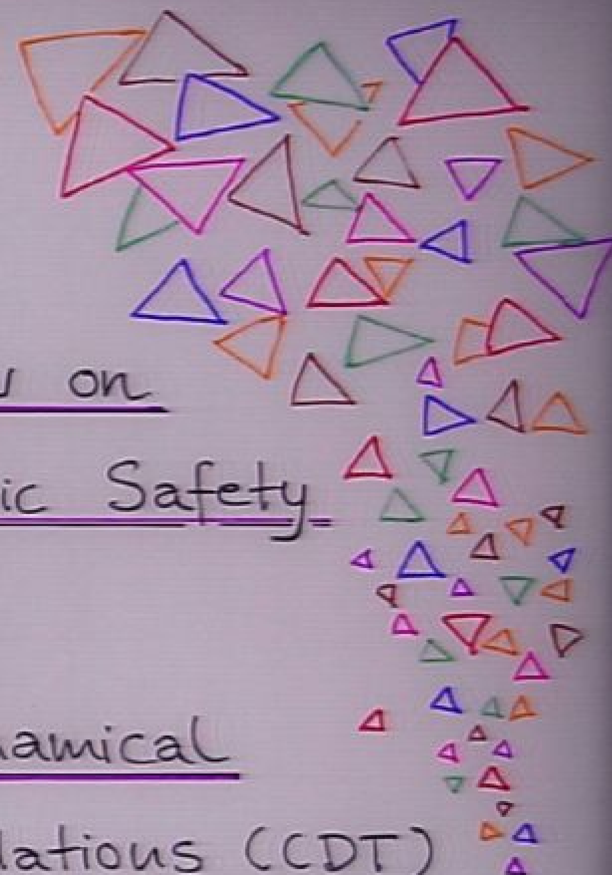
Title: Nonperturbative Insights from Causal Dynamical Triangulations

Date: Nov 06, 2009 11:00 AM

URL: http://pirsa.org/09110045

Abstract:

An $\perp$ view on Asymptotic Safety from Causal Dynamical Triangulations (CDT)



Renate Loll, Utrecht University

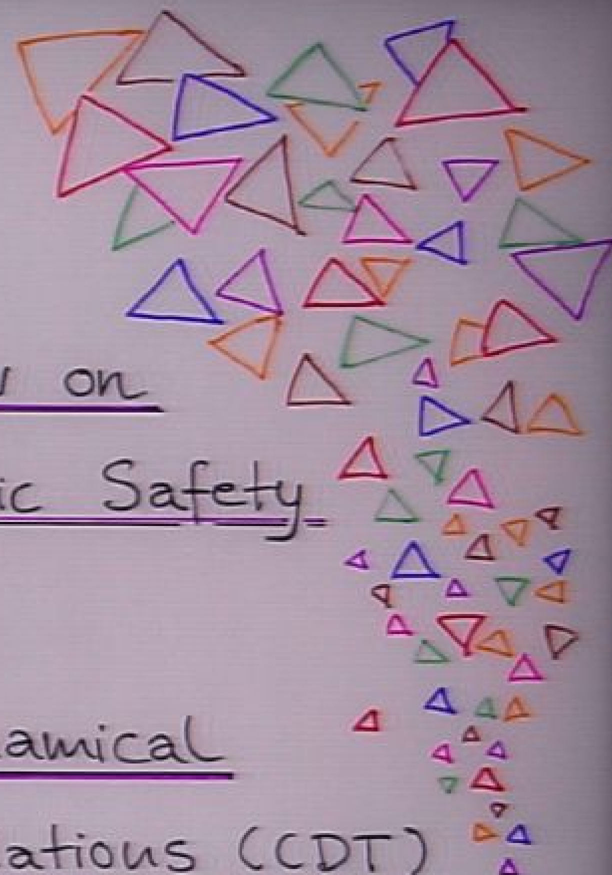
(collaboration w/ J. Ambjørn (Niels Bohr I.), J. Jurkiewicz, A. Görlich (Krakow U.) and S. Jordan (Utrecht))

An $\perp$ view on Asymptotic Safety from Causal Dynamical Triangulations (CDT)

Renate Loll, Utrecht University

(collaboration w/ J. Ambjørn (Niels Bohr I.), J. Jurkiewicz, A. Görlich (Krakow U.) and S. Jordan (Utrecht))

An ⊥ view on Asymptotic Safety from Causal Dynamical Triangulations (CDT)



Renate Loll, Utrecht University

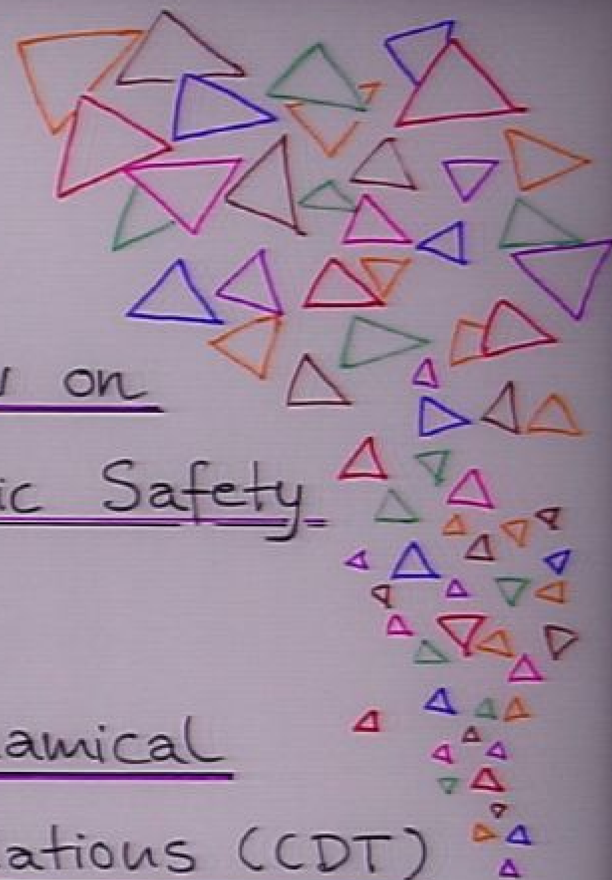
(collaboration w/ J. Ambjørn (Niels Bohr I.), J. Jurkiewicz, A. Görlich (Krakow U.) and S. Jordan (Utrecht))

An ⊥ view on Asymptotic Safety from Causal Dynamical Triangulations (CDT)

