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Information return in Hawking radiation, a Gaussian quantum information theory perspective

Mathematical Physics Seminar @ U Helsinki

Erik Aurell

October 6, 2022

EA, M. Eckstein & P. Horodecki, *JCAP* 2022 (01), 014
EA, L. Hackl, P. Horodecki, R. Jonsson & M. Kieburg (2023) [in prep.]

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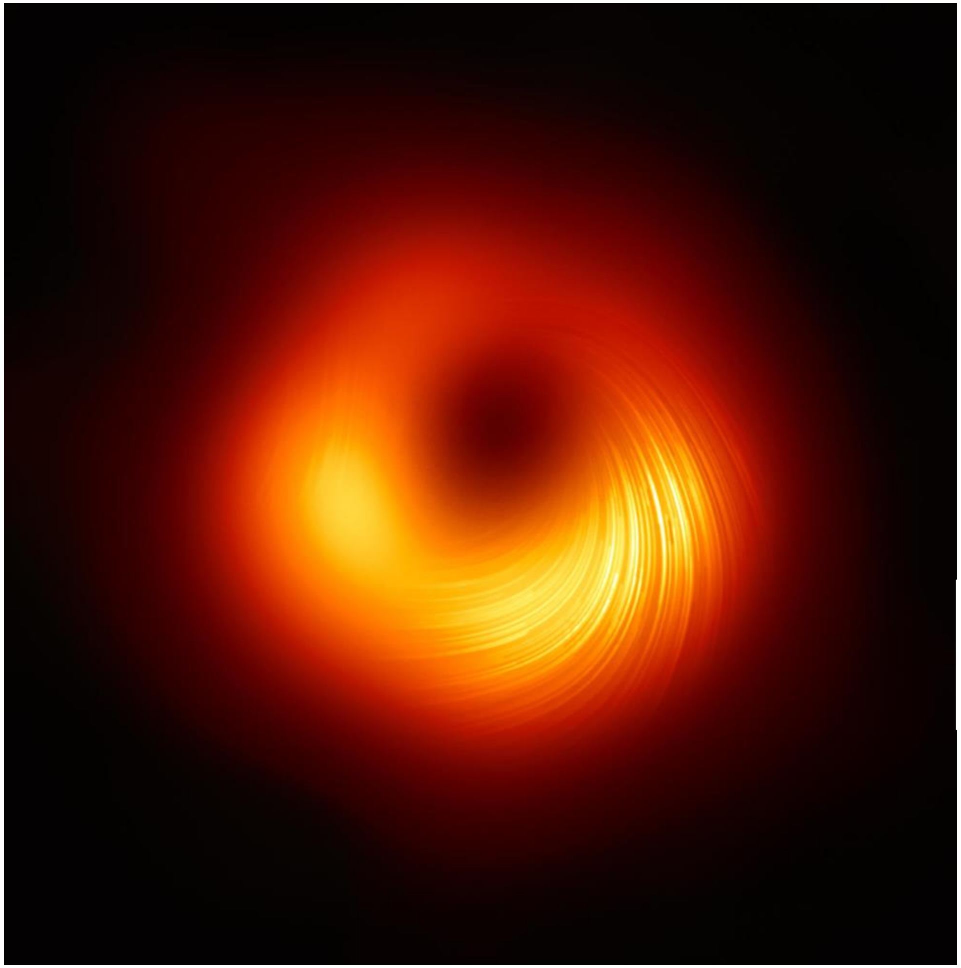
Black holes are real objects in our universe



Stars like the sun end as white dwarfs. Bigger stars as neutron stars or black holes.

At the center of (almost) every galaxy (including ours) there is very big black hole.

Rendering of the black hole M87*
Event Horizon Telescope (EHT)

Collisions of black holes have been observed in gravitational waves by LIGO-VIRGO.

