Title: Continuum Relational Physics in Group Field Theories and Applications to Cosmology

Speakers: Luca Marchetti

Series: Quantum Gravity

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Abstract: It is a general expectation in several approaches to quantum gravity that continuum physics emerges as a macroscopic phenomenon from the collective behavior of fundamental quantum gravity degrees of freedom. However, a physical understanding of this emergence process requires us to address deeply intertwined technical and conceptual issues. In this talk, I will focus on two of them: the localization problem, related to the background independence of the underlying quantum gravity theory, and the coarse-graining problem, related to the extraction of the macroscopic, continuum physics from the microscopic, quantum-gravitational one. After discussing what strategies can be adopted in general to address these issues, I will show a concrete implementation of such strategies in the context of the group field theory approach to quantum gravity. I will then demonstrate how these strategies can be employed to extract cosmological physics from group field theories, allowing to clarify the intrinsically quantum-gravitational nature of cosmic structures and to characterize the impact of quantum gravity effects on the emergent cosmological dynamics.

Zoom link https://pitp.zoom.us/j/99070866809?pwd=Y1VGdGR5clZ0bTFwY2dBRHBwU3ptUT09

Continuum Relational Physics in Group Field Theories and Applications to Cosmology

Luca Marchetti

Quantum Gravity Group Seminars
Perimeter Institute, Waterloo
14 December 2023

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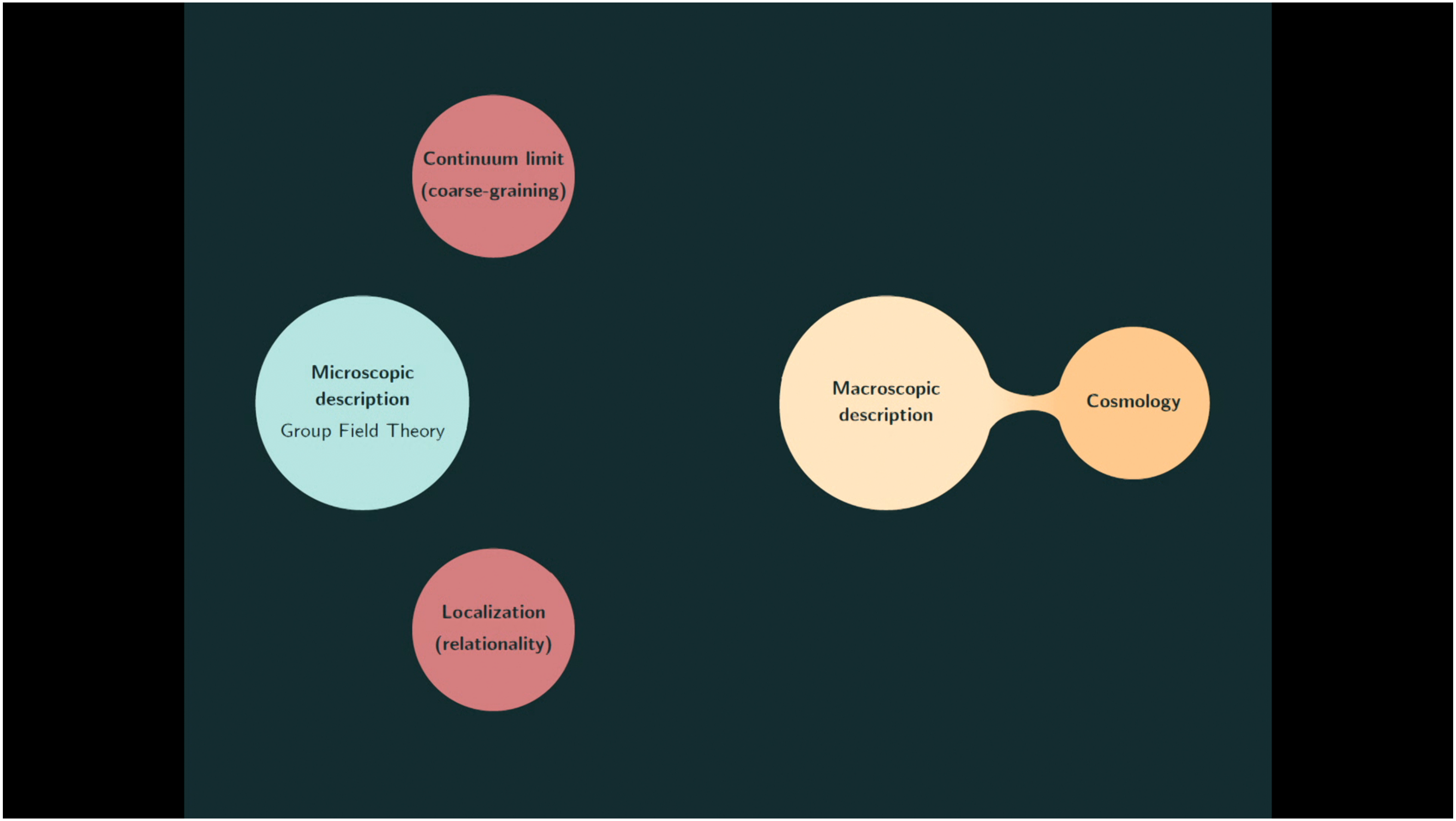
UNB Fredericton


Continuum limit
(coarse-graining)
Microscopic
description
Group Field Theory
Localization
(relationality)
Macroscopic
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Cosmology


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Introduction to GFTs

Group Field Theory and simplicial gravity

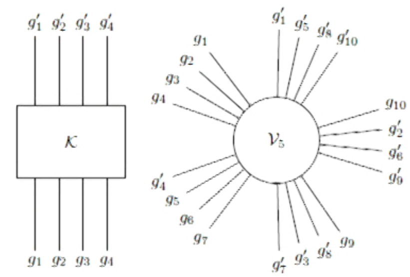
Definition

Group Field Theories: theories of a field $\varphi : G^r \to \mathbb{C}$ defined on r copies of a group manifold G.

r is the dimension of the "spacetime to be" ($r = 4$) and G is the local gauge group of gravity, $G = \mathrm{SL}(2,\mathbb{C})$ or, for some models, $G = \mathrm{SU}(2)$.