Renate Loll, Utrecht University

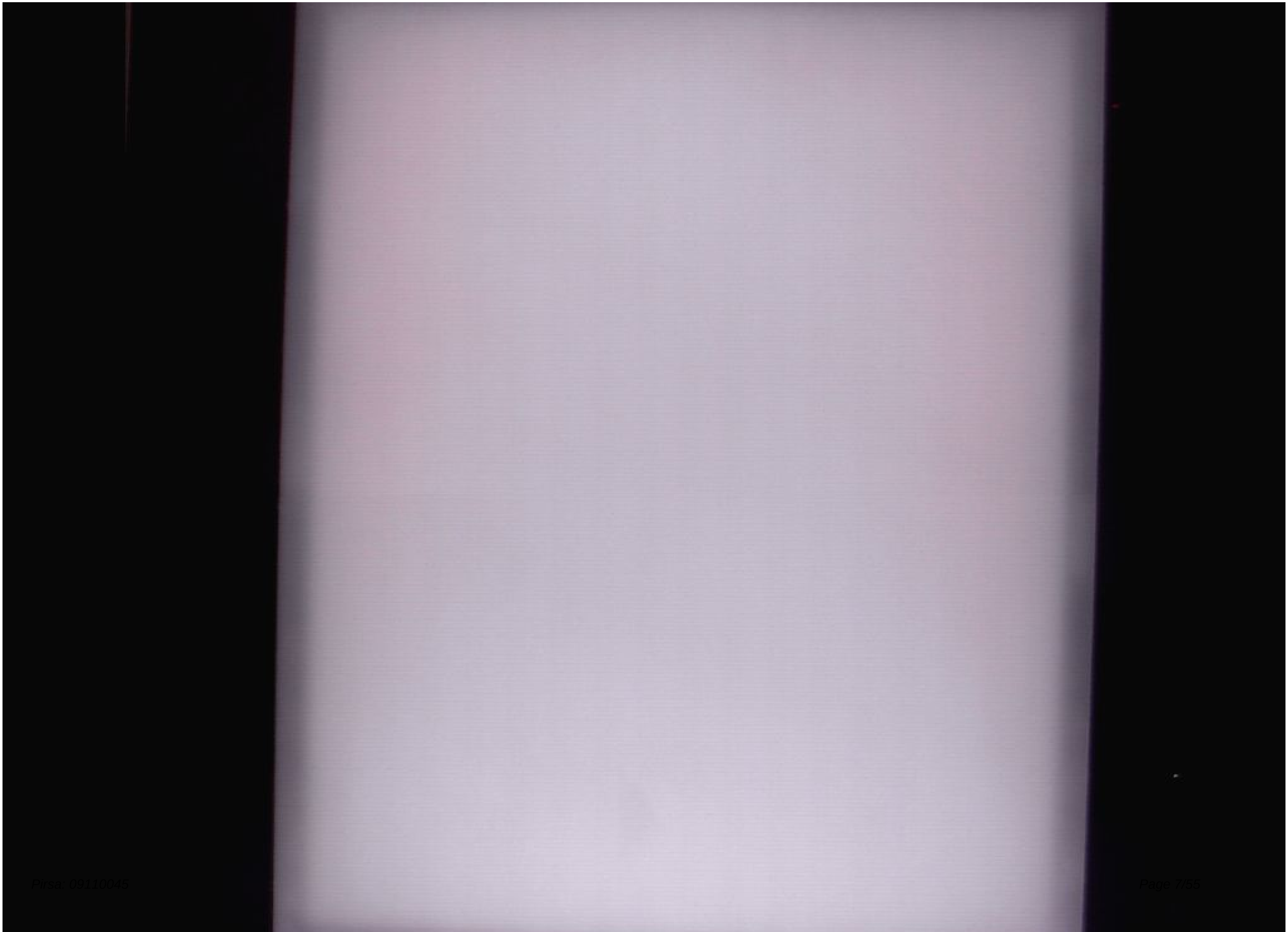
(collaboration w/ J. Ambjørn (Niels Bohr I.), J. Jurkiewicz, A. Görlich (Krakow U.) and S. Jordan (Utrecht))

An $\perp$ view on Asymptotic Safety from Causal Dynamical Triangulations (CDT)



Renate Loll, Utrecht University

(collaboration w/ J. Ambjørn (Niels Bohr I.), J. Jurkiewicz, A. Görlich (Krakow U.) and S. Jordan (Utrecht))



①

The Future of Quantum Gravity*

> The framework of standard QFT is sufficient to construct and understand quantum gravity as a fundamental theory, if the dynamical (causal) and nonperturbative nature of spacetime is taken into account properly.

RADICAL! MINIMALIST!

* pushing the boundaries of "standard" (this is gravity, after all)
* nonperturbative approaches are not all equivalent

One possible UV scenario

Asymptotic Safety

* even if FRG methods establish the existence of a NG fixed point, must still

①

The Future of Quantum Gravity*

The framework of standard causal QFT is sufficient to construct and understand quantum gravity as a fundamental theory, if the dynamical and nonperturbative nature of spacetime is taken into account properly.

RADICAL! MINIMALIST!

* pushing the boundaries of "standard" (this is gravity, after all)
* nonperturbative approaches are not all equivalent

One possible UV scenario

Asymptotic Safety

* even if FRG methods establish the existence of a NG fixed point, must still

① The Future of Quantum Gravity *

The framework of standard (causal) QFT is sufficient to construct and understand quantum gravity as a fundamental theory, if the dynamical and nonperturbative nature of spacetime is taken into account properly.

RADICAL! MINIMALIST!

* pushing the boundaries of "standard" (this is gravity, after all)

* nonperturbative approaches are not all equivalent

One possible UV scenario

Asymptotic Safety

* even if FRG methods establish the existence of a NG fixed point, must still

(1)

The Future of Quantum Gravity*

The framework of standard (causal) QFT is sufficient to construct and understand quantum gravity as a fundamental theory, if the dynamical and nonperturbative nature of spacetime is taken into account properly.

RADICAL! MINIMALIST!

* pushing the boundaries of "standard" (this is gravity, after all)
* nonperturbative approaches are not all equivalent

One possible UV scenario

Asymptotic Safety

* even if FRG methods establish the existence of a NG fixed point, must still

The Future of Quantum Gravity*

> The framework of standard causal QFT is sufficient to construct and understand quantum gravity as a fundamental theory, if the dynamical and nonperturbative nature of spacetime is taken into account properly.

RADICAL! MINIMALIST!

* pushing the boundaries of "standard" (this is gravity, after all)
* nonperturbative approaches are not all equivalent

One possible UV scenario

Asymptotic Safety

* even if FRG methods establish the existence of a NG fixed point, must still work out its physical implications
* inescapable? other "UV completions" thinkab[le]

The Future of Quantum Gravity*

> The framework of standard (causal) QFT is sufficient to construct and understand quantum gravity as a fundamental theory, if the dynamical and nonperturbative nature of spacetime is taken into account properly.

RADICAL! MINIMALIST!

* pushing the boundaries of "standard" (this is gravity, after all)
* nonperturbative approaches are not all equivalent

One possible UV scenario

Asymptotic Safety

* even if FRG methods establish the existence of a NG fixed point, must still work out its physical implications
* inescapable? other "UV completions" thinkable?

The Future of Quantum Gravity [*]

> The framework of standard causal QFT is sufficient to construct and understand quantum gravity as a fundamental theory, if the dynamical and nonperturbative nature of spacetime is taken into account properly.

RADICAL! MINIMALIST!

* pushing the boundaries of "standard" (this is gravity, after all)
* nonperturbative approaches are not all equivalent

One possible UV scenario

Asymptotic Safety

* even if FRG methods establish the existence of a NG fixed point, must still work out its physical implications
* inescapable? other "UV completions" thinkable?

The Future of Quantum Gravity *

The framework of standard causal QFT is sufficient to construct and understand quantum gravity as a fundamental theory, if the dynamical and nonperturbative nature of spacetime is taken into account properly.

RADICAL! MINIMALIST!

* pushing the boundaries of "standard" (this is gravity, after all)
* nonperturbative approaches are not all equivalent

One possible UV scenario

Asymptotic Safety

* even if FRG methods establish the existence of a NG fixed point, must still work out its physical implications
* inescapable? other "UV completions" thinkable?

The Future of Quantum Gravity

> The framework of standard causal QFT is sufficient to construct and understand quantum gravity as a fundamental theory, if the dynamical and nonperturbative nature of spacetime is taken into account properly.

RADICAL! MINIMALIST!

