Title: The universe as a quantum gravity condensate.

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Abstract: <p><strong>I describe how, within the group field theory (GFT) formalism for quantum gravity, we can: </strong></p>

<p> </p>

<p><strong>1) provide a candidate description of the quantum building blocks of spacetime, bringing together ideas and mathematical structures from other quantum gravity formalisms;</strong></p>

<p> </p>

<p><strong>2) apply powerful tools from quantum field theory, like the (perturbative and non-perturbative) renormalization group, to establish the quantum consistency of given GFT models and to study their continuum limit and phase structure;</strong></p>

<p> </p>

<p><strong>3) extract, from the full theory, an effective cosmological dynamics for the universe described as a quantum condensate of GFT building blocks; in the simplest approximation, this dynamics reduces to the Friedmann equations at large scales but replaces the classical big bang singularity with a quantum bounce.</strong></p>

# *The Universe as a Quantum Gravity Condensate*

Daniele Oriti

Albert Einstein Institute

Perimeter Institute for Theoretical Physics
3/10/2016

# Plan of the talk

- disappearance and emergence of Space and Time in Quantum Gravity
- GFTs : what are they?
  - general formalism
  - relation with other QG approaches
- continuum limit in GFT and GFT renormalization
- effective continuum physics
  - cosmology as Quantum Gravity hydrodynamics
  - GFT condensate cosmology

# Intro:
# disappearance and emergence of Space and Time in Quantum Gravity

# Hints for the Disappearance of Space and Time

- challenges to "localization" in semi-classical GR

  minimal length scenarios

  non-commutative spacetimes

- spacetime singularities in GR

  need just quantum corrections to classical GR?

  breakdown of continuum itself?

- black hole thermodynamics

  solution of information loss paradox require non-locality?

  if spacetime itself has entropy, it has microstructure
  if entropy is finite, this implies discreteness

- Einstein's equations as equation of state (Jacobson et al)

  GR dynamics is effective equation of state for any microscopic dofs
  collectively described by a spacetime, a metric and some matter fields

- insights from analog gravity models in condensed matter physics

  effective curved metric and matter fields from non-geometric atomic theory

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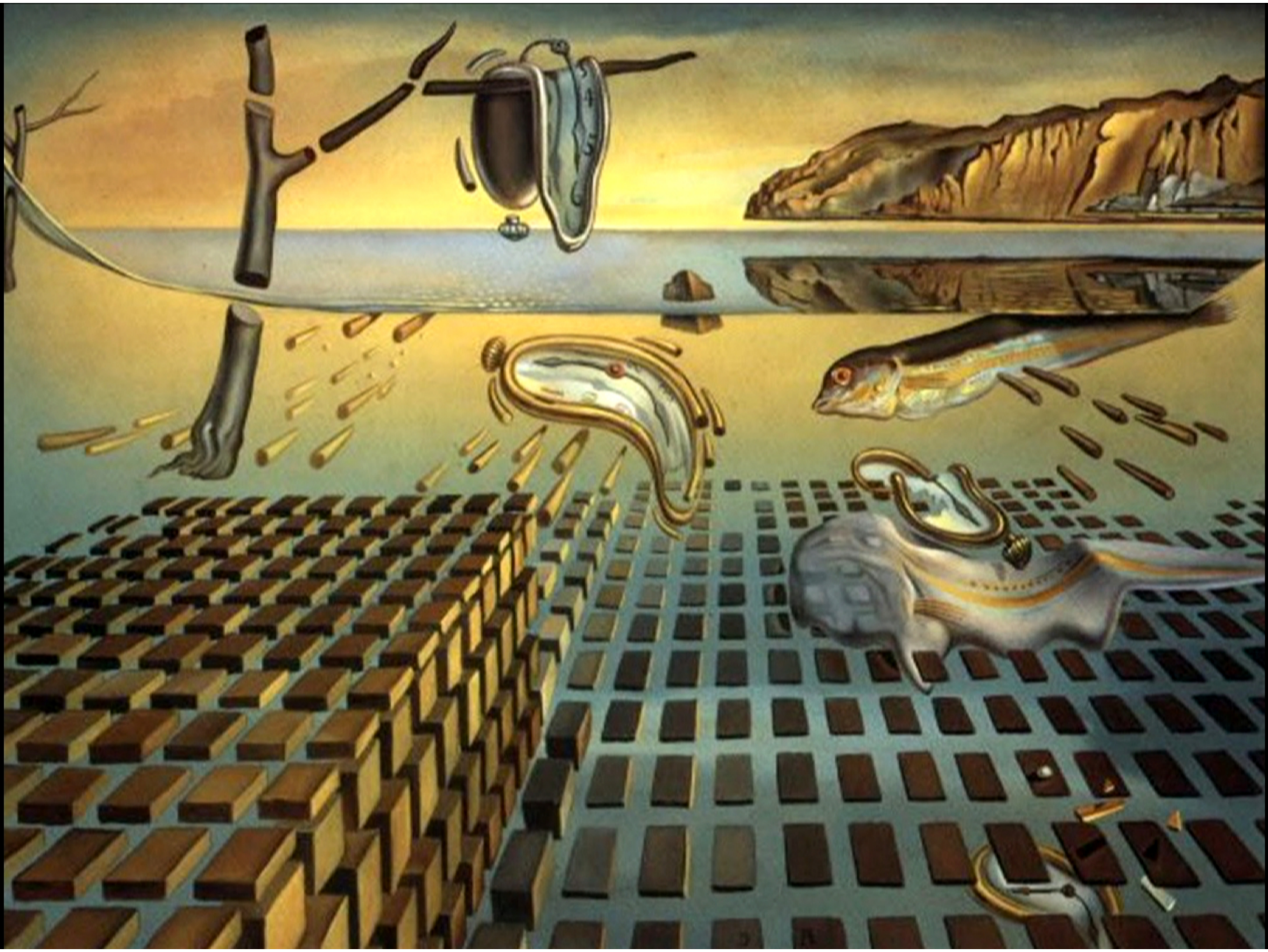
Space and Time disappear in QG ⟶ Space and Time emerge from (discrete?) non-spatiotemporal entities



# Beyond the spacetime continuum?

already imagining and constructing a consistent pre-geometric, pre-continuum picture of spacetime, is highly non-trivial

Einstein (1936): *"the introduction of a space-time continuum may be considered as contrary to nature in view of the molecular structure of everything which happens on a small scale. [...] perhaps the success of the Heisenberg method points to a purely algebraic method of description of nature, that is to the elimination of continuous functions from physics. Then, however, we must also give up, by principle, the space-time continuum. It is not unimaginable that human ingenuity will some day find methods which will make it possible to proceed along such a path. At the present time, however, such a program looks like an attempt to breathe in empty space."*

# Spacetime emergence: phase transition + coarse graining?

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guiding hypotheses

space, time and geometry are the result of the collective behaviour of the microscopic building blocks ("QG atoms")

the universe and its smooth, macroscopic geometry are the result of a phase transition (geometrogenesis) of QG system, from a non-geometric, non-spatio-temporal phase, to a geometric one

the emergent, continuum dynamics of geometry (and GR) should be looked for in the coarse grained description of the fundamental dynamics, in "geometric phase"

