Developments in Group Field Theory Cosmology

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, . . .

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ILQGS
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Overview

- **Introduction to Group Field Theory**
  - Group Field Theory and spinfoam models
  - Group Field Theory and Loop Quantum Gravity
  - Including scalar matter
- **Group Field Theory Cosmology**
  - Basic principles
  - Homogeneous and isotropic sector
    - Volume
    - Matter
  - Inhomogeneous sector
    - First steps and limitations
    - Super-horizon limit
    - Perturbations at all scales

Introduction to Group Field Theory

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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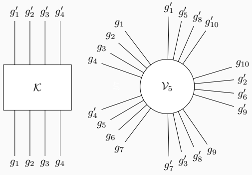
Action

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

- 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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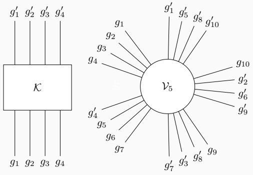

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Partition function

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

- 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.

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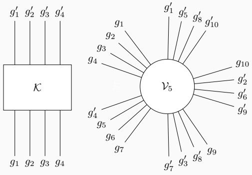

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Partition function

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

- 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.

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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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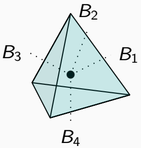

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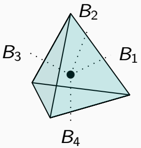

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Group Field Theory and Loop Quantum Gravity

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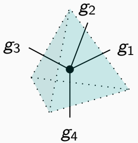

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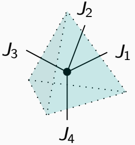

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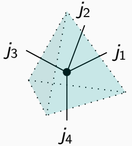

LQG

- 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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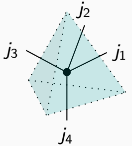

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$$\begin{aligned}\mathcal{H}_{\text{tetra}} &= \bigoplus_{\vec{j}} \text{Inv}\left[\bigotimes_{a=1}^{4} \mathcal{H}_{j_a}\right] \\ &= \text{open spin-network vertex space}\end{aligned}$$

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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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$\xrightarrow[\text{Theory}]{\text{Many-body}}$

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GFT Fock space

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

- $\mathcal{F}_{\mathrm{GFT}}$ generated by action of $\hat{\varphi}^\dagger(g_a)$ on $|0\rangle$, with $[\hat{\varphi}(g_a), \hat{\varphi}^\dagger(g'_a)] = \mathbb{I}_G(g_a, g'_a)$.
- $\mathcal{H}_\Gamma \subset \mathcal{F}_{\mathrm{GFT}}$, $\mathcal{H}_\Gamma$ space of states associated to connected simplicial complexes Γ.
- Generic states do not correspond to connected simplicial lattices nor classical simplicial geometries.
- Similar to $\mathcal{H}_{\mathrm{LQG}}$ 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.

Group Field Theory and matter: scalar fields

Group Field Theories: theories of a field $\varphi : G^d \to \mathbb{C}$ defined on the product G^d.

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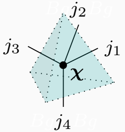
Kinematics

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

- Geometricity constraints imposed analogously as before.

$\mathcal{H}_{\text{tetra}} =$ 

Dynamics

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

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

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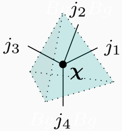
- Scalar field discretized on each d-simplex: each $d-1$-simplex composing it carries values $\boldsymbol{\chi} \in \mathbb{R}^{d_l}$.

$\mathcal{H}_{\text{tetra}} =$ 

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

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

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

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 Cosmology

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 2008.02774; LM, Oriti 2112.12677; Oriti, Sindoni, Wilson-Ewing 1602.05881; Gielen, Oriti, Sindoni 1311.1238; Gielen 1404.2944.

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Effective dynamics

Mean-field approximation

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

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

- Non-perturbative: equivalent to a mean-field (saddle-point) approximation of Z.

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Relationality

Condensate Peaked States

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

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

LM, Oriti 2008.02774; LM, Oriti 2112.12677; Oriti, Sindoni, Wilson-Ewing 1602.05881; Gielen, Oriti, Sindoni 1311.1238; Gielen 1404.2944.

