Title: Effective line-elements in loop quantum gravity

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Abstract: <p>Canonical quantization schemes often suggest modifications to classical dynamics, such as in an effective Friedmann equation. However, although often ignored, they also necessarily imply new effects for quantum space-time leading to new (quantum) symmetries. The invariant line-element, corresponding to new geometrical structures emerging in the presence of holonomy modifications in loop quantum gravity, shall be consistently derived in this talk. We shall use black-hole models to illustrate new features of this quantum space-time, going beyond standard Riemannian manifolds.</p>

Effective line elements in loop quantum gravity

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M. Bojowald, S.B. & D.-h. Yeom, 1803.01119
M. Bojowald, S.B., U. Büyükçam & F. D'Ambrosio, 1610.08355
M. Bojowald & S.B., 1610.08840, *forthcoming*
S.B., 1411.3661

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Motivation

→ Canonical quantization techniques often leads to new effects in quantum gravity ⇒ both in the dynamics and the structure of space-time.

→ First effects: Classical dynamical equations are modified due to background-independent quantizations.

→ Example: The effective Friedmann equation in LQC

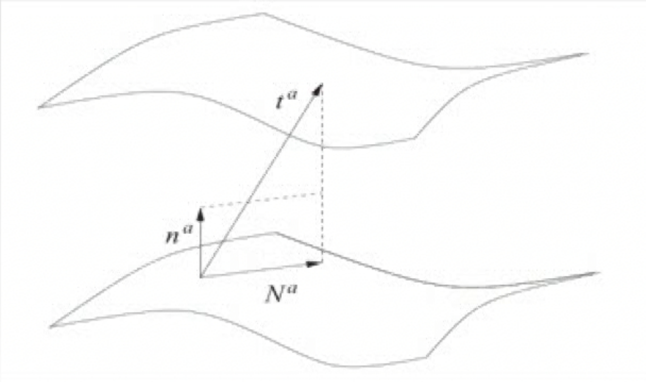
$$H^2 = \frac{8\pi G}{3}\rho\left(1 - \frac{\rho}{\rho_c}\right)$$

Remarkable deviations from classical dynamics ⇒ Singularity resolution due to holonomy modifications ⇒ originates from nontrivial regularizations in the LQG Hamiltonian constraint.

What effects do the same quantum correction have on the structure of space-time? (Different motivation: Deformed symmetries of quantum spacetimes)
Physical consequence ⇒ Derivation of consistent line elements?

Canonical gravity

- In the Lagrangian formulation, space and time are treated equally and on the same footing.
- In the Hamiltonian formulation, split space and time by using an arbitrary (time) function to foliate globally hyperbolic spacetime.
- $\mathrm{d}s^2 = g_{\mu\nu}\mathrm{d}x^\mu \mathrm{d}x^\nu \Rightarrow$ ADM metric:
  $\mathrm{d}s^2 = -N^2\mathrm{d}t^2 + q_{ab}\left(\mathrm{d}x^a + N^a\mathrm{d}t\right)\left(\mathrm{d}x^b + N^b\mathrm{d}t\right)$.
- One-to-one correspondence between $g_{\mu\nu}$ and (q_{ab}, N, N^a) but roles of different components space-time line element crucially different.



GR as a constrained system

Hamiltonian for GR:

$$H_{\text{grav}}^{\text{tot}} = \int d^3x \, (NC_{\text{grav}} + N^a D_a^{\text{grav}})$$

where C_{grav} & D_a^{grav} are the 'Hamiltonian' and (spatial) 'diffeomorphism' constraints respectively. No absolute time.

⇒ These 'first-class' constraints play a dual role:

- Constraints generate the EOMs for the system, for a given choice of the Lagrange multipliers ⇒ EOMs derived in some choice of 'time' (gauge).
- Same constraints also generate gauge transformations, which do not change the physical solutions ⇒ freedom in choice of 'time'.
- Form of both sets of equation very similar but meaning very different.

→ LQG-modified constraints ⇒ Crucial to understand interplay between evolution and gauge.

→ Consistent interplay between EOMs and GTs rely on the off-shell algebra of the (modified) constraints.

