The universe
as
a quantum gravity condensate

Daniele Oriti

Max Planck Institute for Gravitational Physics, Potsdam, Germany
(Albert Einstein Institute - AEI)

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MAX-PLANCK-GESELLSCHAFT

Quantum Gravity

and

the emergence of spacetime and geometry

Quantum Gravity and the nature of spacetime

quantum gravity = microscopic theory of pre-geometric quantum degrees of freedom
(“quantum (field) theory of atoms of space”)

the goals are:

- identify the fundamental (quantum) degrees of freedom of spacetime
  —— the “atoms of space (or spacetime)”
- define a consistent quantum dynamics for them
- show that an approximately continuum, classical spacetime emerges
- show that GR is good effective description of emergent spacetime dynamics

→

gravitational field result of collective dynamics

spacetime and geometry are emergent entities, obtained after
coarse graining of fundamental, non-spatiotemporal dofs

candidate “atoms of quantum space” ——-> how to recover continuum spacetime (and GR)?

1st aspect of “problem of continuum”: emergence of spacetime:

approximation of microscopic building blocks to give effective continuum spatiotemporal description

several results in various approaches (quantum Regge calculus, Loop Quantum Gravity, Group Field Theory, dynamical triangulations, ….)

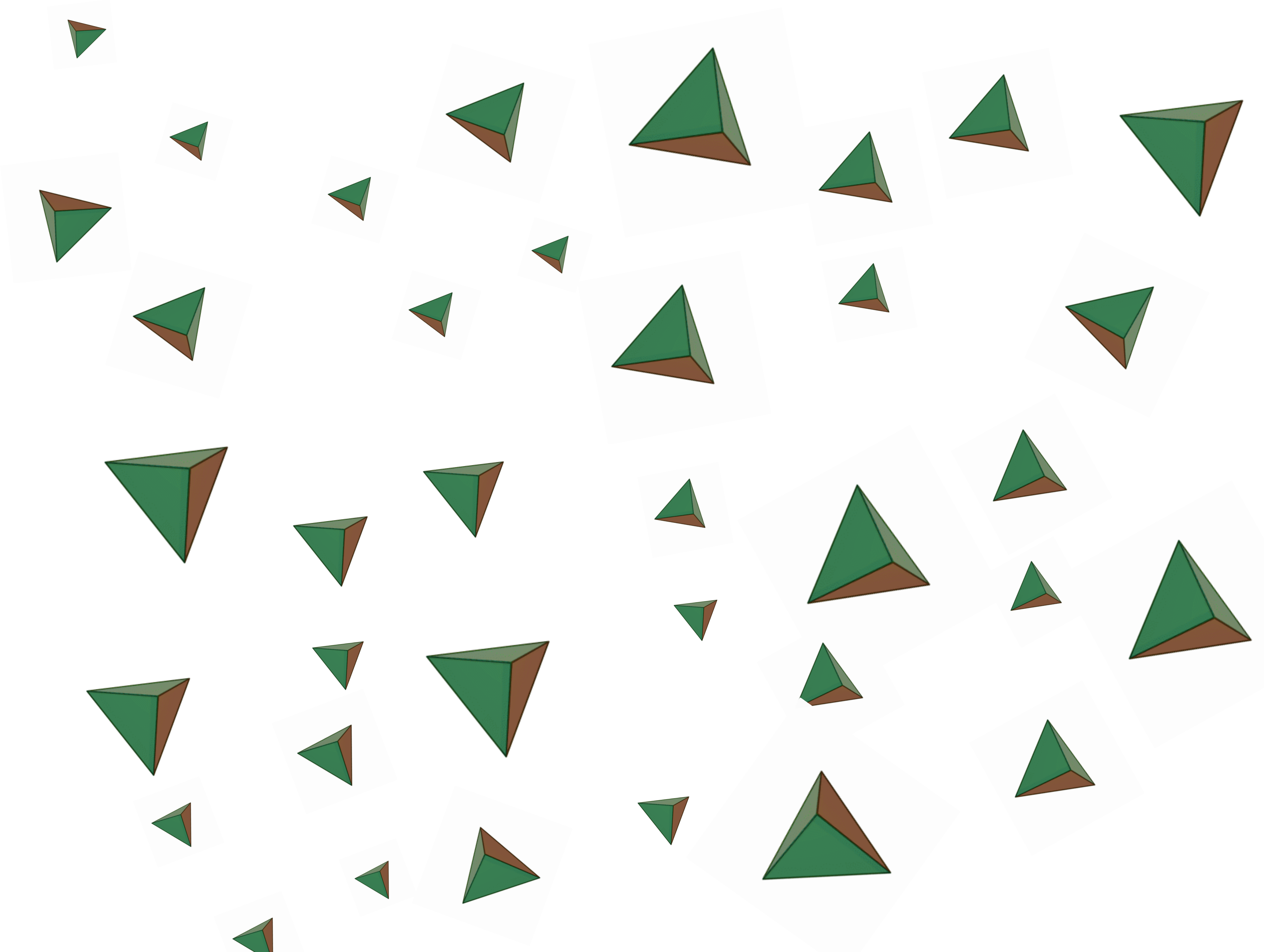
~ extracting macroscopic, collective, coarse-grained physics from atomic physics, in condensed matter systems

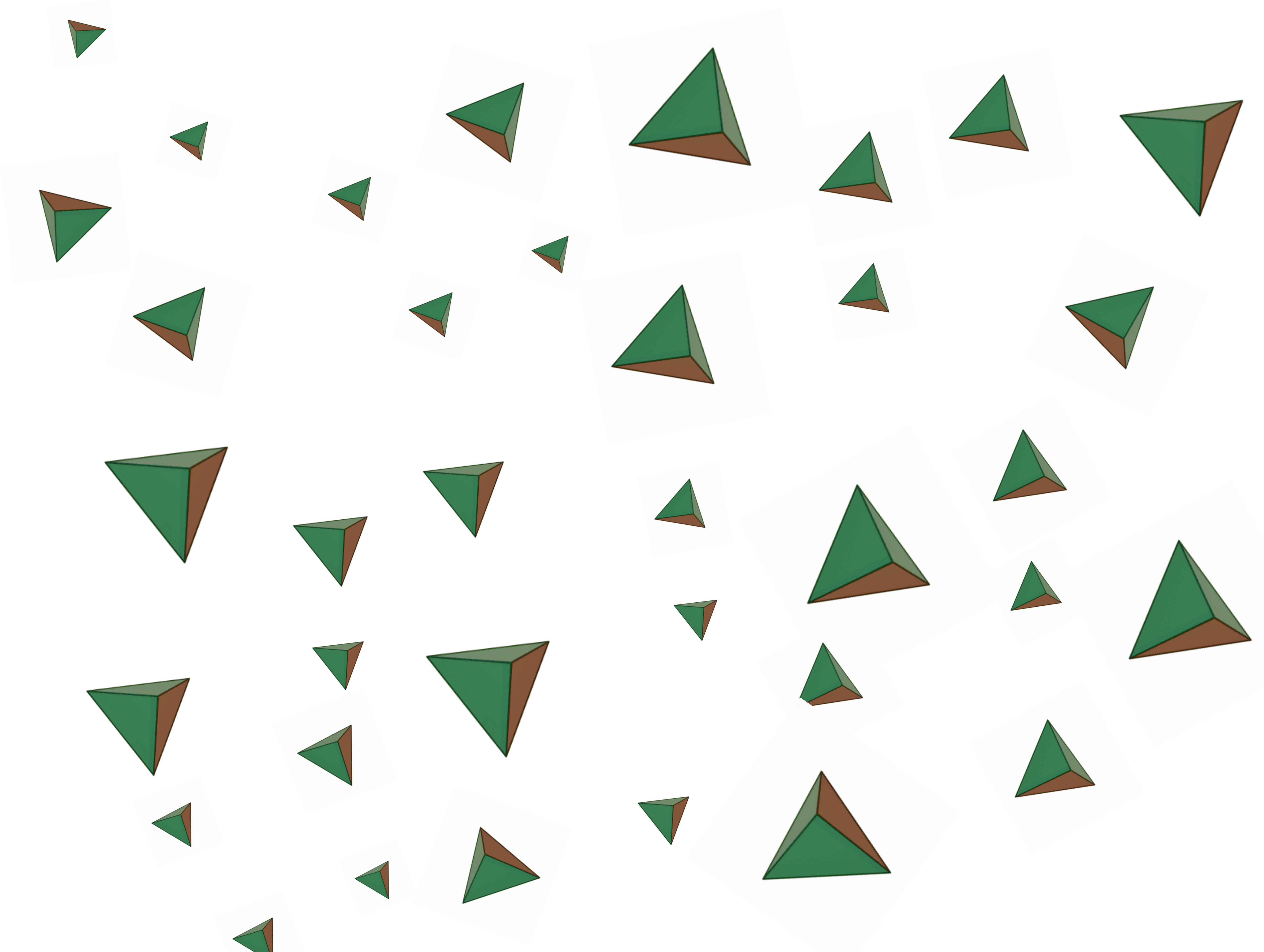
main differences:

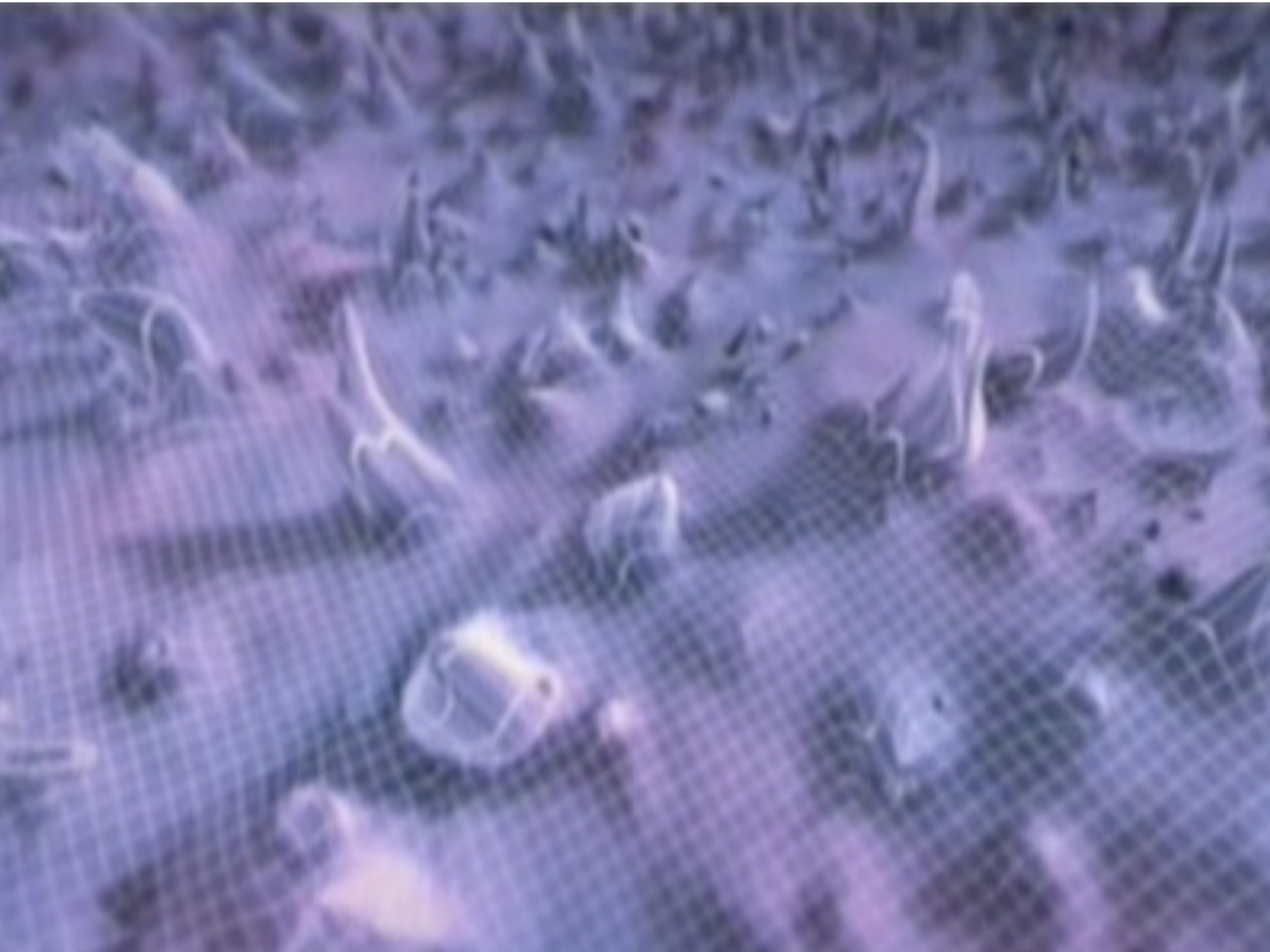
fundamental theory does not live in spacetime and does not deal with spacetime fields

both fundamental dynamics and emergent spacetime dynamics should be describe by relational observables

guiding hypothesis: continuum spacetime and geometry within hydrodynamic approx. of fundamental QG







2nd aspect of problem of continuum: QG phases and geometrogenesis:

different macroscopic phases may correspond to same microscopic fundamental QG system

in other words, continuum limit of QG models will in general give different macroscopic phases

which one is "geometric"/spatiotemporal?

