

Effective continuum physics from quantum gravity

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Central problem: extracting effective continuum physics from quantum gravity

- QG = quantum theory of "spacetime constituents" = "quantum spacetime microphysics"

spacetime fields, including metric, as effective, collective entities



Emergent spacetime!



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 have to be approximately obtained (in relational language) at effective level

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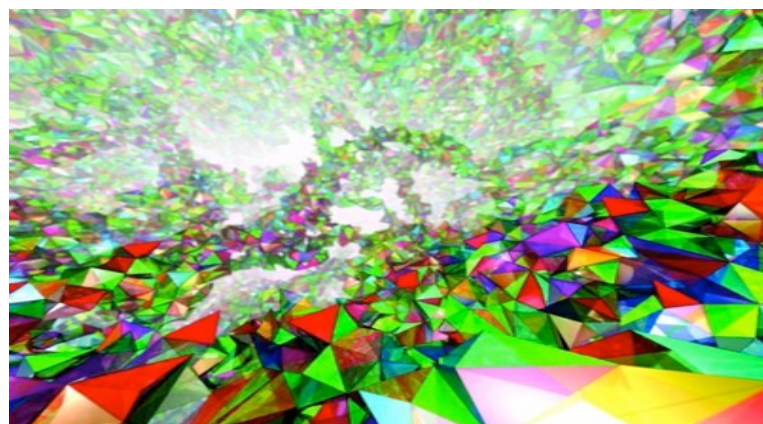
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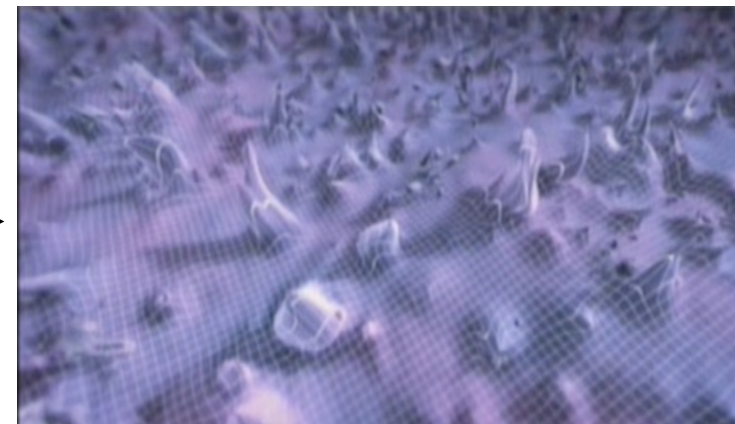
quantum gravity:

quantum theory of spin networks



effective continuum physics:

(Q)FT for gravity+matter



Quantum Gravity: **kinematical states and quantum dynamics**

Quantum Gravity states: spin network states

C. Rovelli, L. Smolin, R. Gambini, J. Pullin, J. Baez, A. Ashtekar, J. Lewandowski, T. Thiemann,

for given graph, basis of: $\mathcal{H}_\gamma = L^2 \left(G^E / G^V, d\mu = \prod_{e=1}^E d\mu_e^{Haar} \right)$

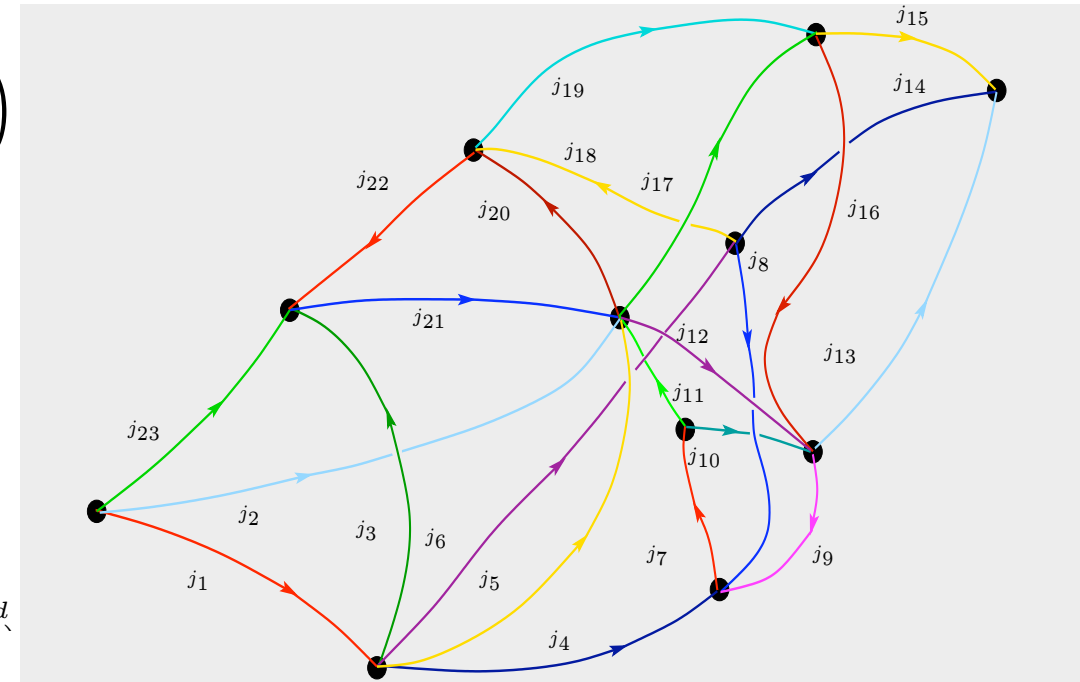
$$f(g_1, \dots, g_d) = \sum_{\mathbf{j}, \mathbf{n}} f_{\mathbf{j}, \mathbf{n}}^\mathbf{j} \psi_{\mathbf{j}, \mathbf{n}}^\mathbf{j}(\mathbf{g}) \quad G = \text{SU}(2)$$

$$\psi_{\mathbf{j}, \mathbf{n}}^\mathbf{j}(\mathbf{g}) := \sum_{p_1 \dots p_d} C_{p_1 \dots p_d}^{j_1 \dots j_d} \prod_i \sqrt{d_{j_i}} D_{p_i n_i}^{j_i}(g_i)$$

intertwiner label

spins $\rightarrow \mathbf{j} := j_1 \dots j_d$ and $\mathbf{n} := n_1 \dots n_d$

$$C_{p_1 \dots p_d}^{j_1 \dots j_d} \in \text{Inv} \left(V^{j_1} \otimes \dots \otimes V^{j_d} \right) =: \mathcal{H}_{j_1 \dots j_d}$$



spin network state
on given graph:

$$|\varphi_\gamma\rangle := \bigoplus_{\mathbf{j}^1 \dots \mathbf{j}^V} \sum_{\mathbf{n}^1 \dots \mathbf{n}^V} \sum_{\ell^1 \dots \ell^V} \varphi_{\{\mathbf{j}^1 \dots \mathbf{j}^V\} \{\mathbf{n}^1 \dots \mathbf{n}^V\} \{\ell^1 \dots \ell^V\}} \prod_{a_{vw}=1} \delta_{j_i^v, j_i^w} \delta_{n_i^v, n_i^w} \bigotimes_v |\mathbf{j}^v \mathbf{n}^v \ell_v\rangle$$

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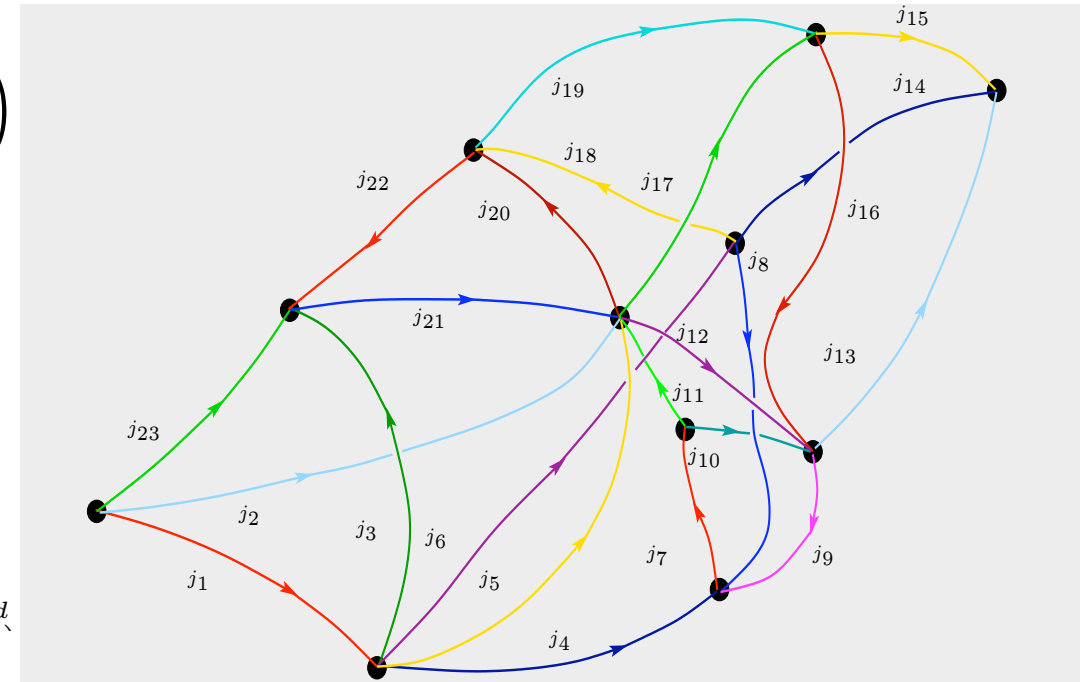
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- SN states in several related QG formalisms
- canonical Loop Quantum Gravity
- spin foam models
- Tensorial Group Field Theory
- simplicial Quantum Gravity

