Fundamental physics without spacetime:
ideas, results and challenges from quantum gravity and beyond

Daniele Oriti
Arnold Sommerfeld Center for Theoretical Physics
Munich Center for Mathematical Philosophy
Munich Center for Quantum Science and Technology
Center for Advanced Studies
Ludwig-Maximilians-University, Munich, Germany, EU

Bayes Forum
Max Planck Institute for Astrophysics, Garching, Germany, EU - 8.12.2023

Plan

1. spacetime as we know it, in GR - and the relational perspective
2. the problem of Quantum Gravity: conceptual, physical, mathematical
3. emergent space, emergent time in QG
4. an example of a fundamental QG formalism and of the emergence of spacetime from it
5. a possible quantum statistical foundation of the formalism based on Jaynes' principle
6. remarks about foundational/philosophical issues (and the role of agency) in light of QG

different kind of talk

this talk

other talks at
the Bayes Forum

goal

outline general issues in QG, and some research directions, more than specific results, as well broader implications

general survey, with lots of material (mostly for later discussion)

mostly focusing on conceptual aspects

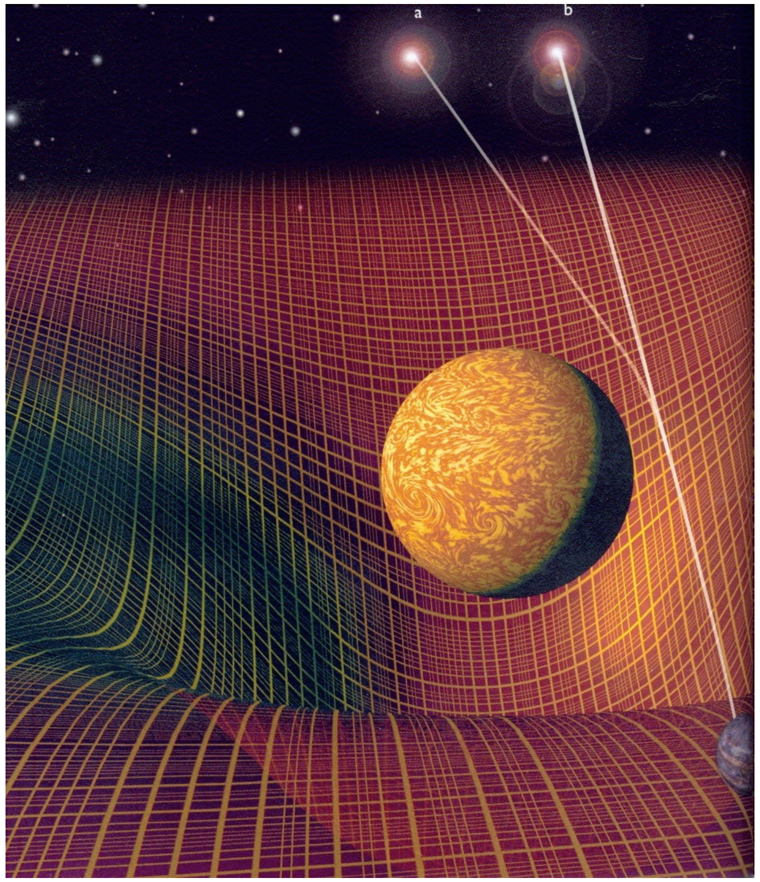
Nature of spacetime:

lessons from General Relativity

Nature of spacetime: lessons from General Relativity

main lesson: spacetime is a physical system itself (own dofs, see gravitational waves)

$$g_{\mu\nu}(t,x) \qquad ds^2 = g_{tt}dt^2 + g_{tx_i}dtdx_i + g_{x_ix_j}dx_idx_j$$



- gravity = spacetime geometry (spatial distances, time intervals, curvature of space, volumes, …..) = field
- spacetime geometry is generically non-flat and dynamical
- matter mass-energy “deformes” spacetime, deformation affects motion of matter
- no preferred space or time direction
- physics is the same in all (idealized) frames
- causal structure non-trivial and dynamical; spatial regions can be causally inaccessible (horizons)

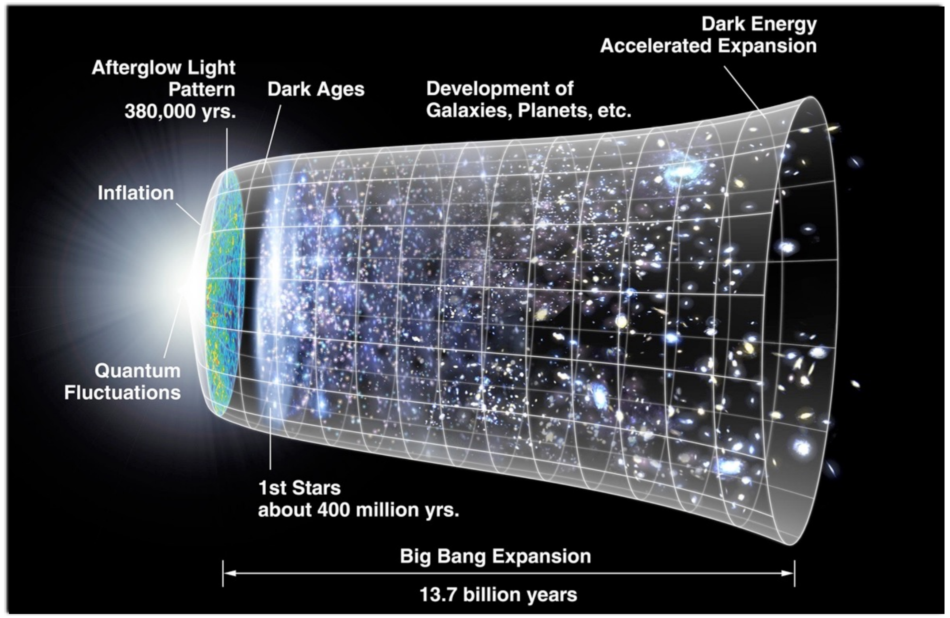
Einstein’s equations

$$R_{\mu\nu}[g(x)] - \frac{1}{2}R[g(x)] + \Lambda g_{\mu\nu}(x) = 8\pi G_N T_{\mu\nu}[\phi(x), ...]$$

give eqns for evolution of universe:

e.g. Friedmann eqn (homogeneity + isotropy):

$$H^2 = \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G\rho}{3} - \frac{kc^2}{a^2}$$



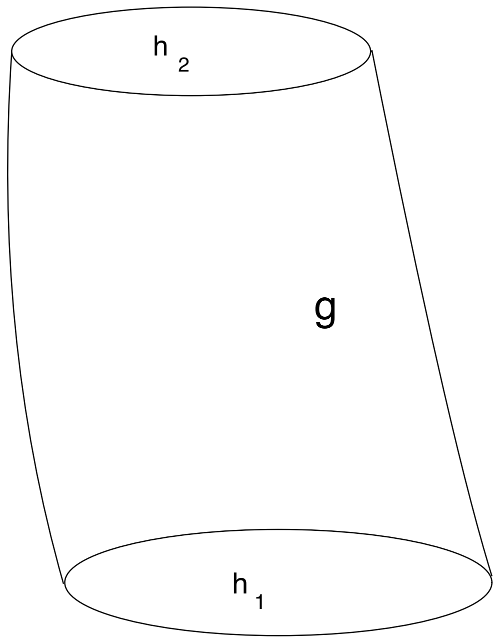
Nature of spacetime:

lessons from General Relativity

in fact, there is more to it .....

Diffeo-invariance, spacetime (local) observables and relational strategy

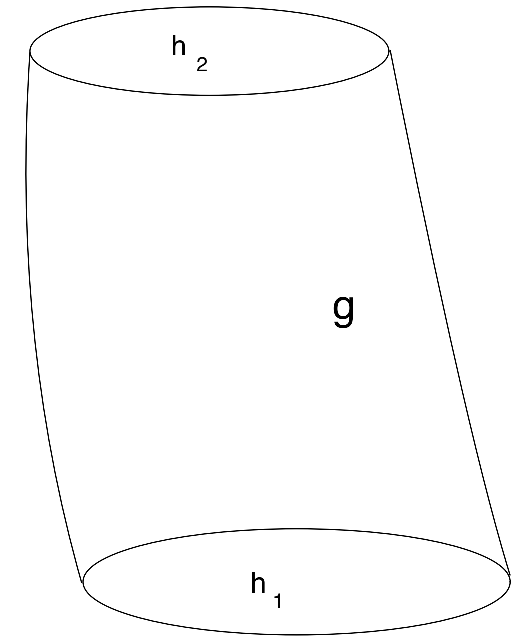
diffeomorphism invariance + background independence D. Giulini, '06



- no absolute notion of temporal or spatial direction/location/distance
- manifold has only global role (topological restriction)
- local manifold structures (points, directions, paths, coordinate frames, ...) have no physical significance
- what is physical is values of (continuum) dynamical fields, among which the metric field, and their relations

Diffeo-invariance, spacetime (local) observables and relational strategy

diffeomorphism invariance + background independence D. Giulini, '06



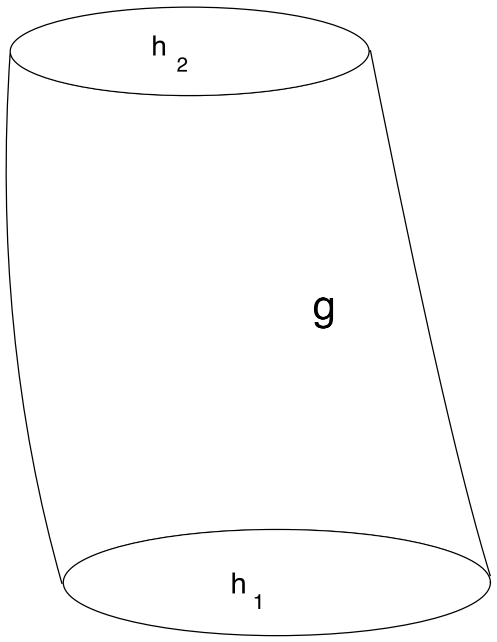
- no absolute notion of temporal or spatial direction/location/distance
- manifold has only global role (topological restriction)
- local manifold structures (points, directions, paths, coordinate frames, ...) have no physical significance
- what is physical is values of (continuum) dynamical fields, among which the metric field, and their relations

so what are spacetime observables? only "global" ones? $\mathcal{O} = \int_{\mathcal{M}} d^4x \sqrt{-g}\, O(g(x), \varphi(x))$

yes, wrt manifold, because manifold is not spacetime but what are "local" spacetime observables, then?

Diffeo-invariance, spacetime (local) observables and relational strategy

diffeomorphism invariance + background independence D. Giulini, '06



- no absolute notion of temporal or spatial direction/location/distance
- manifold has only global role (topological restriction)
- local manifold structures (points, directions, paths, coordinate frames, ...) have no physical significance
- what is physical is values of (continuum) dynamical fields, among which the metric field, and their relations

so what are spacetime observables? only "global" ones?

$$\mathcal{O} = \int_{\mathcal{M}} d^4x \sqrt{-g}\, O(g(x), \varphi(x))$$

yes, wrt manifold, because manifold is not spacetime

but what are "local" spacetime observables, then?

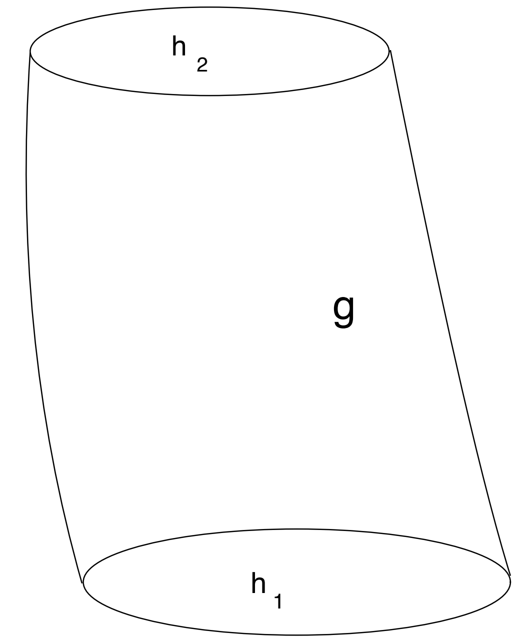
relational strategy: Rovelli '90s+ [related ideas DeWitt '60s; Bargmann & Komar 90's] Hoehn, '00s

- space and time identified in relations among dynamical fields, necessarily including metric field
- identify internal appropriate d.o.f.s, e.g. matter fields, use them as (approximate) clocks and rods to parametrize evolution and location of other dofs

$$R(t) \qquad \Phi(t) \qquad \Longrightarrow \qquad R(t) \qquad t(\Phi) \qquad \Longrightarrow \qquad R(\Phi)$$

Diffeo-invariance, spacetime (local) observables and relational strategy

diffeomorphism invariance + background independence   D. Giulini, '06



- no absolute notion of temporal or spatial direction/location/distance
- manifold has only global role (topological restriction)
- local manifold structures (points, directions, paths, coordinate frames, ...) have no physical significance
- what is physical is values of (continuum) dynamical fields, among which the metric field, and their relations

so what are spacetime observables?   only "global" ones?

$$\mathcal{O} = \int_{\mathcal{M}} d^4x \sqrt{-g}\, O(g(x), \varphi(x))$$

yes, wrt manifold, because manifold is not spacetime   but what are "local" spacetime observables, then?

relational strategy: Rovelli '90s+   [related ideas DeWitt '60s; Bargmann & Komar 90's]   Hoehn, '00s

- space and time identified in relations among dynamical fields, necessarily including metric field
- identify internal appropriate d.o.f.s, e.g. matter fields, use them as (approximate) clocks and rods to parametrize evolution and location of other dofs

$$R(t) \qquad \Phi(t)$$

$$\Longrightarrow \qquad R(t) \qquad t(\Phi)$$

$$\Longrightarrow \qquad R(\Phi)$$

ideally, spacetime physics should only be expressed in terms of such relational quantities

points, coordinates, trajectories on manifold are "useful fictions" representing physical frames (clocks and rods) in the limit in which their physical properties (energy, interactions, …) are negligible relational perspective: physics is in the relations between dynamical fields $g_{\mu\nu}(x)$ $A_\mu(x)$ $\varphi(x)$

(complete, Dirac) observables = correlations on superspace (space of fields)

simplest example: parametrized pendulum

classical single 1d pendulum

physical quantities: pendulum position as function of physical time Q = $Q(T)$ (value of some clock)

dynamics: $\frac{d^2Q}{dT^2} = -\omega\, Q$ ⟶ general solution: $Q(T) = A\,\sin\left(\omega\, T + \phi\right)$

true physical system is pendulum + clock   physics is in the relation Q(T)

Q and T can be measured (partial observables); what can be predicted is only Q(T) (complete observable)

parametrized classical single 1d pendulum

turn dynamical variables into functions of new "time parameter" (i.e. scalar fields in d=1): $Q(\tau)$ $T(\tau)$

$$\frac{dQ}{d\tau} = P_Q \qquad \frac{dT}{d\tau} = P_T \qquad H(Q, P_Q, T, P_T) = P_T(\tau) + \frac{1}{2}P_Q^2(\tau) + \frac{1}{2}\omega^2 Q^2(\tau)$$

$$\frac{dQ}{d\tau} = P_Q = \frac{dH}{dP_Q} \qquad \frac{dT}{d\tau} = P_T = \frac{dH}{dP_T} = 1 \qquad \frac{dP_Q}{d\tau} = P_Q = -\frac{dH}{dQ} = -\omega^2 Q \qquad \frac{dP_T}{d\tau} = -\frac{dH}{dT} = 0$$

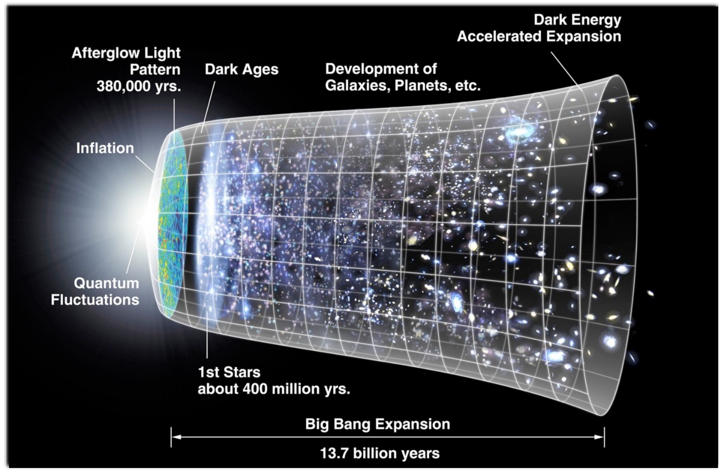
+ invariance (covariance of equations) under 1d diffeos: $\tau \to f(\tau)$ 1d manifold not physical

only diffeo-invariant observable, evaluated on solutions on the dynamics, is: $Q(T) = A\,\sin\left(\omega\, T + \phi\right)$

$Q(\tau)$ $T(\tau)$ are neither measurable nor predictable (as functions of affine parameter)

only Q(T) (complete observable) can be predicted - Q and T are only "physical" in relational sense

diffeomorphism invariance indicates what is physical and what is not general point: physics is on superspace (space of field configurations), not manifold (only auxiliary structure)



difficult to express/extract it in general QG case

things much simpler in cosmological context

restriction to global features of universe: (approximately) homogeneous fields

example: flat Friedmann universe (homogeneous, isotropic) $\mathrm{d}s^2 = -N^2(t)\mathrm{d}t^2 + a^2(t)\delta_{ab}\mathrm{d}x^a\mathrm{d}x^b$

dynamical variables = scale factor (universe volume) and massless scalar field

GR action reduces to: $S = \frac{3}{8\pi G}\int \mathrm{d}t\, N\left(-\frac{aV_0\dot{a}^2}{N^2} + \frac{V}{N}\frac{\dot{\chi}^2}{2N}\right)$ $\quad V \equiv V_0 a^3$ invariant under 1d diffeos

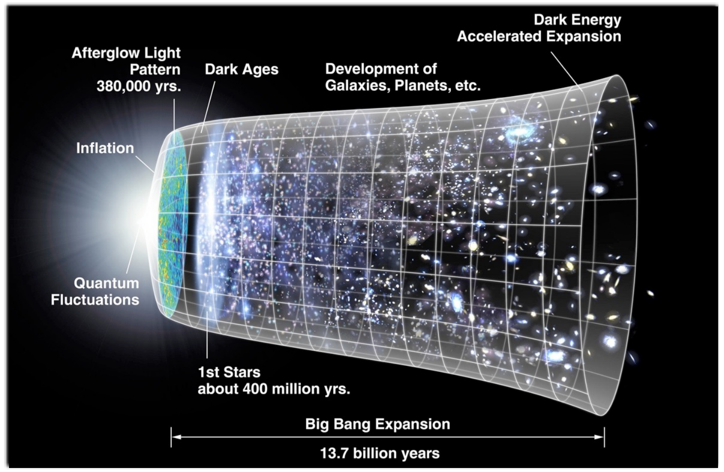
configuration space is 2d flat manifold $\{a, \chi\}$ only relational observable $V(\chi)$

can be fully deparametrized to give relational evolution: $\left(\frac{1}{3V}\frac{\mathrm{d}V}{\mathrm{d}\chi}\right)^2 \equiv \left(\frac{V'}{3V}\right)^2 = \frac{4\pi G}{3}$

no manifold appears

general point: physics is on superspace (space of field configurations), not manifold (only auxiliary structure)

difficult to express/extract it in general QG case



things much simpler in cosmological context

restriction to global features of universe: (approximately) homogeneous fields

example: flat Friedmann universe (homogeneous, isotropic) $\mathrm{d}s^2 = -N^2(t)\mathrm{d}t^2 + a^2(t)\delta_{ab}\mathrm{d}x^a\mathrm{d}x^b$

dynamical variables = scale factor (universe volume) and massless scalar field

GR action reduces to: $S = \frac{3}{8\pi G}\int \mathrm{d}t\, N\left(-\frac{aV_0\dot{a}^2}{N^2} + \frac{V}{N}\frac{\dot{\chi}^2}{2N}\right)$ $\quad V \equiv V_0 a^3$ invariant under 1d diffeos

configuration space is 2d flat manifold $\{a, \chi\}$ only relational observable $V(\chi)$

can be fully deparametrized to give relational evolution: $\left(\frac{1}{3V}\frac{\mathrm{d}V}{\mathrm{d}\chi}\right)^2 \equiv \left(\frac{V'}{3V}\right)^2 = \frac{4\pi G}{3}$

no manifold appears

summary to identify "spacetime = manifold" or "spacetime physics = physics on manifold" is approximation at best

(corresponds to case in which set of four scalar fields behave like test fields covering manifold, and can be used as coordinates for manifold points)

do not expect to find manifold etc neither at fundamental QG level, nor in its effective description

Note: physics may be different with respect to different PHYSICAL reference frames!

Lessons:

spacetime physics is "fields (values) in relation to fields (values)"

physical frames and physical covariance: observer matters

The Quantum Gravity problem

starting point: conceptual, physical, mathematical clash

framework and ingredients of GR are incompatible with what we learned from Quantum Mechanics

GR	QFT
spacetime (geometry) is a dynamical entity itself	spacetime is fixed background for fields' dynamics
there are no preferred temporal (or spatial) directions	evolution is unitary (conserved probabilities) with respect to a given (preferred) temporal direction
physical systems are local and locally interacting	nothing can be perfectly localised
everything (incl. spacetime) evolves deterministically	everything evolves probabilistically
all dynamical fields are continuous entities	interaction and matter fields are made of "quanta"
every property of physical systems (incl. spacetime) and of their interactions can be precisely determined, in principle	every property of physical systems and their interactions is intrinsically uncertain, in general

- in fact, no proper understanding of interaction of geometry with quantum matter, if gravity is not quantized

$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R + \Lambda g_{\mu\nu} = \frac{8\pi G}{c^4} \langle \Psi | \hat{T}_{\mu\nu} | \Psi \rangle$$

not a consistent fundamental theory

starting point: conceptual, physical, mathematical clash

framework and ingredients of GR are incompatible with what we learned from Quantum Mechanics

GR

spacetime (geometry) is a dynamical entity itself

there are no preferred temporal (or spatial) directions

physical systems are local and locally interacting

everything (incl. spacetime) evolves deterministically

all dynamical fields are continuous entities

every property of physical systems (incl. spacetime) and of their interactions can be precisely determined, in principle

QFT

spacetime is fixed background for fields' dynamics

evolution is unitary (conserved probabilities) with respect to a given (preferred) temporal direction

nothing can be perfectly localised

everything evolves probabilistically

interaction and matter fields are made of "quanta"

every property of physical systems and their interactions is intrinsically uncertain, in general

two frameworks come with different associated mathematical language and tools

conceptual + mathematical clash is clear

- in fact, no proper understanding of interaction of geometry with quantum matter, if gravity is not quantized

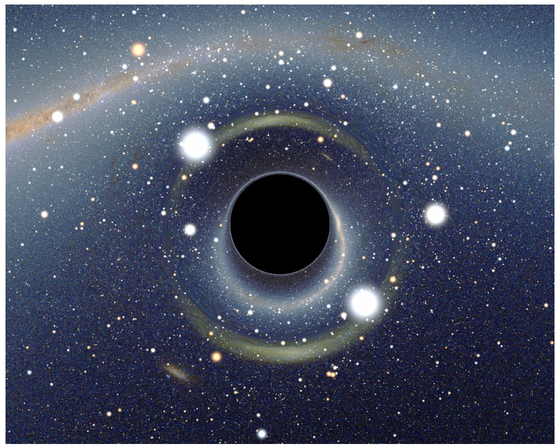
$$R_{\mu\nu} - \frac{1}{2}g_{\mu\nu}R + \Lambda g_{\mu\nu} = \frac{8\pi G}{c^4}\langle\Psi|\hat{T}_{\mu\nu}|\Psi\rangle$$

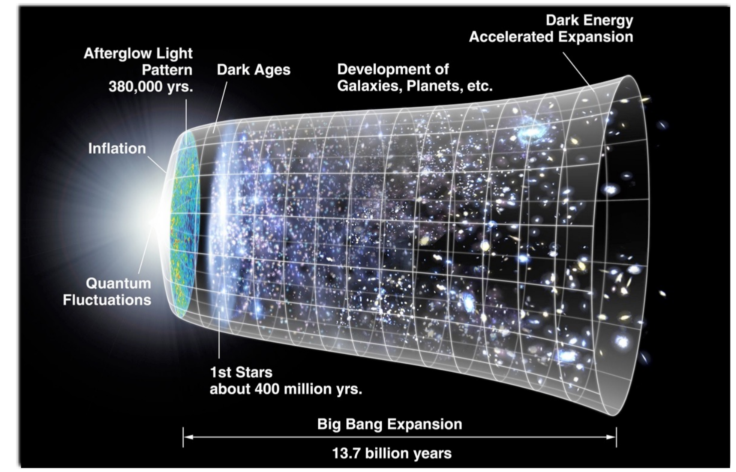
not a consistent fundamental theory

summary of physical issues

- spacetime singularities: breakdown of GR for strong gravitational fields/large energy densities - inevitable in classical GR

center of black holes, big bang - quantum effects expected to be important





- cosmological scenarios for the early universe need QG completion

R. Brandenberger, ’10, ’11, ’14

why a close to homogeneous and isotropic universe?

why an approximately scale invariant power spectrum?

what happens "at" the Big Bang?