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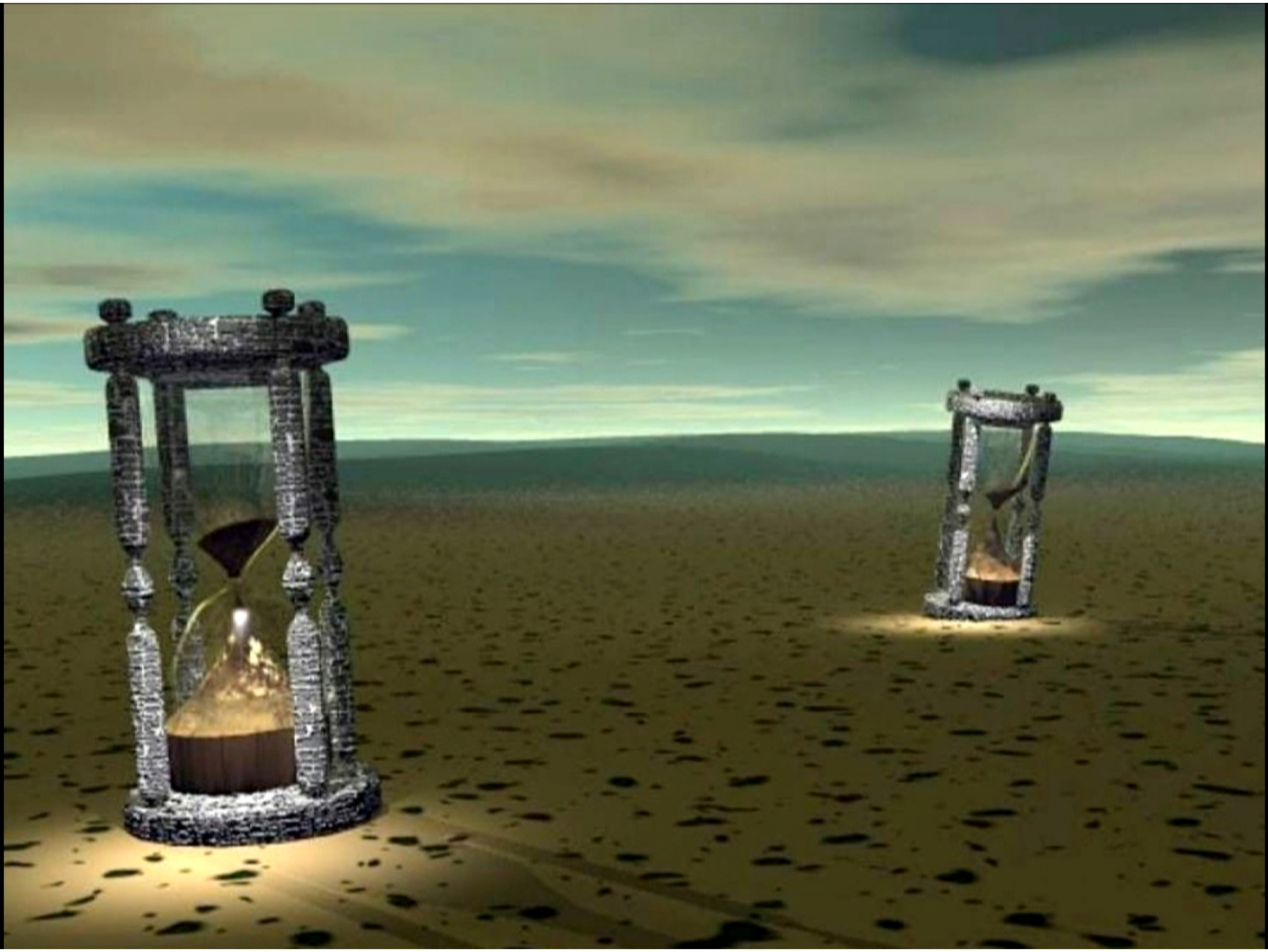
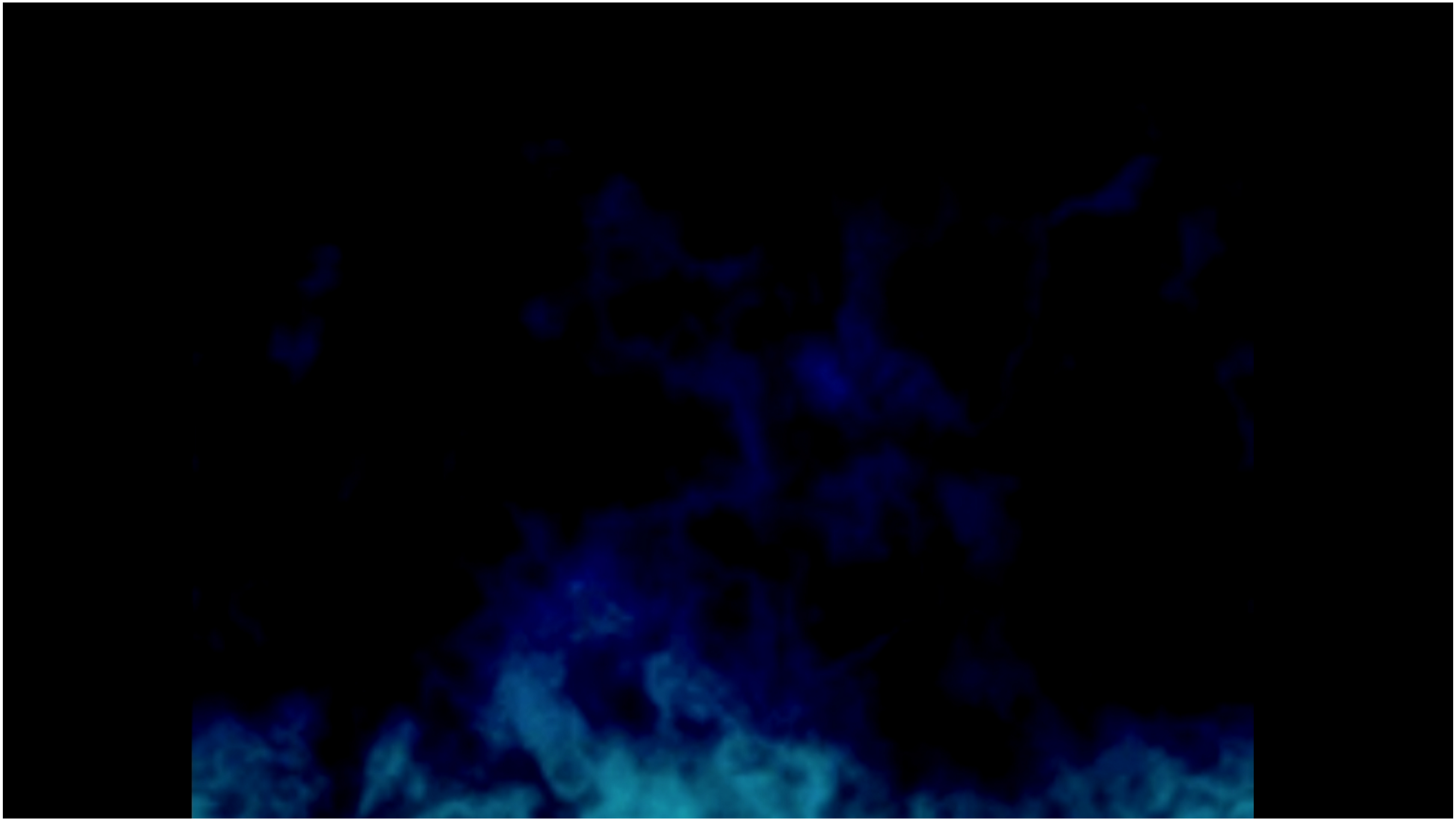
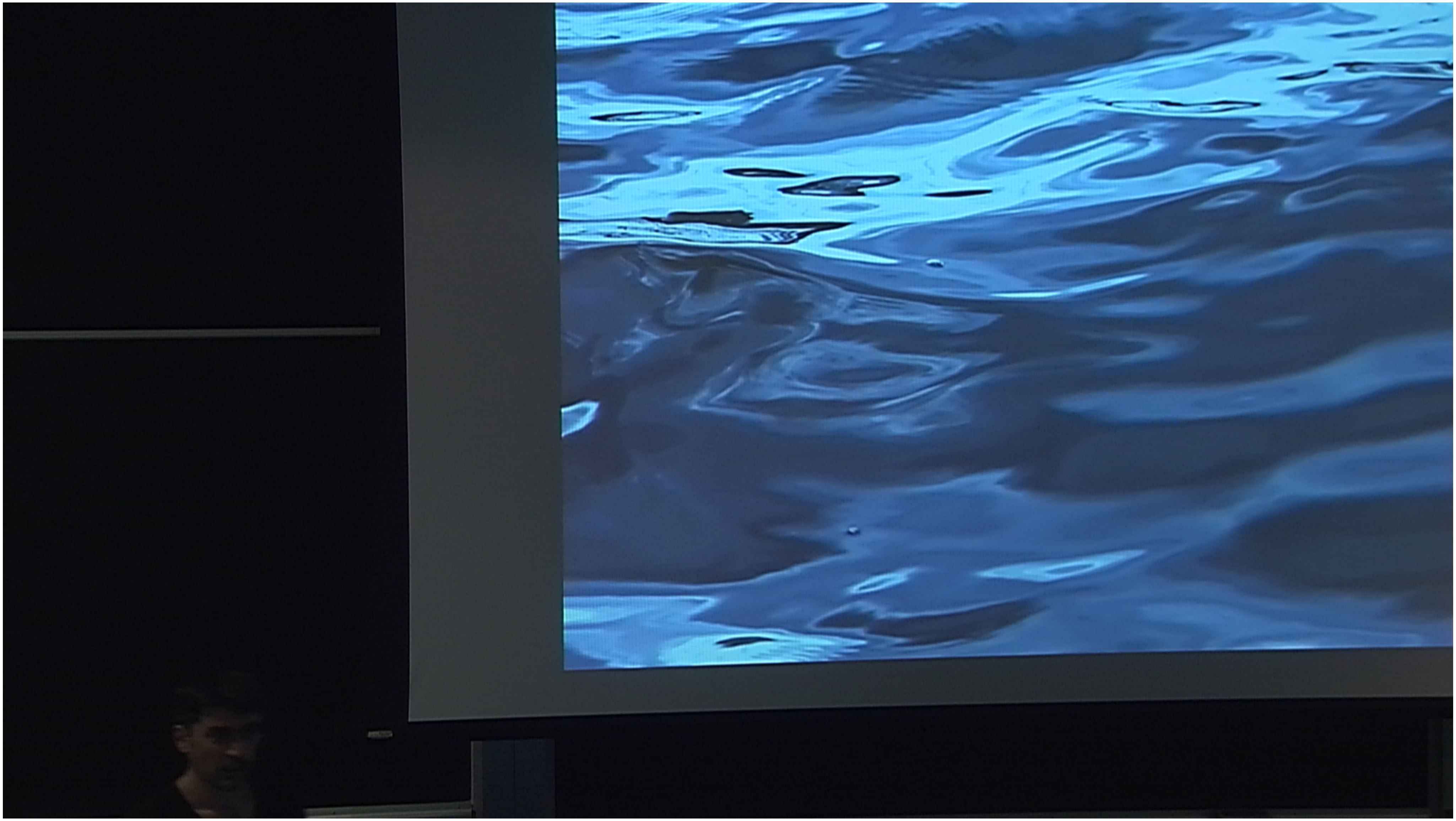
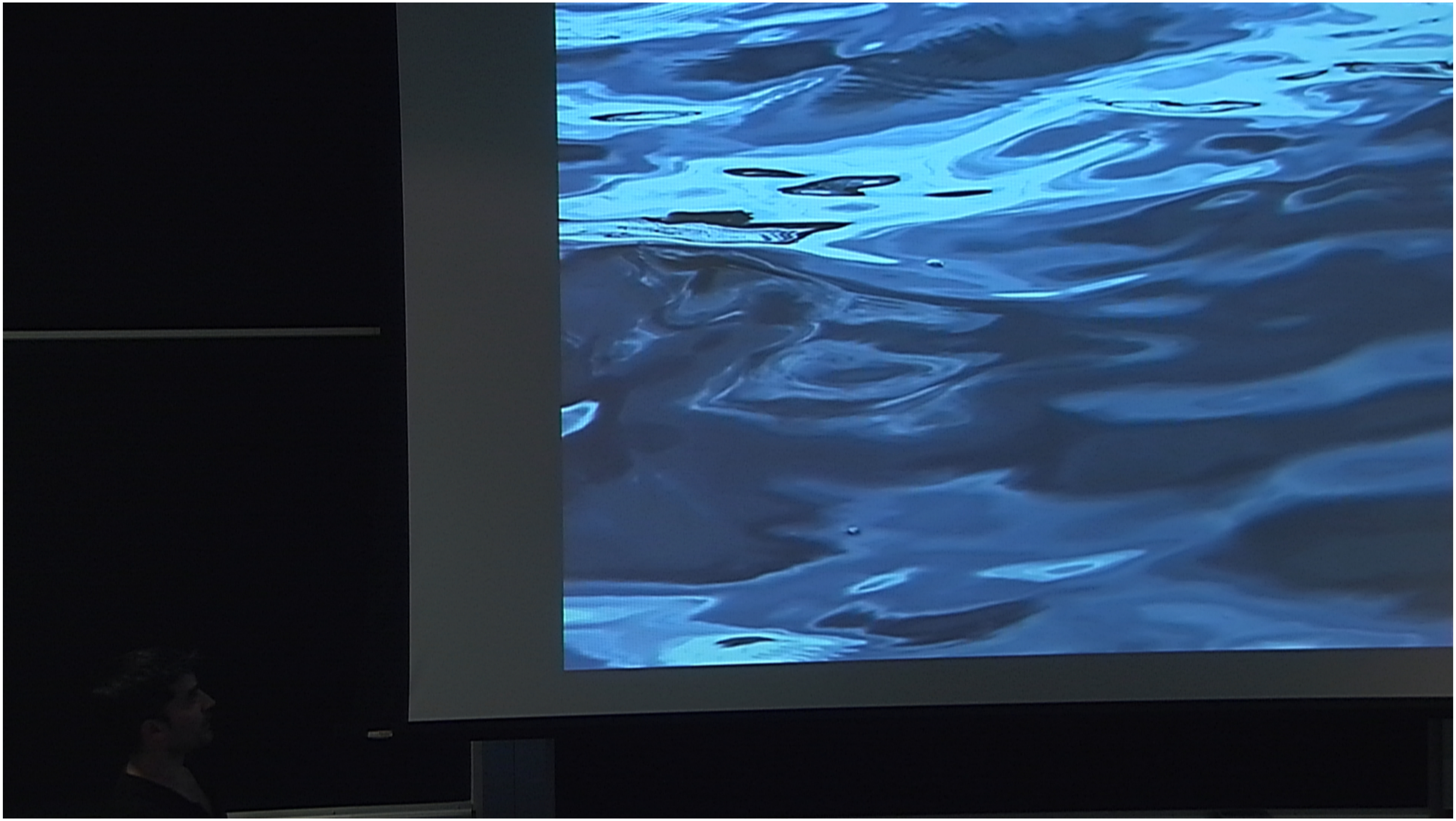
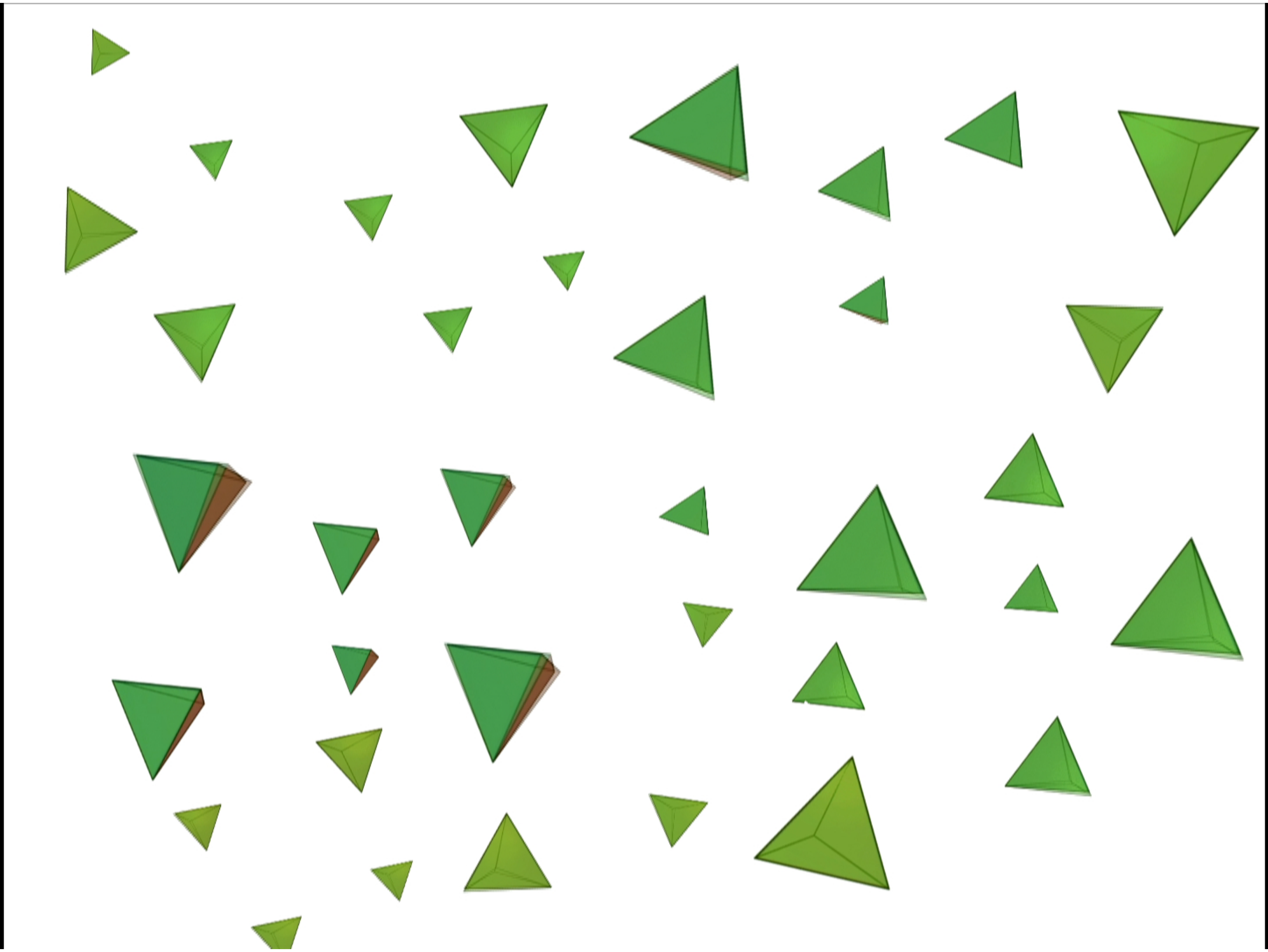
analogy: spacetime is like a condensed matter system, arising from a dynamical "condensation" of QG building blocks (~ "atoms of space")

