Big Bang as a critical point?

Jakub Mielczarek

Jagiellonian University, Cracow
National Centre for Nuclear Research, Warsaw

29 June 2014, Spała

Based on arXiv:1404.0228

Water

Water

- The atomic Hamiltonian of water

$$H = \sum_i \frac{\mathbf{p}_i^2}{2m_i} + V(\mathbf{x_1}, \mathbf{x_2}, \dots)$$

Water

- The atomic Hamiltonian of water

$$H = \sum_i \frac{\mathbf{p}_i^2}{2m_i} + V(\mathbf{x_1}, \mathbf{x_2}, \dots)$$

- Based on this Hamiltonian it is not so easy to predict that the water can be found in the three different phases: liquid, solid and gaseous.

Water

- The atomic Hamiltonian of water

$$H=\sum_i \frac{\mathbf{p}_i^2}{2m_i}+V(\mathbf{x_1},\mathbf{x_2},\dots)$$

- Based on this Hamiltonian it is not so easy to predict that the water can be found in the three different phases: liquid, solid and gaseous.
- Moreover, each phase is described by a different effective theory:

Water

- The atomic Hamiltonian of water

$$H = \sum_i \frac{\mathbf{p}_i^2}{2m_i} + V(\mathbf{x_1}, \mathbf{x_2}, \dots)$$

- Based on this Hamiltonian it is not so easy to predict that the water can be found in the three different phases: liquid, solid and gaseous.
- Moreover, each phase is described by a different effective theory:
  - Water → Hydrodynamics (Navier-Stokes equations)

Water

- The atomic Hamiltonian of water

$$H = \sum_i \frac{\mathbf{p}_i^2}{2m_i} + V(\mathbf{x_1}, \mathbf{x_2}, \dots)$$

- Based on this Hamiltonian it is not so easy to predict that the water can be found in the three different phases: liquid, solid and gaseous.
- Moreover, each phase is described by a different effective theory:
  - Water $\rightarrow$ Hydrodynamics (Navier-Stokes equations)
  - Water vapor $\rightarrow$ Equation of state (e.g. Clapeyron equation)

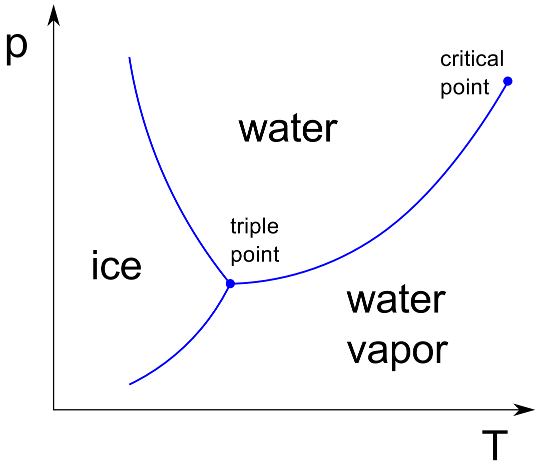
Water

- The atomic Hamiltonian of water

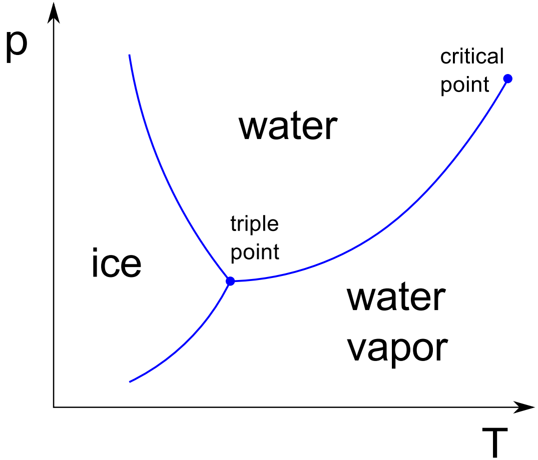
$$H = \sum_i \frac{\mathbf{p}_i^2}{2m_i} + V(\mathbf{x_1}, \mathbf{x_2}, \dots)$$

- Based on this Hamiltonian it is not so easy to predict that the water can be found in the three different phases: liquid, solid and gaseous.
- Moreover, each phase is described by a different effective theory:
  - Water $\rightarrow$ Hydrodynamics (Navier-Stokes equations)
  - Water vapor $\rightarrow$ Equation of state (e.g. Clapeyron equation)
  - Ice $\rightarrow$ Dynamics of rigid body

Phase diagram of water



Phase diagram of water



Different phases: different effective theories, different symmetries.

