Quantum Gravity Corrections: From Background Dynamics to Cosmological Perturbations

Relational scales, spatial dynamics and rotating vacua

Hongguang Liu

Westlake University

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arXiv:2502.07696 arXiv:2512.24960 arXiv:2611.xxxxx (forthcoming)

西湖大學 WESTLAKE UNIVERSITY | INSTITUTE FOR THEORETICAL SCIENCES 理论科学研究院 | WESTLAKE UNIVERSITY DEPARTMENT OF PHYSICS | WESTLAKE UNIVERSITY | 西湖大学天文系 DEPARTMENT OF ASTRONOMY WESTLAKE UNIVERSITY

Quantum geometry, spacetime and fluctuations

A common dynamical description for backgrounds and their response

Quantum gravity must connect microscopic geometric degrees of freedom to spacetime evolution and the correlations of its disturbances.

MEAN GEOMETRY

Cosmological expansion and stationary black-hole geometries describe the large-scale geometry selected by a quantum state.

$$\overline{q}_{ab} = \langle \hat{q}_{ab} \rangle$$

Their evolution probes the physical Hamiltonian and its nonlinear dependence on the geometric momenta.

FLUCTUATIONS

Scalar and tensor correlations also probe spatial couplings and the response around that geometry.

$$\langle \delta\hat{q}_{ab} \delta\hat{q}_{cd} \rangle_c$$

Full LQG calculations already access perturbation equations and one-loop effective actions.
Han–Li–HL ’20, arXiv:2005.00883, Ferrero–Han–HL ’25, arXiv:2502.07696

How does quantum geometry determine a consistent field theory of spacetime?

The information beyond a background

Spatial interactions can change propagation while preserving homogeneous evolution

Symmetry reduction provides valuable quantum input. It selects only part of the information contained in a spatial field theory.

$$\Delta H\,|_{\mathrm{hom}} = 0, \quad \delta\Delta H\,|_{\mathrm{hom}} = 0, \quad (\Delta H)^{(2)}\,|_{\mathrm{FLRW}} \neq 0$$

WHAT THE BACKGROUND FIXES

A homogeneous Hamiltonian constrains the expansion law and the nonlinear momentum–velocity relation in that sector.

Its solutions provide a background on which to study perturbations.

WHAT SPATIAL RESPONSE ADDS

Gradient and curvature operators determine how scalar and tensor modes propagate. Their coefficients need additional dynamical information. Cheung et al. ’08

Rotation tests further directions beyond homogeneous and spherical data.

Quantum matching and local consistency must constrain the same spatial Hamiltonian.

Physical evolution in full LQG: semiclassical dynamics

Coherent-state amplitudes connect quantum operators to spacetime dynamics

$$K(g_f, g_i; \tau) = \left\langle \Psi_{g_f} \,|\, \exp\left(-i\tau \frac{\hat{H}_{\text{phys}}}{\hbar}\right) \,|\, \Psi_{g_i} \right\rangle$$

PATH INTEGRAL AND CLASSICAL LIMIT

Matter-clock evolution gives a coherent-state path integral. Its saddle equations recover classical dust dynamics in the continuum limit.

Han–HL, arXiv:1910.03763
Han–HL, arXiv:2005.00988

SEMICLASSICAL PROPAGATOR

Twisted-geometry coherent states give a propagator from fluctuations around complex evolution trajectories.

Long–HL–Zhang, arXiv:2410.09828

COSMOLOGY AND PERTURBATIONS

Improved $\overline{\mu}$ dynamics for FLRW and Bianchi I; gauge-invariant cosmological perturbations from full LQG.

Han–HL, arXiv:1912.08668
Han–Li–HL, arXiv:2005.00883

QUANTUM MATRIX ELEMENTS

Off-diagonal semiclassical expansions and numerical volume matrix elements connect analytic and quantum calculations.

Li–HL, arXiv:2603.29826
Li–HL, arXiv:2603.29839

ONE-LOOP EFFECTIVE ACTION

The fluctuation determinant yields explicit quantum corrections around a coherent flat background.

Ferrero–Han–HL, arXiv:2502.07696

GEOMETRIC OPERATORS

Spatial curvature and reduced twisted-geometry operators provide building blocks for the Hamiltonian.

Long–HL, arXiv:2402.03154
Long–Zhang–HL, arXiv:2503.02641

Physical evolution in full LQG: spinfoam amplitudes

Semiclassical geometry, quantum corrections and cosmological dynamics

LORENTZIAN GEOMETRY

Regge asymptotics with timelike triangles; vertex convergence with timelike polyhedra and spacelike faces.

HL–Han, arXiv:1810.09042
Han–Kamiński–HL, arXiv:2110.01091

COMPLEX SADDLES AND CURVATURE

Analytic continuation identifies curved Regge geometries and yields effective dynamics on simplicial complexes.

Han–HL, arXiv:2104.06902
Han–Huang–HL–Qu, arXiv:2110.10670
Han–HL–Qu, arXiv:2301.02930

QUANTUM CORRECTIONS

Next-to-leading large-spin corrections for a four-simplex and the 1–5 Pachner move.

Han–Huang–HL–Qu, arXiv:2007.01998
Li–Han–HL–Song–Qu, arXiv:2501.16094

NUMERICAL AMPLITUDES

Lefschetz-thimble propagators, critical-point algorithms and high-performance computing.

