Cosmological Perturbations from Quantum Gravity Entanglement

(Based on 2308.13261-2310.17549, in collaboration with A. Jercher and A. Pithis)

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Loops'24

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09 May 2024

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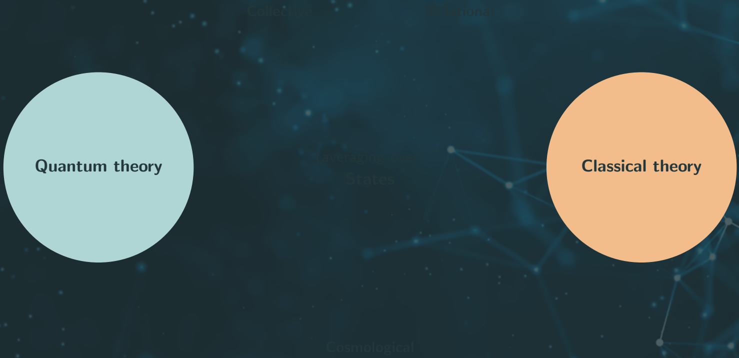
Collective
Relational
Quantum theory
(averaging over)
States
Classical theory
Cosmological

Collective

Relational

Quantum theory

(averaging over)
States

Classical theory

Gravity + 5 MCMF scalar fields (χ^μ, ϕ)

Cosmological

Quantum theory

BC GFT + 5 MCMF scalar fields (χ^μ, ϕ)

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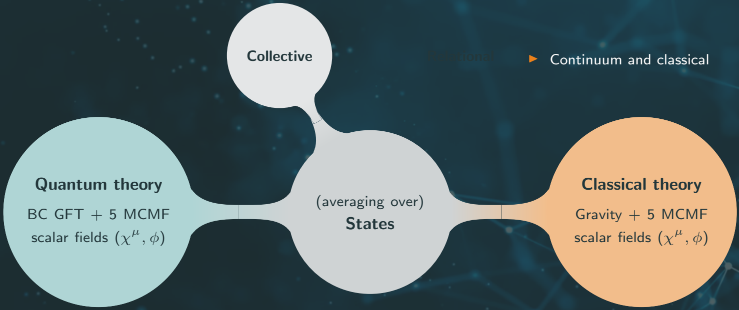
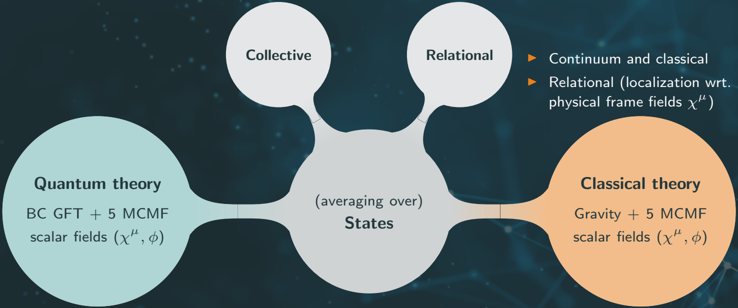
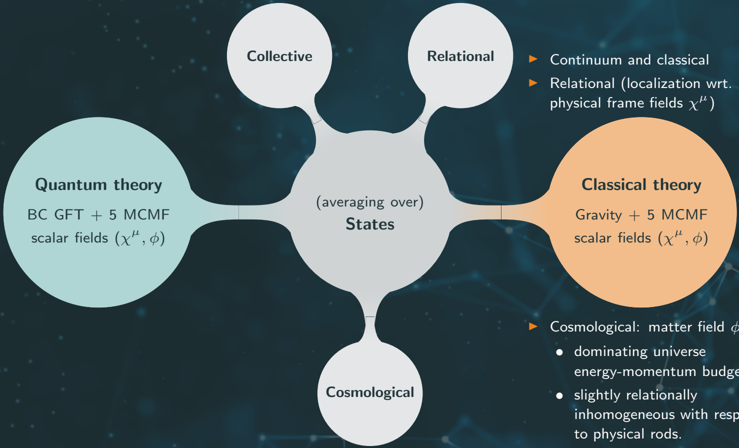
- Continuum and classical



