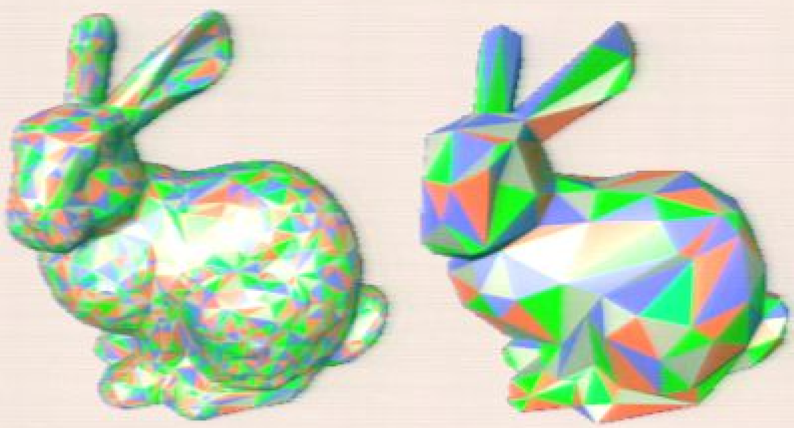
N.B.: no coordinates!

(Regge's 1961 idea of "GR without coordinates")

Quantum Theory: approximating the space of all curved geometries by a space of triangulations one needs to integrate over this space(*)!

(*) *by Monte Carlo simulations* (for CDT models in d=2, 3 have also exact stat. mech. solutions methods, see e.g. D. Benedetti, F. Zamponi, R.L., PRD 76 (2007) 104022; in d=2, the problem becomes purely combinatorial)

Regularizing gravity by "dynamical triangulations"



approximating *classical* curved surfaces through triangulation

A typical path integral history (2d quantum gravity)

triangulation = regularization

N.B.: no coordinates!

(Regge's 1961 idea of "GR without coordinates")

Quantum Theory: approximating the space of all curved geometries by a space of triangulations one needs to integrate over this space(*)!

(*) *by Monte Carlo simulations* (for CDT models in d=2, 3 have also exact stat. mech. solutions methods, see e.g. D. Benedetti, F. Zamponi, R.L., PRD 76 (2007) 104022; in d=2, the problem becomes purely combinatorial)

Making sense of the path integral via causal dynamical triangulations

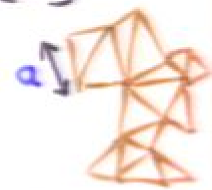
<u>Sum over histories</u> $Z(G_N, \Lambda)$:

$$\int \mathcal{D}g \; e^{iS^{EH}[g]} \underset{CDT}{:=} \lim_{\substack{a\to 0\\ N\to\infty}} \sum_{\substack{\text{inequiv.}\\ \text{triangul.s}\\ T\in\mathcal{G}_{a,N}}} \frac{1}{C(T)} \, e^{iS^{Regge}[T]}$$

spacetime geom.s $g \in \mathcal{G}$

$C(T)$ ← $|Aut(T)|$

curved spacetime geometry g $\underset{\text{CDT regular.}}{\longmapsto}$ gluing T of N simplices (piecewise flat manifold)

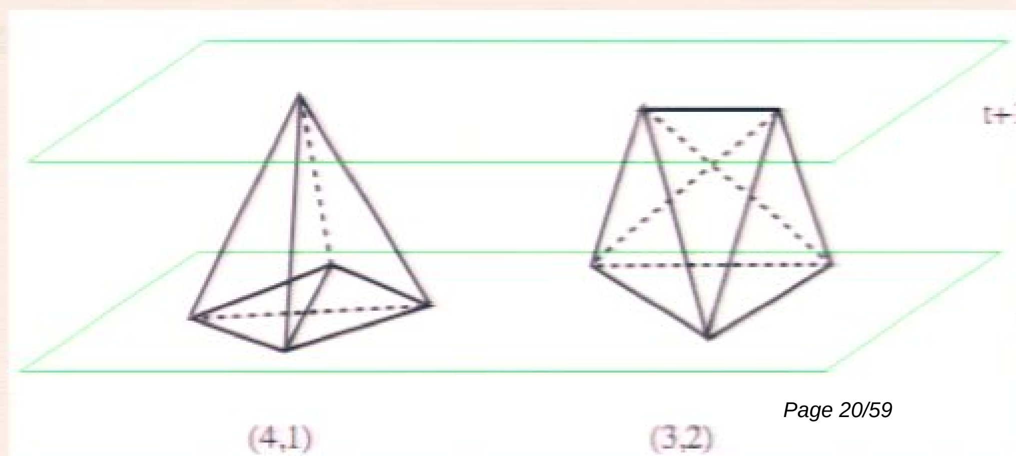


'democratic', regularize
sum over piecewise fla
spacetimes, doesn't nee
coordinates; continuum
limit required to obtain
'universal' results
independent of the
regularization

Elementary four-simplex, building block for a causal dynamical triangulation:

(a ~ edge length; diffeomorphism-invariant UV regulator)

Micro-causality is essential! This does not work in Euclidean signature.



Making sense of the path integral via causal dynamical triangulations

<u>Sum over histories</u> $Z(G_N, \Lambda)$:

$$\int_{\substack{\text{spacetime}\\ \text{geom.s } g \in \mathcal{G}}} \mathcal{D}g \; e^{iS^{EH}[g]} \;\underset{CDT}{:=}\; \lim_{\substack{a \to 0\\ N \to \infty}} \sum_{\substack{\text{inequiv.}\\ \text{triangul.s}\\ T \in \mathcal{G}_{a,N}}} \frac{1}{C(T)} \, e^{iS^{Regge}[T]}$$

$C(T) \leftarrow |Aut(T)|$

curved spacetime geometry g $\underset{\substack{CDT\\ \text{regular.}}}{\longmapsto}$ gluing T of N simplices (piecewise flat manifold)

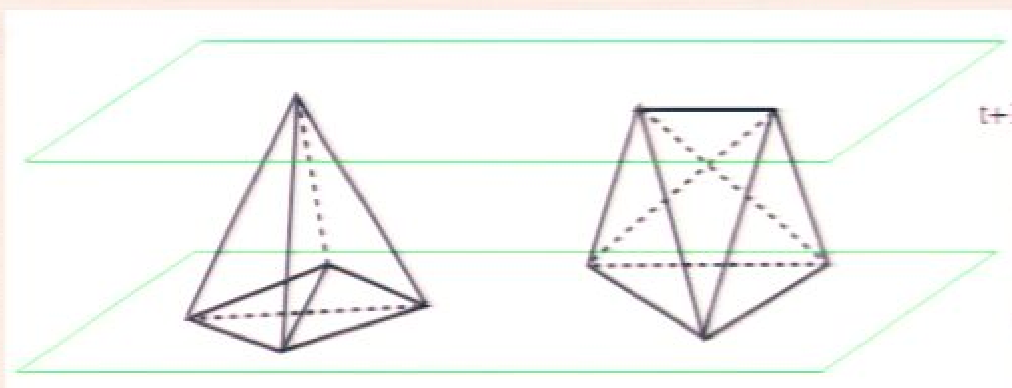
a

'democratic', regularize sum over piecewise flat spacetimes, doesn't nee coordinates; continuum limit required to obtain 'universal' results independent of the regularization

Elementary four-simplex, building block for a causal dynamical triangulation:

(a ~ edge length; diffeomorphism-invariant UV regulator)

Micro-causality is essential! This does not work in Euclidean signature.



Making sense of the path integral via causal dynamical triangulations

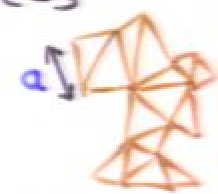
Sum over histories $Z(G_N, \Lambda)$:

$$\int \mathcal{D}g \; e^{iS^{EH}[g]} \underset{CDT}{:=} \lim_{\substack{a\to 0\\ N\to\infty}} \sum_{\substack{\text{inequiv. triangul.s}\\ T\in\mathcal{G}_{a,N}}} \frac{1}{C(T)}\, e^{iS^{Regge}[T]}$$

spacetime geom.s $g \in \mathcal{G}$

$C(T)$ ← $|Aut(T)|$

curved spacetime geometry g $\underset{\text{CDT regular.}}{\longmapsto}$ gluing T of N simplices (piecewise flat manifold)

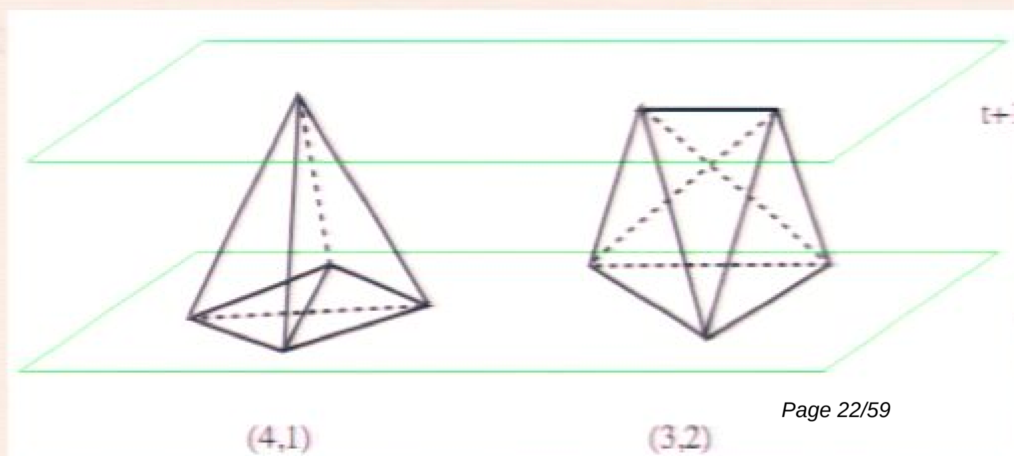


'democratic', regularized sum over piecewise flat spacetimes, doesn't need coordinates; continuum limit required to obtain 'universal' results independent of the regularization

Elementary four-simplex, building block for a causal dynamical triangulation:

(*a* ~ edge length; diffeomorphism-invariant UV regulator)

Micro-causality is essential! This does not work in Euclidean signature.



Making sense of the path integral via causal dynamical triangulations

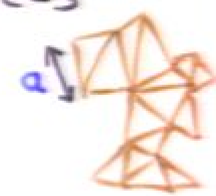
Sum over histories $Z(G_N, \Lambda)$:

$$\int \mathcal{D}g \; e^{iS^{EH}[g]} \;\underset{CDT}{:=}\; \lim_{\substack{a\to 0\\ N\to\infty}} \sum_{\substack{\text{inequiv. triangul.s}\\ T\in\mathcal{G}_{a,N}}} \frac{1}{C(T)}\, e^{iS^{Regge}[T]}$$

spacetime geom.s $g \in \mathcal{G}$

$C(T)$ ← $|Aut(T)|$

curved spacetime geometry g $\underset{\text{CDT regular.}}{\longmapsto}$ gluing T of N simplices (piecewise flat manifold)

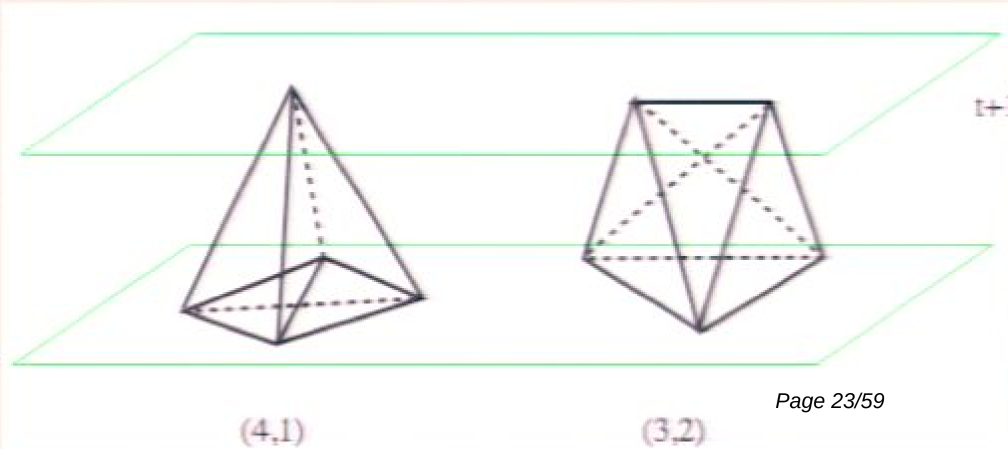


'democratic', regularize sum over piecewise flat spacetimes, doesn't nee coordinates; continuum limit required to obtain 'universal' results independent of the regularization

Elementary four-simplex, building block for a causal dynamical triangulation:

(a ~ edge length; diffeomorphism-invariant UV regulator)

Micro-causality is essential! This does not work in Euclidean signature.