Han–Huang–HL–Qu–Wan, arXiv:2012.11515
Han–HL–Qu, arXiv:2404.10563
Donà–Han–HL, arXiv:2212.14396

SCALAR-MATTER COSMOLOGY

Scalar-coupled EPRL amplitudes give effective Friedmann corrections and bounce-like solutions on hypercube complexes.

Han–HL–Qu–Vidotto–Zhang, arXiv:2402.07984

PHOTONIC QUANTUM SIMULATION

A basic spinfoam transition amplitude is implemented on an integrated photonic processor.

van der Meer et al. (incl. HL), arXiv:2207.00557

RECENT RESULT · FORTHCOMING

Curvature-squared terms computed from the spinfoam effective action.

$$R + \alpha R^2 + \beta W^2$$

$$W^2 = W_{\mu\nu\rho\sigma} W^{\mu\nu\rho\sigma}$$

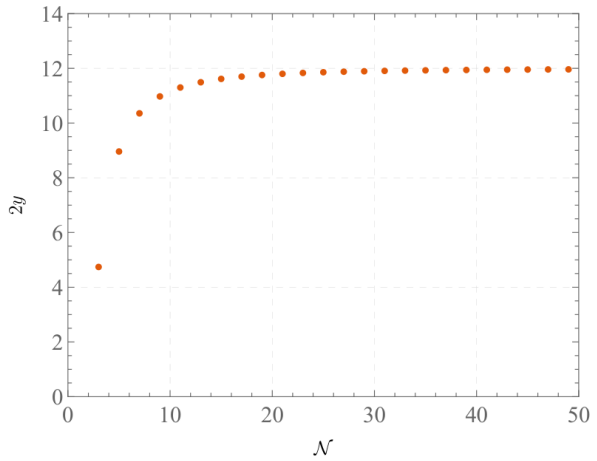
One-loop corrections and the physical scale of geometry

Quantum dynamics constrains the physical scale of the coherent geometry

For coherent flat geometry, the fluctuation determinant depends on the area label j_0:

$$\frac{S_{1\mathrm{L}}(j_0)}{\mathcal{N}^3} \approx i\chi_{\mathcal{N}} \frac{T}{\ell_P \sqrt{j_0}} - y_{\mathcal{N}} \log(j_0), \quad \chi_{\mathcal{N}} = \frac{4\sqrt{2}\pi c'_{\mathcal{N}}}{\sqrt{\beta}}.$$

Full lattice momenta, large T; state-independent terms omitted. β: Barbero–Immirzi parameter.



The mode-sum coefficient $2y_{\mathcal{N}}$ approaches 12. $\mathcal{N}^3$ counts spatial cells.

QUANTUM EQUATION FOR THE AREA

Γ_0 includes the determinant and the Hamiltonian matrix-element correction at the same order.

$$\frac{\partial \Gamma_0}{\partial j_0} = 0$$

The long-wavelength, large-T analysis finds nonzero real stationary points within the family of flat coherent geometries.

BEYOND LONG WAVELENGTHS

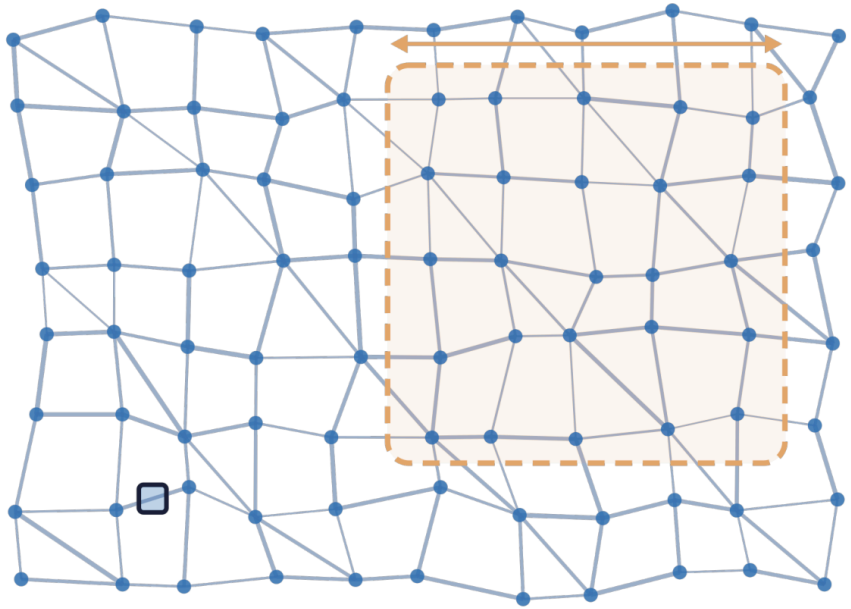
With all lattice momenta, $\chi_{\mathcal{N}}$ is complex; the saddle-point analysis must retain this complex structure.

The physical scale of quantum geometry is itself constrained by quantum dynamics.

Ferrero–Han–HL ’25, arXiv:2502.07696, Eqs. (6.13), (6.17)–(6.18), (7.17); Fig. 7 (lower left).

Geometry supplies the physical ruler

Physical resolution depends on geometric observables and the quantum state



Microscopic geometric cell and a larger resolved region.

Ferrero–Han–HL, ongoing work.

GEOMETRIC SIZE

A graph records adjacency. Geometric data assign physical areas and volumes to its cells, so a fixed graph can support different physical resolutions.

$$A_j = 8\pi\beta\ell_P^2\sqrt{j(j+1)}$$

Ferrero–Han–HL '25, arXiv:2502.07696

RELATIONAL REGION

Matter labels identify a region. Its observable geometry supplies the ruler for distances, volumes and physical wavelengths.

