Emergent Cosmology from Quantum Gravity

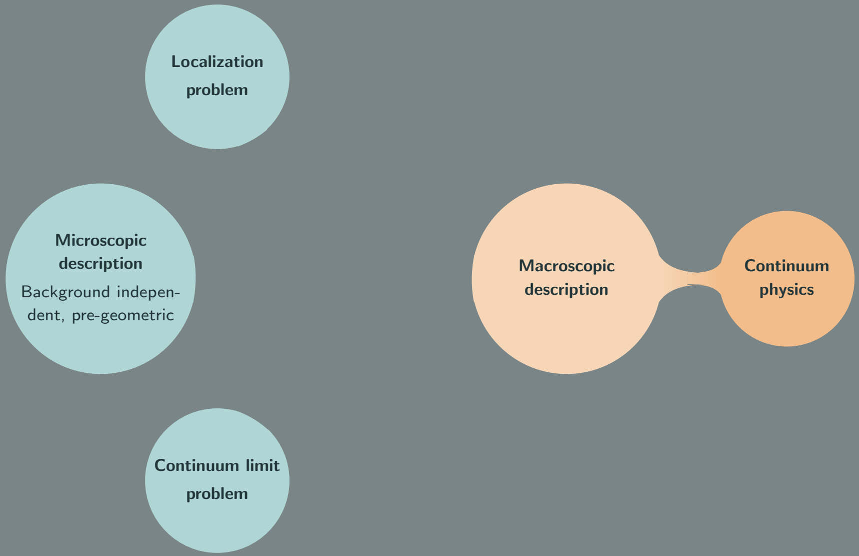
A collective effort: D. Oriti, E. Wilson-Ewing, S. Gielen, M. Sakellariadou, A. Pithis, M. de Cesare, A. Polaczek, A. Jercher, A. Calcinari, R. Dekhil, X. Pang, L. Mickel, T. Ladstätter, P. Fischer, ...

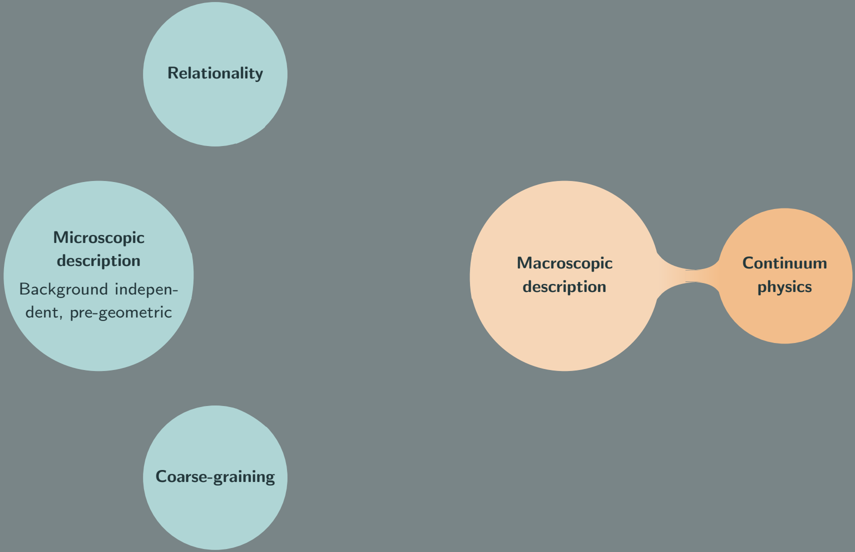
Luca Marchetti

2023 CAP Congress
UNB Fredericton
22 June 2023

Department of Mathematics and Statistics
UNB Fredericton


Microscopic description
Background independent, pre-geometric
Macroscopic description
Continuum physics


Localization problem
Microscopic description
Background independent, pre-geometric
Continuum limit problem
Macroscopic description
Continuum physics


