Scalar cosmological perturbations from full quantum gravity

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

Luca Marchetti

Theory Canada 15
Mount Allison University
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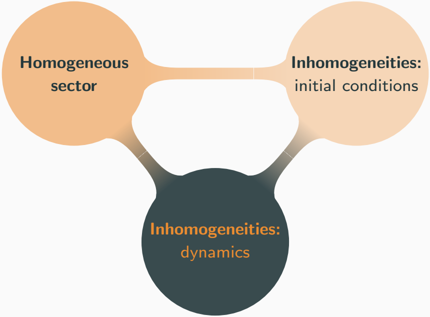
Department of Mathematics and Statistics
UNB Fredericton

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; . . .

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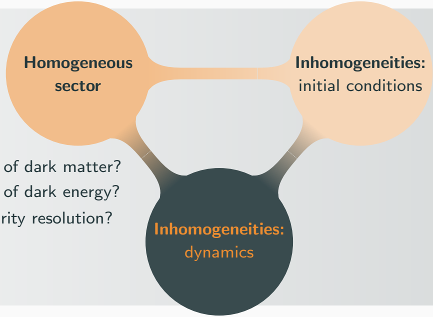

- Nature of dark matter?
- Nature of dark energy?
- Singularity resolution?
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The QG perspective on Cosmology

Homogeneous sector

Inhomogeneities: initial conditions

Inhomogeneities: dynamics

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

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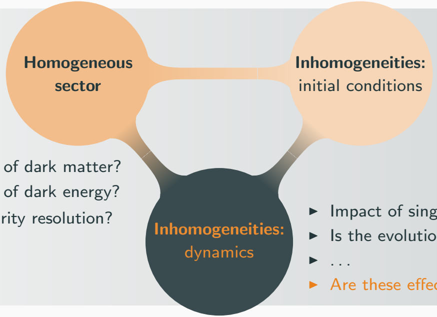

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- How to define (in)homogeneity?
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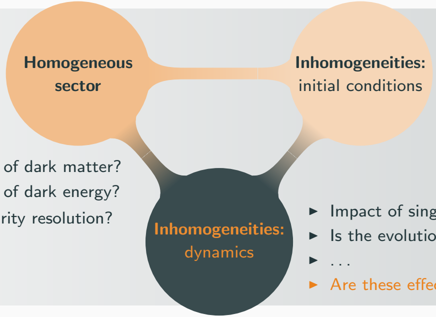

