Scalar cosmological perturbations from full quantum gravity

In collaboration with: D. Oriti, E. Wilson-Ewing, A. Pithis, A. Jercher, P. Fischer

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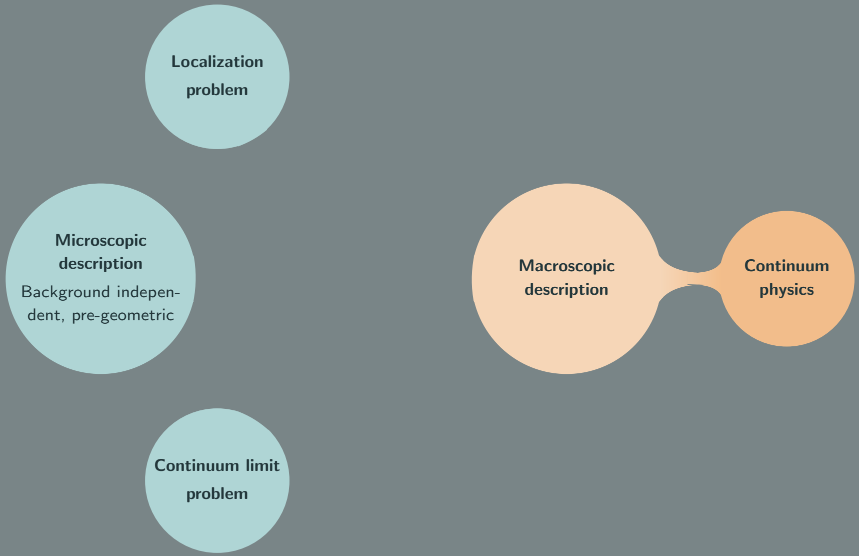
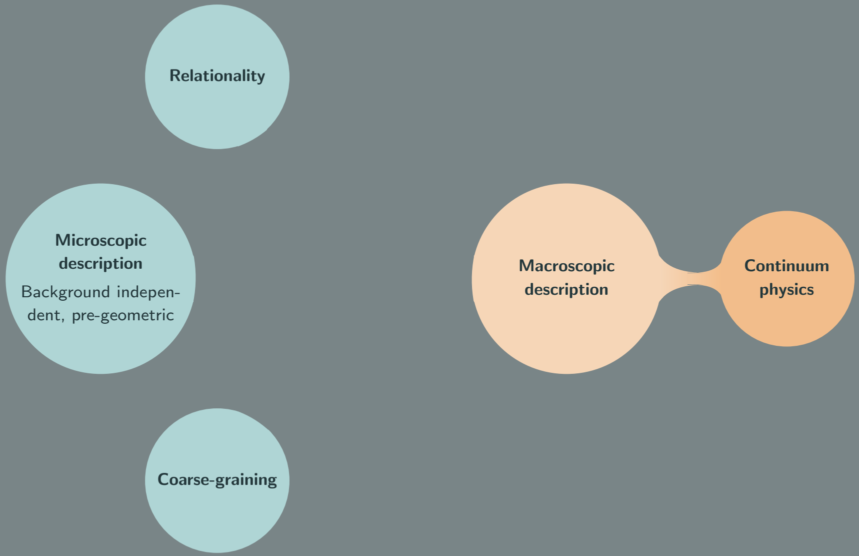
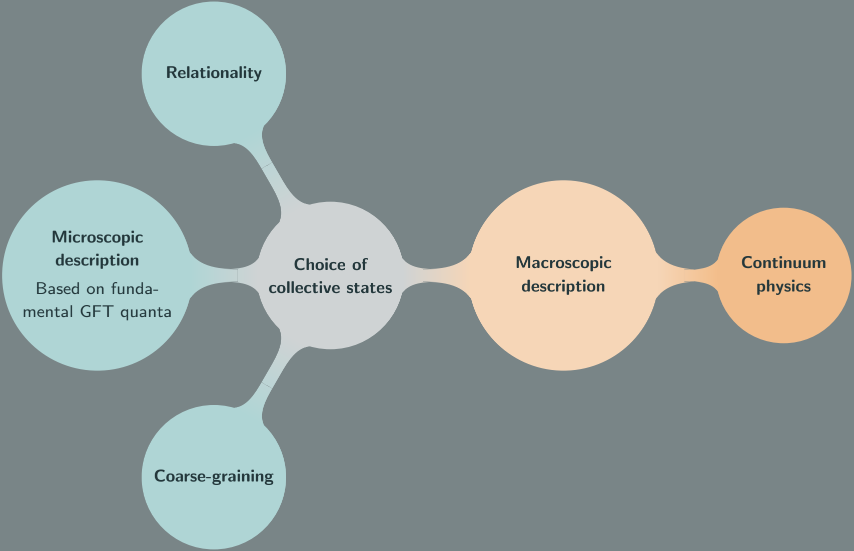
UNB Fredericton


