Title: Relational dynamics in an emergent spacetime context

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Abstract: I discuss the new dimension that the relational approach to the problem of time takes in quantum gravity contexts in which spacetime and geometry are understood as emergent. I argue that, in this case, the relational strategy is best realized at an approximate and effective level, after suitable coarse graining and only in terms of special quantum states. I then show a concrete realization of such effective relational dynamics in the context of a cosmological application of the tensorial group field theory formalism for quantum gravity.


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Relational dynamics in
an emergent spacetime context
(based on 2008.02774, 2010.09700)
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Relational strategy and emergent quantum gravity theories

Background independence → Problem of time → Relational strategy

- Well understood from a classical perspective, less from a quantum perspective.
- Difficulties especially relevant for emergent QG theories.

Microscopic pre-geo

- Fundamental d.o.f. are weakly related to spacetime quantities;
- The latter expected to emerge from the former when a continuum limit is taken.

Macroscopic proto-geo

- Set of collective observables;
- Coarse grained states or probability distributions.

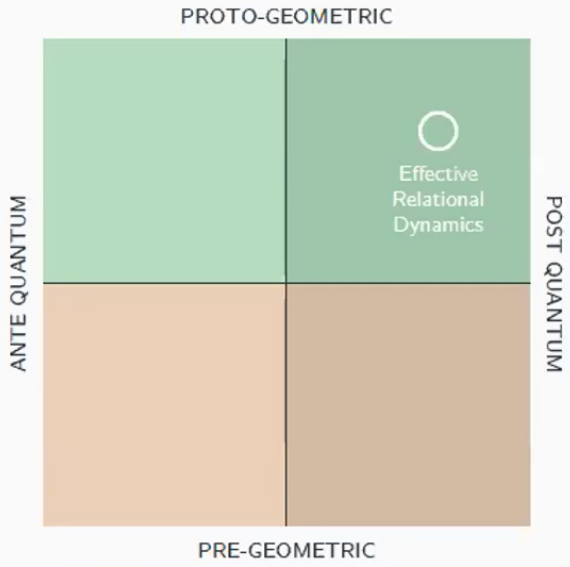
The quantities whose evolution we want to describe relationally are the result of a coarse-graining of some fundamental d.o.f.

Effective approaches to relational dynamics

- Bypass most conceptual and technical difficulties.
- Relevant for observative purposes.

Giulini 0603087; Kuchar Int.J.Mod.Phys.D 20(2011); Isham 9210011; Rovelli Class. Quantum Grav. 8 297; Dittrich 0507106; Hoehn et al. 1912.00033;

Emergent effective relational dynamics



Basic principles

Emergence Relational dynamics should be formulated in terms of collective observables and states defined in the microscopic theory.

Effectivness Relational evolution should be intended to hold on average. Internal clock should have small quantum fluctuations.

Concrete example: scalar field clock

Emergence

- Identify a class of states $|\Psi\rangle$ which encode collective behavior and admit a continuum proto-geometric interpretation.
- Identify a set of collective observables:

$\hat{O}_a$ $\xrightarrow{\langle\cdot\rangle_\Psi}$ Geometric observables

$\hat{\chi}$ $\hat{\Pi}$ $\xrightarrow{\langle\cdot\rangle_\Psi}$ Scalar field and its momentum

$\hat{N}$ $\xrightarrow{\langle\cdot\rangle_\Psi}$ Number of quanta

Effectivness

- It exists a "Hamiltonian" $\hat{H}$ such that

$$i\frac{\mathrm{d}}{\mathrm{d}\langle\hat{\chi}\rangle_\Psi}\langle\hat{O}_a\rangle_\Psi = \langle[\hat{H},\hat{O}_a]\rangle_\Psi \ ,$$

  and whose moments coincide with those of $\hat{\Pi}$.
- Relative variance of $\hat{\chi}$ on $|\Psi\rangle$ should be $\ll 1$ and have the characteristic $\langle\hat{N}\rangle_\Psi^{-1}$ behavior:

$$\sigma^2_\chi \ll 1 \, , \qquad \sigma^2_\chi \sim \langle\hat{N}\rangle_\Psi^{-1} \ .$$

