Title: Dynamical evaporation of quantum horizons

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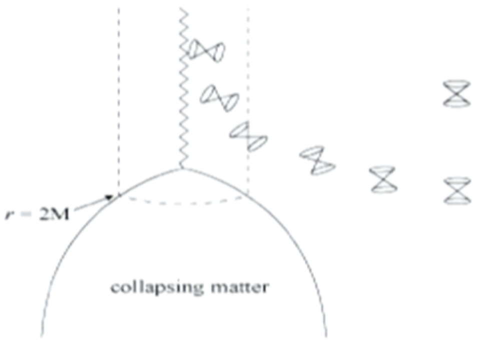
Abstract: We describe of the evaporation process as driven by the dynamical evolution of the quantum gravitational degrees of freedom resident at the horizon, as identified by the Loop Quantum Gravity kinematics. Using a parallel with the Brownian motion, we interpret the first law of quantum dynamical horizon in terms of a fluctuation-dissipation relation applied to this fundamental discrete structure. In this way, the horizon evolution is described in terms of relaxation to an equilibrium state balanced by the excitation of Planck scale constituents of the horizon. We show how from this setting the emergence of several conservative scenarios for the final stage of the evaporation process can be microscopically derived. Namely, the leakage of part of the horizon quantum geometry information prior to the Planckian phase and the stabilization of the hole surface shrinkage forming a massive remnant, which can eventually decay, are shown to take place.

Black hole thermodynamics



Black holes in their stationary phase behaves as thermodynamical systems:
[Bekenstein, Carter ,Hawking]

0th law: the surface gravity κ is constant on the horizon.

1st law: $\delta M = \frac{\kappa_H}{8\pi G}\delta A + \Phi_H\,\delta Q + \Omega_H\,\delta J$

2nd law: $\delta A \geq 0$

3rd law: the surface gravity value $\kappa = 0$ (extremal BH) cannot be reached by any physical process.

$S \longleftrightarrow A/(8\pi\alpha)$ $\qquad$ $T \longleftrightarrow \alpha\kappa$ $\qquad$ But, in classical GR: $T=0$

Hawking radiation:
thermal emission of particles from a BH at

$$T = \frac{\kappa\hbar}{2\pi} \longrightarrow S = \frac{A}{4\ell_p^2}$$

Semiclassical result

Black holes have entropy and evaporate

Questions:

1) Microscopic origin of the entropy
2) Dynamics of BH evaporation

Why do we need a *quantum* theory of gravity to address these questions?

❖ The entropy puzzle

Statistical physics: entropy of any system is given by $S = \ln N$

N = number of states of the system for the given macroscopic parameters

$$N = e^S \sim 10^{10^{77}}$$ for a solar mass black hole

Where do all these d.o.f. live?

⋆ On the horizon: classically forbidden (no-hair th.)

unique geometry of the horizon ➥ $S = \ln 1 = 0$

⋆ In the bulk: classical geometry of the horizon unaffected by different microstates, but...

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❖ The information paradox

Hawking's radiation:

QFT on a curved (BH) background ➡ BH radiate as thermal bodies

i.e. the spectrum does not depend on the structure of the body that collapsed to form the BH

the emitted quanta are in a mixed (thermal) state with excitations which stay inside the hole:

correlations between d.o.f. accessible outside the horizon and d.o.f. unaccessible behind the horizon

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♨ But what happens when the hole evaporates completely??

there is nothing left to be entangled with anymore!

➥ an initial pure state has evolved into a mixed state

Contradiction: GR + QM lead to a non-unitary evolution of a BH

✧ Moreover, how can the initial collapsed matter transfer its information to the radiation quanta??