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

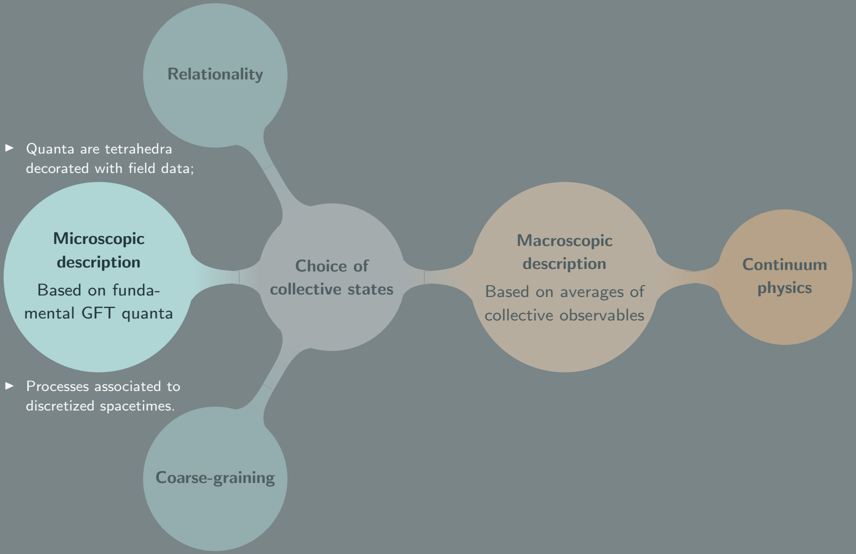

Localization problem
Microscopic description
Background independent, pre-geometric
Continuum limit problem
Macroscopic description
Continuum physics



Relationality
Microscopic description
Background independent, pre-geometric
Coarse-graining
Macroscopic description
Continuum physics



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



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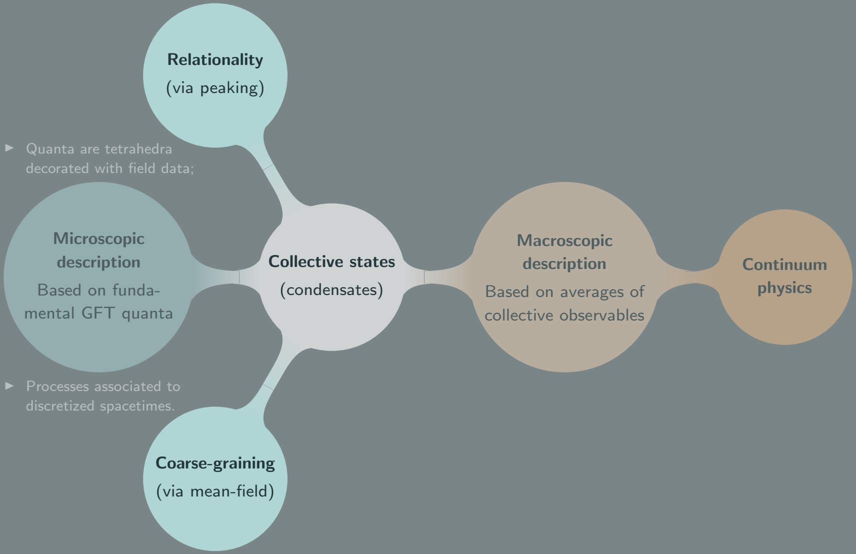