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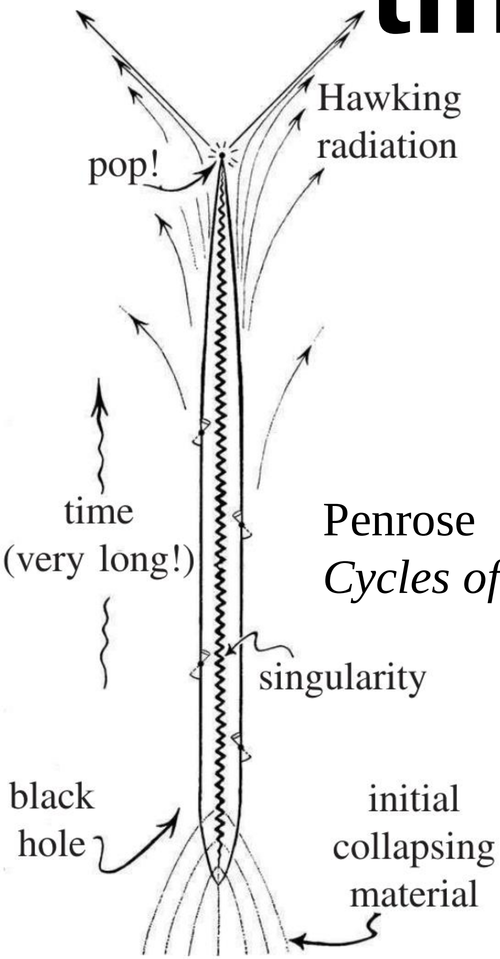
Hawking in 1974: quantum fields in the curved space-time around a black hole give particle creation



S.W. Hawking "Black hole explosions" Nature 248:30 (1974); "Particle creation by black holes" Commun. Math. Phys. 43:199 (1975)

Penrose *Cycles of time* (2010)

Hawking radiation is thermal at a temperature

$$T_H = \frac{m_P c^2}{8\pi k_B} \cdot \left(\frac{M}{m_P}\right)^{-1}$$

(formula for a Schwarzschild black hole)

By Stefan-Boltzmann law radiated power per area of a black body is proportional to T_H^4. A black hole loses mass by *Hawking evaporation*

$$\frac{dM}{dt} = -\frac{\pi^2}{2048}\frac{m_P}{t_P} \cdot \left(\frac{M}{m_P}\right)^{-2}$$

Planck units

When discussing black holes, Planck units are particularly useful. The Schwarzschild black hole radius is $2l_p \frac{M}{m_p}$, its Hawking temperature is $\frac{m_p c^2}{8\pi k_B}\frac{m_p}{M}$, etc.

$$[c] = \frac{L}{T} \qquad \text{Planck mass}: \quad m_p = \sqrt{\frac{\hbar c}{G}} \approx 2.2 \times 10^{-8}\ \text{kg},$$

$$[\hbar] = \frac{ML^2}{T} \qquad \text{Planck length}: \quad l_p = \sqrt{\frac{\hbar G}{c^3}} \approx 1.6 \times 10^{-35}\ \text{m},$$

$$[G] = \frac{L^3}{MT^2} \qquad \text{Planck time}: \quad t_p = \sqrt{\frac{\hbar G}{c^5}} \approx 5.4 \times 10^{-44}\ \text{s}.$$

m_P is about the mass of a grain of sand, the scale of objects of everyday life. It is however very large for an elementary particle mass.

The other two units are very small. Perhaps "It is natural to suppose also that $[l_p]$ determines the limit of applicability of present-day notions of space and causality."

—A.D. Sakharov, *Dokl. Akad. Nauk* **177**:70-71 (1967)

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Black hole information paradox

Ways out?

Take a large piece of matter in a pure quantum state.

Gravity acts. The matter collapses in a black hole.

The black hole evaporates through Hawking radiation.

At the end the black hole is gone, and all that remains is thermal radiation.

A pure state has developed into a mixed state. This breaks unitarity.

Fundamental information loss: actually the dynamics of a quantum black hole is not unitary.

Physics at horizon: firewalls or other physics stops the collapse.

Information return in Hawking radiation: entanglement between modes of the Hawking radiation.

Remnants: evaporation is not complete, something remains that keeps the information.

from S.B. Giddings "Comments on information loss and remnants" Phys Rev D 49:4078 (1988)

Thermal marginals vs global pure states.