Inflation

- what produces inflation?
- physics of trans-Planckian modes (for long inflation)?
- inflation too close to Planck regime?
- inflationary spacetime still contains singularity

Bouncing cosmology

- new physics needed to describe/justify cosmological bounce

Emergent universe
(pre-big bang static phase)

- static phase and phase transition require new physics

summary of physical issues

new QG dofs? primordial (quantum) black holes?

new type of matter? — new QG dof?

cosmological constant? — why doesn't it gravitate?

modified gravity?

why holographic entropy?

spacetime microstructure?

violation of unitarity? locality? .....

all require QG

summary of physical issues

Dark Matter

new QG dofs? primordial (quantum) black holes?

new type of matter? new QG dof?

cosmological constant? why doesn't it gravitate?

modified gravity?

why holographic entropy?

spacetime microstructure? all require QG

violation of unitarity? locality? .....

summary of physical issues

Dark Matter

- new type of matter, not interacting with EM field (thus not visible), and non-standard in other ways

new QG dofs? primordial (quantum) black holes?

new type of matter? new QG dof?

cosmological constant? why doesn't it gravitate?

modified gravity?

why holographic entropy?

spacetime microstructure? all require QG

violation of unitarity? locality? .....

summary of physical issues

Dark Matter

- new type of matter, not interacting with EM field (thus not visible), and non-standard in other ways
- modified gravitational physics (incl. GR) at galactic scales

new QG dofs? primordial (quantum) black holes?

new type of matter? — new QG dof?

cosmological constant? — why doesn't it gravitate?

modified gravity?

why holographic entropy?

spacetime microstructure? — all require QG

violation of unitarity? locality? .....

summary of physical issues

Dark Matter

- new type of matter, not interacting with EM field (thus not visible), and non-standard in other ways
- modified gravitational physics (incl. GR) at galactic scales

new QG dofs? primordial (quantum) black holes?

QG modifying large-scale physics?

new type of matter? — new QG dof?

cosmological constant? — why doesn't it gravitate?

modified gravity?

why holographic entropy?

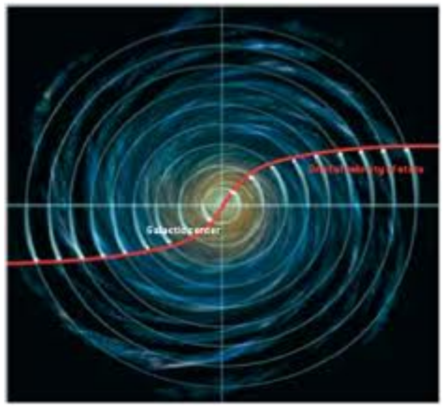
spacetime microstructure?

violation of unitarity? locality? .....

all require QG

summary of physical issues

Dark Matter



- new type of matter, not interacting with EM field (thus not visible), and non-standard in other ways
- modified gravitational physics (incl. GR) at galactic scales

new QG dofs? primordial (quantum) black holes?

QG modifying large-scale physics?

new type of matter? — new QG dof?

cosmological constant? — why doesn't it gravitate?

modified gravity?

why holographic entropy?

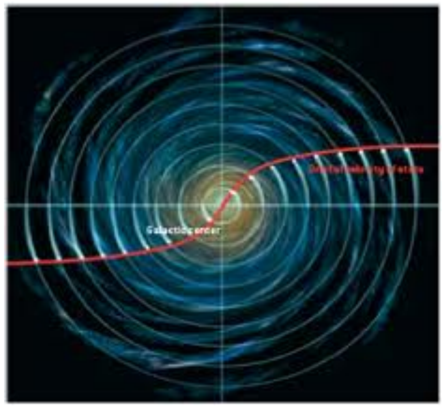
spacetime microstructure?

violation of unitarity? locality? .....

all require QG

summary of physical issues

Dark Matter



- new type of matter, not interacting with EM field (thus not visible), and non-standard in other ways
- modified gravitational physics (incl. GR) at galactic scales

new QG dofs? primordial (quantum) black holes?

QG modifying large-scale physics?

Dark Energy

new type of matter? — new QG dof?

cosmological constant? — why doesn't it gravitate?

modified gravity?

why holographic entropy?

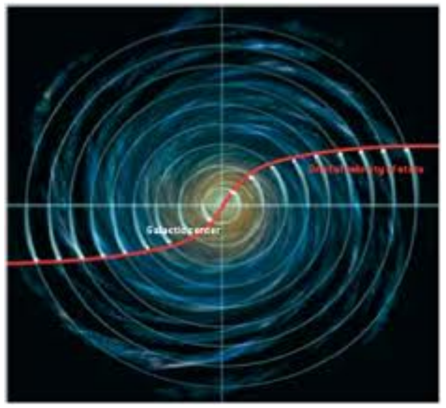
spacetime microstructure?

violation of unitarity? locality? .....

all require QG

summary of physical issues

Dark Matter

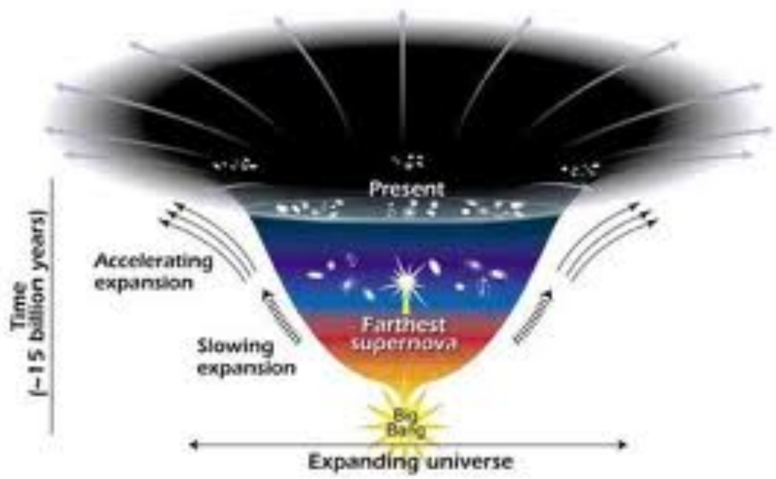


- new type of matter, not interacting with EM field (thus not visible), and non-standard in other ways
- modified gravitational physics (incl. GR) at galactic scales

new QG dofs? primordial (quantum) black holes?

QG modifying large-scale physics?

Dark Energy



new type of matter?

cosmological constant?

modified gravity?

new QG dof?

why doesn't it gravitate?

why holographic entropy?

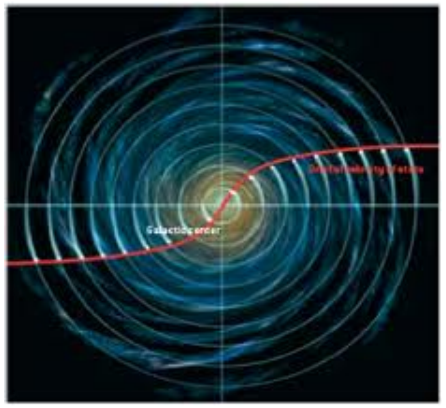
spacetime microstructure?

violation of unitarity? locality? .....

all require QG

summary of physical issues

Dark Matter

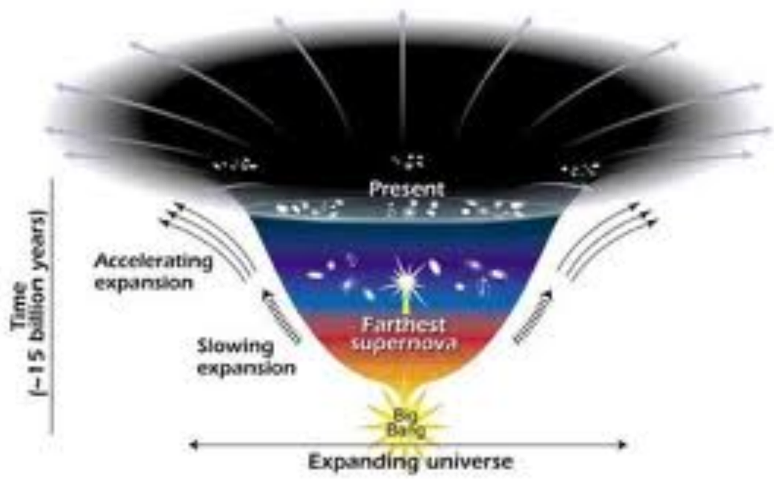


- new type of matter, not interacting with EM field (thus not visible), and non-standard in other ways
- modified gravitational physics (incl. GR) at galactic scales

new QG dofs? primordial (quantum) black holes?

QG modifying large-scale physics?

Dark Energy



new type of matter? — new QG dof?

cosmological constant? — why doesn't it gravitate?

modified gravity? — QG modifying large-scale physics?

why holographic entropy?

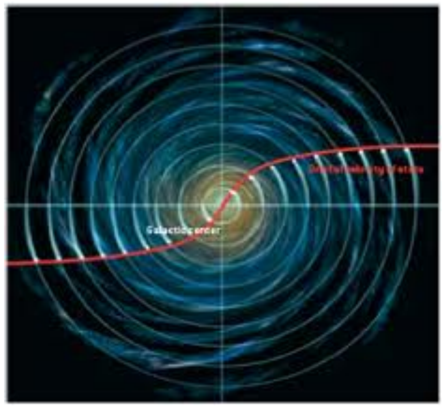
spacetime microstructure?

violation of unitarity? locality? .....

all require QG

summary of physical issues

Dark Matter

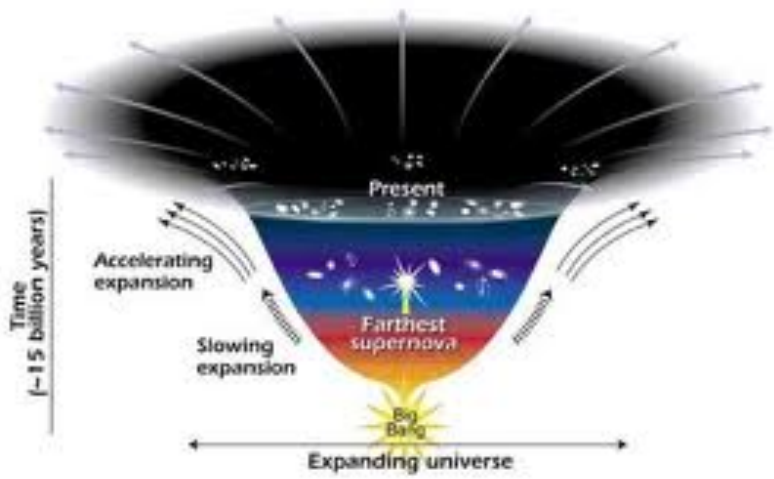


- new type of matter, not interacting with EM field (thus not visible), and non-standard in other ways
- modified gravitational physics (incl. GR) at galactic scales

new QG dofs? primordial (quantum) black holes?

QG modifying large-scale physics?

Dark Energy



new type of matter? — new QG dof?

cosmological constant? — why doesn't it gravitate?

modified gravity? — QG modifying large-scale physics?

Black hole/spacetime thermodynamics + evaporation

why holographic entropy?

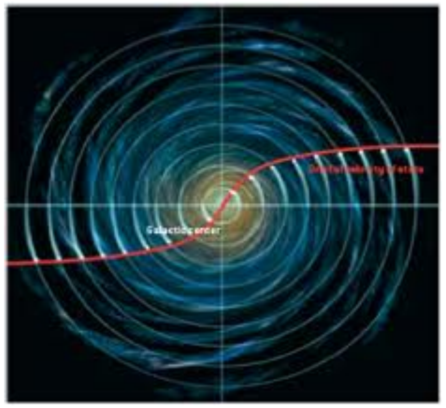
spacetime microstructure?

violation of unitarity? locality? .....

all require QG

summary of physical issues

Dark Matter

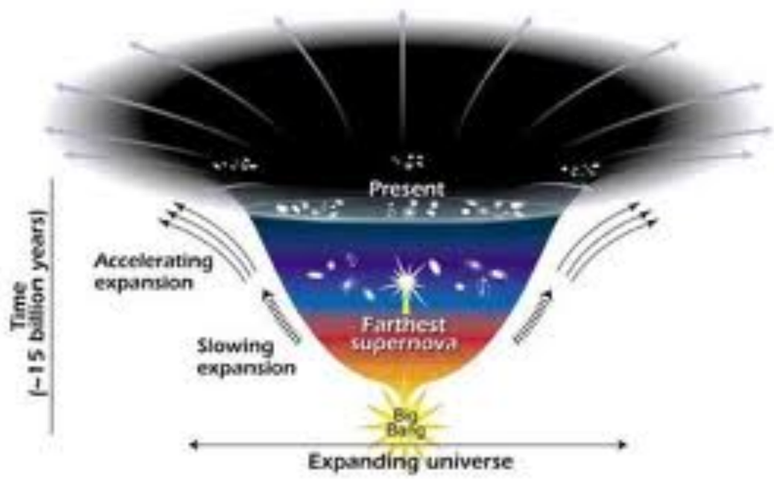


- new type of matter, not interacting with EM field (thus not visible), and non-standard in other ways
- modified gravitational physics (incl. GR) at galactic scales

new QG dofs? primordial (quantum) black holes?

QG modifying large-scale physics?

Dark Energy

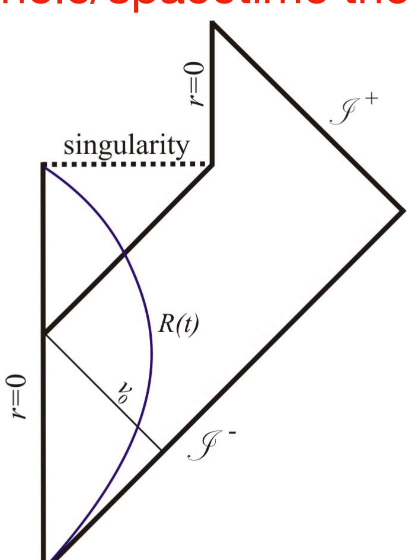


new type of matter? — new QG dof?

cosmological constant? — why doesn't it gravitate?

modified gravity? — QG modifying large-scale physics?

Black hole/spacetime thermodynamics + evaporation



why holographic entropy?

spacetime microstructure?

violation of unitarity? locality? .....

all require QG

The QG problem

why difficult?

spacetime and geometry (and matter) should become "quantum" physical systems themselves

full non-perturbative quantum theory of gravitational field (not just perturbations around spacetime background)

The QG problem

why difficult?

spacetime and geometry (and matter) should become "quantum" physical systems themselves

full non-perturbative quantum theory of gravitational field (not just perturbations around spacetime background)

technical challenges

already classical GR is very mathematically involved

simple perturbative methods fail, non-perturbative methods nightmare

canonical:

Hilbert space of physical (diffeo-invariant) quantum geometries (incl. scalar product)

$\mathcal{H} \ni |h_{ij}\rangle =$ | spatial geometry > =

= | spatial distances, curvature, volumes, ... >

covariant:

non-perturbative QG path integral (sum-over-geometries), incl. measure

$$\langle h_2 | h_1 \rangle = \sum_{g_{\mu\nu} | h_1, h_2} \mathcal{A}(g)$$

algebra of observables (distances, curvature, volumes, ...)

semiclassical approximation

predicted phenomenology? guidance from observations?

The QG problem

why difficult?

spacetime and geometry (and matter) should become "quantum" physical systems themselves

full non-perturbative quantum theory of gravitational field (not just perturbations around spacetime background)

technical challenges — already classical GR is very mathematically involved

simple perturbative methods fail, non-perturbative methods nightmare

canonical:

Hilbert space of physical (diffeo-invariant) quantum geometries (incl. scalar product)

$\mathcal{H} \ni |h_{ij}\rangle =$ | spatial geometry > =

= | spatial distances, curvature, volumes, ... >

covariant:

non-perturbative QG path integral (sum-over-geometries), incl. measure

$$\langle h_2 | h_1 \rangle = \sum_{g_{\mu\nu}|h_1,h_2} \mathcal{A}(g)$$

algebra of observables (distances, curvature, volumes, ...)

semiclassical approximation — predicted phenomenology? guidance from observations?

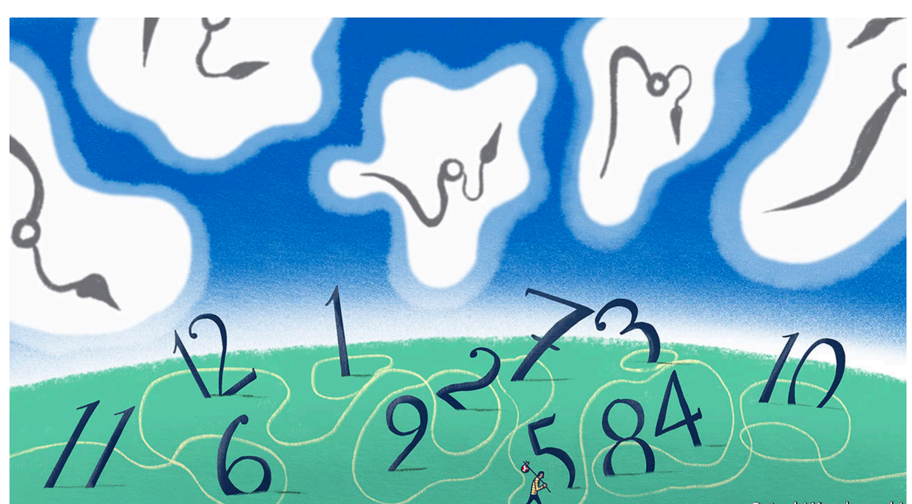
conceptual challenges

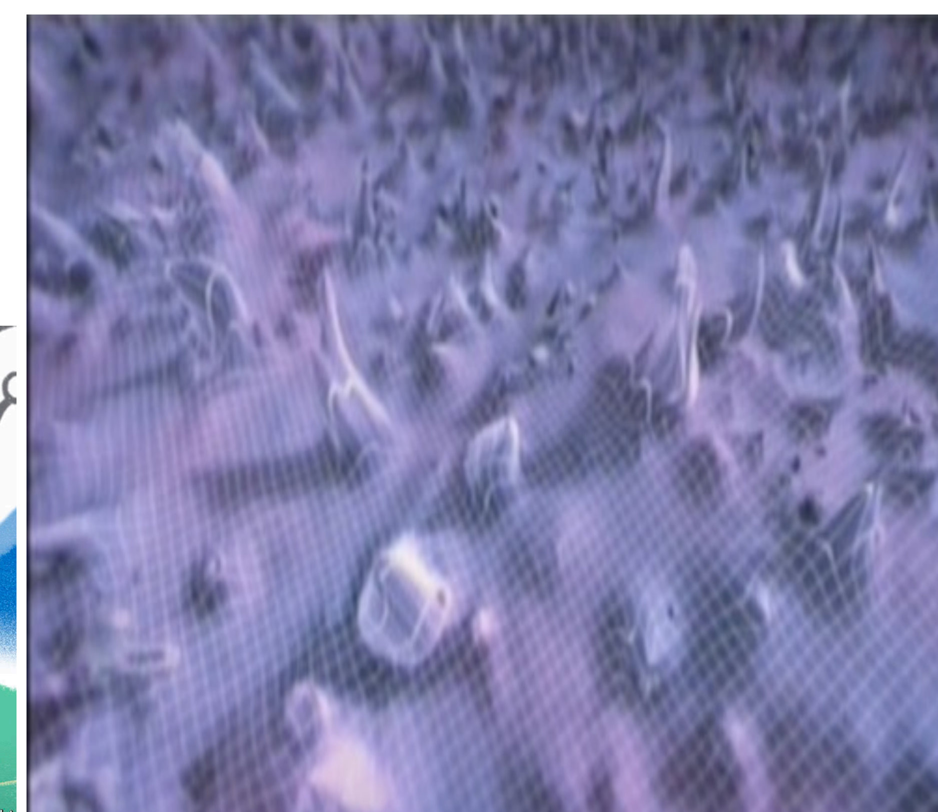
fluctuating geometry/causal structure, entanglement, ...

thinking without fixed background spacetime/geometry

diffeo-invariance, spacetime observables, relational strategy, but fully quantum!

quantum clocks and rods



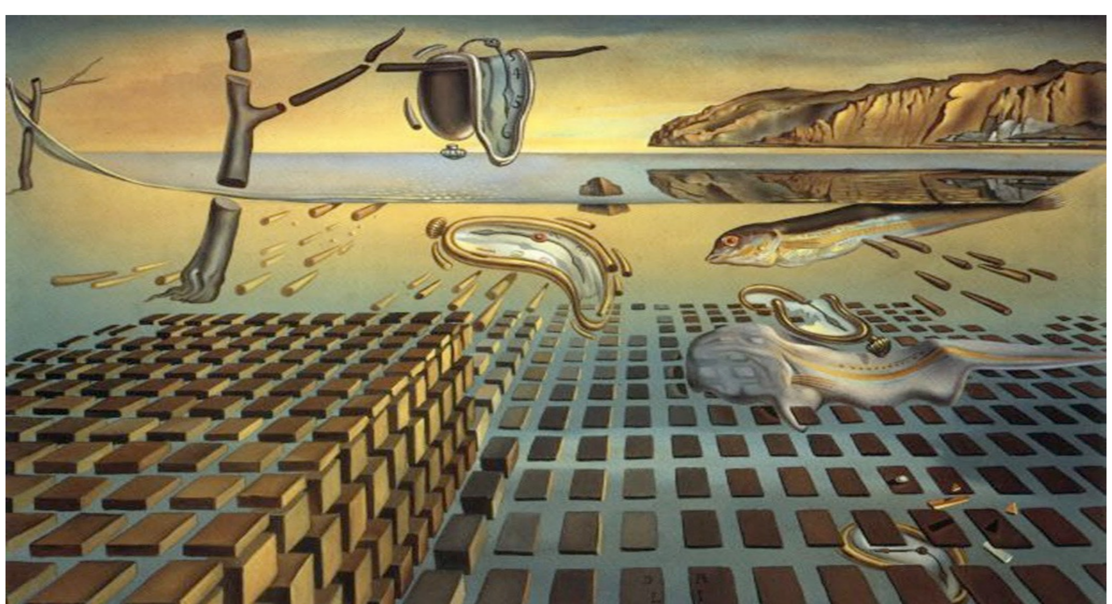


The emergent spacetime scenario

Is spacetime emergent?

suggestions that spacetime and geometry are not fundamental but emergent, collective entities

- challenges to “localization” in semi-classical GR — minimal length scenarios
- spacetime singularities in GR — breakdown of continuum itself?
- black hole thermodynamics — space itself is a thermodynamic system
- black hole information paradox — some fundamental principle has to go: locality?
- Einstein’s equations as equation of state
  GR dynamics is effective equation of state for any microscopic dofs collectively described by a spacetime, a metric and some matter fields
- entanglement ~ geometry
  geometric quantities defined by quantum (information) notions (examples from AdS/CFT, and various quantum many-body systems)
- many suggestions and results from several QG approaches (string theory, LQG, causal sets, ...)



new (quantum) dofs?

discrete structures?

which "dynamics"?

