Scalar cosmological perturbations from full quantum gravity

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

Luca Marchetti

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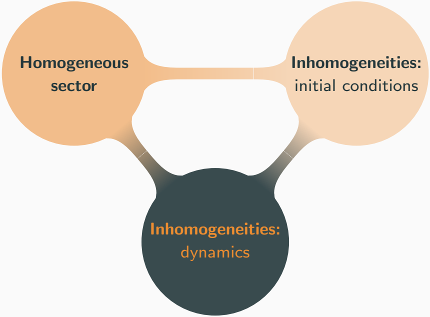
Department of Mathematics and Statistics
UNB Fredericton

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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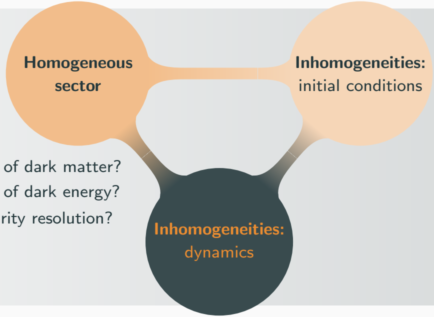

- Nature of dark matter?
- Nature of dark energy?
- Singularity resolution?
- . . .

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The QG perspective on Cosmology

Homogeneous sector

- Nature of dark matter?
- Nature of dark energy?
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Inhomogeneities: initial conditions

Inhomogeneities: dynamics

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

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- Geometric inflation?
- Is the vacuum state a QG modified BD vacuum?
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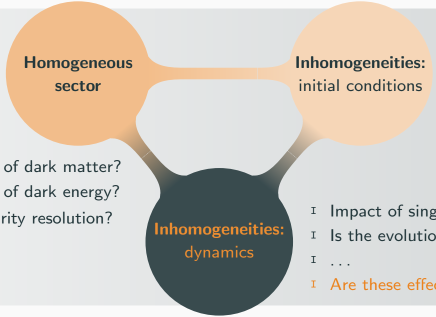

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Challenges in background independent and emergent QG:

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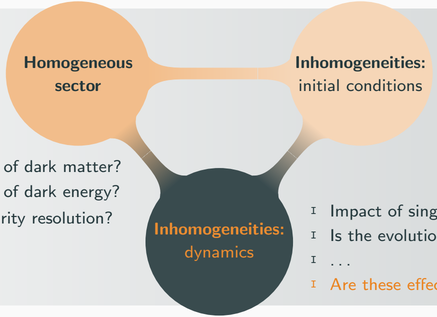

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- How to define (in)homogeneity? → Relational strategy
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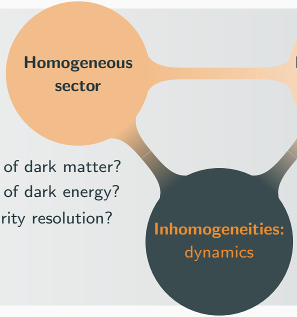

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Challenges in background independent and emergent QG:

