Beyond LQC: cosmology from full (L)QG point of view

Daniele Oriti
Arnold Sommerfeld Center for Theoretical Physics
Munich Center for Mathematical Philosophy
Munich Center for Quantum Science and Technology
Center for Advanced Studies
Ludwig-Maximilians-University, Munich, Germany, EU

LQC Panel Discussion - ILQGS - 17.5.2022

Focus:

Quantum gravity and cosmology from a more fundamental QG viewpoint

Potential to overcome limitations of LQC, to test robustness of results obtained so far, to raise new questions

Closely based on developments in GFT formalism, more general validity (& many connections with LQG)

1. Cosmology as hydrodynamic approximation of QG system: collective, coarse grained QG dynamics

- focus on cosmological dynamics = focus on few global observables = (from point of view of QG theory as well as local effective theory (GR)) focus on collective variables and collective states = result of coarse graining

- symmetry reduction = drastic coarse graining (sharp removal of (infinite) dofs) + restriction to few observables

- such reduction (when performed at quantum level) is singular (from point of view of full theory)

- cosmological wavefunction on minisuperspace = dynamical (order) parameter labelling collective state, not quantum state itself = hydrodynamic density (and phase) on minisuperspace
  no corresponding Hilbert space of "quantum cosmology" within larger Hilbert space of QG states

$$\langle\Omega|\widehat{\varphi}|\Omega\rangle = \Psi(a,\phi) \qquad \Psi(a,\phi) = \rho(a,\phi)e^{i\theta(a,\phi)}$$

- relevant observables are matched with continuum gravitational physics as averages, not eigenvalues

$$a_U = \int a\,\rho^2(a,\phi)$$

- important role, in observables and dynamics, of "number of QG dofs": modulus of cosmological wavefunction = average number operator (literally, in GFT), new observable wrt standard quantum cosmology

- average number also crucial to keep fluctuations small and reach semiclassicality at large universe volumes

1. Cosmology as hydrodynamic approximation of QG system: collective, coarse grained QG dynamics

- focus on cosmological dynamics = focus on few global observables = (from point of view of QG theory as well as local effective theory (GR)) focus on collective variables and collective states = result of coarse graining
- symmetry reduction = drastic coarse graining (sharp removal of (infinite) dofs) + restriction to few observables
- such reduction (when performed at quantum level) is singular (from point of view of full theory)
- cosmological wavefunction on minisuperspace = dynamical (order) parameter labelling collective state, not quantum state itself = hydrodynamic density (and phase) on minisuperspace
  no corresponding Hilbert space of "quantum cosmology" within larger Hilbert space of QG states

$$\langle\Omega|\widehat{\varphi}|\Omega\rangle = \Psi(a,\phi) \qquad \Psi(a,\phi) = \rho(a,\phi)e^{i\theta(a,\phi)}$$

- relevant observables are matched with continuum gravitational physics as averages, not eigenvalues

$$a_U = \int a\,\rho^2(a,\phi)$$

- important role, in observables and dynamics, of "number of QG dofs": modulus of cosmological wavefunction = average number operator (literally, in GFT), new observable wrt standard quantum cosmology
- average number also crucial to keep fluctuations small and reach semiclassicality at large universe volumes

2. Cosmology is emergent dynamics, taking form of non-linear extension of (loop) quantum cosmology

- dynamics of cosmological wavefunction = non-linear extension of LQC, i.e. QG hydrodynamics on minisuperspace

$$\mathcal{K}(a,\phi)\,\Psi(a,\phi) + \lambda_i \int \mathcal{V}(a_1,\phi_1;...;a_i,\phi_i)\Psi(a_1,\phi_1)\cdots\Psi^*(a_i,\phi_i) = 0$$

- gravitational couplings (as seen in cosmological dynamics) are ("dressed") functions of underlying QG ones (not directly interpreted as gravitational, i.e. no 1-1 correspondence)
- "standard" quantum cosmology setting (still without associated Hilbert space) obtained when neglecting non-linear corrections, i.e. underlying QG interactions - here, in GFT, FRW is reproduced at large volumes
- non-linear contributions important; example: in GFT can produce cosmic acceleration (phantom-like dark energy, inflation, asymptotic deSitter universe) without additional dofs
- if cosmology is condensate hydrodynamics, what is the role of out-of-condensate excitations?
  modification of cosmological dynamics for same universe content or new "emergent" content?

3. Cosmological evolution (like any evolution in GR) is relational evolution with respect to physical clock

- relational evolution requires conditions of (good) clock, implemented as conditions on relevant quantum states
(almost ideal clock: no backreaction/selfinteraction, small quantum fluctuations, etc; corrections to be accounted for)

- work with eigenvalues of "clock" (i.e. infinitely peakes states) is problematic (highly fluctuating clock e-m)
  - true also if one "deparametrize" at classical level (then "good clock conditions" are there by construction)

- which clock? possible mismatch between "fundamental" and "effective" clock dofs
  example: "massless free scalar field" at fundamental level =/= massless free scalar field at effective (hydrodynamic) level; choosing it as a clock is problematic + mistaking it for massless free scalar field at effective level certainly gives problems in matching with (expected) GR-like dynamics

- how does the cosmological physics (e.g. bounce, cosmological perturbations, etc) depend on the choice of clock?

- what is invariant under change of physical clock? do we need to focus only on invariant physics? what is general covariance with respect to transformations between (realistic) physical frames?