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:

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

Partition function

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

- Γ = stranded diagrams dual to r-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 spin foam model.

Oriti 1110.5606; Reisenberger, Rovelli 0002083; Freidel 0505016; Baratin, Oriti 1002.4723; Finocchiaro, Oriti 1812.03550.

Group Field Theory and Loop Quantum Gravity

Fundamental quanta

One-particle Hilbert space

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

Lie algebra (metric)		**Lie group (connection)**
$\mathcal{H}_{\Delta_a} = L^2(\mathfrak{g})$	← Non-comm. FT →	$\mathcal{H}_{\Delta_a} = L^2(G)$

Constraints

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

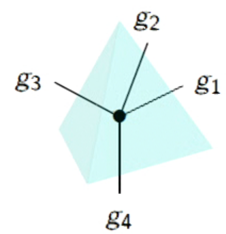
Closure

$\sum_a B_a = 0$

(faces of the tetrahedron close).

Simplicity

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



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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Lie algebra (metric)		**Lie group (connection)**		**Representation space**
$\mathcal{H}_{\Delta_a} = L^2(\mathfrak{g})$	← Non-comm. FT →	$\mathcal{H}_{\Delta_a} = L^2(G)$	← Peter-Weyl Theorem →	$\mathcal{H}_{\Delta_a} = \bigoplus_{J_a} \mathcal{H}_{J_a}$

Constraints

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

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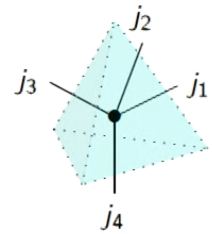


LQG

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

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

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

The Group Field Theory Fock space

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

Many-body Theory →

GFT field operator
$\hat{\varphi}(g_1, \ldots, g_4)$
(subject to constraints)

GFT Fock space

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

- $\mathcal{F}_{\mathsf{GFT}}$ generated by action of $\hat{\varphi}^\dagger(g_a)$ on $|0\rangle$, with $[\hat{\varphi}(g_a), \hat{\varphi}^\dagger(g'_a)] = \mathbb{I}_G(g_a, g'_a)$.
- $\mathcal{H}_\Gamma \subset \mathcal{F}_{\mathsf{GFT}}$, $\mathcal{H}_\Gamma$ space of states associated to connected simplicial complexes Γ.
- Generic states do not correspond to connected simplicial lattices nor classical simplicial geometries.
- Similar to $\mathcal{H}_{\mathsf{LQG}}$ but also different: no continuum intuition, orthogonality wrt nodes, not graphs.

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 $\varphi : G^r \times \mathbb{R}^{d_l} \to \mathbb{C}$ defined on the product of G^r and $\mathbb{R}^{d_l}$.

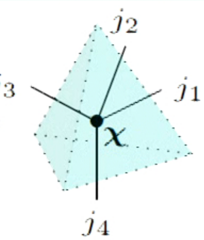
r is the dimension of the "spacetime to be" ($r = 4$) and G is the local gauge group of gravity, $G = \mathrm{SL}(2, \mathbb{C})$ or, for some models, $G = \mathrm{SU}(2)$.

Kinematics

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

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

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



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.
- 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; ...


Continuum limit
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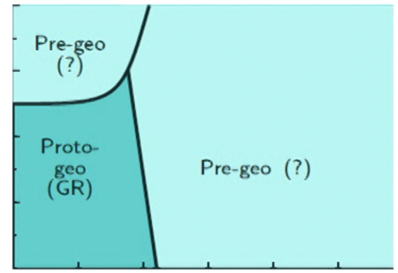
Continuum limit and localization

The continuum limit problem

Continuum physics and QG: the general perspective

Continuum limit in QG ⟷ Large number of dynamical microscopic dof.

Full partition function needed!



The (F)RG perspective

QFT on spacetime

- Energy scale defines the flow from IR and UV.

QG theory

- Only internal scales (localization problem).

UV and IR have different meaning in QG!

- Theory space constrained by symmetries.
- Symmetries of QG models hard to classify.

Little control over QG theory space!

Approximate methods

Approximate methods → Mathematical control → Physical insights → Better approximations → Approximate methods

Mean-field (saddle-point) approx. of Z.

LM, Oriti, Pithis, Thürigen 2211.12768-2209.04297-2110.15336; Oriti 2112.02585, Finocchiaro, Oriti 2004.07361; Reuter, Saueressig 2019; ...

