Emergent Cosmology from Quantum Gravity

(In collaboration with P. Fischer, A. Jercher, T. Ladstätter, D. Oriti, A. Pithis)

Luca Marchetti

Atlantic General Relativity 24

University of New Brunswick, Fredericton, NB

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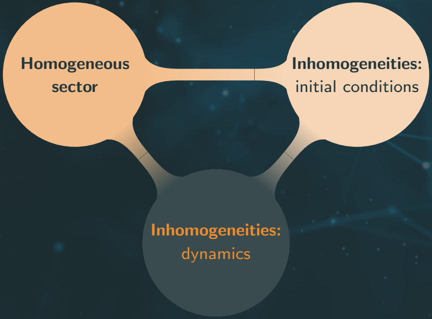
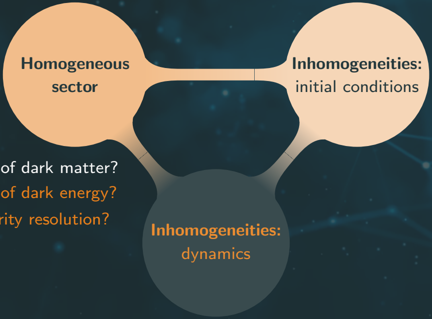
Department of Mathematics and Statistics
UNB Fredericton


Homogeneous sector
Inhomogeneities: initial conditions
Inhomogeneities: dynamics



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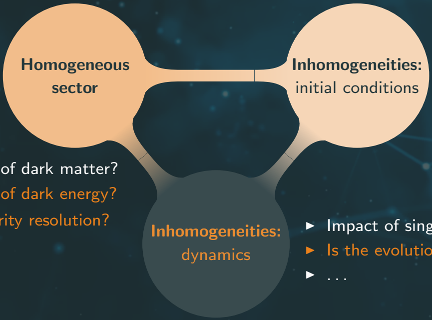
- Nature of dark energy?
- Singularity resolution?



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- Impact of singularity resolution on pert.?
- Is the evolution of pert. modified by QG effects?
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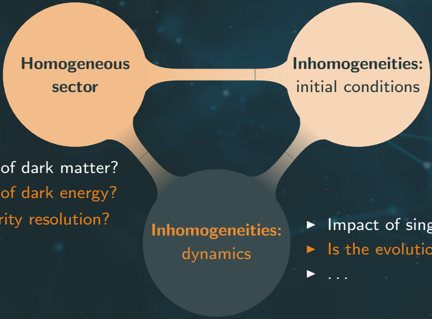

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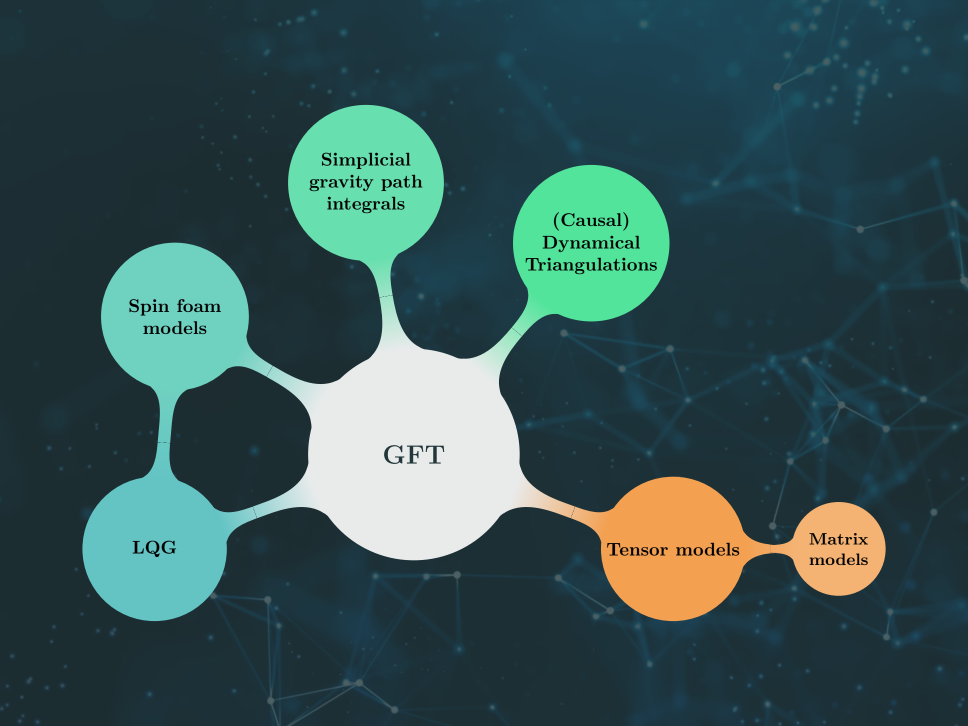
Simplicial gravity path integrals
(Causal) Dynamical Triangulations
Spin foam models
GFT
LQG
Tensor models
Matrix models