The microscopic area scale, the resolution of an effective description and the size probed by an observable answer different physical questions.

A physical coarse-graining prescription must state which geometric information it retains.

Relational resolution and fluctuation modes

The same physical geometry determines the ruler and the ordering of fluctuations

A volume-based prescription uses a region selected by material reference fields. Its volume and a relational spatial operator jointly define resolution.

$$\kappa_{\mathrm{rel}} = \xi V_{\mathrm{obs}}^{-\frac{1}{3}}, \quad \mathcal{C}_{\mathrm{rel}} = (\kappa_{\mathrm{rel}}, \Delta_{\mathrm{rel}})$$

PHYSICAL RULER

V_{obs} fixes the scale assigned to the chosen region. The constant ξ declares the scale-setting convention.

Reference labels and the physical metric specify the volume observable.

SPECTRAL COMPARISON

The eigenvalues of Δ_{rel} order fluctuations relative to that ruler.

$$\frac{\lambda_n(\Delta_{\mathrm{rel}})}{\kappa_{\mathrm{rel}}^2}$$

The operator, measure and geometric dependence belong to the RG prescription.

Clock evolution changes a state at fixed prescription. RG compares descriptions at different physical resolutions.

Relational Hamiltonian RG: ongoing work with Renata Ferrero and Muxin Han.

The canonical data of a running field theory

Hamiltonian interactions and the symplectic structure run together

A first-order effective description retains both the symplectic potential and the spatial Hamiltonian:

$$\Gamma_{H,\kappa} = \int \mathrm{d}t \left[\Theta_{\kappa,A}(z)\dot{z}^A - H_\kappa[z]\right], \quad \Omega_\kappa = -\delta\Theta_\kappa$$

SCHEMATIC FIELD-THEORY FLOW

$$H_\kappa[q,\pi] = \sum_A G_A(\kappa) \int \mathrm{d}^3x \mathcal{O}_A(q,\pi,R_{ab},\nabla\pi,\ldots).$$

$$s = \ln\left(\frac{\kappa}{\kappa_0}\right), \quad \partial_s \tilde{g}_A = \beta_A(\{\tilde{g}\}).$$

The $\mathcal{O}_A$ are spatial scalar densities. The dimensionless $\tilde{g}_A$ include their couplings and the symplectic normalization.

PRESENT PROJECTION

The homogeneous calculation follows the kinetic function and its symplectic normalization.

EQUAL-TIME CONSTRUCTION

We seek a direct readout of $(\Theta_\kappa, H_\kappa)$ from a short-time kernel, with spatial resolution varied before time composition.

Hamiltonian RG and the equal-time construction: ongoing work.

Quantum running generates nonlinear kinetics

A homogeneous projection follows the full momentum dependence

In dust time, take the observable volume variable $Q = \sqrt{V}$ and its canonical momentum P. The chosen projection retains a kinetic function:

$$H_\kappa(P,Q) = \frac{2}{3}Q^2 h_\kappa(X), \quad X = \frac{P^2}{4Q^2}, \quad h_\kappa(X) = g_{0,\kappa} + g_{1,\kappa}X + g_{2,\kappa}X^2 + \dots$$

A GENERATED INTERACTION

In this projection, the quadratic kinetic interaction generically generates a quartic momentum term under the flow.

$$\beta_{g_2}\,|_{g_2=0} \not\equiv 0$$

The running therefore changes the shape of the kinetic function.

DYNAMICAL RESPONSE

In a normalized Darboux frame, this function determines the momentum–velocity relation:

$$\dot{Q} = \partial_P H_\kappa = \frac{P}{3}\partial_X h_\kappa$$

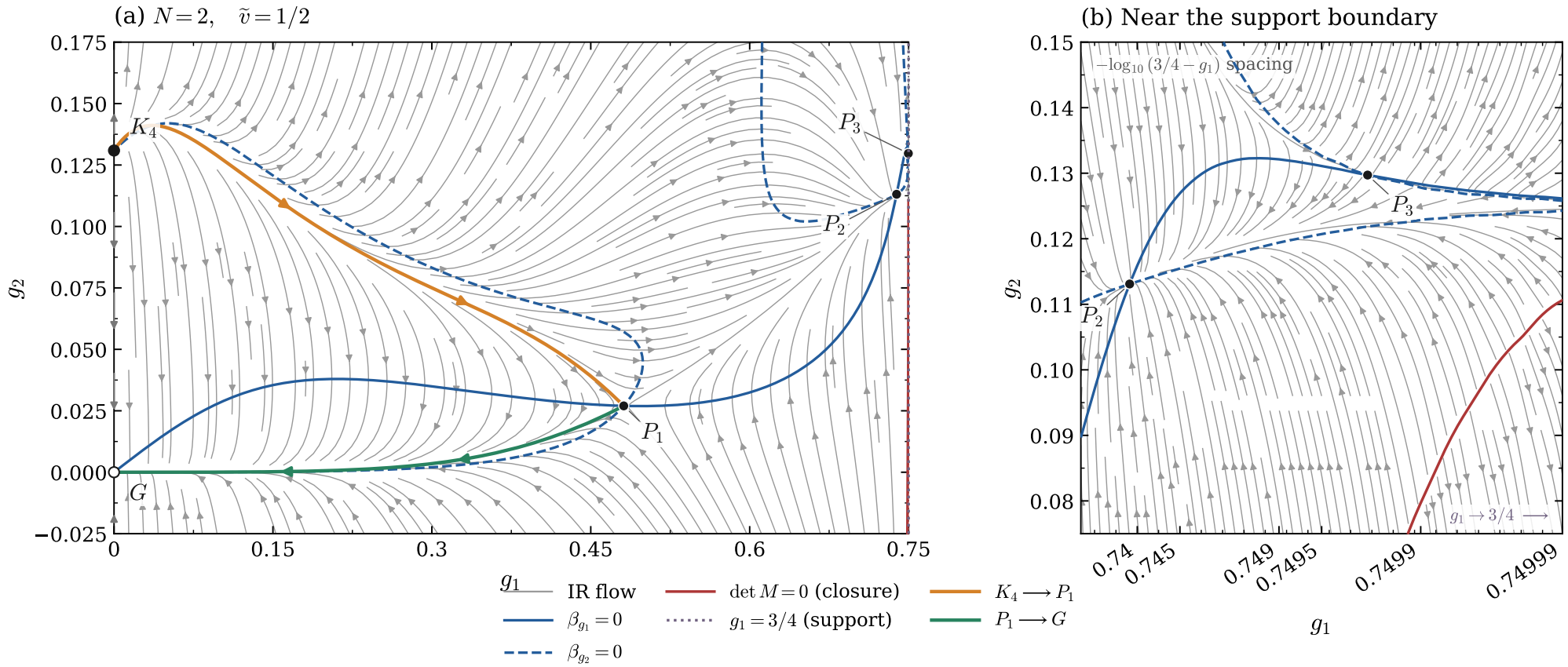
Its derivatives control motion and the local kinetic response.