Homogeneous sector

Macroscopic cosmological variables and effective relationality

Spatial relational homogeneity:
σ depends on a MCMF "clock" scalar field χ^0
($\mathcal{D} =$ minisuperspace $+$ 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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$\xrightarrow[\text{isotropy}]{\text{Wavefunction}}$

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

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

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

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Effective relational volume dynamics

Eff. dynamics

Mean-field approximation

- Mesoscopic regime: large N but negligible interactions.
- Derivative expansion of $\mathcal{K}$ (due to peaking properties).
- Isotropy: $\tilde{\sigma}_\upsilon \equiv \rho_\upsilon e^{i\theta_\upsilon}$ fundamental variables.

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

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

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Classical limit (large ρ_υs, 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.

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Scalar field with potential

Running couplings and effective potentials

- Adding a scalar field ϕ with potential U_ϕ requires (T)GFT interactions, as $\mathcal{V}_\gamma = \mathcal{V}_\gamma(\{g\}, U_\phi)$.
- Interactions studied perturbatively at late times (mesoscopic regime) and in single j approx.

Ladstätter, LM, Oriti (to appear); Oriti, Pang 2105.03751.

(T)GFT interactions and matter

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

$$\mathrm{Tr}^{(m)}_{\mathcal{V}_{\gamma_l}}[\varphi, \bar{\varphi}] \sim (\mathcal{V}^{(m)}_{\gamma_l}, \bar{\varphi}^{(l+1)/2}\varphi^{(l+1)/2})$$

✓ GR matching possible only if $l = 5$, and if

- Macroscopic constants (including G) run with relational time!

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Phantom dark energy

Emergent matter components

- Matter can also emerge as a result of pure QG effects!
- Consider modulus interactions at very late times, but include a subdominant spin j':

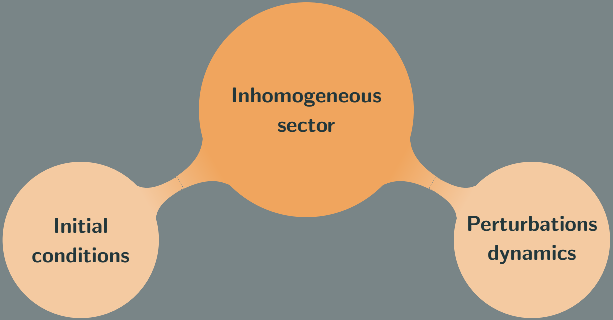
$$w = 3 - 2(VV'')/(V')^2 \simeq -1 - b/V\,, \qquad b > 0\,.$$

- Universe effectively dominated by (non-pathologic) emergent phantom dark energy.

Ladstätter, LM, Oriti (to appear); Oriti, Pang 2105.03751.

Inhomogeneous sector

Two aspects of the inhomogeneity problem



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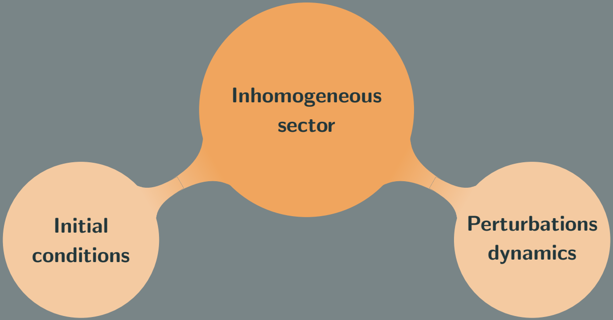

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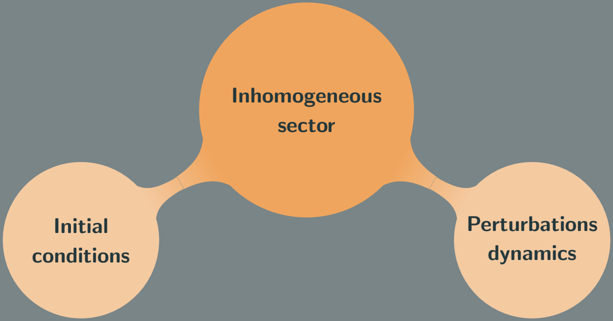

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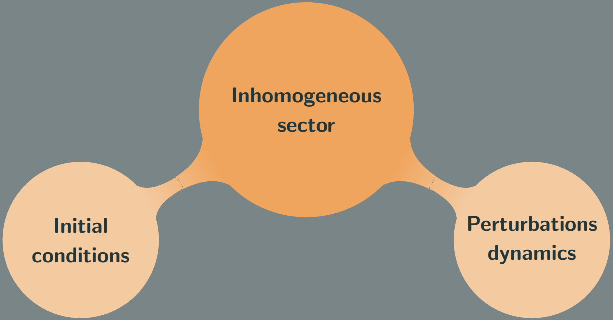

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  - First step in GFT using second moment $\delta^2 \hat{V}$.
  - What about higher moments? Is $\hat{V}$ really relational? Only a background result?