The 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.
- Quantum numbers associated with fields discretized over a tetrahedron (g_a = gravitational, $\mathbf{\Phi}$ = scalar fields).
- GFT field domain is a group manifold G: not spacetime!

$$\varphi^\dagger(g_a, \mathbf{\Phi})\,|0\rangle =$$

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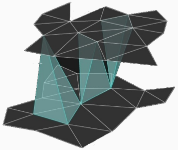
Group Field Theory Processes

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

$$\Gamma \overset{(3d)}{=}$$



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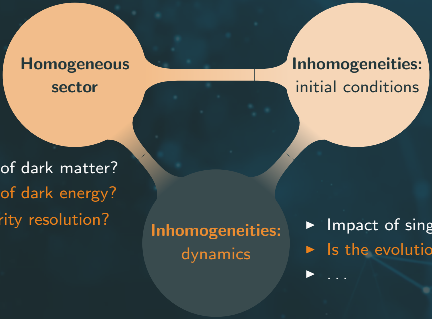

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Challenges in background independent and emergent QG:

- How to define (in)homogeneity?
- How to extract macroscopic dynamics?
- How to construct cosmological geometries?
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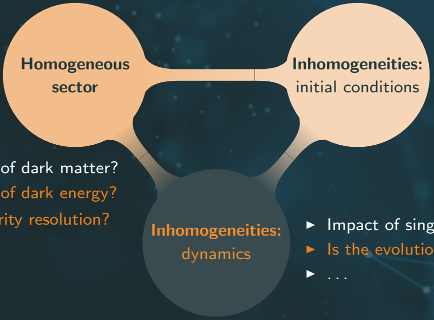

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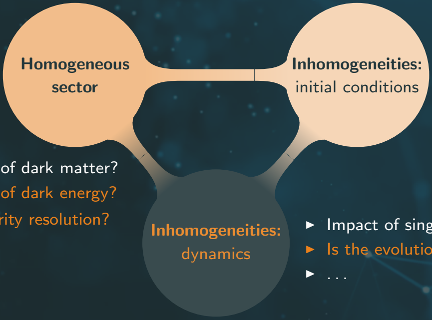
Relational strategy



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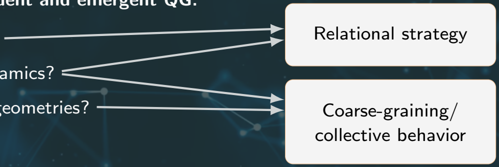


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averaging
Observables
over appropriate
States
Classical gravity
Cosmological

Collective

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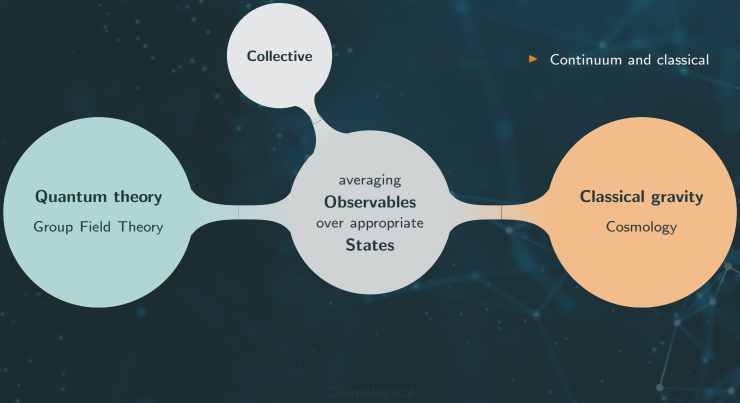