Mean-field approximation in GFT

Local theory

Mean-field

- Mass $m^2 \equiv \mu$; interactions $\lambda\varphi^4$.
- Two different phases:

$$\frac{\delta S}{\delta\varphi} = 0 \; : \; \begin{cases} \varphi_0 = 0\,, & \mu > 0\,, \\ \varphi_0 \neq 0\,, & \mu < 0\,. \end{cases}$$

Fluctuations

- Gaussian approx.: $\varphi = \varphi_0 + \delta\varphi$.
- Correlations: $C = \langle \delta\varphi^2 \rangle$.
- Typical correlation scale ξ^2:

$$\xi^2 \to \infty \text{ as } \mu \to 0\,.$$

Conclusions

- Mean-field valid only if

$$Q = \int_{\Omega_\xi} C / \int_{\Omega_\xi} \varphi_0^2 \ll 1$$

$$Q \ll 1 \longleftrightarrow d \geq d_c = 4$$

Toy GFT

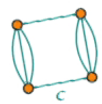
- Rank r, $G = \mathbb{R}^{d_G} \to G_L = T_L^{d_G}$.
- $L \to \infty$, $\mu \to 0$ not commuting.
- Non-local, generic interactions.

- Effective mass $b_j = \mu[1 - \mathcal{X}(j)]$.
- C expands in zero modes.
- Small ξ if $\mu \to 0$ before $L \to \infty$.

Same as FRG

$$d = d_G(r - s_0)\,,$$
$$d_c = 2n_\gamma/(n_\gamma - 2)\,.$$

melonic



$s_0 = 1$, $n_\gamma = 4$

$$\mathcal{X}(j) = 4\Big(\prod_c \delta_{j_c,0} + \prod_{b \neq c} \delta_{j_b,0} + \delta_{j_c,0}\Big)$$

Realistic GFT

- Matter (scalars): local $G_l = \mathbb{R}^{d_l}$.
- BC: $G = \mathrm{SL}(2,\mathbb{C})$+constraints.
- $0 \leq \eta < L$ & Wick rotation.

Analogous to toy GFT.

- $d = d_l + d_g(r - s_0)$.
- $d = d(\xi) \underset{\xi \to \infty}{\longrightarrow} \infty$!
- Flat limit as above.

Universal feature

Mean-field theory is always a good description of the phase transition!

LM, Oriti, Pithis, Thürigen 2211.12768-2209.04297-2110.15336.

The localization problem

Relational strategy and emergent quantum gravity theories

Background independence ⟷ **Problem of localization** ⟷ **Relational strategy**

A genuinely new dimension of the problem arises for emergent QG theories.

Microscopic pre-geo

- Fundamental d.o.f. are weakly related to spacetime quantities;
- The latter expected to emerge from the former when a continuum limit is taken.

Macroscopic proto-geo

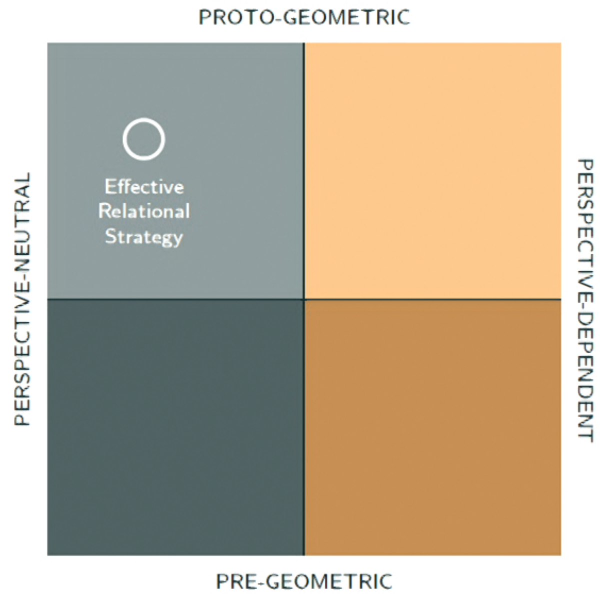
- Set of collective observables;
- Coarse grained states or probability distributions.

The quantities whose localization we want to describe relationally are the result of a coarse-graining of some fundamental d.o.f.

Deeply intertwined with continuum limit problem! Effective approaches!

LM, Oriti 2008.02774; Rovelli Class. Quantum Grav. 8 297; Dittrich 0507106; Goeller, Höhn, Kirklin 2206.01193; ...

Emergent effective relational strategy



Basic principles

Emergence Relational strategy in terms of collective observables and states.

Effectiveness Averaged relational localization. Internal frame not too quantum.

Concrete example: scalar field clock

Emergence

- Identify (collective) states $|\Psi\rangle$ admitting a continuum proto-geometric interpretation.
- Identify a set of collective observables:

$\hat{O}_a$ $\xrightarrow{\langle\cdot\rangle_\Psi}$ Geometric observables

$\hat{\chi}$ $\hat{\Pi}$ $\xrightarrow{\langle\cdot\rangle_\Psi}$ Scalar field and its momentum

$\hat{N}$ $\xrightarrow{\langle\cdot\rangle_\Psi}$ Number of quanta

Effectivness

- It exists a "Hamiltonian" $\hat{H}$ such that

$$i\frac{\mathrm{d}}{\mathrm{d}\,\langle\hat{\chi}\rangle_\Psi}\langle\hat{O}_a\rangle_\Psi = \langle[\hat{H},\hat{O}_a]\rangle_\Psi\,,$$

