Quantum Gravity and Emergent Cosmology: A Group Field Theory Perspective

In collaboration with: D. Oriti, E. Wilson-Ewing, S. Gielen, P. Höhn, V. Husain, A. Pithis, A. Polaczek, A. Jercher, T. Ladstätter, P. Fischer, S. Aguilar, R. Ferrero, H. Mehmood. . .

Luca Marchetti

MS and APEC seminar series

Kavli IPMU, Kashiwa-No-Ha

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Kavli IPMU

Part I

Quantum Gravity: Group Field Theories

- Group Field Theories are third quantized QG theories defined on field space, not spacetime.

A crossroads between different QG approaches

- Formally analogous to string field theories; generalized matrix and tensor models.
- Quantum amplitudes related to simplicial gravity path-integrals.
- Fock representation closely related to canonical (loop) quantum gravity.

Part II

From Quantum to Classical: Coarse-Graining and Localization

- What is local physics in QG?
- What is low-energy in QG? Or how to coarse-grain (renormalize) without energy/length scales?

Two problems, one solution

- Relational strategy: localization and coarse-graining with respect to dynamical frames.
- Realization in GFT with POVM-based QRFs, and effectively with coherent states averages.

Part III

Emergent Cosmology: Acceleration and Cosmological Perturbations

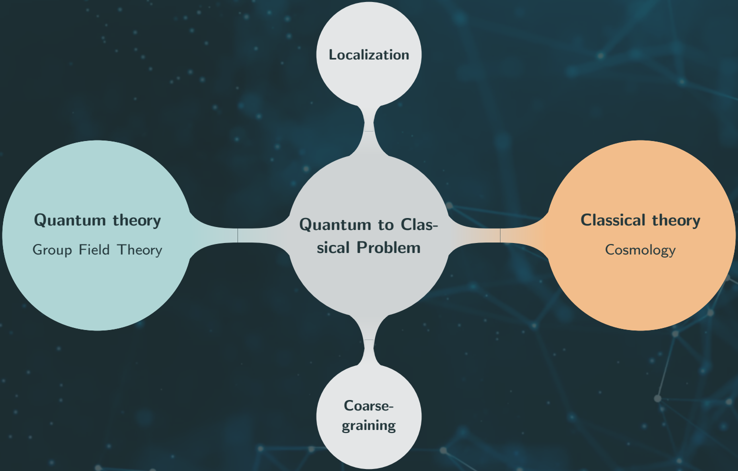
- Averaged QG dynamics and observables on cosmological coherent states (scalar field matter).

Free theory

- Hom. and isotropic sector: singularity res. and GR matching at late times.
- Perturbations emerge from entanglement, with modified trans-Planckian dynamics.

Including interactions

- Some models can produce slow-roll inflation (no inflaton needed).
- Slightly different models produce emergent evolving dark energy.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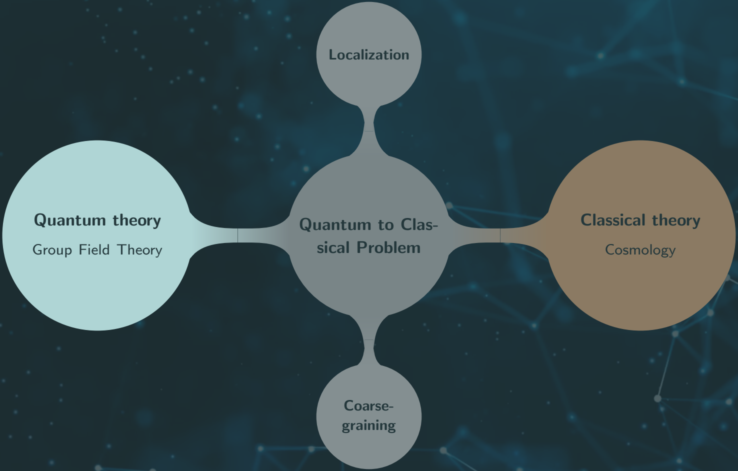
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Group Field Theory: formal definition

Definition

Group Field Theories: Third quantized QG field theory formalism.