➢ Call for a quantum treatment of the gravitational dof

Let's try to kill two birds with one stone:

- ∗ Define a statistical mechanical ensemble in terms of QG dof
- ∗ Use the QG dynamics to describe the evaporation process in terms of the evolution of these dof

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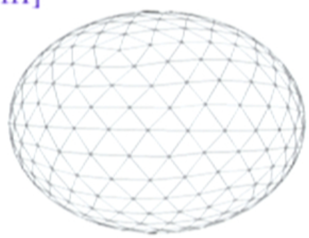
The main idea:

The entropy in the 1st law is the log of the number of states of the black hole that can affect the *exterior* [Bekenstein; Sorkin; Smolin; Jacobson; Rovelli]

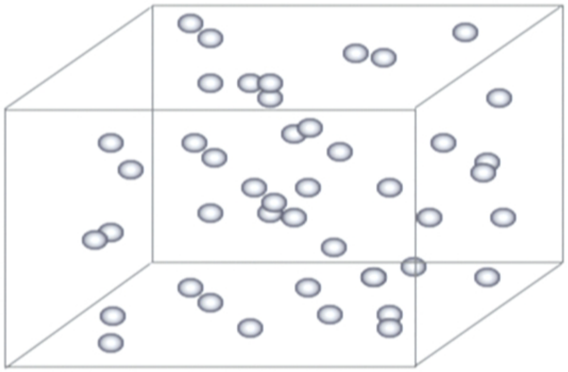
➥ The horizon carries some kind of information with a density of approximately 1 bit per unit area



What these bits of information represent depends on the deep structure of space-time

Analogy with condensed matter physics: Part I

A dilute gas at high temperature



N = number of molecules

Deep structure ⬌ Atomic structure of matter

$$S = N\,k \ln f(T, P, m, h)$$

Finiteness of the number of atoms ➡ Finiteness of S

Quantum horizon $\Leftrightarrow$ gas of particles

Constituents of quantum space ⬌ molecules of the gas

Fundamental discreteness of space at the Planck scale ➡ Finiteness of S

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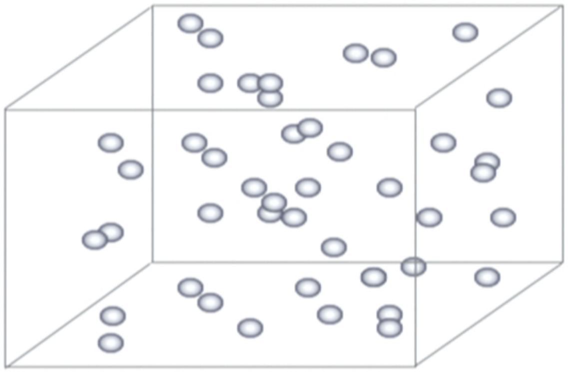

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THE LQG PICTURE: PART I

THE SINGLE INTERTWINER BH MODEL

⁕ **Entropy:** first ideas by
[Krasnov, Rovelli, Smolin]

Local definition of BH (Isolated Horizons)
+
LQG techniques:

Quantum BH d.o.f. described by a Chern-Simons theory on a punctured 2-sphere

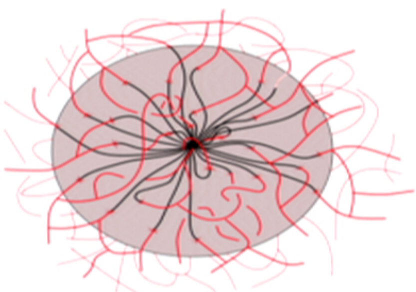
[Ashtekar, Baez, Corichi, Krasnov; Engle, Noui, Perez, DP]

⋆ Area constraint

$$\sum_{p=1}^{n} \sqrt{j_p(j_p+1)} \leq \frac{A}{8\pi\beta\ell_p^2}$$

➥ $\mathrm{dim}[\mathscr{H}^{\mathrm{CS}}(\mathrm{j}_1 \ldots \mathrm{j}_n)] = \mathrm{dim}[\mathrm{Inv}(\mathrm{j}_1 \otimes \cdots \otimes \mathrm{j}_n)]$

