# 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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# 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

**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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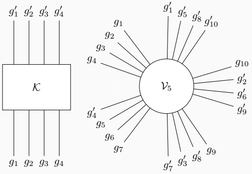
**Action**

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

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

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



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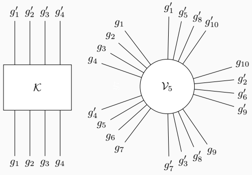


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## Partition function

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

- $\Gamma$ = stranded diagrams dual to $d$-dimensional cellular complexes of arbitrary topology.
- Amplitudes $A_\Gamma$ = sums over group theoretic data associated to the cellular complex.

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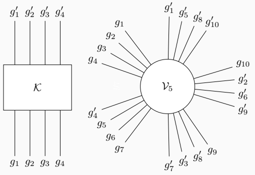


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- Amplitudes $A_\Gamma$ = sums over group theoretic data associated to the cellular complex.
- $\mathcal{K}$ and $\mathcal{V}_\gamma$ chosen to match the desired spinfoam model.


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Fundamental quanta

### 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.

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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 simplicial interpretation of the fundamental quanta:

**Closure**

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

**Simplicity**

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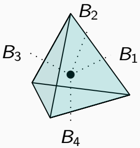


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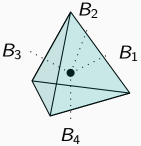


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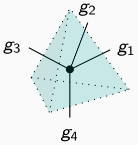


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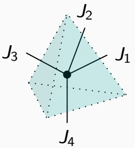


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# Group Field Theory and Loop Quantum Gravity

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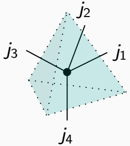


LQG

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

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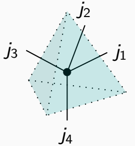


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$$\mathcal{H}_{\text{tetra}} = \bigoplus_{\vec{j}} \text{Inv}\left[\bigotimes_{a=1}^{4} \mathcal{H}_{j_a}\right]$$
$$= \text{open spin-network vertex space}$$


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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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GFT Fock space

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

- $\mathcal{F}_{\text{GFT}}$ 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 $\Gamma$.
- 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 $\hat{\varphi}$.

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## Kinematics

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

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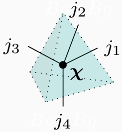
$\mathcal{H}_{\text{tetra}} =$ 


## Dynamics

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

- Geometric data enter the action 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

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

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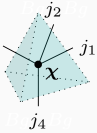
- Scalar field discretized on each $d$-simplex: each $d-1$-simplex composing it carries values $\boldsymbol{\chi} \in \mathbb{R}^{d_l}$.

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

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

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

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# 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 $\sigma$ 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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### Condensate Peaked States

- Constructing relational observables on $\mathcal{F}_{\mathrm{GFT}}$ is difficult (QFT with no continuum intuition).

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

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

Relationality

### Condensate Peaked States

- Constructing relational observables on $\mathcal{F}_{\mathrm{GFT}}$ is difficult (QFT with no continuum intuition).
- Relational localization implemented at an effective level on observable averages.
- If $\chi^\mu$ 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:**
$\sigma$ depends on a single "clock" scalar field $\chi^0$
($\mathcal{D} = \text{minisuperspace} + \text{clock}$)

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

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## Collective Observables

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

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

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

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

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## Relationality

- Averaged evolution wrt $x^0$ is physical:

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

- Emergent effective relational description:
  - Small clock quantum fluctuations.
  - Effective Hamiltonian $H_{\sigma_{x^0}} \simeq \langle \hat{\Pi}^0 \rangle_{\sigma_{x^0}}$.

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$\xrightarrow[\text{isotropy}]{\text{Wavefunction}}$

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

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

- $\upsilon = j \in \mathbb{N}/2$ (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.

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

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**Effective relational Freidmann dynamics**

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

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### Classical limit (large $\rho_\upsilon$s, late times)

- If $\mu_\upsilon^2$ is mildly dependent on $\upsilon$ (or one $\upsilon$ 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; ...

Scalar field with potential

### Running couplings and effective potentials

- Adding a scalar field $\phi$ with potential $U_\phi$ 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.