In these QG formalisms, one has also superposition of graphs $|\Psi\rangle = \sum_{\gamma} c_{\gamma} |\varphi_{\gamma}\rangle$

spin network states as quantum many-body states

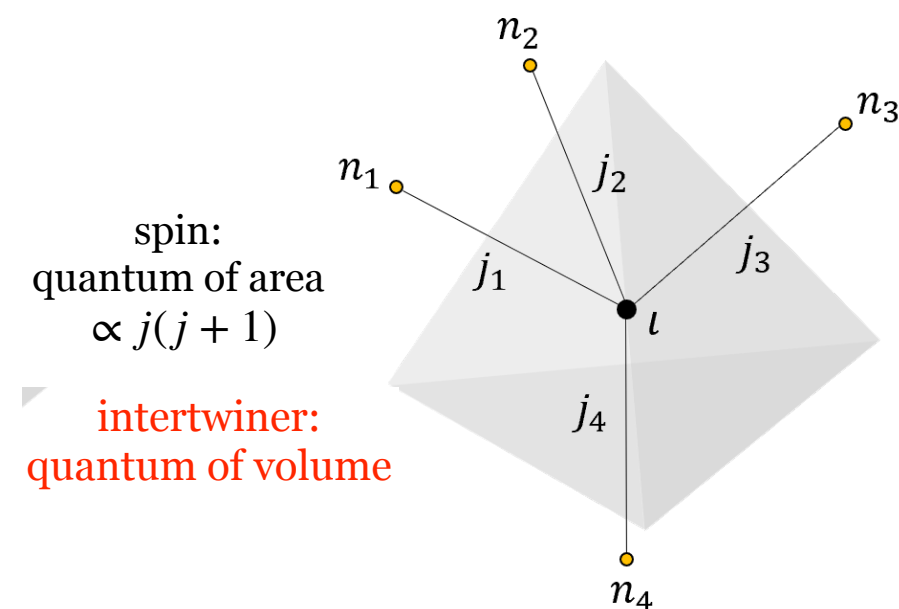
- restrict to 4-valent nodes

spin network states as quantum many-body states

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- elementary building block: single spin network vertex (with 4 open links)

which admits dual interpretation as quantum 3-simplex (tetrahedron)

$$\mathcal{H}_{\triangle} = L^2 \left(SU(2)^4 / SU(2) \right) \quad \ni \quad |f\rangle = \sum_{\vec{n}_l} f_{\vec{n}_l}^{\vec{j}} |\vec{j} \vec{n}_l\rangle$$



spin network states as quantum many-body states

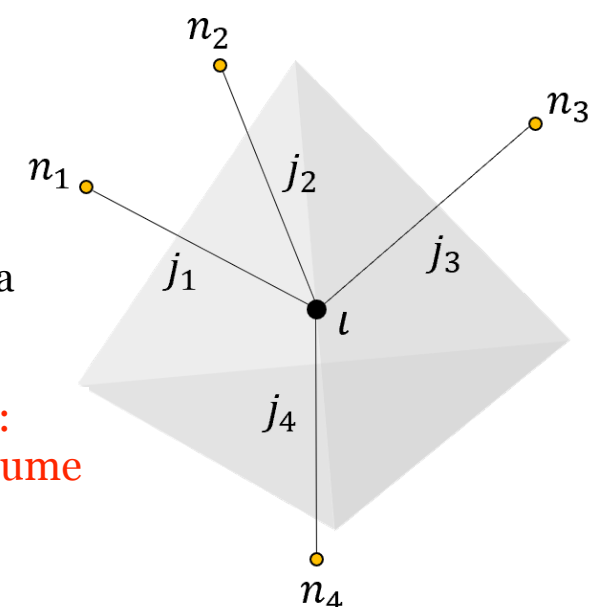
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spin:
quantum of area
 $\propto j(j+1)$

intertwiner:
quantum of volume

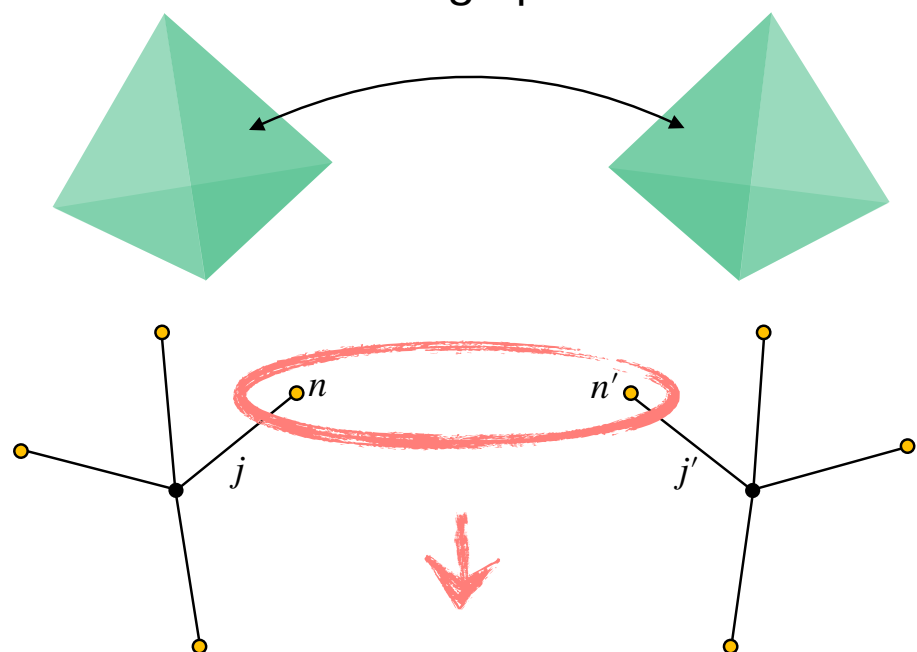


- general spin network states or arbitrary graphs (with open links) built from entanglement:

B. Baytas, E. Bianchi, N. Tokomizo, '18;
E. Colafranceschi, DO, '20

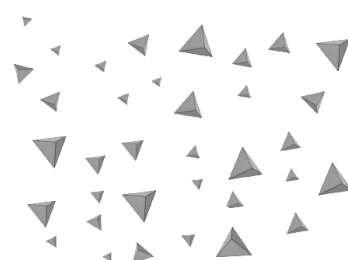
gluing of quantum tetrahedra along faces = gluing of spin
network vertices along open links = maximal entanglement

spin network with N vertices ~ gluing of N tetrahedra
~ entangled N-body state



$$|\ell\rangle = \sum_n \frac{(-1)^{j+n}}{\sqrt{2j+1}} |j, n\rangle |j', -n'\rangle$$

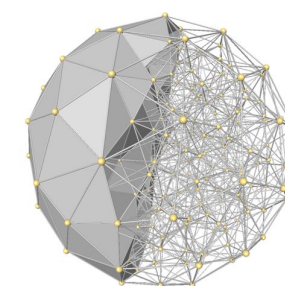
maximally entangled state



$|\psi_N\rangle$

many-body state for
disconnected vertices

gluing
(entangling edge d.o.f.)



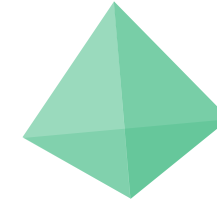
$$|\psi_\gamma\rangle = \left(\bigotimes_{\ell \in \gamma} \langle \ell | \right) |\psi_N\rangle$$

many-body state with **connectivity** γ
= spin network state

Fock space of spin networks

DO, '13; S. Gielen, '25

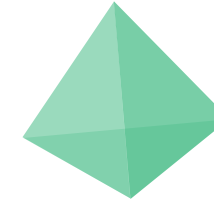
- general kinematical ambient space for (open) spin networks: **Fock space** $\mathcal{F}(\mathcal{H}_\Delta) = \bigoplus_{N=1}^{\infty} \text{sym} \left(\underbrace{\mathcal{H}_\Delta \otimes \dots \otimes \mathcal{H}_\Delta}_N \right)$
- **Fock vacuum**: no topological or geometric excitations $|0\rangle$
- can introduce **creation/annihilation field operators** $\phi^\dagger |0\rangle$ “quantum of space”
(convenient to treat states with many excitations)
- **quantum geometric operators** can be written in “2nd quantized” language (see later)



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- **quantum geometric operators** can be written in “2nd quantized” language (see later)
- note:
 - convenient to: include any graph topology + open links (boundaries) + deal with highly populated states
 - only “kinematical” ambient space, not physical one - dynamics to be imposed - will map out of this Hilbert space
 - admits simple truncation at finite spin network vertices (tetrahedra) N (to be removed while imposing dynamics)
 - kinematical spin network states for given graph embedded faithfully (incl. scalar product)
 - states for different graphs not orthogonal (if same number of vertices)
 - vertex re-labelling invariance (bosonic statistics) makes difficult to reconstruct graph structure
 - no embedding into (canonical) smooth manifold
 - no cylindrical equivalence (when not implicit), no projective limit under graph refinement
 - fixed valence - can generalise, but higher valences also reconstructed by coarse graining



Quantum Gravity dynamics

- "timeless" quantum dynamics = constraint equation
or projection onto physical states

K. Giesel, T. Thiemann, H. Sahlmann, E. Alesci, Y. Ma, A. Laddha,
C. Rovelli, J. Lewandowski, I. Makkinen, M. Assanioussi, ...

$$\hat{H}|\Psi\rangle = 0$$
$$\hat{P}(\hat{H})|\Psi\rangle = |\Psi\rangle \longrightarrow -\hat{C}|\Psi\rangle = \left(\hat{P}(\hat{H}) - \hat{I}\right)|\Psi\rangle = 0$$

e.g. from canonical quantization of classical GR

- generalised "timeless" quantum dynamics = quantum statistical partition function

$$Z_{\mu,\beta} = \text{Tr}_{\mathcal{H}_F} \left[e^{-\beta(\hat{C} - \mu\hat{N})} \right]$$

D. Oriti, '13; G. Chirco, I. Kotecha, D. Oriti, '19;
I. Kotecha, '21

- imposing constraint on average (and in limit) - up to fluctuations
- to be expected when topology change is included (no canonical quantization of GR)
- "ensemble of (canonically quantized) QG theories" (eg from extended QG path integral)

S. Coleman, '88; S.
Giddings, A. Strominger, '89;
D. Marolf, H. Maxfield, '20;
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- "timeless" quantum dynamics ~ spin foam formulation

(as long as quantum dynamics "stays" within same Hilbert space - close to Fock vacuum)

- elementary interaction/evolution processes for spin network vertices:

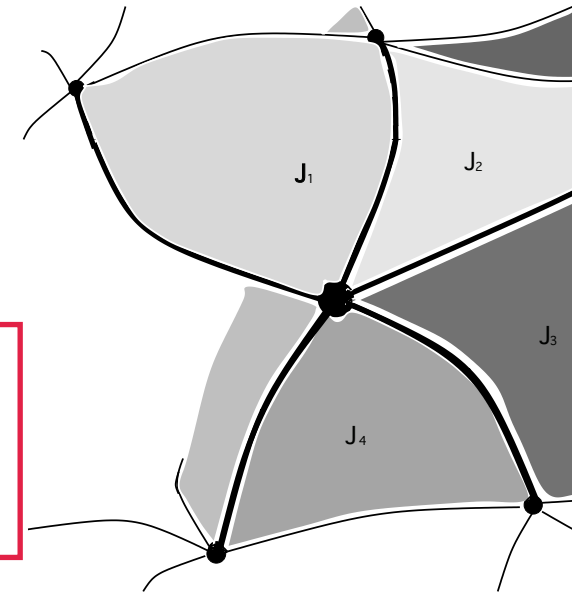
spin foams (labelled 2-complexes)

- each spin foam model assigns: class of allowed spin foams + amplitude to each spin foam + prescription to sum over them

$$Z = \sum_{\Gamma} w(\Gamma) Z(\Gamma)$$

M. Reisenberger, C. Rovelli, J. Baez, J. Barrett, L. Crane,
A. Perez, B. Dittrich, D. Oriti, E. Livine, V. Bonzom, S.
Speziale, R. Pereira, J. Engle, E. Bianchi,

e.g. from (lattice) path integral quantization of GR



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Quantum Gravity dynamics

- TGFT reformulation of operator dynamics - "3rd quantization" realization

(using field coherent states)

$$Z_\beta = \text{Tr}_{\mathcal{H}_F} \left[e^{-\beta \hat{C}} \right] = \int [D\mu(\psi, \bar{\psi})] \left(e^{-\beta C[\bar{\psi}, \psi]} + A_{C, \mathbb{I}}[\bar{\psi}, \psi, \beta] \right)$$

$$C[\bar{\psi}, \psi] = \langle \psi | \hat{C} | \psi \rangle$$

quantum corrections



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quantum corrections

- in general, can encode full quantum dynamics in field theory of spin networks/tetrahedra (TGFT)

$$Z = \int \mathcal{D}[\psi, \psi^*] e^{-S(\psi, \psi^*)}$$

including topology change and (canonical) quantum constraints

with quantum effective action: $\Gamma[\psi, \psi^*] \simeq S(\psi, \psi^*) + \Gamma^{(1)}[\psi, \psi^*] + O(\hbar^2) + \dots$