Quantum gravity problem reloaded

quantum theory of "new" non-spatiotemporal entities

continuum spacetime and geometric quantum observables reconstructed from collective quantum dynamics of "atoms of space"

quantum spacetime as a (background-independent) quantum many-body system

extraction of spacetime and cosmology similar to typical problem in condensed matter theory (from atoms to macroscopic effective continuum physics)

- all GR structures and dynamics are to be approximately obtained (in relational language) at effective level

- not just emergent gravity; flat spacetime itself would be emergent, highly excited, collective state of "QG atoms"

further issues and possibilities open up in "emergent spacetime" scenarios

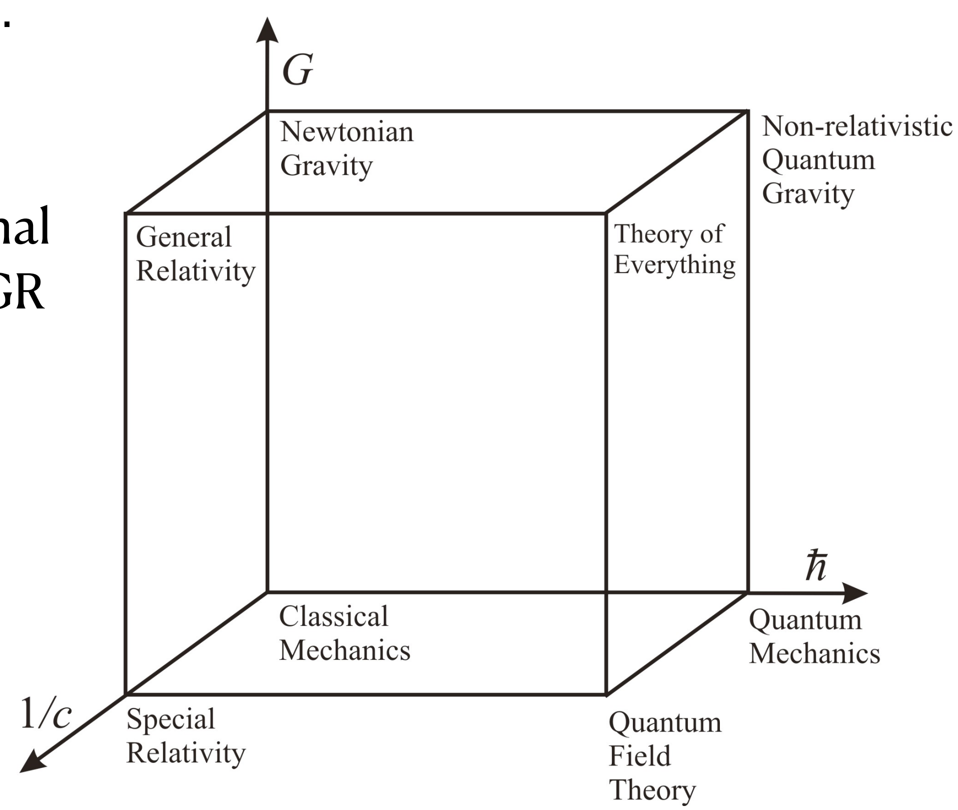
besides quantum effects of spacetime, we will have collective effects of "spacetime constituents"

which may manifest in new (or newly explained) spacetime features

main conceptual point:

the Bronstein cube …..

corresponds to traditional view of QG = quantum GR

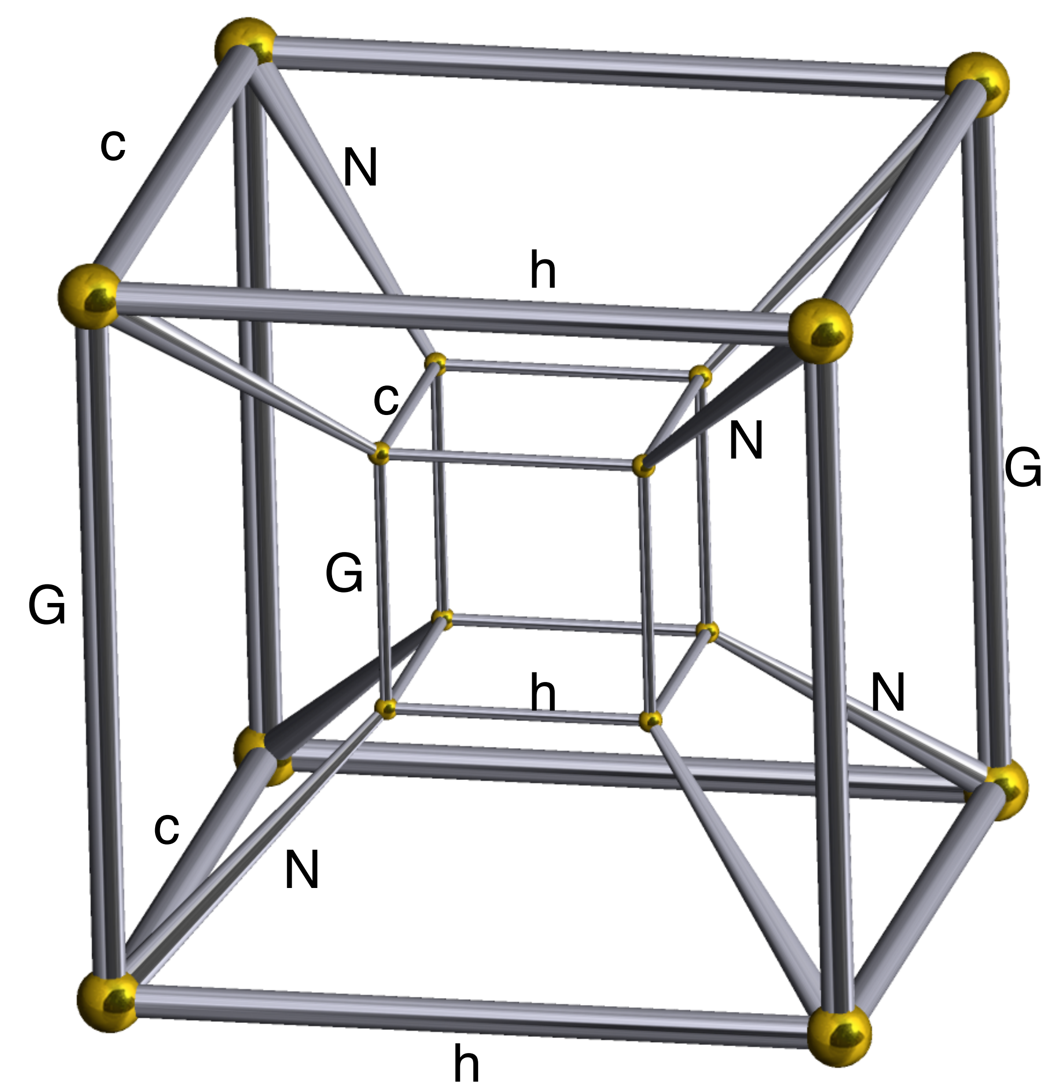


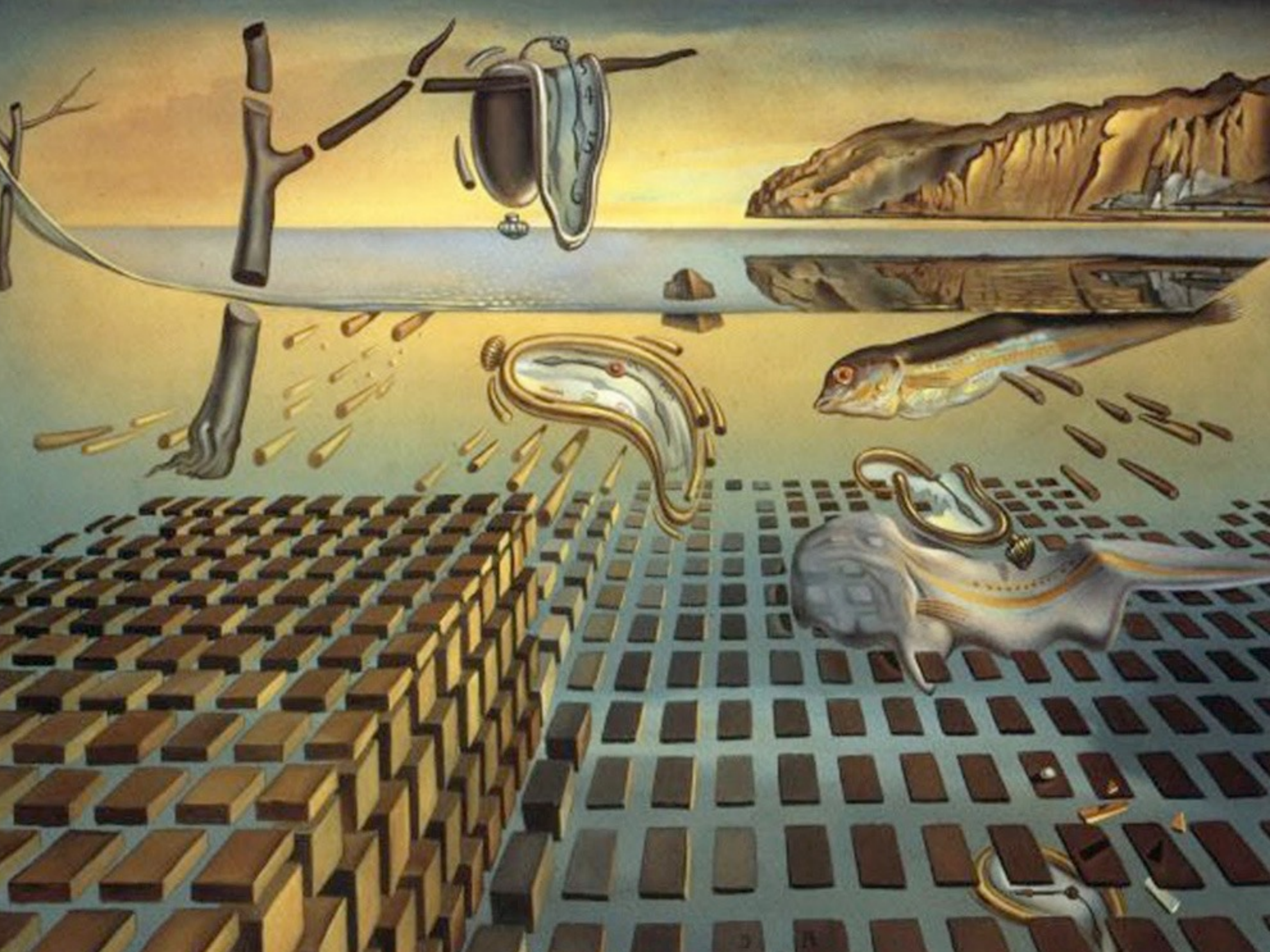
adding a new direction to our understanding of the world….
…. understanding the collective physics of many QG d.o.f.s

N-direction is where emergent behaviour takes place:
"More is different"

but if fundamental d.o.f.s are not smooth spacetimes (geometries) ……

the Bronstein hypercube of Quantum Gravity





Key point:

space and time may not be fundamental

physics may not be "fields (values) in relation to fields (values)"

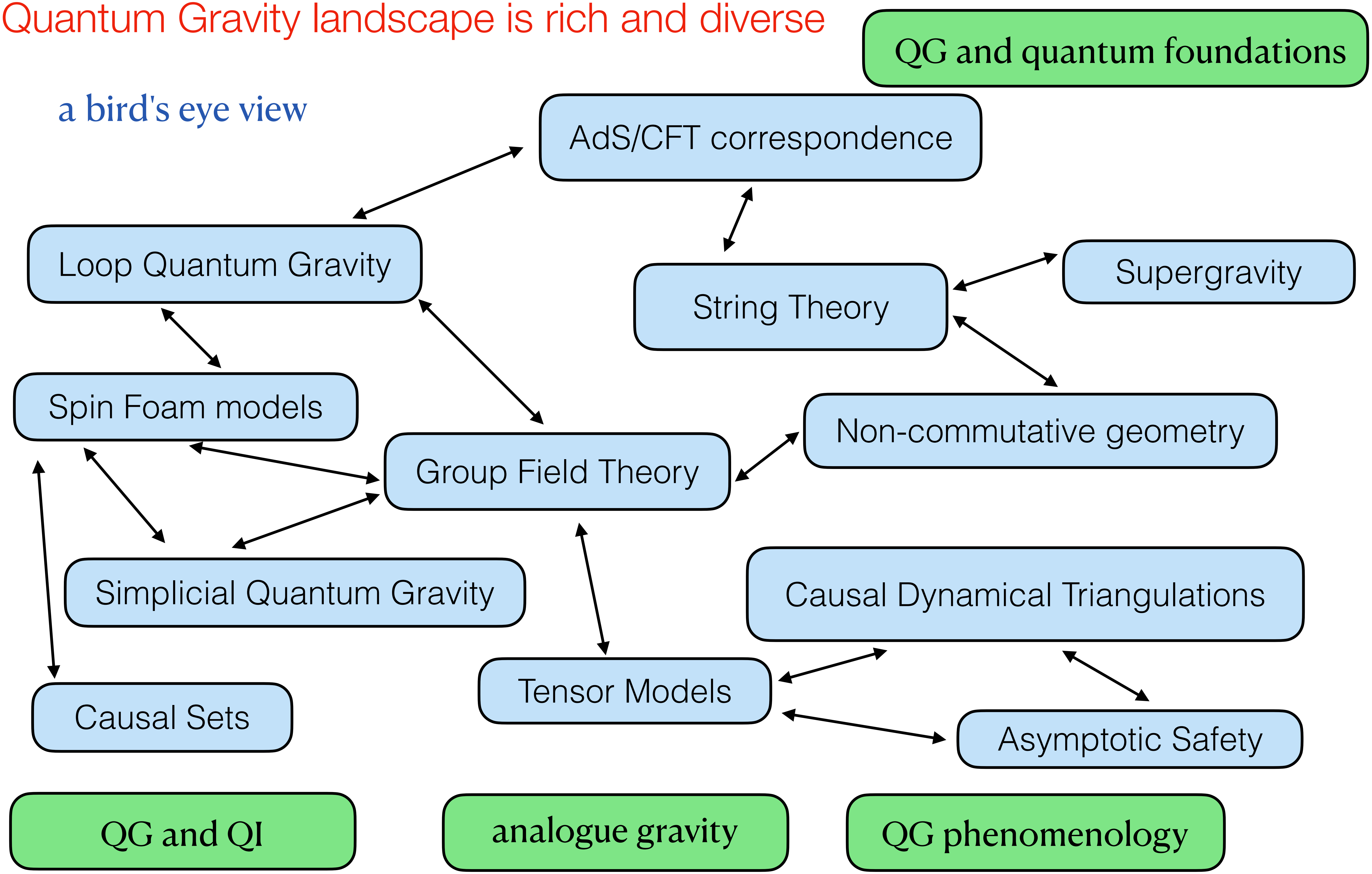
some other structures/entities may replace continuum fields
at more fundamental level

A proviso:

Quantum Gravity landscape is rich and diverse

Quantum Gravity landscape is rich and diverse

a bird's eye view



great variety; many mutual relations; many shared issues; mostly same goals

all approaches incomplete, missing parts (and achievements) depend on chosen strategy

Quantum Gravity landscape is rich and diverse

several sub-communities

with sometimes difficult relationships

very differently-sized communities - strings ~ O(1000) , LQG ~ O(100) , others ~ O(10)

but counting is very ambiguous, because boundaries are not sharp, and actual research directions very diverse

different historical roots of different communities:

some in particle physics tradition, others more in GR tradition; some more mathematical, others more physics-oriented

communication difficult because of different languages, and different definitions of and perspectives on QG problem

scarce resources do not help

A proviso:

Quantum Gravity landscape
is rich and diverse

here, just one example.....

Example:

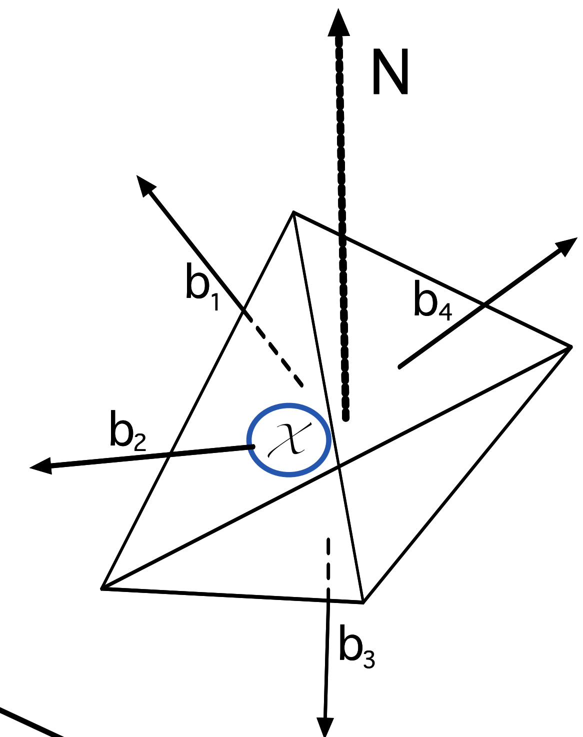
Tensorial Group Field Theories for Quantum Gravity

(here, quantum geometric models)

GFTs: basics

4d case - specific class of models

atoms of space ~ quantum 3-simplices with extra scalar dofs



- geometric variables: triangle vectors ~ su(2) Lie algebra elements

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

4 triangle vectors (with modulus equal to area)

normal vector to 3d hypersurface

all vectors lie in same hypersurface (spacelike if normal is timeline)

triangle vectors close (triangles form closed 3-cell)

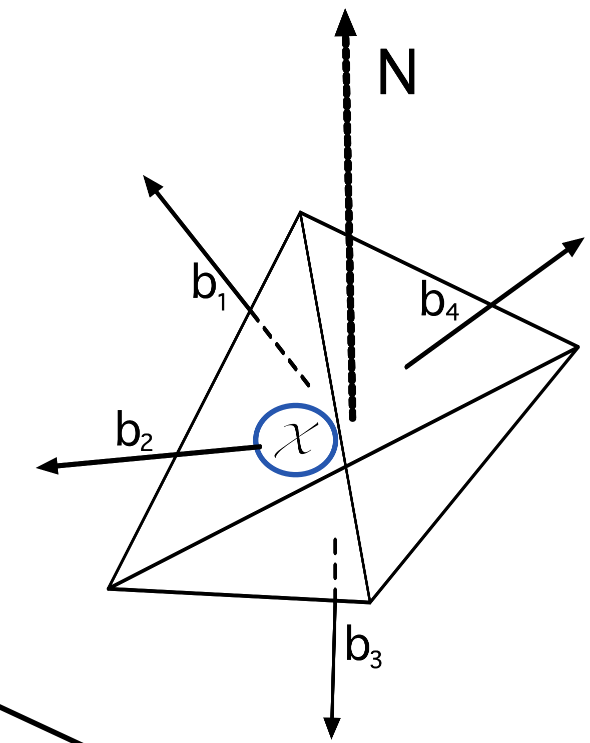
thus vectors are effectively $b_i \in \mathbb{R}^3$

identified with Lie algebra elements $\mathfrak{su}(2) \simeq \mathbb{R}^3$

- observables: e.g. triangle areas, volume $A_i = |b_i| \qquad V = \frac{1}{6}\sqrt{\vec{b_1} \cdot \vec{b_2} \times \vec{b_3}}$ become operators: $\vec{b_i} \rightarrow \hat{\vec{J_i}}$

GFTs: basics

4d case - specific class of models



atoms of space ~ quantum 3-simplices with extra scalar dofs

- geometric variables: triangle vectors ~ su(2) Lie algebra elements

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

4 triangle vectors (with modulus equal to area)

normal vector to 3d hypersurface

all vectors lie in same hypersurface (spacelike if normal is timeline)

triangle vectors close (triangles form closed 3-cell)

thus vectors are effectively $b_i \in \mathbb{R}^3$

identified with Lie algebra elements $\mathfrak{su}(2) \simeq \mathbb{R}^3$

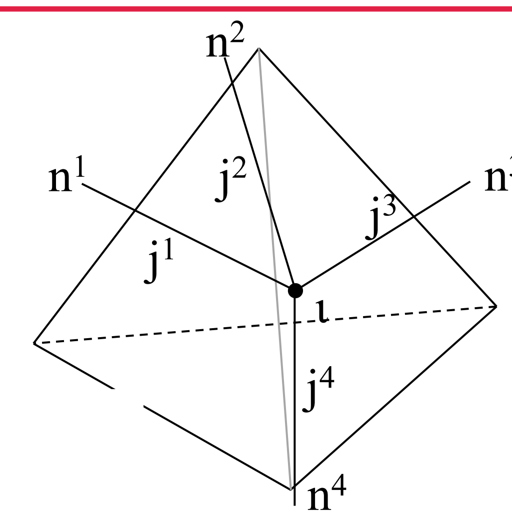
- observables: e.g. triangle areas, volume $A_i = |b_i| \qquad V = \frac{1}{6}\sqrt{\vec{b_1} \cdot \vec{b_2} \times \vec{b_3}}$ become operators: $\vec{b_i} \rightarrow \hat{\vec{J}_i}$

Hilbert space of quantum tetrahedron

spin network vertex ~ quantum tetrahedron

(in terms of SU(2) irreps)

$$\mathcal{H}_v = \bigoplus_{\vec{j}_v} \Big(\underbrace{\bigotimes_{i=1}^{d} V^{j_v^i}}_{\text{repr. space}} \otimes \underbrace{\mathcal{I}^{\vec{j}_v}}_{\text{intertwiner space}} \Big)$$



quantum geometric operators act on this Hilbert space:

$|j^i n^i\rangle \in V^{j^i}$ diagonalises area operator

$|\iota^{\vec{j}}\rangle \in \mathcal{I}^{\vec{j}} = \mathrm{Inv}_G\left[V^{j^1} \otimes \ldots \otimes V^{j^d}\right]$ diagonalises volume operator

+ scalar dofs $\otimes L^2(\mathbb{R} \times \ldots \times \mathbb{R})$

GFTs: basics

4d case - specific class of models

- equivalent representation: $\Psi(g_1, ..., g_4) = \Psi(g_1 h, ..., g_4 h) = \sum_{\{j_i, m_i; I\}} \Psi^{j_1 \dots j_4; I}_{m_1 \dots m_4} D^{j_1}_{m_1 n_1}(g_1) \dots D^{j_4}_{m_4 n_4}(g_4) C^{j_1 \dots j_4 I}_{n_1 \dots n_4}$

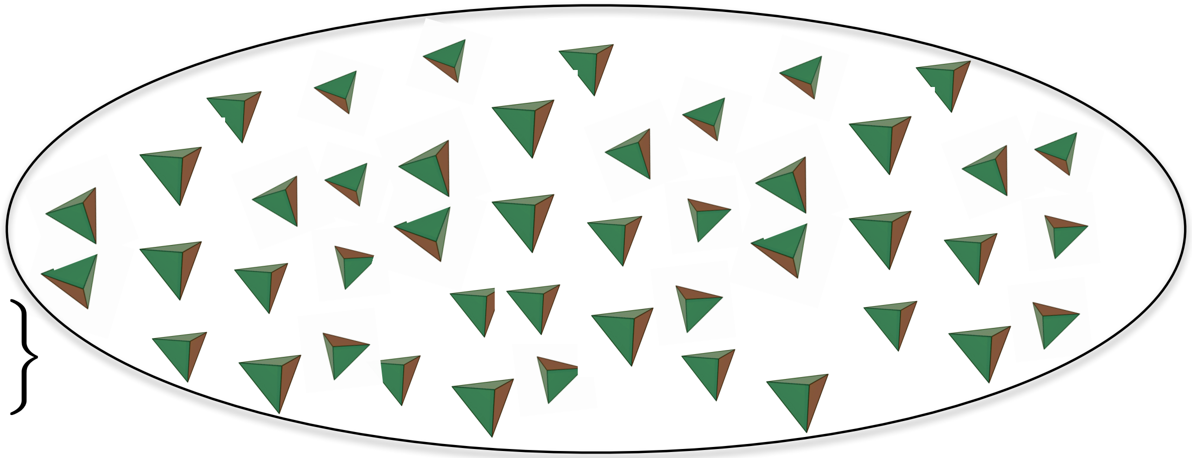
  thus $L^2(SU(2)^4/SU(2))$ (quantum geometry dofs)