Making sense of the path integral via causal dynamical triangulations

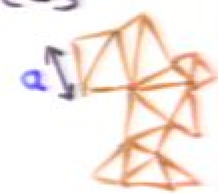
Sum over histories $Z(G_N, \Lambda)$:

$$\int \mathcal{D}g \; e^{iS^{EH}[g]} \underset{CDT}{:=} \lim_{\substack{a\to 0\\ N\to\infty}} \sum_{\substack{\text{inequiv.}\\ \text{triangul.s}\\ T\in\mathcal{G}_{a,N}}} \frac{1}{C(T)}\, e^{iS^{Regge}[T]}$$

spacetime geom.s $g \in \mathcal{G}$

$C(T)$ ← $|Aut(T)|$

curved spacetime geometry g $\underset{\text{CDT regular.}}{\longmapsto}$ gluing T of N simplices (piecewise flat manifold)

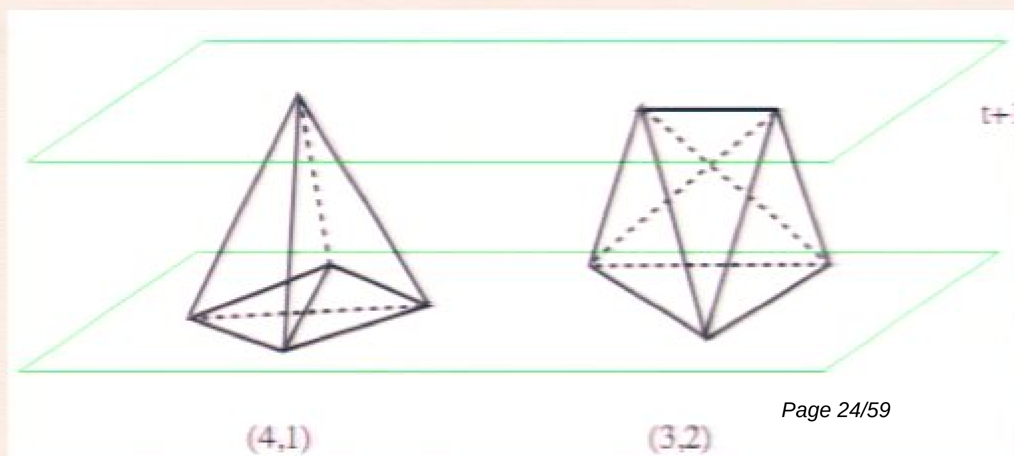


'democratic', regularize sum over piecewise flat spacetimes, doesn't nee coordinates; continuum limit required to obtain 'universal' results independent of the regularization

Elementary four-simplex, building block for a causal dynamical triangulation:

(a ~ edge length; diffeomorphism-invariant UV regulator)

Micro-causality is essential! This does not work in Euclidean signature.



Wick rotation and analogy with statistical mechanics

- each regularized Lorentzian geometry T allows for a rotation to a unique regularized Euclidean geometry T_{eu}, such that the Feynman amplitude of a path is turned into a Boltzmann weight, as in statistical mechanics

$$e^{iS^{\mathrm{Regge}}(T)} \rightarrow e^{-S^{\mathrm{Regge}}_{\mathrm{eu}}(T_{\mathrm{eu}})}$$

- this turns the quantum amplitude Z into a partition function Z_{eu} and allows one to use powerful numerical methods from statistical mechanics, like Monte Carlo simulations

- a 'classical trajectory' is an average over quantum trajectories in the statistical ensemble of trajectories (the Euclideanized 'sum over histories')

- taking the continuum limit of this regularized theory means to study the critical behaviour of the underlying statistical theory

- performing an 'inverse Wick rotation' on quantities computed in the continuum limit is in general nontrivial

Wick rotation and analogy with statistical mechanics

- each regularized Lorentzian geometry T allows for a rotation to a unique regularized Euclidean geometry T_{eu}, such that the Feynman amplitude of a path is turned into a Boltzmann weight, as in statistical mechanics

$$e^{iS^{\mathrm{Regge}}(T)} \to e^{-S^{\mathrm{Regge}}_{\mathrm{eu}}(T_{\mathrm{eu}})}$$

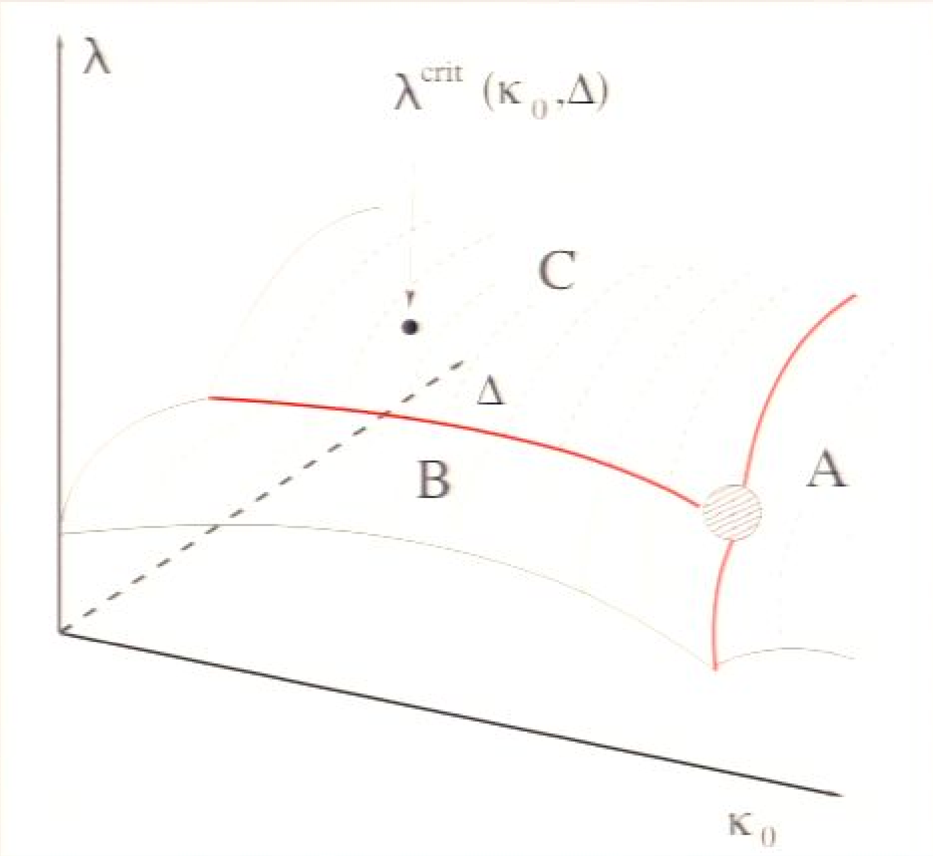
- this turns the quantum amplitude Z into a partition function Z_{eu} and allows one to use powerful numerical methods from statistical mechanics, like Monte Carlo simulations

- a 'classical trajectory' is an average over quantum trajectories in the statistical ensemble of trajectories (the Euclideanized 'sum over histories')

- taking the continuum limit of this regularized theory means to study the critical behaviour of the underlying statistical theory

- performing an 'inverse Wick rotation' on quantities computed in the continuum limit is in general nontrivial

The phase diagram of Causal Dynamical Triangulations



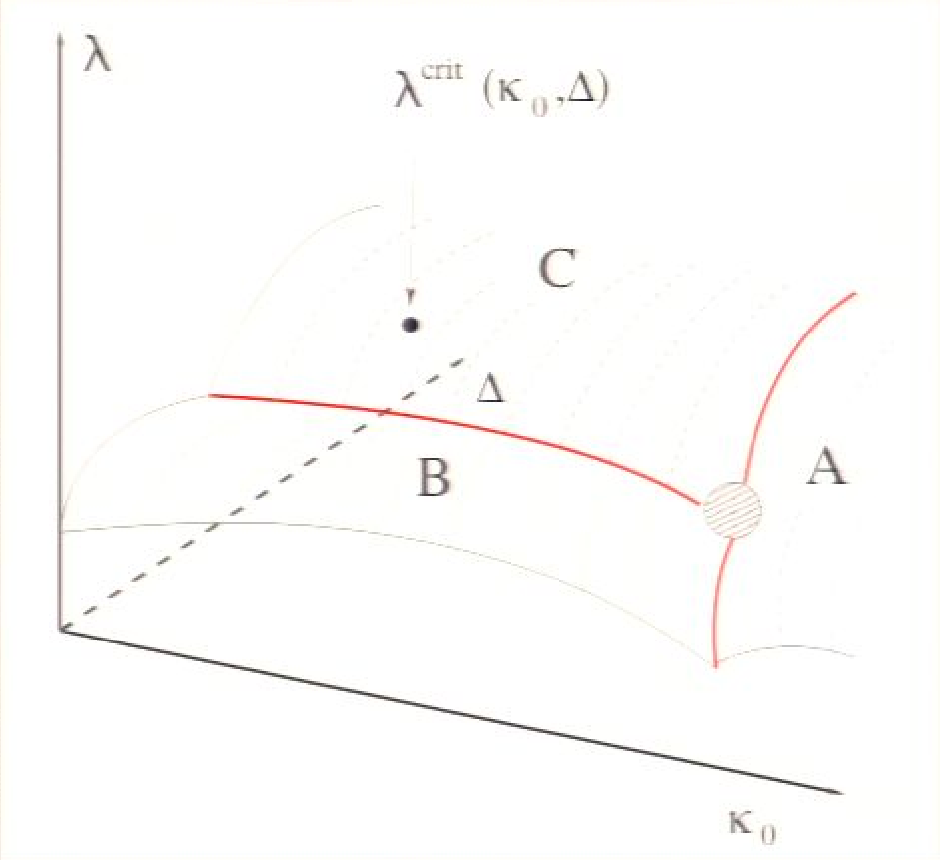
$$S_{eu}^{Regge} = -\kappa_0 N_2 + N_4(c\kappa_0 + \lambda) + \\ +\Delta(2N_4^{(4,1)} + N_4^{(3,2)})$$

- λ ~ cosmological constant
- κ_0 ~ $1/G_N$ inverse Newton's constant
- Δ ~ relative time/space scaling
- c ~ numerical constant, >0
- N_i ~ # of triangular building blocks of dimension i

The partition function is defined for $\lambda > \lambda^{crit}(\kappa_0,\Delta)$;
approaching the critical surface = taking infinite-volume limit.
red lines ~ phase transitions

(J. Ambjørn, J. Jurkiewicz, RL, PRD 72 (2005) 064014;
J. Ambjørn, A. Görlich, S. Jordan, J. Jurkiewicz, RL, PLB 690 (2010) 413)

