Loop Quantum Gravity and its road to phenomenology

Klaus Liegener

klaus.liegener@wmi.badw.de

July 13th 2022, Cost CA18108, Napoli

Motivation

- Viewpoint Theorist: Notrious difficulty in measuring Quantum Gravity (QG) effects of quantum gravity, suggests to turn the table around:
  First construct a theory of QG, then derive predictions
- Road to phenomenology: Ultimately, it must be the goal of any QG theory to make “predictions” and to become falsifiable
- WIP-Disclaimer: As of today, **no** QG theory is complete - also Loop Quantum Gravity (LQG) misses parts in its construction and cannot give final predictions yet!

Motivation

- Introducing assumptions & approximations along the way presents shortcuts to predictions, but a priori its unclear whether they are fully reliable
- Important: Over time assumptions get proven or falsified, modified or replaced. And while different assumptions may lead to different predictions, they represent a continuous strive for improvement
- But as of today, we need to take all of them with a pinch of salt

A motivating example of “assumptions” and notations:

- Assuming the non-existence of closed causal curves, the Einstein-Hilbert action of General Relativity can be recast as a Hamiltonian theory (with constraints) [Arnowitt, Deser, Misner]

$$H = \int_\sigma d^3x(H_{geo}(x) + H_{matter}(x))$$

A motivating example of “assumptions” and notations:

- Assuming the non-existence of closed causal curves, the Einstein-Hilbert action of General Relativity can be recast as a Hamiltonian theory (with constraints) [Arnowitt, Deser, Misner]

$$H = \int_\sigma d^3x (H_{geo}(x) + H_{matter}(x))$$

- Classically, imposing symmetries allows to simlified the Hamiltonian of the field theory, e.g. restrict to Friedmann-Lemaitre-Robertson-Walker (FLRW) cosmology w/ massless scalar field ϕ:

$$H|_{FLRW} = \sqrt{p}c^2/\tilde{\kappa} + \pi_\phi^2/p^{3/2}$$

- It generates evolution in the form of gauge transformations on the phase space of $p = a^2$ (with a being the scale factor), c, its canonical conjugated momentum, and π_ϕ, ϕ
- The classical solution $a(\phi)$ features $a \to 0$ for late times, leading to the initial singularity $\Rightarrow$ We expect QG to resolve this problem

Setting the stage for loops

A motivating example of "assumptions" and notations:

- Assuming the non-existence of closed causal curves, the Einstein-Hilbert action of General Relativity can be recast as a Hamiltonian theory (with constraints) [Arnowitt, Deser, Misner]

$$H = \int_\sigma d^3x (H_{geo}(x) + H_{matter}(x))$$

- H is quantised a la methods of Dirac (more details later)
- Try finding an *effective description* of the semiclassical sector:
    - Given a special classical solution (e.g. FLRW)
    - Find a family of (gaussian) wave functions mostly peaked over some semiclassical trajcetory
    - Deviations from classical become relevant only in the deep quantum regime (close to singularities)
    - Extract the new generating Hamiltonian $H \to H_{eff}$, which is close to the classical but w/ small quantum gravity corrections

Walther Meißner Institut

A motivating example of "assumptions" and notations:

- *How to obtain effective Hamiltonian H_{eff} and what to do with it?*

Polymerisation:

We propose an effective Hamiltonian by replacing $X \to \sin(\epsilon X)/\epsilon$

Walther Meißner Institut

A motivating example of "assumptions" and notations:

- *How to obtain effective Hamiltonian H_{eff} and what to do with it?*

Polymerisation:

We propose an effective Hamiltonian by replacing $X \to \sin(\epsilon X)/\epsilon$

- Example: Harmonic Oscillator

$$H = P^2 + X^2$$

gets polymerised $\to$ study the behaviour of

$$H_{eff} = P^2 + \frac{1}{\epsilon^2}\sin(\epsilon X)^2$$

- $\Rightarrow$ For $\epsilon << 1$ almost no deviation for the low-energy states, but becomes relevant at high energetic configurations .

