Cosmological inhomogeneities and relational perturbations of QG condensates

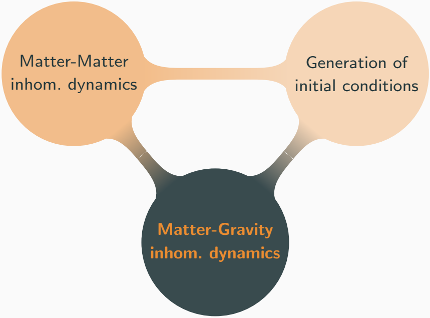
(based on 2112.12677, in collaboration with D. Oriti)

Luca Marchetti

LOOPS '22, 19 July 2022

Arnold Sommerfeld Center
LMU Munich

The QG perspective on cosmological perturbations



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

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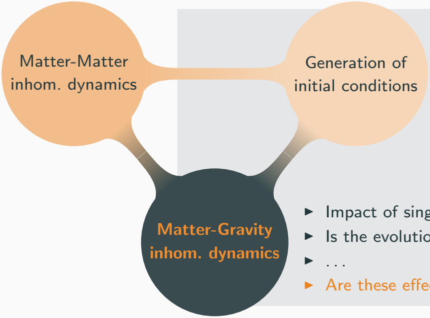

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- Is the evolution of pert. modified by QG effects?
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- Are these effects observable?

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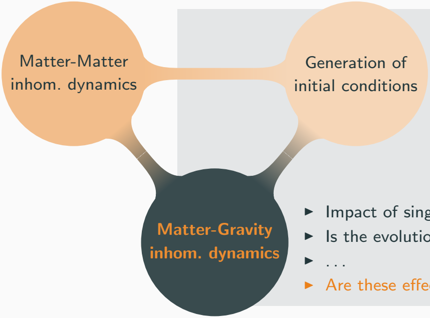

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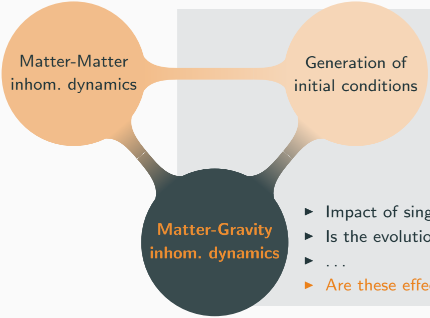

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Challenges from the QG perspective:

- How to define inhomogeneities?
- How to extract macroscopic dynamics?
- How to construct cosmological geometries?
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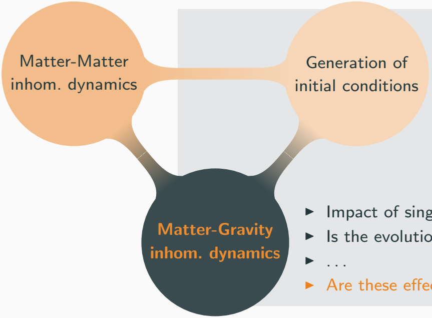

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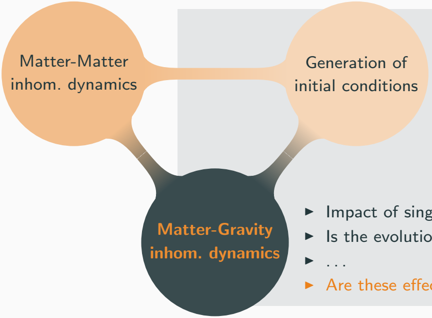

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Challenges from the QG perspective:

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

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(T)GFT condensate cosmology

Collective states

(ciao(T)GFT condensates

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

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

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 $\sigma(g_I, \cdot) = \sigma(hg_I h', \cdot)$, $\mathcal{D} = \mathrm{GL}(3)/\mathrm{O}(3) \times \mathbb{R}^d$:
- If χ^μ constitute a matter ref. frame:

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Relationality

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

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

- $\langle\hat{\chi}^\mu\rangle_{\sigma_x} \simeq x^\mu$, $\langle\hat{O}\rangle_{\sigma_x} \simeq O[\tilde{\sigma}](x)$: evolution with respect to x^μ is effectively relational.

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Eff. dynamics

Mean-field approximation

- Mesoscopic regime: large N (emergence) but negligible interactions.
- Hydrodynamic approx. of kinetic kernel due to peaking properties.
- E.o.m. for reduced wavefunction ⟶ e.o.m. for operator averages.

$$\left\langle \frac{\delta S[\hat{\varphi}, \hat{\varphi}^\dagger]}{\delta\hat{\varphi}(g_I, x^\mu, \cdot)} \right\rangle_{\sigma_x} = 0\,.$$

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Scalar perturbations from (T)GFT condensates

Simplest (slightly) relationally inhomogeneous system

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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.

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

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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 ($\tilde{\sigma} = \rho e^{i\theta}$):
  $\rho = \bar{\rho}(\cdot, \chi^0) + \delta\rho(\cdot, \chi^\mu)$, $\theta = \bar{\theta}(\cdot, \chi^0) + \delta\theta(\cdot, \chi^\mu)$.

