Cosmic Emergence in Quantum Gravity

Luca Marchetti

Cosmology and Quantum Gravity Beyond Spacetime
University of Western Ontario, London
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Department of Mathematics and Statistics
UNB Fredericton

Microscopic description

Background independent, pre-geometric

Macroscopic description

Cosmology

Geometries that are

- smooth;
- almost spatially homogeneous and isotropic;
- time-dependent.

Continuum limit problem

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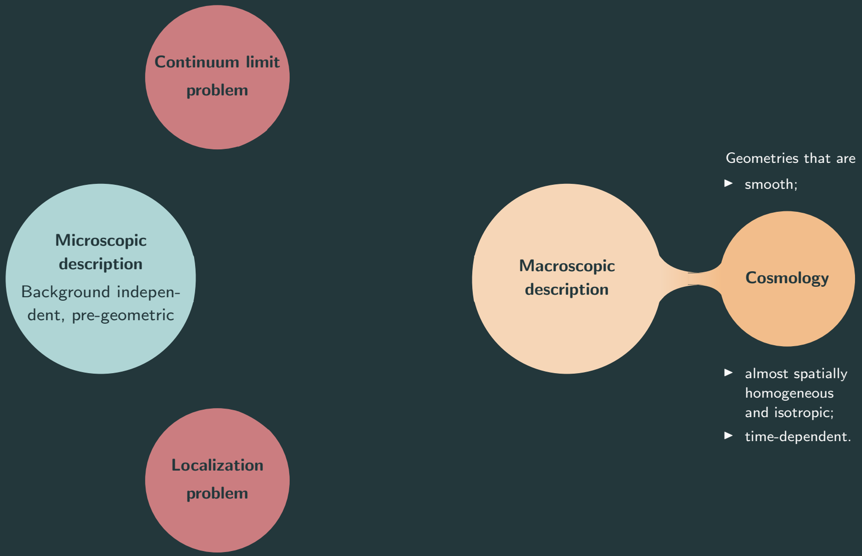
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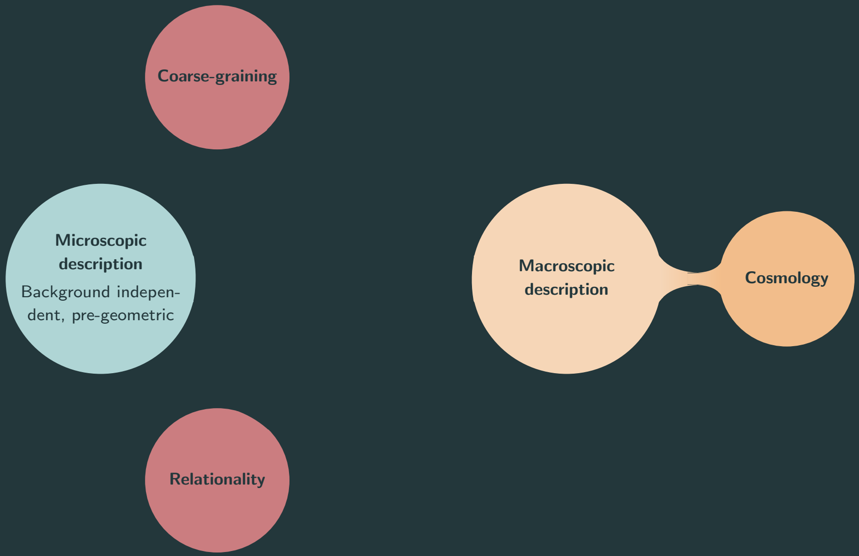
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Relationality
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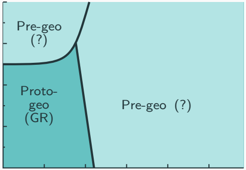
The continuum limit problem

Continuum physics and QG: the general perspective

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

Full partition function needed!



LM, Oriti, Pithis, Thürigen 2211.12768-2209.04297-2110.15336; Oriti 2112.02585, Reuter, Saueressig 2019, Kopietz et al. 2010, Finocchiaro, ...