We can model the IH system by a single SU(2) intertwiner



⇨ BH entropy d.o.f.
=
Quantum shapes of the horizon

polymer-like excitations
of the gravitational field

Semiclassical limit of the SU(2) intertwiner quantum geometry: tesselated surfaces

[Bianchi; Livine, Terno]

$$S = \ln \sum_{j_1 \cdots j_n} \mathrm{dim}[\mathscr{H}^{CS}(j_1 \cdots j_n)] = \frac{A}{4\ell_p^2} + \mu N$$

temperature
introduced by hand

THE LQG PICTURE: PART II

THE QUANTUM RINDLER HORIZON PICTURE

[Bianchi]

Spin networks $SU(2)$ $SL(2,C)$ (γ-simple)

$$Y_\gamma : \; |j,m\rangle \;\to\; |j\rangle \equiv |\gamma(j+1), j; j, m\rangle$$

➡ boundary Hilbert space:

$$|s\rangle = \otimes_f |j_f\rangle$$

spin foam quantization: S tessellated in faces f

boost Hamiltonian: $\hat{H} = \sum_f \hbar \hat{K}^f \;\Rightarrow\; \hat{E} = \hat{H}\ell^{-1}$ $\qquad |s_t\rangle = e^{i\hat{E}t}|s\rangle$

evolution in proper time $t = \eta\ell$
in the presence of a quantum Rindler horizon

energy:

$$E = \langle \hat{E} \rangle = \frac{A}{8\pi G \ell}$$

$$\langle \hat{K} \rangle = \gamma \langle \hat{L} \rangle$$

temperature:

ratio of equilibrium population of the two-level detector $\Rightarrow$ $T = \dfrac{\hbar}{2\pi\ell}$

Unruh temperature

Clausius

$$\delta S = \frac{\delta E}{T} \;\;➡\;\; \delta S = \frac{\delta A}{4\ell_p^2}$$

statistical mechanical interpretation:

entanglement entropy between quantum gravitational d.o.f.

$$\delta S = -\delta\, \mathrm{Tr}\,(\rho \ln \rho)$$

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EVAPORATION PROCESS

STRATEGY:

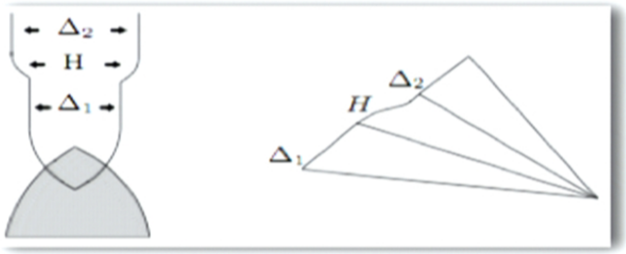
perturbate the equilibrium states by turning on
some weakly dynamical effects near the horizon

$\downarrow$

Local interaction bulk/boundary

$\downarrow$

new equilibrium configuration is reached
with a small change of the horizon state



We need to deparametrize the system near the horizon

➢ locally single out one of the partial observables to play the role of time

➢ use the Hamiltonian operator in the bulk near the horizon to define *evolution* of the boundary quantum states with respect to this observable

☆ Key idea:

matching the dynamical horizons framework of [Ashtekar, Krishnan; Booth, Fairhurst]
with the local thermodynamical description of [Frodden, Ghosh, Perez]

Analogy with condensed matter physics: Part II

Brownian motion

Einstein's treatment of Brownian motion ⇨ First example of fluctuation-dissipation theorem

Einstein relation $D = \mu\, k\, T$ ➡ First proof of atomic theory of matter

[Candelas, Sciama]: study of the thermodynamics of dissipative processes associated to black holes physics

- Onsager's principle: a linear system behaves on average in the same way in a given configuration whether it reached that configuration by a spontaneous fluctuation or by an externally induced perturbation