Comment: Polymer Quantum Mechanics [Amelino-Camelia, Corichi, Morales-Técotl, Rastgoo, Zapata,...] is indeed very closely related to LQG!

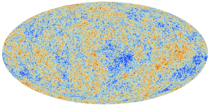
1) Phenomenological Predictions

Three pillars of LQG phenomenology

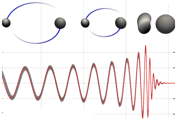
Historically, beginning of the 2000s the most prominent version of LQG featured an involved quantisation of the constraints.

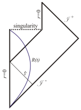
Due to its complexity no solutions were known and lot of work went into simplifying the settings with high ammount of symmetries.

Therefore, three pillars of the LQG phenomenology emerged:



- Cosmology
- Gravitational Waves
- (Black Holes)





(Hence, even today complicated settings such as table-top-QG remain largely unexplored in LQG community)

Walther Meißner Institut

Earliest assumption of Loop Quantum Cosmology (LQC):

Restriction to FLRW and quantisation may commute.

Classical starting point:

$$H|_{FLRW} = \sqrt{p}c^2/\tilde{\kappa} + \pi_\phi^2/p^{3/2} \tag{1}$$

→ quantisation a la Dirac would lead to Wheeler-De-Witt theory
→ integrate LQG features into the framework, i.e. *polymerisation*
Obtain new effective Hamiltonian [Bojowald 2000]

$$H_{eff} = \sqrt{p}\sin(\epsilon c)^2/(\epsilon^2\tilde{\kappa}) + \pi_\phi^2/p^{3/2} \tag{2}$$

But how is it related to quantum theory?

Earliest assumption of Loop Quantum Cosmology (LQC):

Restriction to FLRW and quantisation may commute.

Classical starting point:

$$H|_{FLRW} = \sqrt{p}c^2/\tilde{\kappa} + \pi_\phi^2/p^{3/2} \tag{1}$$

$\to$ quantisation a la Dirac would lead to Wheeler-De-Witt theory

$\to$ integrate LQG features into the framework, i.e. *polymerisation*

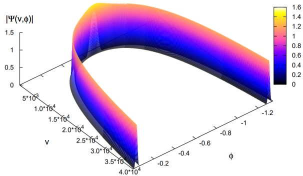
Obtain new effective Hamiltonian [Bojowald 2000]

$$H_{eff} = \sqrt{p}\sin(\epsilon c)^2/(\epsilon^2\tilde{\kappa}) + \pi_\phi^2/p^{3/2} \tag{2}$$

But how is it related to quantum theory? [Ashektar, Pawlowski, Singh 2006, Taveras 2008]

$\to$ Promote $v = p^{3/2}$ to multiplication operator and $N = e^{i\epsilon c}$ to shift operator:

$$\hat{v}|v\rangle = v|v\rangle, \quad \hat{N}|v\rangle = |v+1\rangle$$



Evolution of Gaussian $\Psi(\phi)$ resolves the singularity and $a_{eff}(\phi) := \langle\Psi(\phi),\ \hat{a}\ \Psi(\phi)\rangle$

We ask for modifications of LQC to the power spectrum that appear when including scalar perturbations:

Assumption: Effective Background [Agullo et al. 2013]

Using $a_{class}(\phi) \mapsto a_{eff}(\phi)$ in the standard calculus of perturbations gives a valid approximation.

- Perturbation field Q gets decomposed into Fourier modes

$$Q(x) = \int d^3k [\hat{A}_k q_k(\eta) + \hat{A}^\dagger_{-k} q_k^*(\eta)] e^{ik\cdot x}$$

- Q obeying the Klein-Gordon equation $[\Box - V]Q = 0$ with $\Box$ the D'Alembertian with the effective metric, hence:

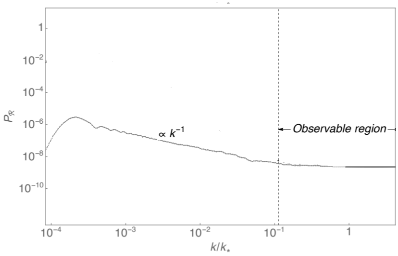
$$q_k'' + 2\frac{a_{eff}'}{a_{eff}} q_k' + (k^2 + a_{eff}^2 V) q_k = 0$$

