Emergent Cosmology from (T)GFT Condensates

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Quantum gravity, Hydrodynamics and Emergent Cosmology
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Arnold Sommerfeld Center
LMU Munich

The QG perspective on Cosmology

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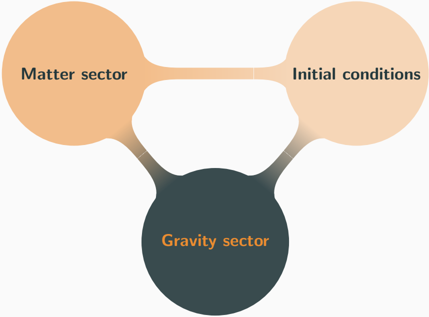

Ashtekar, Kaminski, Lewandowski 0901.0933; Agullo, Ashtekar, Nelson 1302.0254; Gielen, Oriti 1709.01095; Gerhart, Oriti, Wilson-Ewing 1805.03099; ...

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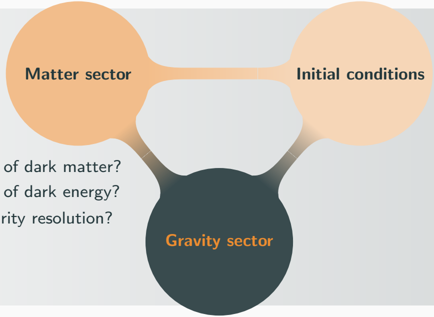

- Nature of dark matter?
- Nature of dark energy?
- Singularity resolution?
- ...

The QG perspective on Cosmology

Matter sector

Initial conditions

Gravity sector

- Nature of dark matter?
- Nature of dark energy?
- Singularity resolution?
- ...

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

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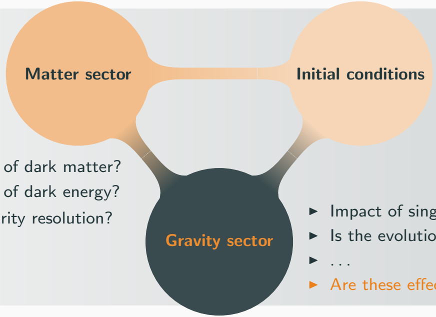

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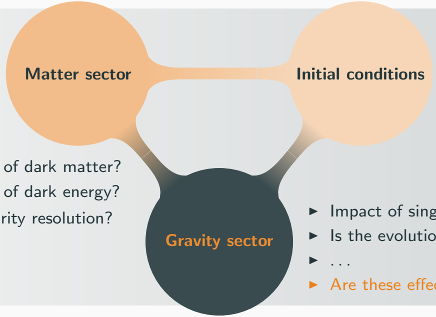

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Challenges from the QG perspective:

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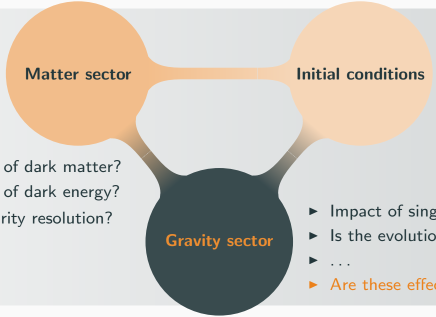

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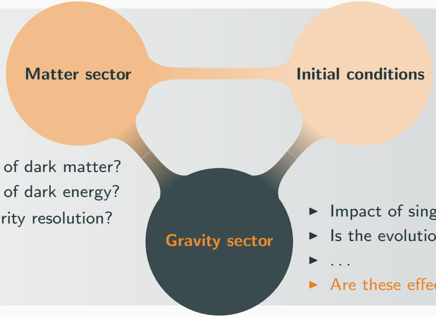

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Relational description

Coarse-graining/ collective behavior

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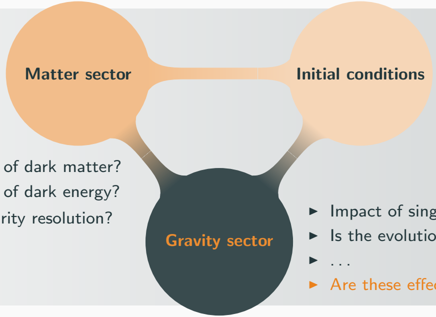

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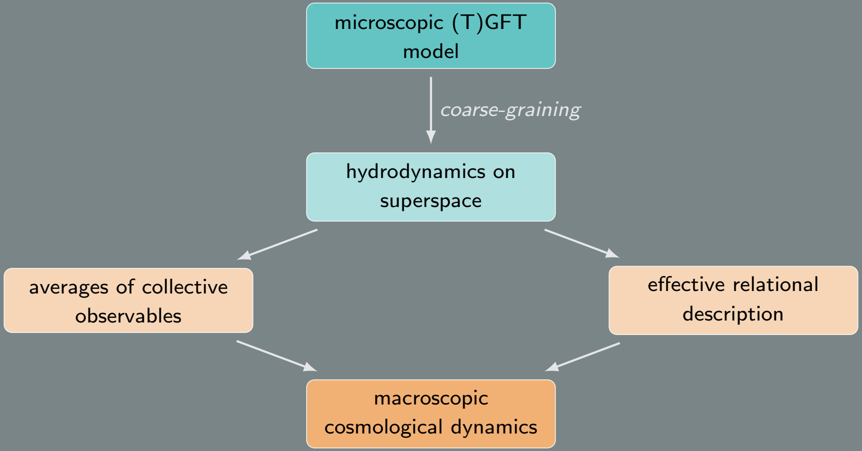
Challenges from the QG perspective:

- How to define (in)homogeneity? → Relational description
- How to extract macroscopic dynamics? → Relational description; Coarse-graining/ collective behavior
- How to construct cosmological geometries? → Coarse-graining/ collective behavior
- . . .

