Emergent Cosmology from Quantum Gravity Hydrodynamics

A collective effort: D. Oriti, E. Wilson-Ewing, A. Jercher, T. Ladstätter, A. Pithis, S. Gielen, V. Husain, H. Mehmood, P. Höhn, S. Aguilar, R. Ferrero, L. Mickel, A. Calcinari, . . .

Luca Marchetti

The Universe in the Math, in the Sky and in the Lab

UCM, Madrid

30 Sep 2025

OIST
Kavli IPMU

Part I

Quantum Gravity: Group Field Theories

- Group Field Theories are QFTs of spacetime atoms which collectively create spacetime structures.

Quantum many-body theories on superspace, not spacetime

- Natural to import techniques and ideas from condensed matter physics.
- A crossroads between different approaches to QG: "universal" language for QG phenomena?

Part II

Emergence: Coarse-Graining and Localization on Superspace

- What is local physics in QG? How to coarse-grain (renormalize) without energy/length scales?
- Relational strategy: localization and coarse-graining with respect to dynamical frames.

Superspace Hydrodynamics

- Realization in GFT with mean-field theory (simplest coarse-graining).
- Macroscopic observables as coherent states averages of collective operators.

Part III

Emergent Cosmology: Acceleration and Cosmological Perturbations

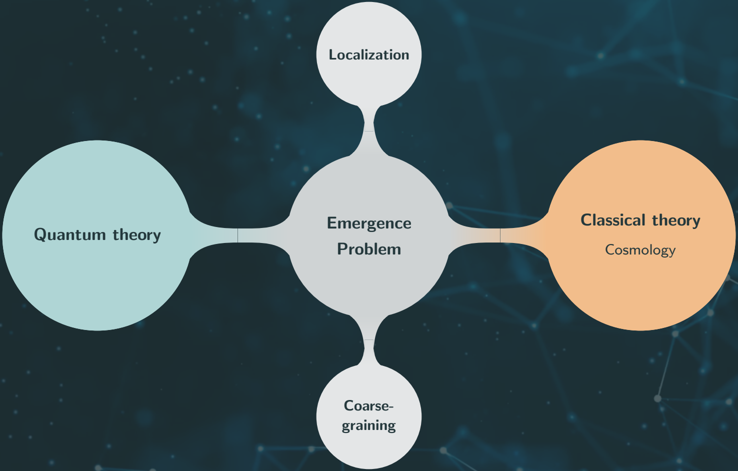
- Averaged QG dynamics and observables on cosmological coherent states (scalar field matter).

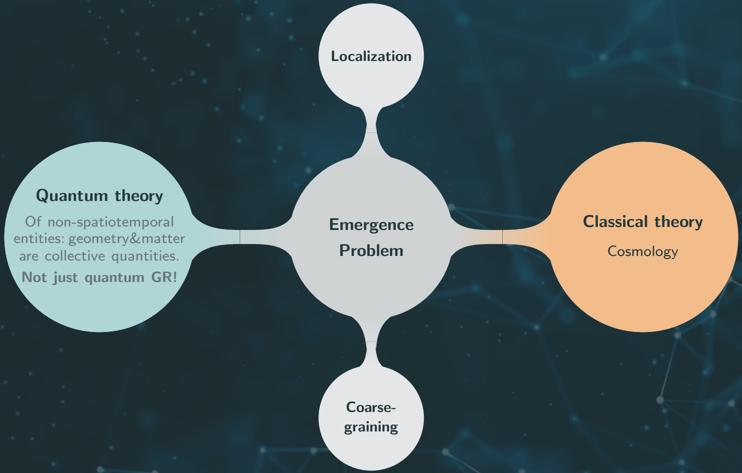
Free theory

- 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 dynamical dark energy.