Homogeneous data constrain this momentum dependence. Spatial curvature and gradient interactions require the full field-theory construction.

Relational Hamiltonian RG: ongoing work with Renata Ferrero and Muxin Han.

FRG phase portrait of the effective Hamiltonian

$$H_{\mathrm{eff},\kappa}(b) \equiv \frac{3H_\kappa}{2V} = g_{0,\kappa} + g_{1,\kappa} b^2 + g_{2,\kappa} b^4 + \ldots, \quad b = \frac{P}{2Q}.$$



The polynomial uses the schematic normalization above. Figure labels retain the original plotting convention. Homogeneous projection: $N = 2$, $\tilde{v} = \frac{1}{2}$. Ferrero–Han–HL, ongoing work.

From cosmology to black holes and beyond

Cosmological perturbations and black holes require a full field-theory perspective

We now have effective cosmological dynamics. How can the same quantum-gravity input describe black holes and the fluctuations of spacetime?

BLACK HOLES AND ROTATION

Inhomogeneous collapse introduces radial structure. Rotating vacua also probe angular interactions beyond homogeneous evolution.

We need a theory that connects the cosmological input to these geometries.

COSMOLOGICAL PERTURBATIONS

Scalar and tensor modes probe spatial gradients and the kinetic response around the cosmological background.

Their propagation and nonlinear interactions must follow from the same dynamics as the background.

A full spatial Hamiltonian must connect cosmological evolution, black-hole solutions and perturbations within one consistent theory.

The first requirement: compatible local evolution.

Compatible local evolution

The physical clock constrains the local Hamiltonian algebra

In the selected clock representative $\mathcal{C}_T = P_T + \mathcal{H}$, the density $\mathcal{H}$ has no dependence on clock gradients or clock momentum. Define

$$H[N] = \int \mathrm{d}^3x N(x)\mathcal{H}(x), \quad H_{\mathrm{phys}} = H[1].$$

$$\{H[N], H[M]\} = D[\beta(N,M)] + G[\alpha(N,M)] \underset{D,G}{\approx} 0.$$

LOCAL COMPATIBILITY

Arbitrary smearings test whether local clock advances are compatible modulo spatial gauge transformations. In ADM variables only D remains.

The lapse-dependent algebra contains information absent from a homogeneous evolution equation.

VACUUM PRESERVATION

For autonomous dust and a fixed smearing,

$$\frac{\mathrm{d}H[N]}{\mathrm{d}\tau} = \{H[N], H[1]\} \underset{D,G}{\approx} 0.$$

Initial data with $\mathcal{H}(x) = 0$ remain in the zero-density sector. The physical Hamiltonian is generally nonzero away from that sector.

Clock framework: Brown–Kuchař ’95, Giesel–Thiemann ’15. Spatial construction: ongoing work.

One vacuum for freely falling observers

The same invariant geometry must be recovered on different dust slicings

Freely falling observers follow dust geodesics. In the independent-shell dust–LTB class, each shell obeys an **FLRW-type Friedmann equation**:

$$\dot{r}(\tau,x)^2 = \mathcal{E}(x) + r(\tau,x)^2\,\tilde{f}\left(\frac{\mu(x)}{r(\tau,x)^3}\right).$$

Here x labels the geodesic and $\dot{r} = \partial_\tau r$. In vacuum, $\mu(x) = \mu = 2GM$ is constant.

TRAJECTORIES CAN CHANGE

The shell energy $\mathcal{E}(x)$ labels the freely falling congruence. Changing it changes radial speeds and the associated coordinates.

THE VACUUM MUST AGREE

At fixed mass charge $\mu = 2GM$ and areal radius r, the invariant norm of the radial gradient must be independent of $\mathcal{E}(x)$.

$$g^{ab}\partial_a r\partial_b r = 1 + \mathcal{E}(x) - \dot{r}(\tau,x)^2 = F(r(\tau,x);\mu).$$

$$F(r;\mu) = 1 - r^2\,\tilde{f}\left(\frac{\mu}{r^3}\right).$$

The common vacuum connects cosmological input to spherical dynamics.

