Existence and uniqueness of a class of semiclassical gravity solutions and the gravitational quantum stealth effect

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Outline

QFT in curved spacetime and semiclassical gravity

A new class of semiclassical gravity solutions

Remarks on the 'stealth' property and strong cosmic censorship

Outlook

QFT in curved spacetimes

- In recent years, QFT in curved spacetimes has gained increased attention – Avenues QFT in CS 2025 @ Tours.
- The task at hand is to generalise well-known QFT in Minkowski spacetime to curved backgrounds.
- Examples: Cosmology (structure formation), black holes (Hawking radiation).
- Plenty of interesting questions, RQI, entropy, entanglement, etc.

QFT in curved spacetimes

- The language of algebraic QFT has proven to be extremely useful – almost necessary – to develop QFT in curved spacetimes.
- The approach here is to see
  1. observables as elements of an abstract ($\star$ or C-$\star$ or W-$\star$) algebra (with some extra conditions) and
  2. states as linear maps from the algebra of observables to the complex numbers, which can be thought of as expectation values (with some extra conditions).
- The Hilbert space notion of QFT is then recovered by constructing a representation for observables in Hilbert space (via the GNS construction).
- Especially useful because in curved spacetime there are **no distinguished vacua** – hence no distinguished representations. (There is no Poincaré covariance!)
- Rather than give you a precise definition, let us look at a simple example.

QFT in curved spacetimes – KG field

- Let us give the simplest possible example.
- Klein-Gordon theory in curved spacetime:

Let (M, g_{ab}) be glob. hyp. The Klein-Gordon algebra, $\mathcal{A}_{\mathrm{KG}}$, is the unital $\star$-algebra generated by "smeared fields" $\Phi(f)$ with $f \in C_0^\infty(M)$ subject to the relations

KG1 $f \mapsto \Phi(f)$ is linear (linearity),

KG2 $\Phi(f)^\star = \Phi(\bar{f})$ (hermiticity),

KG3 $\Phi(Pf) = 0$, where $P := \Box - m^2 - \xi R$ (field equation) and

KG4 $[\Phi(f), \Phi(g)] = -\mathrm{i} E_P(f, g) \mathbb{1}$, for $g \in C_0^\infty(M)$ (commutation relations),

where $E_P^\pm$ are the (unique) advanced (-) and retarded (+) Green operators of P and $E_P := E_P^- - E_P^+$ is the causal propagator.

QFT in curved spacetimes: states

Where are the states?!

- States are linear maps from an algebra of observables to complex numbers.
- $\omega : \mathcal{A} \to \mathbb{C}$ is a state if (i) $\omega(\mathbb{1}) = 1$ and (ii) $\omega(A^\star A) \geq 0$ for any $A \in \mathcal{A}$.

Where are the Hilbert spaces?!

- The GNS construction allows one to produce, out of an algebra with algebraic state a tuple $(\mathcal{D}_\omega \subset \mathcal{H}_\omega, \Omega_\omega, \pi_\omega)$ where observables are represented as operators in Hilbert space.
  - Here, $\pi_\omega(\Phi) = \hat{\Phi}$.
  - $\omega(\Phi(f_1) \ldots \Phi(f_n)) = \langle \Omega_\omega | \hat{\Phi}(f_1) \ldots \hat{\Phi}(f_n) \Omega \rangle$.
- Despite this huge generality, one can still calculate some stuff: E.g. distinguished vacua and representations, e.g. in spacetimes with symmetries or asymptotic symmetries.

What does QFT in curved spacetime tell us?

QFT in curved spacetime has made amazing predictions. For example:

1. That black holes radiate at infinity at a temperature proportional to their surface gravity, the Hawking temperature. E.g., for Schwarzschild $T_{\mathrm{H}} = \kappa/(2\pi) = 1/(8\pi M)$ (Hawking, 1975).
2. That in cosmology (or more generally non-stationary situations) there is spontaneous particle creation (Parker, 1969).
3. That in non-inertial frames, observers can perceive the vacuum as filled with particles. Notably, uniformly linearly accelerated observers feel the vacuum as a thermal state at a temperature proportional to their acceleration, the Unruh temperature, $T_{\mathrm{U}} = a/(2\pi)$ (Fulling, 1972), (Davies, 1975), (Unruh, 1976).