* pushing the boundaries of "standard" (this is gravity, after all)

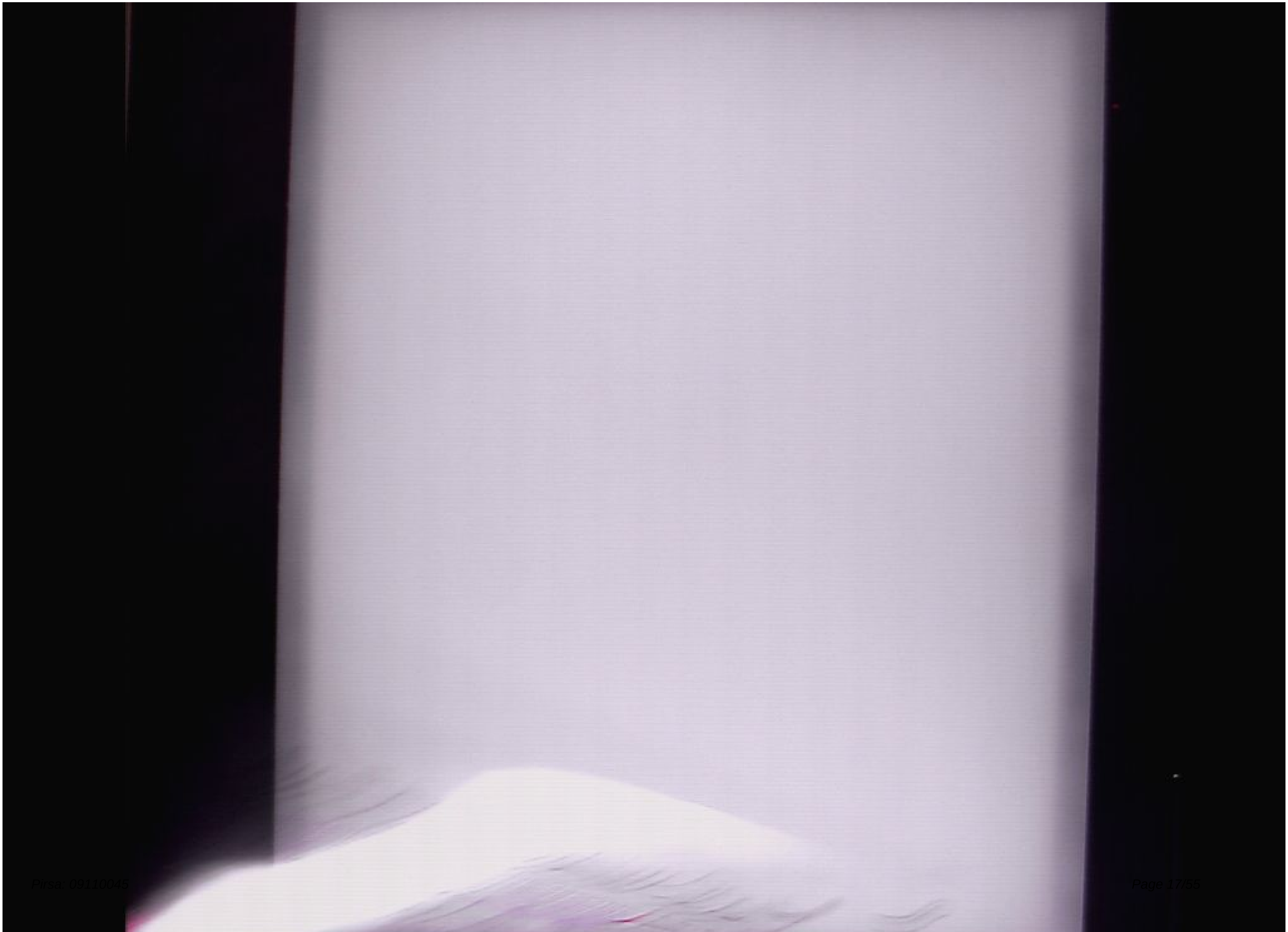
* nonperturbative approaches are not all equivalent

One possible UV scenario

Asymptotic Safety

* even if FRG methods establish the existence of a NG fixed point, must still work out its physical implications

* inescapable? other "UV completions" thinkable?



Why not? – always assume certain variables/tools/concepts remain usable/valid near ℓ_{Pl}.
May be difficult to check.

> Is the existence of a nontrivial fixed point a physical observable in quantum gravity?

Best we can do currenty:
"web of quantum gravities"
– some right, some wrong (too early to tell)

> The road forward: "observables" ≃ invariantly defined geometric quantities

- beautiful example: short-distance spectral dimension found across disparate approaches
  (J. Ambjørn, J. Jurkiewicz, R.L., hep-th/0505113;
  O. Lauscher, M. Reuter, hep-th/0508202;
  D. Benedetti, 0811.1396; P. Hořava, 0902.3657;
  L. Modesto, 0905.1665; S. Carlip, 0909.3329)

↪ unique underlying QG theory?

②

Why not? - always assume certain variables/tools/concepts remain usable/valid near ℓ_{Pl}. May be difficult to check.

Is the existence of a nontrivial fixed point a physical observable in quantum gravity?

Best we can do currenty:
"web of quantum gravities"
- some right, some wrong (too early to tell)

The road forward: "observables" ≃ invariantly defined geometric quantities

- beautiful example: short-distance spectral dimension found across disparate approaches (J. Ambjørn, J. Jurkiewicz, R.L., hep-th/0505113; O. Lauscher, M. Reuter, hep-th/0508202; D. Benedetti, 0811.1396; P. Hořava, 0902.3657; L. Modesto, 0905.1665; S. Carlip, 0909.3329)

↪ unique underlying QG theory?

②

Why not? - always assume certain variables/tools/concepts remain usable/valid near ℓ_{Pl}.
May be difficult to check.

Is the existence of a nontrivial fixed point a physical observable in quantum gravity?

Best we can do currenty:

"web of quantum gravities"

- some right, some wrong (too early to tell)

The road forward: "observables" ≃ invariantly defined geometric quantities

- beautiful example: short-distance spectral dimension found across disparate approaches
(J. Ambjørn, J. Jurkiewicz, R.L., hep-th/0505113; O. Lauscher, M. Reuter, hep-th/0508202; D. Benedetti, 0811.1396; P. Hořava, 0902.3657; L. Modesto, 0905.1665; S. Carlip, 0909.3329)

↪ unique underlying QG theory?

Why not? - always assume certain variables/ tools / concepts remain usable / valid near ℓ_{PL}. May be difficult to check.

> Is the existence of a nontrivial fixed point a physical observable in quantum gravity?

Best we can do currenty:

"web of quantum gravities"

- some right, some wrong (too early to tell)

> The road forward: "observables" ≃ invariantly defined geometric quantities

- beautiful example: short-distance spectral dimension found across disparate approaches

(J. Ambjørn, J. Jurkiewicz, R.L., hep-th/0505113; O. Lauscher, M. Reuter, hep-th/0508202; D. Benedetti, 0811.1396; P. Hořava, 0902.3657; L. Modesto, 0905.1665; S. Carlip, 0909.3329)

↪ unique underlying QG theory?

②

Why not? – always assume certain variables/tools/concepts remain usable/valid near ℓ_{Pl}. May be difficult to check.

Is the existence of a nontrivial fixed point a physical observable in quantum gravity?

Best we can do currenty:

"web of quantum gravities"

– some right, some wrong (too early to tell)

The road forward: "observables" ≃ invariantly defined geometric quantities

- beautiful example: short-distance spectral dimension found across disparate approaches (J. Ambjørn, J. Jurkiewicz, R.L., hep-th/0505113; O. Lauscher, M. Reuter, hep-th/0508202; D. Benedetti, 0811.1396; P. Hořava, 0902.3657; L. Modesto, 0905.1665; S. Carlip, 0909.3329)

↪ unique underlying QG theory?