Giesel–Liu–Soranidis, work in progress.

Reconstructing the spherical Hamiltonian

Vacuum slicing independence relates momentum and curvature dependence

Use the normalized shell mass generator μ, with

$$v = r^3, \quad s = \frac{\mathcal{E}}{r^2}, \quad \{v, b_{\rm sh}\}_{\rm sh} = \frac{3}{2}, \quad \mu = vh(b_{\rm sh}, s).$$

The geometric condition becomes a differential equation for the full shell Hamiltonian:

$$\frac{1}{4}\left(\partial_{b_{\rm sh}} h\right)^2 = s + \tilde{f}(h).$$

PHYSICAL INPUT

Fix the vacuum profile, regular branch and momentum origin. A homogeneous law specifies the $s = 0$ data.

For example, $\tilde{f}(X) = X - \lambda X^2$.

RECONSTRUCTED DATA

The classical limit is $h_0 = b_{\rm sh}^2 - s$. On the radial constraint surface, the field density is

$$\overline{C}_\lambda = \frac{\partial_x [v h_\lambda]}{2\sqrt{1+\mathcal{E}}}.$$

$$h_\lambda(b_{\rm sh}, s) = \frac{1 - \sqrt{1+4\lambda s}\cos\left(2\sqrt{\lambda} b_{\rm sh}\right)}{2\lambda}.$$

The full spherical dynamics, including inhomogeneous collapse, is fixed within this class.

$\lambda > 0$, $1 + 4\lambda s > 0$; GR-connected, zero-phase branch in the stated shell convention.

Constructing consistent spatial dynamics

Canonical transport preserves closure and correlates the spatial couplings

Start from a closed seed $H_0[N]$. Choose a canonical map Φ_λ that preserves spatial gauge generators and matches the supplied spherical dynamics:

$$H_\lambda[N] = H_0[N] \circ \Phi_\lambda^{-1}, \quad D \circ \Phi_\lambda = D.$$

$$\{H_\lambda[N], H_\lambda[M]\} = \{H_0[N], H_0[M]\} \circ \Phi_\lambda^{-1} \underset{D,G}{\approx} 0.$$

MATCH THE PHYSICAL SECTOR

$$\mathrm{Res}_{\mathrm{sph}}\, H_\lambda = H_{\mathrm{sph}}[h_\lambda].$$

The generator is spatially covariant and its full vector field preserves the selected sector. In connection variables it also preserves G.

GENERATE SPATIAL INTERACTIONS

$$\partial_\lambda H_\lambda[N] = \{H_\lambda[N], W_\lambda\}.$$

Repeated brackets generate correlated momentum, curvature and derivative terms. Their derivative order can grow along the construction.

Each fixed order is local for a local seed and generator; a finite realization requires its stated domain. The parameter λ is distinct from RG resolution.

The field interactions behind the geometry

A representative first correction contains correlated curvature and momentum terms

Use the momentum-defined matrix $K = \frac{1}{2}\,\mathrm{Tr}(P)\mathbf{1} - P$, with $P = \pi\frac{q}{\sqrt{\det q}}$. Write $t = \mathrm{Tr}\,K$, $t_2 = \mathrm{Tr}\,K^2$, and $t_3 = \mathrm{Tr}\,K^3$.

$$H_\lambda[1] = \int \mathrm{d}^3x\sqrt{\det q}[R + t^2 - t_2 + \lambda h_1 + O(\lambda^2)].$$

$$\begin{aligned} h_1 \supset & -\frac{5}{18}t^4 + t^2t_2 + \frac{1}{6}t_2^2 - \frac{8}{9}tt_3 \\ & + \frac{1}{3}(t^2 - t_2)R + 12K^i_jK^j_lR^l_i - \frac{16}{3}tK^i_jR^j_i \\ & + \frac{20}{3}R_{ij}R^{ij} - \frac{5}{2}R^2. \end{aligned}$$

The same construction also generates spatial-gradient terms, a nonpolynomial reference contribution and angular terms required by the rotating target. The displayed terms are a selected part of the complete correction.

These couplings determine the response of neighboring fields. A background tests their value on one solution; perturbations probe their functional derivatives.

Giesel–Liu–Soranidis, work in progress; selected polynomial terms at first order.

What makes the construction physical?

The metric, clock and matter coupling define the observable dictionary

A canonical map preserves the symplectic structure. Physical predictions also depend on which phase-space functions represent distances, clocks and matter measurements.

CANONICAL EQUIVALENCE

Transforming both the dynamics and every observable preserves the predictions of the original description:

$$H_0 \mapsto H_0 \circ \Phi^{-1}, \quad O_0 \mapsto O_0 \circ \Phi^{-1}.$$

Symplecticity alone does not establish a new measurable effect.

PHYSICAL MATCHING

The proposed field theory keeps a specified physical geometry and clock, and matches its Hamiltonian to quantum and geometric input.

$$q_{ij} \to \mathrm{d}\ell^2 = q_{ij}\,\mathrm{d}x^i\,\mathrm{d}x^j.$$

Matter coupling and observable readout must be specified consistently with that identification.

Rotation now tests the same reconstruction: can the real canonical Schwarzschild–Kerr map be transported into H_λ while preserving its vacuum constraints?

A common theory for spherical and rotating vacua

The spatially covariant completion acts on the full metric and momentum

The reconstructed $h_\lambda(b_{\rm sh}, s)$ supplies the spherical input. One spatially invariant generator W_λ extends it to the full fields and transports both vacuum families.