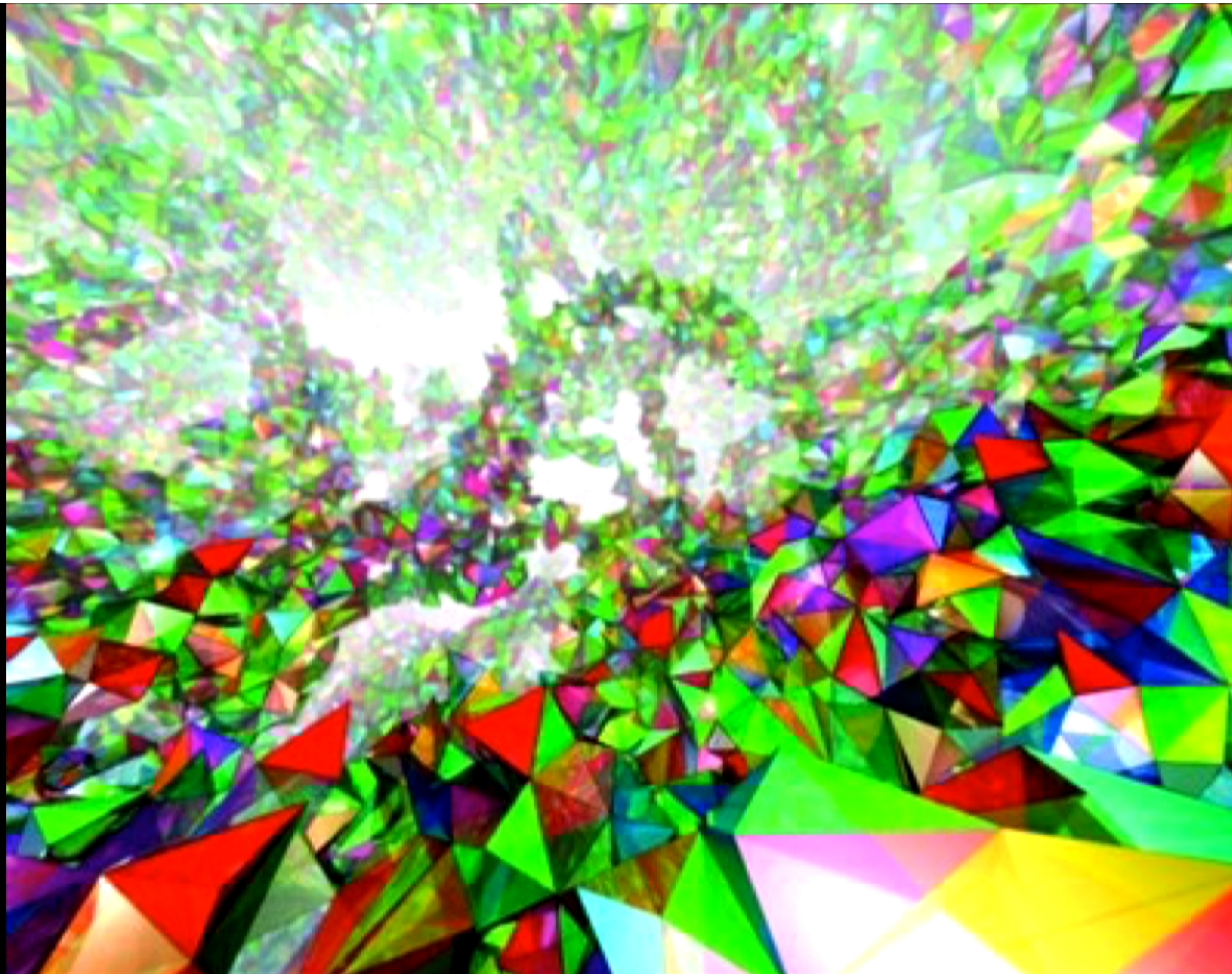


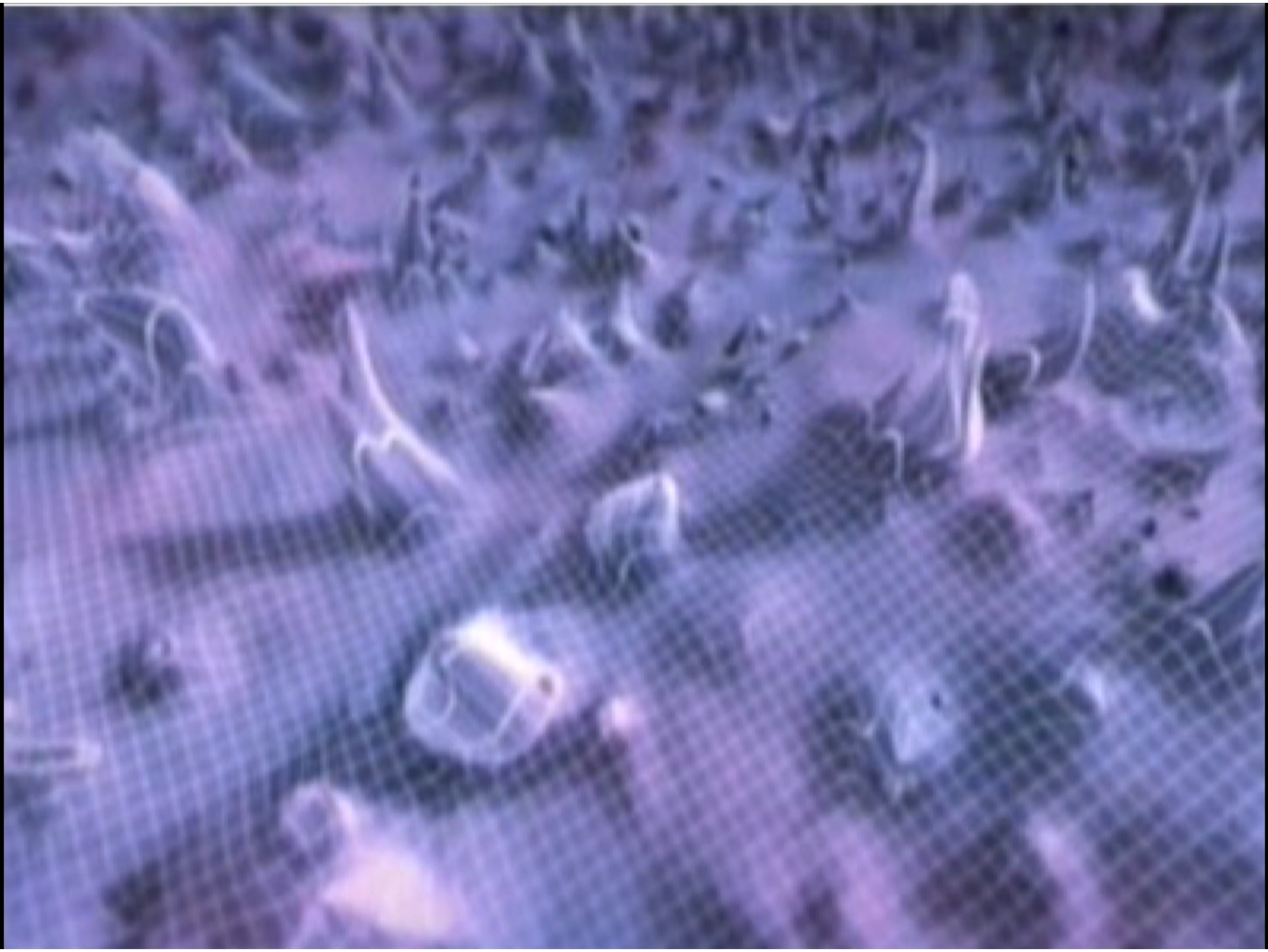












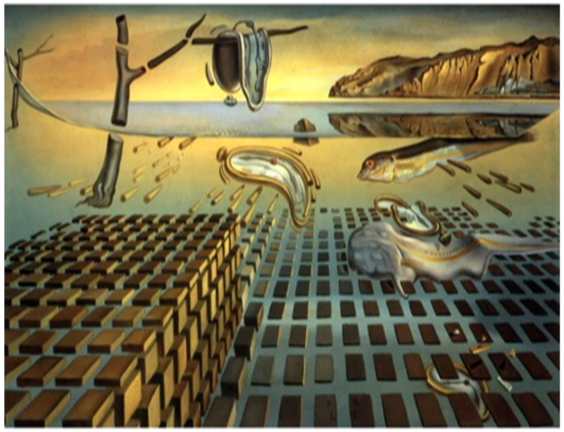
# Emergence for space and time in QG

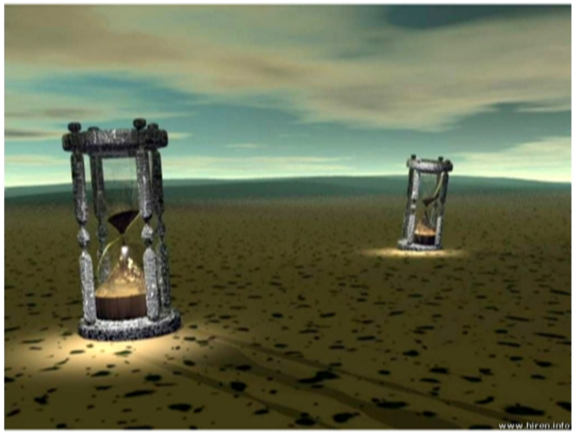
There is no Space and no Time in Quantum Gravity, both have to emerge in some approximation

The world is fundamentally Quantum and its building blocks do not have spatiotemporal features

Continuum, spatiotemporal physics to be looked for in collective behaviour of fundamental building blocks

Cosmology is sector of such collective physics, hydrodynamics of microscopic building blocks





Question n.1:
what are the QG building blocks of space(time)?