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Approximate only

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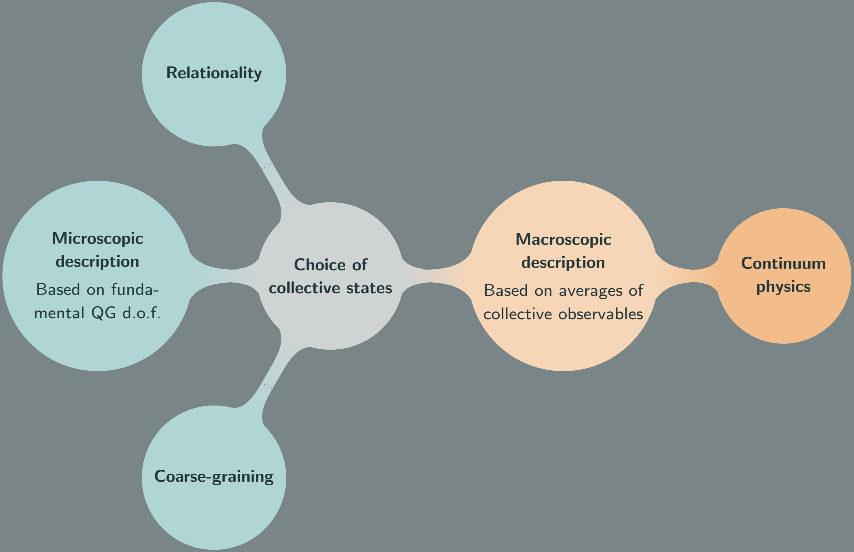
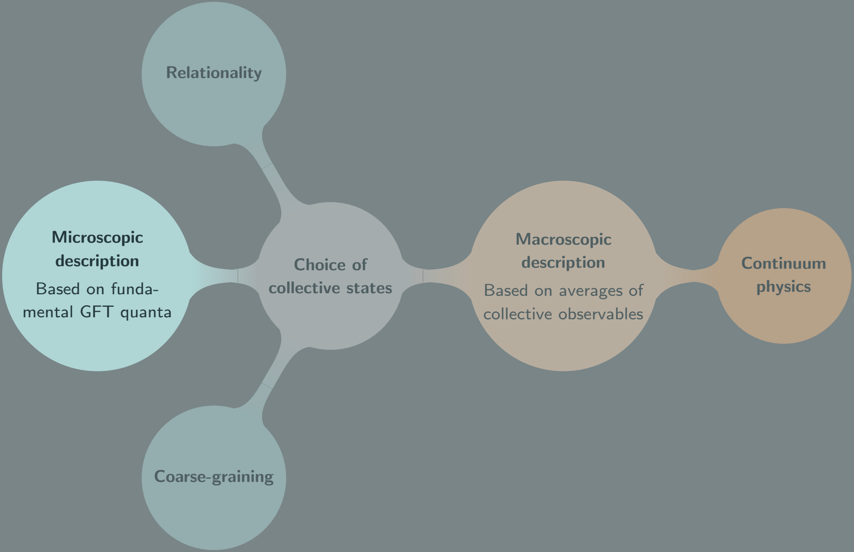

Relationality
Microscopic description
Based on fundamental QG d.o.f.
Choice of collective states
Coarse-graining
Macroscopic description
Based on averages of collective observables
Continuum physics



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Microscopic description
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Introduction to Group Field Theory

The (T)GFT approach to quantum gravity

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

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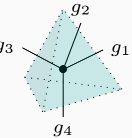
$\mathcal{H}_{\text{1-p}} =$ 

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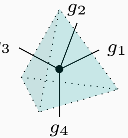
$\mathcal{H}_{\text{1-p}} =$ 

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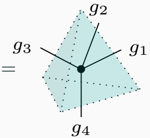
$\mathcal{H}_{\text{1-p}} =$ 

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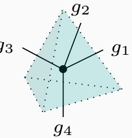
$\mathcal{H}_{\text{1-p}} =$ 

Processes: Discrete spacetimes

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

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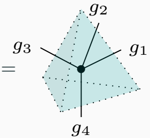
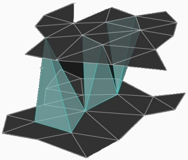


Processes: Discrete spacetimes

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

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

$$Z_{\text{GFT}} = \sum_{\Gamma} w_\Gamma(\{\lambda_\gamma\}) A_\Gamma = \text{discrete gravity path-integral.}$$



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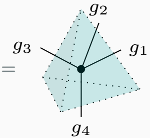
$\mathcal{H}_{\text{1-p}} =$ 

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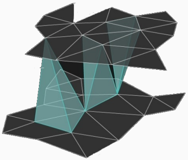

GFTs are QFTs of atoms of spacetime.