GR Schwarzschild $z_S = (q_S, \pi_S)$	$N_a^{\rm cc} \longrightarrow$	**GR Kerr** $z_K(a) = (q_K, \pi_K)$
$\Phi_\lambda \downarrow$		$\Phi_\lambda \downarrow$
Reconstructed spherical vacuum $z_{\lambda,S} = \Phi_\lambda z_S$	$N_{\lambda,a} \longrightarrow$	**Kerr-connected rotating vacuum** $z_{\lambda,K} = \Phi_\lambda z_K$

$$H_\lambda[N] = H_0[N] \circ \Phi_\lambda^{-1}, \quad \{W_\lambda, D[\xi]\} = 0.$$

The vertical map changes the dynamics. The horizontal map adds spin within its vacuum sector. Angular terms beyond spherical data select the rotating geometry and its field-theory response.

$N_a^{\rm cc}$ is the local formal constraint-completed spin map introduced next. The physical metric and clock remain fixed.

Newman–Janis as a real canonical spin map

The lift specifies the complete ADM data and admits a constraint-compatible completion

In a regular ADM chart, let $\Delta q_a = q_K - q_S$ and $C_a = \pi_S - \pi_K$, evaluated at the mass coordinate $u = \mathcal{U}_a[\Pi]$, with $u^2 = 2GM$ on the Kerr family. A generating functional gives

$$F_a[q, \Pi] = \langle \Pi, q + \Delta q_a(u) \rangle + \langle C_a(u), q - q_S \rangle.$$

$$\pi = \frac{\delta F_a}{\delta q}, \quad Q = \frac{\delta F_a}{\delta \Pi}, \quad \left(N_a^{\mathrm{kin}}\right)^* \Omega = \Omega, \quad N_a^{\mathrm{kin}} z_S = z_K(a).$$

FINITE-SPIN CANONICAL LIFT

The mixed Hessian is an invertible rank-one perturbation of the identity. The map fixes both metric and momentum and is exact in spin on its stated chart.

A chosen axis, frame and averaging profile specify its extension.

VACUUM-CONSTRAINT COMPLETION

A completed generator retains the Kerr tangent and satisfies

$$\{R_a^{\mathrm{cc}}, D[\xi]\} = 0, \quad \{H_0[N], R_a^{\mathrm{cc}}\} \approx 0.$$

Its flow N_a^{cc} gives a local formal vacuum map near massive Schwarzschild on the regular bounded domain.

Current work. The exact finite-spin kinematic lift and the local formal constraint completion have distinct domains.

The spherical and rotating constructions commute

Canonical conjugation carries the spin map into the reconstructed field theory

The lower arrow in the diagram is determined by the same transport that constructs H_λ:

$$N_{\lambda,a} = \Phi_\lambda \circ N_a^{\mathrm{cc}} \circ \Phi_\lambda^{-1}, \quad N_{\lambda,a} z_{\lambda,S} = z_{\lambda,K}.$$

VACUUM REMAINS VACUUM

$$H_\lambda[N](\Phi_\lambda z) = H_0[N](z).$$

Every transported vacuum satisfies the deformed vacuum constraints. The spin normalizer preserves this complete constraint ideal. A nonzero dust source is not required.

SYMMETRIES REMAIN COMPATIBLE

Spatial equivariance preserves axisymmetry. A time-independent transport preserves stationary evolution with the common shift β_K.

Kerr therefore supplies a stationary, axisymmetric vacuum in the reconstructed theory.

$$X_{H_\lambda[1]+D[\beta_K]}(z_{\lambda,K}) = D\Phi_\lambda \,|_{z_K}\, X_{H_0[1]+D[\beta_K]}(z_K) = 0.$$

We provide a full modified effective theory behind the Newman–Janis transform.

The same Hamiltonian determines the spherical and rotating vacua, their constraints and their perturbative interactions.

Equalities hold on a common canonical domain, or coefficientwise in the local formal construction.

Selecting the spherical-to-Kerr completion

Match the rotating geometry while preserving the spherical dynamics

Scalar functionals that vanish with their first variation on spherical fields supply the remaining angular freedom:

$$\Phi_\lambda^{\mathrm{tar}} = \Phi_\lambda^{\mathrm{ref}} \circ \exp\!\left(-X_{Z_\lambda}\right), \quad Z_\lambda \,|_{\mathrm{sph}} = 0, \quad \delta Z_\lambda \,|_{\mathrm{sph}} = 0.$$

The selected Carter geometry directly retains the spherical profile F_λ:

$$\mathrm{d}s^2 = -\frac{\Delta_\lambda}{\Sigma}\left(\mathrm{d}T - a\sin^2\theta\,\mathrm{d}\varphi\right)^2 + \frac{\Sigma}{\Delta_\lambda}\,\mathrm{d}r^2 + \Sigma\,\mathrm{d}\theta^2$$
$$+\frac{\sin^2\theta}{\Sigma}\left[\left(r^2+a^2\right)\mathrm{d}\varphi - a\,\mathrm{d}T\right]^2.$$

$$\Delta_\lambda = r^2 F_\lambda(r) + a^2, \quad \Sigma = r^2 + a^2\cos^2\theta.$$

For $F_\lambda(r) = 1 - \frac{\mu}{r} + \lambda\frac{\mu^2}{r^4}$, matching is explicit through λa^3 and $\lambda^2 a^2$.