The phase diagram of Causal Dynamical Triangulations



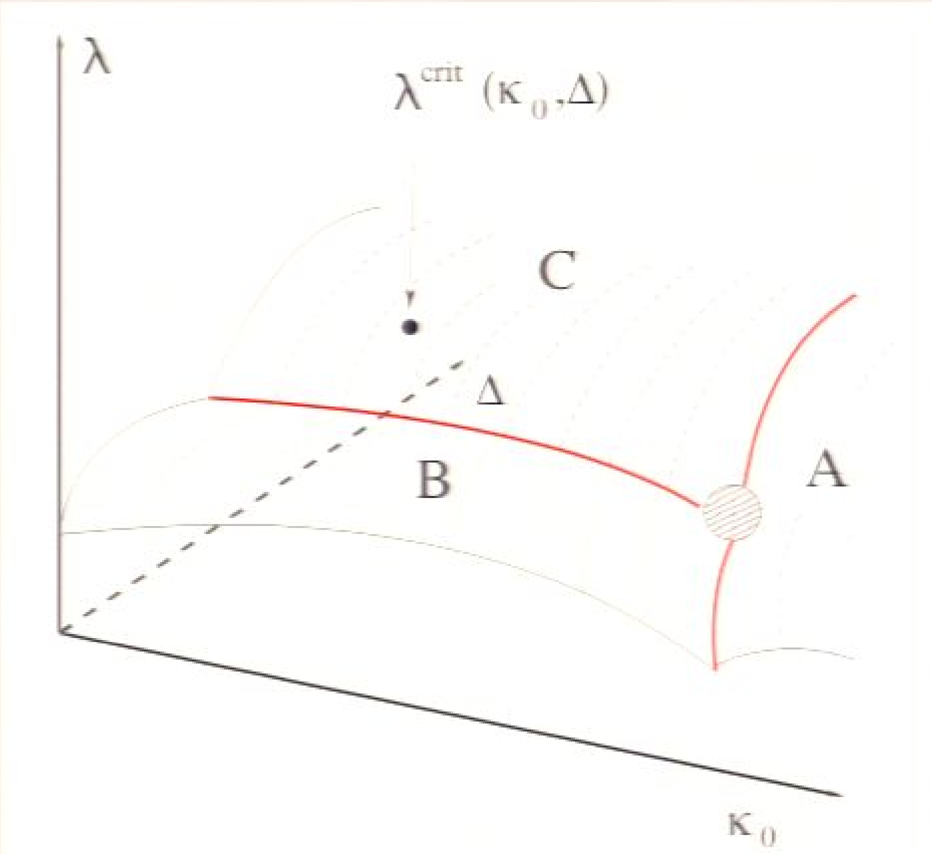
$$S_{\text{eu}}^{\text{Regge}} = -\kappa_0 N_2 + N_4(c\kappa_0 + \lambda) + +\Delta(2N_4^{(4,1)} + N_4^{(3,2)})$$

- λ ~ cosmological constant
- κ_0 ~ $1/G_N$ inverse Newton's constant
- Δ ~ relative time/space scaling
- c ~ numerical constant, >0
- N_i ~ # of triangular building blocks of dimension i

The partition function is defined for $\lambda > \lambda^{\text{crit}}(\kappa_0,\Delta)$;
approaching the critical surface = taking infinite-volume limit.
red lines ~ phase transitions

(J. Ambjørn, J. Jurkiewicz, RL, PRD 72 (2005) 064014;
J. Ambjørn, A. Görlich, S. Jordan, J. Jurkiewicz, RL, PLB 690 (2010) 413)

The phase diagram of Causal Dynamical Triangulations

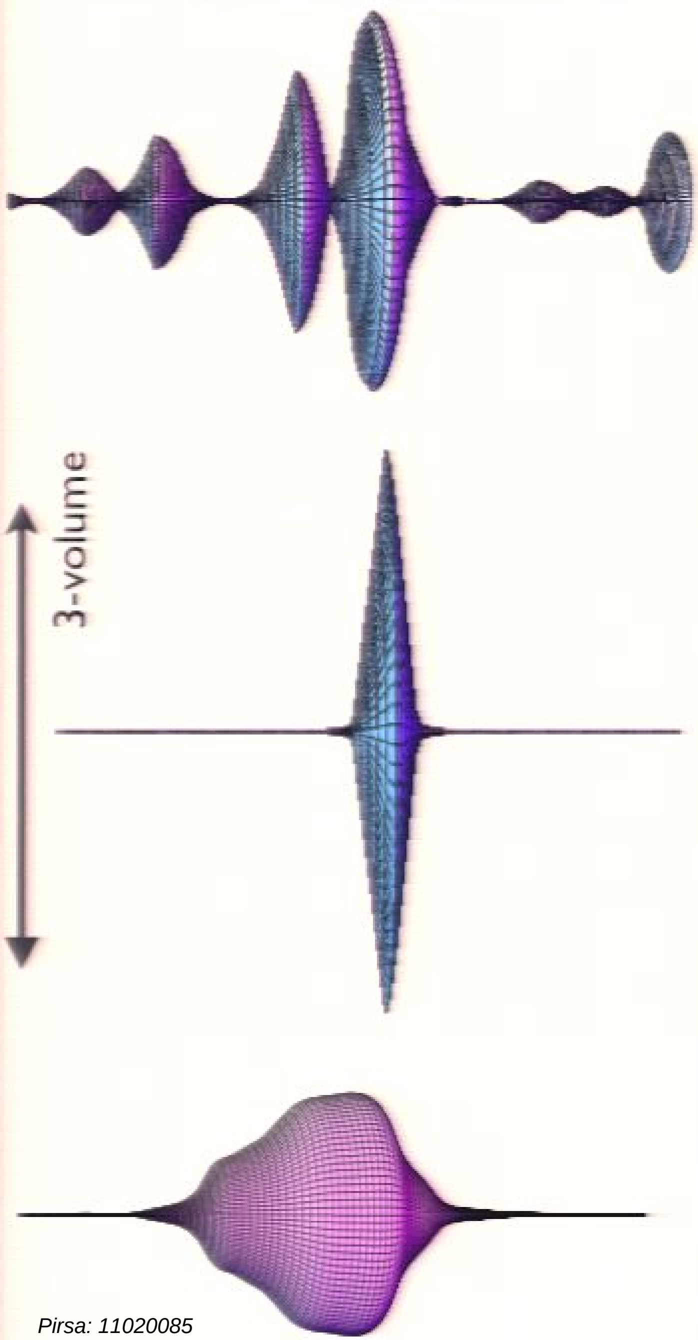


$$S_{eu}^{Regge} = -\kappa_0 N_2 + N_4(c\kappa_0 + \lambda) + \\ +\Delta(2N_4^{(4,1)} + N_4^{(3,2)})$$

- λ ~ cosmological constant
- κ_0 ~ $1/G_N$ inverse Newton's constant
- Δ ~ relative time/space scaling
- c ~ numerical constant, >0
- N_i ~ # of triangular building blocks of dimension i

The partition function is defined for $\lambda > \lambda^{crit}(\kappa_0,\Delta)$;
approaching the critical surface = taking infinite-volume limit.
red lines ~ phase transitions

(J. Ambjørn, J. Jurkiewicz, RL, PRD 72 (2005) 064014;
J. Ambjørn, A. Görlich, S. Jordan, J. Jurkiewicz, RL, PLB 690 (2010) 413)

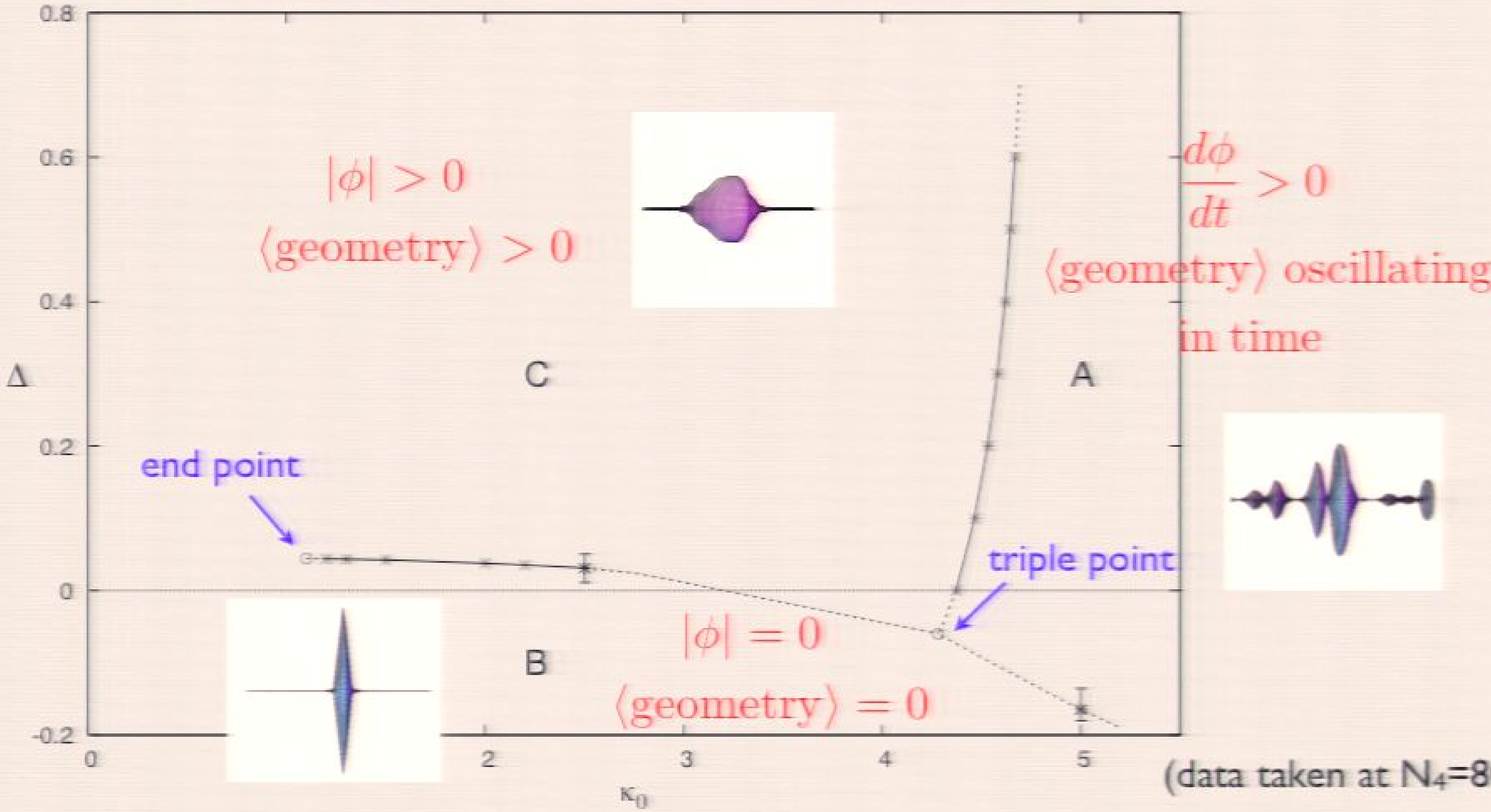


- Phase A: (sufficiently large $\kappa_0=1/G_N$) inhomogeneous in time, a Lorentzian version of conformal factor dominance, individual "universes" remain small

- Phase B: (small κ_0, small Δ) phase of "no geometry" - collapse along the time direction, but also space is "crumpled", without linear extension (Hausdorff dimension $d_H \approx \infty$!)