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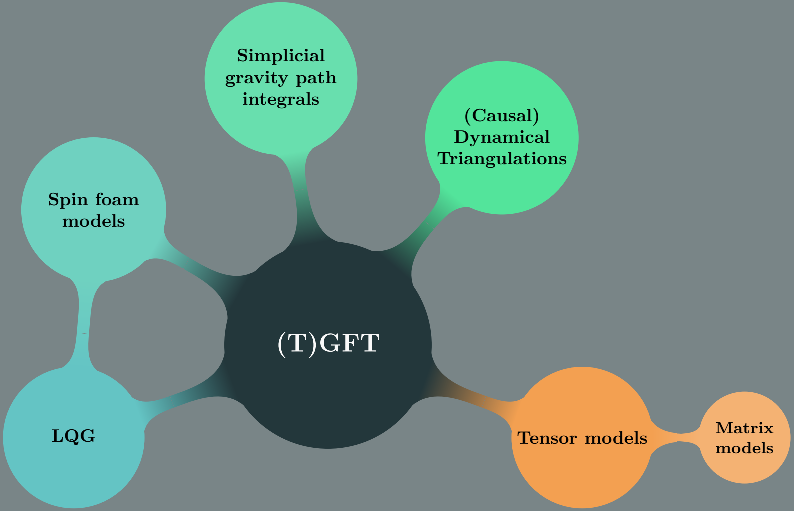
Simplicial gravity path integrals
(Causal) Dynamical Triangulations
Spin foam models
(T)GFT
LQG
Tensor models
Matrix models

Group Field Theory and matter: scalar fields

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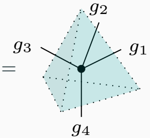

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S_{GFT} obtained by comparing Z_{GFT} with simplicial gravity + scalar fields path integral.

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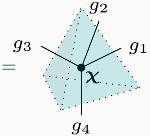
$\mathcal{H}_{\text{1-p}} =$ 

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- For minimally coupled, free, massless scalars:

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

$$\mathcal{V}_5(g_a^{(1)}, \dots, g_a^{(5)}, \chi) = \mathcal{V}_5(g_a^{(1)}, \dots, g_a^{(5)})$$

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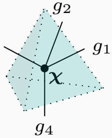
$\mathcal{H}_{1\text{-p}} =$ 

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Domain of GFTs is the space of (discretized) continuum fields

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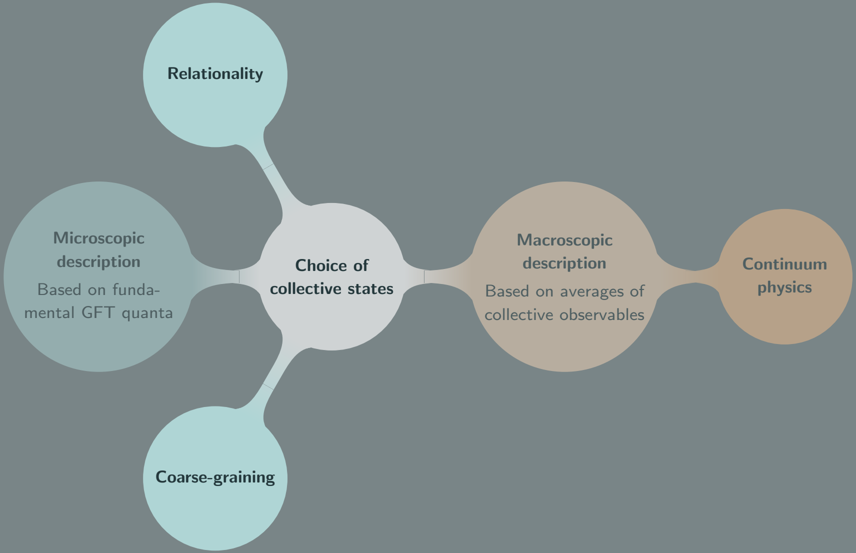
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Collective states

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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Effective dynamics