# Part 1:
# the GFT formalism

# Group field theories

(Boulatov, Ooguri, De Pietri, Freidel, Krasnov, Rovelli, Perez, DO, Livine, Baratin, ……)

QFT -of- spacetime, not -on- spacetime

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a QFT for the building blocks of (quantum) space

Quantum field theories over group manifold G (or corresponding Lie algebra) $\varphi : G^{\times d} \rightarrow \mathbb{C}$

relevant classical phase space for "GFT quanta": $(\mathcal{T}^* G)^{\times d} \simeq (\mathfrak{g} \times G)^{\times d}$

can reduce to subspaces in specific models depending on conditions on the field

d is dimension of "spacetime-to-be"; for gravity models, G = local gauge group of gravity (e.g. Lorentz group)

example: d=4 $\varphi(g_1, g_2, g_3, g_4) \leftrightarrow \varphi(B_1, B_2, B_3, B_4) \rightarrow \mathbb{C}$

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very general framework; interest rests on specific models/use
(most interesting QG models are for Lorentz group in 4d)

# Group field theories

QFT of spacetime, not defined on spacetime

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$$\mathcal{F}(\mathcal{H}_v) = \bigoplus_{V=0}^{\infty} sym\left\{\left(\mathcal{H}_v^{(1)} \otimes \mathcal{H}_v^{(2)} \otimes \cdots \otimes \mathcal{H}_v^{(V)}\right)\right\}$$

$$\mathcal{H}_v = L^2\left(G^d; d\mu_{Haar}\right)$$

boson statistics is -assumption-
(can construct, e.g., fermionic models)

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in GFT models, this is fundamental Hilbert space of dofs of universe

spacetime, geometry and matter fields should emerge from these quantum data

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Fock vacuum: "no-space" ("emptiest") state $|0>$

(d=4)

single field "quantum": spin network vertex or tetrahedron
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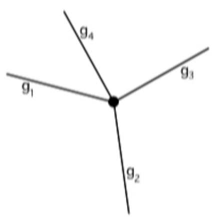


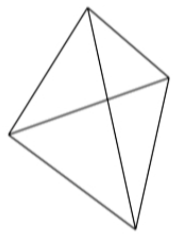

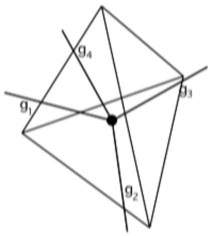

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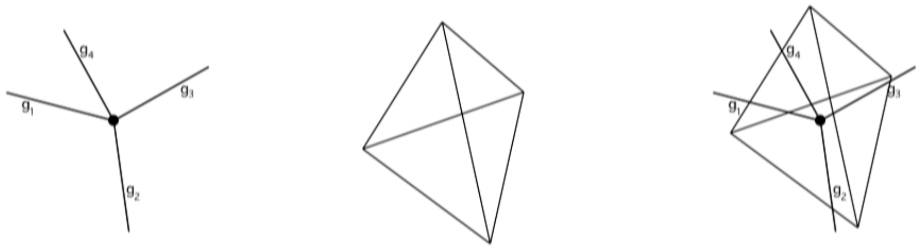
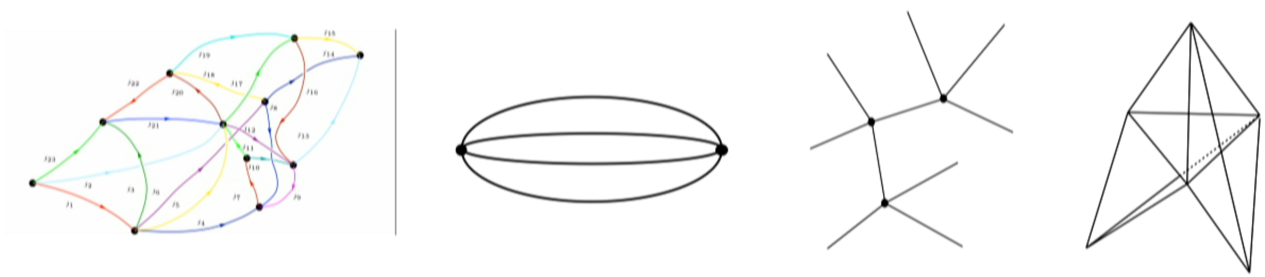



generic quantum state: arbitrary collection of spin network vertices (including glued ones) or tetrahedra (including glued ones)



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a QFT for the building blocks of (quantum) space

classical action: kinetic (quadratic) term + (higher order) interaction (convolution of GFT fields)

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combinatorics of field arguments in interaction: gluing of 5 tetrahedra across common triangles, to form 4-simplex ("building block of spacetime")

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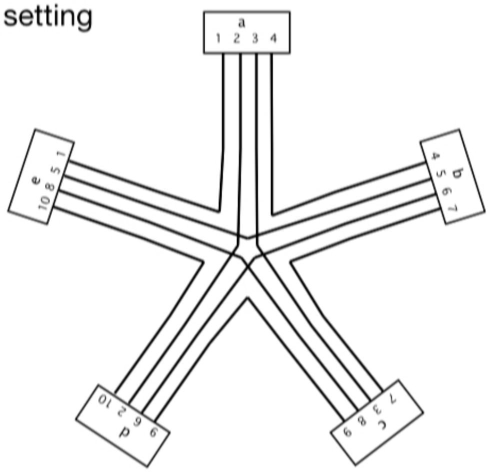


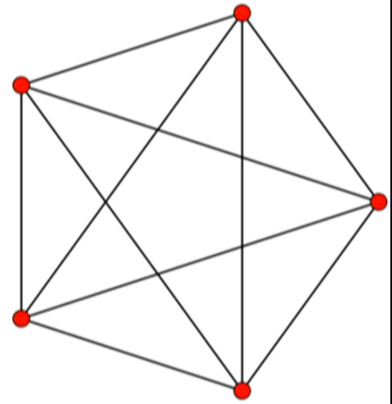

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Feynman perturbative expansion around trivial vacuum

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= stranded diagrams dual to cellular complexes of arbitrary topology

(simplicial case: simplicial complexes obtained by gluing d-simplices)

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Feynman amplitudes (model-dependent):

equivalently:

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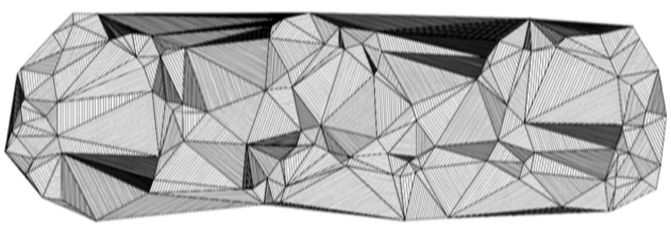

Question n.2:
what have GFTs to do with geometry and gravity?

# GFTs and tensor models

(Ambjorn, Durhuus, Sasakura, …, Gurau, Rivasseau, Bonzom, Ryan, …..)

same combinatorics (of states/observables and histories/Feynman diagrams), no group-theoretic data

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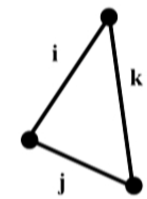
example: d=3

dropping group/algebra data
(or restricting to finite group)

$$\varphi(g_1, g_2, g_3) : G^{\times 3} \to \mathbb{C} \longrightarrow \begin{array}{l} T_{ijk} : \mathbb{Z}_N^{\times 3} \to \mathbb{C} \\ T_{ijk} : X^{\times 3} \to \mathbb{C} \end{array}$$

$X = 1, 2, ..., N$



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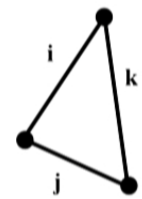
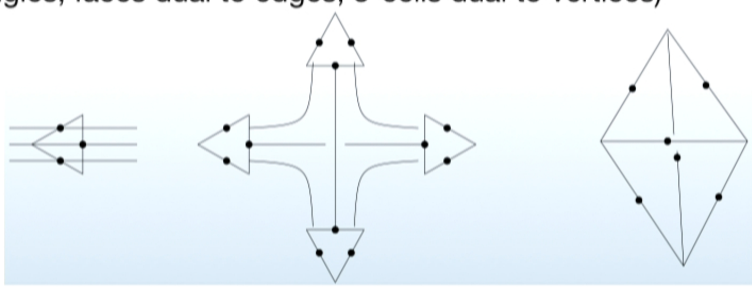



$$S(T) = \frac{1}{2} \sum_{i,j,k} T_{ijk} T_{kji} - \frac{\lambda}{4! \sqrt{N^3}} \sum_{ijklmn} T_{ijk} T_{klm} T_{mjn} T_{nli}$$

Feynman diagrams are stranded graphs dual to 3d simplicial complexes
(nodes dual to tetrahedra, lines dual to triangles, faces dual to edges, 3-cells dual to vertices)



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Random tensors ——> random geometries

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(Ambjorn, Durhuus, Sasakura, …, Gurau, Rivasseau, Bonzom, Ryan, …..)

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GFTs = tensor models + group data

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richer models, richer dynamics

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model building guided by simplicial geometry:

GFT quanta are discrete geometric structures with group-theoretic variables

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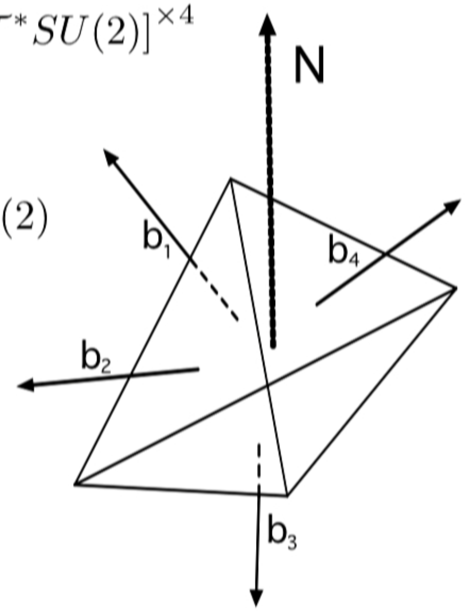
d = 4; G = local gauge group of gravity = SO(3,1) (in riemannian signature, SO(4))

phase space before geometricity constraints: $[\mathcal{T}^* Spin(4)]^{\times 4} \simeq [\mathcal{T}^* SU(2) \times \mathcal{T}^* SU(2)]^{\times 4}$

classical tetrahedron in 4d:

$$A_i\, n_i^I = b_i^I \in \mathbb{R}^4 \qquad b_i \cdot N = 0 \qquad \sum_i b_i = 0$$

$$b_i \simeq \mathfrak{su}(2)$$

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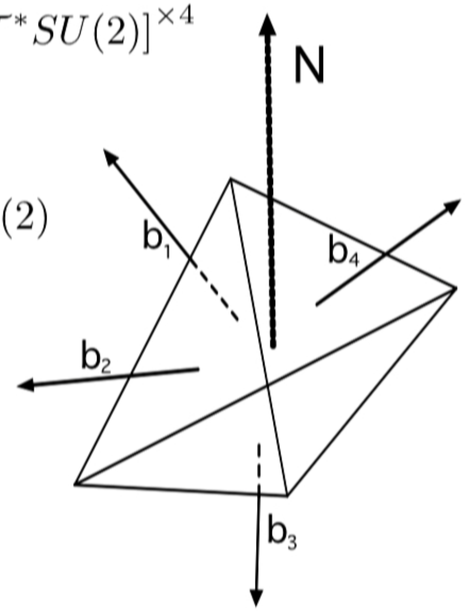

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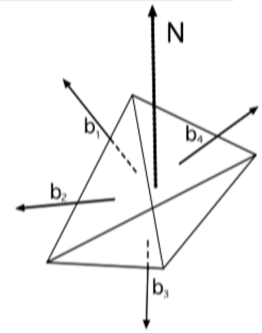