Gravitational phase transitions?

Gravitational phase transitions?

- Can gravitational field exist in different phases?

Gravitational phase transitions?

- Can gravitational field exist in different phases?
- Let us look *e.g.* at the Hamiltonian constraint in LQG

$$H = \lim_{\epsilon \to 0} \sum_I N_I \epsilon^{abc} \mathrm{tr} \left[(\hat{h}_{\alpha^I_{ab}}[A] - \hat{h}^{-1}_{\alpha^I_{ab}}[A]) \hat{h}^{-1}_{e^I_c}[A] \left\{ \hat{h}_{e^I_c}, \hat{V} \right\} \right] - \ldots$$

Gravitational phase transitions?

- Can gravitational field exist in different phases?
- Let us look *e.g.* at the Hamiltonian constraint in LQG

$$H = \lim_{\epsilon\to 0}\sum_I N_I \epsilon^{abc}\mathrm{tr}\left[(\hat{h}_{\alpha^I_{ab}}[A] - \hat{h}^{-1}_{\alpha^I_{ab}}[A])\hat{h}^{-1}_{e^I_c}[A]\left\{\hat{h}_{e^I_c}, \hat{V}\right\}\right] - \dots$$

- An analogue of the atomic Hamiltonian of water.

Gravitational phase transitions?

- Can gravitational field exist in different phases?
- Let us look *e.g.* at the Hamiltonian constraint in LQG

$$H = \lim_{\epsilon \to 0} \sum_I N_I \epsilon^{abc} \mathrm{tr} \left[(\hat{h}_{\alpha^I_{ab}}[A] - \hat{h}^{-1}_{\alpha^I_{ab}}[A]) \hat{h}^{-1}_{e^I_c}[A] \left\{ \hat{h}_{e^I_c}, \hat{V} \right\} \right] - \dots$$

- An analogue of the atomic Hamiltonian of water.
- Space of parameters has to be explored in order to identify different phases.

Gravitational phase transitions?

- Can gravitational field exist in different phases?
- Let us look *e.g.* at the Hamiltonian constraint in LQG

$$H = \lim_{\epsilon \to 0} \sum_{I} N_I \epsilon^{abc} \mathrm{tr} \left[(\hat{h}_{\alpha^I_{ab}}[A] - \hat{h}^{-1}_{\alpha^I_{ab}}[A]) \hat{h}^{-1}_{e^I_c}[A] \left\{ \hat{h}_{e^I_c}, \hat{V} \right\} \right] - \ldots$$

- An analogue of the atomic Hamiltonian of water.
- Space of parameters has to be explored in order to identify different phases.
- Monte-Carlo simulations.

A bit of history

A bit of history

- Three-dimensional Euclidean quantum gravity (Ambjorn *et al.* 1992). First order phase transition.

A bit of history

- Three-dimensional Euclidean quantum gravity (Ambjorn *et al.* 1992). First order phase transition.
- Four-dimensional Euclidean gravity. Gravity exhibits two phases: the *crumpled* phase and the *branched polymer* phase (Ambjorn, Jurkiewicz 1992).

A bit of history

- Three-dimensional Euclidean quantum gravity (Ambjorn *et al.* 1992). First order phase transition.
- Four-dimensional Euclidean gravity. Gravity exhibits two phases: the *crumpled* phase and the *branched polymer* phase (Ambjorn, Jurkiewicz 1992).
- Four-dimensional gravity with an imposed causality condition, formulation known as Causal Dynamical Triangulations (CDT). Emergence of the four-dimensional spacetime (Ambjorn, Jurkiewicz, Loll, 2004).

A bit of history

- Three-dimensional Euclidean quantum gravity (Ambjorn *et al.* 1992). First order phase transition.
- Four-dimensional Euclidean gravity. Gravity exhibits two phases: the *crumpled* phase and the *branched polymer* phase (Ambjorn, Jurkiewicz 1992).
- Four-dimensional gravity with an imposed causality condition, formulation known as Causal Dynamical Triangulations (CDT). Emergence of the four-dimensional spacetime (Ambjorn, Jurkiewicz, Loll, 2004).
- Hořava-Lifshitz gravity (Hořava, 2009). The power-counting renormalizable theory of gravity at a triple point (Lifshitz point).