Semiclassical gravity: beyond QFT in curved spacetimes

- Question: How do quantum fields affect the spacetime geometry? QG...
- At least to a good approximation, in some regime, semiclassical gravity should provide us with some insights or questions.
- Consider a black hole spacetime with a radiating quantum field. Radiation suggests evaporation.
- Black hole information loss...

Semiclassical gravity

- Let us unfreeze the gravitational degrees of freedom!
- Consider the semiclassical gravity equations with a Klein-Gordon field,

$$G_{ab} + \Lambda^{\mathrm{b}} g_{ab} = 8\pi G_{\mathrm{N}}^{\mathrm{b}} \omega(T_{ab}), \tag{1a}$$

$$(\Box - m^2 - \xi R)\Phi = (g^{ab}\nabla_a \nabla_b - m^2 - \xi R)\Phi = 0. \tag{1b}$$

- g_{ab}: spacetime metric (with inverse g^{ab}).
- Φ: Klein-Gordon field with mass $m^2 \geq 0$ and curvature coupling $\xi \in \mathbb{R}$.
- $G_{ab} = R_{ab} - (1/2) g_{ab} R$: Einstein tensor, where $R^a{}_{bcd}$: Riemann tensor, $R_{bd} = R^c{}_{bcd}$: Ricci tensor and $R = g^{ab} R_{ab}$: Ricci scalar.
- $\omega(T_{ab})$: Expectation value of the stress-energy tensor of Φ in the (algebraic) state ω.
- Λ^{b} and $G_{\mathrm{N}}^{\mathrm{b}}$: "bare" cosmological and Newton's constant, resp.

The stress-energy tensor & the need for renormalisation

- How can we define $\omega(T_{ab})$?
- Consider the classical analogue. We could define it for the KG field in a convoluted way as follows:
  1. Define the "point-split" differential operator

$$\mathcal{T}_{ab} := (1-2\xi)g_b{}^{b'}\nabla_a\nabla_{b'} + \left(2\xi - \frac{1}{2}\right) g_{ab}g^{cd'}\nabla_c\nabla_{d'} - \frac{1}{2}g_{ab}m^2 + 2\xi\Big[-g_a{}^{a'}g_b{}^{b'}\nabla_{a'}\nabla_{b'} + g_{ab}g^{cd}\nabla_c\nabla_d + \frac{1}{2}G_{ab}\Big]. \qquad (2)$$

  2. Apply $\mathcal{T}_{ab}$ to the product $\phi(\mathrm{x})\phi(\mathrm{x}')$ at spacetime points x and x'.
  3. Define $T_{ab}^{\mathrm{class}}(\mathrm{x}) = \lim_{\mathrm{x}'\to\mathrm{x}} \mathcal{T}_{ab}\phi(\mathrm{x})\phi(\mathrm{x}')$. This coincides with the usual definition.
- One could hope that replacing in the procedure above $\phi(\mathrm{x})\phi(\mathrm{x}')$ by $\omega(\Phi(\mathrm{x}), \Phi(\mathrm{x}'))$ would yield a definition for $\omega(T_{ab})$.
- However, typically the limit $\mathrm{x}' \to \mathrm{x}$ in $\omega(\Phi(\mathrm{x}), \Phi(\mathrm{x}'))$ diverges! (Convince yourself in Minkowski spacetime.)

Quantum field theory in curved spacetimes: states

- The Wightman function of the Klein-Gordon field:

$$\omega(\Phi(f_1)\Phi(f_2)) = \int_{M\times M} \mathrm{dvol}(\mathrm{x})\mathrm{dvol}(\mathrm{x}')f_1(\mathrm{x})f_2(\mathrm{x}')G^+(\mathrm{x},\mathrm{x}').$$

$$(\Box_{\mathrm{x}} - m^2 - \xi R(\mathrm{x}))G^+(\mathrm{x},\mathrm{x}') = (\Box_{\mathrm{x}'} - m^2 - \xi R(\mathrm{x}'))G^+(\mathrm{x},\mathrm{x}') = 0.$$