Relationality
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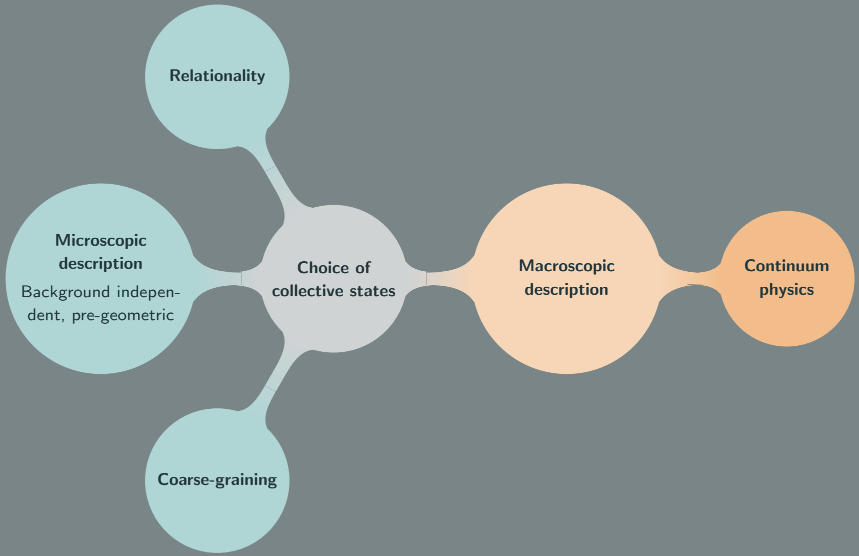
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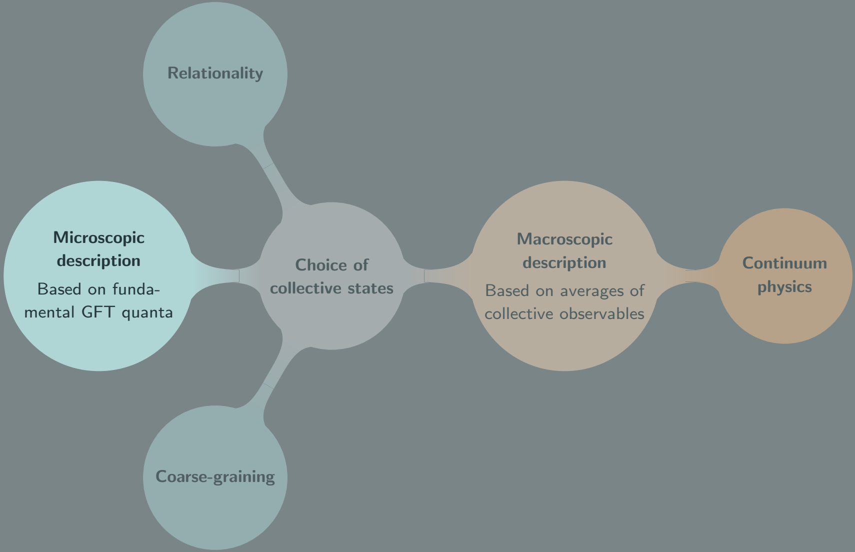
Relationality
Microscopic description
Based on fundamental GFT quanta
Choice of collective states
Macroscopic description
Based on averages of collective observables
Continuum physics
Coarse-graining

The (T)GFT approach to quantum gravity

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.
- Access to powerful field theoretic methods (Fock space, RG. . .)!

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

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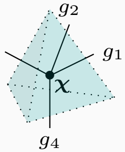
Group Field Theory Quanta

- GFT quanta are atoms of quantum of $d-1$-space, i.e. $d-1$-dimensional simplices.
- Data associated to a single quantum are field data of a $d-1$-simplex (g_a = gravitational, χ = scalar fields).