Approximate only

Homogeneous cosmologies from (T)GFT condensates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coarse-graining
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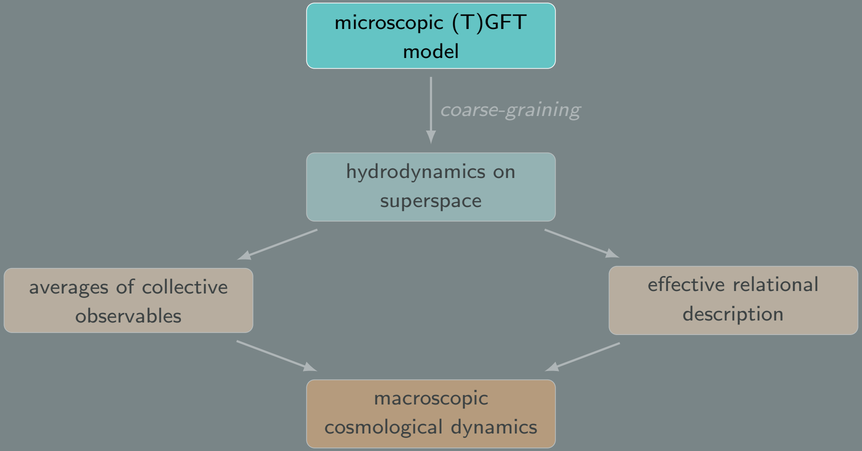
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The (T)GFT approach to QG

(Tensorial) 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, for some models, $G = \mathrm{SU}(2)$.

Oriti 0912.2441; Oriti 1408.7112; Krajewski 1210.6257; Gielen, Oriti 1311.1238; Oriti, Sindoni, Wilson-Ewing 1602.05881; Gielen, Sindoni 1602.08104; ...

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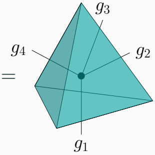
Kinematical states: $d-1$-simplices decorated with discretized field data

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

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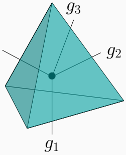
$\mathcal{H}_{\text{1-p}} =$ 

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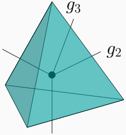
$\mathcal{H}_{\text{1-p}} =$ 

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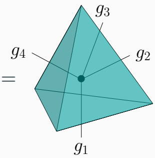
$\mathcal{H}_{\text{1-p}} =$ 

Dynamics: connection with simplicial/spinfoam models

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

$$Z_{\mathrm{GFT}} = \sum_{\Gamma} \frac{\prod_i \lambda_i^{n_i(\Gamma)}}{\mathrm{sym}(\Gamma)} Z_{\mathrm{GFT}}(\Gamma)$$

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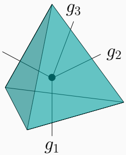
$\mathcal{H}_{\text{1-p}} =$ 

Dynamics: connection with simplicial/spinfoam models

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

- Non-local and combinatorial interactions guarantee the gluing of $d - 1$-simplices into d-simplices.
- Γ are dual to spacetime triangulations.

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The (T)GFT approach to QG

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

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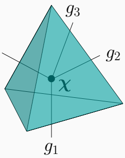
Kinematical states: $d-1$-simplices decorated with discretized field data

- Group (Lie algebra) variables associated to discretized gravitational quantities.
- Appropriate (geometricity) constraints allow the simplicial interpretation.
- Scalar field discretized on each d-simplex: each $d-1$-simplex composing it carries values $\chi \in \mathbb{R}^{d_l}$.

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

Dynamics: connection with simplicial/spinfoam models

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

- Non-local and combinatorial interactions guarantee the gluing of $d-1$-simplices into d-simplices.
- Γ are dual to spacetime triangulations.
- Scalar field data are local in interactions.

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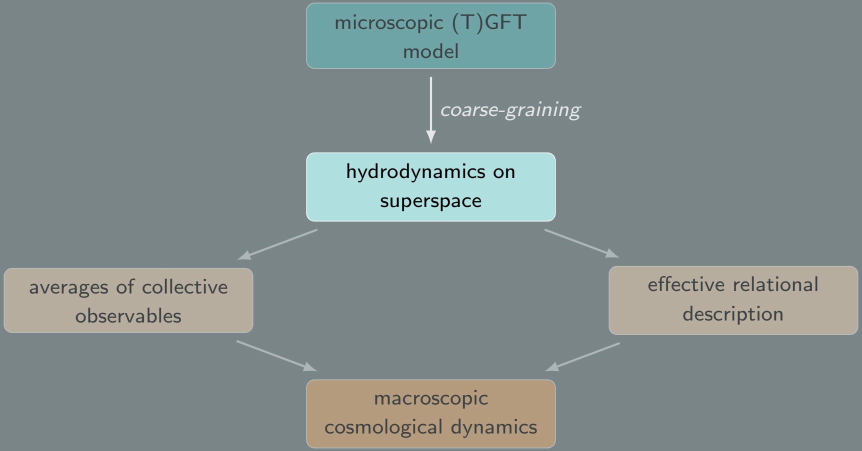
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QG condensates and peaked states

Collective states

(T)GFT condensates

Simplest collective behavior: macroscopic σ dynamics well described in the mean-field approx.