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with

$$S(\psi, \psi^*) = \langle : \hat{C}(\hat{\varphi}, \hat{\varphi}^\dagger) : \rangle$$

mean field (classical) action

$$\Gamma^{(1)}[\psi, \psi^*] = \frac{1}{2} \text{Tr} \ln[\hat{C}''(\psi, \psi^*)]$$

1-loop corrections ~ Bogolubov spectrum

interaction terms ~ matrix elements of projection operator: $\hat{P}_{n,m} = \int [dg][dh] \hat{\varphi}^\dagger(g_1) \dots \hat{\varphi}^\dagger(g_n) \mathcal{V}([g], [h]) \hat{\varphi}(h_1) \dots \hat{\varphi}(h_m)$

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- TGFT formulation of spin foam dynamics (~ lattice gravity path integral)

M. Reisenberger, C. Rovelli, '00; A. Baratin, D. Oriti, '10;
M. Finocchiaro, D. Oriti, '20

perturbative expansion in Feynman diagrams
(close to Fock vacuum)

$$Z = \int \mathcal{D}[\psi, \psi^*] e^{-S(\psi, \psi^*)} = \sum_{\Gamma} \frac{\lambda^{N_\Gamma}}{\text{sym}(\Gamma)} \mathcal{A}(\Gamma)$$

- Feynman diagrams ~ spin foams (simplicial lattices) of arbitrary topology

- Feynman amplitudes ~ spin foam amplitudes (lattice gravity path integrals) for given complex $Z(\Gamma) \equiv \mathcal{A}(\Gamma)$

- correspondence is 1-1 (up to field redefinitions): spin foam model <-> TGFT model

**Effective cosmology and matter field theory
(gravitational continuum physics) from QG dynamics**

insights to take onboard

from lattice gravity (Regge calculus):

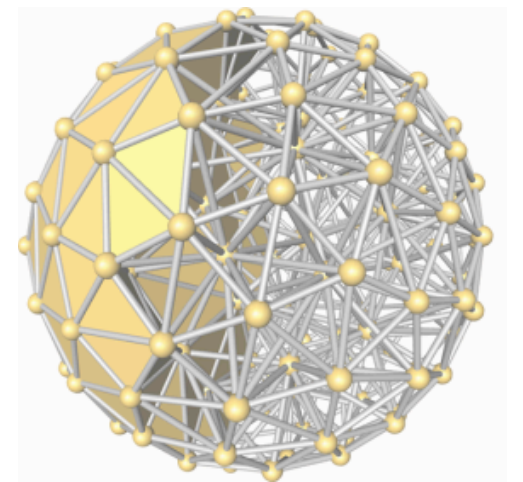
continuum gravitational physics approximately recovered for:

large number of dofs

+ small curvature

+ smallish elementary distances/volumes

T. Regge, R. Williams, H. Hamber, M. Rocek,



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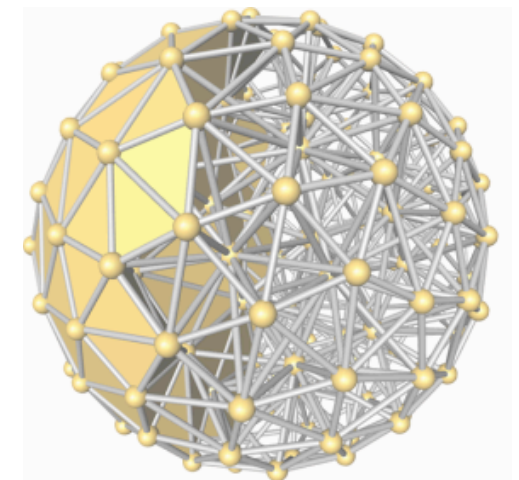
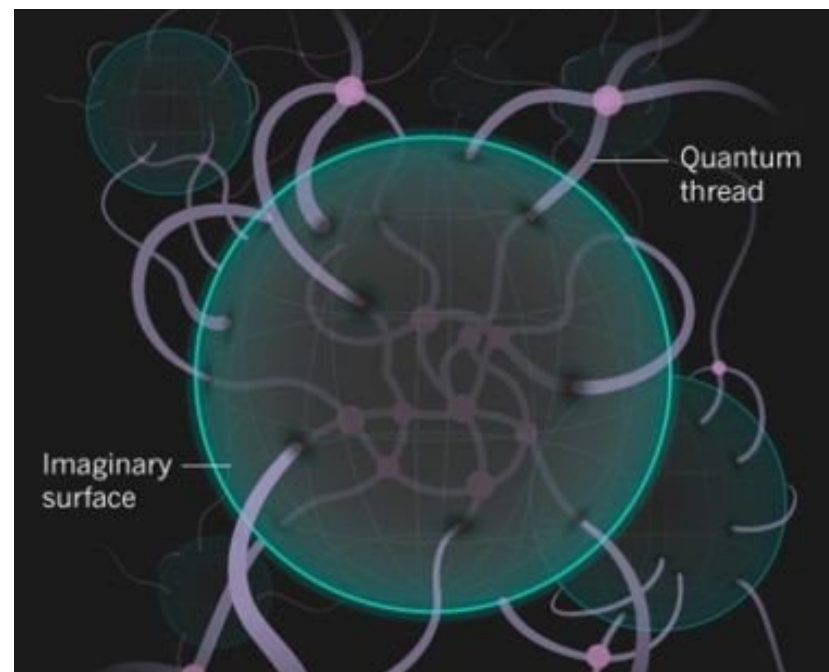
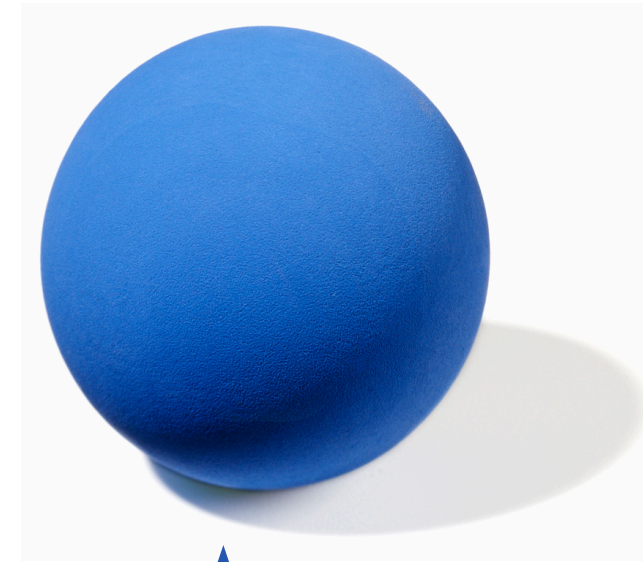
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also LQG: $A \approx \langle j \rangle \langle N \rangle$

T. Regge, R. Williams, H. Hamber, M. Rocek,



aligns with:

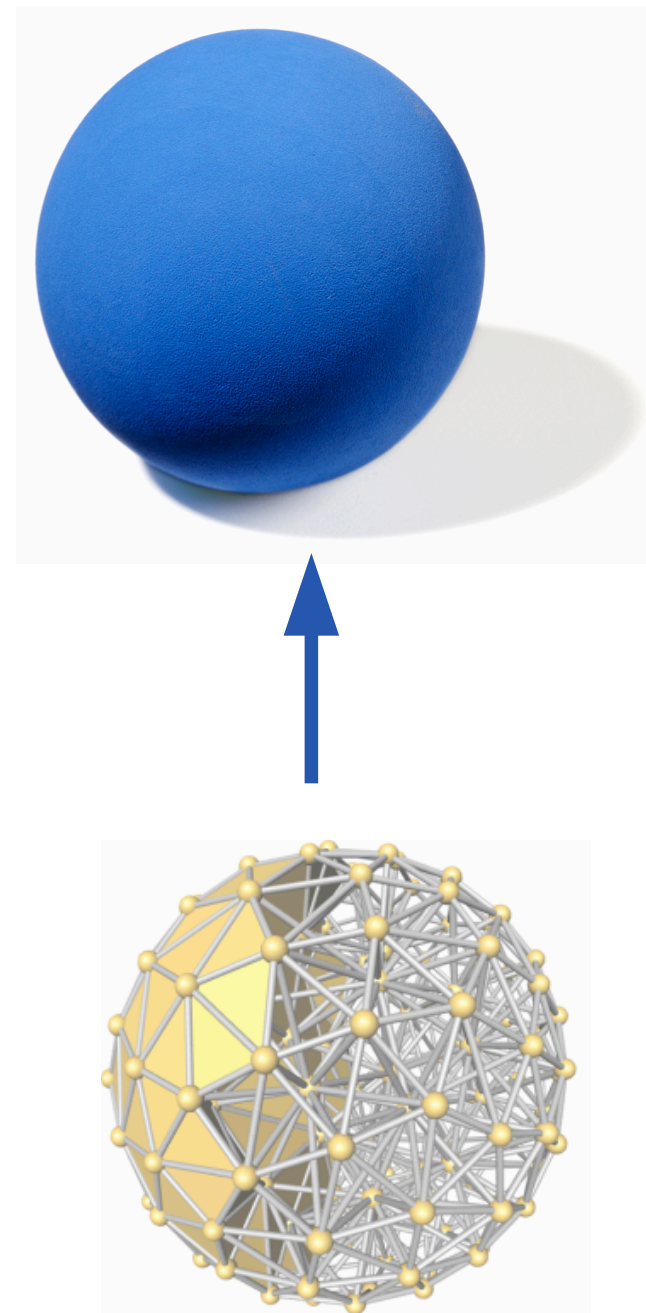
- (kinematical) constructions of LQG coherent states approximating continuum geometries

T. Thiemann, B. Bahr, A. Stottmeister, H. Sahlmann,

- "quantum reduced LQG" E. Alesci, F. Cianfrani,

- LQC construction M. Bojowald, A. Ashtekar, P. Singh, T. Pawłowski, J. Lewandowski,