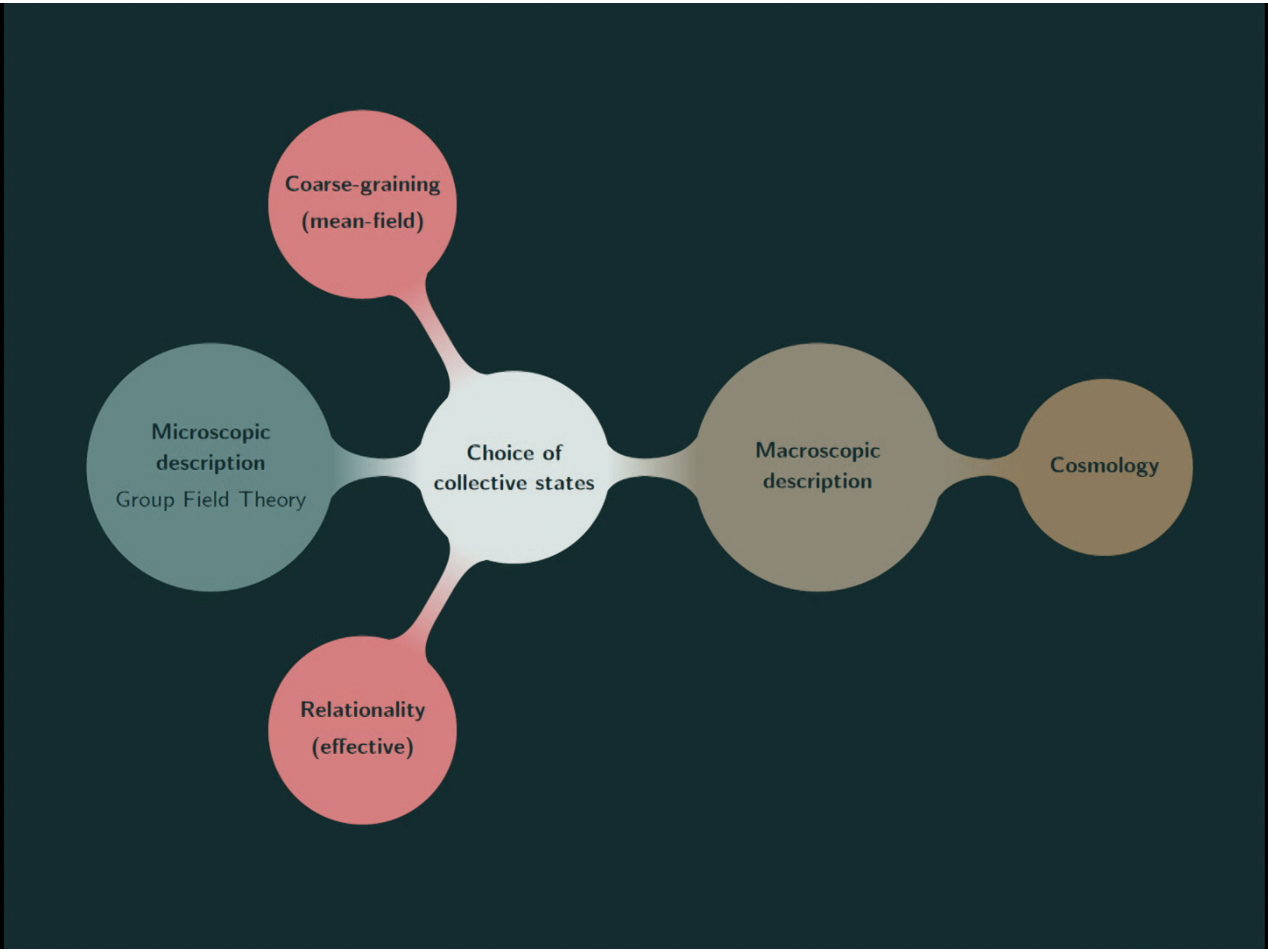
and whose moments coincide with those of $\hat{\Pi}$.

- Relative fluctuations of $\hat{\chi}$ on $|\Psi\rangle$ should be $\ll 1$.

$$\Delta^2\chi \ll 1\,, \qquad \Delta^2\chi \sim \langle\hat{N}\rangle_\Psi^{-1}\,.$$

LM, Oriti 2008.02774; Bojowald, Hoehn, Tsobanjan 1011.3040; Bojowald, Tsobanjan 0906.1772;


Coarse-graining
(mean-field)
Microscopic
description
Group Field Theory
Macroscopic
description
Cosmology
Relationality
(effective)