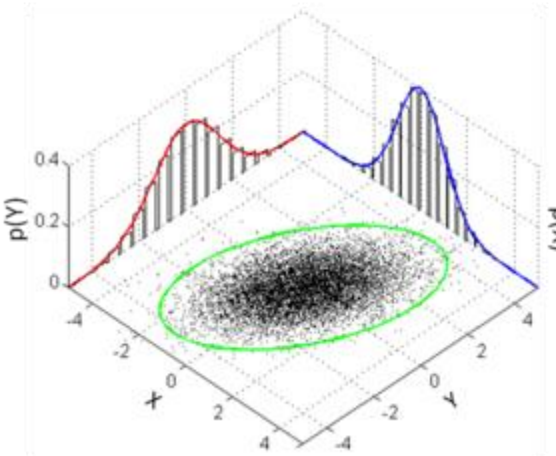
EA, Michał Eckstein & Paweł Horodecki, *JCAP* 2022 (01), 014

Building on advances in continuous-variable quantum information, in particular

J. Eisert et al "Gaussian Quantum Marginal Problem"
Commun Math Phys **280**:263 (2008)

The marginals problem

classical



$$P_X(x) = \sum_y P_{X,Y}(x,y)$$

The marginals of a pure classical state are pure.

quantum

$$|\psi\rangle_{AB} = \sum_i \alpha_i |i\rangle_A |i\rangle_B$$

$$\rho_A = \mathrm{Tr}_B[|\psi\rangle\langle\psi|] \quad \rho_B = \mathrm{Tr}_A[|\psi\rangle\langle\psi|]$$

Quantum marginals are typically not pure. There exists a general theory on the existence (or not) of a total pure quantum state with given (mixed) marginals:

A. Klyachko [arXiv:quant-ph/0409113]

It is quite complicated.

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Gaussian Quantum Marginal Problem (1/2)

("*when physics gets difficult, try harmonic oscillators*" [anonymous])

Gaussian oscillator states are completely specified by a correlation matrix C. For quantum states C satisfies Robertson-Schrödinger uncertainty relation.

$$\boldsymbol{z} = (q_1, p_1, q_2, p_2, \cdots, q_N, p_N)$$

$$C_{ij} = \mathrm{Tr}\left[\left(\hat{z}_i\hat{z}_j + \hat{z}_j\hat{z}_i\right)\hat{\rho}\right]$$

$$C + i\Omega \geq 0 \quad \Omega = \mathbf{1}_{ij} \otimes \begin{pmatrix} 0 & 1 \\ -1 & 0 \end{pmatrix}$$

A real symmetric C can be put in diagonal form by a symplectic transformation S. Gaussian pure states have $d_1 = d_2 = \cdots = d_N = 1$.

$$C = S\,\mathrm{diag}(d_1, d_1, d_2, d_2, \cdots, d_N, d_N)\,S^T$$

The density matrix marginalized over one mode is also Gaussian, and given by $\begin{pmatrix} C_{2k-1,2k-1} & C_{2k-1,2k} \\ C_{2k,2k-1} & C_{2k,2k} \end{pmatrix} = S_k^{(1)}\,\mathrm{diag}(c_k, c_k)\left(S_k^{(1)}\right)^T$

Gaussian Quantum Marginal Problem (2/2)

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Given *symplectic spectra* of C and its 2-block diagonal $\mathrm{diag}_2(C)$:

$$\mathrm{sspec}(C) = (d_1, d_2, \cdots, d_N) \quad , 1 \leq d_1 \leq d_2 \leq \cdots \leq d_N$$

$$\mathrm{sspec}\big(\mathrm{diag}_2(C)\big) = (c_1, c_2, \cdots, c_N) \quad , 1 \leq c_1 \leq c_2 \leq \cdots \leq c_N$$

J. Eisert et al "Gaussian Quantum Marginal Problem" *Commun Math Phys* **280**:263 (2008):

Necessary conditions, and a construction using 2-mode operations

$$\sum_{j=1}^{k} c_j \geq \sum_{j=1}^{k} d_j \text{ for } k = 1, .., \mathrm{N}, \qquad \text{and} \qquad c_N - d_N \leq \sum_{m<N} c_m - \sum_{m<N} d_m$$

$$S = \left(\mathbf{1}_{2(N-1)} \oplus S^{(2)}_{N-1,N}\right) \circ \cdots \circ \left(\mathbf{1}_2 \oplus S^{(2)}_{2,k_2} \oplus \mathbf{1}_{2(N-2)}\right) \circ \left(S^{(2)}_{1,k_1} \oplus \mathbf{1}_{2(N-1)}\right)$$

Global purity?

