Emergent Cosmological Physics from Quantum Gravity

Luca Marchetti

Foundations of Observational, Classical and Semi-Classical Gravitational Physics and The Problem of Agency and Laws of Nature
Munich, 28 March 2023

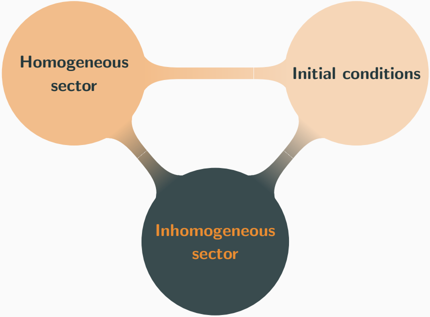
Department of Mathematics and Statistics
UNB Fredericton

Overview

- **The problem of cosmic emergence**
- **Physical localization and continuum limit in Quantum Gravity**
  - The continuum limit in Quantum Gravity
  - Relational strategy: the classical and quantum perspectives
  - Relational strategy: the quantum emergent perspective
- **Introduction to (T)GFTs**
- **Cosmology from (T)GFT**
  - (T)GFT condensates and effective relationality
  - Emergent effective Friedmann dynamics
  - Inhomogeneities, inflation, dark energy and running couplings

The problem of cosmic emergence

Cosmic emergence from QG: the main challenges



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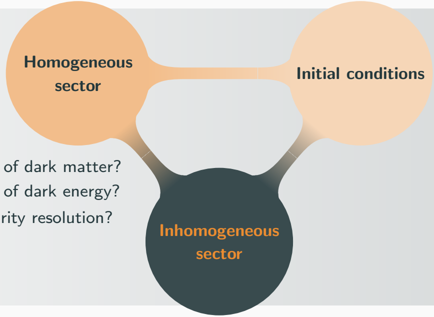

- Nature of dark matter?
- Nature of dark energy?
- Singularity resolution?
- ...

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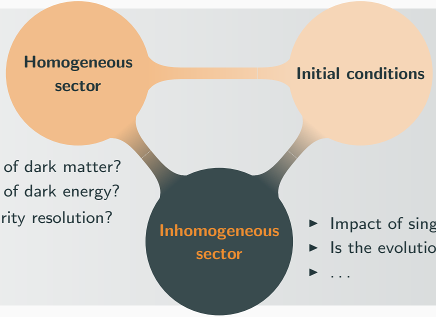

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- Impact of singularity resolution on pert.?
- Is the evolution of pert. modified by QG effects?
- ...

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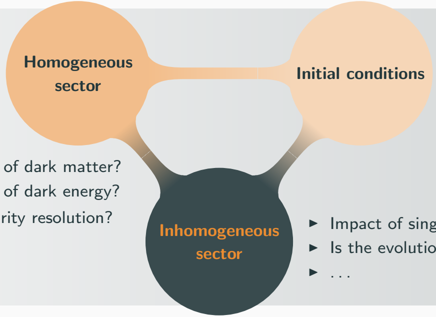

Initial conditions:

- Trans-Planckian problem?
- Geometric inflation?
- ...

Homogeneous sector:

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

Inhomogeneous sector:

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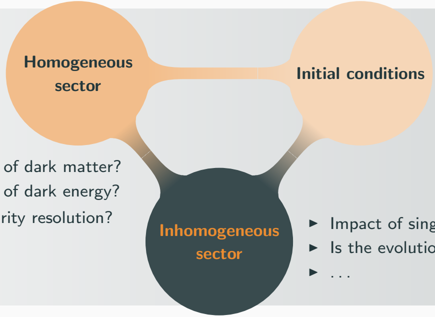

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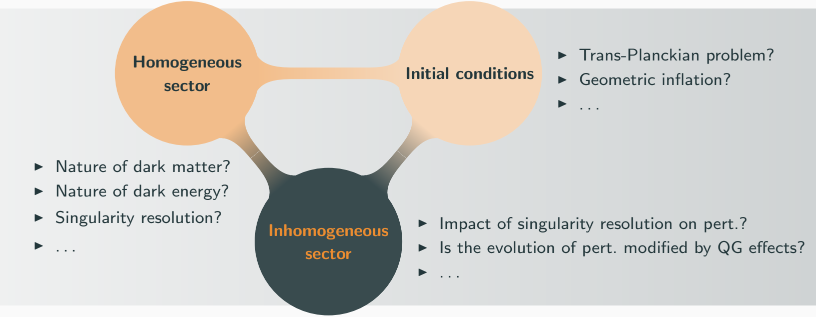

How to extract cosmology from quantum gravity?