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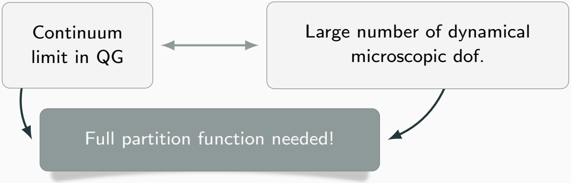

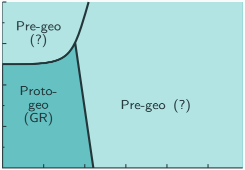

The (F)RG perspective

QFT on spacetime

- Energy scale defines the flow from IR and UV.

QG theory

- Only internal "timeless" scales available.

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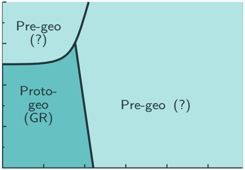

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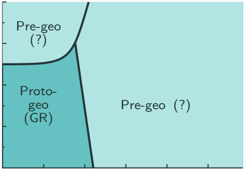

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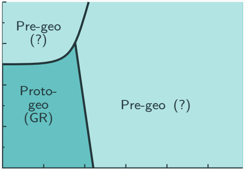

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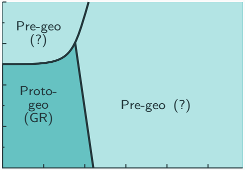

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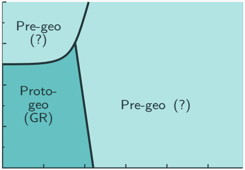

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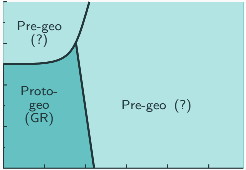

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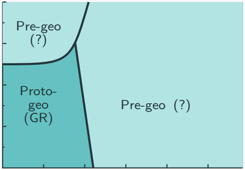

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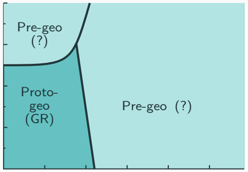

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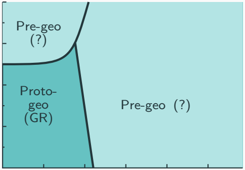

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Mean-field (saddle-point) approx. of Z.

The localization problem

Relational strategy: the classical and quantum GR perspective

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

Quite well understood from a classical perspective, less from a quantum perspective.

Isham 9210011; Rovelli Class. Quantum Grav. 8 297; Dittrich 0507106; Hoehn et al. 1912.00033 and 2007.00580; Tambornino 1109.0740; ...

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Classical

Physical localization via relational observables:

- Take two phase space functions, f and T with $\{T, C_H\} \neq 0$ (T relational clock).
- The relational extension $F_{f,T}(\tau)$ of f encodes the value of f when T reads τ.
- Evolution in τ is relational.
- $F_{f,T}(\tau)$ is a very complicated function.
- Applications almost only for very simple systems.

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Dirac approach: Quantize first.

- Perspective neutral.
- Poor control of the physical Hilbert space.

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Reduced approach: Relationality first.

- No quantum constraint to solve.
- Not perspective neutral. Too complicated to implement in most of the cases.

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Relational strategy and emergent quantum gravity theories

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

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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.

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Effective approaches:

- More mathematical control and physical insights.
- Relevant for observative purposes.