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

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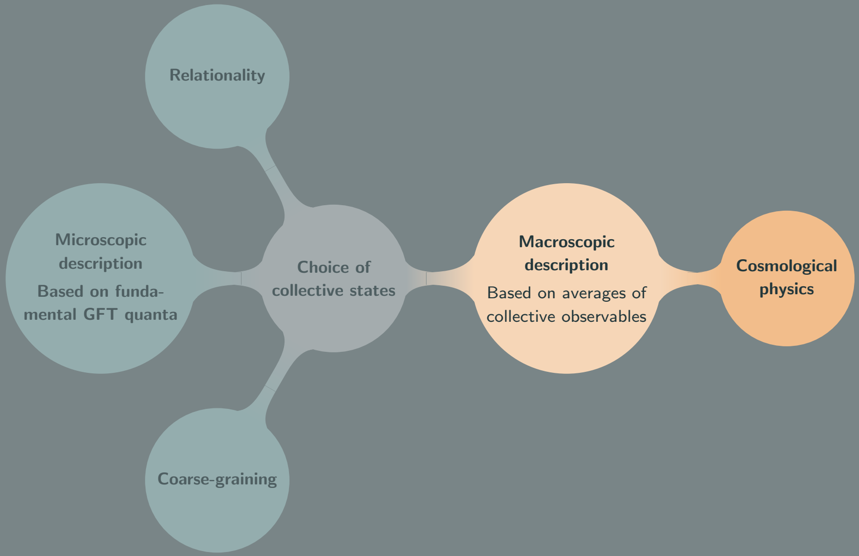
- Relational localization implemented at an effective level on observable averages on condensates.
- If χ^μ constitute a physical reference frame, this can be achieved by assuming

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

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


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

Group Field Theory Cosmology

Homogeneous sector

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

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

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Effective relational Freidmann dynamics

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

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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 $3\pi G$

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

- 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.

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

Inhomogeneous sector (dynamics)

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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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).

single label $\longrightarrow$ 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.

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

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Perturbations

- ✓ Large scales ("super-horizon") GR matching.

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Background

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

Perturbations

- ✓ Large scales ("super-horizon") GR matching.
- Unphysical behavior of spatial derivative terms.

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

Super-horizon scalar perturbations

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Super-horizon volume and matter dynamics

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

single $\longrightarrow$ spin: 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!

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

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

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- 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.

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

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Effective dynamics

Scalar 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.

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

Scalar perturbations from quantum correlations

Collective states

Two-body correlations

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- Perturbations = nearest neighbour 2-body correlations.

Effective dynamics

Scalar 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.

$$\delta V_\psi \propto \mathrm{Re}(\delta\Psi, \tilde{\sigma}\tilde{\tau}) + \mathrm{Re}(\delta\Phi, \tilde{\sigma}^2)$$

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

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

Scalar perturbations from quantum correlations

Collective states

Two-body correlations

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

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

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

- $\widehat{\delta\Phi} = (\delta\Phi, \hat{\varphi}_+^\dagger\hat{\varphi}_+^\dagger)$, $\widehat{\delta\Psi} = (\delta\Psi, \hat{\varphi}_+^\dagger\hat{\varphi}_-^\dagger)$, $\widehat{\delta\Xi} = (\delta\Xi, \hat{\varphi}_-^\dagger\hat{\varphi}_-^\dagger)$.
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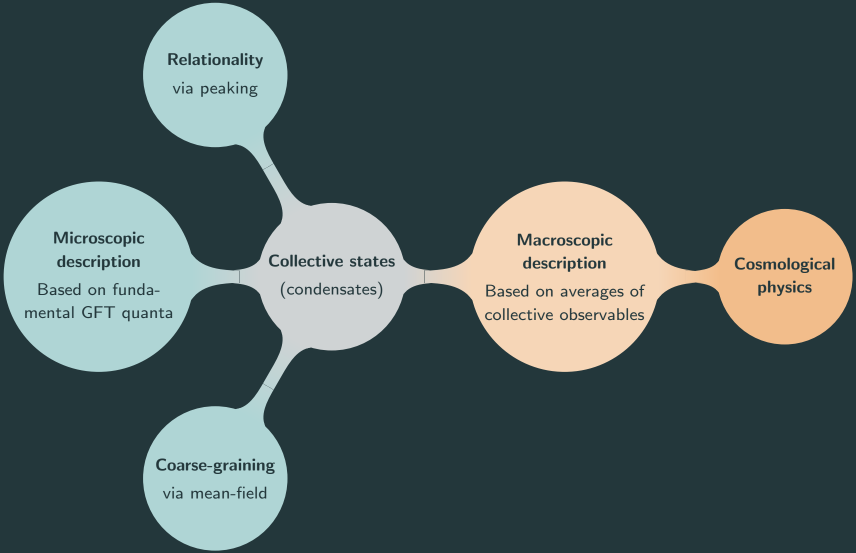
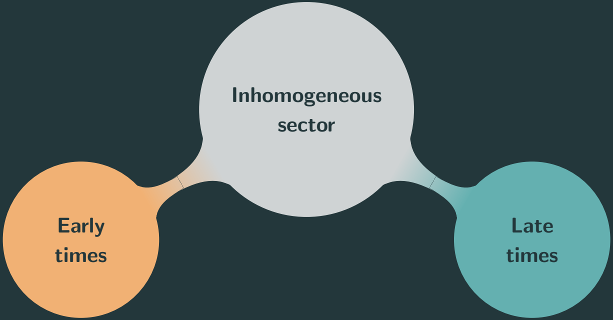
Late times volume perturbations