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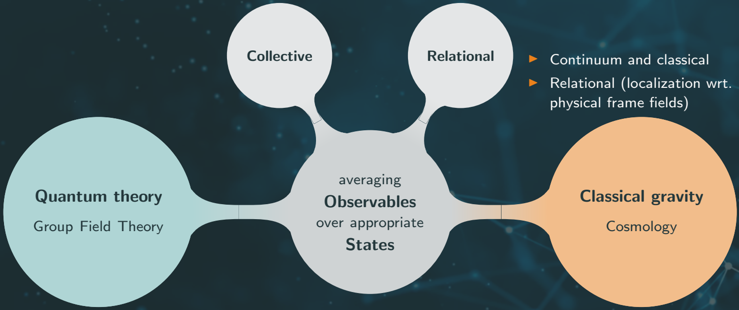
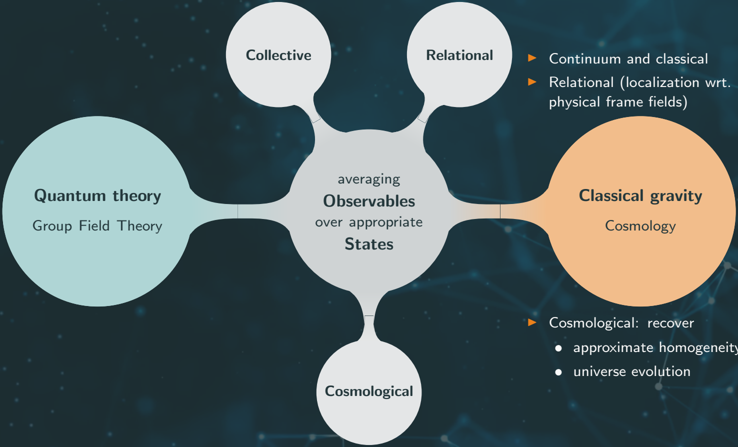


- Continuum and classical
- Relational (localization wrt. physical frame fields)

Cosmological



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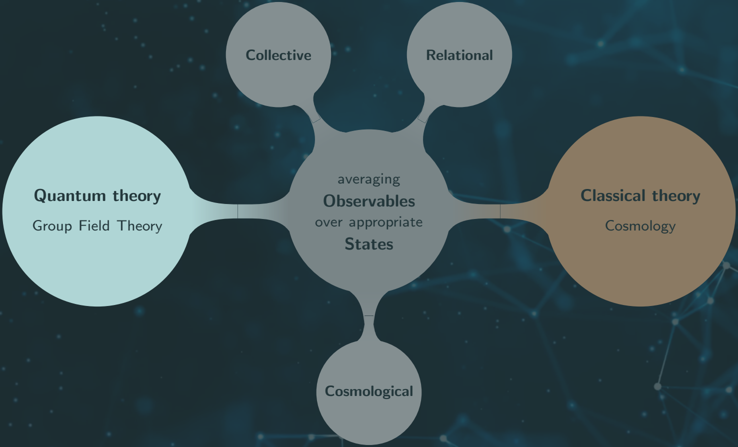
- Cosmological: recover
  - approximate homogeneity
  - universe evolution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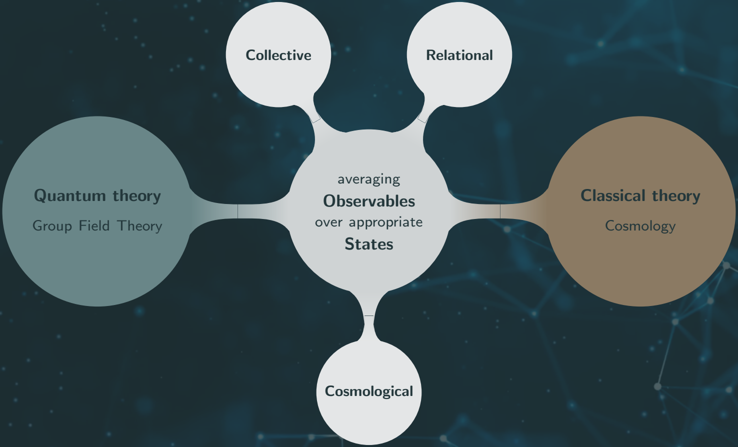
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Collective states and observables

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.