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

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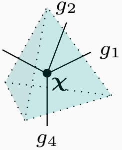
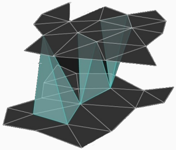


Group Field Theory Processes

- GFT Feynman diagrams (QG processes) are associated to d-dimensional triangulated manifolds.
- Data associated to QG processes are field data of d-dimensional triangulated manifolds.
- Z_{GFT} = discrete matter-gravity path-integral.



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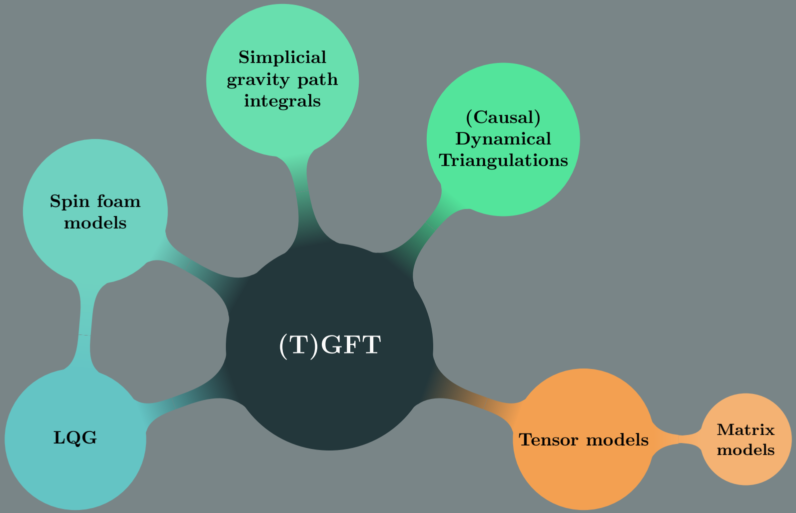
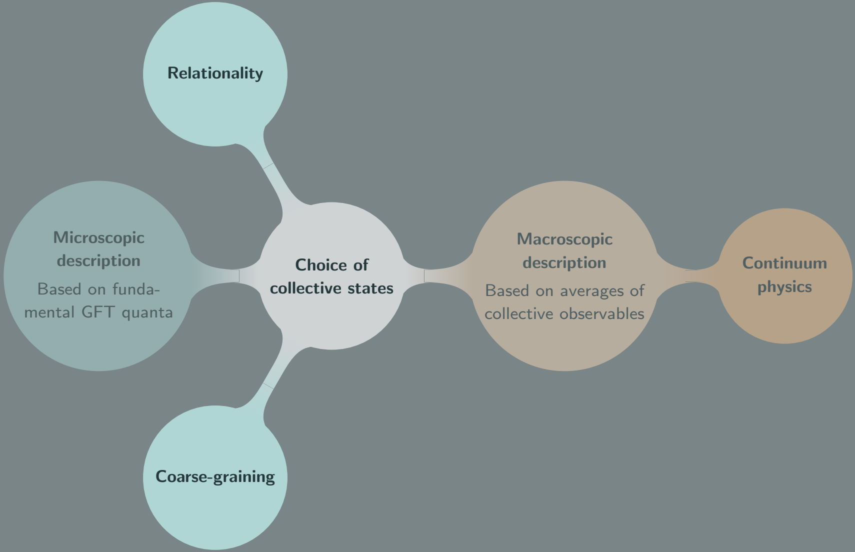

Simplicial gravity path integrals
(Causal) Dynamical Triangulations
Spin foam models
(T)GFT
LQG
Tensor models
Matrix models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The main ingredients

Collective states

GFT condensates

- From the GFT perspective, continuum geometries are associated to large number of quanta.
- The simplest states that can accommodate infinite number of quanta are condensate states:

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

LM, Oriti, Pithis, Thürigen 2211.12768 ; LM, Oriti 2008.02774-2112.12677; Oriti, Sindoni, Wilson-Ewing 1602.05881; Gielen, Oriti, Sindoni 1311.1238.