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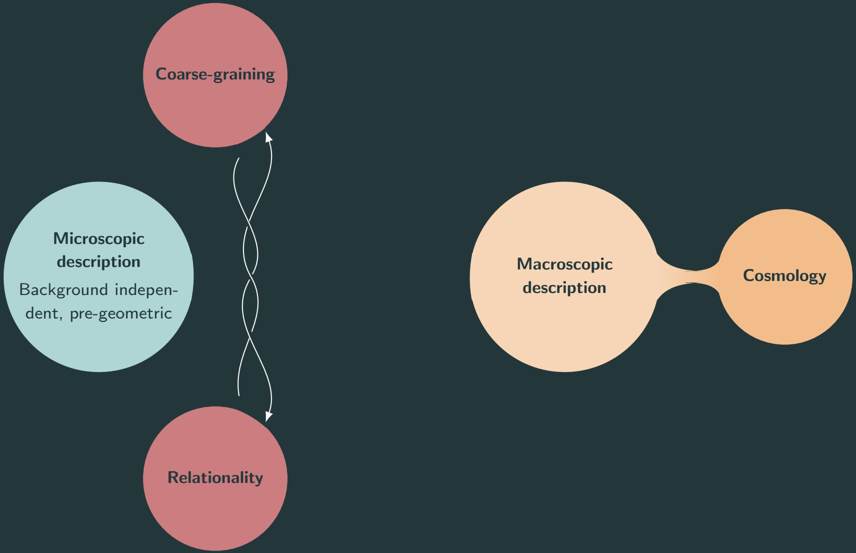
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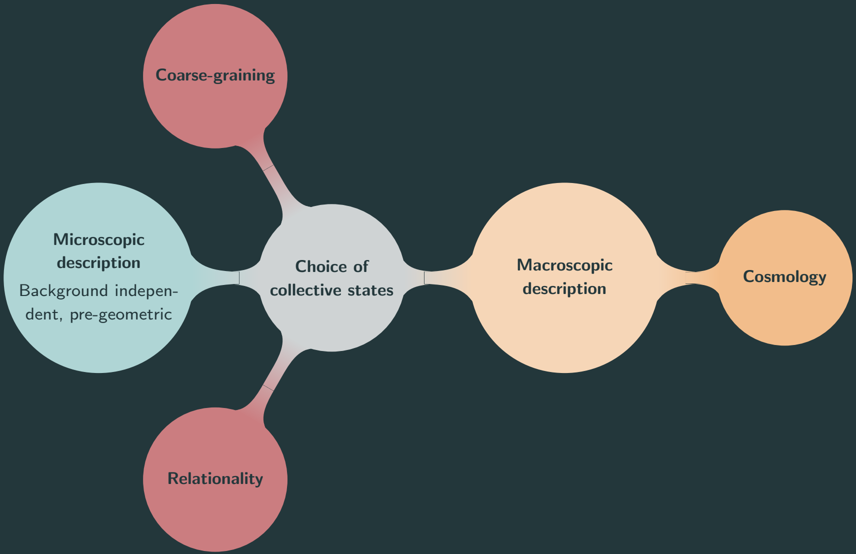
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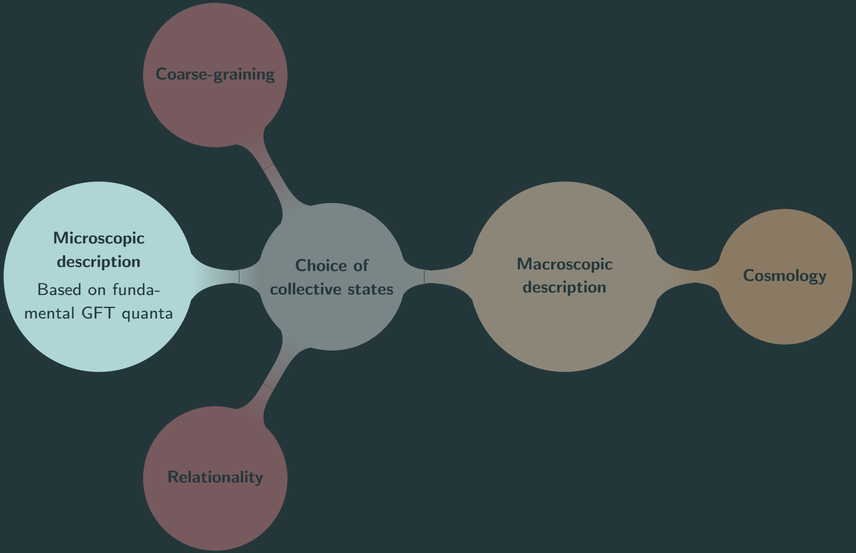
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The (T)GFT approach to quantum gravity

GFTs are QFTs of atoms of spacetime.