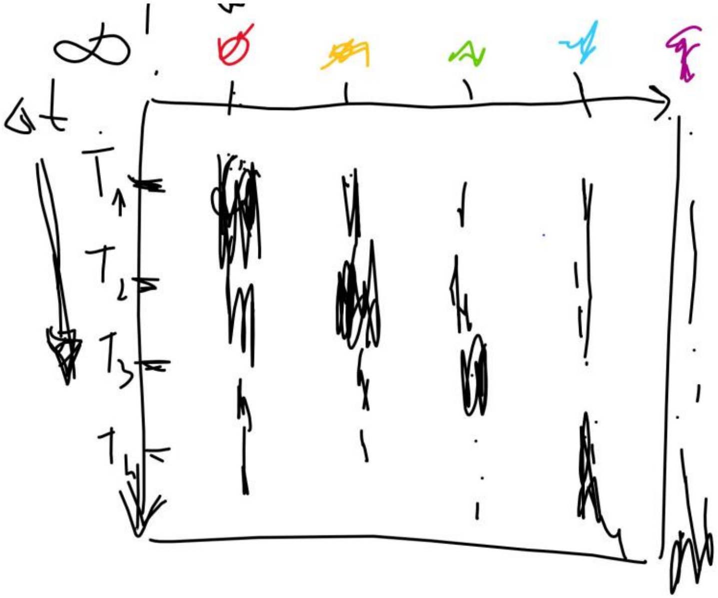
Translate the previous to marginal thermal states

$$\rho = \frac{1}{Z}\sum_n e^{-\beta\hbar\omega\left(n+\frac{1}{2}\right)}|n\rangle\langle n| \sim \exp\left(-\frac{1}{2(1+b)}(\hat{p}^2+\hat{q}^2)\right) \quad b = 2\left(e^{\beta\hbar\omega}-1\right)^{-1}$$

The symplectic spectrum of a globally pure Gaussian state is $d_1 = d_2 = \cdots = d_N = 1$. Hence Eisert et al conditions read

$$b_N \leq \sum_{m<N} b_m$$

These conditions are quite easy to satisfy for an initially large black hole, except perhaps for the very last emitted Hawking particles (photons).



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The size of random two-mode correlations.

Sketch of a theory of random symplectic transformations.

"Hawking radiation and high-dimensional Gaussian random pure states"
EA, L. Hackl, P. Horodecki, R. Jonsson & M. Kieburg (2023) [in prep.]

Random Gaussian states

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Start from the correlation matrix of a pure state

$$C = SS^T \qquad S \in \mathrm{Sp}(2N) \text{ a real symplectic matrix} \qquad S = S^* \quad \text{and} \quad S^{-1} = \hat{\tau}_2 S^T \hat{\tau}_2$$

Consider a random matrix S constrained to be symplectic and by the diagonal blocks of the correlation matrix

$$d\mu_{\mathrm{Sp}(2N)}(S) = \delta(\hat{\tau}_2 - S\hat{\tau}_2 S^T) d\mu_{\mathrm{Gl}_{\mathbb{R}}(2N)}(S) = \delta(\hat{\tau}_2 - S\hat{\tau}_2 S^T) dS$$

$$C^{(i)} = \frac{1}{2}\begin{bmatrix} 2\langle\Psi|q_i q_j|\Psi\rangle & \langle\Psi|q_i p_i + p_i q_i|\Psi\rangle \\ \langle\Psi|q_i p_i + p_i q_i|\psi\rangle & 2\langle\Psi|p_i p_i|\Psi\rangle \end{bmatrix}$$

Then one finds […] the distribution of the off-diagonal blocks

$$\rho(C^{(12)}|\widehat{C}) = \frac{1}{\pi^2}\frac{\exp\left(\alpha\,\mathrm{Tr}\left[\tau_2 C^{(12)}\tau_2 (C^{(12)})^T\right] - \beta\,\mathrm{Tr}\left[G^{(1)}C^{(12)}G^{(2)}(C^{(12)})^T\right]\right)}{\sqrt{\beta[G^{(1)}\otimes G^{(2)} + (G^{(1)})^T\otimes(G^{(2)})^T]/2 - \alpha\tau_2\otimes\tau_2}}.$$

$$G^{(i)} = (\tau_2 + C^{(i)})^{-1}$$

$$\alpha = \sum_{i=3}^{N}\frac{\mu_i^2(\mu_i^2-1)}{(\mu_i^2\mu_1^2-1)(\mu_i^2\mu_2^2-1)} \quad \text{and} \quad \beta = \sum_{i=3}^{N}\frac{(\mu_i^2-1)[\mu_i^2(\mu_1^2+\mu_2^2-2)+\mu_i^2-1]}{(\mu_i^2\mu_1^2-1)(\mu_i^2\mu_2^2-1)}.$$