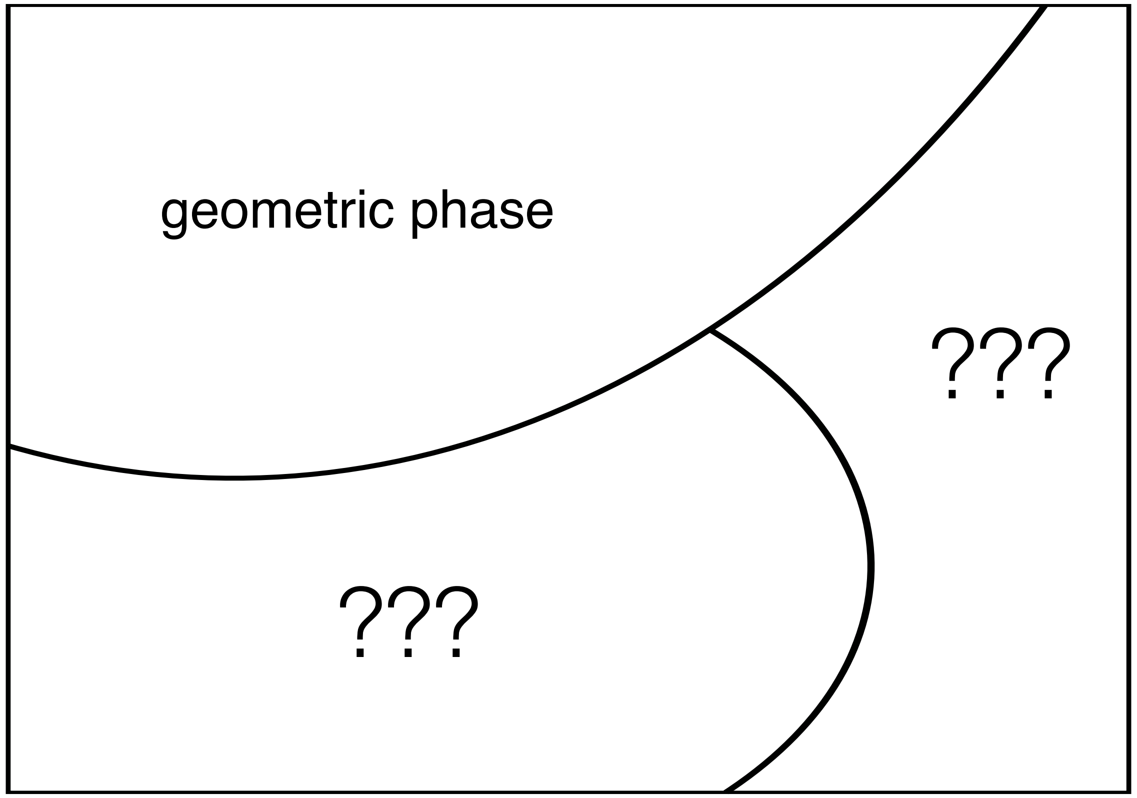
this is realised (to different degrees and in different ways) in most QG approaches:

CDT and simplicial quantum gravity

Loop Quantum Gravity

spin foam models (via generalised lattice gauge theory renormalization) see Bianca's talk

Group Field Theory (spin foam models) (via Functional RG)



The idea of “Geometrogenesis”

non-trivial phase diagram (different possible phases) → phase transitions

from non-geometric phase (no spacetime and geometry even at macroscopic scales)

Geometrogenesis

to geometric phase (spacetime and geometry emerge at macroscopic scales)

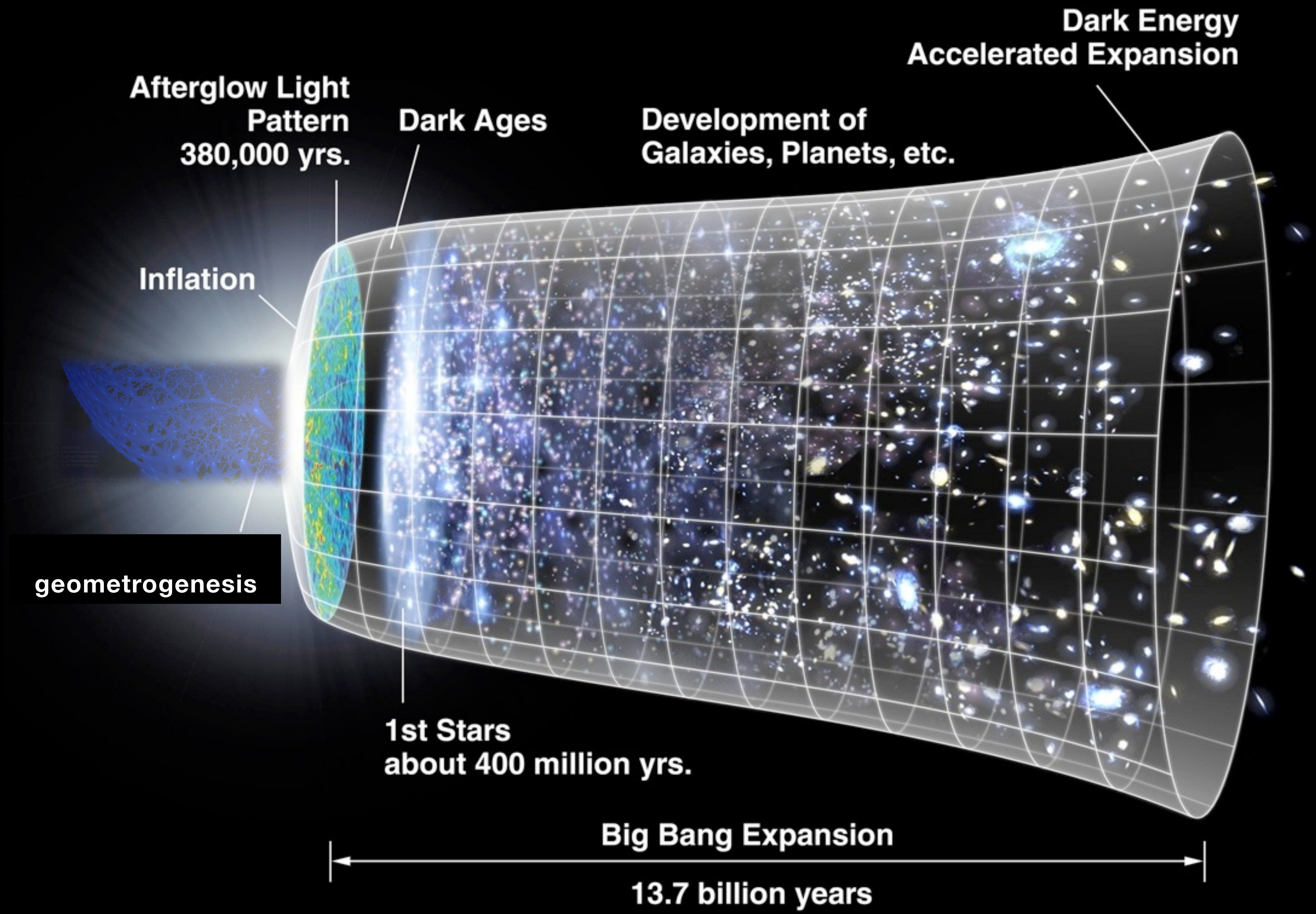
is geometrogenesis a physical “process”?

if it is physical, what physics does it capture?

hypothesis: cosmological interpretation

geometrogenesis is what replaces the Big Bang in Quantum Gravity

possible realisation: GFT condensation



Afterglow Light
Pattern
380,000 yrs.

Dark Ages

Development of
Galaxies, Planets, etc.

Dark Energy
Accelerated Expansion

Inflation

geometrogenesis

1st Stars
about 400 million yrs.

Big Bang Expansion

13.7 billion years

Group Field theory:

a quantum field theory for the atoms of space

Group Field Theory (QFT of spin networks, QFT of simplicial geometries):

same type of states of LQG (i.e. generalised simplicial geometries), but organised in Fock space

GFT quanta = spin network vertices = quantised simplices (tetrahedra)

GFT Feynman diagrams (elementary processes) = simplicial lattices + (generalised) simplicial geometries

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"
(space of classical geometries of single tetrahedron): $(\mathcal{T}^* G)^{\times d} \simeq (\mathfrak{g} \times G)^{\times d}$

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fundamental Hilbert space = space of states for arbitrary collections of tetrahedra

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

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

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

$$\left[\hat{\varphi}(\vec{g})\,,\,\hat{\varphi}^{\dagger}(\vec{g}')\right] \;=\; \mathbb{I}_G(\vec{g},\vec{g}') \qquad \left[\hat{\varphi}(\vec{g})\,,\,\hat{\varphi}(\vec{g}')\right] = \left[\hat{\varphi}^{\dagger}(\vec{g})\,,\,\hat{\varphi}^{\dagger}(\vec{g}')\right] \;=\; 0$$

additional conditions (e.g. symmetries) on fields → restrictions on Hilbert space

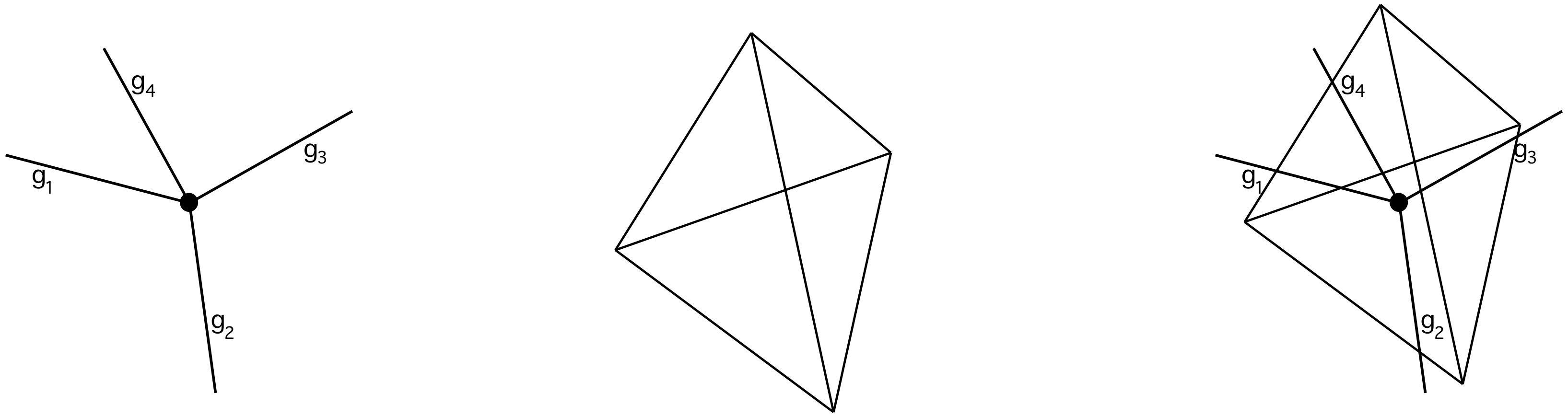
Group Field Theory (QFT of spin networks, QFT of simplicial geometries):

Fock vacuum: “no-space” (“emptiest”) state $|0>$ (no topology, no geometry)

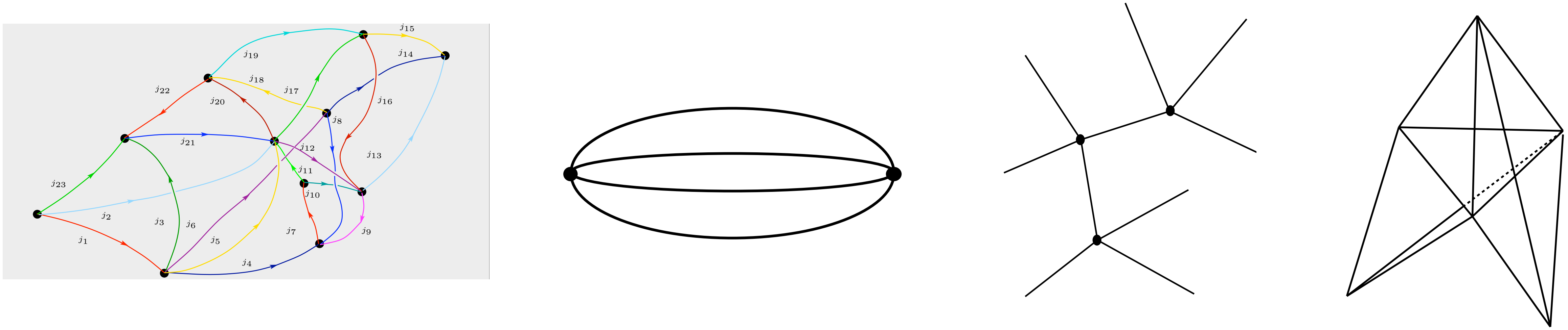
(d=4)

single field “quantum”: spin network vertex or tetrahedron
(“building block of space”)

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



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



a QFT of spin networks/simplicial structures

example: quantum tetrahedron

classical tetrahedron in 4d:

4 vectors normal to triangles that close (lying in hypersurface with normal N)

→ unique intrinsic geometry (up to rotations)

equivalently: constrained 4d area 2-forms:

group-theoretic phase space variables:

$$B_i \in \mathfrak{so}(3,1) \qquad b_i \in \mathfrak{so}(3) \subset \mathfrak{so}(3,1)$$

part of phase space:

$$\left(\mathcal{T}^* SO(3,1)\right)^4 \simeq \left(\mathfrak{so}(3,1) \times SO(3,1)\right)^4 \supset \left(\mathfrak{so}(3) \times SO(3)\right)^4 \simeq \left(\mathcal{T}^* SO(3)\right)^4$$

quantised, e.g., via geometric quantisation

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$$A_i\, n_i^I = b_i^I \in \mathbb{R}^{3,1} \qquad b_i \cdot N = 0 \qquad \sum_i b_i = 0$$