- How to define (in)homogeneity? → Relational strategy
- How to extract macroscopic dynamics? → Relational strategy; Coarse-graining/ collective behavior
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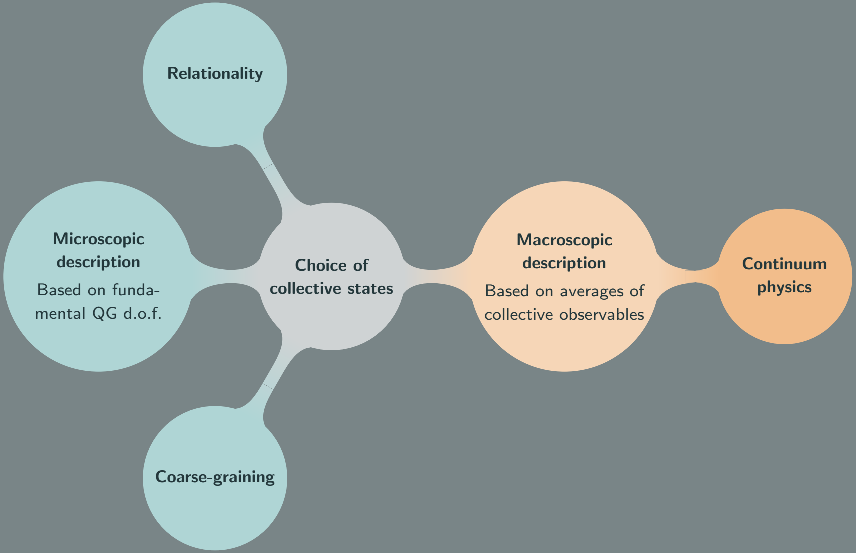
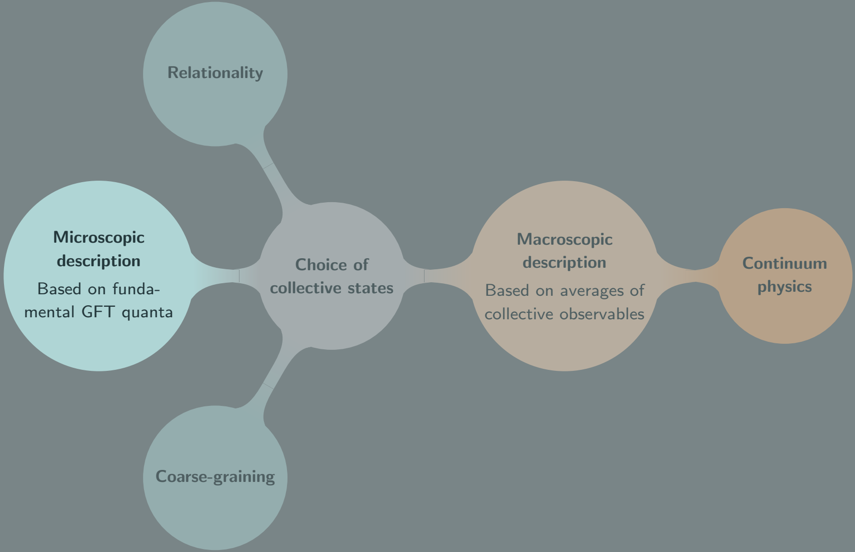
Relational strategy

Coarse-graining/ collective behavior

Approximate only

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


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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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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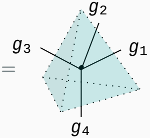
Quanta: Spacetime atoms

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

$H_{\text{1-p}} =$



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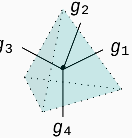

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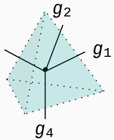

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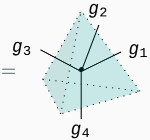

Processes: Discrete spacetimes

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

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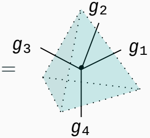
$H_{1\text{-p}} =$ 

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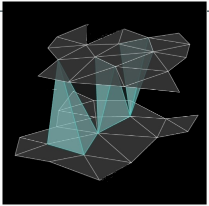

S_{GFT} obtained by comparing Z_{GFT} with simplicial gravity path integral.

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

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

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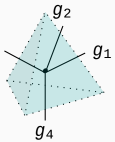
$H_{1\text{-p}} =$ 