- Phase C: (small κ_0, large Δ) *physical phase of extended geometry!* - canonical scaling in the large, $\langle T \rangle \propto N_4^{1/4}$, $\langle V_3 \rangle \propto N_4^{3/4}$, $d_H \approx 4$

The phase diagram of CDT in the κ_0-Δ plane

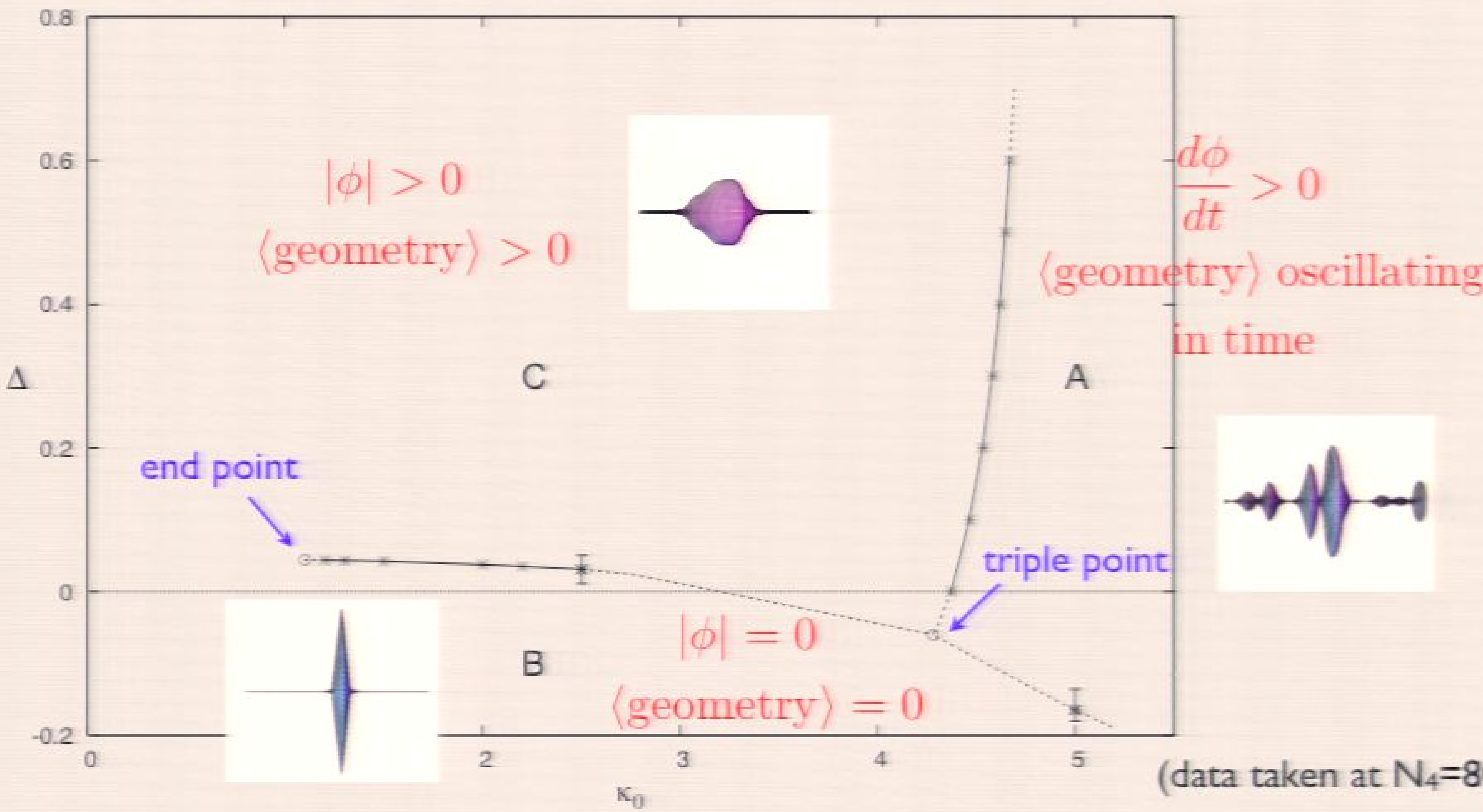


(data taken at N_4=80.00

Similar to a Lifshitz phase diagram (cf. P. Hořava's anisotropic gravities), where Φ is an order parameter of a mean field Lifshitz theory, with free energy

$$F = a_2\phi^2 + a_4\phi^4 + \cdots + c_2(\partial_x\phi)^2 + d_2(\partial_t\phi)^2 + \ldots$$

The phase diagram of CDT in the κ_0-Δ plane

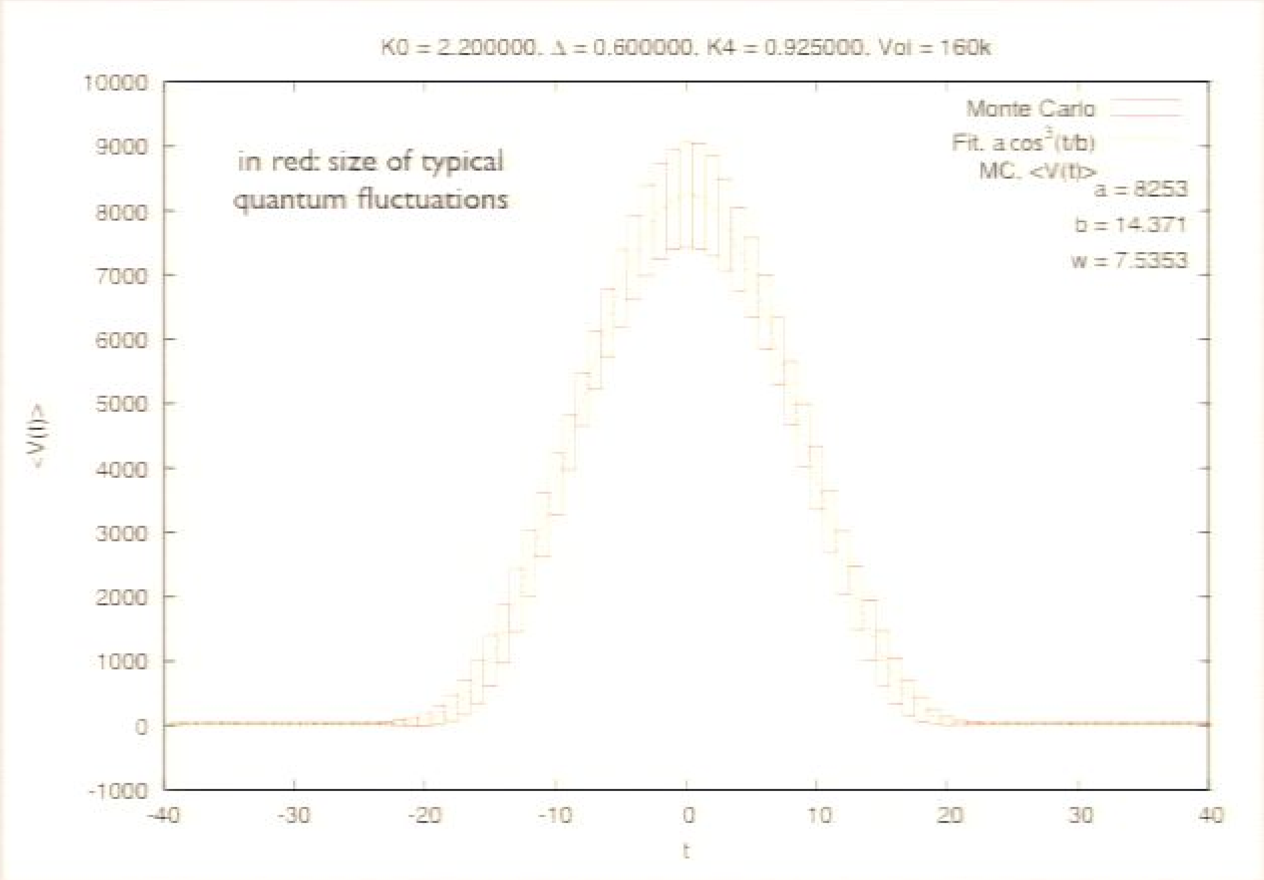


(data taken at N_4=80.00

Similar to a Lifshitz phase diagram (cf. P. Hořava's anisotropic gravities), where Φ is an order parameter of a mean field Lifshitz theory, with free energy

$$F = a_2\phi^2 + a_4\phi^4 + \cdots + c_2(\partial_x\phi)^2 + d_2(\partial_t\phi)^2 + \ldots$$

What *is* the extended universe emergent in phase C?



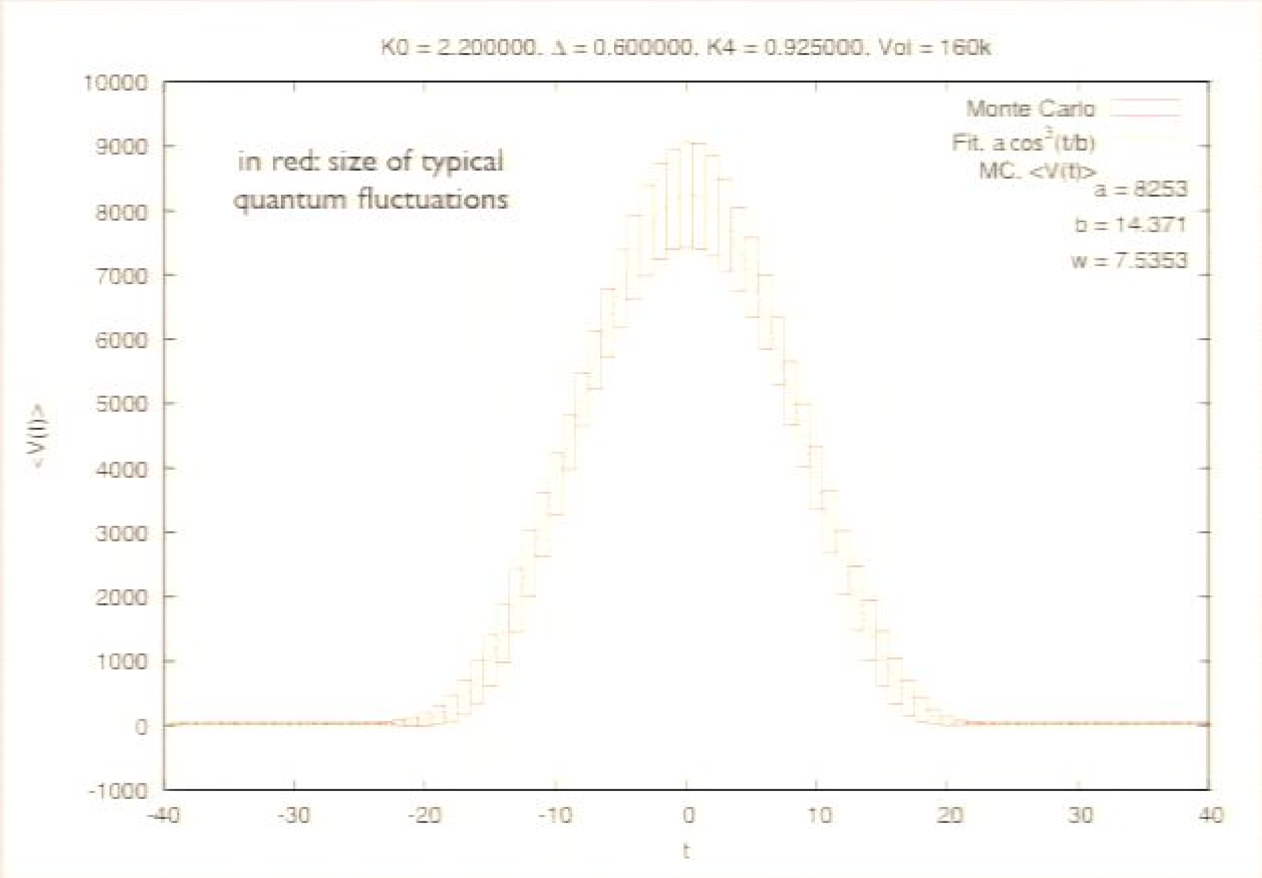
The volume profile <V3(t)>, as function of Euclidean proper time t=iτ, perfectly matches that of a Euclidean *de Sitter space*, with scale factor a(t)²,

$$ds^2 = dt^2 + a(t)^2 d\Omega^2_{(3)} = dt^2 + c^2 \cos^2\left(\frac{t}{c}\right) d\Omega^2_{(3)}$$

← volume el. S^3

(J. Ambjørn, A. Görlich, J. Jurkiewicz, RL, PRL 100 (2008) 091304,

What *is* the extended universe emergent in phase C?