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**Modulus interactions**

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 $j'$:

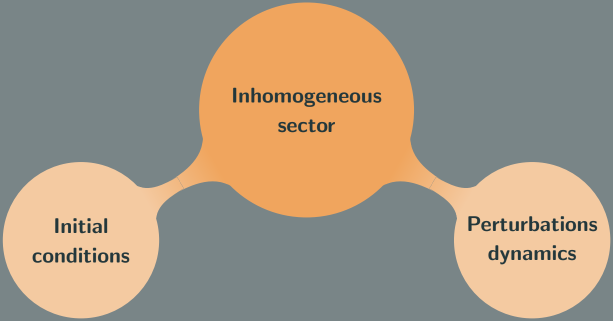
$$w = 3 - 2(VV'')/(V')^2 \simeq -1 - b/V\,, \qquad b > 0\,.$$

- 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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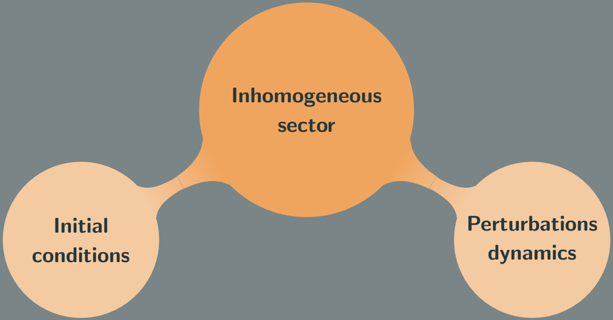


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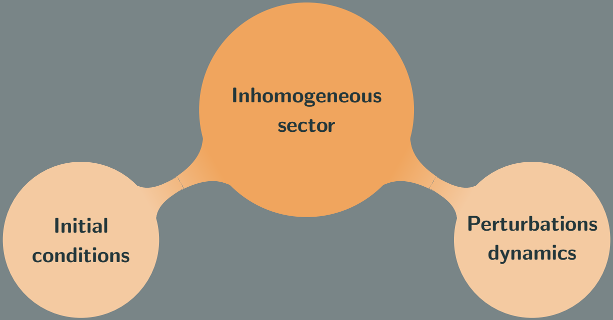


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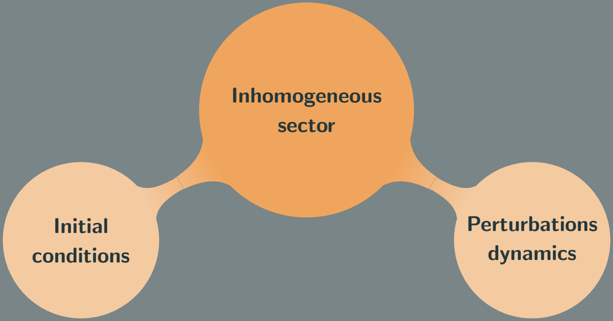


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  - What about higher moments? Is $\hat{V}$ really relational? Only a background result?

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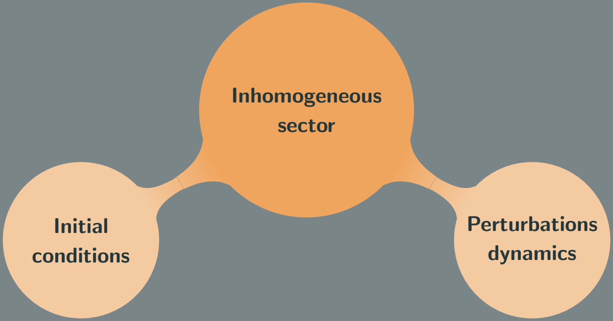


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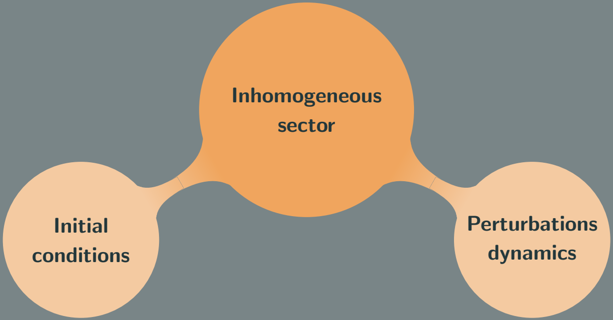


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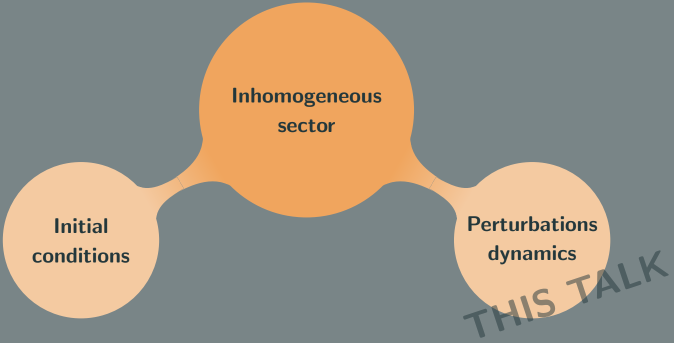


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# Scalar perturbations from GFT condensates

**Simplest (slightly) relationally inhomogeneous system**

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

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**Classical**

- 4 MCMF reference fields $(\chi^0, \chi^i)$, with Lorentz/Euclidean invariant $S_\chi$ in field space.
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**Quantum**

- GFT field: $\varphi(g_a, \chi^\mu, \phi)$, depends on 5 discretized scalar variables.
- EPRL-like model with $S_{\mathrm{GFT}}$ respecting the classical matter symmetries.