- Initial conditions are set at bounce as adiabatic 'vacuum' (becomes extremly close to BD at onset of inflation)

Primordial power spectrum at end of inflation

$$P(k) = (\frac{H(\eta)}{\dot{\phi}(\eta)})^2 \hbar \frac{k^3}{2\pi^2} |q_k(\eta)|^2$$

The LQG power spectrum is indistinguishable from that of standard inflation up to infra-red (IR) scales, where it is $P \sim k^{-1}$. [Agullo et al 2012]



Gray: polymerised LQC,

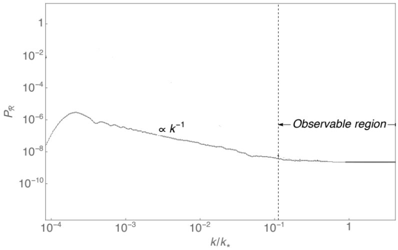
Walther Meißner Institut

Primordial power spectrum at end of inflation

$$P(k) = (\frac{H(\eta)}{\dot{\phi}(\eta)})^2 \hbar \frac{k^3}{2\pi^2} |q_k(\eta)|^2$$

The LQG power spectrum is indistinguishable from that of standard inflation up to infra-red (IR) scales, where it is $P \sim k^{-1}$. [Agullo et al 2012]

Alternative: Relax 'polymerisation' and instead compute the full Hamiltonian discretised on a lattice [Dapor, KL 2017]



Gray: polymerised LQC,

LQC: Fully discretised Hamiltonian

Alternative: Relax 'polymerisation' and instead compute the full Hamiltonian discretised on a lattice [Dapor, KL 2017]

Assumption: Discrete space:

Space is fundamentally discrete & approximate H w/ lattice variables.

$$C = C_E + C_L = (F^j_{ab} - (1+\beta^2)\epsilon_{jmn} K^m_a K^n_b) e^j_c \epsilon^{abc} / \kappa$$

$$\begin{array}{ccc} F_{ab} & \mapsto & h(\Box) \\ \downarrow & & \downarrow \\ c^2 & & \sin(\epsilon c)^2/\epsilon^2 \end{array}$$

Alternative: Relax 'polymerisation' and instead compute the full Hamiltonian discretised on a lattice [Dapor, KL 2017]

Assumption: Discrete space:

Space is fundamentally discrete & approximate H w/ lattice variables.

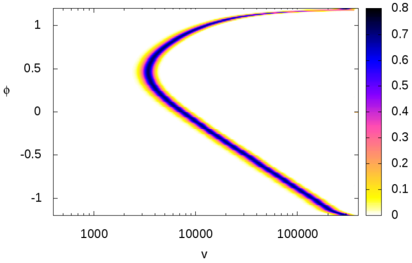
$$C = C_E + C_L = (F^j_{ab} - (1+\beta^2)\epsilon_{jmn} K^m_a K^n_b) e^j_c \epsilon^{abc} / \kappa$$

$$\begin{array}{ccc} F_{ab} & \mapsto & h(\Box) \\ \downarrow & & \downarrow \\ c^2 & & \sin(\epsilon c)^2/\epsilon^2 \end{array}$$

But evaluating the full constraint C gives:

$$C \sim (\sin(\epsilon c)^2 + s(\beta)\ \sin(2\epsilon c)^2)$$

Gaussian states remain stable giving a past universe with huge cosm. constant: $\Lambda \approx 1.03 \ell_P^{-2}$. [Assanioussi, Dapor, KL, Pawlowski 2018]

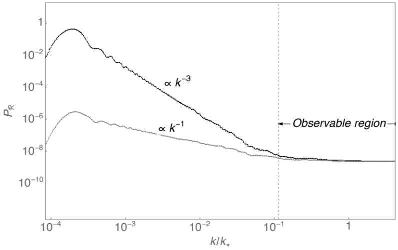


Primordial power spectrum at end of inflation

$$P(k) = \left(\frac{H(\eta)}{\dot{\phi}(\eta)}\right)^2 \hbar \frac{k^3}{2\pi^2} |q_k(\eta)|^2$$

The LQG power spectrum is indistinguishable from that of standard inflation up to infra-red (IR) scales, where it is $P \sim k^{-1}$. [Agullo et al 2012]

Alternative: Relax 'polymerisation' and instead compute the full Hamiltonian discretised on a lattice [Dapor, KL 2017]



Gray: polymerised LQC, Black: full-lattice LQC

As initial condition the BD vacuum is choosen in the far past.