LM, Oriti 2008.02774; Bojowald, Hoehn, Tsobanjan 1011.3040; Bojowald, Tsobanjan 0906.1772;

Effective relational dynamics in GFT cosmology

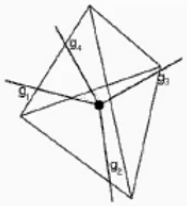
GFTs and GFT cosmology

Group field theories: theories of a field $\varphi : G^d \to \mathbb{C}$ defined on d copies of a group manifold G with action given by

$$S[\varphi, \bar{\varphi}] = \int \mathrm{d}g_I \, \mathrm{d}h_I \bar{\varphi}(g_I) \mathcal{K}(g_I, h_I) \varphi(h_I) + V_{\text{non-loc,combinatorial}}$$

- For simplicial GFT models S is obtained by comparison of the perturbative expansion of the partition function with lattice gravity path integral.

d are the dimensions of the "spacetime to be" ($d = 4$) and G is the local gauge group of gravity, $G = \mathrm{SL}(2, \mathbb{C})$ or, for most applications, $G = \mathbf{SU}(2)$.



$$H_v = L^2(\mathrm{SU}(2)^4, \mathrm{d}\mu_{\text{Haar}})$$

Closure condition

$$H_v = L^2(\mathrm{SU}(2)^4/\mathrm{SU}(2)_{\text{diag}}, \mathrm{d}\mu_{\text{Haar}})$$

GFTs are QFTs of building blocks of space.

GFT condensate cosmology

Classical cosmology ~ continuous homogeneous 3-geometries

Quantum

infinite d.o.f. + quantum coherence = GFT condensate hypothesis

- Neglecting correlations between different quanta.
- Same geometric data for each quantum.

$$|\sigma\rangle = N \exp\left[\int \mathrm{d}g_I \, \sigma(g_I) \hat{\varphi}^\dagger(g_I)\right] |0\rangle$$

Oriti 0912.2441; Oriti 1408.7112; Gielen, Oriti 1311.1238; Oriti, Sindoni, Wilson-Ewing 1602.05881; Gielen, Sindoni 1602.08104; ...

Effective relational dynamics in GFT cosmology

Including a minimally coupled massless scalar field clock

A value of the scalar field is assigned to each 4-simplex.

$$|\sigma\rangle = N \exp\left[\int \mathrm{d}g_I \, \mathrm{d}\chi \, \sigma(g_I,\chi)\hat{\varphi}^\dagger(g_I,\chi)\right]|0\rangle \qquad \hat{X} = \int \mathrm{d}g_I \, \mathrm{d}\chi \hat{\varphi}^\dagger(g_I,\chi)\chi\hat{\varphi}(g_I,\chi)$$

$$\hat{V} = \int \mathrm{d}^2 g_I \, \mathrm{d}\chi \hat{\varphi}^\dagger(g_I^1,\chi)V(g_I^1,g_I^2)\hat{\varphi}(g_I^2,\chi) \qquad \hat{\Pi} = \frac{1}{i}\int \mathrm{d}g_I \, \mathrm{d}\chi \hat{\varphi}^\dagger(g_I,\chi)\partial_\chi\hat{\varphi}(g_I,\chi)$$

Identifying a suitable class of states: Coherent Peaked States

Quantum

decompose the spacetime into a foliation made of constant-χ leaves

Fixed

"χ-localized" condensate states

Dynamically determined

Ansatz: σ factorizes into a peaking function η_ϵ and a reduced wavefunction $\tilde{\sigma}$

$$\sigma_{\epsilon;\chi_0,\pi_0}(g_I,\chi) \equiv \eta_\epsilon(g_I;\chi-\chi_0,\pi_0)\tilde{\sigma}(g_I,\chi)\,, \quad \eta_\epsilon(\chi-\chi_0,\pi_0) \equiv \mathcal{N}_\epsilon e^{-(\chi-\chi_0)^2/(2\epsilon)} e^{i\pi_0(\chi-\chi_0)}$$

- $\epsilon \ll 1$ controls localization around the "leaf label" χ_0 ($\epsilon = 0$ excluded by QM).