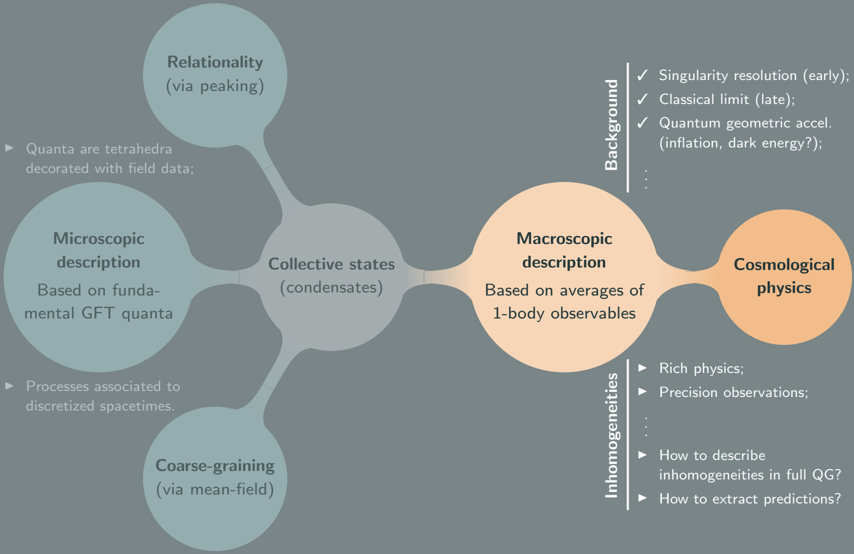
Relationality
(via peaking)
Quanta are tetrahedra decorated with field data;
Microscopic description
Based on fundamental GFT quanta
Processes associated to discretized spacetimes.
Coarse-graining
(via mean-field)
Collective states
(condensates)
Macroscopic description
Based on averages of 1-body observables
Cosmological physics
Background
✓ Singularity resolution (early);
✓ Classical limit (late);
✓ Quantum geometric accel. (inflation, dark energy?);
Inhomogeneities
Rich physics;
Precision observations;
How to describe inhomogeneities in full QG?
How to extract predictions?

Inhomogeneities in GFT cosmology

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

- $\hat{\varphi}(g_a, \chi^\mu, \phi)$ depends on 5 discretized scalar variables and is associated to spacelike tetrahedra.
- S_{GFT} from EPRL-like model.

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

$$\hat{\Phi} = (\hat{\varphi}^\dagger, \phi\hat{\varphi}) \qquad \hat{\Pi}_\phi = -i(\hat{\varphi}^\dagger, \partial_\phi \hat{\varphi})$$

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States

- Peaked $|\sigma\rangle_x$ around $\chi^\mu = x^\mu$, with $\sigma = \eta \times \tilde{\sigma}$:
  - 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

- $\langle \delta S/\delta\hat{\varphi}\rangle_{\sigma_x} = 0$ (no interactions) $\longrightarrow$ coupled eqs. for (ρ, θ).
- Decoupling for a range of values of $|\sigma\rangle_x$ and large N (late times).

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

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Background

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

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Perturbations

- ✓ "Deep super-horizon" ($k \to 0$) GR matching.

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- ✓ "Deep super-horizon" $(k \to 0)$ GR matching.
- Unphysical behavior of spatial derivative terms.

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Super-horizon scalar perturbations

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- Averaged q.e.o.m. (no interactions) $\longrightarrow$ coupled eqs. for (ρ, θ).
- Restrict to deep super-horizon modes but at 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 deep super-horizon scalar pert. can be obtained generically for any MG theory.

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Perturbing background dynamics

- Study deep super-horizon scalar pert. by perturbing background QG volume equation.

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Modified gravity

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Perturbing background dynamics

- Study deep super-horizon scalar pert. by perturbing background QG volume equation.

No matching at early times with full effective GFT volume dynamics: different d.o.f.!

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Two-body correlations

Including timelike tetrahedra: better coupling of the physical frame. Two-sector $(+,-)$ GFT (BC)!

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

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

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- $\hat{\sigma} = (\sigma, \hat{\varphi}_+^\dagger)$: spacelike condensate.
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- τ, σ peaked; $\tilde{\tau}$, $\tilde{\sigma}$ homogeneous.