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Random-Gaussian-Hawking

When applying the previous to Hawking radiation one has to recall (or learn) that Hawking's theory is built on wave packets of a certain width $\Delta\omega$. To this corresponds a time $\Delta t = \frac{1}{\Delta\omega}$ which must be shorter than the black hole time scale. Mode index $i = (n, j)$ is hence split into n denoting the time, and j which counts the spectral band. A convenient choice:

$$\Delta\omega_n = \mathcal{O}\left[\frac{2\pi}{t_{\rm P}}\left(\frac{m_{\rm P}}{M(\bar{t}_n)}\right)^2\right]$$

It then turns out that the coefficients in the Gaussian distribution for the off-diagonal correlation blocks are large, except for the first bands (lowest frequency modes).

It hence seems that Hawking radiation is *very unlikely* to be in a global pure Gaussian state (NB, but this induced measure).

Questions and speculations.

EA, Michał Eckstein & Paweł Horodecki, *Found. Phys.* **51**:54 (2021)

EA [arXiv:2206.11870]

J. Bekenstein, Phys.Rev. D 9, 3292, (1974)
V. Mukhanov, Pis. Eksp. Teor. Fiz. 44, 50 (1986)
J. Bekenstein & V. Mukhanov, Phys. Lett. B360 7-12 (1995)
V. Mukhanov, in *Jacob Bekenstein* (2018) [arXiv:1810.03525]

Temperature to entropy

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In thermodynamics temperature is the partial derivative of entropy with respect to energy. The energy of a black hole as seen from far away is its mass $\cdot\, c^2$. Hence (for a Schwarzschild black hole)

$$\frac{1}{k_B T_H} = \frac{\partial S_{BH}}{c^2 \partial M} \quad \Longrightarrow \quad S_{BH} = 4\pi k_B \cdot \left(\frac{M}{m_P}\right)^2$$

This entropy function is convex. The canonical ensemble does not exist at any temperature (at least not without precaution)

$$\forall T\colon\, Z_{BM}(T) = \int_0^\infty e^{-\frac{Mc^2}{k_B T}} e^{S_{BH}(M)} dM = \infty$$

The black hole could be in a microcanonical state (fixed mass). Hawking temperature would then have to be microcanonical.

Quantum black holes?

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Bekenstein and Mukhanov introduced toy models of quantum black holes where for a Scharzschild black hole state $|n\rangle$ has mass $m_P C\sqrt{n}$ and degeneracy 2^{n-1}. The constant C is chosen such that area of the black hole horizon is quantized in units of l_P^2 $\left(C = \sqrt{\ln 2/4\pi}\right)$. These models also have no canonical distribution:

$$\forall T\colon\ Z_{BM}(T) = \sum_{n=1}^{\infty} e^{-\frac{m_P c^2}{k_B T} C\sqrt{n}} 2^{n-1} = \infty$$

One interesting feature of these models is that such black holes do not radiate at long wavelengths. Hence their Hawking radiation could be in a global pure Gaussian state. Plus, question for mathematical physicists: Do there exist positive Hermitian operators on some space with density of states growing exponentially-quadratically with energy?

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A basic mystery

(you can get all numbers from Google)

Entropy of a star of the size of the sun: $10^{35} \frac{\mathrm{J}}{\mathrm{K}}$

Entropy of a black hole of solar mass: $10^{54} \frac{\mathrm{J}}{\mathrm{K}}$

$$S = \log \mathcal{N}?$$

Which phase space volume $\mathcal{N}$ can increase by a factor 10^{19} in a collapse to a black hole?

BH entropy grows quadratically with mass. More than 99.99999% of the entropy in the universe today has been estimated to be S_{BH} of black holes in the center of galaxies.

Egan & Lineweaver, "A larger estimate of the entropy of the universe", Astrophys. J. 710:1825 (2010)

What is the $\mathcal{N}$ opened by a gravitational collapse?

