Swampland and the Bunch-Davies vacuum

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H0 tension and Swampland: theory confronts reality

In peer review (2018) [arXiv:1809.01277] (with Md. W. Hossain)
Phys. Rev. D 98, 083537 (2018) [arXiv:1808.01744] (with D.-h Yeom)
Phys. Rev. Lett. 121, 201301 (2018) [arXiv:1810.09871] (with M. Bojowald)

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→ Theoretical considerations:

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But perhaps some quantum gravity corrections can *rescue* the Bunch-Davies vacuum?

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Consistent model-building for single-field inflation

Swampland and inflation

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Constraints on Single-field inflation

→ The Swampland constraints are as follows [P. Agrawal, G. Obeid, P. Steinhardt & C. Vafa; H. Ooguri & C. Vafa]:

- S1: The range of excursion for a scalar field is bounded from above by $|\Delta\varphi| < \Delta \sim \mathcal{O}(1)$
- S2: The slope of the scalar field potential satisfies a lower bound $|V'|/V > c \sim \mathcal{O}(1)$ with $V > 0$.

→ Naively, serious conflict with usual slow-roll definition $\epsilon_V \sim c^2/2 \sim \mathcal{O}(1)$! Of course, the parameter c does not have be *exactly* $\mathcal{O}(1)$ but say $c \sim 0.5$
⇒ Conjectures are parametric! [M. Dias, J. Frazer, A. Retolaza & A. Westphal]

→ Real problem is the small observed values of $r < 0.07$ and from the single-field consistency relation $r = 16\epsilon \Rightarrow \epsilon \leq 4.4 \times 10^{-3} \rightarrow c < \mathcal{O}(0.1)$.

→ Need to *violate* the consistency relation above ⇒ Going beyond vanilla 'single-clock' models of inflation by adding new dofs → Multi-field models of inflation (curvaton), warm inflation (radiation), ... [A. Kehagias & A. Riotto; S. Das;...]

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Non-Bunch-Davies Initial state

→ For generic excited states:

$$P_\eta(k) = \frac{H^2}{2\epsilon M_p^2}\frac{1}{2k^3}|\alpha_k^{(s)} + \beta_k^{(s)}|^2$$

$$P_h^p(k) = \frac{4H^2}{M_p^2}\frac{1}{2k^3}|\alpha_k^{(t)} + \beta_k^{(t)}|^2$$

with $|\alpha_k|^2 - |\beta_k|^2 = 1$ and $\beta^{(s)(t)}(k) \to 0$ sufficiently fast subject to back reaction constraints.

→ Tensor-to-scalar ratio: $r = \frac{\Sigma_p P_h^p}{P_\zeta} = 16\epsilon \frac{|\alpha_k^{(t)}+\beta_k^{(t)}|^2}{|\alpha_k^{(s)}+\beta_k^{(s)}|^2} =: 16\epsilon\,\gamma$

→ If $\gamma < 1 \Rightarrow r$ can be *suppressed* even for $c \sim \mathcal{O}(1)$. [S.B. & W. Hossain]

→ Two ways to achieve $\gamma < 1$

- $|\beta^{(s)}| > 1 \Rightarrow$ Large excitation numbers for scalar modes $\Rightarrow$ unacceptably high values of local NG for $c \sim \mathcal{O}(1)$
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Example: Quintessential inflation

→ Quintessential inflation with a steep potential and a brane correction term [T. Shiromizu, K. Maeda & M. Sasaki, 2000; V. Sahni, M. Sami & T. Souradeep, 2002]

$$H^2 = \frac{\rho}{3M_p^2}\left(1 + \frac{\rho}{2\lambda_{\rm B}}\right)$$

→ Modified slow-roll parameters [R. Maartens, D. Wands, B. Bassett & I. Heard, 2000]

$$\epsilon = \epsilon_V \frac{1 + V/\lambda_{\rm B}}{(1 + V/2\lambda_{\rm B})^2}$$

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$\lambda_{\rm B}$ is the brane tension and V is the scalar potential.

→ Clearly shows that $\epsilon \ll 1$ possible *even when* $\epsilon_V \sim c^2/2 \sim \mathcal{O}(1)$ due to additional friction terms. Not specific to this model ⇒ similar "magnetic drift" term in chromo-natural inflation. [P. Adshead & M. Wyman, 2012]

Typically, ϵ_V can be large in these class of models.

→ An obstruction is $r = 24/(N+1)$ for these models ⇒ ruled out by observations for $N \sim 60$.