Coarse-graining
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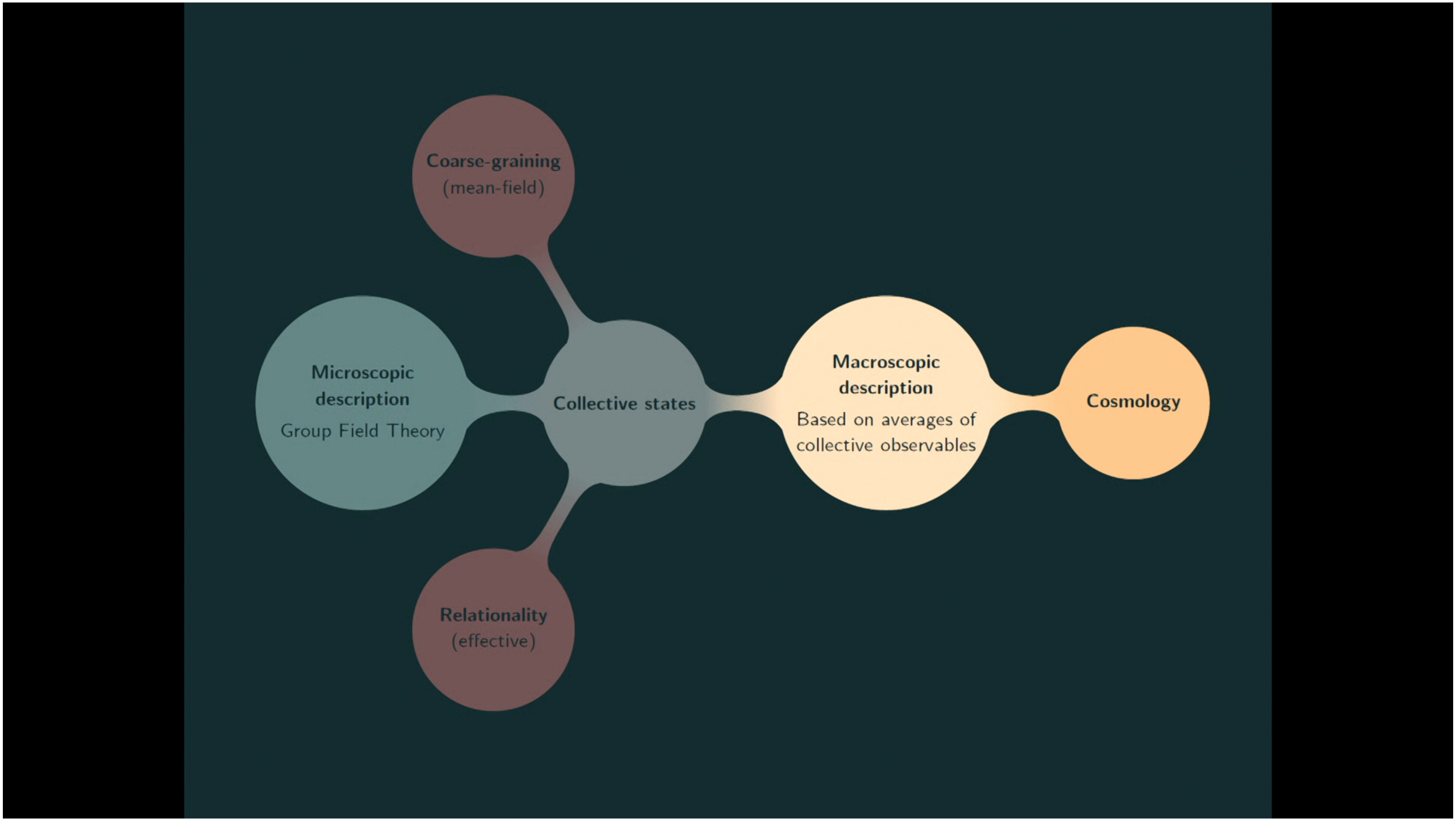
Coarse-graining
(mean-field)
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Collective states
Relationality
(effective)
Macroscopic
description
Based on averages of
collective observables
Cosmology

FLRW sector

Quantum gravity coherent states

Collective states

Coarse-graining

Localization

GFT coherent states

- From the GFT perspective, continuum geometries are associated to large number of quanta.
- The simplest states that can accommodate infinite number of quanta are coherent states:

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

Mean-field approximation

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

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

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

Relational peaking

- Relational localization implemented at an effective level on observable averages. E.g., χ^μ-frame:

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

$$\mathcal{O}(x) \equiv \langle\hat{\mathcal{O}}\rangle_{\sigma_x} \simeq \mathcal{O}[\tilde{\sigma}]|_{\chi^\mu = x^\mu} \qquad \hat{N} = \int \mathrm{d}g_a\, \mathrm{d}^4\chi^\mu\, \hat{\varphi}^\dagger(g_a,\chi^\mu)\hat{\varphi}(g_a,\chi^\mu)$$

e.g.

$$\langle\hat{\chi}^\mu\rangle_{\sigma_x} \simeq x^\mu \qquad N(x) = \int \mathrm{d}g_a\, |\tilde{\sigma}(g_a,x^\mu)|^2$$

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

Effective FLRW cosmological dynamics

Effective dynamics

Mean-field approximation

- Homogeneity: $\tilde{\sigma}$ depends only on MCMF clock χ^0.
- Isotropy: $\tilde{\sigma}_\upsilon \equiv \rho_\upsilon e^{i\theta_\upsilon}$ ($\upsilon_{\text{EPRL}} \in \mathbb{N}/2$, $\upsilon_{\text{BC}} \in \mathbb{R}$).
- Mesoscopic regime: negligible interactions.

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

$$V(x^0) = \sum_\upsilon V_\upsilon |\tilde{\sigma}_\upsilon|^2(x^0).$$

Effective volume dynamics

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

Quantum bounce

Smaller number of quanta (smaller volume and early times)

- For a large range of initial conditions (at least one $Q_\upsilon \neq 0$ or one $\mathcal{E}_\upsilon < 0$)
- Volume quantum fluctuations may be large!

Singularity res. into quantum bounce?

- x^0 may not coincide with $\langle\hat{\chi}^0\rangle_{\sigma_{x^0}}$ anymore!
- Clock quantum fluctuations may be large!
- $\langle\hat{\Pi}^0\rangle_{\sigma_{x^0}} \neq \langle\hat{H}_\sigma\rangle_{\sigma_{x^0}}$ (higher moments $\neq 0$).

Effective rel. framework may break down!

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

A state-agnostic approach

Effective approach for quantum systems

Quantum systems

Construction of the effective system

Step 1: definition of the quantum phase space

- Describe the system with $\langle \hat{A}_i \rangle$ and moments.
- Inherited Poisson structure: $\{\langle\cdot\rangle, \langle\cdot\rangle\} = (i\hbar)^{-1}\langle[\cdot,\cdot]\rangle$

Step 2: definition of the constraints

- $\langle \hat{C} \rangle = 0$ and $\langle (\widehat{\text{pol}} - \langle \widehat{\text{pol}} \rangle)\hat{C} \rangle = 0$ eff. constraints;

Step 3: truncation scheme (e.g. semiclassicality)

Relational description

Step 1: choose a clock $\hat{T}$ ($[\hat{T}, \hat{P}]$ closes)

Step 2: gauge fixing

- 1st order: $\Delta(TA_i) = 0$, $A_i \in \mathcal{A} \setminus \{\hat{P}\}$.