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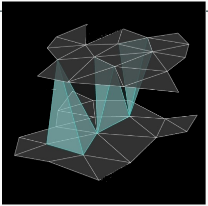
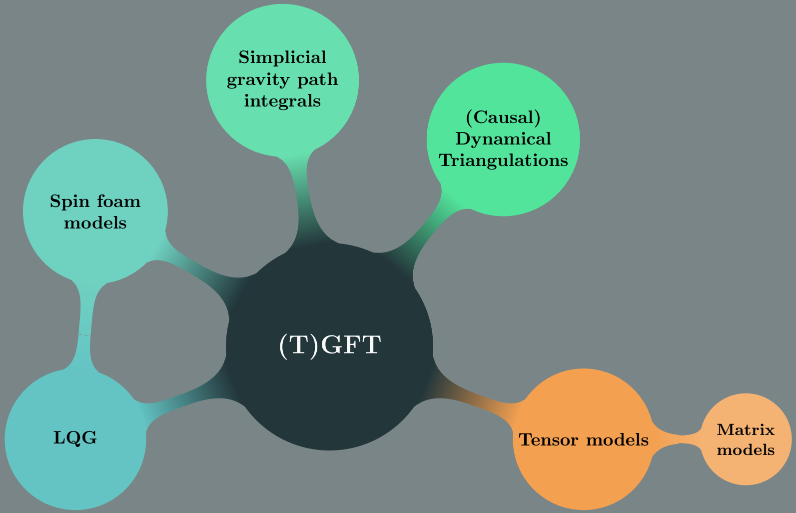


GFTs are QFTs of atoms of spacetime.

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


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

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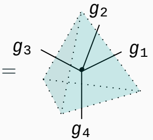
$H_{\text{1-p}} =$ 

Processes: Discrete spacetimes

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

- Geometric data enter interactions in a non-local and combinatorial fashion.

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

Group Field Theory and matter: scalar fields

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

$$K(g_a; g_b; \quad ; \quad ^0) = K(g_a; g_b; (\qquad ^0)^2)$$

$$V_5(g_a^{(1)}; :::; g_a^{(5)}; \quad) = V_5(g_a^{(1)}; :::; g_a^{(5)})$$

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

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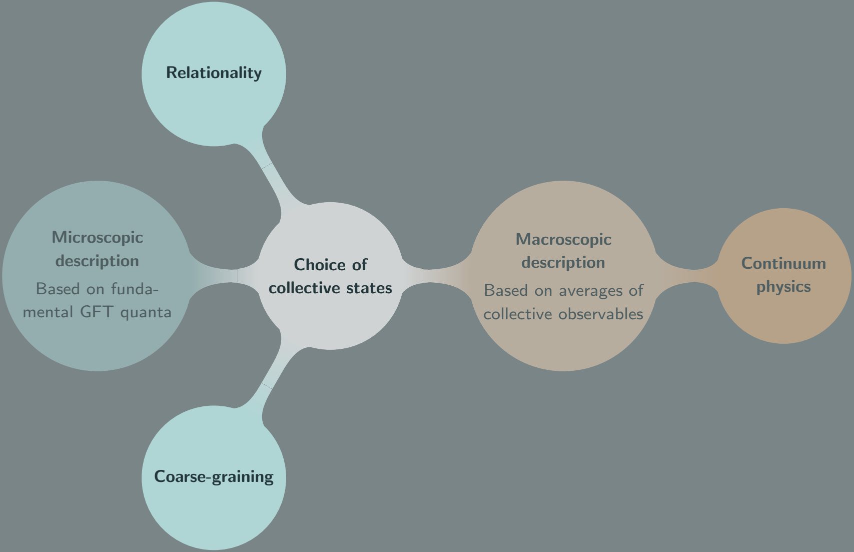
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Based on averages of collective observables
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Coarse-graining

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:

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

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

The main ingredients

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Effective dynamics

Mean-field approximation

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

$$\left\langle \frac{\delta S[\hat{};\hat{}^{\dagger}]}{\delta \hat{}(g_l;x\;)} \right\rangle = \int \mathrm{d}h_a \int \mathrm{d} \;\; K(g_a;h_a;(x\;)^2)\,(h_a;\;) + \frac{\delta V[\,';\,'\,]}{\delta\,'(g_a;x\;)}\bigg|_{'=} = 0\,.$$