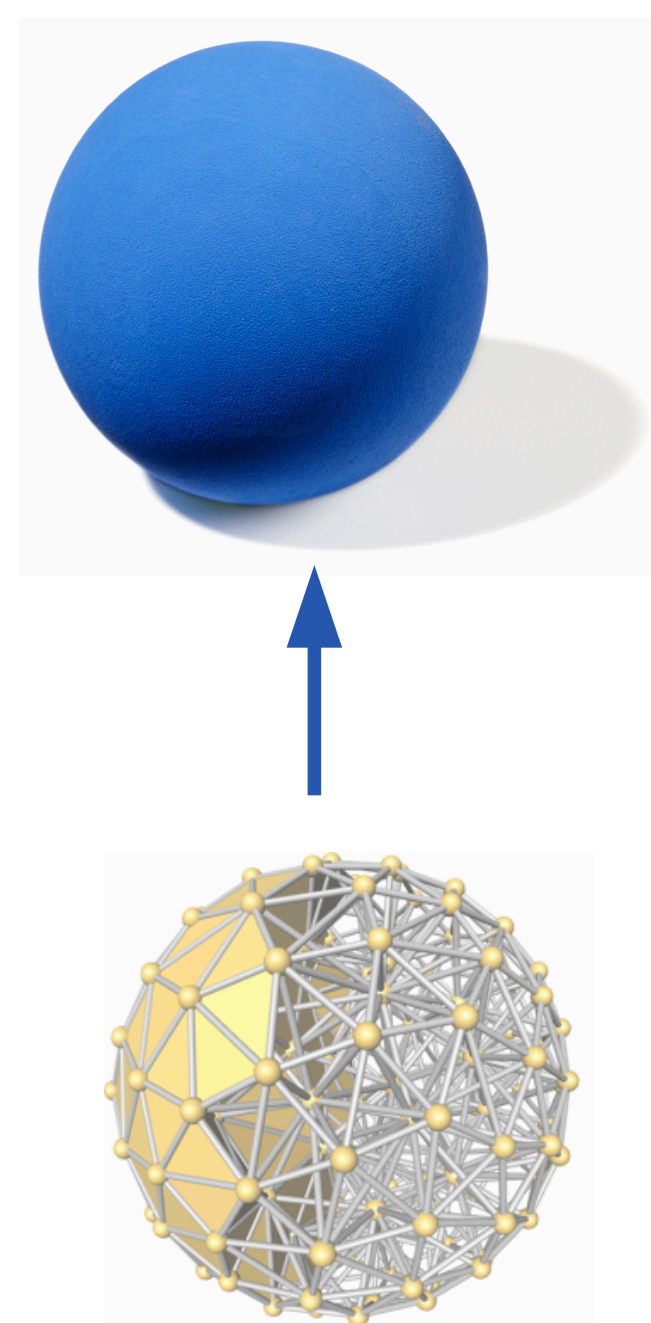
expectations and focus



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(this would suggest -not- to use the asymptotic expressions for the spin foam amplitudes, and that quantum aspects of the fundamental theory are relevant in order to obtain correct continuum gravitational physics, even classical one)



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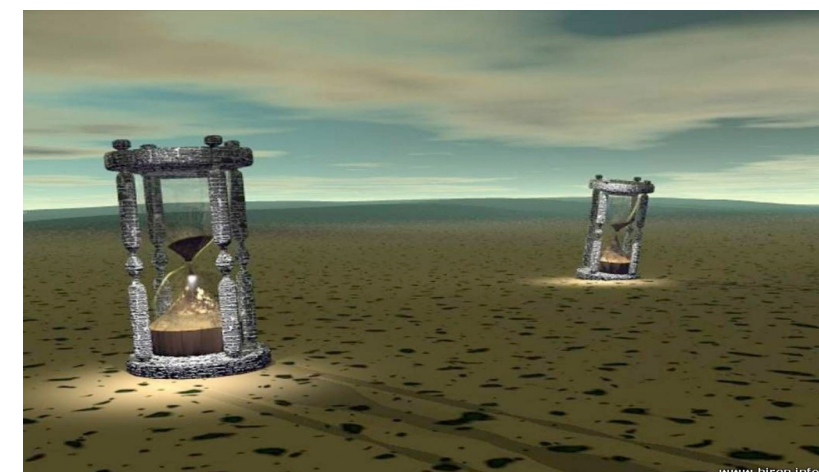
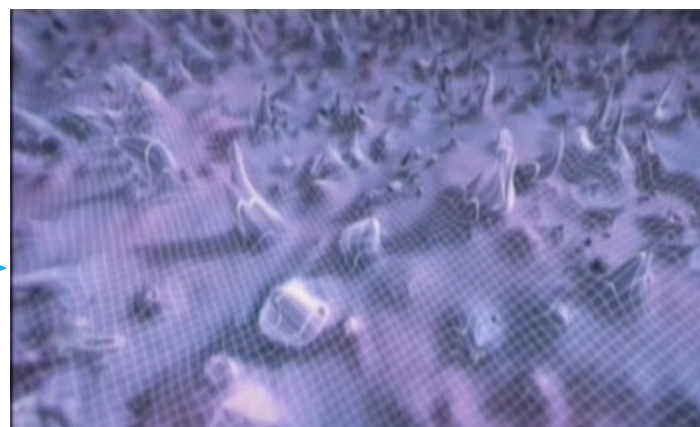
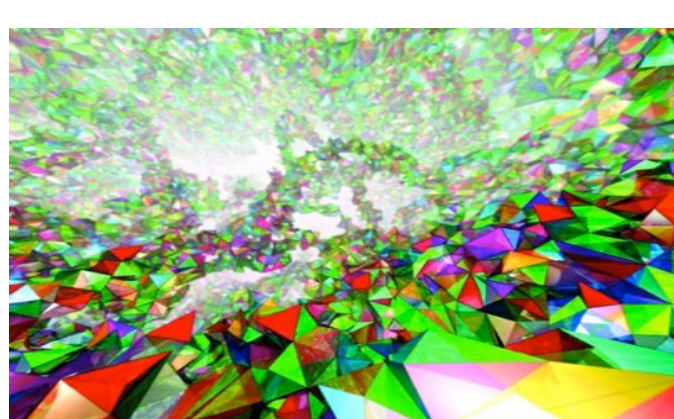
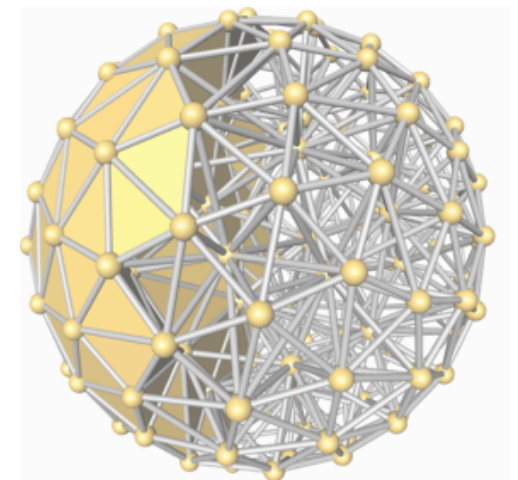
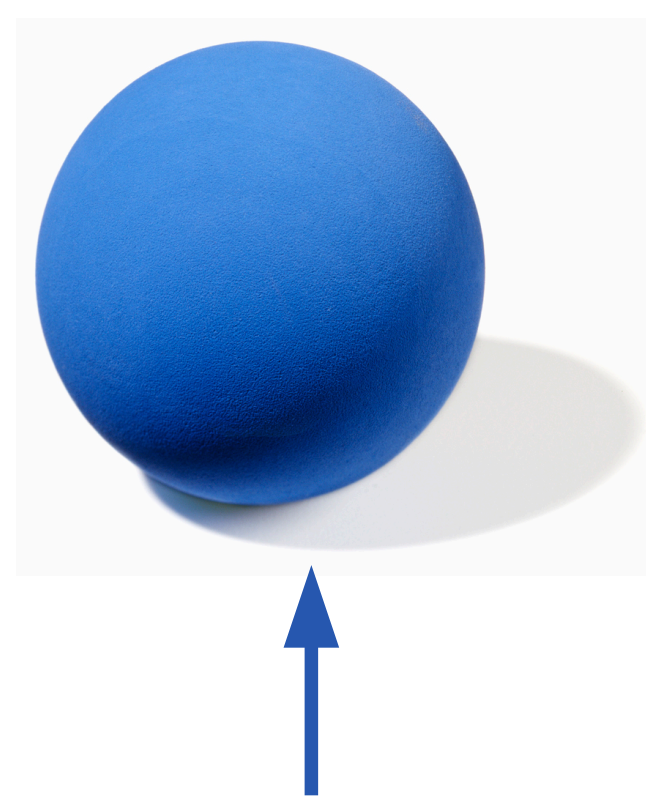
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- kinematically: **relevant quantum states involve superpositions of refined graphs**
- dynamically: **relevant quantum amplitudes involve superpositions of refined complexes**

i.e. collective physics, from perspective of spin networks and spin foams
(seen as fundamental microscopic QG dofs)

at weak coupling (since spin networks appear in Fock space, and spin foams in perturbative expansion)



TGFT formulation of QG states and (spin foam) dynamics

- well suited for renormalization, coarse graining, continuum limits, critical behaviour
 - methods from standard QFT have been adapted and applied
 - perturbative renormalizability of several TGFT models
 - non-perturbative FRG analyses of several TGFT models
 - large-N expansions - dominance of simple topologies
 - critical behaviour and phase transitions

R. Gurau, V. Bonzom, J. Ryan, V. Rivasseau, S. Carrozza, J. Ben Geloun, J. Thuerigen, D. Oriti, A. Tanasa, D. Ousmane-Samary, V. Lahoche, A. Pithis, A. Pereira, D. Benedetti, A. Eichhorn, R. Martini, R. Toriumi, T. Krajewski,

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- first steps for extraction of collective physics

- mean field approximation

* simplest approximation:
mean field hydrodynamics

saddle point evaluation of path integral - quantum
effective action $\sim$ classical action

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

- reliability of mean field description supported (not proven) by Landau-Ginsburg analysis:
Gaussian critical point in "IR" (i.e. small-j), fluctuations suppressed, condensate phase

A. Pithis, J. Thuerigen, L. Marchetti, R. Dekhil, DO, '22, '23

- quantum collective excitations ("bogolons") over mean field and 1-loop corrections

A. Calcinari, A. Delhom, D. Oriti, '26

key features of GFT mean field hydrodynamics

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- corresponding quantum states:

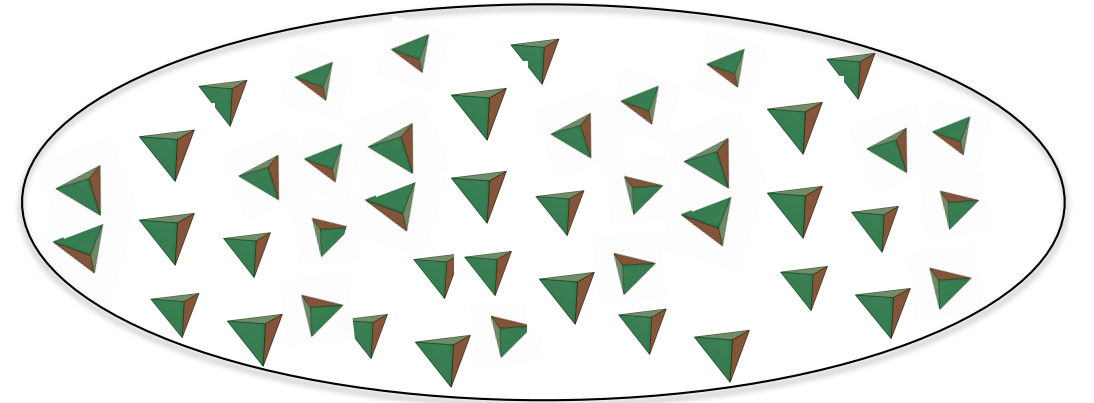
(simplest): GFT field coherent state

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

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

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

coherent states capture infinite QG dofs: infinite superposition of “refined” spin networks, but neglecting connectivity (probably only good for “extensive” geometric properties (eg universe volume))



