Emergent Cosmology from (T)GFT condensates

based on 2008.02774, 2010.09700, 2110.11176 and 2112.12677; with D. Oriti, S. Gielen, A. Polaczek

Luca Marchetti

QUAST seminar

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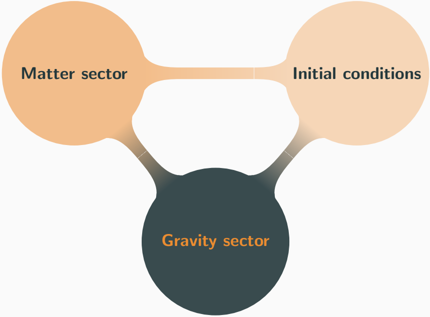
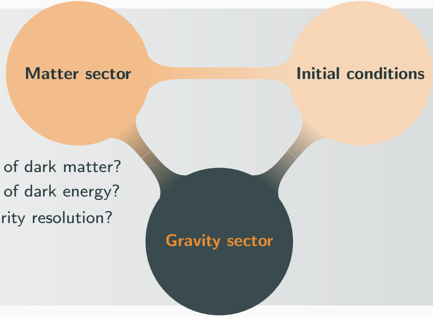
Arnold Sommerfeld Center
LMU Munich

LUDWIG-MAXIMILIANS-UNIVERSITÄT MÜNCHEN
ARNOLD SOMMERFELD CENTER FOR THEORETICAL PHYSICS

The QG perspective on Cosmology



Ashtekar, Kaminski, Lewandowski 0901.0933; Agullo, Ashtekar, Nelson 1302.0254; Gielen, Oriti 1709.01095; Gerhart, Oriti, Wilson-Ewing 1805.03099; ...



- Nature of dark matter?
- Nature of dark energy?
- Singularity resolution?
- ...

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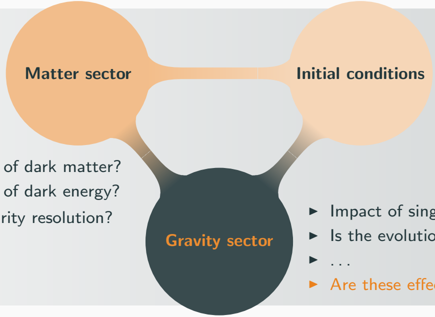

- Nature of dark matter?
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- Impact of singularity resolution on pert.?
- Is the evolution of pert. modified by QG effects?
- ...
- Are these effects observable?

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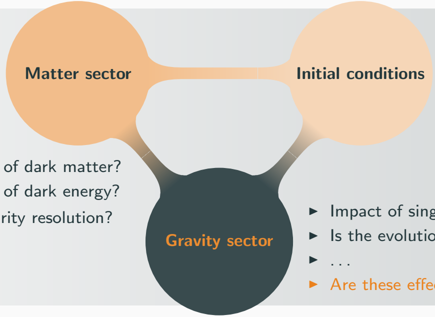

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- Is the vacuum state a QG modified BD vacuum?
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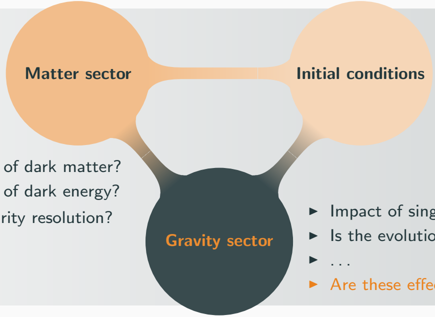

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Challenges from the QG perspective:

- How to define (in)homogeneity?
- How to extract macroscopic dynamics?
- How to construct cosmological geometries?
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The QG perspective on Cosmology

Matter sector

- Nature of dark matter?
- Nature of dark energy?
- Singularity resolution?
- ...

Initial conditions

- Geometric inflation?
- Is the vacuum state a QG modified BD vacuum?
- ...
- Are these effects observable?