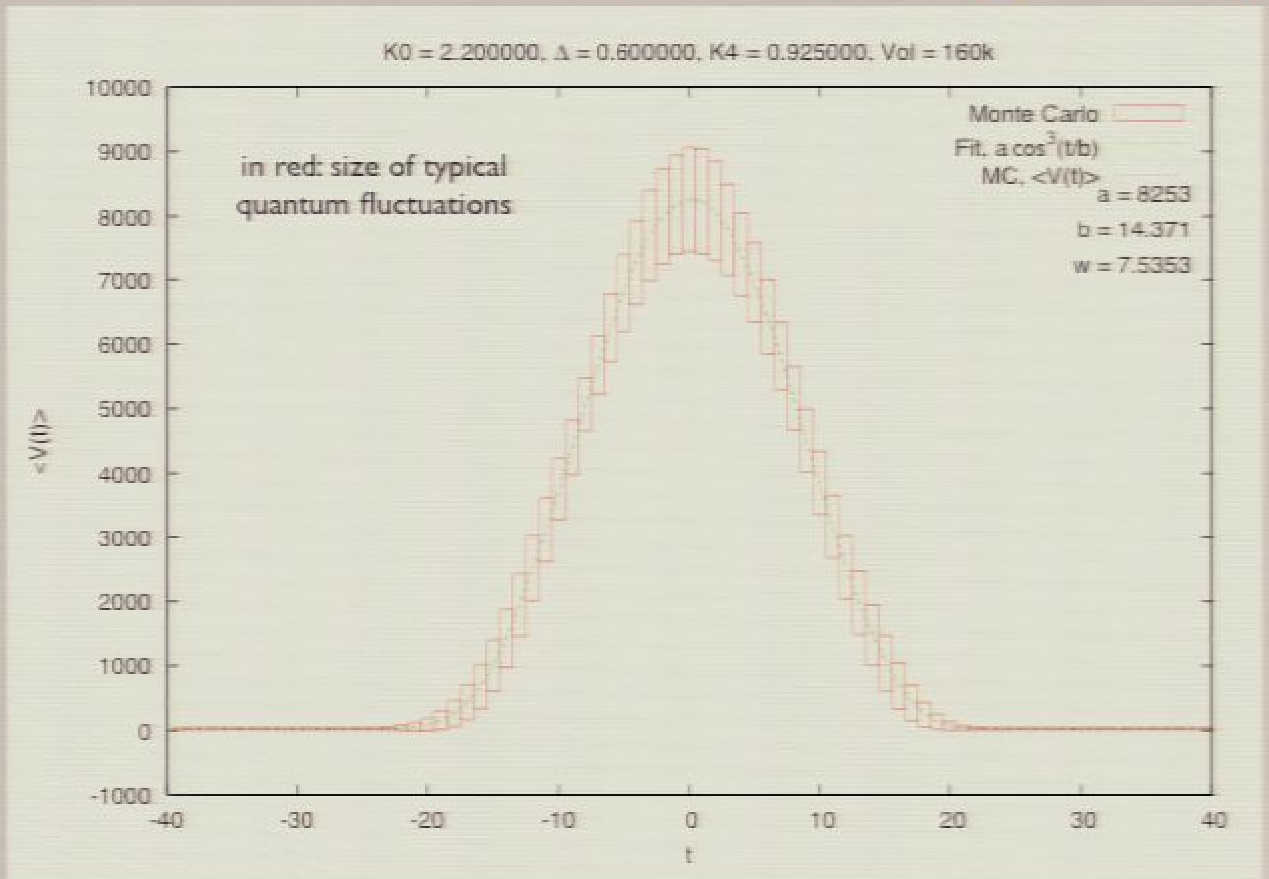
The volume profile <V3(t)>, as function of Euclidean proper time t=iτ, perfectly matches that of a Euclidean *de Sitter space*, with scale factor a(t)²,

$$ds^2 = dt^2 + a(t)^2 d\Omega^2_{(3)} = dt^2 + c^2 \cos^2\left(\frac{t}{c}\right) d\Omega^2_{(3)}$$

volume el. S^3

(J. Ambjørn, A. Görlich, J. Jurkiewicz, RL, PRL 100 (2008) 091304,

What *is* the extended universe emergent in phase C?



The volume profile <V3(t)>, as function of Euclidean proper time t=iτ, perfectly matches that of a Euclidean *de Sitter space*, with scale factor $a(t)^2$,

$$ds^2 = dt^2 + a(t)^2 d\Omega^2_{(3)} = dt^2 + c^2 \cos^2\left(\frac{t}{c}\right) d\Omega^2_{(3)}$$

volume el. S^3

(J. Ambjørn, A. Görlich, J. Jurkiewicz, RL, PRL 100 (2008) 091304,

Remarkably, having started from the Wick-rotated path integral,

$$\int \mathcal{D}[g]\, \mathrm{e}^{-S_{\mathrm{eu}}}, \quad S_{\mathrm{eu}} = \int dt\, (-\frac{\dot{V}_3^2}{V_3} - V_3^{1/3} + \dots)$$

by integrating out everything *but* the global scaling mode $V_3(t)$, we obtain an effective dynamics for $V_3(t)$, given by

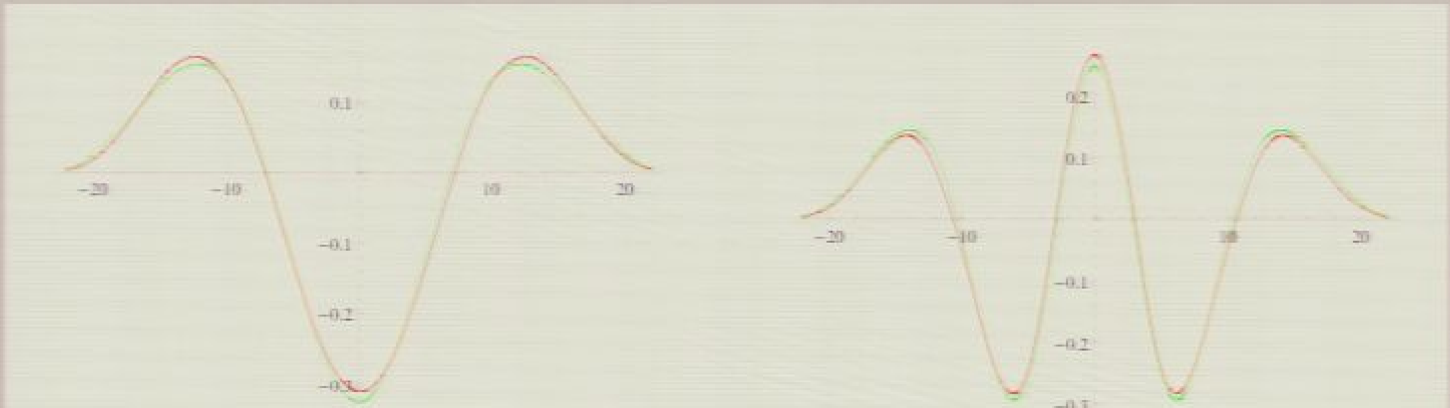
$$\mathrm{e}^{-S_{\mathrm{eu}}^{\mathrm{eff}}}, \quad S_{\mathrm{eu}}^{\mathrm{eff}} = \int dt\, (+\frac{\dot{V}_3^2}{V_3} + V_3^{1/3} + \dots)$$

This is entirely due to nonperturbative, entropic effects (the PI measure).

Expanding the minisuperspace action around the de Sitter solution,

$$S_{\mathrm{eu}}(V_3) = S(V_3^{\mathrm{dS}}) + \kappa \int dt\, \delta V_3(t) \hat{H} \delta V_3(t)$$

the eigenmodes of $\hat{H}$ match well with those extracted from the simulations:



(N.B.: no further fitting necessary

Remarkably, having started from the Wick-rotated path integral,

$$\int \mathcal{D}[g]\ \mathrm{e}^{-S_{\mathrm{eu}}}, \quad S_{\mathrm{eu}} = \int dt\ (-\frac{\dot{V}_3^2}{V_3} - V_3^{1/3} + \ldots)$$

by integrating out everything *but* the global scaling mode $V_3(t)$, we obtain an effective dynamics for $V_3(t)$, given by

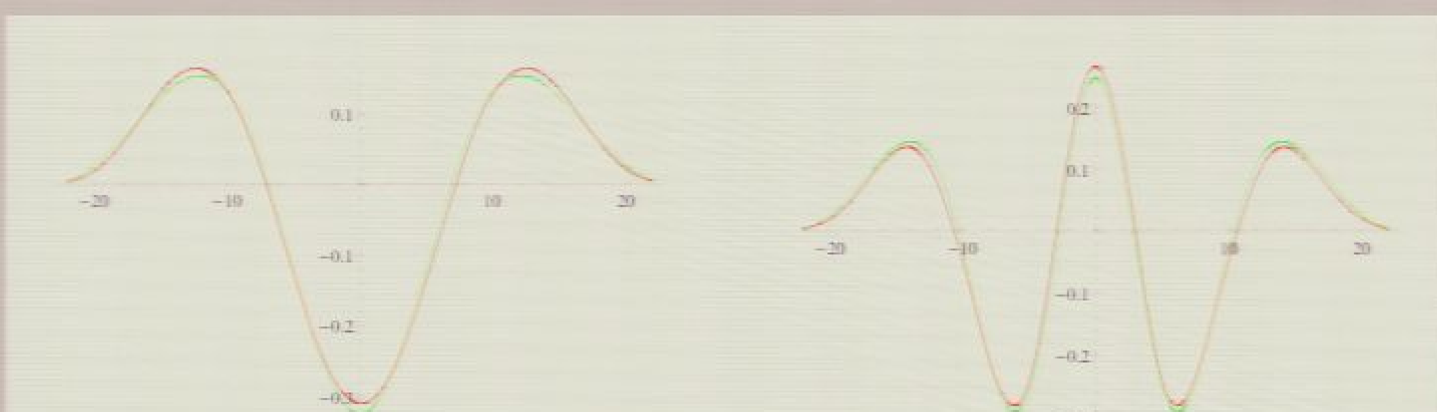
$$\mathrm{e}^{-S_{\mathrm{eu}}^{\mathrm{eff}}}, \quad S_{\mathrm{eu}}^{\mathrm{eff}} = \int dt\ (+\frac{\dot{V}_3^2}{V_3} + V_3^{1/3} + \ldots)$$

This is entirely due to nonperturbative, entropic effects (the PI measure).