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

LM, Oriti 2008.02774; LM, Oriti 2112.12677; Oriti, Sindoni, Wilson-Ewing 1602.05881; Gielen, Oriti, Sindoni 1311.1238; Gielen 1404.2944;

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- Assuming $\sigma(g_I,\cdot) = \sigma(hg_Ih',\cdot)$, $\mathcal{D} = \mathrm{GL}(3)/\mathrm{O}(3)\times\mathbb{R}^{d_l}$:
- $\mathcal{D}$ = space of spatial geometries + matter at a point.
- If χ^μ, $\mu = 0,\dots,d-1$ constitute a matter ref. frame:

→ $\sigma(g_I,\chi^a;\chi^\mu) \sim$ distrib. of spatial geometries and matter at χ^μ.

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Relationality

Condensate Peaked States

- If σ is peaked on $\chi^\mu \simeq x^\mu$, $|\sigma\rangle_x$ encodes relational info. about spatial geometry + matter at x^μ.

  σ = (fixed peaking function η) $\times$ (dynamically determined reduced wavefunction $\tilde{\sigma}$)

- Relational strategy implemented at an effective level on "hydrodynamic" (averaged) quantities.

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Spatial relational homogeneity: σ depends on a single "clock" scalar field χ^0
($\mathcal{D}$ = minisuperspace + homogeneous massless free clock)

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Mean-field approximation and QG hydrodynamics

σ-hydrodynamics

Mean-field approximation: A non-linear and non-local extension of QC

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

- Non-localities present in geometric (g_I) and pre-matter (χ) variables.
- Non-linearities prevent any quantum-mechanical interpretation for σ (no superposition principle).

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$\sigma \neq$ Wavefunction of the Universe (though they share the same domain)

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Simplified σ-dynamics

Working approximations

- Mesoscopic regime: large N but negligible interactions.
- Linearized dynamics.

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- Mesoscopic regime: large N but negligible interactions.
- Hydrodynamic truncation of kinetic kernel due to peaking properties.
- Linearized dynamics.
- Differential equation in x^0.

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

Mean-field approximation and QG hydrodynamics

σ-hydrodynamics

Mean-field approximation: A non-linear and non-local extension of QC

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

- Non-localities present in geometric (g_I) and pre-matter (χ) variables.
- Non-linearities prevent any quantum-mechanical interpretation for σ (no superposition principle).

$\sigma \neq$ Wavefunction of the Universe (though they share the same domain)

- Only statistical interpretation of σ, as a distribution producing observable averages.

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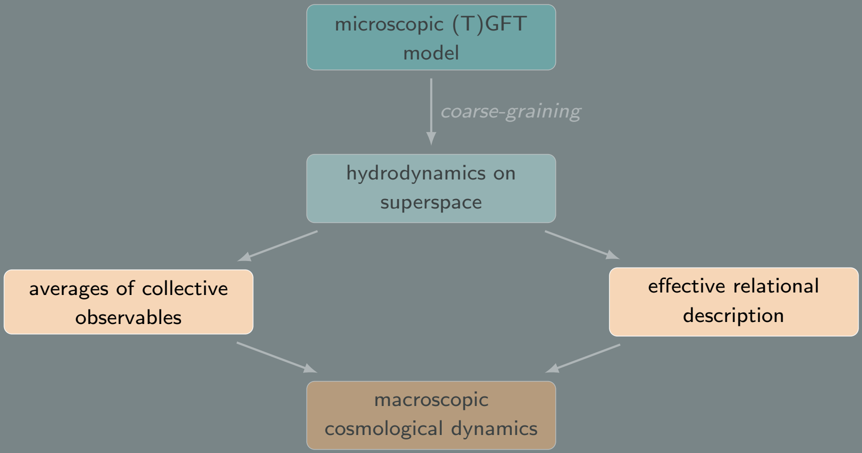
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Cosmology from QG condensates: observables and relationality

Spatial relational homogeneity:
σ depends on a single "clock" scalar field χ^0
($\mathcal{D} = \text{minisuperspace} + \text{clock}$)

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

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

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Relationality

- Averaged evolution wrt x^0 is physical:

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

- 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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Wavefunction $\longrightarrow$ isotropy

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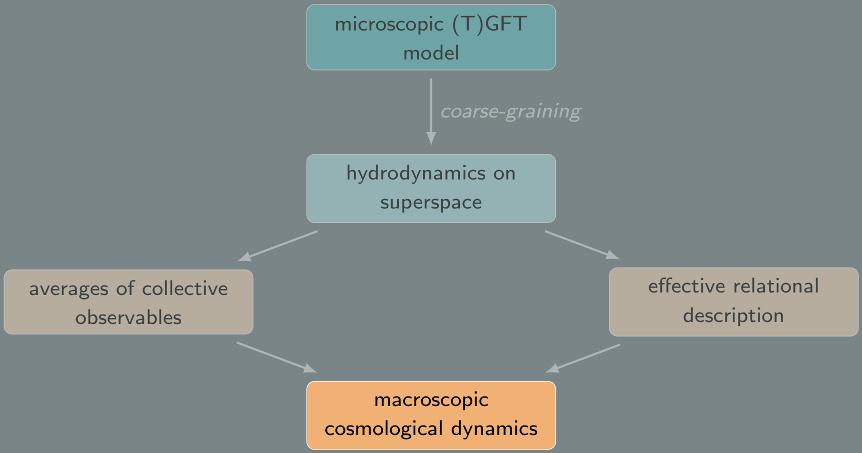
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$$\left(\frac{V'}{3V}\right)^2 \simeq \left(\frac{2\sum\!\!\!\!\!\!\int_\upsilon V_\upsilon \rho_\upsilon \operatorname{sgn}(\rho'_\upsilon)\sqrt{\mathcal{E}_\upsilon - Q^2_\upsilon/\rho^2_\upsilon + \mu^2_\upsilon\rho^2_\upsilon}}{3\sum\!\!\!\!\!\!\int_\upsilon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

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Classical limit (large ρ_υs, late times)

- If μ_υ^2 is mildly dependent on υ (or one υ is dominating) and equal to $3\pi G$

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

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

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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 $\mathcal{E}_\upsilon < 0$).
- The average singularity resolution may still be spoiled by quantum effects on geometric and clock variables.