Gravity sector

- Impact of singularity resolution on pert.?
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Relational description

Ashtekar, Kaminski, Lewandowski 0901.0933; Agullo, Ashtekar, Nelson 1302.0254; Gielen, Oriti 1709.01095; Gerhart, Oriti, Wilson-Ewing 1805.03099; ...

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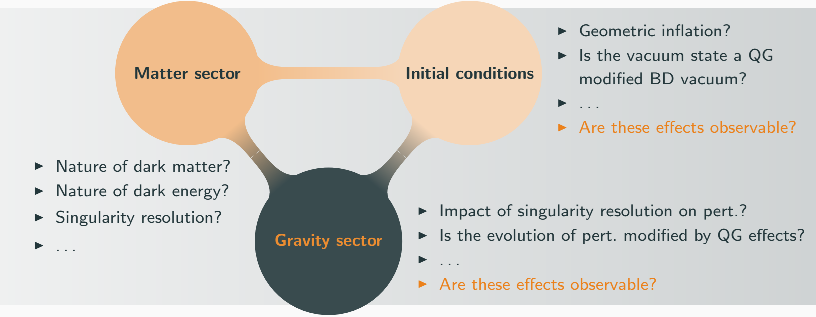

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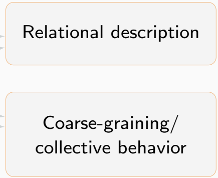

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Relational dynamics

Relational strategy: the classical and quantum GR perspective

Background independence ⟷ **Problem of time** ⟷ **Relational strategy**

Quite well understood from a classical perspective, less from a quantum perspective.

Isham 9210011; Rovelli Class. Quantum Grav. 8 297; Dittrich 0507106; Hoehn et al. 1912.00033 and 2007.00580; Tambornino 1109.0740; ...

Relational strategy: the classical and quantum GR perspective

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Classical

Notion of relationality can be classically encoded in relational observables:

- Take two phase space functions, f and T with $\{T, C_H\} \neq 0$ (T relational clock).
- The relational extension $F_{f,T}(\tau)$ of f encodes the value of f when T reads τ.
- Evolution in τ is relational.
- $F_{f,T}(\tau)$ is a very complicated function, often written in series form.
- Applications only for (almost) deparametrizable systems, such as GR plus pressureless dust or massless scalar fields.

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Quantum GR

Dirac approach: first quantize, then implement relationality

- Perspective neutral approach: all variables are treated on the same footing.
- Poor control of the physical Hilbert space.

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Quantum GR

Dirac approach: first quantize, then implement relationality

- Perspective neutral approach: all variables are treated on the same footing.
- Poor control of the physical Hilbert space.

Reduced phase space approach: first implment relationality, then quantize

- No quantum constraint to solve.
- Led to quantization of simple deparametrizable models (LQG).
- Not perspective neutral. Too complicated to implement in most of the cases.

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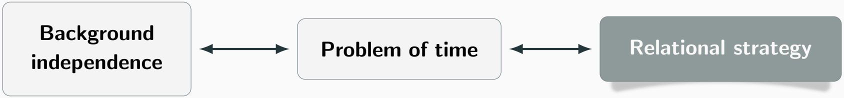
Relational strategy and emergent quantum gravity theories



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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.

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Effective approaches:

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

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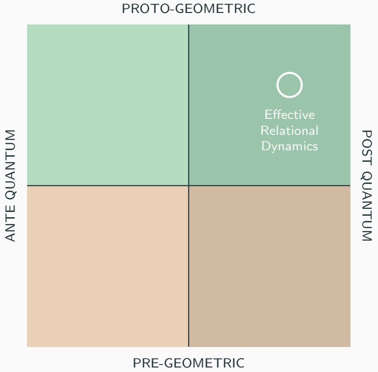
Emergent effective relational dynamics



Basic principles

Emergence Rel. dynamics formulated in terms of collective observables and states defined in the microscopic theory.