Expanding the minisuperspace action around the de Sitter solution,

$$S_{\mathrm{eu}}(V_3) = S(V_3^{\mathrm{dS}}) + \kappa \int dt\ \delta V_3(t) \hat{H} \delta V_3(t)$$

the eigenmodes of $\hat{H}$ match well with those extracted from the simulations:



(N.B.: no further fitting necessary

Remarkably, having started from the Wick-rotated path integral,

$$\int \mathcal{D}[g]\, \mathrm{e}^{-S_{\mathrm{eu}}}, \quad S_{\mathrm{eu}} = \int dt\, (-\frac{\dot{V}_3^2}{V_3} - V_3^{1/3} + \ldots)$$

by integrating out everything *but* the global scaling mode $V_3(t)$, we obtain an effective dynamics for $V_3(t)$, given by

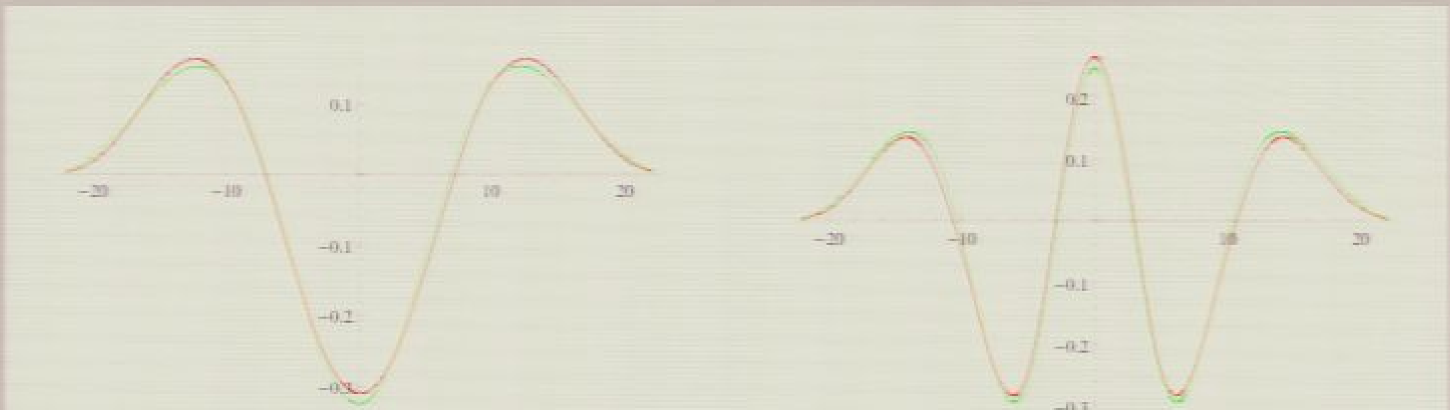
$$\mathrm{e}^{-S_{\mathrm{eu}}^{\mathrm{eff}}}, \quad S_{\mathrm{eu}}^{\mathrm{eff}} = \int dt\, (+\frac{\dot{V}_3^2}{V_3} + V_3^{1/3} + \ldots)$$

This is entirely due to nonperturbative, entropic effects (the PI measure).

Expanding the minisuperspace action around the de Sitter solution,

$$S_{\mathrm{eu}}(V_3) = S(V_3^{\mathrm{dS}}) + \kappa \int dt\, \delta V_3(t) \hat{H} \delta V_3(t)$$

the eigenmodes of $\hat{H}$ match well with those extracted from the simulations:



(N.B.: no further fitting necessary)

Remarkably, having started from the Wick-rotated path integral,

$$\int \mathcal{D}[g]\, \mathrm{e}^{-S_{\rm eu}}, \quad S_{\rm eu} = \int dt\, (-\frac{\dot{V}_3^2}{V_3} - V_3^{1/3} + \dots)$$

by integrating out everything *but* the global scaling mode $V_3(t)$, we obtain an effective dynamics for $V_3(t)$, given by

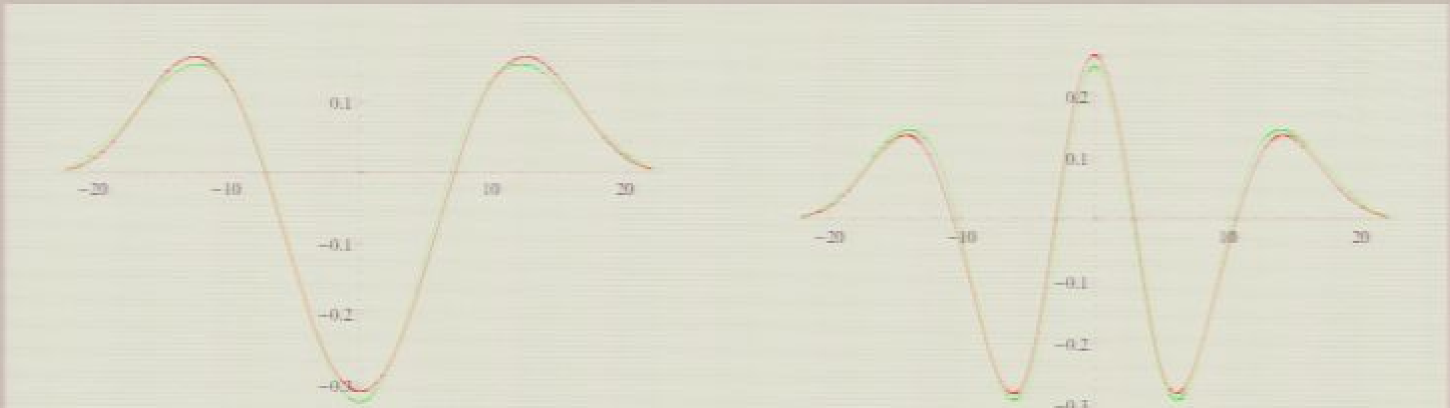
$$\mathrm{e}^{-S_{\rm eu}^{\rm eff}}, \quad S_{\rm eu}^{\rm eff} = \int dt\, (+\frac{\dot{V}_3^2}{V_3} + V_3^{1/3} + \dots)$$

This is entirely due to nonperturbative, entropic effects (the PI measure).

Expanding the minisuperspace action around the de Sitter solution,

$$S_{\rm eu}(V_3) = S(V_3^{\rm dS}) + \kappa \int dt\, \delta V_3(t) \hat{H} \delta V_3(t)$$

the eigenmodes of $\hat{H}$ match well with those extracted from the simulations:



(N.B.: no further fitting necessary

Nonperturbative semiclassicality

The semiclassical limit of CDT quantum gravity which gives rise to the de Sitter universe is truly nonperturbative: it is located in a region of coupling constant space where the entropy of the geometric configurations is *as* important as the contribution from the exponential of the action.

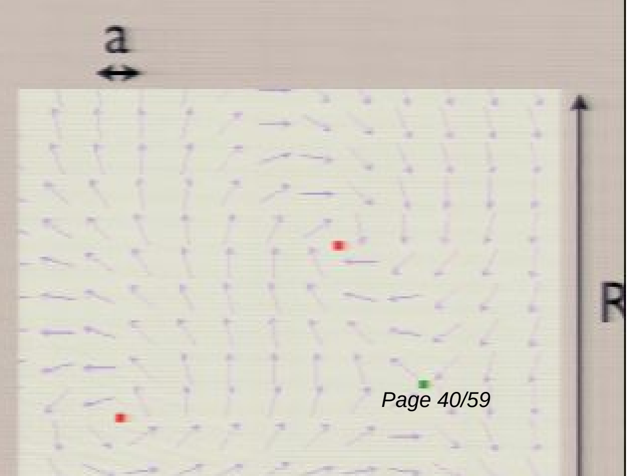
This is similar to what happens at a Kosterlitz-Thouless transition in the XY model of 2D spins on a two-dimensional lattice.

$$Z = \mathrm{e}^{-F/k_B T} = \sum_{\text{spin configs}} \mathrm{e}^{-E[spin]/k_B T} \simeq \left(\frac{R}{a}\right)^2 \mathrm{e}^{-[\kappa \ln(R/a)]/k_B T}$$

a single vortex has E = κ ln(R/a)

$$F = E - ST = (\kappa - 2k_B T)\ln(R/a)$$

F=0 is far away from the naive weak coupling limit.



(J. Ambjørn, A. Görlich, J. Jurkiewicz, J. Gizbert-Studnicki, T. Trzesniewski, RL, to appear)

Nonperturbative semiclassicality

The semiclassical limit of CDT quantum gravity which gives rise to the de Sitter universe is truly nonperturbative: it is located in a region of coupling constant space where the entropy of the geometric configurations is *as* important as the contribution from the exponential of the action.

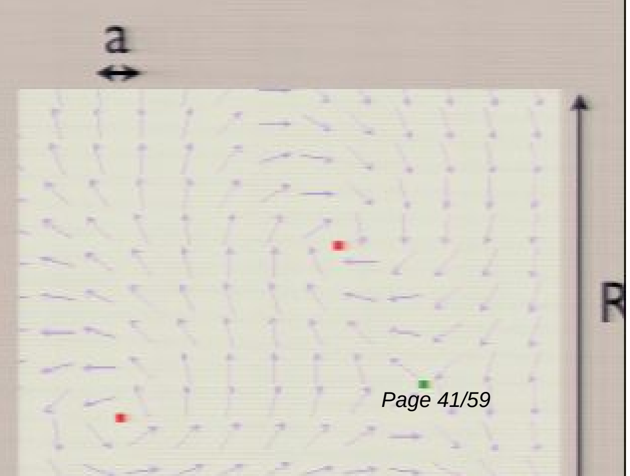
This is similar to what happens at a Kosterlitz-Thouless transition in the XY model of 2D spins on a two-dimensional lattice.

$$Z = \mathrm{e}^{-F/k_B T} = \sum_{\text{spin configs}} \mathrm{e}^{-E[spin]/k_B T} \simeq \left(\frac{R}{a}\right)^2 \mathrm{e}^{-[\kappa \ln(R/a)]/k_B T}$$

a single vortex has E = κ ln(R/a)

$$F = E - ST = (\kappa - 2k_B T)\ln(R/a)$$

F=0 is far away from the naive weak coupling limit.



(J. Ambjørn, A. Görlich, J. Jurkiewicz, J. Gizbert-Studnicki, T. Trzesniewski, RL, to appear)

Nonperturbative semiclassicality

The semiclassical limit of CDT quantum gravity which gives rise to the de Sitter universe is truly nonperturbative: it is located in a region of coupling constant space where the entropy of the geometric configurations is *as* important as the contribution from the exponential of the action.

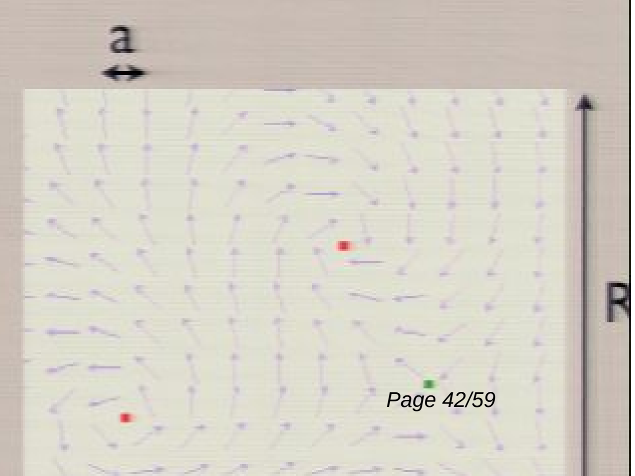
This is similar to what happens at a Kosterlitz-Thouless transition in the XY model of 2D spins on a two-dimensional lattice.

$$Z = \mathrm{e}^{-F/k_B T} = \sum_{\text{spin configs}} \mathrm{e}^{-E[spin]/k_B T} \simeq \left(\frac{R}{a}\right)^2 \mathrm{e}^{-[\kappa \ln(R/a)]/k_B T}$$

a single vortex has E = κ ln(R/a)

$$F = E - ST = (\kappa - 2k_B T)\ln(R/a)$$

F=0 is far away from the naive weak coupling limit.