GFTs: basics

4d case - specific class of models

- equivalent representation: $\Psi(g_1, ..., g_4) = \Psi(g_1 h, ..., g_4 h) = \sum_{\{j_i, m_i; I\}} \Psi^{j_1 \dots j_4; I}_{m_1 \dots m_4} D^{j_1}_{m_1 n_1}(g_1) \dots D^{j_4}_{m_4 n_4}(g_4) C^{j_1 \dots j_4 I}_{n_1 \dots n_4}$

  thus $L^2(SU(2)^4/SU(2))$ (quantum geometry dofs)



- Fock space

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

- GFT field operators (creating/annihilating tetrahedra):

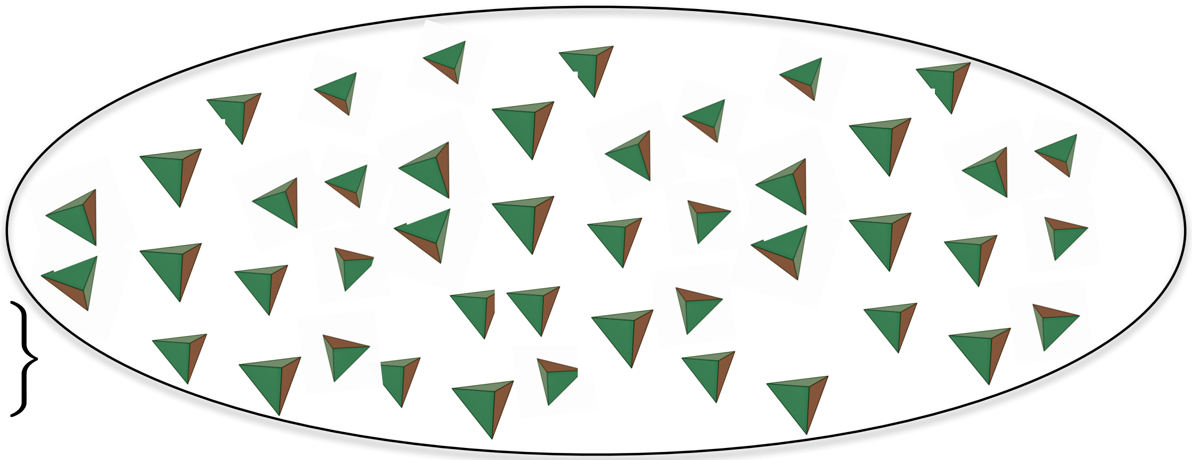
$$\hat{\varphi}(g_I, \chi^a) \;\equiv\; \hat{\varphi}(g_I, \chi^1, \dots, \chi^n) \qquad \left[\hat{\varphi}(\vec{g}) \, , \, \hat{\varphi}^\dagger(\vec{g}') \right] \;=\; \mathbb{I}_G(\vec{g}, \vec{g}') \qquad \left[\hat{\varphi}(\vec{g}) \, , \, \hat{\varphi}(\vec{g}') \right] \;=\; \left[\hat{\varphi}^\dagger(\vec{g}) \, , \, \hat{\varphi}^\dagger(\vec{g}') \right] \;=\; 0$$

GFTs: basics

4d case - specific class of models

- equivalent representation: $\Psi(g_1,...,g_4) = \Psi(g_1 h,...,g_4 h) = \sum_{\{j_i,m_i;I\}} \Psi^{j_1...j_4;I}_{m_1...m_4} D^{j_1}_{m_1 n_1}(g_1)...D^{j_4}_{m_4 n_4}(g_4) C^{j_1...j_4 I}_{n_1...n_4}$

  thus $L^2(SU(2)^4/SU(2))$ (quantum geometry dofs)



- Fock space

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

- GFT field operators (creating/annihilating tetrahedra):

$$\hat{\varphi}(g_I,\chi^a) \equiv \hat{\varphi}(g_I,\chi^1,\ldots,\chi^n) \qquad \left[\hat{\varphi}(\vec{g}),\hat{\varphi}^\dagger(\vec{g}')\right] = \mathbb{I}_G(\vec{g},\vec{g}') \qquad \left[\hat{\varphi}(\vec{g}),\hat{\varphi}(\vec{g}')\right] = \left[\hat{\varphi}^\dagger(\vec{g}),\hat{\varphi}^\dagger(\vec{g}')\right] = 0$$

- discrete (collective) quantum geometric observables

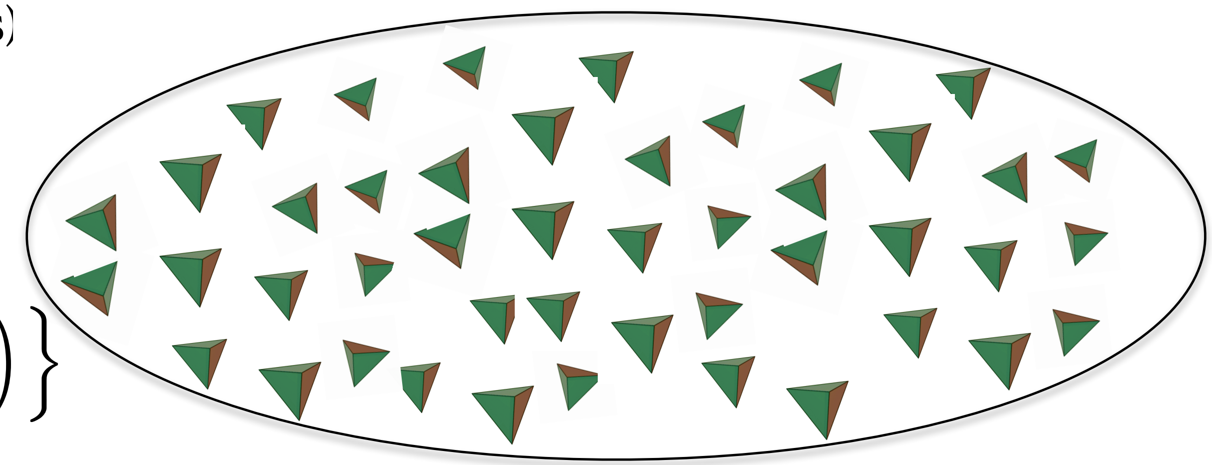
  e.g. volume $\hat{V}_{tot} = \int [dg_i][dg'_j]\hat{\varphi}^\dagger(g_i)\, V(g_i,g'_j)\, \hat{\varphi}(g'_j) = \sum_{J_i} \hat{\varphi}^\dagger(J_i)\, V(J_i)\, \hat{\varphi}(J_j)$

GFTs: basics

4d case - specific class of models

- equivalent representation: $\Psi(g_1, ..., g_4) = \Psi(g_1 h, ..., g_4 h) = \sum_{\{j_i, m_i; I\}} \Psi^{j_1 ... j_4; I}_{m_1 ... m_4} D^{j_1}_{m_1 n_1}(g_1) ... D^{j_4}_{m_4 n_4}(g_4) C^{j_1 ... j_4 I}_{n_1 ... n_4}$

  thus $L^2(SU(2)^4 / SU(2))$ (quantum geometry dofs)



- Fock space

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

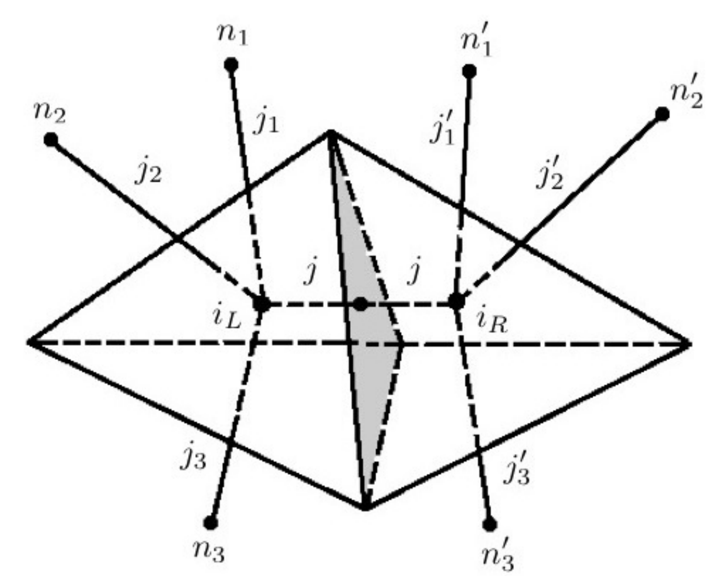
- GFT field operators (creating/annihilating tetrahedra):

$$\hat{\varphi}(g_I, \chi^a) \;\equiv\; \hat{\varphi}(g_I, \chi^1, \ldots, \chi^n) \qquad \left[\hat{\varphi}(\vec{g})\,,\,\hat{\varphi}^\dagger(\vec{g}')\right] = \mathbb{I}_G(\vec{g}, \vec{g}') \qquad \left[\hat{\varphi}(\vec{g})\,,\,\hat{\varphi}(\vec{g}')\right] = \left[\hat{\varphi}^\dagger(\vec{g})\,,\,\hat{\varphi}^\dagger(\vec{g}')\right] = 0$$

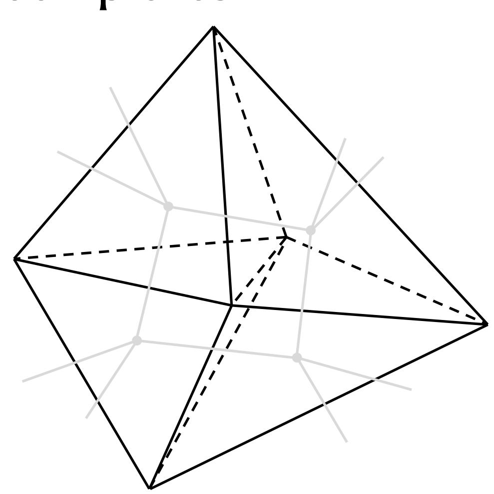
- discrete (collective) quantum geometric observables

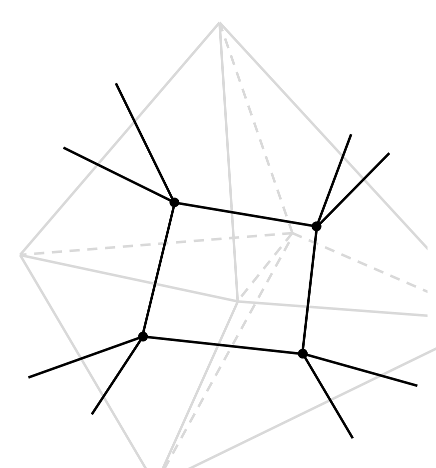
  e.g. volume $\hat{V}_{tot} \;=\; \int [dg_i][dg'_j] \hat{\varphi}^\dagger(g_i)\, V(g_i, g'_j)\, \hat{\varphi}(g'_j) \;=\; \sum_{J_i} \hat{\varphi}^\dagger(J_i)\, V(J_i)\, \hat{\varphi}(J_j)$

- maximal entanglement of "triangle dofs" ~ gluing of tetrahedra across triangle



entangled states ~ extended simplicial complexes



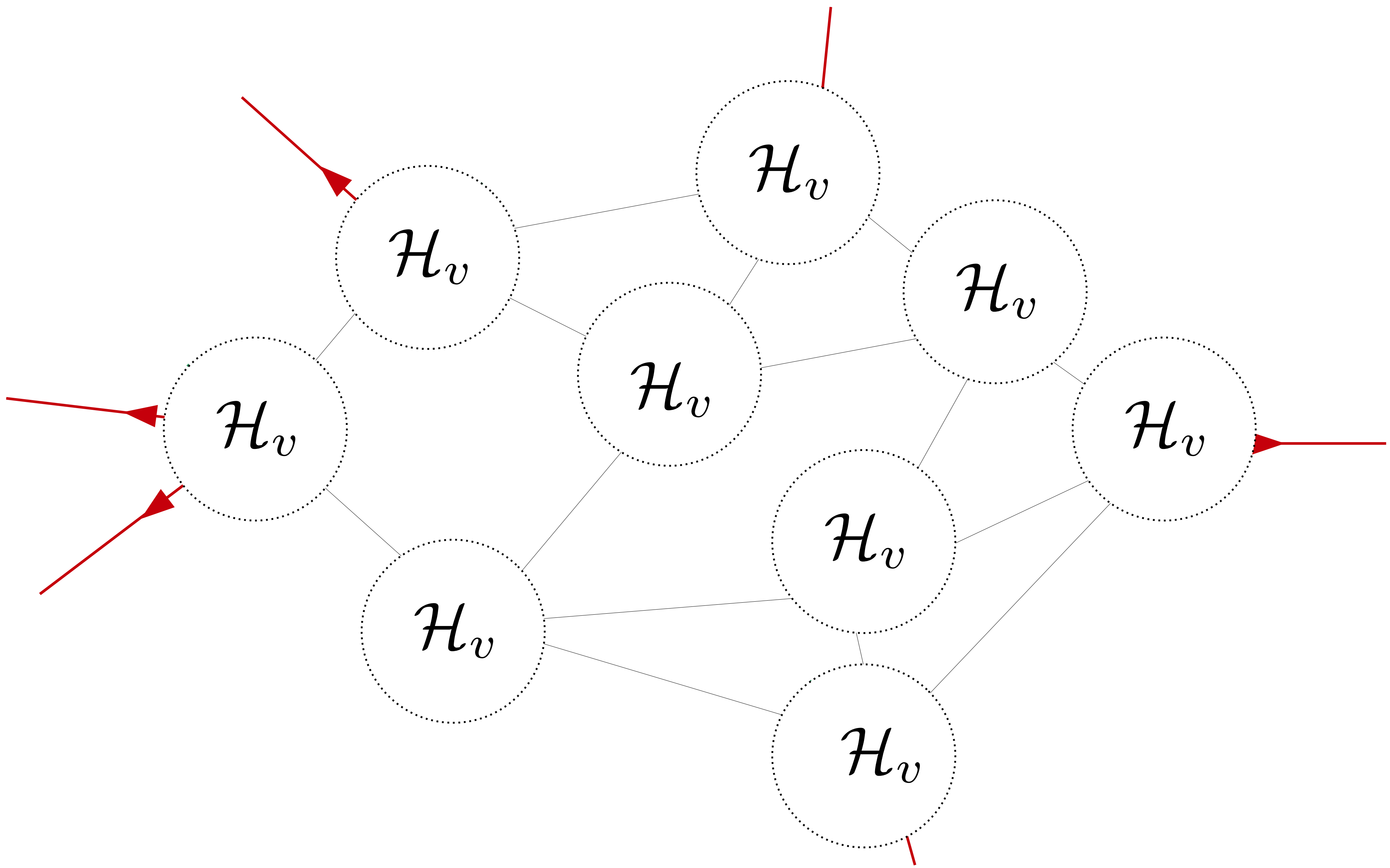


QG states = entanglement networks of quantum geometric blocks

algebraic data on graph

elementary quantum systems on nodes

graph ~ pattern of entanglement across nodes



structure shared by several QG formalisms (LQG, spin foams, lattice QG, TGFT)

GFTs: basics

4d case - specific class of models

dynamics of quantum atomic geometry

GFT action = prescription for weights associated to building blocks of 4d lattice in sum over discrete geometries

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

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

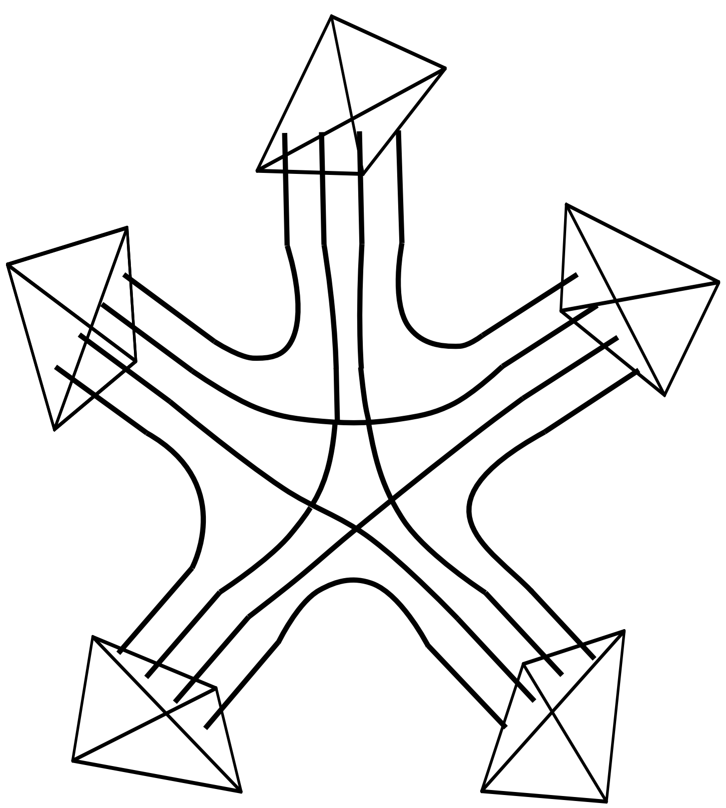
Feynman diagrams = stranded diagrams dual to cellular complexes of arbitrary topology

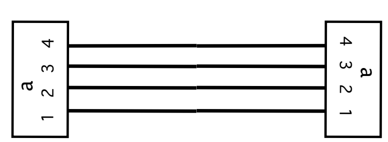
De Pietri, Petronio, '00; R. Gurau, '10; ...

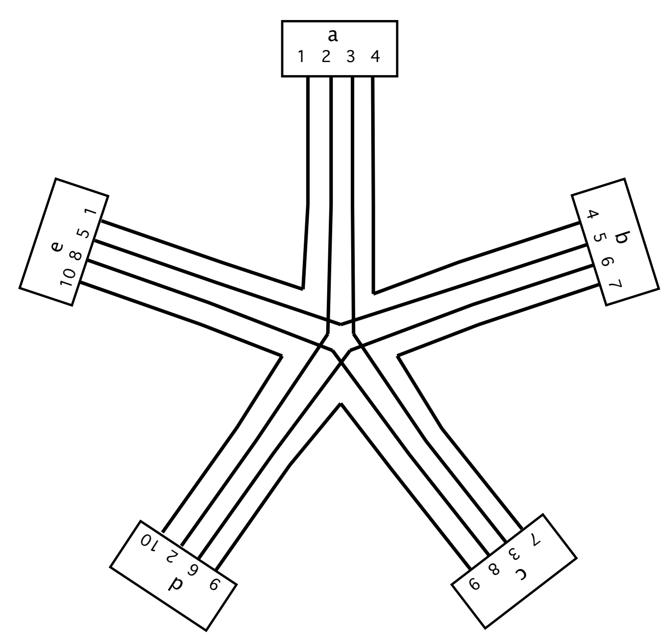
labelled by group-theoretic data (group elements, group irreps, ...)

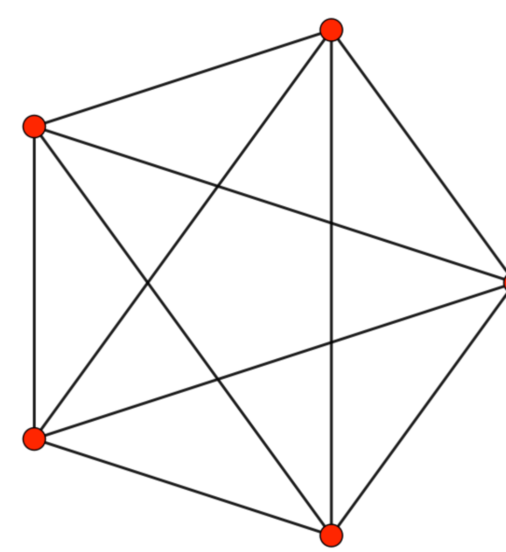
example: 3-simplices/4-tensors (4d)

generalises to any dimension (rank of tensor)









GFTs: basics

4d case - specific class of models

dynamics of quantum atomic geometry

GFT action = prescription for weights associated to building blocks of 4d lattice in sum over discrete geometries

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

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

Feynman diagrams = stranded diagrams dual to cellular complexes of arbitrary topology

De Pietri, Petronio, '00; R. Gurau, '10; ...

labelled by group-theoretic data (group elements, group irreps, ...)