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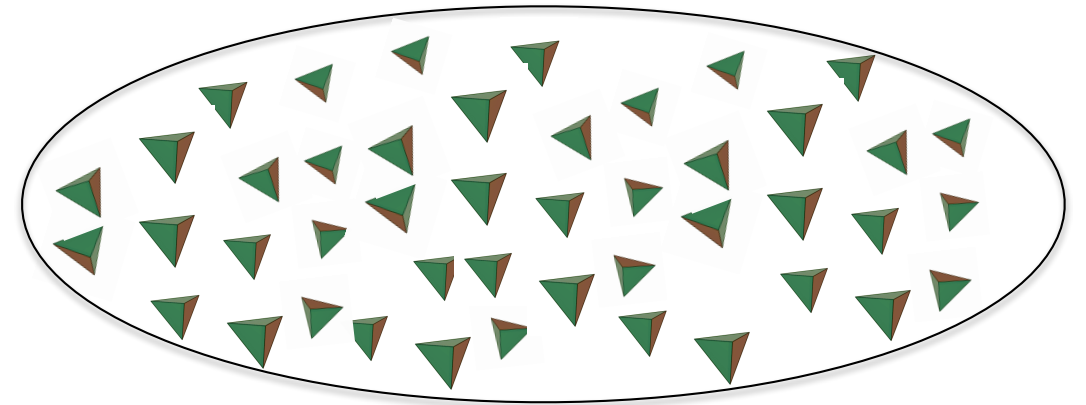
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L. Freidel, '06

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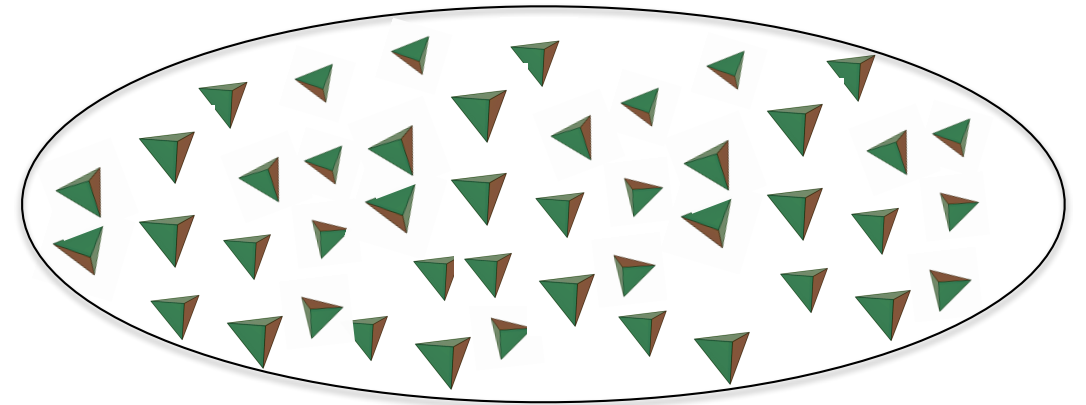
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L. Freidel, '06

how to improve:

- “more quantum” quantum states (squeezed states, connected states,)
- quantum corrections to dynamics: loop corrections, quasi-particle excitations over condensate

A. Calcinari, A. Delhom, D. Oriti, '26

what to compute?

quantum transition amplitudes are obviously important (definition of quantum gravity dynamics)

but

need to express (effective) dynamics in terms of

relational observables involving continuum fields,

to compare reliably with continuum gravitational physics (and other gravity theories)

Rovelli '90s+ [related ideas DeWitt '60s; Bargmann & Komar 90's]

Dittrich, ..., Hoehn, '00s

$$\begin{array}{ccccc} R(t) & \Phi(t) & & & \\ & \implies & R(t) & t(\Phi) & \\ & & & \implies & R(\Phi) \end{array}$$

why?

- work with diffeo-invariant quantities
- matching boundary states and amplitudes with continuum geometries relies on ambiguous embedding procedures; rather, want to -reconstruct- continuum geometries/dynamics from our quantum states/amplitudes, via observables
- even more important if we truncate/approximate full quantum dynamics, since cannot assume diffeomorphism invariance having been imposed (it would be imposed by the -full- QG path integral)

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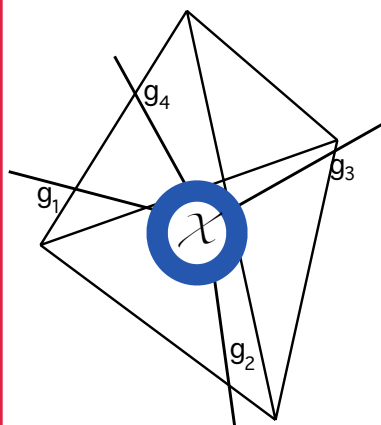
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extension to "matter" dofs - example: scalar matter

- domain of wavefunctions extended to include values of scalar fields $\hat{\varphi}(g_I, \chi^a) \equiv \hat{\varphi}(g_I, \chi^1, \dots, \chi^n)$ with consequent extension of field operators, quantum states and operators on Fock space

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Gielen, '15

Jercher, Pithis, DO, '23

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- mean field hydrodynamics = non-linear (and non-local) extension of loop quantum cosmology - appropriate for result of coarse graining up to global (cosmological observables)

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

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

cosmology as QG hydrodynamics on (mini)superspace

polynomial functional of
condensate wavefunction

- can be extracted for any concrete TGFT model

(domain extended to include scalar matter)

next steps in construction of effective cosmological dynamics

from quantum GFT observables (defined on fundamental Fock space)

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e.g.

$$\hat{V} = \sum_j \int d\phi \varphi_j^\dagger(\phi) j^{3/2} \varphi_j(\phi)$$

- "particle" number

$$N = \sum_j \int d\phi \sigma_j^*(\phi) \sigma_j(\phi)$$

- universe volume

$$V = a_p^3 \sum_j \int d\phi \sigma_j^*(\phi) j^3 \sigma_j(\phi)$$

- value of matter scalar field

$$\Phi = \sum_j \int d\phi \sigma_j^*(\phi) \phi \sigma_j(\phi)$$

- momentum of matter scalar field

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- going relational - to obtain relational time evolution:

choose one of scalar field variables in domain as "clock" - use it label evolution

- effective approach:

peaked condensate wavefunctions: $\sigma_\epsilon(j, \phi) \equiv \eta_\epsilon(j, \phi - \phi_0; \pi_0) \tilde{\sigma}(j, \phi)$

other approaches

A. Calcinari, S. Gielen, E. Wilson-Ewing,

peaking function around ϕ_0
with a typical width given by $\epsilon \ll 1$

fluctuations in (conjugate) scalar field
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- effective relational observables (localized "at given moment in time"):

$$N(\phi_0), V(\phi_0), \Phi(\phi_0) \simeq \phi_0, \Pi_\phi(\phi_0)$$

Bona fide quantum relational observables via POVMs

L. Marchetti, E. Wilson-Ewing, '25

- with respect to usual QFT, the GFT context is different: focus is on probability measures associated with the frame fields, not GFT field. Frame fields are part of GFT field domain
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- **effect density:**

$$\begin{aligned}\hat{E}_\chi(d\chi) &= d\chi \sum_{n=1}^{\infty} \frac{1}{n!} \sum_{\vec{\kappa}_1, \dots, \vec{\kappa}_n} \int \left[\prod_{i=1}^n d\chi_i \right] \frac{\sum_{i=1}^n \delta(\chi_i - \chi)}{n} \left[\prod_{i=1}^n \hat{\varphi}_{\vec{\kappa}_i}^\dagger(\chi_i) \right] |0\rangle \langle 0| \left[\prod_{i=1}^n \hat{\varphi}_{\vec{\kappa}_i}(\chi_i) \right] \\ &= d\chi \sum_{n=1}^{\infty} \sum_{\vec{\kappa}_1, \dots, \vec{\kappa}_n} \int \left[\prod_{i=1}^n d\chi_i \right] \frac{\sum_{i=1}^n \delta(\chi_i - \chi)}{n} \hat{F}_{\vec{\kappa}_1, \dots, \vec{\kappa}_n}^{(n)}(\chi_1, \dots, \chi_n),\end{aligned}$$

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- divergences can be avoided smearing the effect density ("finite resources" frame):

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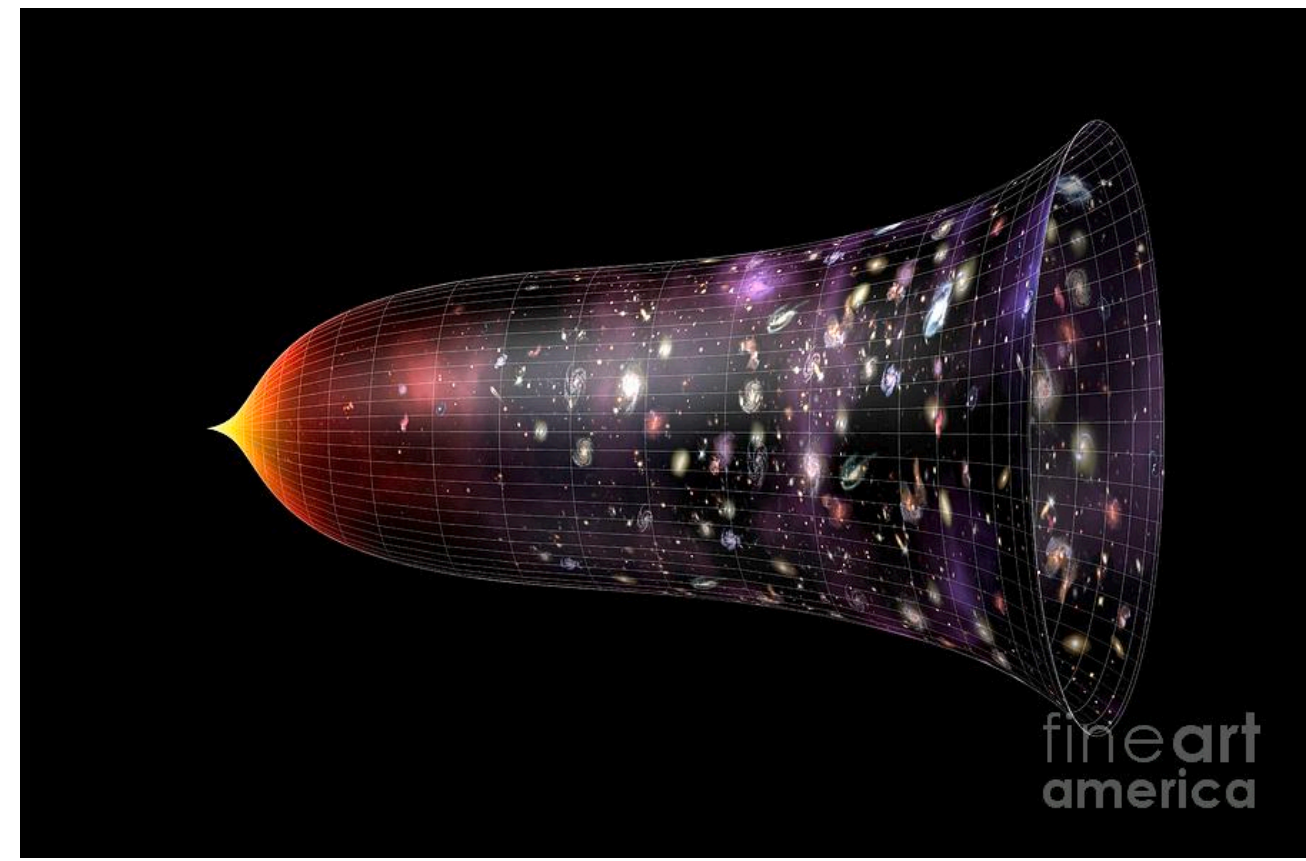
- to leading order in smearing parameter, the expectation values on coherent states give the same relational observables as in coherent peaked states strategy