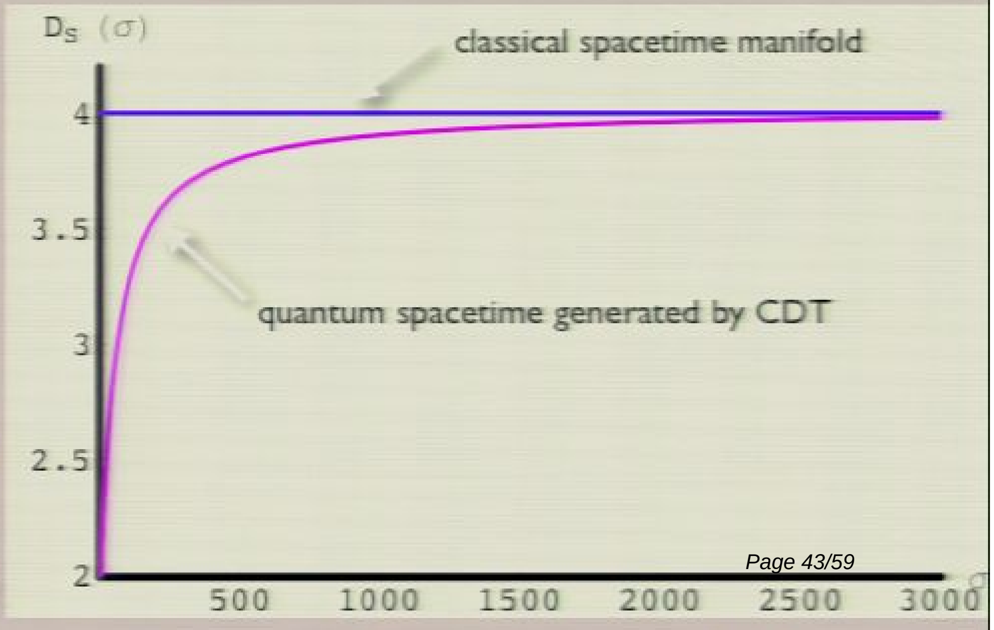
(J. Ambjørn, A. Görlich, J. Jurkiewicz, J. Gizbert-Studnicki, T. Trzesniewski, RL, to appear)

Where are we in the universe of candidate theories of quantum gravity?

The CDT approach is based on the premise that the framework of standard quantum field theory is sufficient to construct and understand quantum gravity as a fundamental theory. The dynamical, causal and nonperturbative nature of spacetime must be taken into account properly, but no "exotic" ingredients are needed.

A similar philosophy underlies also the application of the *exact renormalization group* to gravity, which tries to verify S. Weinberg's *asymptotic safety* scenario.

Intriguingly, another key result of CDT, that of "*dynamical dimensional reduction*" near the Planck scale (PRL 95 (2004) 171301) has also been corroborated in this approach (M.Reuter, O. Lauscher, JHEP 0510:050, 2005), as well as in "Lifshitz gravity" (P. Hořava, PRL 102 (2009) 161301), a completely different QFT-based approach to quantum gravity.

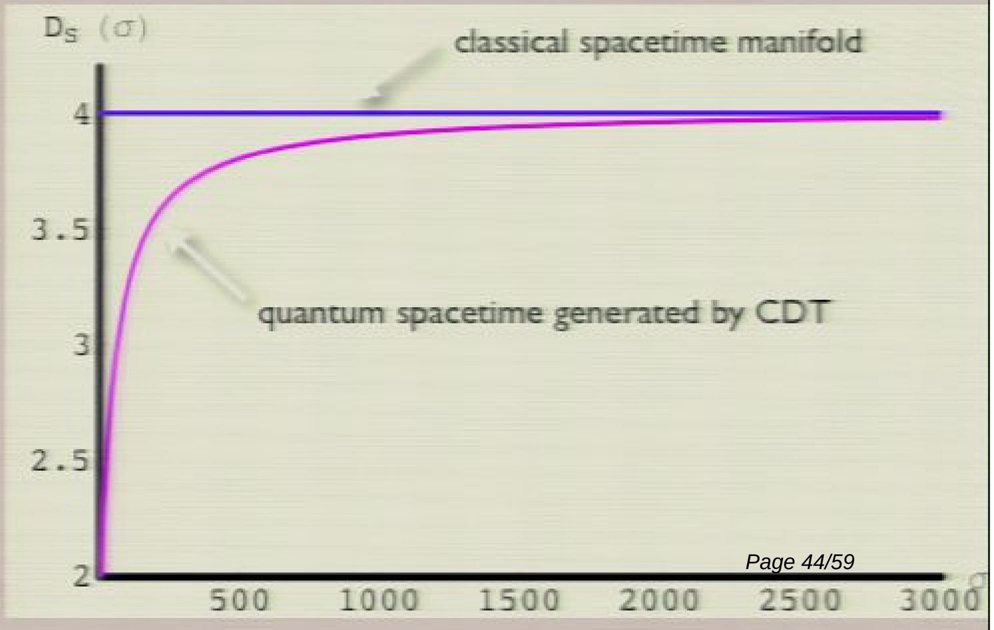


Where are we in the universe of candidate theories of quantum gravity?

The CDT approach is based on the premise that the framework of standard quantum field theory is sufficient to construct and understand quantum gravity as a fundamental theory. The dynamical, causal and nonperturbative nature of spacetime must be taken into account properly, but no "exotic" ingredients are needed.

A similar philosophy underlies also the application of the *exact renormalization group* to gravity, which tries to verify S. Weinberg's *asymptotic safety* scenario.

Intriguingly, another key result of CDT, that of "*dynamical dimensional reduction*" near the Planck scale (PRL 95 (2004) 171301) has also been corroborated in this approach (M.Reuter, O. Lauscher, JHEP 0510:050, 2005), as well as in "Lifshitz gravity" (P. Hořava, PRL 102 (2009) 161301), a completely different QFT-based approach to quantum gravity.

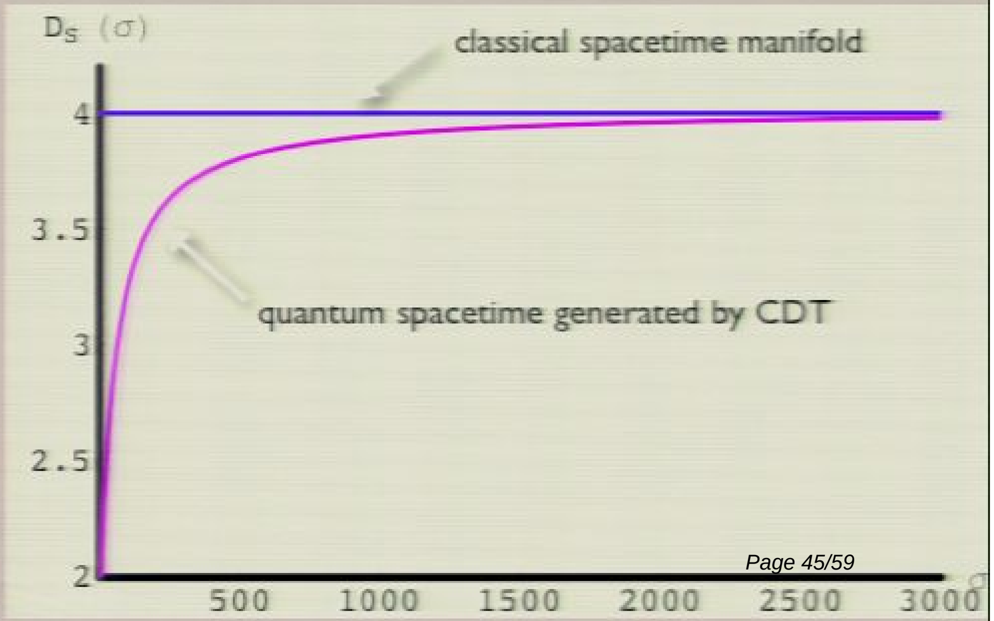


Where are we in the universe of candidate theories of quantum gravity?

The CDT approach is based on the premise that the framework of standard quantum field theory is sufficient to construct and understand quantum gravity as a fundamental theory. The dynamical, causal and nonperturbative nature of spacetime must be taken into account properly, but no "exotic" ingredients are needed.

A similar philosophy underlies also the application of the *exact renormalization group* to gravity, which tries to verify S. Weinberg's *asymptotic safety* scenario.

Intriguingly, another key result of CDT, that of "*dynamical dimensional reduction*" near the Planck scale (PRL 95 (2004) 171301) has also been corroborated in this approach (M.Reuter, O. Lauscher, JHEP 0510:050, 2005), as well as in "Lifshitz gravity" (P. Hořava, PRL 102 (2009) 161301), a completely different QFT-based approach to quantum gravity.

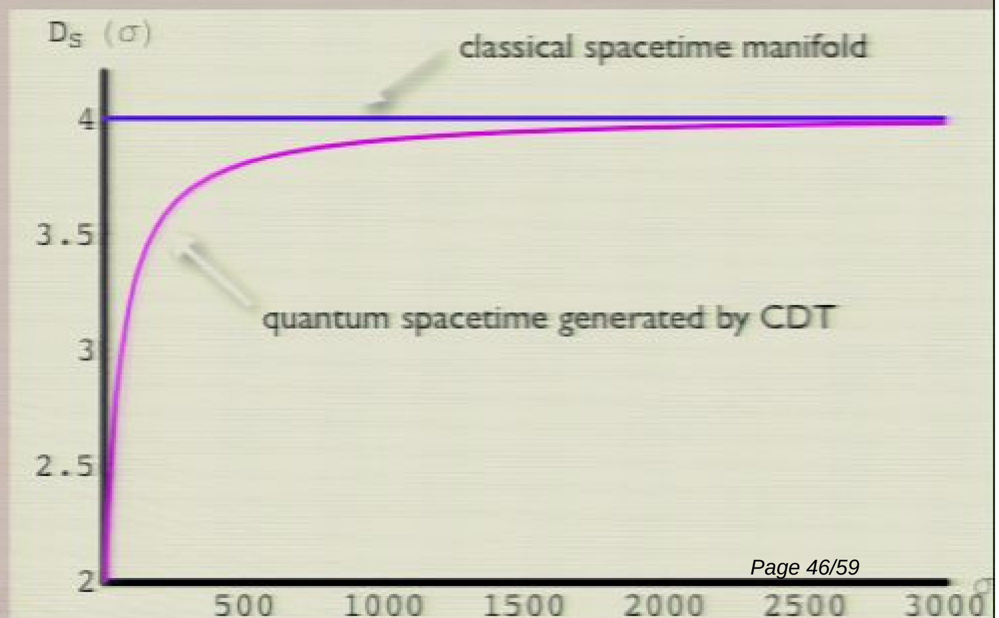


Where are we in the universe of candidate theories of quantum gravity?

The CDT approach is based on the premise that the framework of standard quantum field theory is sufficient to construct and understand quantum gravity as a fundamental theory. The dynamical, causal and nonperturbative nature of spacetime must be taken into account properly, but no "exotic" ingredients are needed.

A similar philosophy underlies also the application of the *exact renormalization group* to gravity, which tries to verify S. Weinberg's *asymptotic safety* scenario.

Intriguingly, another key result of CDT, that of "*dynamical dimensional reduction*" near the Planck scale (PRL 95 (2004) 171301) has also been corroborated in this approach (M.Reuter, O. Lauscher, JHEP 0510:050, 2005), as well as in "Lifshitz gravity" (P. Hořava, PRL 102 (2009) 161301), a completely different QFT-based approach to quantum gravity.