Feynman amplitudes (model-dependent) = convolution of propagation kernels with interaction kernels = sum over group-theoretic data (group elements, Lie algebra elements, group irreps) associated to complex dual to Feynman diagram

Reisenberger,Rovelli, '00

- GFT Feynman amplitudes = lattice gravity path integrals (in group/algebra variables) on lattice dual to GFT Feynman diagram = spin foam models (in irreps variables)

A. Baratin, DO, '11

M. Finocchiaro, DO, '18

basic guideline for model-building (choosing GFT action):

GFT Feynman amplitudes = simplicial path integrals for gravity coupled to scalar fields

Quantum "transition amplitudes" for QG processes

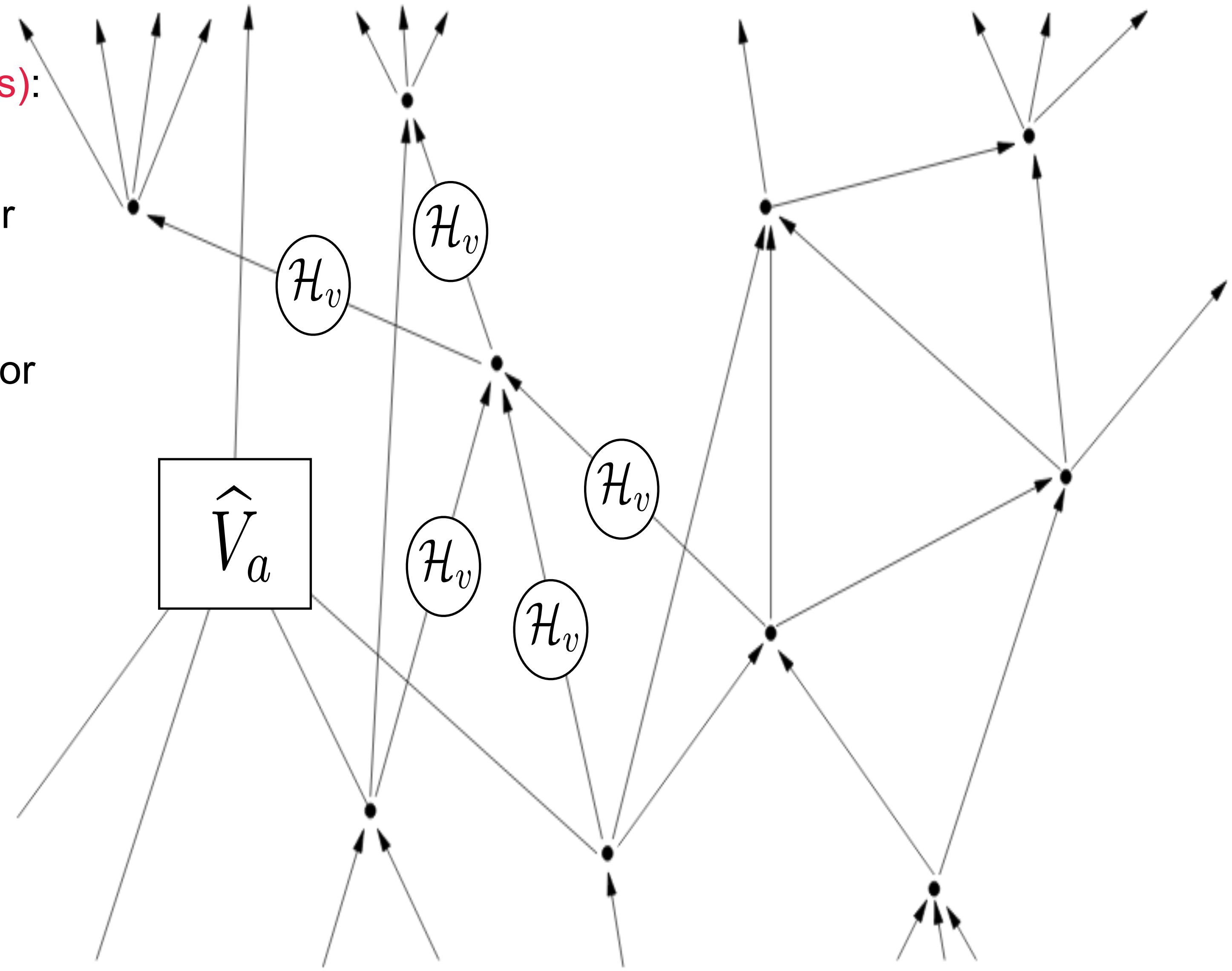
- quantum dynamics: assignment of quantum amplitude to each possible process (directed graph ~ cellular complex)

- full amplitude obtained from elementary operators (kernels):

$$\mathscr{V}_{\mathfrak{a}} \;:\; \bigotimes_{\mathfrak{p}\in\partial\mathfrak{a}} \mathcal{H}_{\mathfrak{p}} \longrightarrow \mathbb{C}$$ node operator

$$\mathscr{K}_e \;:\; \mathcal{H}_{\mathfrak{p}_1} \otimes \mathcal{H}_{\mathfrak{p}_2} \longrightarrow \mathbb{C}$$ gluing operator

with appropriate dualization reflecting orientation



- amplitude associated to whole complex):

$$\mathcal{A}(\mathfrak{m}) \;=\; \mathrm{Tr}_{\mathfrak{p}\in\mathfrak{m}}\left(\prod_{e|\mathfrak{m}} \mathscr{K}_e \prod_{\mathfrak{a}\in\mathfrak{m}} \mathscr{V}_{\mathfrak{a}}\right)$$

(trace defined over complete basis in link Hilbert spaces

- different quantum gravity models (spin foam, LQG, lattice QG, TGFT) = different choices of elementary operators (and Hilbert spaces)

note: classical approx on given lattice ---> sum over saddles of discrete gravity path integral = good simplicial geometries on given lattice

$$\mathcal{A}(\mathfrak{m}) \sim \sum_{g_\Delta = classical} e^{i\,S(g_\Delta)}$$

GFTs: example

Boulatov model - topological 3d euclidean QG (no matter)

$\varphi : SU(2)^{\times 3} \to \mathbb{C}$ ~ quantum triangles

$$S(\varphi) = \frac{1}{2} \int [dg] \varphi^2(g_1, g_2, g_3) + \frac{\lambda}{4!} \int [dg] \varphi(g_1, g_2, g_3) \varphi(g_3, g_4, g_5) \varphi(g_5, g_2, g_6) \varphi(g_6, g_4, g_1) + \text{cc}$$

for fields satisfying: $\varphi(g_1, g_2, g_3) = \varphi(hg_1, hg_2, hg_3) \quad \forall h \in SU(2)$

partition function & perturbative expansion

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

Feynman diagrams dual to 3d simplicial lattices

GFTs: example

Boulatov model - topological 3d euclidean QG (no matter)

$\varphi : SU(2)^{\times 3} \to \mathbb{C}$ ~ quantum triangles

$$S(\varphi) = \frac{1}{2}\int [dg]\varphi^2(g_1, g_2, g_3) + \frac{\lambda}{4!}\int [dg]\varphi(g_1, g_2, g_3)\,\varphi(g_3, g_4, g_5)\,\varphi(g_5, g_2, g_6)\,\varphi(g_6, g_4, g_1) + \text{cc}$$

for fields satisfying: $\varphi(g_1, g_2, g_3) = \varphi(hg_1, hg_2, hg_3) \quad \forall h \in SU(2)$

partition function & perturbative expansion

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

Feynman diagrams dual to 3d simplicial lattices

Feynman amplitudes in different representations:

$$\mathcal{A}_\Gamma = \int \prod_l \mathrm{d}h_l \prod_f \delta\left(H_f(h_l)\right) = \int \prod_l \mathrm{d}h_l \prod_f \delta\left(\overrightarrow{\prod}_{l\in\partial f} h_l\right) =$$

$$= \sum_{\{j_e\}} \prod_e d_{j_e} \prod_\tau \begin{Bmatrix} j_1^\tau & j_2^\tau & j_3^\tau \\ j_4^\tau & j_5^\tau & j_6^\tau \end{Bmatrix} = \int \prod_l [\mathrm{d}h_l] \prod_e [\mathrm{d}^3 x_e]\, e^{i\sum_e \mathrm{Tr}\, x_e H_e}$$

GFTs: example

Boulatov model - topological 3d euclidean QG (no matter)

$\varphi : SU(2)^{\times 3} \to \mathbb{C}$ ~ quantum triangles

$$S(\varphi) = \frac{1}{2} \int [dg] \varphi^2(g_1, g_2, g_3) + \frac{\lambda}{4!} \int [dg] \varphi(g_1, g_2, g_3)\, \varphi(g_3, g_4, g_5)\, \varphi(g_5, g_2, g_6)\, \varphi(g_6, g_4, g_1) + \text{cc}$$

for fields satisfying: $\varphi(g_1, g_2, g_3) = \varphi(hg_1, hg_2, hg_3) \qquad \forall h \in SU(2)$

partition function & perturbative expansion

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

Feynman diagrams dual to 3d simplicial lattices

Feynman amplitudes in different representations:

$$\mathcal{A}_\Gamma = \int \prod_l \mathrm{d}h_l \prod_f \delta\left(H_f(h_l)\right) = \int \prod_l \mathrm{d}h_l \prod_f \delta\left(\overrightarrow{\prod}_{l \in \partial f} h_l \right) =$$

$$= \sum_{\{j_e\}} \prod_e d_{j_e} \prod_\tau \left\{ \begin{array}{ccc} j_1^\tau & j_2^\tau & j_3^\tau \\ j_4^\tau & j_5^\tau & j_6^\tau \end{array} \right\} = \int \prod_l [\mathrm{d}h_l] \prod_e [\mathrm{d}^3 x_e]\, e^{i \sum_e \mathrm{Tr}\, x_e H_e}$$

lattice gauge theory formulation of 3d gravity/BF theory

GFTs: example

Boulatov model - topological 3d euclidean QG (no matter)

$\varphi : SU(2)^{\times 3} \to \mathbb{C}$ ~ quantum triangles

$$S(\varphi) = \frac{1}{2}\int [dg]\varphi^2(g_1, g_2, g_3) + \frac{\lambda}{4!}\int [dg]\varphi(g_1, g_2, g_3)\,\varphi(g_3, g_4, g_5)\,\varphi(g_5, g_2, g_6)\,\varphi(g_6, g_4, g_1) + cc$$

for fields satisfying: $\varphi(g_1, g_2, g_3) = \varphi(hg_1, hg_2, hg_3) \qquad \forall h \in SU(2)$

partition function & perturbative expansion

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

Feynman diagrams dual to 3d simplicial lattices

Feynman amplitudes in different representations:

$$\mathcal{A}_\Gamma = \int \prod_l \mathrm{d}h_l \prod_f \delta\left(H_f(h_l)\right) = \int \prod_l \mathrm{d}h_l \prod_f \delta\left(\overrightarrow{\prod}_{l\in\partial f} h_l\right) =$$

lattice gauge theory formulation of 3d gravity/BF theory

$$= \sum_{\{j_e\}} \prod_e d_{j_e} \prod_\tau \left\{ \begin{array}{ccc} j_1^\tau & j_2^\tau & j_3^\tau \\ j_4^\tau & j_5^\tau & j_6^\tau \end{array} \right\} = \int \prod_l [\mathrm{d}h_l] \prod_e [\mathrm{d}^3 x_e]\, e^{i\sum_e \mathrm{Tr}\, x_e H_e}$$

spin foam formulation of 3d gravity

i.e. quantum covariant dynamics
of spin networks (LQG)

GFTs: example

Boulatov model - topological 3d euclidean QG (no matter)

$\varphi : SU(2)^{\times 3} \to \mathbb{C}$ ~ quantum triangles

$$S(\varphi) = \frac{1}{2}\int [dg]\varphi^2(g_1, g_2, g_3) + \frac{\lambda}{4!}\int [dg]\varphi(g_1, g_2, g_3)\,\varphi(g_3, g_4, g_5)\,\varphi(g_5, g_2, g_6)\,\varphi(g_6, g_4, g_1) + \text{cc}$$

for fields satisfying: $\varphi(g_1, g_2, g_3) = \varphi(hg_1, hg_2, hg_3) \quad \forall h \in SU(2)$

partition function & perturbative expansion

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

Feynman diagrams dual to 3d simplicial lattices

Feynman amplitudes in different representations:

$$\mathcal{A}_\Gamma = \int \prod_l \mathrm{d}h_l \prod_f \delta\left(H_f(h_l)\right) = \int \prod_l \mathrm{d}h_l \prod_f \delta\left(\overrightarrow{\prod}_{l\in\partial f} h_l\right) =$$

lattice gauge theory formulation of 3d gravity/BF theory

$$= \sum_{\{j_e\}} \prod_e d_{j_e} \prod_\tau \begin{Bmatrix} j_1^\tau & j_2^\tau & j_3^\tau \\ j_4^\tau & j_5^\tau & j_6^\tau \end{Bmatrix} = \int \prod_l [\mathrm{d}h_l] \prod_e [\mathrm{d}^3 x_e]\, e^{i\sum_e \mathrm{Tr}\, x_e H_e}$$

spin foam formulation of 3d gravity

i.e. quantum covariant dynamics of spin networks (LQG)

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

GFTs: example

Boulatov model - topological 3d euclidean QG (no matter)

$\varphi : SU(2)^{\times 3} \to \mathbb{C}$ ~ quantum triangles

$$S(\varphi) = \frac{1}{2}\int [dg]\varphi^2(g_1, g_2, g_3) + \frac{\lambda}{4!}\int [dg]\varphi(g_1, g_2, g_3)\,\varphi(g_3, g_4, g_5)\,\varphi(g_5, g_2, g_6)\,\varphi(g_6, g_4, g_1) + \text{cc}$$

for fields satisfying: $\varphi(g_1, g_2, g_3) = \varphi(hg_1, hg_2, hg_3) \qquad \forall h \in SU(2)$

partition function & perturbative expansion

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

Feynman diagrams dual to 3d simplicial lattices

Feynman amplitudes in different representations:

$$\mathcal{A}_\Gamma = \int \prod_l \mathrm{d}h_l \prod_f \delta\left(H_f(h_l)\right) = \int \prod_l \mathrm{d}h_l \prod_f \delta\left(\overrightarrow{\prod}_{l\in\partial f} h_l\right) =$$

lattice gauge theory formulation of 3d gravity/BF theory

$$= \sum_{\{j_e\}} \prod_e d_{j_e} \prod_\tau \left\{ \begin{array}{ccc} j_1^\tau & j_2^\tau & j_3^\tau \\ j_4^\tau & j_5^\tau & j_6^\tau \end{array} \right\} = \int \prod_l [\mathrm{d}h_l] \prod_e [\mathrm{d}^3 x_e]\, e^{i\sum_e \mathrm{Tr}\, x_e H_e}$$

spin foam formulation of 3d gravity

i.e. quantum covariant dynamics of spin networks (LQG)

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

discretization of Palatini gravity: $S(e,\omega) = \int Tr(e \wedge F(\omega))$

GFT example - 4d Lorentzian QG

(motivated by: LQG + simplicial quantum geometry)

EPRL model $$S = \sum_{\substack{j_{v_{a_i}} \\ m_{v_{a_i}}, \iota_a}} \bar{\varphi}^{j_{v_1}\iota_1}_{m_{v_1}} \varphi^{j_{v_2}\iota_2}_{m_2} \, (\mathscr{K}_2)^{j_{v_1}j_{v_2}\iota_1\iota_2}_{m_{v_1},m_{v_2}} + V$$

$$V = \sum_{j_i, m_i, \iota_i} \left[\varphi^{j_1 j_2 j_3 j_4 \iota_1}_{m_1 m_2 m_3 m_4} \; \varphi^{j_4 j_5 j_6 j_7 \iota_2}_{m_4 m_5 m_6 m_7} \; \varphi^{j_7 j_3 j_8 j_9 \iota_3}_{m_7 m_3 m_8 m_9} \; \varphi^{j_9 j_6 j_2 j_{10} \iota_4}_{m_9 m_6 m_2 m_{10}} \; \varphi^{j_{10} j_8 j_5 j_1 \iota_5}_{m_{10} m_8 m_5 m_1} \times \tilde{\mathscr{V}}_5(j_1, \dots, j_{10}; \iota_1, \dots, \iota_5) \right]$$

$$\tilde{\mathscr{V}}_5(j_{ab}, i_a) = \sum_{n_a} \int d\rho_a (n_a^2 + \rho_a^2) \left(\bigotimes_a f^{i_a}_{n_a \rho_a}(j_{ab}) \right) 15j_{SL(2,\mathbb{C})}\left((2j_{ab}, 2j_{ab}\gamma); (n_a, \rho_a)\right)$$

$$f^i_{n\rho} := i^{m_1 \dots m_4} \; \bar{C}^{n\rho}_{(j_1,m_1)\dots(j_4,m_4)} \qquad \rho = \gamma n \qquad n = 2j$$

based on SU(2) group and irreps - relation between SL(2,C) and SU(2) data; (almost) SU(2) spin network states

Feynman amplitudes: no need here

specific form of action implements:

conditions for well-defined simplicial quantum geometry of GFT quanta (3-simplices)

conditions for producing 4d lattices with proper simplicial quantum geometry in perturbative expansion

Example:

TGFT cosmology

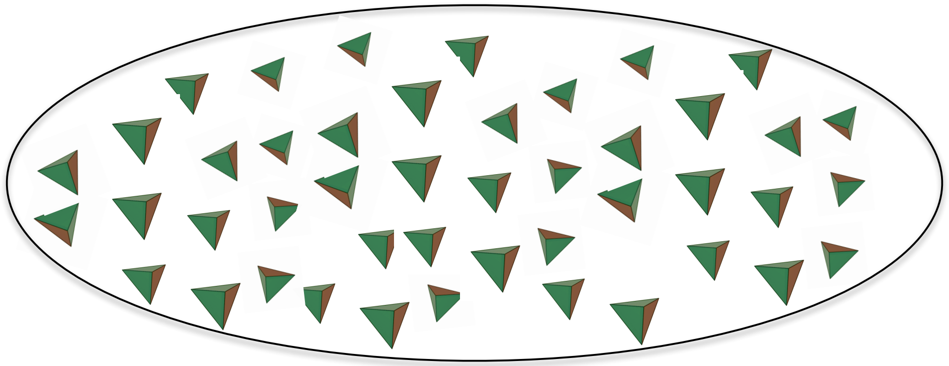
emergent spacetime physics from QG

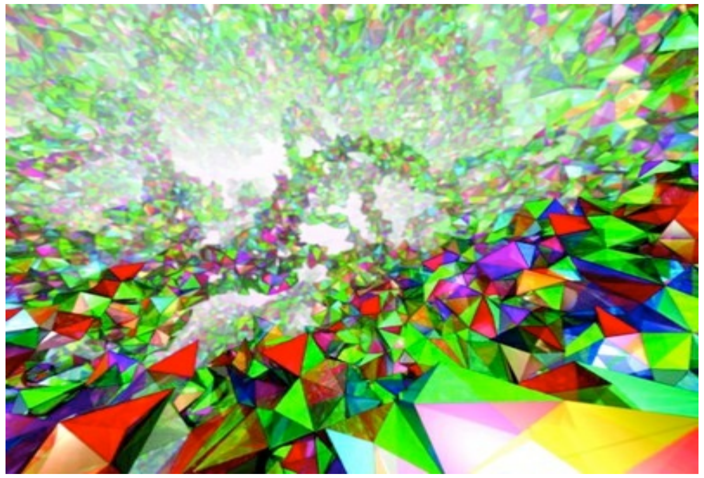
spacetime and geometry are emergent in GFT

from perspective of fundamental QG atoms of space:

continuum geometry = coarse-grained description of discrete geometry of many (infinite) QG atoms

GR dynamics = approximate description of collective quantum dynamics of many (infinite) QG atoms



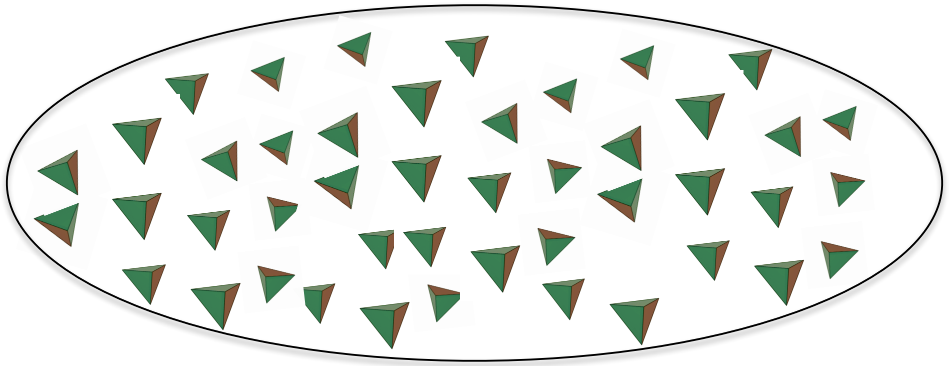


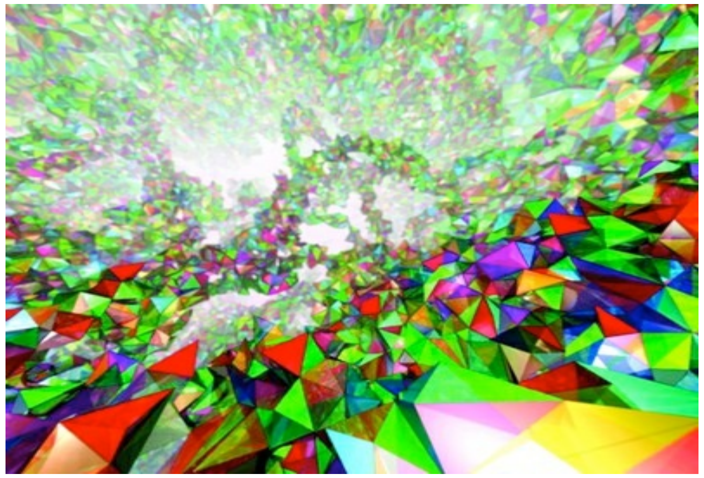
spacetime and geometry are emergent in GFT

from perspective of fundamental QG atoms of space:

continuum geometry = coarse-grained description of discrete geometry of many (infinite) QG atoms

GR dynamics = approximate description of collective quantum dynamics of many (infinite) QG atoms





cosmology expected to correspond to "most coarse-grained" dynamics

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

GFT cosmology

- general strategy:
  - hypothesis: universe as QG quantum fluid (condensate)
  - extract approximate hydrodynamic eqns for QG fluid (density and phase)
  - compute relational cosmological observables in hydrodynamic approximation, as functions of density & phase
  - translate hydrodynamic eqns into eqns for cosmological observables

GFT cosmology

- general strategy:
  - hypothesis: universe as QG quantum fluid (condensate)
  - extract approximate hydrodynamic eqns for QG fluid (density and phase)
  - compute relational cosmological observables in hydrodynamic approximation, as functions of density & phase
  - translate hydrodynamic eqns into eqns for cosmological observables

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

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

$$F_\lambda(J) \;=\; \ln Z_\lambda[J] \qquad \Gamma[\phi] \;=\; sup_J\left(J\cdot\phi - F(J)\right) \quad \langle\varphi\rangle = \phi$$

✳ simplest approximation: mean field hydrodynamics

$$\Gamma[\phi] \;\approx\; S_\lambda(\phi)$$

mean field ~ condensate wavefunction

- corresponding quantum states:

(simplest): GFT condensate, GFT field coherent state

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

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

GFT cosmology

general facts

- cosmological interpretation natural and clear:

isomorphism between domain of TGFT condensate wavefunction and minisuperpsace

$$\sigma\left(\mathcal{D}\right) \qquad \mathcal{D} \simeq \{\text{geometries of tetrahedron}\} \simeq$$
$$\simeq \{\text{continuum spatial geometries at a point}\} \simeq$$
$$\simeq \text{minisuperspace of homogeneous geometries}$$

S. Gielen, DO, L. Sindoni, '13

- general form of resulting (Gross-Pitaevskii) equations of motion for condensate wavefunction (mean field):

$$\int [dg'] d\chi' \mathcal{K}(g,\chi;g',\chi')\sigma(g',\chi') + \lambda \frac{\delta}{\delta\varphi}\mathcal{V}(\varphi)|_{\varphi\equiv\sigma} = 0$$

Gielen, DO, Sindoni, '13; DO, Sindoni, Wilson-Ewing, '16

polynomial functional of condensate wavefunction

cosmology as QG hydrodynamics ~ non-linear extension of (loop) quantum cosmology

that is, in isotropic restriction and with just one matter field:

$\sigma(a,\phi)$ "wavefunction" on minisuperspace

$\mathcal{K}(a,\partial_a,\phi,\partial_\phi)\sigma(a,\phi) + \mathcal{V}\left[\sigma(a,\phi)\right] = 0$ hydrodynamic (non-linear, possibly non-local) eqn on minisuperspace

GFT cosmology

general facts

- cosmological interpretation natural and clear:

isomorphism between domain of TGFT condensate wavefunction and minisuperpsace

$$\sigma(\mathcal{D}) \qquad \mathcal{D} \simeq \{\text{geometries of tetrahedron}\} \simeq$$
$$\simeq \{\text{continuum spatial geometries at a point}\} \simeq$$
$$\simeq \text{minisuperspace of homogeneous geometries}$$

S. Gielen, DO, L. Sindoni, '13

- general form of resulting (Gross-Pitaevskii) equations of motion for condensate wavefunction (mean field):

$$\int [dg'] d\chi' \mathcal{K}(g,\chi;g',\chi')\sigma(g',\chi') + \lambda \frac{\delta}{\delta\varphi}\mathcal{V}(\varphi)|_{\varphi\equiv\sigma} = 0$$

Gielen, DO, Sindoni, '13; DO, Sindoni, Wilson-Ewing, '16

polynomial functional of condensate wavefunction

cosmology as QG hydrodynamics ~ non-linear extension of (loop) quantum cosmology

- cosmological observables are fluid averages = mean values of fundamental QG operators in Fock space

relationally localized in time/space as functions of values of physical (e.g. scalar matter) dofs, specified by the GFT state (for GFT models including such dofs)

e.g. volume operator

$$\hat{V} = \int \mathrm{d}^n\chi \int \mathrm{d}g_I\, \mathrm{d}g'_I\, \hat{\varphi}^\dagger(g_I,\chi^a) V(g_I,g'_I)\hat{\varphi}(g'_I,\chi^a) \longrightarrow V(x^0,x^i) = \langle\sigma_{(x^0,x^i)}|\hat{V}|\sigma_{(x^0,x^i)}\rangle|\sigma_{(x^0,x^i)}$$

- eqn for condensate wavefunction ------> eqn for geometric/cosmological observables

