A speculation on the nature of black hole horizon

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Based on J. Mei, JHEP 1310 (2013) 195
arXiv:1305.4461 [gr-qc]

IHEP - CAS, 06 March 2014

Black hole horizon

Schwarzschild: $ds^2 = -\Delta dt^2 + \dfrac{dr^2}{\Delta} + r^2 d\theta^2 + r^2 \sin^2\theta d\phi^2.$

Removing divergence in the metric:

$$\begin{aligned} -\Delta dt^2 + \frac{dr^2}{\Delta} &= -\Delta(dt^2 - \frac{dr^2}{\Delta^2}) = -\Delta du_+ du_- \, , \\ du_\pm &= dt \pm \frac{dr}{\Delta} \, . \end{aligned}$$

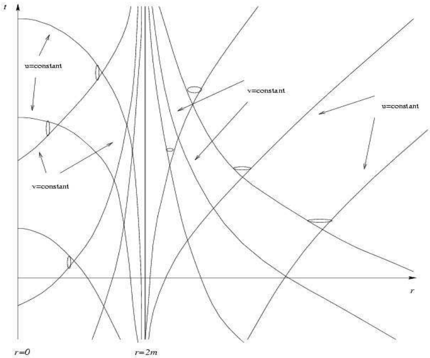

Figure: Light-cones of near the horizon of a Schwarzschild black hole. Figure: C.N.POPE

Equivalence principle vs Schwinger effect

Equivalence principle (foundation of GR):

- local gravitational field $\Longleftrightarrow$ free fall;
- non-singular curved spacetime $\Longleftrightarrow$ locally flat.

Schwinger effect:

- Strong electric field $\Longrightarrow$ unstable electromagnetic vacuum,

$$eE_c \times \frac{1}{m_e} = m_e \,, \quad \Longrightarrow \quad E_c = \frac{m_e^2}{e} \,.$$

  The key quantity is acceleration.

- Applying to gravity:

$$|a| = \frac{M}{r^2} \bigg/ \sqrt{1 - \frac{r_s}{r}} \,.$$

  The acceleration diverges:
  $\Longrightarrow$ Breaking down of the gravitational vacuum (Hawking radiation).

Reason for concern:
The gravitational kick diverges
$\Longrightarrow$ Breaking down of classical gravity (and also the equivalence principle)?

The information paradox

Pure state $\longrightarrow$ Black hole $\longrightarrow$ Mixed state: Loss of information
$\Longrightarrow$ Loss of unitarity in quantum mechanics + gravity

Possible solutions (Preskill, '92):

- information return through Hawking radiation;
- information saved in stable or long lived remnants;
- information return "at the end";
- information in quantum hair;
- information in baby universe.

Black hole in a box: AdS/CFT correspondence
$\Longrightarrow$ No loss of information! Information back in Hawking radiation.

Black hole complementary

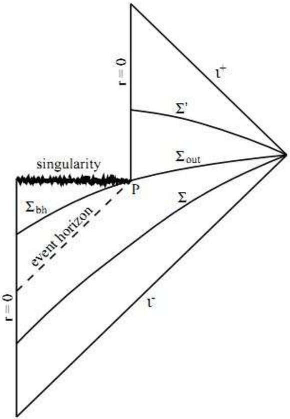

Figure: The existence of a state $\Psi(\Sigma_P)$ that describes both the outside and inside of a black hole is suspicious. (Susskind, Thorlacius and Uglum '93)

The firewall

Assuming (1) Purity, (2) EFT and (3) No drama, it is possible for Alice to see both $S_{AB} = 0$ and $S_{BC} = 0$. (Almheiri, Marolf, Polchinski and Sully, 2012)
Strong subadditivity:

$$S_{ABC} + S_B \leq S_{AB} + S_{BC} \; .$$

One intriguing objection: Alice will not have enough time to verify $S_{BC} = 0$.