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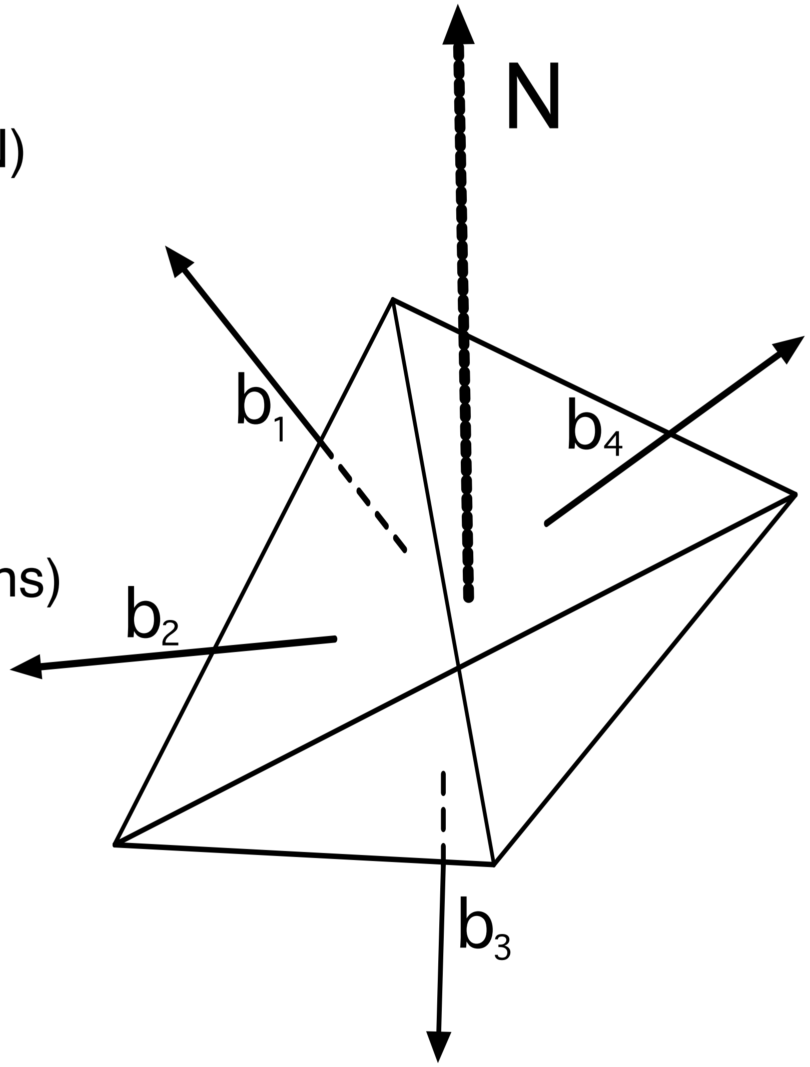

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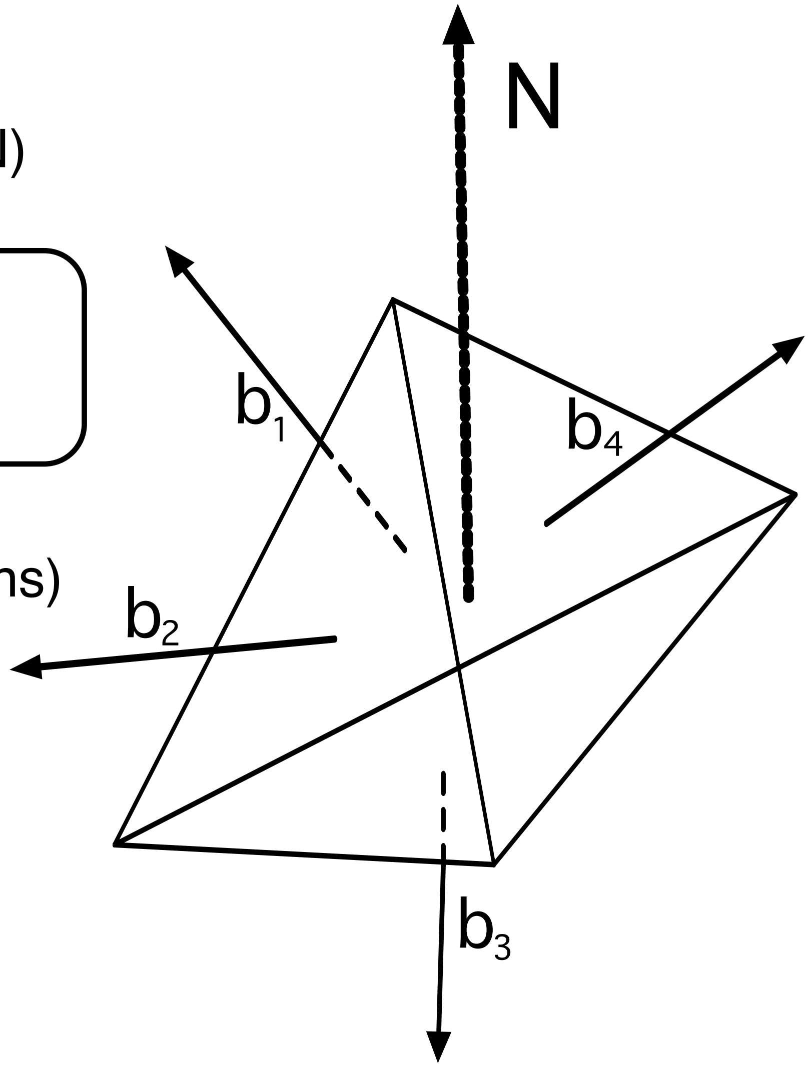

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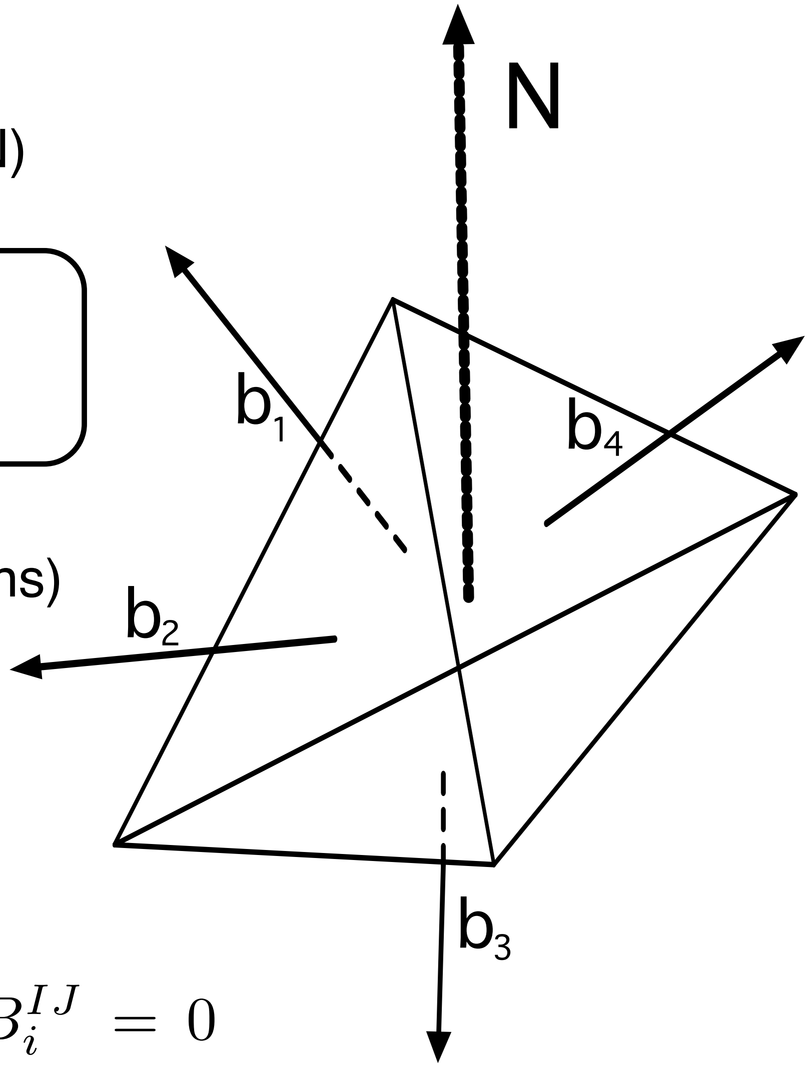

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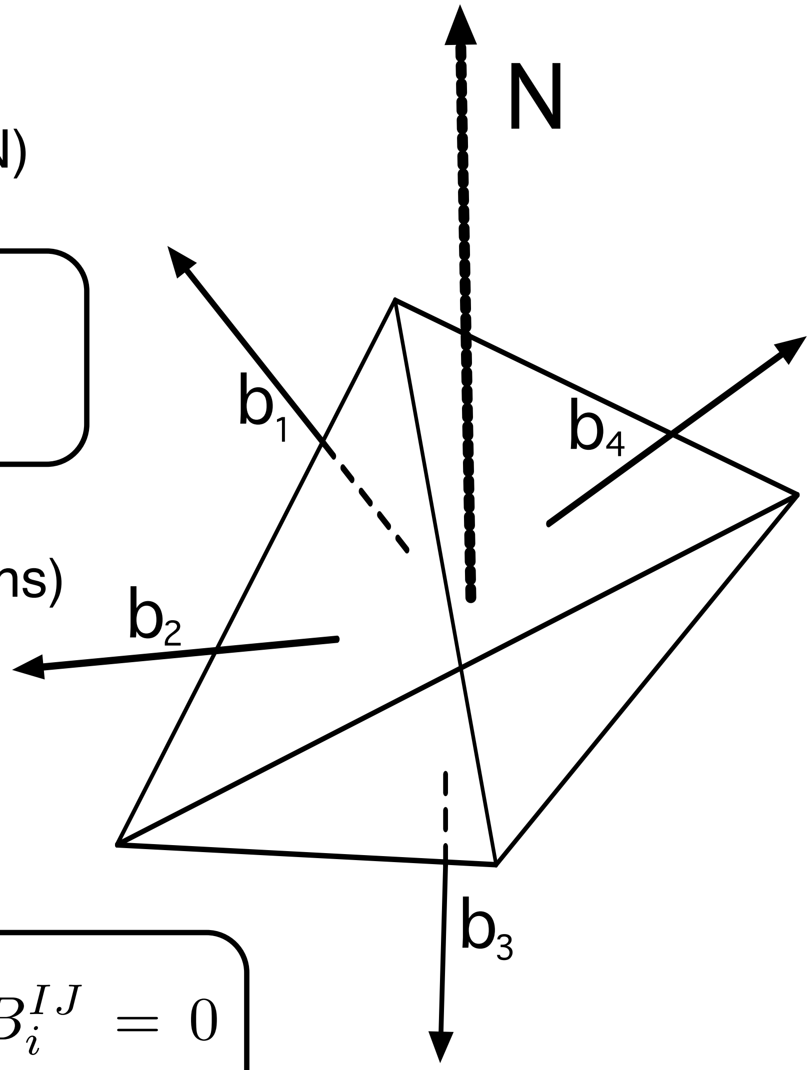

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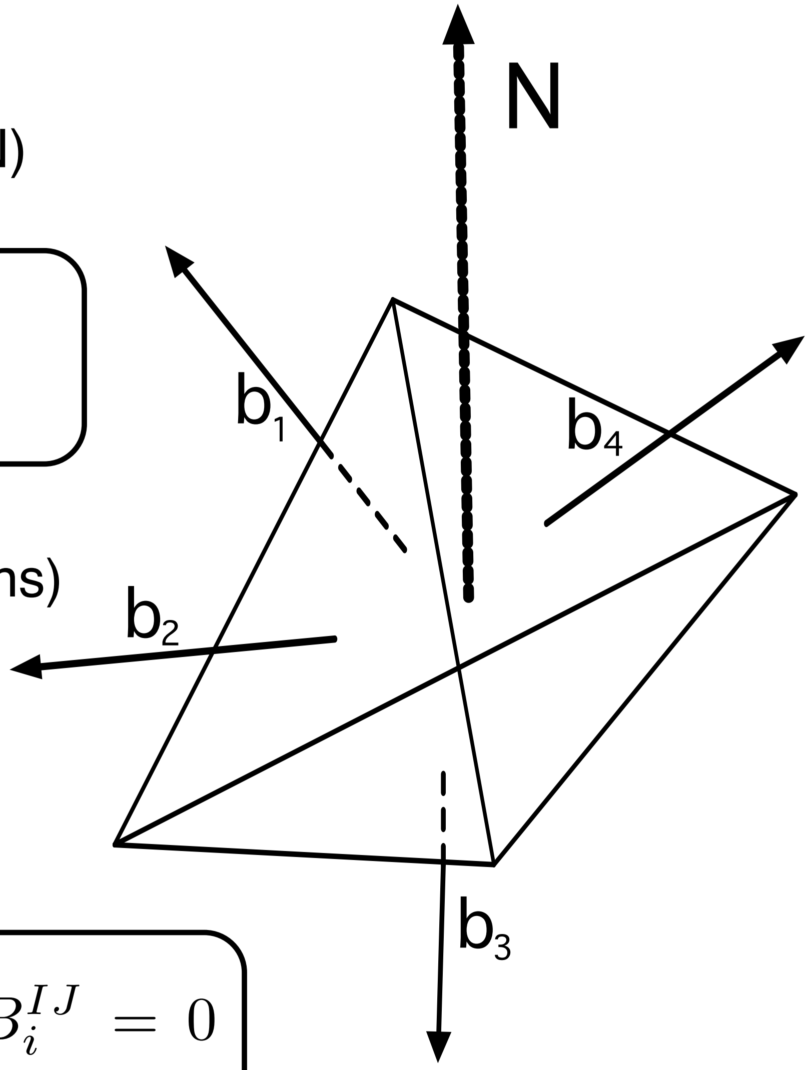

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classical action: kinetic (quadratic) term + (higher order) interaction

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

"combinatorial non-locality"
in pairing of field arguments

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

Feynman diagrams = stranded diagrams dual to cellular complexes (lattices) of arbitrary topology