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

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Relationality

Condensate Peaked States

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

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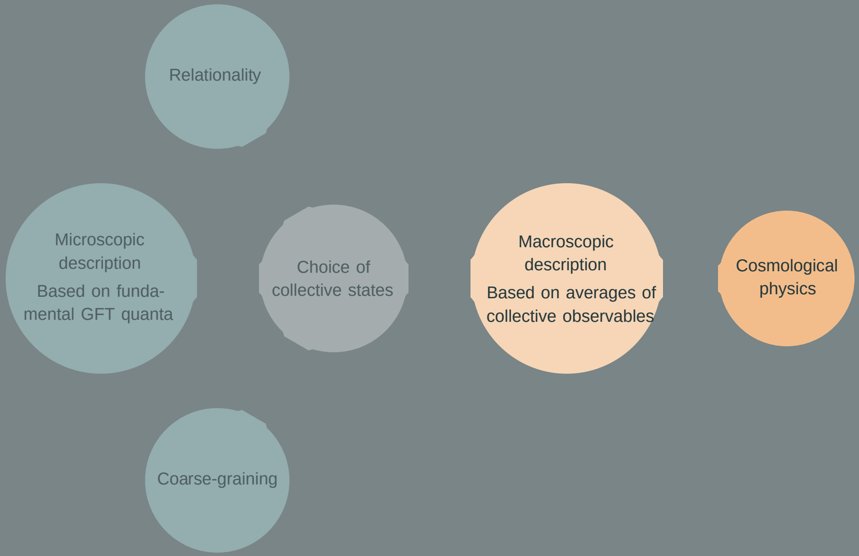
Condensate Peaked States

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

$= ($ xed peaking function $) \quad ($dynamically determined reduced wavefunction $\sim)$

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 funda-mental GFT quanta
Choice of collective states
Macroscopic description
Based on averages of collective observables
Cosmological physics
Coarse-graining

Group Field Theory Cosmology

Homogeneous sector

E ective relational homogeneous volume dynamics

Assumptions

(Relational) Homogeneity

- depends on a single clock MCFM eld ^{0}.
- D = minisuperspace + clock:

Isotropy

- depends only on a single rep. label .
- 2 N=2 (EPRL-like) or 2 R (ext. BC).

Volume operator captures the relevant physics: $V \quad h\,\hat{V}\,i_{x^0} = \sum \quad V \quad {}^2(x^0)\,; \quad j \;\; \tilde{\;}j\,.$

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E ective relational Freidmann dynamics

$$\left(\frac{V^{0}}{3V}\right)^2 \simeq \left(\frac{2\sum V \quad \mathrm{sgn}(\ ^{0})\sqrt{E \quad Q^2 = \ ^2 + \quad ^2 \ ^2}}{3\sum V \quad ^2}\right)^2 ; \qquad \frac{V^{00}}{V} \simeq \frac{2\sum V \quad E + 2 \quad ^2 \ ^2}{\sum V \quad ^2}$$

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Classical limit (large N, late times)

- If ^{2} is mildly dependent on (or one is dominating) and equal to 3 G

$(V^0 = 3V)^2$ ' 4 G=3 ⟶ at FLRW

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

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$$(V^{0}=3V)^{2} ' \ 4 \ G=3 \longrightarrow \text{at FLRW}$$

- Quantum uctuations 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 $\neq$ 0 or one E < 0).
- The average singularity resolution may still be spoiled by quantum e ects 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 elds (^{0}; ^{i}),
- 1 MCMF matter eld dominating the e.m. budget and relationally inhomog. wrt. ^{i}.

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Quantum

- ' (g_a; ;) depends on 5 discretized scalar variables and is associated to spacelike tetrahedra.
- S_{GFT} respecting the classical matter symmetries.

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- S_{GFT} respecting the classical matter symmetries.

Observables

notation: (;) = Z d^4 d d g$_a$

Frame: $\hat{X}$ = (^ ^{y}; '^) ^ = i('^ ^{y}; @ '^)

Vol.: Only isotropic info: $\hat{V}$ = (^ ^{y}; V ['^])

Mat.: ^= (^' ^{y}; '^) ^ = i('^ ^{y}; @ '^)

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

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Observables

notation: (;) = $\int d^4 \; d \; d g_a$

Mat. Vol. Frame

$\hat{X} = (\hat{}^{y}; \hat{}) \quad \hat{} = i(\hat{}^{y}; @ \hat{})$

Only isotropic info: $\hat{V} = (\hat{}^{y}; V[\hat{}])$

$\hat{} = (\hat{}^{y}; \hat{}) \quad \hat{} = i(\hat{}^{y}; @ \hat{})$

States

- CPSs around = x , with
  - ^ : Isotropic peaking on rods;
  - ^ ~: Isotropic distribution of geometric data.
- Small relational ~-inhomogeneities (~ = e^{i}):

  = (; ^{0}) + (;), = (; ^{0}) + (;).