→ Non-BD states can suppress r also for this class of models, to turn them viable, as before.

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The Quantum Swampland?

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Bunch-Davies (à la Hartle and Hawking) doomed?

The no-boundary proposal - I

→ Famous idea of the no-boundary wave function of the universe due to Hartle & Hawking → Wave function specified by the value of the 3−metric and spatial field configuration on a final spacelike surface Σ

$$\Psi = \Psi[h_{ab}, \chi]$$

→ NBWF: The quantum mechanical amplitude for a given three-geometry Σ is given by the Feynman path integral over all compact four-geometries bounded only by $\Sigma \Rightarrow$ Resolution of classical big-bang singularity.

→ Quantum completion for inflation ⇒ NBWF explains the quantum origin of spacetime and provides initial condition for inflation.

→ Important for us: NBWF predicts classical Lorentzian, inflating spacetime with the Bunch-Davies vacuum ⇒ A priori, not guaranteed.

→ A complementary interpretation is that the universe nucleates out of "nothing", since the total Hamiltonian for the system vanishes on-shell.[A. Vilenkin, 1982]

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The no-boundary proposal - II

→ Restrict to minisuperspace, spatially closed cosmologies with a cosmological constant or a single scalar field.

→ Saddle-point approximation [J. Hartle & S. Hawking, 1983]

$$\Psi[h_{ab},\chi] := \int^{(h,\chi)} \mathcal{D}[g]\mathcal{D}[\varphi] e^{-S[g,\varphi]/\hbar} \approx \sum_{\mathrm{ext}} c_{\mathrm{ext}} e^{-S_{\mathrm{ext}}[h_{ab},\chi]/\hbar}$$

→ No-boundary saddle-points: Extrema of the action (generally complex but Euclidean for the simplest cases), with (h_{ab},χ) on the boundary at late times and are regular everywhere else.

→ For minisuperspace models, this implies the boundary conditions $a(0) = 0, \;\; \dot{\varphi}(0) = 0$. (Regularity at the South Pole).

→ Dynamics governed by Einstein gravity ⇒ There is a one-parameter family of solutions of no-boundary instantons, specified for the value of the scalar field at the 'South Pole'.

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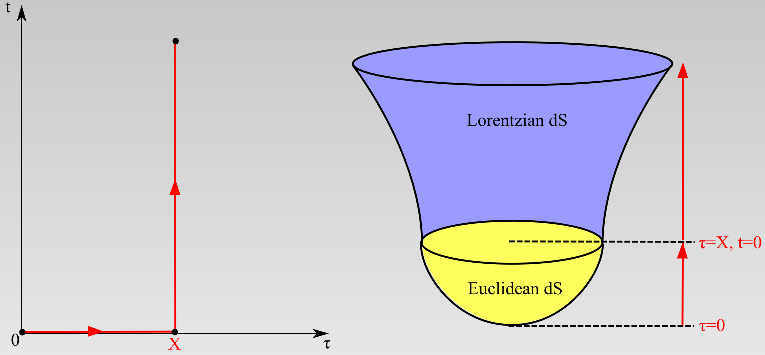

Left: A typical time contour over the complex time, where $X = \pi/2H_0$. Right: Euclidean and Lorentzian manifold along the given time contour.

Hartle-Hawking doomed?

→ Euclidean $\int^h \mathcal{D}[g] e^{-S_E/\hbar}$ (compact Euclidean 4-geometries bounded by h) vs. Lorentzian $\int_\emptyset^h \mathcal{D}[g] e^{iS/\hbar}$ (Lorentzian 4-geometries interpolating between a vanishing initial 3-geometries and h).

→ Cosmological Euclidean path integral plagued by divergences ⇒ Conformal mode problem renders unbounded from below

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⇒The PI for real Lorentzian metrics cannot be deformed to a Euclidean contour, which corresponds to the HH saddle-point.[J. Feldbrugge, J. Lehners & N. Turok, 2017]

→ Work with the Lorentzian path integral (with real lapse) and use Picard-Lefshetz theory to improve the convergence property of oscillatory integrals ⇒ Cauchy's theorem allows us deform a complex integration contour while PL tells us how to deform it.