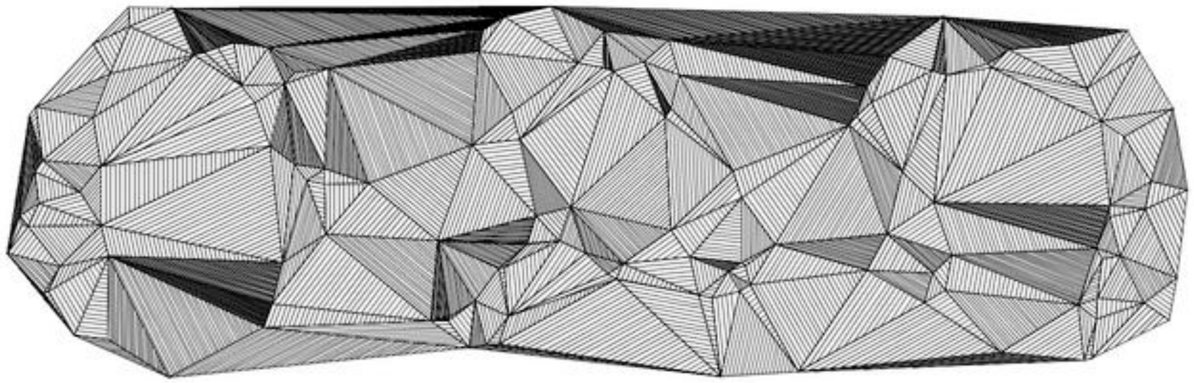
(simplicial case: simplicial complexes obtained by gluing d-simplices) ~ "discrete spacetimes"

Feynman amplitudes (model-dependent):

equivalently:

- spin foam models (sum-over-histories of spin networks ~ covariant LQG)
- lattice path integrals (with group+Lie algebra variables)

~ "quantum discrete spacetime geometries"



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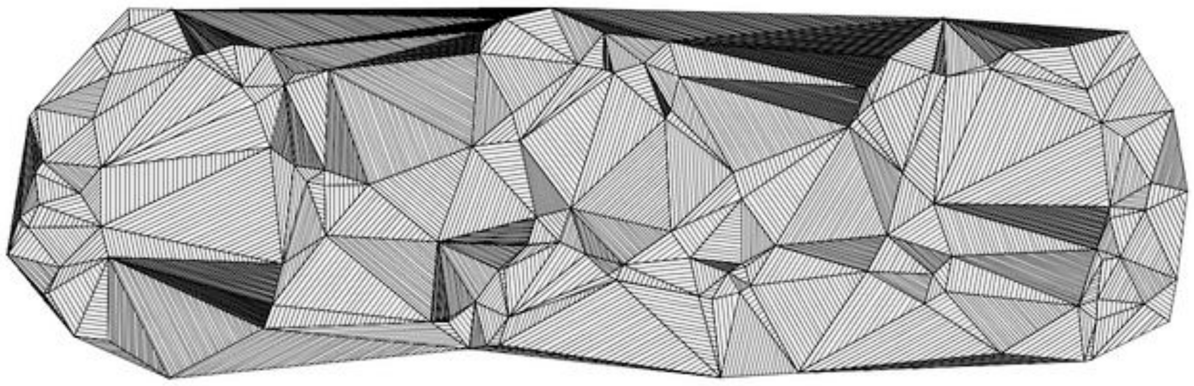

GFT as lattice quantum gravity:

dynamical triangulations + quantum Regge calculus

Group Field Theory and Tensor Models

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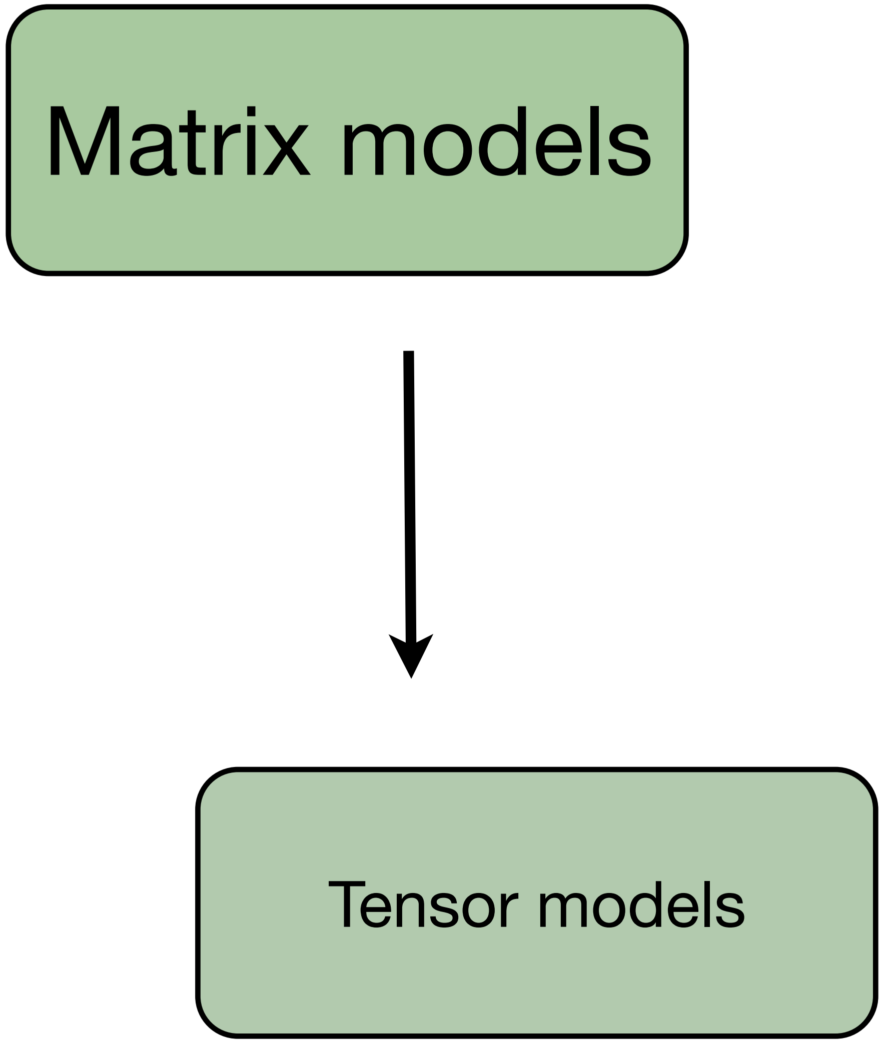
Matrix models

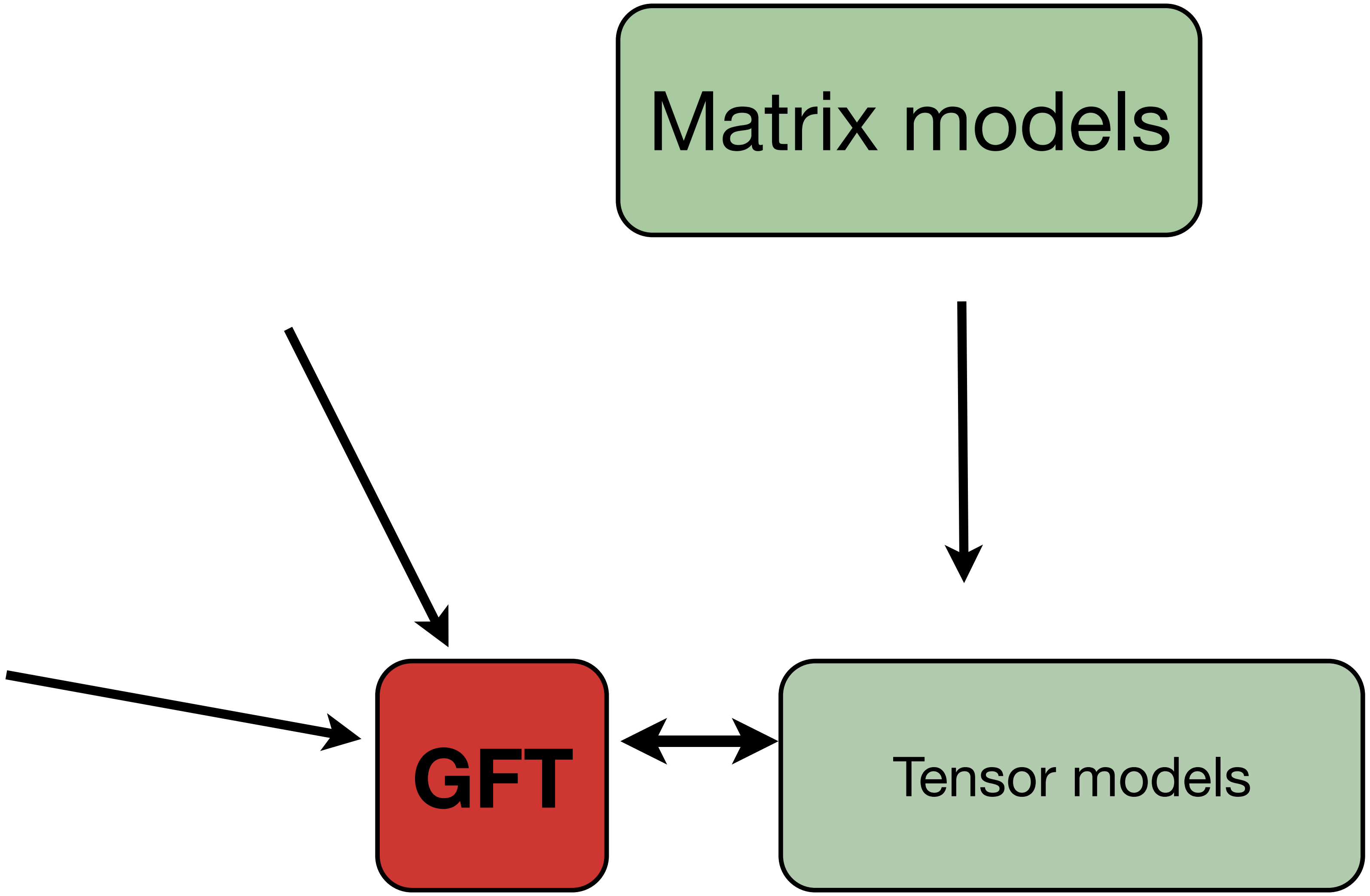
Group Field Theory and Tensor Models



Matrix models

Tensor models

Group Field Theory and Tensor Models



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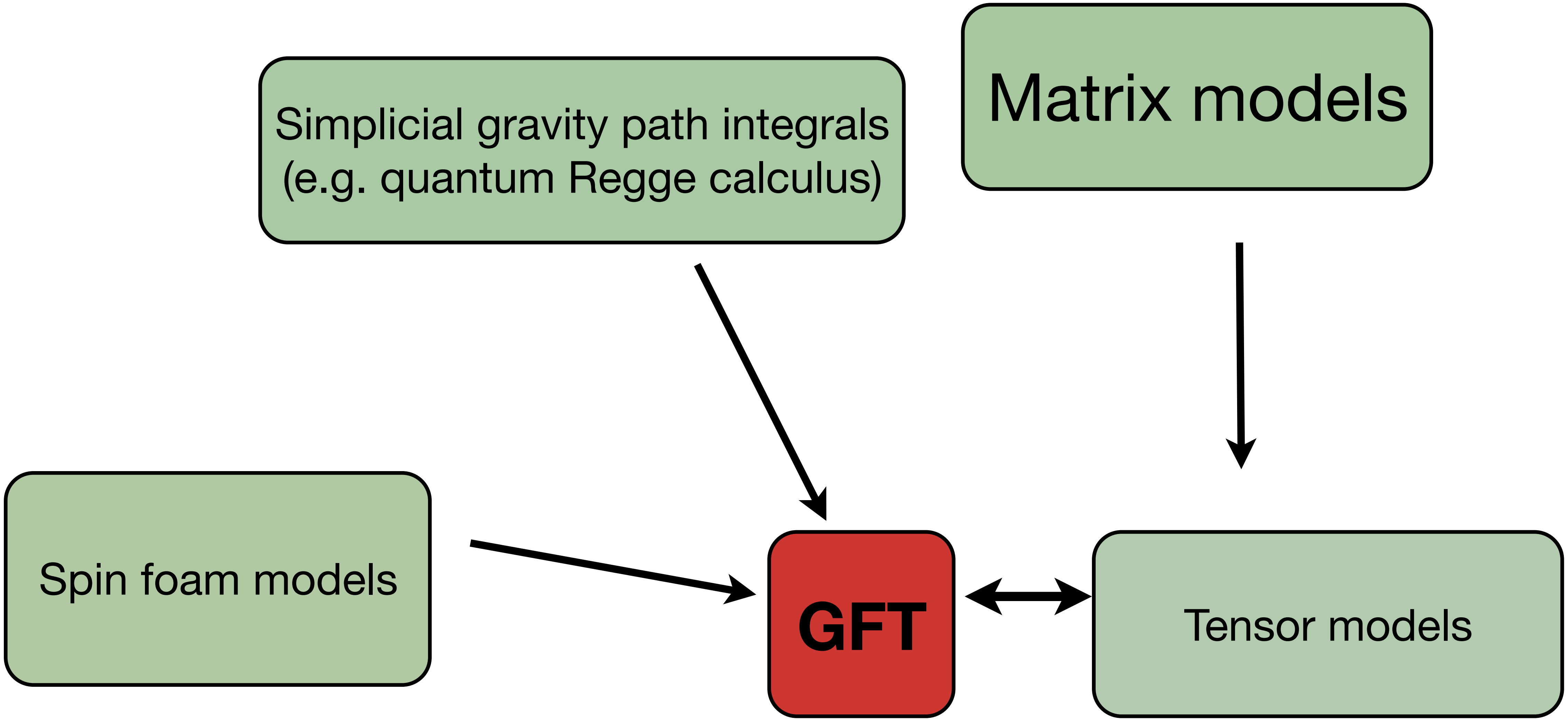

Simplicial gravity path integrals (e.g. quantum Regge calculus)