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Mean-field approximation

- When interactions are small (certainly satisfied in an appropriate regime) the dynamics of σ is:

$$\left\langle \frac{\delta S[\hat{\varphi},\hat{\varphi}^\dagger]}{\delta\hat{\varphi}(g_I,x^\alpha)}\right\rangle_\sigma = \int \mathrm{d}h_a \int \mathrm{d}\chi\, \mathcal{K}(g_a,h_a,(x^\alpha-\chi^\alpha)^2)\sigma(h_a,\chi^\alpha) + \lambda \frac{\delta V[\varphi,\varphi^*]}{\delta\varphi^*(g_a,x^\alpha)}\bigg|_{\varphi=\sigma} = 0\,.$$

- Equivalent to mean-field (saddle-point) approx. of Z_{GFT} (reliable for physical models).

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Condensate Peaked States

- Constructing relational observables in full QG is difficult (QFT with no continuum intuition).

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- Constructing relational observables in full QG is difficult (QFT with no continuum intuition).
- Relational localization implemented at an effective level on observable averages on condensates.
- If χ^μ constitute a physical reference frame, this can be achieved by assuming

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

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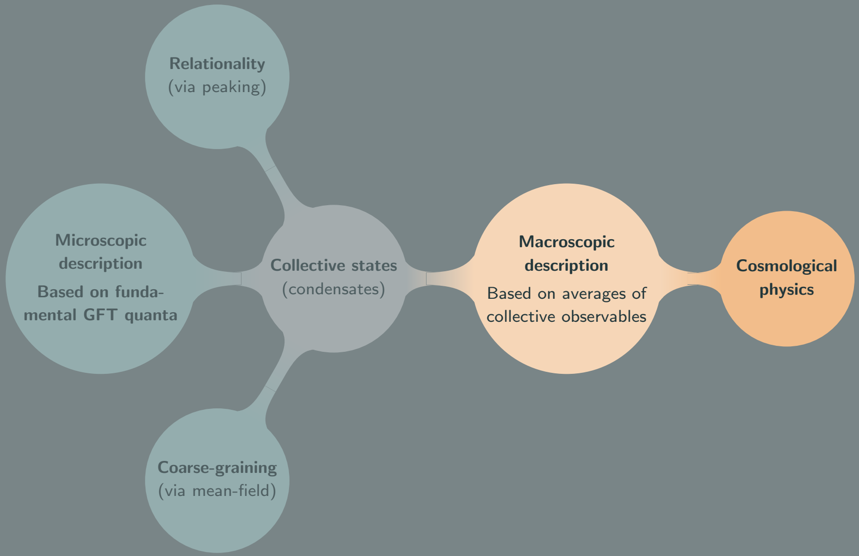
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Cosmological
physics

Group Field Theory Cosmology

Homogeneous (non-symmetry-reduced) sector

No interactions

Modified Friedmann dynamics

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Modified Friedmann dynamics

Early times: quantum bounce

✓ (Universal, average) Singularity resolution into quantum bounce.

✓ Impact of quantum effects on bounce quantified.

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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Interacting scalar fields and running couplings

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

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

Inhomogeneous (scalar and isotropic) sector

Setting

Classical

- 4 MCMF reference fields (χ^0, χ^i),
- 1 MCMF matter field ϕ dominating e.m. budget and relationally inhomog. wrt. χ^i.

Quantum

- Two-sector GFT: timelike and spacelike tetrahedra.

Inhomogeneities = quantum correlations

Jercher, LM, Pithis (to appear); Fischer, LM, Oriti (to appear); LM, Oriti 2112.12677; Jercher, Oriti, Pithis 2206.15442 ; Gielen, Mickel 2211.04500.

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Classical dynamics with trans-Planckian QG effects

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✓ QG corrections to the dynamics of trans-Planckian volume pert.

✓ Good GR matching at larger scales.

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⚠ Physical (perhaps observable) consequences of trans-Planckian mismatch?