→ The path integral amplitude for a tensor perturbation ϕ_1 on the final 3−geometry is doomed due to an inverse-Gaussian weighting $\int \mathcal{D}[g]\, e^{iS[g]/\hbar} \propto \exp\left(\frac{-12\pi^2}{\hbar\Lambda} + \frac{3l(l+1)(l+2)\phi_1^2}{2\hbar\Lambda}\right)$

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Hartle-Hawking rescued by (loop) quantum gravity

Loop quantum gravity corrections

→ Basic continuum quantities of spatial geometry, such as areas and volumes, are represented by operators with discrete spectra.
An infinitesimal change of these quantities in time — or, more geometrically, the extrinsic curvature of space — no longer has a linear and local expression in space but is instead exponentiated and extended one-dimensionally, along an eponymous loop.[A. Ashtekar, M. Bojowald, J. Lewandowski, C. Rovelli, L. Smolin, T. Thiemann ...]

→ For a cosmological model, they imply two main corrections:

- Holonomy modifications: No operator for extrinsic curvature $\dot{a}$ or the Hubble parameter $\dot{a}/a \Rightarrow$ Well-defined operators only for $SU(2)$ holonomy matrix elements, which are periodic functions such as $\dot{a} \to \sin(\ell(a)\dot{a})/\ell(a)$ with $\ell(a) \sim l_P/a$.
- Inverse-volume corrections: Using $\hat{h}^{-1}[\hat{h}, \sqrt{\hat{a}}] = -\frac{1}{2}\hbar\widehat{\ell a^{-1/2}}$ (where $\hat{h} = \widehat{\exp(i\ell p_a)}$) to get $a^{-1} = f(a)/a$ with $f(a)$ some quantum correction function which goes to 1 for large a. The small-a behaviour eliminates the divergence of a direct inverse at $a = 0$.

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Loop corrections in the no-boundary proposal

→ In the path integral form for the no-boundary proposal, this implies replacing the Einstein-Hilbert action by an effective LQC action, which includes the said corrections.

→ In the canonical picture, instead of solving the standard WDW operator, one solves a "difference" equation in LQC ⇒ Quantum geometry corrections imply a modified Hamiltonian constraint in $\hat{\mathcal{H}}_{\mathrm{LQC}}\,\Psi = 0$. Still need boundary conditions for specific solutions.
Naturally, the Friedmann equation is also modified in LQC as a result.

→ The role played by modified constraints crucial in LQG ⇒ They result in deformed gauge transformations. Since background is modified, covariant perturbatons imply an effective line-element $\mathrm{d}s_\beta^2 = -\beta N^2 \mathrm{d}t^2 + a(t)^2 \mathrm{d}\Omega_k$ where $\beta(a, \dot{a})$ changes sign at large curvature resulting in dynamical signature change.

South-Pole regularity conditions modified for LQC –
EH: $a(0) = 0, \quad \dot{a}(0) = 1 \Leftrightarrow$ LQC: $a(0) = 0, \quad \dot{a}(0) = 0$

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→ The role played by modified constraints crucial in LQG ⇒ They result in deformed gauge transformations. Since background is modified, covariant perturbatons imply an effective line-element $ds_\beta^2 = -\beta N^2 dt^2 + a(t)^2 d\Omega_k$ where $\beta(a, \dot{a})$ changes sign at large curvature resulting in dynamical signature change.

South-Pole regularity conditions modified for LQC –
EH: $a(0) = 0, \quad \dot{a}(0) = 1 \Leftrightarrow$ LQC: $a(0) = 0, \quad \dot{a}(0) = 0$

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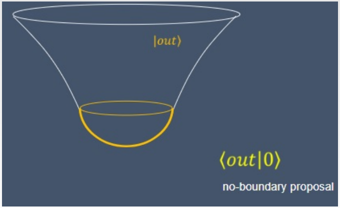
Hartle-Hawking proposal: Recap

$\rightarrow$ For minisuperspace cosmologies, in the saddle-point approximation, the no-boundary wavefunction simplifies

$$\Psi^{\mathrm{HH}}[\tilde{a},\chi] \approx e^{-S_{\mathrm{E}}^{\mathrm{EH}}[\tilde{a},\chi]/\hbar}$$

$\rightarrow$ For simplest models, say with only a cosmological constant, our (Lorentzian) universe tunnels from nothing via an Euclidean region.