- Take seriously the idea of a microscopic structure of spacetime.
- Access to powerful field theoretic methods (Fock space, RG. . .)!

Oriti 0912.2441; Oriti 1110.5606; Oriti 1408.7112; Krajewski 1210.6257; Oriti 1807.04875; Gielen, Sindoni 1602.08104; . . .

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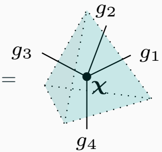
Group Field Theory Quanta

- GFT quanta are atoms of quantum 3-space, i.e. tetrahedra.
- Data associated to a single quantum are field data of a tetrahedron (g_a = gravitational, χ = scalar fields).

$\varphi^\dagger(g_a, \chi)\,|0\rangle =$ 

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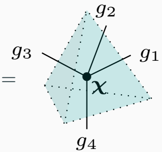
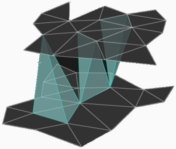


Group Field Theory Processes

- GFT Feynman diagrams (QG processes) are associated with 4d triangulated (pseudo-)manifolds.
- Z_{GFT} = discrete matter-gravity path-integral.



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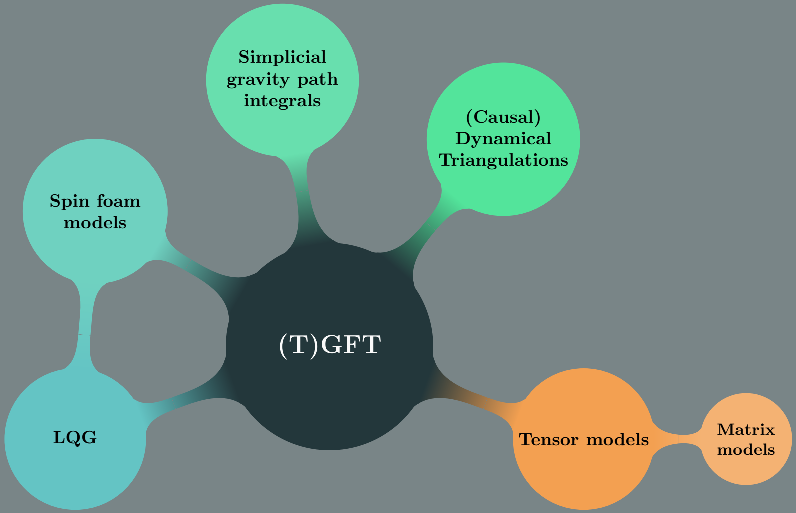
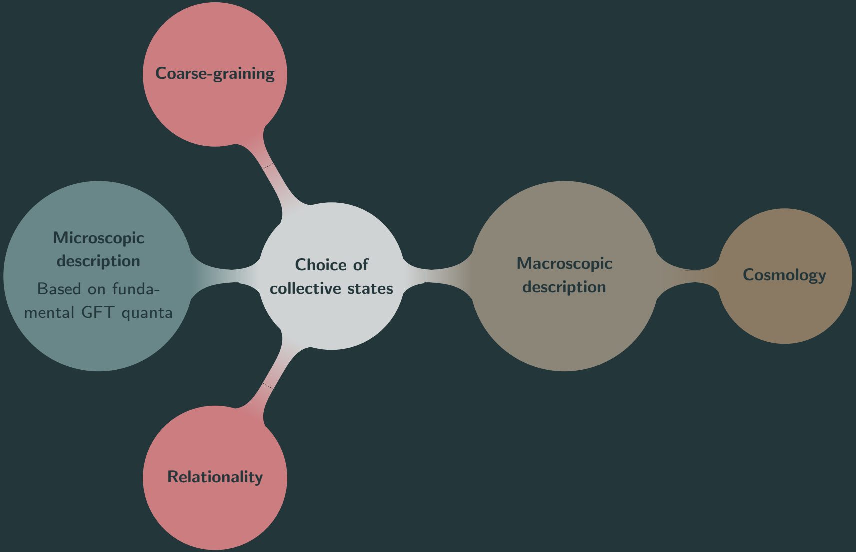