GFT cosmology

concrete example of cosmology from "quantum geometric" GFT models

valid for EPRL & BC models, possibly more

general mean field eqns for quantum geometry coupled to 5 scalar fields in peaked states

general form of dynamics - work with parametrized ambiguities

$$S_{\mathrm{GFT}} = K + U + U^*$$

$$K = \int \mathrm{d}g_I\, \mathrm{d}h_I \int \mathrm{d}^d\chi\, \mathrm{d}^d\chi'\, \mathrm{d}\phi\, \mathrm{d}\phi'\, \bar{\varphi}(g_I,\chi)\mathcal{K}(g_I,h_I;(\chi-\chi')^2_\lambda,(\phi-\phi')^2)\varphi(h_I,(\chi')^\mu,\phi')$$

$$U = \int \mathrm{d}^d\chi\, \mathrm{d}\phi \int \left(\prod_{a=1}^{5} \mathrm{d}g_I^a\right) \mathcal{U}(g_I^1,\ldots,g_I^5) \prod_{\ell=1}^{5} \varphi(g_I^\ell,\chi^\mu,\phi)$$

simple mean field approx. - classical GFT eqns

S. Gielen, DO, L. Sindoni, '13

$$\left\langle \frac{\delta S_{\mathrm{GFT}}[\hat{\varphi},\hat{\varphi}^\dagger]}{\delta\hat{\varphi}^\dagger(g_I,\chi_0)} \right\rangle_{\sigma_{\epsilon^\mu};x^\mu,\pi_\mu} \equiv \left\langle \sigma_{\epsilon^\mu};x^\mu,\pi_\mu \left| \frac{\delta S_{\mathrm{GFT}}[\hat{\varphi},\hat{\varphi}^\dagger]}{\delta\hat{\varphi}^\dagger(g_I,\chi_0)} \right| \sigma_{\epsilon^\mu};x^\mu,\pi_\mu \right\rangle = 0$$

restriction to "good clock+rods" condensate states - peakedness properties on clock/rod values

peaked functions (e.g. Gaussians)

$$\sigma_{\epsilon,\delta,\pi_0,\pi_x;x^\mu}(g_I,\chi^\mu,\phi) = \eta_\epsilon(\chi^0-x^0;\pi_0)\eta_\delta(|\boldsymbol{\chi}-\mathbf{x}|;\pi_x)\tilde{\sigma}(g_I,\chi^\mu,\phi)$$

L. Marchetti, DO, '20, '21

$|\boldsymbol{\chi}-\mathbf{x}|^2 = \sum_{i=1}^d(\chi^i-x^i)^2$ $\quad \mathbb{C} \ni \delta = \delta_r + i\delta_i$ $\quad \delta_r > 0$ $\quad \epsilon, |\delta| \ll 1$ $\quad z_0 \equiv \epsilon\pi_0^2/2$ $\quad z \equiv \delta\pi_x^2/2$

GFT cosmology

Observables and their relational (mean) values

- number operator $$\hat{N} = \int \mathrm{d}^n\chi \int \mathrm{d}g_I \, \hat{\varphi}^\dagger(g_I, \chi^a)\hat{\varphi}(g_I, \chi^a)$$
- universe volume $$\hat{V} = \int \mathrm{d}^n\chi \int \mathrm{d}g_I \, \mathrm{d}g'_I \, \hat{\varphi}^\dagger(g_I, \chi^a)V(g_I, g'_I)\hat{\varphi}(g'_I, \chi^a)$$
- value of clock/rods scalar fields $$\hat{X}^b \equiv \int \mathrm{d}^n\chi \int \mathrm{d}g_I \, \chi^b \hat{\varphi}^\dagger(g_I, \chi^a)\hat{\varphi}(g_I, \chi^a)$$
- momentum of clock/rods scalar fields $$\hat{\Pi}_b = \frac{1}{i}\int \mathrm{d}^n\chi \int \mathrm{d}g_I \left[\hat{\varphi}^\dagger(g_I, \chi^a)\left(\frac{\partial}{\partial\chi^b}\hat{\varphi}(g_I, \chi^a)\right)\right]$$
- value of matter scalar field $$\hat{\Phi} = \frac{1}{i}\int \mathrm{d}g_I \int \mathrm{d}^4\chi \int \mathrm{d}\pi_\phi \, \hat{\varphi}^\dagger(g_I, \chi^\mu, \pi_\phi)\partial_{\pi_\phi}\hat{\varphi}(g_I, \chi^\mu, \pi_\phi)$$
- momentum of matter scalar field $$\hat{\Pi}_\phi = \int \mathrm{d}g_I \int \mathrm{d}^4\chi \int \mathrm{d}\pi_\phi \, \pi_\phi \hat{\varphi}^\dagger(g_I, \chi^\mu, \pi_\phi)\hat{\varphi}(g_I, \chi^\mu, \pi_\phi)$$

GFT cosmology

Observables and their relational (mean) values

- number operator $$\hat{N} = \int \mathrm{d}^n\chi \int \mathrm{d}g_I\, \hat{\varphi}^\dagger(g_I,\chi^a)\hat{\varphi}(g_I,\chi^a)$$
- universe volume $$\hat{V} = \int \mathrm{d}^n\chi \int \mathrm{d}g_I\, \mathrm{d}g_I'\, \hat{\varphi}^\dagger(g_I,\chi^a)V(g_I,g_I')\hat{\varphi}(g_I',\chi^a)$$
- value of clock/rods scalar fields $$\hat{X}^b \equiv \int \mathrm{d}^n\chi \int \mathrm{d}g_I\, \chi^b\hat{\varphi}^\dagger(g_I,\chi^a)\hat{\varphi}(g_I,\chi^a)$$
- momentum of clock/rods scalar fields $$\hat{\Pi}_b = \frac{1}{i}\int \mathrm{d}^n\chi \int \mathrm{d}g_I \left[\hat{\varphi}^\dagger(g_I,\chi^a)\left(\frac{\partial}{\partial\chi^b}\hat{\varphi}(g_I,\chi^a)\right)\right]$$
- value of matter scalar field $$\hat{\Phi} = \frac{1}{i}\int \mathrm{d}g_I \int \mathrm{d}^4\chi \int \mathrm{d}\pi_\phi\, \hat{\varphi}^\dagger(g_I,\chi^\mu,\pi_\phi)\partial_{\pi_\phi}\hat{\varphi}(g_I,\chi^\mu,\pi_\phi)$$
- momentum of matter scalar field $$\hat{\Pi}_\phi = \int \mathrm{d}g_I \int \mathrm{d}^4\chi \int \mathrm{d}\pi_\phi\, \pi_\phi\hat{\varphi}^\dagger(g_I,\chi^\mu,\pi_\phi)\hat{\varphi}(g_I,\chi^\mu,\pi_\phi)$$

operators defined in full QG theory

used to define collective relational (spacetime localized) observables for effective continuum dynamics

as expectation values in "good clock+rods" condensate states

$$N(x^0,x^i) \equiv \langle\sigma_{\epsilon,\delta,\pi_0,\pi_x,x^\mu}|\hat{N}|\sigma_{\epsilon,\delta,\pi_0,\pi_x,x^\mu}\rangle \qquad V(x^0,x^i) \equiv \langle\sigma_{\epsilon,\delta,\pi_0,\pi_x,x^\mu}|\hat{V}|\sigma_{\epsilon,\delta,\pi_0,\pi_x,x^\mu}\rangle$$

$$X^\mu(x^0,x^i) \equiv \langle\sigma_{\epsilon,\delta,\pi_0,\pi_x,x^\mu}|\hat{V}|\sigma_{\epsilon,\delta,\pi_0,\pi_x,x^\mu}\rangle \simeq x^\mu \qquad \Pi(x^0,x^i) \equiv \langle\sigma_{\epsilon,\delta,\pi_0,\pi_x,x^\mu}|\widehat{\Pi_\nu}|\sigma_{\epsilon,\delta,\pi_0,\pi_x,x^\mu}\rangle$$

$$\phi(x^0,x^i) \equiv \langle\sigma_{\epsilon,\delta,\pi_0,\pi_x,x^\mu}|\hat{\Phi}|\sigma_{\epsilon,\delta,\pi_0,\pi_x,x^\mu}\rangle \qquad \Pi_\phi(x^0,x^i) \equiv \langle\sigma_{\epsilon,\delta,\pi_0,\pi_x,x^\mu}|\widehat{\Pi}_\phi|\sigma_{\epsilon,\delta,\pi_0,\pi_x,x^\mu}\rangle$$

concrete example of cosmology from "quantum geometric" TGFT models

valid for EPRL & BC models, possibly more

hydrodynamics eqns for cosmological observables

(with some assumptions on states + approximations)

using: $\tilde{\sigma}_j \equiv \rho_j \exp[i\theta_j]$ rewrite in standard hydrodynamic form (fluid density, phase)

homogeneous background + inhomogeneous perturbations (spacetime localization defined in relational terms)

$$\rho_j = \bar{\rho}_j + \delta\rho_j \qquad \theta_j \equiv \bar{\theta}_j + \delta\theta_j \qquad \bar{\rho} = \bar{\rho}(x^0, \pi_\phi) \qquad \bar{\theta} = \bar{\theta}(x^0, \pi_\phi)$$

can also extract

effective dynamics for scalar cosmological perturbations

L. Marchetti, DO, '22; A. Jercher, L. Marchetti, A. Pithis, '23;
R. Dekhil, S. Liberati, DO, to appear

can be recast in standard local QFT language)

n.b. localization is relational - non-trivial spatial dependence comes from
non-trivial dependence of mean field perturbations on the relational rods

concrete example of cosmology from "quantum geometric" TGFT models   valid for EPRL & BC models, possibly more

hydrodynamics eqns for cosmological observables   (with some assumptions on states + approximations)

using: $\tilde{\sigma}_j \equiv \rho_j \exp[i\theta_j]$ rewrite in standard hydrodynamic form (fluid density, phase)

homogeneous background + inhomogeneous perturbations (spacetime localization defined in relational terms)

$$\rho_j = \bar{\rho}_j + \delta\rho_j \qquad \theta_j \equiv \bar{\theta}_j + \delta\theta_j \qquad \bar{\rho} = \bar{\rho}(x^0, \pi_\phi) \qquad \bar{\theta} = \bar{\theta}(x^0, \pi_\phi)$$

background volume dynamics: L. Marchetti, DO, '21   A. Jercher, DO, A. Pithis, 21

$$\left(\frac{V'}{3V}\right)^2 \simeq \left(\frac{2\sum_j \int d\pi_\phi V_j \, \mathrm{sgn}(\rho')\rho_j \sqrt{\mathcal{E}_j - Q_j^2/\rho_j^2 + \mu_j^2\rho_j^2}}{3\sum_j \int d\pi_\phi V_j \rho_j^2}\right)^2$$

$$\frac{V''}{V} \simeq \frac{2\sum_j \int d\pi_\phi V_j \, \left[\mathcal{E}_j + 2\mu_j^2\rho_j^2\right]}{\sum_j \int d\pi_\phi V_j \rho_j^2}$$

can also extract

effective dynamics for scalar cosmological perturbations

L. Marchetti, DO, '22; A. Jercher, L. Marchetti, A. Pithis, '23;
R. Dekhil, S. Liberati, DO, to appear

can be recast in standard local QFT language)

n.b. localization is relational - non-trivial spatial dependence comes from
non-trivial dependence of mean field perturbations on the relational rods

GFT cosmology

some results (among many....)

M. Assanioussi, G. Calcagni, A. Calcinari, M. De Cesare, G. Chirco, R. Dekhil, F. Gerhardt, S. Gielen, A. Jercher, I. Kotecha, S. Liberati, L. Marchetti, DO, X. Pang, A. Pithis, A. Polaczek, M. Sakellariadou, L. Sindoni, A. Tomov, Y. Wang, E. Wilson-Ewing, ...

general analysis specialized to specific models (EPRL, BC GFTs)

GFT cosmology

some results (among many....)

M. Assanioussi, G. Calcagni, A. Calcinari, M. De Cesare, G. Chirco, R. Dekhil, F. Gerhardt, S. Gielen, A. Jercher, I. Kotecha, S. Liberati, L. Marchetti, DO, X. Pang, A. Pithis, A. Polaczek, M. Sakellariadou, L. Sindoni, A. Tomov, Y. Wang, E. Wilson-Ewing, ...

general analysis specialized to specific models (EPRL, BC GFTs)

DO, L. Sindoni, E. Wilson-Ewing, '16;
L. Marchetti, DO, '20, '21

- very early times: very small volume - QG interactions subdominant

for large class of states:

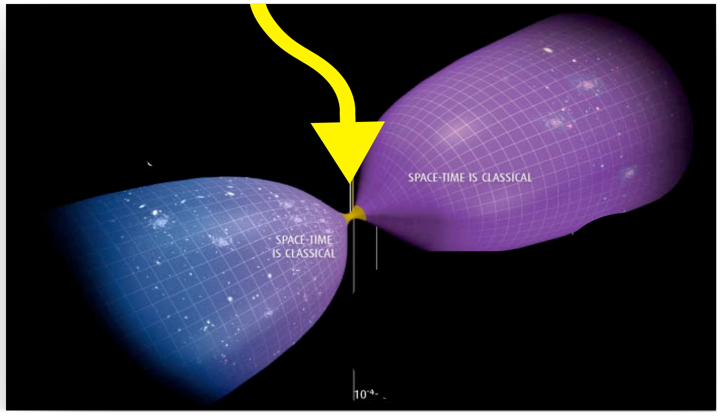
$$\exists j \; / \; \rho_j(\chi) \neq 0 \; \forall \chi$$

$$V = \sum_j V_j \rho_j^2$$

remains positive at all times (with single turning point)

and fluctuations remain under control)

quantum bounce (no big bang singularity)!



- intermediate times: large volume - QG interactions still subdominant

under some (rather mild) conditions on parameters of GFT model

(here written neglecting matter contribution)

$$\left(\frac{V'}{V}\right)^2 = \frac{V''}{V} = 12\pi\tilde{G}$$

classical Friedmann dynamics in GR (wrt relational clock, with effective Newton constant) - flat FRW

GFT cosmology

some results (among many....)

M. Assanioussi, G. Calcagni, A. Calcinari, M. De Cesare, G. Chirco, R. Dekhil, F. Gerhardt, S. Gielen, A. Jercher, I. Kotecha, S. Liberati, L. Marchetti, DO, X. Pang, A. Pithis, A. Polaczek, M. Sakellariadou, L. Sindoni, A. Tomov, Y. Wang, E. Wilson-Ewing, ...

general analysis specialized to specific models (EPRL, BC GFTs)

DO, L. Sindoni, E. Wilson-Ewing, '16;
L. Marchetti, DO, '20, '21

- very early times: very small volume - QG interactions subdominant

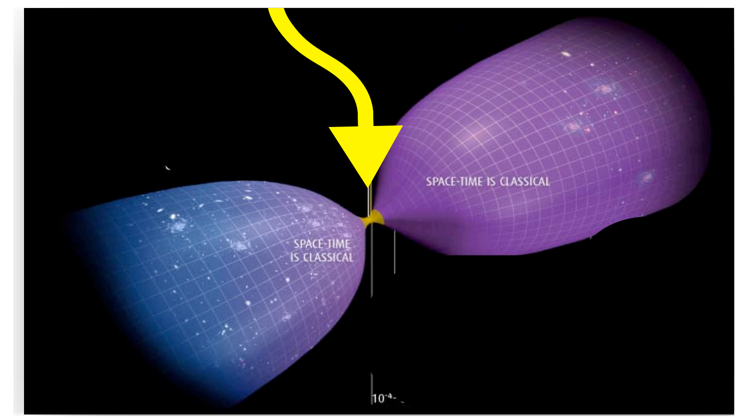
for large class of states:

$$\exists j \;/\; \rho_j(\chi) \neq 0 \;\forall \chi \quad \longrightarrow \quad V = \sum_j V_j \rho_j^2$$

remains positive at all times (with single turning point)

and fluctuations remain under control)

quantum bounce
(no big bang singularity)!



- intermediate times: large volume - QG interactions still subdominant

under some (rather mild) conditions on parameters of GFT model

(here written neglecting matter contribution)

$$\left(\frac{V'}{V}\right)^2 = \frac{V''}{V} = 12\pi\tilde{G}$$

classical Friedmann dynamics in GR (wrt relational clock, with effective Newton constant) - flat FRW

- late times: as universe expands, interactions become more relevant, until they drive evolution

⟶ accelerated cosmological expansion

X. Pang, DO, '21

- "phenomenological" approach:

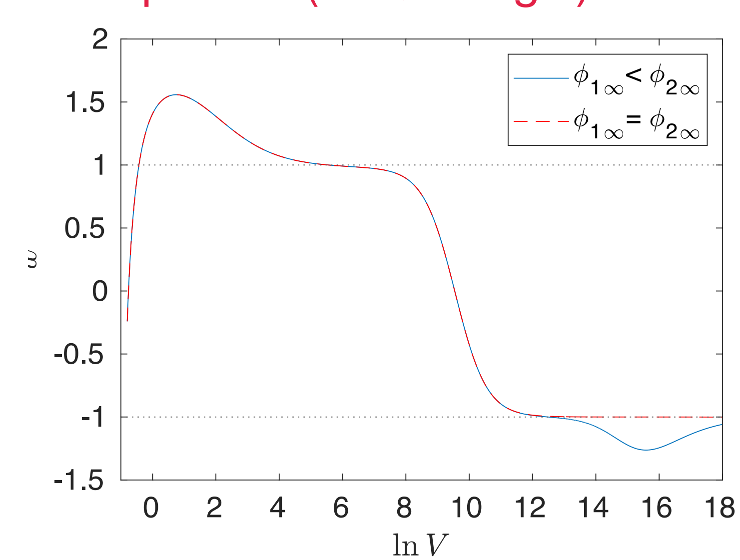
- effective cosmological dynamics $\quad w = 3 - \frac{2VV''}{(V')^2} \quad$ for "emergent matter" component (of QG origin)

order-6 interactions

2 modes ⟶ effective phantom-like dark energy (of pure QG origin)

+ asymptotic De Sitter universe

X. Pang, DO, '21



GFT cosmology

some results (among many....)

M. Assanioussi, G. Calcagni, A. Calcinari, M. De Cesare, G. Chirco, R. Dekhil, F. Gerhardt, S. Gielen, A. Jercher, I. Kotecha, S. Liberati, L. Marchetti, DO, X. Pang, A. Pithis, A. Polaczek, M. Sakellariadou, L. Sindoni, A. Tomov, Y. Wang, E. Wilson-Ewing, ...

general analysis specialized to specific models (EPRL, BC GFTs)

DO, L. Sindoni, E. Wilson-Ewing, '16;
L. Marchetti, DO, '20, '21

- very early times: very small volume - QG interactions subdominant

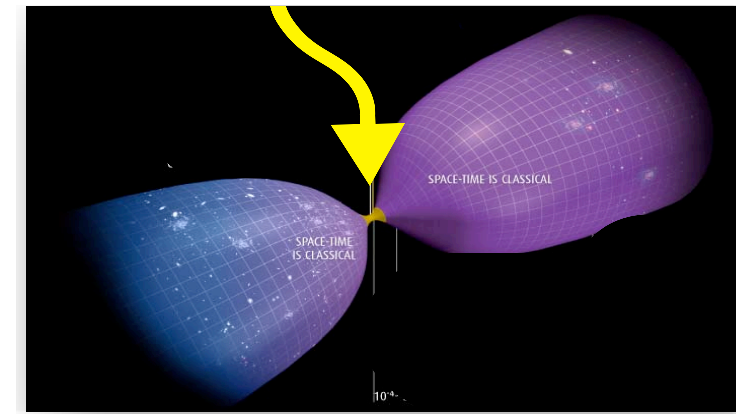
for large class of states:
$\exists j \; / \; \rho_j(\chi) \neq 0 \; \forall \chi$ →

$$V = \sum_j V_j \rho_j^2$$

remains positive at all times
(with single turning point)

and fluctuations remain under control)

quantum bounce
(no big bang singularity)!



- intermediate times: large volume - QG interactions still subdominant

under some (rather mild) conditions
on parameters of GFT model

(here written neglecting matter contribution)

$$\left(\frac{V'}{V}\right)^2 = \frac{V''}{V} = 12\pi\tilde{G}$$

classical Friedmann dynamics in GR (wrt relational clock, with effective Newton constant) - flat FRW

- late times: as universe expands, interactions become more relevant, until they drive evolution

→ accelerated cosmological expansion

X. Pang, DO, '21

- "phenomenological" approach:

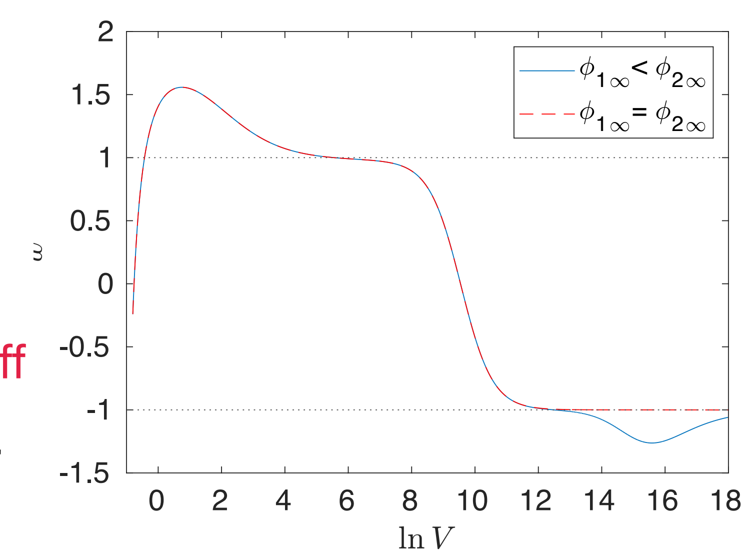
- effective cosmological dynamics $\quad w = 3 - \frac{2VV''}{(V')^2} \quad$ for "emergent matter" component (of QG origin)

order-6 interactions

2 modes → effective phantom-like dark energy (of pure QG origin)

X. Pang, DO, '21

+ asymptotic De Sitter universe



- early-time acceleration (inflation) of pure QG origin possible - but hard to switch off

however, QG affects dynamics of inflaton

T. Landstätter, L. Marchetti, DO, to appear

Foundations of TGFTs (and other "non-spatiotemporal QG")

and

Jaynes' maximal entropy principle

Possible foundations of TGFTs (and other "non-spatiotemporal QG")

how can the quantum dynamics be defined, from first principles?

(recall, lacking straightforward classical mechanics foundations as well as canonical quantization justification, due to absence of preferred temporal variable and due to non-local nature)

(also, TGFTs are not the result of quantizing, by any standard technique, classical GR)

- covariant (quantum statistical) path integral

treat TGFTs as statistical (field) systems, defined by a "equilibrium" probability distribution

probability distribution, in turn, defined by standard path integral in terms of "action"

Possible foundations of TGFTs (and other "non-spatiotemporal QG")

how can the quantum dynamics be defined, from first principles?

(recall, lacking straightforward classical mechanics foundations as well as canonical quantization justification, due to absence of preferred temporal variable and due to non-local nature)

(also, TGFTs are not the result of quantizing, by any standard technique, classical GR)

- covariant (quantum statistical) path integral

treat TGFTs as statistical (field) systems, defined by a "equilibrium" probability distribution

probability distribution, in turn, defined by standard path integral in terms of "action"

but how to choose it? and what is "equilibrium" in absence of time?

General problem in background independent (classical and) quantum gravity: what is "equilibrium" in absence of (preferred) temporal direction?