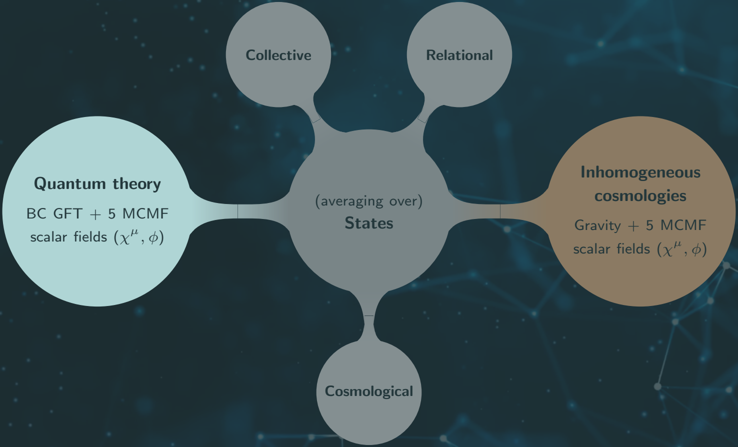


- Continuum and classical
- Relational (localization wrt. physical frame fields χ^μ)



- Continuum and classical
- Relational (localization wrt. physical frame fields χ^μ)

- Cosmological: matter field ϕ
  - dominating universe energy-momentum budget;
  - slightly relationally inhomogeneous with respect to physical rods.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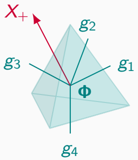
Extended BC model and causal frame coupling

Model

Two-sector GFT

4d BC model with spacelike ($+$) and timelike ($-$) quanta: $\varphi_\pm \equiv \varphi(g_a, X_\pm, \boldsymbol{\Phi})$



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

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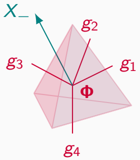

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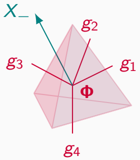

- Reference χ^μ and matter ϕ scalars encoded in $\mathbf{\Phi} = (\chi^\mu, \phi) \in \mathbb{R}^5$.
- Geometry: $g_a \in G = \mathrm{SL}(2, \mathbb{C})$ and $X_\pm \in G/U_\pm$, $U_\pm$ stabilizer of $X_\pm$.
- BC geometricity constraints imposed using normal: $\mathcal{G}_{X_\pm}[\varphi_\pm] = \varphi_\pm$.
- Sectors only kinematically decoupled: $K_{\mathrm{GFT}} = K_+ + K_-$

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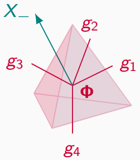

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Kinetic restriction

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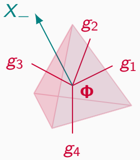
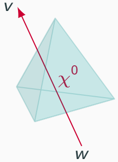


Frame coupling

Kinetic restriction

- Since χ^0 propagates along timelike edges (across spacelike tetrahedra):

$\mathcal{K}_+$ independent of χ^i.



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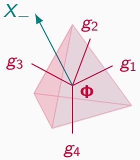

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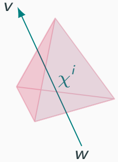

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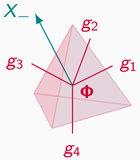

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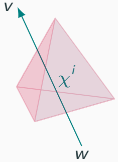

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Fock structure

Field operators and observables

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

- Tensor Fock structure: $\mathcal{F} = \mathcal{F}_+ \otimes \mathcal{F}_-$, with $\mathcal{F}_\pm$ generated by repeated action of $\hat{\varphi}^\dagger_\pm$ on $|0\rangle_\pm$.
- Collective observables are second quantized operators: e.g. **number**, **matter** and **volume**

$$\hat{N} = \sum\nolimits_\pm \hat{\varphi}^\dagger_\pm \cdot \hat{\varphi}_\pm\,, \qquad \hat{\mathbf{\Phi}}_\pm = \hat{\varphi}^\dagger_\pm \cdot (\phi\hat{\varphi}_\pm)\,, \qquad \hat{V} = \hat{\varphi}^\dagger_+ \cdot V[\hat{\varphi}_+]\,.$$