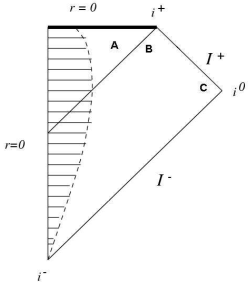

Figure: Collapsing to a black hole.

A second (very different) motivation

Understanding the spectrum of elementary particles:

- Yukawa coupling;
- particles as excitations of strings (String theory);
- particles as excitations of other extended objects (Dirac '62).

$\Longleftrightarrow$ Dynamics of extended objects (String theory and beyond)

An example: Dirac Brane (Trzetrzelewski, 2012),

$$S_p = -\lambda \int \sqrt{|G|}\, d^{p+1}\sigma\,, \quad G = \det G_{\alpha\beta}\,, \quad G_{\alpha\beta} = \partial_\alpha X^\mu \partial_\beta X^\nu g_{\mu\nu}\,,$$

$$\mathcal{P}_\mu := \frac{\delta S_p}{\delta \dot{X}^\mu} = -\lambda\sqrt{|G|}\, G^{\alpha\tau} g_{\mu\nu}\partial_\alpha X^\nu\,, \quad g^{\mu\nu}\mathcal{P}_\mu\mathcal{P}_\nu = \lambda^2 |G| G^{\tau\tau}\,,$$

$$\Longrightarrow \gamma^\mu \mathcal{P}_\mu + \lambda\sqrt{|G|G^{\tau\tau}} = 0\,, \quad \mathcal{P}_\mu = -i\frac{\delta}{\delta X^\mu}\,,$$

$$\Longrightarrow \quad \left(-i\gamma^\mu \frac{\delta}{\delta X^\mu} + \lambda\sqrt{|G|G^{\tau\tau}}\right)\Psi = 0\,.$$

Horizon as a boundary

Assumption:

- Horizon as a *physical* boundary to the spacetime;
- Dynamics determined like a brane (more detail later).

Hints:

- Horizon is a causal boundary;
- Membrane paradigm;
- Conformal symmetry on the horizon (phase transition?);
- Firewall: making it physical .

Boundary action

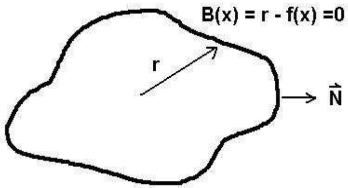

Figure: The profile of a boundary.

Assumption:
The dynamics of a boundary brane is governed by
the bulk action + boundary term.

The total action,

$$
\begin{aligned}
S_{tot} &= \frac{1}{16\pi} \int d^n x \sqrt{-g}\,(R - 2\Lambda) + S_B\,, \\
S_B &= \frac{1}{16\pi \ell_p^2} \int_B (d^{n-1}x)_\mu N^\mu \sqrt{-g}\, K\,,
\end{aligned}
$$

- $K = g^{\mu\nu} K_{\mu\nu}$, $K_{\mu\nu} = \nabla_\mu N_\nu + \nabla_\nu N_\mu$;
- $N_\mu = \partial_\mu B / |\partial B|$, $|\partial B| = \sqrt{g^{\varrho\sigma} \partial_\varrho B \partial_\sigma B}$;
- $B(x) = 0$ defines the boundary.

Boundary contributions

Varying the fields ($\mathcal{P}_{\alpha\beta} = g_{\alpha\beta} - N_\alpha N_\beta$, $\widetilde{\nabla}_\alpha = \mathcal{P}_\alpha^\beta \nabla_\beta$),

$$\begin{aligned}
\delta S_{tot} &= \frac{1}{16\pi}\int d^n x\sqrt{-g}\,\delta g^{\mu\nu}\left(R_{\mu\nu} - \frac{R-2\Lambda}{2}g_{\mu\nu}\right) + \delta S_B'\,, \\
\delta S_B' &= \frac{1}{16\pi}\int_B d^{n-1}x\sqrt{-h}\,\frac{\delta g^{\alpha\beta}}{2}\mathcal{T}_{\alpha\beta}\,, \\
\mathcal{T}_{\alpha\beta} &= \widetilde{\nabla}_\alpha N_\beta + \widetilde{\nabla}_\beta N_\alpha - K\mathcal{P}_{\alpha\beta}\,.
\end{aligned}$$