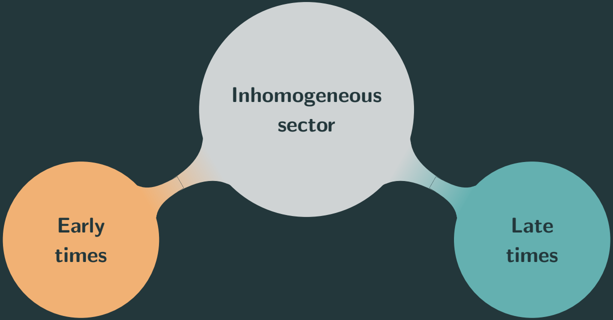
- QG corrections to trans-Planckian modes dynamics.
- GR matching at larger scales.

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



Relationality
via peaking
Microscopic description
Based on fundamental GFT quanta
Collective states
(condensates)
Coarse-graining
via mean-field
Macroscopic description
Based on averages of collective observables
Cosmological physics

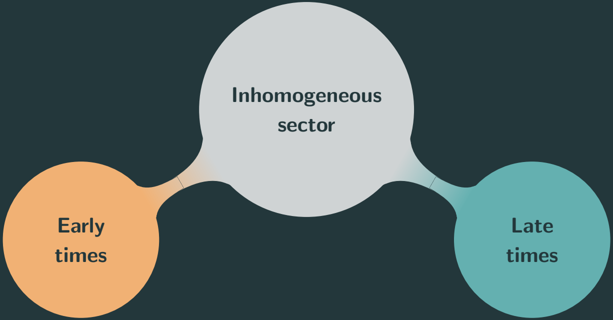

Inhomogeneous sector
Early times
Late times



Results

- ✓ Super-horizon analysis with MCMF scalar fields:
  - ✓ Scalar pert. dynamics differs from any MG model.
  - ✓ Full QG scalar pert. dynamics differs from QG perturbed background one.

LM, Oriti 2112.12677; Fischer, LM, Oriti (to appear); Jercher, LM, Pithis (to appear); Gerhart, Oriti, Wilson-Ewing 1805.03099.



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  - ✓ Scalar pert. dynamics differs from any MG model.
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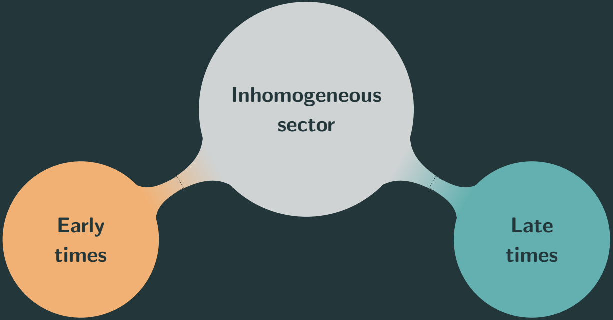
Results

- ✓ All scales analysis with MCMF scalar fields:
  - ✓ Manifest causal properties of quanta allow for a careful coupling of the physical ref. frame.
  - ✓ Scalar pert. $\longleftrightarrow$ quantum correlations!
  - ✓ Late-times volume pert. dynamics matches GR at large scales. . .
  - ✓ . . . but receives corrections for trans-Planckian modes!