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- CPSs around $\chi^\mu = x^\mu$, with
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- Small relational $\tilde{\sigma}$-inhomogeneities ($\tilde{\sigma} = \rho e^{i\theta}$):
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**Late times volume and matter dynamics**

- Averaged q.e.o.m. (no interactions) $\longrightarrow$ coupled eqs. for $(\rho,\theta)$.
- 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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**States**

- CPSs around $\chi^\mu = x^\mu$, with
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**Late times volume and matter dynamics**

- Averaged q.e.o.m. (no interactions) $\longrightarrow$ coupled eqs. for $(\rho, \theta)$.
- 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.

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

# Scalar perturbations from GFT condensates

**Observables**

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

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**Perturbations**

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

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# Super-horizon scalar perturbations

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

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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.
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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.

**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.

Complete extended BC

## Causal frame fields coupling

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

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

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

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- 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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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.
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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.

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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 $\tau$ dynamics;
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Late times volume perturbations dynamics matches GR at all scales!

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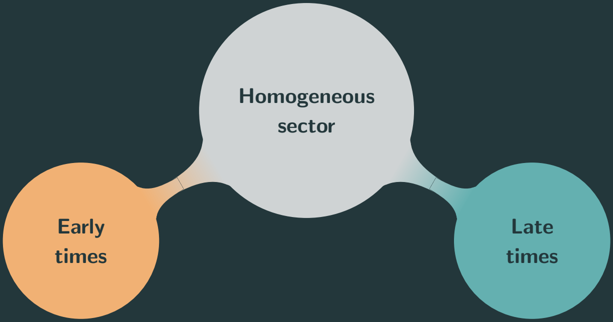
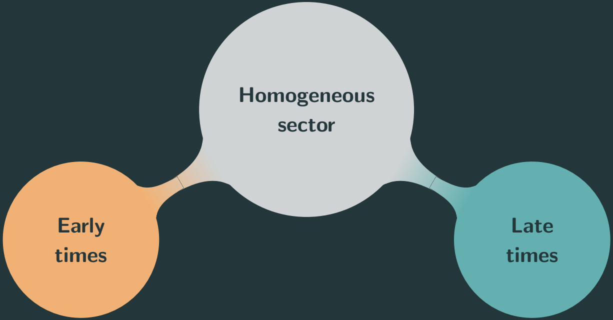

Homogeneous sector
Early times
Late times




## 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;
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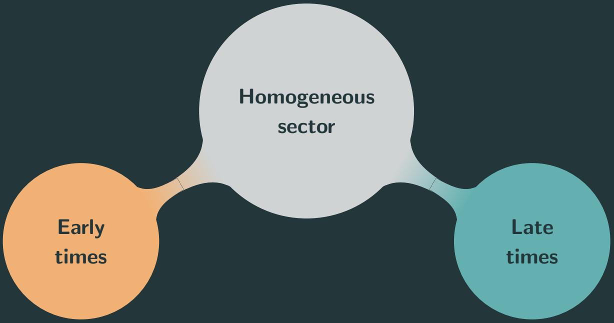


| **Results** | **Results** |
|---|---|
| ✓ Singularity resolution into quantum bounce.<br>✓ Universal bounce (for MCMF scalar field).<br>✓ Impact of quantum effects on the bounce (and interplay with relationality).<br>► Acceleration produced by the bounce not long enough to sustain inflation. | ✓ Small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

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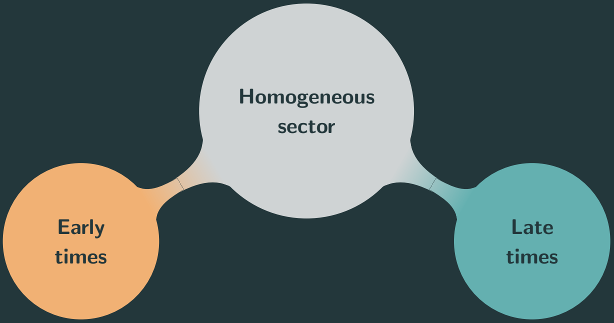
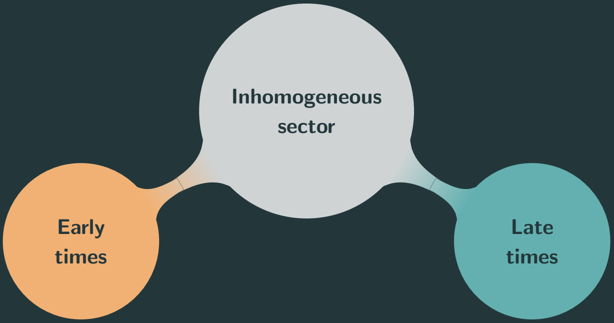