Charges ($T_{\mu\nu} = -\frac{2}{\sqrt{-g}}\frac{\delta S_B'}{\delta g^{\mu\nu}}$),

$$H = -\frac{1}{16\pi}\int_B d^{n-1}x\sqrt{-h}\,\mathcal{T}_t^t\,, \quad J_\phi = -\frac{1}{16\pi}\int_B d^{n-1}x\sqrt{-h}\,\mathcal{T}_\phi^t\,.$$

The Kerr background

The Kerr metric

$$\begin{aligned} ds^2 &= f\Big(\frac{dr^2}{\Delta} - \frac{\Delta}{v^2}dt^2\Big) + \frac{f dx^2}{1-x^2} + \frac{v^2(1-x^2)}{f}(d\phi - w dt)^2 \,, \\ \Delta &= (r-r_+)(r-r_-)\,, \quad w = \frac{r}{v^2}\sqrt{r_+ r_-}\,(r_+ + r_-)\,, \\ f &= r^2 + r_+ r_- x^2\,, \quad v^2 = (r^2 + r_+ r_-)^2 - \Delta\, r_+ r_- (1-x^2)\,, \end{aligned}$$

where $x = \cos\theta$, $r_\pm = M \pm \sqrt{M^2 - J^2/M^2}$ and

$$T = \frac{r_+ - r_-}{4\pi r_+ (r_+ + r_-)}\,, \quad \Omega = \frac{\sqrt{r_- r_+}}{r_+(r_+ + r_-)}\,, \quad S = \pi r_+ (r_+ + r_-)\,,$$

$$M = \frac{r_+ + r_-}{2}\,, \quad J = M\sqrt{r_+ r_-}\,.$$

The configuration function

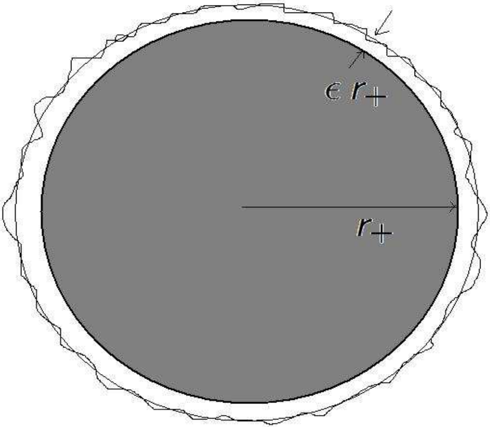

Figure: $B = r - r_+\left\{1 + \epsilon\left[1 + \Phi(x, \phi, t)\right]\right\} = 0.$

Miscellaneous

$$N_r = \frac{1}{|\partial B|}\,, \quad N_i = -\epsilon\, r_+ \frac{\partial_i \Phi}{|\partial B|}\,, \quad i = x, \phi, t\,,$$

$$|\partial B|^2 = \frac{\Delta}{f} + (\epsilon\, r_+)^2 \Big\{ \frac{1-x^2}{f}(\partial_x \Phi)^2 + \frac{f(\partial_\phi \Phi)^2}{v^2(1-x^2)} - \frac{v^2}{f\Delta}[(\partial_t + w\partial_\phi)\Phi]^2 \Big\}\,.$$

The induced metric on the boundary is

$$\begin{aligned} ds_H^2 \quad &= \quad -\frac{f\Delta}{v^2}dt^2 + \frac{f dx^2}{1-x^2} + \frac{v^2(1-x^2)}{f}d\phi^2 \\ &\quad +(\epsilon r_+)^2 \frac{f}{\Delta}\Big(\partial_x \Phi dx + \partial_\phi \Phi d\phi + \partial_t \Phi dt\Big)^2\,. \end{aligned}$$