Scalar perturbations from GFT condensates

Observables

notation: (;) = $\int d^4 \; d \; d \, g_a$

Mat. Vol. Frame

$\hat{X} = (\hat{} ^{y} ; \quad \hat{\varphi}) \quad \hat{} \; = \; i(\hat{\varphi}^{y} ; @ \, \hat{\varphi})$

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

$\hat{} = (\hat{\varphi}^{y} ; \; \hat{\varphi}) \quad \hat{} \; = \; i(\hat{\varphi}^{y} ; @ \, \hat{\varphi})$

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Late times volume and matter dynamics

- Averaged q.e.o.m. (no interactions) ! coupled eqs. for (;).
- Decoupling for a range of values of CPSs and large N (late times).

single label → Dynamic equations for $\langle \hat{V} \rangle_{x^0}$, $\langle \hat{} \rangle_{x^0}$.

Scalar perturbations from GFT condensates

Observables

notation: $(\; ; \;) = \int d^4 \; d \; d g_a$

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$\hat{X} = (\hat{\ }^{y} ; \; \hat{'}) \quad \hat{\ } = i(\hat{'}^{y} ; @ \hat{'})$

Only isotropic info: $\hat{V} = (\hat{\ }^{y} ; V[\hat{'}])$

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Background

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

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

Scalar perturbations from GFT condensates

Observables

notation: $(\, ; \,) = \int d^4 \; d \; d\, g_a$

$\hat{X} = (\hat{\ }^{y}; \quad \hat{'}) \quad \hat{\ } = \quad i(\hat{'}^{y}; @\, \hat{'})$

Only isotropic info: $\hat{V} = (\hat{\ }^{y}; V[\hat{'}])$

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Mat. Vol. Frame

States

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Background

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

Perturbations

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

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

Scalar perturbations from GFT condensates

Observables

notation: $(\; ; \;) = \int d^4 \; d \; d g_a$

Mat. Vol. Frame

$\hat{X} = (\hat{\;}^{y} ; \quad \hat{\varphi}) \quad \hat{\;} = \quad i(\hat{\varphi}^{y} ; @ \hat{\varphi})$

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$\hat{\;} = (\hat{\varphi}'^{y} ; \quad \hat{\varphi}) \quad \hat{\;} = \quad i(\hat{\varphi}^{y} ; @ \hat{\varphi})$

States

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  - $\hat{\;}$: Isotropic peaking on rods;
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Background

- ✓ Matching with GR possible.
- Macro. couplings de ned 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

Observables

notation: (;) = $\int d^4 \; d \; d g_a$

Mat. Vol. Frame

$\hat{X} = (\hat{}^{y}; \;\; \hat{\varphi}) \quad \hat{} = \; i(\hat{\varphi}^{y}; @ \hat{\varphi})$

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Super-horizon volume and matter dynamics

- Averaged q.e.o.m. (no interactions) ! coupled eqs. for (;).
- Restrict to super-horizon modes but study also early times.

single spin → Dynamic equations for $h\hat{V}i_{x^0}$, $h\hat{}i_{x^0}$

Observables

notation: (;) = $\int d^4 \; d \; d g_a$

Mat. Vol. Frame

X̂ = (^ y; '^) ^ = i('^ y; @ '^)

Only isotropic info: V̂ = (^ y; V['^])

^= (^' y; '^) ^ = i('^ y; @ '^)

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- CPSs around = x , with
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Modi ed gravity