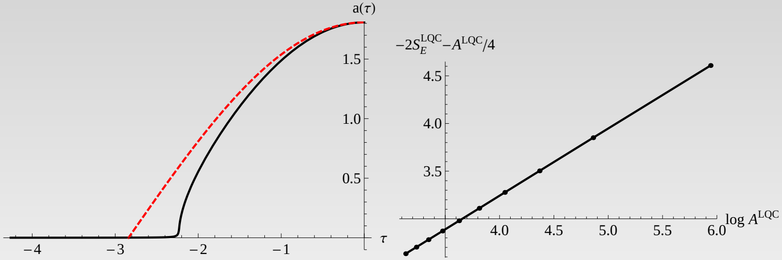
$\rightarrow$ Friedmann equation: $\dot{a}^2 = -\mathcal{V}(a)$ and on-shell action $S_{\mathrm{E}}^{\mathrm{EH}} = -\frac{3\pi}{2}\int_0^{\tilde{a}} a\sqrt{|\mathcal{V}(a)|}$.
The nucleation probability of a universe $\mathcal{P} \simeq e^{-2S_{\mathrm{E}}^{\mathrm{LQC}}}$.



Pure de Sitter

[S.B. & D.-h. Yeom, 2018]

$$-\dot{a}^2 = \mathcal{V} := \frac{8\pi a^2}{3} f^2(a) \left[\frac{\rho}{f(a)} - \rho_1 \right] \left[\frac{\rho_2 - \frac{\rho}{f(a)}}{\rho_c} \right]$$



→ A typical solution $a(\tau)$ for some numerical values of Λ & l_{Pl}.

→ $-2S_{\rm E}^{\rm LQC} \simeq \frac{\mathcal{A}}{4} + c + d \log \mathcal{A}$, $\quad d > 0$ where $\mathcal{A} = 4\pi\tilde{a}^2$

→ LQC correction rather small ⇒ There is a potential barrier for both EH ($-\dot{a}^2 \sim -1 + \Lambda a^2$) and LQC scenarios.

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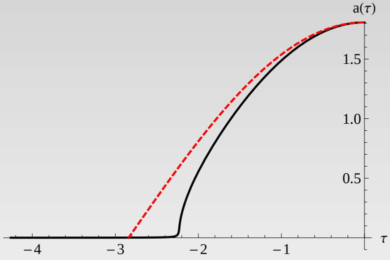

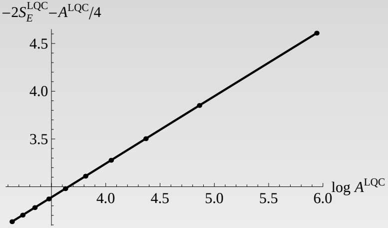

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Massless scalar field

→ Usual KG equation $\ddot{\varphi} + 3H\dot{\varphi} = 0 \Rightarrow \dot{\varphi} = 0$ and non-dynamical solution. In EH theory, no way to get interesting solutions.

→ Modified equations of motion [S.B. & D.-h. Yeom 2018]

$$\mathcal{V} = \frac{8\pi G}{3} a^2 f^2(a) \left[\frac{a^6 \pi}{4\sqrt{3}\gamma^3 l_{Pl}^6} \left(\frac{\rho}{\rho_c}\right) \left(\frac{g(a)}{f(a)}\right) - \rho_1 \right] \left[\frac{1}{\rho_c} \left(\rho_2 - \frac{a^6 \pi}{4\sqrt{3}\gamma^3 l_{Pl}^6} \left(\frac{\rho}{\rho_c}\right) \left(\frac{g(a)}{f(a)}\right) \right) \right]$$

$$\ddot{\varphi} - \left(\frac{\dot{B}(a)}{B(a)}\right) \dot{\varphi} = 0 \quad \text{Classically,} \quad B(a) \sim a^{-3} \quad \& \quad B(a) \sim a^{12} \quad \text{in QG regime}$$

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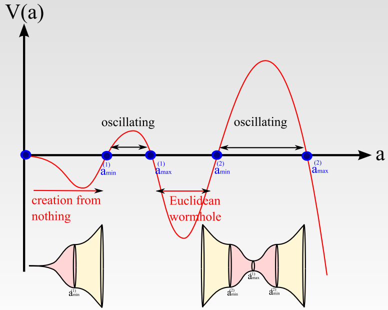

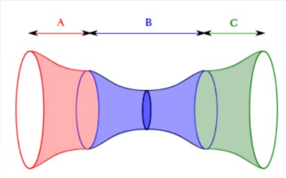

Creation of two universes via an Euclidean wormhole

Loops rescue the no-boundary proposal

→ Euclidean path integral diverges for $\Lambda > 0$ for all contours of the lapse ⇒ Lorentzian path integral can be made well-defined by applying Piecard-Lefshetz theory to yield a convergent integral by deforming the lapse contour.