Effective action

Action at $r = r_+\{1+\epsilon[1+\Phi(x,\phi,t)]\}$,

$$S_B = \frac{r_+ - r_-}{4} - \frac{\mu}{2}\int_B dx d\phi dt \left[\mathcal{L}_0 + \frac{2r_+(r_+ + r_-)^2\Phi(\partial_t + \Omega\partial_\phi)^2\Phi}{r_+ - r_-} + \mathcal{O}(\Phi^3)\right] + \mathcal{O}(\sqrt{\epsilon}),$$

$$\mathcal{L}_0 = \frac{2r_+(r_+ + r_-)^2}{r_+ - r_-}[(\partial_t + \Omega\,\partial_\phi)\Phi]^2 - (1-x^2)(\sqrt{\epsilon}\,\partial_x\Phi)^2 - \frac{(r_+ + r_- x^2)^2(\sqrt{\epsilon}\,\partial_\phi\Phi)^2}{(r_+ + r_-)^2(1-x^2)},$$

where $\mu = r_+/(8\pi)$.

At $r = r_+(1+\epsilon)$,

$$S_H = -\frac{r_+ - r_-}{4} + \frac{\mu}{2}\int_H dx d\phi dt \left[\mathcal{L}_0 + \mathcal{O}(\Phi^3)\right] + \mathcal{O}(\sqrt{\epsilon}).$$

Charges

Charges at $r = r_+(1+\epsilon)$,

$$
\begin{aligned}
H &= -\Omega J_\phi + \frac{\mu}{2}\int_H dxd\phi dt \Big\{ \frac{2r_+(r_+ + r_-)^2}{r_+ - r_-}[(\partial_t + \Omega\,\partial_\phi)\Phi]^2 - \mathcal{L}_0 \Big\}\,, \qquad (1) \\
J_\phi &= \frac{\mu}{2}\int_H dxd\phi dt \Big\{ \frac{2r_+(r_+ + r_-)^2}{r_+ - r_-}(\partial_t + \Omega\,\partial_\phi)\Phi\,\partial_\phi\Phi \\
&\qquad + \Omega\frac{(r_+ + r_-)^2(1-x^2)}{(r_+ + r_- x^2)^2}\Big[3r_+^2 - r_-^2 x^2 + r_+ r_-(1+x^2)\Big]\Big\} \\
&= J + \frac{\mu}{2}\int_H dxd\phi dt \Big[\frac{2r_+(r_+ + r_-)^2}{r_+ - r_-}(\partial_t + \Omega\,\partial_\phi)\Phi\,\partial_\phi\Phi \Big]\,.
\end{aligned}
$$

The canonical momentum

$$
\Pi_\Phi = \mu\frac{r_+(r_+ + r_-)^2}{r_+ - r_-}(\partial_t + \Omega\,\partial_\phi)\Phi = \frac{1}{2}\frac{\delta S_H}{\delta(\partial_t\Phi)}\,.
$$

Classical solutions

In the small rotation limit ($\Omega \to 0 \;\Rightarrow\; \rho \equiv r_-/r_+ \to 0$),

$$
\begin{aligned}
\mathcal{L}_0 &= 2r_+^2(1+3\rho)[(\partial_t + \Omega\,\partial_\phi)\Phi]^2 - (1-x^2)(\sqrt{\epsilon}\,\partial_x\Phi)^2 \\
&\quad -\Big(\frac{1}{1-x^2} - 2\rho\Big)(\sqrt{\epsilon}\,\partial_\phi\Phi)^2\,, \\
H &= -\Omega J_\phi + \frac{\mu}{2}\int_H dx d\phi \Big\{(1-x^2)(\sqrt{\epsilon}\,\partial_x\Phi)^2 + \Big(\frac{1}{1-x^2} - 2\rho\Big)(\sqrt{\epsilon}\,\partial_\phi\Phi)^2\Big\}\,, \\
J_\phi &= J + \int_H dx d\phi\,\mu\, r_+^2(1+3\rho)(\partial_t + \Omega\,\partial_\phi)\Phi\,\partial_\phi\Phi\,.
\end{aligned}
$$