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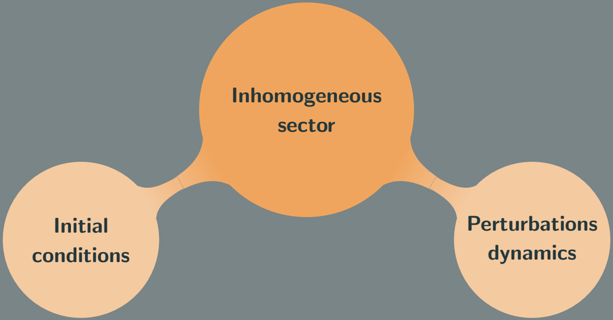

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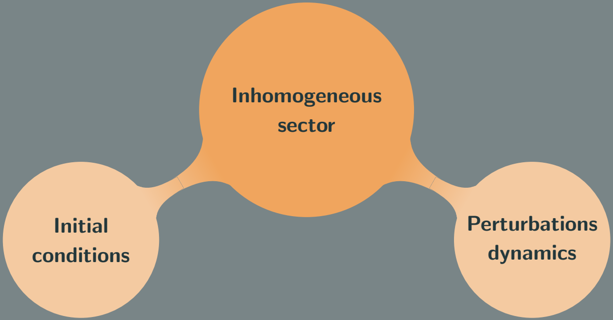

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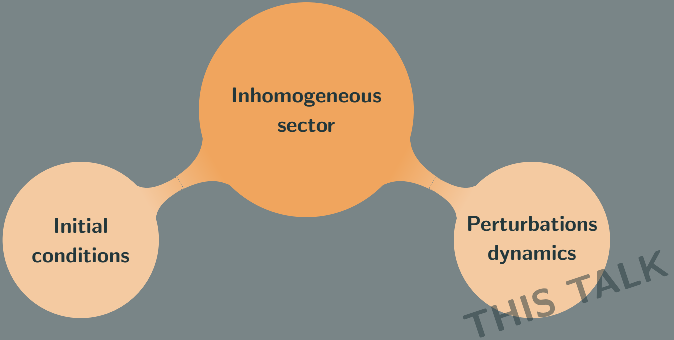

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Scalar perturbations from GFT condensates

Simplest (slightly) relationally inhomogeneous system

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

Scalar perturbations from GFT condensates

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Classical

- 4 MCMF reference fields (χ^0, χ^i), with Lorentz/Euclidean invariant S_χ in field space.
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- 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).

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

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Background

- ✓ Matching with GR possible.
- Emergent matter and G defined in terms of microscopic parameters.

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

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 ($\tilde{\sigma}=\rho e^{i\theta}$):

  $\rho=\bar{\rho}(\cdot,\chi^0)+\delta\rho(\cdot,\chi^\mu)$, $\theta=\bar{\theta}(\cdot,\chi^0)+\delta\theta(\cdot,\chi^\mu)$.

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).

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

Background

- ✓ Matching with GR possible.
- Emergent matter and G defined in terms of microscopic parameters.

Perturbations

- ✓ Super-horizon GR matching.

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

Scalar perturbations from GFT condensates

Observables

Mat. Vol. Frame

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

$$\hat{X}^\mu = (\hat{\varphi}^\dagger, \chi^\mu \hat{\varphi}) \quad \hat{\Pi}^\mu = -i(\hat{\varphi}^\dagger, \partial_\mu \hat{\varphi})$$

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

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- ✓ Matching with GR possible.
- Emergent matter and G defined in terms of microscopic parameters.

Perturbations

- ✓ Super-horizon GR matching.
- No matching for intermediate and subhorizon modes. Frame coupling issues?