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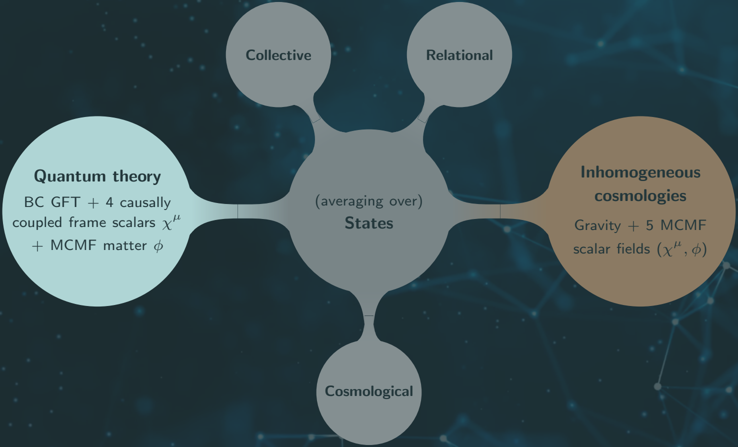
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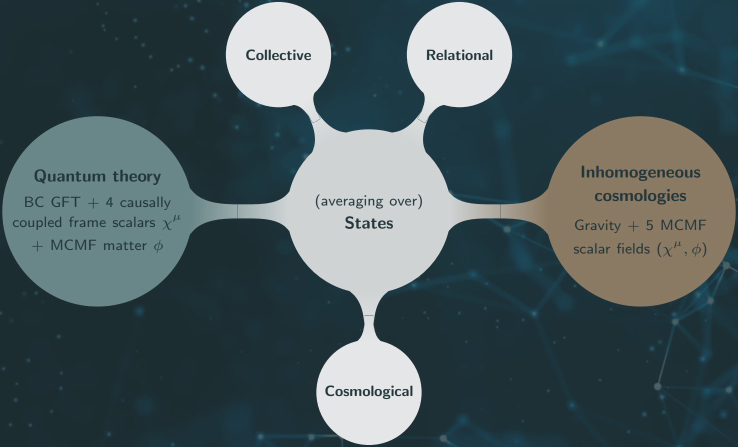

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Collective entangled QG states

Collective states

Macroscopically entangled states

- Background cosmological geometries associated with uncorrelated collective states (condensates).
- Since non-trivial geometries = quantum entanglement, look for macroscopically entangled states:

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

Jercher, LM, Pithis 2310.17549-2308.13261; LM, Oriti 2008.02774-2112.12677; Oriti, Sindoni, Wilson-Ewing 1602.05881; Gielen, Oriti, Sindoni 1311.1238.

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Background

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

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

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Localization

Peaking and effective relational observables

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

$(\sigma_x, \tau_x) =$ (fixed peaking function η_x) $\times$ (dynamically determined reduced wavefunction $(\tilde{\sigma}, \tilde{\tau})$) ,

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$$\langle \hat{\mathcal{O}} \rangle_\Delta \equiv \mathcal{O}_\Delta(x) = \bar{\mathcal{O}}_\Delta[\tilde{\sigma}, \tilde{\tau}]|_{\chi^0 = x^0} + \delta\mathcal{O}_\Delta[\delta\Phi, \delta\Psi, \delta\Xi]|_{\chi^\mu = x^\mu}$$

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- Since $\langle \hat{\chi}^\mu \rangle_\Delta \simeq x^\mu$, $\mathcal{O}_\Delta(x)$ is an effective relationally localized observable.

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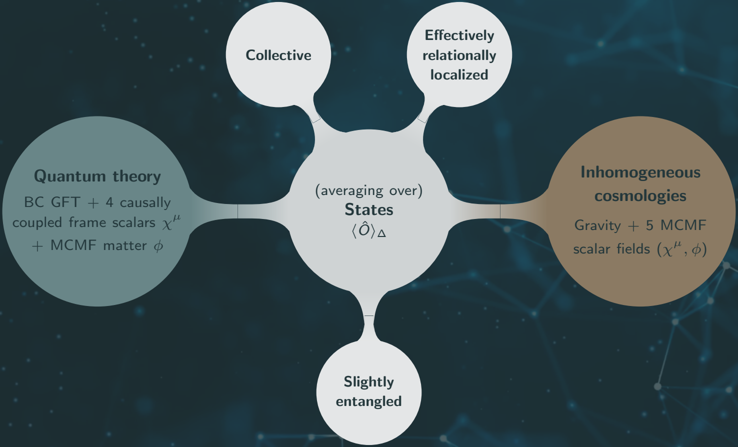