The universe as a quantum condensate (in the TGFT formalism)

- TGFT condensate cosmology
 - reconstruction of effective gravitational dynamics for (diffeo-invariant, relational) observables

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

Extraction of effective cosmological dynamics

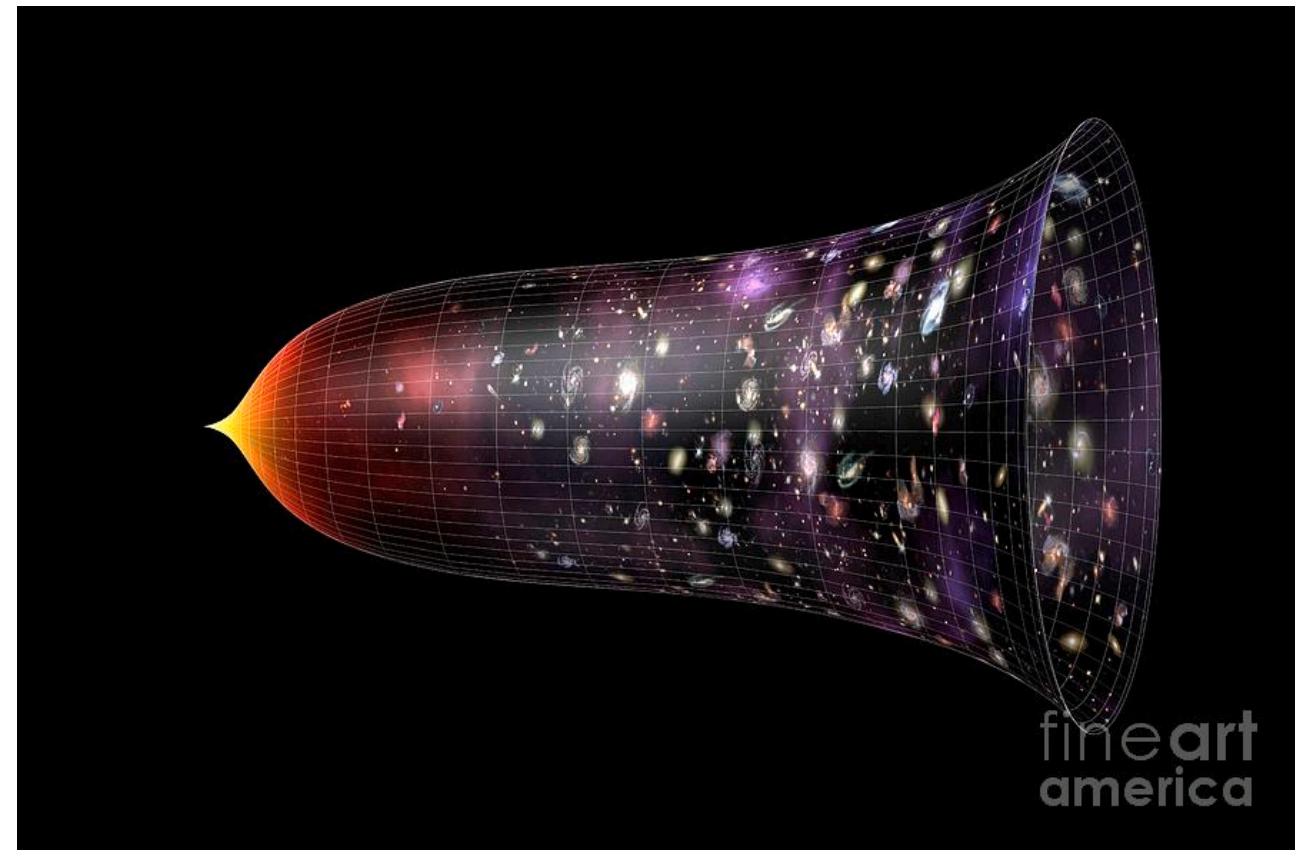


Extraction of effective cosmological dynamics

- starting point: relational mean field hydrodynamics (derivatives are with respect to clock time):

example:

$$\sigma_j''(\phi_0) + A\sigma_j'(\phi_0) + B\sigma_j(\phi_0) + \mathcal{V}[\sigma_j(\phi_0)] = 0$$



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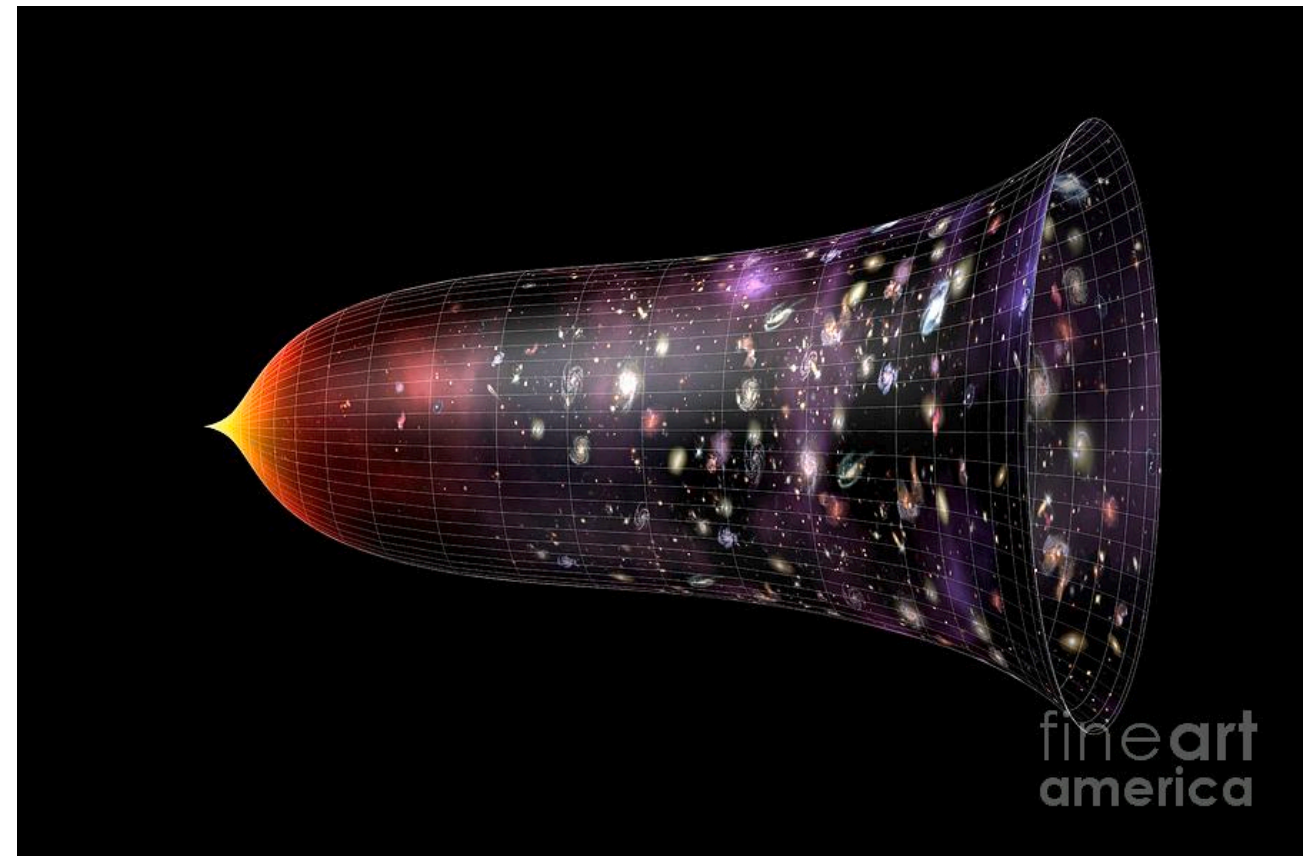
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- next step from relational hydrodynamics to dynamics of relational observables

example: $\left(\frac{V'}{V}\right)^2 = H^2 = f(V, \phi, \varphi, \sigma, \dots)$



Quantum geometric model (EPRL, mildly generalised) with 4 scalar dofs (1 clock+ 3 rods + 1 matter scalar field)

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

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

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

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


 peaked functions (e.g. Gaussians)


 parameters governing peaking properties

L. Marchetti, DO, '20, '21

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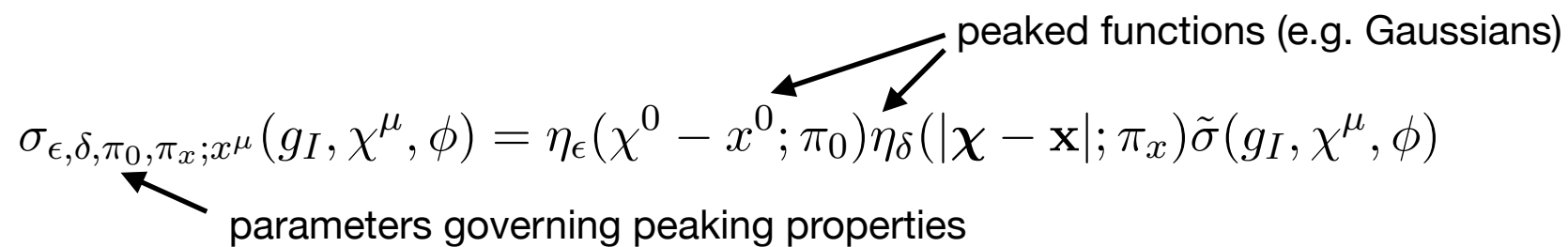
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L. Marchetti, DO, '20, '21

simplifying assumptions:

- **small (sub-dominant) TGFT interactions:** $U \ll K$ (consistent with LQG and discrete gravity, and mean field approx)
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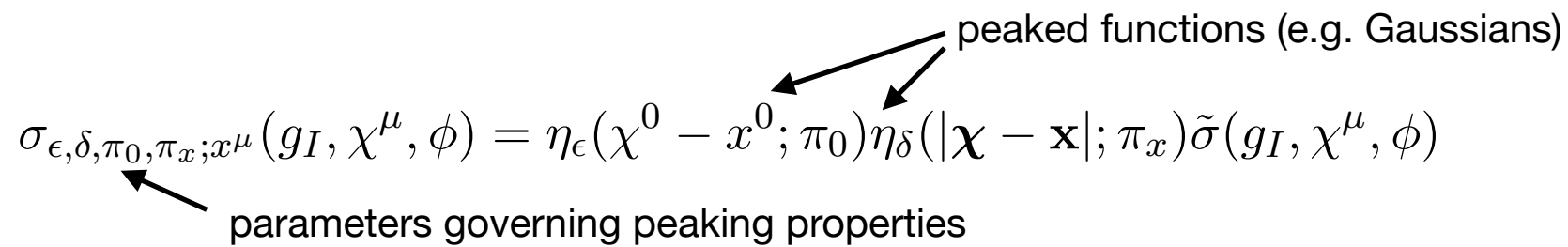
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- **isotropy:** condensate wavefunction depends on single j (plus clock/rods/matter)

resulting (free) mean field hydrodynamics eqn:

$$\partial_0^2 \tilde{\sigma}_j(x, \pi_\phi) - i\gamma \partial_0 \tilde{\sigma}_j(x, \pi_\phi) - {}^{(\lambda)}E_j^2(\pi_\phi) \tilde{\sigma}_j(x, \pi_\phi) + \alpha^2 \nabla^2 \tilde{\sigma}_j(x, \pi_\phi) = 0$$