First law of DH ⇨ Fluctuation-dissipation theorem

Radiation spectrum ➡ Proof of atomic structure of quantum space

⋆ Brownian motion

∗ I part: stochastic process understanding; description of the stochastic variable $x(t)$ in terms of probability theory

Diffusion equation

$$\frac{\partial n(x,t)}{\partial t} = D\frac{\partial^2 n}{\partial x^2} \quad \Longrightarrow \quad \langle x(t)^2 \rangle = 2Dt$$

n = density of Brownian particles

mean squared displacement

∗ II part: physical assumptions

equipartition law

$$m\langle v^2 \rangle = kT$$

Stoke's law

$$F_S = -m\gamma v, \quad m\gamma = 6\pi a\eta$$

fluid viscosity

particle radius

Langevin equation

$$m\frac{dv}{dt} = -m\gamma v + R(t) \quad \overset{\text{Wiener-Khintchine th}}{\Longrightarrow} \quad \mu = \frac{1}{m\gamma} = \frac{1}{kT}\int_0^\infty \langle v(t_0)v(t_0+t)\rangle dt$$

F-D theorem

Frictional force

Random force driving the BM

Response function (mobility)

➢ I part + II part: **Einstein relation**

$$D = \mu kT = \frac{RT}{6\pi\eta a N_A}$$

Link between the microscopic and macroscopic levels of description

⇩

determination of N_A from experimentally accessible macroscopic quantities

⋆ Black hole dissipation of a gravitational perturbation

(ex: slowing down of a black hole by a non-axisymmetric slowly varying gravitational field produced by distant masses)

[Hawking, Hartle]

$$\frac{dA}{dt} = \frac{2}{\kappa}\int \sigma\sigma^* dA$$

σ = shear encoding all the non-trivial perturbation of the metric

[Candelas, Sciama]

interpreting σ as a quantum operator ➡

$$\underbrace{\frac{dA}{dt}}_{\text{response function (dissipation rate)}} = \frac{2}{\kappa}\int \underbrace{\langle\sigma\sigma^*\rangle}_{\text{shear fluctuations with the stochastic properties of black-body radiation at } T=\kappa/2\pi} dA$$

Onsager's principle:

$\Downarrow$ externally induced perturbation = spontaneous fluctuation

Black hole mass dissipation via Hawking *gravitational* radiation

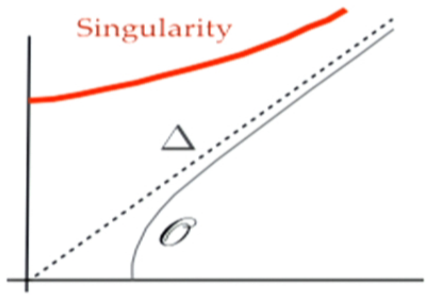
Energy grand canonical ensemble

- No unique notion of quasilocal energy function in the context of IH;

no unique time evolution vector field can be single out: $\chi^a \to \chi'^a = c\chi^a$, $\kappa_{(\chi)} \to \kappa'_{(\chi)} = c\kappa_{(\chi)}$

[Frodden, Ghosh, Perez]: unique local first law for IH, once a physical argument is introduced

for a preferred family of stationary local observers $\mathscr{O}$, at a proper distance ℓ from the horizon ($\ell^2 << A$)



$$dE = \frac{\bar{\kappa}}{8\pi G} dA \quad \text{where} \quad \bar{\kappa} = 1/\ell + o(\ell)$$

universal local surface gravity

$$E = \frac{\bar{\kappa}}{8\pi G} A \quad \Rightarrow \quad \hat{H}|\{s_j\}\rangle = \sum_j s_j E_j |\{s_j\}\rangle = \frac{\bar{\kappa}\gamma\ell_p^2}{G} \sum_j s_j \sqrt{j(j+1)} |\{s_j\}\rangle$$