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Perturbations

- $\widehat{\delta\Phi} = (\delta\Phi, \hat{\varphi}_+^\dagger\hat{\varphi}_+^\dagger)$, $\widehat{\delta\Psi} = (\delta\Psi, \hat{\varphi}_+^\dagger\hat{\varphi}_-^\dagger)$, $\widehat{\delta\Xi} = (\delta\Xi, \hat{\varphi}_-^\dagger\hat{\varphi}_-^\dagger)$.
- $\delta\Phi$, $\delta\Psi$ and $\delta\Xi$ small and relationally inhomogeneous.
- Perturbations = nearest neighbour 2-body correlations.

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Effective dynamics

Scalar isotropic perturbations

- 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 and single (spacelike) rep. label.

$$\delta V_\psi \propto \mathrm{Re}(\delta\Psi, \tilde{\sigma}\tilde{\tau}) + \mathrm{Re}(\delta\Phi, \tilde{\sigma}^2)$$
$$\delta\phi_\psi = \bar{\phi}_\psi(\delta V_\psi/\bar{V}_\psi)$$

- Physical behavior of spatial derivative terms fixes dynamical freedom (e.g. in $\delta\Phi$).

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Two-body correlations

Including timelike tetrahedra: better coupling of the physical frame. Two-sector $(+,-)$ GFT (BC)!

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

Background

- $\hat{\sigma} = (\sigma, \hat{\varphi}_+^\dagger)$: spacelike condensate.
- $\hat{\tau} = (\tau, \hat{\varphi}_-^\dagger)$: timelike condensate.
- τ, σ peaked; $\tilde{\tau}$, $\tilde{\sigma}$ homogeneous.

Perturbations

- $\widehat{\delta\Phi} = (\delta\Phi, \hat{\varphi}_+^\dagger\hat{\varphi}_+^\dagger)$, $\widehat{\delta\Psi} = (\delta\Psi, \hat{\varphi}_+^\dagger\hat{\varphi}_-^\dagger)$, $\widehat{\delta\Xi} = (\delta\Xi, \hat{\varphi}_-^\dagger\hat{\varphi}_-^\dagger)$.
- $\delta\Phi$, $\delta\Psi$ and $\delta\Xi$ small and relationally inhomogeneous.
- Perturbations = nearest neighbour 2-body correlations.

Effective dynamics

Scalar isotropic perturbations

- 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.

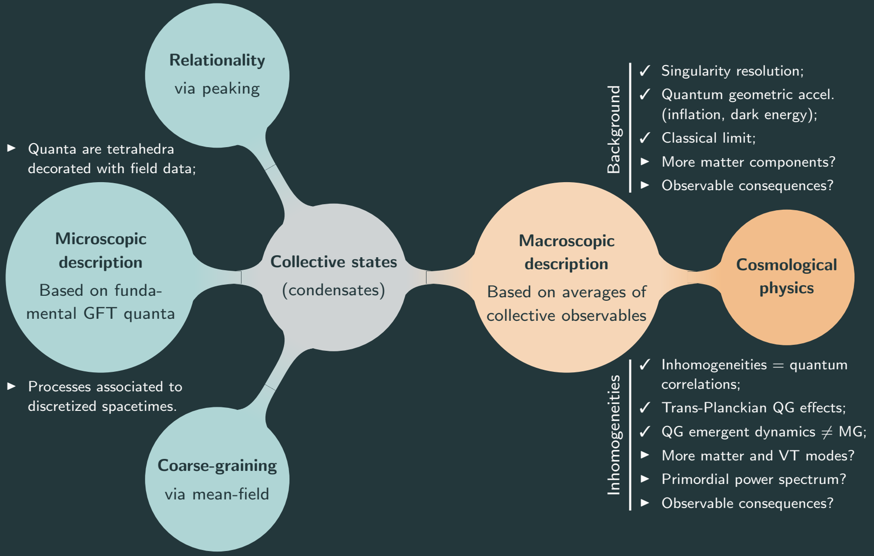
$$\delta V_\psi \propto \mathrm{Re}(\delta\Psi, \tilde{\sigma}\tilde{\tau}) + \mathrm{Re}(\delta\Phi, \tilde{\sigma}^2)$$
$$\delta\phi_\psi = \bar{\phi}_\psi(\delta V_\psi/\bar{V}_\psi)$$

- Physical behavior of spatial derivative terms fixes dynamical freedom (e.g. in $\delta\Phi$).

Late times scalar isotropic perturbations

- QG corrections at (relationally) trans-Planckian scales.
- GR matching at larger scales.