Now, a different modification is found for IR modes: $P \sim k^{-3}$ [Agullo 2020]

Expanding on perturbations by including a LQG signature on them:

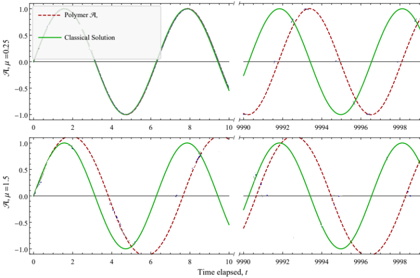
$$g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}$$

Restricting the full Hamiltonian to the perturbed regime $h_{\mu\nu} << 1$ gives

$$H|_{GW} = \frac{1}{2\kappa} \int dz \, [p_+^2 + (\partial_z h_+)^2 + p_\times^2 + (\partial_z h_\times)^2]$$

Assumption: Polymerised effective theory [Bojowald, Hossain 2007] [Rastgoo et. al 2021]

- Restrict to classical $H|_{GW}$ and obtain H_{eff} by polymerisation $X \to \frac{sin(\mu X)}{\mu}$, with X a suitable choosen coordinate
- Finding a modified wave form, and phase shift accumulating over time
- Speed of light decreased: $1 - (k\mu/4)^2$



Comment: Many try to quantise small perturbations after polymerisation, however none of those has reached predictions so far [Ashtekar et al., Fahn et al., Hinterleitner et. al, Neville,...]

Walther Meißner Institut

Assumption: Full lattice discretisation [Dapor, KL 2020]

- Derive the effective Hamiltonian by discretising space as a cubic lattice (replacement $\{p_i\} \to \{hol(p_i)\}$)
- Small wave approximation: Evaluate the discretised Hamiltonian on GW using $p_i, h_i << 1$
- Due to small h_i, p_i-approximation, the equations of motion become: ($i = +, \times$ and $s = (1+\beta^2)/\beta^2$)

$$\ddot{p}_i = \frac{\beta^2}{8\epsilon^2}(sp_i^{+3} - 2p_i^{+2} - sp_i^{+} + 4p_i - sp_i^{-} - 2p_i^{-2} + sp_i^{-3})$$

- With *ansatz* $p(z) = \frac{\epsilon}{2\pi}\int_{\mathcal{B}} dk\, e^{ikz} u(k)$ we find again a wave equation with modified dispersion relation

$$\ddot{u}(k) = -\omega(k)^2 u(k), \quad \omega(k)^2 = \frac{\sin(k\epsilon)^2}{\epsilon^2}((1+\beta^2)\cos(k\epsilon) - \beta^2) \tag{3}$$

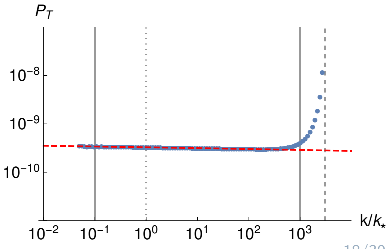
- Here too, speed of light decreases: $1 - (k\epsilon/4)^2(5+3\beta^2) + \mathcal{O}(k^4\epsilon^4)$

- Fixed background: Combine GW solution with LQC scale factor a_{eff}
- Minimally coupled scalar field with $V = m^2\phi^2/2$ but due to the new dispersion relation $\omega(k)$ we get:

$$q_k'' + (\omega(k)^2 - \frac{a_{eff}''}{a_{eff}})q_k = 0 \qquad (4)$$

- Numerics (N=62.45 e-folds, $m = 1.3 \times 10^{-6}, \epsilon = 0.015$, $\beta = 0.2375$, $k_* = 0.002 Mpc^{-1}$): Modified power spectrum at high k/k_* values