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Exploring the physics of (T)GFT condensates

Geometric acceleration from interactions

De Cesare, Oriti, Pithis 1606.00352; LM, Oriti 2112.12677; Oriti, Pang 2105.03751; Ladstätter, LM, Oriti (to appear); Jercher, LM, Pithis (to appear)

Physics of (T)GFT cosmology

Including interactions

Geometric acceleration from interactions

Early times: geometric inflation

✓ Geometric inflation from QG interactions.

⚠ For some models bottom-up natural and slow-roll.

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Effective dynamics of cosmological scalar perturbations

- ► Classical system: gravity + 5 m.c.m.f. scalar fields, 4 of which constitute the relational frame.
- ► Perturbations at the level of σ.
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- ⚠ Full relational frame requires quanta with different causal properties.
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Geometry from quantum correlations!

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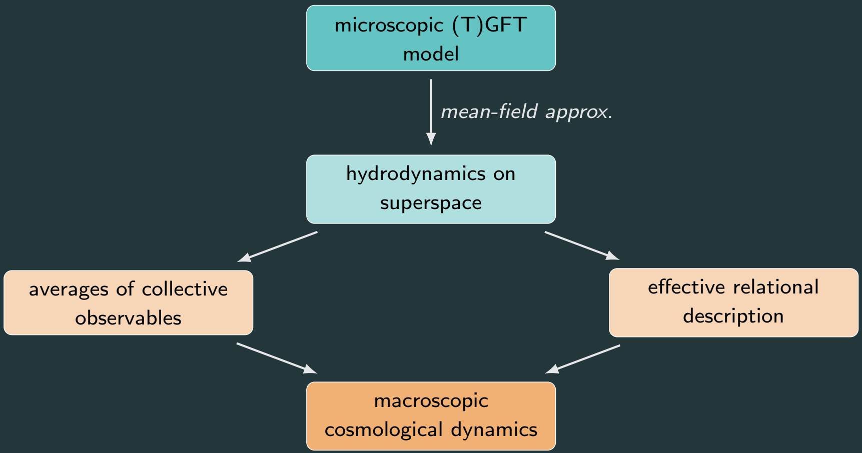
microscopic (T)GFT model
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- Quanta: simplices decorated with discretized fields.
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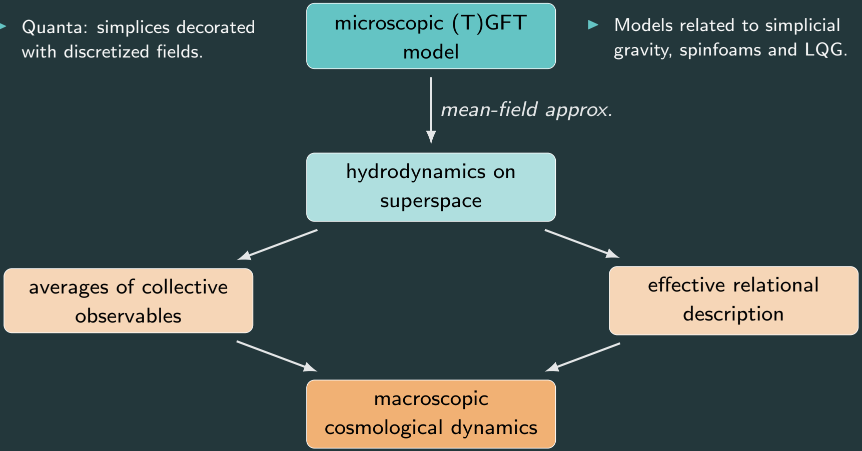

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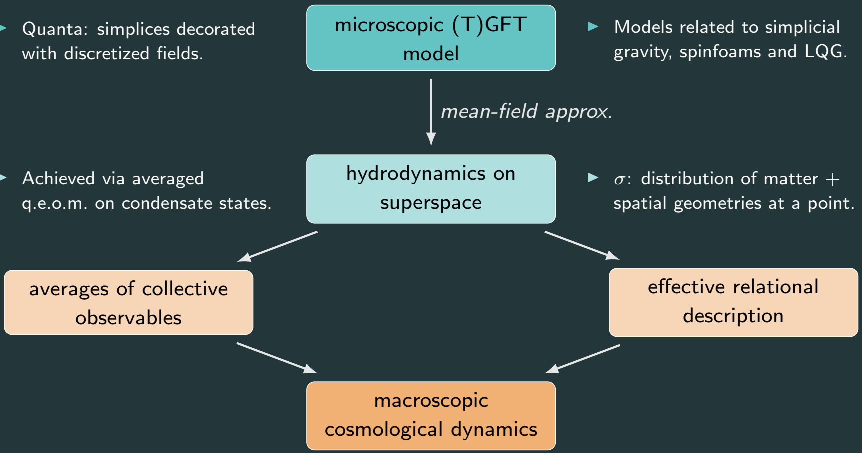