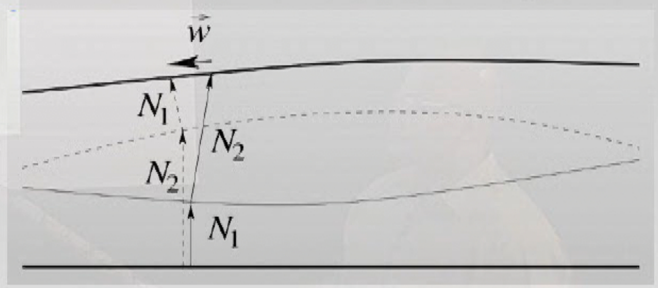
Dirac algebra

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

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

with (lapse) N: function on space, (shift) w: vector field and q: metric on spatial slice.

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



→ Modified constraints, including LQG corrections, still form a closed algebra avoiding gauge anomalies. But deformations appear.

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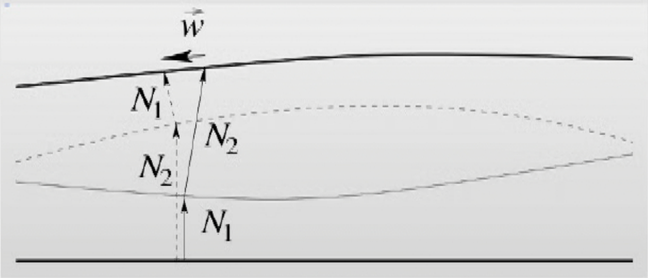

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Gauge transformations and the HDA

- The phase space is given by the spatial metric (q_{ab}) and its conjugate momenta (π^{ab}). The algebra of classical constraints calculated on this phase space.
- Gauge transformations represent coordinate freedom: space-time Lie derivative of any (phase-space) function, $f(q_{ab}, \pi^{ab})$, given by $\mathcal{L}_{(\epsilon^0/N, \epsilon^i - \epsilon^0 N^i/N)} f = \{f, H[\epsilon^0] + D[\epsilon^i]\}$ if constraints are satisfied (time direction $t^a = Nn^a + N^a$).
- EOMs: $\dot{f} := \{f, H[N] + D[N^a]\}$ & GTs: $\delta_\epsilon f := \{f, H[\epsilon^0] + D[\epsilon^i]\}$.
- Commutation property: Evolution of gauge-transformed initial data = Gauge transformation of evolved initial data.
- Since a commutation relation is involved ⇒ Interplay between evolution and gauge relies on Dirac algebra.

→ This is what happens classically. For the LQG scenario, the constraints are modified and, as a result, the HDA gets deformed.

A small puzzle?

- GTs, generated by $H[\epsilon^0] + D[\epsilon^i]$, act on q_{ab} and π^{ab} but not on (N, N^a).
- However, a generic coordinate transformation can clearly change both q_{ab} as well as g_{0a} components of the metric $\mathrm{d}s^2 = -N^2\mathrm{d}t^2 + q_{ab}\left(\mathrm{d}x^a + N^a\mathrm{d}t\right)\left(\mathrm{d}x^b + N^b\mathrm{d}t\right) \Rightarrow$ Role of (N, N^a) crucially different from q_{ab}.

There are two ways to resolve this puzzle:

- Consider the extended phase space with p_N and p_{N^a} (primary constraints not solved). [J. M. Pons, D. C. Salisbury, and L. C. Shepley, 1997]
- Require canonical EOMs are gauge-covariant $\Rightarrow$ This approach explicitly shows the important role played by the Dirac algebra.

$\rightarrow$ Once the classical case is demonstrated, extend results for the LQG-deformed HDA.

Transformation of the Lapse and Shift

→ Canonical EOMs, in a particluar gauge, must transform consistently with the GTs of the canonical variables ⇒ Possible only if $N^A := (N, N^i)$ transform properly!