The fundamental field $\varphi : \Omega \to \mathbb{C}$ is called "group field", while Ω is an appropriate "configuration space".

Ooguri 9205090; Oriti 1110.5606; Reisenberger, Rovelli 0002083; Freidel 0505016; Faizal, Shabir, Khan 2407.12313; Witten '85; Thorn '89.

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$$S_{\mathrm{GFT}}[\varphi] = \int \bar{\varphi} \star \mathcal{K} \star \varphi + \sum_{\gamma} \int \mathcal{V}_{\gamma} \star \left(\bigstar_{a=1}^{n_\gamma} \varphi_a \right) + \text{h.c.}$$

- $\int$ is an integral over Ω.
- $\varphi \star \psi$ non-commutative product.
- $(\mathcal{K}, \mathcal{V}_{\gamma}, \star)$ identify variables and enforce gluing.
- $S_{\mathrm{GFT}}[\varphi]$ invariant under gauge transf. $\delta\varphi = G[\varphi]$.

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EXAMPLE

$$S_{\mathrm{SFT}}[\varphi] = -\frac{1}{2} \int \varphi \star Q \varphi - \frac{g}{3} \int \bigstar_{a=1}^{3} \varphi_a$$

- Ω = space of string configurations.
- $\star$-product glues strings together.
- Gauge symmetry: $\delta\varphi = Q\Lambda - \Lambda \star \varphi + \varphi \star \Lambda$.

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Reps.

Lie algebra

$\varphi = \varphi(B)$

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Lie group	Non-comm. FT (↔)	**Lie algebra**
$\varphi = \varphi(g)$		$\varphi = \varphi(B)$

- The non-commutative FT turns $\star$-product into pointwise product in group representation.

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Lie group	Non-comm. FT	**Lie algebra**	Peter-Weyl Theorem	**Representation space**
$\varphi = \varphi(g)$	⟷	$\varphi = \varphi(B)$	⟷	$\varphi = \varphi_{\boldsymbol{\Upsilon}}$

- The non-commutative FT turns $\star$-product into pointwise product in group representation.
- If G is a product, $\varphi_{\boldsymbol{\Upsilon}} \equiv \varphi_{\boldsymbol{\upsilon}_1,\dots,\boldsymbol{\upsilon}_n}$: GFTs can be seen as generalized matrix and tensor models.

$$S = \mathrm{Tr}(M^2)/2 - g\mathrm{Tr}(M^3)/\sqrt{N}$$

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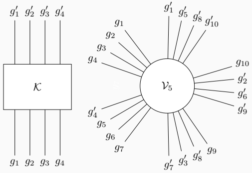
- Field arguments convoluted pairwise following the combinatorial pattern dictated by the graph γ (gluing pattern):

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



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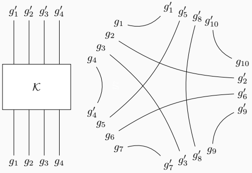

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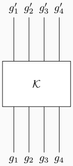

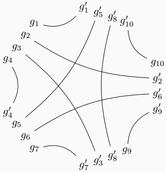

Boundary states

Geometricity conditions (imposed on φ or as a symmetry of S_{GFT}):

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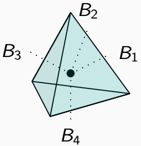

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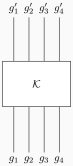

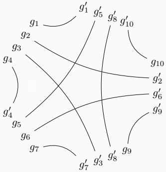

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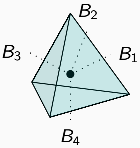

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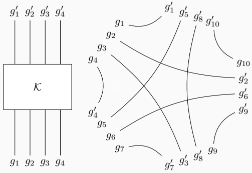

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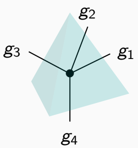

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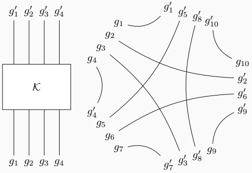

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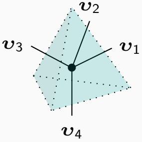
φ = tetrahedron wavefunction (or open spin-network vertex)



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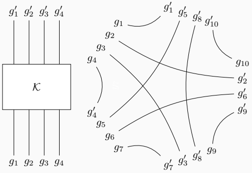

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Partition func.

$$Z[\varphi,\bar\varphi] = \sum_\Gamma w_\Gamma A_\Gamma$$

- 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 simpicial gravity model.