Effectiveness Rel. evolution intended to hold on average. Internal clock not too quantum.

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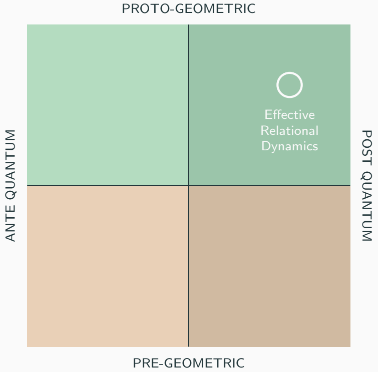

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Concrete example: scalar field clock

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:

$\hat{O}_a$	$\hat{\chi}$ $\hat{\Pi}$	$\hat{N}$
$\downarrow \langle\cdot\rangle_\Psi$	$\downarrow \langle\cdot\rangle_\Psi$	$\downarrow \langle\cdot\rangle_\Psi$
Geometric observables	Scalar field and its momentum	Number of quanta

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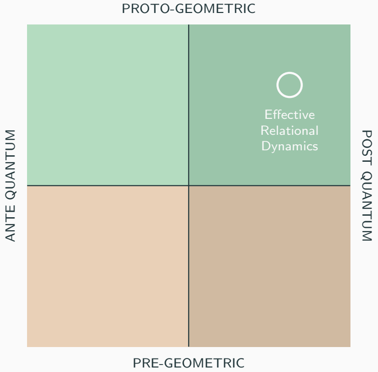

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Effectivness

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

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Homogeneous cosmologies from (T)GFT condensates

The (T)GFT approach to QG

(Tensorial) Group Field Theories: theories of a field $\varphi : G^d \to \mathbb{C}$ defined on d copies of a group manifold G.

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

Oriti 0912.2441; Oriti 1408.7112; Krajewski 1210.6257; Gielen, Oriti 1311.1238; Oriti, Sindoni, Wilson-Ewing 1602.05881; Gielen, Sindoni 1602.08104; ...

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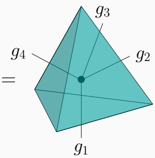
Kinematics

Boundary states are $d-1$-simplices decorated with quantum geometric data:

$\mathcal{H}_{\text{1-p}} =$ 

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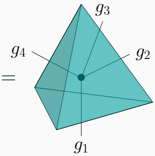
$\mathcal{H}_{\text{1-p}} =$ 

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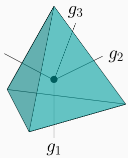
$\mathcal{H}_{\text{1-p}} =$ 

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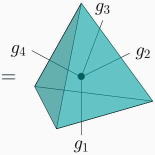
$\mathcal{H}_{\text{1-p}} =$ 

Dynamics

S_{GFT} obtained by comparing Z_{GFT} with simplicial gravity path integral.

$$Z_{\mathrm{GFT}} = \sum_{\Gamma} \frac{\prod_i \lambda_i^{n_i(\Gamma)}}{\mathrm{sym}(\Gamma)} Z_{\mathrm{GFT}}(\Gamma)$$

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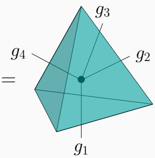
$\mathcal{H}_{1\text{-p}} =$ 

Dynamics

S_{GFT} obtained by comparing Z_{GFT} with simplicial gravity path integral.

- Non-local and combinatorial interactions guarantee the gluing of $d-1$-simplices into d-simplices.
- Γ are dual to spacetime triangulations.

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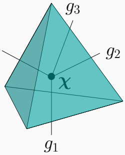
Kinematics

Boundary states are $d - 1$-simplices decorated with quantum geometric and scalar data:

- Group (Lie algebra) variables associated to discretized gravitational quantities.
- Appropriate (geometricity) constraints allow the simplicial interpretation.
- Scalar field discretized on each d-simplex: each $d - 1$-simplex composing it carries values $\chi \in \mathbb{R}^{d_l}$.