- A state is Hadamard if in a convex normal neighbourhood

$$G^+(\mathrm{x},\mathrm{x}') = \frac{1}{2(2\pi)^2}\left(\frac{\Delta^{1/2}(\mathrm{x},\mathrm{x}')}{\sigma_\epsilon(\mathrm{x},\mathrm{x}')} + v(\mathrm{x},\mathrm{x}')\ln\left(\frac{\sigma_\epsilon(\mathrm{x},\mathrm{x}')}{\ell^2}\right)\right) + w_\ell(\mathrm{x},\mathrm{x}')$$

- Δ is the van Vleck-Morette determinant.
- $\sigma_\epsilon(\mathrm{x},\mathrm{x}') := \sigma(\mathrm{x},\mathrm{x}') + \mathrm{i}\epsilon(t(\mathrm{x}) - t(\mathrm{x}')) + \frac{1}{2}\epsilon^2$: regularised half-squared geodesic distance.
- v and w_ℓ are smooth and symmetric coefficients – v is state independent and w_ℓ depends on the state.
- $\ell \in \mathbb{R}$ is an arbitrary length scale.

Quantum field theory: states

- Coefficient v fixed formally by Hadamard recursion relations:

$$v(\mathrm{x},\mathrm{x}') = \sum_{n=0}^{\infty} v_n(\mathrm{x},\mathrm{x}')\sigma^n(\mathrm{x},\mathrm{x}'),$$

- Similar expansion for w, but w_0 is "free" – state-dependent.
- The first two terms in

$$G^+(\mathrm{x},\mathrm{x}') = \frac{1}{2(2\pi)^2}\left(\frac{\Delta^{1/2}(\mathrm{x},\mathrm{x}')}{\sigma_\epsilon(\mathrm{x},\mathrm{x}')} + v(\mathrm{x},\mathrm{x}')\ln\left(\frac{\sigma_\epsilon(\mathrm{x},\mathrm{x}')}{\ell^2}\right)\right) + w_\ell(\mathrm{x},\mathrm{x}')$$

depend only on the spacetime geometry, and the parameters m^2 and ξ of the field, and coincide with the Hadamard bi-distribution of the KG operator $\Box - m^2 - \xi R$, H_ℓ, namely

$$H_\ell(\mathrm{x},\mathrm{x}') = \frac{1}{2(2\pi)^2}\left(\frac{\Delta^{1/2}(\mathrm{x},\mathrm{x}')}{\sigma_\epsilon(\mathrm{x},\mathrm{x}')} + v(\mathrm{x},\mathrm{x}')\ln\left(\frac{\sigma_\epsilon(\mathrm{x},\mathrm{x}')}{\ell^2}\right)\right).$$

- Distributional singularities in G^+ are state-independent.

The renormalised stress-energy tensor

The expectation value of the renormalised stress-energy tensor:

$$\omega(T_{ab}(\mathrm{x})) := \lim_{\mathrm{x}'\to\mathrm{x}} \mathcal{T}_{ab}(G^+(\mathrm{x},\mathrm{x}') - H_\ell(\mathrm{x},\mathrm{x}')) + \frac{1}{4\pi^2} g_{ab}[v_1](\mathrm{x}) + \Theta_{ab}(\mathrm{x}).$$

$$\mathcal{T}_{ab} = (1-2\xi) g_b{}^{b'} \nabla_a \nabla_{b'} + \left(2\xi - \frac{1}{2}\right) g_{ab} g^{cd'} \nabla_c \nabla_{d'} - \frac{1}{2} g_{ab} m^2$$
$$+ 2\xi \left[- g_a{}^{a'} g_b{}^{b'} \nabla_{a'} \nabla_{b'} + g_{ab} g^{cd} \nabla_c \nabla_d + \frac{1}{2} G_{ab} \right],$$

$$[v_1] := \lim_{\mathrm{x}'\to\mathrm{x}} v_1(\mathrm{x},\mathrm{x}') = \frac{1}{8} m^4 + \frac{1}{4}\left(\xi - \frac{1}{6}\right) m^2 R - \frac{1}{24}\left(\xi - \frac{1}{5}\right) \Box R$$
$$+ \frac{1}{8}\left(\xi - \frac{1}{6}\right)^2 R^2 - \frac{1}{720} R_{ab} R^{ab} + \frac{1}{720} R_{abcd} R^{abcd},$$

$$\Theta_{ab} = \alpha_1 g_{ab} + \alpha_2 G_{ab} + \alpha_3 I_{ab} + \alpha_4 J_{ab}, \qquad \text{with}$$