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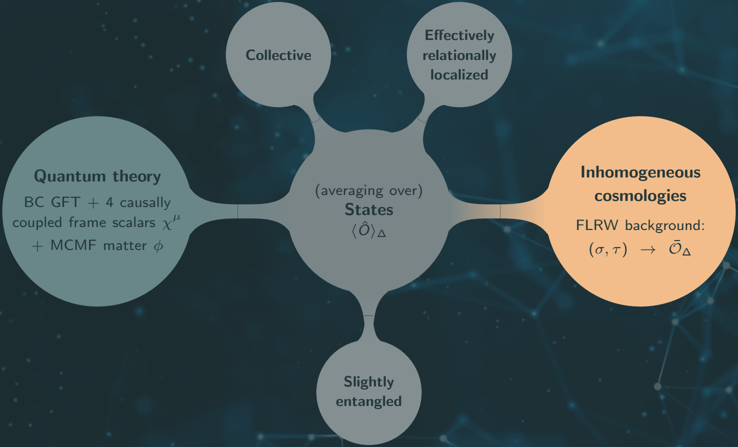
Slightly entangled



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FLRW background:
$(\sigma, \tau) \rightarrow \bar{O}_\Delta$
Slightly entangled

Background: effective FLRW dynamics

Mean-field approximation

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

$$\text{0th-order:} \quad \left\langle \frac{\delta S_{\text{GFT}}[\hat{\varphi}, \hat{\varphi}^\dagger]}{\delta \hat{\varphi}(g_a, X_\pm, x^\mu, \phi)} \right\rangle_\Delta = \left\langle \frac{\delta S_{\text{GFT}}[\hat{\varphi}, \hat{\varphi}^\dagger]}{\delta \hat{\varphi}(g_a, X_\pm, x^\mu, \phi)} \right\rangle_\Delta \Bigg|_{\delta\Psi=\delta\Phi=\delta\Xi=0} = 0\,.$$

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- Homogeneity: $\tilde{\sigma}$ and $\tilde{\tau}$ depend only on MCMF clock χ^0.
- Isotropy: $\tilde{\sigma}$ and $\tilde{\tau}$ depend on a single spacelike rep. label.
- Mesoscopic regime: negligible interactions.

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

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Classical limit

Large number of quanta (large volume and late times)

rep. label υ_o suppressed

- Assume one single υ_o is dominating.
- Consider large $\bar{N}_\Delta = \bar{N}_+ + \bar{N}_-$ $(\mu_+ > \mu_-)$:

$$\bar{N}_+ = |\tilde{\sigma}|^2 \propto e^{\mu_+ x^0}, \quad \bar{N}_- = |\tilde{\tau}|^2 \propto e^{\mu_- x^0}.$$

Small observables quantum fluctuations!

Jercher, LM, Pithis 2310.17549-2308.13261; LM, Oriti 2112.12677, 2008.02774-2010.09700; Oriti, Sindoni, Wilson-Ewing 1602.05881.

Background: effective FLRW dynamics

Effective dynamics

Mean-field approximation

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

$$\text{0th-order:} \quad \left\langle \frac{\delta S_{\mathrm{GFT}}[\hat{\varphi}, \hat{\varphi}^\dagger]}{\delta \hat{\varphi}(g_a, X_\pm, x^\mu, \phi)} \right\rangle_\Delta = \left\langle \frac{\delta S_{\mathrm{GFT}}[\hat{\varphi}, \hat{\varphi}^\dagger]}{\delta \hat{\varphi}(g_a, X_\pm, x^\mu, \phi)} \right\rangle_\Delta \Bigg|_{\delta\Psi=\delta\Phi=\delta\Xi=0} = 0\,.$$

- Homogeneity: $\tilde{\sigma}$ and $\tilde{\tau}$ depend only on MCMF clock χ^0.
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Small observables quantum fluctuations!