Matrix models

Spin foam models

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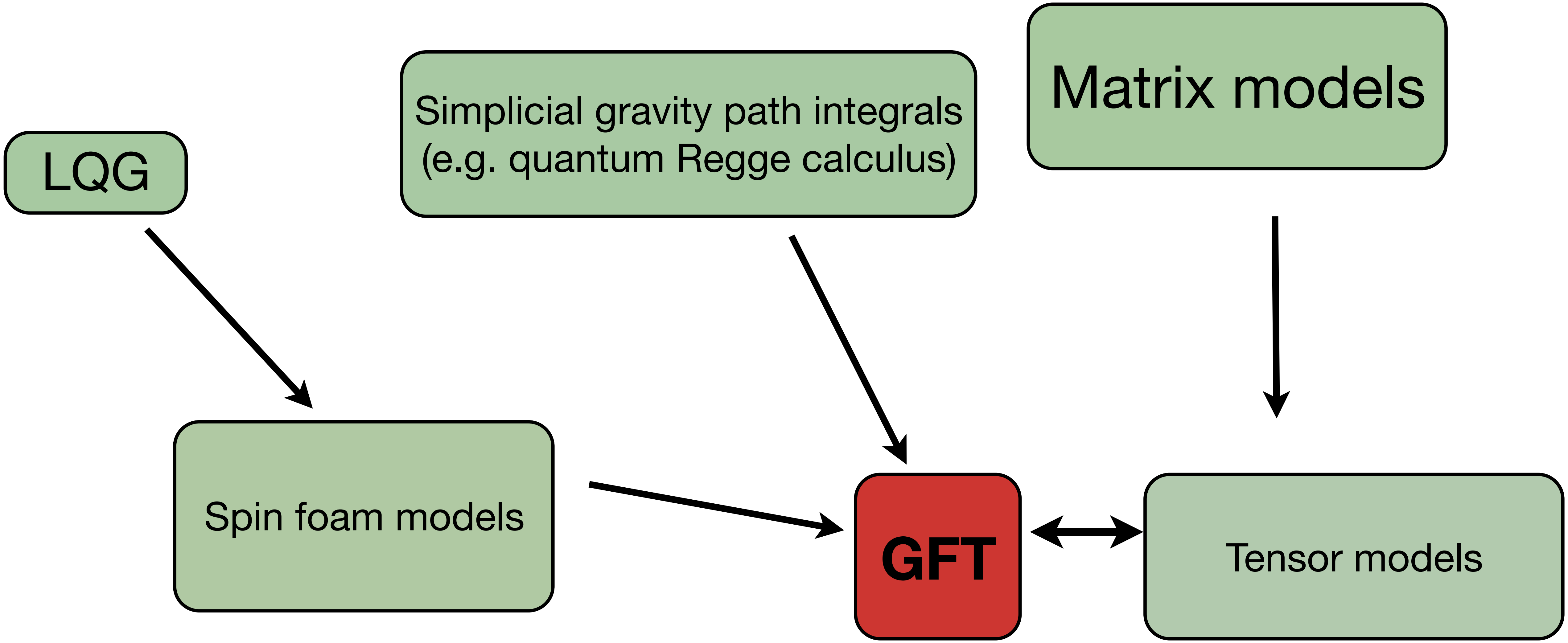

LQG

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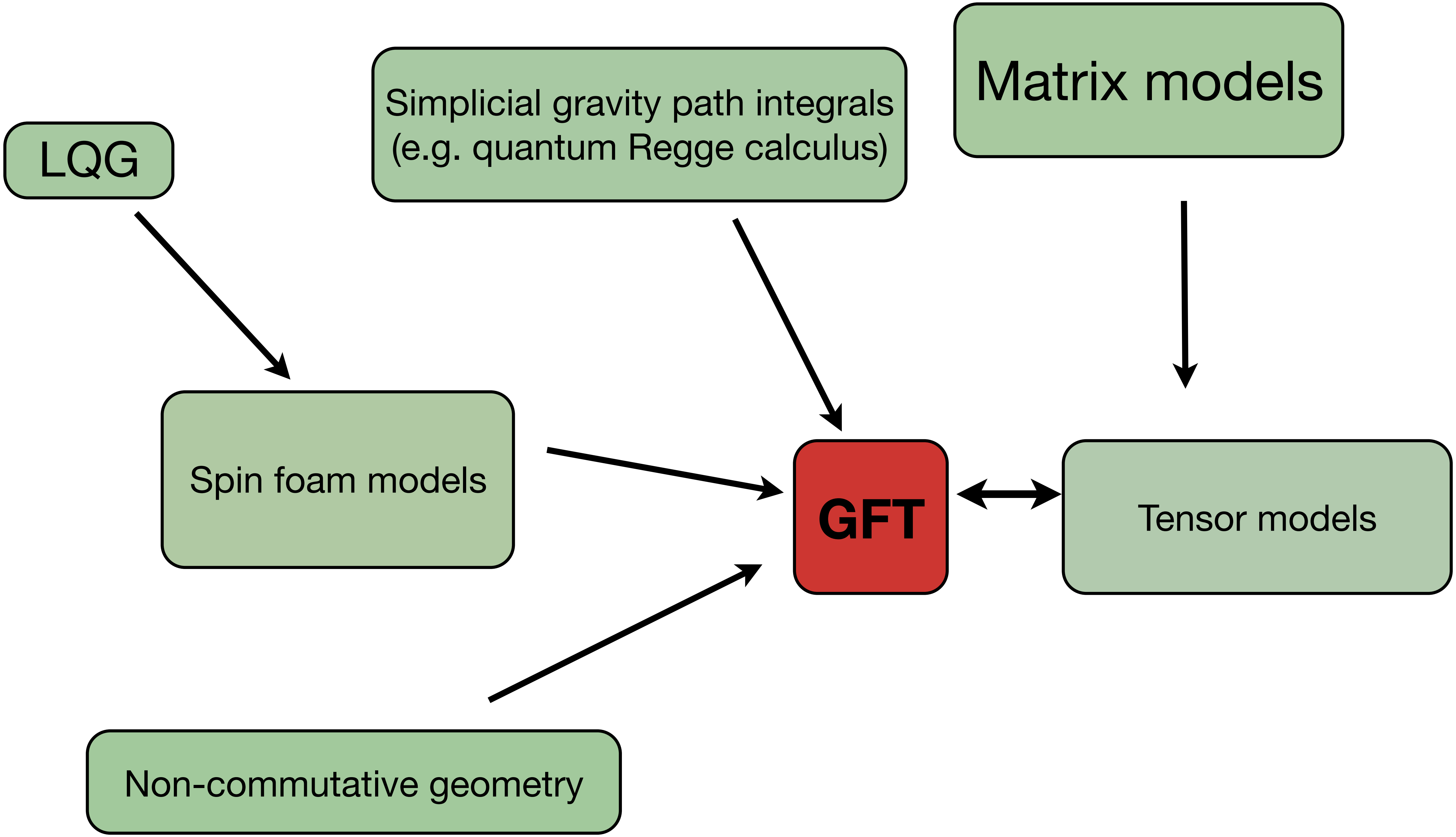

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GFT

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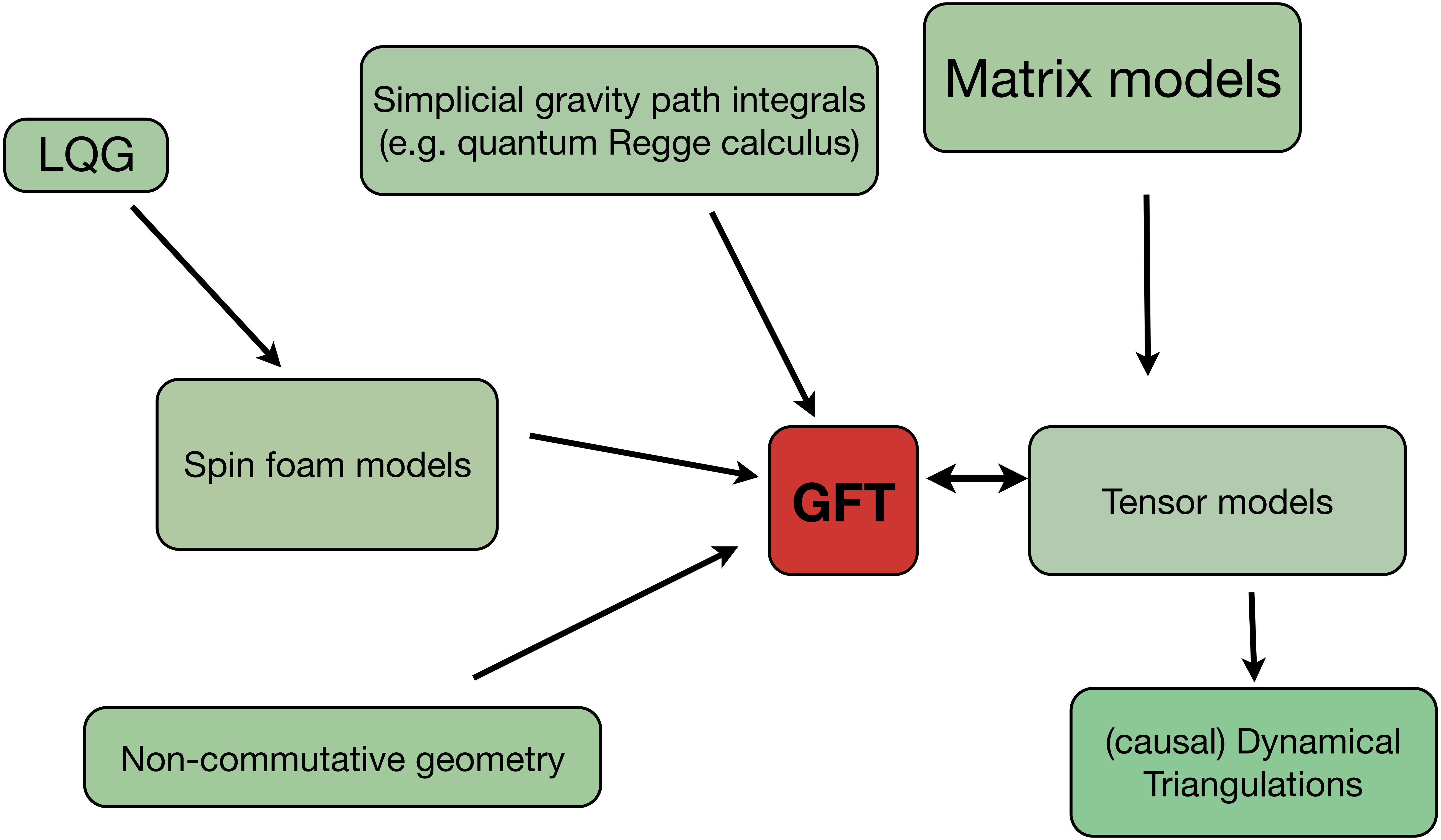
Non-commutative geometry

Group Field Theory and Tensor Models



LQG

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Matrix models

Spin foam models

GFT

Tensor models

Non-commutative geometry

(causal) Dynamical
Triangulations

Cosmology from QG perspective

very important to connect fundamental QG formalisms to effective cosmological models for the early universe

for cosmology: need for Quantum Gravity foundation

due to issues concerning:

- more solid grounds for semiclassical description commonly used
- initial singularity (or bouncing regime in bouncing scenarios, or phase transition in emergent universe scenarios)
- transplanckian problem
- nature of inflaton (in inflationary scenarios) or quantum gravity inflation

for Quantum Gravity: cosmology is simplest type of emergent continuum relativistic physics

cosmology offers most concrete prospects for observational tests

Quantum Gravity could:

- provide solid ground for existing cosmological scenarios (and justifying their assumptions)
- suggest altogether new cosmological scenarios
- suggest modifications to effective field theory (e.g. modified dispersion relations) modifying/complementing usual scenarios

Two points of view on cosmology

two views:

1. dynamics of (spatially) homogeneous geometries and matter fields
   (special configurations of gravitational field - homogeneous sector of General Relativity)

small number of observables, all of global nature

↓

to go beyond, quantise these geometries and fields:

quantum cosmology

see talk by Wilson-Ewing

beautiful work with lots of interesting insights

especially in Loop Quantum Cosmology (Bojowald, Ashtekar, Singh, Agullo, Pawlowski, Wilson-Ewing, …..)

just a toy model or may indeed capture features of real universe?
how to embed it in full theory?

Two points of view on cosmology

two views:

1. dynamics of (spatially) homogeneous geometries
   (special configurations of gravitational field - homogeneous sector of General Relativity)

2. result of coarse graining gravitational dofs (inhomogeneities, local info) up to global quantities only

in other words: effective dynamics of
special (global) observables of full theory

this is necessarily the case if fundamental QG theory is based on non-spatiotemporal structures, and spacetime and geometry themselves are emergent

Homogeneous cosmology from full QG

- few “macroscopic” observables, of “global” nature (understood as suitably defined averages over fundamental degrees of freedom, e.g. inhomogeneities, microscopic dofs, …)
- close to equilibrium
- insensitive to (or not too much affected by) microstructure

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hydrodynamics regime!

The hydrodynamics of Quantum Gravity: what to do, what to expect

Hydrodynamics of Quantum Gravity?

heuristic

what could be the relevant hydrodynamic observables in QG?

e.g. simple averages of “one-body” observables, extensive in the “number of atoms of space”

e.g. the total volume V of space, if each “atom of space” gives a contribution to it

n.b. total volume is basic observable in homogeneous cosmology

what would key hydrodynamic quantities look like in QG?

one key hydrodynamic quantity would be reduced “one-body” density,
with the “single-body” corresponding to the “atom of space”

i.e. some function on the space of data associated with a single “atom of space”

Cosmology as hydrodynamics of (quantum) spacetime

what would a “coarse graining of geometric dof of Universe” be?
how to define the basic cosmological hydrodynamic variable?