Both technical and conceptual challenges:

- How to define (in)homogeneity?
- How to extract macroscopic dynamics?
- How to construct cosmological geometries?

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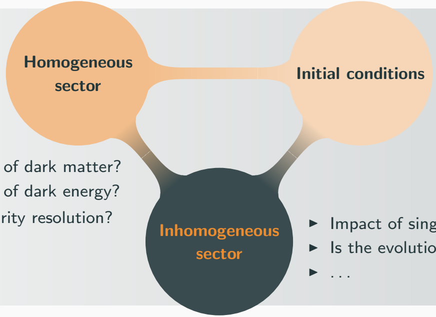

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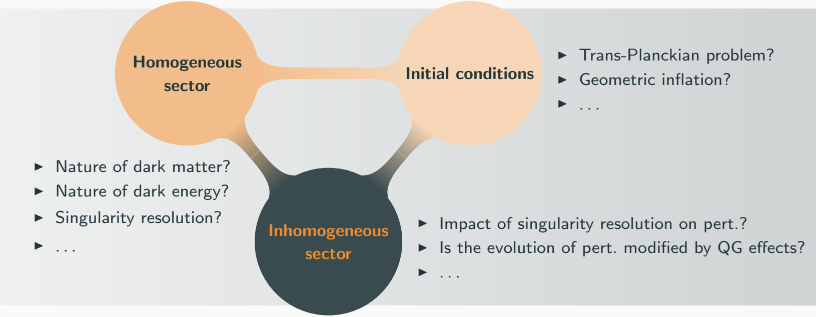

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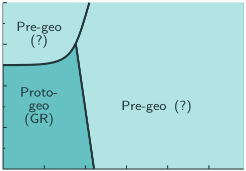
Continuum limit in Quantum Gravity

Continuum physics and QG: the general perspective

Continuum limit in QG ⟷ Large number of dynamical microscopic dof.

Full partition function needed!



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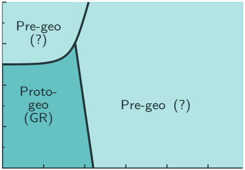

The (F)RG perspective

QFT on spacetime

- Energy scale defines the flow from IR and UV.

QG theory

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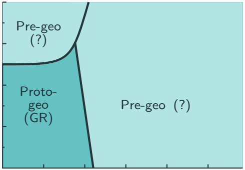

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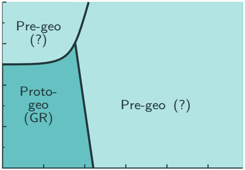

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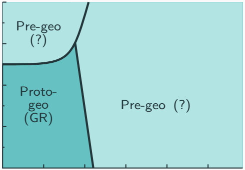

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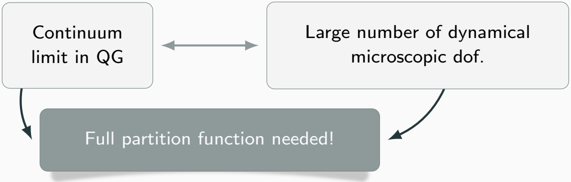

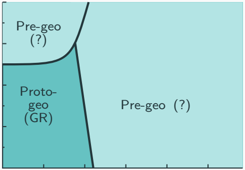

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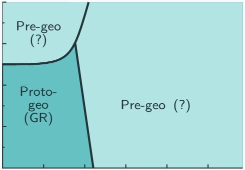

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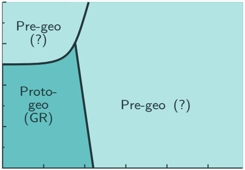

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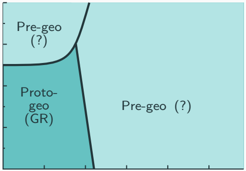

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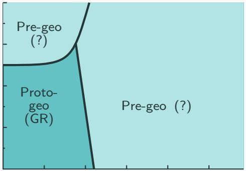

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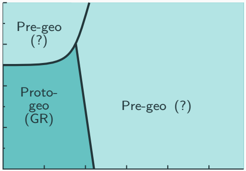

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Mean-field (saddle-point) approx. of Z.