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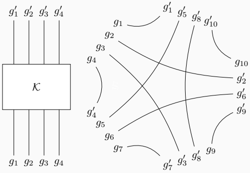

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The Group Field Theory Fock space

Tetrahedron wavefunction

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

LM, Mehmood, Husain 2412.09851; Oriti 1310.7786; Oriti 1408.7112; Sahlman, Sherif 2302.03612; Chirco et al. 1903.07344.

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Many-body → Theory

GFT field operator

$\hat{\varphi}(g_1, \ldots, g_4)$
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Many-body → Theory

GFT field operator

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

QFT of spacetime "atoms"

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
- States in $\mathcal{H}_\Gamma$ can be seen as generalized tensor network states.
- Generic states do not correspond to connected simplicial lattices, only entangled ones do!
- Similar to $\mathcal{H}_{\mathrm{LQG}}$ but also different: no continuum intuition, orthogonality wrt nodes, not graphs.

LM, Mehmood, Husain 2412.09851; Oriti 1310.7786; Oriti 1408.7112; Sahlman, Sherif 2302.03612; Chirco et al. 1903.07344.

The Group Field Theory Fock space

Tetrahedron wavefunction

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

Many-body → Theory

GFT field operator

$\hat{\varphi}(g_1, \ldots, g_4)$
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QFT of spacetime "atoms"

GFT Fock space

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

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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 $\hat{\varphi}$.

LM, Mehmood, Husain 2412.09851; Oriti 1310.7786; Oriti 1408.7112; Sahlman, Sherif 2302.03612; Chirco et al. 1903.07344.

Group Field Theory and matter: scalar fields

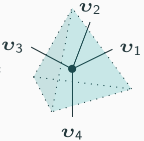
Group Field Theories: theories of a field $\varphi : G^r \to \mathbb{C}$ defined on the product G^r.

$r = 4$ is the dimension of the "spacetime to be" and G is the configuration space 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 data:

- Geometricity constraints imposed analogously as before.

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

Dynamics

S_{GFT} obtained by comparing Z_{GFT} with simplicial gravity 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

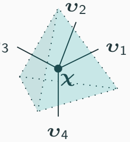
Group Field Theories: theories of a field $\varphi : G^r \times \mathbb{R}^{d_l} \to \mathbb{C}$ defined on the product of G^r and $\mathbb{R}^{d_l}$.

$r = 4$ is the dimension of the "spacetime to be" and G and $\mathbb{R}^{d_l}$ are configuration spaces of gravity + d_l scalar fields.

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

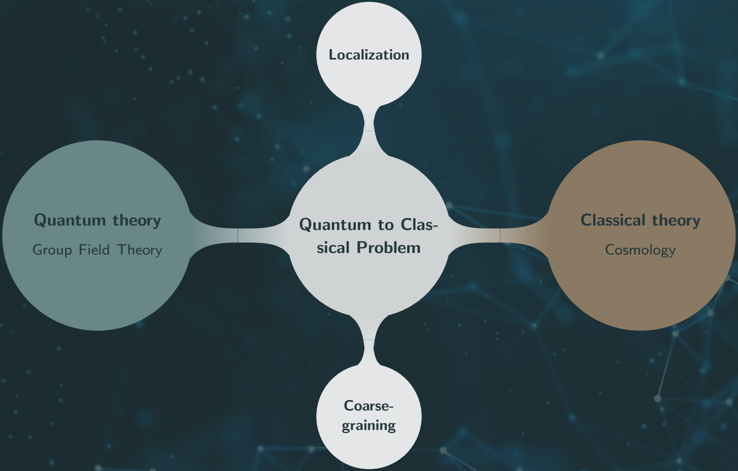
S_{GFT} obtained by comparing Z_{GFT} with simplicial gravity + scalar fields path integral.