- Evolution of any phase space variable: $\dot{q} = \{q, C[N^A]\}$.
- Coordinate transform $\tilde{q} = q + \delta_{\epsilon^A} q$ with $\delta_{\epsilon^A} q = \{q, C[\epsilon^A]\}$.
- Transformed q satisfy the same EOMs $\dot{\tilde{q}} = \{\tilde{q}, C[\tilde{N}^A]\}$, if there is a nontrivial transformation $\tilde{N}^A = N^A + \delta_{\epsilon^B} N^A$.
- Using the constraint algebra (HDA) and equating the LHS and RHS of the above equation, possible to calculate $\delta_{\epsilon^B} N^A$.

→ Given $\{C_A, C_B\} = F^D_{AB} C_D$, we get $\delta_\epsilon N^A = \dot{\epsilon}^A + N^B \epsilon^C F^A_{BC}$. Explicitly,

$$\delta_\epsilon N = \dot{\epsilon}^0 + \epsilon^i \partial_i N - N^i \partial_i \epsilon^0 \quad (1)$$

$$\delta_\epsilon N^i = \dot{\epsilon}^i + \epsilon^j \partial_j N^i - N^j \partial_j \epsilon^i - q^{ij}(N \partial_j \epsilon^0 - \epsilon^0 \partial_j N) \quad (2)$$

crucially depend on the HDA (above, we use the classical HDA).


LOOK AT THESE SCANDALOUS EMAILS!
GLOBAL WARMING
NICK ANDERSON 12-8-09
HOUSTON CHRONICLE

The Big Picture

Say, we have some (infinitesimal) coordinate transformation $t' \to t + \xi^0$ & $x' \to x^a + \xi^a$.

The spatial metric transforms as $\tilde{q}_{ab} = \{q_{ab}, H + D\}$.

For the line element
$\mathrm{d}s^2 = -\tilde{N}^2 \mathrm{d}t'^2 + \tilde{q}_{ab} \left(\mathrm{d}x'^a + \tilde{N}^a \mathrm{d}t'\right) \left(\mathrm{d}x'^b + \tilde{N}^b \mathrm{d}t'\right)$ to be meaningful,
i.e. invariant (co-ordinate independent), the lapse $\tilde{N}$ and shift $\tilde{N}^a$ must transform in an appropriate manner, which depends on the HDA, as demonstrated.

In the presence of LQG (holonomy) modifications, the HDA is deformed. What is the corresponding invariant line-element for such LQG-modified (effective) space-times?

Spherically symmetric gravity

- Ashtekar-Barbero variables:
  $\{K_\phi(x), E^\phi(y)\} = G\delta(x,y) = \frac{1}{2}\{K_x(x), E^x(y)\}$.
- Line-element: $\mathrm{d}s^2 = -N^2\mathrm{d}t^2 + q_{xx}\left(\mathrm{d}x + N^x\mathrm{d}t\right)^2 + q_{\varphi\varphi}\mathrm{d}\Omega^2$ with $q_{xx} = (E^\phi)^2/E^x$, $q_{\varphi\varphi} = E^x$.
- Spherically symmetric coordinate transformation
  $t' = t + \xi^0$, $x' = x + \xi^x$, with $(\xi^0, \xi^x) = \left(\epsilon^0/N, \epsilon^x - (N^x/N)\epsilon^0\right)$.
- Insert transformed coordinates $(x^a + \xi^a)$ in the line element directly to collect coefficients of $\mathrm{d}x^2, \mathrm{d}t^2$ & $\mathrm{d}x\mathrm{d}t$. E.g.,
  $\mathrm{d}t' = \mathrm{d}(t + \epsilon^0/N) = \mathrm{d}t + (\epsilon^0/N)^\bullet \mathrm{d}t + (\epsilon^0/N)'\mathrm{d}x$.

From this one can evaluate δq_{xx} and δN^x directly, using which, one can also get δN.

- $\delta q_{xx} = \{q_{xx}, H[\epsilon^0] + D[\epsilon^x]\}$
- $\delta N^x = \dot{\epsilon}^x + \epsilon^x(N^x)' - N^x(\epsilon^x)' - q^{xx}\left(N(\epsilon^0)' - \epsilon^0 N'\right)$
- $\delta N = \dot{\epsilon}^0 + N'\epsilon^x - N^x(\epsilon^0)'$

The only structure function for this system:
$\{H[N_1], H[N_2]\} = D\left[q^{xx}\left(N_1 N_2' - N_2 N_1'\right)\right]$.