- Volume expands as $\bar{N}_+$ grows: $\bar{V}_\Delta = v\bar{N}_+$.
- Compare with GR in harmonic gauge.
- ✓ Matching requires $\mu_+ = 3\bar{\pi}_\phi/(8M_{\mathrm{pl}}^2)$.

$(\bar{V}_\Delta'/3\bar{V}_\Delta)^2 = 2\mu_+/3$ ⟶ flat FLRW

Jercher, LM, Pithis 2310.17549-2308.13261; LM, Oriti 2112.12677, 2008.02774-2010.09700; Oriti, Sindoni, Wilson-Ewing 1602.05881.

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Small observables quantum fluctuations!

- ϕ_Δ obtained combining intensive quantities

$$\phi_\Delta = \Phi_+(N_+/N_\Delta) + \Phi_-(N_-/N_\Delta)\,.$$

- In the limit of dominating $\bar{N}_+$, $\bar{\phi}_\Delta = \bar{\Phi}_+$:

$\bar{\phi}''_\Delta = 0 \longrightarrow$ Harmonic dynamics

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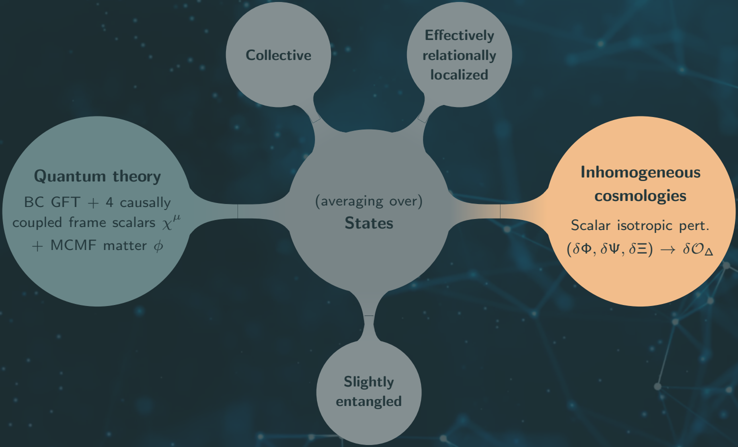
Collective
Effectively relationally localized
Quantum theory
BC GFT + 4 causally coupled frame scalars χ^μ + MCMF matter ϕ
(averaging over)
States
Inhomogeneous cosmologies
Scalar isotropic pert.
$(\delta\Phi, \delta\Psi, \delta\Xi) \to \delta\mathcal{O}_\Delta$
Slightly entangled

Perturbations: emergent dynamics of cosmic inhomogeneities

Effective dynamics

Mean-field approximation

- When interactions are small (satisfied in an appropriate regime) the dynamics of $(\delta\Psi, \delta\Phi, \delta\Xi)$ are:

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- 2 equations for 3 functions. . .
- But dynamical freedom completely fixed by classical limit!

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Scalar isotropic perturbations

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Classical dynamics with trans-Planckian QG effects

Scalar isotropic pert. $(\delta\phi_\Delta, \tilde{\mathcal{R}}_\Delta)[\delta\Phi, \delta\Psi, \delta\Xi]$

- "Curvature-like" $\tilde{\mathcal{R}}_\Delta$ from δV_Δ and $\delta\phi_\Delta$.

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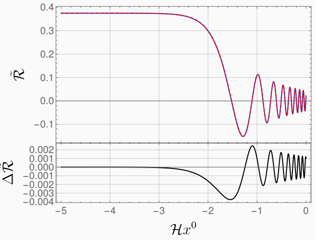
- "Curvature-like" $\tilde{\mathcal{R}}_\Delta$ from δV_Δ and $\delta\phi_\Delta$.
- Late times and single spacelike label:

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

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

Trans-Planckian QG corrections

✓ Remarkable agreement with GR at larger scales.



$\tilde{\mathcal{R}}_\Delta$, $\tilde{\mathcal{R}}_{\rm GR}$ and their difference; $k/M_{\rm Pl} = 10^2$.