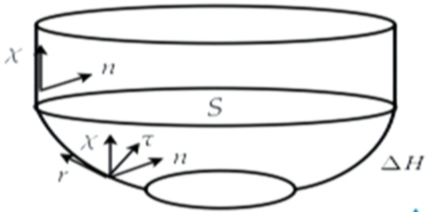
where $\{s_j\}$ represents a given quantum configuration where s_j punctures carry the spin-j

- The grand canonical partition function: $\mathscr{Z}(\beta) = \sum_{N=0}^{\infty} z^N Z(\beta, N)$

$z = \exp(\beta\mu)$
μ chemical potential

canonical partition function $Z(\beta, N) = \sum_{\{s_j\}} \prod_j \frac{N!}{s_j!} (2j+1)^{s_j} e^{-\beta s_j E_j}$

Dynamical horizons



[Ashtekar, Krishnan; Booth, Fairhurst]

$$\frac{1}{16\pi G}\int_{\Delta H} N_r H\, d^3V = 0$$

$$\Downarrow$$

Area balance law
(dynamical process version of the I law)

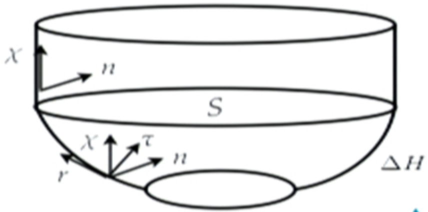
$$\frac{\bar\kappa_r}{8\pi G}\frac{dA}{dr} = \frac{1}{8\pi G}\overbrace{\int_S \sigma^2 d^2V}^{\text{flux of gravitational energy associated with } \xi_r^a}$$

Freedom to rescale the surface gravity

$$\bar\kappa_r = (2r)^{-1} \qquad \bar\kappa_f = \frac{df}{dr}\bar\kappa_r \qquad \longleftrightarrow \qquad \xi_f^a \overset{\text{permissible lapse associated with the radial function } f}{=} N_f\chi^a = \frac{df}{dr}\xi_r^a$$

f(r) encodes the dynamical nature of the previous version of the first law;
but it also represents an ambiguity in the description of the horizon dynamics.

Dynamical horizons



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➢ Solve the ambiguity:

$$\bar{\kappa}_f = \bar{\kappa}$$

Ashtekar, Krishnan   Ghosh, Perez

$$\Longrightarrow \qquad f(r) = \ell(r) \qquad N_f = N_\ell = 1 \qquad t^a = N_\ell \chi^a$$

time vector field for the local observer

$$\dot{E} \equiv \frac{dE}{d\ell} = \frac{1}{8\pi G}\underbrace{\int_S \sigma^2 d^2V}_{\text{perturbation induced by the near-horizon bulk dynamics}}$$

Quantum Dynamics

$$\hat{H} = \hat{p}_\ell + \hat{H}_0 = 0 \qquad \hat{p}_\ell = \Delta\hat{E} \qquad \hat{H}_0 = \frac{\hat{\sigma}^2}{8\pi G}$$

momentum conjugate to the time variable ℓ = energy of the quantum of radiation emitted

Hamiltonian related to a shear operator driving the area variation

✶ Heisenberg picture:

ℓ and E *partial observables* [Rovelli; Dittrich]

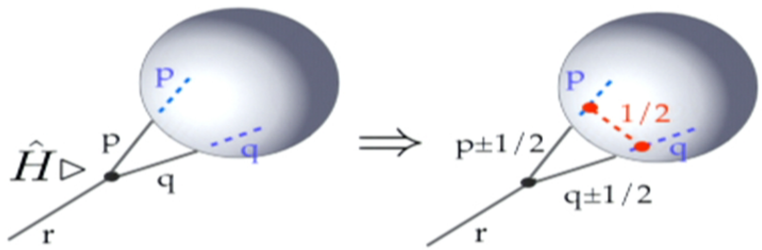
$$\langle f|\dot{\hat{E}}|i\rangle = \langle f|[\hat{E},\hat{H}]|i\rangle = \Delta E\langle f|\hat{H}|i\rangle$$

➡ Quantum fluctuations of $\hat{H}$ lead to the emission of gravitational radiation

✣ Use the local deparametrization of the system to interpret the bulk quantum dynamics near the horizon as a generator of boundary states evolution.