A bit of history

- Three-dimensional Euclidean quantum gravity (Ambjorn *et al.* 1992). First order phase transition.
- Four-dimensional Euclidean gravity. Gravity exhibits two phases: the *crumpled* phase and the *branched polymer* phase (Ambjorn, Jurkiewicz 1992).
- Four-dimensional gravity with an imposed causality condition, formulation known as Causal Dynamical Triangulations (CDT). Emergence of the four-dimensional spacetime (Ambjorn, Jurkiewicz, Loll, 2004).
- Hořava-Lifshitz gravity (Hořava, 2009). The power-counting renormalizable theory of gravity at a triple point (Lifshitz point).
- Quantum Graphity utilizes the idea of *geometrogenesis* - a transition between geometric and non-geometric phases of gravity (Konopka, Markopoulu, Smolin, 2006).

Where they are?

Where they are?

- The basic question one can ask, assuming the existence of the different phases of gravity, is where the other phases can be found?

Where they are?

- The basic question one can ask, assuming the existence of the different phases of gravity, is where the other phases can be found?
- A natural place to search for them are high curvature regions such as interiors of the black holes and the early universe.

Where they are?

- The basic question one can ask, assuming the existence of the different phases of gravity, is where the other phases can be found?
- A natural place to search for them are high curvature regions such as interiors of the black holes and the early universe.
- Because of a horizon, a possibility of empirical verification of a phase change inside of black holes is out of reach.

Where they are?

- The basic question one can ask, assuming the existence of the different phases of gravity, is where the other phases can be found?
- A natural place to search for them are high curvature regions such as interiors of the black holes and the early universe.
- Because of a horizon, a possibility of empirical verification of a phase change inside of black holes is out of reach.
- More promising is a search for signatures of the gravitational phase transitions which took place in the early universe.

Where they are?

- The basic question one can ask, assuming the existence of the different phases of gravity, is where the other phases can be found?
- A natural place to search for them are high curvature regions such as interiors of the black holes and the early universe.
- Because of a horizon, a possibility of empirical verification of a phase change inside of black holes is out of reach.
- More promising is a search for signatures of the gravitational phase transitions which took place in the early universe.
- So far, there has been very little attention devoted to this issue in the literature.

Where they are?

- The basic question one can ask, assuming the existence of the different phases of gravity, is where the other phases can be found?
- A natural place to search for them are high curvature regions such as interiors of the black holes and the early universe.
- Because of a horizon, a possibility of empirical verification of a phase change inside of black holes is out of reach.
- More promising is a search for signatures of the gravitational phase transitions which took place in the early universe.
- So far, there has been very little attention devoted to this issue in the literature.
- Most studies of the phase transitions in the early universe were dedicated to the matter sector, rather than gravity (Kibble,1976; Zurek, 1985).

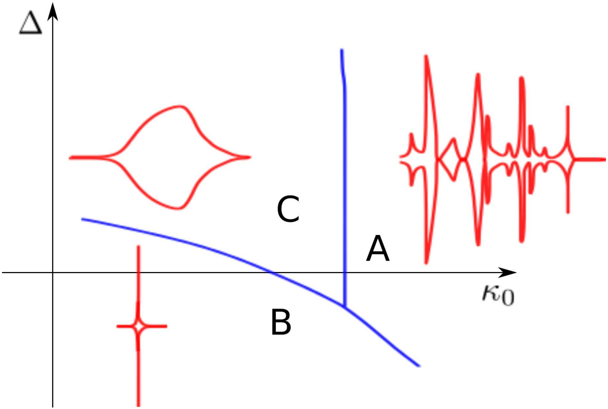
- Among the few studies on the gravitational phase transitions in the early universe, the work of (Magueijo, Smolin, Contaldi, 2006; Dreyer, 2013) is especially noteworthy.

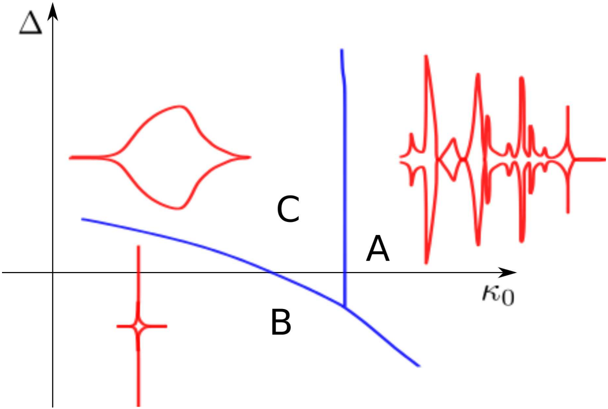
- Among the few studies on the gravitational phase transitions in the early universe, the work of (Magueijo, Smolin, Contaldi, 2006; Dreyer, 2013) is especially noteworthy.
- In (Magueijo, Smolin, Contaldi, 2006) a specific model of geometrogenesis, through a second order phase transition, has been proposed. It was shown that by assuming the holographic principle to be fulfilled in the high temperature phase, it is possible to generate a power spectrum of primordial perturbations that is in agreement with observations.