⚠ Scalar field perturbations? EFT description?

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✓ Volume pert. dynamics differs from MG.

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⚠ Different fundamental d.o.f. $\longrightarrow$ different perturbation dynamics?

⚠ Scalar field perturbations? EFT description?

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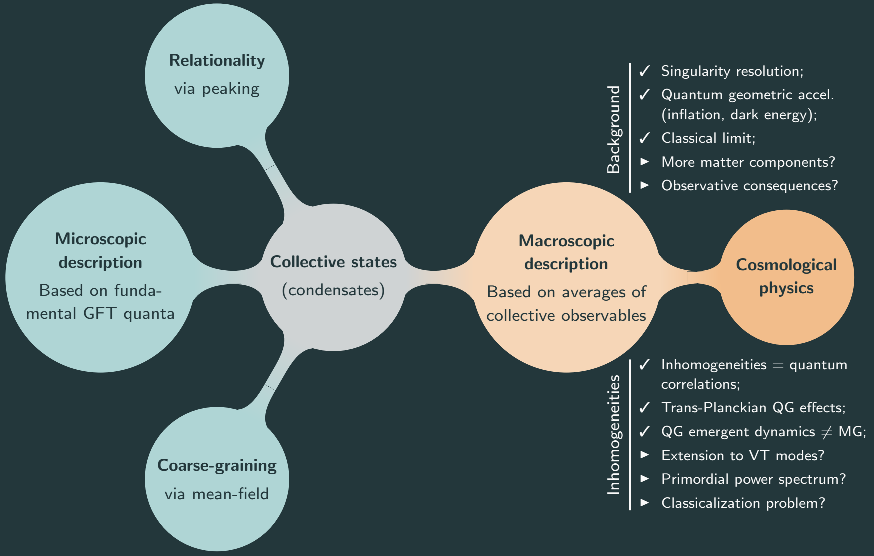

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via peaking
Microscopic description
Based on fundamental GFT quanta
Coarse-graining
via mean-field
Collective states
(condensates)
Macroscopic description
Based on averages of collective observables
Cosmological physics
Background
✓ Singularity resolution;
✓ Quantum geometric accel. (inflation, dark energy);
✓ Classical limit;
► More matter components?
► Observative consequences?
Inhomogeneities
✓ Inhomogeneities = quantum correlations;
✓ Trans-Planckian QG effects;
✓ QG emergent dynamics ≠ MG;
► Extension to VT modes?
► Primordial power spectrum?
► Classicalization problem?

Backup

Group Field Theory and spinfoam models

Definition

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

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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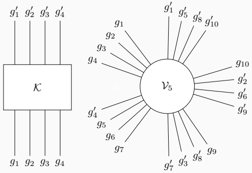
Action

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



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

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

Oriti 1110.5606; Reisenberger, Rovelli 0002083; De Pietri, Petronio 0004045; Gurau 1006.0714; Baratin, Oriti 1002.4723; Finocchiaro, Oriti 1812.03550.

Group Field Theory and spinfoam models

Definition

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

Action

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

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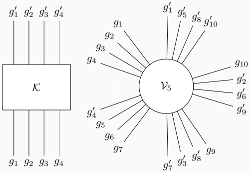

Partition function

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

- Γ = stranded diagrams dual to d-dimensional cellular complexes of arbitrary topology.
- Amplitudes A_Γ = sums over group theoretic data associated to the cellular complex.

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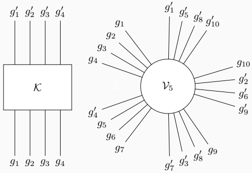

Partition function

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

- Γ = stranded diagrams dual to d-dimensional cellular complexes of arbitrary topology.
- Amplitudes A_Γ = sums over group theoretic data associated to the cellular complex.
- $\mathcal{K}$ and $\mathcal{V}_\gamma$ chosen to match the desired spinfoam model.