- Potential implications for prim. BH, microhalos etc.?
- Conversely, if $\epsilon \approx \ell_P$ and modifications are supposed to be outside of observable range $\epsilon k^P_{max} < 0.5$ then inflation is bounded around $N = 62$ e-folds



2) Resumee of Loop Quantum Gravity

Covariant:
space time $\mathcal{M}$, metric $g_{\mu\nu}$, vacuum Einst. eq. $R_{\mu\nu} - R\, g_{\mu\nu}/2 = 0$

$$g_{\mu\nu}(x)$$
$$\downarrow$$
$$\{P^{ab}(x), q_{cd}(y)\} = \kappa\delta^a_{(c}\delta^b_{d)}\delta^{(3)}(x,y)$$
$$\downarrow$$
$$\{E^a_I(x), A^J_b(y)\} = \frac{\beta\kappa}{2}\delta^J_I\delta^a_b\delta^{(3)}(x,y)$$
$$\downarrow$$
$$\{E^I(S_{e'}), h(e)\} = \frac{\beta\kappa}{2}\delta(e,e')\tau^I h(e)$$

- ADM-formalism: ['62]
  3+1 foliation $\mathcal{M} = \sigma \times t$
  with Hamiltonian H
- Ashtekar-Barbero variables:
  ['86-'95] Gravity $\equiv \mathrm{SU}(2)$
  Yang-Mills gauge theory
- Analogous to Lattice QCD:
  smeared fields (Holonomies and Fluxes) can be quantised

Kinematical Hilbert space of LQG

- Choose the set of all (cubic) graphs γ, with $\gamma < \gamma'$ iff $\gamma \subset \gamma'$
- For any edge $e \in \gamma$, the space of square-integrable functions over SU(2) is $\mathcal{H}_e = L_2(SU(2), d\mu_H)$ and

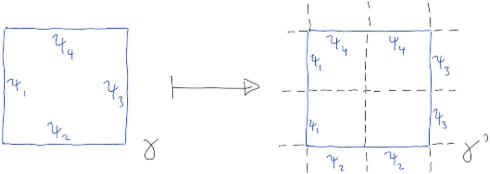
$$\mathcal{H}_\gamma = \otimes_{e\in\gamma}\mathcal{H}_e \tag{5}$$

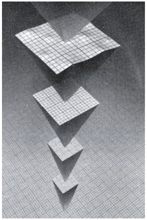
Kinematical Hilbert space of LQG

- Choose the set of all (cubic) graphs γ, with $\gamma < \gamma'$ iff $\gamma \subset \gamma'$
- For any edge $e \in \gamma$, the space of square-integrable functions over SU(2) is $\mathcal{H}_e = L_2(SU(2), d\mu_H)$ and

$$\mathcal{H}_\gamma = \otimes_{e\in\gamma}\mathcal{H}_e \tag{5}$$

- As *embedding maps* $J_{\gamma\to\gamma'}$ take:





- Then, Hilbert space family has an inductive limit: the *Ashtekar-Isham-Lewandowski measure*:

$$\mu_{\mathrm{AIL}}(F\ \hat{E}(S_{e_1})...\hat{E}(S_{e_N})) = \begin{cases} 0 & \text{if} \quad N > 0 \\ \mu_H(F) & \text{else} \end{cases} \tag{6}$$

Discretisation ambiguities

Einstein Equations are equivalent to a set of constraints C, C_a, G^j.
In Ashtekar-Barbero variables, e.g.:

$$C = \frac{1}{\kappa}\left(F^j_{ab} - (1+\beta^2)\epsilon_{jmn}K^m_a K^n_b\right)\epsilon_{jkl}\frac{E^a_k E^b_l}{\sqrt{\det E|}} \tag{7}$$

Quantisation: rewrite (7) via holonomies along *finite* paths.