Action of $\hat{H}$ ➡ jump to a different horizon area eigenstate: energy flux across the horizon (radiation)

Thiemann's prescription for the Euclidean part



Spectrum

★ Fluctuation-dissipation th. interpretation of the first law of DH

$\hat{H}$ action $\longleftrightarrow$ $\hat{A}$ spectrum ➡ BH evaporation

Intensity of the spectrum lines:
(Fermi golden rule)

$$I_{pq} = \bar{s}_p \bar{s}_q |\langle \hat{H} \rangle|^2 \Delta E_{pq}^3$$

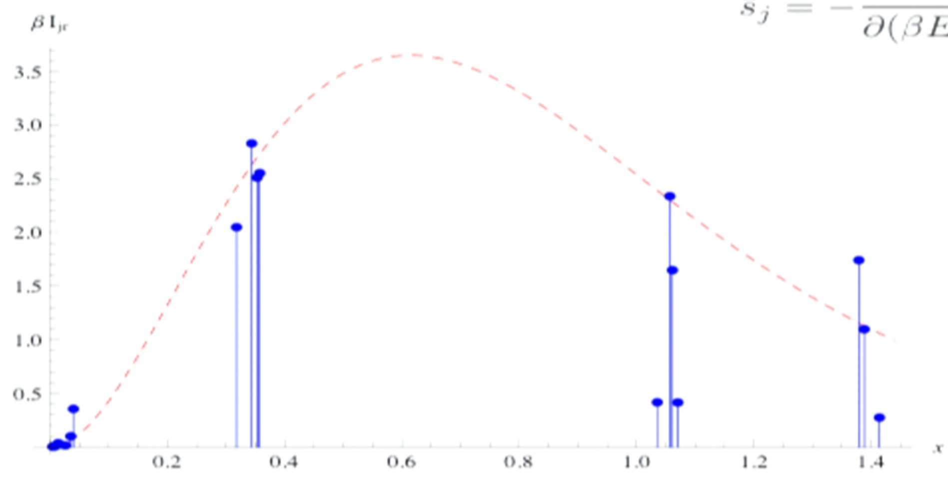
[Borissov, De Pietri, Rovelli]

$x \equiv \beta \Delta_{pq}^{\pm}$

$\beta \bar{\kappa} \gamma \ell_p^2 / G \sim o(1)$

expectation value for the occupation numbers

$$\bar{s}_j = -\frac{\partial}{\partial(\beta E_j)} \log \mathscr{Z} = \frac{z(2j+1)e^{-\beta E_j}}{1 - z\sum_j (2j+1)e^{-\beta E_j}}$$



Discrete spectrum

macroscopic window
on the microscopic world

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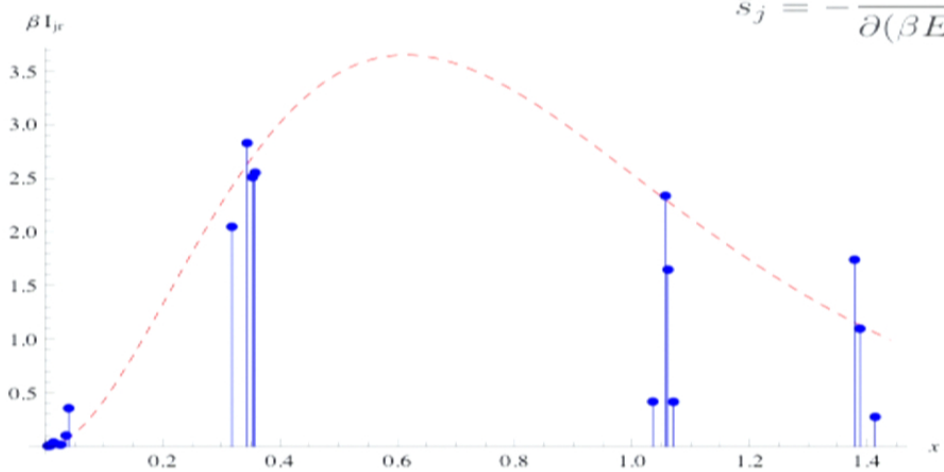