Our spherical reconstructions also include **Bardeen and Hayward** profiles Giesel–HL–Singh–Weigl ’25, arXiv:2405.03554 and **AdS-core vacua**. HL–Soranidis ’26, arXiv:2604.27880

These provide alternative spherical inputs; each rotating completion requires its own angular matching.

Giesel–Liu–Soranidis, work in progress. Exact geometric target with the stated order-by-order dynamical realization.

Rotating geometry and its field-theory response

One completed Hamiltonian supplies the vacuum and the neighboring dynamics

GEOMETRY OF THE SELECTED TARGET

Orthogonal Killing-orbit and (r, θ) blocks give circularity. For nonzero spin, the Carter family admits a principal closed conformal Killing–Yano tensor.

$$h = \mathrm{d}\boldsymbol{b}, \quad \mathrm{d}h = 0, \quad f = \star\, h.$$

In a principal null tetrad,

$$\Psi_0 = \Psi_1 = \Psi_3 = \Psi_4 = 0.$$

Where $\Psi_2 \neq 0$, the metric is type D. The Killing tensor built from f supplies the Carter constant and separates geodesic motion. Kubizňák–Krtouš ’07, Frolov–Krtouš–Kubizňák ’17

DYNAMICS OF THE COMPLETED THEORY

$$H_\lambda[N] = H_0[N] \circ \left(\Phi_\lambda^{\mathrm{tar}}\right)^{-1}.$$

Differentiate the full Hamiltonian, evaluate on the rotating background, and reduce the constraints:

$$\dot{\xi} = \mathbb{L}_\lambda \xi, \quad \mathbb{L}_\lambda = DX_{H_\lambda^{\mathrm{tot}}}|_{z_{\lambda,K}}.$$

Here $H_\lambda^{\mathrm{tot}} = H_\lambda[1] + D[\beta_K]$ in the common clock and shift. The same spatial couplings also determine the cosmological scalar and tensor response.

The principal tensor organizes geometry and separation. The completed field theory determines gravitational interactions and propagation, with the chosen matter and radiation conditions.

Rotation and cosmological perturbations test the same spatial dynamics.

Backgrounds and fluctuations under one map

The derivatives of the canonical transport determine the neighboring dynamics

The canonical transport used for both vacuum families also transports their neighboring fields. Let $\overline{z}_\lambda = \Phi_\lambda(\overline{z}_0)$ and evaluate $S_\lambda = D\Phi_\lambda$ and $R_\lambda = D^2\Phi_\lambda$ along the background.

LINEAR RESPONSE

$$\xi_\lambda = S_\lambda \xi_0.$$

If $\dot{\xi}_0 = \mathbb{L}_0 \xi_0$, the transported equation is

$$\mathbb{L}_\lambda = \dot{S}_\lambda S_\lambda^{-1} + S_\lambda \mathbb{L}_0 S_\lambda^{-1}.$$

The first term is essential on a time-dependent background.

NONLINEAR RESPONSE

For $z = \overline{z} + \varepsilon\xi + \frac{1}{2}\varepsilon^2\eta + \ldots$,

$$\eta_\lambda = S_\lambda \eta_0 + R_\lambda[\xi_0, \xi_0].$$

The second derivative of the map transports the leading coupling between fluctuations, as well as their linear propagation.

Differentiate the full spatial Hamiltonian before evaluating on a background and reducing the constraints. In reduced canonical coordinates, $\mathbb{L} = \mathbb{J}\delta^2 H$ supplies the linear evolution operator.

Quadratic order in fluctuations can retain all orders in spatial derivatives.

Scalar and tensor response in cosmology

The spatial Hamiltonian fixes kinetic and propagation kernels

In a diagonal, single-scalar sector on FLRW, after constraint reduction, write $Q_s = \zeta$, $Q_{+,\times} = \gamma_{+,\times}$ and $\mathcal{P} = -\frac{\partial^2}{a_c^2}$.

$$S^{(2)} = \frac{1}{2}\sum_I \int \mathrm{d}\tau \mathrm{d}^3x a_c^3 \left[\dot{Q}_I \mathcal{K}_I(\tau, \mathcal{P})\dot{Q}_I - Q_I \mathcal{V}_I(\tau, \mathcal{P})Q_I\right].$$

For a Fourier mode, $p = \frac{q_{\mathrm{com}}}{a_c}$ is its physical wave number:

$$\partial_\tau \left[a_c^3 \mathcal{K}_I(\tau, p^2)\dot{Q}_{I,q}\right] + a_c^3 \mathcal{V}_I(\tau, p^2) Q_{I,q} = 0.$$

KINETIC RESPONSE

$\mathcal{K}_I > 0$ selects a positive kinetic branch. Its time dependence changes normalization and damping; its momentum dependence retains spatial structure.

PROPAGATION

On a frozen background, $\omega_I^2(p) = \frac{\mathcal{V}_I}{\mathcal{K}_I}$. If the kernels are analytic and $\mathcal{K}_I(0) \neq 0$, the small-p expansion is

$$m_I^2 + c_I^2 p^2 + \alpha_I p^4 + \ldots.$$

Even polynomial kernels can have a nonpolynomial ratio.

The kernels depend on the selected completion and matter realization.

From field dynamics to physical correlations

An observable prediction requires the response, state and causal boundary data

PRIMORDIAL FLUCTUATIONS

Evolve the scalar and tensor mode functions with a specified initial state. Their normalization and propagation determine the two-point functions.