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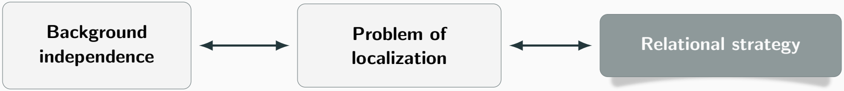
Physical localization

Relational strategy: the classical and quantum GR perspective



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

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Relational strategy: the classical and quantum GR perspective

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

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

Classical

Physical localization via 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.
- Applications almost only for very simple systems.

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Dirac approach: Quantize first.

- Perspective neutral.
- Poor control of the physical Hilbert space.

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Reduced approach: Relationality first

- No quantum constraint to solve.
- Not perspective neutral. Too complicated to implement in most of the cases.

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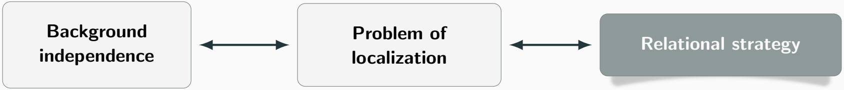

A genuinely new dimension of the problem arises for emergent QG theories.

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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.

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Effective approaches:

- More mathematical control and physical insights.
- Relevant for observative purposes.

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Introduction to (T)GFTs

The (T)GFT approach to quantum gravity

(Tensorial) Group Field Theories:
theories of a field $\varphi : G^d \times \mathcal{M} \to \mathbb{C}$

d is the dimension of the "spacetime to be" ($d = 4$); G local gauge group of gravity, $G = \mathrm{SL}(2, \mathbb{C})$ or $\mathrm{SU}(2)$; $\mathcal{M}$ matter manifold, $\mathcal{M} = \mathbb{R}$ for scalar field.

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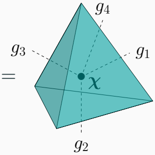
$\mathcal{H}_{\text{1-p}} =$ 

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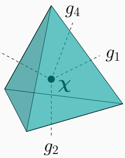
$\mathcal{H}_{\text{1-p}} =$ 

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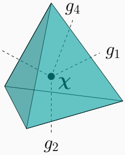
- G (Lie algebra $\mathfrak{g}$) variables associated to discretized gravitational quantities.
- $\chi^\alpha \in \mathbb{R}^{d_l} = \mathcal{M}$ associated to d_l discretized scalar fields.

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

The (T)GFT approach to quantum gravity

(Tensorial) Group Field Theories:
theories of a field $\varphi : G^d \times \mathcal{M} \to \mathbb{C}$

d is the dimension of the "spacetime to be" ($d = 4$); G local gauge group of gravity, $G = \mathrm{SL}(2, \mathbb{C})$ or $\mathrm{SU}(2)$; $\mathcal{M}$ matter manifold, $\mathcal{M} = \mathbb{R}$ for scalar field.

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Quanta are $d - 1$-simplices decorated with group theoretic data:

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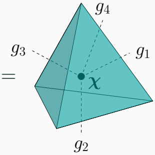
$\mathcal{H}_{\text{1-p}} =$ 

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S_{GFT} obtained by comparing Z_{GFT} with simplicial gravity (+ matter) path integral.

$$Z_{\mathrm{GFT}} = \sum_\Gamma w_\Gamma(\{\lambda_\gamma\}) A_\Gamma$$

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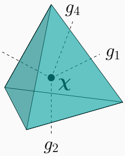
$\mathcal{H}_{\text{1-p}} =$ 

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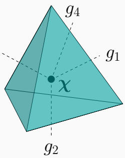
$\mathcal{H}_{1\text{-p}} =$ 