3. Cosmological evolution (like any evolution in GR) is relational evolution with respect to physical clock

- relational evolution requires conditions of (good) clock, implemented as conditions on relevant quantum states
(almost ideal clock: no backreaction/selfinteraction, small quantum fluctuations, etc; corrections to be accounted for)

- work with eigenvalues of "clock" (i.e. infinitely peakes states) is problematic (highly fluctuating clock e-m)
  - true also if one "deparametrize" at classical level (then "good clock conditions" are there by construction)

- which clock? possible mismatch between "fundamental" and "effective" clock dofs
  example: "massless free scalar field" at fundamental level =/= massless free scalar field at effective (hydrodynamic) level; choosing it as a clock is problematic + mistaking it for massless free scalar field at effective level certainly gives problems in matching with (expected) GR-like dynamics

- how does the cosmological physics (e.g. bounce, cosmological perturbations, etc) depend on the choice of clock?

- what is invariant under change of physical clock? do we need to focus only on invariant physics? what is general covariance with respect to transformations between (realistic) physical frames?

4. Also spatial localization and thus local physics, including cosmological perturbations, is relational

- cosmological perturbations: spatial localization to be defined also via relational strategy, i.e. by additional rod fields
  - dynamics obtained for each choice of relational frame should be compared with GR dynamics in particular gauge
  - need precise dictionary between physical frames and gauge choices: which physical fields correspond to which gauge? in which approximation? with which corrections?
  - can be already described in (extended) minisuperspace, i.e. using values of rod fields;
    but not full story (missing geometric and matter dof), which would require full superspace (not just minisuperspace)
    but how does it differ from full story? in which approximation can it be enough?

- alternative is that one should/could introduce "redundant" manifold dependence (and coordinates etc)
  why? how to do it, precisely and unambiguously?

5. Effective cosmological dynamics is affected by RG flow of underlying QG dynamics

- effective cosmological dynamics takes place within one particular phase of underlying QG system, thus need to check values of couplings, their running and what happens close to criticality
- fluctuations also depend on (running) couplings
- bounce (when reproduced) happens in hydrodynamic approximation of full QG
    - assuming universe volume is an extensive quantity, this happens at small values of (average) number operator, thus in the "danger zone" for validity of hydrodynamic approximation
    - bounce scenario may not be viable and one may need to resort to more fundamental QG dynamics with no fully "geometric/spatiotemporal description"

5. Effective cosmological dynamics is affected by RG flow of underlying QG dynamics

- effective cosmological dynamics takes place within one particular phase of underlying QG system, thus need to check values of couplings, their running and what happens close to criticality
- fluctuations also depend on (running) couplings
- bounce (when reproduced) happens in hydrodynamic approximation of full QG
  - assuming universe volume is an extensive quantity, this happens at small values of (average) number operator, thus in the "danger zone" for validity of hydrodynamic approximation
  - bounce scenario may not be viable and one may need to resort to more fundamental QG dynamics with no fully "geometric/spatiotemporal description"

6. Other "foundational" open issues

- arrow of time and "initial" state from "cosmology as relational QG hydrodynamics" perspective
- entropy of universe and its relational evolution vs entropy of underlying QG system, including clock/rods (need better foundation for statistical mechanics of QG degrees of freedom)
- cosmological interpretation of underlying QG phase transitions? if early universe is close to QG phase transition, what is impact on cosmological observables, e.g. CMB spectrum?

5. Effective cosmological dynamics is affected by RG flow of underlying QG dynamics

- effective cosmological dynamics takes place within one particular phase of underlying QG system, thus need to check values of couplings, their running and what happens close to criticality
- fluctuations also depend on (running) couplings
- bounce (when reproduced) happens in hydrodynamic approximation of full QG
    - assuming universe volume is an extensive quantity, this happens at small values of (average) number operator, thus in the "danger zone" for validity of hydrodynamic approximation
    - bounce scenario may not be viable and one may need to resort to more fundamental QG dynamics with no fully "geometric/spatiotemporal description"

6. Other "foundational" open issues

- arrow of time and "initial" state from "cosmology as relational QG hydrodynamics" perspective
- entropy of universe and its relational evolution vs entropy of underlying QG system, including clock/rods (need better foundation for statistical mechanics of QG degrees of freedom)
- cosmological interpretation of underlying QG phase transitions? if early universe is close to QG phase transition, what is impact on cosmological observables, e.g. CMB spectrum?

....

5. Effective cosmological dynamics is affected by RG flow of underlying QG dynamics

- effective cosmological dynamics takes place within one particular phase of underlying QG system, thus need to check values of couplings, their running and what happens close to criticality
- fluctuations also depend on (running) couplings
- bounce (when reproduced) happens in hydrodynamic approximation of full QG
  - assuming universe volume is an extensive quantity, this happens at small values of (average) number operator, thus in the "danger zone" for validity of hydrodynamic approximation
  - bounce scenario may not be viable and one may need to resort to more fundamental QG dynamics with no fully "geometric/spatiotemporal description"

6. Other "foundational" open issues

- arrow of time and "initial" state from "cosmology as relational QG hydrodynamics" perspective
- entropy of universe and its relational evolution vs entropy of underlying QG system, including clock/rods (need better foundation for statistical mechanics of QG degrees of freedom)
- cosmological interpretation of underlying QG phase transitions? if early universe is close to QG phase transition, what is impact on cosmological observables, e.g. CMB spectrum?

....

Thanks!