The role of gravitational energy in the quantum gravity phenomenology

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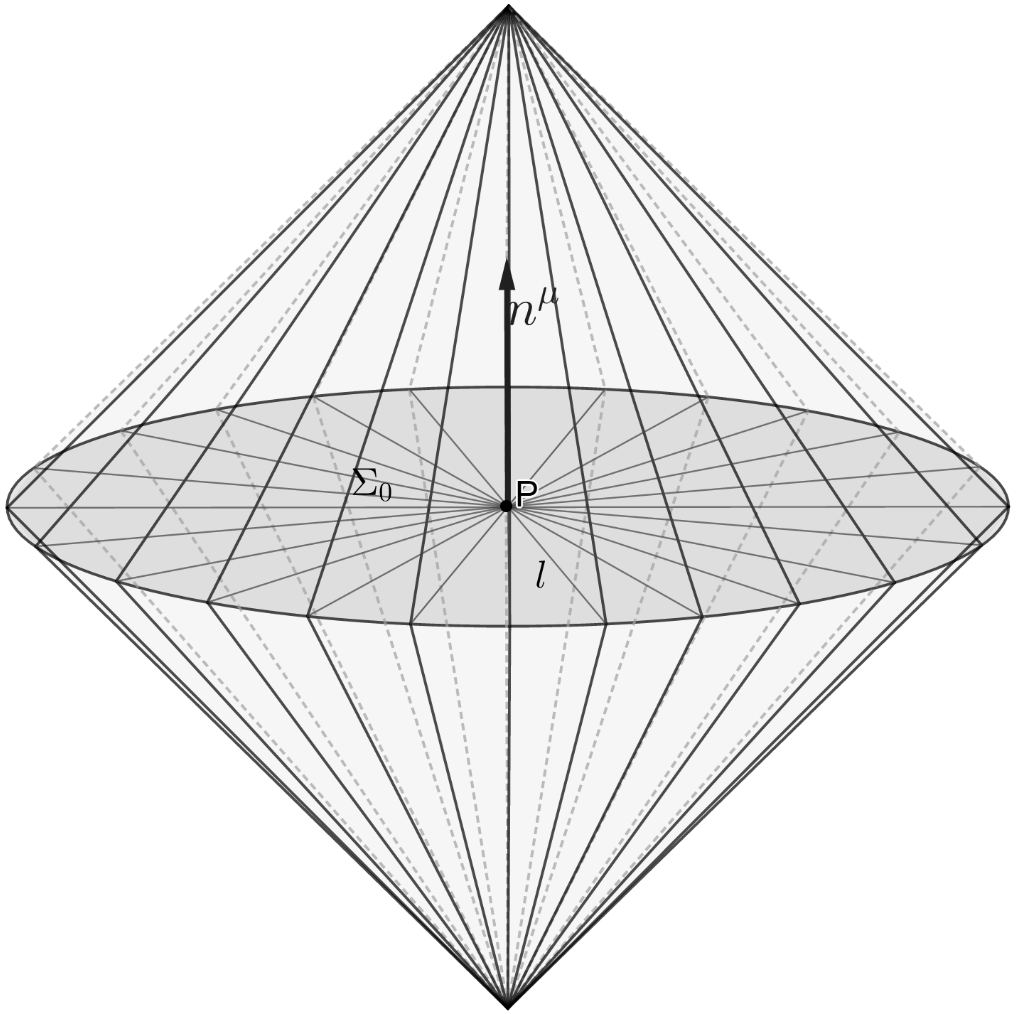
Thermodynamics of causal diamonds

- a causal diamond is a thermodynamic object
- its horizon has entropy proportional to the area $S = \eta \mathcal{A}$
- equilibrium between the matter entropy flux and area changes encodes the traceless Einstein equations

$$R_{\mu\nu} - \frac{1}{4} g_{\mu\nu} = \frac{2\pi}{\hbar\eta}\left(T_{\mu\nu} - \frac{1}{4} T g_{\mu\nu}\right)$$

Newtonian limit **defines** $G = 1/\left(4\hbar\eta\right)$

- we assumed the Einstein equivalence principle, locality and purely metric gravity



G. Chirco and S. Liberati, Phys Rev D 81 (2010); A. Svesko, Phys. Rev. D 99 (2019); A. Alonso-Serrano, ML, Phys. Rev. D 102 (2020)

Higher order contributions in vacuum

- the change of the horizon area is encoded in its expansion θ

$$\theta = \theta_{\text{flat}} + \theta_{\text{curvature}}$$

$$\theta_{\text{curvature}} = -\lambda R_{\mu\nu}(P)\, k^{\mu} k^{\nu} - \frac{1}{3}\lambda^{3} C_{\mu\alpha\nu\beta}(P)\, C_{\rho}{}^{\alpha}{}_{\sigma}{}^{\beta}(P)\, k^{\mu} k^{\nu} k^{\rho} k^{\sigma} + \text{“terms irrelevant in vacuum”}$$

affine parameter along the horizon

null vector tangent to the horizon

- if $S = \eta \mathcal{A}$ and gravity is local → no corrections to Einstein equations (dependence on an arbitrary diamond’s size parameter)

Logarithmic term in entropy

$$S = \eta \mathcal{A} + \mathcal{C} \ln \left(\mathcal{A} / \mathcal{A}_0 \right)$$

- nearly universal form of horizon entropy (strings, LQG, entanglement, GUP, …)
- $\mathcal{C}$ is a theory-dependent number, $\mathcal{A}_0$ some constant Planck-scale area
- allows nontrivial local corrections to gravitational dynamics

A. Alonso-Serrano, ML, JHEP 2020 (2020)

- equilibrium condition $\Delta S = 0$ implies (perturbatively)

$$\left(R_{\mu\nu} - \frac{1}{4} R g_{\mu\nu} \right) n^\mu n^\nu = \frac{4}{5\pi} \mathcal{C} l_{\mathrm{P}}^2 T_{\mu\nu\rho\sigma} n^\mu n^\nu n^\rho n^\sigma$$

- **Bel-Robinson tensor**: quadratic in Weyl tensor, $T_{\mu\nu\rho\sigma} n^\mu n^\nu n^\rho n^\sigma$ non-negative, quasilocal areal density of gravitational energy (?), in 4D symmetric and traceless

J. M. M. Senovilla, Class. Quant. Grav. 17 (2000); T. Jacobson, A. J. Speranza, J. M. M. Senovilla, Class. Quant. Grav. 35 (2018)

Interpreting the result

$$\left(R_{\mu\nu} - \frac{1}{4}Rg_{\mu\nu}\right) n^\mu n^\nu = \frac{4}{5\pi}\mathcal{C}l_{\mathrm{P}}^2 T_{\mu\nu\rho\sigma}n^\mu n^\nu n^\rho n^\sigma$$

- local Lorentz invariance: no dependence on n^μ ⟹ we again recover vacuum Einstein equations!
- let us allow explicit dependence on n^μ
  - the result resembles a Hamiltonian constraint
  - we can write (ADM + EM decomposition of Bel-Robinson)
    $$\frac{1}{2}\left({}^{(3)}R + K^2 - K_{\mu\nu}K^{\mu\nu}\right) - N^2\Lambda = \frac{4}{5\pi}\mathcal{C}l_{\mathrm{P}}^2\left(E^2 + B^2\right)$$
  - reminiscent of the Hamiltonian constraint for an electrovacuum spacetime
  - not the full dynamics
  - consistency of breaking the local Lorentz invariance?
  - non-vacuum case?
  - to be continued…

Thank you!