→ Unsuppressed runaway perturbations on the final 3-geometry due to an inverse Gaussian weighting for perturbations ⇒ Old problem of the scale factor having wrong-sign kinetic term. $S = \int \mathrm{d}tN \left(-3a\frac{\dot{a}^2}{N^2} + a^3\frac{\dot{\phi}^2}{2N^2} + \dots\right)$ [J. Feldbrugge, J.-l. Lehners & N. Turok, 2017]

→ Dynamical signature change in makes these inverted Gaussians have the correct sign for having a Bunch-Davies state at the onset of inflation. [M. Bojowald & S.B., 2018]

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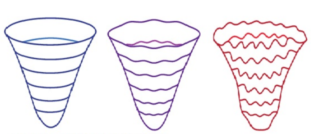

Photo from FLT (arXiv:1705.00192)

Timeless stability of perturbations

→ The mode equation

$$\ddot{v} \approx \frac{1}{4}\left((n-2\epsilon)(n+2)+\epsilon(\epsilon+2)-\beta\frac{N^2\ell(\ell+2)}{c^2}\right)\frac{v}{t^2},$$

and its solution is $v_+ = v_1 t^{\frac{1}{2}(1+\gamma)}$ where

$$\gamma = \sqrt{1+n(n+2)-\beta\frac{\ell(\ell+2)N^2}{c^2}}$$

→ For EH, $\beta = 1$, $n = 0 = \epsilon$, γ and the solutions $v_\pm$ have branch cuts on the real N-axis ⇒ The action evaluated on the regular solution v_+ is equal to $S_+(v_1) = \frac{1}{4}N^{-1}(\gamma-1)v_1^2$ and has a negative imaginary part above the branch cut. This result leads to a Gaussian with positive exponent in the path integral of perturbations.

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Summary

→ Conclusions:

- Swampland has opened a window of possibilities for cosmologists to model reality in a consistent manner.
- Conceptual reasons to move away from the Bunch-Davies vacuum for dS ⇒ Ironically, this strengthens the argument for a (quantum) Swampland.
- The no-boundary proposal also seems to suffer from some obstructions to constructing a BD vacuum for inflation.
- Quantum-geometry effects can give us hope as far as BD is concerned ⇒ Confluence of different approaches to quantum gravity might be fruitful.

→ Looking ahead:

- Looking beyond the simplest models of quintessence, what does the swampland have to say for more sophisticated models (higher derivative terms, coupled-quintessence, ...)?
- Quantum-geometry corrected Hartle-Hawking proposal gives a new path towards dS/CFT? ($Z_{\mathrm{EAdS}_4} = |\Psi_{\mathrm{dS}_4}|_{\mathrm{HH}}$) [Anninos, Strominger, Hartle, Hertog, Hawking ...]

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EXTRA SLIDES

Instantaneous Minkowski vacuum: $a_k(\eta_{k,0})|0, \eta_{k,0}\rangle = 0$ at $\eta_{k,0} = -\frac{\Lambda}{Hk}$

Even if it had been possible to find a vacuum already at the classical level, the quantum contributions are still expected to be much larger than our fine tuned value of the cosmological constant.

If dS is unstable, there is a spontaneous breakdown of dS invariance at the quantum level.

The particle production will through conservation of energy drain the cosmological constant and induce a time dependence.

The process can not end until the cosmological constant has reached zero $\Rightarrow$ As the Hubble constant decreases in value, the quantum effects go away. In a time-dependent background, no reason to exclude terms with $p \neq -\rho$ based on lack of right symmetry.

The inconsistency of the Bunch-Davies vacuum supports a quantum version of the swampland conjecture.

Quantum gravity = Quantum space-time

→ The LQG corrections strongly modifies the dynamics through regularized (diffeomorphism and scalar) constraints.

Example: The effective Friedmann equation in LQC: $H^2 = \frac{8\pi G}{3}\rho\left(1 - \frac{\rho}{\rho_c}\right)$ due to the LQC Hamiltonian constraint: $\mathcal{H} = -\frac{3NV_0}{8\pi G}\, a \sin^2(\ell(a)\frac{\dot{a}}{N})/\ell^2(a)$

→ Gauge transformations, generated by constraints, represent coordinate freedom: space-time Lie derivative of a function given by $\{f, H[\epsilon] + D[\xi^a]\} = \mathcal{L}_{(\epsilon/N, \xi^a + \epsilon N^a/N)} f$ on-shell (time direction $t^a = Nn^a + N^a$).