Simplicial gravity path integrals
(Causal) Dynamical Triangulations
Spin foam models
(T)GFT
LQG
Tensor models
Matrix models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GFT coherent states

- 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:

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

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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Mean-field approximation

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

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

- Simplest coarse-graining: equivalent to a mean-field (saddle-point) approximation of Z.

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Localization

Relational peaking

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

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

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

$$\langle\hat{\chi}^\mu\rangle_{\sigma_x} \simeq x^\mu$$

e.g.

$$\hat{N} = \int \mathrm{d}g_a\, \mathrm{d}^4\chi^\mu\, \hat{\varphi}^\dagger(g_a,\chi^\mu)\hat{\varphi}(g_a,\chi^\mu)$$

$$N(x) = \int \mathrm{d}g_a\, |\tilde{\sigma}(g_a,x^\mu)|^2$$

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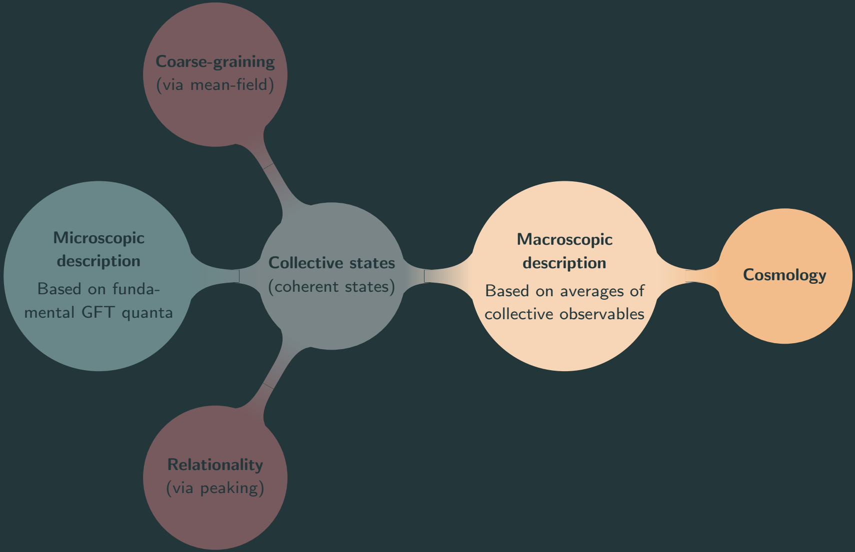
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(via peaking)

Emergent QG phenomena in cosmology: three explicit examples

Quantum bounce and classical limit

Quantum bounce and classical limit

Eff. dynamics

Setting

- 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.

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

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

Quantum bounce and classical limit

Eff. dynamics

Setting

- Homogeneity: $\tilde{\sigma}$ depends only on MCMF clock χ^0.
- Isotropy: $\tilde{\sigma}_\upsilon \equiv \rho_\upsilon e^{i\theta_\upsilon}$ ($\upsilon_{\rm EPRL} \in \mathbb{N}/2$, $\upsilon_{\rm BC} \in \mathbb{R}$).
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Effective relational Freidmann dynamics

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

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Classical limit

- When ρ_υ is large (late times) and $\mu_\upsilon^2 \simeq 3\pi G$ is mildly υ-dependent (or one υ dominates)

$$(V'/3V)^2 \simeq 4\pi G/3 \longrightarrow \text{flat FLRW}$$

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

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

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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 $\mathcal{E}_\upsilon < 0$).
- If $N(x^0_{\mathrm{bounce}})$ gets too small, the average singularity resolution may 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; ...