Step 3: relational rewriting

- Write evolution of the remaining variables wrt. T (classical clock).

How can this framework be generalized to a **field theory context**?

Infinitely many algebra generators.

Infinitely many quantum constraints.

Additional truncation scheme

Motivations

- Interest in a coarse grained system characterized by a small number of macroscopic (1-body) observables.
- Expected to be the case for cosmology.

Coarse-graining truncation

- When the e.o.m. are linear, consider an integrated 1-body quantum constraint.
- Algebra generated by minimal set of physically relevant operators (including constraint).

LM, Gielen, Oriti, Polaczek 2110.11176; Bojowald, Sandhoefer, Skirzewski, Tsobanjan 0804.3365; Bojowald Tsobanjan 0906.1772.

A state agnostic approach: application to GFT

How can this framework be generalized to a **field theory context**?

Infinitely many algebra generators. Infinitely many quantum constraints.

Additional truncation scheme

Motivations

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Coarse-graining truncation

- When the e.o.m. are linear, consider an integrated 1-body quantum constraint.
- Algebra generated by minimal set of physically relevant operators (including constraint).

Setting

GFT with MCMF scalar field

- Free e.o.m.: $\mathcal{D}\varphi \equiv (m^2 + \hbar^2\Delta_g + \lambda\hbar^2\,\partial_\chi^2)\varphi = 0$.
- Quantum constr. $\hat{C} = \int \hat{\varphi}^\dagger \mathcal{D}\hat{\varphi} = m^2\hat{N} - \hat{\Lambda} - \lambda\hat{\Pi}_2$.
- Generators: $\hat{\chi}$, $\hat{\Pi}$, $\hat{\Pi}_2$, $\hat{N}$, $\hat{\Lambda}$ and $\hat{K}$.
- $\hat{K}$ such that $[\hat{\Lambda}, \hat{K}] = i\hbar\alpha\hat{K}$.

Results

Expectation values and variances

- Choose $\hat{K}$ as clock variable.
- Relational evolution of $\langle\hat{\chi}\rangle$ in agreement with classical cosmology.
- Fluctuations are decoupled from expect. values.
- If they are small at small $\langle\hat{K}\rangle$ they stay small even at large $\langle\hat{K}\rangle$ (due to a constant $\langle\hat{N}\rangle$).

LM, Gielen, Oriti, Polaczek 2110.11176.

Inhomogeneous sector

Scalar perturbations from quantum entanglement

Setting

Classical

- 4 MCMF reference fields (χ^0, χ^i).
- 1 MCMF matter field ϕ dominating the energy-momentum budget and slightly relationally inhomogeneous wrt. χ^i.

Quantum

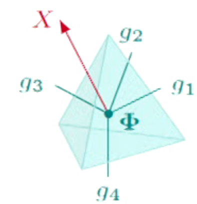
- Quanta with spacelike $(+)$ and timelike $(-)$ character to causally couple the physical frame.
- Geometry from quantum entanglement: inhomogeneities from QG correlations.

Model

Two-sector GFT

- BC model: $\varphi_\pm \equiv \varphi(g_a, X_\pm, \mathbf{\Phi})$, with $\mathbf{\Phi} = (\chi^\mu, \phi) \in \mathbb{R}^5$ and $K_{\text{GFT}} = K_+ + K_-$
- Since χ^0 (χ^i) propagates along timelike (spacelike) edges:

K_+ independent of χ^i. K_- independent of χ^0.



Collective states

Two-body correlations

notation: $(\cdot, \cdot) = \int_\Omega \mathrm{d}\Omega \cdot \times \cdot$

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

Background

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

Perturbations

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

Jercher, LM, Pithis 2310.17549-2308.13261; LM, Oriti 2112.12677; Jercher, Oriti, Pithis 2206.15442.

Emergent dynamics of cosmic inhomogeneities

E.o.m.

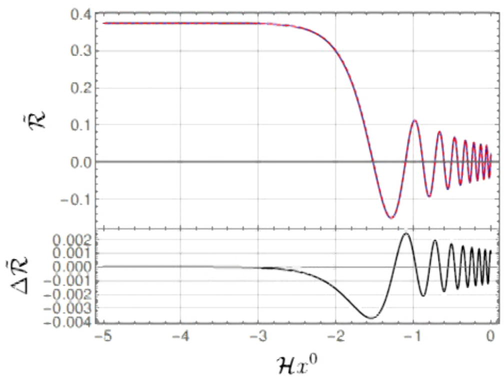
Mean-field dynamics

- 2 mean-field eqs. for 3 variables $(\delta\Phi, \delta\Psi, \delta\Xi)$:
$$\langle \delta S/\delta\hat{\varphi}_+^\dagger \rangle_\Delta = 0 = \langle \delta S/\delta\hat{\varphi}_-^\dagger \rangle_\Delta$$
- Late times and single (spacelike) rep. label.
- Physics captured by rel. localized averages:
$$\langle \hat{\mathcal{O}}_{\mathrm{GFT}} \rangle_\Delta = \bar{\mathcal{O}}_{\mathrm{GFT}}(x^0) + \delta\mathcal{O}_{\mathrm{GFT}}(x^0, \boldsymbol{x})\,.$$
- Classical limit fixes dynamical freedom.