- Among the few studies on the gravitational phase transitions in the early universe, the work of (Magueijo, Smolin, Contaldi, 2006; Dreyer, 2013) is especially noteworthy.
- In (Magueijo, Smolin, Contaldi, 2006) a specific model of geometrogenesis, through a second order phase transition, has been proposed. It was shown that by assuming the holographic principle to be fulfilled in the high temperature phase, it is possible to generate a power spectrum of primordial perturbations that is in agreement with observations.
- In (Dreyer, 2013) the cosmological relevance of second order phase transitions is discussed. Arguments supporting generation of "inflationary" power spectrum from critical behavior of the gravitational field have been presented.

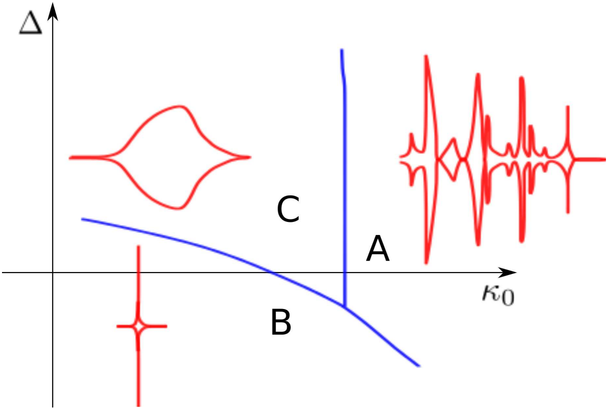
- Among the few studies on the gravitational phase transitions in the early universe, the work of (Magueijo, Smolin, Contaldi, 2006; Dreyer, 2013) is especially noteworthy.
- In (Magueijo, Smolin, Contaldi, 2006) a specific model of geometrogenesis, through a second order phase transition, has been proposed. It was shown that by assuming the holographic principle to be fulfilled in the high temperature phase, it is possible to generate a power spectrum of primordial perturbations that is in agreement with observations.
- In (Dreyer, 2013) the cosmological relevance of second order phase transitions is discussed. Arguments supporting generation of "inflationary" power spectrum from critical behavior of the gravitational field have been presented.
- In what follows we discuss phase transitions in CDT and LQC and their possible cosmological relevance.

CDT





CB - second order transition line



CB - second order transition line

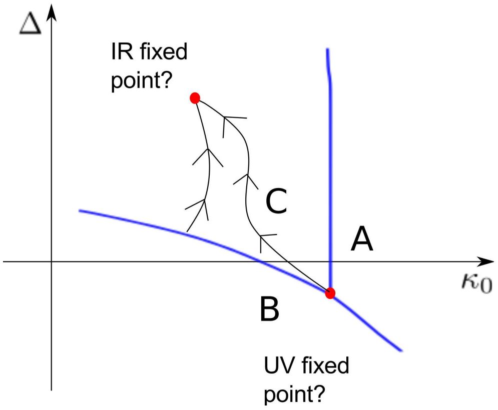
CA - first order transition line

Phase B, resembling the *crumpled* phase in Euclidean gravity, is characterized by a large (tending to infinity in the $\infty-$volume limit) Haussdorf and spectral dimension. Phase B shares features of the high temperature phase postulated in Quantum Graphity. Moreover, this phase is separated with the low energetic phase C by the second order phase transition. This is in one-to-one correspondence to the Quantum Graphity case. Based on this observation, we hypothesize the following:

Phase B, resembling the *crumpled* phase in Euclidean gravity, is characterized by a large (tending to infinity in the $\infty-$volume limit) Haussdorf and spectral dimension. Phase B shares features of the high temperature phase postulated in Quantum Graphity. Moreover, this phase is separated with the low energetic phase C by the second order phase transition. This is in one-to-one correspondence to the Quantum Graphity case. Based on this observation, we hypothesize the following:

Hypothesis 1. In the early universe, there is a second order phase transition from the high temperature phase B to the low temperature phase C. The transition is associated with a change of the connectivity structure between the elementary chunks of space.