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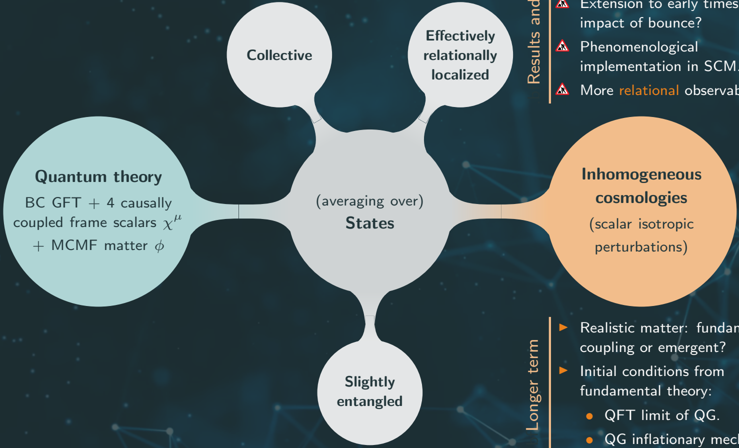

Results and short-term

- ✓ Pert. = QG entanglement.
- ✓ Good classical limit.
- ✓ Trans-Planckian QG effects.
- ⚠ Extension to EPRL-FK!
- ⚠ Extension to early times: impact of bounce?
- ⚠ Phenomenological implementation in SCM.
- ⚠ More relational observables.

Longer term

- Realistic matter: fundamental coupling or emergent?
- Initial conditions from fundamental theory:
  - QFT limit of QG.
  - QG inflationary mechanism.

Backup

Group Field Theories with matter scalars

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

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

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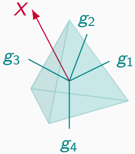
Kinematics

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

- Interpretation guaranteed by geometricity constraints.
- Causal properties encoded in normal X.

$\mathcal{H}_{\text{1-p}} =$ 

Li, Oriti, Zhang 1701.08719; Oriti 0912.2441; Oriti, Sindoni, Wilson-Ewing 1602.05881; Gielen, Sindoni 1602.08104; ...

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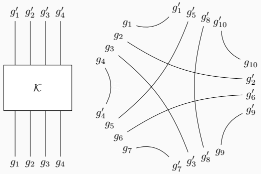
Dynamics

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

S_{GFT}: compare Z_{GFT} with simplicial gravity path integral (A_Γ = spinfoam amplitudes).

$$S_{\text{GFT}} = K + V = \bar{\varphi} \cdot \mathcal{K}[\varphi] + \sum_\gamma \frac{\lambda_\gamma}{n_\gamma} \mathrm{Tr}_\gamma[\varphi] + \text{c.c.}$$

- $\mathcal{K}$ encodes propagation of (geometry) data between neighboring d-simplices.
- Interactions: non-local in g_a, following the combinatorial pattern of γ.



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Group Field Theories with matter scalars

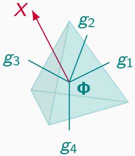
Group Field Theories: theories of a field $\varphi : G^d \times \mathcal{X} \times \mathbb{R}^{d_l} \to \mathbb{C}$ defined on the product of $G^d \times \mathcal{X}$ and $\mathbb{R}^{d_l}$.

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

Kinematics

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

- Interpretation guaranteed by geometricity constraints.
- Causal properties encoded in normal X.
- Scalar field discretized on each d-simplex: each $d - 1$-simplex composing it carries values $\mathbf{\Phi} \in \mathbb{R}^{d_l}$.

$\mathcal{H}_{\text{1-p}} =$ 

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- $\mathcal{K}$ encodes propagation of (geometry and matter) data between neighboring d-simplices.
- Interactions: non-local in g_a, local in $\mathbf{\Phi}$.
- For minimally coupled, free, massless scalars:

$$\mathcal{K}(g_a^{(v)}, g_b^{(w)}; \mathbf{\Phi}^{(v)}, \mathbf{\Phi}^{(w)}) = \mathcal{K}(g_a^{(v)}, g_b^{(w)}; \mathbf{\Delta}^2_{vw}\mathbf{\Phi})$$

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

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