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Macroscopic dynamics = mean-field approximation

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

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E.g.: $$\left\langle \frac{\delta S_{\mathrm{GFT}}[\hat{\varphi}, \hat{\varphi}^\dagger]}{\delta \hat{\varphi}(g_a, x^\alpha)} \right\rangle_\sigma = [K \cdot \sigma](g_a, x^\alpha) + \left. \frac{\delta V[\varphi, \varphi^*]}{\delta \varphi^*(g_a, x^\alpha)} \right|_{\varphi = \sigma} = 0 \, .$$

- Equivalent to a mean-field (saddle-point) approximation of Z_{GFT}.

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- Collective behavior is captured by (second quantized) one-body operators $\hat{O}$, such as

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

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

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Relational peaking

- Constructing relational observables in GFT is not easy (QFT with no continuum intuition).
- Relational localization implemented at an effective level on observable averages.

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E.g.: χ^μ frame and $|\sigma\rangle$:

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

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

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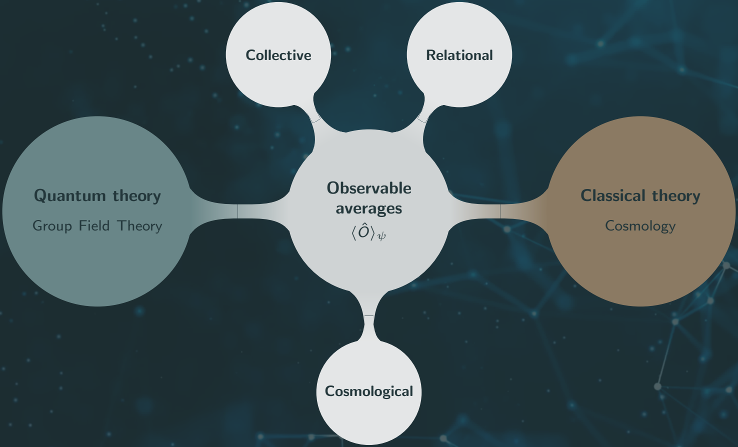
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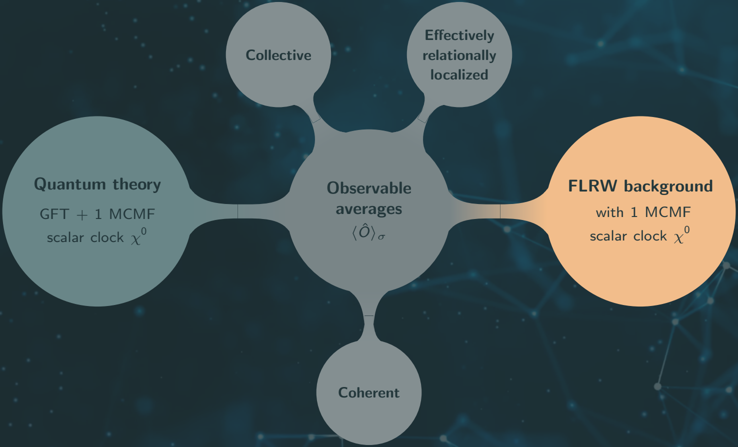
Collective
Effectively relationally localized
Quantum theory
GFT + 1 MCMF scalar clock χ^0
Observable averages
$\langle \hat{O} \rangle_\sigma$
FLRW background
with 1 MCMF scalar clock χ^0
Coherent

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.

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

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

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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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Classical limit

Large number of quanta (large volume and late times)

- ✓ Volume quantum fluctuations under control.
- If μ^2_υ is mildly dependent on υ (or one υ_o is dominating) and equal to $3\pi G$

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

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: $\tilde{\sigma}_\upsilon \equiv \rho_\upsilon e^{i\theta_\upsilon}$ ($\upsilon_{\text{EPRL}} \in \mathbb{N}/2$, $\upsilon_{\text{BC}} \in \mathbb{R}$).
- Mesoscopic regime: negligible interactions.

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

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- ✓ Matching with GR (in harmonic gauge)!
- ✓ $x^0 = \langle\hat{\chi}^0\rangle_{\sigma_{x^0}}$, clock quantum fluct. $\simeq 0$.
- ✓ $\langle\hat{\Pi}^0\rangle_{\sigma_{x^0}} = \langle\hat{H}_\sigma\rangle_{\sigma_{x^0}}$ (higher moments $\simeq 0$).