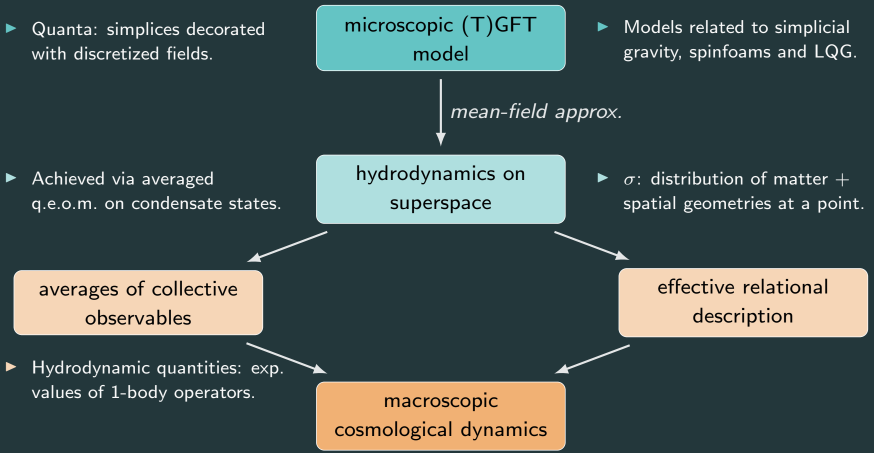
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- Late times: FRLW flat classical dynamics.
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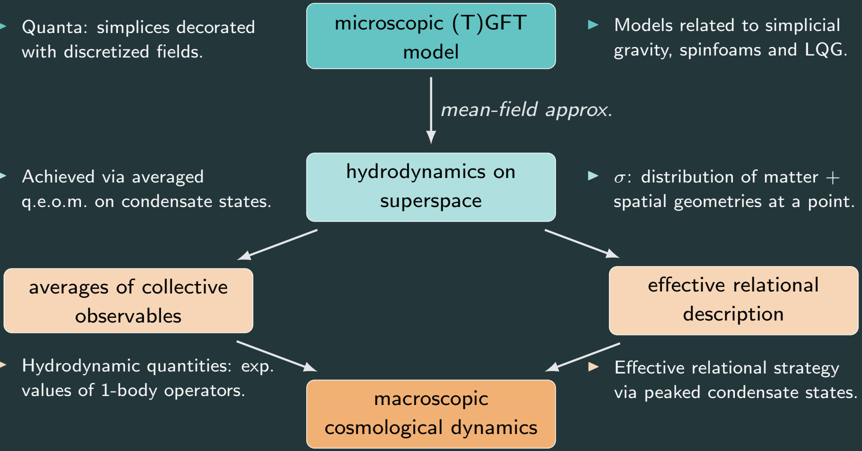

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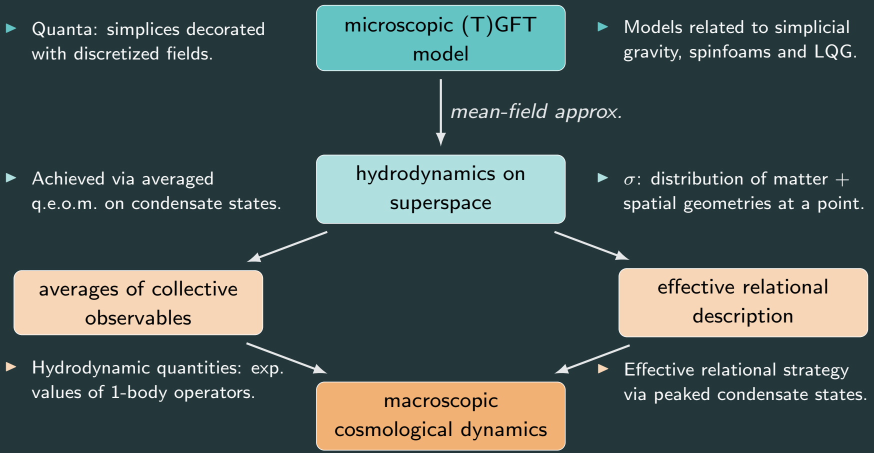
Homogeneous, interacting

- Late times: emergence of phantom dark energy.
- Early times: possible geometric slow-roll inflation.



Homogeneous, free

- Late times: FRLW flat classical dynamics.
- Early times: averaged quantum bounce.

Homogeneous, interacting

- Late times: emergence of phantom dark energy.
- Early times: possible geometric slow-roll inflation.

(Scalar) Inhomogeneities, free

- Late times: strong indications for GR matching.
- Early times: deviations from classical gravity.

Backup

Relational strategy: the classical and quantum GR perspective

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

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

Classical

Notion of relationality can be classically encoded in 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, often written in series form.
- Applications only for (almost) deparametrizable systems, such as GR plus pressureless dust or massless scalar fields.

Quantum GR

Dirac approach: first quantize, then implement relationality

- Perspective neutral approach: all variables are treated on the same footing.
- Poor control of the physical Hilbert space.

Reduced phase space approach: first implment relationality, then quantize

- No quantum constraint to solve.
- Led to quantization of simple deparametrizable models (LQG).
- Not perspective neutral. Too complicated to implement in most of the cases.

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

Relational strategy and emergent quantum gravity theories

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

- Well understood from a classical perspective, less from a quantum perspective.
- Difficulties especially relevant for emergent QG theories.

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.