Why not? – always assume certain variables/ tools / concepts remain usable / valid near ℓ_{Pl}.
May be difficult to check.

Is the existence of a nontrivial fixed point a physical observable in quantum gravity?

Best we can do currenty:
"web of quantum gravities"
– some right, some wrong (too early to tell)

The road forward : "observables" ≃ invariantly defined geometric quantities

- beautiful example : short-distance spectral dimension found across disparate approaches
(J. Ambjørn, J. Jurkiewicz, R.L., hep-th/0505113; O. Lauscher, M. Reuter, hep-th/0508202; D. Benedetti, 0811.1396; P. Hořava, 0902.3657; L. Modesto, 0905.1665; S. Carlip, 0909.3329)

↪ unique underlying QG theory ?

Why not? - always assume certain variables/tools/concepts remain usable/valid near ℓ_{Pl}.
May be difficult to check.

Is the existence of a nontrivial fixed point a physical observable in quantum gravity?

Best we can do currenty:

"web of quantum gravities"

- some right, some wrong (too early to tell)

The road forward: "observables" ≃ invariantly defined geometric quantities

- beautiful example: short-distance spectral dimension found across disparate approaches
(J. Ambjørn, J. Jurkiewicz, R.L., hep-th/0505113; O. Lauscher, M. Reuter, hep-th/0508202; D. Benedetti, 0811.1396; P. Hořava, 0902.3657; L. Modesto, 0905.1665; S. Carlip, 0909.3329)

↪ unique underlying QG theory?

Why not? – always assume certain variables/ tools / concepts remain usable / valid near ℓ_{Pl}.
May be difficult to check.

Is the existence of a nontrivial fixed point a physical observable in quantum gravity ?

Best we can do currenty:
"web of quantum gravities"
– some right, some wrong (too early to tell)

The road forward : "observables" ≃ invariantly defined geometric quantities

- beautiful example : short-distance spectral dimension found across disparate approaches
(J. Ambjørn, J. Jurkiewicz, R.L., hep-th/0505113;
O. Lauscher, M. Reuter, hep-th/0508202;
D. Benedetti, 0811.1396; P. Hořava, 0902.3657;
L. Modesto, 0905.1665; S. Carlip, 0909.3329)

↪ unique underlying QG theory ?

Why not? - always assume certain variables/tools/concepts remain usable/valid near ℓ_{Pl}.
May be difficult to check.

> Is the existence of a nontrivial fixed point a physical observable in quantum gravity?

Best we can do currenty:
"web of quantum gravities"
- some right, some wrong (too early to tell)

> The road forward: "observables" ≃ invariantly defined geometric quantities

- beautiful example: short-distance spectral dimension found across disparate approaches
(J. Ambjørn, J. Jurkiewicz, R.L., hep-th/0505113; O. Lauscher, M. Reuter, hep-th/0508202; D. Benedetti, 0811.1396; P. Hořava, 0902.3657; L. Modesto, 0905.1665; S. Carlip, 0909.3329)

↪ unique underlying QG theory?

Why not? - always assume certain variables/tools/concepts remain usable/valid near ℓ_{Pl}.
May be difficult to check.

> Is the existence of a nontrivial fixed point a physical observable in quantum gravity?

Best we can do currenty:
"web of quantum gravities"
- some right, some wrong (too early to tell)

> The road forward: "observables" ≃ invariantly defined geometric quantities

- beautiful example: short-distance spectral dimension found across disparate approaches
(J. Ambjørn, J. Jurkiewicz, R.L., hep-th/0505113;
O. Lauscher, M. Reuter, hep-th/0508202;
D. Benedetti, 0811.1396; P. Hořava, 0902.3657;
L. Modesto, 0905.1665; S. Carlip, 0909.3329)

↪ unique underlying QG theory?

Why not? - always assume certain variables/tools/concepts remain usable/valid near ℓ_{Pl}. May be difficult to check.

Is the existence of a nontrivial fixed point a physical observable in quantum gravity?

Best we can do currenty:

"web of quantum gravities"

- some right, some wrong (too early to tell)

The road forward: "observables" ≃ invariantly defined geometric quantities

- beautiful example: short-distance spectral dimension found across disparate approaches

(J. Ambjørn, J. Jurkiewicz, R.L., hep-th/0505113; O. Lauscher, M. Reuter, hep-th/0508202; D. Benedetti, 0811.1396; P. Hořava, 0902.3657; L. Modesto, 0905.1665; S. Carlip, 0909.3329)

↪ unique underlying QG theory?

Why not? – always assume certain variables/tools/concepts remain usable/valid near ℓ_{Pl}.
May be difficult to check.

Is the existence of a nontrivial fixed point a physical observable in quantum gravity?

Best we can do currenty:
"web of quantum gravities"
– some right, some wrong (too early to tell)

The road forward: "observables" ≃ invariantly defined geometric quantities

- beautiful example: short-distance spectral dimension found across disparate approaches
(J. Ambjørn, J. Jurkiewicz, R.L., hep-th/0505113; O. Lauscher, M. Reuter, hep-th/0508202; D. Benedetti, 0811.1396; P. Hořava, 0902.3657; L. Modesto, 0905.1665; S. Carlip, 0909.3329)

↪ unique underlying QG theory?

Why not? - always assume certain variables/ tools / concepts remain usable / valid near ℓ_{Pl}.
May be difficult to check.

> Is the existence of a nontrivial fixed point a physical observable in quantum gravity?

Best we can do currenty:
"web of quantum gravities"
- some right, some wrong (too early to tell)

> The road forward: "observables" ≃ invariantly defined geometric quantities

- beautiful example: short-distance spectral dimension found across disparate approaches
(J. Ambjørn, J. Jurkiewicz, R.L., hep-th/0505113; O. Lauscher, M. Reuter, hep-th/0508202; D. Benedetti, 0811.1396; P. Hořava, 0902.3657; L. Modesto, 0905.1665; S. Carlip, 0909.3329)

↳ unique underlying QG theory?

How can we test for asymptotic safety?

- QG à la FRG (functional renormal. group)
  → taylor-made
- QG à la CDT (causal dynam. triangulations)
  → perhaps (c.f. J. Ambjørn's talk)

Common features

- covariant, action-based approaches, with full dynamics incorporated
- vital input from numerical tools
- can look for scaling behaviour in UV
- conceptually and computationally "tight" (no exotic ingredients) ⇒ falsifiable ?*

Differences

FRG		CDT
algebraic	⟷	geometric
continuum formulation,	⟷	"discrete" formulation
needs gauge-fixing	⟷	no gauge d.o.f.
Euclidean	⟷	causal structure essential

* Euclidean version already falsified

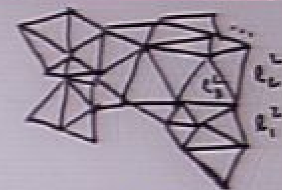
What CDT quantum gravity can do for you

Given a model of full, nonperturbative QG (microscopic d.o.f. + dynamical principle + ...), we typically cannot work out its dynamics and predictions analytically.