Open are the double doors of the horizon
Unlocked are its bolts

Akhnaten, Act I, Scene I

Pyramid of Unas (d. c. 2345 BC)
Wikipedia / Jon Bodsworth

What is a paradox?

(using philosophy as a device to finish this talk)

A tenet contrary to received opinion; an assertion contrary to appearance; a position in appearance absurd.

Samuel Johnson, *Dictionary*

Sometimes it happens, that as we are deceived in the position of terms, so also deception arises as to opinions…

Aristotle, *Prior Analytics* B:21

A slightly later passage adapted to the topic treated today

By universal knowledge [*quantum mechanics*] then we observe particulars [*quantum black holes*], but we do not know them by peculiar knowledge [*an accepted and tested theory of quantum gravity*], hence we may be deceived by them…

Aristotle, *idem*

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Thanks

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Don Page for very
useful comments

Vetenskapsrådet

KTH VETENSKAP OCH KONST
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Gravitational chaos?

Homogeneous cosmology has an instability called Belinski–Khalatnikov–Lifshitz (BKL). The gravitational field then oscillates chaotically. The literature is not conclusive, but there are at least some who claim that a similar process happens in inhomogeneous collapse.

cf.
V. A. Belinskii, *Pisma v Zhurnal Eksperimentalnoi i Teoreticheskoi Fiziki* **56**:437 (1992)
L. Andersson et al *Phys. Rev. Lett*. **94:**051101 (2005)

There is hence a mechanism for generating information in a collapse to a black hole which does not exist in collapse to a neutron star. This produces extra entropy.

E.A. arXiv:2206.11870

However, unclear why that entropy should be S_{BM} and the same for every black hole with the same mass, charge and angular momentum.

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Entangled entanglement and information return

Hilbert space $\mathcal{H}_M \otimes \mathcal{H}_{BH} \otimes \mathcal{H}_{HR}$ (matter-black hole-Hawking rad.)

i. Initially $|\Psi\rangle_{in} = |\psi_{in}\rangle_M \otimes |0\rangle_{BH} \otimes |0\rangle_{HR}$

0. After matter collapse $|\Psi^{(0)}\rangle = \sum_i a_i \left|\psi_i^{(0)}\right\rangle_M \otimes \left|\chi_i^{(0)}\right\rangle_{BH} \otimes |0\rangle_{HR}$

1. When a Hawking particle is emitted at the horizon it is entangled with its partner which falls into the black hole region, and the combined state will be $|\Psi^{(1)}\rangle = \sum_{i,j} c_{i,j} \left|\psi_i^{(1)}\right\rangle_M \otimes \left|\chi_i^{(1)}\right\rangle_{BH} \otimes \left|\phi_j^{(1)}\right\rangle_{HR}$.

2. Ditto $|\Psi^{(2)}\rangle = \sum_{i,j,k} d_{i,j,k} \left|\psi_i^{(2)}\right\rangle_M \otimes \left|\chi_i^{(2)}\right\rangle_{BH} \otimes \left|\phi_j^{(1)}\right\rangle_{HR} \otimes \left|\phi_k^{(2)}\right\rangle_{HR}$

f. $|\Psi^f\rangle = \sum_{i,\boldsymbol{k}} e_{i,\boldsymbol{k}} \left|\psi_i^{(f)}\right\rangle_M \otimes |0\rangle_{BH} \otimes \left|\phi_{k_1}^{(1)}\right\rangle_{HR} \otimes \left|\phi_{k_2}^{(2)}\right\rangle_{HR} \otimes \cdots \otimes \left|\phi_{k_N}^{(N)}\right\rangle_{HR}$

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Quantum version of "awakening of gravity"

$$|\psi\rangle_{init} = \left(\sum b_i |S\rangle_i |A\rangle_i\right) \otimes |G\rangle$$

Initial state of a star and an ancilla and a pure quantum gravity state. *e.g.* gravitational vacuum

$$|\psi\rangle_{final} = \sum b_i' |A\rangle_i \left(\sum c_i^k |B\rangle_k |G\rangle_k\right)$$

Final state of black hole + gravitation with the ancilla

This is an "entangled entanglement" state [Krenn & Zeilinger, *Phys Rev A* 54;1793:263 (1996); Walther, Resch, Brukner & Zeilinger, *Phys*. *Rev. Lett*. **97**:020501 (2006)].