- 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; . . .


Localization
Quantum theory
Group Field Theory
Quantum to Classical Problem
Classical theory
Cosmology
Coarse-graining

Two problems - one solution: relational physics

What is locality in QG?

How to coarse-grain in QG?

LM, Aguilar, Ferrero, Höhn (to appear), Goeller, Höhn, Kirklin 2206.01193; Rovelli '91; Dittrich 0507106; Gary, Giddings 0612191...

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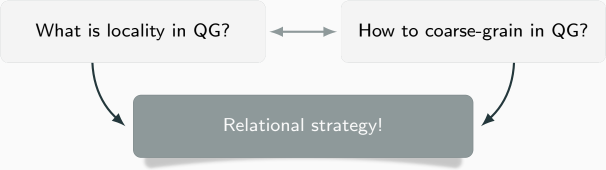

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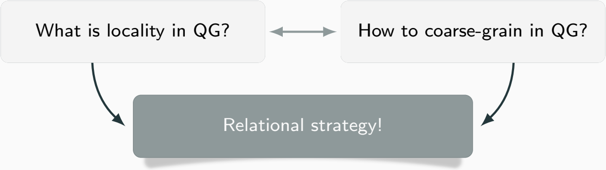

Relational locality

Background independence $\longrightarrow$ no spacetime local observables.

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Relational strategy!

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Background independence ⟶ no spacetime local observables.

- Dynamical frames $R : F \to \mathcal{M}$, $R[\phi] \mapsto f \circ R[\phi]$.
  E.g.: Geodesic frame, Brown-Kučar dust...
- Covariant obs. $A[\phi] \mapsto A[f_\star \phi] = f_\star A[\phi]$.
- Relational obs. $O_{A,R}[\phi] = (R[\phi])^\star A[\phi] \mapsto O_{A,R}[\phi]$
- $(R[\phi])^\star$: spacetime locality ⟶ frame locality.

$O_{A,R}[\phi]$ is local in frame space!

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Background independence $\longrightarrow$ ambiguous coarse-graining.

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Relational coarse-graining

Background independence $\longrightarrow$ ambiguous coarse-graining.

- Typical solutions: gauge-fixing, background field methods...
- Issues: Gribov problem, gauge-invariance only on-shell, physical meaning of RG scale...
- Solution: relational EAA $\Gamma_{k_R}[O_{\varphi,R}]$.

Flow with respect to relational RG scale!

LM, Aguilar, Ferrero, Höhn (to appear), Goeller, Höhn, Kirklin 2206.01193; Rovelli '91; Dittrich 0507106; Gary, Giddings 0612191...

Collective states

GFT coherent states

notation: $\varphi \cdot \psi = \int_\Omega \mathrm{d}\Omega \, \varphi \psi$

- From the GFT perspective, continuum geometries are associated to large number of quanta.
- Look for states that can accommodate an infinite number of quanta

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

Coarse-graining: collective states and observables

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E.g.: coherent states $|\sigma\rangle = \mathcal{N}_\sigma \exp\left[\sigma \cdot \hat{\varphi}^\dagger\right] |0\rangle$

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- GFT dynamics is captured by quantum equations of motion, or Schwinger-Dyson (SD) equations.
- Simplest SD equations are the averaged quantum equations of motion: $\langle \delta S_{\mathrm{GFT}}/\delta\hat{\varphi}^\dagger\rangle_\psi = 0$.

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

- Associate macroscopic quantities with averages $\langle\hat{\mathcal{O}}\rangle_\psi$.

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

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Relational strategy in GFT

Effective

Relational peaking

LM, Wilson-Ewing 2412.14622, LM, Oriti 2008.02774-2010.09700-2112.12677.