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COMMENTS:

- Resolution of ambiguities present in the quantization of the Hamiltonian constraint

- Thermodynamical argument à la Jacobson in the case of non-vanishing shear:
  [Eling, Guedens, Jacobson; Chirco, Liberati]

generalized Clausius relation

non-equilibrium considerations ➡ $$dS = dS_{ex} + dS_{in} = \frac{\delta Q}{T} + \delta N$$

viscous work on the microscopic\gravitational d.o.f. whose macroscopic effect is encoded in the horizon shear

★ connection with the modified I law proposed by [Ghosh, Perez]

non-equilibrium entropy contribution $\Longleftrightarrow$ entanglement entropy due to the radiation process

Hydrodynamics: macroscopic, coarse grained interpretation of $\hat{H}$ action as a non-equilibrium dissipative process (***membrane*** and ***stretched horizon*** paradigms)

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Hawking's argument:

- `Nice slices' conditions giving *local* Hamiltonian evolution
- Information-free horizon

$\Longrightarrow$ Quantum unitarity violation!

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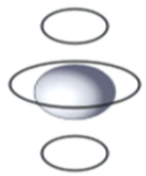
LQG proposal: information encoded in a ***quantum hair*** at each puncture piercing the horizon

[Bowick, Giddings, Harvey, Horowitz, Strominger]

Axionic charge



[Coleman, Krauss, Preskill, Wilczek]

Discrete gauge charge

[Moss]

Non–perturbative corrections to the area law

Aharonov-Bohm effect

Isolated horizons

$$F(A) = \frac{4\pi}{k}\,\Sigma$$

[Sahlmann, Thiemann] Stokes th.

$$h_\gamma[A] = P\exp \oiint_S F[A] = P\exp \oiint_S \frac{4\pi}{k}\Sigma$$

U(1) case

$$\hat{h}_\gamma \Psi = e^{-\frac{2\pi i}{k} m_p}\,\Psi$$

$\mathbb{Z}_k$ charge

Last phase of evaporation

- Γ: arbitrary spin network state on the canonical hypersurface
- B: connected bounded region of Γ graph (finite set of vertices and edges)
- ∂B: set of n edges with only one vertex in B (boundary data: $j_1, \ldots, j_n$)
- Boundary states: states of the edges $e \in \partial B$, irrespectively of the details of Γ_B

➢ Statistical mechanical approach: tracing over the bulk d.o.f.
an outside observer has no access to any information about Γ_B $\longrightarrow$ coarse-graining to a single vertex

Dimension of the intertwiner space ➡ Boundary entropy

In general, the coarse-grained intertwiner in $\mathscr{H}_{\partial B}$ will depend on the coarse graining data $\{g_{e \in B}\}$

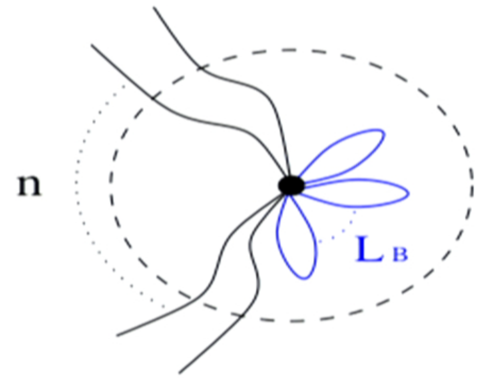
[Livine, Terno]