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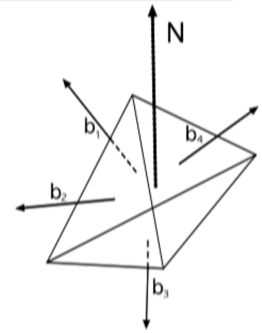


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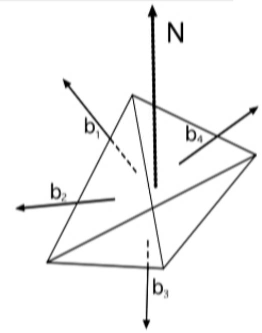


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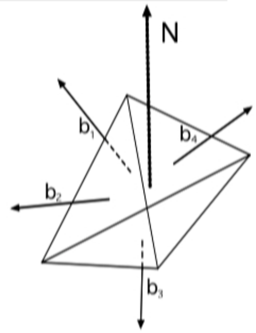


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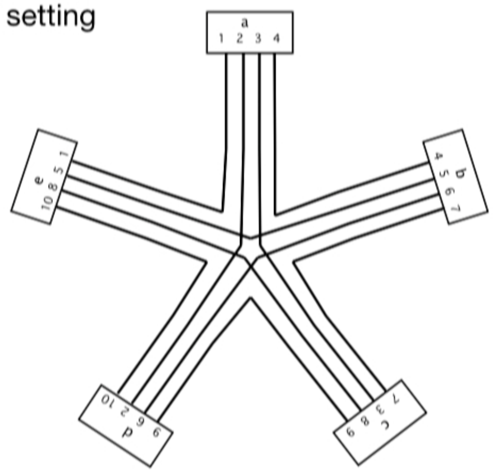
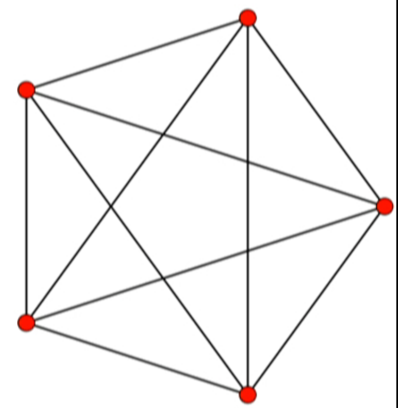
specific combinatorics depends on model

simplest example (case d=4): simplicial setting





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= stranded diagrams dual to cellular complexes of arbitrary topology

(simplicial case: simplicial complexes obtained by gluing d-simplices)

Feynman amplitudes (model-dependent):

equivalently:

- spin foam model (sum-over-histories of spin networks ~ covariant LQG)
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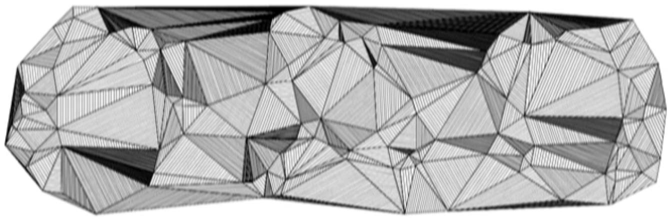

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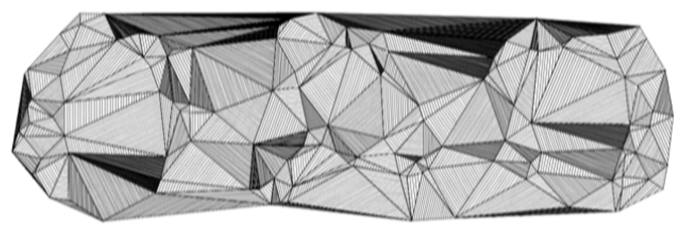

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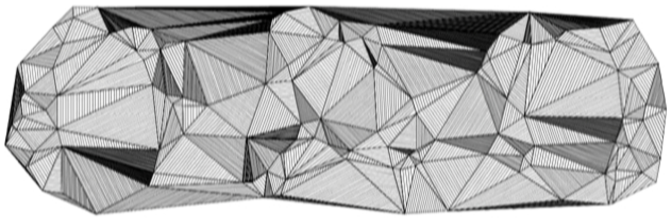
discrete semiclassical limit —-> Regge calculus



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appropriate conditions on GFT fields or GFT dynamics (and choice of data) turn GFT Feynman amplitudes into lattice gauge theories/discrete gravity path integrals/spin foam models

e.g. gauge invariance of GFT fields under diagonal action of group G

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lattice gauge theory formulation of 3d gravity/BF theory

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spin foam formulation of 3d gravity/BF theory

discrete 1st order path integral for 3d gravity/BF theory on simplicial complex dual to GFT Feynman diagram

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second quantized version of Loop Quantum Gravity
but dynamics not derived from canonical quantization of GR

DO, 1310.7786 [gr-qc]

DO, J. Ryan, J. Thurigen, '14

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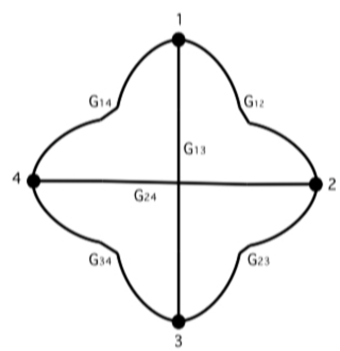

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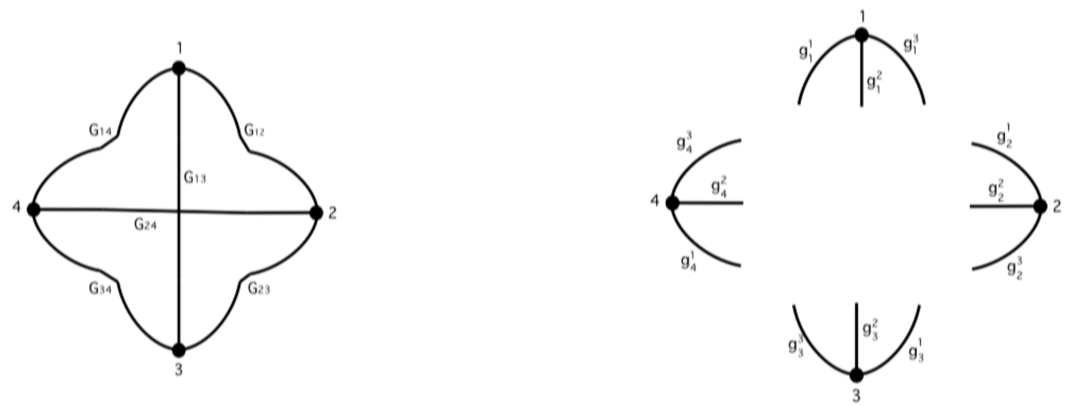

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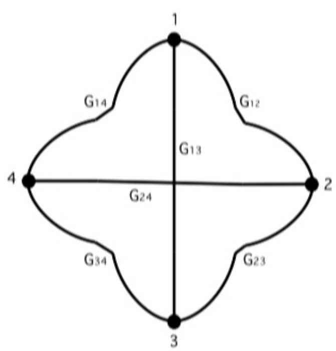
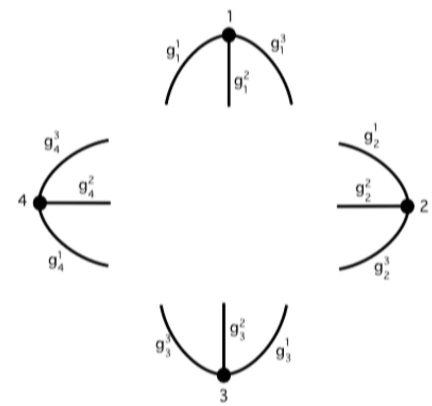


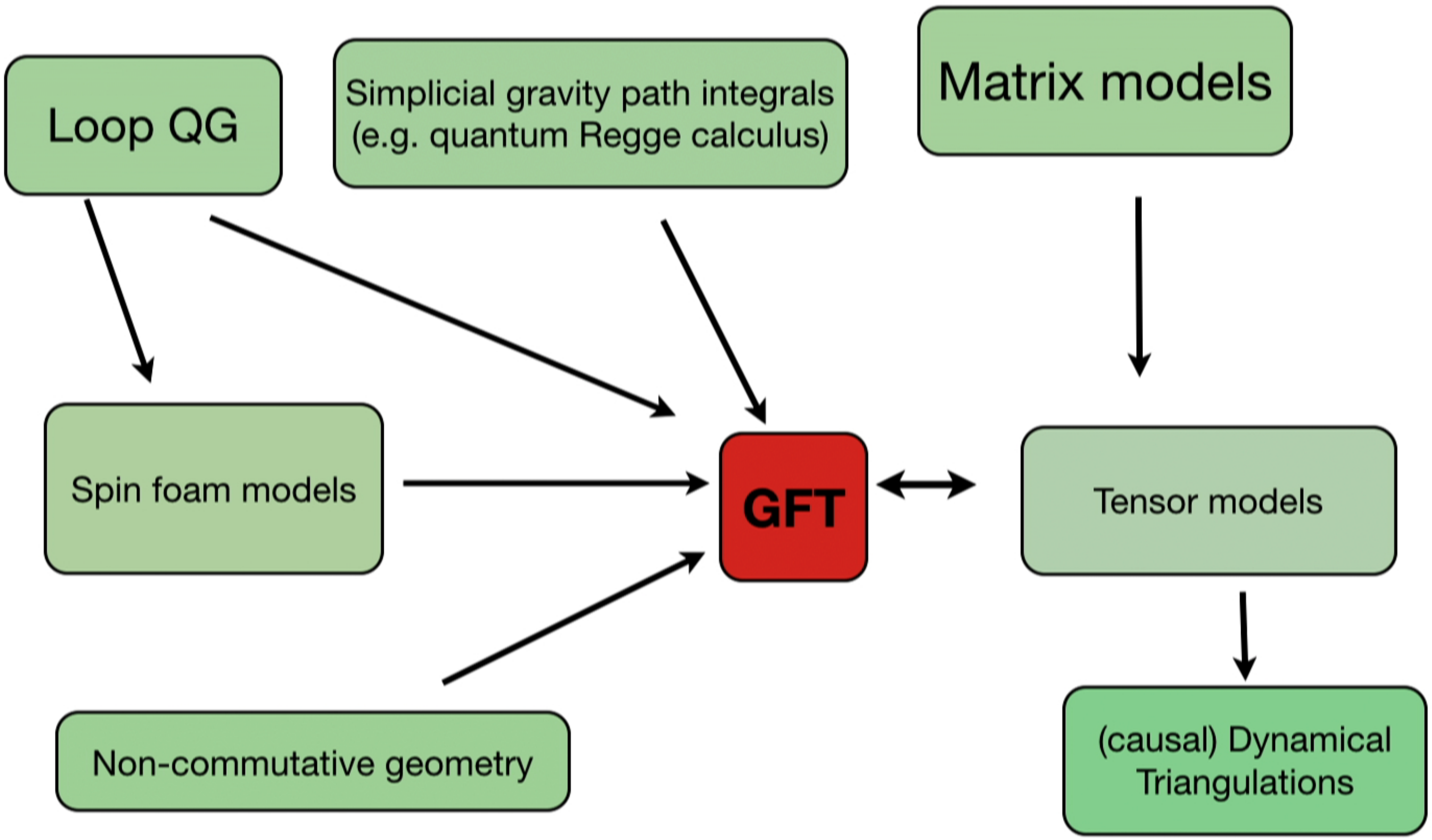




GFT Hilbert space = Fock space of open spin network vertices - contains any LQG state (all spin networks)

any LQG observable has a 2nd quantised, GFT counterpart

choice of LQG dynamics (Hamiltonian constraint operator) translates into choice of GFT action

# Group Field Theory: crossroad of approaches



Questions n.3:
are these models consistent?
how do you define a continuum limit?