## Perspectives

- 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?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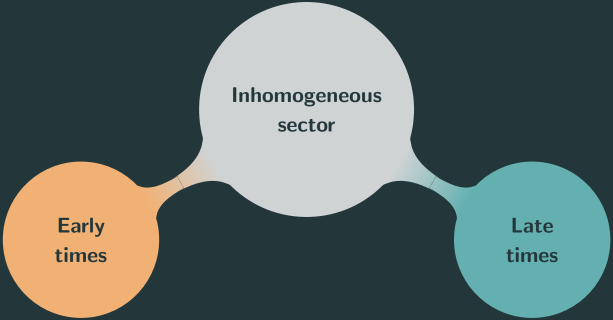


## Results

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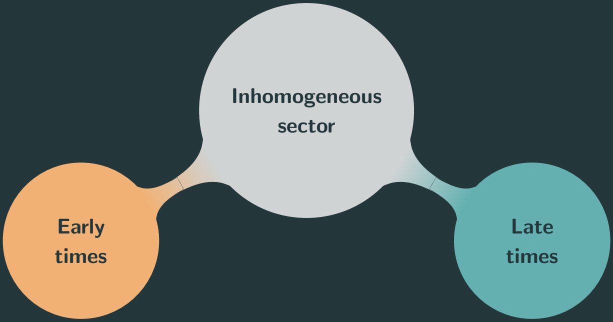


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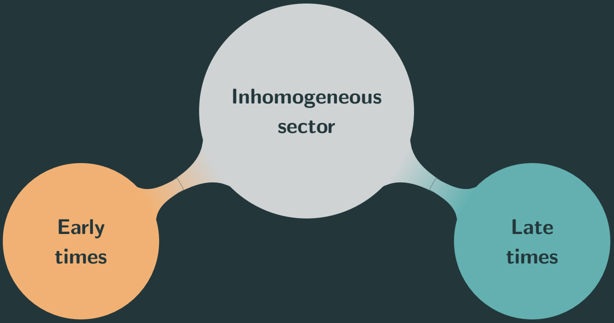
### Results

- ✓ 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**

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

$$V_5 = \frac{1}{5} \sum_{\{j_a\},\{m_a\},\{\iota_b\}} \varphi^{j_1 j_2 j_3 j_4 \iota_1}_{m_1 m_2 m_3 m_4} \varphi^{j_4 j_5 j_6 j_7 \iota_2}_{-m_4 m_5 m_6 m_7} \varphi^{j_7 j_3 j_8 j_9 \iota_3}_{-m_7 -m_3 m_8 m_9} \varphi^{j_9 j_6 j_2 j_{10} \iota_4}_{-m_9 -m_6 -m_2 m_{10}} \varphi^{j_{10} j_8 j_5 j_1 \iota_5}_{-m_{10} -m_8 -m_5 -m_1}$$
$$\times \prod_{c=1}^{10} (-1)^{j_c - m_c} \mathcal{V}_5(j_1, \ldots, j_{10}; \iota_1, \ldots, \iota_5) \,,$$

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

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

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**

$$S = \left[ \prod_i \int \mathrm{d}\rho_i \, 4\rho_i^2 \sum_{j_i m_i} \right] \bar{\varphi}^{\rho_i}_{j_i m_i} \varphi^{\rho_i}_{j_i m_i} + \frac{\lambda}{5} \left[ \prod_{a=1}^{10} \int \mathrm{d}\rho_a \, 4\rho_a^2 \sum_{j_a m_a} \right] \left[ \prod_{a=1}^{10} (-1)^{-j_a - m_a} \right] \{10\rho\}_{\mathrm{BC}}$$
$$\times \varphi^{\rho_1 \rho_2 \rho_3 \rho_4}_{j_1 m_1 j_2 m_2 j_3 m_3 j_4 m_4} \varphi^{\rho_4 \rho_5 \rho_6 \rho_7}_{j_4 -m_4 j_5 m_5 j_6 m_6 j_7 m_7} \varphi^{\rho_7 \rho_3 \rho_8 \rho_9}_{j_7 -m_7 j_3 -m_3 j_8 m_8 j_9 m_9}$$
$$\times \varphi^{\rho_9 \rho_6 \rho_2 \rho_{10}}_{j_9 -m_9 j_6 -m_6 j_2 -m_2 j_{10} m_{10}} \varphi^{\rho_{10} \rho_8 \rho_5 \rho_1}_{j_{10} -m_{10} j_8 -m_8 j_5 -m_5 j_1 -m_1} + \text{c.c.}$$

Engle, Livine, Pereira, Rovelli 0711.0146; Gielen, Oriti, Sindoni 1311.1238; Jercher, Oriti, Pithis 2112.00091.