* technical tool box of CDT (Monte Carlo simulations + finite-size scaling) allows us to do this
* can obtain nonperturbative info not easily accessible by other methods (c.f. lattice QCD)
* potentially, can obtain the correct theory of quantum gravity (if limiting process $a \to 0$ converges)
* evaluating suitable diffeo-invariant quantities gives us hints of how to construct an effective theory of the (sub-) Planckian "atoms of spacetime"
* as we'll see, one uncovers many nonperturbative surprises

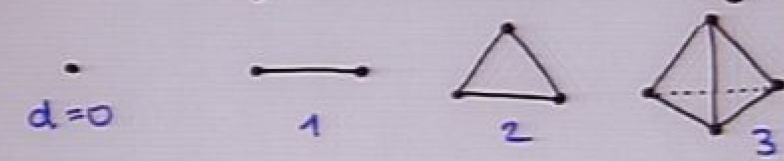
Beautiful idea: "GR without coordinates" (5)

(T. Regge 1961) ~ simplicial approximation of curved manifolds M

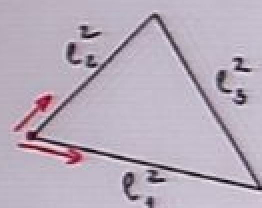


$$(M, g_{\mu\nu}(x)) \underset{\text{approx.}}{\simeq} (T, \{\ell_i^2 \,;\, i=1,\dots,n\})$$

- piecewise flat geometry is encoded entirely in geodesic edge lengths and connectivity of T
- works in any dimension and signature



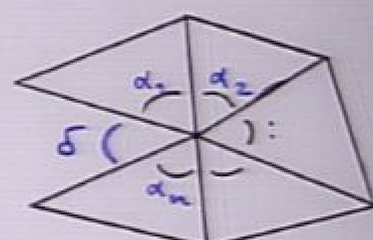
- re-introducing $g_{\mu\nu}$ for a 2-simplex, e.g.



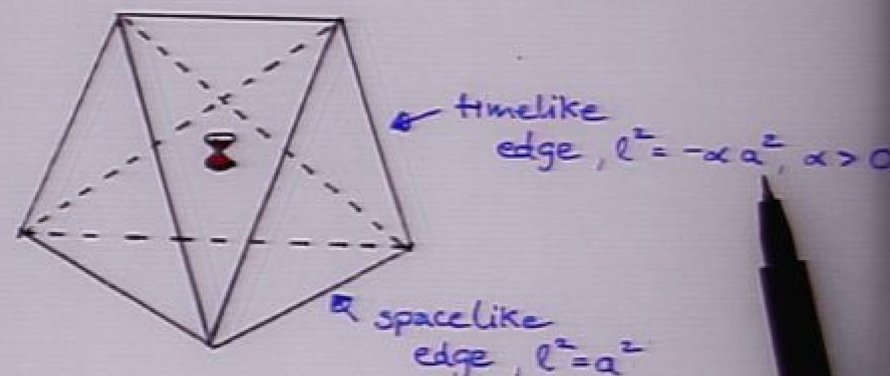
$$\rightsquigarrow \quad g_{\mu\nu} = \begin{pmatrix} \ell_1^2 & \frac{\ell_1^2+\ell_2^2-\ell_3^2}{2} \\ \frac{\ell_1^2+\ell_2^2-\ell_3^2}{2} & \ell_2^2 \end{pmatrix}$$

- curvature ~ deficit angle

$$\delta = 2\pi - \sum_{i \ni v} \alpha_i$$



in general, concentrated at $(d-2)$-subsimplices



elementary four-simplex, building block for causal dynamical triangulation (unphysical*)

[* no assumption of fundamental spacetime discreteness]

⑥

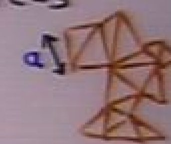
What is CDT-quantum gravity?

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

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

$C(T)$ ← $|Aut(T)|$

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



Key features

→ PIC

Regge '61

- works directly on space of geometries
- nonperturbative: g's far away from class. sol.s
- background-independent: "democracy of g's"
- can evaluate Z quantitatively
- minimalist ingredients
- only QG theory which can dynamically generate its own (physically realistic) background
- results are by construction robust: many microscopic details of the regularization are irrelevant ("universality")

CDT Key Achievements I

Demonstrating the need for causality

Euclidean quantum gravity (with metric signature (++++)) gives different and (in d=4) wrong results
(⇒ don't do the path integral Hawking's way!)

First explicit and exactly soluble example of a system of dynamical geometry where (in d=2) Lorentzian QG ≠ Euclidean QG.

Comparing cylinder amplitudes:

typical Lorentzian PI history in 2d CDT (hep-th/9805108, w/ J. Ambjørn)

typical Euclidean PI history (× ~ causality-violat. pt.)

N.B.: ∃ well-defined "Wick rotation" $\mathcal{W}$ for the Lorentzian histories s.t.

$\mathcal{W}$ (Lor. PI histories) $\subsetneq$ Euclid. PI histories

(7)

In $d=4$, encoding causality into the gluing rules for the 4-simplices (*) is essential for obtaining a good classical limit.

[(*) aligning light cones, no CTCs]

* a nonperturbative quantum superposition of Euclidean (DT) curved "spacetimes" does not lead to a macroscopically extended 4dim. geometry (instead, Hausdorff dim. $d_H = 2$ or $d_H = \infty$)

(Bialas et al. hep-lat/9601024, 9608030)

* instead, restricting to spacetimes satisfying "microcausality" (CDT) ~~does~~ can lead to an extended quantum universe

(J. Ambjørn, J. Jurkiewicz, RL, hep-th/0404156, 0505154)

→ this reveals an intriguing relation between microstructure (micro-causality = suppression of "baby universes" in time direction) and (the existence of) ...

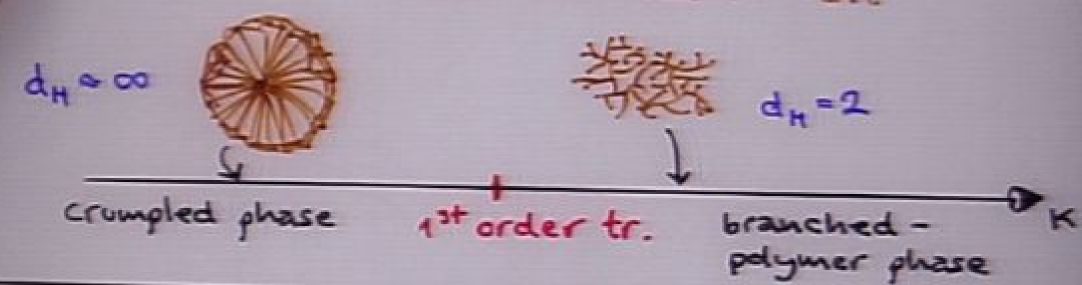
Comparing phase diagrams

(N_i = # of i-dim. simplicial building blocks)

bare Euclidean Einstein-Hilbert action:

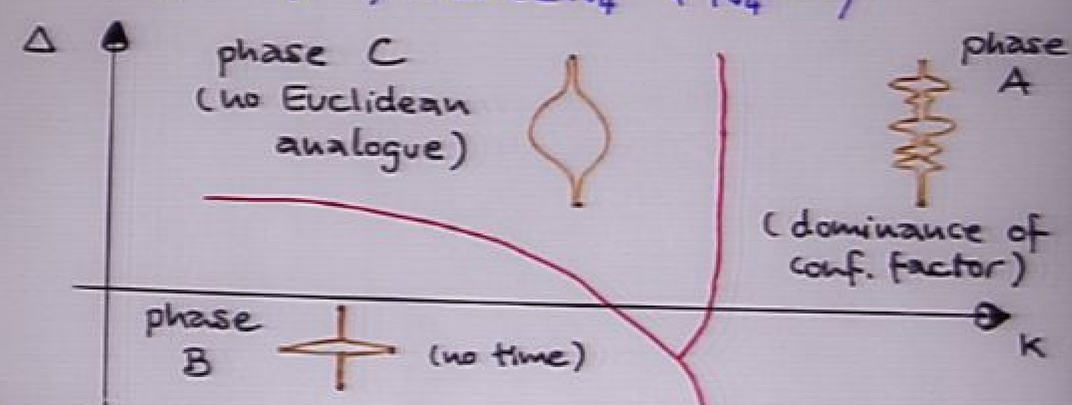
$$S_E^{DT}\left[\kappa = \frac{1}{G_N}, \lambda\right] = -\kappa N_0 + \kappa_4(\lambda, \kappa)\, N_4$$