Cosmic acceleration from QG interaction

Emergent inflation and phantom dark energys

Interactions

Tensor (modulus)	Cellular (phase)

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

Emergent inflation and phantom dark energys

notation: $(\cdot,\,\cdot) = \int \mathrm{d}^n \mathbf{\Phi} \mathrm{d}g_a$

Interactions

Tensor (modulus)

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

- Highly symmetric, studied in renormalization.
- Modulus-only dependence after σ-isotropy.

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Modulus

Phantom Dark Energy

- Consider $l = 5$ modulus interactions at very late times, but include a subdominant spin υ':

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

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

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Slow-roll phase

- Initial conditions: $l=5$, $\mathrm{Re}[\lambda_\upsilon \bar{\tilde{\sigma}}^l_\upsilon]$ close to a maximum, θ_υ determines slow-roll.
- Long-lasting quasi-deSitter phase!

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

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- Long-lasting quasi-deSitter phase!

Graceful exit and fast oscillations

- Natural slow-roll breakdown: fast oscillations.
- Interactions washed away on average.
- Graceful exit: matter (clock) dominated phase!

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

Inhomogeneities from QG entanglement

Cosmic inhomogeneities from quantum gravity 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

- Beyond condensates: time- and spacelike tetrahedra.

Inhomogeneities = Quantum Entanglement

$$|\Delta; x\rangle = \mathcal{N}_\Delta e^{\hat{\sigma}\otimes\mathbb{I}_- + \mathbb{I}_+\otimes\hat{\tau} + \widehat{\delta\Phi}\otimes\mathbb{I}_- + \widehat{\delta\Psi} + \mathbb{I}_+\otimes\widehat{\delta\Xi}} |0\rangle \,.$$

Jercher, LM, Pithis 2310.17549-2308.13261; LM, Oriti 2112.12677; Jercher, Oriti, Pithis 2206.15442; Gielen, Mickel 2211.04500.

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Effective dynamics

Classical dynamics with trans-Planckian QG effects

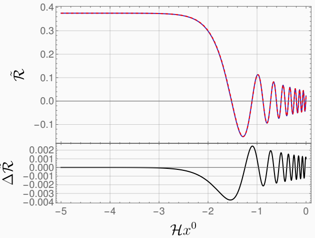
- Matter $\delta\phi_{\mathrm{GFT}}$ and "curvature-like" (isotropic) pert. $\tilde{\mathcal{R}}$ emerge from to two-body relational nearest-neighbor QG correlations $(\widehat{\delta\Phi}, \widehat{\delta\Psi}, \widehat{\delta\Xi})$.

$$\delta\phi''_{\mathrm{GFT}} + k^2 a^4 \delta\phi_{\mathrm{GFT}} = \left(\frac{a^2 k}{M_{\mathrm{pl}}}\right) j_\phi[\bar{\phi}] \,,$$

$$\tilde{\mathcal{R}}''_{\mathrm{GFT}} + k^2 a^4 \tilde{\mathcal{R}}_{\mathrm{GFT}} = \left(\frac{a^2 k}{M_{\mathrm{pl}}}\right) j_{\tilde{\mathcal{R}}}[\bar{\phi}] \,,$$

- 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 $\Delta\tilde{\mathcal{R}}$.