The solution is

$$
\begin{aligned}
\Phi &= P_\ell^m(x)\exp\{i[m(\phi - \Omega t) - \mathcal{E}_{\ell,m} t]\}\,, \\
2r_+^2(1+3\rho)\mathcal{E}_{\ell,m}^2 f_\ell^m + \epsilon\,\partial_x\Big[(1-x^2)\partial_x f_\ell^m\Big] - \Big(\frac{1}{1-x^2} - 2\rho\Big)\epsilon\, m^2 f_\ell^m &= 0\,, \\
\mathcal{E}_{\ell,m} = \sqrt{\epsilon\,\frac{\ell(\ell+1) - 2m^2\rho}{2r_+^2(1+3\rho)}} &\approx \frac{\ell}{r_+}\sqrt{\frac{\epsilon}{2}}\,\Big[1 - \rho\Big(\frac{3}{2} + \frac{m^2}{\ell^2}\Big)\Big]\,, \\
\ell = 0, 1, \cdots, \infty\,, \quad m &= -\ell, \cdots, \ell\,.
\end{aligned}
$$

Quantization

General solution, $\Phi = \sum_{\ell,m} \Phi_\ell^m$,

$$\begin{aligned} \Phi_\ell^m &= N_\ell^m P_\ell^m(x)\left\{ a_{\ell,m} e^{i[m(\phi-\Omega t)-\mathcal{E}_{\ell,m} t]} + a_{\ell,m}^\dagger e^{-i[m(\phi-\Omega t)-\mathcal{E}_{\ell,m} t]} \right\}, \\ N_\ell^m &= \sqrt{\frac{1}{2\mu\, r_+^2(1+3\rho)\mathcal{E}_{\ell,m}} \frac{2\ell+1}{4\pi} \frac{(\ell-m)!}{(\ell+m)!}}, \end{aligned}$$

Commutators,

$$\begin{aligned} [\hat\Phi(x,\phi,t), \hat\Pi_\Phi(x',\phi',t)] &= i\delta(x-x')\delta(\phi-\phi'), \\ [\hat\Pi_\Phi(x,\phi,t), \hat\Pi_\Phi(x',\phi',t)] &= [\hat\Phi(x,\phi,t), \hat\Phi(x',\phi',t)] = 0, \\ [\hat a_{\ell,m}\,,\, \hat a_{p,q}^\dagger] = \delta_{\ell,p}\,\delta_{m,q} \quad &, \quad [\hat a_{\ell,m}\,,\, \hat a_{p,q}] = [\hat a_{\ell,m}^\dagger\,,\, \hat a_{p,q}^\dagger] = 0\,. \end{aligned}$$

Fock space and charges

- $\hat{a}_{\ell,m} |0\rangle = 0$;
- multiparticle states, $|N_{\ell,m}\rangle \sim (\hat{a}^\dagger_{\ell,m})^{N_{\ell,m}} |0\rangle$,

$$\hat{N}_{\ell,m} |N_{\ell',m'}\rangle = \delta_{\ell\ell'}\delta_{mm'} N_{\ell,m} |N_{\ell,m}\rangle \ , \quad \langle N_{\ell,m}|N_{\ell',m'}\rangle = \delta_{\ell\ell'}\delta_{mm'} \ ,$$

where $\hat{N}_{\ell,m} = \hat{a}^\dagger_{\ell,m}\hat{a}_{\ell,m}$;