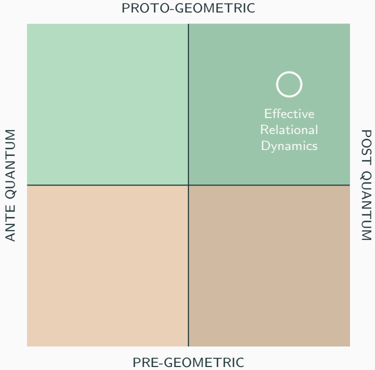
The quantities whose evolution we want to describe relationally are the result of a coarse-graining of some fundamental d.o.f.

Effective approaches:

- Bypass most conceptual and technical difficulties;
- Relevant for observative purposes.

LM, Oriti 2008.02774; Giulini 0603087; Kuchar Int.J.Mod.Phys.D 20(2011); Isham 9210011; Rovelli Class. Quantum Grav. 8 297;

Emergent effective relational dynamics



Basic principles

Emergence Rel. dynamics formulated in terms of collective observables and states defined in the microscopic theory.

Effectiveness Rel. evolution intended to hold on average. Internal clock not too quantum.

Concrete example: scalar field clock

Emergence

- Identify a class of states $|\Psi\rangle$ which encode collective behavior and admit a continuum proto-geometric interpretation.
- Identify a set of collective observables:

$\hat{O}_a \xrightarrow{\langle\cdot\rangle_\Psi}$ Geometric observables

$\hat{\chi}\quad\hat{\Pi} \xrightarrow{\langle\cdot\rangle_\Psi}$ Scalar field and its momentum

$\hat{N} \xrightarrow{\langle\cdot\rangle_\Psi}$ Number of quanta

Effectivness

- It exists a "Hamiltonian" $\hat{H}$ such that

$$i\frac{\mathrm{d}}{\mathrm{d}\,\langle\hat{\chi}\rangle_\Psi}\langle\hat{O}_a\rangle_\Psi = \langle[\hat{H},\hat{O}_a]\rangle_\Psi\ ,$$

  and whose moments coincide with those of $\hat{\Pi}$.
- Relative variance of $\hat{\chi}$ on $|\Psi\rangle$ should be $\ll 1$ and have the characteristic $\langle\hat{N}\rangle_\Psi^{-1}$ behavior:

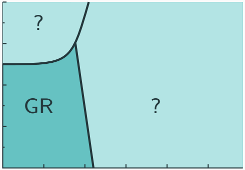
$$\sigma_\chi^2 \ll 1\,,\qquad \sigma_\chi^2\sim\langle\hat{N}\rangle_\Psi^{-1}\ .$$

LM, Oriti 2008.02774; Bojowald, Hoehn, Tsobanian 1011.3040; Bojowald, Tsobanian 0906.1772;

Continuum physics and QG: the general perspective

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

Full partition function needed!



The (F)RG perspective

Spacetime QFT

- Energy scale defines the flow from IR and UV.

QG theory

- Only internal "timeless" scales available.

UV and IR have different meaning in QG!

- Theory space constrained by symmetries.
- Symmetries of QG models hard to classify.

Little control over QG theory space!

Approximate methods: mean-field theory

- Based on collective quantity: order parameter.
- Mean-field (saddle-point) approx. of Z: "simple" computations!
- Good description of quantum condensate phase transitions.
- QG counterpart of the Gross-Pitaevskii approximation in the hydrodynamics of quantum fluids.

Oriti 2112.02585, Reuter, Saueressig 2019, Kopietz et al. 2010, Finocchiaro, Oriti 2004.07361, Carrozza 1603.01902 . . .

Scalar perturbations from (T)GFT condensates

Simplest (slightly) relationally inhomogeneous system

LM, Oriti 2112.12677; Gerhart, Oriti, Wilson-Ewing 1805.03099

Scalar perturbations from (T)GFT condensates

Simplest (slightly) relationally inhomogeneous system

Classical

- 4 MCM reference fields (χ^0, χ^i), with Lorentz/Euclidean invariant S_χ in field space.
- 1 MCM matter field ϕ dominating the e.m. budget and relationally inhomog. wrt. χ^i.

LM, Oriti 2112.12677; Gerhart, Oriti, Wilson-Ewing 1805.03099

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Quantum

- (T)GFT field: $\varphi(g_I, \chi^\mu, \phi)$, depends on 5 discretized scalar variables.
- EPRL-like or extended BC model with S_{GFT} respecting the classical matter symmetries.

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Observables

notation: $(\cdot,\cdot) = \int \mathrm{d}^4\chi \mathrm{d}\phi \mathrm{d}g_I$

Mat. Vol. Frame

$$\hat{X}^\mu = (\hat{\varphi}^\dagger, \chi^\mu \hat{\varphi}) \quad \hat{\Pi}^\mu = -i(\hat{\varphi}^\dagger, \partial_\mu \hat{\varphi})$$

Only isotropic info: $\hat{V} = (\hat{\varphi}^\dagger, V[\hat{\varphi}])$

$$\hat{\Phi} = (\hat{\varphi}^\dagger, \phi\hat{\varphi}) \qquad \hat{\Pi}_\phi = -i(\hat{\varphi}^\dagger, \partial_\phi \hat{\varphi})$$

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States

- CPSs around $\chi^\mu = x^\mu$, with
  - η: Isotropic peaking on rods;
  - $\tilde{\sigma}$: Isotropic distribution of geometric data.
- Small relational $\tilde{\sigma}$-inhomogeneities ($\tilde{\sigma} = \rho e^{i\theta}$): $\rho = \bar{\rho}(\cdot, \chi^0) + \delta\rho(\cdot, \chi^\mu)$, $\theta = \bar{\theta}(\cdot, \chi^0) + \delta\theta(\cdot, \chi^\mu)$.