C. Rovelli, '12; G. Chirco, T. Josset,
C. Rovelli, '15; I. Kotecha, '19

one strategy based on Jaynes' entropy maximization

I. Kotecha, DO, '17; G. Chirco,
I. Kotecha, DO, '18

TGFT (quantum) statistical mechanics

one strategy for identifying/constructing equilibrium states, applied to TGFT context:

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

TGFT (quantum) statistical mechanics

one strategy for identifying/constructing equilibrium states, applied to TGFT context:

Jaynes' entropy maximization principle

M. Montesinos, C. Rovelli, '01; G. Chirco, I. Kotecha, DO, '18

Maximising $S[\rho] = -\langle \ln \rho \rangle_\rho$ under

a set of macrostate constraints $\{\langle \mathcal{O}_a \rangle_\rho = U_a\}$

gives $\rho_{\{\beta_a\}} = \frac{1}{Z_{\{\beta_a\}}} e^{-\sum_a \beta_a \mathcal{O}_a}$

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

TGFT (quantum) statistical mechanics

one strategy for identifying/constructing equilibrium states, applied to TGFT context:

Jaynes' entropy maximization principle

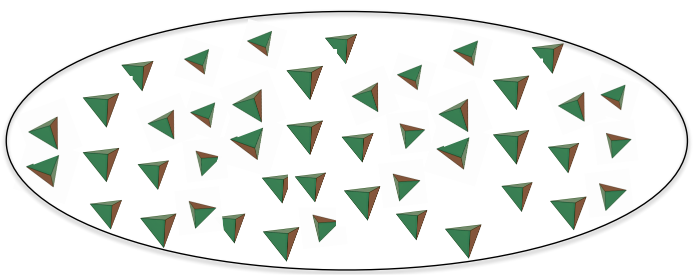
M. Montesinos, C. Rovelli, '01; G. Chirco, I. Kotecha, DO, '18

Maximising $S[\rho] = -\langle \ln \rho \rangle_\rho$ under

a set of macrostate constraints $\{\langle \mathcal{O}_a \rangle_\rho = U_a\}$

gives $\rho_{\{\beta_a\}} = \frac{1}{Z_{\{\beta_a\}}} e^{-\sum_a \beta_a \mathcal{O}_a}$

applied to system of quantum simplices



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

$$Z_{\mu,\beta} = \mathrm{Tr}_{\mathcal{H}_F}\left[e^{-\beta(\hat{C}-\mu\hat{N})}\right] = \mathrm{Tr}_{\mathcal{H}_F}\left[e^{-\beta(\sum_a \frac{\beta_a}{\beta}\hat{C}_a - \frac{\tilde{\mu}}{\beta}\hat{N})}\right]$$

- Use a basis of field coherent states

$$|\psi\rangle = e^{-\frac{||\psi||^2}{2}} e^{\int_{SU(2)^4} d\vec{g}\, \psi(\vec{g})\hat{\varphi}^\dagger(\vec{g})} |0\rangle \quad , \quad \hat{\varphi}(\vec{g})\,|\psi\rangle = \psi(\vec{g})\,|\psi\rangle$$

- For dynamical constraint operator $\hat{C}$

$$Z = \mathrm{Tr}_{\mathcal{H}_F}(e^{-\beta\hat{C}}) = \int [D\mu(\psi,\bar{\psi})]\, \langle\psi|\, e^{-\beta\hat{C}}\, |\psi\rangle$$

$$= \int [D\mu(\psi,\bar{\psi})](e^{-\beta\langle\psi|\hat{C}|\psi\rangle} + \langle\psi| : \mathrm{po}(\hat{\varphi},\hat{\varphi}^\dagger,\beta) : |\psi\rangle)$$

various choices for C

(determine TGFT model):

geometric operators,
dynamical constraints, ...

- Effective statistical field theory $Z \approx Z_{\mathrm{eff}} = \int [D\mu(\psi,\bar{\psi})] e^{-C_{\mathrm{eff}}(\psi,\bar{\psi})}$

GFT partition function DO, '13

G. Chirco, I. Kotecha, DO, '18

TGFT (quantum) statistical mechanics

one strategy for identifying/constructing equilibrium states, applied to TGFT context:

Jaynes' entropy maximization principle

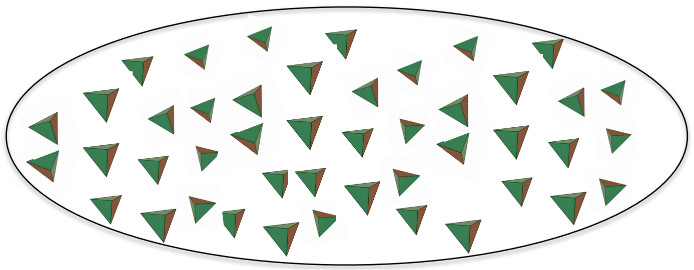
M. Montesinos, C. Rovelli, '01; G. Chirco, I. Kotecha, DO, '18

Maximising $S[\rho] = -\langle \ln \rho \rangle_\rho$ under

a set of macrostate constraints $\{\langle \mathcal{O}_a \rangle_\rho = U_a\}$

gives $\rho_{\{\beta_a\}} = \frac{1}{Z_{\{\beta_a\}}} e^{-\sum_a \beta_a \mathcal{O}_a}$

applied to system of quantum simplices



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

$$Z_{\mu,\beta} = \mathrm{Tr}_{\mathcal{H}_F} \left[e^{-\beta(\hat{C} - \mu \hat{N})} \right] = \mathrm{Tr}_{\mathcal{H}_F} \left[e^{-\beta(\sum_a \frac{\beta_a}{\beta} \hat{C}_a - \frac{\tilde{\mu}}{\beta} \hat{N})} \right]$$

- Use a basis of field coherent states

$$|\psi\rangle = e^{-\frac{||\psi||^2}{2}} e^{\int_{SU(2)^4} d\vec{g}\, \psi(\vec{g}) \hat{\varphi}^\dagger(\vec{g})} |0\rangle \quad , \quad \hat{\varphi}(\vec{g}) |\psi\rangle = \psi(\vec{g}) |\psi\rangle$$

- For dynamical constraint operator $\hat{C}$

$$Z = \mathrm{Tr}_{\mathcal{H}_F}(e^{-\beta \hat{C}}) = \int [D\mu(\psi, \bar{\psi})] \langle \psi | e^{-\beta \hat{C}} | \psi \rangle$$
$$= \int [D\mu(\psi, \bar{\psi})] (e^{-\beta \langle \psi | \hat{C} | \psi \rangle} + \langle \psi | : \mathrm{po}(\hat{\varphi}, \hat{\varphi}^\dagger, \beta) : | \psi \rangle)$$

various choices for C

(determine TGFT model):

geometric operators,
dynamical constraints, ...

- Effective statistical field theory $Z \approx Z_{\mathrm{eff}} = \int [D\mu(\psi, \bar{\psi})] e^{-C_{\mathrm{eff}}(\psi, \bar{\psi})}$

GFT partition function DO, '13

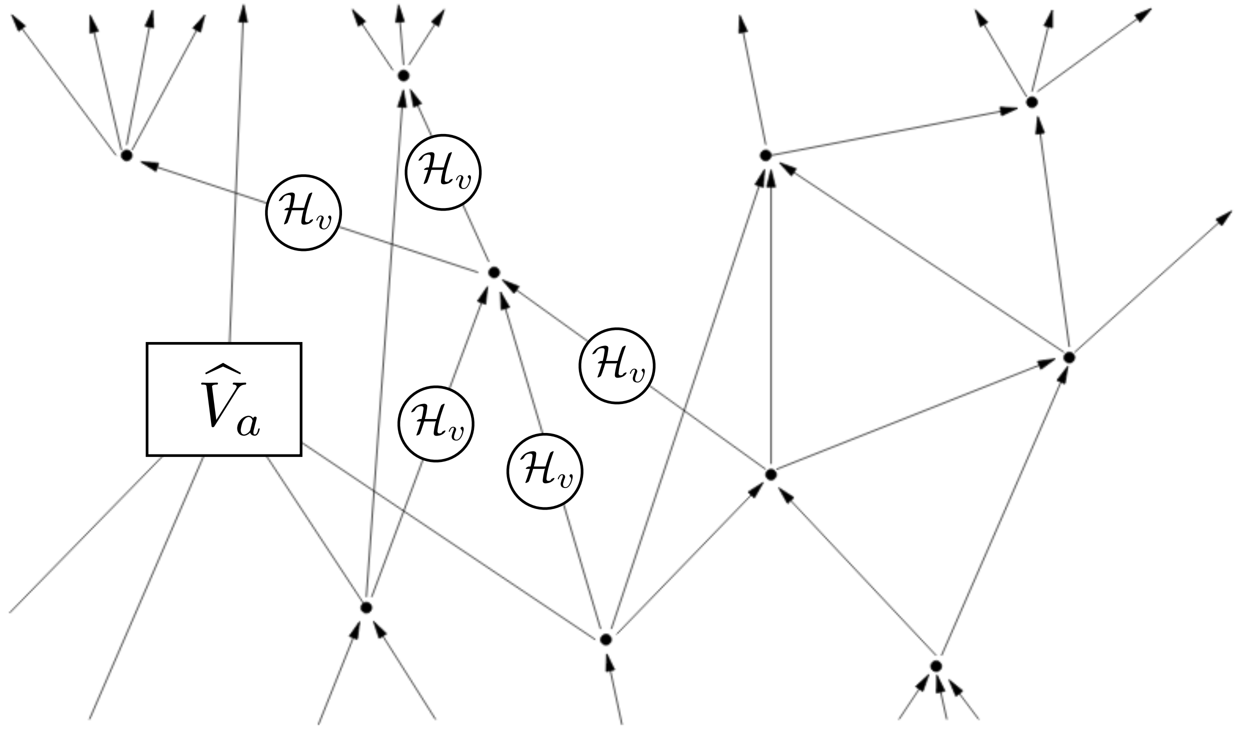
G. Chirco, I. Kotecha, DO, '18

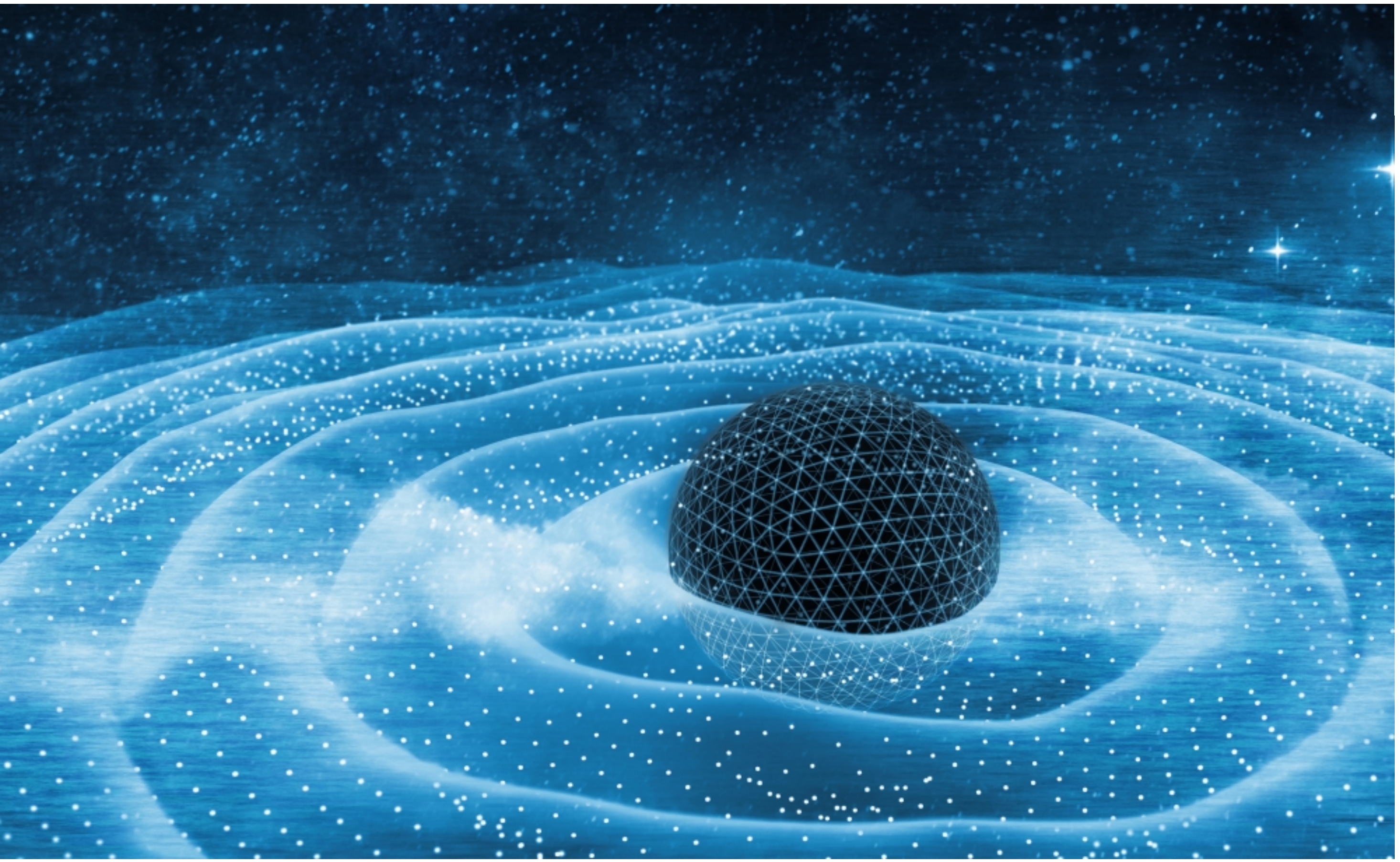
note: Jaynes' principle (and entropy) is epistemic: role of observer/epistemic agent

remarks:
foundational/philosophical issues in light of QG
(and the role of agency)

- (quantum) information and computation
- interpretation of Quantum Mechanics
- laws of nature

QG, (quantum) information and computation





QG, (quantum) information and computation

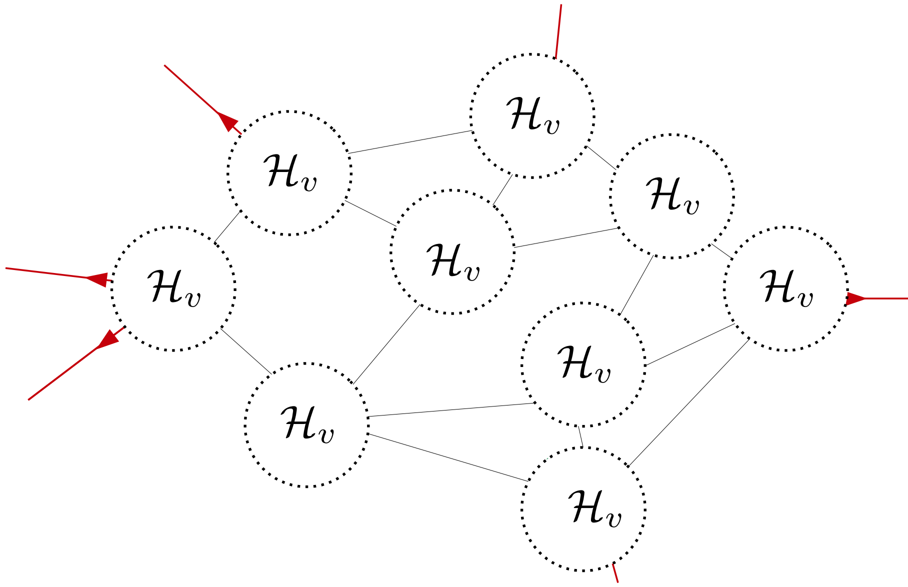
- both semiclassical considerations and QG formalisms suggest that
  - spacetime and gravity as we known them are not fundamental, but emergent, collective notions
  - the universe is a (peculiar, background independent) quantum many-body system of pre-geometric "entities"

- several QG formalisms (eg TGFTs) have combinatorial and algebraic quantum structures as quantum states: quantized simplicial structures & spin networks
  - these quantum states can be framed as quantum circuits

G. Chirco, E. Colafranceschi, DO, '21a,'21b

E. Colafranceschi, S. Langenscheidt, DO, '22 + to appear

Q. Chen, E. Livine, '21; G. Czelusta, J. Mielczarek, '20, '23

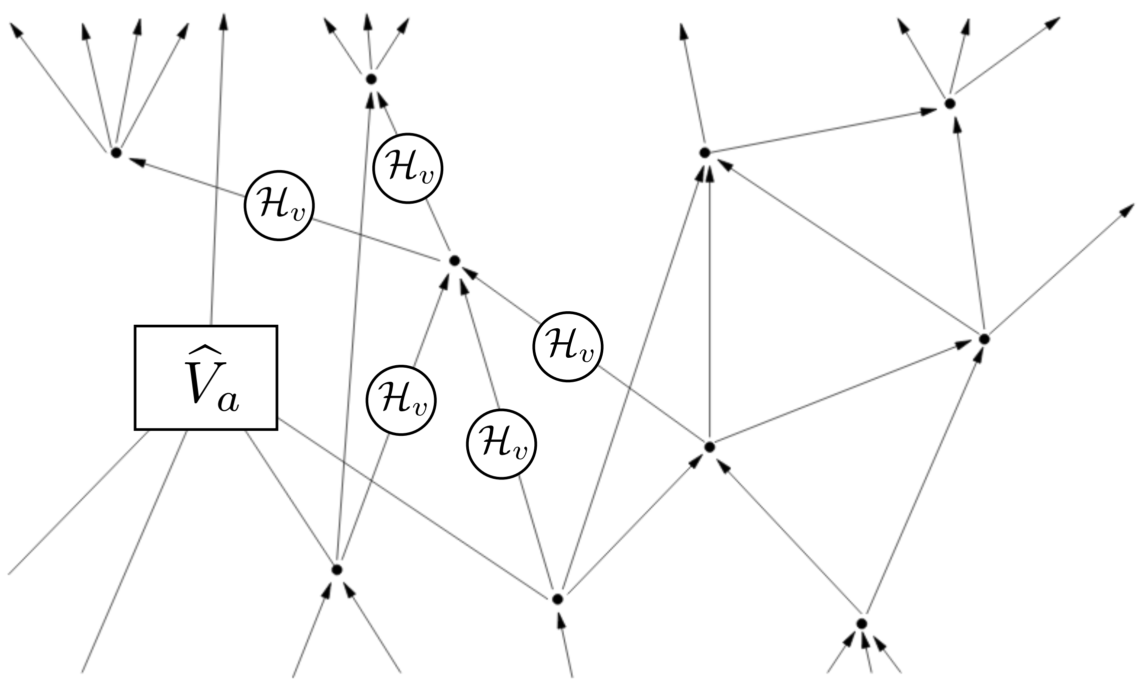


- in the same QG formalisms (eg TGFTs), possible dynamical processes take the form of spin foam models (or algebraic versions of lattice gravity path integrals)
  - spin foam models can be recast as quantum causal histories
  - quantum causal histories can be framed as quantum circuits

F. Markopoulou, '99; E. Livine, DO, '02; E. Hawkins, F. Markopoulou, H. Sahlmann, '03

E. Livine, D. Terno, '06

O. Oreshkov, F. Costa, C. Brukner, '11; E. Castro-Ruiz, F. Giacomini, C. Brukner, '17



QG, (quantum) information and computation

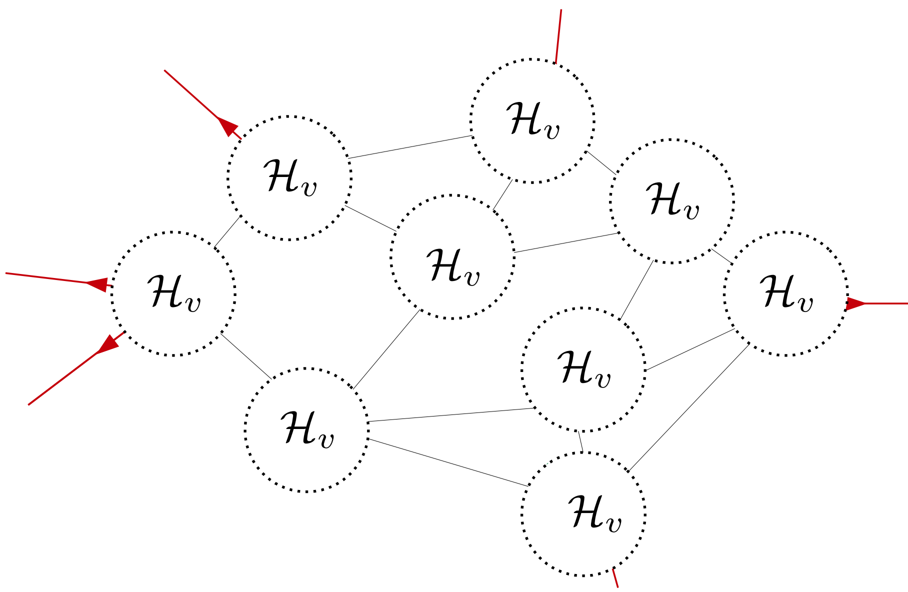
- both semiclassical considerations and QG formalisms suggest that
  - spacetime and gravity as we known them are not fundamental, but emergent, collective notions
  - the universe is a (peculiar, background independent) quantum many-body system of pre-geometric "entities"

- several QG formalisms (eg TGFTs) have combinatorial and algebraic quantum structures as quantum states: quantized simplicial structures & spin networks
  - these quantum states can be framed as quantum circuits

G. Chirco, E. Colafranceschi, DO, '21a,'21b

E. Colafranceschi, S. Langenscheidt, DO, '22 + to appear

Q. Chen, E. Livine, '21; G. Czelusta, J. Mielczarek, '20, '23

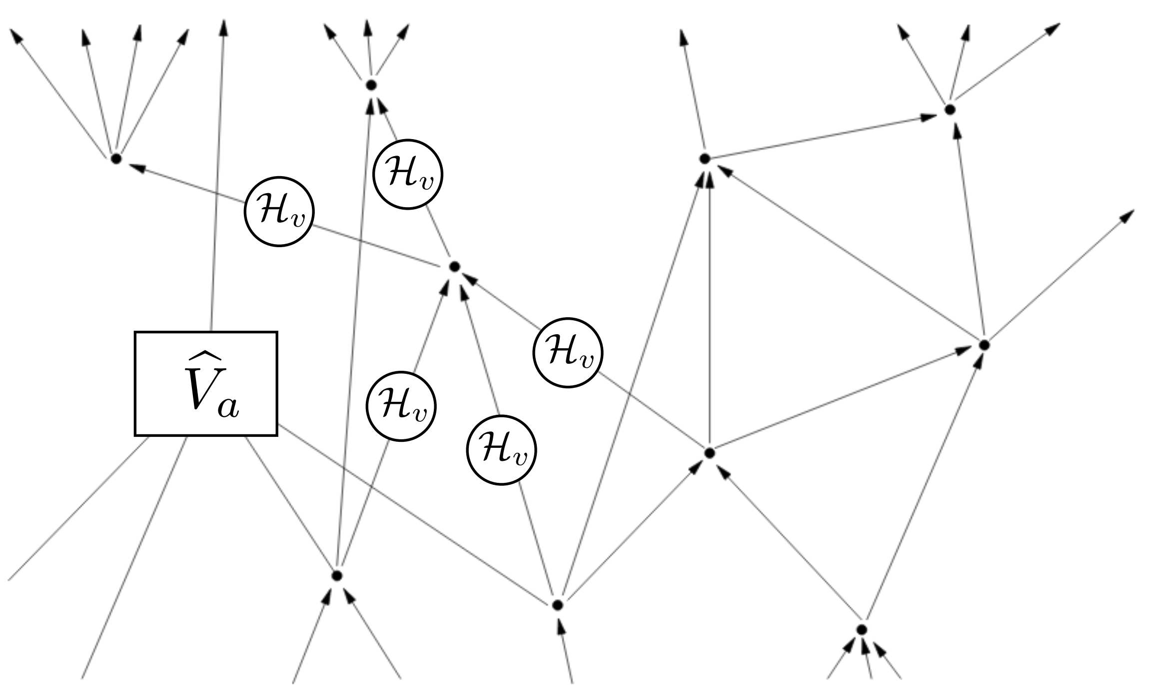


- in the same QG formalisms (eg TGFTs), possible dynamical processes take the form of spin foam models (or algebraic versions of lattice gravity path integrals)
  - spin foam models can be recast as quantum causal histories
  - quantum causal histories can be framed as quantum circuits

F. Markopoulou, '99; E. Livine, DO, '02; E. Hawkins, F. Markopoulou, H. Sahlmann, '03

E. Livine, D. Terno, '06

O. Oreshkov, F. Costa, C. Brukner, '11; E. Castro-Ruiz, F. Giacomini, C. Brukner, '17



so: is the universe a quantum computer?

so: is the universe a quantum computer?

standpoint and general perspective: an epistemic view on physical laws and the role of agency (see later)

- laws of nature are the product of intelligent agents; their role is irreducible and not negligible (outside ideaiizations)