→ Hypersurface deformation algebra of classical space-time (generalization of local Poincaré algebra):

$$\begin{aligned}
\left\{D(w_1^a), D(w_2^b)\right\} &= D\left(\mathcal{L}_{w_1} w_2^a\right)\\
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- Invariance under HDA implies general covariance. [Dirac, 1951]
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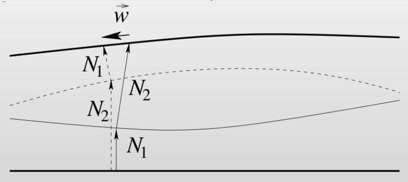
$\rightarrow$ Gauge transformations, generated by constraints, represent coordinate freedom: space-time Lie derivative of a function given by
$\{f, H[\epsilon] + D[\xi^a]\} = \mathcal{L}_{(\epsilon/N, \xi^a + \epsilon N^a/N)} f$ on-shell (time direction $t^a = Nn^a + N^a$).

$\rightarrow$ Hypersurface deformation algebra of classical space-time (generalization of local Poincaré algebra):

$$
\begin{aligned}
\left\{D(w_1^a), D(w_2^b)\right\} &= D\left(\mathcal{L}_{w_1} w_2^a\right) \\
\{H(N), D(w^a)\} &= -H\left(\mathcal{L}_w N\right) \\
\{H(N_1), H(N_2)\} &= D\left(q^{ab}\left(N_1\partial_b N_2 - N_2\partial_b N_1\right)\right)
\end{aligned}
$$

- Invariance under HDA implies general covariance. [Dirac, 1951]
- Second-order field equations invariant under HDA must equal GR. [Hojman, Kukař & Teitelboim, 1974-76]



Signature change

→ Modified constraints, including LQG corrections, still form a closed algebra avoiding gauge anomalies. But deformations appear.
$\{H(N_1), H(N_2)\} = D\left(\beta q^{ab}\left(N_1\partial_b N_2 - N_2\partial_b N_1\right)\right)$, $\beta = \frac{\mathrm{d}^2 f}{\mathrm{d}K^2}$ ($\beta \to 1$ classical).

→ Both the Lagrangian density (dynamics) as well as the measure (structure of space-time itself) subject to quantum corrections
$S[g] = \frac{1}{2\kappa}\int \mathrm{d}^4x\,\sqrt{|\det g|}\,\left(R[g] + \cdots\right)$.

→ Field redefinition can absorb β to give standard HDA brackets *as long as* β does not change sign. EOMs are obviously still modified due to LQG corrections, but space-time can be classical locally.

→ 'Dynamical Signature change' resolves classical singularity ⇒ New model of quantum spacetime with no Riemannian structure.

→ Invariant line-elements consistent with the deformed gauge transformations in LQG $\mathrm{d}s^2 = -\beta N^2\mathrm{d}t^2 + q_{ab}\left(\mathrm{d}x^a + N^a\mathrm{d}t\right)\left(\mathrm{d}x^b + N^b\mathrm{d}t\right)$,

We see how space-time structures are strongly affected by the same corrections which alter dynamics ⇒ new factor of β in the time-time component of the space-time line element. Signature change for $\beta < 0$ is an immediate consequence.

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Emergence of non-Riemannian geometry

→ Lie algebroid: $(A, [.,.]_A, \rho)$ with $\rho : \Gamma(A) \to \Gamma(TB)$, such that ρ satisfies a homomorphism of Lie algebras and a Leibnitz identity.

→ Hypersurface deformation brackets form a Lie algebroid → Phase space (q_{ab}, K^{ab}) forms base manifold → Lagrangian multipliers (N, N^a) forms $(4 \times \infty)-$dimensional fibers. [C. Blohmann, M.Fernandez & A. Weinstein, 2010]

→ Deriving HDA: "g-Gaussian" vector fields ⇒ $n^\mu \mathcal{L}_\nu g_{\mu\nu} = 0$, preserving Gaussian form of the metric $\mathrm{d}s^2 = -\epsilon \mathrm{d}t^2 + q_{ab}\mathrm{d}x^a \mathrm{d}x^b$.

→ Lie algebroid morphisms can change the deformation function $\beta(q_{ab}, K^{ab})$:[M. Bojowald, S.B., U. Büyükçam & F. D'Ambrosio, 2016]

- $q_{ab} \mapsto |\beta|^{-1} q_{ab}$ generated by base transformations.
- $N \mapsto \sqrt{|\beta|^{-1}} N$ generated by fiber maps (same as a non-standard normal for β spatially constant).

No algebroid morphisms can remove $\mathrm{sgn}(\beta)$ ⇒ No (global) Riemannian structure when β changes sign.