Localization
Quantum theory
Emergence Problem
Classical theory
Cosmology
Coarse-graining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Of non-spatiotemporal entities: geometry&matter are collective quantities.
Not just quantum GR!
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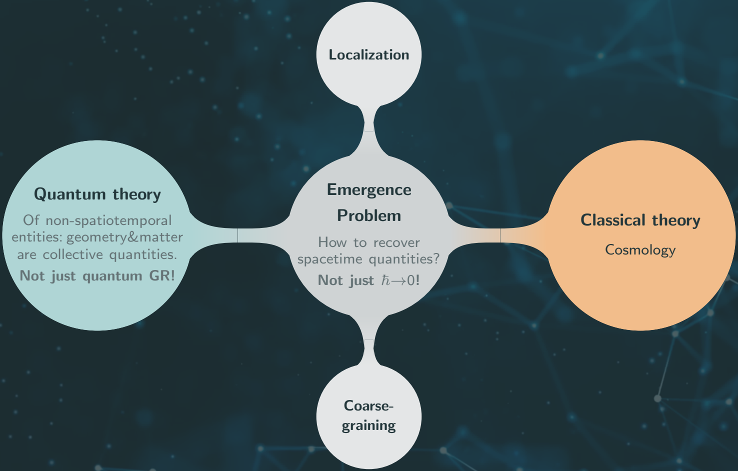

Localization
Emergence Problem
How to recover spacetime quantities?
Not just $\hbar \to 0$!
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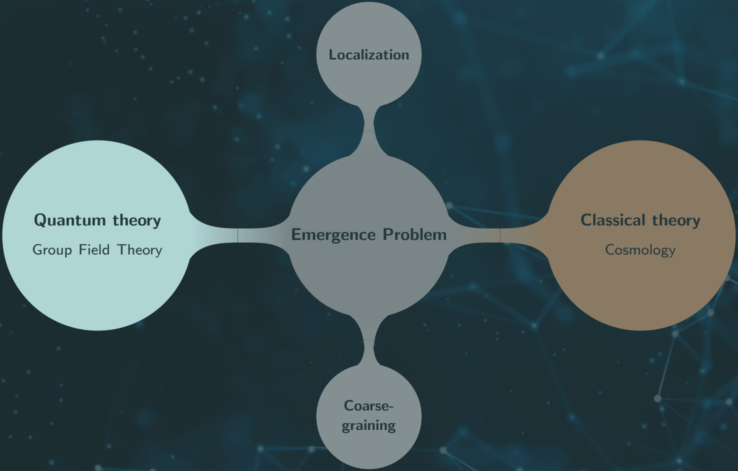
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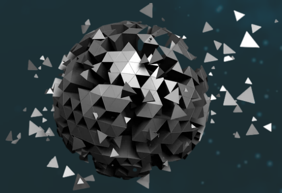
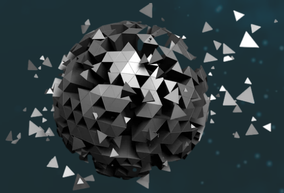


Kinematics: GFT quanta

- Take an elementary building block of a discrete (3d-)boundary (tetrahedron).



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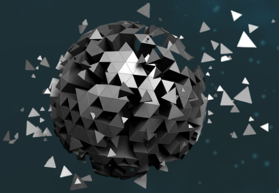
- Decorate it with quantum numbers associated with fields discretized over it (gravitational $= g_a \in \mathrm{SL}(2,\mathbb{C})$, scalar fields $= \mathbf{\Phi} \in \mathbb{R}^n$).



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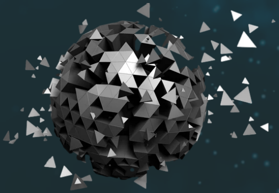
$\varphi(g_a, \mathbf{\Phi}) \quad \leftarrow$



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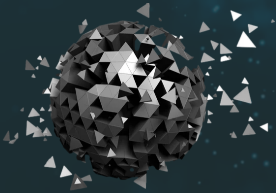
- Promote $\varphi \to \hat{\varphi}$; construct Fock space and second-quantized observables.



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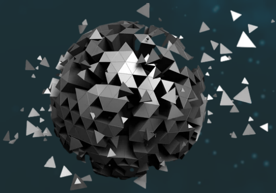

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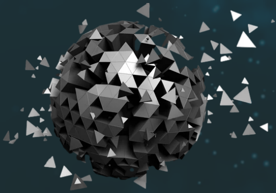
$$\Gamma \overset{(3d)}{=}$$



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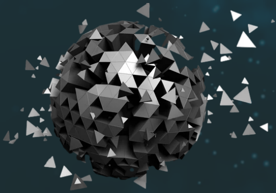
$Z_{\mathrm{GFT}} =$ background independent QG-matter path-integral.