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

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

Super-horizon scalar perturbations

Observables

notation: (;) = Z d4 d d ga

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single spin → Dynamic equations for hV̂i x0 , h^i x0

Modi ed gravity

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

Perturbing background dynamics

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

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

Two-body correlations

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

$$j \quad i = N \quad \exp(\hat{} \quad I \quad + I_{+} \quad b + {}^{c} \quad I \quad + {}^{c} + \quad I_{+} \quad {}^{c}) \; j0i$$

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

Scalar perturbations from quantum correlations

Collective states

Two-body correlations

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Background

- ^ = (; '^$^{y}_{+}$): spacelike condensate.
- ^ = (; '^^{y}): timelike condensate.
- , peaked; ~, ~ homogeneous.

Collective states

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Background

- $\hat{} = (\; ; \; '\hat{}^{y}_{+})$: spacelike condensate.
- $\hat{} = (\; ; \; '\hat{}^{y} \;)$: timelike condensate.
- , peaked; ~, ~ homogeneous.

Perturbations

- ${}^{c} = (\quad ; '\hat{}^{y}_{+}'\hat{}^{y}_{+})$, ${}^{c} = (\quad ; '\hat{}^{y}_{+}'\hat{}^{y} \;)$, ${}^{c} = (\quad ; '\hat{}^{y} \; '\hat{}^{y} \;)$.
- , and small and relationally inhomogeneous.
- Perturbations = nearest neighbour 2-body correlations.

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

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- ^ = (; '^^{y}): timelike condensate.
- , peaked; ~, ~ homogeneous.

Perturbations

- c = (; '^$^{y}_{+}$'^$^{y}_{+}$), c = (; '^$^{y}_{+}$'^^{y}), c = (; '^^{y} '^^{y}).
- , and small and relationally inhomogeneous.
- Perturbations = nearest neighbour 2-body correlations.

E ective dynamics

Scalar perturbations

- 2 mean- eld eqs. for 3 variables (; ;):

$$h \;\; S= \;\; '\hat{}^{y}_{+} \, i \quad = 0 = \quad h \;\; S= \;\; '\hat{}^{y} \;\; i$$

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

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

Scalar perturbations from quantum correlations

Collective states

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

j i = N exp(^ I + I+ b + c I + c + I+ c) j0i

Background

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Perturbations

- c = (; '^y+'^y+), c = (; '^y+'^y), c = (; '^y '^y).
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V / Re(; ~~) + Re(; ~²)

- Physical behavior of spatial derivative terms xes dynamical freedom (e.g. in).

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Collective states

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$$j \; i = N \; \exp(\hat{\;} \; I \; + I_+ \; b + {}^{c} \; I \; + {}^{c} + I_+ \; {}^{c}) \; j0i$$

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$$h \; S = \; '^{y}_{+} \, i \;\; = 0 = \; h \; S = \; '^{y} \; i$$

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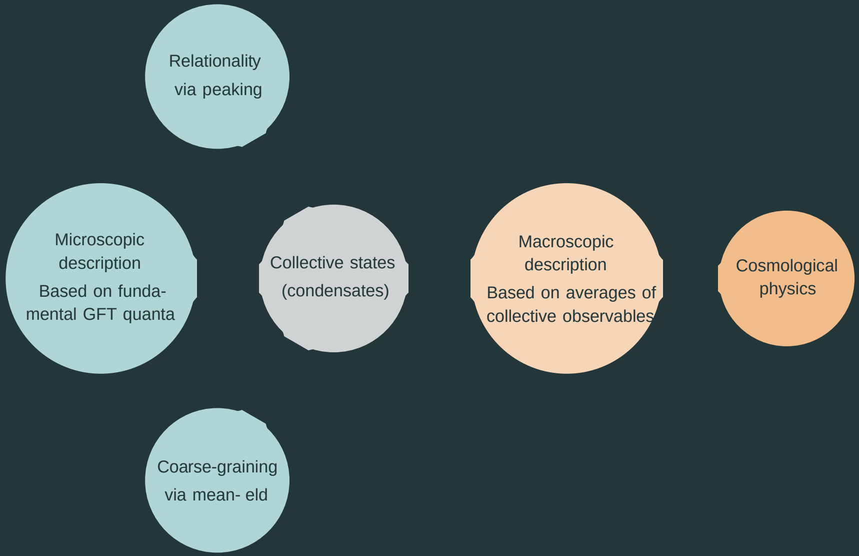
$$V \;\; / \;\; \mathrm{Re}(\;\; ; \sim\sim) + \mathrm{Re}(\;\; ; \sim^2)$$