Newton's constant ↗ ; ↖ cosmol. const., must be tuned to λ_{crit}



bare Euclideanized Einstein-Hilbert action:

$$S_E^{CDT}[\kappa, \lambda, \Delta] = -(\kappa + 6\Delta) N_0 + \kappa_4(\lambda, \kappa) \cdot$$
$$\cdot \left(N_4^{(4,1)} + N_4^{(3,2)}\right) + \Delta \left(2 N_4^{(4,1)} + N_4^{(3,2)}\right)$$



Δ ~ "asymmetry" – finite scaling between time- & spacelike length ($\Delta = 0 \Leftrightarrow$ symmetry)

Comparing phase diagrams

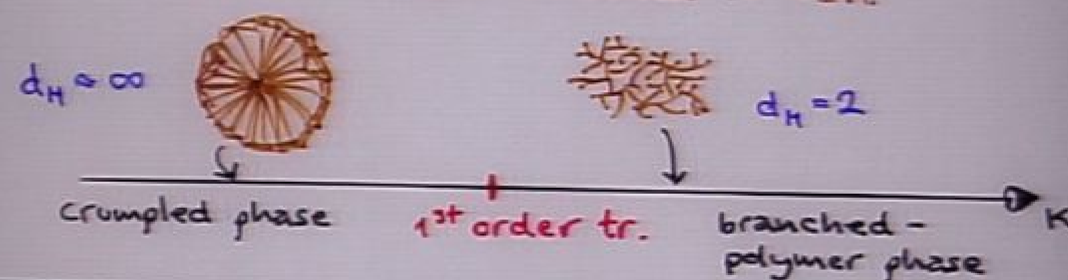
(8)

(N_i = # of i-dim. simplicial building blocks)

bare Euclidean Einstein-Hilbert action:

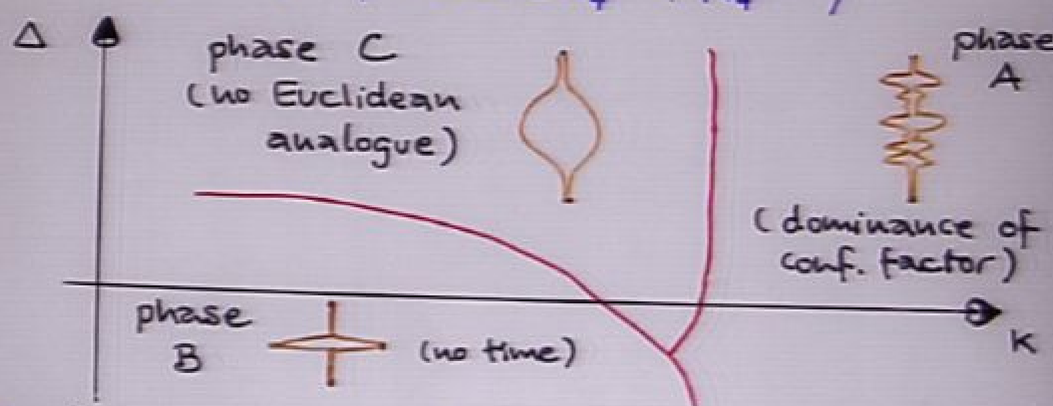
$$S_E^{DT}\,[\kappa = \tfrac{1}{G_N}, \lambda] = -\kappa N_0 + \kappa_4(\lambda, \kappa)\, N_4$$

Newton's constant ↗ ; ↖ cosmol. const., must be tuned to λ_{crit}



bare Euclideanized Einstein-Hilbert action:

$$S_E^{CDT}\,[\kappa, \lambda, \Delta] = -(\kappa + 6\Delta)\, N_0 + \kappa_4(\lambda, \kappa)\cdot$$
$$\cdot\,(N_4^{(4,1)} + N_4^{(3,2)}) + \Delta\,(2 N_4^{(4,1)} + N_4^{(3,2)})$$



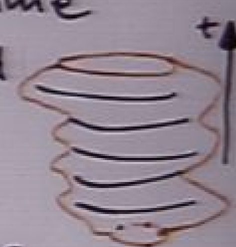
Δ ~ "asymmetry" - finite scaling between time- & spacelike length ($\Delta = 0 \Leftrightarrow$ symmetry)

(8')

Lessons

1) "Causality" is not emergent, but needs to be put in by hand as microcausality on each spacetime history.

2) "Time" is not emergent: we need to put in the "potentiality" of time
   – in CDT this is implemented as a discrete, global time slicing for each PI history (which may or may not survive the continuum limit)



KEY ACHIEVEMENT of CDT QG II

The dynamical emergence of spacetime as we know it

CDT is the only theory of quantum gravity where a classical extended geometry is generated from Planck-scale excitations.

How? – nonperturbative, entropic mechanism:

> Magically, the many microscopic building blocks in the quantum superposition arrange themselves into an extended quantum spacetime whose macroscopic shape is that of a well-known cosmology.

When – from all the gravitational d.o.f.s present* – we monitor only the spatial 3-volume $\langle V_3(t) \rangle$ as a function of (proper) time t, we find that it matches exactly that of a de Sitter universe. → pic snapshot