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- Relational localization implemented at an effective level on observable averages.

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E.g.: χ^μ frame and $|\sigma\rangle$:

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$$\mathcal{O}_\sigma(x) \equiv \langle \hat{\mathcal{O}} \rangle_{\sigma_x} \simeq \mathcal{O}[\tilde{\sigma}]|_{\chi^\mu = x^\mu}\,, \qquad \langle \hat{\chi}^\mu \rangle_{\sigma_x} \simeq x^\mu$$

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Construction in full QG

Quantum reference frames

- QRFs can be constructed in constrained QM systems in terms of covariant POVMs.
- POVMs are difficult to construct in standard QFT (measurement problem). But not in GFTs...

$$\hat{E}_{\boldsymbol{\chi}}(\mathrm{d}\boldsymbol{\chi}) = \mathrm{d}^m\chi \sum_{n=1}^{\infty} \int \left[\prod_{i=1}^{n} \mathrm{d}^m\chi_i \, \mathrm{d}^\ell\phi_i\right] \frac{1}{n} \sum_{i=1}^{n} \delta^{(m)}(\boldsymbol{\chi}_i - \boldsymbol{\chi}) \hat{F}^{(n)}(\boldsymbol{\chi}_1, \vec{\phi}_1, \dots, \boldsymbol{\chi}_n, \vec{\phi}_n)$$

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$\hat{E}_{\boldsymbol{\chi}}$ is a covariant QRF

Relational observables

$$\hat{\mathcal{O}}_{\boldsymbol{\chi}}(\mathrm{d}\boldsymbol{\chi}) \equiv \left\{ \hat{\mathcal{O}}, \hat{E}_{\boldsymbol{\chi}}(\mathrm{d}\boldsymbol{\chi}) \right\}$$

- Matches with quantum mechanical case
- Averaging over $|\sigma\rangle$ matches effective approach.

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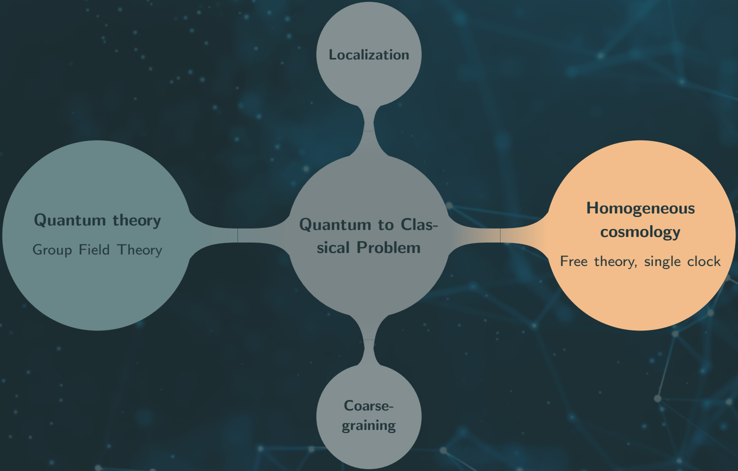
Localization
Quantum theory
Group Field Theory
Quantum to Classical Problem
Homogeneous cosmology
Free theory, single clock
Coarse-graining

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.
- V_σ increases as ρ_υ (thus N_σ) increases.

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

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LM, Oriti 2008.02774-2010.09700; Oriti, Sindoni, Wilson-Ewing 1602.05881; Jercher, Oriti, Pithis 2112.00091; Gielen, Polaczek 1912.06143.

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Effective volume dynamics

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

LM, Oriti 2008.02774-2010.09700; Oriti, Sindoni, Wilson-Ewing 1602.05881; Jercher, Oriti, Pithis 2112.00091; Gielen, Polaczek 1912.06143.