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

Super-horizon scalar perturbations

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- Restrict to super-horizon modes but study also early times.

$\xrightarrow[\text{spin}]{\text{single}}$ Dynamic equations for $\langle \hat{V} \rangle_\sigma$, $\langle \hat{\Phi} \rangle_\sigma$

Bertschinger 0604485; Fischer, LM, Oriti (to appear); 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.

Super-horizon scalar perturbations

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- No matching at early times with effective GFT volume dynamics.

Perturbing background dynamics

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

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

Scalar perturbations at all scales

Complete extended BC

Causal frame fields coupling

Causal properties of frame fields can be easily implemented in the complete extended BC model.

- $\varphi_\alpha \equiv \varphi(g_a, X_\alpha, \chi^\mu, \phi)$, $g \in \mathrm{SL}(2,\mathbb{C})$, X_α tetrahedron normal defining its causal character, $\alpha = \pm$.

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

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Two-sector Fock space

- Generic operators on $\mathcal{F} = \mathcal{F}_+ \otimes \mathcal{F}_-$ correlate spacelike and timelike tetrahedra.
- Volume operator is an exception: $\hat{V} = \hat{V}_+ \otimes \mathbb{I}_-$.

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$$\mathcal{K}_+ = \mathcal{K}_+(\cdot, (\chi^0 - \chi^{0\prime})^2)\,,$$
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Collective states

Including two-body correlations

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

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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

- Mean-field equations (negligible interactions):

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

- 2 coupled eqs. for 3 variables: $(\delta\Phi, \delta\Psi, \delta\Xi)$!
- Late times and single (spacelike) rep. label.

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

Scalar perturbations at all scales

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

- Late time GR matching fixes:
  - Parameters determining τ dynamics;
  - Dynamical freedom (e.g. in $\delta\Phi$).

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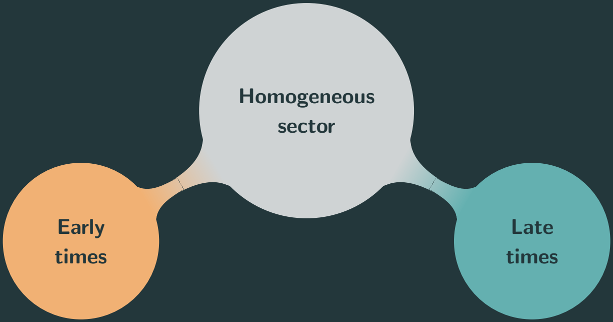
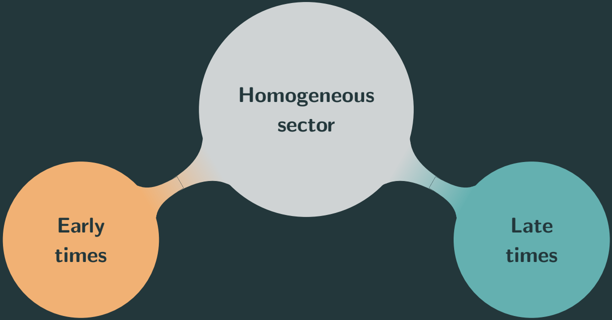
Late times volume perturbations dynamics matches GR at all scales!

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

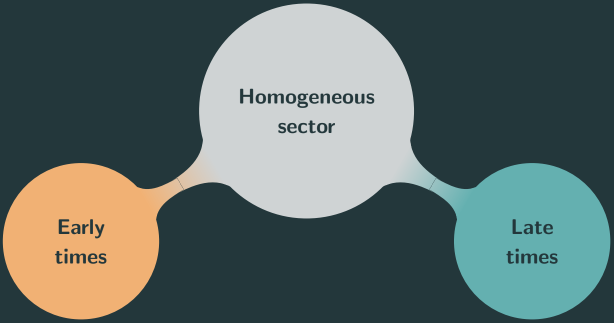

Homogeneous sector
Early times
Late times



Results

- ✓ Singularity resolution into quantum bounce.
- ✓ Universal bounce (for MCMF scalar field).
- ✓ Impact of quantum effects on the bounce (and interplay with relationality).
- ► Acceleration produced by the bounce not long enough to sustain inflation.