- Physical behavior of spatial derivative terms xes dynamical freedom (e.g. in).

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 funda-
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Collective states
(condensates)
Macroscopic
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Based on averages of
collective observables
Cosmological
physics
Coarse-graining
via mean- eld


Inhomogeneous sector
Early times
Late times

Results

- ✓ Super-horizon analysis with MCMF scalar elds:
  - ✓ Scalar pert. dynamics di ers from any MG model.
  - ✓ Full QG scalar pert. dynamics di ers 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.

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.

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. ! 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

- ⚠ Di erent fundamental d.o.f. ! di erent perturbation dynamics?
- ⚠ Scalar eld perturbations? EFT description?
- Generalization to physically interesting uids.
- 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 eld perturbations? EFT description?
- Generalization to physically interesting uids.
- 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, $G = SL(2, \mathbb{C})$ or, in some cases, $G = SU(2)$.

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

De nition

Group Field Theories: theories of a eld ' : G^d ! C de ned 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 = SL(2 ; C) or, in some cases, G = SU(2).

Action

$$S[';\ '] = \int dg_a\, '(g_a) K['](g_a) + \sum \frac{}{n} \mathrm{Tr}_V['] + \text{c.c.}\ ;$$

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

$$\mathrm{Tr}_V['] = \int \prod_{i=1}^{n} dg_a \prod_{(a;i;b;j)} V(g_a^{(i)}; g_b^{(j)}) \prod_{i=1}^{n} '(g_a^{(i)})\ ;$$

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

$$\mathrm{Tr}_V\ [' \ ] = \int \prod_{i=1}^{n} d g_a \prod_{(a;i;b;j)} V\ (g_a^{(i)}; g_b^{(j)}) \prod_{i=1}^{n} '\ (g_a^{(i)})\ :$$

Partition function

$$Z[';\ '\ ] = \sum w\ (f\ \ g) A$$

- = stranded diagrams dual to d-dimensional cellular complexes of arbitrary topology.
- Amplitudes A = 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.

Group Field Theory and spinfoam models

De nition

Group Field Theories: theories of a eld ' : G^d ! C de ned 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 = SL(2 ; C) or, in some cases, G = SU(2).

Action

$$S[';\ '\ ] = \int dg_a\ '\ (g_a) K['\ ](g_a) + \sum \frac{}{n} \mathrm{Tr}_V\ ['\ ] + \text{c.c.} :$$

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

$$\mathrm{Tr}_V\ ['\ ] = \int \prod_{i=1} dg_a \prod_{(a;i;b;j)} V\ (g_a^{(i)}; g_b^{(j)}) \prod_{i=1} '\ (g_a^{(i)}) :$$

Partition function

$$Z[';\ '\ ] = \sum w\ (f\ \ g) A\ \ = \text{complete spinfoam model.}$$

- = stranded diagrams dual to d-dimensional cellular complexes of arbitrary topology.
- Amplitudes A = sums over group theoretic data associated to the cellular complex.
- K and V chosen to match the desired spinfoam model.

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Fundamental quanta

One-particle Hilbert space

The one-particle Hilbert space is $H_{tetra} \quad {}^{4}_{a=1} H_{a}$ (subset de ned by the imposition of constraints)

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

Group Field Theory and Loop Quantum Gravity

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

Lie algebra (metric)

$$H_{\Delta_a} = L^2(\mathrm{g})$$

Constraints

Geometricity constraints (appropriately encoded in K and V) allow for a d 1-simplicial interpretation of the fundamental quanta:

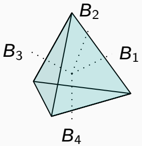
Closure

$$\sum_a B_a = 0$$

(faces of the tetrahedron close).