LM, Oriti 2112.12677; Fischer, LM, Oriti (to appear); Jercher, LM, Pithis (to appear); Gerhart, Oriti, Wilson-Ewing 1805.03099.



Perspectives

- Different fundamental d.o.f. $\longrightarrow$ different perturbation dynamics?
- Scalar field perturbations? EFT description?
- Generalization to physically interesting fluids.
- Extension to VT modes: more observables!
- Initial conditions and power spectra?
  - Fock quantization of early-times dynamics.
  - Can we derive it from full QG?

Perspectives

- Physical (perhaps observable) consequences of trans-Planckian mismatch?
- Scalar field perturbations? EFT description?
- Generalization to physically interesting fluids.
- Extension to VT modes: more observables!
- How do quantum perturbations classicalize?

Fischer, LM, Oriti (to appear); Jercher, LM, Pithis (to appear); Dekhil, Liberati, Oriti (to appear); Calcinari, Gielen 2210.03149.

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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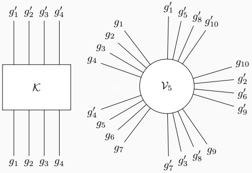
Action

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

- 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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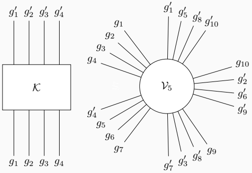

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Partition function

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

- 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.

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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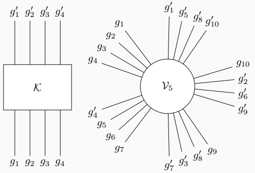

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- Γ = stranded diagrams dual to d-dimensional cellular complexes of arbitrary topology.
- Amplitudes A_Γ = sums over group theoretic data associated to the cellular complex.
- $\mathcal{K}$ and $\mathcal{V}_\gamma$ chosen to match the desired spinfoam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

Group Field Theory and Loop Quantum Gravity

Fundamental quanta

One-particle Hilbert space

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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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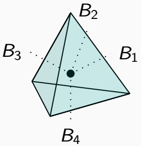

Finocchiaro, Oriti 1812.03550; Baez, Barrett 9903060; Baratin, Oriti 1002.4723; Gielen, Oriti 1004.5371; Oriti 1310.7786.

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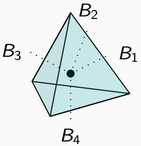

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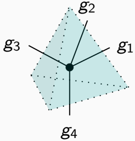

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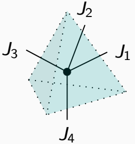

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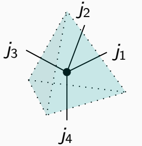

LQG

- 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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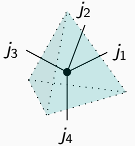

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$$\mathcal{H}_{\text{tetra}} = \bigoplus_{\vec{j}} \text{Inv}\left[\bigotimes_{a=1}^{4} \mathcal{H}_{j_a}\right]$$
$$= \text{open spin-network vertex space}$$

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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Many-body → Theory

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

- $\mathcal{F}_{\mathsf{GFT}}$ 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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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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- $\langle \hat{O} \rangle_{\sigma_{x^0}} = O[\tilde{\sigma}]|_{\chi^0 = x^0}$: functionals of $\tilde{\sigma}$ localized at x^0.

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

Macroscopic cosmological variables and effective relationality

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

Collective Observables

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

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

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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).

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