Holonomy modifications

- Regularize the constraint via holonomies of extrinsic curvatures $K_\phi \to f(K_\phi)$ (Keep (bounded) function arbitrary for our purposes to allow for quantization ambiguities).
- The constraint algebra is closed, but deformed (only $[H, H]$).

$$[H[N_1], H[N_2]] = D\left[\beta q^{ab}\left(N_1 N_2' - N_2 N_1'\right)\right];$$
$$\beta = d^2 f/dK_\phi^2 \;\Rightarrow\; \beta \to 1 \text{ classical limit}$$

- Typically, $f(K_\phi) = \sin^2(\delta K_\phi)/\delta^2 \Rightarrow \beta = \cos(2\delta K_\phi)$.
- Given (deformed) HDA, derivation follows the classical case to get $\delta N^x = \dot{\epsilon}^x + \epsilon^x (N^x)' - N^x (\epsilon^x)' - \beta q^{xx}\left(N(\epsilon^0)' - \epsilon^0 N'\right)$.
- But transformation of the lapse keeps the same form (since no structure functions are involved).
- Since the term in δN^x relevant to derive δN is multiplied by β, to get required cancellations, we need coordinate transformations not of the classical line element, but of an effective line element $\mathrm{d}s^2 = -\beta N^2 \mathrm{d}t^2 + q_{xx}\left(\mathrm{d}x + N^x \mathrm{d}t\right)^2 + q_{\varphi\varphi}\mathrm{d}\Omega^2$

Recap

→ For the classical HDA, coordinate transformations $t' = t + \xi^0$, $x' = x + \xi^x$ imply that the spatial metric transforms as $\{q_{xx}, H[\epsilon^0] + D[\epsilon^x]\}$ and the invariant line element is coordinate independent only when lapse and shift transform in a specific way.

→ When corrections are introduced in the LQG-regularized constraints, the HDA is deformed. Consequently, the line element which remains invariant under coordinate transformations has to be modified by a factor. Transformation of $(\delta q_{xx}, \delta N^x, \delta N)$ consistent only with this effective line element.

→ We see how space-time structures are strongly affected by the same corrections which alter dynamics in LQG.

> Holonomy modifications not only imply corrections to the spatial metric by modified equations of motion generated by the Hamiltonian constraint, they also require a new factor of β of N^2 in the time-time component of the space-time line element. Signature change for $\beta < 0$ is an immediate consequence.

Implications for other physical scenarios

→ Effective line elements shall involve correction to the lapse in LQG models wherever one gets a deformed algebra of a similar form.

$$[D(w_1^a), D(w_2^b)] = D(\mathcal{L}_{w_1} w_2^a)$$

$$[H(N), D(w^a)] = -H(\mathcal{L}_w N)$$

$$[H(N_1), H(N_2)] = D\left(\beta q^{ab}(N_1\partial_b N_2 - N_2\partial_b N_1)\right)$$

- LQC with perturbations [A. Barrau, T. Cailleteau, L. Linsefors & J. Grain, 2012; M. Bojowald & Mielczarek, 2015]
- CGHS and Schwarzschild Black hole [M. Bojowald & S.B., 2016]
- 2−dimensional dilaton gravity [M. Bojowald & S.B., 2016]

→ Holonomy modifications necessarily lead to signature changing deformations.

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

→ Fluctuations and higher moments of the quantum state, related to higher curvature corrections, cannot *undo* these deformations from LQG [M. Bojowald & S.B., 2014].