$$I_{ab} = 2 R_a{}^c{}_{;bc} - \Box R_{ab} - \frac{1}{2} g_{ab} \Box R + 2 R_a{}^c R_{cb} - \frac{1}{2} g_{ab} R^{cd} R_{cd},$$

$$J_{ab} = 2 R_{;ab} - 2 g_{ab} \Box R - \frac{1}{2} g_{ab} R^2 + 2 R R_{ab}.$$

Semiclassical gravity

To summarise, semiclassical gravity is

$$G_{ab}(\mathrm{x}) + \Lambda g_{ab}(\mathrm{x}) = 8\pi G_{\mathrm{N}} \lim_{\mathrm{x}' \to \mathrm{x}} \mathcal{T}_{ab}\left(G^{+}(\mathrm{x},\mathrm{x}') - H_{\ell}(\mathrm{x},\mathrm{x}') \right) + \frac{2 G_{\mathrm{N}}}{\pi} g_{ab}[v_1](\mathrm{x}) + \alpha I_{ab}(\mathrm{x}) + \beta J_{ab}(\mathrm{x}), \quad (3a)$$

$$\left(\Box_{\mathrm{x}} - m^2 - \xi R(\mathrm{x}) \right) G^{+}(\mathrm{x},\mathrm{x}') = \left(\Box_{\mathrm{x}'} - m^2 - \xi R(\mathrm{x}') \right) G^{+}(\mathrm{x},\mathrm{x}') = 0. \quad (3b)$$

S: initial value surface,

- Metric initial data: $g_{ab}|_S$, $\dot{g}_{ab}|_S$, $\ddot{g}_{ab}|_S$, $\dddot{g}_{ab}|_S$.
- Matter initial data: $\omega(\varphi\pi')$, $\omega(\varphi\pi')$, $\omega(\pi\varphi')$ and $\omega(\pi\pi')$ on S satisfying CCR. (Further data for one-point function if non-zero.)

Semiclassical gravity: Constraints

Semiclassical gravity contains four constraint equations.

- If the semiclassical gravity equations are $\mathcal{E}_{ab} = 0$, then
- Hamilton-like constraint: $n^a n^b \mathcal{E}_{ab} = 0$
- Gauss-like constraints: $n^a h^c{}_b \mathcal{E}_{ac} = 0$
- Constraints follow from the Gauss-Codazzi relations (as in GR).
- Constraints in the sense of semiclassical gravity means that they contain up to order 3 time derivatives.
- All good initial data should satisfy the constraints.

What can we say about semiclassical gravity?

- The mathematical structure of semiclassical gravity is not very well understood.
- Advances include:
  - Solutions in de Sitter space (BAJ-A, 2019), (Gottschalk, Rothe & Siemssen, 2022) and Anti-de Sitter (BAJ-A, Mamani-Leqque, 2024).
  - Solutions in static situations (Sanders, 2020), (BAJ-A, 2021).
  - Cosmological solutions (FLRW symmetry) (Pinamonti & Siemssen, 2013), (Gottschalk & Siemssen, 2018), (Meda, Pinamonti & Siemssen, 2020).
  - Conformally static spacetimes, (BAJ-A & Modak, 2022).
  - Some advances in spherical symmetry – not there yet! (Meda, Pinamonti, Roncallo & Zanghì, 2022), (Verch & Janssen, 2023).
  - Some advances in perturbation theory – not there yet! (BAJ-A, Miramontes & Sudarsky, 2020).
  - Towards the IVP (BAJ-A, Kay, Miramontes & Sudarsky, 2023), (ibid, 2024).

A new class of semiclassical gravity solutions

- Let us take a different approach – instead of imposing constraints on spacetime, let us constraint the class of states. We consider the Klein-Gordon equation,

$$(\Box_{\mathrm{x}} - m^2 - (1/2)R(\mathrm{x}))\,G^+(\mathrm{x},\mathrm{x}') = 0, \tag{4}$$

  and similarly in x' and look for some special Hadamard states.
- We can write the Hadamard property as

$$G^+(\mathrm{x},\mathrm{x}') = \frac{1}{2(2\pi)^2}\left(\frac{\Delta^{1/2}(\mathrm{x},\mathrm{x}')}{\sigma_\epsilon(\mathrm{x},\mathrm{x}')} + v(\mathrm{x},\mathrm{x}')\ln\left(\frac{\sigma_\epsilon(\mathrm{x},\mathrm{x}')}{\ell^2}\right)\right) + w(\mathrm{x},\mathrm{x}').$$