The charges become

$$\begin{aligned}
\hat{H} &= -\Omega\hat{J}_\phi + \sum_{\ell,m} \mathcal{E}_{\ell,m}\Big(\hat{N}_{\ell,m} + \frac{1}{2}\hat{N}_0\Big) \\
&= \Big(-\Omega J + \sum_{\ell,m} \frac{\mathcal{E}_{\ell,m}}{2}\Big)\hat{N}_0 + \sum_{\ell,m} \mathcal{E}'_{\ell,m}\hat{N}_{\ell,m} \ , \\
\hat{J}_\phi &= J\hat{N}_0 - \sum_{\ell,m} m\hat{N}_{\ell,m} \ ,
\end{aligned}$$

where $\mathcal{E}'_{\ell,m} = \mathcal{E}_{\ell,m} + m\Omega$, and $\hat{N}_0$ is the number operator for the vacuum state,

$$\hat{N}_0 |0\rangle = |0\rangle \ , \quad \hat{N}_0 |N_{\ell,m}\rangle = 0 \, .$$

Zero point energy

- Zero point energy contributes to gravity;
- Need a cutoff to render the contribution finite;
- Existence of substructure $\Longleftrightarrow$ cutoff

$$N_c = \ell_{max} = m_{max} \approx \frac{2\pi r_+}{a} ,$$

where a is lattice spacing of substructure of spacetime.

With the cutoff, the contribution from the zero point energy is

$$M_0 = \sum_{\ell=0}^{N_c} \sum_{m=-\ell}^{\ell} \frac{\mathcal{E}_{\ell,m}}{2} \approx \frac{N_c^3}{3r_+} \sqrt{\frac{\epsilon}{2}} \left(1 - \frac{11\rho}{6}\right) .$$

The thermal state

System with temperature T and angular velocity Ω is

$$
\begin{aligned}
|\Psi\rangle &= |0\rangle + \sum_{\ell,m} \sum_{N_{\ell,m}} \left(\frac{e^{-N_{\ell,m}(\beta \mathcal{E}'_{\ell,m} + \alpha m)}}{\Xi_{\ell,m}} \right)^{1/2} |N_{\ell,m}\rangle \\
&= |0\rangle + \sum_{\ell,m} \sum_{N_{\ell,m}} \left(\frac{e^{-N_{\ell,m}\beta \mathcal{E}_{\ell,m}}}{\Xi_{\ell,m}} \right)^{1/2} |N_{\ell,m}\rangle \; ,
\end{aligned}
$$

where $\Xi_{\ell,m} = \sum_{N_{\ell,m}} e^{-N_{\ell,m}\beta\mathcal{E}_{\ell,m}} = 1/(1 - e^{-\beta\mathcal{E}_{\ell,m}})$, $\beta = 1/T$ and $\alpha = -\beta\Omega$. (The minus sign in α is due to the fact that $\beta\Omega$ is a chemical potential.) Note

$$
\left\langle \Psi | \hat{N}_0 | \Psi \right\rangle = 1 \, , \quad \left\langle \Psi | \hat{N}_{\ell,m} | \Psi \right\rangle = \sum_{N_{\ell,m}} \frac{e^{-N_{\ell,m}\beta\mathcal{E}_{\ell,m}}}{\Xi_{\ell,m}} N_{\ell,m} \, .
$$

Localization of charges

$\mathcal{E}_{\ell,m}$ is an even function in m. So "particles" with $m > 0$ and $m < 0$ are evenly excited. Hence

$$\begin{aligned}
E &= \langle\Psi|\,\hat{H}\,|\Psi\rangle = -\Omega J + \sum_{\ell,m} \frac{\mathcal{E}_{\ell,m}}{2} + \sum_{\ell,m} \sum_{N_{\ell,m}} \mathcal{E}'_{\ell,m} N_{\ell,m} \frac{e^{-N_{\ell,m}\beta\mathcal{E}_{\ell,m}}}{\Xi_{\ell,m}} \\
&= -\Omega J + \sum_{\ell,m} \frac{\mathcal{E}_{\ell,m}}{2} - \partial_\beta \sum_{\ell,m} \ln \Xi_{\ell,m}\,, \\
J_\phi &= \left\langle \Psi|\hat{J}_\phi|\Psi \right\rangle = J\,.
\end{aligned}$$

The result for J_ϕ suggests that all the angular momentum of the black hole is carried by the boundary, i.e., the horizon.