‘Fuzzy’ Euclidean regime - I

→ Why fuzzy?

$$H[N] = -\frac{1}{2G}\int \mathrm{d}x N\left(\frac{f_1(K_\varphi)E^\varphi}{\sqrt{E^x}} + 2\sqrt{E^x}K_x f_2(K_\varphi) - \frac{1}{2}E^\varphi V(E^x) - \frac{((E^x)')^2}{4E^\varphi\sqrt{E^x}} + \frac{\sqrt{E^x}(E^x)'(E^\varphi)'}{(E^\varphi)^2} - \frac{\sqrt{E^x}(E^x)''}{E^\varphi}\right)$$

- Spherically symmetry: $V(E^x) = -2/\sqrt{E^x}$
- Other choices of V for CGHS model, Gowdy model etc.
- Standard choice for holonomy modification function $f_1(K_\varphi) = \sin^2(\delta K_\varphi)/\delta^2$, ($f_2 = \dot{f}_1/2$ necessarily)
- The maximum is obtained for $\delta K_\varphi = \pi/2$. Expanding around this point, we write $\delta K_\varphi = \pi/2 + \delta k_{\mathrm{E}}$ with small δk_{E}.

The curvature-dependent part of the Hamiltonian constraint

$$\frac{E^\varphi}{\sqrt{E^x}}f_1(K_\varphi) + 2\sqrt{E^x}f_2(K_\varphi)K_x = -\left(\frac{E^\varphi}{\sqrt{E^x}}k_{\mathrm{E}}^2 + 2\sqrt{E^x}k_{\mathrm{E}}K_x\right) + \frac{E^\varphi}{\delta^2\sqrt{E^x}} + \cdots.$$

‘Fuzzy’ Euclidean regime - II

[M. Bojowald & S.B., *forthcoming*]

- The sign of the curvature term has changed, as it should for a Euclidean gravity model.
- Moreover, there is a new contribution depending only on the triad variables, which can be combined with the original dilaton potential $V(E^x)$ from the Lorentzian phase if it is changed by adding $\delta V(E^x) = -2/(\delta^2\sqrt{E^x})$.
- For $\delta = 1$, this shift happens to be identical with the dilaton potential of spherically symmetric gravity. Holonomy-modified model, which is spherically symmetric gravity in the Lorentzian phase, has twice the spherically symmetric potential in the Euclidean phase. It is therefore different from spherically symmetric Euclidean gravity.
- Holonomy-modified CGHS model in the Lorentzian phase is equal to spherically symmetric gravity with a cosmological constant in the Euclidean phase.
- The new term makes a huge contribution to the potential as it is inversely proportional to the ‘area-gap’.
- Similar results available for LQC models where the new perturbative contributions are consistent with a cosmological-constant term $\Lambda \sim 1/\ell_{Pl}^2$ added to the full Hamiltonian density.

HDA as a Lie algebroid

→ 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 Riemannian structure when β changes sign.

Specific solutions: Black holes

$$\dot{E}^x = 2N\sqrt{E^x}\, f_2(K_\phi) + N^x (E^x)'$$
$$\dot{E}^\phi = N\sqrt{E^x} K_x \frac{\mathrm{d}f_2(K_\phi)}{\mathrm{d}K_\phi} + \frac{NE^\phi}{2\sqrt{E^x}} \frac{\mathrm{d}f_1(K_\phi)}{\mathrm{d}K_\phi} + (N^x E^\phi)'$$

- EOMs are set of coupled, non-linear, PDEs $\Rightarrow$ Important class of solutions easier to derive are stationary ones. LHS of $\dot{E}^x$ eqn must be zero, as must be the shift vector $\Rightarrow$ Looking for one of the zeros of $f_2(K_\phi) \Rightarrow K_\phi = 0, \pi/(2\delta), \ldots$
- "Stationary" has to be generalized to imply a solution with a Killing vector transversal to the hypersurfaces in a $(3+1)$-decomposition.
- Fixed K_ϕ can correspond to a gauge condition on the entire spacetime region (outside the Schwarzschild horizon) OR a unique spatial slice within a homogeneous gauge (inside the horizon).
- More alternating Lorentzian and Euclidean solutions $\Rightarrow$ concentrate on the first Euclidean regime.