- We will expand the coefficients v and w as follows

A new class of semiclassical gravity solutions

$$v(\mathrm{x}, \mathrm{x}') = \sum_{n=0}^{\infty} V_n(\mathrm{x}, \mathrm{x}')\sigma^n(\mathrm{x}, \mathrm{x}'), \tag{5}$$

$$w(\mathrm{x}, \mathrm{x}') = \sum_{n=0}^{\infty} W_n(\mathrm{x}, \mathrm{x}')\sigma^n(\mathrm{x}, \mathrm{x}'), \tag{6}$$

and each bi-function V_n and W_n can be written using covariant Taylor series as

$$V_n(\mathrm{x}, \mathrm{x}') = v_n(\mathrm{x}) + \sum_{k=1}^{\infty} \frac{(-1)^k}{k!} v_{n(k)}(\mathrm{x}, \mathrm{x}'), \text{ with}$$
$$v_{n(k)}(\mathrm{x}, \mathrm{x}') = v_{n a_1 \ldots a_k}(\mathrm{x}) \sigma^{;a_1}(\mathrm{x}, \mathrm{x}') \ldots \sigma^{;a_k}(\mathrm{x}, \mathrm{x}'), \tag{7}$$
$$W_n(\mathrm{x}, \mathrm{x}') = w_n(\mathrm{x}) + \sum_{k=1}^{\infty} \frac{(-1)^k}{k!} w_{n(k)}(\mathrm{x}, \mathrm{x}'), \text{ with}$$
$$w_{n(k)}(\mathrm{x}, \mathrm{x}') = w_{n a_1 \ldots a_k}(\mathrm{x}) \sigma^{;a_1}(\mathrm{x}, \mathrm{x}') \ldots \sigma^{;a_k}(\mathrm{x}, \mathrm{x}'). \tag{8}$$

A new class of semiclassical gravity solutions

- The freedom in the coefficient W is freedom of choosing W_0, since the Klein-Gordon equation determines W_{n+1} in terms of W_n (and V) – these are the Hadamard recursion relations.
- Equivalently, freedom providing covariant Taylor series even coefficients of W_0: w_0, w_{0ab}, w_{0abcd}, ...
- It is possible to write the stress-energy tensor in terms of these coefficients. It takes the form

$$\begin{aligned}\omega(T_{ab}) = \frac{1}{2(2\pi)^2}\Bigg[&-w_{0ab} + \frac{1}{4}w_{0c}{}^{c}g_{ab} \\ &+ \frac{1}{2}(1-2\xi)w_{0;ab} + \frac{1}{2}\left(2\xi - \frac{1}{2}\right)\Box w_0 g_{ab} \\ &+ \left(-\frac{m^2}{4}g_{ab} + \xi\left(R_{ab} - \frac{1}{4}Rg_{ab}\right)\right)w_0\Bigg] \\ &+ \frac{1}{4(2\pi)^2}v_1 g_{ab} + \alpha_1 g_{ab} + \alpha_2 G_{ab} + \alpha_3 I_{ab} + \alpha_4 J_{ab}. \qquad (9)\end{aligned}$$

A new class of semiclassical gravity solutions

- Can one obtain equations for these coefficients? The classical analogy is that

$$\nabla^a T_{ab}^{\text{class}} = \varphi_{;b}(\Box - m^2 - \xi R)\varphi = 0. \qquad (10)$$

- Imposing $\nabla^a \omega(T_{ab}) = 0$ gives a complicated equation – hard to solve, a priori third order.
- Idea! Constraint the class of states by constraining the covariant Taylor series coefficients of W_0 – make this equations easy to solve. We choose:

$$w_{0ab} = \frac{1}{2} R_{ab} w_0 - J g_{ab}, \qquad (11)$$

where J is an analytic function.
Conservation of stress-energy tensor imposes

$$(\Box - m^2) w_0 = 12J - 2v_1 + 8(2\pi)^2 \alpha_0, \qquad (12)$$

where α_0 is a real constant.