The expansion history alone does not determine $\mathcal{P}_\zeta$ or $\mathcal{P}_T$. Equal backgrounds can have different spatial response kernels. Han–Li–HL '20, arXiv:2005.00883

ROTATING SPACETIME

The same Hamiltonian assigns a perturbation operator to the rotating background. Radiation conditions and the physical readout select its causal response.

Hidden symmetry organizes the geometry. Modified gravitational-wave equations must be derived from the complete dynamics.

$$\left\langle Q_{I,\boldsymbol{q}} Q_{I,\boldsymbol{q}'} \right\rangle = (2\pi)^3 \delta^3(\boldsymbol{q}+\boldsymbol{q}') \frac{2\pi^2}{q^3} \mathcal{P}_I(q).$$

Quantum matching should constrain the kernels and the state preparation. Explicit spectra and rotating-wave responses are calculational targets of the resulting field theory.

Quantum matching of the spatial response

Microscopic calculations and consistency conditions constrain complementary data

QUANTUM INPUT

Coherent-state amplitudes supply semiclassical background dynamics, fluctuation operators and one-loop information.

Relational resolution specifies the geometric ruler and the mode ordering. Hamiltonian RG compares retained canonical data across those resolutions.

Han–HL ’20, arXiv:1910.03763, Han–Li–HL ’20, arXiv:2005.00883, Ferrero–Han–HL ’25, arXiv:2502.07696

SPATIAL CONSISTENCY

Local clock compatibility constrains the algebra. Slicing independence constrains the spherical sector. The canonical spin lift tests the real phase space and the vacuum constraints.

The remaining spatial interactions determine the kernels that quantum calculations must select.

$$(\Theta_\kappa, H_\kappa; \text{physical geometry, clock and matter}) \quad \to \quad (\overline{z}, \mathcal{K}_I, \mathcal{V}_I).$$

The current results provide calculated quantum input and explicit consistency constructions. Matching the full spatial couplings and their relational running remains an open step; it is not fixed by homogeneous data alone.

Quantum gravity as spacetime dynamics

Relational scales, canonical fields and quantum correlations

QUANTUM GEOMETRY PROVIDES DYNAMICAL INPUT

Full-theory amplitudes reach beyond a background evolution law: they supply fluctuation and loop information. Relational geometry defines both physical resolution and the ordering of modes.

CONSISTENCY ORGANIZES THE SPATIAL FIELD THEORY

Local clock compatibility and observer-independent vacuum geometry constrain a full Hamiltonian. Canonical transport correlates its momentum, curvature and spatial derivative interactions.

ONE FIELD THEORY CONNECTS SPHERICAL AND ROTATING VACUA

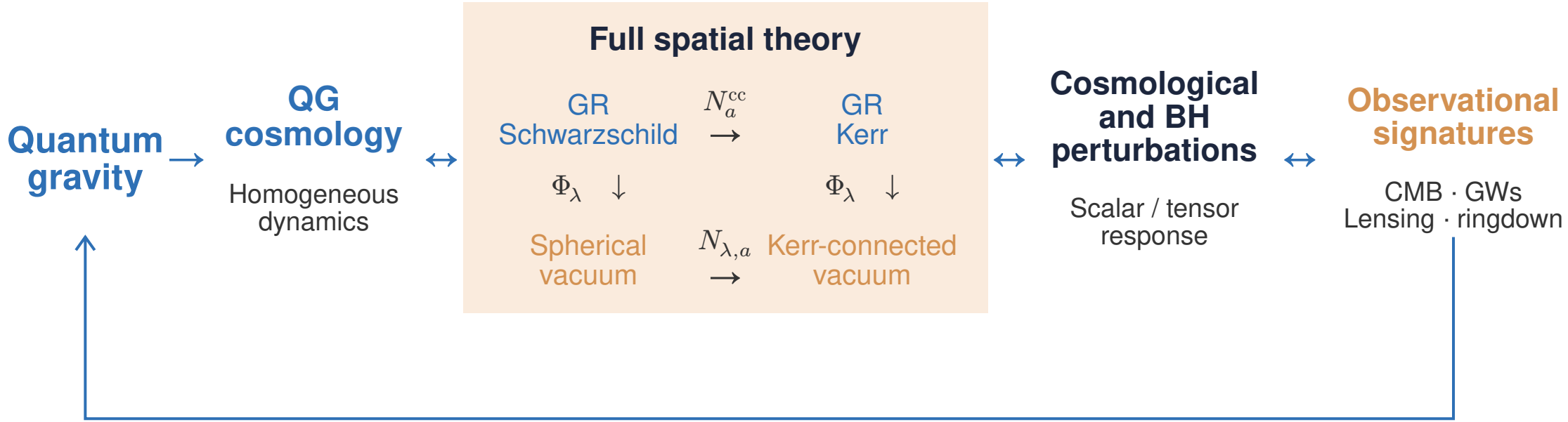
Canonical conjugation connects the spherical and rotating sectors. The real Newman–Janis lift and its local formal constraint completion give this relation within the same spatial field theory that determines the fluctuations.

The next physical target is quantum matching of the spatial response and its correlations.

From quantum gravity to observations and back

Cosmology, black holes and perturbations within one effective theory

Quantum input, consistent reconstruction and observational inference constrain one another.



Observational constraints feed back to quantum states and effective couplings.

One theory must account for the backgrounds and their measurable fluctuations.

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理学院公众号

官网：physics.westlake.edu.cn ｜ 邮箱：admission_science@westlake.edu.cn ｜ 电话：0571-88112051 / 88113027 ｜ 地址：杭州市西湖区墩余路600号