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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 $\langle\hat{V}\rangle_\sigma$, $\langle\hat{\Phi}\rangle_\sigma$

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

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- Matching with GR (assuming peaking on matter momenta).
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Perturbations

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

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Conclusions

Results and perspectives

Results

- ✓ Bkg: Effective bkg dynamics: classical limit & possible singularity resolution.
- ✓ Bkg: Emergent matter/gravity constants in terms of microscopic ones.
- ✓ Pert: Effective relational localization of (scalar) perturbations.
- ✓ Pert: Derivation from full theory of scalar isotr. pert. effective relational dynamics:
  - ✓ Super-horizon GR matching.
  - ✗ No matching with GR at intermediate scales.

Perspectives (short term)

- Bkg: Inclusion of different matter fields, e.g. scalar field with potential.
- Pert: Bounce impact on perturbations?
- Pert: Why sub-horizon GR mismatch?
  - What (modified) gravity models do match?
  - QG model building issues?
  - Breakdown of some approximations?
- Pert: Out-of-condensate perturbations?

Perspectives (long term)

- Extend the analysis to geometric operators other than the volume (relax isotropy).
- Study more realistic types of matter.
- Construct a pert. effective metric and perform a proper SVT decomposition.
- QG effects on the CMB power spectrum?

Backup

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, in many applications, $G = \mathrm{SU}(2)$.

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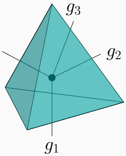
$\mathcal{H}_{\text{1-p}} =$ 

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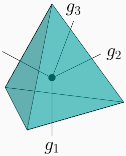
$\mathcal{H}_{\text{1-p}} =$ 

Dynamics

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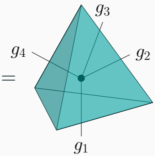
(Tensorial) Group Field Theories: theories of a field $\varphi : G^d \to \mathbb{C}$ defined on d copies of a group manifold G.

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, in many applications, $G = \mathrm{SU}(2)$.

Kinematics

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

- Appropriate (geometricity) constraints allow the simplicial interpretation.
- Group (Lie algebra) variables associated to discretized gravitational quantities.

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

Dynamics

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.

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

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

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

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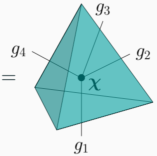

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S_{GFT} obtained by comparing Z_{GFT} with simplicial gravity + matter path integral.

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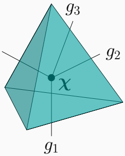
$\mathcal{H}_{\text{1-p}} =$ 

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GFTs are QFTs of atoms of spacetime.

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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.

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

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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.

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Quantum GR

Dirac approach: first quantize, then implement relationality

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

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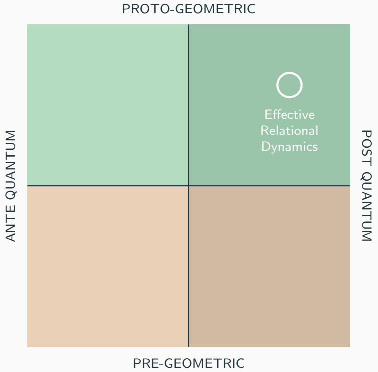
- Clock neutral approach: all variables are treated on the same footing.
- Poor control of the physical Hilbert space.

Reduced phase space approach: first implment relationality, then quantize

- No quantum constraint to solve.
- Led to quantization of simple deparametrizable models.
- Not clock neutral. Too complicated to implement for most of the cases.

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

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.

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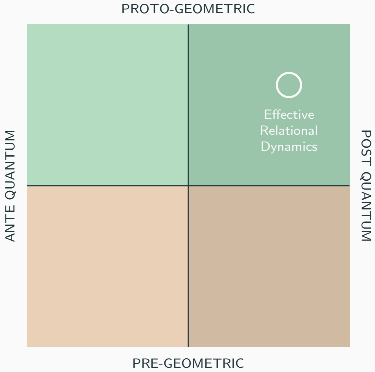

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Concrete example: scalar field clock

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:

$\hat{O}_a$	$\hat{\chi}$ $\hat{\Pi}$	$\hat{N}$
$\downarrow \langle\cdot\rangle_\Psi$	$\downarrow \langle\cdot\rangle_\Psi$	$\downarrow \langle\cdot\rangle_\Psi$
Geometric observables	Scalar field and its momentum	Number of quanta

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

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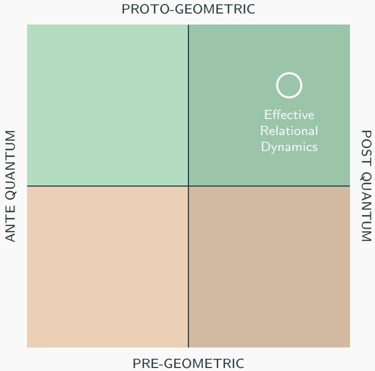

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Effectivness

- 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, Tsobanjan 1011.3040; Bojowald, Tsobanjan 0906.1772;

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 $4c_{\upsilon_o}^2 = 12\pi G$.

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Perturbations

Classical

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

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

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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

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

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

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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.
- $\phi \equiv \langle \hat{\Phi} \rangle_{\bar{\sigma}} = -c_{\upsilon_o}^{-1} + \tilde{\pi}_\phi x^0$, $Q_{\upsilon_o} \simeq \pi_\phi^2$!
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$$\delta\phi = \delta V / \bar{V} + \bar{N} [\partial_{\pi_\phi} \theta_{\upsilon_o}]_{\pi_\phi = \tilde{\pi}_\phi}\,.$$

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

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