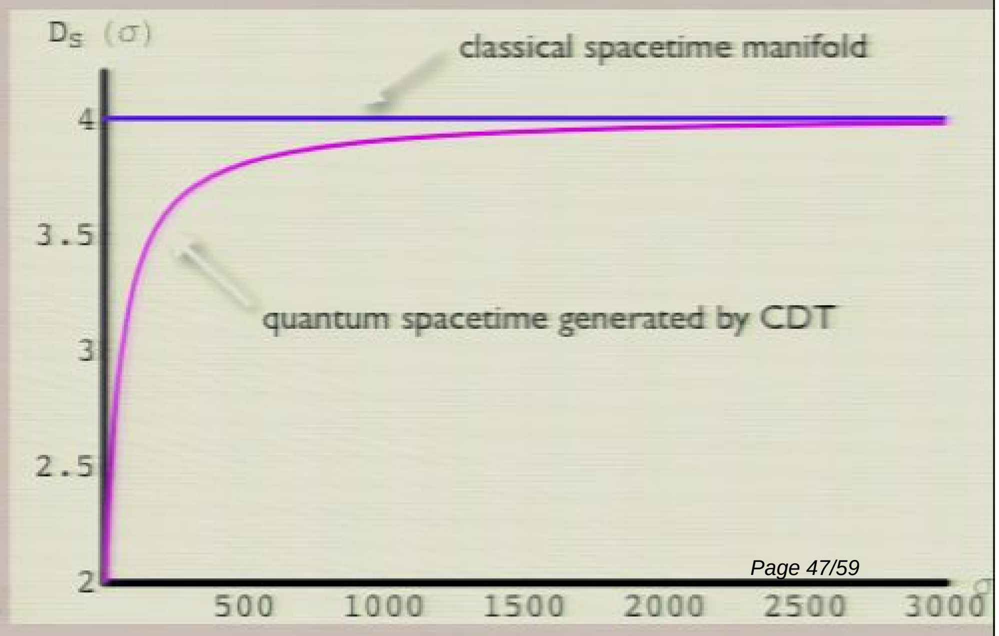


Where are we in the universe of candidate theories of quantum gravity?

The CDT approach is based on the premise that the framework of standard quantum field theory is sufficient to construct and understand quantum gravity as a fundamental theory. The dynamical, causal and nonperturbative nature of spacetime must be taken into account properly, but no "exotic" ingredients are needed.

A similar philosophy underlies also the application of the *exact renormalization group* to gravity, which tries to verify S. Weinberg's *asymptotic safety* scenario.

Intriguingly, another key result of CDT, that of "*dynamical dimensional reduction*" near the Planck scale (PRL 95 (2004) 171301) has also been corroborated in this approach (M.Reuter, O. Lauscher, JHEP 0510:050, 2005), as well as in "Lifshitz gravity" (P. Hořava, PRL 102 (2009) 161301), a completely different QFT-based approach to quantum gravity.

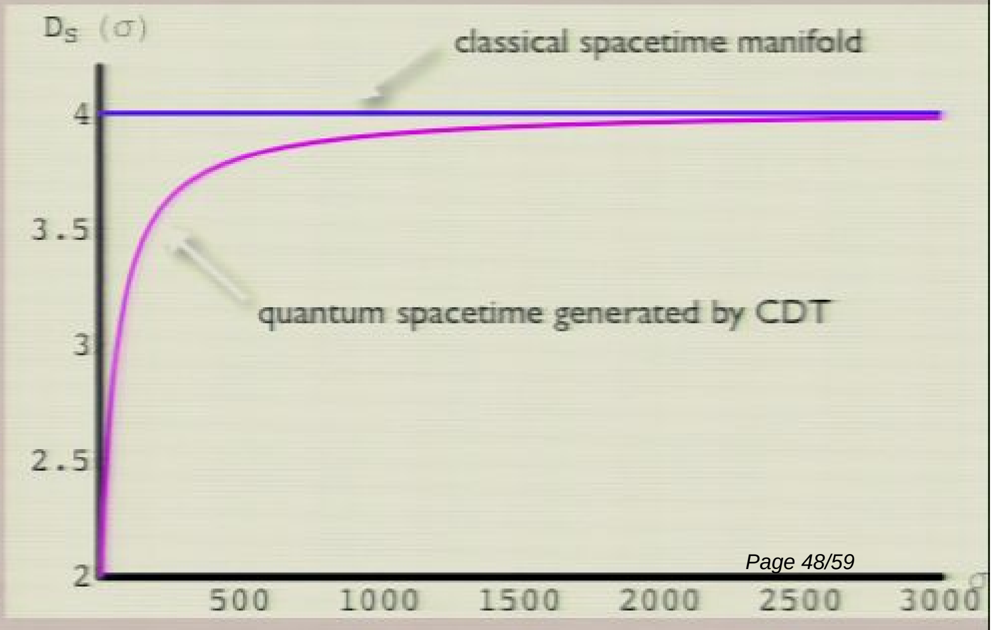


Where are we in the universe of candidate theories of quantum gravity?

The CDT approach is based on the premise that the framework of standard quantum field theory is sufficient to construct and understand quantum gravity as a fundamental theory. The dynamical, causal and nonperturbative nature of spacetime must be taken into account properly, but no "exotic" ingredients are needed.

A similar philosophy underlies also the application of the *exact renormalization group* to gravity, which tries to verify S. Weinberg's *asymptotic safety* scenario.

Intriguingly, another key result of CDT, that of "*dynamical dimensional reduction*" near the Planck scale (PRL 95 (2004) 171301) has also been corroborated in this approach (M.Reuter, O. Lauscher, JHEP 0510:050, 2005), as well as in "Lifshitz gravity" (P. Hořava, PRL 102 (2009) 161301), a completely different QFT-based approach to quantum gravity.



CDT - fresh from the press

- analyzing the phase structure of QG from CDT, establishing order of critical transition lines/points (J. Ambjørn, A. Görlich, S. Jordan, J. Jurkiewicz, RL, PLB 690 (2010) 413, and ongoing work)

- establishing a functional relation with the renormalization group flows of studies of the 'asymptotic safety scenario' (J. Ambjørn, A. Görlich, J. Jurkiewicz, RL, to appear), verify/falsify the existence of a UV fixed point

- studying matter coupling (influence of matter on geometry, extract Newton's law, the early universe coupled to a scalar field) - we have recently been able to quantify the expected effect of a single pointlike mass on the volume profile of CDT's de Sitter background (I. Khavkine, P. Reska, RL, Class. Quant. Grav. 27 (2010) 185025)

- investigating short-scale quantum structure of spacetime, and coming up with an effective description of Planckian dynamics - we have recently analyzed the fractality of the quantum geometry by using geodesic shell decompositions (J. Ambjørn, A. Görlich, J. Jurkiewicz, RL, PLB 690 (2010) 420)

CDT - fresh from the press

- analyzing the phase structure of QG from CDT, establishing order of critical transition lines/points (J. Ambjørn, A. Görlich, S. Jordan, J. Jurkiewicz, RL, PLB 690 (2010) 413, and ongoing work)

- establishing a functional relation with the renormalization group flows of studies of the 'asymptotic safety scenario' (J. Ambjørn, A. Görlich, J. Jurkiewicz, RL, to appear), verify/falsify the existence of a UV fixed point

- studying matter coupling (influence of matter on geometry, extract Newton's law, the early universe coupled to a scalar field) - we have recently been able to quantify the expected effect of a single pointlike mass on the volume profile of CDT's de Sitter background (I. Khavkine, P. Reska, RL, Class. Quant. Grav. 27 (2010) 185025)

- investigating short-scale quantum structure of spacetime, and coming up with an effective description of Planckian dynamics - we have recently analyzed the fractality of the quantum geometry by using geodesic shell decompositions (J. Ambjørn, A. Görlich, J. Jurkiewicz, RL, PLB 690 (2010) 420)

Causal Dynamical Triangulations - Summary & Outlook

CDT is a path integral formulation of gravity, which encorporates the dynamical and causal nature of geometry. It depends on a minimal number of assumptions and ingredients and has few free parameters. Its associated toolbox provides us with an "experimental lab" - a nonperturbative calculational handle on (near-)Planckian physics (c.f. lattice QCD).

- → We have begun to make quantitative statements/predictions.
- → We can also test nonperturbative predictions from other fundamental theories containing gravity.
- → Many nonperturbative lessons learned so far: emergence of classicality from quantum dynamics; dynamical nature of "dimension" on short scales; "time" and "causality" are fundamental, and not merely emergent, macroscopic properties of spacetime.
- → All of this corroborates our *best hope*. - Watch this space!

Causal Dynamical Triangulations - Summary & Outlook

CDT is a path integral formulation of gravity, which encorporates the dynamical and causal nature of geometry. It depends on a minimal number of assumptions and ingredients and has few free parameters. Its associated toolbox provides us with an "experimental lab" - a nonperturbative calculational handle on (near-)Planckian physics (c.f. lattice QCD).

- We have begun to make quantitative statements/predictions.
- We can also test nonperturbative predictions from other fundamental theories containing gravity.
- Many nonperturbative lessons learned so far: emergence of classicality from quantum dynamics; dynamical nature of "dimension" on short scales; "time" and "causality" are fundamental, and not merely emergent, macroscopic properties of spacetime.
- All of this corroborates our *best hope*. - Watch this space!

Causal Dynamical Triangulations - Summary & Outlook

CDT is a path integral formulation of gravity, which encorporates the dynamical and causal nature of geometry. It depends on a minimal number of assumptions and ingredients and has few free parameters. Its associated toolbox provides us with an "experimental lab" - a nonperturbative calculational handle on (near-)Planckian physics (c.f. lattice QCD).

- → We have begun to make quantitative statements/predictions.
- → We can also test nonperturbative predictions from other fundamental theories containing gravity.
- → Many nonperturbative lessons learned so far: emergence of classicality from quantum dynamics; dynamical nature of "dimension" on short scales; "time" and "causality" are fundamental, and not merely emergent, macroscopic properties of spacetime.
- → All of this corroborates our *best hope*. - Watch this space!

Where to learn more

- CDT light: "The self-organizing quantum universe", by J. Ambjørn, J. Jurkiewicz, RL (Scientific American, July 2008)
- A reasonably nontechnical review in Contemp. Phys. 47 (2006) [arxiv: hep-th/0509010]
- recent reviews: arXiv 0906.3947, 1004.0352, 1007.2560
- links to both review and popular science material can be found on my homepage http://www.phys.uu.nl/~loll

Where to learn more

- CDT light: "The self-organizing quantum universe", by J. Ambjørn, J. Jurkiewicz, RL (Scientific American, July 2008)
- A reasonably nontechnical review in Contemp. Phys. 47 (2006) [arxiv: hep-th/0509010]
- recent reviews: arXiv 0906.3947, 1004.0352, 1007.2560
- links to both review and popular science material can be found on my homepage http://www.phys.uu.nl/~loll

Where to learn more

- CDT light: "The self-organizing quantum universe", by J. Ambjørn, J. Jurkiewicz, RL (Scientific American, July 2008)
- A reasonably nontechnical review in Contemp. Phys. 47 (2006) [arxiv: hep-th/0509010]
- recent reviews: arXiv 0906.3947, 1004.0352, 1007.2560
- links to both review and popular science material can be found on my homepage http://www.phys.uu.nl/~loll

Where to learn more

• CDT light: "The self-organizing quantum universe", by J. Ambjørn, J. Jurkiewicz, RL (Scientific American, July 2008)

• A reasonably nontechnical review in Contemp. Phys. 47 (2006) [arxiv: hep-th/0509010]

• recent reviews: arXiv 0906.3947, 1004.0352, 1007.2560

• links to both review and popular science material can be found on my homepage http://www.phys.uu.nl/~loll

Where to learn more

- CDT light: "The self-organizing quantum universe", by J. Ambjørn, J. Jurkiewicz, RL (Scientific American, July 2008)
- A reasonably nontechnical review in Contemp. Phys. 47 (2006) [arxiv: hep-th/0509010]
- recent reviews: arXiv 0906.3947, 1004.0352, 1007.2560
- links to both review and popular science material can be found on my homepage http://www.phys.uu.nl/~loll

Where to learn more

- CDT light: "The self-organizing quantum universe", by J. Ambjørn, J. Jurkiewicz, RL (Scientific American, July 2008)
- A reasonably nontechnical review in Contemp. Phys. 47 (2006) [arxiv: hep-th/0509010]
- recent reviews: arXiv 0906.3947, 1004.0352, 1007.2560
- links to both review and popular science material can be found on my homepage http://www.phys.uu.nl/~loll