!!! heuristic !!!

phase space of GR: → classical probability density in phase space:

$$\left\{h_{ij}(x), K^{ij}(x)\right\} \qquad \forall x \in \Sigma$$

$$D_\Sigma\left(h_{ij}(x), K^{ij}(x)\right)$$

analogue of 1-particle reduced density (treating each point as a “constituent of the spacetime fluid”):

$$\rho(h_{ij}, K^{ij}) \;=\; \rho(h_{ij}(x_0, K^{ij}(x_0) \;=\; \int_{y\neq x_0} \mathcal{D}h_{ij}(y)\mathcal{D}K^{ij}(y)\; D_\Sigma\left(h_{ij}(x), K^{ij}(x)\right)$$

which point is chosen is irrelevant because of diffeomorphism symmetry

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basic variable: “single-body density” function of geometric data of minisuperspace (~ geometry at a point)

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

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which point is chosen is irrelevant because of diffeomorphism symmetry

basic variable: “single-body density” function of geometric data of minisuperspace (~ geometry at a point)

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

single-body density (reduced to half phase space) is formally analogous to quantum cosmology wave function

QG hydrodynamics ~ non-linear quantum cosmology

Cosmology as hydrodynamics of (quantum) spacetime

what would a “coarse graining of geometric dof of Universe” be?
how to define the basic cosmological hydrodynamic variable?

!!! heuristic !!!

phase space of GR: → classical probability density in phase space:

$\{h_{ij}(x), K^{ij}(x)\} \qquad \forall x \in \Sigma$

$D_\Sigma\left(h_{ij}(x), K^{ij}(x)\right)$

analogue of 1-particle reduced density (treating each point as a “constituent of the spacetime fluid”):

$$\rho(h_{ij}, K^{ij}) \,=\, \rho(h_{ij}(x_0, K^{ij}(x_0) \,=\, \int_{y \neq x_0} \mathcal{D}h_{ij}(y)\mathcal{D}K^{ij}(y)\; D_\Sigma\left(h_{ij}(x), K^{ij}(x)\right)$$

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QG hydrodynamics ~ non-linear quantum cosmology

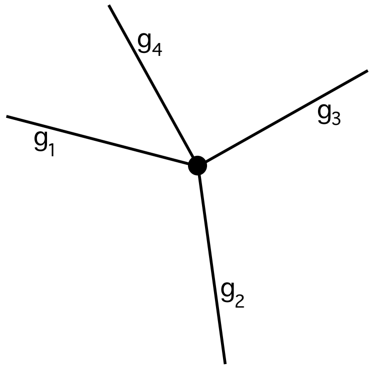
to make it better defined, need well-defined notion of “atom of space”

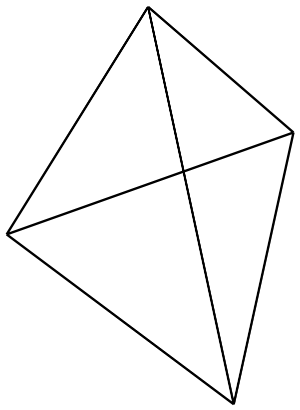
Cosmology as hydrodynamics of (quantum) spacetime

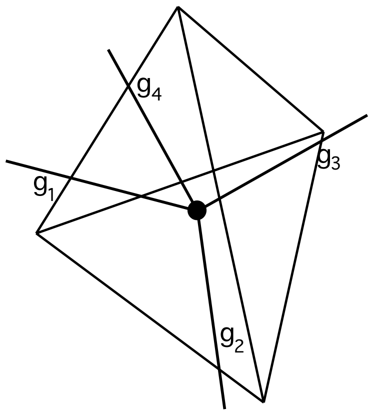
- Quantum Gravity formalisms suggest “atoms of space”: fundamental quantum simplex or spin network vertex
- they provide “many-body” observables, e.g. volume operators, extensive in the number of “atoms of space”
- they propose a fundamental dynamics for them, i.e. means to compute (dynamical) averages of observables

GFT is convenient framework:

- a Fock space description of the fundamental constituents of quantum space
- a 2nd quantised language for observables
- a field theoretic description of the dynamics, suitable for many-body physics







expect key variable to be density over space of data for single simplex or single spin network vertex

space of geometry for tetrahedron ~ minisuperspace of homogeneous geometries ——>>>
non-linear equation for QG hydrodynamic density ~ non-linear quantum cosmology

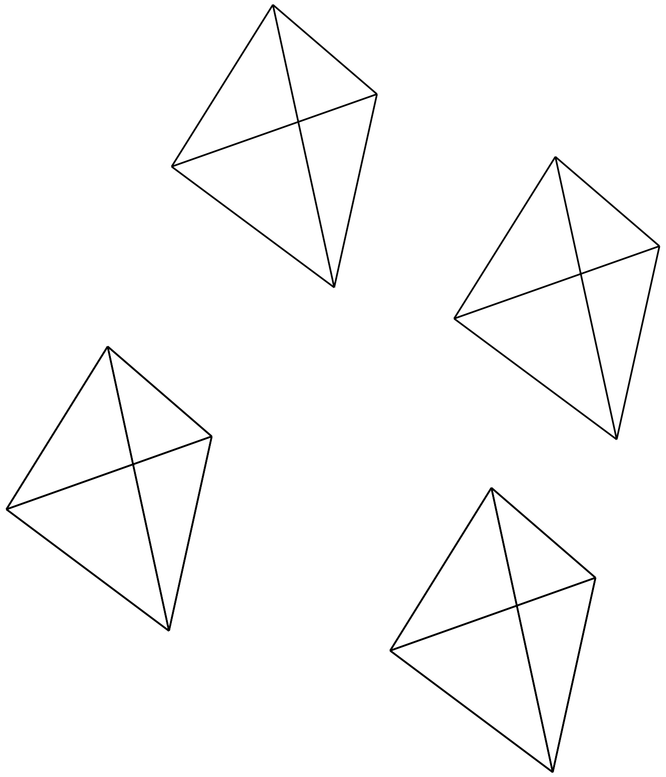
Group field theory (condensate) cosmology:

cosmology as QG hydrodynamics (an example)

(Quantum) Cosmology from GFT condensates

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

start with fundamental (Fock) space of GFT states (arbitrary collections of tetrahedra labelled by SU(2) data



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

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

$$\left[\hat{\varphi}(\vec{g})\,,\,\hat{\varphi}^{\dagger}(\vec{g}')\right] = \mathbb{I}_G(\vec{g},\vec{g}') \qquad \left[\hat{\varphi}(\vec{g})\,,\,\hat{\varphi}(\vec{g}')\right] = \left[\hat{\varphi}^{\dagger}(\vec{g})\,,\,\hat{\varphi}^{\dagger}(\vec{g}')\right] = 0$$

!!! generic quantum states have no spatiotemporal/geometric interpretation (in the sense of continuum spacetime fields) !!!

no spacetime manifold, no differential structure, no continuum fields, fully diffeomorphism invariant (of course, no coordinates, time vector fields, etc)

(Quantum) Cosmology from GFT condensates

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

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problem 1:
identify quantum states in fundamental theory with continuum spacetime interpretation

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problem 1:
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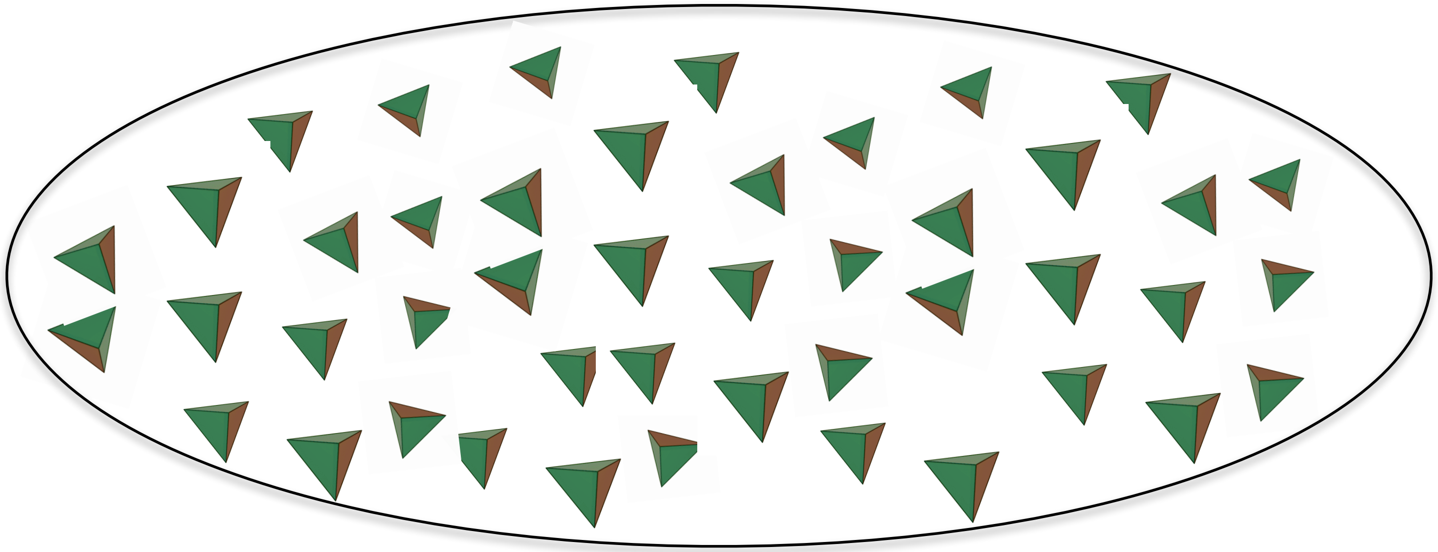
Quantum GFT condensates are continuum homogeneous (quantum) spaces

e.g. (simplest): GFT field coherent state

$$|\sigma\rangle := \exp\left(\hat{\sigma}\right)|0\rangle$$

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

superposition of infinitely many spin networks dofs,
“gas”of tetrahedra, all associated with same state



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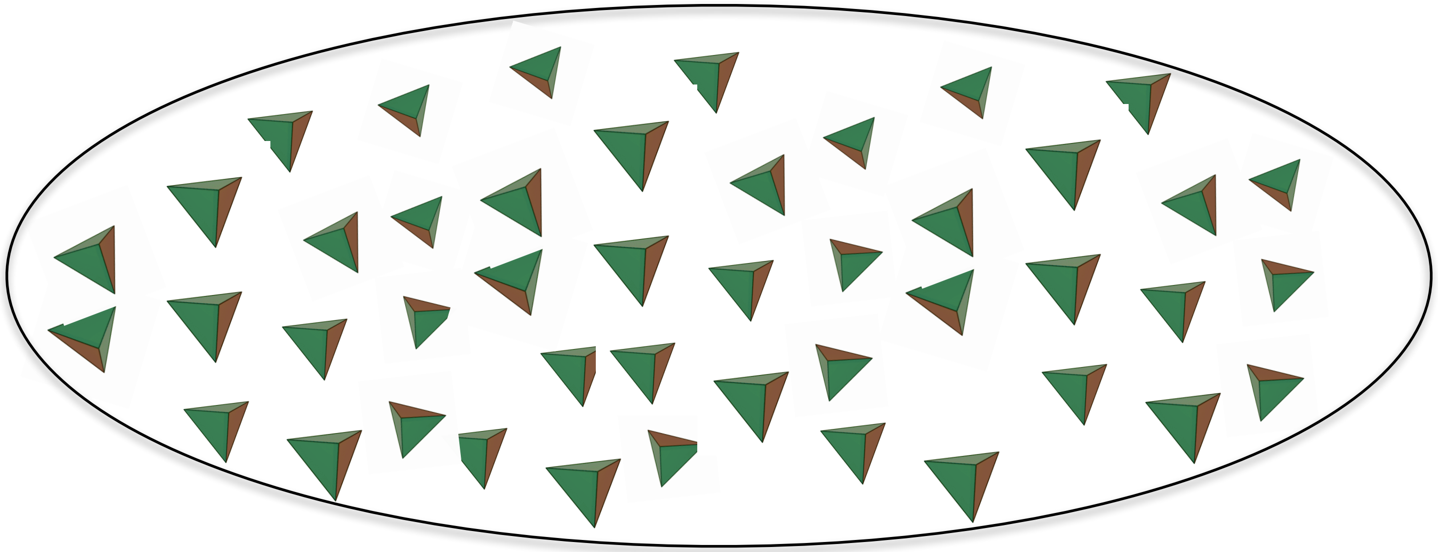

special states with (plausible) continuum geometric interpretation:

infinite dofs, such that, if one tries to reconstruct continuum geometry from them, one obtains same geometric data at each “point”, i.e. homogeneous spatial (quantum) geometry (still, fully diffeo-invariant)