RG flow

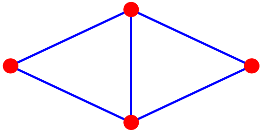


UV fixed point at the triple point (à la Hořava-Lifshitz) or UV fixed line? The first step has already been made[1].

[1] J. Ambjorn, A. Goerlich, J. Jurkiewicz, A. Kreienbuehl and R. Loll, "Renormalization Group Flow in CDT," arXiv:1405.4585 [hep-th].

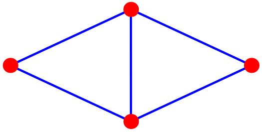
Toy models of the phases B and C

Let us consider a toy model of the universe composed of the N chunks of space. They will be represented by the nodes of a graph. A structure of adjacency is represented by the links.



Toy models of the phases B and C

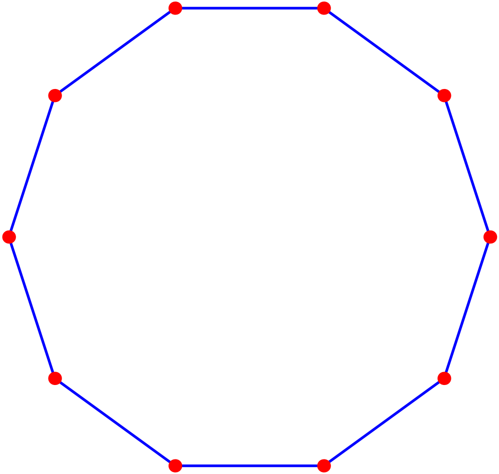
Let us consider a toy model of the universe composed of the N chunks of space. They will be represented by the nodes of a graph. A structure of adjacency is represented by the links.



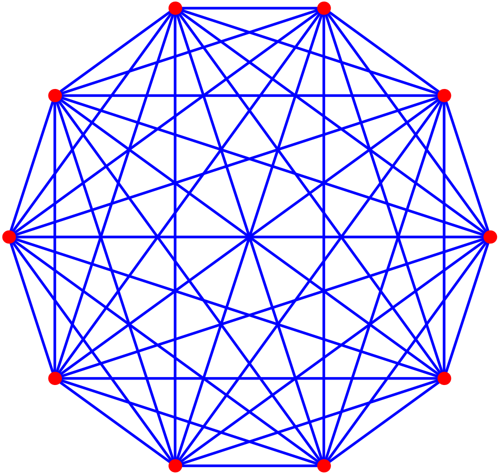
The spectral dimension of this graph can be found by determining spectrum (eigenvalues λ_n) of the Laplace operator $\Delta \equiv A - D$, where A is an adjacency matrix and D is a degree matrix:

$$A = \begin{pmatrix} 0 & 1 & 1 & 1 \\ 1 & 0 & 1 & 1 \\ 1 & 1 & 0 & 0 \\ 1 & 1 & 0 & 0 \end{pmatrix}, \qquad D = \begin{pmatrix} 3 & 0 & 0 & 0 \\ 0 & 3 & 0 & 0 \\ 0 & 0 & 2 & 0 \\ 0 & 0 & 0 & 2 \end{pmatrix}.$$

Ring graph being a toy model of the low temperature geometric state of gravity - phase C



Complete graph being a model of high temperature non-geometric state of gravity - phase B



Spectral dimension

Heat kernel equation:

$$\frac{\partial}{\partial \sigma} K(x, y; \sigma) = \Delta_x K(x, y; \sigma),$$

where σ is a diffusion time.

Spectral dimension

Heat kernel equation:

$$\frac{\partial}{\partial \sigma} K(x, y; \sigma) = \Delta_x K(x, y; \sigma),$$

where σ is a diffusion time. Eigenproblem:

$$\Delta_x \phi_n(x) = \lambda_n \phi_n(x).$$

Spectral dimension

Heat kernel equation:

$$\frac{\partial}{\partial \sigma} K(x, y; \sigma) = \Delta_x K(x, y; \sigma),$$

where σ is a diffusion time. Eigenproblem:

$$\Delta_x \phi_n(x) = \lambda_n \phi_n(x).$$

The heat kernel can be decomposed as follows:

$$K(x, y; \sigma) = \sum_n e^{\sigma \lambda_n} \phi_n(x) \phi_n^*(y).$$

Spectral dimension

Heat kernel equation:

$$\frac{\partial}{\partial \sigma} K(x, y; \sigma) = \Delta_x K(x, y; \sigma),$$

where σ is a diffusion time. Eigenproblem:

$$\Delta_x \phi_n(x) = \lambda_n \phi_n(x).$$

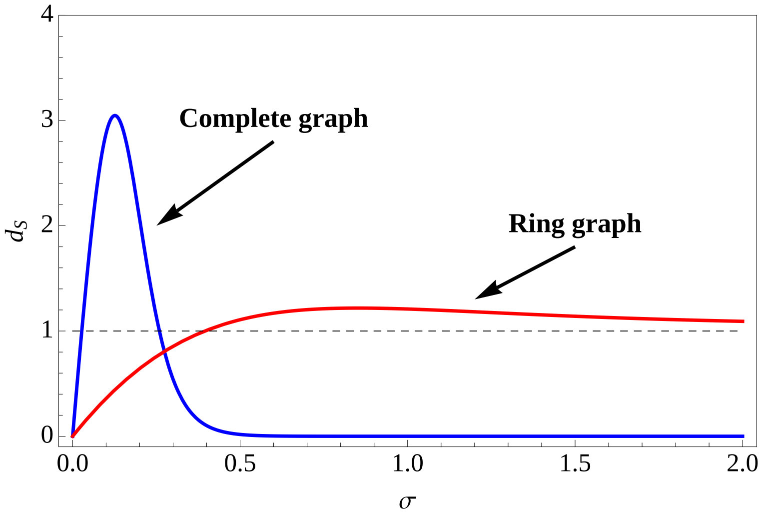
The heat kernel can be decomposed as follows:

$$K(x, y; \sigma) = \sum_n e^{\sigma \lambda_n} \phi_n(x) \phi_n^*(y).$$

By using the expression for the trace of the heat kernel one can find that

$$d_S \equiv -2 \frac{\partial \log \mathrm{tr} K}{\partial \log \sigma} = -2\sigma \frac{\sum_{i=1}^N \lambda_n e^{\lambda_n \sigma}}{\sum_{i=1}^N e^{\lambda_n \sigma}}.$$

.


Complete graph
Ring graph
d_S
σ
0
1
2
3
4
0.0
0.5
1.0
1.5
2.0

LQC

- Recent developments in LQC indicate that the hypersurface deformation algebra (HDA) is deformed due to the quantum gravitational effects (See e.g. Bojowald, Paily, 2012). This means that the general covariance is quantum deformed, but not broken.

- Recent developments in LQC indicate that the hypersurface deformation algebra (HDA) is deformed due to the quantum gravitational effects (See e.g. Bojowald, Paily, 2012). This means that the general covariance is quantum deformed, but not broken.
- The change of symmetry reflects a change of phase?

LQC

- Recent developments in LQC indicate that the hypersurface deformation algebra (HDA) is deformed due to the quantum gravitational effects (See e.g. Bojowald, Paily, 2012). This means that the general covariance is quantum deformed, but not broken.
- The change of symmetry reflects a change of phase?
- In condensed matter physics, a change of symmetry is often associated with the occurrence of a phase transition. By extrapolating this observation to the sector of gravitational interactions, we make the following hypothesis:

Hypothesis 2. Gravitational phase transitions are associated with deformations of the hypersurface deformation algebra.

In LQC with holonomy corrections the HDA is deformed to[2]

$$\{S, S\} = \Omega D, \quad \{S, D\} = -S, \quad \{D, D\} = D,$$

where S are scalar constraints and D is a diffeomorphism constraint, and the remaining brackets are unchanged. The $\Omega = 1 - 2\frac{\rho}{\rho_c}$ is a deformation factor, ρ denotes energy density of matter and ρ_c is a maximal energy density expected to be of the order of the Planck energy density.

[2]T. Cailleteau, J. Mielczarek, A. Barrau, J. Grain, Class. Quantum Grav. 29 (2012) 095010

In LQC with holonomy corrections the HDA is deformed to[2]

$$\{S, S\} = \Omega D, \quad \{S, D\} = -S, \quad \{D, D\} = D,$$

where S are scalar constraints and D is a diffeomorphism constraint, and the remaining brackets are unchanged. The $\Omega = 1 - 2\frac{\rho}{\rho_c}$ is a deformation factor, ρ denotes energy density of matter and ρ_c is a maximal energy density expected to be of the order of the Planck energy density.
At low energy densities, the classical Lorentzian HDA with $\Omega = 1$ is recovered, while at $\rho = \rho_c$, $\Omega = -1$ corresponding to Euclidean space.