 Fourier mode of matter field variable

with $\alpha^2 \equiv \frac{1}{3} \frac{\delta z^2}{\epsilon z_0^2}$ (function of peaking parameters)

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)

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

- expectation values of "microscopic observables" in peaked condensate states: relational spacetime-localized observables

$$\begin{aligned} N(x^0, x^i) &\equiv \langle \sigma_{\epsilon, \delta, \pi_0, \pi_x, x^\mu} | \hat{N} | \sigma_{\epsilon, \delta, \pi_0, \pi_x, x^\mu} \rangle & V(x^0, x^i) &\equiv \langle \sigma_{\epsilon, \delta, \pi_0, \pi_x, x^\mu} | \hat{V} | \sigma_{\epsilon, \delta, \pi_0, \pi_x, x^\mu} \rangle \\ X^\mu(x^0, x^i) &\equiv \langle \sigma_{\epsilon, \delta, \pi_0, \pi_x, x^\mu} | \hat{V} | \sigma_{\epsilon, \delta, \pi_0, \pi_x, x^\mu} \rangle \simeq x^\mu & \Pi(x^0, x^i) &\equiv \langle \sigma_{\epsilon, \delta, \pi_0, \pi_x, x^\mu} | \hat{\Pi}_\nu | \sigma_{\epsilon, \delta, \pi_0, \pi_x, x^\mu} \rangle \\ \phi(x^0, x^i) &\equiv \langle \sigma_{\epsilon, \delta, \pi_0, \pi_x, x^\mu} | \hat{\Phi} | \sigma_{\epsilon, \delta, \pi_0, \pi_x, x^\mu} \rangle & \Pi_\phi(x^0, x^i) &\equiv \langle \sigma_{\epsilon, \delta, \pi_0, \pi_x, x^\mu} | \hat{\Pi}_\phi | \sigma_{\epsilon, \delta, \pi_0, \pi_x, x^\mu} \rangle \end{aligned}$$

quantities of interest for effective continuum gravitational physics emerge as
coarse-grained, collective observables, averages in suitable class of QG states

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→ **background eqns:** $\bar{\rho}_j''(x^0, \pi_\phi) - \left[(\bar{\theta}_j'(x^0, \pi_\phi))^2 + {}^{(\lambda)}\eta_j^2(\pi_\phi) - \gamma \bar{\theta}_j'(x^0, \pi_\phi) \right] \bar{\rho}_j(x^0, \pi_\phi) = 0$

$$\bar{\theta}_j''(x^0, \pi_\phi) + (\bar{\theta}_j'(x^0, \pi_\phi) - \gamma/2) \frac{(\bar{\rho}_j^2)'(x^0, \pi_\phi)}{\bar{\rho}_j^2(x^0, \pi_\phi)} - {}^{(\lambda)}\beta_j^2 = 0$$

→ **perturbations eqns:** eg for large N (late time) and specific range of parameters

$$0 \simeq \delta\rho_j''(x, \pi_\phi) + \text{Re } \alpha \nabla^2 \delta\rho_j(x, \pi_\phi) - {}^{(\lambda)}\eta_j^2(\pi_\phi) \delta\rho_j(x, \pi_\phi),$$

$$0 \simeq \delta\theta_j''(x, \pi_\phi) + 2\delta\theta_j'(x, \pi_\phi) \frac{\bar{\rho}_j'(x^0, \pi_\phi)}{\bar{\rho}_j(x^0, \pi_\phi)} + \text{Re } \alpha \nabla^2 \delta\theta_j(x, \pi_\phi)$$

note: coefficients/parameters coming from fundamental model and choice of states

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

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

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TGFT cosmology: background dynamics

by inserting dynamics of condensate background into expression for universe volume: background universe dynamics

background volume dynamics:

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- intermediate times: large volume - QG interactions still subdominant

(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
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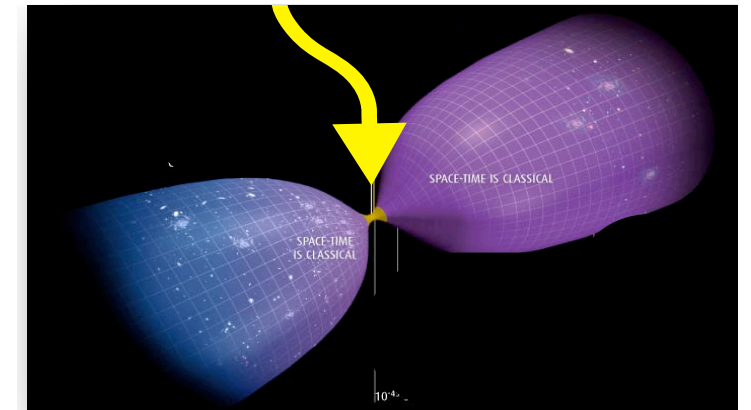
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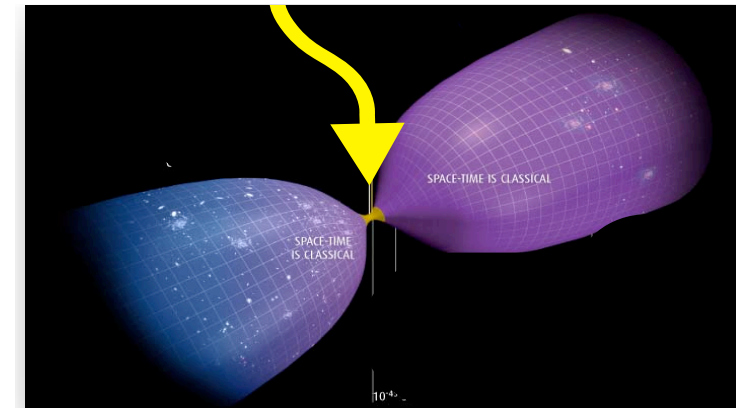
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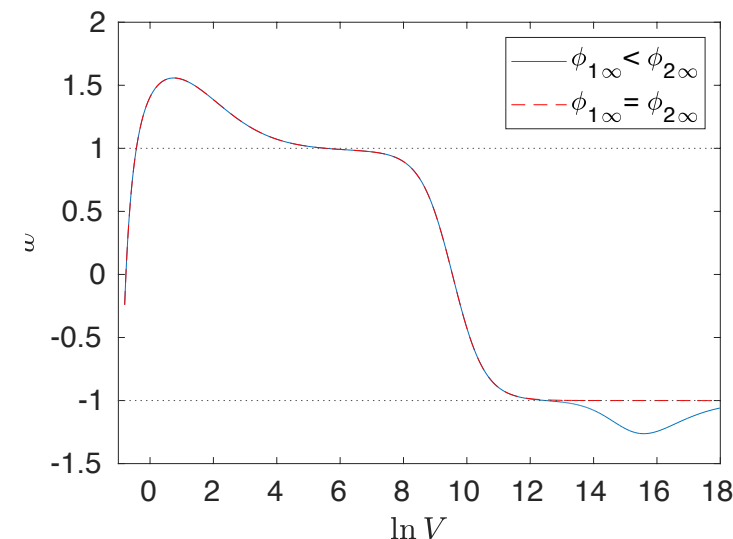
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X. Pang, DO, '21

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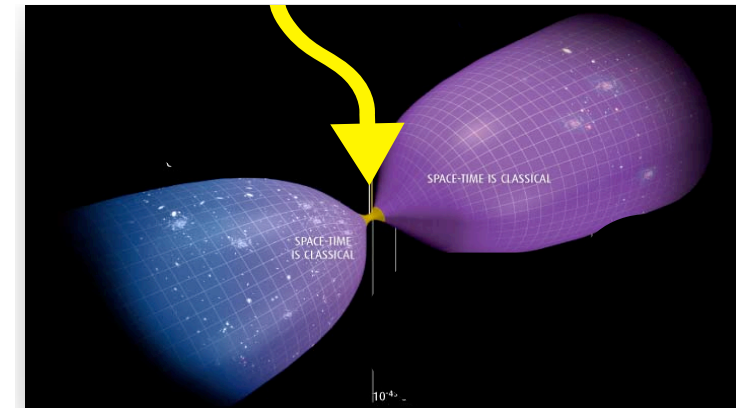
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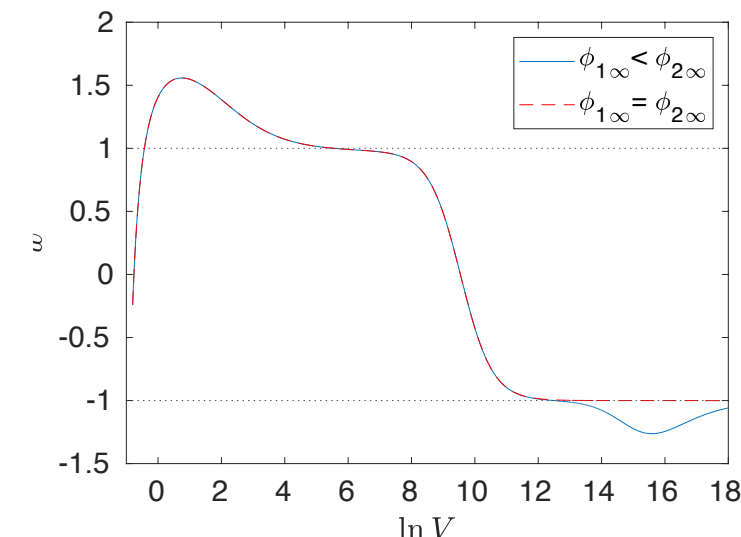
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- QG-produced early-time acceleration (QG-inflation)

M. De Cesare, A. Pithis, M. Sakellariadou, '17; M. De Sousa, A. Barrau, K. Martineau, '23
T. Landstätter, L. Marchetti, DO, '25

Background scalar field dynamics

R. Dekhil, F. Greco, S. Liberati, DO, to appear

Background scalar field (as function of hydrodynamic variables): $\langle \hat{\Phi} \rangle := \phi_0 \simeq \rho_0^2 \partial_{\pi_\phi} \theta_0 = N_0 \partial_{\pi_\phi} \theta_0,$
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it has evolution equation: $\ddot{\phi}_0 - 3\mathcal{H}\dot{\phi}_0 - 3\dot{\mathcal{H}}\phi_0 + J_0(x^0, \pi_\phi) = 0$

with "source" $J_0(x^0, \pi_\phi) := \rho_0^2 (2\dot{\theta}_0 - \gamma) \partial_\pi \left(\frac{\dot{\rho}_0}{\rho_0} \right) = \frac{2V}{3V_j} (2\dot{\theta}_0 - \gamma) \partial_\pi \mathcal{H}$

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scalar field theory on FRW geometry with modified kinetic operator



QG-modified scalar field dynamics
(wrt classical free massless scalar field)

TGFT cosmology:
cosmological perturbations
and
effective (scalar) field theory

Dynamical eqns for volume and matter perturbations, at late times

L. Marchetti, DO, '21

with identifications: $\phi = \langle \hat{\Phi} \rangle_\sigma$ $\pi_\phi = \langle \hat{\Pi}_\phi \rangle_\sigma / \bar{N}$

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- eqn for volume perturbations: $\delta V'' - 2\mu_{v_o}\delta V' + \text{Re } \alpha \nabla^2 \delta V = \delta V'' - 3\mathcal{H}\delta V' + \text{Re } \alpha \nabla^2 \delta V = 0$