Oriti 1110.5606; Reisenberger, Rovelli 0002083; De Pietri, Petronio 0004045; Gurau 1006.0714; Baratin, Oriti 1002.4723; Finocchiaro, Oriti 1812.03550.

One-particle Hilbert space

The one-particle Hilbert space is $\mathcal{H}_{\text{tetra}} \subset \bigotimes_{a=1}^{4} \mathcal{H}_{\Delta_a}$ (subset defined by the imposition of constraints)

Finocchiaro, Oriti 1812.03550; Baez, Barrett 9903060; Baratin, Oriti 1002.4723; Gielen, Oriti 1004.5371; Oriti 1310.7786.

Fundamental quanta

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Lie algebra (metric)

$$\mathcal{H}_{\Delta_a} = L^2(\mathfrak{g})$$

Constraints

Geometricity constraints (appropriately encoded in $\mathcal{K}$ and $\mathcal{V}_\gamma$) allow for a $d-1$-simplicial interpretation of the fundamental quanta:

Closure

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

Simplicity

- $X \cdot (B - \gamma \star B)_a = 0$ (EPRL);
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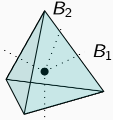

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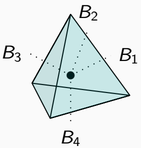

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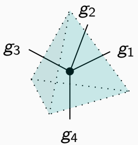

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Group Field Theory and Loop Quantum Gravity

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$\mathcal{H}_{\Delta_a} = L^2(\mathfrak{g})$	← Non-comm. FT →	$\mathcal{H}_{\Delta_a} = L^2(G)$	← Peter-Weyl Theorem →	$\mathcal{H}_{\Delta_a} = \bigoplus_{J_a} \mathcal{H}_{J_a}$

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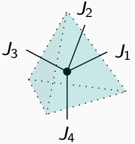

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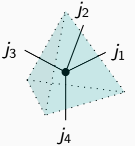

LQG

- Impose simplicity and reduce to $G = \mathrm{SU}(2)$.
- Impose closure (gauge invariance).

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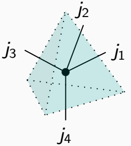

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$$\mathcal{H}_{\text{tetra}} = \bigoplus_{\vec{j}} \text{Inv}\left[\bigotimes_{a=1}^{4} \mathcal{H}_{j_a}\right]$$
= open spin-network vertex space

Finocchiaro, Oriti 1812.03550; Baez, Barrett 9903060; Baratin, Oriti 1002.4723; Gielen, Oriti 1004.5371; Oriti 1310.7786.

The Group Field Theory Fock space

Tetrahedron wavefunction

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

Oriti 1310.7786; Oriti 1408.7112; Sahlman, Sherif 2302.03612.

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Many-body → Theory

GFT field operator

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

- $\mathcal{F}_{\mathsf{GFT}}$ generated by action of $\hat{\varphi}^\dagger(g_a)$ on $|0\rangle$, with $[\hat{\varphi}(g_a), \hat{\varphi}^\dagger(g'_a)] = \mathbb{I}_G(g_a, g'_a)$.
- $\mathcal{H}_\Gamma \subset \mathcal{F}_{\mathsf{GFT}}$, $\mathcal{H}_\Gamma$ space of states associated to connected simplicial complexes Γ.
- Generic states do not correspond to connected simplicial lattices nor classical simplicial geometries.
- Similar to $\mathcal{H}_{\mathsf{LQG}}$ but also different: no continuum intuition, orthogonality wrt nodes, not graphs.

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Operators

Volume operator $\hat{V} = \int \mathrm{d}g^{(1)}_a \,\mathrm{d}g^{(2)}_a V(g^{(1)}_a, g^{(2)}_a)\hat{\varphi}^\dagger(g^{(1)}_a)\hat{\varphi}(g^{(2)}_a) = \sum_{j_a, m_a, \iota} V_{j_a,\iota}\hat{\varphi}^\dagger_{j_a,m_a,\iota}\hat{\varphi}_{j_a,m_a,\iota}$.