- epistemic nature of laws and role of intelligent agents has concrete implication for (our understanding and formulation of) fundamental physics

  - resonances with (and inclinations towards) epistemic perspectives on QM

  - epistemic perspective on (dynamical) quantum causality, as foundation of quantum geometry

  - perspective on implementation of causality in spin foam models, lattice quantum gravity, group field theory and loop quantum gravity

so: is the universe a quantum computer?

standpoint and general perspective: an epistemic view on physical laws and the role of agency (see later)

- laws of nature are the product of intelligent agents; their role is irreducible and not negligible (outside ideaiizations)

- epistemic nature of laws and role of intelligent agents has concrete implication for (our understanding and formulation of) fundamental physics

  - resonances with (and inclinations towards) epistemic perspectives on QM
  - epistemic perspective on (dynamical) quantum causality, as foundation of quantum geometry
  - perspective on implementation of causality in spin foam models, lattice quantum gravity, group field theory and loop quantum gravity

→ the universe is (largely) what we think it is (or what we model it as)

so: is the universe a quantum computer?

standpoint and general perspective: an epistemic view on physical laws and the role of agency (see later)

- laws of nature are the product of intelligent agents; their role is irreducible and not negligible (outside ideaiizations)
- epistemic nature of laws and role of intelligent agents has concrete implication for (our understanding and formulation of) fundamental physics
    - resonances with (and inclinations towards) epistemic perspectives on QM
    - epistemic perspective on (dynamical) quantum causality, as foundation of quantum geometry
    - perspective on implementation of causality in spin foam models, lattice quantum gravity, group field theory and loop quantum gravity

→ the universe is (largely) what we think it is (or what we model it as)

in fundamental QG:

- in the QG context, we have no spacetime notions to rely on
- we have to think the world (and model it) without spacetime
- without spacetime, we are left with combinatorics, algebra and information processing
- (quantum) computers are abstract models of (quantum) information processing, and of our own reasoning

so: is the universe a quantum computer?

standpoint and general perspective: an epistemic view on physical laws and the role of agency (see later)

- laws of nature are the product of intelligent agents; their role is irreducible and not negligible (outside ideaiizations)
- epistemic nature of laws and role of intelligent agents has concrete implication for (our understanding and formulation of) fundamental physics
  - resonances with (and inclinations towards) epistemic perspectives on QM
  - epistemic perspective on (dynamical) quantum causality, as foundation of quantum geometry
  - perspective on implementation of causality in spin foam models, lattice quantum gravity, group field theory and loop quantum gravity

→ the universe is (largely) what we think it is (or what we model it as)

in fundamental QG:

- in the QG context, we have no spacetime notions to rely on
- we have to think the world (and model it) without spacetime
- without spacetime, we are left with combinatorics, algebra and information processing
- (quantum) computers are abstract models of (quantum) information processing, and of our own reasoning

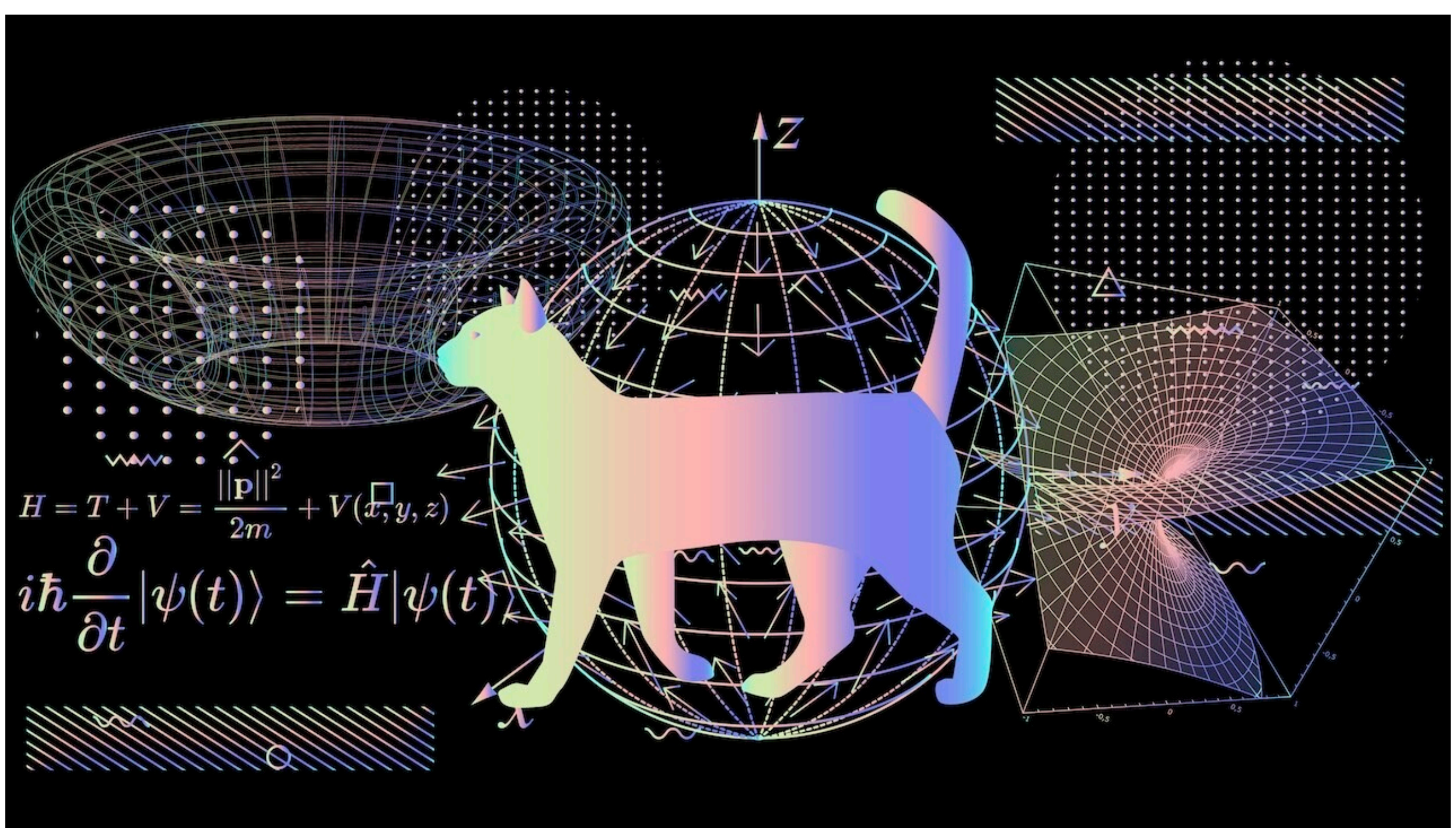
→ the universe is (largely) what we think it is, and we think like computers

→ the quantum (non-spatiotemporal) universe is naturally modeled as a quantum computer

Foundations and interpretations of Quantum Mechanics

the foundational issues in Quantum Mechanics

and how Quantum Gravity changes them



QG requires abandoning/generalizing (one or more) basic principles of QM and QFT

locality, unitarity, local Lorentz symmetry?

probably worse in "emergent spacetime" scenarios

but QG generalization
will necessarily impact
also QM interpretation!

....

QG requires abandoning/generalizing (one or more) basic principles of QM and QFT

locality, unitarity, local Lorentz symmetry?

probably worse in "emergent spacetime" scenarios

→ Quantum Gravity meets Quantum Foundations

even if we focus mostly on spacetime (gravitational) aspects of QG, our understanding of QM needs to be re-assessed

but QG generalization
will necessarily impact
also QM interpretation!

....

QG requires abandoning/generalizing (one or more) basic principles of QM and QFT

locality, unitarity, local Lorentz symmetry?

probably worse in "emergent spacetime" scenarios

→ Quantum Gravity meets Quantum Foundations

even if we focus mostly on spacetime (gravitational) aspects of QG, our understanding of QM needs to be re-assessed

two directions at theoretical/mathematical level:

- how to generalize QM in presence of key (expected) aspects of QG?
- which generalization of QM give best framework for QG?

but QG generalization will necessarily impact also QM interpretation!

....

QG requires abandoning/generalizing (one or more) basic principles of QM and QFT

locality, unitarity, local Lorentz symmetry?

probably worse in "emergent spacetime" scenarios

→ Quantum Gravity meets Quantum Foundations

even if we focus mostly on spacetime (gravitational) aspects of QG, our understanding of QM needs to be re-assessed

two directions at theoretical/mathematical level:

- how to generalize QM in presence of key (expected) aspects of QG?
- which generalization of QM give best framework for QG?

topics in quantum foundations of interest for QG

indefinite causality

quantum reference frames

generalised probability theories

beyond unitary quantum evolution

....

but QG generalization will necessarily impact also QM interpretation!

Key issues and QM interpretations

1. measurement problem (what is the collapse of wavefunction?)

2. nature of quantum states (are they real?)

Key issues and QM interpretations

1. measurement problem (what is the collapse of wavefunction?)

2. nature of quantum states (are they real?)

ontic quantum states — quantum states are elements of reality; they are real properties of system

Bohmian mechanics

dynamical collapse models

wavefunction collapse is physical process,
QM should be modified to describe it

many-worlds interpretation

there is no wavefunction collapse, every measurement outcome actually occurs

Key issues and QM interpretations

1. measurement problem (what is the collapse of wavefunction?)

2. nature of quantum states (are they real?)

ontic quantum states — quantum states are elements of reality; they are real properties of system

- **Bohmian mechanics**, **dynamical collapse models**: wavefunction collapse is physical process, QM should be modified to describe it
- **many-worlds interpretation**: there is no wavefunction collapse, every measurement outcome actually occurs

epistemic quantum states — quantum states are not part of reality of system; they represents knowledge, information or beliefs about system

- wavefunction collapse is just information updating

Key issues and QM interpretations

1. measurement problem (what is the collapse of wavefunction?)

2. nature of quantum states (are they real?)

ontic quantum states — quantum states are elements of reality; they are real properties of system

Bohmian mechanics — dynamical collapse models

wavefunction collapse is physical process,
QM should be modified to describe it

many-worlds interpretation

there is no wavefunction collapse, every measurement outcome actually occurs

epistemic quantum states — quantum states are not part of reality of system; they represents knowledge, information or beliefs about system

wavefunction collapse is just information updating

over a (hidden) ontic state space

(hidden variables formulations)

(Bohmian mechanics, Spekkens' models)

there is an underlying level of objective reality

Key issues and QM interpretations

1. measurement problem (what is the collapse of wavefunction?)

2. nature of quantum states (are they real?)

ontic quantum states — quantum states are elements of reality; they are real properties of system

Bohmian mechanics — dynamical collapse models

wavefunction collapse is physical process,
QM should be modified to describe it

many-worlds interpretation

there is no wavefunction collapse, every
measurement outcome actually occurs

epistemic quantum states — quantum states are not part of reality of system; they represents knowledge, information or beliefs about system

wavefunction collapse is
just information updating

over a (hidden) ontic state space

(hidden variables formulations)

(Bohmian mechanics, Spekkens' models)

there is an underlying level
of objective reality

stand alone

epistemic-pragmatist perspectives

(or "neo-Copenhagen")

(Relational QM, Müller's interpretation, Healey's
interpretation, Brukner-Zeilinger interpretation, QBism)

there are only relative
(to observer) facts

J. Pienaar, '21; A. Barzegar, DO, '22

QM interpretations: impact of QG considerations

ontic quantum states — quantum states are elements of reality; they are real properties of system

- Bohmian mechanics
- dynamical collapse models
- many-worlds interpretation

epistemic quantum states — quantum states are not part of reality of system; they represents knowledge, information or beliefs about system

- over a (hidden) ontic state space

  (hidden variables formulations)

  (Bohmian mechanics, Spekkens' models)

- stand alone

  epistemic-pragmatist perspectives

  (or "neo-Copenhagen")

  (Relational QM, Müller's interpretation, Healey's interpretation, Brukner-Zeilinger interpretation, QBism)

QM interpretations: impact of QG considerations

ontic quantum states — quantum states are elements of reality; they are real properties of system

Bohmian mechanics — dynamical collapse models

very difficult generalization to relativistic and QG context: need to argue that gravity stays classical or relativity only apparent

many-worlds interpretation

epistemic quantum states — quantum states are not part of reality of system; they represents knowledge, information or beliefs about system

over a (hidden) ontic state space

(hidden variables formulations)

(Bohmian mechanics, Spekkens' models)

stand alone

epistemic-pragmatist perspectives

(or "neo-Copenhagen")

(Relational QM, Müller's interpretation, Healey's interpretation, Brukner-Zeilinger interpretation, QBism)

QM interpretations: impact of QG considerations

ontic quantum states — quantum states are elements of reality; they are real properties of system

Bohmian mechanics — dynamical collapse models

very difficult generalization to relativistic and QG context: need to argue that gravity stays classical or relativity only apparent

many-worlds interpretation

straightforward generalization to QG context, but even weirder

epistemic quantum states — quantum states are not part of reality of system; they represents knowledge, information or beliefs about system

over a (hidden) ontic state space

(hidden variables formulations)

(Bohmian mechanics, Spekkens' models)

stand alone

epistemic-pragmatist perspectives

(or "neo-Copenhagen")

(Relational QM, Müller's interpretation, Healey's interpretation, Brukner-Zeilinger interpretation, QBism)

QM interpretations: impact of QG considerations

ontic quantum states — quantum states are elements of reality; they are real properties of system

Bohmian mechanics — dynamical collapse models

very difficult generalization to relativistic and QG context: need to argue that gravity stays classical or relativity only apparent

many-worlds interpretation

straightforward generalization to QG context, but even weirder

epistemic quantum states — quantum states are not part of reality of system; they represents knowledge, information or beliefs about system

over a (hidden) ontic state space

(hidden variables formulations)

(Bohmian mechanics, Spekkens' models)

underlying ontology is not spatiotemporal

stand alone

epistemic-pragmatist perspectives

(or "neo-Copenhagen")

(Relational QM, Müller's interpretation, Healey's interpretation, Brukner-Zeilinger interpretation, QBism)

QM interpretations: impact of QG considerations

ontic quantum states — quantum states are elements of reality; they are real properties of system

- Bohmian mechanics, dynamical collapse models
  - very difficult generalization to relativistic and QG context: need to argue that gravity stays classical or relativity only apparent
- many-worlds interpretation
  - straightforward generalization to QG context, but even weirder

epistemic quantum states — quantum states are not part of reality of system; they represents knowledge, information or beliefs about system

- over a (hidden) ontic state space
  - (hidden variables formulations)
  - (Bohmian mechanics, Spekkens' models)
  - underlying ontology is not spatiotemporal
- stand alone
  - epistemic-pragmatist perspectives (or "neo-Copenhagen")
  - (Relational QM, Müller's interpretation, Healey's interpretation, Brukner-Zeilinger interpretation, QBism)
  - observer very far from object (no direct experience)
    epistemic aspects (not operational) are even more dominant

Laws of nature

what are they?

very long-standing issue in philosophy (phil. science, epistemology, metaphysics, ...)

(Armstrong, Ayer, Callender, Cartwright, Cohen, Dretske, Giere, Hüttermann, Lewis, Maudlin, Mill, Psillos, Ramsey, Skyrms, Van Frassen, ...)

vague notion: "general relations among properties of physical systems"

are they objective and intrinsic to the world or epistemic in nature?

and how does QG change the story?

S. Hartmann, DO, in prog

V. Lam, DO, in prog.

Humeanism

"laws as patterns of facts in the world (and in spacetime)"

- Ontological picture: fundamental basis of non-modal facts, on which laws (and everything else…) supervene
- Humean basis (D. Lewis): distribution of fundamental intrinsic properties over spacetime.
  - Spacetime relations as 'world-making' (or 'gluing') relations.

Humeanism

"laws as patterns of facts in the world (and in spacetime)"

- Ontological picture: fundamental basis of non-modal facts, on which laws (and everything else…) supervene
- Humean basis (D. Lewis): distribution of fundamental intrinsic properties over spacetime.
  - Spacetime relations as 'world-making' (or 'gluing') relations.

Regularity theory

"…all that is required for there to be a law in nature is the existence of *de facto* regularities. In the most straightforward case, the constancy consists in the fact that events, or properties, or processes of different types are invariably conjoined with one another." (A.J. Ayer: 'What is a Law of Nature?')

but which regularities are laws and why?

regularities are out there, but is their lawfulness the result of an epistemic attitude toward them?

Humeanism

"laws as patterns of facts in the world (and in spacetime)"

- Ontological picture: fundamental basis of non-modal facts, on which laws (and everything else…) supervene
- Humean basis (D. Lewis): distribution of fundamental intrinsic properties over spacetime.
  - Spacetime relations as 'world-making' (or 'gluing') relations.

Regularity theory

> "…all that is required for there to be a law in nature is the existence of *de facto* regularities. In the most straightforward case, the constancy consists in the fact that events, or properties, or processes of different types are invariably conjoined with one another." (A.J. Ayer: 'What is a Law of Nature?')

but which regularities are laws and why?

regularities are out there, but is their lawfulness the result of an epistemic attitude toward them?

Best systems

laws as propositions in the best systematizations of regularities

D. K. Lewis: *Counterfactuals*

"[…] a contingent generalization is a law of nature if and only if it appears as a theorem (or axiom) in each of the true deductive systems that achieves a best combination of simplicity and strength."

but how to "measure" simplicity and strength? are they subjective?

essential epistemic elements

Humeanism

"laws as patterns of facts in the world (and in spacetime)"

- Ontological picture: fundamental basis of non-modal facts, on which laws (and everything else…) supervene
- Humean basis (D. Lewis): distribution of fundamental intrinsic properties over spacetime.
  - Spacetime relations as 'world-making' (or 'gluing') relations.

Regularity theory

> "…all that is required for there to be a law in nature is the existence of *de facto* regularities. In the most straightforward case, the constancy consists in the fact that events, or properties, or processes of different types are invariably conjoined with one another." (A.J. Ayer: 'What is a Law of Nature?')

but which regularities are laws and why?

regularities are out there, but is their lawfulness the result of an epistemic attitude toward them?

Best systems

laws as propositions in the best systematizations of regularities

D. K. Lewis: *Counterfactuals*

"[…] a contingent generalization is a law of nature if and only if it appears as a theorem (or axiom) in each of the true deductive systems that achieves a best combination of simplicity and strength."

but how to "measure" simplicity and strength? are they subjective?

essential epistemic elements

Primitivism/dispositionalism

- Ontological picture: some (irreducible) primitive modality gives rise to ("produces") the spatiotemporal distribution of particular facts.
  - Primitivism (Maudlin): fundamental physical laws are ontological primitives
  - Dispositionalism: laws are grounded in the fundamentally dispositional or causal nature of properties.

an strong epistemic view on laws is close to law antirealism:

S. Hartmann, DO, in prog

Why laws are not real

Van Frassen, Cartwright, Giere, ...

because that's the simplest solution of the conceptual problems raised by assuming they exist

because they are simply not factual (they do not even represent observed facts)

(scientific theories are collections of models, all "laws" actually used by scientists are approximate and ad hoc rules tailored to specific, limited situations, with no real claim of generality or fundamentality)

can we be content with this blunt anti-realist view on laws?

• only provided one can account for the many functions laws fulfil in science, without assuming their existence "out there"

• this may require a different understanding of scientific explanations of natural phenomena, not metaphysically loaded, possibly more limited (empirical adequacy); scientific theories understood as "guiding clues" for belief about the world

an strong epistemic view on laws is close to law antirealism:

S. Hartmann, DO, in prog

Van Frassen, Cartwright, Giere, ...

Why laws are not real

because that's the simplest solution of the conceptual problems raised by assuming they exist

because they are simply not factual (they do not even represent observed facts)

(scientific theories are collections of models, all "laws" actually used by scientists are approximate and ad hoc rules tailored to specific, limited situations, with no real claim of generality or fundamentality)

can we be content with this blunt anti-realist view on laws?

- only provided one can account for the many functions laws fulfil in science, without assuming their existence "out there"
- this may require a different understanding of scientific explanations of natural phenomena, not metaphysically loaded, possibly more limited (empirical adequacy); scientific theories understood as "guiding clues" for belief about the world

in any case:

any philosophical perspective on laws should be compatible with, informed from and possibly supported by our best scientific theories.

an strong epistemic view on laws is close to law antirealism:

S. Hartmann, DO, in prog

Why laws are not real

Van Frassen, Cartwright, Giere, ...

because that's the simplest solution of the conceptual problems raised by assuming they exist

because they are simply not factual (they do not even represent observed facts)

(scientific theories are collections of models, all "laws" actually used by scientists are approximate and ad hoc rules tailored to specific, limited situations, with no real claim of generality or fundamentality)

can we be content with this blunt anti-realist view on laws?

- only provided one can account for the many functions laws fulfil in science, without assuming their existence "out there"
- this may require a different understanding of scientific explanations of natural phenomena, not metaphysically loaded, possibly more limited (empirical adequacy); scientific theories understood as "guiding clues" for belief about the world

in any case:

any philosophical perspective on laws should be compatible with, informed from and possibly supported by our best scientific theories.

QG poses several new challenges to existing accounts of laws

Humeanism

- Humean basis: if spacetime is not fundamental, the traditional Humean "basis" is not fundamental
- More general challenge from quantum theory (Maudlin): quantum entanglement relations do not supervene on the Humean basis (are "non-local")

- Crucial difficulty: what provides and how to characterise the Humean basis in a context without spacetime?
  - The non-spatio-temporal characterisation of the Humean basis will be based on fundamental QG entities
  - Some QG approaches suggest quantum entanglement relations (between QG entities) as ‘gluing relations'

Humeanism

- Humean basis: if spacetime is not fundamental, the traditional Humean "basis" is not fundamental
- More general challenge from quantum theory (Maudlin): quantum entanglement relations do not supervene on the Humean basis (are "non-local")

- Crucial difficulty: what provides and how to characterise the Humean basis in a context without spacetime?
  - The non-spatio-temporal characterisation of the Humean basis will be based on fundamental QG entities
  - Some QG approaches suggest quantum entanglement relations (between QG entities) as 'gluing relations'

Best systems

- this could be viable also in QG: laws will be theorems in our QG 'best system'
- issue: neither the underlying Humean mosaic nor (most of) the theorems would refer to spacetime; theorems will be statements about 'theoretical entities' and severely underdetermined by observations

Humeanism

- Humean basis: if spacetime is not fundamental, the traditional Humean "basis" is not fundamental
- More general challenge from quantum theory (Maudlin): quantum entanglement relations do not supervene on the Humean basis (are "non-local")

- Crucial difficulty: what provides and how to characterise the Humean basis in a context without spacetime?
  - The non-spatio-temporal characterisation of the Humean basis will be based on fundamental QG entities
  - Some QG approaches suggest quantum entanglement relations (between QG entities) as 'gluing relations'

Best systems

- this could be viable also in QG: laws will be theorems in our QG 'best system'
- issue: neither the underlying Humean mosaic nor (most of) the theorems would refer to spacetime; theorems will be statements about 'theoretical entities' and severely underdetermined by observations

Primitivism/ dispositionalism

- These non-Humean conceptions operate against a primitive temporal and causal background
  - Maudlin (2007, 182): "the total state of the universe is, in a certain sense, derivative: it is the product of the operation of the laws on the initial state"
- difficulty: how to articulate a non-temporal nomic production without spacetime?
  - QG 'processes' that could instantiate it: spin foam / GFT transition amplitudes; primitive combinatorial/algebraic structures endowed with fundamental dispositions.
- difficulty: notion of 'production' seems to involve some ("causal") asymmetry
  - some form of 'ordering' in QG amplitudes should be present ("proto-causality")

QG challenges to agent-first (epistemic) accounts (or law anti-realism)

- an epistemic view on laws could be more flexible to adapt to the absence of spacetime at the fundamental level
- key challenge: build a QG theory with strong explanatory power, despite being remote from experience (thus also far from operationalism) and underdetermined by observations
- its laws will be grounded in its epistemic virtues, and so will be its suggested ontology
- strongly relying (concerning non-directly observable QG entities) on epistemic tools of abstraction, imagination, counterfactuals, hypothetical reasoning, analogies

Thank you for your attention!