(in regime: large volume, negligible TGFT interactions, single spin mode)

where correct Lorentzian signature is obtained if: $\text{Re } \alpha^2 = \frac{\pi_x^2}{6\epsilon z_0^2} (\delta_r^2 - \delta_i^2) < 0$

and standard D'Alembertian is obtained for specific state parameters only

- volume perturbations dynamics only matches GR in superhorizon ($k \rightarrow 0$) regime

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- eqn for scalar field can be obtained in same way:

effective scalar field $\delta\phi = \delta \langle \hat{\Phi} \rangle_\sigma = \left[\frac{\delta N}{\bar{N}} \bar{\phi} + \bar{N} \partial_{\pi_\phi} \delta\theta_{v_o} \right]_{\pi_\phi = \tilde{\pi}_\phi}$ $\delta N / \bar{N} = 2\delta\rho_{v_o} / \bar{\rho}_{v_o} \equiv 2\delta\rho_{v_o}$

with the ingredient satisfying same equation: $\delta''_{\rho_{v_o}} + 2\mu_{v_o} \delta'_{\rho_{v_o}} + \text{Re } \alpha \nabla^2 \delta\rho_{v_o} = 0 = \delta''_{\theta_{v_o}} + 2\mu_{v_o} \delta'_{\theta_{v_o}} + \text{Re } \alpha \nabla^2 \delta\theta_{v_o}$

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Late-time dynamics of cosmological perturbations: improved construction

- correct GR dynamics of higher-momenta (but still sub-planckian) perturbations (volume and scalar field) can be recovered by extended construction, involving more details of discrete causal structure:

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- extended TGFT with both timelike and spacelike fields** (creating timelike and spacelike tetrahedra) with kinetic kernels:

$$\mathcal{K}_+ = \mathcal{K}_+(g_v, g_w; (\chi_v^0 - \chi_w^0)^2, (\phi_v - \phi_w)^2) \quad \text{(timelike/spacelike scalar frame components)}$$

$$\mathcal{K}_- = \mathcal{K}_-(g_v, g_w; |\chi_v - \chi_w|^2, (\phi_v - \phi_w)^2)$$

- extended TGFT condensate of both timelike and spacelike quantum tetrahedra** (previously only spacelike ones)

$$|\Delta; x^0, \mathbf{x}\rangle = \mathcal{N}_\Delta e^{\hat{\sigma} \otimes \mathbb{1}_- + \mathbb{1}_+ \otimes \hat{\tau} + \delta \hat{\Phi} \otimes \mathbb{1}_- + \delta \hat{\Psi} + \mathbb{1}_+ \otimes \delta \hat{\Xi}} |\emptyset\rangle$$

key role of entanglement between timelike and spacelike components

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- dynamics of volume and scalar field perturbations at late times:

$$\left(\frac{\delta V}{\bar{V}}\right)'' + a^4 k^2 \left(\frac{\delta V}{\bar{V}}\right) = -3\mathcal{H} \left(\frac{\delta V}{\bar{V}}\right)' \quad \delta\phi'' + a^4 k^2 \delta\phi = J_\phi \quad \text{which match GR dynamics}$$

with QG corrections (very small in sub-Planckian regime):

$$J_\phi = -c \left(\frac{a^2 k}{M_{\text{Pl}}}\right) \bar{\phi}' \left[-\frac{3}{\sqrt{6}} \bar{\phi} + 2M_{\text{Pl}}\right] \Gamma\left(\frac{7}{4}\right) \times \left(\frac{4\mathcal{H}}{a^2 k}\right)^{3/4} J_{7/4}\left(\frac{a^2 k}{2\mathcal{H}}\right),$$

Complete (early- and late-time) dynamics of cosmological perturbations: effective scalar field theory

R. Dekhil, F. Greco, S. Liberati, DO, to appear

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using hydrodynamic eqns, we get effective dynamics:

$$\delta\ddot{\phi} + f_1\delta\dot{\phi} + f_2\nabla^2\delta\dot{\phi} + f_3\nabla^2\delta\phi + f_4\nabla^4\delta\phi + f_5\delta\phi + J = 0$$

with $f_1(x^0, \pi_\phi) = \frac{B(x^0, \pi_\phi)}{A(x^0, \pi_\phi)} - 6\mathcal{H}(x^0, \pi_\phi)$, $f_2(x^0, \pi_\phi) = \frac{D(x^0, \pi_\phi)}{A(x^0, \pi_\phi)}$,

$$f_3(x^0, \pi_\phi) = \frac{C(x^0, \pi_\phi)}{A(x^0, \pi_\phi)} - 3\mathcal{H}(x^0, \pi_\phi)\frac{D(x^0, \pi_\phi)}{A(x^0, \pi_\phi)},$$

$$f_4(x^0, \pi_\phi) = \frac{E(x^0, \pi_\phi)}{A(x^0, \pi_\phi)},$$

$$f_5(x^0, \pi_\phi) = 3\left(3\mathcal{H}(x^0, \pi_\phi)^2 - \frac{B(x^0, \pi_\phi)}{A(x^0, \pi_\phi)}\mathcal{H}(x^0, \pi_\phi) - \dot{\mathcal{H}}(x^0, \pi_\phi)\right)$$

and "source" $\tilde{J}(x^0, x^i, \pi_\phi)$

function of density and scalar
field perturbation and explicit
time dependence

Complete (early- and late-time) dynamics of cosmological perturbations: effective scalar field theory

R. Dekhil, F. Greco, S. Liberati, DO, to appear

scalar field perturbation

$$\delta\phi = \delta\langle\hat{\Phi}\rangle_\sigma = \frac{\delta N}{N_0}\phi_0 + N_0\partial_{\pi_\phi}\delta\theta = 2\rho_0\delta\rho\partial_\pi\theta + \rho_0^2\partial_\pi\delta\theta$$

using hydrodynamic eqns, we get effective dynamics:

$$\delta\ddot{\phi} + f_1\delta\dot{\phi} + f_2\nabla^2\delta\dot{\phi} + f_3\nabla^2\delta\phi + f_4\nabla^4\delta\phi + f_5\delta\phi + J = 0$$

$$\text{with } f_1(x^0, \pi_\phi) = \frac{B(x^0, \pi_\phi)}{A(x^0, \pi_\phi)} - 6\mathcal{H}(x^0, \pi_\phi), \quad f_2(x^0, \pi_\phi) = \frac{D(x^0, \pi_\phi)}{A(x^0, \pi_\phi)},$$

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function of density and scalar field perturbation and explicit time dependence

under some assumptions (decoupling of density and phase), the equation simplifies:

the non-standard terms disappear (they are thus due to the interaction of density and phase of the "QG condensate")

writing it in terms of scale factor, we have:

$$\text{at early times: } \delta\ddot{\phi} - 3\mathcal{H} \frac{1 + 12c^2 a^{-6}}{1 + 4c^2 a^{-6}} \delta\dot{\phi} + 3\left(24\mathcal{H}^2 \frac{c^2 a^{-6}}{1 + 4c^2 a^{-6}} - \dot{\mathcal{H}}\right) \delta\phi + \frac{\alpha}{1 + 4c^2 a^{-6}} \nabla^2 \delta\phi + \tilde{J} = 0,$$

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QG-modified scalar field dynamics
(wrt classical free massless scalar field)

Complete (early- and late-time) dynamics of cosmological perturbations: effective scalar field theory

looking again at the effective scalar field dynamics

$$\delta\ddot{\phi} + f_1 \delta\dot{\phi} + f_2 \nabla^2 \delta\dot{\phi} + f_3 \nabla^2 \delta\phi + f_4 \nabla^4 \delta\phi + f_5 \delta\phi + J = 0$$

from the kinetic part, we can derive the effective dispersion relations

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- take Fourier transform of the equation (without source term) $\delta\phi(x^0, x^i) = \int \frac{d^3k}{(2\pi)^3} \delta\phi_k(x^0) e^{i k_i x^i}$
- take WKB approx for the time-dependent part $\delta\phi_k(x^0) \simeq \frac{1}{\sqrt{2\Omega_k(x^0)}} e^{-i \int^{x^0} ds \Omega_k(s)} \quad \left| \frac{\dot{\Omega}_k(x^0)}{\Omega_k(x^0)^2} \right| \ll 1$

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dispersion relations

$$\Omega_k(x^0) = \frac{i}{2} \Gamma_k(x^0) \pm \sqrt{\Gamma_k(x^0)^2 + 4 [k^4 f_4(x^0) - k^2 f_3(x^0) + f_5(x^0)]}$$

$$\Gamma_k(x^0) := k^2 f_2(x^0) - f_1(x^0)$$

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- the real part shows **modifications to the standard relativistic dispersion relations**

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Central problem: extracting effective continuum physics from quantum gravity

- QG = quantum theory of "spacetime constituents" = "quantum spacetime microphysics"

spacetime fields, including metric, as effective, collective entities



Emergent spacetime!



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

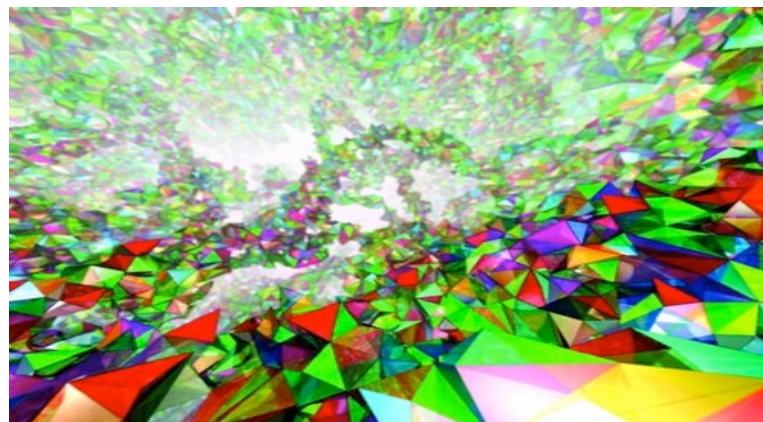
extraction of spacetime and cosmology similar to typical problem in condensed matter theory
(from atoms to macroscopic effective continuum physics)

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

here:

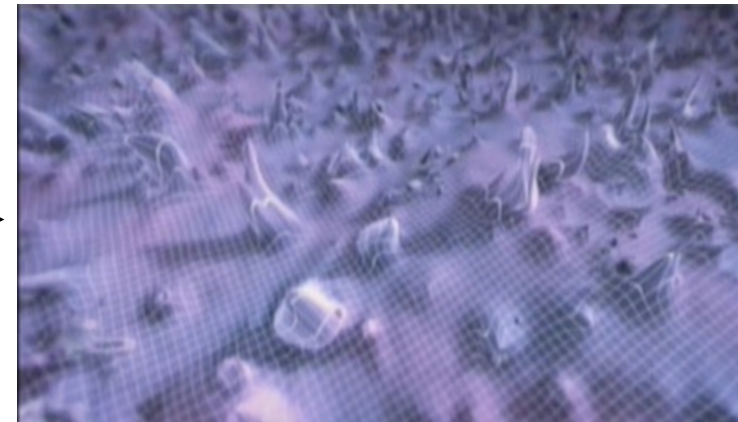
quantum gravity:

quantum theory of spin networks



effective continuum physics:

(Q)FT for gravity+matter





Thank you for your attention!