# Part 2:
# the continuum limit of GFTs
# -
# GFT renormalization

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# The problem of the continuum limit in QG

new (non-geometric, non-spatio-temporal) physical degrees of freedom ("building blocks") for space-time

→ new direction to explore: number of fundamental degrees of freedom

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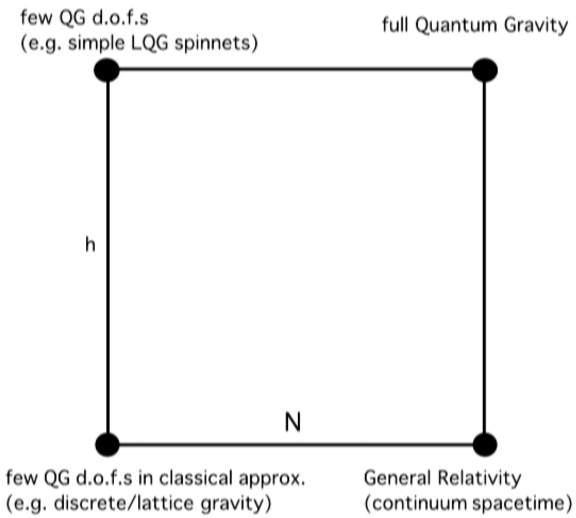
N-direction
(collective behaviour of many interacting degrees of freedom):
continuum approximation

h-direction: classical approximation



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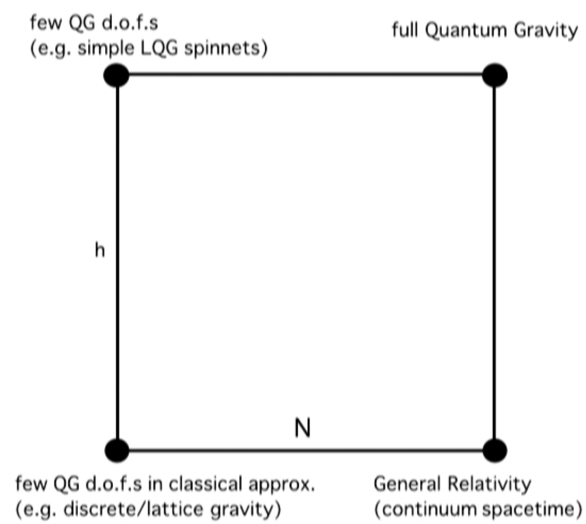


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(collective behaviour of many interacting degrees of freedom):
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h-direction: classical approximation

↑

"well-understood" in spin foam models and discrete gravity

# Problem of the continuum in QG: role of RG

Renormalization Group is crucial tool

for taking into account the physics of more and more d.o.f.s

- for our QG models, do not expect to have a unique continuum limit

collective behaviour of (interacting) fundamental d.o.f.s should lead to different macroscopic phases, separated by phase transitions

- for a non-spatio-temporal QG system (e.g. LQG in GFT formulation), which of the macroscopic phases is described by a smooth geometry with matter fields?

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many results in related formalisms:

- renormalization in SF models (~ lattice gauge theories) Dittrich, Bahr, Steinhaus, Martin-Benito, ……
- different (kinematical) phases in LQG Ashtekar-Lewandowski, Koslowski-Sahlmann, Dittrich-Geiller)
- phase diagrams (numerically) in (causal) dynamical triangulations Ambjorn, Loll, Jurkiewicz, …..

# GFT renormalisation - general scheme

$$\mathcal{Z} = \int \mathcal{D}\varphi \mathcal{D}\overline{\varphi} \; e^{i\, S_\lambda(\varphi,\overline{\varphi})} \quad = \quad \sum_\Gamma \frac{\lambda^{N_\Gamma}}{sym(\Gamma)} \mathcal{A}_\Gamma$$

$$S(\varphi,\overline{\varphi}) = \frac{1}{2}\int [dg_i] \overline{\varphi(g_i)} \mathcal{K}(g_i) \varphi(g_i) + \frac{\lambda}{D!}\int [dg_{ia}] \varphi(g_{i1}) \ldots \varphi(\bar{g}_{iD}) \mathcal{V}(g_{ia}, \bar{g}_{iD}) \quad + \quad c.c.$$

general strategy:

treat GFTs as ordinary QFTs defined on Lie group manifold

use group structures (Killing form, topology, etc) to define notion of scale and to set up mode integration

subtleties of quantum gravity context at the level of interpretation

scales:

defined by propagator: e.g. spectrum of Laplacian on G = indexed by group representations

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scales:

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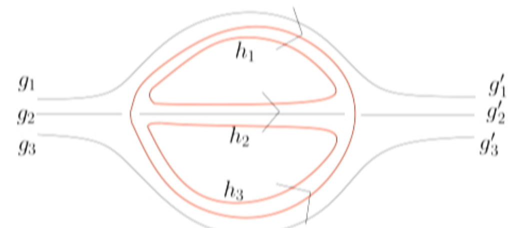
- need to have control over "theory space" (e.g. via symmetries) A. Kegeles, DO, '15,'16
- main difficulty:
  controlling the combinatorics of GFT Feynman diagrams and interactions to control RG flow and divergences
  need to adapt/redefine many QFT notions: connectedness, subgraph contraction, Wick ordering, …..

# GFT perturbative renormalisation

# GFT perturbative renormalisation




step by step, towards renormalizable 4d gravity models:

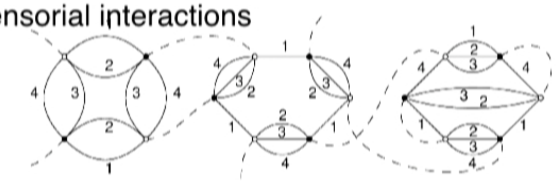
- scale indexed by group representations
- interplay between algebraic data and combinatorics of diagrams

- calculation of some radiative corrections T. Krajewski, J. Magnen, V. Rivasseau, A. Tanasa, P. Vitale, '10; A. Riello, '13; Bonzom, Dittrich, '15
- finiteness results in 3d simplicial models (Boulatov with Laplacian kinetic term) Ben Geloun, Bonzom, '11; Ben Geloun, '13

- renormalizable TGFT models (3d, 4d, and higher) - Laplacian + tensorial interactions

Ben Geloun, Rivasseau, '11
Carrozza, DO, Rivasseau, '12. '13

$$S(\varphi,\overline{\varphi}) = \sum_{b\in\mathcal{B}} t_b I_b(\varphi,\overline{\varphi})$$



-> with gauge invariance

—> non-abelian ( SU(2) )

— —> SO(4) or SO(3,1) with simplicity constraints: first results on BC-like 4d models Lahoche, DO, '15; Carrozza, Lahoche, DO, '16

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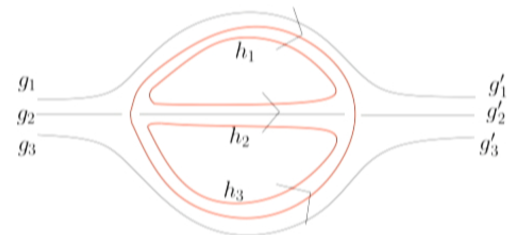


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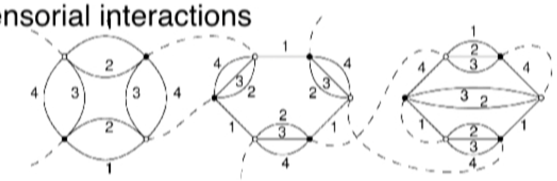

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many important lessons

(e.g. learnt to deal with combinatorics and topology of spin foam complex)

main open issues:

- characterise better theory space (kinetic term, combinatorics of interactions, …)
- deal with non-group structures (due to Immirzi parameter)

understand in full the geometric interpretation of UV/IR and of RG flow

# GFT non-perturbative renormalisation

the GFT proposal:

$$\mathcal{Z} = \int \mathcal{D}\varphi \mathcal{D}\overline{\varphi}\, e^{i\, S_\lambda(\varphi,\overline{\varphi})} \quad = \quad \sum_\Gamma \frac{\lambda^{N_\Gamma}}{sym(\Gamma)} \mathcal{A}_\Gamma$$

controlling the continuum limit ~ evaluating GFT path integral (in some non-perturbative approximation)

Benedetti, Ben Geloun, DO, Martini, Lahoche, Carrozza, Ousmane-Samary, Duarte, ….

Freidel, Louapre, Noui, Magnen, Smerlak, Gurau, Rivasseau, Tanasa, Dartois, Delpouve, …..

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two directions:

- GFT non-perturbative renormalization and “IR” fixed points (e.g. FRG analysis - e.g. a la Wetterich

  Benedetti, Ben Geloun, DO, Martini, Lahoche, Carrozza, Ousmane-Samary, Duarte, ….

- GFT constructive analysis

  Freidel, Louapre, Noui, Magnen, Smerlak, Gurau, Rivasseau, Tanasa, Dartois, Delpouve, …..

  non-perturbative resummation of perturbative (SF) series

  variety of techniques:
  - intermediate field method
  - loop-vertex expansion
  - Borel summability

# FRG analysis of GFT models

D. Benedetti, J. Ben Geloun, DO, '14

regularised path integral: $\mathcal{Z}_k[J,\overline{J}] = e^{W_{k'}[J,\overline{J}]} = \int d\phi d\overline{\phi}\; e^{-S[\phi,\overline{\phi}]-\Delta S_{k'}[\phi,\overline{\phi}]+\mathrm{Tr}(J\cdot\overline{\phi})+\mathrm{Tr}(\overline{J}\cdot\phi)}$

regulator cutting off IR modes (UV well-defined with appropriate choice of IR regulator)

$$\Delta S_k[\phi,\overline{\phi}] = \mathrm{Tr}(\overline{\phi}\cdot R_k\cdot\phi) = \sum_{\mathbf{P},\mathbf{P}'} \overline{\phi}_{\mathbf{P}}\, R_k(\mathbf{P};\mathbf{P}')\,\phi_{\mathbf{P}'}$$

$$R_k(\mathbf{p},\mathbf{p}') = \theta(k^2-\Sigma_s p_s^2)Z_k(k^2-\Sigma_s p_s^2)\delta(\mathbf{p}-\mathbf{p}')$$

effective action: $\Gamma_k[\varphi,\overline{\varphi}] = \sup_{J,\overline{J}}\left\{\mathrm{Tr}(J\cdot\overline{\varphi})+\mathrm{Tr}(\overline{J}\cdot\varphi) - W_k[J,\overline{J}] - \Delta S_k[\varphi,\overline{\varphi}]\right\}$

Wetterich equation: $\partial_t\Gamma_k = \mathrm{Tr}[\partial_t R_k\cdot(\Gamma_k^{(2)}+R_k)^{-1}]$ $\quad t=\log k$

boundary conditions: $\Gamma_{k=0}[\varphi,\overline{\varphi}] = \Gamma[\varphi,\overline{\varphi}]\,,\qquad \Gamma_{k=\Lambda}[\varphi,\overline{\varphi}] = S[\varphi,\overline{\varphi}]\qquad \varphi = \langle\phi\rangle$

computing the effective action solving the Wetterich equation amounts to solving the GFT path integral

need truncation of effective action up to some order of interactions

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recent results:

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## recent results:

FRG for (tensorial) GFT models (similar to matrix model but distinctively field-theoretic)

Eichhorn, Koslowski, '14

- Polchinski formulation based on SD equations Krajewski, Toriumi, '14
- general set-up for Wetterich formulation based on effective action
  - analysis of TGFT on compact U(1)^d Benedetti, Ben Geloun, DO, '14 ; Ben Geloun, Martini, DO, '15, '16, Benedetti, Lahoche, '15; Duarte, DO, '16
    - RG flow and phase diagram established
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  - analysis of TGFT on non-compact R^d with gauge invariance
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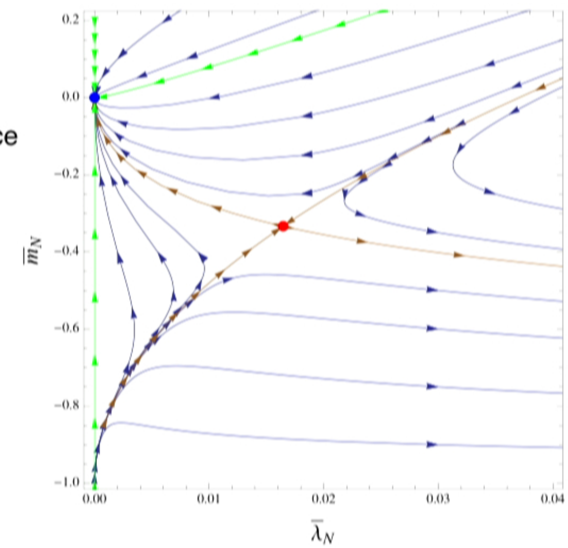
  - analysis of TGFT on SU(2)^3 Carrozza, Lahoche, '16




generically (so far):

two FPs (Gaussian-UV, Wilson-Fisher-IR)

asymptotic freedom

one symmetric phase

one broken or condensate phase

Question n.4:
what effective continuum physics?
where is gravitational dynamics?