Effective FLRW cosmological dynamics

Effective dynamics

Mean-field approximation

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

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

$$V_\sigma(x^0) = \sum\!\!\!\!\!\!\int_\upsilon V_\upsilon|\tilde{\sigma}_\upsilon|^2(x^0).$$

Effective volume dynamics

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Late/early times

Large/small number of quanta

- ✓ Volume quantum fluctuations under control.
- ✓ If one υ_o is dominating and $\mu^2_{\upsilon_o} = 3\pi G$, GR matching in harmonic gauge:

$(V'_\sigma/3V_\sigma)^2 \simeq 4\pi G/3$ ⟶ flat FLRW

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

Singularity res. into quantum bounce!

LM, Oriti 2008.02774-2010.09700; Oriti, Sindoni, Wilson-Ewing 1602.05881; Jercher, Oriti, Pithis 2112.00091; Gielen, Polaczek 1912.06143.

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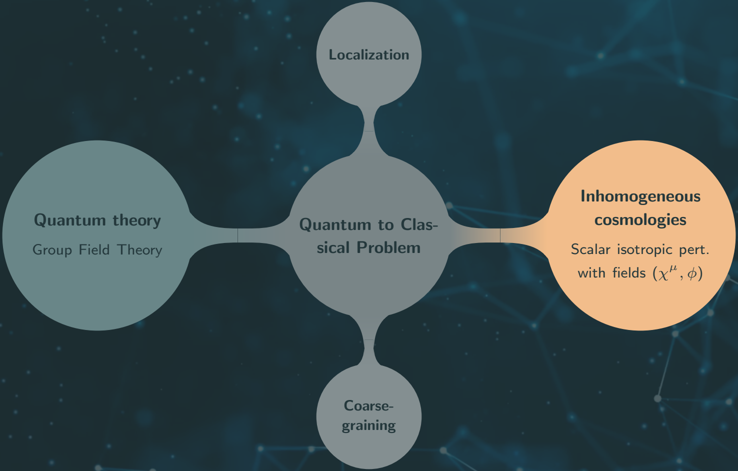
- For a large range of initial conditions (at least one $Q_\upsilon \neq 0$ or one $\mathcal{E}_\upsilon < 0$)
- Volume quantum fluctuations may be large!

Singularity res. into quantum bounce!*

LM, Oriti 2008.02774-2010.09700; Oriti, Sindoni, Wilson-Ewing 1602.05881; Jercher, Oriti, Pithis 2112.00091; Gielen, Polaczek 1912.06143.


Localization
Quantum theory
Group Field Theory
Quantum to Classical Problem
Inhomogeneous cosmologies
Scalar isotropic pert. with fields (χ^μ, ϕ)
Coarse-graining

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.

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

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

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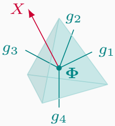
Model

Two-sector GFT

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

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



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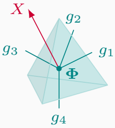

Collective states

Two-body correlations

notation: $(\varphi, \psi) = \int_\Omega \mathrm{d}\Omega \varphi\psi$

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

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

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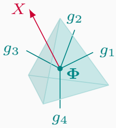

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Background

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

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

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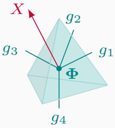

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Perturbations

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

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

E.o.m.

Mean-field dynamics

- 2 mean-field eqs. for 3 variables $(\delta\Phi, \delta\Psi, \delta\Xi)$:

$$\langle \delta S_{\text{GFT}}/\delta\hat{\varphi}_{+}^{\dagger}\rangle_{\Delta} = 0 = \langle \delta S_{\text{GFT}}/\delta\hat{\varphi}_{-}^{\dagger}\rangle_{\Delta}$$

- Free theory, late times and single rep. label.

Jercher, LM, Pithis 2310.17549-2308.13261.

Emergent dynamics of cosmic inhomogeneities

E.o.m.

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- Free theory, late times and single rep. label.
- Physics captured by rel. localized averages:
$$\langle \hat{\mathcal{O}}_{\rm GFT} \rangle_\Delta = \bar{\mathcal{O}}_{\rm GFT}(x^0) + \delta\mathcal{O}_{\rm GFT}(x^0, \boldsymbol{x})\,.$$
- Classical limit fixes dynamical freedom.