E.g. arbitrary small loop $\Box^\epsilon$ of length ϵ:

$$F^J_{ab} \approx \frac{1}{2\epsilon^2}\left(h(\Box^\epsilon) - h(\Box^\epsilon)^\dagger\right) \tag{8}$$

Equality is only for $\epsilon \to 0$. For $\epsilon > 0$ there exists a huge freedom for various corrections, whose influence remain when taking *after* quantisation the limit $\epsilon \to 0$ $\Rightarrow$ Discretisation Ambiguities!

Einstein Equations are equivalent to a set of constraints C, C_a, G^j.
In Ashtekar-Barbero variables, e.g.:

$$C = \frac{1}{\kappa}\left(F^j_{ab} - (1+\beta^2)\epsilon_{jmn}K^m_a K^n_b\right)\epsilon_{jkl}\frac{E^a_k E^b_l}{\sqrt{|\det E|}} \tag{9}$$

Quantisation: rewrite (9) via holonomies along *finite* paths.

In literature:

$$C \approx \epsilon_{ijk} tr([h(\square^\epsilon_{ij}) - h^\dagger(\square^\epsilon_{ij})]h_k\{h^\dagger_k, V\}) + \alpha\epsilon_{ijk} tr(h_i\{h^\dagger_i, K\}h_j\{h^\dagger_j, K\}h_k\{h^\dagger_k, V\}) \tag{10}$$

[Thiemann 1998]

$$\approx \alpha'\epsilon_{ijk} tr([h(\square^\epsilon_{ij})) - h^\dagger(\square^\epsilon_{ij})]h_k\{h^\dagger_k, V\}) + \alpha''\sqrt{Y^\epsilon}(\pi + \arccos[\frac{E(S)^I E(S')_J}{||E(S)||||E(S')||}]) \tag{11}$$

[Assanioussi,Lewandowski,Mäkinen 2015]

LQG - Status Quo

LQG Kinematics: well-understood and commonly agreed upon

LQG Dynamics: no common senus found as of today

- ∃ proposal for a continuum Hamiltonian constraints (inductive limit of lattice versions) however they are intractable for actual computations [Thiemann 1998, Assanioussi et al. 2105]
- A continuum Hamiltonian constraint with relation to the matrix elments at finite resolution needs still to be found via renormalisation [Bahr, Dittrich, KL, Thiemann,...] or fixations of the hypersurface deformation algebra [Bojowald, Brahma, Amelino-Camleia, Marciano...]
- Alternatively, by assuming discrete space, the arbitrary regulatisations can immediately be used for semiclassical computations [Dapor, KL, Weigl, Zwicknagel,...]

How to get the effective Hamiltonian?

- Given a (discretised) $\hat{H}$ generating the evolution/gauge transformations
- Find a suitable family of coherent states $\Psi_{z(\tau)}$: (a) peaked on classical phase space $z(\tau)$ and (b) stable under dynamics, i.e.

$$e^{i\tau\hat{H}}\Psi_{z(0)} \approx \Psi_{z(\tau)} \tag{12}$$

- Then the effective Hamiltonian H_{eff} is defined as the generator of the classical trajector $z(\tau)$. I.o.w. H_{eff} is the solution to the equation $\dot{z} = \{H_{eff}, z\}$

How to get the effective Hamiltonian?

- Given a (discretised) $\hat{H}$ generating the evolution/gauge transformations
- Find a suitable family of coherent states $\Psi_{z(\tau)}$: (a) peaked on classical phase space $z(\tau)$ and (b) stable under dynamics, i.e.

$$e^{i\tau\hat{H}}\Psi_{z(0)} \approx \Psi_{z(\tau)} \tag{12}$$

- Then the effective Hamiltonian H_{eff} is defined as the generator of the classical trajector $z(\tau)$. I.o.w. H_{eff} is the solution to the equation $\dot{z} = \{H_{eff}, z\}$

Assumption: Semiclassicality

For very sharply peaked coherent states, the effective Hamiltonian is given by the expectation value of $\hat{H}$ in said states:

$$H_{eff}(z) := \langle \Psi_z, \hat{H}\Psi_z \rangle$$

3) Computational & Conceptual Assumptions

Common assumptions & their combatants

Polymerisation:

We propose an effective Hamiltonian by replacing $X \to \sin(\epsilon X)/\epsilon$

- Great initial guess, leading to many novel results
- In general incomplete! (Even symmetry restriction to FLRW and discretisation of complicated expression do not commute)
- To be replaced by full lattice computations

Polymerisation:

We propose an effective Hamiltonian by replacing $X \to \sin(\epsilon X)/\epsilon$

- Great initial guess, leading to many novel results
- In general incomplete! (Even symmetry restriction to FLRW and discretisation of complicated expression do not commute)
- To be replaced by full lattice computations

Effective Background

Using $a_{class}(\phi) \mapsto a_{eff}(\phi)$ in the standard calculus of perturbations gives a valid approximation.

- Ignores effect comming from non-commutativity of polymerisation and symmetry restriction
- Generalisation is work in progress [Mena-Marugán et al.] [Schander, Thiemann 2022], but no predictive results obtained so far

Discrete space

Space is fundamentally discrete & approximate H w/ lattice variables.

- Only allows a phase-independent polymerisation parameter
- Not complementary with quantum *field* theory of continuum GR
- Dependent on discretisation ambiguities (influencing predictions)
- Ultimately to be replaced by a renormalised theory (but wip)

Common assumptions & their combatants

Discrete space

Space is fundamentally discrete & approximate H w/ lattice variables.

- Only allows a phase-independent polymerisation parameter
- Not complementary with quantum *field* theory of continuum GR
- Dependent on discretisation ambiguities (influencing predictions)
- Ultimately to be replaced by a renormalised theory (but wip)

Semiclassicality

Effective Hamiltonian is the expectation value of $\hat{H}$ in Gaussians.

- Straightforward computation, however stability of a family of coherent states is not valid in general
- Dynamics is hard to investigate and needs further work
- At least consistency checks for proposal of stable families are available [KL, Rudnicki 2022]

4) Conclusion & Outlook

Conclusion

What is LQG?

- Canonical quantisation of GR close to Lattice Gauge Theory
- Fundamentally continous theory w/ discrete spectra of operator

Conclusion

What is LQG?

- Canonical quantisation of GR close to Lattice Gauge Theory
- Fundamentally continous theory w/ discrete spectra of operator

What is still missing in LQG?

- Ambiguitiy-free, feasible proposal of dynamics
- Stable, semiclassical states leading to QG effects

Conclusion

What is LQG?

- Canonical quantisation of GR close to Lattice Gauge Theory
- Fundamentally continous theory w/ discrete spectra of operator

What is still missing in LQG?

- Ambiguitiy-free, feasible proposal of dynamics
- Stable, semiclassical states leading to QG effects

What do we assume?

- Different polymerisations/discretisations of the Hamiltonian
- Semiclassical effects captured by effective classical theories

Conclusion

Walther Meißner Institut

What is LQG?

- Canonical quantisation of GR close to Lattice Gauge Theory
- Fundamentally continous theory w/ discrete spectra of operator

What is still missing in LQG?

- Ambiguitiy-free, feasible proposal of dynamics
- Stable, semiclassical states leading to QG effects

What do we assume?

- Different polymerisations/discretisations of the Hamiltonian
- Semiclassical effects captured by effective classical theories

What does it predicit?

- Novel dispersion relation for GW, to evolve slower than c
- Modification to the cosmological power spectrum, outside of the observable spectrum but both at high and low values of k

What is LQG?

- Canonical quantisation of GR close to Lattice Gauge Theory
- Fundamentally continous theory w/ discrete spectra of operator

What is still missing in LQG?

- Ambiguitiy-free, feasible proposal of dynamics
- Stable, semiclassical states leading to QG effects

What do we assume?

- Different polymerisations/discretisations of the Hamiltonian
- Semiclassical effects captured by effective classical theories

What does it predicit?

- Novel dispersion relation for GW, to evolve slower than c
- Modification to the cosmological power spectrum, outside of the observable spectrum but both at high and low values of k

THANK YOU!