Internal B-G entanglement can be much greater than the one between the joint system B+G and rest of the Universe represented by ancilla.

Re sub-additivity

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$$S = \left(1+\frac{b}{2}\right)\log\left(1+\frac{b}{2}\right) - \frac{b}{2}\log\frac{b}{2} \equiv f(b)$$

$$b_n \leq \sum_{m\neq n} b_m$$ is hence on entropies $$S_n \leq f\left[\sum_{m\neq n} f^{-1}(S_m)\right]$$

This is much stronger than the bound from sub-additivity $$S_n \leq \sum_{m\neq n} S_m$$

This bounds from Gaussian quantum marginal problem hence give something qualitatively new.

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caveats

NB, not everyone agrees that a very large number $\mathcal{N}$ of physical degrees of freedom must be opened up to the universe in a gravitational collapse. For an opposite point of view, see e.g. Hossenfelder & Smolin, *Phys. Rev. D* **81:**064009 (2010).

From the point of view of statistical physics, Smolin & Hosselfelder's is a subjective interpretation. Hence, if "…thermodynamics is the only physical theory that will never be over-turned…", there has to be an $\mathcal{N}$.

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Motivation and outline

Entropy is a concept of statistical physics. It is not simple. Perhaps a non-black-hole expert can contribute to black hole physics from this perspective. At least, a renewed sense of mystery.

Thermal marginals vs global pure states.

EA, Michał Eckstein & Paweł Horodecki, *JCAP* 2022 (01), 014

Loose ends, and a conjecture.

EA, Michał Eckstein & Paweł Horodecki, *Found. Phys.* **51**:54 (2021)
EA [arXiv:2206.11870]

Bekenstein reviewed this question in 2008

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Bekenstein-Hawking entropy

Jacob D. Bekenstein (2008), Scholarpedia, 3(10):7375. doi:10.4249/scholarpedia.7375

- **Jacob D. Bekenstein**, Racah Institute of Physics, The Hebrew University of Jerusalem, Jerusalem, Israel

One should start by going through the explanations Bekenstein surveyed. I will enumerate them as Bekenstein did, but group them in a different order.

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(1/3) explanations that depend on new physics

4. Black hole entropy is a conserved quantity connected with coordinate invariance of the gravitational action.

6. Black hole entropy counts the number of states or excitations of a fundamental string.

7. Black hole entropy is equivalent to the thermal entropy of the radiation residing on the boundary of the spacetime containing the black hole.

The first of these (no. 4) is by Wald, something in the same direction was proposed by Penrose. No. 6 is a theory of quantum gravity as a limit of another theory. All three suppose physics beyond quantum field theory in curved space-time.

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(2/3) explanations which focus on the horizon

2. Black hole entropy is the entropy of entanglement between degrees of freedom inside and outside the horizon.

3. Black hole entropy counts the number of horizon gravitational states.

5. Black hole entropy is thermal entropy of the gas of quanta constituting the thermal atmosphere of the black hole.

No. 2 implies the question why there is no such large entropy for an arbitrary closed surface. Explanations of this type are possibly also verifiable/falsifiable in future observations on astrophysical black holes and their surroundings.

(3/3) an explanation which faces the question

1. Black hole entropy counts the number of internal states of matter and gravity.

Bekenstein's extended explanation however doesn't mention $\mathcal{N}$:

> As mentioned earlier, the perception that a particular black hole (specific M, J and Q) can be formed in many ways originally suggested the notion of black hole entropy; in this approach the internal states of matter and/or gravity are the sought for microstates. Examples of this viewpoint are provided by Frolov and Novikov (1993) and by Mukhanov (2003).