Effective dynamics

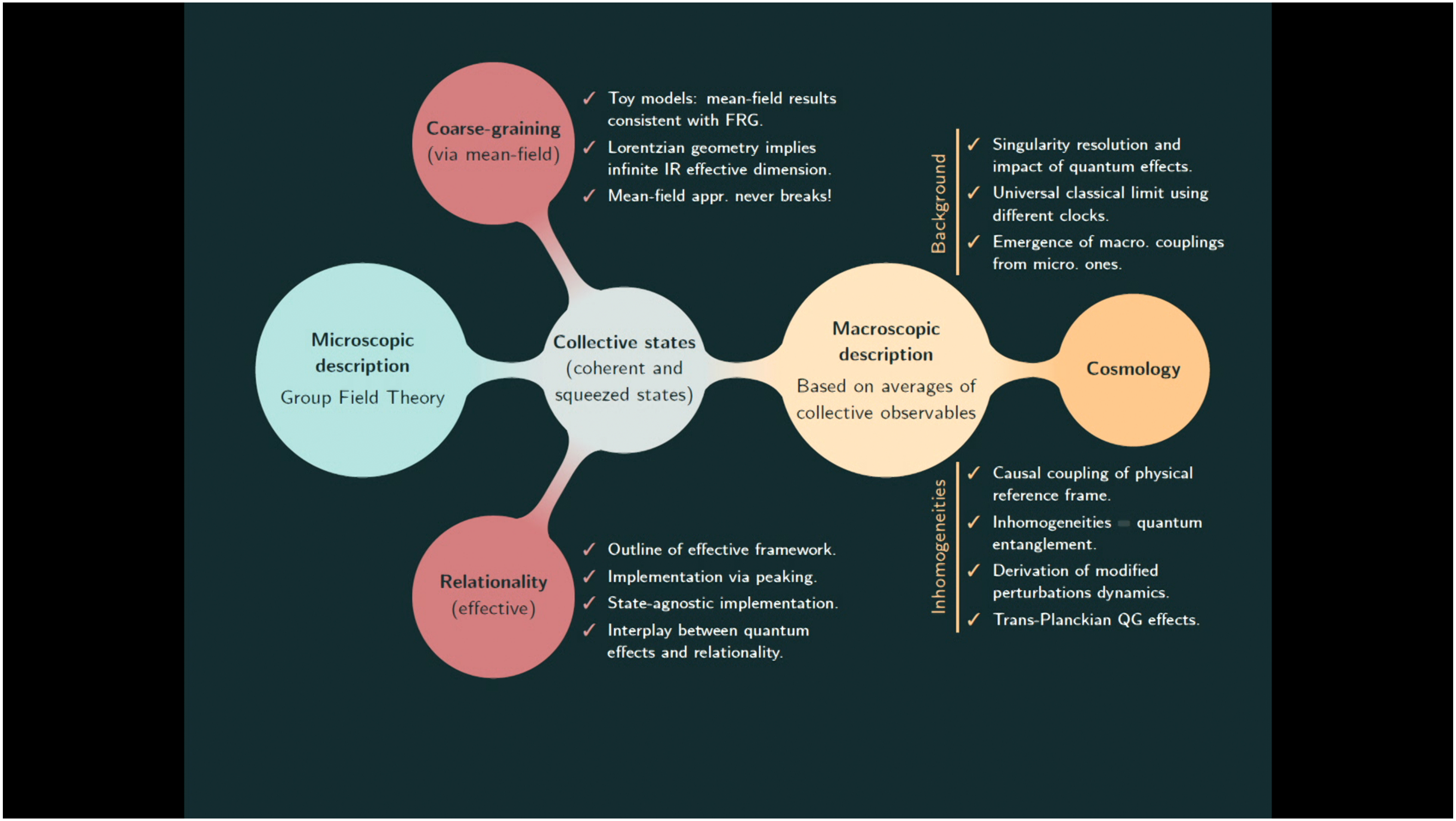
Classical dynamics with trans-Planckian QG effects

- Scalar (isotropic) perturbations dynamics from dynamics of QG correlations $(\delta\Phi, \delta\Psi, \delta\Xi)$.
- E.g.: matter $\delta\phi_{\mathrm{GFT}}$ and "curvature-like" $\tilde{\mathcal{R}}$:
$$\delta\phi''_{\mathrm{GFT}} + k^2 a^4 \delta\phi_{\mathrm{GFT}} = \left(\frac{a^2 k}{M_{\mathrm{pl}}}\right) j_\phi[\bar{\phi}]\,,$$
$$\tilde{\mathcal{R}}''_{\mathrm{GFT}} + k^2 a^4 \tilde{\mathcal{R}}_{\mathrm{GFT}} = \left(\frac{a^2 k}{M_{\mathrm{pl}}}\right) j_{\tilde{\mathcal{R}}}[\bar{\phi}]\,,$$
- Trans-Planckian QG corrections to the dynamics of scalar isotropic perturbations.
- ✓ Remarkable agreement with GR at larger scales.