(Quantum) Cosmology from GFT condensates

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

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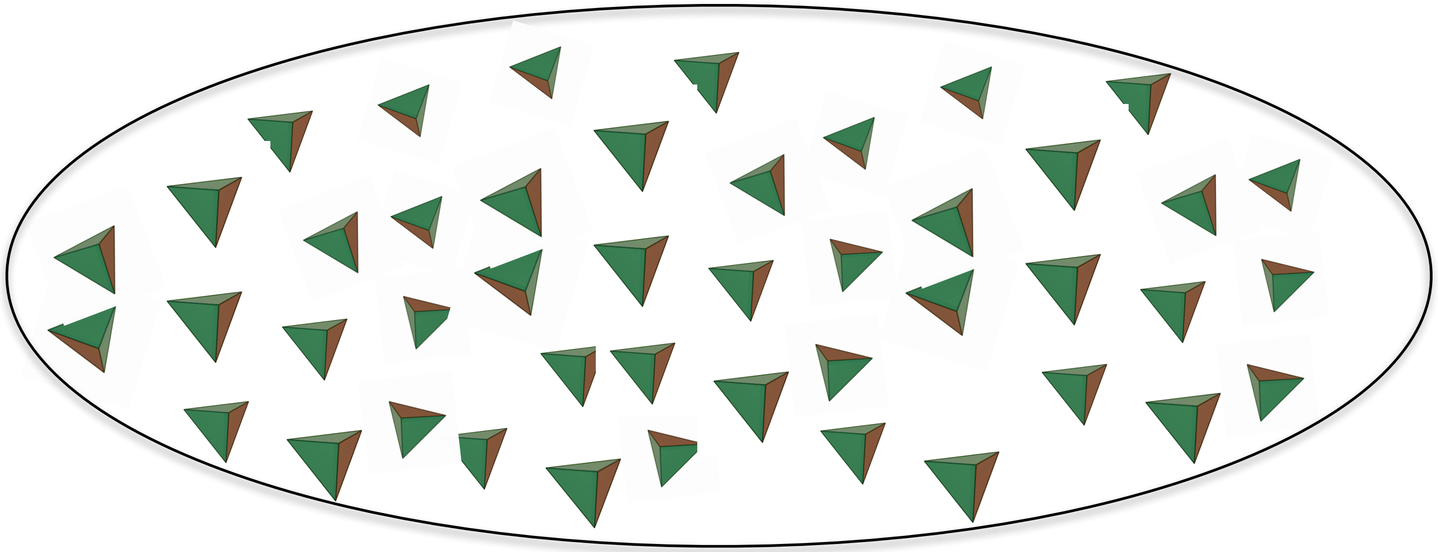

superposition of infinitely many spin networks dofs,
“gas”of tetrahedra, all associated with same state

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

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

$$\simeq \{\text{continuum spatial geometries at a point}\} \simeq$$

$$\simeq \text{minisuperspace of homogeneous geometries}$$

(Quantum) Cosmology from GFT condensates

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Quantum GFT condensates are continuum homogeneous (quantum) spaces

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

problem 2:
extract from fundamental theory an effective macroscopic dynamics for such states

Effective cosmological dynamics from GFT

follow closely procedure used in real BECs

single-particle GFT condensate:

$$|\sigma\rangle := \exp\left(\hat{\sigma}\right)|0\rangle \qquad \hat{\sigma} := \int d^4g\, \sigma(g_I)\hat{\varphi}^\dagger(g_I) \qquad \sigma(g_I k) \;=\; \sigma(g_I)$$

impose that these states satisfy (approximately) fundamental quantum dynamics of given GFT model

gives equation for “condensate wave function”:

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

infinite superposition of Feynman diagrams (infinite sum over discrete “spacetime” lattices)

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

formally similar to quantum cosmology, but:

no Hilbert space structure (no superposition of “states of universe”, no “collapse of cosmological wave function

“statistical nature” of wave function; still, fluctuations of all geometric quantities

(Quantum) Cosmology from GFT condensates

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

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non-linear extension of quantum cosmology equation for collective wave function

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non-linear extension of quantum cosmology equation for collective wave function

cosmology as QG hydrodynamics!!!

Emergent bouncing cosmology from full QG

DO, Sindoni, Wilson-Ewing, ‘16

details of effective dynamics depend on microscopic model + want to recast emergent QG hydrodynamics as dynamical equations for geometric observables, evolving in “time”

- start with fundamental (Fock) space of GFT states (arbitrary collections of tetrahedra labelled by SU(2) data
- starting from (generalised) EPRL model for 4d Lorentzian QG, coupled to (discretised) (pre-)scalar field

- coupling of free massless scalar field

$\hat{\varphi}(g_v) \to \hat{\varphi}(g_v, \phi)$

$$|\sigma\rangle \sim \exp\left(\int \mathrm{d}g_v \mathrm{d}\phi \, \sigma(g_v, \phi) \hat{\phi}^\dagger(g_v, \phi) \right) |\mathbf{0}\rangle$$

no spacetime/geometric interpretation, no manifolds nor fields correspond to generic states, at microscopic level

they (may) acquire this interpretation at macroscopic, effective, hydrodynamic level

use effective scalar field variable as “physical clock” to define “time”

- reduction to isotropic condensate configurations (depending on single variable j): $\sigma(g_v, \phi) \to \sigma_j(\phi)$

Emergent bouncing cosmology from full QG

DO, Sindoni, Wilson-Ewing, '16

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

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

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

GFT interaction terms sub-dominant

$$\sigma_j(\phi) = \rho_j(\phi)e^{i\theta_j(\phi)}$$

$$\boxed{\rho_j'' - \frac{Q_j^2}{\rho_j^3} - m_j^2\rho_j \approx 0}$$

$$m_j^2 = B_j/A_j$$

- two (approximately) conserved quantities (per mode): E, Q

Emergent bouncing cosmology from full QG

DO, Sindoni, Wilson-Ewing, ‘16

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

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- two (approximately) conserved quantities (per mode): E, Q

- key relational observables (expectation values in condensate state) with scalar field as clock:

universe volume (at fixed “time”)

$$V(\phi) = \sum_j V_j \bar{\sigma}_j(\phi) \sigma_j(\phi) = \sum_j V_j \rho_j(\phi)^2 \qquad V_j \sim j^{3/2} \ell_{\rm Pl}^3$$

momentum of scalar field (at fixed “time”)

$$\pi_\phi = \langle \sigma | \hat{\pi}_\phi(\phi) | \sigma \rangle = \hbar \sum_j Q_j$$

energy density of scalar field (at fixed “time”)

$$\rho = \frac{\pi_\phi^2}{2V^2} = \frac{\hbar^2 (\sum_j Q_j)^2}{2(\sum_j V_j \rho_j^2)^2}$$

Emergent bouncing cosmology from full QG

DO, Sindoni, Wilson-Ewing, '16

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energy density of scalar field (at fixed "time")

$$\rho = \frac{\pi_\phi^2}{2V^2} = \frac{\hbar^2 (\sum_j Q_j)^2}{2(\sum_j V_j \rho_j^2)^2}$$

observables defined in fundamental Hilbert space; intuition comes from discrete geometric interpretation of fundamental dofs; full continuum geometric interpretation emerges at collective, hydrodynamic level

Emergent bouncing cosmology from full QG

DO, Sindoni, Wilson-Ewing, '16

(GFT interaction terms sub-dominant)

effective dynamics for volume - generalised Friedmann equations:

$$\boxed{\left(\frac{V'}{3V}\right)^2 = \left(\frac{2\sum_j V_j\,\rho_j\sqrt{E_j - \frac{Q_j^2}{\rho_j^2} + m_j^2\rho_j^2}}{3\sum_j V_j\rho_j^2}\right)^2}$$

$$\boxed{\frac{V''}{V} = \frac{2\sum_j V_j\left[E_j + 2m_j^2\rho_j^2\right]}{\sum_j V_j\rho_j^2}}$$

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$$\frac{V''}{V} = \frac{2\sum_j V_j\left[E_j + 2m_j^2\rho_j^2\right]}{\sum_j V_j\rho_j^2}$$

$\rightarrow$ $\exists j\ /\ \rho_j(\phi) \neq 0\ \forall\phi$ $\rightarrow$

$V = \sum_j V_j\rho_j^2$

remains positive at all times

(with single turning point)

generic quantum bounce!

Emergent bouncing cosmology from full QG

DO, Sindoni, Wilson-Ewing, ‘16

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$$\frac{V''}{V} = \frac{2\sum_j V_j\left[E_j + 2m_j^2\rho_j^2\right]}{\sum_j V_j\rho_j^2}$$

classical approx. $\rho_j^2 \gg |E_j|/m_j^2$ and $\rho_j^4 \gg Q_j^2/m_j^2$

$$\left(\frac{V'}{3V}\right)^2 = \left(\frac{2\sum_j V_j\,m_j\,\rho_j^2}{3\sum_j V_j\rho_j^2}\right)^2 \qquad \frac{V''}{V} = \frac{4\sum_j V_j m_j^2\rho_j^2}{\sum_j V_j\rho_j^2}$$

approx. classical Friedmann eqns if $m_j^2 \approx 3G_N$

$\exists j \;/\; \rho_j(\phi) \neq 0 \;\forall\phi$

$V = \sum_j V_j\rho_j^2$ remains positive at all times (with single turning point)

generic quantum bounce!

Special case: single spin condensate

cosmological dynamics entirely due to growth (in relational time) of number of “atoms of space”

DO, Sindoni, Wilson-Ewing, ‘16

interactions are also much simpler to study, for such simple condensates

dominance of single-spin condensate realised in several contexts:

- mean field analysis of static GFT models in isotropic restriction: vacua strongly peaked on single spin

A. Pithis, M. Sakellariadou, P. Tomov, ‘16

- mean field analysis of evolution (in relational time) of isotropic models: single spin dominates at late times
  - free GFT models (subdominant interactions) S. Gielen, ‘16
  - interacting GFT models: single-spin enhanced as universe expands A. Pithis, M. Sakellariadou, ‘16

Special case: single spin condensate

cosmological dynamics entirely due to growth (in relational time) of number of "atoms of space"

simple condensate:

$$\sigma_j(\phi) = 0, \text{ for all } j \neq j_o$$

→

$$\left(\frac{V'}{3V}\right)^2 = \frac{4\pi G}{3}\left(1 - \frac{\rho}{\rho_c}\right) + \frac{V_{j_o} E_{j_o}}{9V}$$

$$\rho_c = 6\pi G \hbar^2 / V_{j_o}^2 \sim (6\pi / j_o^3)\rho_{\rm Pl}$$

LQC-like modified dynamics!

DO, Sindoni, Wilson-Ewing, '16

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Emergent bouncing cosmology from full QG

M. De Cesare, M. Sakellariadou, ‘16

for single-spin condensate,

emergent cosmological dynamics can also be recast as:

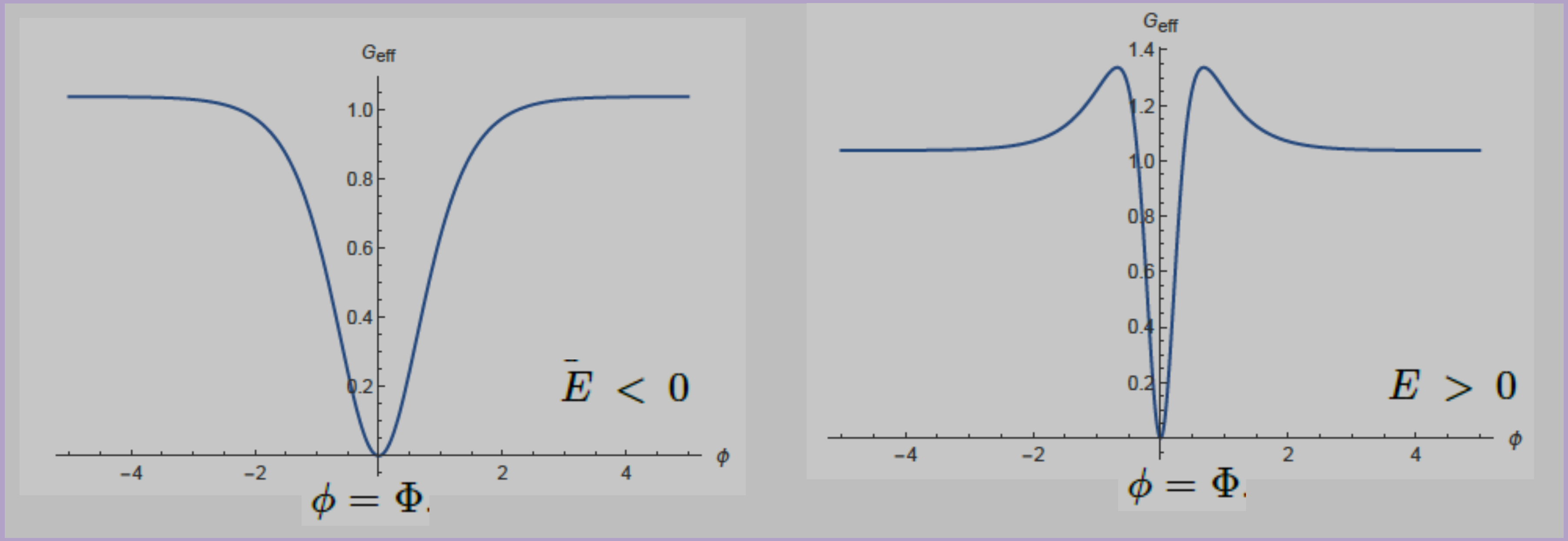
Friedmann eqn with: $$G_{\text{eff}} = \frac{1}{3\pi} g^2$$ effective time-varying gravitational constant (coming from collective behaviour of “atoms of spacetime”)

energy density

$$H^2 = \left(\frac{V'}{3V}\right)^2 \dot{\phi}^2 \equiv \frac{8}{9} g^2 \varepsilon$$

asymptotic value for large ϕ is the same in both cases and coincides with newton’s constant

bounce happens when g = 0



a bounce replacing the classical singularity

energy density has a max at the bounce where volume reaches its minimum

$$\varepsilon_{\text{max}} = \frac{1}{2} \frac{Q^2}{V_{\text{bounce}}^2}$$

$$V_{\text{bounce}} = \frac{V_{j_0}\left(\sqrt{E^2 + 12\pi G Q^2} - E\right)}{6\pi G}$$

the singularity is alway avoided for E<0 and provided Q is nonzero, it is also avoided for E>

Accelerated phase after bounce: QG inflation?

for: $V = a^3$ we have: $$\frac{\ddot{a}}{a} = \frac{1}{3}\left(\frac{\pi_\phi}{V}\right)^2 \left[\frac{\partial_\phi^2 V}{V} - \frac{5}{3}\left(\frac{\partial_\phi V}{V}\right)^2\right]$$