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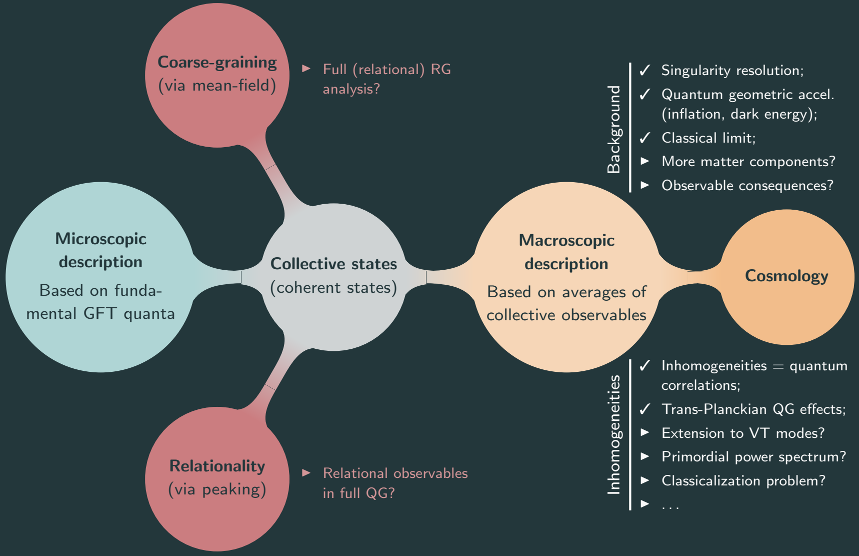
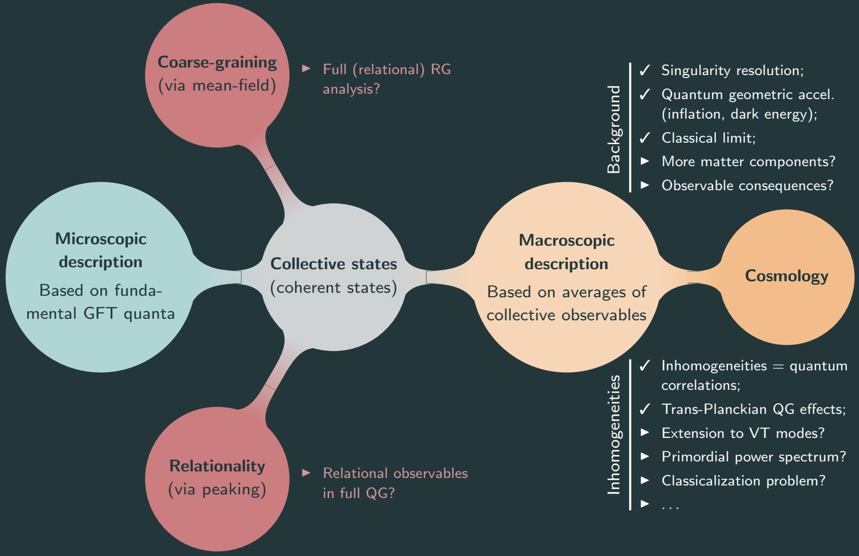

Coarse-graining
(via mean-field)
Full (relational) RG analysis?
Microscopic description
Based on fundamental GFT quanta
Collective states
(coherent states)
Macroscopic description
Based on averages of collective observables
Cosmology
Relationality
(via peaking)
Relational observables in full QG?
Background
✓ Singularity resolution;
✓ Quantum geometric accel. (inflation, dark energy);
✓ Classical limit;
More matter components?
Observable consequences?
Inhomogeneities
✓ Inhomogeneities = quantum correlations;
✓ Trans-Planckian QG effects;
Extension to VT modes?
Primordial power spectrum?
Classicalization problem?
. . .



Challenging goals, every bit of input is important!

Backup

Group Field Theory and spinfoam models

Definition

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

d is the dimension of the "spacetime to be" ($d = 4$) and G is the local gauge group of gravity, $G = \mathrm{SL}(2, \mathbb{C})$ 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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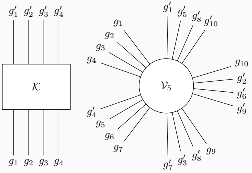
Action

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

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

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



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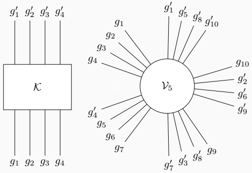

Partition function

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

- Γ = stranded diagrams dual to d-dimensional cellular complexes of arbitrary topology.
- Amplitudes A_Γ = sums over group theoretic data associated to the cellular complex.