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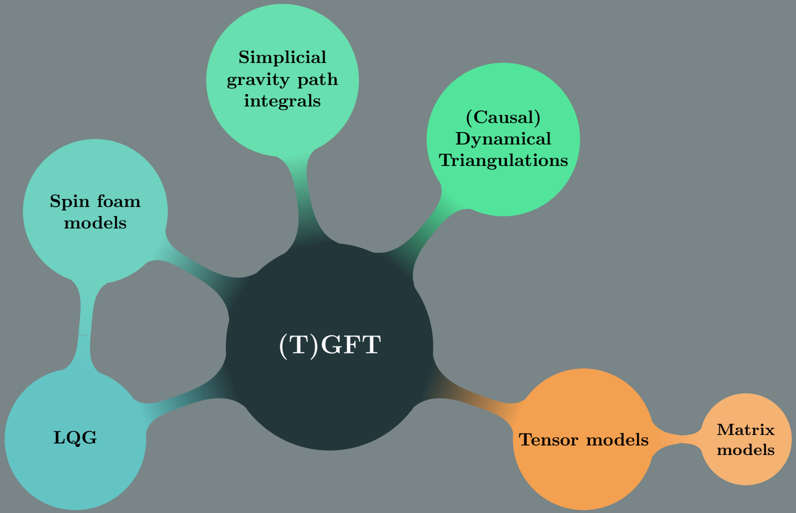
Simplicial gravity path integrals
(Causal) Dynamical Triangulations
Spin foam models
(T)GFT
LQG
Tensor models
Matrix models

Cosmology from (T)GFT

Mean-field approximation and (T)GFT condensates

Collective states

(T)GFT condensates

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

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

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- $\mathcal{D} =$ space of spatial geometries + matter at a point.

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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Relationality

Condensate Peaked States

- If σ is peaked on 4 $\chi^\mu \simeq x^\mu$, $|\sigma\rangle_x$ encodes local info. about spatial geometry + matter at x^μ.

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

- Relational localization implemented at an effective level on "hydrodynamic" (averaged) quantities.

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Eff. dynamics

Mean-field approximation

- QG (non-local and non-linear) counterpart of Gross-Pitaevskii eq.
- Quantum fluid description of the QG system.
- Valid only in a mesoscopic regime: large N but negligible interactions.

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

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Cosmology: macroscopic variables and effective relational dynamics

Macroscopic cosmological variables and effective relationality

Spatial relational homogeneity:
σ depends on a single "clock" scalar field χ^0
$(\mathcal{D} = \text{minisuperspace} + \text{clock})$

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

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

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- Observables $\leftrightarrow$ collective operators on Fock space.

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Relationality

- Averaged evolution wrt x^0 is physical:

$$\text{Intensive} \longleftarrow \langle \hat{\chi} \rangle_{\sigma_{x^0}} \equiv \langle \hat{X} \rangle_{\sigma_{x^0}} / \langle \hat{N} \rangle_{\sigma_{x^0}} \simeq x^0$$

- Emergent effective relational description:
  - Small clock quantum fluctuations.
  - Effective Hamiltonian $H_{\sigma_{x^0}} \simeq \langle \hat{\Pi}^0 \rangle_{\sigma_{x^0}}$.

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Wavefunction → isotropy

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Emergent cosmological physics

Effective relational volume dynamics

Eff. dynamics

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.

$$\tilde{\sigma}_\upsilon'' - 2i\tilde{\pi}_0\tilde{\sigma}_\upsilon' - E_\upsilon^2\tilde{\sigma} = 0.$$

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Classical limit (large ρ_υs, late times)

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

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

- 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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Geometric acceleration from interactions

Physics of (T)GFT cosmology

Geometric acceleration from interactions

Early times: geometric inflation

✓ Geometric inflation from QG interactions.

⚠ For some models bottom-up natural and slow-roll.

De Cesare, Oriti, Pithis 1606.00352; LM, Oriti 2112.12677; Oriti, Pang 2105.03751; Ladstätter, LM, Oriti (to appear); Jercher, LM, Pithis (to appear)

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- ► Small inhomogeneities at the level of σ.
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- ✓ Only late times super-horizon matching with GR.
- ✓ Near-bounce super-horizon behavior different even from modified gravity.

Why the mismatch?

- ⚠ Full relational frame requires quanta with different causal properties.
- ⚠ Including quantum correlations seems to substantially help the matching.