LM, Oriti 2112.12677; Gerhart, Oriti, Wilson-Ewing 1805.03099

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Late times volume and matter dynamics

- Averaged q.e.o.m. $\longrightarrow$ coupled differential equations for ρ and θ.
- Decoupling for a range of values of CPSs and large N (late times).

$\longrightarrow$ Dynamic equations for $\langle\hat V\rangle_\sigma$, $\langle\hat\Phi\rangle_\sigma$

LM, Oriti 2112.12677; Gerhart, Oriti, Wilson-Ewing 1805.03099

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Background

- Matching with GR (assuming peaking on matter momenta).
- Emergent matter and G defined in terms of microscopic parameters.

LM, Oriti 2112.12677; Gerhart, Oriti, Wilson-Ewing 1805.03099

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Perturbations

- Super-horizon GR matching.

LM, Oriti 2112.12677; Gerhart, Oriti, Wilson-Ewing 1805.03099

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Background

- Matching with GR (assuming peaking on matter momenta).
- Emergent matter and G defined in terms of microscopic parameters.

Perturbations

- Super-horizon GR matching.
- No matching for intermediate modes (because of different coupling with bkg effective metric)!
- Effective metric signature determined by CPSs.

LM, Oriti 2112.12677; Gerhart, Oriti, Wilson-Ewing 1805.03099

Volume at late times

Background

Classical

- Harmonic gauge: $N = a^3$.
- Negligible contribution of reference matter.

$$(\bar{V}'/\bar{V})^2 = 12\pi G \pi_\phi^{(c)}$$
$$(\bar{V}'/\bar{V})' = 0$$

Quantum

- Wavefunction peaked on $\pi_\phi = \tilde{\pi}_\phi$.
- Domination of single spin υ_o.
- $\mu_{\upsilon_o}(\pi_\phi) \simeq c_{\upsilon_o}\pi_\phi$, with $4c_{\upsilon_o}^2 = 12\pi G$.

$$(\bar{V}'/\bar{V})^2 = 12\pi G\tilde{\pi}_\phi \quad (\bar{V}'/\bar{V})' = 0$$

Perturbations

Classical

- First order harmonic gauge.
- Negligible contribution of reference matter.
- Define $V(x) = \sqrt{\det q_{ij}} \equiv \bar{V} + \delta V$.

$$\delta V'' - 6\mathcal{H}\delta V' + 9\mathcal{H}^2\delta V - \bar{V}^{4/3}\nabla^2\delta V = 0\,.$$

Quantum

- Wavefunction peaked on $\pi_\phi = \tilde{\pi}_\phi$.
- Domination of single υ_o: $\delta V \equiv 2\bar{\rho}_{\upsilon_o}\delta\rho_{\upsilon_o}$.
- $\mu_{\upsilon_o}(\pi_\phi) \simeq c_{\upsilon_o}\pi_\phi$, with $4c_{\upsilon_o}^2 = 12\pi G$.

$$\delta V'' - 3\mathcal{H}\delta V' + \mathrm{Re}(\alpha^2)\nabla^2\delta V = 0\,.$$

Super-horizon

- Matches the classical solution $\delta V \propto \bar{V}$.

Sub-horizon

- Same diff. structure but different powers of $\bar{V}$.

No matching with GR for arbitrary modes.

LM, Oriti 2112.12677; Gerhart, Oriti, Wilson-Ewing 1805.03099;

Matter at late times

Background

Classical

- Harmonic gauge: $N = a^3$.
- Negligible contribution of ref. matter.

$$\bar{\phi}'' = 0\,,$$
$$\pi_\phi^{(c)} = \text{const.}\,.$$

Quantum

- Wavefunction peaked on $\pi_\phi = \tilde{\pi}_\phi$.
- Domination of single υ_o.

$$\langle \hat{\Pi}_\phi \rangle_{\bar{\sigma}} = \tilde{\pi}_\phi \bar{N}\,,$$
$$\langle \Phi \rangle_{\bar{\sigma}} = \left[-\partial_{\pi_\phi} \left[\frac{Q_{\upsilon_o}}{\mu_{\upsilon_o}} \right] + Q_{\upsilon_o} \frac{\partial_{\pi_\phi} \mu_{\upsilon_o}}{\mu_{\upsilon_o}} x^0 \right]_{\pi_\phi = \tilde{\pi}_\phi}$$

Matching conditions

- $\pi_\phi^{(c)} \equiv \langle \hat{\Pi}_\phi \rangle_{\bar{\sigma}} / \bar{N} = \tilde{\pi}_\phi$.
- Peaking in $\pi_\phi \longrightarrow$ peaking in matter field momenta.
- $\phi \equiv \langle \hat{\Phi} \rangle_{\bar{\sigma}} = -c_{\upsilon_o}^{-1} + \tilde{\pi}_\phi x^0$, $Q_{\upsilon_o} \simeq \pi_\phi^2$!
- Emergent G related to matter content!

Perturbations

Classical

- First order harmonic gauge.
- Negligible contribution of ref. matter.

$$\delta\phi'' - \bar{V}^{4/3} \nabla^2 \delta\phi = 0\,.$$

Quantum

- Wavefunction peaked on $\pi_\phi = \tilde{\pi}_\phi$.
- Domination of single spin υ_o: $\delta V \equiv 2\bar{\rho}_{\upsilon_o} \delta\rho_{\upsilon_o}$.

$$\delta\phi = \delta V / \bar{V} + \bar{N} [\partial_{\pi_\phi} \theta_{\upsilon_o}]_{\pi_\phi = \tilde{\pi}_\phi}\,.$$

- Matching at super-horizon scales
- No matching for intermediate scales.