# Part IV:
# effective cosmology from GFTs
# -
# Cosmology as QG hydrodynamics

# Quantum spacetime:
# the difficult path from microstructure to cosmology

the issue:

identify relevant phase for effective continuum geometry
extract effective continuum dynamics and relate it to GR

Quantum Gravity problem:
identify microscopic d.o.f. of quantum spacetime and their fundamental dynamics

derive effective (QG-inspired) models for fundamental (quantum) cosmology:
explain features of early Universe, obtain testable QG predictions

various models: loop quantum cosmology, ....

also work by:

C. Rovelli, F. Vidotto (perturbative GFT (spin foam) context); E. Alesci, F. Cianfrani (canonical LQG context); .....

# What is cosmology, then?

two views on quantum gravity:

1. quantum gravity = quantum theory of gravitational field ~ quantum General Relativity

2. quantum gravity = microscopic theory of pre-geometric quantum degrees of freedom
("quantum (field) theory of atoms of space")

→ gravitational field result of collective dynamics
spacetime and geometry are emergent entities

in case 2.

cosmology is necessarily to be understood as result of coarse graining of microscopic dofs up to global observables only, homogeneous sector of (quantum) GR

(quantum) cosmological degrees of freedom governed by statistical distribution
not quantum theory of homogeneous geometries

cosmological dynamics to be looked for in the hydrodynamic approximation of full quantum gravity
(most macroscopic, coarse grained, global description of the microscopic pre-geometric system)

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# Cosmology as hydrodynamics of (quantum) spacetime

re-thinking the "Cosmological Principle":

"every point is equivalent to any other" ~ homogeneity of space

really means: a certain approximation is assumed valid:

universe is in state where inhomogeneities can be neglected, in relation to dynamics of homogeneous modes

~ universe is in state where effects on largest wavelengths of shorter wavelengths is negligible

~ can neglect wavelengths (much) shorter than scale factor

very similar in spirit to hydrodynamic approximation:

dynamics of microscopic degrees of freedom can be neglected + effects of small wavelengths can be neglected

degrees of freedom of local region can describe whole of system (in a coarse grained, statistical sense)

i.e. whole universe (dynamics) well-approximated by local patch (dynamics)

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end result:

basic variable is "fluid density" with arguments the geometric data of minisuperspace

cosmology is (non-linear) dynamics for such density and for geometric (global) observables computed from it

# From Quantum Gravity to Cosmological hydrodynamics

key strategy:

coarse graining of QG configurations

→

coarse graining of QG (quantum) dynamics

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one special case:

quantum condensates (BEC)

effective hydrodynamics directly read out of microscopic quantum dynamics (in simplest approximation)

# (Quantum) Cosmology from GFT condensates

S. Gielen, DO, L. Sindoni, PRL, arXiv:1303.3576 [gr-qc]; JHEP, arXiv:1311.1238 [gr-qc]

S. Gielen, '14; G. Calcagni, '14; L. Sindoni, '14; S. Gielen, DO, '14; S. Gielen, '14; S. Gielen, '15; DO, L. Sindoni, E. Wilson-Ewing, '16; M. De Cesare, M. Sakellariadou, '16; S. Gielen, '16; M. De Cesare, A. Pithis, M. Sakellariadou, '16

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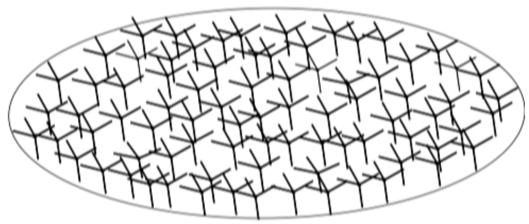
Quantum GFT condensates are continuum homogeneous (quantum) spaces

e.g. (simplest): $|\sigma\rangle := \exp(\hat{\sigma})\,|0\rangle$

GFT field coherent state $\hat{\sigma} := \int d^4g\; \sigma(g_I)\hat{\varphi}^\dagger(g_I) \qquad \sigma(g_I k) = \sigma(g_I)$



superposition of
infinitely many SN dofs

described by single collective wave function
(depending on homogeneous anisotropic geometric data)

$$\sigma(\mathcal{D}) \qquad \mathcal{D} \simeq \{\text{geometries of tetrahedron}\} \simeq$$
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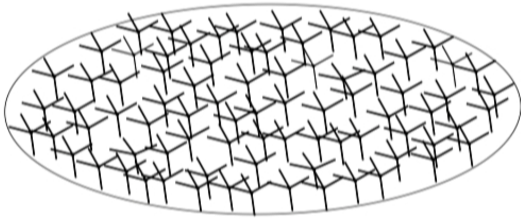

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# Homogeneous geometries & GFT condensates

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- lift homogeneity criterion to quantum level (and include conjugate information):

all GFT quanta have the same (gauge invariant) “wave function”, i.e. are in the same quantum state

$$\Psi\left(B_{i(1)}, ...., B_{i(N)}\right) = \frac{1}{N!}\prod_{m=1}^{N}\Phi(B_i(m))$$

- in GFT: such states can be expressed in 2nd quantized language and one can consider superpositions of states of arbitrary N

- sending N to infinity means improving arbitrarily the accuracy of the sampling

→ quantum GFT condensates are continuum homogeneous (quantum) spaces

# Effective cosmological dynamics from GFT

follow closely procedure used in real BECs

S. Gielen, DO, L. Sindoni,

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single-particle GFT condensate:

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from truncation of SD equations for GFT model applied to (coherent) GFT condensate state, gives equation for "wave function":

$$\int [dg_i']\,\tilde{\mathcal{K}}(g_i, g_i')\sigma(g_i') + \lambda \frac{\delta\tilde{\mathcal{V}}}{\delta\varphi(g_i)}|_{\varphi\equiv\sigma} = 0$$

basically (up to some approximations), the "classical GFT eqns"

similar equations to M. Bojowald et al., arXiv:1210.8138 [gr-qc]

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non-linear and non-local extension of quantum cosmology-like equation for "collective wave function"

QG (GFT) analogue of Gross-Pitaevskii hydrodynamic equation in BECs

# Cosmology from GFT condensates

summary of recent results:

- general scheme, geometric interpretation and effective dynamics (GP and dipole condensates) S. Gielen, DO, L. Sindoni, '13
- generalised condensate states (also for spherical black holes) DO, D. Pranzetti, J. Ryan, L. Sindoni, '15; DO, D. Pranzetti, L. Sindoni, '15
- lattice refinement and GFT cosmological observables S. Gielen, DO, '14
- relation with LQC S. Gielen, '14, '15, '16; G. Calcagni, '14
- effective cosmological dynamics from EPRL model DO, L. Sindoni, E. Wilson-Ewing, '16; M. De Cesare, M. Sakellariadou, '16; S. Gielen, '16
    - isotropic reduction, scalar field coupling, relational observables
    - generalised Friedmann equations
    - generic big bounce resolution of classical singularity
    - reduction to LQC dynamics
- effect of GFT interaction in emergent cosmological dynamics
    - long-lasting acceleration after bounce (no inflation) M. De Cesare, A. Pithis, M. Sakellariadou, '16
    - non-normalisable condensate states (hints of GFT phase transition?) A. Pithis, M. Sakellariadou, P. Tomov, '16
- first steps with cosmological perturbations S. Gielen, '14, '15

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- effective condensate hydrodynamics (non-linear quantum cosmology):

$$A_j \partial_\phi^2 \sigma_j(\phi) - B_j \sigma_j(\phi) + w_j \sigma_j(\phi)^4 = 0$$

functions A, B, w define the details of the EPRL model

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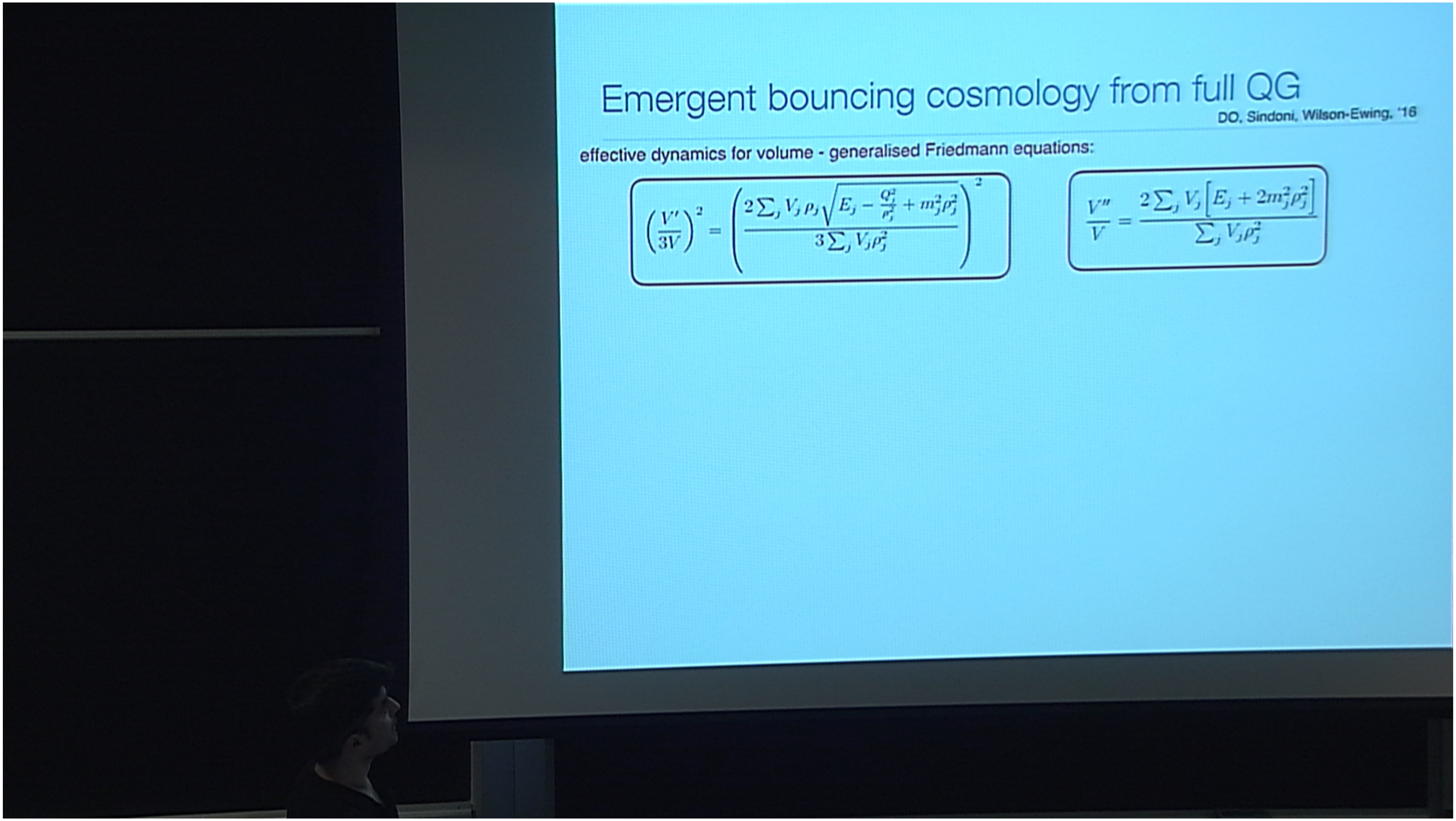

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1) generic solutions approximate such simple condensates at late times — Gielen, '16 — De Cesare, Pithis, Sakellariadou, '16

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More questions….
what's next?