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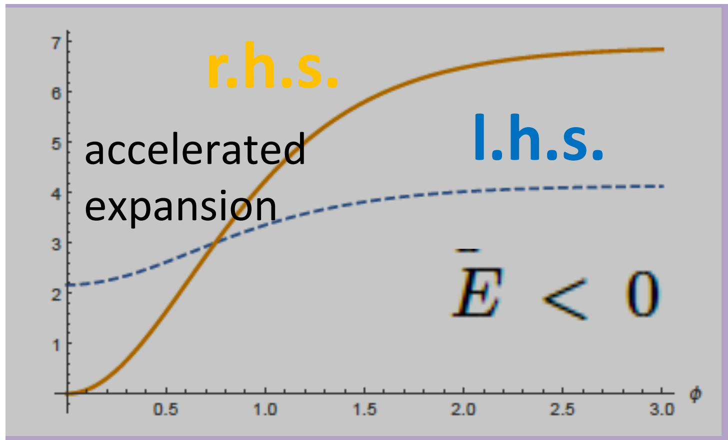
M. De Cesare, A. Pithis, M. Sakellariadou, ‘16

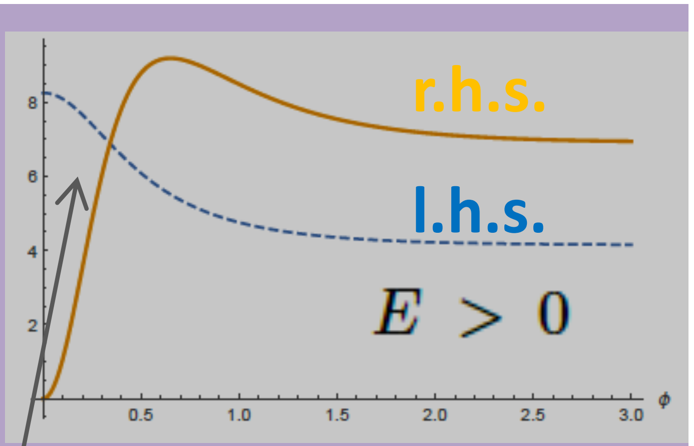
existence of accelerated expansion translates in relational time as:

$$\frac{V''}{V} > \frac{5}{3}\left(\frac{V'}{V}\right)^2$$

$$\underbrace{4m^2 + \frac{2E}{\rho^2}}_{\text{positive}} > \frac{20}{3}\underset{\text{zero}}{g^2}$$

near the bounce





accelerated expansion,
followed by a maximal
deceleration

thus, following the bounce, we have accelerated expansion

issue is: number of e-folds

$$N = \frac{2}{3}\log\left(\frac{\rho_{\text{end}}}{\rho_{\text{bounce}}}\right)$$

can we get at least N ~ 60?

Accelerated phase after bounce: QG inflation?

M. De Cesare, A. Pithis, M. Sakellariadou, ‘16

- in effective cosmological dynamics neglecting GFT interactions:

$$0.119 \lesssim N \lesssim 0.186$$

acceleration is too short-lived to be physically useful

- including effects of GFT interactions (in phenomenological way):

$$S = \int \mathrm{d}\phi \ \left(A \, |\partial_\phi \sigma|^2 + \mathcal{V}(\sigma)\right)$$

$$\mathcal{V}(\sigma) = B|\sigma(\phi)|^2 + \frac{2}{n} w|\sigma|^n + \frac{2}{n'} w'|\sigma|^{n'}$$

$$\sigma = \rho \, \mathrm{e}^{i\theta}$$

$$\partial_\phi^2 \rho - m^2 \rho - \frac{Q^2}{\rho^3} + \lambda \rho^{n-1} + \mu \rho^{n'-1} = 0$$

one finds:

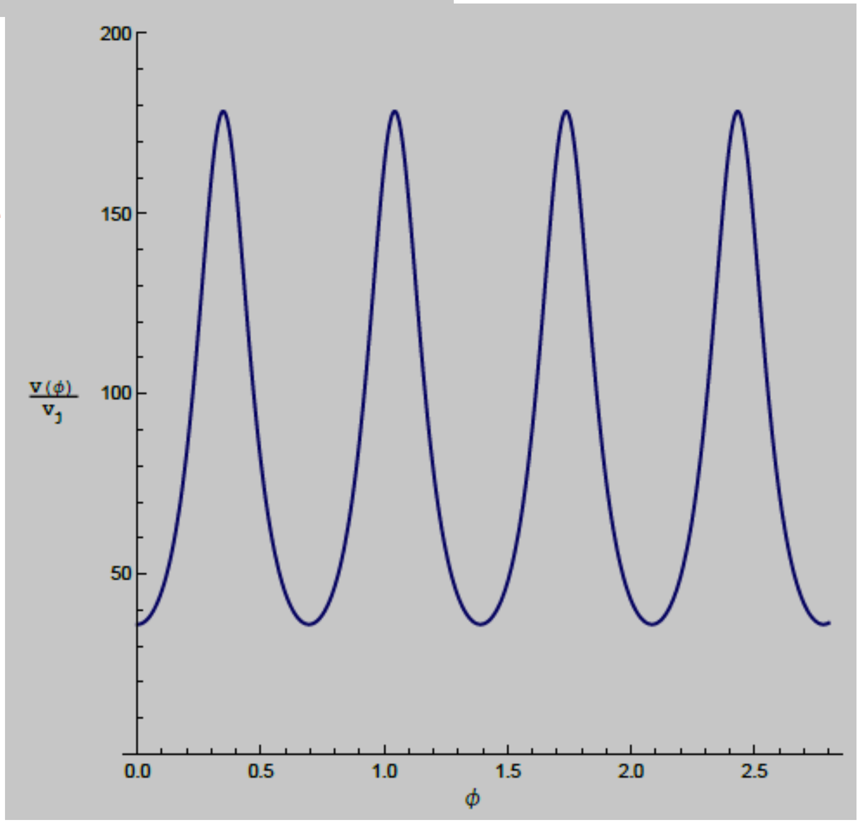
- bounce
- accelerated expansion following bounce → cyclic universe
- decelerated phase and recollapse

moreover:

- N at least ~ 60 → $\lambda < 0$ and $n \geq 5$ $(n' > n)$
- no intermediate deceleration between beginning and end of accelerated phase

QG-inflation from GFT condensates

(under certain conditions for interactions)



Dynamics of anisotropies - first steps

analysis at mean field level - subdominant interactions

GFT kinetic term = SU(2) Laplacian (special case)

A. Pithis, M. Sakellariadou, ’16

M. De Cesare, DO, A. Pithis, M. Sakellariadou, ‘17

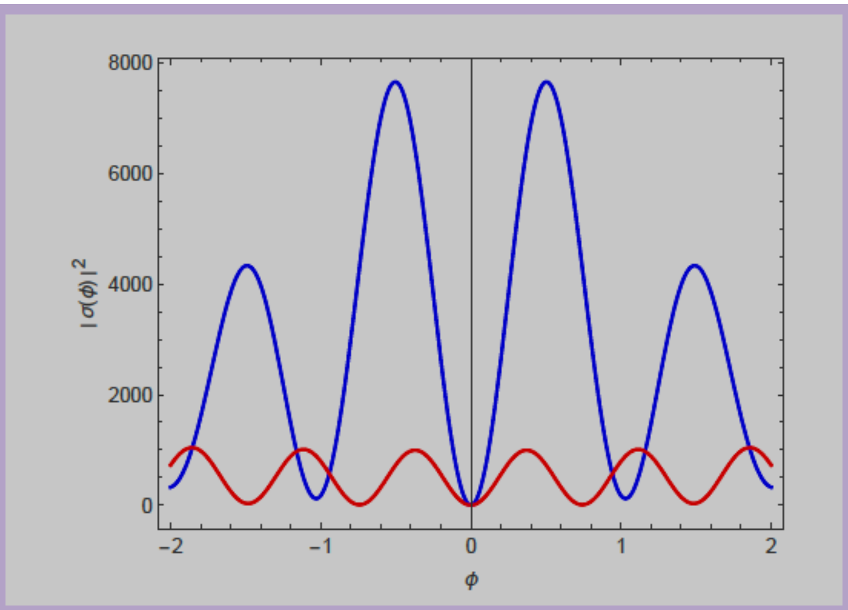
different notions of (an-)isotropy

isotropic mean field = all j’s equal + conditions on intertwiners = equilateral tetrahedra

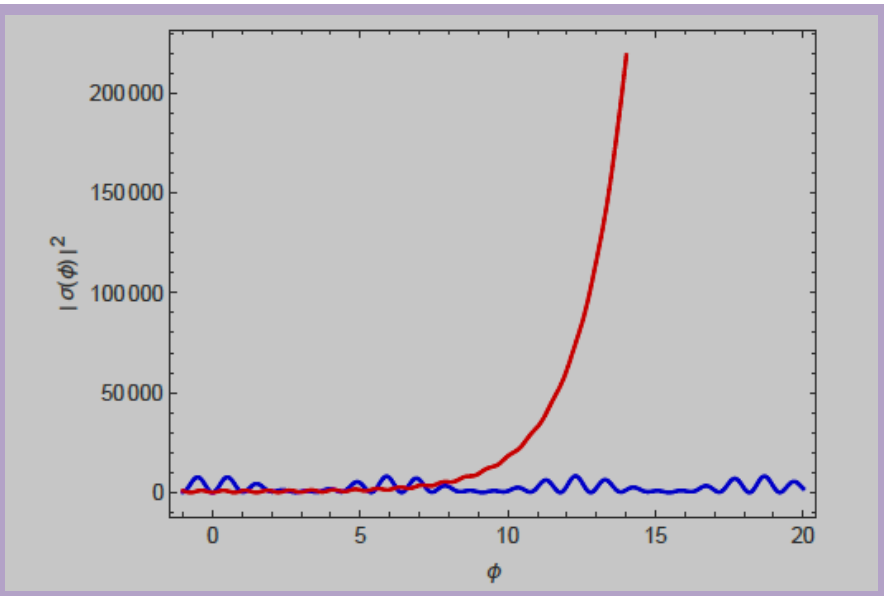
or

isotropic mean field = tri-orthogonal tetrahedra with 3 equal j’s (triangle areas)

different types of simple anisotropic configurations



probability density of the mean field for the isotropic and anisotropic parts for ***small values of the relational clock***



probability density of the mean field for the isotropic and anisotropic parts for ***large values of the relational clock***

similar results in both cases

(assuming isotropic mean field dominated by single spin value)

anisotropies only play an important role at small values of the relational clock (small volumes), whereas at late times the isotropic mode dominates

Cosmological perturbations from full QG

S. Gielen, DO, '17

GFT for 4d gravity coupled to 4 free massless scalar fields used as clock and rods

+

isotropic reduction of geometric sector

$$\sigma(g_I, \phi^J) = \sum_{j=0}^{\infty} \sigma_j(\phi^J)\, \mathbf{D}^j(g_I)$$

GFT hydrodynamics equation for isotropic condensates (weak coupling)

$$\left(-B_j + A_j \partial^2_{\phi^0} + C_j\, \Delta_{\phi^i}\right) \sigma_j(\phi^J) = 0$$

small perturbations around homogeneous condensate universes

$$\sigma_j(\phi^J) = \sigma_j^0(\phi^0)(1 + \epsilon\, \psi_j(\phi^J))$$

volume fluctuations and cosmological power spectrum

$$\Delta V(\phi_0, k_i; \Phi_0, K_i) \equiv \langle \hat{\tilde{V}}(\phi^0, k_i) \hat{\tilde{V}}(\Phi^0, K_i)\rangle - \langle \hat{\tilde{V}}(\phi^0, k_i)\rangle \langle \hat{\tilde{V}}(\Phi^0, K_i)\rangle$$

$$= \delta(\phi^0 - \Phi^0) \sum_j V_j^2\, |\sigma_j^0(\phi^0)|^2 \left[(2\pi)^3 \delta^3(k_i + K_i) + \epsilon\, (\tilde{\psi}_j(\phi^0, k_i + K_i) + \overline{\tilde{\psi}_j}(\phi^0, -k_i - K_i))\right]$$

non-zero even in purely homogeneous background (condensate), due to intrinsic quantum nature

naturally approximate scale invariance

- dominant part (computed on exactly homogeneous condensate) exactly scale invariant
- scale invariance tied to translation invariance of condensate
- deviations suppressed as universe expands and when inhomogeneities are negligible

small relative amplitude $\dfrac{\Delta V(\phi_0, k_i; \Phi_0, K_i)}{\langle \hat{V}(\phi_0)\rangle^2}$

- dominant term ~ 1/N ~ 1/V
- perturbations further suppressed as universe expands
- if accelerated phase, further suppression of deviations from scale invariance
- QG inflation without inflation

GFT condensate cosmology: going further

- detailed study of effects of GFT interactions (on both background and perturbations)
- precise estimate of limits of approximations and different regimes
- spatial curvature, effective cosmological constant, role of topology (maybe need for connectivity information)
- effective cosmological dynamics of generalised condensates (beyond Bogolubov approx.) (also used for BHs)

DO, D. Pranzetti, J. Ryan, L. Sindoni, ’15; DO, D. Pranzetti, L. Sindoni, ‘15

- detailed dynamics of anisotropies
- detailed analysis of modified homogeneous dynamics
- more general GFT hydrodynamics and cosmological signatures of QG condensation
- detailed analysis of cosmological perturbations and their power spectrum (observations!)
- overall cosmological scenario: QG inflation? bouncing universe? emergent universe (geometrogenesis)?

example of “cosmology from full QG”: GFT condensate cosmology

- underlying non-spatiotemporal “atoms of space”
- spacetime/geometric interpretation only approximate and for special configurations
- cosmology as QG hydrodynamics
- QG phase transitions (universe as QG condensate)
- modified effective cosmological dynamics (bouncing cosmology)
- resolution of classical singularity (bounce or cosmological phase transition)
- cosmological perturbations theory from full QG

Thank you for your attention!