LM, Oriti 2008.02774 - 2010.09700; Oriti, Sindoni, Wilson-Ewing 1602.05881; Jercher, Oriti, Pithis 2112.00091;
de Cesare, Pithis, Sakellariadou 1606.00352; Ladstätter, LM, Oriti (to appear); Oriti, Pang 2105.03751; Gielen, Polaczek 1912.06143 ; . . .



Results	**Results**
✓ Singularity resolution into quantum bounce. ✓ Universal bounce (for MCMF scalar field). ✓ Impact of quantum effects on the bounce (and interplay with relationality). ► Acceleration produced by the bounce not long enough to sustain inflation.	✓ Small interactions: classical regime identified (small quantum fluctuations and GR matching). ✓ Universal classical limit (for MCMF scalar field). ✓ Inclusion of scalar field with potential: emergent running couplings. ► Exotic matter can emerge from GFT interactions.

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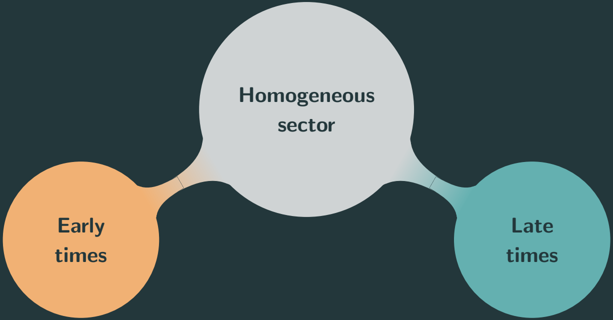
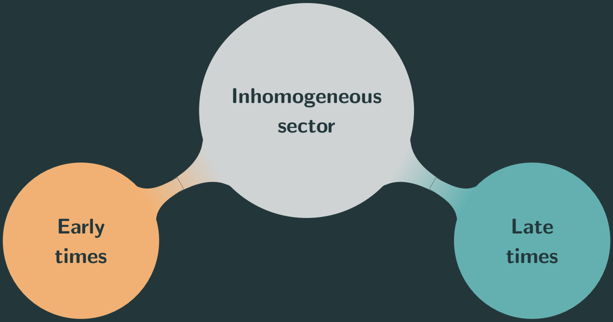


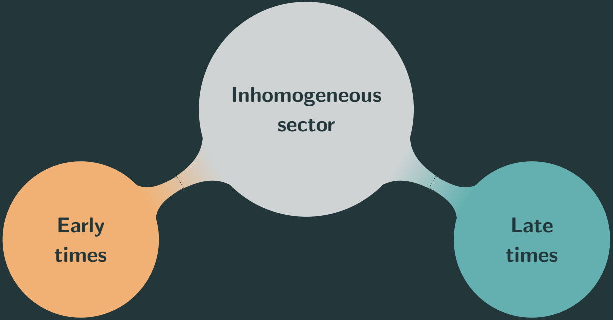
Perspectives

- Extend the analysis to more generic fluids.
- Universal bounce also for generic fluids?
- In particular, would trigonometric modifications to a scalar field potential appear at early times?
- What kind of inflationary physics is generated?

Perspectives

- Extend the analysis to more generic fluids.
- Universal classical limit also for generic fluids?
- Insights on the renormalization properties of GFTs from emergent running couplings?
- Can we rely on mean-field approx. at late times?

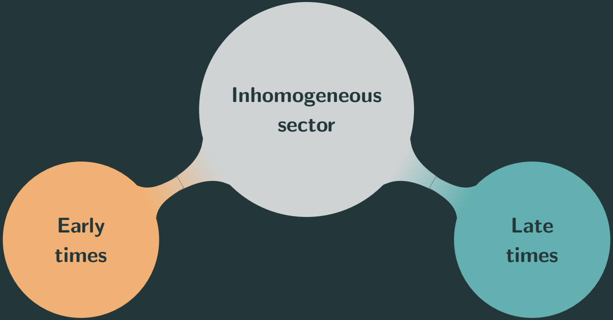

Inhomogeneous sector
Early times
Late times



Results

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

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



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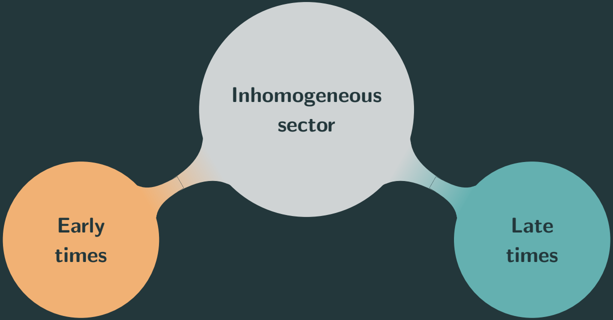
Results

- ✓ All scales analysis for complete BC model 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 scalar pert. dynamics matches GR!