Jercher, LM, Pithis 2310.17549-2308.13261.

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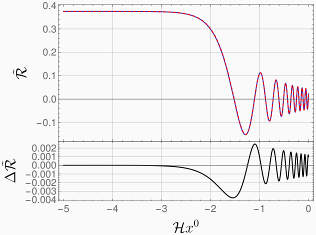
Effective dynamics

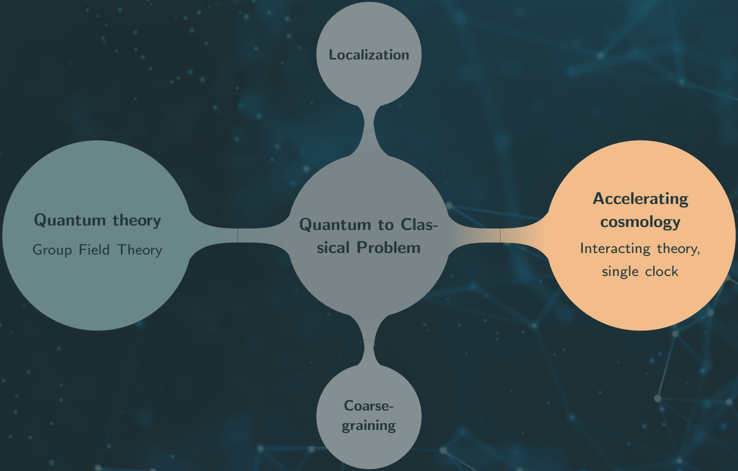
Classical dynamics with trans-Planckian QG effects

- 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.


Localization
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Quantum to Classical Problem
Accelerating cosmology
Interacting theory, single clock
Coarse-graining

Emergent evolving dark energy

Pseudotensorial

Emergent cosmological components

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

- Highly symmetric, studied in renormalization.

Ladstätter, LM, Oriti (to appear); de Cesare, Pithis, Sakellariadou 1606.00352; Oriti, Pang 2105.03751; De Sousa, Barrau, Martineau 2305.05438.

Pseudotensorial

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$$\rho_\upsilon'' - E_\upsilon^2 \rho_\upsilon - \lambda_\upsilon \rho_\upsilon' = 0$$

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- Assume dominating interactions (true eventually).

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$\rho'_{\upsilon_o} \propto \rho^{l+1}_{\upsilon_o}$: l specifies emergent matter!

w	l
-1	5
0	3
1	1
1/3	7/2

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$$\mathrm{Tr}^{(s)}_{\mathcal{V}_{\gamma_l}}[\varphi, \bar{\varphi}] \sim \mathcal{V}^{(s)}_{\gamma_l} \cdot \varphi^{(l+1)} + \text{c.c}$$

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Pseudosimplicial

Evolving dark energy

$$\rho_\upsilon'' - [(\theta_\upsilon')^2 + E_\upsilon^2]\rho_\upsilon - \lambda_\upsilon \cos\vartheta_\upsilon \rho_\upsilon'^{l} = 0$$

$$\rho_\upsilon \theta_\upsilon'' + 2\rho_\upsilon' \theta_\upsilon' - \lambda_\upsilon \sin\vartheta_\upsilon \rho_\upsilon'^{l} = 0$$

- More physically motivated interactions are less symmetric.
- Both phase and modulus dependence after σ-isotropy.
- $\vartheta_\upsilon = \varphi_\upsilon - (l+1)\theta_\upsilon$.

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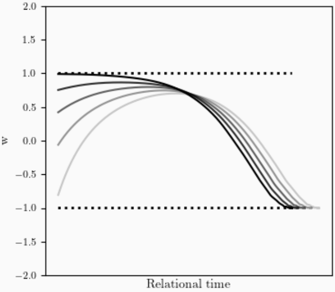
Emergent evolving dark energy!