$\mathcal{H}_{\text{1-p}} =$ 

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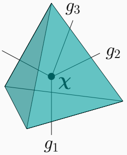

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GFTs are QFTs of atoms of spacetime.

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QG condensates and peaked states

Extracting continuum physics

- Identify coarse-grained states and collective observables with a continuum interpretation.
- Obtain macroscopic, effective, and relational dynamics from the microscopic one.

Collective states

(ciao)(T)GFT condensates

Simplest collective behavior: macroscopic σ dynamics well described in the mean-field approx.

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

LM, Oriti 2008.02774; LM, Oriti 2112.12677; Oriti, Sindoni, Wilson-Ewing 1602.05881; Gielen, Oriti, Sindoni 1311.1238; Gielen 1404.2944;

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- Assuming $\sigma(g_I,\cdot) = \sigma(hg_I h',\cdot)$, $\mathcal{D} = \mathrm{GL}(3)/\mathrm{O}(3)\times\mathbb{R}^d$:
- If χ^μ constitute a matter ref. frame:

⟶ $\sigma(g_I,\chi^\mu) \sim$ distribution of spatial geometries at χ^μ.

LM, Oriti 2008.02774; LM, Oriti 2112.12677; Oriti, Sindoni, Wilson-Ewing 1602.05881; Gielen, Oriti, Sindoni 1311.1238; Gielen 1404.2944;

QG condensates and peaked states

Extracting continuum physics

- Identify coarse-grained states and collective observables with a continuum interpretation.
- Obtain macroscopic, effective, and relational dynamics from the microscopic one.

Collective states

(ciao(T)GFT condensates

Simplest collective behavior: macroscopic σ dynamics well described in the mean-field approx.

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

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$\longrightarrow$ $\sigma(g_I,\chi^\mu)\sim$ distribution of spatial geometries at χ^μ.

Relationality

(ciaoCondensate Peaked States(

- If σ is peaked on $\chi^\mu \simeq x^\mu$, $|\sigma\rangle_x$ encodes relational information about the spatial geometry at x^μ.

$$\sigma = (\text{fixed peaking function } \eta)\times(\text{dynamically determined reduced wavefunction } \tilde{\sigma})$$

- Peaking function e.g. Gaussian with non-zero width; reduced wavefunction assumed not to spoil peaking properties.

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Cosmology from QG condensates: observables and relationality

Spatial relational homogeneity:
σ depends on a single "clock" scalar field χ^0

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Observables

Number, **volume** (determined e.g. by the mapping with LQG) and **matter** operators (notation: $(\cdot,\cdot) = \int \mathrm{d}\chi^0 \mathrm{d}g_I$):

$$\hat{N} = (\hat{\varphi}^\dagger, \hat{\varphi}) \qquad \hat{V} = (\hat{\varphi}^\dagger, V[\hat{\varphi}])$$

$$\hat{X}^0 = \left(\hat{\varphi}^\dagger, \chi^0 \hat{\varphi}\right) \qquad \hat{\Pi}^0 = -i(\hat{\varphi}^\dagger, \partial_0 \hat{\varphi})$$

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Relationality

- Averaged evolution wrt x^0 is physical:

$$\langle \hat{\chi} \rangle_\sigma \equiv \langle \hat{X} \rangle_\sigma / \langle \hat{N} \rangle_\sigma \simeq x^0$$

- ...and satisfies the requirements of effective relational dynamics (in the emergent limit).

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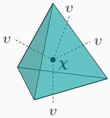
Wavefunction → isotropy



$$\langle \hat{V} \rangle_\sigma = \sum_\upsilon V_\upsilon |\tilde{\sigma}_\upsilon|^2(x^0) \qquad \upsilon \text{ rep. label}$$

- $\upsilon = j \in \mathbb{N}/2$ for SU(2) (EPRL-like);
- $\upsilon = \rho \in \mathbb{R}$ for SL(2, $\mathbb{C}$) (ext. BC).