De Cesare, Oriti, Pithis 1606.00352; LM, Oriti 2112.12677; Oriti, Pang 2105.03751; Ladstätter, LM, Oriti (to appear); Jercher, LM, Pithis (to appear)

Physics of (T)GFT cosmology

Including interactions

Geometric acceleration from interactions

Early times: geometric inflation

- ✓ Geometric inflation from QG interactions.
- ⚠ For some models bottom-up natural and slow-roll.
- ⚠ Comparison with observations?

Late times: phantom dark energy

- ✓ Phantom dark energy generated by QG effects (no field theoretic issue).
- ⚠ Comparison with observations?

Including more realistic matter: running couplings

- ✓ Matching with GR requires the macroscopic constants (including G) to run with time.
- ⚠ Insights on renormalization?
- ⚠ Connection with asymptotic safety?

Inhomogeneities

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Geometry from quantum correlations!

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microscopic QG model

- What are the fundamental QG degrees of freedom?

microscopic QG model

- (T)GFT: simplices decorated with discretized fields.

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How to coarse grain? ↓ *Mean-field approx. (condensate states).*

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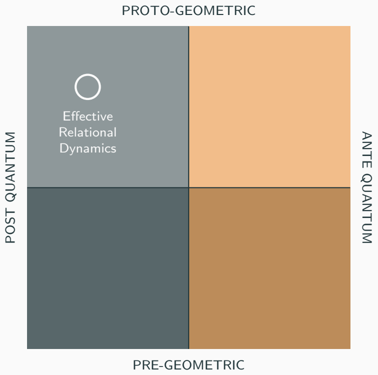
(Scalar) Inhomogeneities, free

- Late times: indications for GR matching at all scales.
- Early times: deviations from classical and modified gravity.

Backup

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.

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

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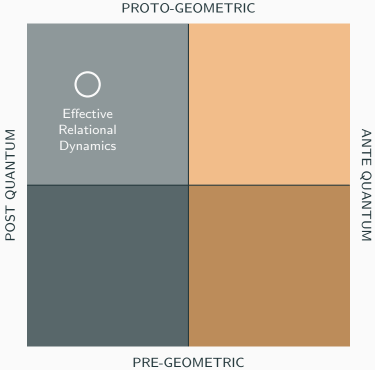

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Concrete example: scalar field clock

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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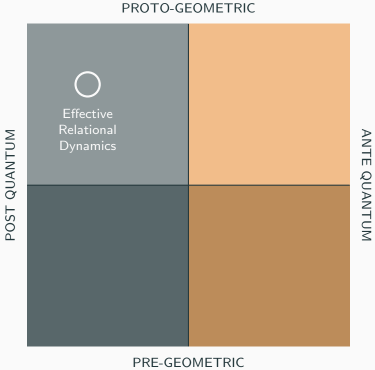

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$\hat{O}_a \xrightarrow{\langle\cdot\rangle_\Psi}$ Geometric observables

$\hat{\chi}\quad\hat{\Pi} \xrightarrow{\langle\cdot\rangle_\Psi}$ 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:

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

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The (T)GFT approach to QG

GFTs are QFTs of atoms of spacetime.

- Take seriously the idea of a microscopic structure of spacetime.
- Related to canonical and discrete path-integral approaches to QG.
- Physical insights from canonical approaches combined with powerful field theoretic methods!

Oriti 0912.2441; Oriti 1110.5606; Oriti 1408.7112; Krajewski 1210.6257; Oriti 1807.04875; Gielen, Sindoni 1602.08104; ...

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Group Field Theory Quanta

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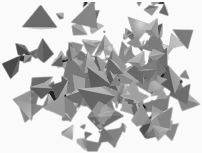
- Data associated to a single quantum are geometric data of a $d-1$-simplex.



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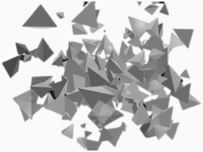
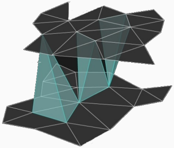


Group Field Theory Processes

- GFT Feynman diagrams (QG processes) are associated to d-dimensional triangulated manifolds.
- Data associated to QG processes are geometric data of d-dimensional triangulated manifolds.