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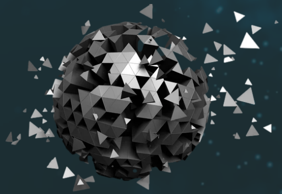

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- Spacetime quantities emerge from microscopic QG atoms!

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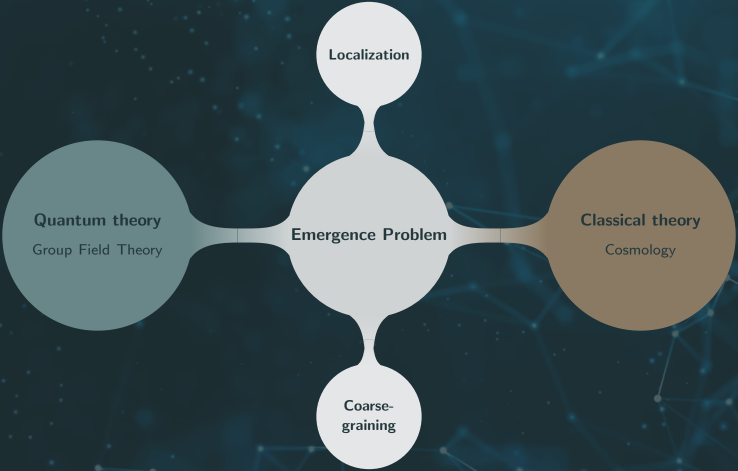
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The emergence problem

Localization

No spacetime local observables in gravity: How to localize in QG?

Aguilar, Höhn, Ferrero, LM (to appear); LM, Oriti, Pithis, Thürigen 2211.12768-2209.04297-2110.15336; LM, Wilson-Ewing 2412.14622.

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Continuum QG

- **Relational obs.**: localized wrt dynamical QRFs.
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Average relational strategy

- Only on average for collective observables and states.
- Internal frame not too quantum.

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Mean-field theory

- Saddle-point evaluation of Z_{GFT}: QG hydrodynamics on superspace!
- Collective and non-perturbative (all tree-level graphs)!

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Implementation in GFT: superspace hydrodynamics

States

GFT coherent states

- Collectivity: States should accommodate an infinite number of quanta. E.g.: coherent states $|\sigma\rangle$.
- Hydrodynamic: $\sigma \sim$ density distribution on superspace. It characterizes the emergent system.
- Relationality: $|\sigma\rangle$ is frame-localized (can alternatively be implemented on observables).

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

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Macroscopic dynamics = mean-field approximation

- Mean-field equations from σ-averaged quantum equations of motion: $\langle \delta S_{\mathrm{GFT}} / \delta \hat{\varphi}^\dagger \rangle_\sigma = 0$.

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- Usually $\mathcal{K}$ is a 2nd order differential operator. $\mathcal{U}$ generally non-local and non-linear.
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notation: $\varphi \cdot \psi = \int_\Omega \mathrm{d}\Omega\, \varphi\psi$

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- E.g. number $N_\sigma \equiv \langle\hat{N}\rangle_\sigma = \sigma^*\cdot\sigma$ and volume $V_\sigma \equiv \langle\hat{V}\rangle_\sigma = \sigma^*\cdot V[\sigma]$

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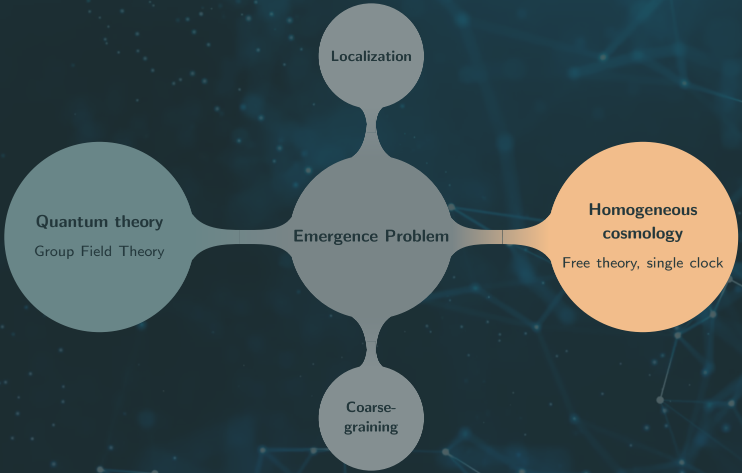
Localization
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Homogeneous cosmology
Free theory, single clock
Coarse-graining