- 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 $\hat{\varphi}$.

Oriti 1310.7786; Oriti 1408.7112; Sahlman, Sherif 2302.03612.

Macroscopic cosmological variables and effective relationality

Spatial relational homogeneity:
σ depends on a MCMF "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, Oriti, Pithis 2112.00091.

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Collective Observables

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

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

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

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

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Relationality

- Averaged evolution wrt x^0 is physical:

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

- 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

$$\langle \hat{V} \rangle_{\sigma^0_x} = \sum_\upsilon V_\upsilon |\tilde{\sigma}_\upsilon|^2(x^0)$$

$$\langle \hat{N} \rangle_{\sigma^0_x} = \sum_\upsilon |\tilde{\sigma}_\upsilon|^2(x^0)$$

- $\upsilon = j \in \mathbb{N}/2$ (EPRL);
- $\upsilon = \rho \in \mathbb{R}$ (ext. BC).

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

Effective relational homogeneous volume dynamics

Assumptions

(Relational) Homogeneity

- σ depends on a single clock MCFM field χ^0.
- $\mathcal{D}$ = minisuperspace + clock.

Isotropy

- σ depends only on a single rep. label υ.
- $\upsilon \in \mathbb{N}/2$ (EPRL-like) or $\upsilon \in \mathbb{R}$ (ext. BC).

Volume operator captures the relevant physics: $V \equiv \langle \hat{V} \rangle_{\sigma^0_x} = \sum\!\!\!\!\!\!\int_\upsilon V_\upsilon \rho^2_\upsilon(x^0)\,, \quad \rho \equiv |\tilde{\sigma}|.$

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Effective relational Freidmann dynamics

$$\left(\frac{V'}{3V}\right)^2 \simeq \left(\frac{2 \sum\!\!\!\!\!\!\int_\upsilon V_\upsilon \rho_\upsilon \mathrm{sgn}(\rho'_\upsilon)\sqrt{\mathcal{E}_\upsilon - Q^2_\upsilon/\rho^2_\upsilon + \mu^2_\upsilon \rho^2_\upsilon}}{3 \sum\!\!\!\!\!\!\int_\upsilon V_\upsilon \rho^2_\upsilon}\right)^2, \quad \frac{V''}{V} \simeq \frac{2 \sum\!\!\!\!\!\!\int_\upsilon V_\upsilon \left[\mathcal{E}_\upsilon + 2\mu^2_\upsilon \rho^2_\upsilon\right]}{\sum\!\!\!\!\!\!\int_\upsilon V_\upsilon \rho^2_\upsilon}$$

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Classical limit (large N, late times)

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

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

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

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

Effective relational homogeneous volume dynamics

Assumptions

(Relational) Homogeneity

- σ depends on a single clock MCFM field χ^0.
- $\mathcal{D}$ = minisuperspace + clock.

Isotropy

- σ depends only on a single rep. label υ.
- $\upsilon \in \mathbb{N}/2$ (EPRL-like) or $\upsilon \in \mathbb{R}$ (ext. BC).

Volume operator captures the relevant physics: $V \equiv \langle \hat{V} \rangle_{\sigma^0_x} = \sum\!\!\!\!\!\!\int_\upsilon V_\upsilon \rho_\upsilon^2(x^0)\,, \quad \rho \equiv |\tilde{\sigma}|.$