[2] T. Cailleteau, J. Mielczarek, A. Barrau, J. Grain, Class. Quantum Grav. 29 (2012) 095010

In LQC with holonomy corrections the HDA is deformed to[2]

$$\{S,S\} = \Omega D, \quad \{S,D\} = -S, \quad \{D,D\} = D,$$

where S are scalar constraints and D is a diffeomorphism constraint, and the remaining brackets are unchanged. The $\Omega = 1 - 2\frac{\rho}{\rho_c}$ is a deformation factor, ρ denotes energy density of matter and ρ_c is a maximal energy density expected to be of the order of the Planck energy density.

At low energy densities, the classical Lorentzian HDA with $\Omega = 1$ is recovered, while at $\rho = \rho_c$, $\Omega = -1$ corresponding to Euclidean space.

Interestingly, at $\rho = \rho_c/2$ the HDA reduces to the ultralocal form ($\{S,S\} = 0$) describing a state of *silence*. This state shares properties of phase A in CDT, giving a first indication for the relationship between the phase of gravity and deformation of HDA.

[2] T. Cailleteau, J. Mielczarek, A. Barrau, J. Grain, Class. Quantum Grav. 29 (2012) 095010

See J. Mielczarek, “Asymptotic silence in loop quantum cosmology,” AIP Conf. Proc. **1514** (2012) 81 and

for more about silence in LQC, CDT, BKL and other approaches.

- The signature change can be interpreted as a spontaneous symmetry breaking (SBB) associated with a second order phase transition.

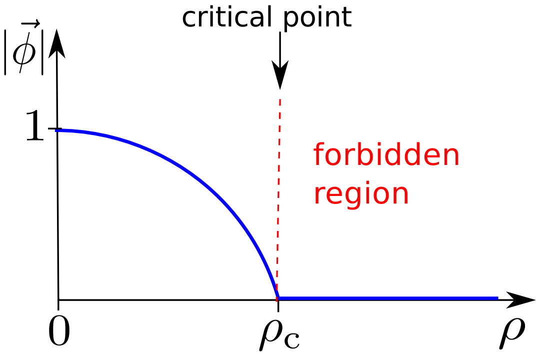
- The signature change can be interpreted as a spontaneous symmetry breaking (SBB) associated with a second order phase transition.
- The symmetry breaking is from $SO(4)$ to $SO(3)$ at the level of an effective homogeneous vector field ϕ_μ. This translates to a symmetry change from $SO(4)$ to $SO(3,1)$, at the level of geometry described by the metric $g_{\mu\nu} = \delta_{\mu\nu} - 2\phi_\mu\phi_\nu$.

- The signature change can be interpreted as a spontaneous symmetry breaking (SBB) associated with a second order phase transition.
- The symmetry breaking is from $SO(4)$ to $SO(3)$ at the level of an effective homogeneous vector field ϕ_μ. This translates to a symmetry change from $SO(4)$ to $SO(3,1)$, at the level of geometry described by the metric $g_{\mu\nu} = \delta_{\mu\nu} - 2\phi_\mu\phi_\nu$.
- Let us assume that the free energy for the model with a massless scalar field v is

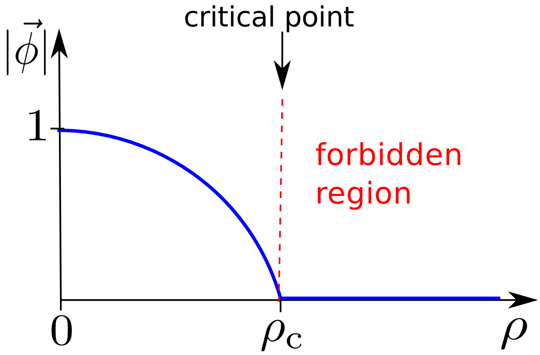
$$F = \int dV \underbrace{\left(\delta^{\mu\nu} + \frac{2\phi^\mu\phi^\nu}{1-2|\vec{\phi}|^2}\right)}_{g^{\mu\nu}} \partial_\mu v \partial_\nu v + \underbrace{\beta\left[\left(\frac{\rho}{\rho_c} - 1\right)|\vec{\phi}|^2 + \frac{1}{2}|\vec{\phi}|^4\right]}_{V(\phi^\mu,\rho)},$$

where $|\vec{\phi}| = \sqrt{\delta^{\mu\nu}\phi_\mu\phi_\nu}$ and β is a constant.