LM, Oriti 2112.12677; Gerhart, Oriti, Wilson-Ewing 1805.03099;

Scalar perturbations from causal (T)GFT condensates

Model

- Spacelike and timelike tetrahedra, generated respectively by ($g_I \in \mathrm{SL}(2,\mathbb{C})$):
$$\hat{\varphi}_+(g_I, X_+, \chi^\mu, \cdot)\,, \qquad X_+ \in \mathrm{H}^3\,,$$
$$\hat{\varphi}_-(g_I, X_-, \chi^\mu, \cdot)\,, \qquad X_- \in \mathrm{H}^{1,2}\,.$$
- Causal properties of the frame encoded in $K = K_+ + K_-$, with $K_\pm = (\varphi^*_\pm, \mathcal{K}_\pm \varphi_\pm)$:
$$\mathcal{K}_+ = \mathcal{K}_+(g_I, g'_I; (\chi^0 - \chi'^0)^2, \cdot),$$
$$\mathcal{K}_- = \mathcal{K}_-(g_I, g'_I; |\chi^i - \chi'^i|^2, \cdot).$$

States

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

Background:

- Two-sectors condensation: $\hat{\sigma} = (\sigma, \hat{\varphi}^\dagger_+)$, $\hat{\tau} = (\tau, \hat{\varphi}^\dagger_-)$;
- σ peaked on time, τ on space and time;
- $\tilde{\sigma}$ and $\tilde{\tau}$ only time dependent (homogeneity).

Perturbations: nearest neighbour two-body correlations

$$\delta\hat{\Phi} = (\delta\Phi, \hat{\varphi}^{\dagger 2}_+)\;\; \delta\hat{\Psi} = (\delta\Psi, \hat{\varphi}^\dagger_+ \otimes \hat{\varphi}^\dagger_-)\;\; \delta\hat{\Xi} = (\delta\Xi, \hat{\varphi}^{\dagger 2}_-).$$

Volume dynamics

$$\langle \hat{V} \rangle_\psi = \bar{V}(x^0) + \delta\bar{V}(x^0) + \delta V(x^0, \mathrm{x})\,.$$

- $\delta\bar{V} \sim (\delta\Phi, (\sigma^*)^2)$ (bkg quantum correction).
- $\delta\bar{V} \sim (\delta\Psi, \sigma^* \tau^*)$ (inhomogeneities).
- Only two mean-field equations.
- ⚠ Move beyond mean-field?
- ⚠ Physical implications of $\delta\bar{V}$?

$$\delta V'' + c_1 \delta V' + c_2 \delta V'' + f(x^0)\nabla^2 \delta V = 0\,.$$

- Isotropy and single spin approximation.
- ✓ Structure of equation essentially fixed.
- ✓ Matching for sub-horizon modes possible with appropriate choice of τ.
- ⚠ Values of c_1 and c_2 to be detrmined.

Jercher, LM, Pithis (to appear)

Interactions: inflation and running couplings

Interactions

Perturbative analysis

$$U = (\mathcal{U}, \phi_l[\varphi^*, \varphi]) \ , \qquad \phi_l[\varphi^*, \varphi] \sim \begin{cases} \phi^{l+1} & \text{(phase dependent interactions)} \\ (\phi^*)^{(l+1)/2}\phi^{(l+1)/2} & \text{(modulus interactions)} \end{cases}$$

- $l+1$ order of interaction ($l = 4$ simplicial).
- $\mathcal{U} = \mathcal{U}(\cdot, \psi)$ only if $V_\psi^{(c)} \neq 0$.
- Effective dynamics from mean-field approx.
- Perturbative analysis: small interactions.

Interacting scalar

Including more realistic matter: running couplings

Classical

$$\mathcal{H}^2 = \frac{8\pi G}{3}\left(\pi_\psi^2/\pi_\chi^2 + (V^2/\pi_\chi^2)V_\psi^{(c)}\right) ,$$
$$0 = \psi'' + (V^2/\pi_\chi^2)V^{(c)}_{\psi,\psi} \, .$$

Quantum

$$\mathcal{H}^2 = c_1 + c_2 V^2 V_\psi^{(q)} ,$$
$$0 = \psi'' + c_3\chi^2 V^2 V^{(q)}_{\psi,\psi} \, .$$

- $V_\psi^{(c)}$ classical scalar potential: $V_\psi^{(c)} \sim a_n\psi^n$.
- $V_\psi^{(q)}$ quantum scalar effective potential:

$$V_\psi^{(q)} = \begin{cases} V_\psi^{(c)} & \text{(modulus int.)} \\ V^{(c)}F & \text{(phase int., } F \text{ trig. function)} \end{cases}$$

- GR matching: $l = 5$ and running couplings:

$$G \to G/\chi^2, \ \pi_\psi \to \pi_\psi\chi, \ a_n \to \chi^2 a_n .$$

Acceleration

Geometric inflation

- $l = 5$ generate cosmic acceleration.
- Modulus interactions produce a de Sitter phase (no graceful exit).
- Phase int. produce quantum gravity induced trig. potential: $V = c_1\sin(\omega\chi) + c_2\cos(\omega\chi)$.
- ⚠ Detailed slow-roll analysis?

Ladstätter, LM, Oriti (to appear)