The partition function

$$\ln \Xi = \sum_{\ell,m} \ln \Xi_{\ell,m} = -\sum_{\ell=0}^{N_c} \sum_{m=-\ell}^{\ell} \ln\left(1 - e^{-\beta \mathcal{E}_{\ell,m}}\right).$$

Calculate in the small rotation limit:

$$M \approx \frac{r_+}{2}(1+\rho), \quad J \approx \frac{r_+^2}{2}\sqrt{\rho}(1+\rho), \quad \Omega \approx \frac{\sqrt{\rho}}{r_+}(1-\rho),$$
$$T \approx \frac{1-2\rho}{4\pi r_+}, \quad S \approx \pi r_+^2(1+\rho), \quad \rho = \frac{r_-}{r_+} \to 0.$$

The result is (note $y = kn$ and $k = \frac{\beta}{r_+}\sqrt{\frac{\epsilon}{2}}$)

$$\begin{aligned}
\ln \Xi &\approx -\frac{2}{k^2}\int_0^{kN_c} dy f_1(y) = -\frac{2}{k^2}\Big[f_2(kN_c) - f_2(0)\Big], \\
f_1(y) &= f_2'(y) = y\ln(1-e^{-y}) - \frac{11\rho y^2}{6(e^y-1)}, \quad f_1(0) = 0, \\
f_2(y) &= yLi_2(e^{-y}) + Li_3(e^{-y}) + \frac{11\rho}{3}f_3(y), \quad f_2(0) = \zeta(3)\left(1 + \frac{11\rho}{3}\right), \\
f_3(y) &= yLi_2(e^{-y}) + Li_3(e^{-y}) - \frac{y^2}{2}\ln(1-e^{-y}), \quad f_3(0) = \zeta(3),
\end{aligned}$$

where $Li_s(z)$ is the polylogarithm.

Energy and Entropy

The total energy and the entropy are

$$
\begin{aligned}
H &= -\Omega J + M_0 - \partial_\beta \ln \Xi = \frac{\ell_p^2}{4\pi^3 r_+^2 \epsilon_0}\left[\zeta(3) - f_3(c_0) + \frac{c_0^3}{12} + \mathcal{O}(\rho)\right] M\,, \\
S' &= (1-\beta\partial_\beta)\ln \Xi = \frac{3\ell_p^2}{4\pi^3 r_+^2 \epsilon_0}\left[\zeta(3) - f_3(c_0) - \frac{c_0^2}{6}\ln(1-e^{-c_0}) + \mathcal{O}(\rho)\right] S\,,
\end{aligned}
$$

where we have let $\epsilon = \epsilon_0 + \epsilon_1 \rho + \mathcal{O}(\rho^2)$, $N_c = N_0 + N_1 \rho + \mathcal{O}(\rho^2)$, and $c_0 = 2\pi\sqrt{2\epsilon_0}\, N_0$. Assuming $H = M$ and $S' = S$,

$$
\sqrt{\epsilon_0} \approx \frac{\ell_p}{7.27 r_+}\,, \quad N_0 \approx \frac{2\pi r_+}{2.84 \ell_p}
$$

- The putative lattice spacing is $a \approx 2.84 \ell_p$.
- Coordinate deviation: $\delta \approx r_+ \epsilon_0 \sim \dfrac{\ell_p^2}{r_+}$;

  $\Longrightarrow$ Physical deviation: $\delta' \approx r_+\sqrt{\epsilon_0} \approx \dfrac{\ell_p}{7.27}$.
- The cutoff energy: $\mathcal{E}_{N_0,m} \approx \frac{N_0}{r_+}\sqrt{\frac{\epsilon_0}{2}} \approx \frac{0.22}{r_+}$.

Summary

- An effective action for the black hole horizon, treated as a physical boundary of the spacetime, is derived;
- The model is capable of explain the charges of the black hole in a natural way;
- Such a model presumably does not induce loss of information;
- The relation to a CFT description is not clear so far.