Modulus of the filed ϕ^{μ} as a function of the energy density ρ. The region $\rho > \rho_c$ is forbidden within the model.



Modulus of the filed ϕ^μ as a function of the energy density ρ. The region $\rho > \rho_c$ is forbidden within the model.



An interesting possibility is that the system has been maintained at the critical point before the energy density started to drop. This may not require a fine-tuning if the dynamics of the system exhibited Self Organized Criticality (SOC), which is observed in various complex systems.

- Without loss of generality, let us assume that the SSB takes place in direction ϕ_0, for which

$$g_{00} = 1 - 2\phi_0\phi_0 = 1 - 2\left(1 - \frac{\rho}{\rho_c}\right) = -1 + 2\frac{\rho}{\rho_c} = -\Omega, \quad g_{ii} = 1,$$

leading to the effective speed of light $c_{\text{eff}}^2 = \Omega$.

- Without loss of generality, let us assume that the SSB takes place in direction ϕ_0, for which

$$g_{00} = 1 - 2\phi_0\phi_0 = 1 - 2\left(1 - \frac{\rho}{\rho_c}\right) = -1 + 2\frac{\rho}{\rho_c} = -\Omega, \quad g_{ii} = 1,$$

leading to the effective speed of light $c_{\text{eff}}^2 = \Omega$.

- As a consequence, the equation of motion for the scalar field v takes the form

$$g^{\mu\nu}\partial_\mu\partial_\nu v = -\frac{1}{c_{\text{eff}}^2}\frac{\partial^2}{\partial t^2}v + \Delta v = 0,$$

manifesting $SO(4)$ symmetry at the critical point ($\Omega = -1$), and $SO(3,1)$ symmetry in the low temperature limit ($\Omega = 1$).

- Without loss of generality, let us assume that the SSB takes place in direction ϕ_0, for which

$$g_{00} = 1 - 2\phi_0\phi_0 = 1 - 2\left(1 - \frac{\rho}{\rho_c}\right) = -1 + 2\frac{\rho}{\rho_c} = -\Omega, \quad g_{ii} = 1,$$

leading to the effective speed of light $c_{\text{eff}}^2 = \Omega$.

- As a consequence, the equation of motion for the scalar field v takes the form

$$g^{\mu\nu}\partial_\mu\partial_\nu v = -\frac{1}{c_{\text{eff}}^2}\frac{\partial^2}{\partial t^2}v + \Delta v = 0,$$

manifesting $SO(4)$ symmetry at the critical point ($\Omega = -1$), and $SO(3,1)$ symmetry in the low temperature limit ($\Omega = 1$).

- The form of the above equation agrees with the one derived from the holonomy deformations of the HDA.

Summary and outlook

Summary and outlook

- CDT offers a concrete realization of geometrogenesis, having a second order gravitational phase transition between the non-geometric and geometric phase.

Summary and outlook

- CDT offers a concrete realization of geometrogenesis, having a second order gravitational phase transition between the non-geometric and geometric phase.
- The critical nature of the emergence of classical spacetime in the early universe may give a first possibility of testing CDT.

Summary and outlook

- CDT offers a concrete realization of geometrogenesis, having a second order gravitational phase transition between the non-geometric and geometric phase.
- The critical nature of the emergence of classical spacetime in the early universe may give a first possibility of testing CDT.
- In LQC a gravitational second order phase transition may explain a signature change in the Planck epoch.

Summary and outlook

- CDT offers a concrete realization of geometrogenesis, having a second order gravitational phase transition between the non-geometric and geometric phase.
- The critical nature of the emergence of classical spacetime in the early universe may give a first possibility of testing CDT.
- In LQC a gravitational second order phase transition may explain a signature change in the Planck epoch.
- In the presented toy model, the universe originates just at the critical point.

Summary and outlook

- CDT offers a concrete realization of geometrogenesis, having a second order gravitational phase transition between the non-geometric and geometric phase.
- The critical nature of the emergence of classical spacetime in the early universe may give a first possibility of testing CDT.
- In LQC a gravitational second order phase transition may explain a signature change in the Planck epoch.
- In the presented toy model, the universe originates just at the critical point.
- Gravitational phase transitions offer a way to study interrelations between different approaches to quantum gravity and paradigm shift in our understanding of the early stages of the Universe.