Effective relational framework reliable!

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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 $\mathcal{E}_\upsilon < 0$)

Singularity res. into quantum bounce!

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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; Gielen, Polaczek 1912.06143.

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: $\varphi \cdot \psi = \int_\Omega d\Omega\, \varphi\psi$

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

- Highly symmetric, studied in renormalization.
- 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!

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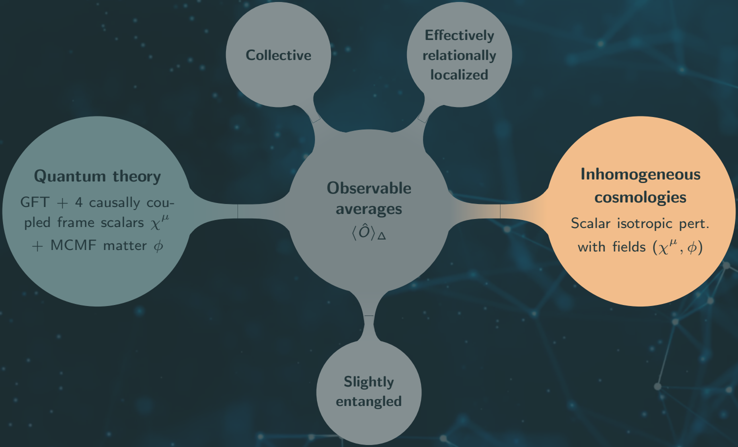
Graceful exit and fast oscillations

- 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.



Collective
Effectively relationally localized
Quantum theory
GFT + 4 causally coupled frame scalars χ^μ + MCMF matter ϕ
Observable averages
$\langle \hat{O} \rangle_\Delta$
Inhomogeneous cosmologies
Scalar isotropic pert. with fields (χ^μ, ϕ)
Slightly entangled

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

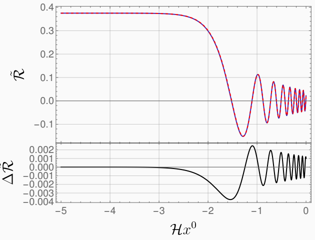
- Matter $\delta\phi_{\mathrm{GFT}}$ and "curvature-like" (isotropic) pert. $\tilde{\mathcal{R}}$ emerge from to two-body relational nearest-neighbor QG correlations $(\widehat{\delta\Phi}, \widehat{\delta\Psi}, \widehat{\delta\Xi})$.

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

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

- 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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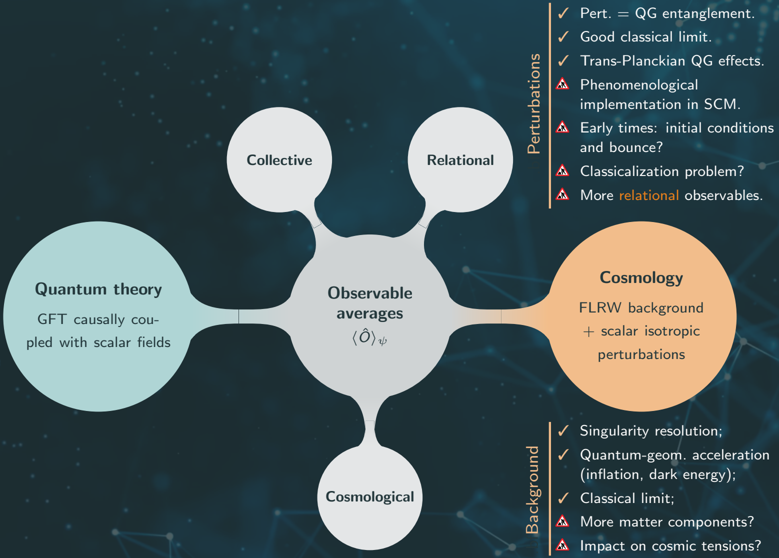
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Cosmological
Cosmology
FLRW background
+ scalar isotropic
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Perturbations
✓ Pert. = QG entanglement.
✓ Good classical limit.
✓ Trans-Planckian QG effects.
⚠ Phenomenological implementation in SCM.
⚠ Early times: initial conditions and bounce?
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