Effective FLRW cosmological dynamics

Effective dynamics

Mean-field approximation

- Homogeneity: σ depends on geometry + clock χ^0.
- Isotropy: $\sigma_\upsilon \equiv \rho_\upsilon e^{i\theta_\upsilon}$ ($\upsilon_{\text{EPRL}} \in \mathbb{N}/2$, $\upsilon_{\text{BC}} \in \mathbb{R}$).
- Mesoscopic regime: negligible interactions.
- V_σ (thus a) increases as ρ_υ (thus N_σ) increases.

$$0 = \mathcal{K}[\sigma],$$

$$V_\sigma(x^0) = \sum\!\!\!\!\!\!\int_\upsilon V_\upsilon |\sigma_\upsilon|^2(x^0).$$

$$= \bar{V}_0 a^3 \quad \longrightarrow \quad \{\mathcal{H}(V_\sigma), w(V_\sigma)\}\,.$$

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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Late/early times

Large/small number of quanta

- ✓ Volume quantum fluctuations under control.
- ✓ If one υ_o is dominating and $\mu_{\upsilon_o}^2 = 3\pi G$, matching with relational GR dynamics:

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

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: σ depends on geometry + clock χ^0.
- Isotropy: $\sigma_\upsilon \equiv \rho_\upsilon e^{i\theta_\upsilon}$ ($\upsilon_{\text{EPRL}} \in \mathbb{N}/2$, $\upsilon_{\text{BC}} \in \mathbb{R}$).
- Mesoscopic regime: negligible interactions.
- V_σ (thus a) increases as ρ_υ (thus N_σ) increases.

$$
\begin{aligned}
0 &= \mathcal{K}[\sigma],\\
V_\sigma(x^0) &= \sum\!\!\!\!\!\!\int_\upsilon V_\upsilon |\sigma_\upsilon|^2(x^0).\\
&= \bar{V}_0 a^3 \quad \longrightarrow \quad \{\mathcal{H}(V_\sigma), w(V_\sigma)\}\,.
\end{aligned}
$$

$$
\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, \quad \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}
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Late/early times

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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!

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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!

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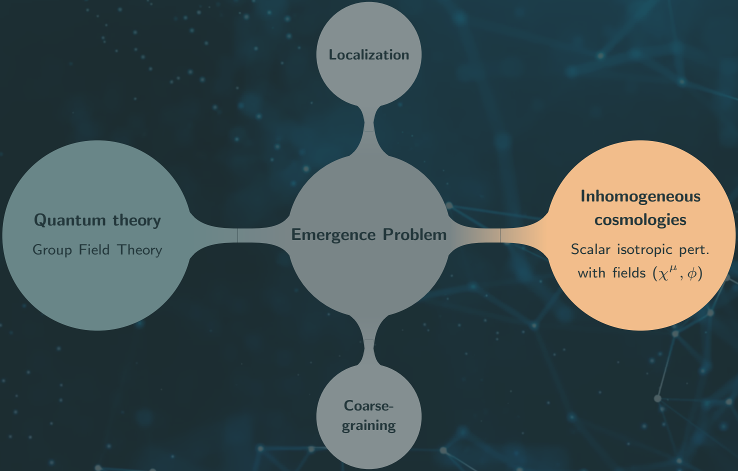
Localization
Quantum theory
Group Field Theory
Emergence Problem
Inhomogeneous cosmologies
Scalar isotropic pert. with fields (χ^μ, ϕ)
Coarse-graining

Scalar perturbations from quantum entanglement

Setting

Classical

- 4 MCMF reference fields (χ^0, χ^i),
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Jercher, LM, Pithis 2310.17549-2308.13261; LM, Oriti 2112.12677; Jercher, Oriti, Pithis 2206.15442.