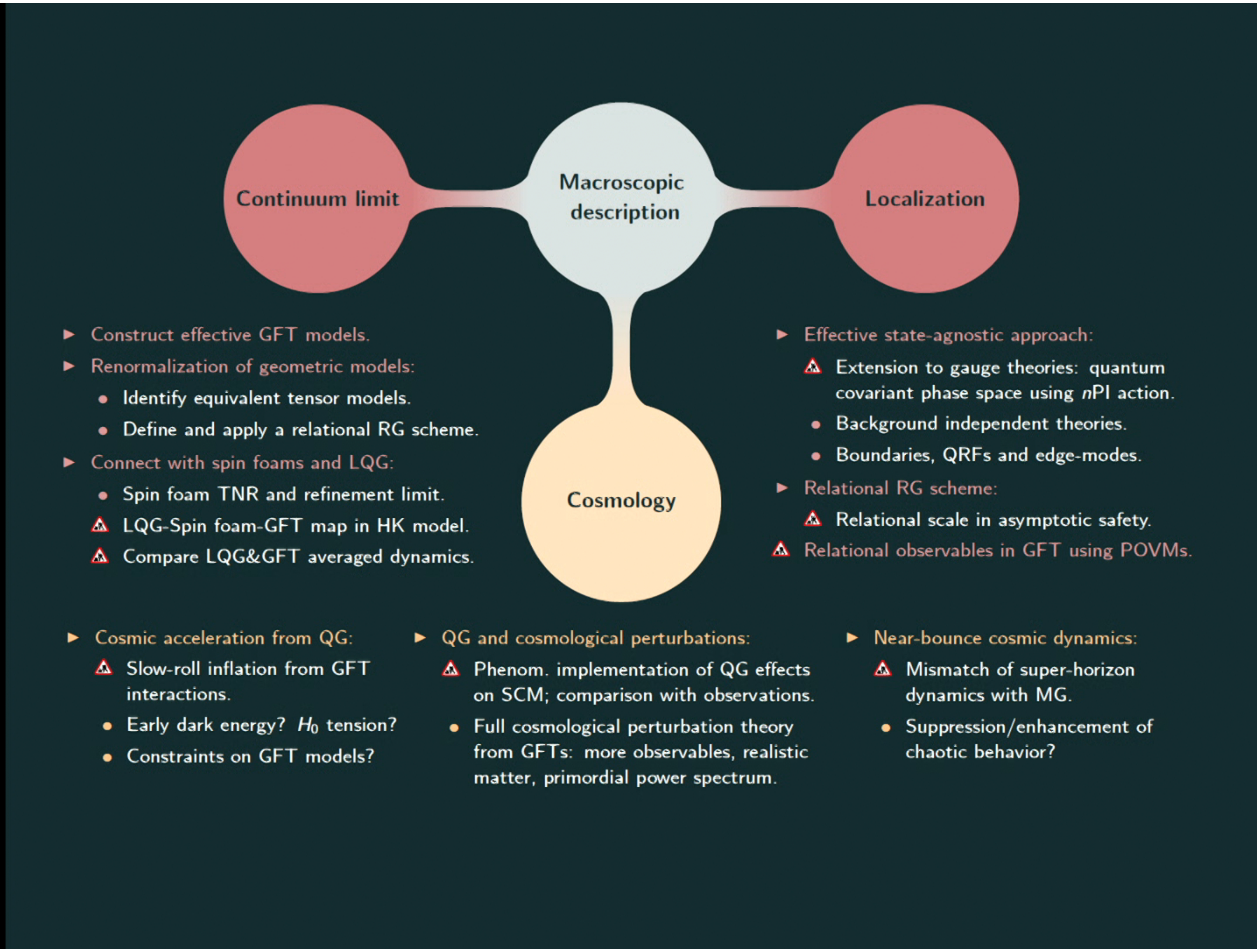


Top: $\tilde{\mathcal{R}}_{\mathrm{GFT}}$ (blue) and $\tilde{\mathcal{R}}_{\mathrm{GR}}$ (dashed red) for $k/M_{\mathrm{Pl}} = 10^2$. Bottom: their difference $\Delta\tilde{\mathcal{R}}$.

Jercher, LM, Pithis 2310.17549-2308.13261.



Coarse-graining
(via mean-field)
✓ Toy models: mean-field results consistent with FRG.
✓ Lorentzian geometry implies infinite IR effective dimension.
✓ Mean-field appr. never breaks!
Background
✓ Singularity resolution and impact of quantum effects.
✓ Universal classical limit using different clocks.
✓ Emergence of macro. couplings from micro. ones.
Microscopic description
Group Field Theory
Collective states
(coherent and squeezed states)
Macroscopic description
Based on averages of collective observables
Cosmology
Inhomogeneities
✓ Causal coupling of physical reference frame.
✓ Inhomogeneities quantum entanglement.
✓ Derivation of modified perturbations dynamics.
✓ Trans-Planckian QG effects.
Relationality
(effective)
✓ Outline of effective framework.
✓ Implementation via peaking.
✓ State-agnostic implementation.
✓ Interplay between quantum effects and relationality.



Continuum limit
Macroscopic description
Localization
Cosmology
Construct effective GFT models.
Renormalization of geometric models:
Identify equivalent tensor models.
Define and apply a relational RG scheme.
Connect with spin foams and LQG:
Spin foam TNR and refinement limit.
LQG-Spin foam-GFT map in HK model.
Compare LQG&GFT averaged dynamics.
Effective state-agnostic approach:
Extension to gauge theories: quantum covariant phase space using nPI action.
Background independent theories.
Boundaries, QRFs and edge-modes.
Relational RG scheme:
Relational scale in asymptotic safety.
Relational observables in GFT using POVMs.
Cosmic acceleration from QG:
Slow-roll inflation from GFT interactions.
Early dark energy? H_0 tension?
Constraints on GFT models?
QG and cosmological perturbations:
Phenom. implementation of QG effects on SCM; comparison with observations.
Full cosmological perturbation theory from GFTs: more observables, realistic matter, primordial power spectrum.
Near-bounce cosmic dynamics:
Mismatch of super-horizon dynamics with MG.
Suppression/enhancement of chaotic behavior?