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Atoms of spacetime

Classical tetrahedron

A Euclidean tetrahedron is described by 4 bivectors $B_a \in \wedge^2 R^4$, with

- Closure: $\sum_a B_a = 0$ (faces of the tetrahedron close).
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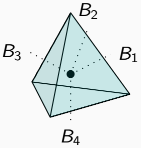

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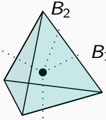

Quantum tetrahedron

- Using $\wedge^2 \mathbb{R}^4 \simeq \mathfrak{spin}(4)$ the face phase space is $\mathcal{T}^*(\mathrm{Spin}(4)) \sim \mathrm{Spin}(4) \times \mathfrak{spin}(4)$.
- $\mathcal{T}^*(\mathrm{Spin}(4))$ has a natural Poisson structure which can be canonically quantized.
- $\mathcal{H}_{\text{tetra}} \subset \otimes_{a=1}^4 \mathcal{H}_{\Delta_a}$ (subset defined by the imposition of constraints).

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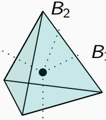

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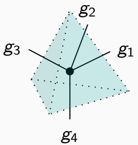

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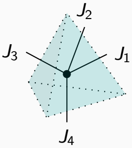

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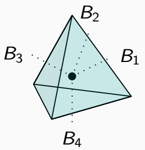

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Gravity

Discretized gravity

- Discretized Palatini gravity can be written as constrained BF theory.
- $B \sim e \wedge e$ and $g \sim \mathcal{P} \exp \omega$.

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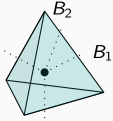

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Loop Quantum Gravity

- Fix the normal and reduce to $\mathrm{SU}(2)$.

$$\mathcal{H}_{\text{tetra}} = \text{open spin-network space} = \bigoplus_{\vec{j}} \left[\bigotimes_{a=1}^4 \mathcal{H}_{j_a} \otimes \mathcal{I}^{\vec{j}} \right]$$

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A many-body theory for spacetime atoms

Tetrahedron wavefunction

$\varphi(g_1, \ldots, g_4)$
(subject to constraints)

Oriti 1310.7786; Gielen, Oriti 1407.8167; Gielen, Sindoni 1602.08104; Oriti, Sindoni, Wilson-Ewing 1602.05881; ...

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GFT Fock space

$$\mathcal{F}_{\text{GFT}} = \bigoplus_{V=0}^{\infty} \text{sym}\left[\mathcal{H}^{(1)}_{\text{tetra}} \otimes \mathcal{H}^{(2)}_{\text{tetra}} \otimes \ldots \mathcal{H}^{(V)}_{\text{tetra}}\right]$$

- $\mathcal{F}_{\text{GFT}}$ generated by action of $\hat{\varphi}^\dagger(g_a)$ on $|0\rangle$, with $[\hat{\varphi}(g_a), \hat{\varphi}^\dagger(g'_a)] = \mathbb{I}_G(g_a, g'_a)$.
- $\mathcal{H}_\Gamma \subset \mathcal{F}_{\text{GFT}}$, $\mathcal{H}_\Gamma$ space of states associated to connected simplicial complexes Γ.
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Operators

Volume operator $V = \int \mathrm{d}g_a^{(1)}\, \mathrm{d}g_a^{(2)}\, V(g_a^{(1)}, g_a^{(2)})\hat{\varphi}^\dagger(g_a^{(1)})\hat{\varphi}(g_a^{(2)}) = \sum_{J_a} V_{J_a}\hat{\varphi}^\dagger_{J_a}\hat{\varphi}_{J_a}.$

- Generic second quantization prescription to build a $m+n$-body operator: sandwich matrix elements between spin-network states between m powers of $\hat{\varphi}^\dagger$ and n powers of $\hat{\varphi}$.