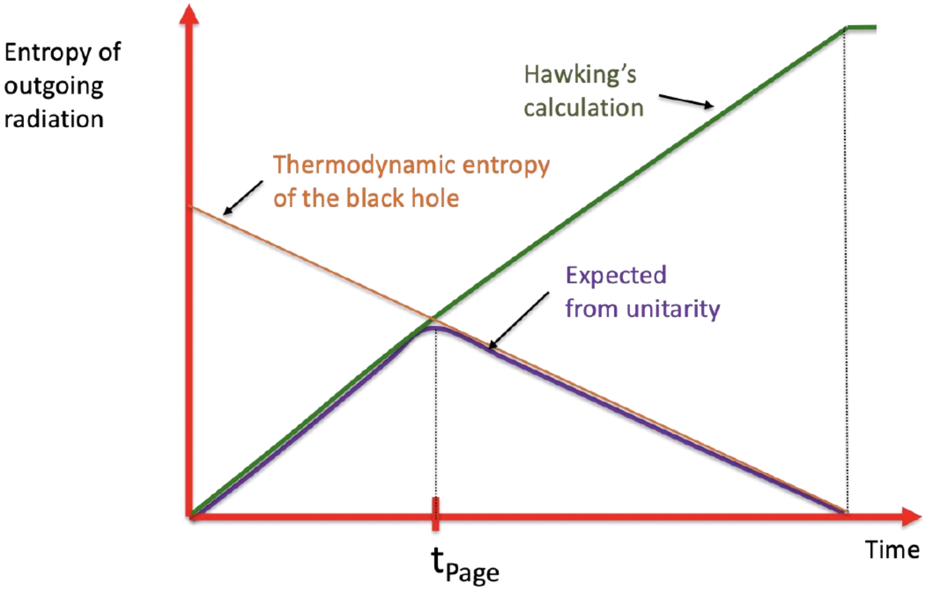
The arguments of Frolov and Novikov (1993) and Mukhanov (2003) count the possible initial states of the matter that went down the black hole. There are many for the same black hole. First such estimate: Bekenstein in *Phys. Rev. D* **7**:2333 (1973).

Two kinds of entropy

1. *Information-theoretic entropy (“fine-grained entropy”)* does not change under unitary evolution.

2. *Thermodynamic entropy (“coarse-grained entropy”)*. tends to a maximum given external constraints.

Suppose initially a pure state black hole. It has zero entropy. The final Hawking radiation after evaporation must then also have zero information-theoretic entropy. This leads to constraints usually called the “Page curve”.



Don Page. Phys Rev Lett 71:3743 (1993); figure from A. Almheiri et al., arXiv:2006.06872

Is BH entropy then a thermodynamic entropy?

Argument 1: The entropy of Hawking radiation was computed by Zurek in 1982 from classical thermodynamics. The answer is $\frac{4}{3}S_{BH}$; a more detailed calculation was later done by Page. The factor $\frac{4}{3}$ can be attributed to evaporation being an irreversible process. Going backwards, S_{BH} should also be a thermodynamic entropy.

Argument 2: The (ordinary) entropy of a star is so much less than black hole entropy. The von Neumann entropy (Shannon entropy) of all the matter and fields in the star region cannot reasonably increase by a factor about 10^{20} in a gravitational collapse.

Argument 3: A late paper by Hawking can be interpreted this way.

S. Hawking "Information Preservation and Weather Forecasting for Black Holes", [arXiv:1401.5761]

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Two views of thermodynamic entropy

Entropy as ignorance (Jaynes, Mandelbrot,…). “*The subjective interpretation of thermodynamics*”. The black hole is classically characterized by mass, electric charge and angular momentum. All other information was lost in the collapse. Such a black hole entropy as ignorance was estimated by Bekenstein and others *op cit*.

Entropy of ensemble (Boltzmann, Khinchin, Lebowitz, Vulpiani,…). “*The objective interpretation of thermodynamics*”. The ensembles of equilibrium statistical mechanics describe the distribution of outcomes of reasonably simple experiments that can in principle be done on a high-dimensional system. This second view is the dominant one in modern statistical mechanics.

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Open problems black holes and marginal states

Mathematics: a total pure state which has Hawking one-mode marginals require multi-mode quantum correlations. How large? If everything is Gaussian perhaps one can estimate from random symplectic transformations giving C, constrained by $\mathrm{diag}_2(C)$. Work in progress (EA, Kieburg, Heckl, Horodecki & Jonsson).

Physics: when one Hawking particle is emitted the black hole recoils and moves in opposite direction. This entangles one Hawking particle with all later Hawking particles. Unfortunately it is a rather weak effect [Don Page, 1981]. Are there other such mechanisms. Which ones?

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Earlier use of Gaussian states in the black hole theory.

"Einstein A and B coefficients for a black hole"
Jacob D. Bekenstein &Amnon Meisels
Phys. Rev. D 15, 2775 (1977)