Canonical (trivial) choice $\{g_{e \in B} = 1\}$

$\Updownarrow$

Trivial topology of the interior graph

$$L_B = E_B - V_B + 1 = 0$$



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- First law

macroscopic:	local thermodynamics perspective	➥	flux of matter: imprint on the horizon
microscopic:	matter d.o.f. live on spin network links	➥	flux of matter: surface system in a new ensemble

LQG picture: the quantum horizon can keep track of the entropy it gains as a bit of energy flows through

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radiation emission ➡ new petals inside

entanglement entropy $\overset{?}{\Longrightarrow}$ quantum proof of GSL

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LQG horizon Boltzmann entropy $\overset{?}{\Longleftrightarrow}$ LQG horizon Von Neumann entropy

[Bianchi]

Information paradox

- Discrete radiation spectrum:

lines intensity ➡ boundary data

$$I_{pq} = \bar{s}_p \bar{s}_q |\langle \hat{H} \rangle|^2 \Delta E^3_{pq}$$

- Non-singular final state:

quantum dynamical effects ➡ massive remnant

hornlike geometry
('bag of gold')
[Wheeler, Banks]

Can the remnant decay?

non-local effects
(disordered locality)
[Markopoulou, Smolin]

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Information leakage prior to the Planckian phase ☞ internal infinite degeneracy not required

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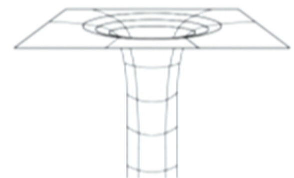

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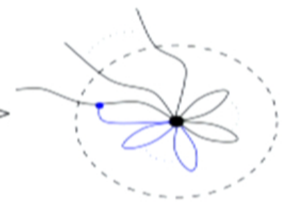
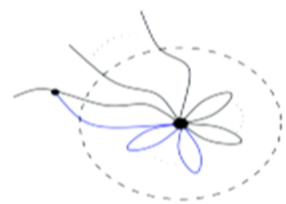
$\hat{H} \triangleright$  $\Rightarrow$ 

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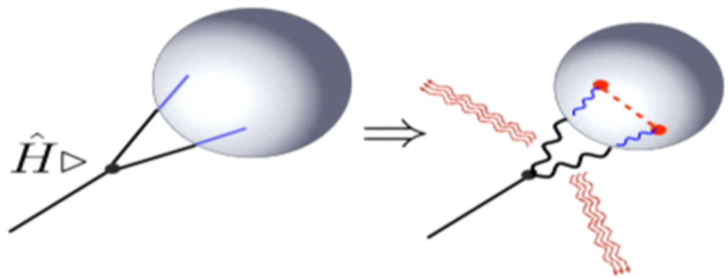
LQG description of the evaporation process



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(another piece to the puzzle of BH physics in the framework of thermodynamics)

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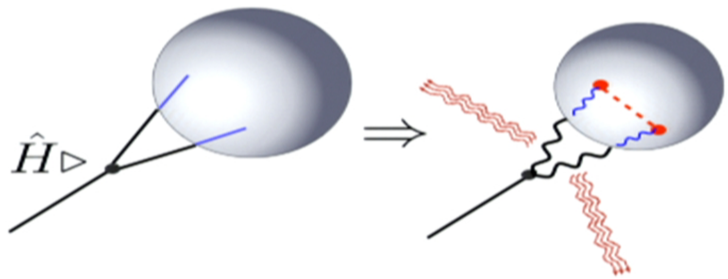

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- Resolution of ambiguities present in the quantization of the Hamiltonian constraint

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  [Eling, Guedens, Jacobson; Chirco, Liberati]

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