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Emergent inflation

Pseudosimplicial

Phenomenological models and inflation

- Rich phenom.: $l = 5$, $\vartheta_\upsilon = \varphi_\upsilon + (l+1)\theta_\upsilon$.
- dS is not an attractor anymore: ϑ_υ runs away from $\vartheta = 0$!

Ladstätter, LM, Oriti (to appear); Mukhanov 1409.2335.

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Pseudosimplicial

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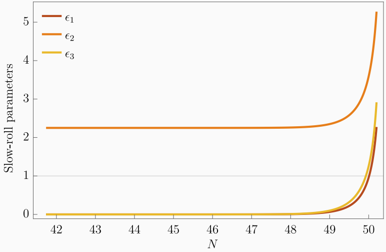
Emergent inflation!

- Long-lasting accel.: $N_{\text{end}} \gg 1$ if $\vartheta_{\upsilon,\text{in}} \simeq 0$.
- Almost slow-roll: $\epsilon_{1,3} \ll 1$ during inflation.
- Post-inflation $w = 1$ on average.



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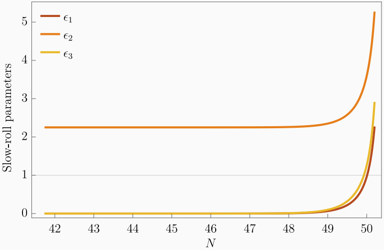

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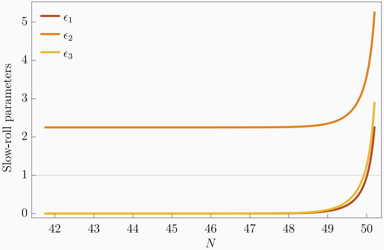
Pseudosimplicial

Phenomenological models and inflation

- Rich phenom.: $I=5$, $\vartheta_\upsilon = \varphi_\upsilon + (I+1)\theta_\upsilon$.
- dS is not an attractor anymore: ϑ_υ runs away from $\vartheta = 0$!

Emergent inflation!*

- Long-lasting accel.: $N_{\text{end}} \gg 1$ if $\vartheta_{\upsilon,\text{in}} \simeq 0$.
- Almost slow-roll: $\epsilon_{1,3} \ll 1$ during inflation.
- Post-inflation $w = 1$ on average.



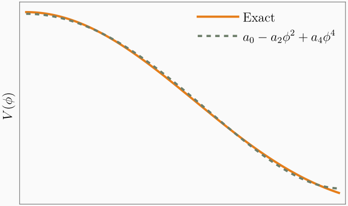
Inflaton description

Effective single-field inflation

- One can construct a ϕ with potential $V(\phi)$ driving the inflationary dynamics $\epsilon_1(N)$.

GFT inflation can be effectively described as standard single field inflation.

- No analytic form for $V(\phi)$, but numerically well approximated by a Mexican-hat potential.



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Part I

Quantum Gravity: Group Field Theories

- Group Field Theories are third quantized QG theories defined on field space, not spacetime.

A crossroads between different QG approaches

- Formally analogous to string field theories; generalized matrix and tensor models.
- Quantum amplitudes related to simplicial gravity path-integrals.
- Fock representation closely related to canonical (loop) quantum gravity.

Part II

From Quantum to Classical: Coarse-Graining and Localization

- What is local physics in QG??
- What is low-energy in QG? Or how to coarse-grain (renormalize) without energy/length scales?

Two problems, one solution

- Relational strategy: localization and coarse-graining with respect to dynamical frames.
- Realization in GFT with POVM-based QRFs, and effectively with coherent states averages.

Part III

Emergent Cosmology: Acceleration and Cosmological Perturbations

- Averaged QG dynamics and observables on cosmological coherent states (scalar field matter).

Free theory

- Hom. and isotropic sector: singularity res. and GR matching at late times.
- Perturbations emerge from entanglement, with modified trans-Planckian dynamics.

Including interactions

- Some models can produce slow-roll inflation (no inflaton needed).
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More examples

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More realistic matter

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Phenomenological consequences?