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?
- Are the results universal? Analysis in BC!
- 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 interpretation and consequences of matching conditions?
- Scalar field perturbations? EFT description?
- Are the results universal? Extension to EPRL!
- Generalization to physically interesting fluids.
- Extension to VT modes: more observables!
- How do quantum perturbations classicalize?
- How do GFT interactions change the picture?

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

Backup

Specifics of GFT models

EPRL model

$$S = \sum_{\{j_a\},\{j'_a\},\{m_a\},\{m'_a\},\iota,\iota'} \bar{\varphi}^{\{j_a\}\iota}_{\{m_a\}} \varphi^{\{j'_a\}\iota'}_{\{m'_a\}} \mathcal{K}^{\{j_a\}\{j'_a\}\iota\iota'}_{\{m_a\}\{m'_a\}} + V_5\,,$$

$$V_5 = \frac{1}{5}\sum_{\{j_a\},\{m_a\},\{\iota_b\}} \varphi^{j_1j_2j_3j_4\,\iota_1}_{m_1m_2m_3m_4} \varphi^{j_4j_5j_6j_7\,\iota_2}_{-m_4m_5m_6m_7} \varphi^{j_7j_3j_8j_9\,\iota_3}_{-m_7-m_3m_8m_9} \varphi^{j_9j_6j_2j_{10}\,\iota_4}_{-m_9-m_6-m_2m_{10}} \varphi^{j_{10}j_8j_5j_1\,\iota_5}_{-m_{10}-m_8-m_5-m_1}$$
$$\times \prod_{c=1}^{10}(-1)^{j_c-m_c}\mathcal{V}_5(j_1,\dots,j_{10};\iota_1,\dots,\iota_5)\,,$$

$$a = 1,\dots,4 \qquad b = 1,\dots,5 \qquad c = 1,\dots,10$$

$$\mathcal{V}_5(\{j_c\},\{\iota_b\}) = \sum_{\{n_A\}}\int\left[\prod_A \mathrm{d}\rho_A(n_A^2+\rho_A^2)\right]\left[\bigotimes_b f^{\iota_b}_{\{n_A\}\{\rho_A\}}(\{j_a\})\right]\{15j\}_{\mathrm{SL}(2,\mathbb{C})}\,,$$

where f maps $\mathrm{SL}(2,\mathbb{C})$ data into $\mathrm{SU}(2)$ ones by imposing the constraints $n = 2j$ and $\rho = 2j\gamma$.

Extended BC model

$$S = \left[\prod_i\int \mathrm{d}\rho_i\,4\rho_i^2\sum_{j_im_i}\right]\bar{\varphi}^{\rho_i}_{j_im_i}\varphi^{\rho_i}_{j_im_i} + \frac{\lambda}{5}\left[\prod_{a=1}^{10}\int \mathrm{d}\rho_a\,4\rho_a^2\sum_{j_am_a}\right]\left[\prod_{a=1}^{10}(-1)^{-j_a-m_a}\right]\{10\rho\}_{\mathrm{BC}}$$
$$\times\,\varphi^{\rho_1\rho_2\rho_3\rho_4}_{j_1m_1j_2m_2j_3m_3j_4m_4}\varphi^{\rho_4\rho_5\rho_6\rho_7}_{j_4-m_4j_5m_5j_6m_6j_7m_7}\varphi^{\rho_7\rho_3\rho_8\rho_9}_{j_7-m_7j_3-m_3j_8m_8j_9m_9}$$
$$\times\,\varphi^{\rho_9\rho_6\rho_2\rho_{10}}_{j_9-m_9j_6-m_6j_2-m_2j_{10}m_{10}}\varphi^{\rho_{10}\rho_8\rho_5\rho_1}_{j_{10}-m_{10}j_8-m_8j_5-m_5j_1-m_1} + \text{c.c.}$$

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