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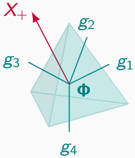
Two-sector GFT

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

$$K_+ \text{ independent of } \chi^i. \; K_- \text{ independent of } \chi^0.$$



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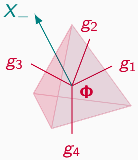

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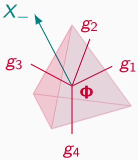

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Collective states

Two-body correlations

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

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

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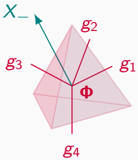

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Background

- $\hat{\sigma} = (\sigma, \hat{\varphi}_+^\dagger)$: spacelike condensate.
- $\hat{\tau} = (\tau, \hat{\varphi}_-^\dagger)$: timelike condensate.
- τ, σ background and frame-local.

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

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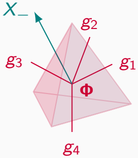

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Perturbations

- $\widehat{\delta\Phi} = (\delta\Phi, \hat\varphi_+^\dagger \hat\varphi_+^\dagger)$, $\widehat{\delta\Psi} = (\delta\Psi, \hat\varphi_+^\dagger \hat\varphi_-^\dagger)$, $\widehat{\delta\Xi} = (\delta\Xi, \hat\varphi_-^\dagger \hat\varphi_-^\dagger)$.
- $\delta\Phi$, $\delta\Psi$ 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.

Emergent dynamics of cosmic inhomogeneities

E.o.m.

Mean-field dynamics

- 2 mean-field eqs. for 3 variables $(\delta\Phi, \delta\Psi, \delta\Xi)$:
$$\langle \delta S_{\mathrm{GFT}}/\delta\hat{\varphi}_{+}^{\dagger}\rangle_{\Delta} = 0 = \langle \delta S_{\mathrm{GFT}}/\delta\hat{\varphi}_{-}^{\dagger}\rangle_{\Delta}$$
- Free theory, late times and single rep. label.

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- Physics captured by rel. localized averages:
$$\langle \hat{\mathcal{O}}_{\rm GFT}\rangle_\Delta = \bar{\mathcal{O}}_{\rm GFT}(x^0) + \delta\mathcal{O}_{\rm GFT}(x^0, \boldsymbol{x})\,.$$
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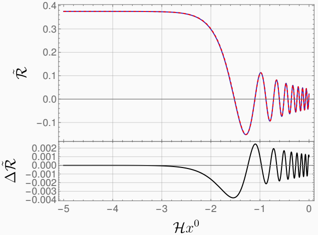
Effective dynamics

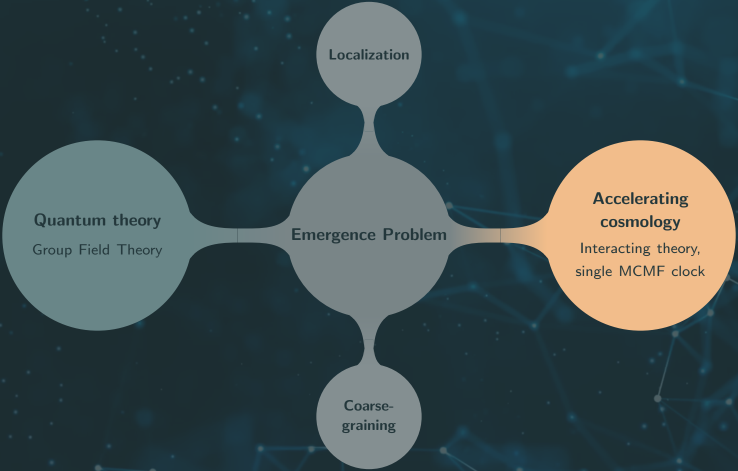
Classical dynamics with trans-Planckian QG effects

- 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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Pseudosimplicial: Attractor

Model and Assumptions

- (Pseudo-)Simplicial interactions: Inspired from the ones producing simplicial gravity amplitudes.
- Phase dependence: As $m \neq 0$ equations depend on ρ_υ and θ_υ (also in $\varphi_\upsilon \equiv \vartheta_\upsilon + m\theta_\upsilon$).
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Ladstätter, LM, Oriti (to appear); Ladstätter, LM 2508.16194; Oriti, Pang 2105.03751-2502.12419; De Cesare, Pithis, Sakellariadou 1606.00352...