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Effective relational volume dynamics

(ciao)Mean-field approximation

- Mesoscopic regime: large N but negligible interactions.
- Hydrodynamic approx. of kinetic kernel.
- Isotropy: $\tilde{\sigma}_\upsilon \equiv \rho_\upsilon e^{i\theta_\upsilon}$ fundamental variables.

$$\left\langle \frac{\delta S[\hat{\varphi}, \hat{\varphi}^\dagger]}{\delta \hat{\varphi}(g_I, x^0, \cdot)} \right\rangle_{\sigma_{x^0}} = 0 \,.$$

LM, Oriti 2008.02774; LM, Oriti 2010.09700; Oriti, Sindoni, Wilson-Ewing 1602.05881; Jercher, Pithis 2112.00091; Assanioussi, Kotecha 2003.01097;

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Effective relational Friedmann equations

$$\left(\frac{V'}{3V}\right)^2 \simeq \left(\frac{2\sum_\upsilon V_\upsilon \rho_\upsilon \operatorname{sgn}(\rho'_\upsilon)\sqrt{\mathcal{E}_\upsilon - Q_\upsilon^2/\rho_\upsilon^2 + \mu_\upsilon^2\rho_\upsilon^2}}{3\sum_\upsilon V_\upsilon \rho_\upsilon^2}\right)^2 \qquad \frac{V''}{V} \simeq \frac{2\sum_\upsilon V_\upsilon\left[\mathcal{E}_\upsilon + 2\mu_\upsilon^2\rho_\upsilon^2\right]}{\sum_\upsilon V_\upsilon \rho_\upsilon^2}$$

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Classical limit (large ρ_υs, late times)

- If μ_υ^2 is mildly dependent on υ (or one υ is dominating) and equal to $3\pi G$

$(V'/3V)^2 \simeq 4\pi G/3 \longrightarrow$ flat FLRW

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

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Bounce

- A non-zero volume bounce happens for a large range of initial conditions (at least one $Q_\upsilon \neq 0$ or one $\mathcal{E}_\upsilon < 0$).
- The average singularity resolution may still be spoiled by quantum effects on geometric and clock variables.

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Towards inhomogeneities

Scalar perturbations from (T)GFT condensates

Simplest (slightly) relationally inhomogeneous system

LM, Oriti 2112.12677; Gerhart, Oriti, Wilson-Ewing 1805.03099;

Scalar perturbations from (T)GFT condensates

Simplest (slightly) relationally inhomogeneous system

Classical

- 4 MCM reference fields (χ^0, χ^i), with Lorentz/Euclidean invariant S_χ in field space.
- 1 MCM matter field ϕ dominating the e.m. budget and relationally inhomog. wrt. χ^i.

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Quantum

- (T)GFT field: $\varphi(g_I, \chi^\mu, \phi)$, depends on 5 discretized scalar variables.
- EPRL-like or extended BC model with S_{GFT} respecting the classical matter symmetries.

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Observables

notation: $(\cdot,\cdot) = \int \mathrm{d}^4\chi \mathrm{d}\phi \mathrm{d}g_I$

Mat. Vol. Frame

$$\hat{X}^\mu = (\hat{\varphi}^\dagger, \chi^\mu \hat{\varphi}) \quad \hat{\Pi}^\mu = -i(\hat{\varphi}^\dagger, \partial_\mu \hat{\varphi})$$

Only isotropic info: $\hat{V} = (\hat{\varphi}^\dagger, V[\hat{\varphi}])$

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States

- CPSs around $\chi^\mu = x^\mu$, with
  - η: Isotropic peaking on rods;
  - $\tilde{\sigma}$: Isotropic distribution of geometric data.
- Small relational $\tilde{\sigma}$-inhomogeneities ($\tilde{\sigma} = \rho e^{i\theta}$):

$$\rho = \bar{\rho}(\cdot, \chi^0) + \delta\rho(\cdot, \chi^\mu), \; \theta = \bar{\theta}(\cdot, \chi^0) + \delta\theta(\cdot, \chi^\mu).$$

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Late times volume and matter dynamics

- Averaged q.e.o.m. $\longrightarrow$ coupled differential equations for ρ and θ.
- Decoupling for a range of values of CPSs and large N (late times).