A new class of semiclassical gravity solutions

- It turns out that these states have the property that

$$\omega(T_{ab}) = (\alpha_0 + \alpha_1) g_{ab} + \alpha_2 G_{ab} + \alpha_3 I_{ab} + \alpha_4 J_{ab}. \qquad (13)$$

- The stress-energy tensor – up to ambiguities – gives only a cosmological constant contribution to the eq. of motion.
- This renders the semiclassical gravity equations solvable. Namely, one has the system

$$\begin{aligned} E_{ab} := {} & G_{ab} + (\Lambda - \kappa\alpha_0) g_{ab} \\ & - \kappa_1 \left(R_{;ab} - \frac{1}{2} g_{ab} \Box R - \Box R_{ab} + \frac{1}{2} g_{ab} R^{cd} R_{cd} - 2 R^{cd} R_{cdab} \right) \\ & - \kappa_2 \left(2R_{;ab} - 2 g_{ab} \Box R + \frac{1}{2} g_{ab} R^2 - 2 R R_{ab} \right) = 0, \end{aligned}$$

$$(\Box - m^2) w_0 = 12J - 2v_1 + 8(2\pi)^2 \alpha_0.$$

A new class of semiclassical gravity solutions

$$
\begin{aligned}
E_{ab} &:= G_{ab} + (\Lambda - \kappa\alpha_0)g_{ab} \\
&\quad - \kappa_1 \left(R_{;ab} - \frac{1}{2}g_{ab}\Box R - \Box R_{ab} + \frac{1}{2}g_{ab}R^{cd}R_{cd} - 2R^{cd}R_{cdab} \right) \\
&\quad - \kappa_2 \left(2R_{;ab} - 2g_{ab}\Box R + \frac{1}{2}g_{ab}R^2 - 2RR_{ab} \right) = 0, && \text{(15a)} \\
(\Box - m^2)w_0 &= 12J - 2v_1 + 8(2\pi)^2\alpha_0. && \text{(15b)}
\end{aligned}
$$

- System (15) is indeed a well-posed system. This is higher derivative gravity (Noakes, 1983) + a linear wave equation.
- Out of w_0, w_{0ab} (as prescribed) and other $w_{0ab\ldots}$, we can in principle reconstruct a two-point function algebraically.
- Rather than state a precise theorem (Theorem 1 in BAJ-A, 2024) let me explain in words...

The ‘stealth’ property and strong cosmic censorship

- Stealth property: Clearly, if we set $\alpha_0 = 0$ (our cosmological constant contribution), the stress-energy tensor vanishes (up to renormalisation ambiguities).
- In classical gravity, non-trivial solutions in curved spacetimes that have a trivial $T_{ab}^{\rm class}$ are called ‘stealth’ configurations.
- Plenty of work by Zanelli, the Chilean gravitational community, etc. I thank E Ayón-Beato for explaining me many things about stealths!
- Classical stealths have complicated non-trivial potentials in general – in QFT this can be achieved for linear quantum fields.

The ‘stealth’ property and strong cosmic censorship

- Consider a spacetime like Reissner-Nordström-de Sitter. It posseses an inner horizon, which is a Cauchy horizon.
- We expect Cauchy horizons to be unstable. This is strong-cosmic censorship.
- There is a quantum version of strong cosmic censorship, see (BAJ-A, 2024).
- Our class of solutions includes spacetimes with Cauchy horizons and T_{ab} regular (even analytic!) at the horizon!
- Situation analogous to (Krasnikov, 1996), (Shushkov, 1995).
- KRW theorems (Kay, Radzikowski, Wald, 1997)– having to do with the details of w_0 near the horizon.

Final remarks

- We found an interesting (somewhat non-generic) class of solutions to semiclassical gravity without spacetime symmetries.
- The 'reduced' system (in terms of w_0) is possibly numerically implementable – opens up interesting explorations.
- We know there exist states with the properties that we demanded, but in general the positivity condition remain open.
- High regularity required for now.

Thanks!

More details here:

B. A. Juárez-Aubry, "A new class of semiclassical gravity solutions, gravitational quantum stealths and regular Cauchy horizons", (2024) [arXiv:2412.08402 [gr-qc]].

See you soon @ Avenues of Quantum Field Theory in Curved Spacetime 2025!