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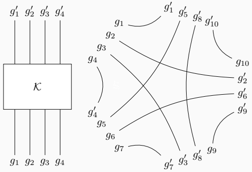
Group Field Theory dynamics

GFT action

$$S[\varphi,\bar\varphi]=\int \mathrm{d}g_a\,\bar\varphi(g_a)\mathcal{K}[\varphi](g_a)+\sum_\gamma \frac{\lambda_\gamma}{n_\gamma}\,\mathrm{Tr}_\gamma[\varphi]+\text{c.c.}\,.$$

- Interaction terms are combinatorially non-local.
- Field arguments convoluted pairwise following the combinatorial pattern dictated by the graph γ:

$$\mathrm{Tr}_\gamma[\varphi]=\int\prod_{i=1}^{n_\gamma}\mathrm{d}g_a\prod_{(a,i;b,j)}\mathcal{V}(g_a^{(i)},g_b^{(j)})\prod_{i=1}^{n_\gamma}\varphi(g_a^{(i)})\,.$$



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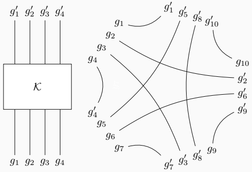
$$S[\varphi,\bar\varphi]=\int \mathrm{d}g_a\bar\varphi(g_a)\mathcal{K}[\varphi](g_a)+\sum_\gamma\frac{\lambda_\gamma}{n_\gamma}\mathrm{Tr}_\gamma[\varphi]+\text{c.c.}\,.$$

- Interaction terms are combinatorially non-local.
- Field arguments convoluted pairwise following the combinatorial pattern dictated by the graph γ:

$$\mathrm{Tr}_\gamma[\varphi]=\int\prod_{i=1}^{n_\gamma}\mathrm{d}g_a\prod_{(a,i;b,j)}\mathcal{V}(g_a^{(i)},g_b^{(j)})\prod_{i=1}^{n_\gamma}\varphi(g_a^{(i)})\,.$$



Partition function

$$Z[\varphi,\bar\varphi]=\sum_\Gamma w_\Gamma(\{\lambda_\gamma\})A_\Gamma\,.$$

- Diagrams Γ = stranded diagrams dual to d-dimensional cellular complexes of arbitrary topology.
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Oriti 1110.5606; Reisenberger, Rovelli 0002083; De Pietri, Petronio 0004045; Gurau 1006.0714; Baratin, Oriti 1002.4723; Finocchiaro, Oriti 1812.03550;

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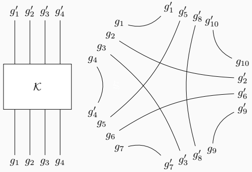

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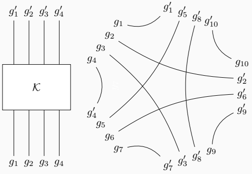

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3d gravity on lattice dual to Γ

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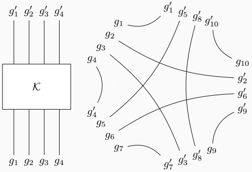

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Spinfoam amplitude on lattice dual to Γ

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Mean-field approximation and QG hydrodynamics

σ-hydrodynamics

Mean-field approximation: A non-linear and non-local extension of QC

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LM, Oriti 2008.02774; LM, Oriti 2010.09700; Oriti, Sindoni, Wilson-Ewing 1602.05881; Jercher, Pithis 2112.00091; ...

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(T)GFT and matter: scalar fields

(Tensorial) Group Field Theories:
theories of a field $\varphi : G^d \times \mathbb{R}^{d_l} \to \mathbb{C}$
defined on the product of G^d and $\mathbb{R}^{d_l}$.

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, $G = \mathrm{SU}(2)$.

Kinematics

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

Li, Oriti, Zhang 1701.08719; Oriti 0912.2441; Gielen, Oriti 1311.1238; Oriti, Sindoni, Wilson-Ewing 1602.05881; Gielen, Sindoni 1602.08104; ...

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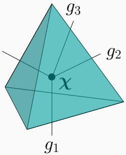
$\mathcal{H}_{\text{1-p}} =$ 

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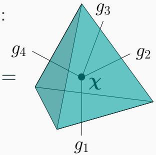
$\mathcal{H}_{\text{1-p}} =$ 

Dynamics

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

- Geometric data enter the action in a non-local and combinatorial fashion.
- Scalar field data are local in interactions.
- For minimally coupled, free, massless scalars:

$$\mathcal{K}(g_a, g_b; \chi, \chi') = \mathcal{K}(g_a, g_b; |\chi - \chi'|^2)$$

$$\mathcal{V}(g_a^{(1)}, \ldots, g_a^{(5)}, \chi) = \mathcal{V}(g_a^{(1)}, \ldots, g_a^{(5)})$$

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