Outside the horizon: Classical Schwarzschild

→ Gauge conditions: $E^x = x^2,\ K_\phi = 0$

→ Solutions are given by

$$
\begin{aligned}
E^\phi &= \frac{x}{\sqrt{1-\frac{2M}{x}}} \\
N &= \sqrt{1-\frac{2M}{x}} \\
\beta &= 1
\end{aligned}
$$

→ The effective line element is the classical one

$$ds^2 = -\left(1-\frac{2M}{x}\right)dt^2 + \frac{1}{1-2M/x}dx^2 + x^2 d\Omega^2$$

Holonomy modified interior

- $(x \leftrightarrow t)$ exchanges role inside the horizon but metric depends on x.
- $K_\phi = 0$ not available as a gauge choice if metric depends on 'time' coordinate. $E^x = x^2$ is also not a good gauge choice.
- Classically, $E^\phi(t) = t\sqrt{\frac{2M}{t} - 1}$, $K_\phi(t) = \sqrt{\frac{2M}{t} - 1}$, $N(t) = 1/\sqrt{\frac{2M}{t} - 1}$, $E^x(t) = t^2$.

$\rightarrow$ Suitable gauge choices: $N = \sqrt{E^x}$, $N^x = 0$, an anisotropic version of conformal time

$$E^\phi = M \sin\left(\sqrt{1+\delta^2}\,\eta\right)$$

$$\begin{aligned} E^\phi &= M\sin(\eta) \\ E^x &= 4M^2\cos(\eta/2) \\ K_\phi &= -\tan(\eta/2) \\ K_x &= \frac{1}{8M}\sec^4(\eta/2) \end{aligned} \qquad \begin{aligned} E^x &= \left(\frac{M}{1+\delta^2}\right)^2 \left[1 + 2\delta^2 + \cos\left(\sqrt{1+\delta^2}\,\eta\right)\right]^2 \\ K_\phi &= \frac{1}{\delta}\arctan\left[-\frac{\delta}{\sqrt{1+\delta^2}}\tan\left(\sqrt{1+\delta^2}\,\eta/2\right)\right] \\ K_x &= [\cdots] \end{aligned}$$

Effective line element in deep quantum regime

→ Can calculate β inside the horizon

$$\beta(\eta) = \frac{1 - \left(\frac{\delta^2}{1+\delta^2}\right)\tan\left(-\sqrt{1+\delta^2}\,\eta/2\right)}{1 + \left(\frac{\delta^2}{1+\delta^2}\right)\tan\left(-\sqrt{1+\delta^2}\,\eta/2\right)}$$

$$\beta = -1 \Rightarrow \eta = -\frac{\pi}{\sqrt{1+\delta^2}}(\delta K_\phi = \pi/2)$$

→ "After" time $\frac{\delta}{\sqrt{1+\delta^2}}\tan(\cdots) = 1$, η can be treated as a fourth spatial coordinate but not as time.

→ K_ϕ increases in the homogeneous interior and ultimately reaches $\beta = 0$. Formally, *assume* that K_ϕ keeps increasing in the direction normal to Σ. At this point, we switch to a 2−dimensional boundary value problem ⇒ Not clear what appropriate b.c. should be!

→ Gauge conditions: $E^x = x^2$, $\delta K_\phi = \pi/2$

→ The effective line element is the classical one

$$\mathrm{d}s^2 = \left(1 - \frac{2M}{x}\right)\mathrm{d}\tau^2 + \frac{\bar{\delta}}{1 - 2M/x}\mathrm{d}x^2 + x^2\mathrm{d}\Omega^2$$

with $\bar{\delta} = (1 + 1/\delta^2)^{-1}$.

Summary

→ Conclusions:

- Introducing QG corrections gives rise to new space-time structures, going beyond corrections to the classical dynamics.
- Only consistent effective line element is Euclidean when holonomy effects are strong ⇒ only boundary-value problems well posed in this region.
- Important to understand the role of quantum symmetries ⇒ Deformation of general covariance. NCG: Deformations generic to different approaches? [M. Bojowald, S.B., U. Büyükçam & M. Ronco, 2017]

→ Looking ahead:

- Similar line-elements needs to be derived for early-universe cosmology ⇒ Cannot interpret 'signature-change' as *instabilities* of matter ot metric perturbations on an otherwise Lorentzian manifold.
- Implications for the initial state? Smooth 'no-boundary' state compatible with dynamical signature-change? [M. Bojowald & S.B., *forthcoming*]