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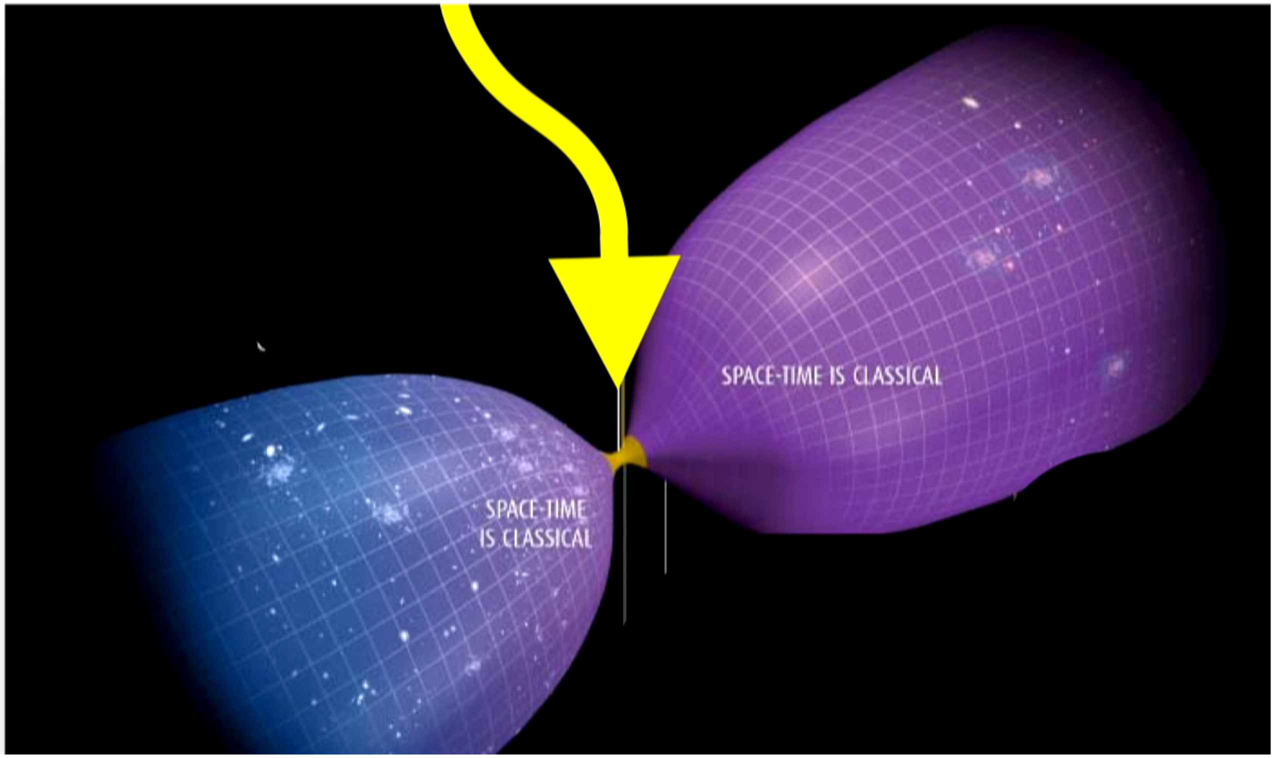

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it can be derived via the same type of calculations done in LQC …. (Big Bounce from the full theory!)

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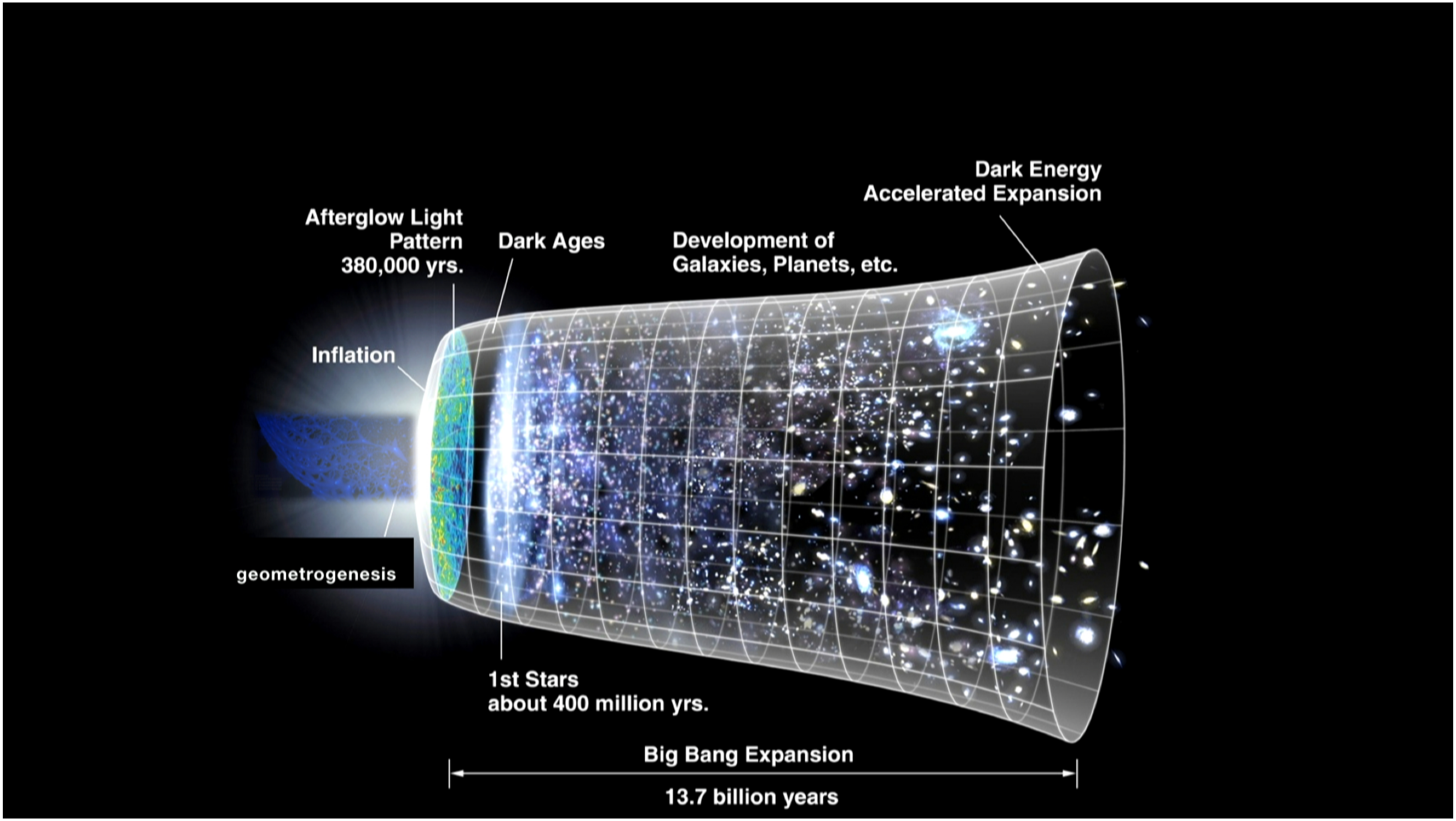
novelty: it can be done!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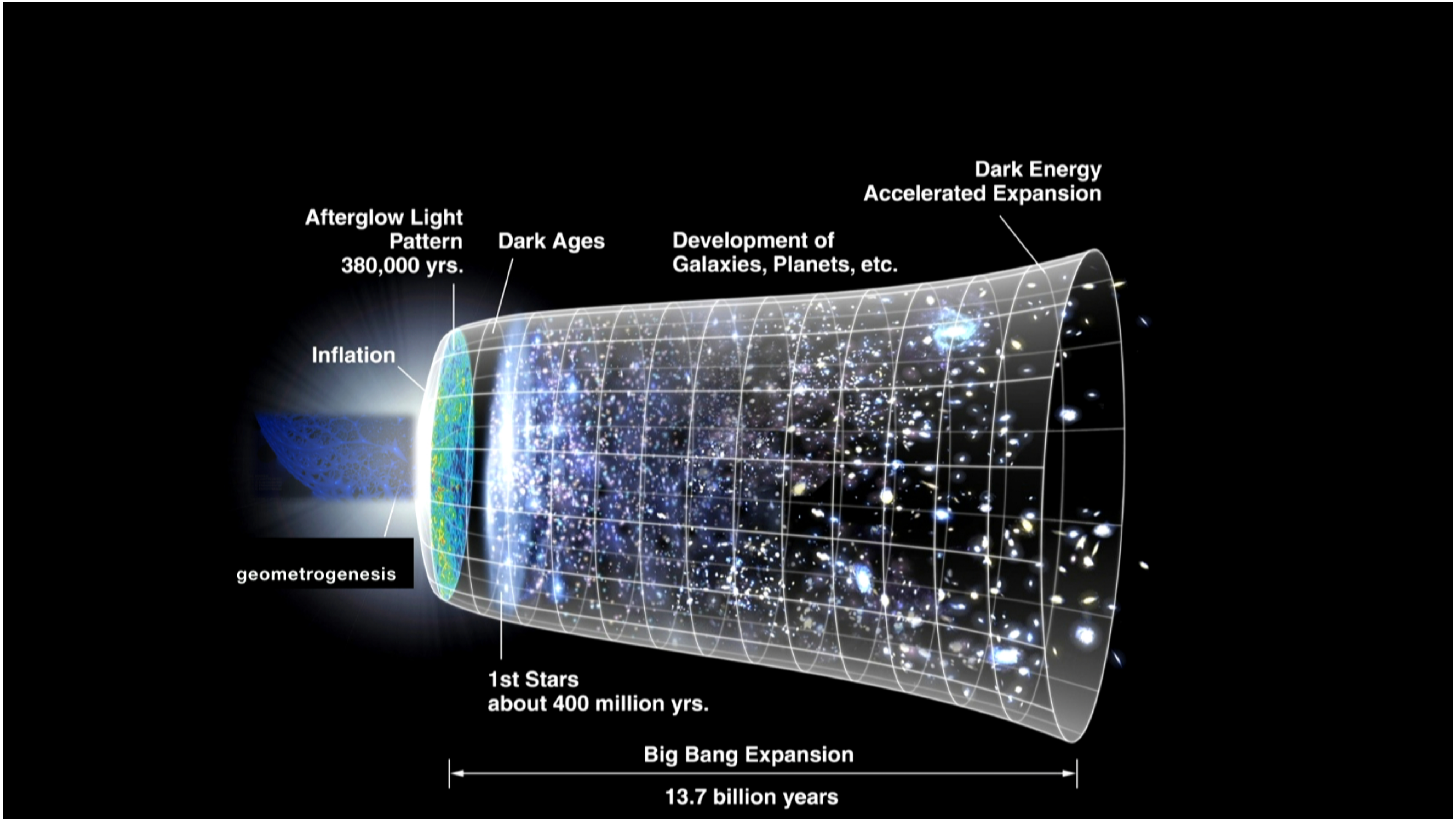
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expect deformation of standard QFT:

- from holonomization of the connection and non-commutativity of triad variables
- derivation of effective dynamics of perturbations around mean field in topological GFT:
non-commutative scalar field theory on non-commutative flat space

W. Fairbairn, E. Livine, '07; F. Girelli, E. Livine, DO, '09

Still a long journey ahead….

Thank you for your attention!