$\longrightarrow$ Dynamic equations for $\langle \hat{V} \rangle_\sigma$, $\langle \hat{\Phi} \rangle_\sigma$

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Perturbations

- Super-horizon GR matching.
- No matching for intermediate modes (because of different coupling with bkg effective metric)!
- Effective metric signature determined by CPSs.

LM, Oriti 2112.12677; Gerhart, Oriti, Wilson-Ewing 1805.03099;

A state-agnostic approach

Effective approach for constrained quantum systems

How does our scheme for extraction of relational cosmological physics depend on the specific choice of states? ⟷ **A "state-agnostic" strategy is needed!**

LM, Gielen, Oriti, Polaczek 2110.11176; Bojowald, Sandhoefer, Skirzewski, Tsobanjan 0804.3365; Bojowald Tsobanjan 0906.1772;

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Construction of the effective system

Step 1: definition of the quantum phase space

- Describe the system with exp. values $\langle \hat{A}_i \rangle$ and moments:
- Poisson structure inherited from the algebra structure

$$\left\{ \langle \hat{A}_i \rangle \,, \langle \hat{A}_j \rangle \right\} = (i\hbar)^{-1} \left\langle [\hat{A}_i, \hat{A}_j] \right\rangle \text{ (same for } \Delta\text{s).}$$

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Step 2: definition of the constraints

- $\langle \hat{C} \rangle = 0$ and $\langle (\widehat{\mathrm{pol}} - \langle \widehat{\mathrm{pol}} \rangle) \hat{C} \rangle = 0$ eff. constraints;
- Generate gauge transf. on the quantum phase space.

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- $\langle \hat{C} \rangle = 0$ and $\langle (\widehat{\text{pol}} - \langle \widehat{\text{pol}} \rangle) \hat{C} \rangle = 0$ eff. constraints;
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LM, Gielen, Oriti, Polaczek 2110.11176; Bojowald, Sandhoefer, Skirzewski, Tsobanjan 0804.3365; Bojowald Tsobanjan 0906.1772;

Effective approach for constrained quantum systems

How does our scheme for extraction of relational cosmological physics depend on the specific choice of states? ⟷ **A "state-agnostic" strategy is needed!**

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Step 3: relational rewriting

- Determine the remaining gauge flow which preserves the gauge conditions.
- Write evolution of the remaining variables wrt. T (classical clock).

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A state agnostic approach: application to (T)GFT

How can this framework be generalized to a **field theory context**?

Infinitely many algebra generators. Infinitely many quantum constraints.

LM, Gielen, Oriti, Polaczek 2110.11176;

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How can this framework be generalized to a **field theory context**?

Infinitely many algebra generators. → **Need for an additional truncation scheme!** ← Infinitely many quantum constraints.

Motivations

- Interest in a coarse grained system characterized by a small number of macroscopic (1-body) observables.
- Expected to be the case for cosmology.

Coarse-graining truncation

- When the e.o.m. are linear, consider an integrated 1-body quantum constraint.
- Algebra generated by minimal set of physically relevant operators (including constraint).

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Rank-4 istropic GFT minimally coupled to a massless scalar field with negligible interactions:

- E.o.m.: $\mathcal{D}\varphi \equiv (m^2 + \hbar^2\Delta_g + \lambda\hbar^2\,\partial_\chi^2)\varphi = 0$.
- Quantum constr. $\hat{C} = \int \hat{\varphi}^\dagger \mathcal{D}\hat{\varphi} = m^2\hat{N} - \hat{\Lambda} - \lambda\hat{\Pi}_2$
- Generators: $\hat{X}$, $\hat{\Pi}$, $\hat{\Pi}_2$, $\hat{N}$, $\hat{\Lambda}$ and $\hat{K}$.
- $\hat{K}$ such that $[\hat{\Lambda}, \hat{K}] = i\hbar\alpha\hat{K}$.