KEY ACHIEVEMENT of CDT QG II

The dynamical emergence of spacetime as we know it

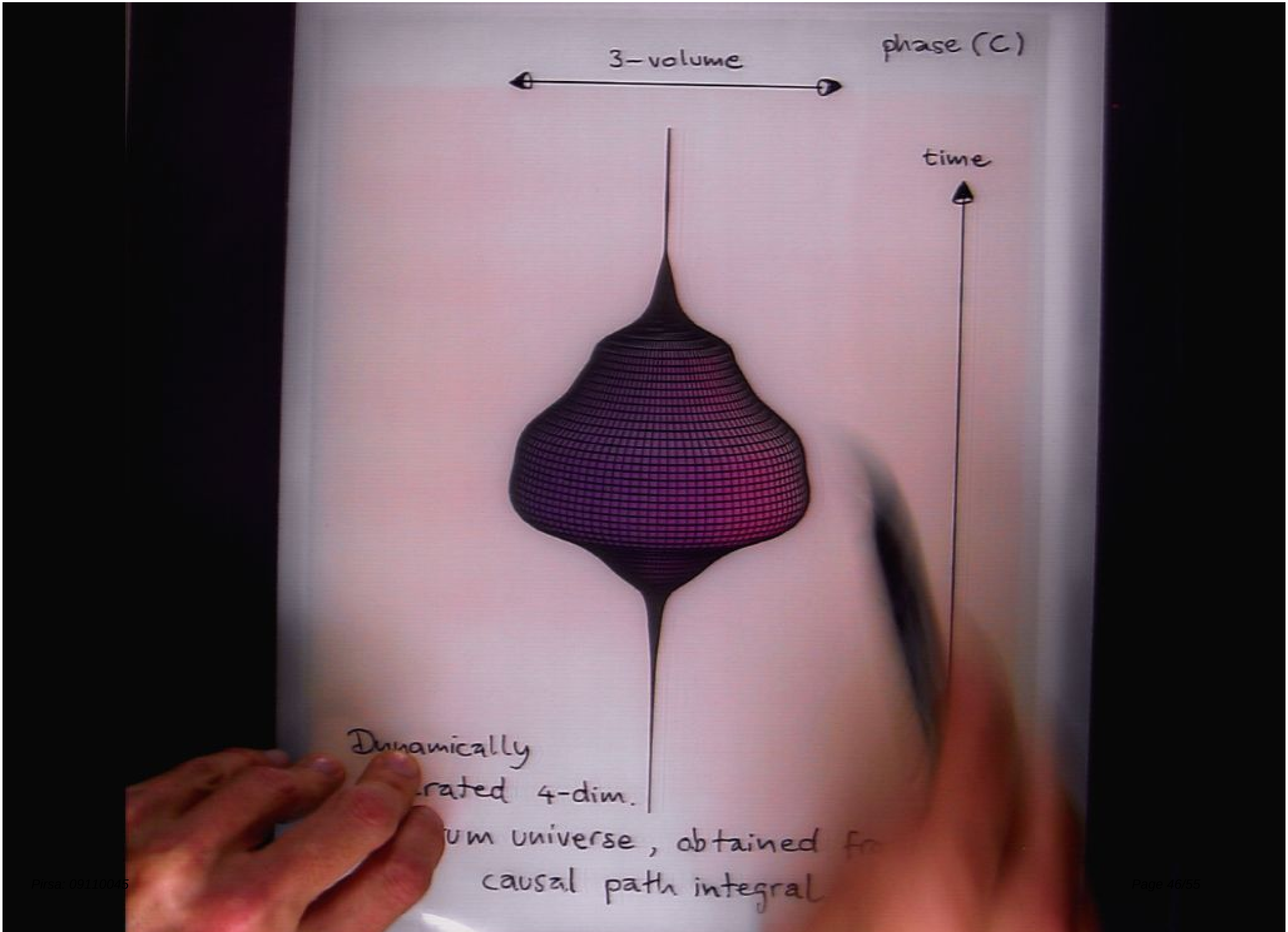
CDT is the only theory of quantum gravity where a classical extended geometry is generated from Planck-scale excitations.

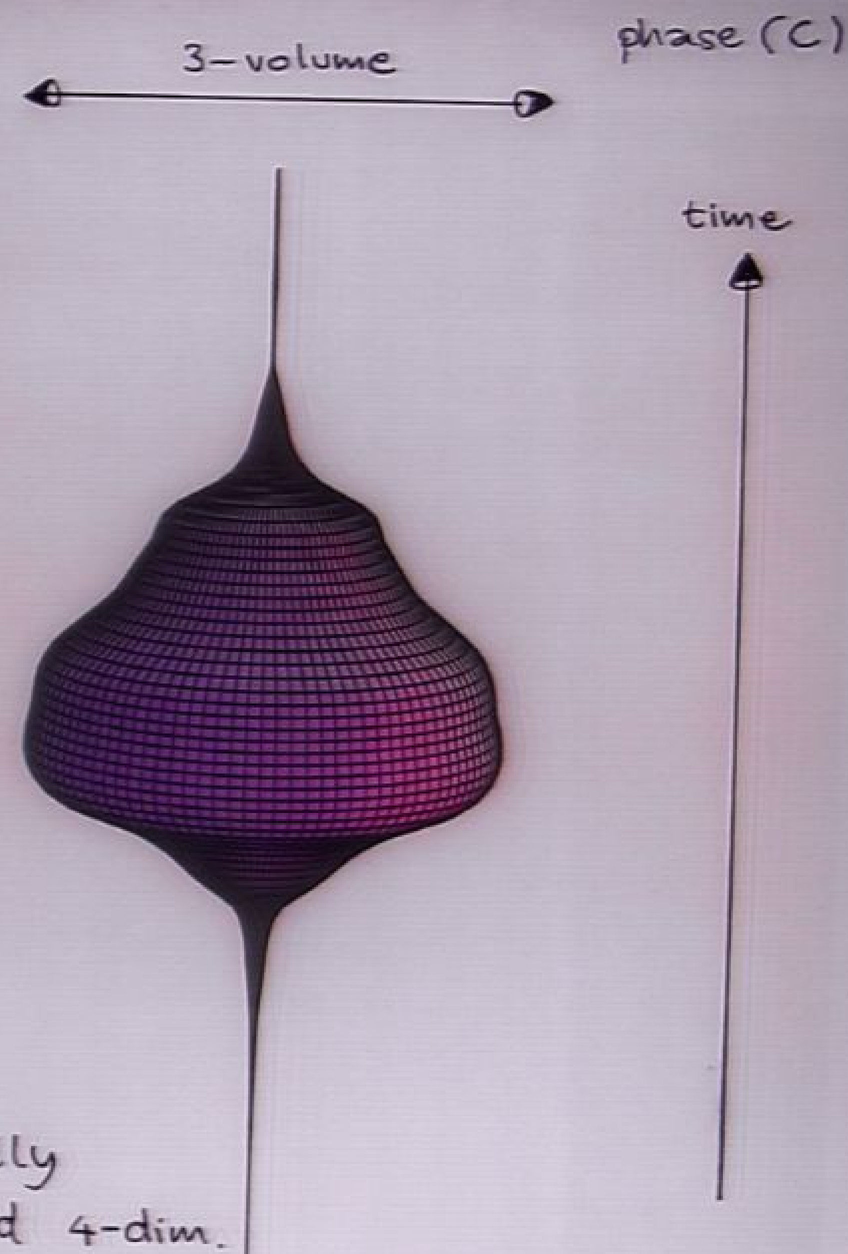
How? – nonperturbative, entropic mechanism:

> Magically, the many microscopic building blocks in the quantum superposition arrange themselves into an extended quantum spacetime whose macroscopic shape is that of a well-known cosmology.

When – from all the gravitational d.o.f.s present[⊕] – we monitor only the spatial 3-volume $\langle V_3(t) \rangle$ as a function of (proper) time t, we find that it matches exactly that of a de Sitter universe. → PIC snapshot

[⊕] N.B. we are not doing quantum cosmology, i.e. we are not truncating d.o.f.s before quantizing


phase (C)
3-volume
time
Dynamically
rated 4-dim.
um universe, obtained
causal path integral



Dynamically generated 4-dim. quantum universe, obtained from a causal path integral.

The dynamical emergence of spacetime as we know it

CDT is the only theory of quantum gravity where a classical extended geometry is generated from Planck-scale excitations.

How? – nonperturbative, entropic mechanism:

> Magically, the many microscopic building blocks in the quantum superposition arrange themselves into an extended quantum spacetime whose macroscopic shape is that of a well-known cosmology.

When – from all the gravitational d.o.f.s present[⊕] – we monitor only the spatial 3-volume $\langle V_3(t) \rangle$ as a function of (proper) time t, we find that it matches exactly that of a de Sitter universe. → PIC snapshot

[⊕] N.B. we are not doing quantum cosmology, i.e. we are not truncating d.o.f.s before quantizing

(10)

This is a solution to the class. Einstein equations in the presence of "dark energy" (Λ).

Classical de Sitter space has

$$V_3(\tau) = 2\pi^2 (c \cosh \frac{\tau}{c})^3 \quad \leftarrow \text{constant} \; ,$$

giving rise to an exponentially expanding universe, $V_3 \sim e^{c'\tau}$, for $\tau > 0$.