Simplicity

- X $(B \quad ?\, B)_a = 0$ (EPRL);
- X $B_a = 0$ (BC).



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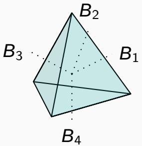

Group Field Theory and Loop Quantum Gravity

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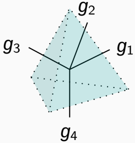

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$H_{\Delta_a} = L^2(\mathrm{g})$	Non-comm. FT	$H_{\Delta_a} = L^2(G)$	Peter-Weyl Theorem	$H_{\Delta_a} = \text{L}_{J_a} H_{J_a}$

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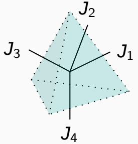

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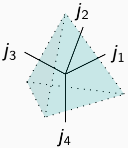

LQG

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

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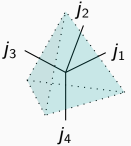

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$H_{\text{tetra}} = {}^{\text{L}}{}_{\jmath}\ \text{Inv}\ {}^{\text{N}}{}^{4}_{a=1} H_{j_a}$

= open spin-network vertex space

The Group Field Theory Fock space

Tetrahedron wavefunction

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

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Many-body → Theory

GFT field operator

$\hat{\varphi}(g_1,\ldots,g_4)$
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Oriti 1310.7786; Oriti 1408.7112; Sahlman, Sherif 2302.03612.

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

- $\mathcal{F}_{\text{GFT}}$ 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.
- Generic states do not correspond to connected simplicial lattices nor classical simplicial geometries.
- Similar to $\mathcal{H}_{\text{LQG}}$ 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:
depends on a MCMF "clock" scalar field 0
(D = minisuperspace + clock)

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

Macroscopic cosmological variables and effective relationality

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Collective Observables

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

$$\hat{N} = (\hat{\ }^{y};\hat{\ }) \qquad \hat{V} = (\hat{\ }^{y}; V[\hat{\ }])$$

$$\hat{X}^{0} = \quad \hat{\ }^{y};\;\;^{0}\,\hat{\ } \qquad \hat{\Pi}^{0} = \quad i(\hat{\ }^{y}; @_{0}\,\hat{\ })$$

I Observables $ collective operators on Fock space.

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- $h\hat{O}i_{x^0} = O[\tilde{\ }] j_{\ ^0 = x^0}$: functionals of $\tilde{\ }$ localized at x^0.

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Relationality

- Averaged evolution wrt x^0 is physical:

Intensive ⟵ $h\,\hat{}^{0}i_{x^0} \quad h\hat{X}^{0}i_{x^0} = h\hat{N}i_{x^0} \; ' \; x^0$

- Emergent effective relational description:
  - Small clock quantum fluctuations.
  - Effective Hamiltonian $H_{x^0} \; ' \; h\hat{\Pi}^{0}i_{x^0}$.

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- Observables $\leftrightarrow$ collective operators on Fock space.
- $\langle\hat{O}\rangle_{x^0} = O[\tilde{\ }]|_{^0=x^0}$: functionals of $\tilde{\ }$ localized at x^0.

Wavefunction → isotropy

$$\langle\hat{V}\rangle_{x^0} = \int \quad V_{\ } |\tilde{\ }_{\ }|^2(x^0)$$

$$\langle\hat{N}\rangle_{x^0} = \int \quad |\tilde{\ }_{\ }|^2(x^0)$$

- $= j \quad 2 \; \text{N}/2$ (EPRL);
- $= \quad 2 \; \text{R}$ (ext. BC).

Relationality

- Averaged evolution wrt x^0 is physical:

$$\langle\hat{\ }^0\rangle_{x^0} \quad \langle\hat{X}^0\rangle_{x^0} = \langle\hat{N}\rangle_{x^0} \simeq x^0$$

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