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Results

- The procedure can naturally be carried over by choosing as clock variable $\hat{K}$.
- Relational evolution of $\langle \hat{X} \rangle$ in agreement with classical cosmology.
- Fluctuations are decoupled from expect. values.
- If they are small at small $\langle \hat{K} \rangle$ they stay small even at large $\langle \hat{K} \rangle$ (probably associated to the constancy of $\hat{N}$).

LM, Gielen, Oriti, Polaczek 2110.11176;

Conclusions

Results and perspectives

Relational Dynamics and Emergent QG

Conclusions

- ✓ Presentation of a scheme to define effective relational dynamics for emergent QG theories.
- ✓ Concrete realization in (T)GFT cosmology.
- ✓ The interplay between quantum effects, emergence and relationality was highlighted.

Perspectives

- How to change frame in an effective relational context? (Crucial to study unitarity and frame covariance.)
- When are QG material frames ideal RFs?
- Extension of state-agnostic approach to QFT?

Cosmology from Full QG

Conclusions

- ✓ Bkg: Effective volume dynamics with correct classical limit and possible singularity resolution.
- ✓ Bkg: Investigation of the impact of quantum fluctuations.
- ✓ Bkg: (almost) state-agnostic extraction of cosmological relational dynamics.
- ✓ Pert: First steps towards a relational cosmological perturbation theory from full QG:
  - ✓ Super-horizon matching with GR.
  - ✗ No matching with GR at intermediate scales.

Perspectives

- Bkg: Inclusion of different matter fields, e.g. scalar field with potential.
- Pert: Impact of bounce on perturbations.
- Pert: Investigate sub-horizon GR mismatch.
  - What gravity models do match?
  - Model building? Breakdown of approximations?
- Pert: Study out of condensate perturbations.
- Pert: Reconstruct an effective metric (produce operators with geometric macro-interpretation).

Backup

Volume at late times

Background

Classical

- Harmonic gauge: $N = a^3$.
- Negligible contribution of reference matter.

$$(\bar{V}'/\bar{V})^2 = 12\pi G \pi_\phi^{(c)}$$
$$(\bar{V}'/\bar{V})' = 0$$

Quantum

- Wavefunction peaked on $\pi_\phi = \tilde{\pi}_\phi$.
- Domination of single spin υ_o.
- $\mu_{\upsilon_o}(\pi_\phi) \simeq c_{\upsilon_o}\pi_\phi$, with $4c_{\upsilon_o}^2 = 12\pi G$.

$$(\bar{V}'/\bar{V})^2 = 12\pi G \tilde{\pi}_\phi \quad (\bar{V}'/\bar{V})' = 0$$

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Perturbations

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- First order harmonic gauge.
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- Define $V(x) = \sqrt{\det q_{ij}} \equiv \bar{V} + \delta V$.

$$\delta V'' - 6\mathcal{H}\delta V' + 9\mathcal{H}^2\delta V - \bar{V}^{4/3}\nabla^2\delta V = 0\,.$$

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Super-horizon

- Matches the classical solution $\delta V \propto \bar{V}$.

Sub-horizon

- Same diff. structure but different powers of $\bar{V}$.

No matching with GR for arbitrary modes.

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Matter at late times

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$$\langle \hat{\Pi}_\phi \rangle_{\bar{\sigma}} = \tilde{\pi}_\phi \bar{N}\,,$$
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Matching conditions

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- $\phi \equiv \langle \hat{\Phi} \rangle_{\bar{\sigma}} = -c_{\upsilon_o}^{-1} + \tilde{\pi}_\phi x^0$, $Q_{\upsilon_o} \simeq \pi_\phi^2$!
- Emergent G related to matter content!

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