Effective relational Freidmann dynamics

$$\left(\frac{V'}{3V}\right)^2 \simeq \left(\frac{2\sum\!\!\!\!\!\!\int_\upsilon V_\upsilon \rho_\upsilon \mathrm{sgn}(\rho'_\upsilon)\sqrt{\mathcal{E}_\upsilon - Q_\upsilon^2/\rho_\upsilon^2 + \mu_\upsilon^2\rho_\upsilon^2}}{3\sum\!\!\!\!\!\!\int_\upsilon V_\upsilon \rho_\upsilon^2}\right)^2, \quad \frac{V''}{V} \simeq \frac{2\sum\!\!\!\!\!\!\int_\upsilon V_\upsilon \left[\mathcal{E}_\upsilon + 2\mu_\upsilon^2\rho_\upsilon^2\right]}{\sum\!\!\!\!\!\!\int_\upsilon V_\upsilon \rho_\upsilon^2}$$

Classical limit (large N, 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.

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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Scalar perturbations from GFT condensates

Simplest (slightly) relationally inhomogeneous system

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

Scalar perturbations from GFT condensates

Simplest (slightly) relationally inhomogeneous system

Classical

- 4 MCMF reference fields (χ^0, χ^i),
- 1 MCMF matter field ϕ dominating the e.m. budget and relationally inhomog. wrt. χ^i.

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Quantum

- $\varphi(g_a, \chi^\mu, \phi)$ depends on 5 discretized scalar variables and is associated to spacelike tetrahedra.
- S_{GFT} respecting the classical matter symmetries.

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Observables

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

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. (no interactions) $\longrightarrow$ coupled eqs. for (ρ, θ).
- Decoupling for a range of values of CPSs and large N (late times).

$\xrightarrow[\text{label}]{\text{single}}$ Dynamic equations for $\langle \hat{V} \rangle_{\sigma_{x^0}}$, $\langle \hat{\Phi} \rangle_{\sigma_{x^0}}$.

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Background

- ✓ Matching with GR possible.
- Macro. couplings defined in terms of GFT ones.

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- Unphysical behavior of spatial derivative terms.

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- Averaged q.e.o.m. (no interactions) $\longrightarrow$ coupled eqs. for (ρ, θ).
- Restrict to super-horizon modes but study also early times.

single spin $\longrightarrow$ Dynamic equations for $\langle\hat{V}\rangle_{\sigma_{x^0}}$, $\langle\hat{\Phi}\rangle_{\sigma_{x^0}}$

Fischer, LM, Oriti (to appear); Bertschinger 0604485; LM, Oriti 2112.12677; Gielen, Mickel 2211.04500.

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Modified gravity

- Dynamics of super-horizon scalar perturbations can be obtained generically for any MG theory.
- No matching at early times with effective GFT volume dynamics.

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Perturbing background dynamics

- Study super-horizon scalar perturbations by perturbing background QG volume equation.
- No matching at early times with full effective GFT volume dynamics.

Fischer, LM, Oriti (to appear); Bertschinger 0604485; LM, Oriti 2112.12677; Gielen, Mickel 2211.04500.

Scalar perturbations from quantum correlations

Collective states

Two-body correlations

Including timelike tetrahedra allows to better couple the physical frame: two-sector $(+,-)$ GFT!

$$|\psi\rangle = \mathcal{N}_\psi \exp(\hat{\sigma}\otimes\mathbb{I}_- + \mathbb{I}_+\otimes\hat{\tau} + \widehat{\delta\Phi}\otimes\mathbb{I}_- + \widehat{\delta\Psi} + \mathbb{I}_+\otimes\widehat{\delta\Xi})\,|0\rangle$$

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Effective dynamics

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- 2 mean-field eqs. for 3 variables $(\delta\Phi, \delta\Psi, \delta\Xi)$:

$$\langle \delta S/\delta\hat{\varphi}_+^\dagger\rangle_\psi = 0 = \langle \delta S/\delta\hat{\varphi}_-^\dagger\rangle_\psi$$

- Late times and single (spacelike) rep. label.

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Late times volume perturbations

- QG corrections to trans-Planckian modes dynamics.
- GR matching at larger scales.

Jercher, LM, Pithis (to appear); Jercher, Oriti, Pithis 2206.15442.