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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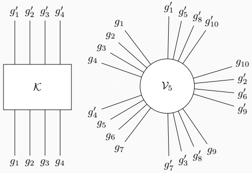

Partition function

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

- Γ = stranded diagrams dual to d-dimensional cellular complexes of arbitrary topology.
- Amplitudes A_Γ = sums over group theoretic data associated to the cellular complex.
- $\mathcal{K}$ and $\mathcal{V}_\gamma$ chosen to match the desired spinfoam model.

Oriti 1110.5606; Reisenberger, Rovelli 0002083; De Pietri, Petronio 0004045; Gurau 1006.0714; Baratin, Oriti 1002.4723; Finocchiaro, Oriti 1812.03550.

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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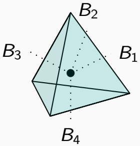
Lie algebra (metric)

$\mathcal{H}_{\Delta_a} = L^2(\mathfrak{g})$

Constraints

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



Closure

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

Simplicity

- $X \cdot (B - \gamma \star B)_a = 0$ (EPRL);
- $X \cdot B_a = 0$ (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) $\mathcal{H}_{\Delta_a} = L^2(\mathfrak{g}) \xleftrightarrow[\text{FT}]{\text{Non-comm.}}$ **Lie group (connection)** $\mathcal{H}_{\Delta_a} = L^2(G)$

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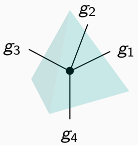

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Lie algebra (metric)		**Lie group (connection)**		**Representation space**
$\mathcal{H}_{\Delta_a} = L^2(\mathfrak{g})$	$\xleftrightarrow[\text{FT}]{\text{Non-comm.}}$	$\mathcal{H}_{\Delta_a} = L^2(G)$	$\xleftrightarrow[\text{Theorem}]{\text{Peter-Weyl}}$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

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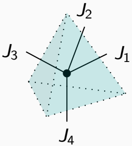

Finocchiaro, Oriti 1812.03550; Baez, Barrett 9903060; Baratin, Oriti 1002.4723; Gielen, Oriti 1004.5371; Oriti 1310.7786.

Group Field Theory and Loop Quantum Gravity

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)		Representation space
$\mathcal{H}_{\Delta_a} = L^2(\mathfrak{g})$	$\xleftrightarrow[\text{FT}]{\text{Non-comm.}}$	$\mathcal{H}_{\Delta_a} = L^2(G)$	$\xleftrightarrow[\text{Theorem}]{\text{Peter-Weyl}}$	$\mathcal{H}_{\Delta_a} = \bigoplus_{J_a} \mathcal{H}_{J_a}$

Constraints

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

Closure

$$\sum_a B_a = 0$$

(faces of the tetrahedron close).

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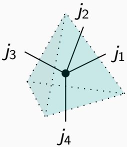

LQG

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

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

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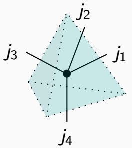

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$$\mathcal{H}_{\text{tetra}} = \bigoplus_{\vec{j}} \text{Inv}\left[\bigotimes_{a=1}^{4} \mathcal{H}_{j_a}\right] = \text{open spin-network vertex space}$$

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

- $\mathcal{F}_{\mathsf{GFT}}$ 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.

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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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Macroscopic cosmological variables and effective relationality

Spatial relational homogeneity:
σ depends on a MCMF "clock" scalar field χ^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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$$\hat{N} = (\hat{\varphi}^\dagger, \hat{\varphi}) \qquad \hat{V} = (\hat{\varphi}^\dagger, V[\hat{\varphi}])$$

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

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

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Relationality

- Averaged evolution wrt x^0 is physical:

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

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

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

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

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

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Scalar perturbations from quantum correlations

Collective states

Two-body correlations

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

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

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

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Eff. dynamics

Scalar isotropic perturbations

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

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

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$$\langle \hat{\mathcal{O}}_{\mathrm{GFT}}\rangle_{\Delta;x} = \bar{\mathcal{O}}_{\mathrm{GFT}}(x^0) + \delta\mathcal{O}_{\mathrm{GFT}}(x^\mu).$$

- Physical behavior of spatial derivative terms fixes dynamical freedom (e.g. in $\delta\Phi$).

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