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


Relationality
via peaking
► Quanta are tetrahedra decorated with field data;
Microscopic description
Based on fundamental GFT quanta
► Processes associated to discretized spacetimes.
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?
► Observable consequences?
Inhomogeneities
✓ Inhomogeneities = quantum correlations;
✓ Trans-Planckian QG effects;
✓ QG emergent dynamics ≠ MG;
► More matter and VT modes?
► Primordial power spectrum?
► Observable consequences?

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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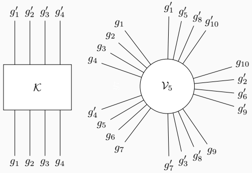
Action

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



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

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

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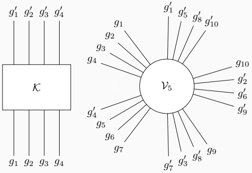

Partition function

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

- 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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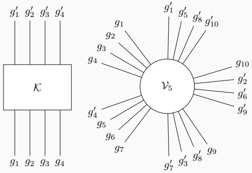

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$$Z[\varphi,\bar{\varphi}] = \sum_{\Gamma} w_\Gamma(\{\lambda_\gamma\})A_\Gamma = \text{complete spinfoam model.}$$

- 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

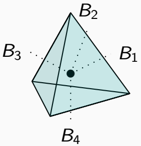
Geometricity constraints (appropriately encoded in $\mathcal{K}$ and $\mathcal{V}_\gamma$) allow for a $d-1$-simplicial interpretation of the fundamental quanta:

Closure

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

Simplicity

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



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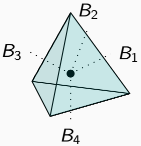

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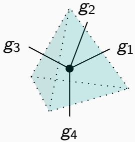

Group Field Theory and Loop Quantum Gravity

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Lie algebra (metric)		**Lie group (connection)**		**Representation space**
$\mathcal{H}_{\Delta_a} = L^2(\mathfrak{g})$	←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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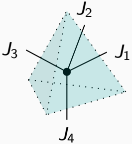

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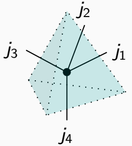

LQG

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

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

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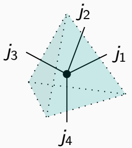

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$$\mathcal{H}_{\text{tetra}} = \bigoplus_{\vec{j}} \text{Inv}\left[\bigotimes_{a=1}^{4} \mathcal{H}_{j_a}\right]$$
$$= \text{open spin-network vertex space}$$

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

- 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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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 $H_{\sigma_{x^0}} \simeq \langle \hat{\Pi}^0 \rangle_{\sigma_{x^0}}$.

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

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Wavefunction $\longrightarrow$ 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).

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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:

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

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Effective dynamics

Mean-field approximation

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

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- 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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Relationality

Condensate Peaked States

- 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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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: $V \equiv \langle \hat{V} \rangle_{\sigma_{x^0}} = \sum\!\!\!\!\!\!\int_{\upsilon} V_\upsilon \rho_\upsilon^2(x^0)\,, \quad \rho \equiv |\tilde{\sigma}|.$

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

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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.

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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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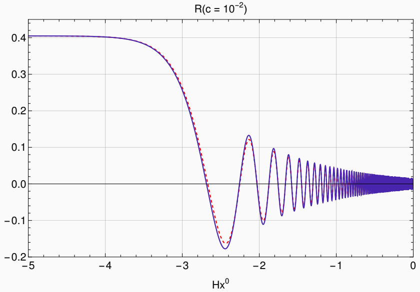
Dynamics of a comoving curvature-like variable

$$\tilde{\mathcal{R}} \equiv -\frac{\delta V}{3\bar{V}} + \mathcal{H}\frac{\delta\phi}{\bar{\phi}'}\,, \qquad \tilde{\mathcal{R}}'' - a^4\nabla^2\tilde{\mathcal{R}} = -\left[\mathcal{H} - \frac{1}{4}(\bar{\phi}^2)'\right]\left(\frac{\delta V}{\bar{V}}\right)'.$$



- c = ratio between volume and matter pert. initial conditions.
- Deep sub-horizon modes are trans-Planckian in the physical reference frame.

As c increases, QG dynamics (blue line) differs more and more from the GR one (red dotted line) at (relational) trans-Planckian scales.

Jercher, LM, Pithis (to appear).