Relationality

- Averaged evolution wrt χ_0 is physical: $\langle\hat{\chi}\rangle_{\sigma_\epsilon} \equiv \langle\hat{X}\rangle_{\sigma_\epsilon}/N \simeq \chi_0$.
- There exists $\hat{H}$ generating averaged evolution for geometric observables ($\hat{V}$).

Effectivness (in the emergent limit)

- $\langle\hat{H}\rangle_{\sigma_\epsilon} = \langle\hat{\Pi}\rangle_{\sigma_\epsilon}$ (on shell).
- Relative variances of clock variables are negligible: $\sim N^{-1}$.

LM, Oriti 2008.02774; LM, Oriti 2010.09700; Oriti, Sindoni, Wilson-Ewing 1602.05881;

Effective relational volume dynamics

Averaged quantum equations of motion: $\left\langle \sigma_\epsilon; \chi_0, \pi_0 \left| \frac{\delta S[\hat{\varphi}, \hat{\varphi}^\dagger]}{\delta \hat{\varphi}^\dagger(g_I, \chi_0)} \right| \sigma_\epsilon; \chi_0, \pi_0 \right\rangle = 0$

Assumptions

- Isotropy, negligible interactions and the good slice approximation (kinetic truncation scheme).

Results

- Evolution equations for $\tilde{\sigma}_j \equiv \rho_j e^{i\theta_j}$: ρ_j^2 controls N

$$\langle \hat{N} \rangle_{\sigma_\epsilon} \equiv N = \textstyle\sum_j \rho_j^2 \,, \quad \langle \hat{V} \rangle_{\sigma_\epsilon} \equiv V = \textstyle\sum_j V_j \rho_j^2 \,.$$

Effective relational Friedmann equations

$$\left(\frac{V'}{3V}\right)^2 \simeq \left(\frac{2\sum_j V_j \rho_j \mathrm{sgn}(\rho_j') \sqrt{\mathcal{E}_j - Q_j^2/\rho_j^2 + \mu_j^2 \rho_j^2}}{3\sum_j V_j \rho_j^2} \right)^2 \qquad \frac{V''}{V} \simeq \frac{2\sum_j V_j \left[\mathcal{E}_j + 2\mu_j^2 \rho_j^2\right]}{\sum_j V_j \rho_j^2}$$

- μ_j is fixed by CPS parameters and GFT model. Q_j and $\mathcal{E}_j$ are integration constants.

Classical limit (large ρ_js, late times)

- If μ_j^2 is mildly dependent on j (or one j is dominating) and equal to $3\pi\tilde{G}$

$$(V'/3V)^2 \simeq (2\mu_j/3)^2 = 4\pi\tilde{G}/3 \,.$$

- Quantum fluctuations on clock and geometric variables are under control.

Bounce

- A non-zero volume bounce happens if at least one $Q_j \neq 0$ or one $\mathcal{E}_j < 0$.
- The average singularity resolution may still be spoiled by quantum effects on geometric and clock variables.

LM, Oriti 2008.02774; LM, Oriti 2010.09700; Oriti, Sindoni, Wilson-Ewing 1602.05881;

Conclusions and perspectives

Conclusions

- A scheme to define an effective notion of relational dynamics for emergent QG theories was outlined. ✓
- The advocated framework was realized concretely in GFT cosmology: ✓
  - An effective volume relational dynamics with correct classical limit and possible singularity resolution has been obtained. ✓
  - The role of quantum fluctuations on the relational picture has been investigated: ✓
    - They are unimportant in the classical, emergent limit.
    - They may become relevant around the bounce depending on initial conditions.
- The interplay between quantum effects, emergence and relationality was highlighted. ✓

Perspectives

- Extend the framework to include additional matter and different matter field clocks. 
- Include rod fields to study small inhomogeneities and anisotropies. 
- Investigate the relations between this approach and other effective approaches to the problem of time already present in literature. 
- Investigate in more detail the role of interactions.
- ...

Conclusions and perspectives