- We measure this for Euclidean time $t = i\tau$ → PIC
- Moreover, when we study the fluctuations $\delta V_3(t)$ around $\langle V_3(t) \rangle$, they are well described by a semiclassical minisuperspace treatment around de Sitter space, even for rather small universes ($\sim 20\, \ell_{Pl}$).
  (0712.2485 & 0807.4481)
  w/ Ambjørn, Görlich, Jurkiewicz
- a very nontrivial test of the class. limit!
- strong flavour of condensed matter phenomena:

  "self-organizing quantum universe"
- original $S^1 \times S^3$ -topology "dynamically

(10)

This is a solution to the class. Einstein equations in the presence of "dark energy" (Λ).

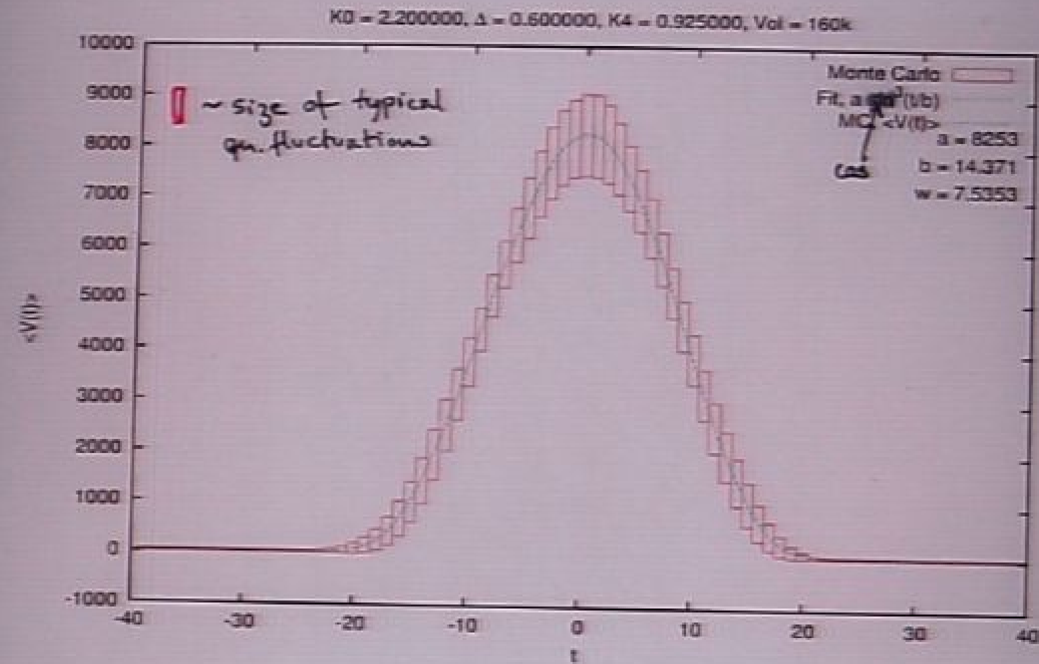
Classical de Sitter space has

$$V_3(\tau) = 2\pi^2 \left(c \cosh \frac{\tau}{c}\right)^3 \quad \leftarrow \text{constant},$$

giving rise to an exponentially expanding universe, $V_3 \sim e^{c'\tau}$, for $\tau > 0$.

- We measure this for Euclidean time $t = i\tau$ → PIC
- Moreover, when we study the fluctuations $\delta V_3(t)$ around $\langle V_3(t) \rangle$, they are well described by a semiclassical minisuperspace treatment around de Sitter space, even for rather small universes ($\sim 20\, \ell_{Pl}$).
  (0712.2485 & 0807.4481)
  w/ Ambjørn, Görlich, Jurkiewicz
- a very nontrivial test of the class. Limit!
- strong flavour of condensed matter phenomena:
  "self-organizing quantum universe"
- original $S^1 \times S^3$-topology "dynamically deformed" to an S^4!

Emergence of de Sitter space!



The shape $\langle V_3(t)\rangle$ of the universe, as function of Euclidean proper time $t = i\tau$, fitted to Euclidean de Sitter space,

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

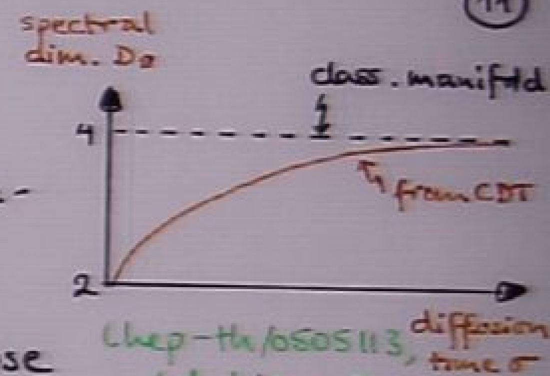
↖ squared "scale factor" $a(t)$

N.B.: maximally symmetric spacetime!
& restoration of isotropy!

- We measure this for Euclidean time $t = i\tau$
  → PIC
- Moreover, when we study the fluctuations $\delta V_3(t)$ around $\langle V_3(t) \rangle$, they are well described by a semiclassical minisuperspace treatment around de Sitter space, even for rather small universes ($\sim 20\, \ell_{Pl}$).
  (0712.2485 & 0807.4481)
  w/ Ambjørn, Görlich, Jurkiewicz
- a very nontrivial test of the class. limit!
- strong flavour of condensed matter phenomena:
  "self-organizing quantum universe"
- original $S^1 \times S^3$ -topology "dynamically deformed" to an S^4 !

(11)

More Lessons



1) topology and dimensionality become dynamical in QT; this can happen because

(hep-th/0505113, w/ Ambjørn, Jurkiewicz)

- short-scale fluctuations are large
- we are taking a nontrivial continuum limit

2) contribution from "microstates" (local excitations) is crucial for obtaining de Sitter space

- (Euclidean) minisuperspace action (classical reduction of GR):

$$S^{MSS} = \frac{1}{G_N}\int dt\,(-a\dot{a}^2 - a + \dots)$$

↑ "conformal sickness"

- effective Euclidean action for $a(t)$, obtained from CDT path integral

$$S^{CDT}_{eff} = \frac{1}{G_N}\int dt\,(+a\dot{a}^2 + a + \dots)$$

(12)

What's new in CDT?

- having a closer look at the phase diagram (ongoing work w/ J. Ambjørn, A. Görlich, S. Jordan, J. Jurkiewicz)

  ↪ J. Ambjørn's talk

- CDT string field theory (2d!, allows for causality-violating points), e.g. w/ J. Ambjørn, W. Westra, S. Zohren, 0908.4224

- changes to de Sitter volume profile in presence of a point mass (ongoing work w/ I. Khavkine, P. Reska)

- nailing down factor-ordering ambiguities in quantum cosmology (ongoing work w/ R. Maitra; R. Maitra, 0910.2117)

- spectral geometry in 3d CDT (D. Benedetti, J. Henson, 0911.0401)

By way of a summary

With CDT and its associated tool box, we have an "experimental lab" – a non-perturbative calculational handle on (near-) Planckian physics (c.f. lattice QCD).

* get a bunch of exciting results and new nonperturbative (geometric) insights
* relies on few ingredients and fundamental principles ($>$ (quantum?) causal sets, $\approx$ FRG gravity, $<$ LQG, $\ll$ ...)

→ If there is a unique theory of QG, obtainable with "standard" QFT methods, the CDT approach will see it.

* CDT can also test nonperturbative predictions from other fundamental theories containing gravity.

TO LEARN MORE:

→ Jan Ambjørn's talk(s) on Sunday

→ CDT reviews: 0906.3947, 0711.0273, hep-th/0604212