Emergent dynamical dark energy

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Evolving Dark Energy

- Asymptotically autonomous system: standard stability analysis possible.

$$x = \theta\,, \quad y = \rho'/\rho^3\,, \quad z = \theta'\,.$$

$$\begin{aligned} x' &= z\,,\\ y' &= -3\rho^2 y^2 + (z^2 + m^2)/\rho^2 + \lambda\rho^{l-3}\cos\varphi(x)\,,\\ z' &= -2\rho^2 yz + \lambda\rho^{l-1}\sin\varphi(x)\,. \end{aligned}$$

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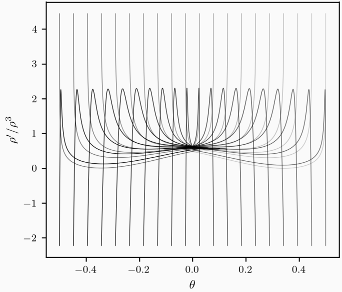

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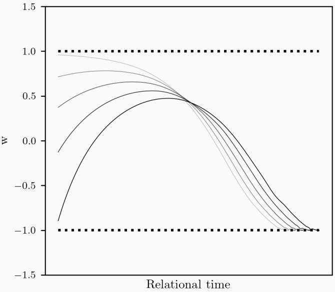

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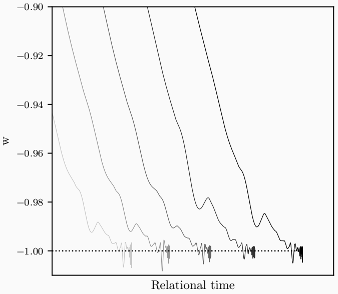

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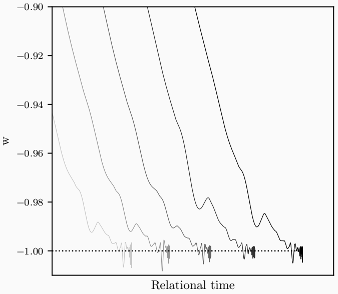

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Non-Hermitian: fixed point instability

Model and Assumptions

- Non-Hermitian interactions: Cannot be generated by a real polynomial interaction term.
- Dissipative hydrodynamics? Non-Hermitian dynamics typically relevant in dissipative systems.
- Single-mode and $l = 5$: All computations done in a single-mode υ_o scenario and with $l = 5$.

Ladstätter, LM, Oriti (to appear); Ladstätter, LM 2508.16194; Mukhanov 1409.2335.

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- dS not an attractor: unstable fixed point!

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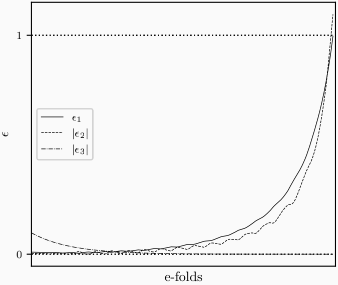

Ladstätter, LM, Oriti (to appear); Ladstätter, LM 2508.16194; Mukhanov 1409.2335.

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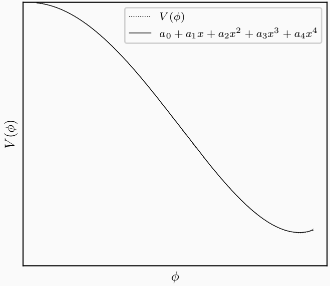

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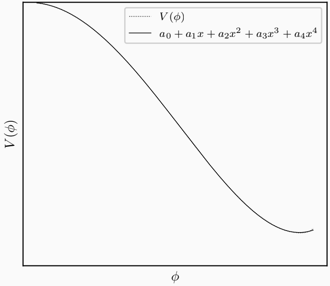

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Quantum Gravity: Group Field Theories

- Group Field Theories are QFTs of spacetime atoms which collectively create spacetime structures.

Quantum many-body theories on superspace, not spacetime

- Natural to import techniques and ideas from condensed matter physics.
- A crossroads between different approaches to QG: "universal" language for QG phenomena?

Part II

Emergence: Coarse-Graining and Localization on Superspace

- What is local physics in QG? How to coarse-grain (renormalize) without energy/length scales?
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Phenomenological consequences?